Title: The Hairstyles of Compact Objects

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Abstract: While gravitational waves offer a new, and in many ways clean, view of compact objects, most of what we presently know about these has been obtained by careful study of their messy interactions with surrounding material. I will summarize what we know about a variety of potential gravitational wave sources, how this astrophysical hair has helped to illuminate some of the same questions gravitational wave observations promise to address, and how future observations may begin to relate the gravitational and electromagnetic properties of compact objects.

The Hairstyles of Compact Objects

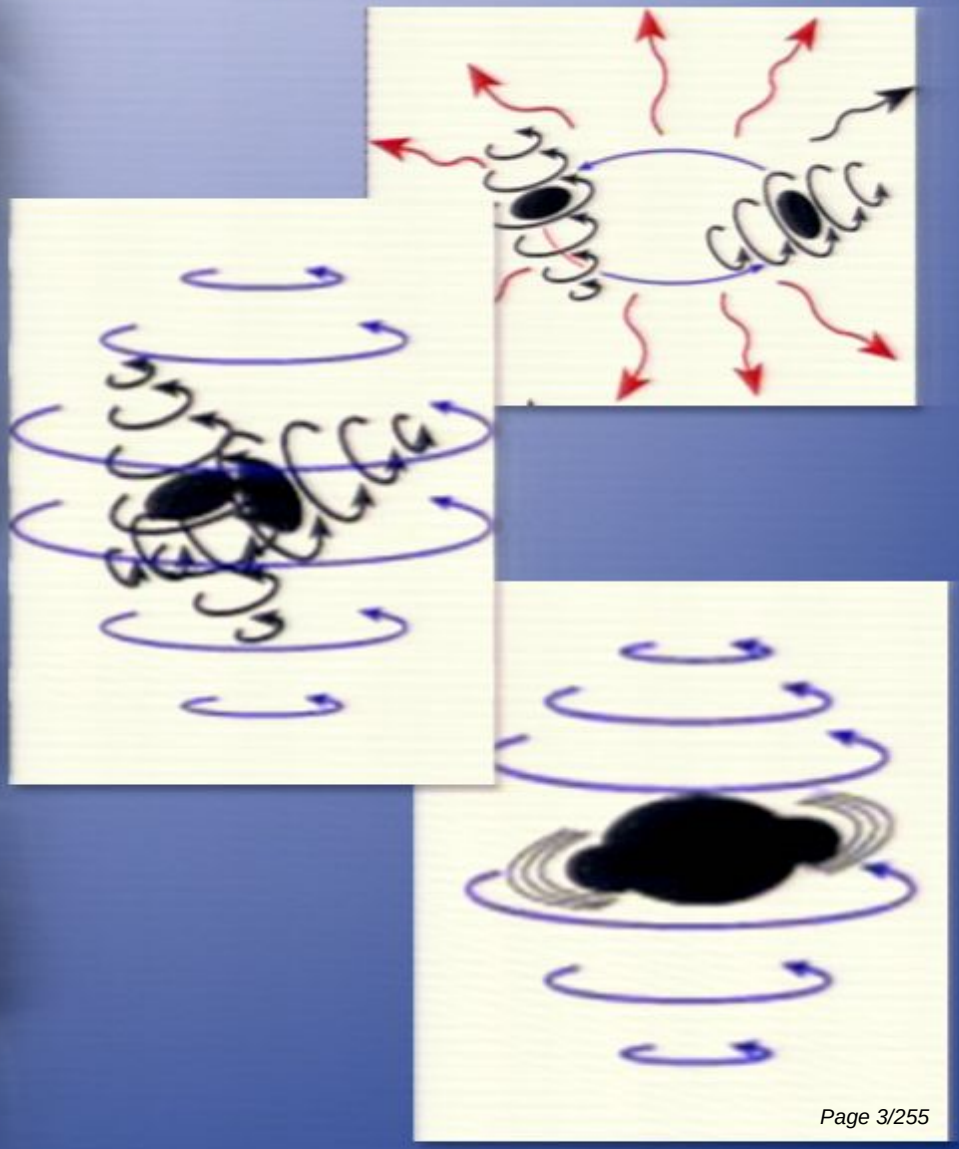
Avery E Broderick

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

Clean vs. Messy Compact Objects

GW view

- Inspiral
- Merger
- Ringdown
- Exotic?



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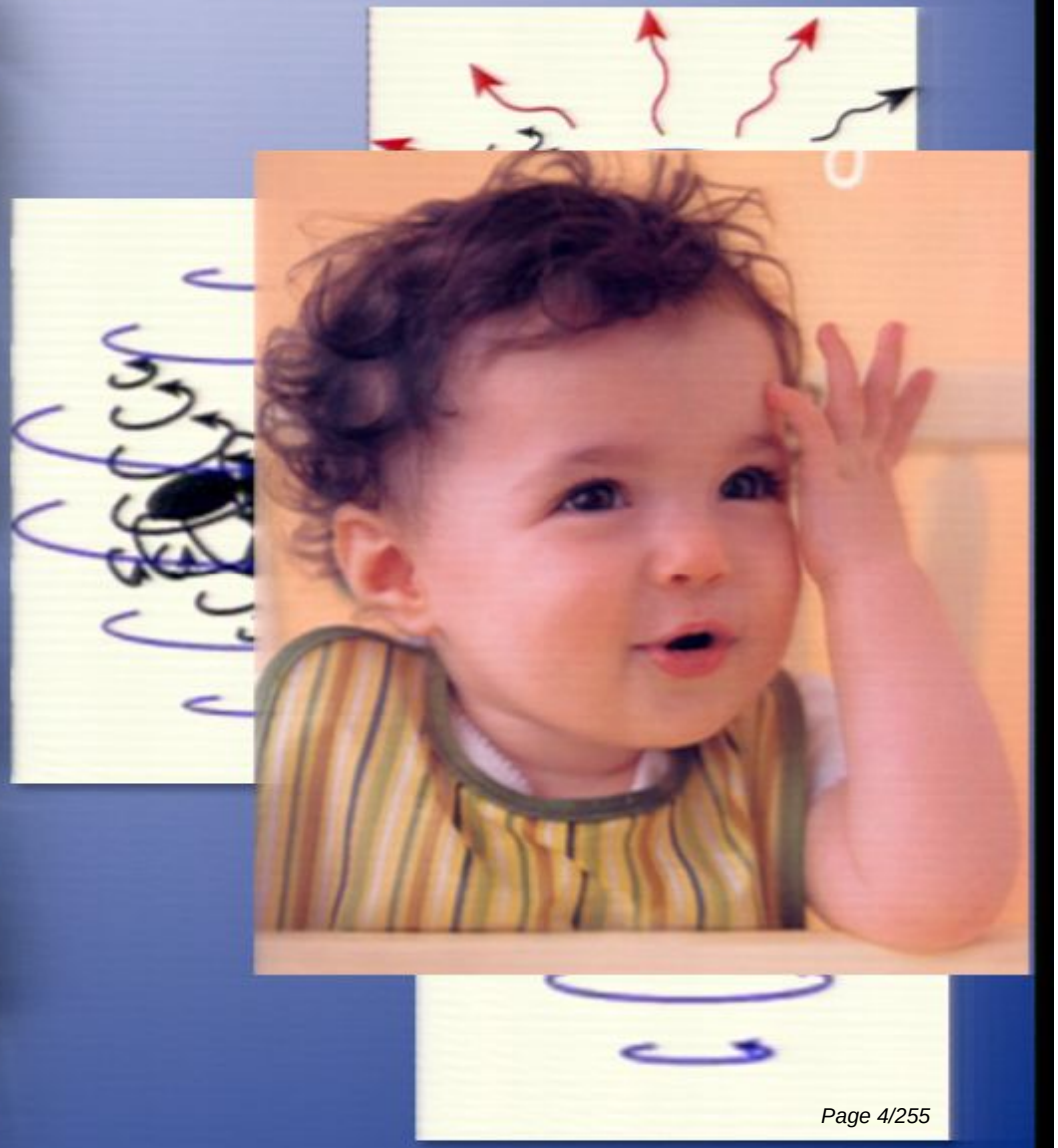

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Present view

- Microlensing
- Jets
- Polarization & polarized variability
- Broad iron lines
- Spectra & Spectral states
- Companion interactions
- QPOs
- Pulsars & sub-pulse structures
- X-ray bursts & superbursts
- Soft-gamma repeaters & giant flares
- Gamma-ray bursts/X-ray flashes
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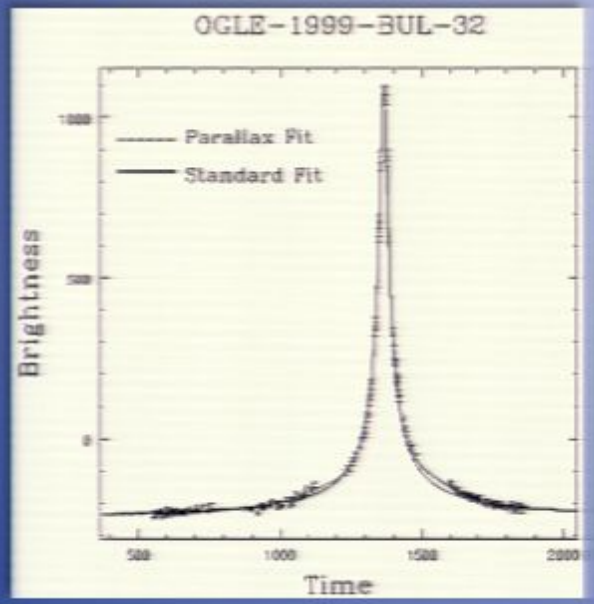

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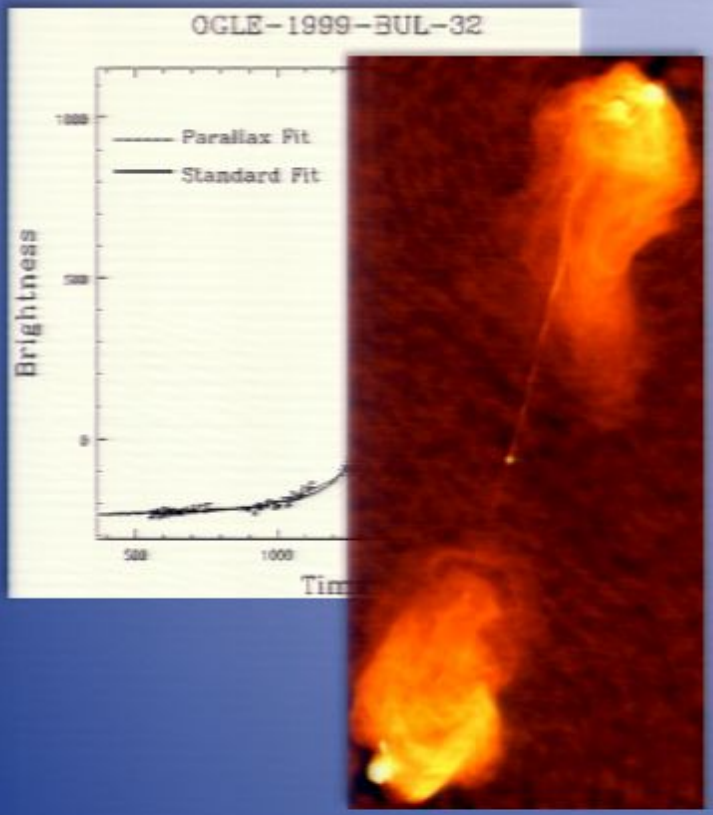

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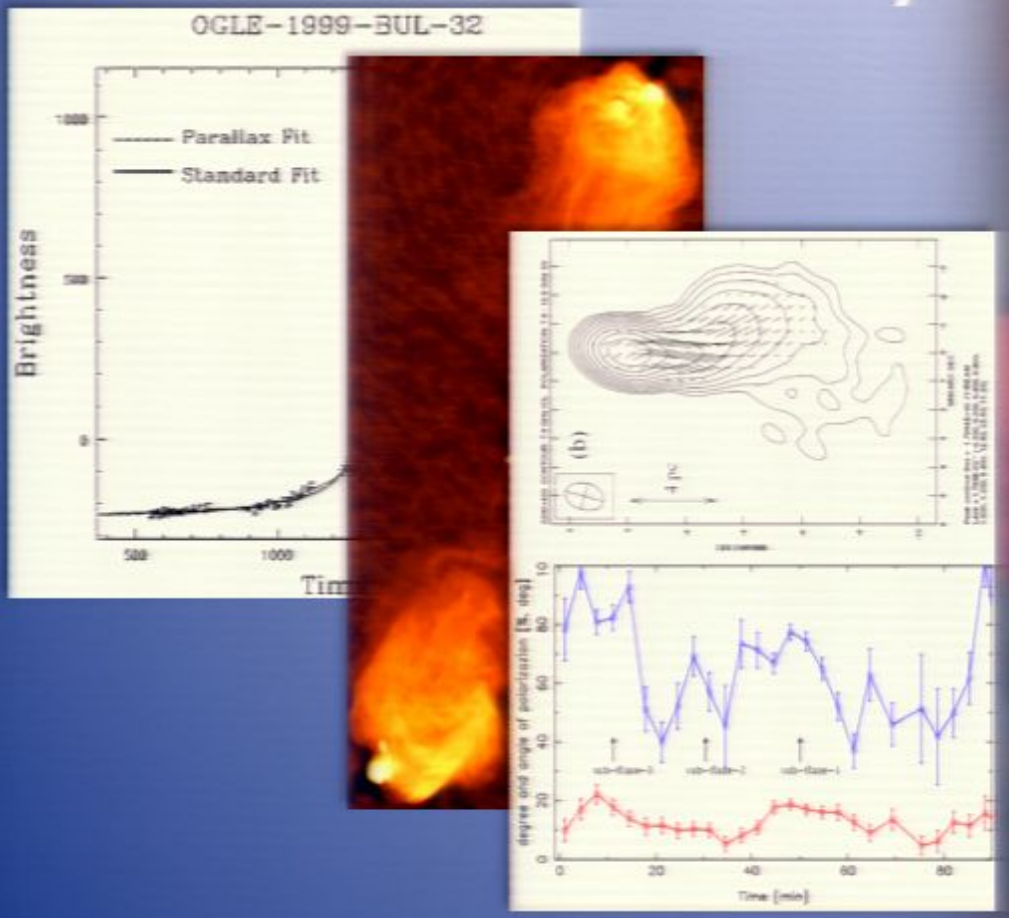

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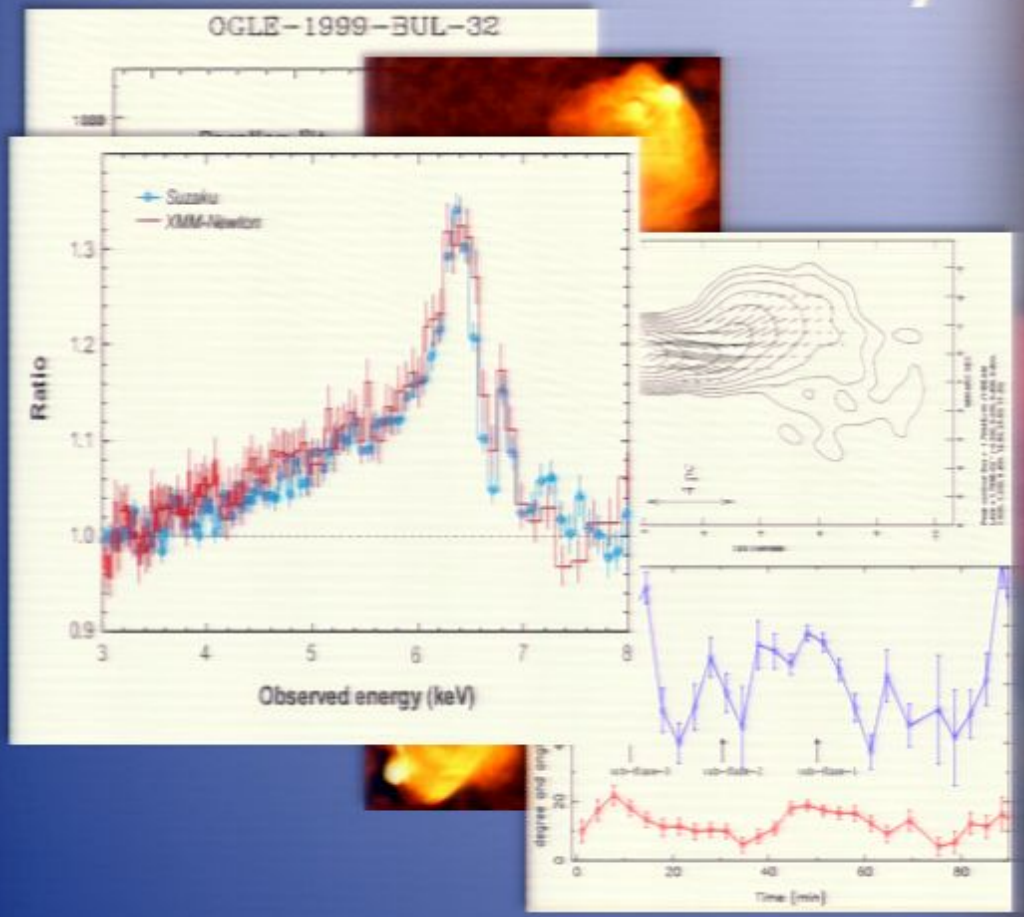

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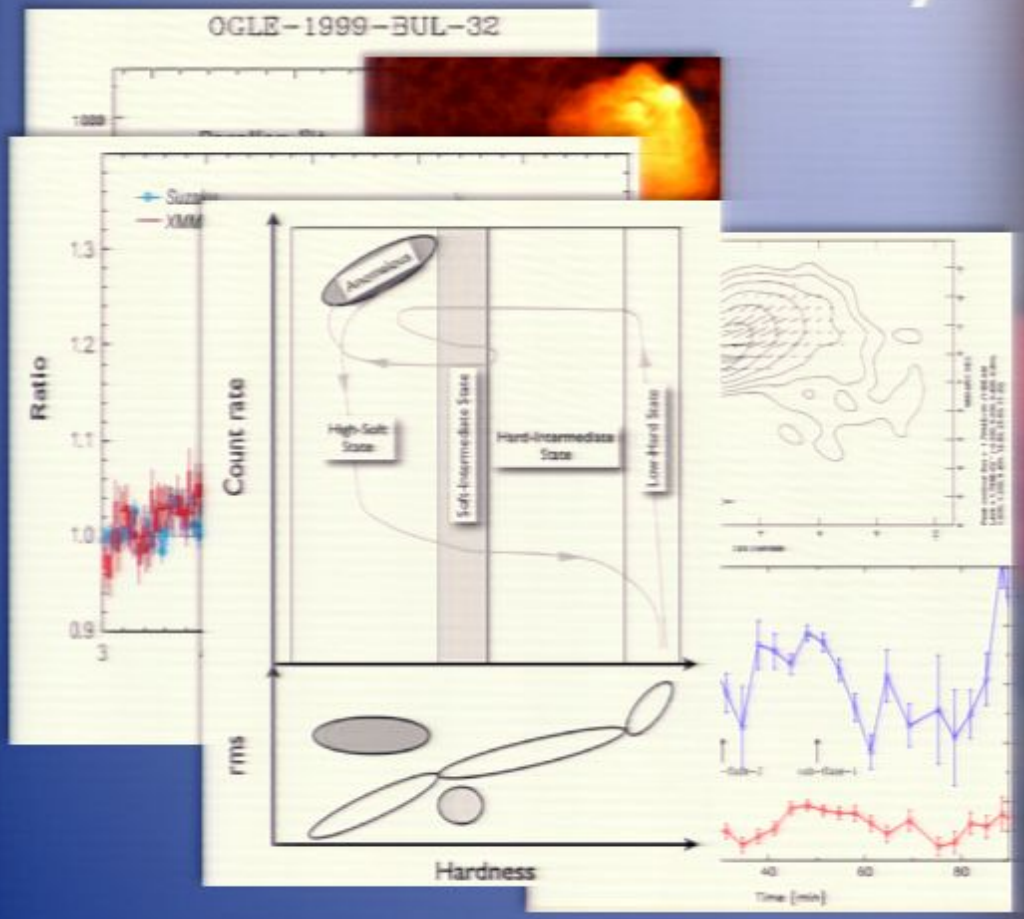

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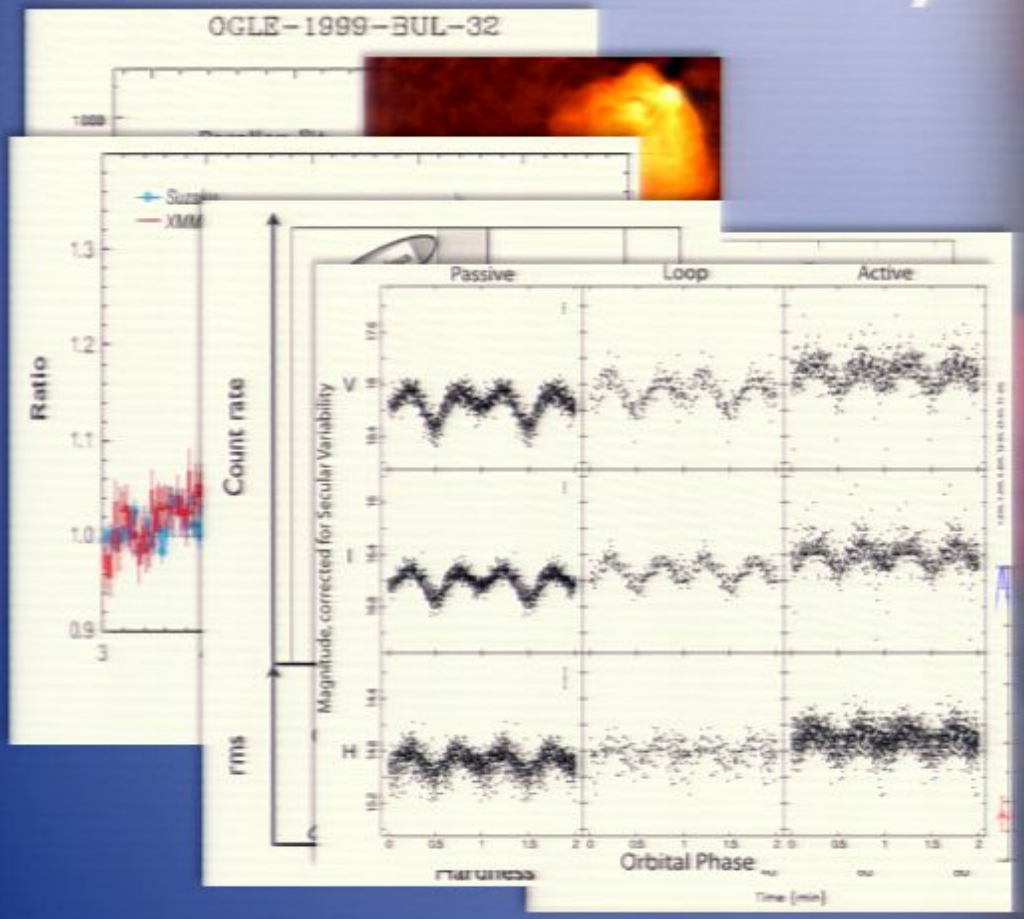

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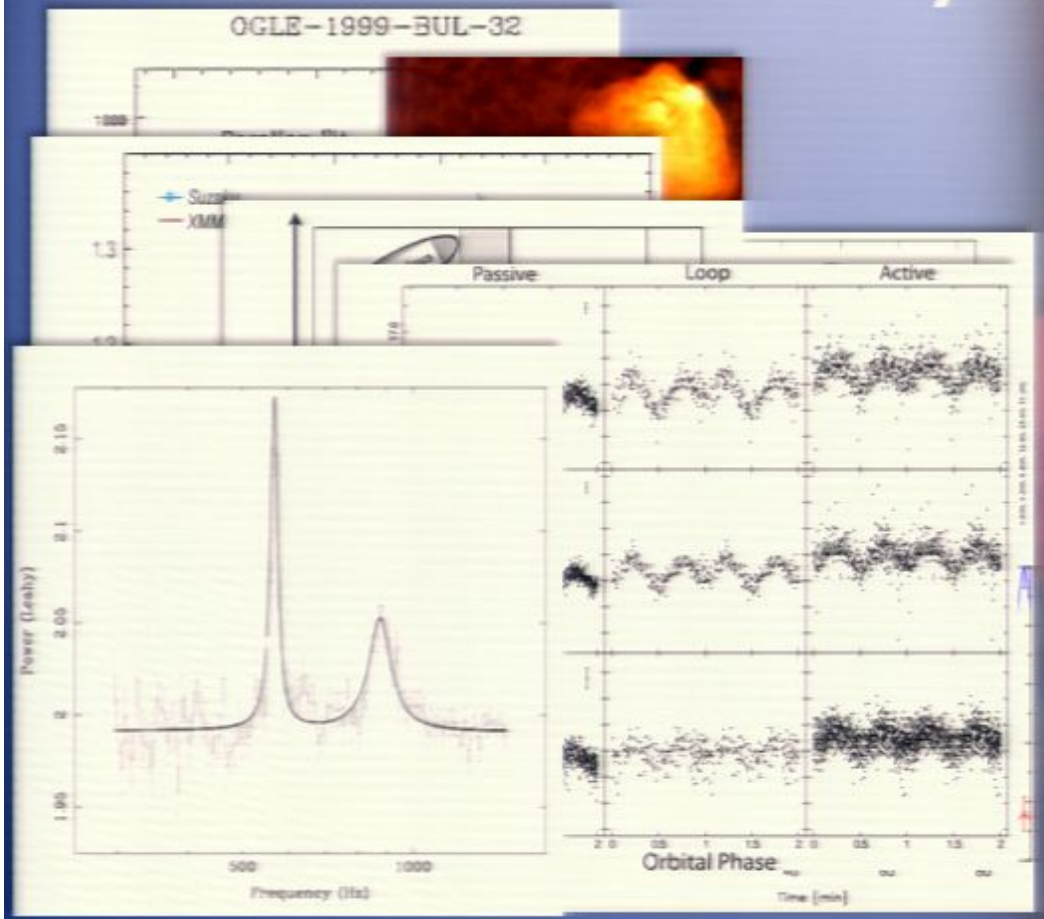

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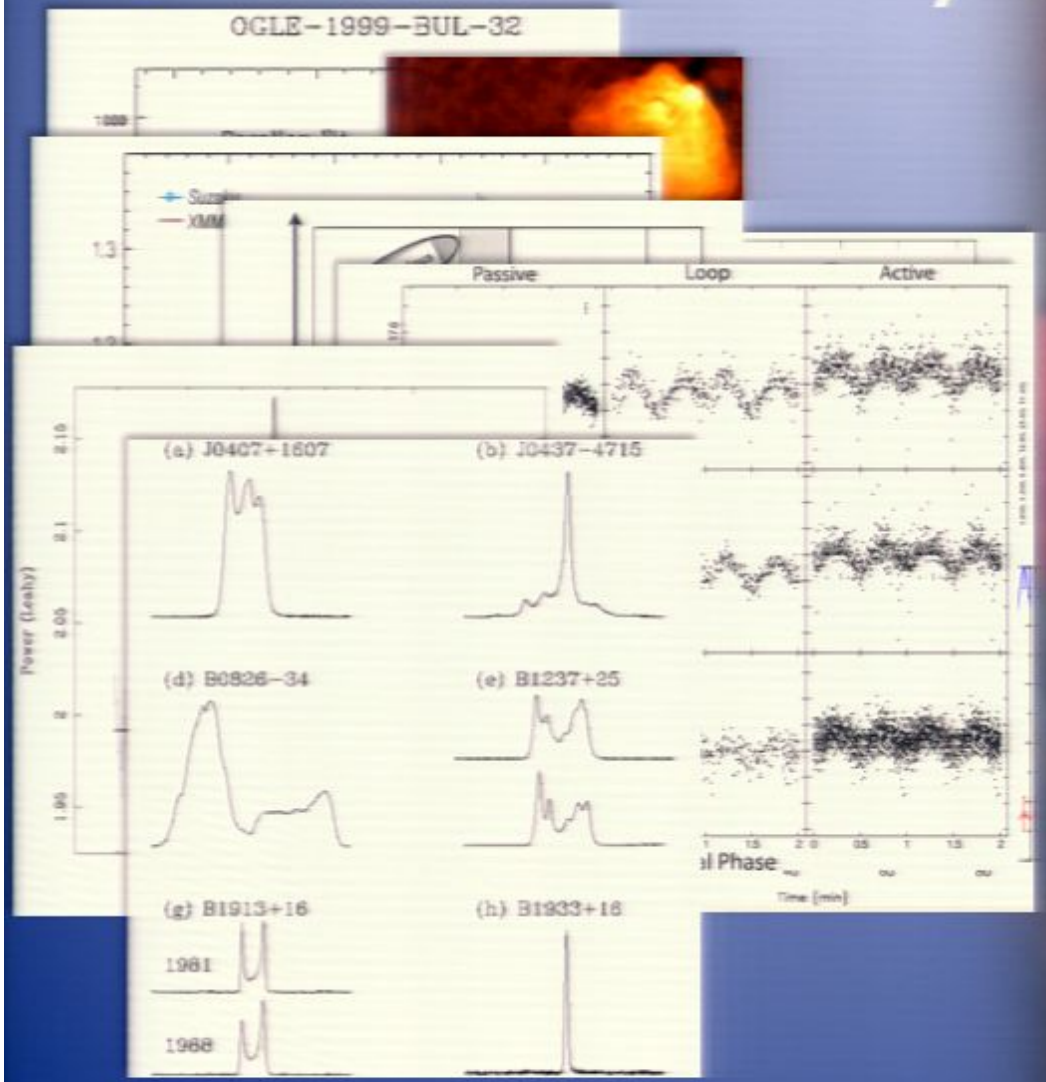

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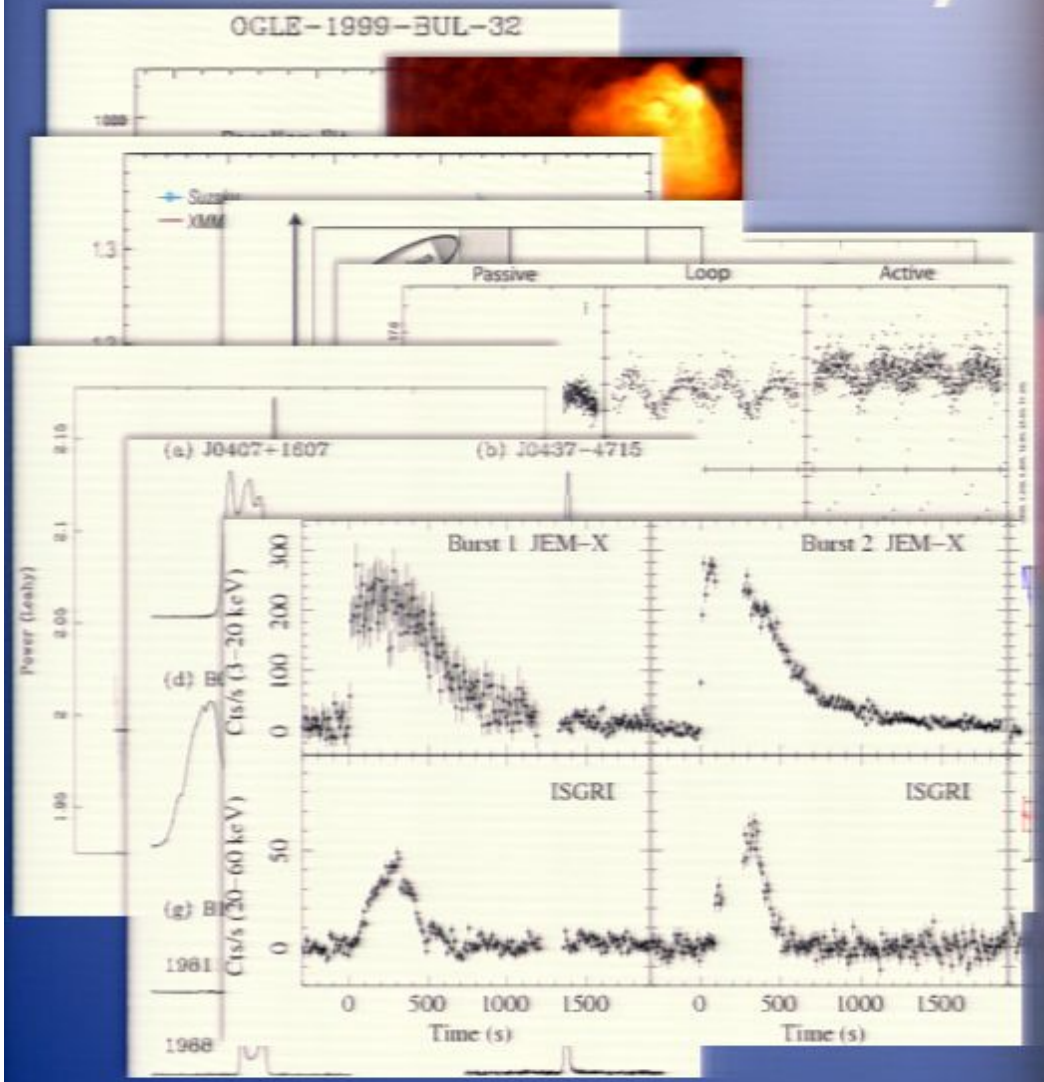

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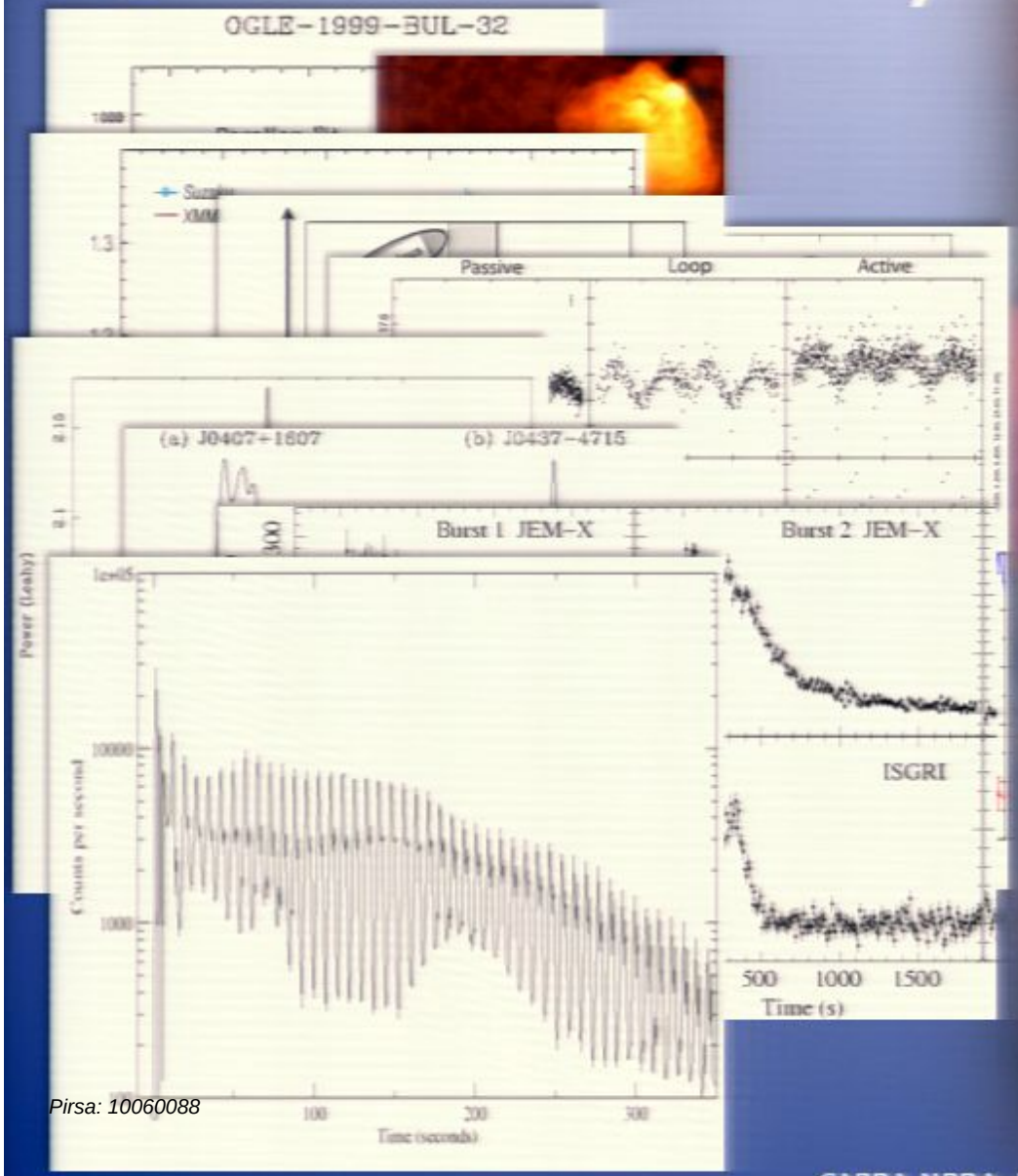

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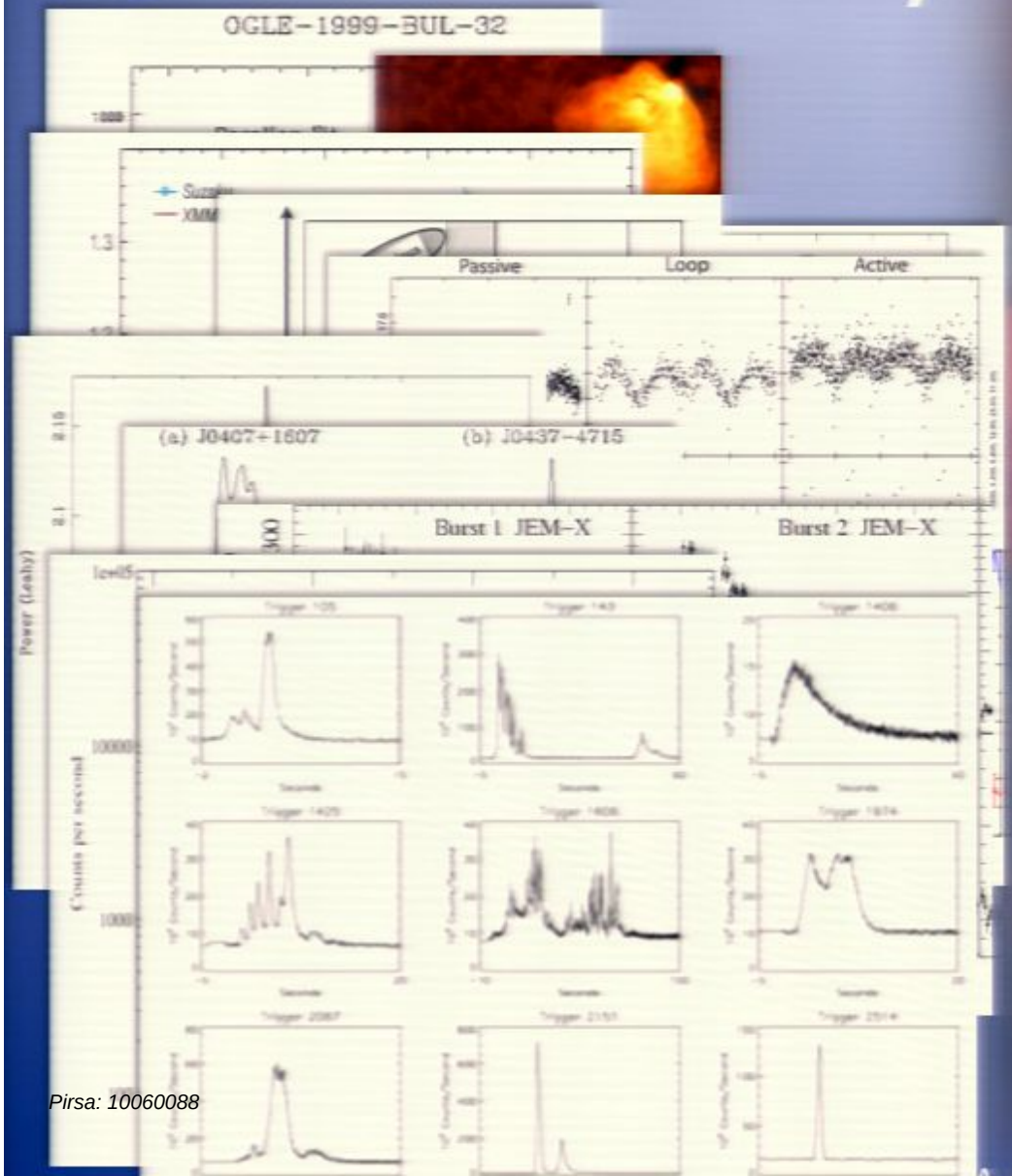

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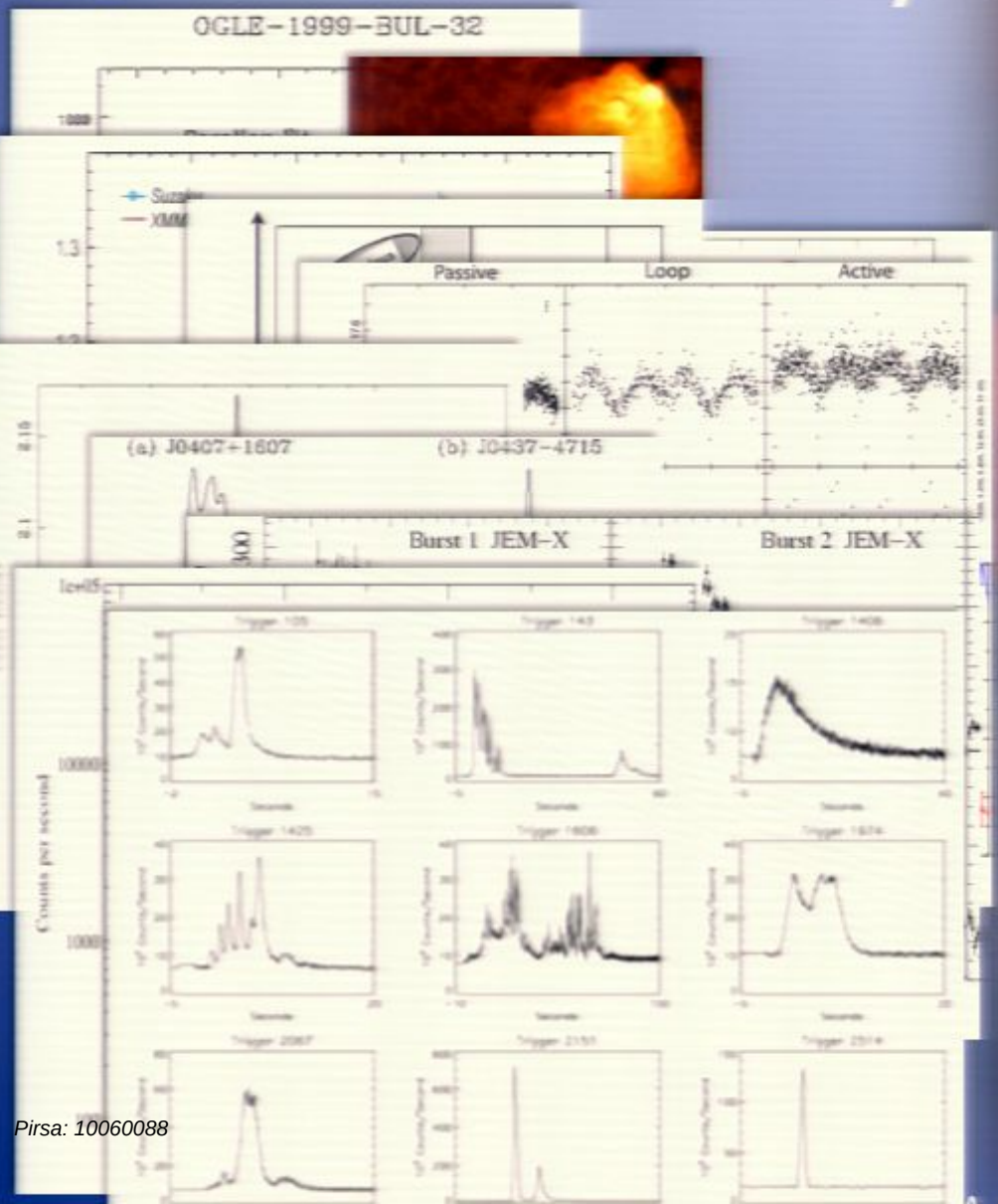

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Rich phenomenology to be mined!

Topics

- Accretion
- Jet formation and implications
- Variability in accreting systems

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- **Accretion**
- **Jet formation and implications**
- **Variability in accreting systems**

- *How does GR critically affect compact object physics?*
- *How can we learn about GR from the dirty observations?*

The Engines of Quasars

690 NATURE, VOL. 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL

Royal Greenwich Observatory, Herstmonceux Castle, Sussex

Powerful emissions from the centres of nearby galaxies may represent dead quasars.

RYLE gives good evidence[1] that quasars evolve into powerful radio sources with two well separated radio components, one on each side of the dead or dying quasar. The energies involved in the total radio outbursts are calculated to be of the order of 10^{60} erg, and the optical variability of some quasars indicates that the outbursts probably originate in a volume no larger than the solar system. Now 10^{61} erg have a mass of 10^{40} g or nearly 10^7 Suns. If this were to come from the conversion of hydrogen into helium, it can only represent the nuclear binding energy, which is 3/400 of the mass of hydrogen involved. Hence 10^9 solar masses would be needed within a volume the size of the solar system, which we take to be 10^{15} cm (10 light h). But the gravitational binding energy of 10^9 solar masses within 10^{15} cm is GM^2/r which is 10^{62} erg. Thus we are wrong to neglect gravity as an equal if not a dominant source of energy. This was suggested by Fowler and Hoyle[2], who at once asked whether the red-shifts can also have a gravitational origin. Greenstein and Schmidt[3], however, earlier showed that this is unlikely because the differential red-shift would wash out the lines. Attempts to avoid this difficulty have looked unconvincing, so I shall adopt the cosmological origin for quasar red-shifts. Even with this hypothesis the numbers of quasar-like objects are very large, or rather they were so in the past. I shall assume that the quasars were common for an initial epoch lasting 10^9 yr, but that each one only remained bright for 10^8 yr, and take Sandage's estimate (quoted in ref. 4) of 10^7 quasar-like objects in the sky down to magnitude 22. This must represent a snapshot of the quasar era, so only one in a thousand would be bright. If these represent all the quasar-like objects that there are, then the density of dead ones should be $10^7 \times 10^9 = 10^{10}$ per [illegible]me. The distance between neighbouring dead [illegible]

which we shall call the Schwarzschild throat. We would be wrong to conclude that such massive objects in space-time should be unobservable, however. It is my thesis that we have been observing them indirectly for many years.

Effects of Collapsed Masses

As Schwarzschild throats are considerable centres of gravitation, we expect to find matter concentrated toward them. We therefore expect that the throats are to be found at the centres of massive aggregates of stars, and the centres of the nuclei of galaxies are the obvious choice. My first prediction is that when the light from the nucleus of a galaxy is predominantly starlight, the mass-to-light ratio of the nucleus should be anomalously large.

We may expect the collapsed bodies to have a broad spectrum of masses. True dead quasars may have 10^{10} or 10^{11} $M_\odot$ while normal galaxies like ours may have only 10^7–10^8 $M_\odot$ down their throats. A simple calculation shows that the last stable circular orbit has a diameter of $12\,GM/c^2 = 12m$ so we shall call the sphere of this diameter the Schwarzschild mouth. Simple calculations on circular orbits yield the following results, where M_7 is the mass of the collapsed body in units of 10^7 $M_\odot$, so that M_7 ranges from 1 to 10^8.

Circular velocity

$$V_c = [GM/(r-2m)]^{1/2} \text{ where } r > 3m \qquad (1)$$

Binding energy of a mass m^* in circular orbit

$$m^*\epsilon = m^*c^2\{1-(r-2m)[r(r-3m)]^{-1/2}\} \qquad (2)$$

Angular momentum of circular orbit per unit mass

$$h = [mc^2 r^2/(r-3m)]^{1/2} \qquad (3)$$

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- Power
- Variability
- Inevitability

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History of "Accretion Power"

*"**That some form of the meteoric theory is certainly the true and complete explanation of solar heat can scarcely be doubted**, when the following reasons are considered: (1) No other natural explanation, except by chemical action, can be conceived. (2) The chemical theory is quite insufficient, because the most energetic chemical action we know, taking place between substances amounting to the whole sun's mass, would only generate about 3,000 years' heat. (3) There is no difficulty in accounting for 20,000,000 years' heat by the meteoric theory."*

Lord Kelvin 1862

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Preston (1878)

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The Age of the Sun's Heat in Relation to Geological Evidence

1. It is an admitted fact that the age of the sun's heat will not harmonise with the evidence of geology, on the supposition that this heat was *solely* derived from the approach of matter under the action of gravity. Dr. James Croll, in dealing with

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COMPARISON OF STELLAR ATMOSPHERE AND EARTH'S CRUST

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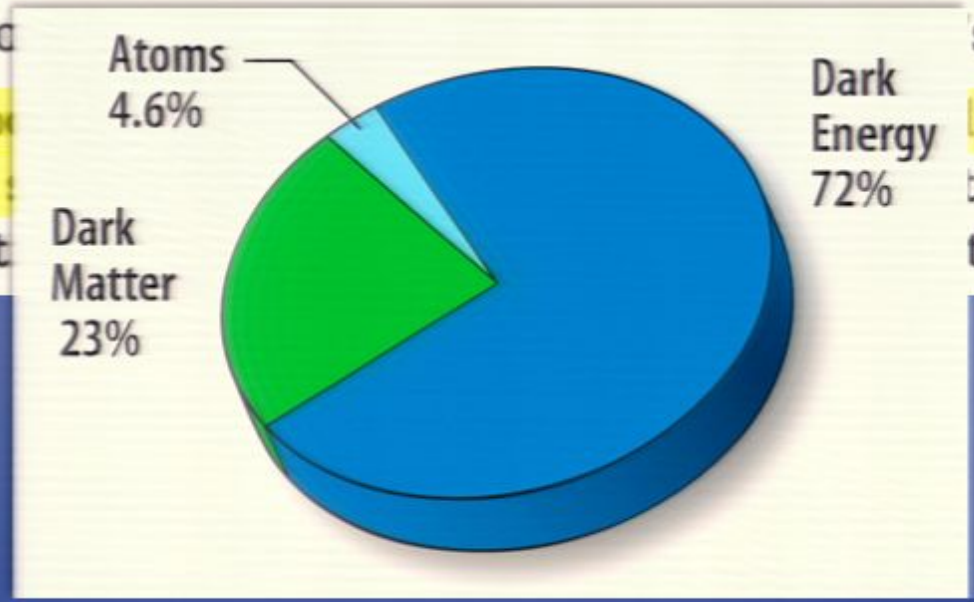

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Accretion onto "Black Holes"

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Source	η_r
Sgr A*	~0.1%
Quasar	~10%
Max in GR	33%

Accretion onto "Stars"

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$$L_{obs} = \eta_r \Delta\varepsilon_g \dot{M} c^2$$

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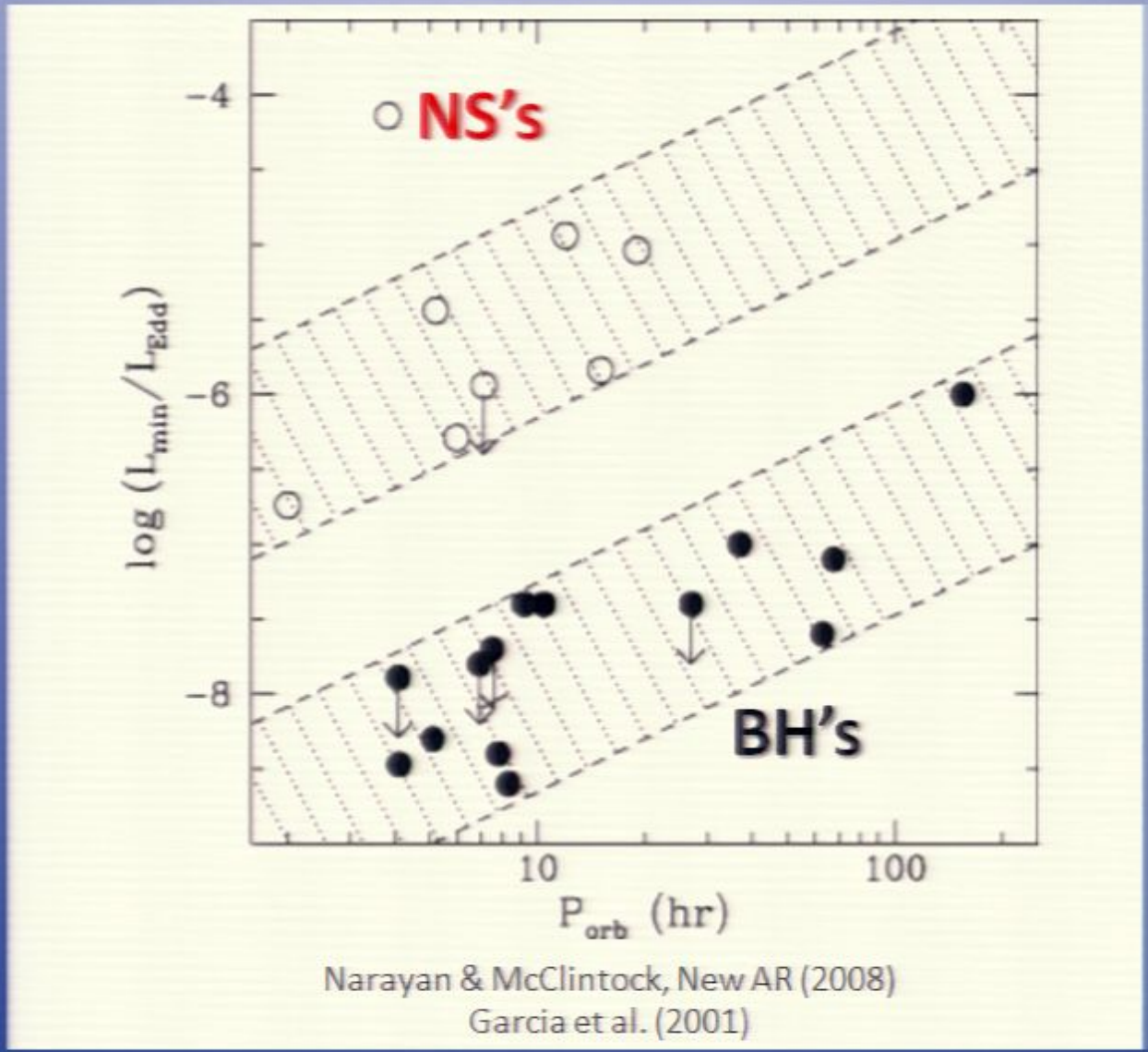
$$\geq \frac{1 - \eta_r - \eta_k}{\eta_r + \eta_k} L_{obs}$$

Accretion

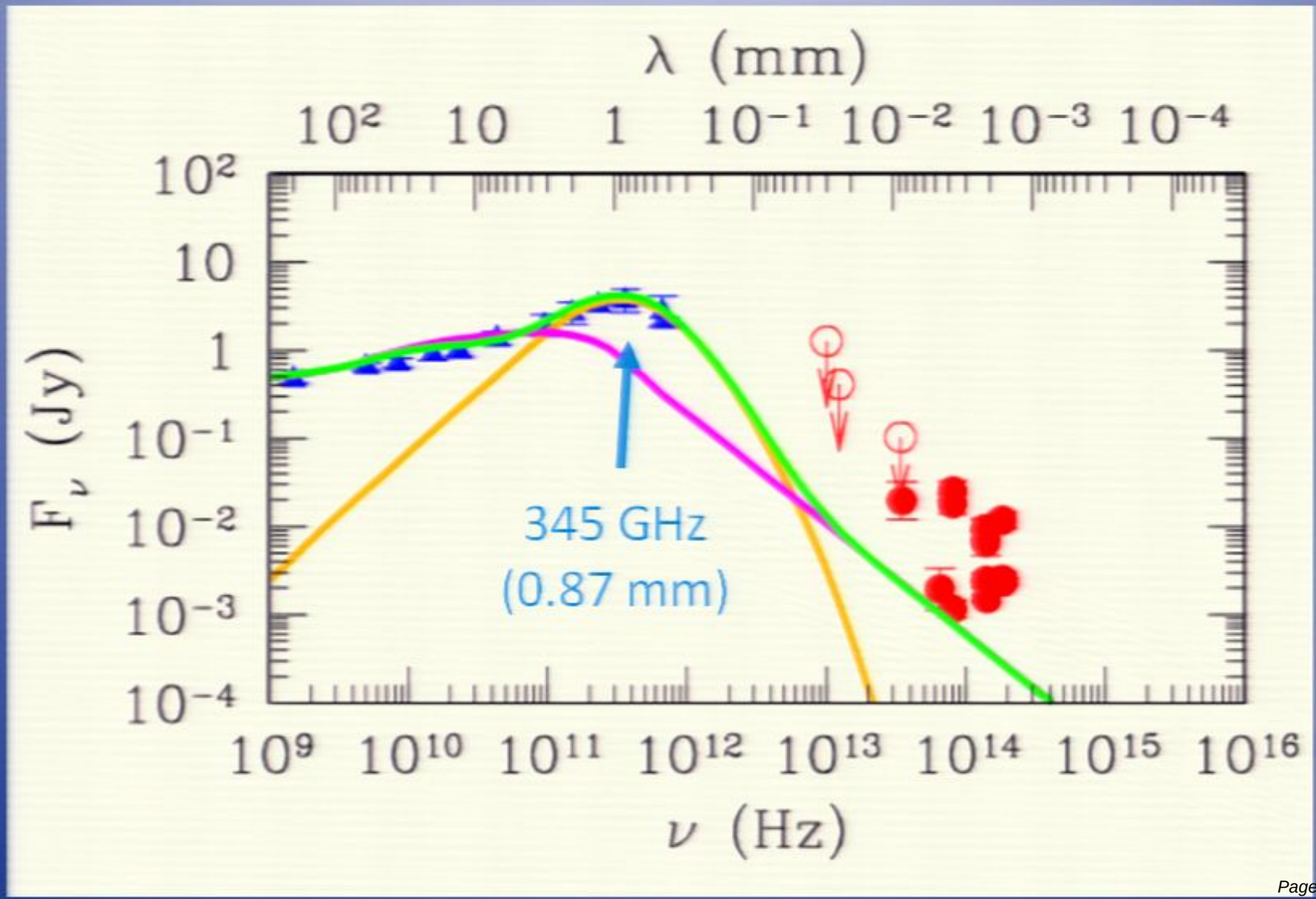
"Black Holes" vs. Neutron Stars



Narayan & McClintock, New AR (2008)
Garcia et al. (2001)

Accretion

Is Sagittarius A* a "Black Hole"?



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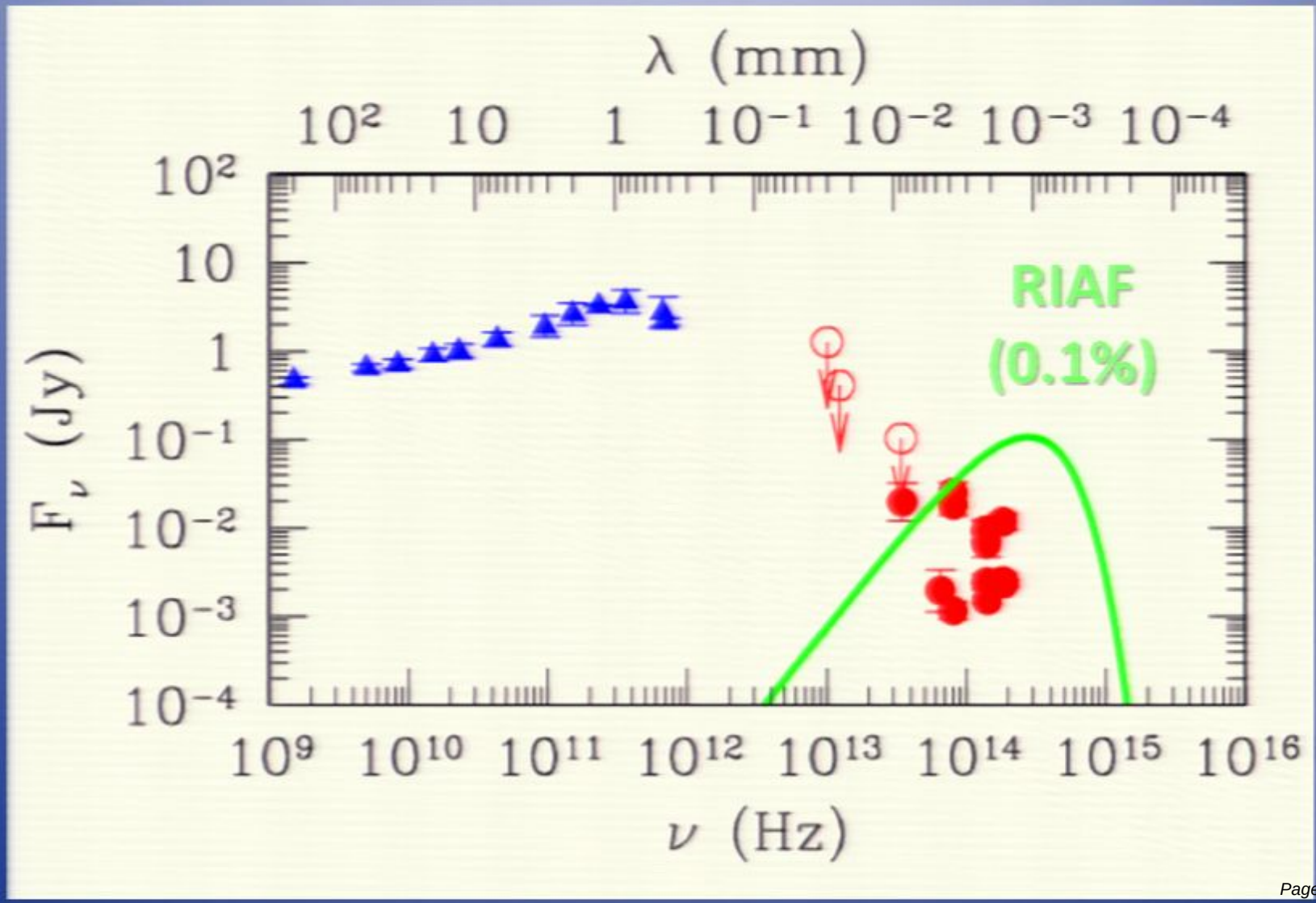

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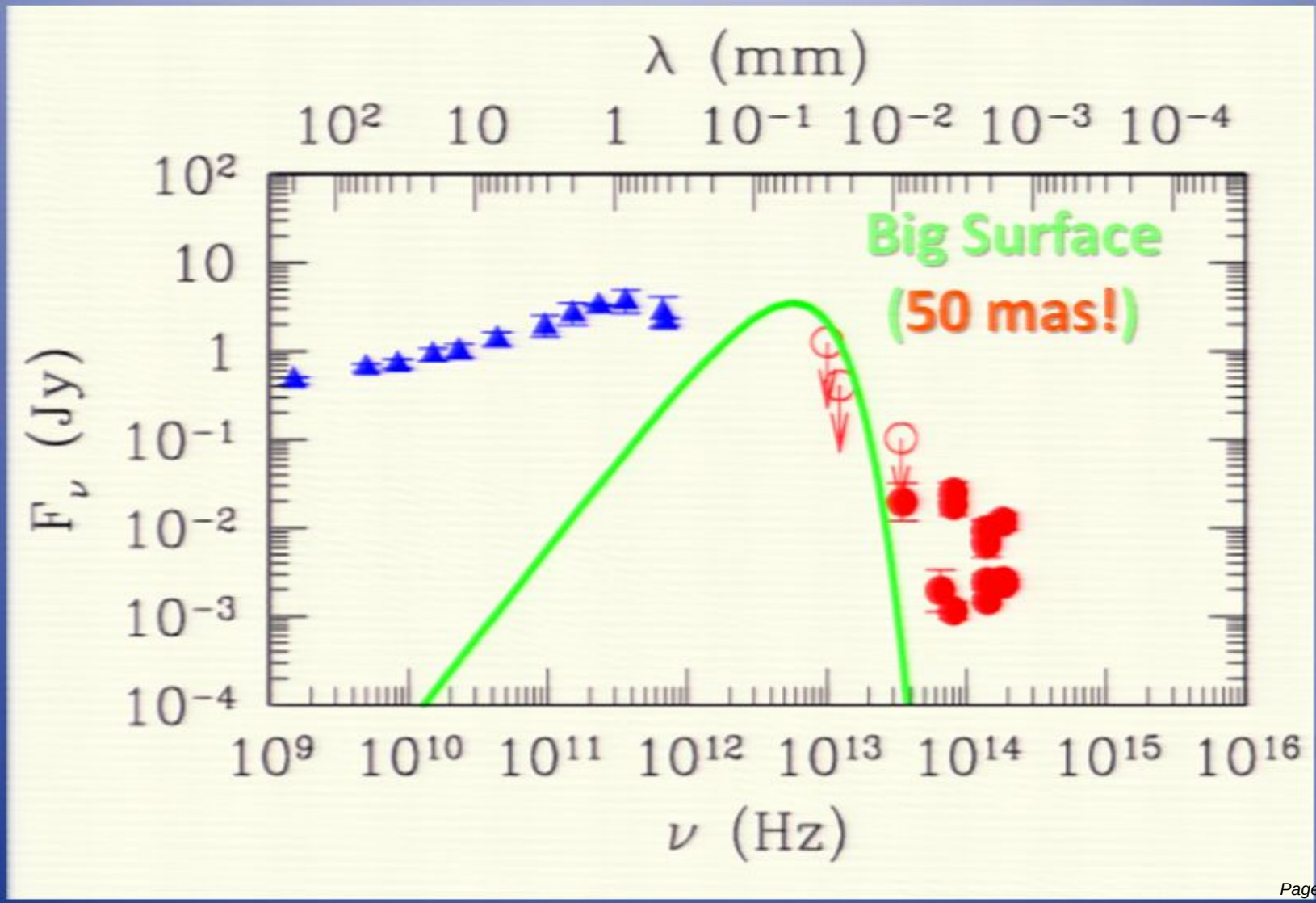

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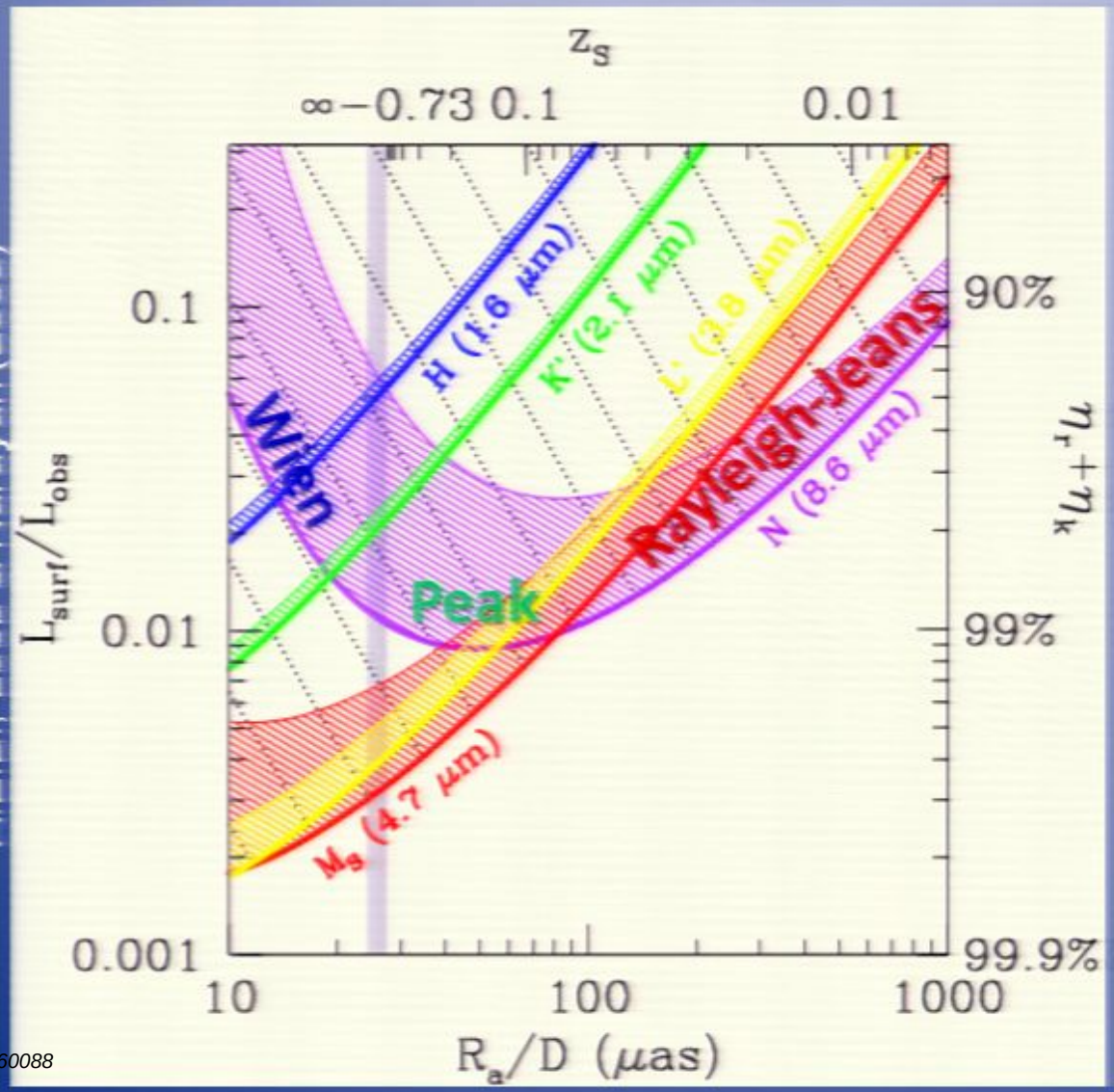

A.E.B., Loeb & Narayan (2009)

Accretion

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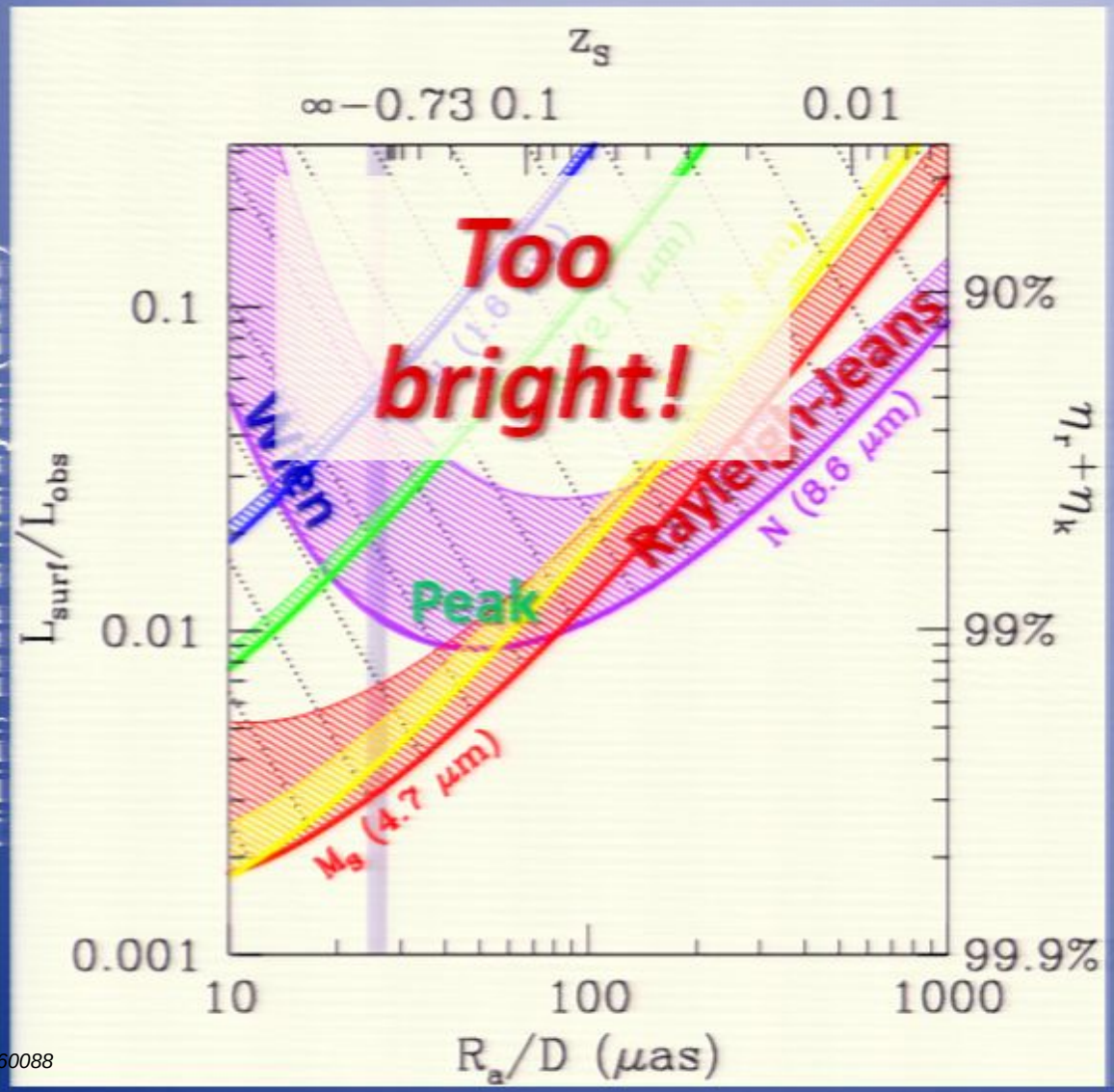
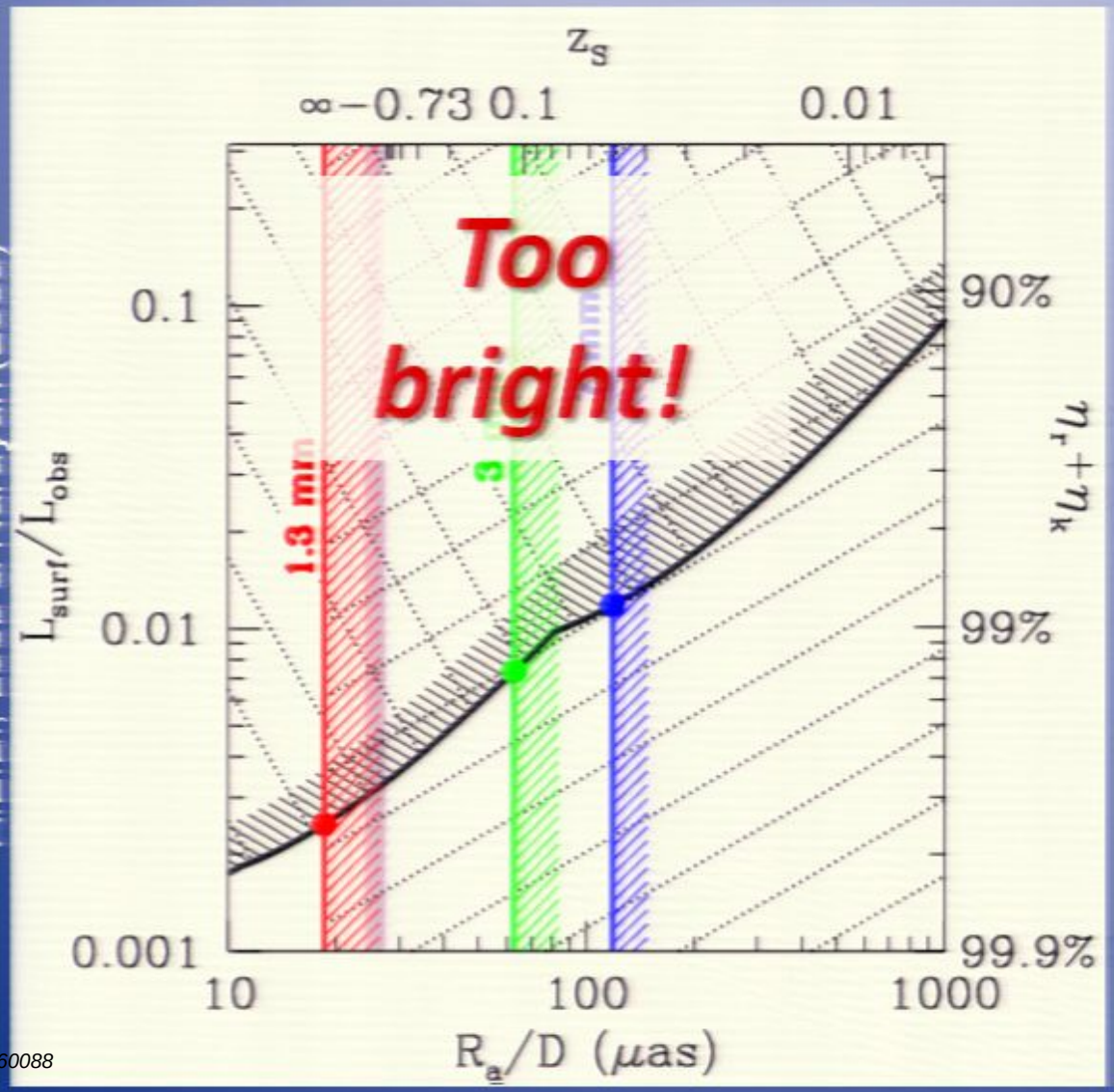


A.E.B., Loeb & Narayan (2009)

Accretion

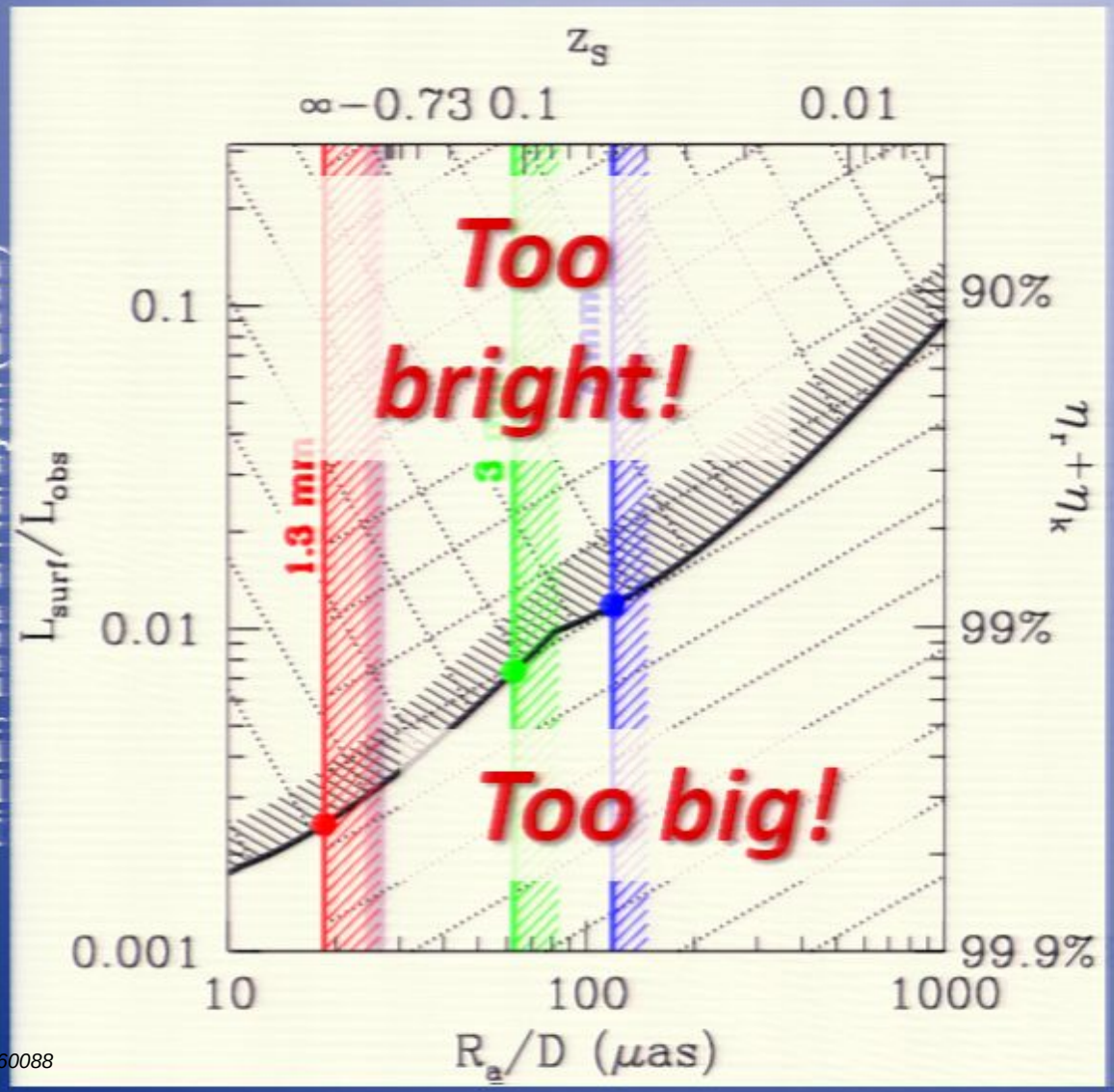
Is Sagittarius A* a "Black Hole"?



A.E.B., Loeb & Narayan (2009)

Accretion

Is Sagittarius A* a "Black Hole"?



A.E.B., Loeb & Narayan (2009)

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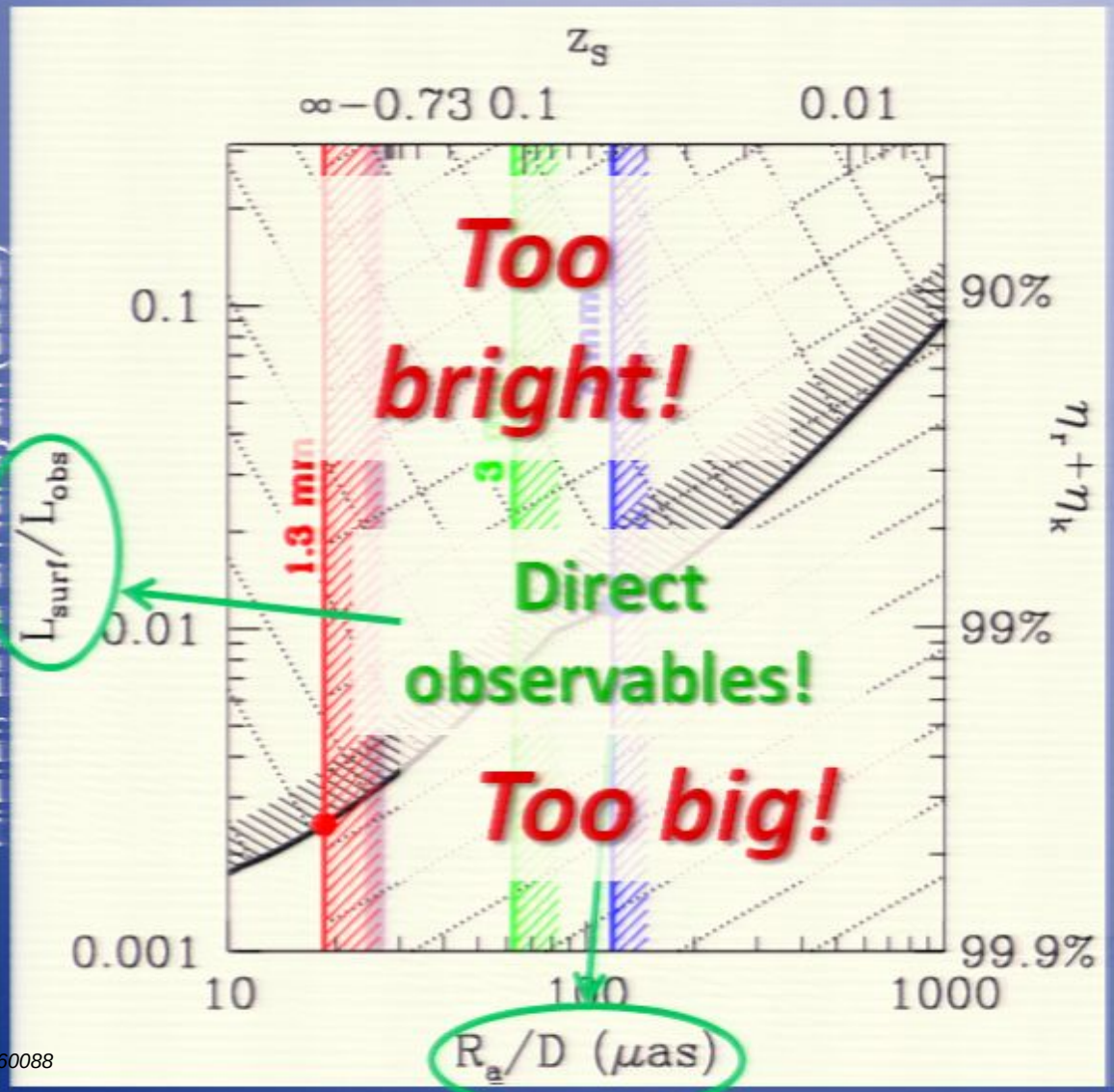
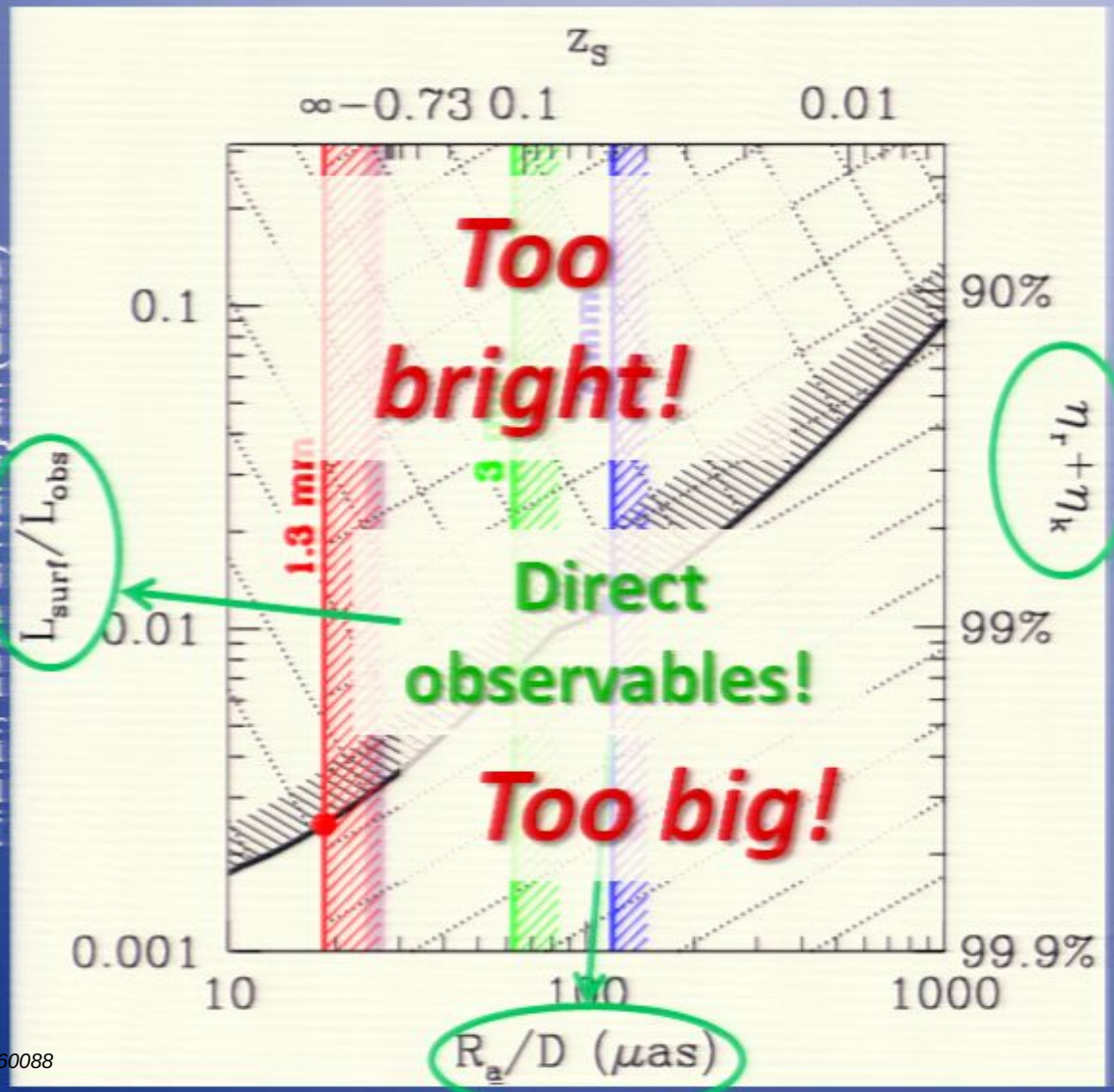


A.E.B., Loeb & Narayan (2009)

Accretion

Is Sagittarius A* a "Black Hole"?



Property of the accretion flow!

- lab densities
- lab temperatures
- lab B-fields

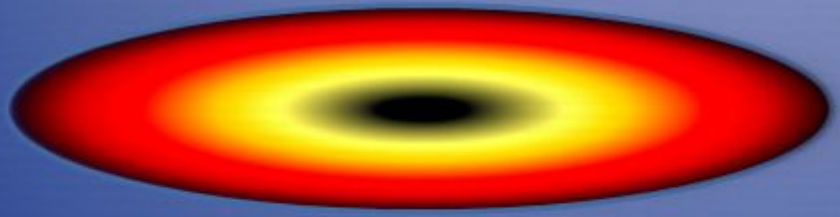
$$L_{surf} \leq 0.004 L_{obs}!$$

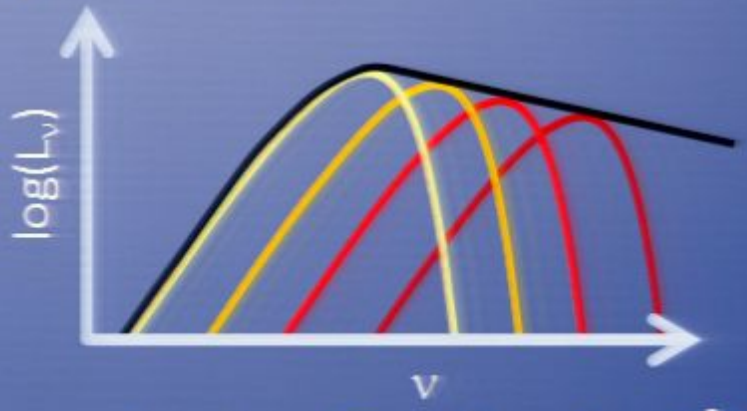
$$\eta_r + \eta_k \geq 99.6\%!$$

Accretion

Thin disks and Black Hole Spin

- Optically thick → Luminosity entirely local
- Radiatively efficient → Geometrically thin
- α-disk, Shakura-Sunyaev, Novikov-Thorne
- α controls transport of L, but not E



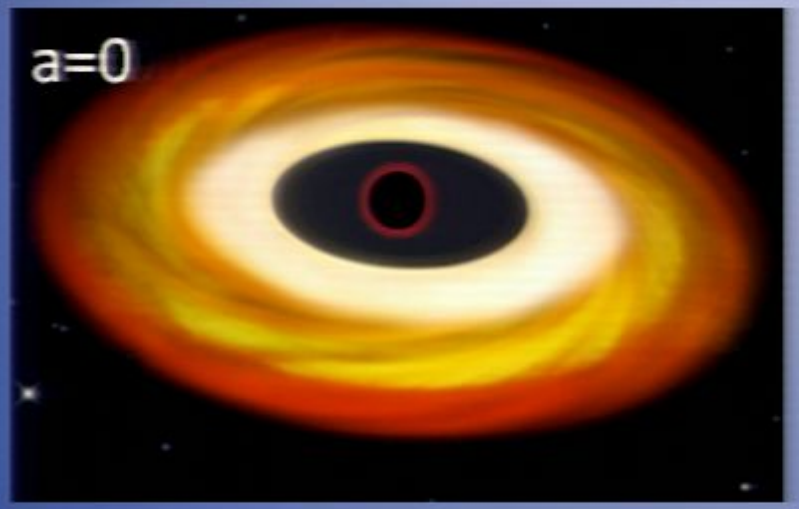


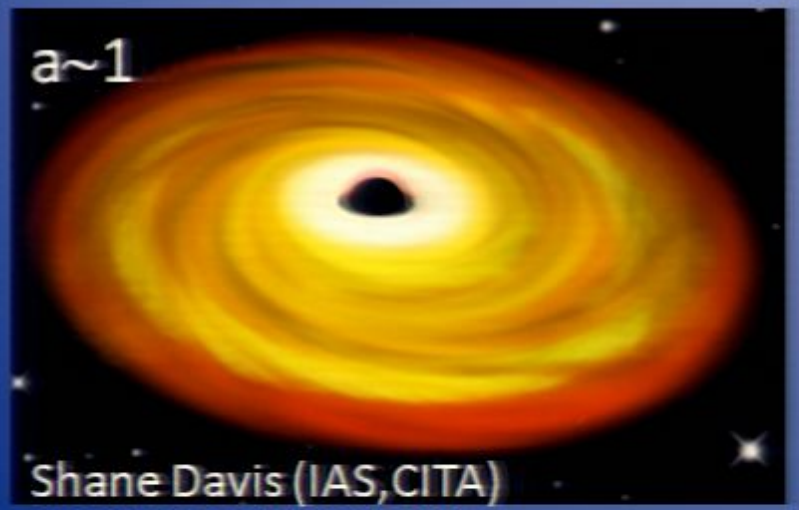
→ Luminosity independent of α (only Ṁ)!

→ Spectrum independent of α (only Ṁ)!

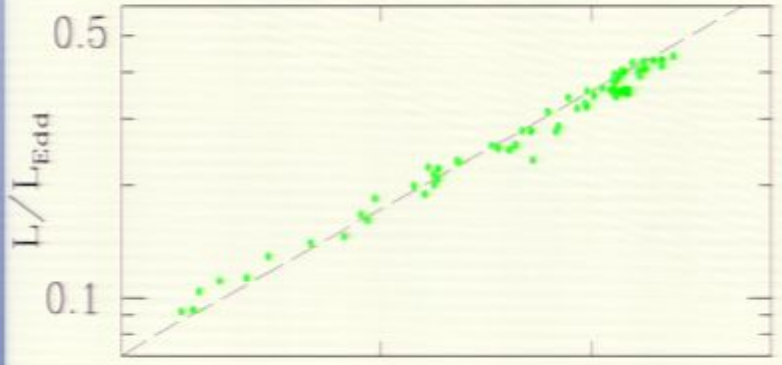
Accretion

Thin disks and Black Hole Spin





$$L \propto r_{\mathrm{ISCO}}^2 \cos i \left(f_C T\right)^4$$



Measure:

- T from spectrum
- (M,i) from binary light curves

→ Get r_{ISCO} → get a!

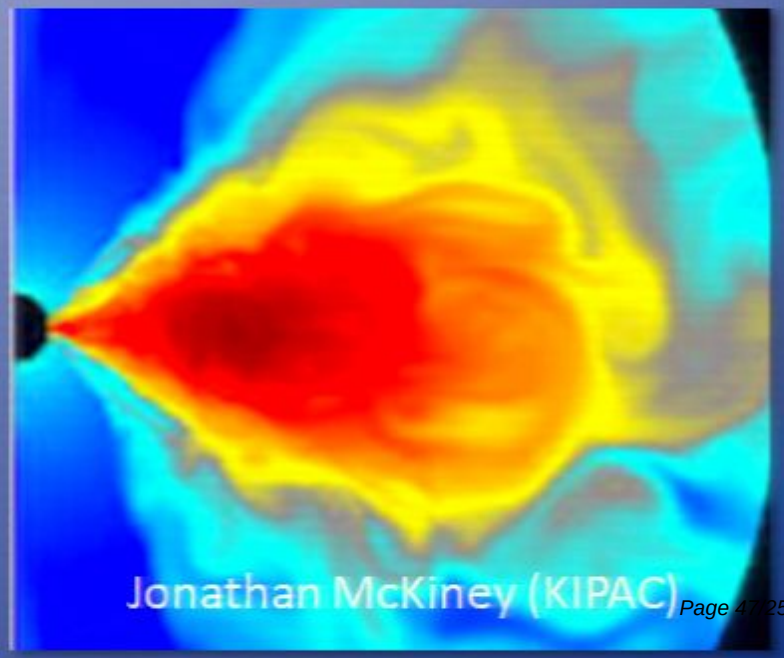
Stellar Mass Black Hole Spins

System	a	Reference
GRO J1655-40	0.65 - 0.75	Shafee et al. 2006
	~0.7	Davis et al. 2006
4U 1543-47	0.75 - 0.85	Shafee et al. 2006
LMC X-3	< 0.26	Davis et al. 2006
	TBD	Steiner et al.
XTE J1550-564	0-0.7	Davis et al. 2006
	TBD	Steiner et al.
GRS 1915+105	0.98 - 1	McClintock et al. 2006
	~0.8	Middleton et al. 2006
M33 X-7	0.77 ± 0.05	Liu et al. 2007
LMC X-1	0.92 (+0.05, -0.07)	Gou et al. 2009
A0620--00	0.12 (+0.18, -0.20)	Gou et al. 2010
Cygnus X-1	TBD	Gou et al.

Accretion

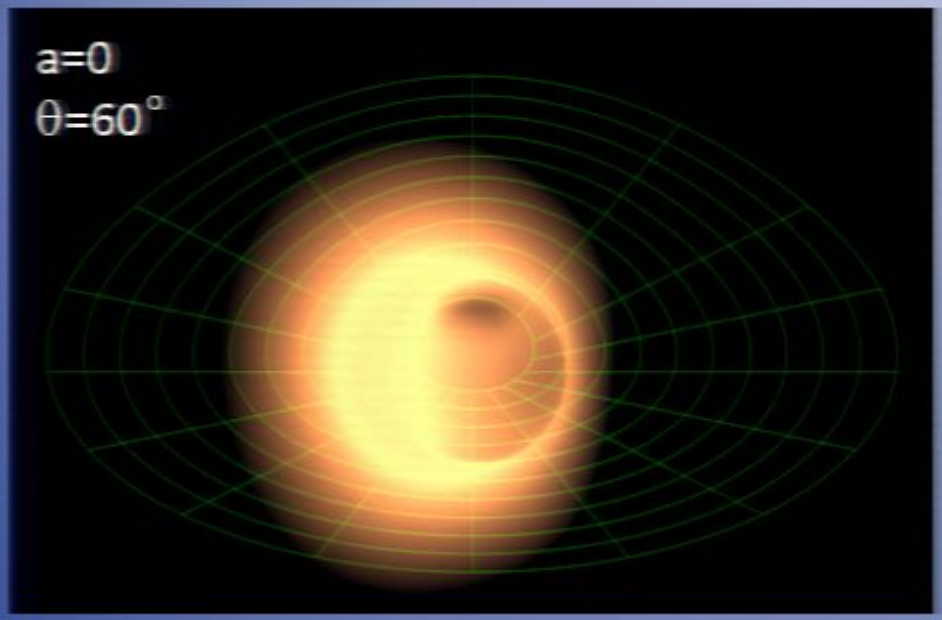
Thick Disks and Black Hole Spin

- Optically thin
  → Luminosity globally correlated & nonthermal
- Radiatively inefficient → Geometrically thick
- Strongly dependent upon non-linear MHD
  - Need simulations!
  - Generally power-laws
  - Outflows
  - Two-temperature

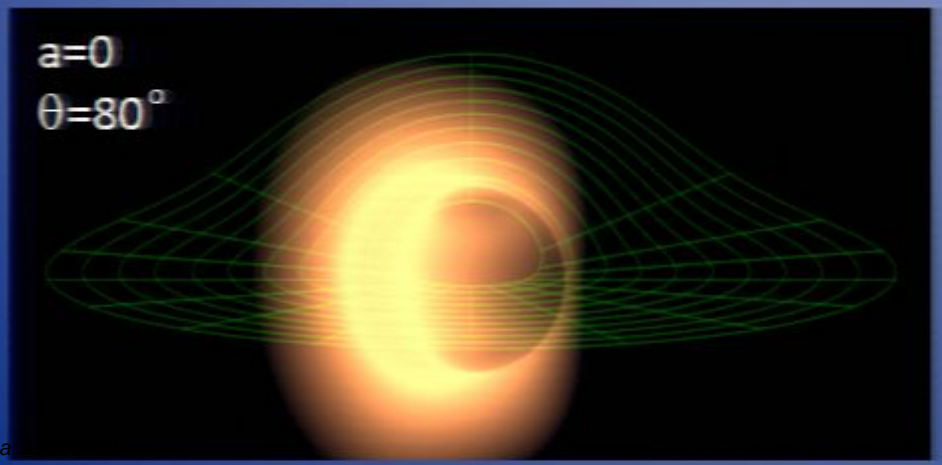


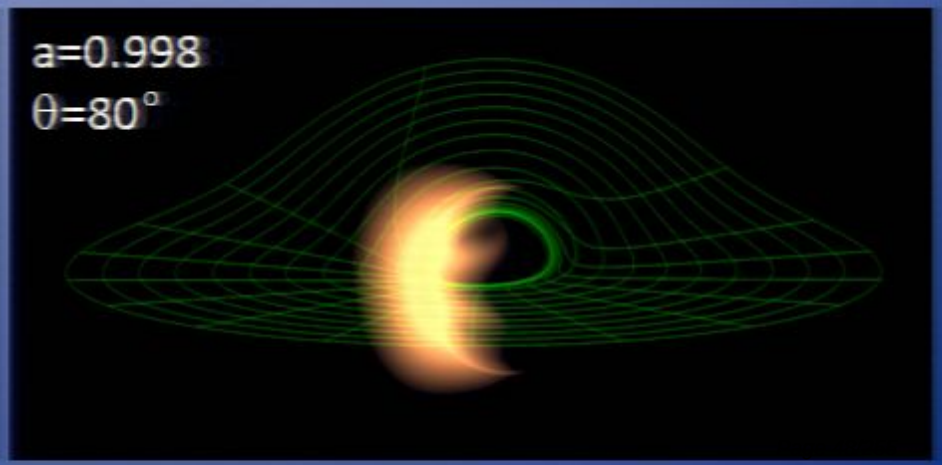
Accretion

Thick Disks and Black Hole Spin

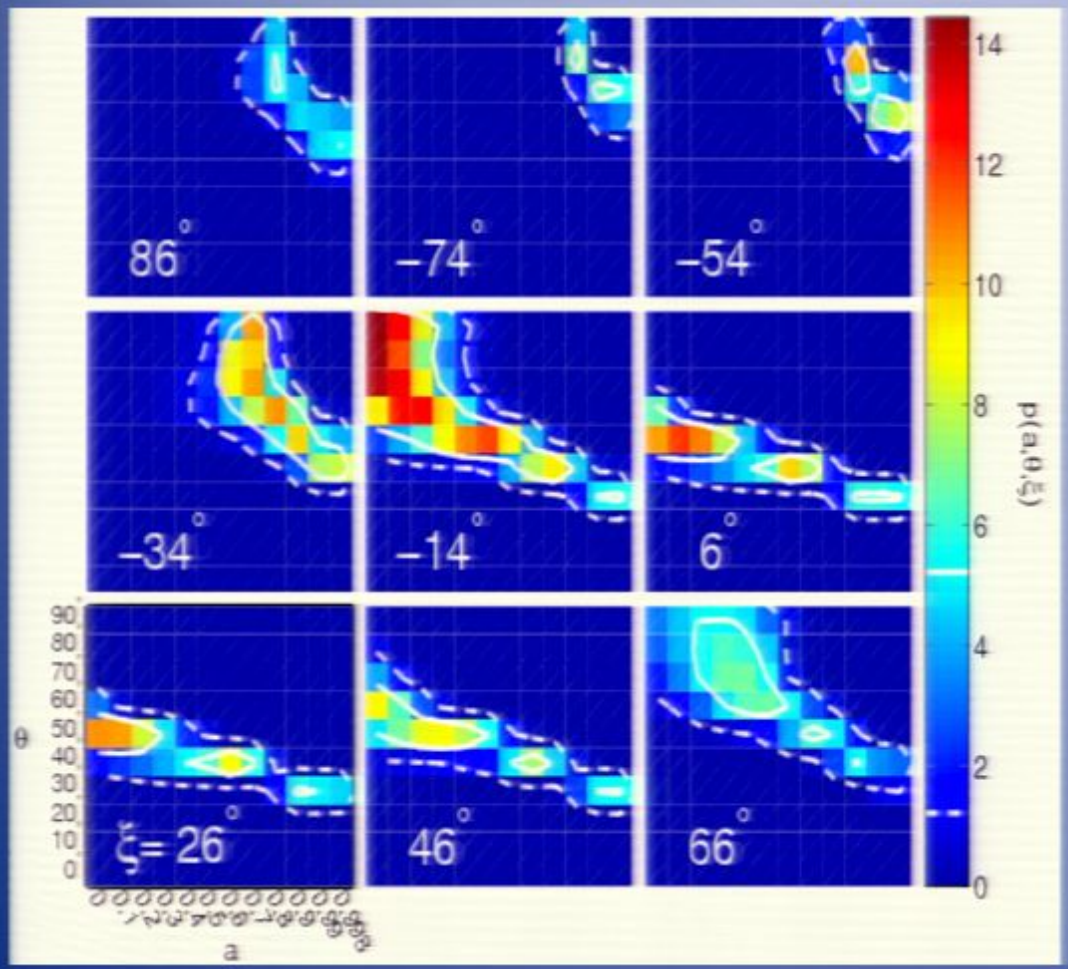


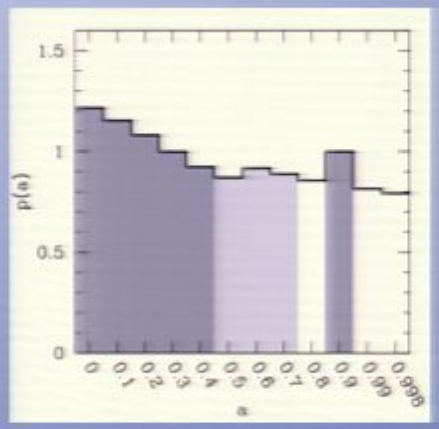
- Characteristic shape
  - Lensing
  - Orbital motion
  - Opacity
- Depends upon a & θ

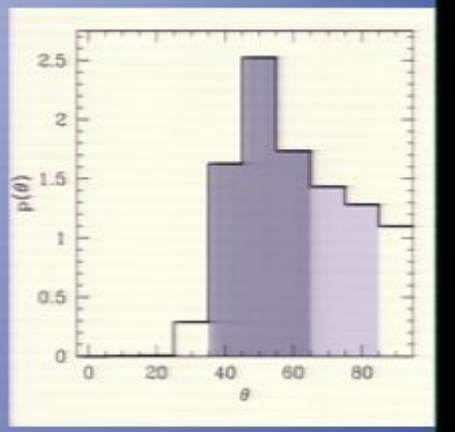


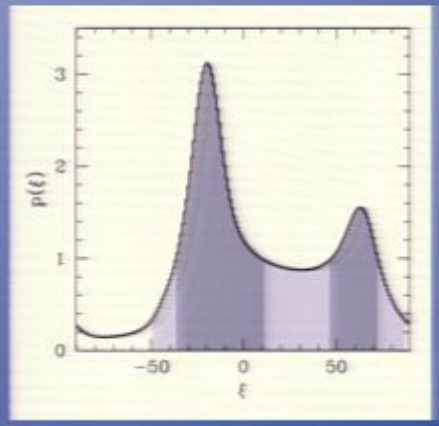


The Spin of Sagittarius A*







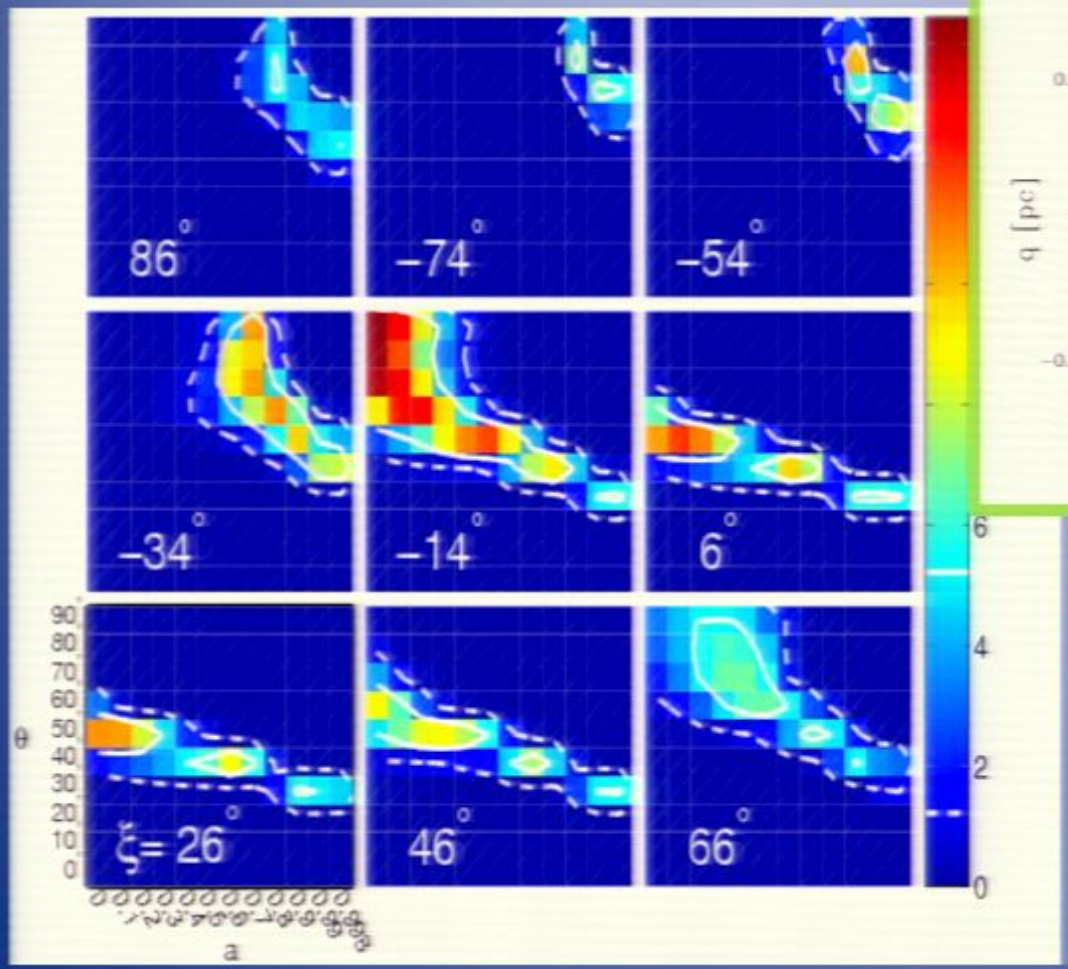


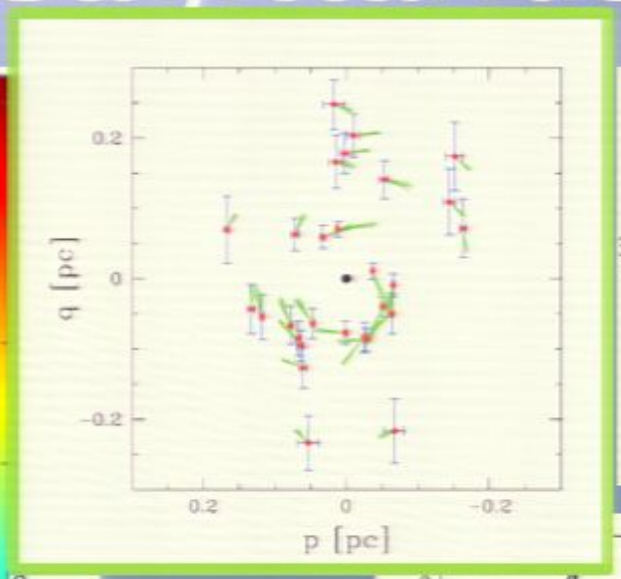
AEB, Fish, Doeleman & Loeb (2009)

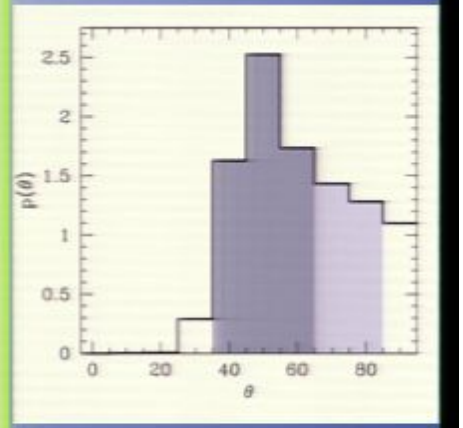
- Similar results from:
  Huang, Takahashi & Shen (2009), Dexter et al. (2010)

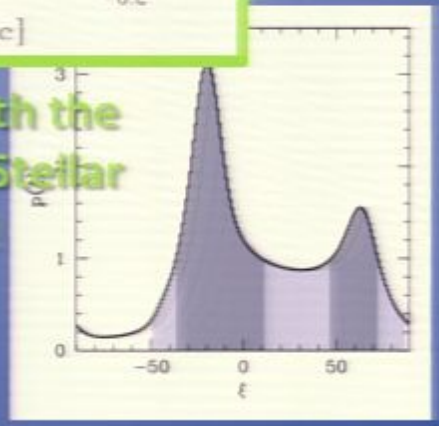
Accretion

The Spin of Sagittarius A*









Aligned with the Clockwise Stellar Disk!

AEB, Fish, Doeleman & Loeb (2009)

- Similar results from:

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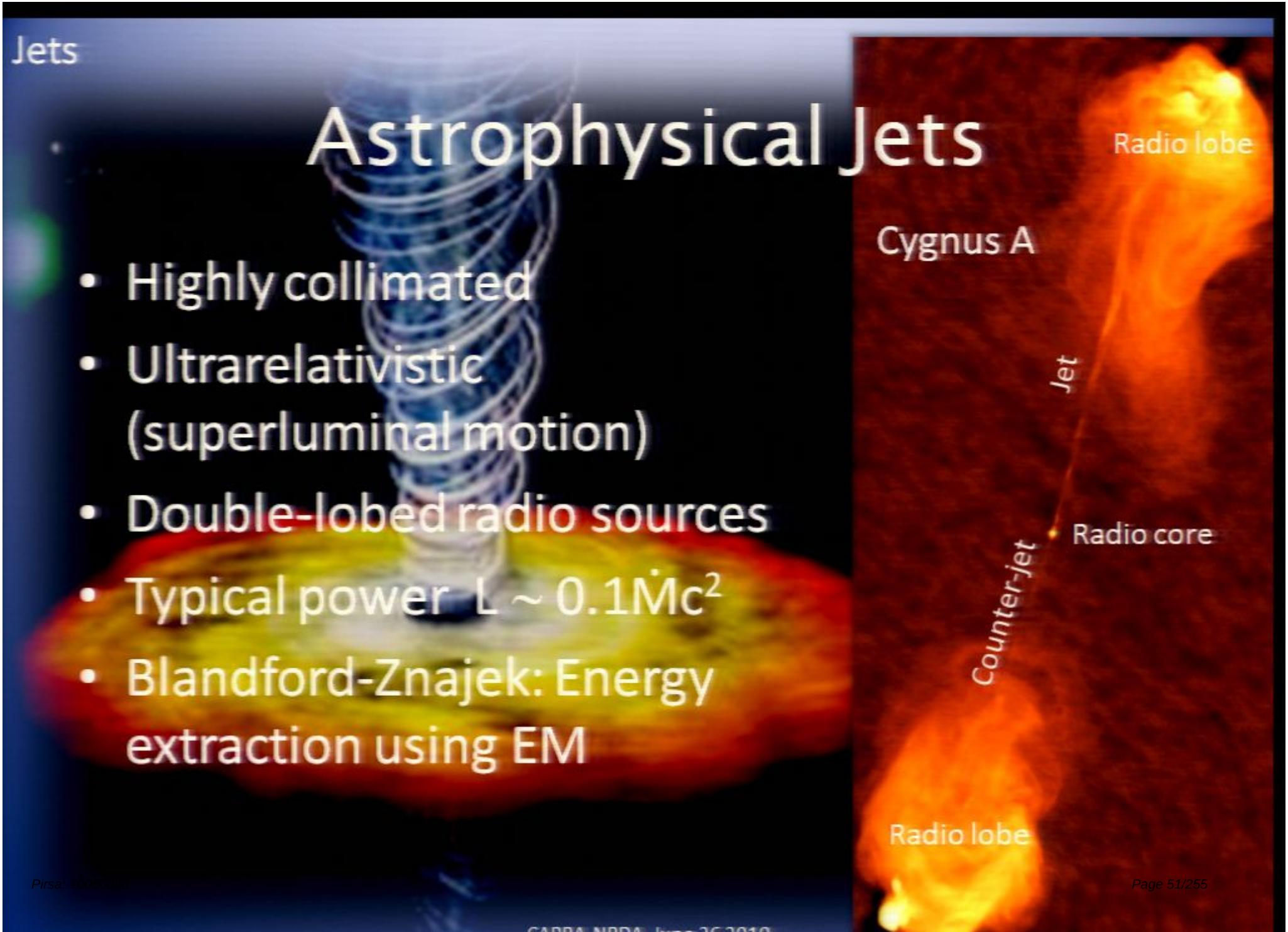
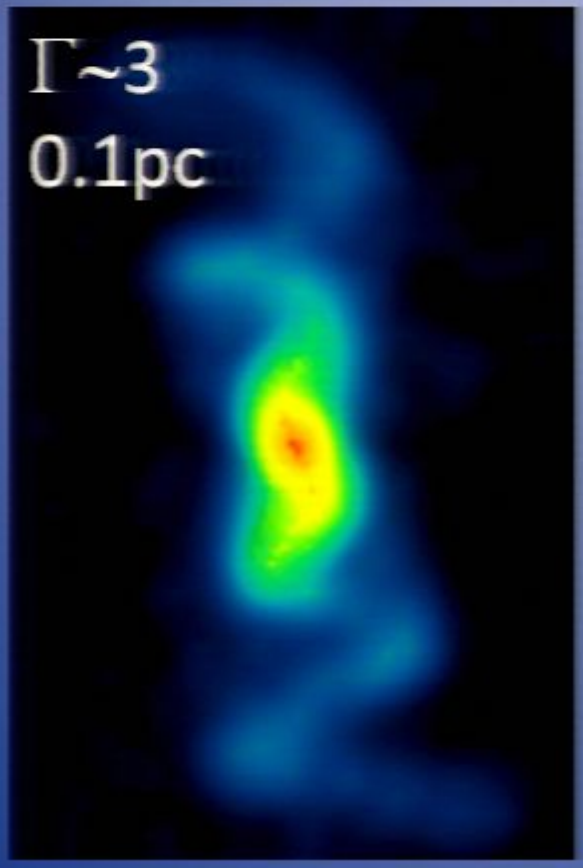
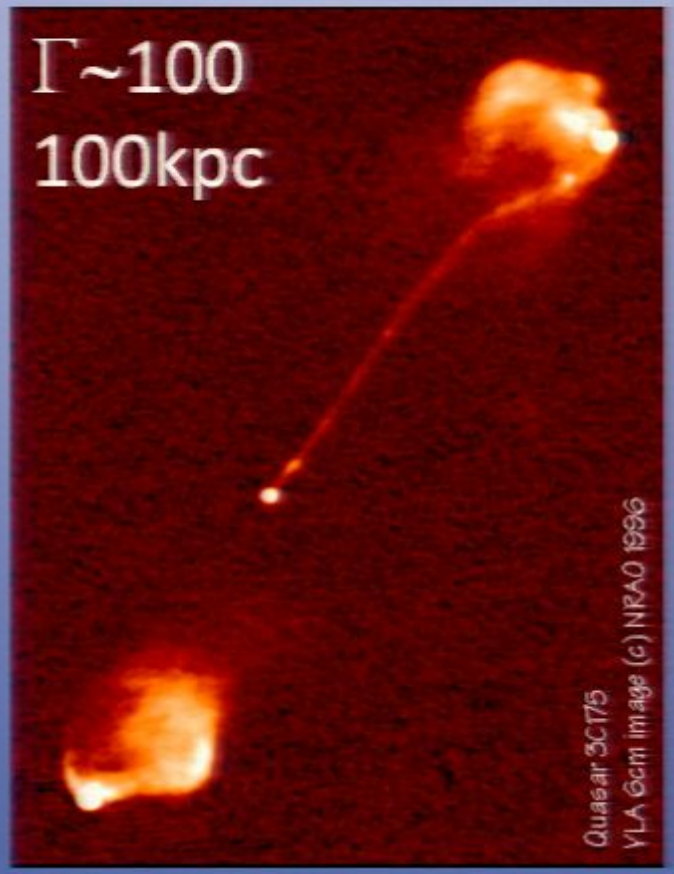

Jets
Astrophysical Jets
Radio lobe
Cygnus A
Jet
Radio core
Counter-jet
Radio lobe
• Highly collimated
• Ultrarelativistic (superluminal motion)
• Double-lobed radio sources
• Typical power $L \sim 0.1\dot{M}c^2$
• Blandford-Znajek: Energy extraction using EM

Jets are Generic



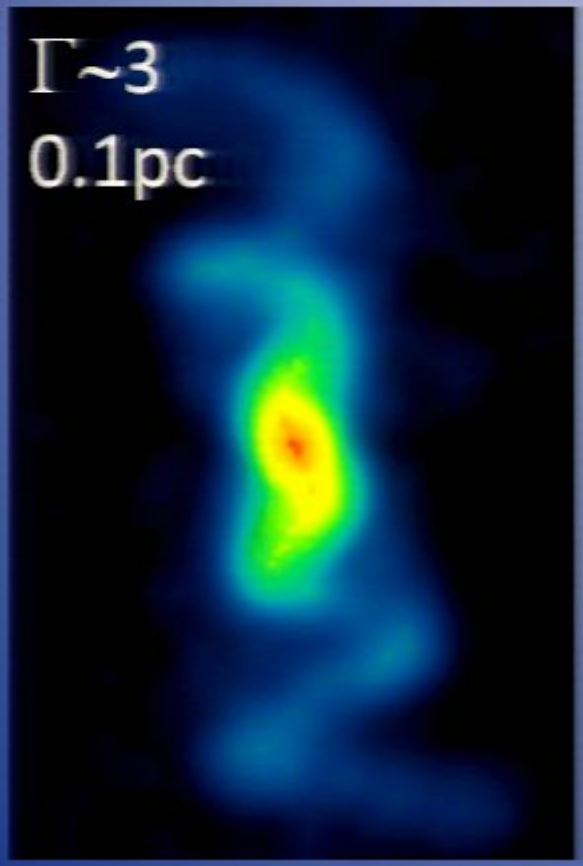


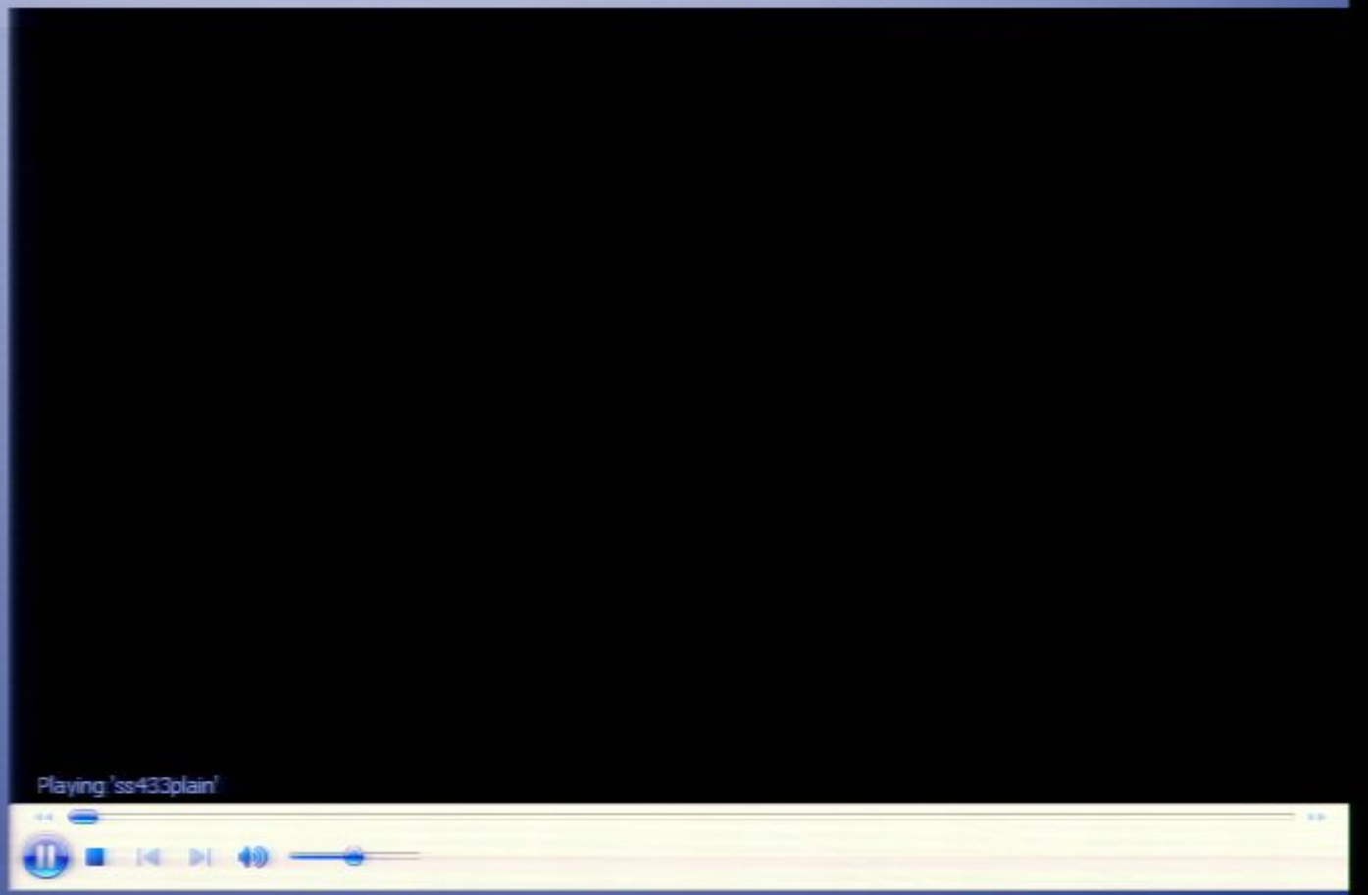
X-ray binaries (SS433)

AGN (3C175)

GRBs

Jets are Generic





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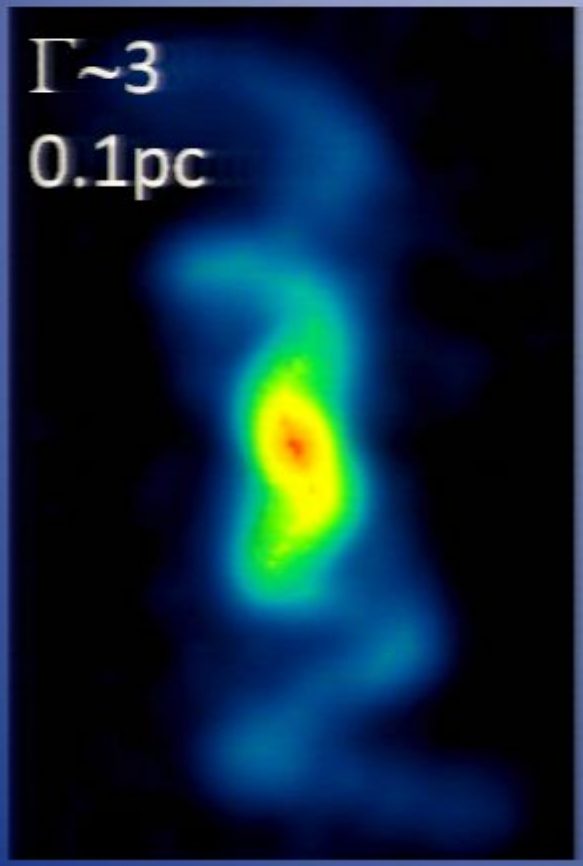

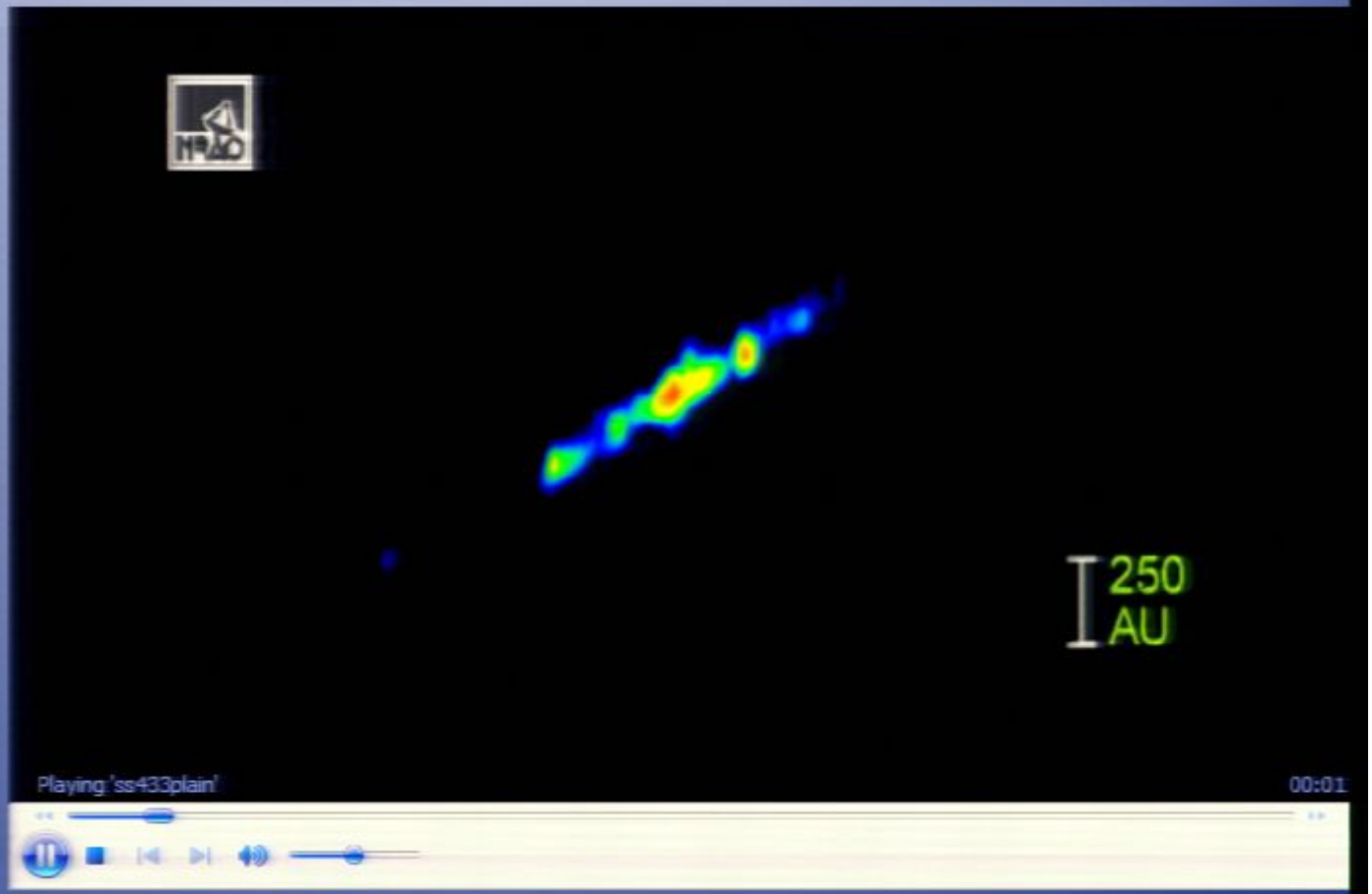

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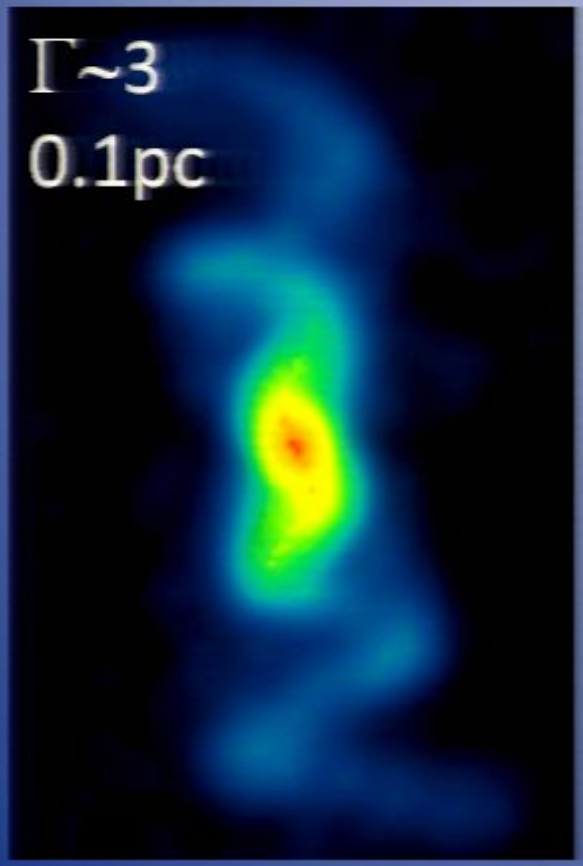

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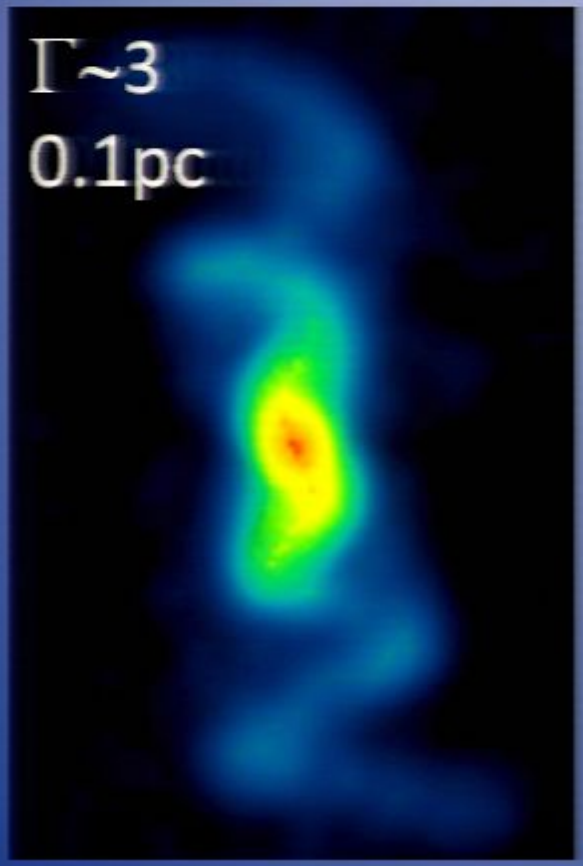

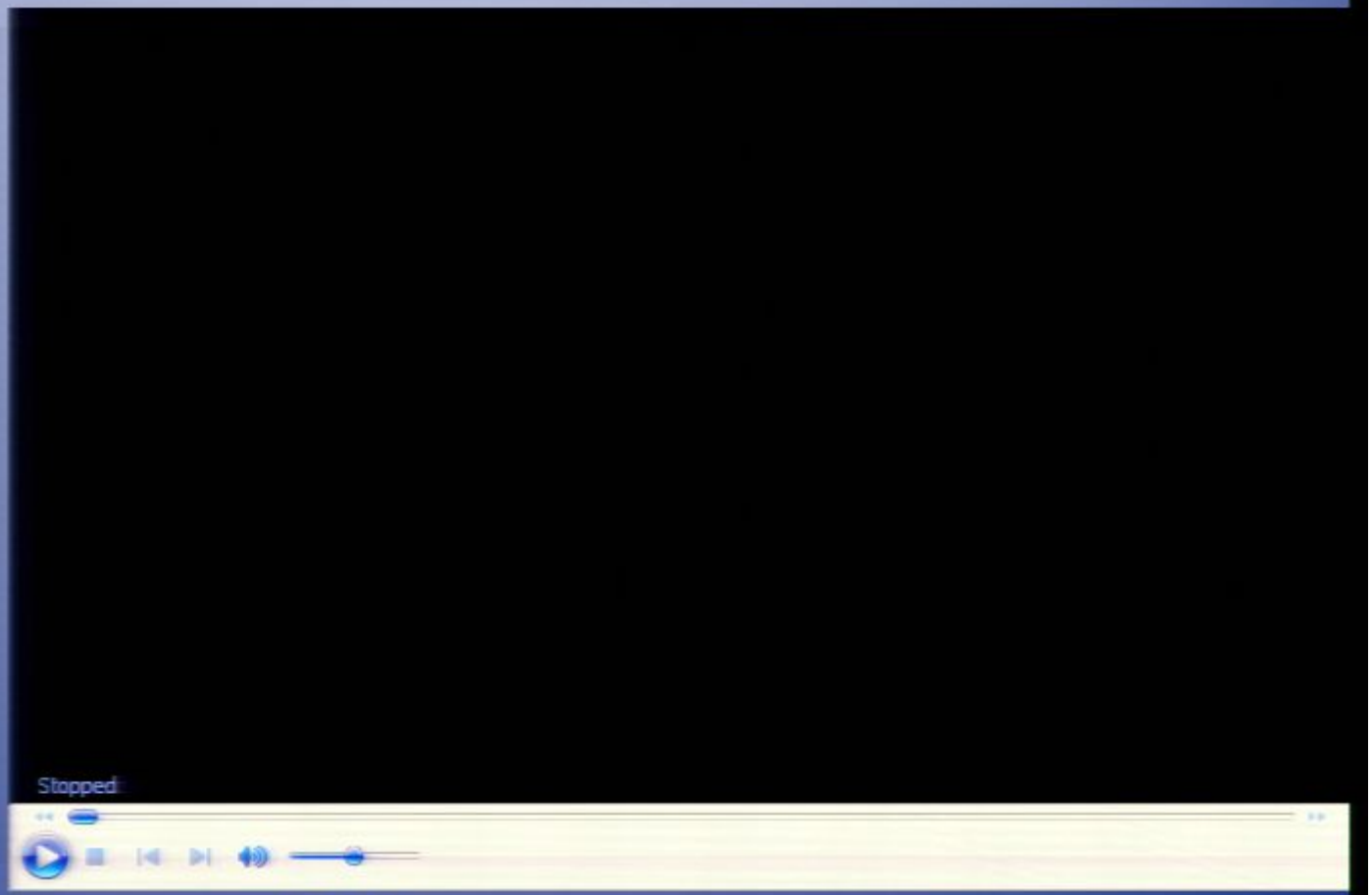

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AGN (3C175)

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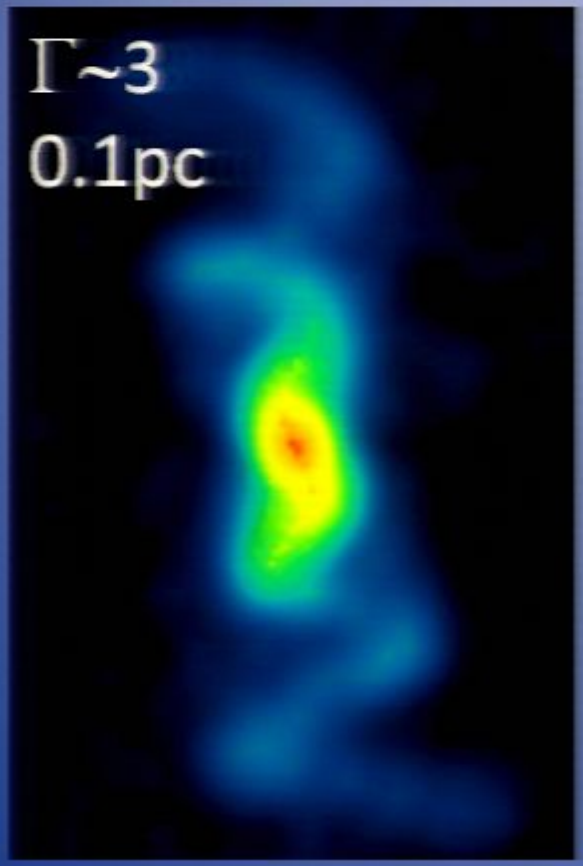

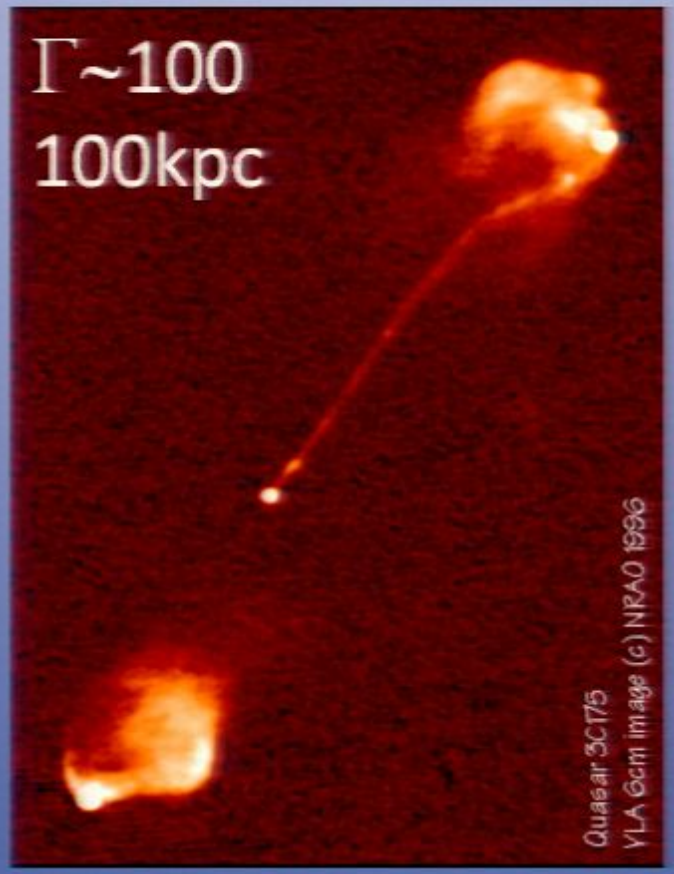

X-ray binaries (SS433)

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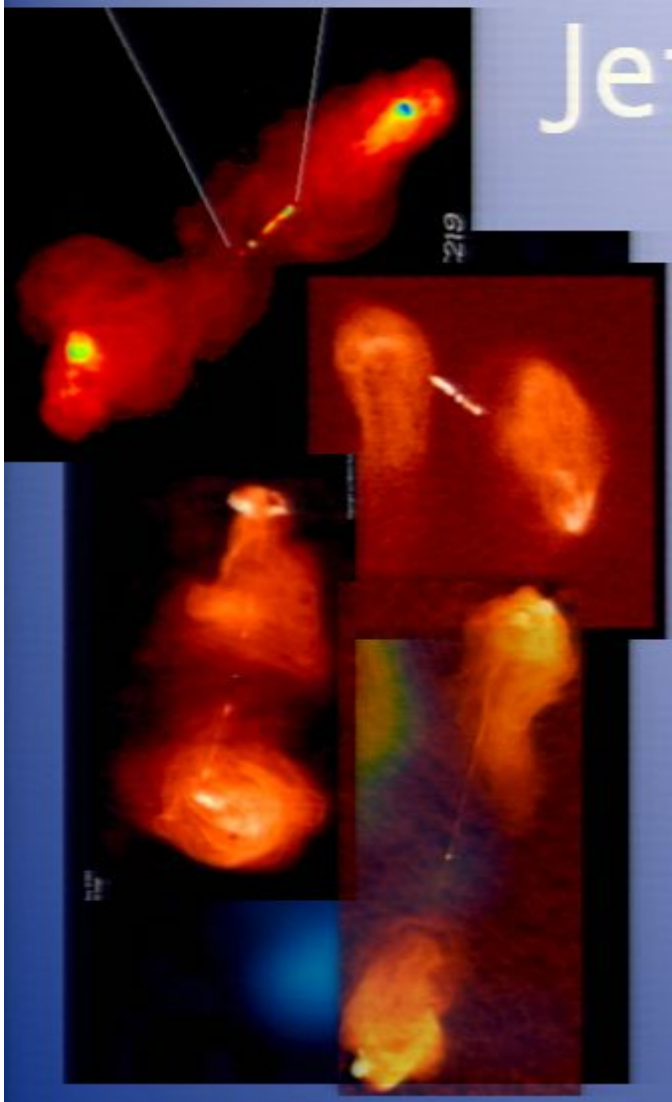
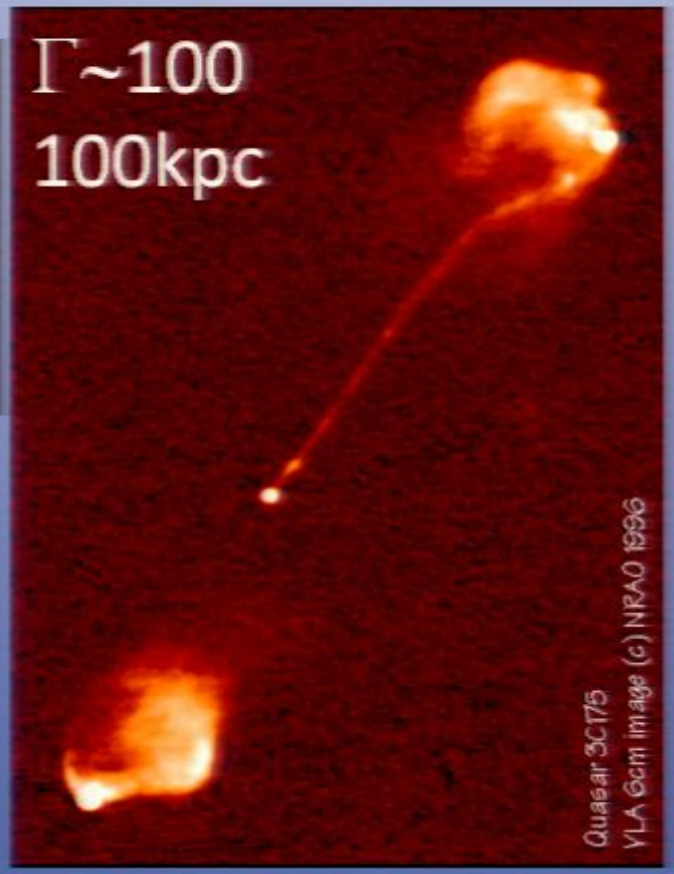
GRBs

Jets are Generic



X-ray binaries
(SS433)

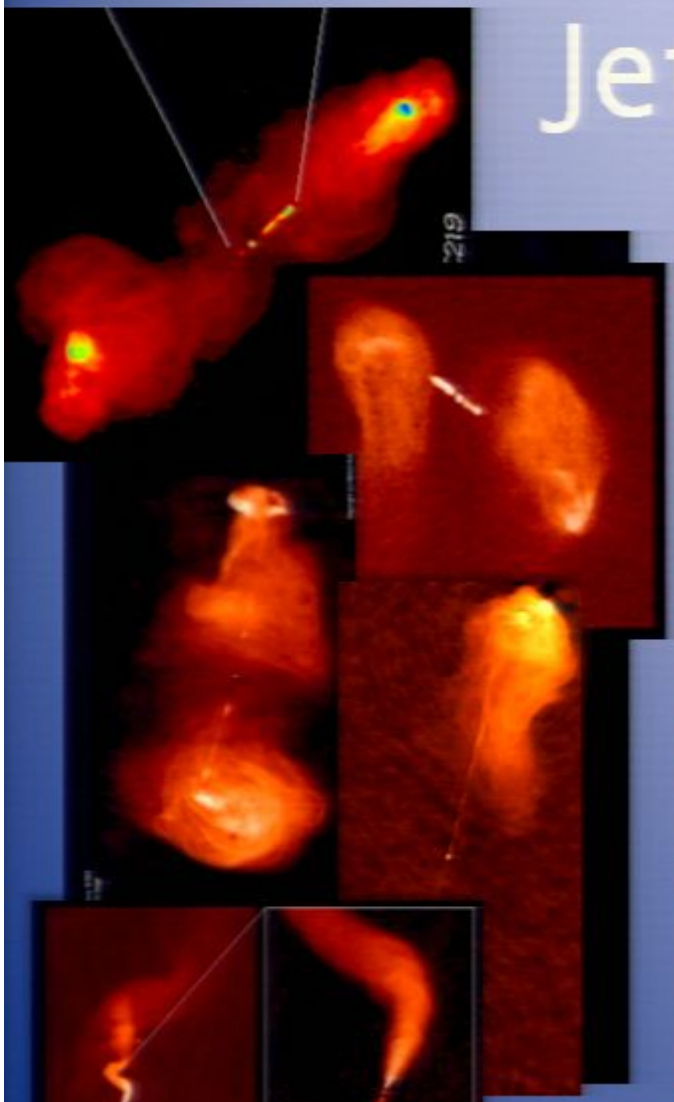


AGN
(3C175)

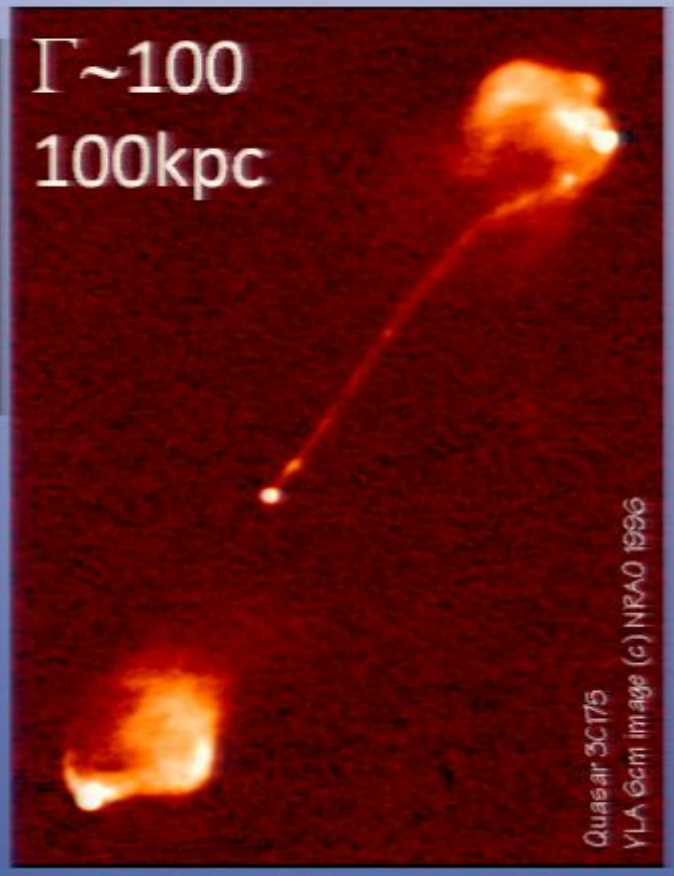
GRBs

Jets

Jets are Generic



es

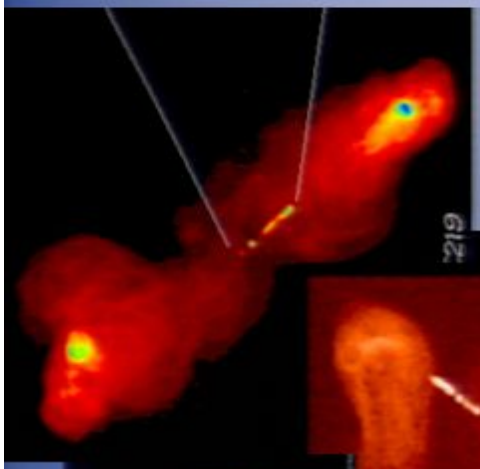


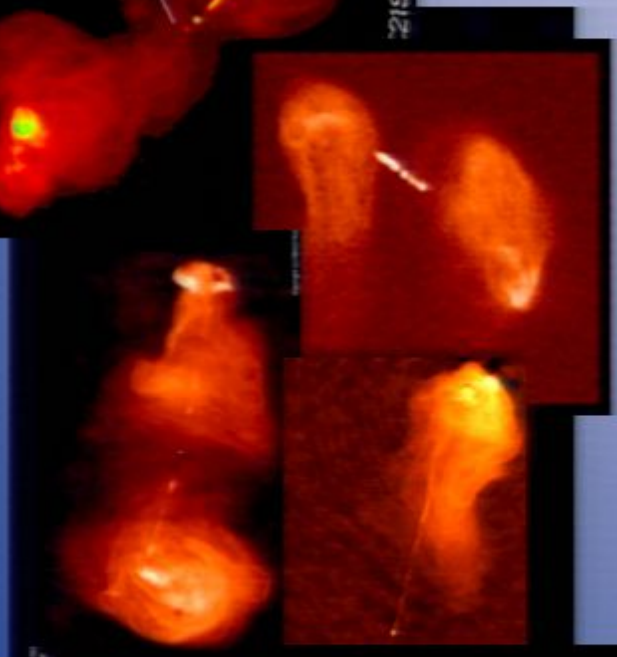
AGN
(3C175)

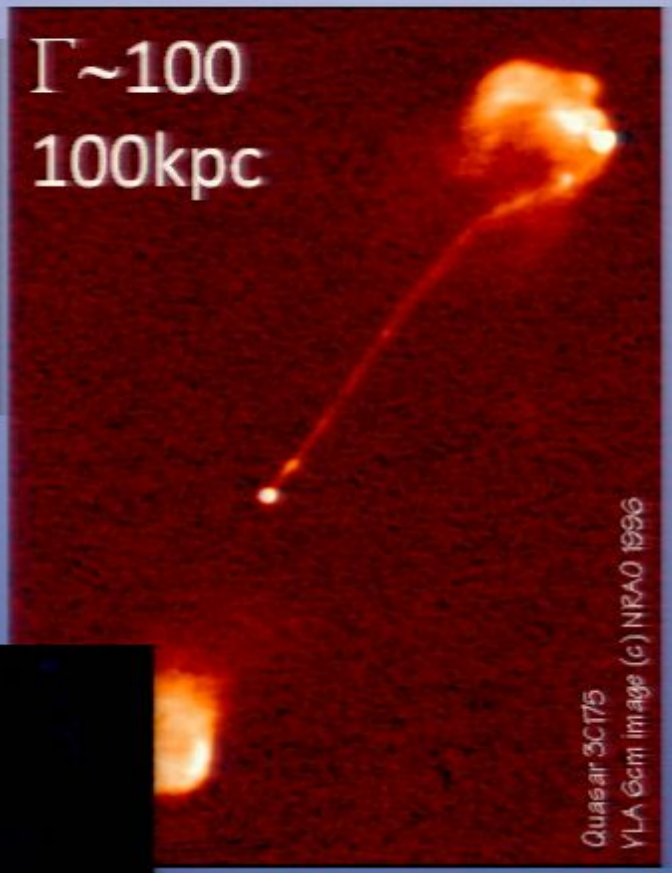
GRBs

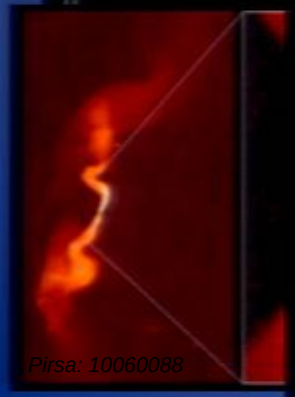
Jets

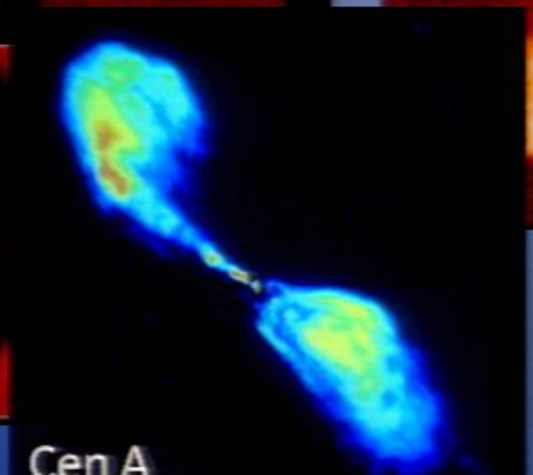
Jets are Generic







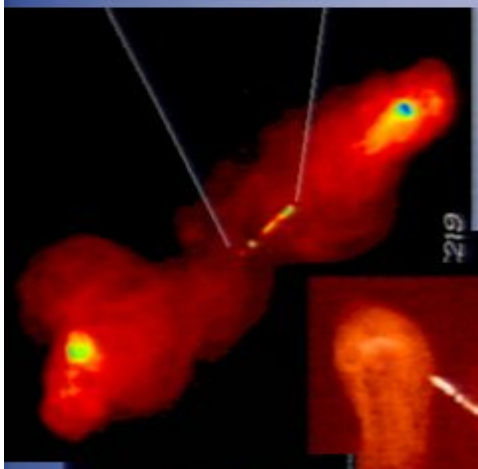


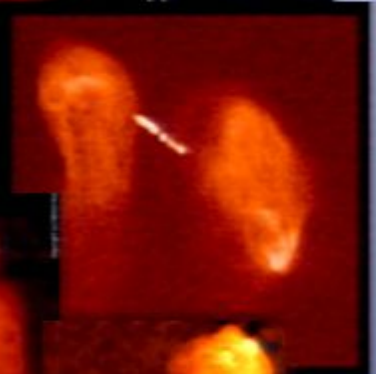


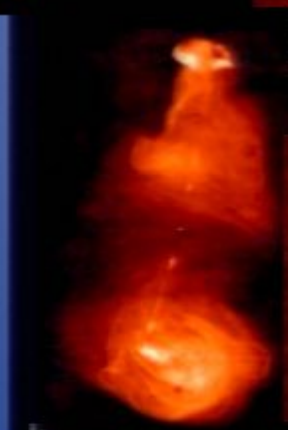
AGN
(3C175)

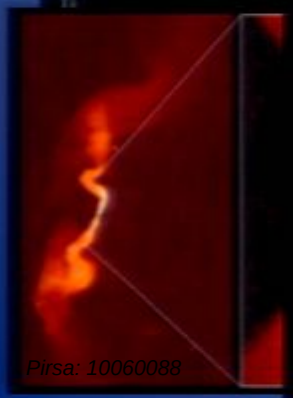
GRBs

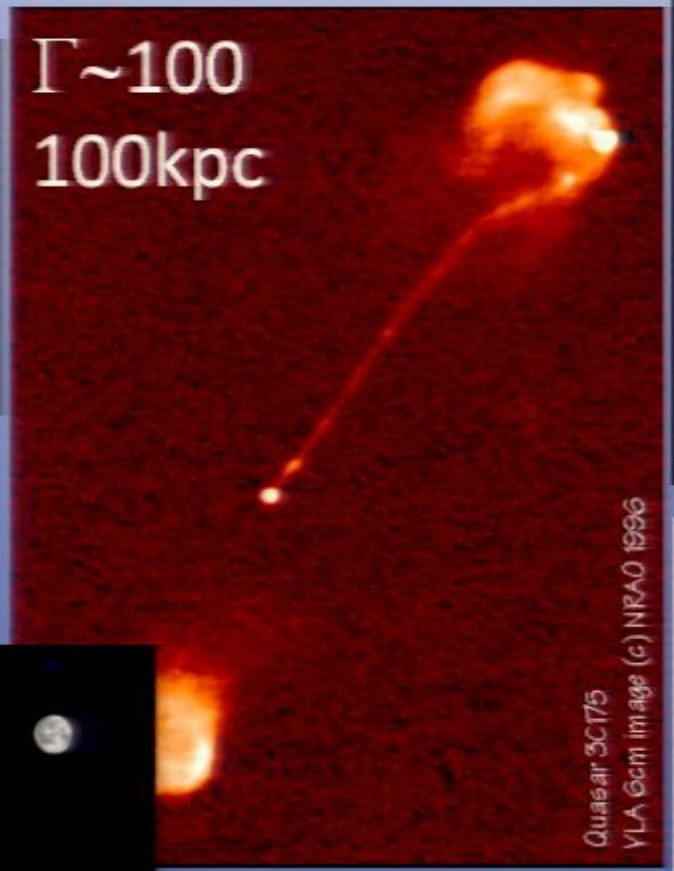
Jets are Generic



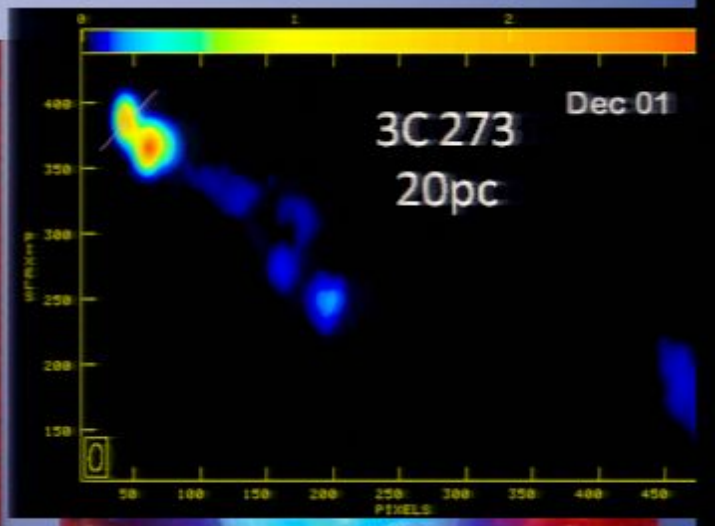


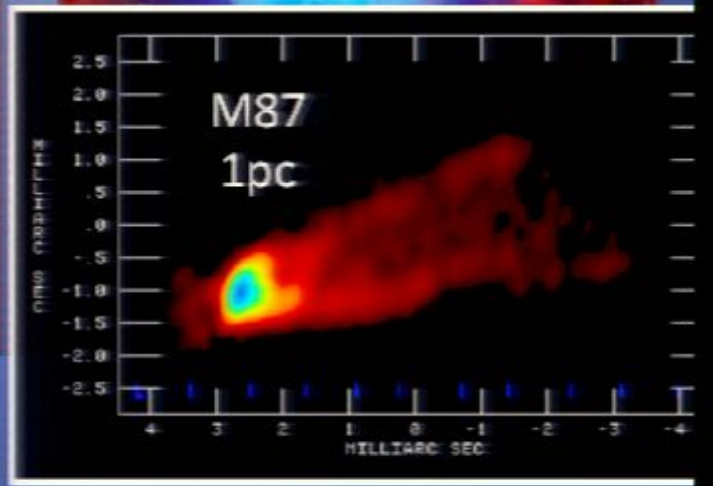




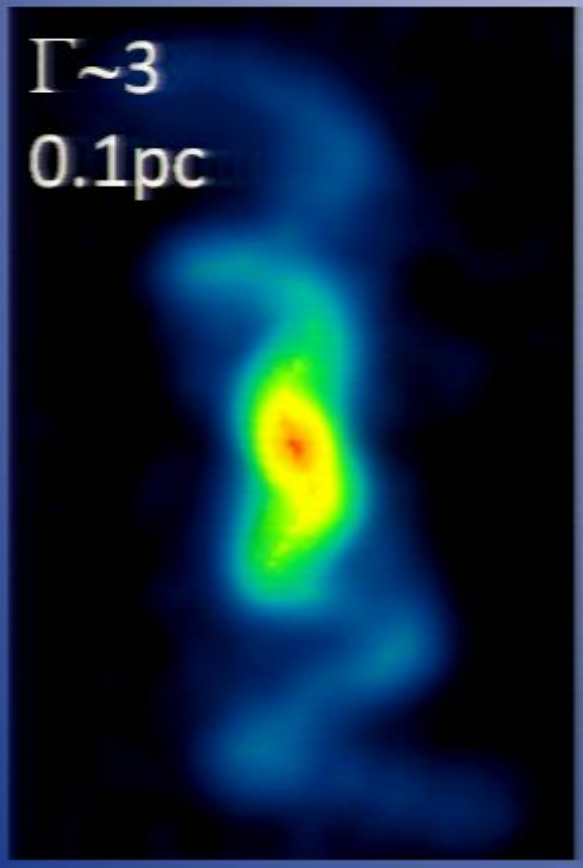


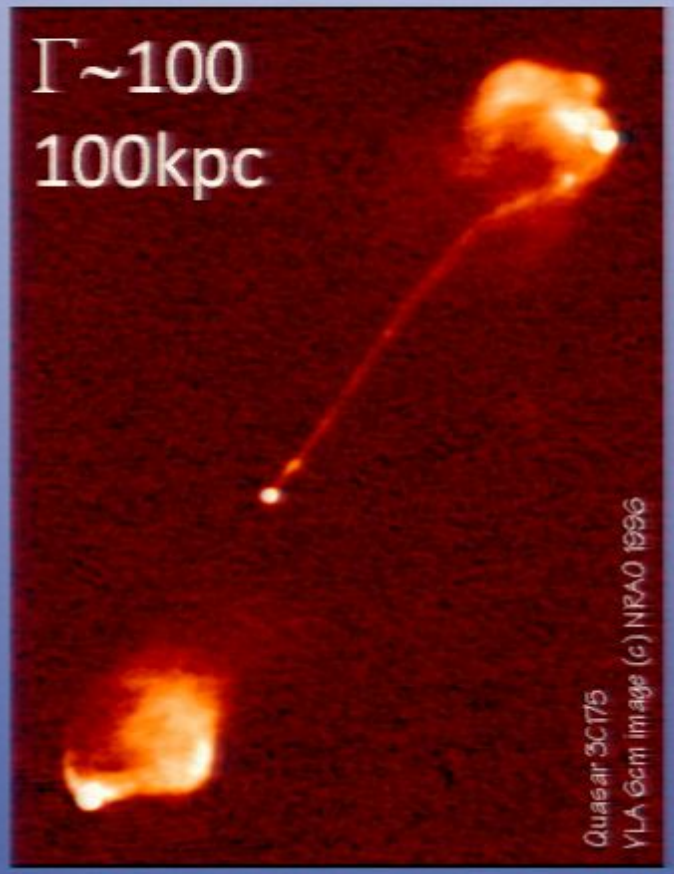
AGN
(3C175)





Jets are Generic





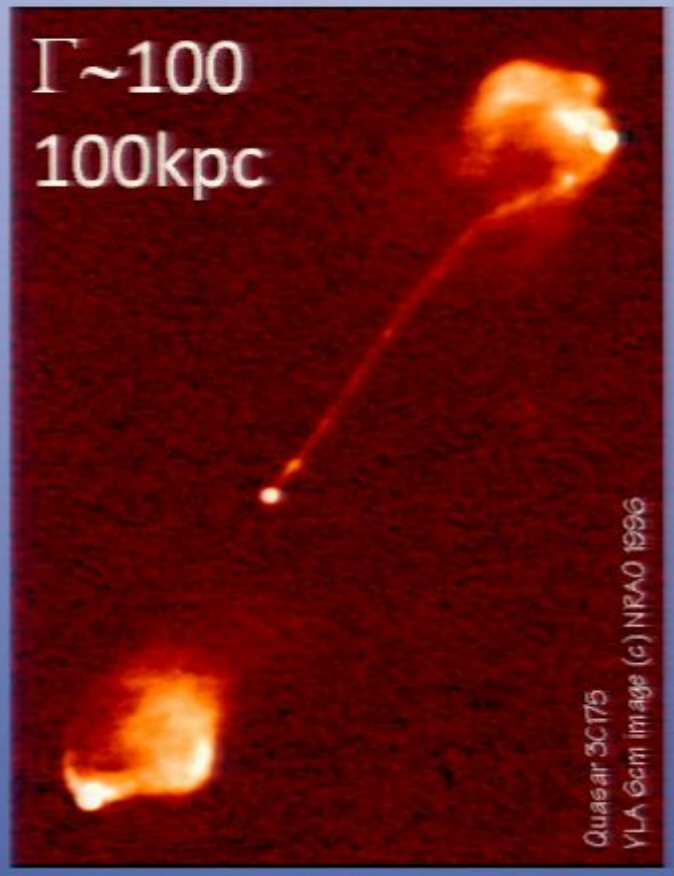
X-ray binaries (SS433)

AGN (3C175)

GRBs

Jets are Generic

- Large Γ:
  Pair production

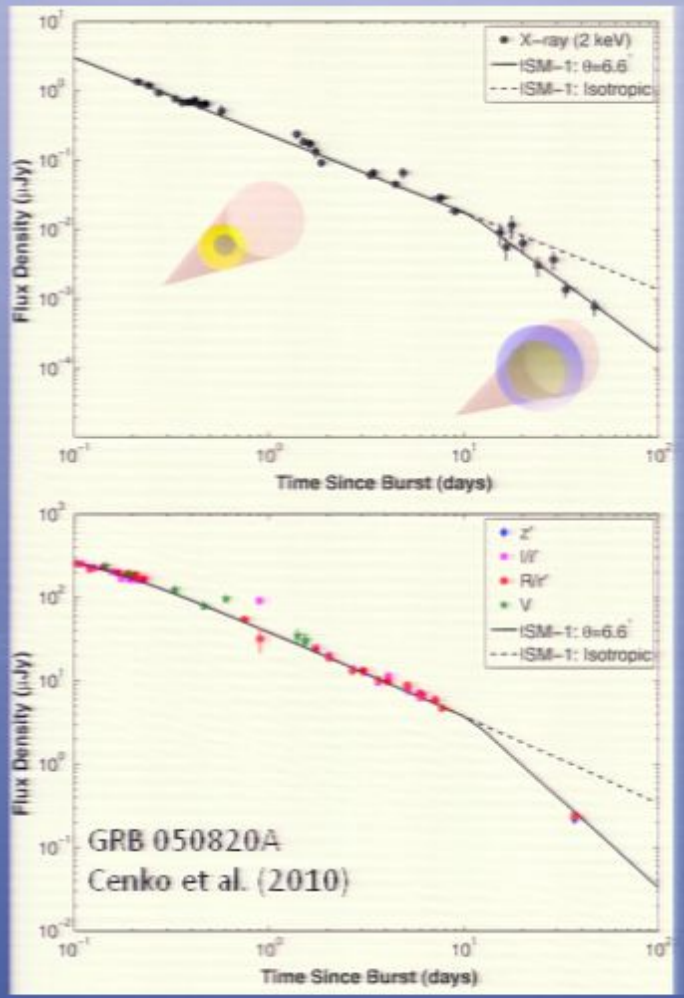


AGN
(3C175)

GRBs

Jets are Generic

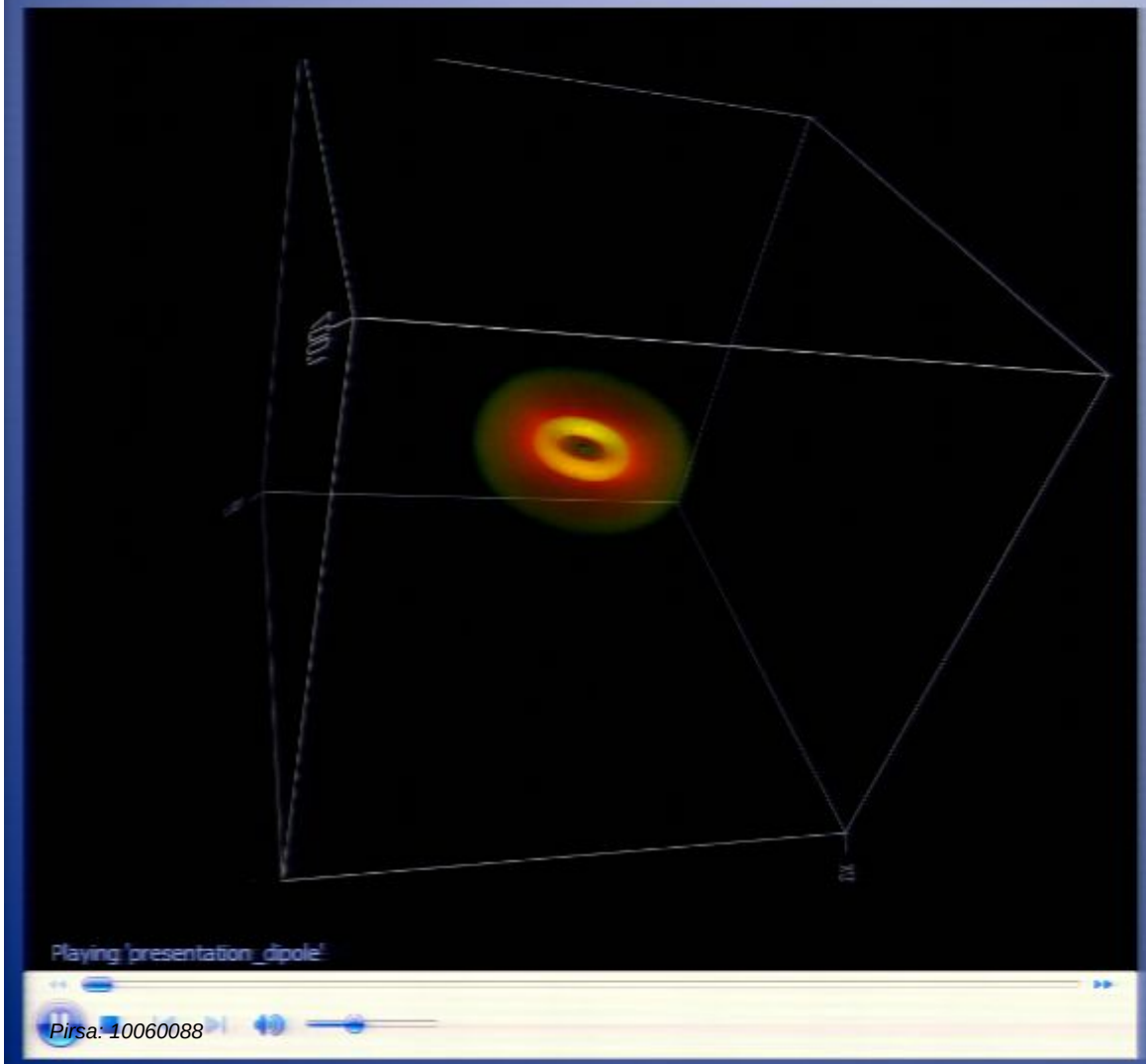
- Large Γ:
  Pair production
  - $\varepsilon_1\varepsilon_2/2\Gamma^2 > m_e^2$
  - Length contraction
- Collimation:
  - Energetics
  - Achromatic brakes



GRBs

(3C175)

Jets in Theory: Simulations



- Large-scale toroidal magnetic fields
- Marginally kink stable
- Canonical structure:
  - MHD disk
  - Magnetically dominated wind
  - Force-free jet

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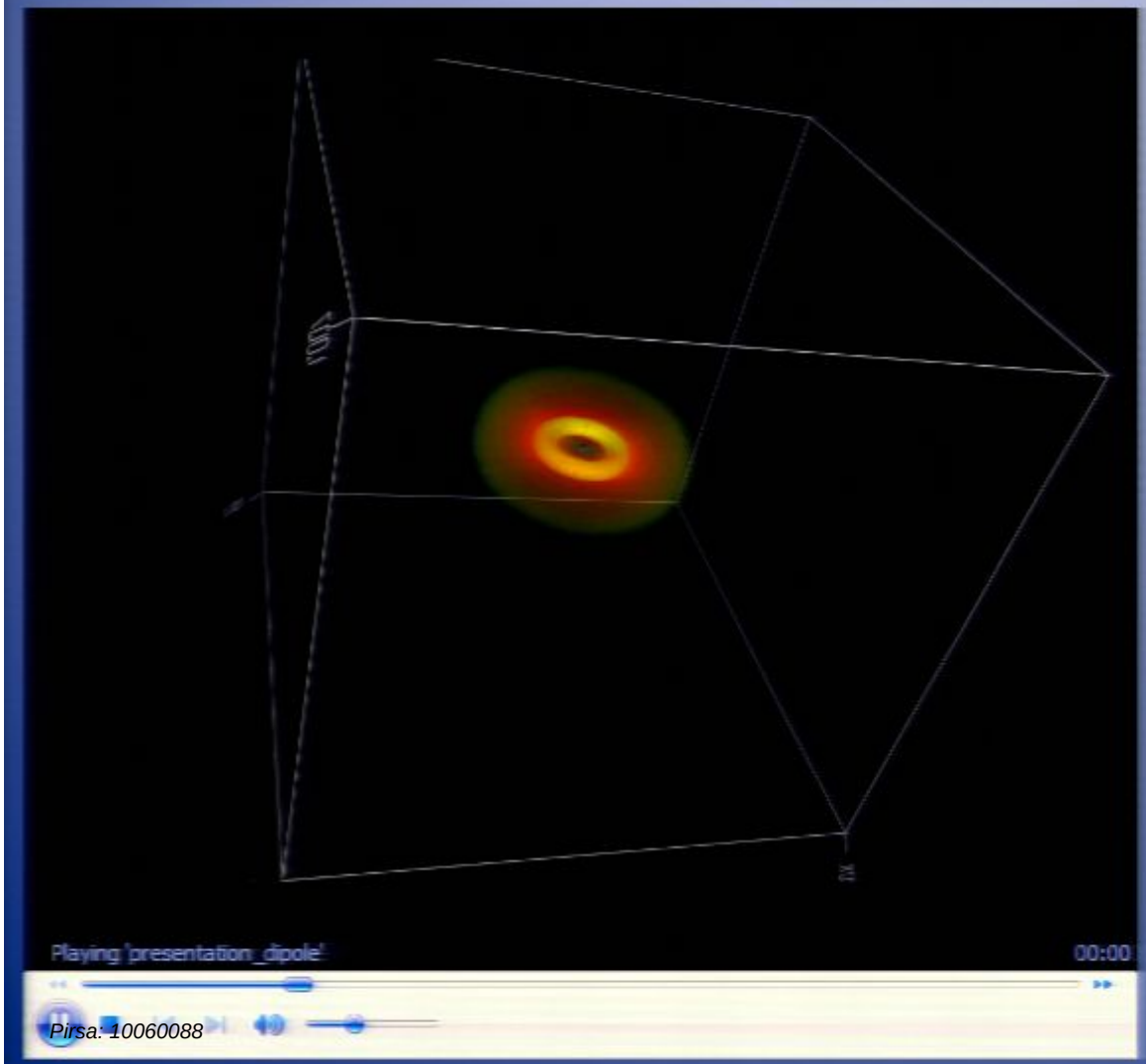

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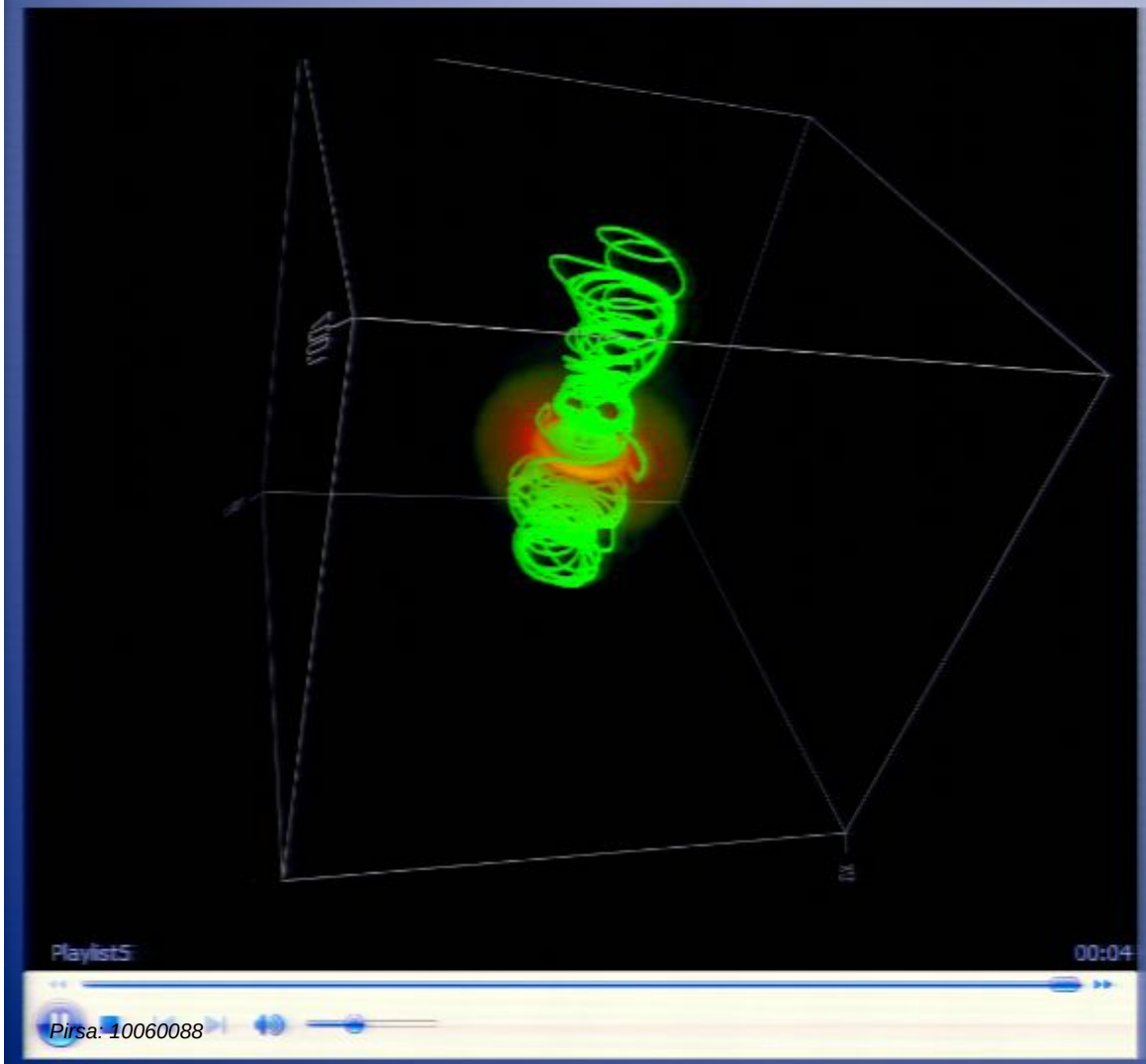

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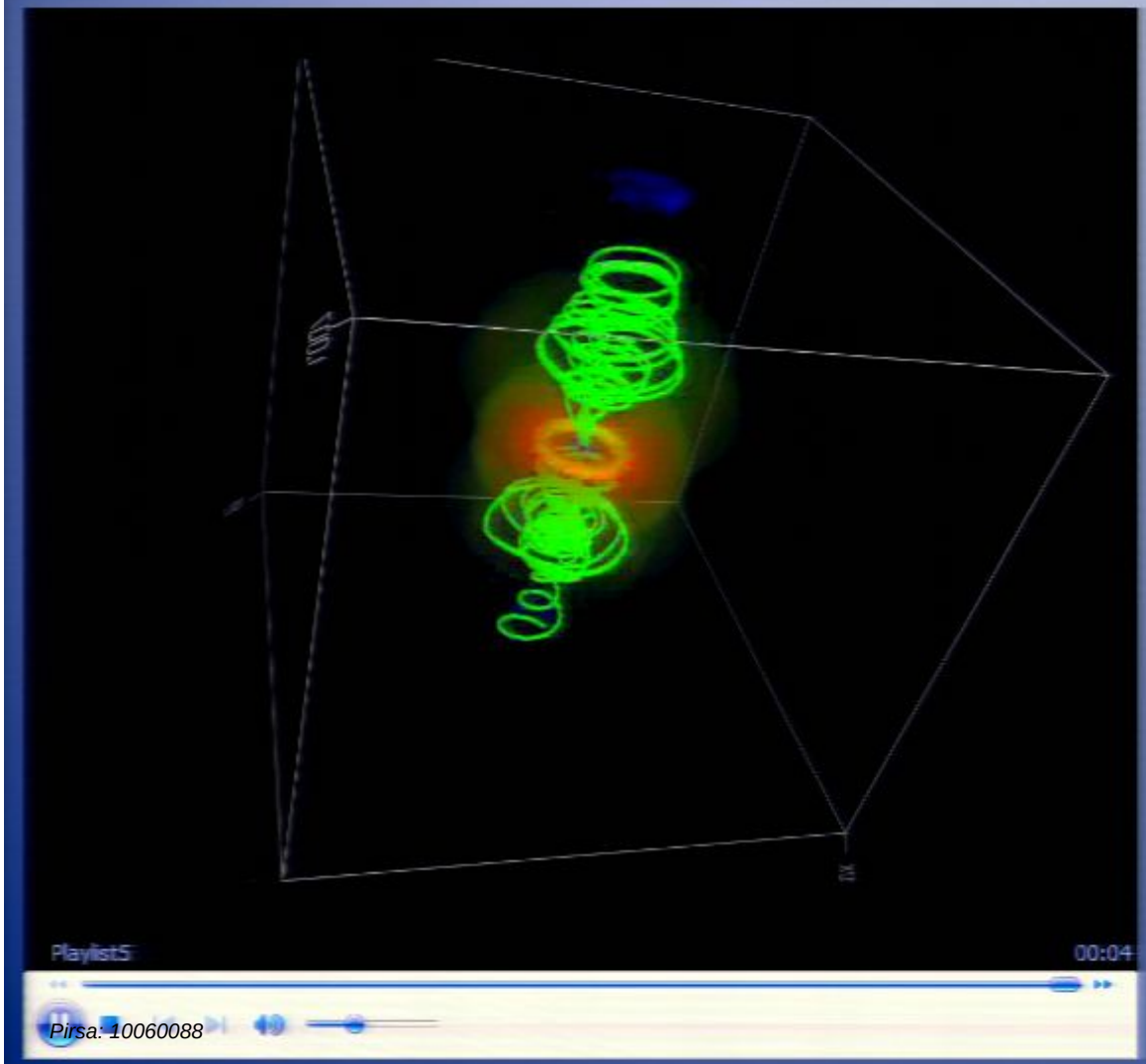

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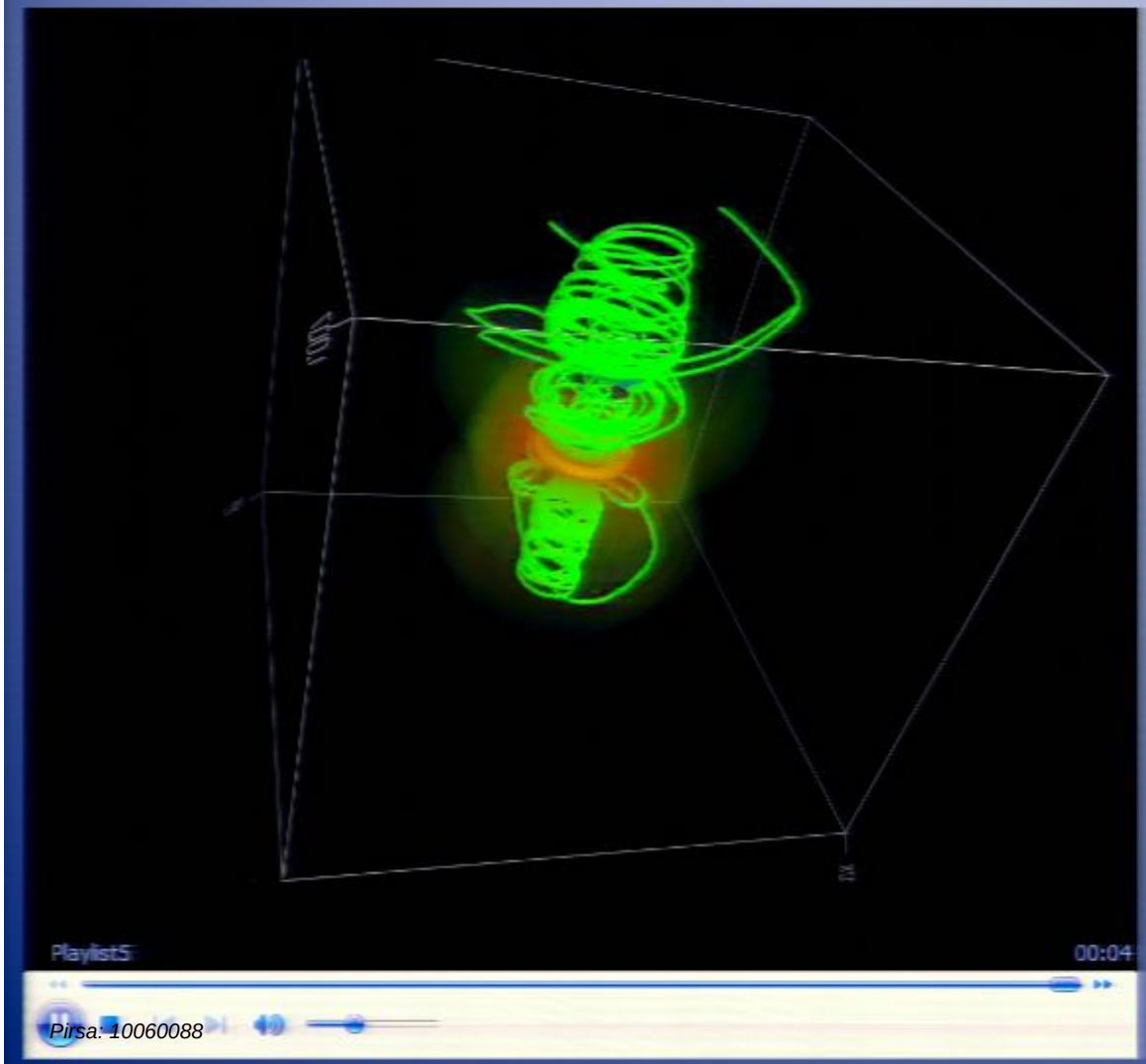

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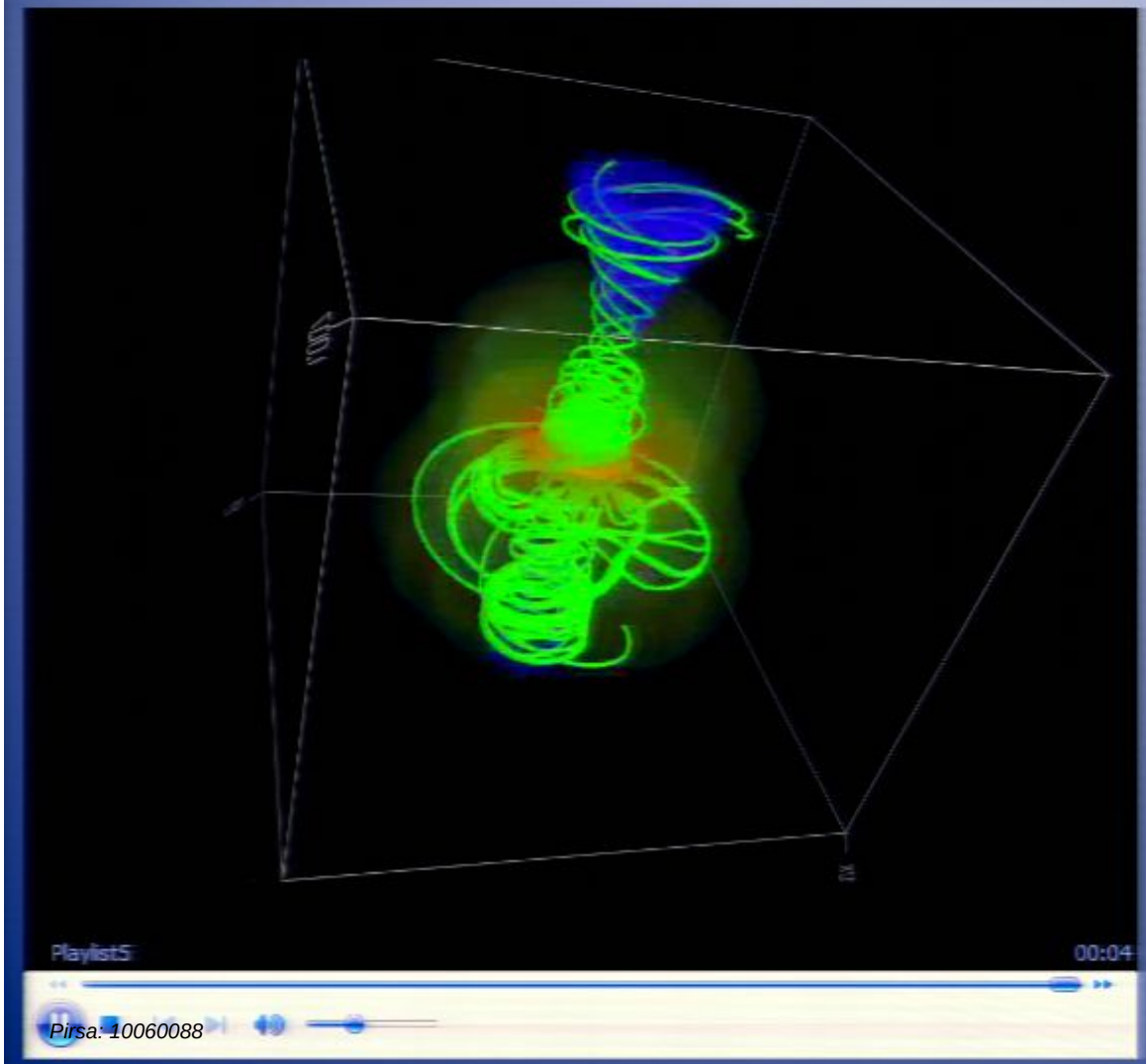

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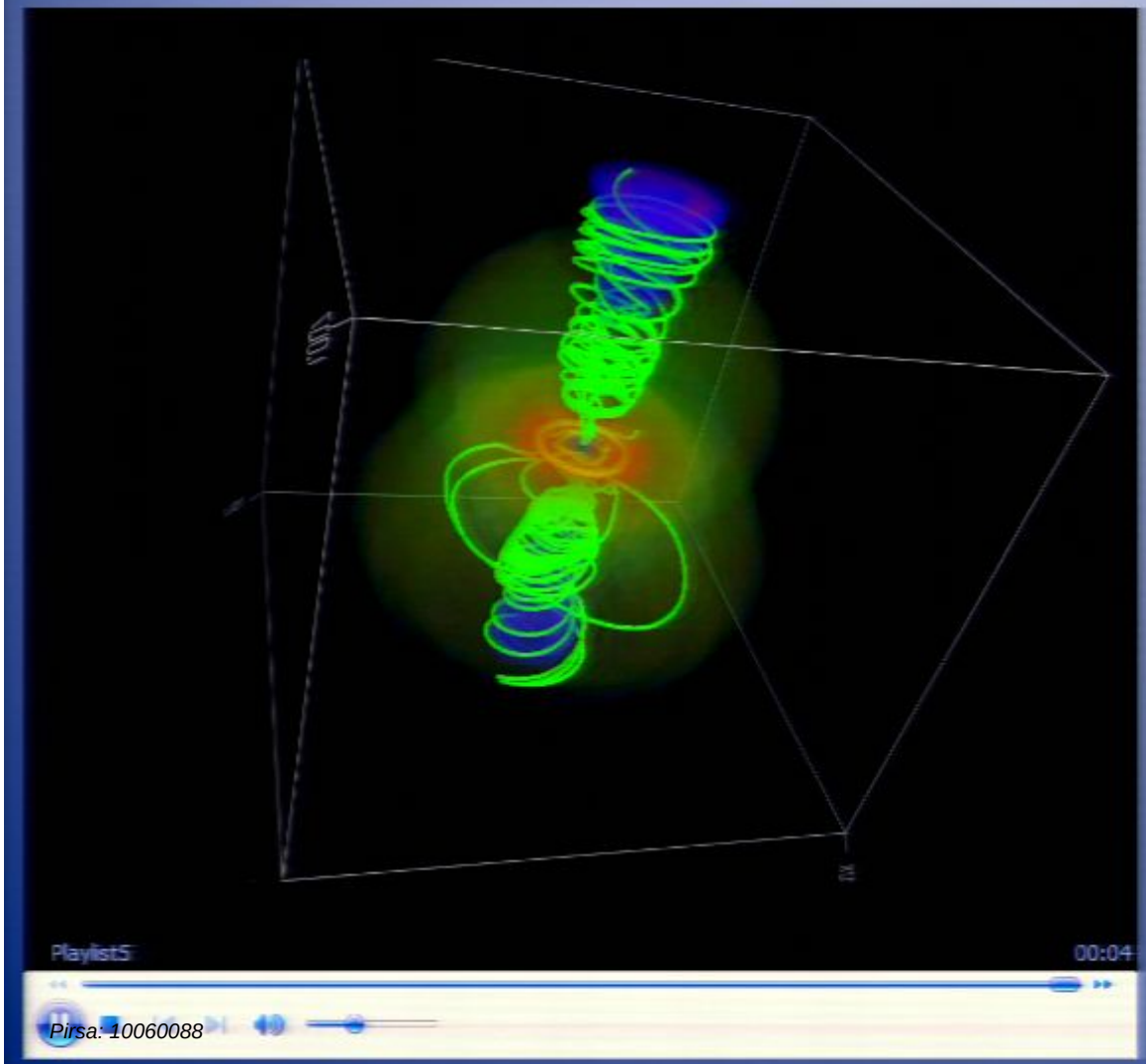

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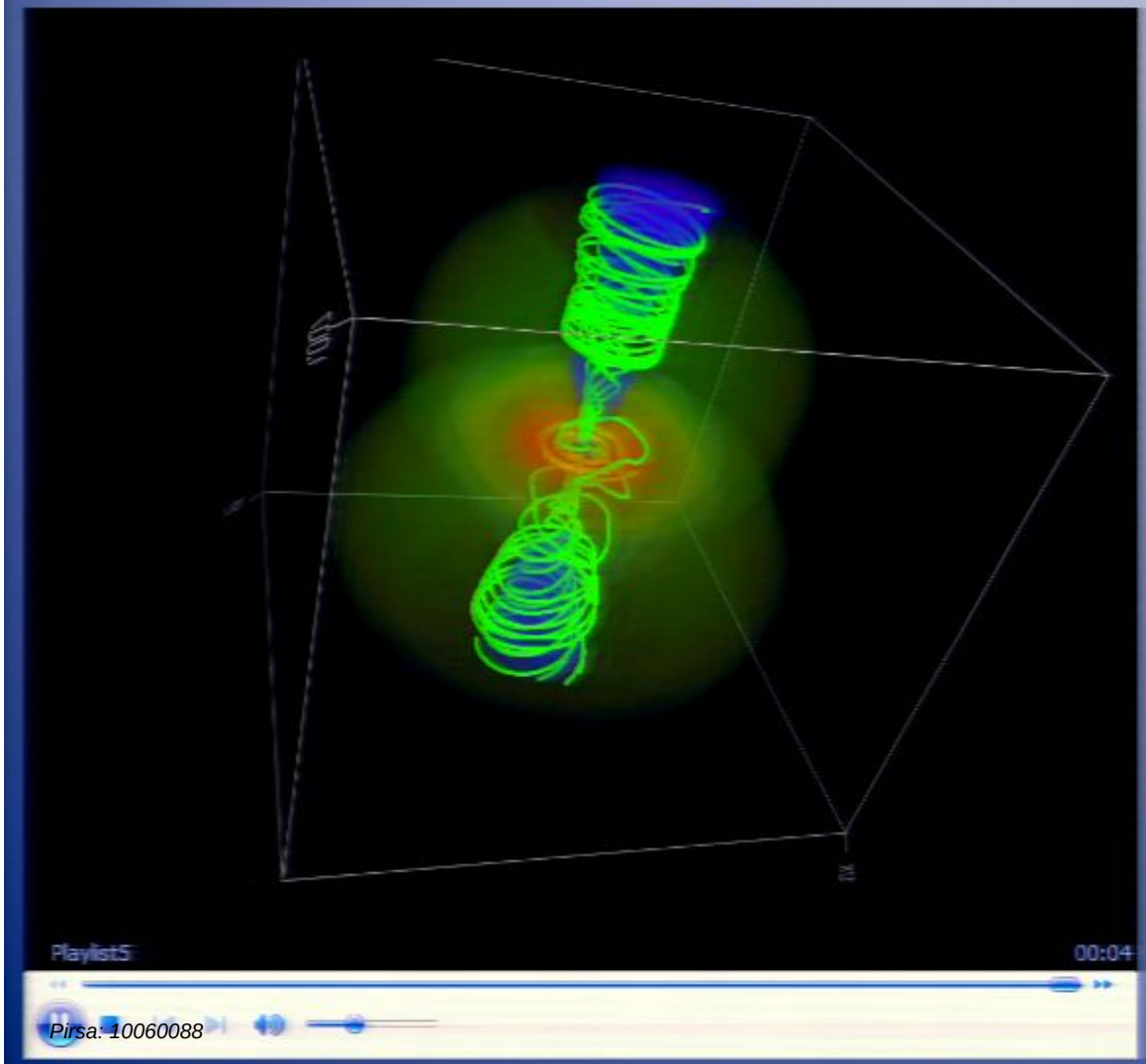

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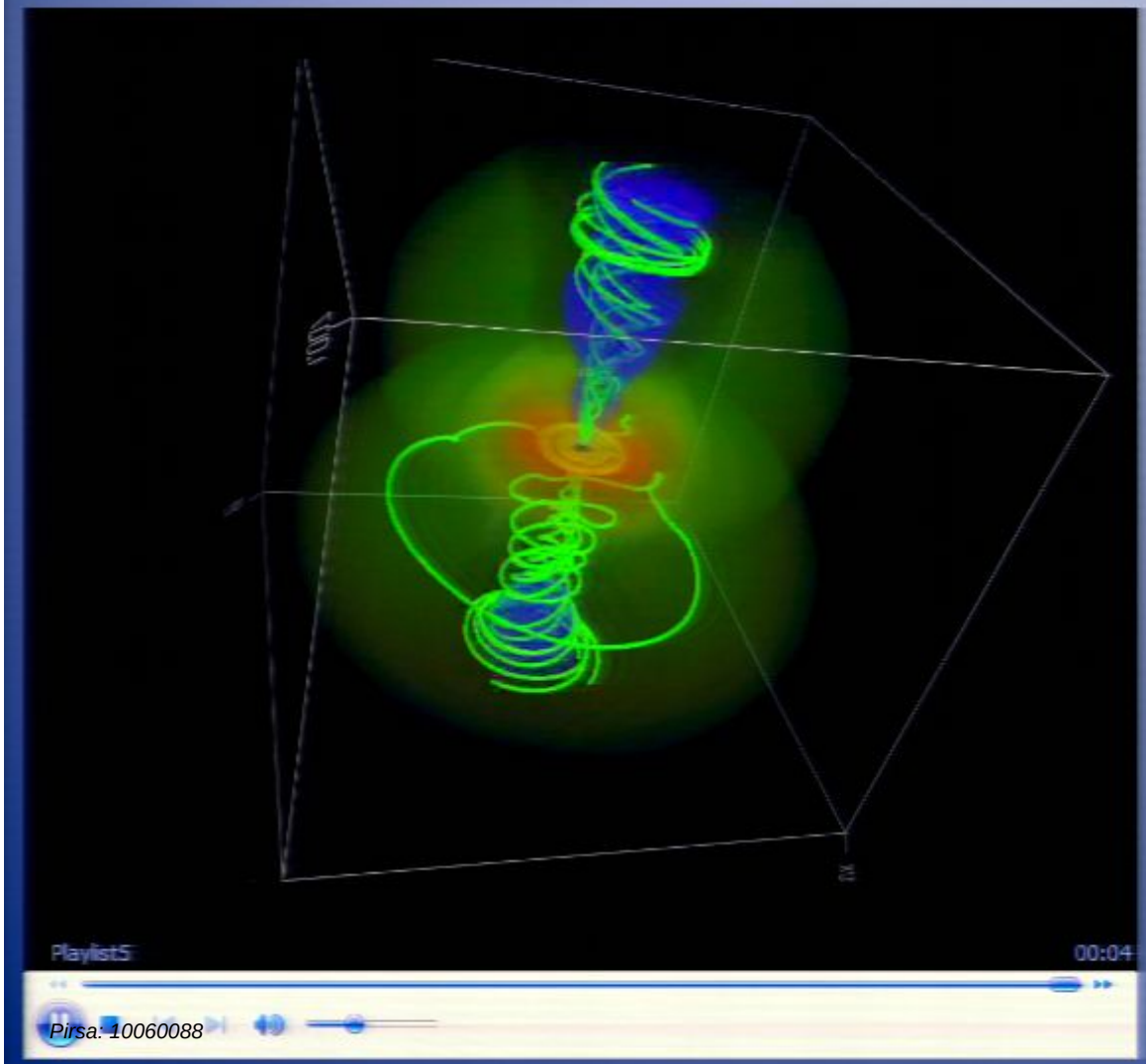

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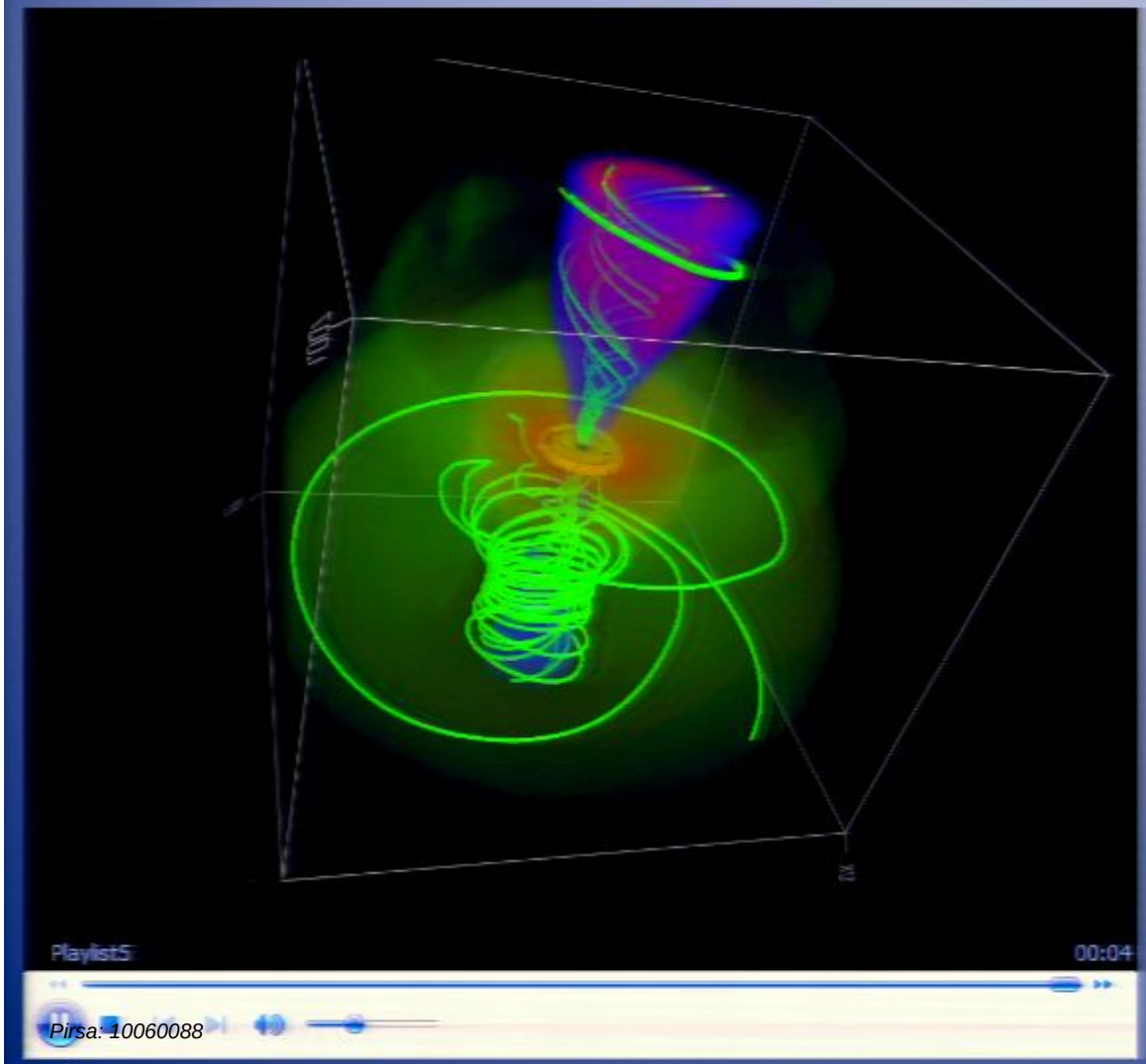

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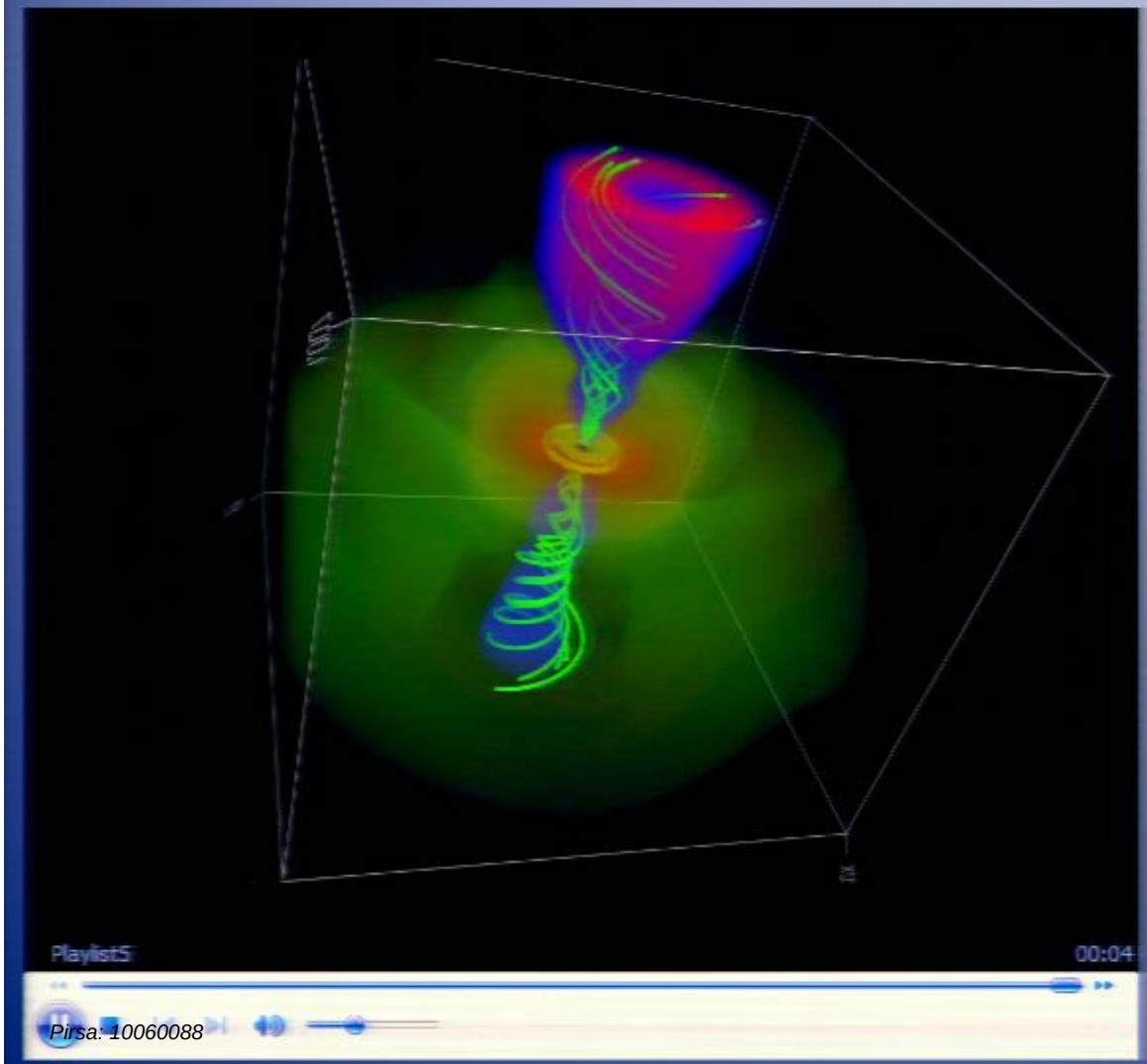

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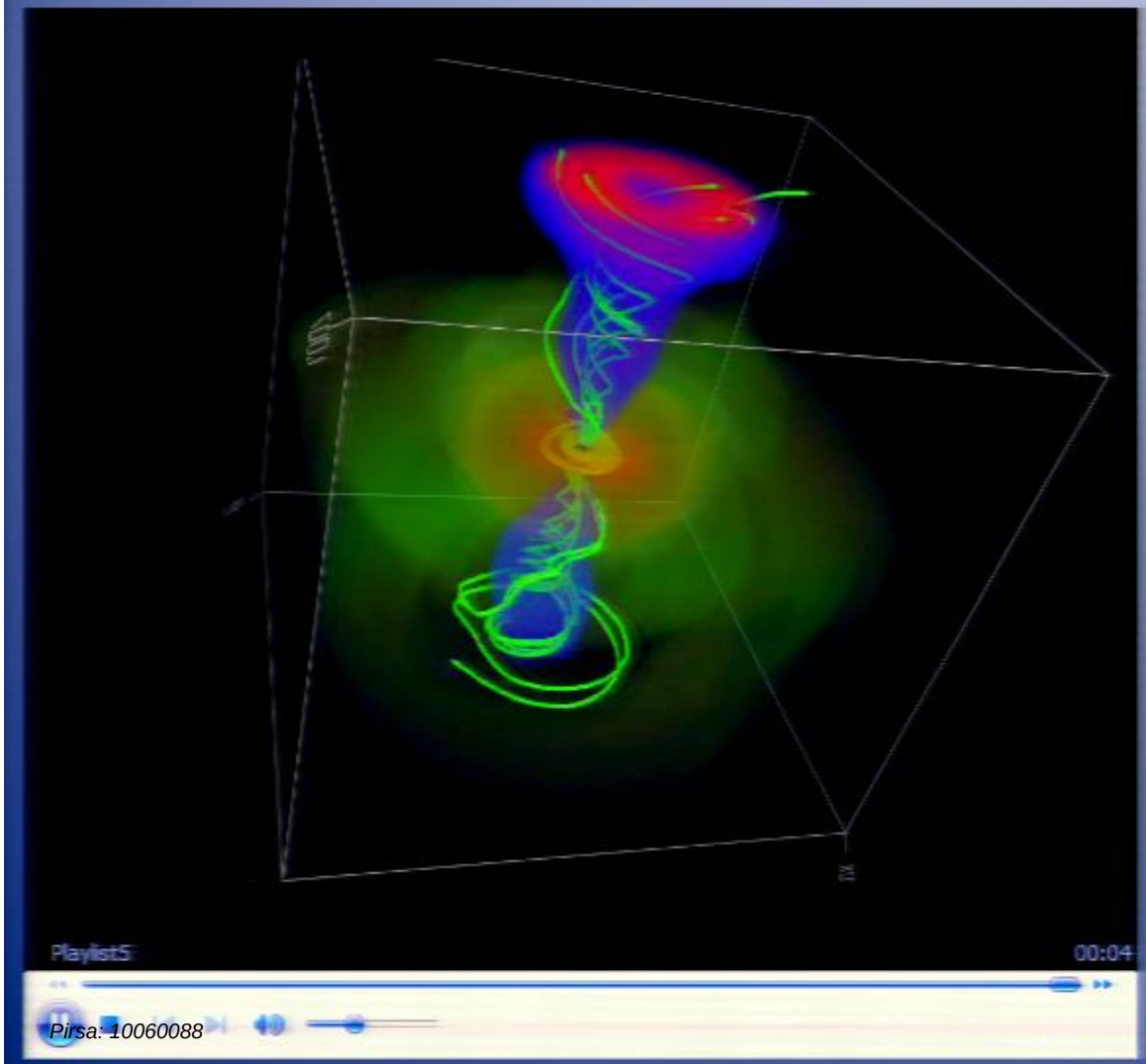

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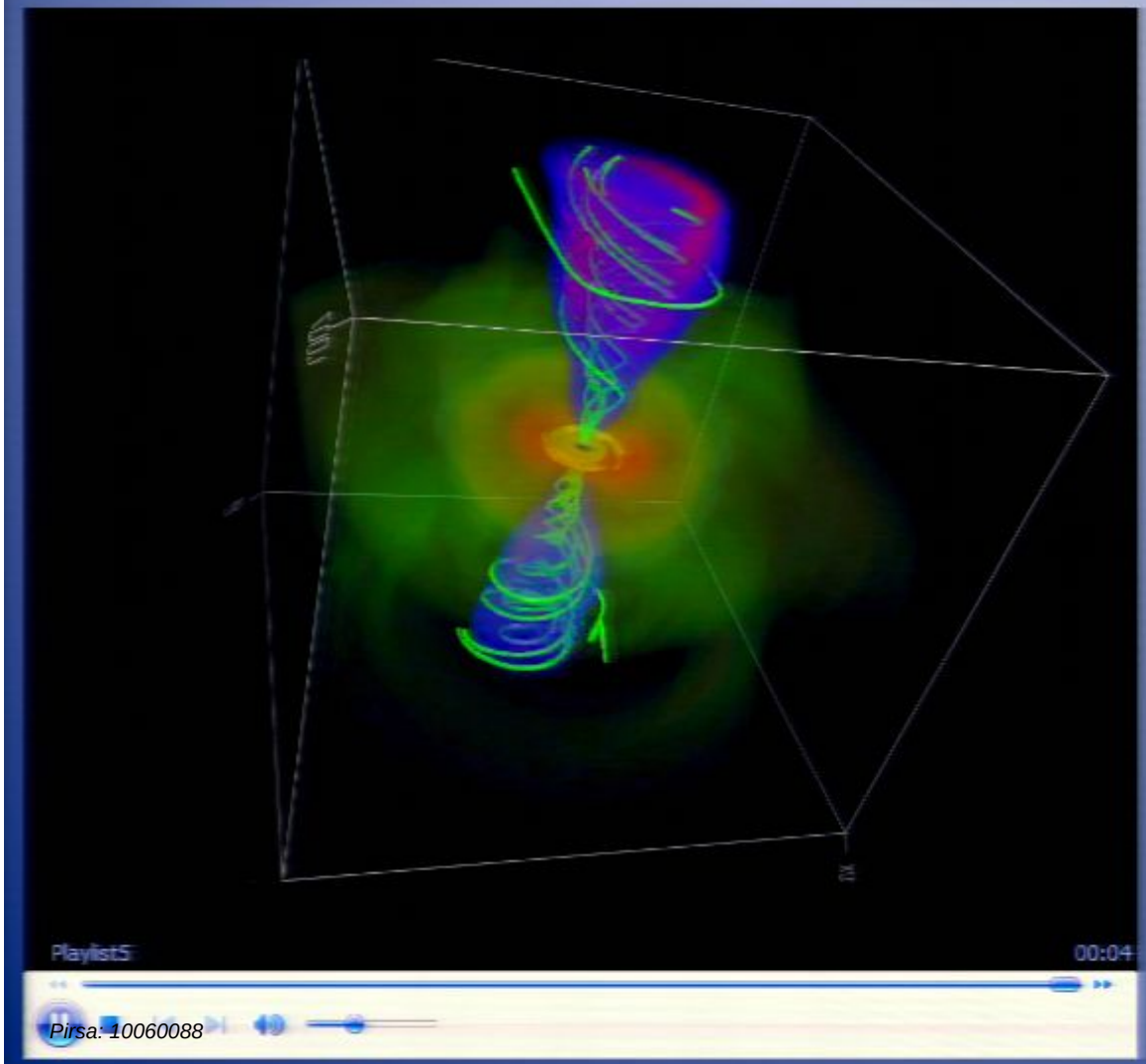

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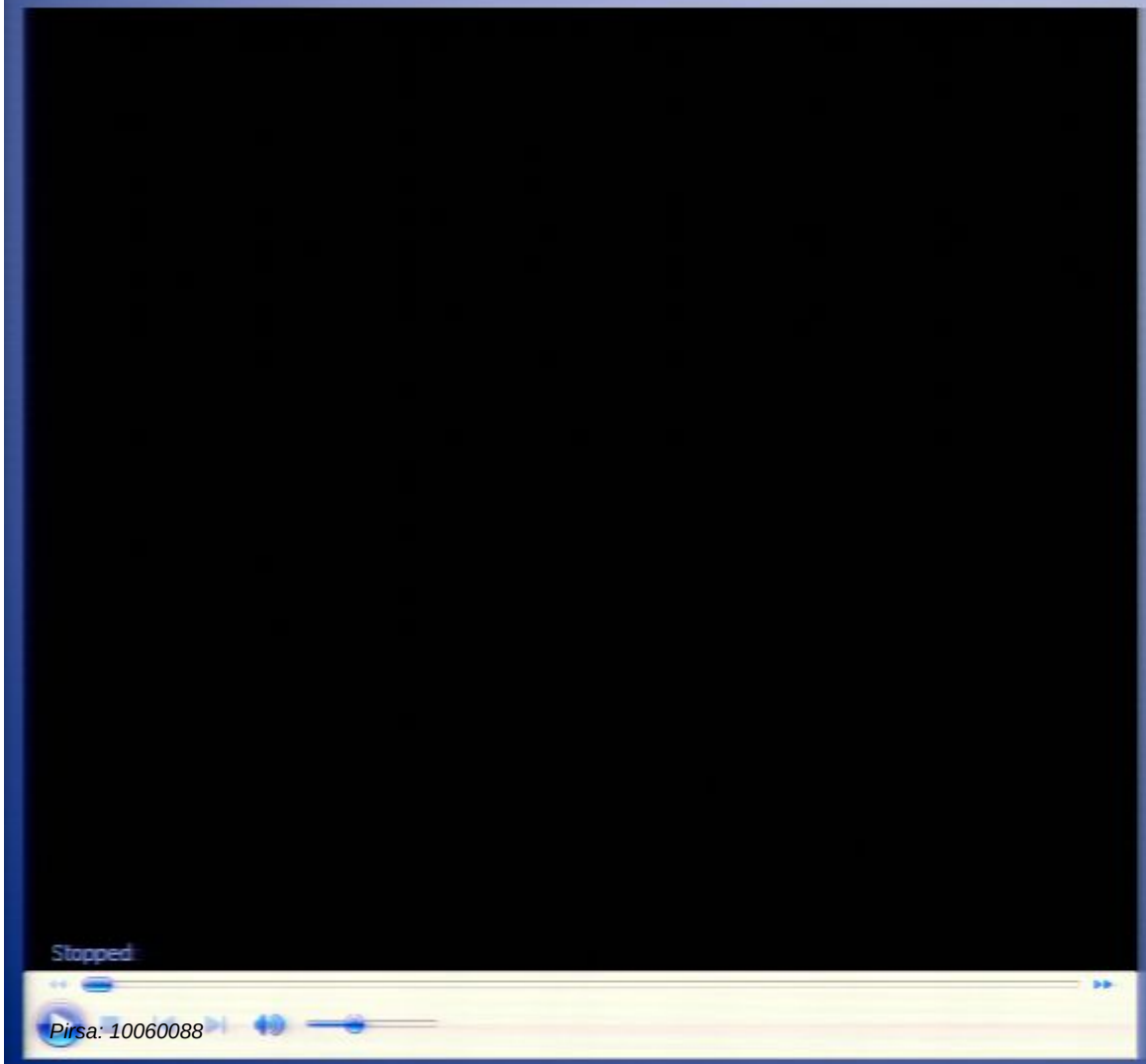

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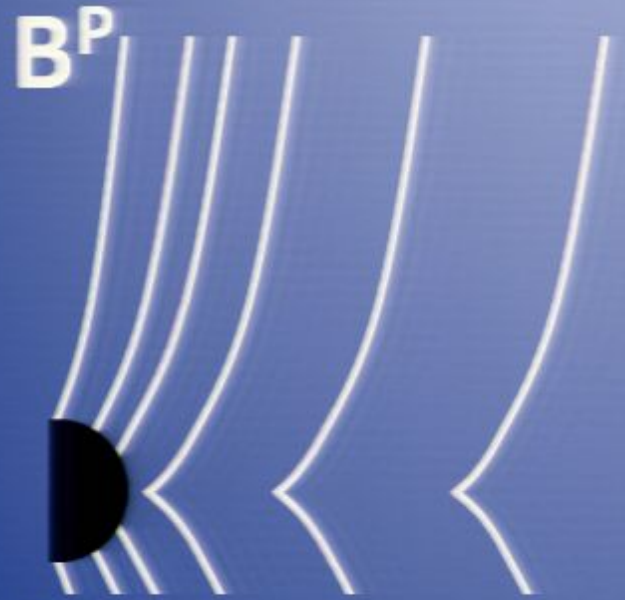

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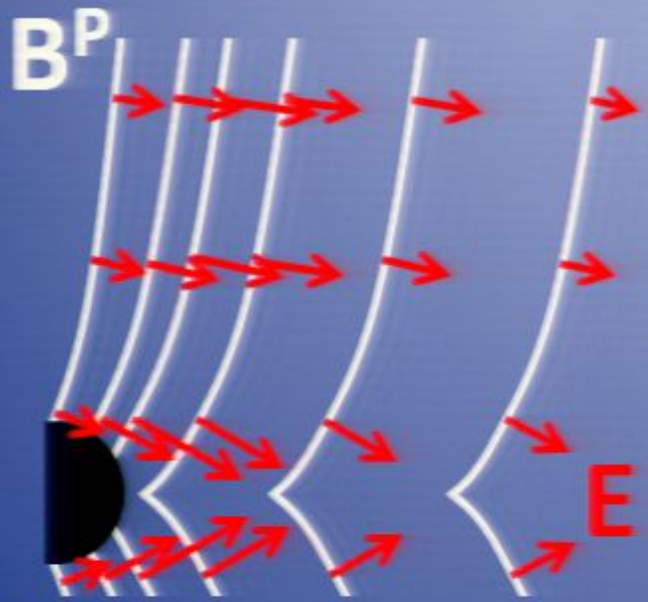

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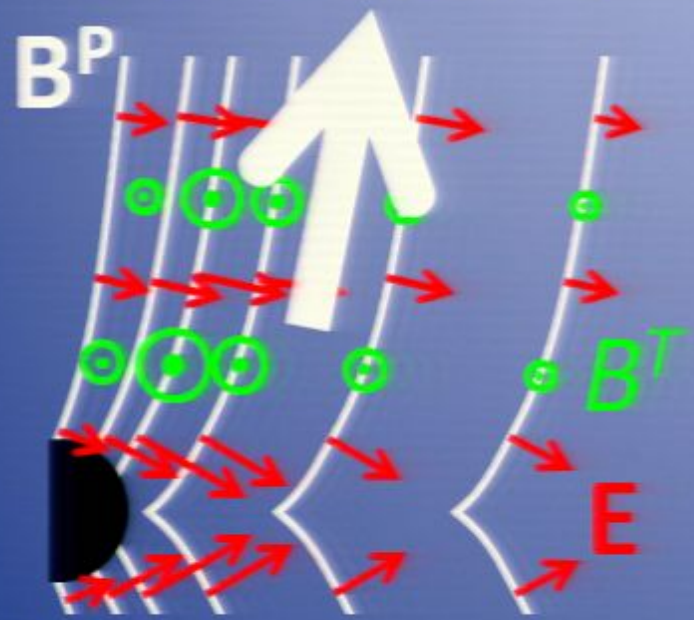

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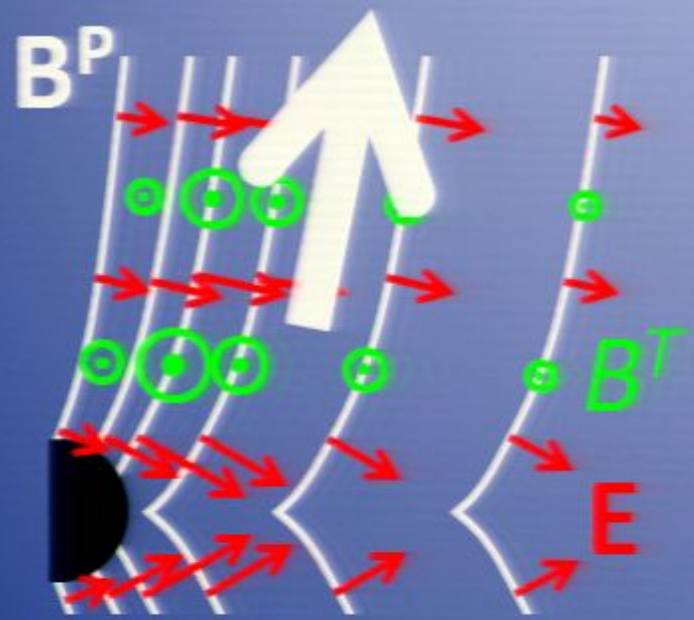

Blandford-Znajek (1977)

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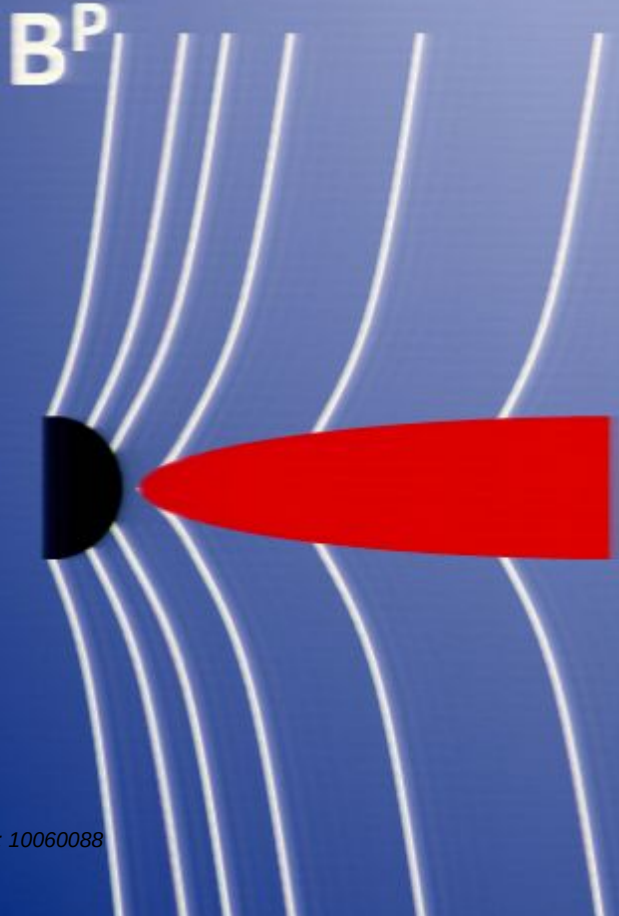

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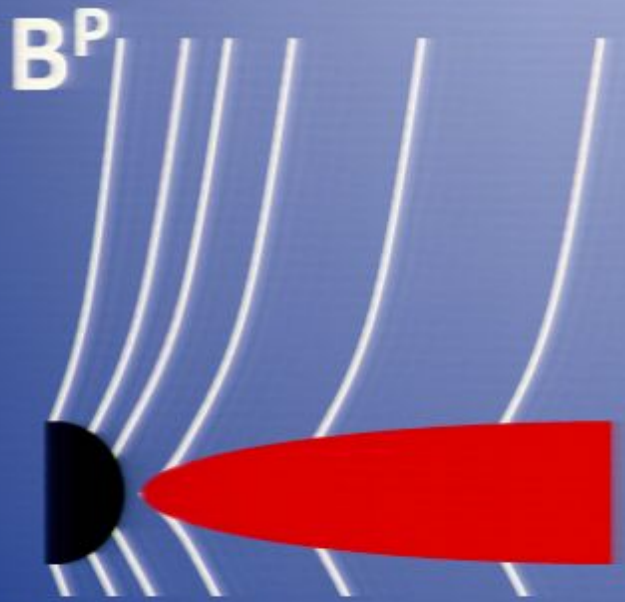

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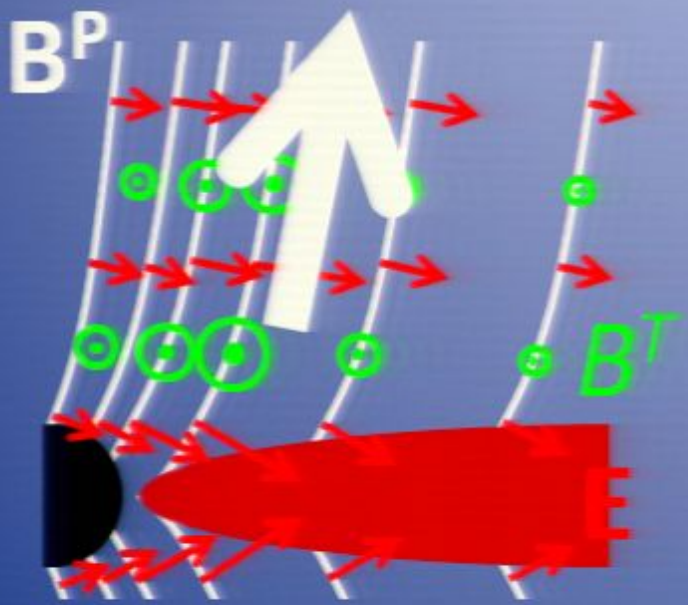

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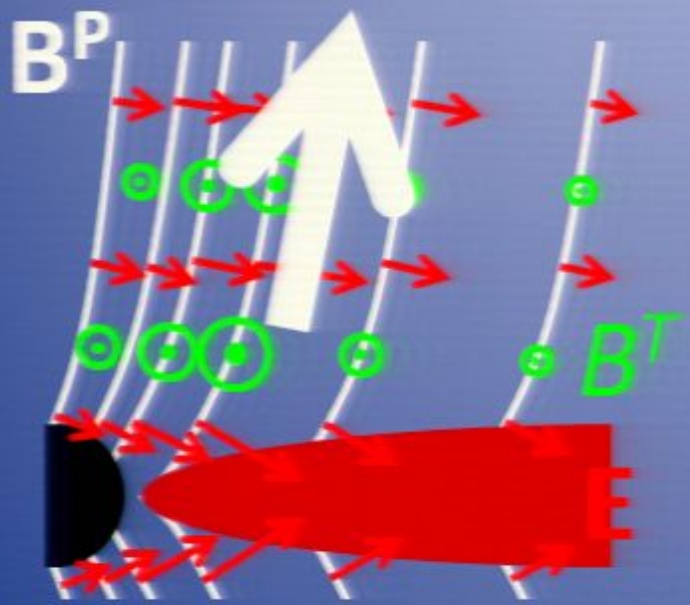

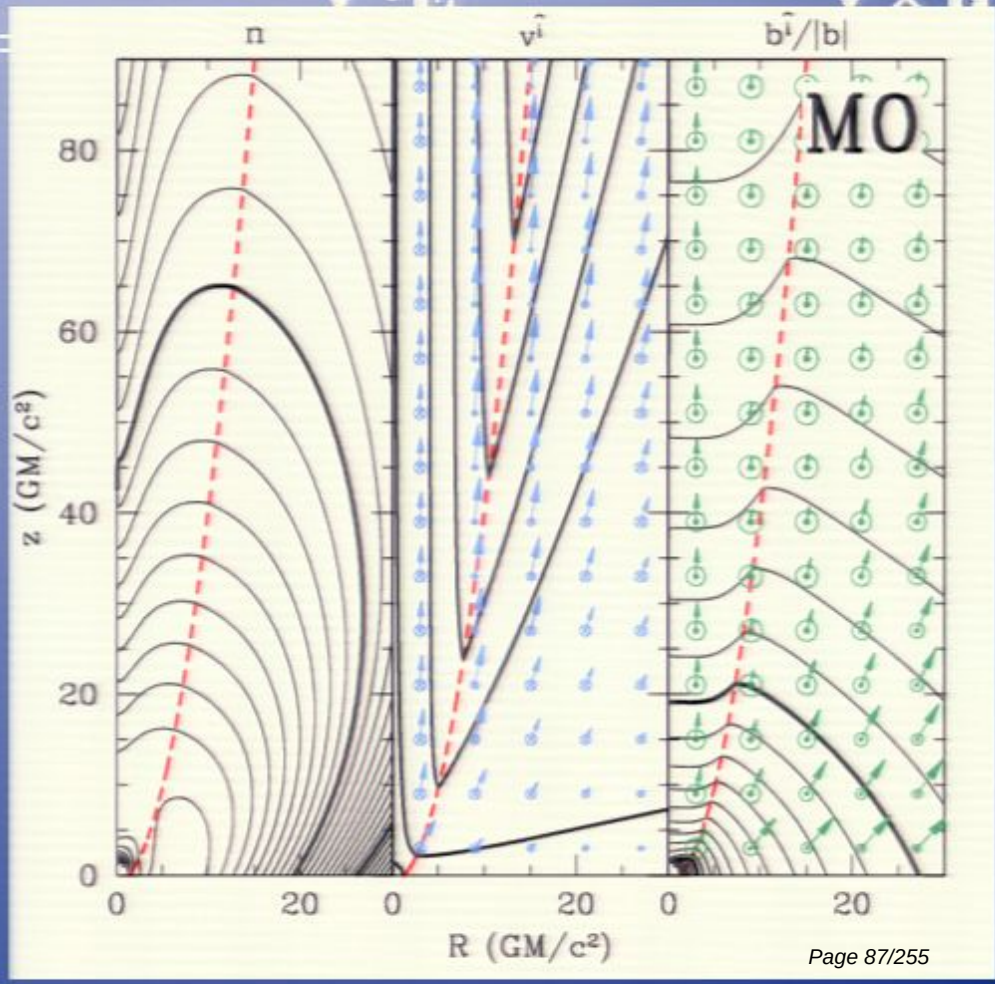

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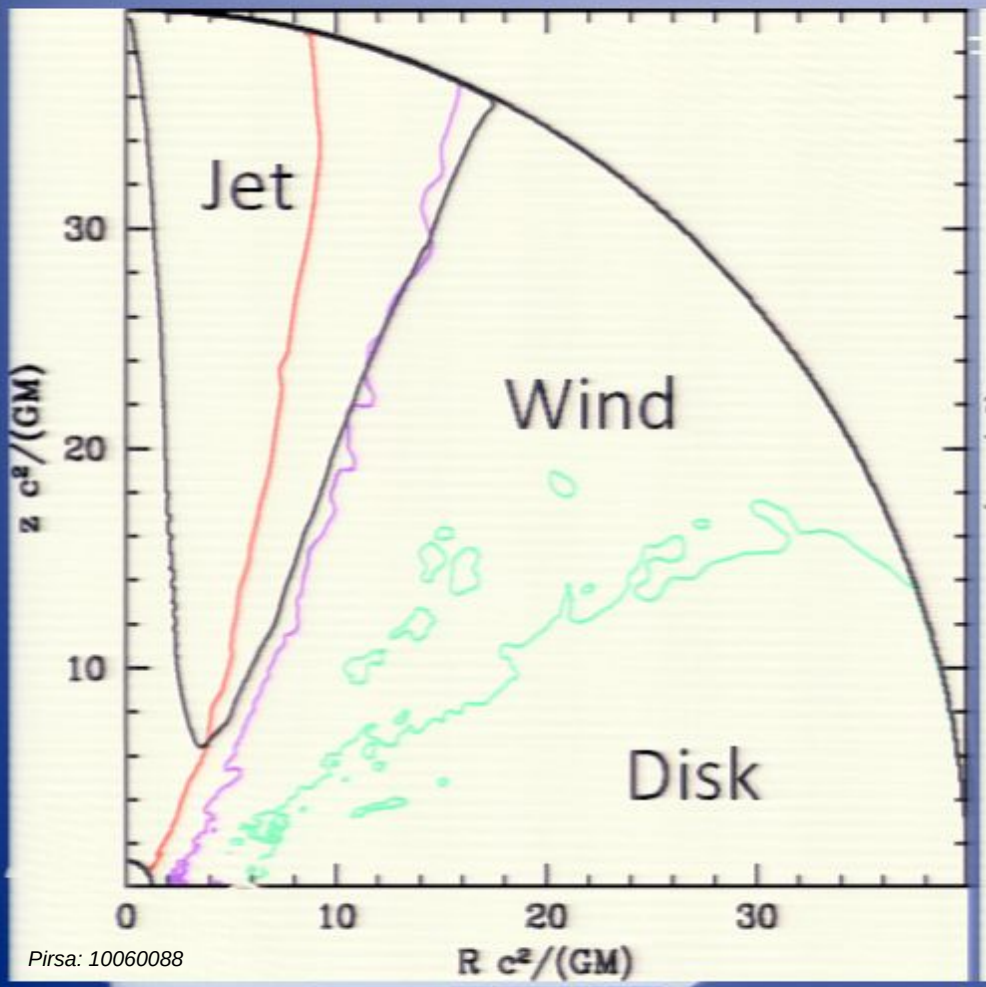

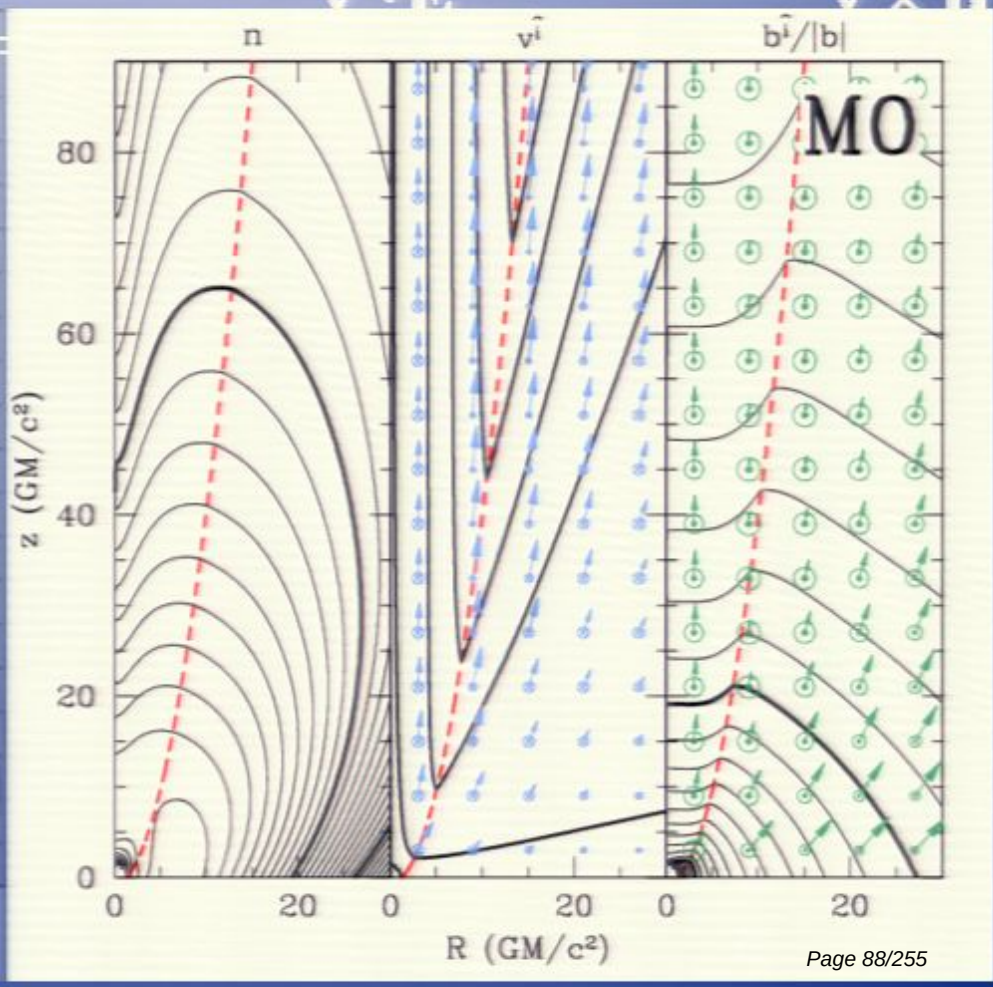

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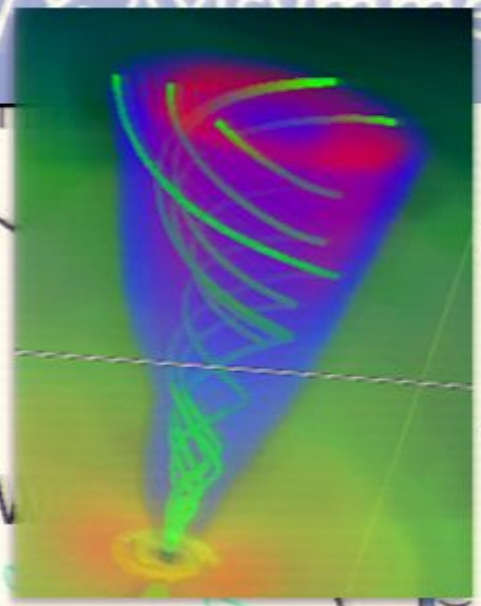
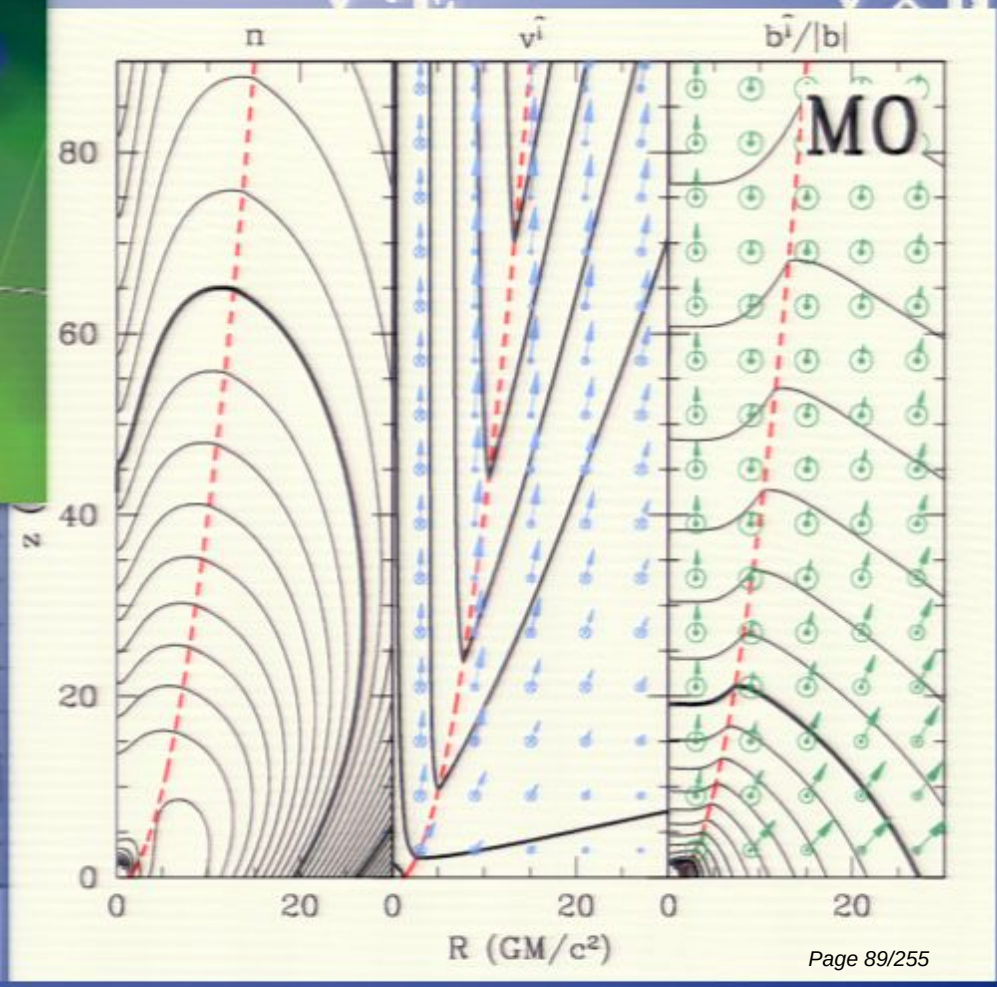
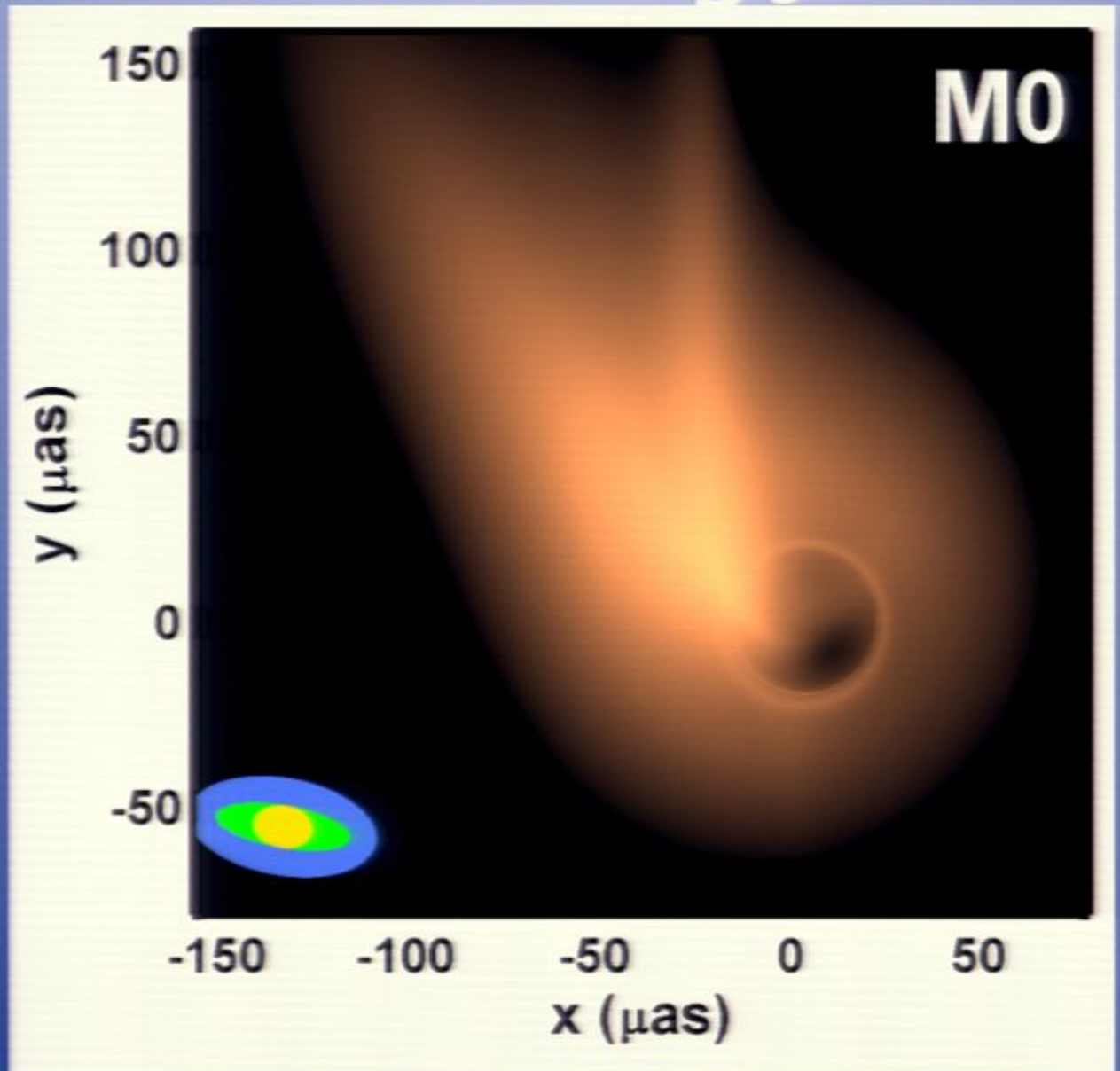




Horizon-resolving Jet Images



AEB & Loeb (2009)

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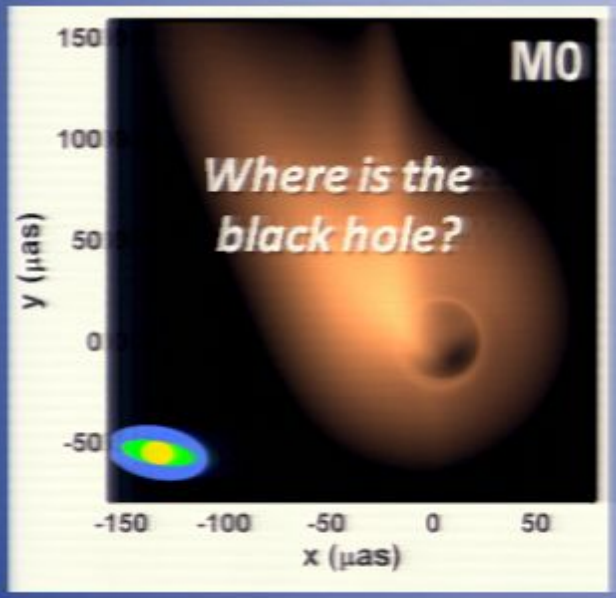

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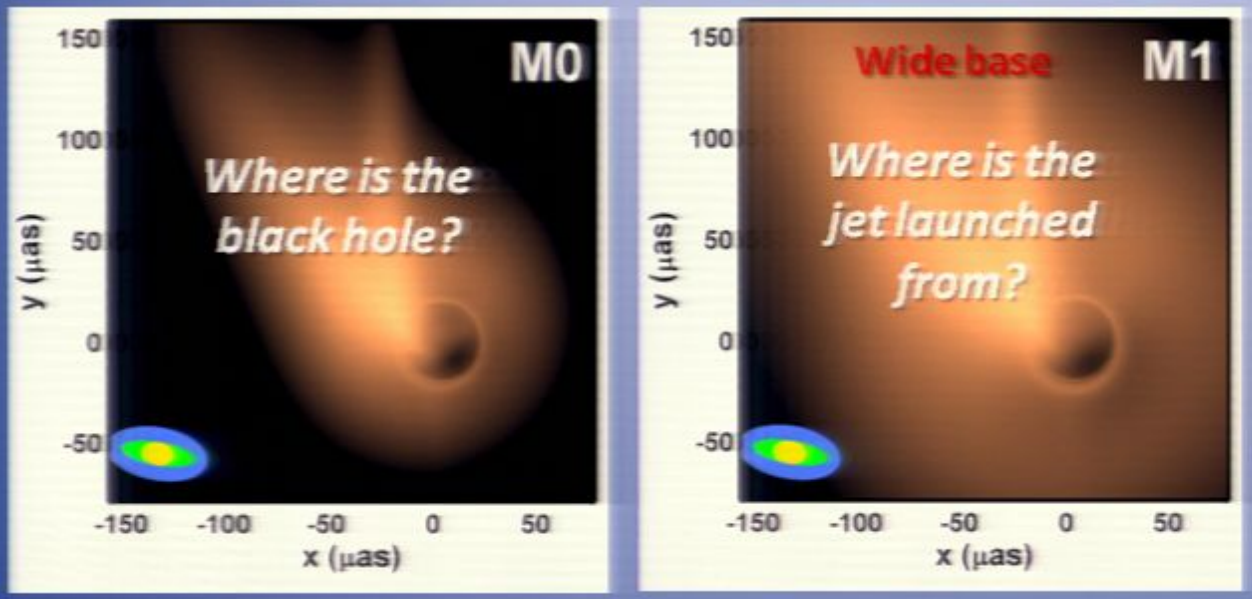

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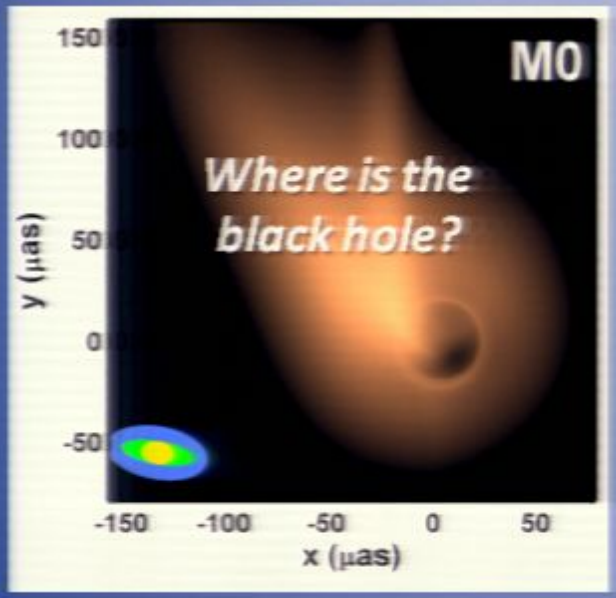

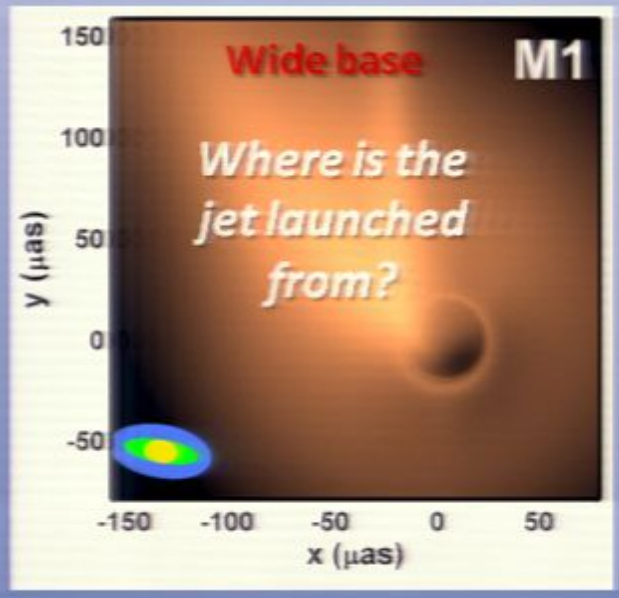

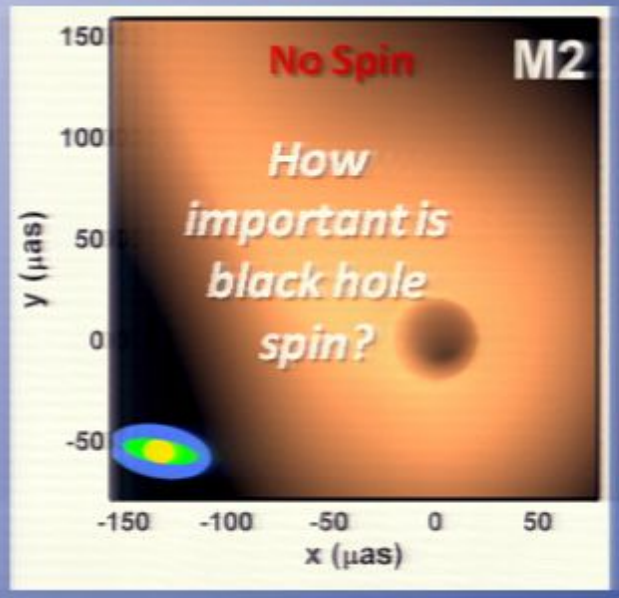

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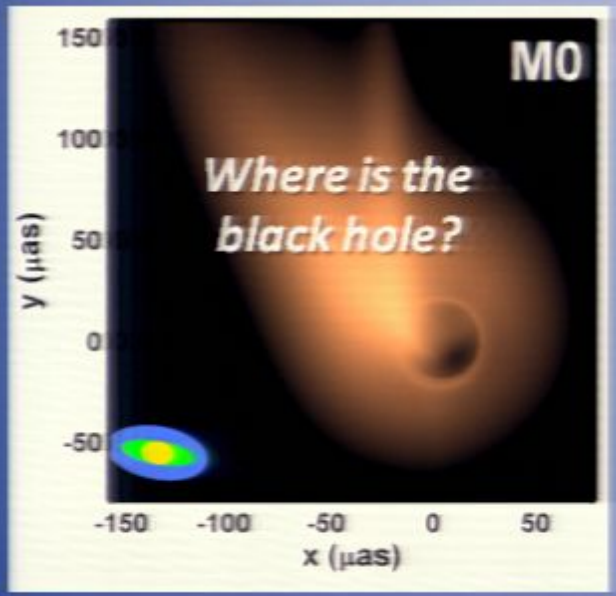
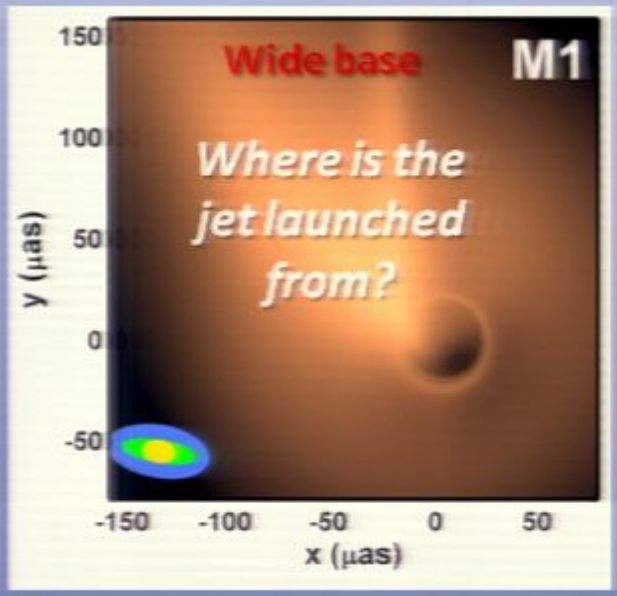
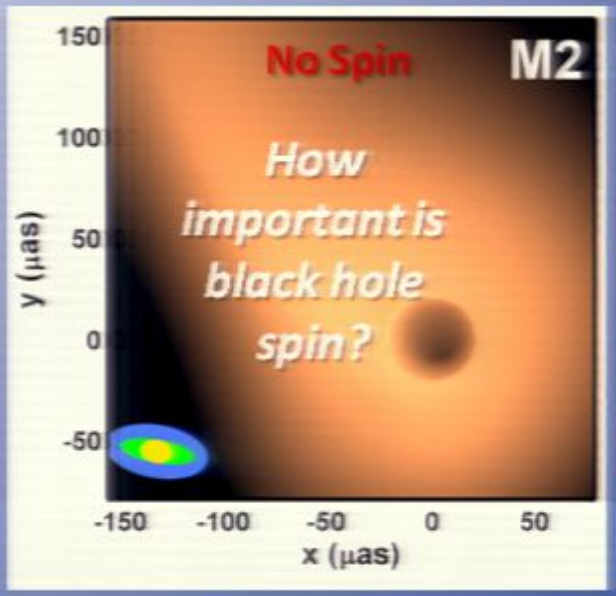
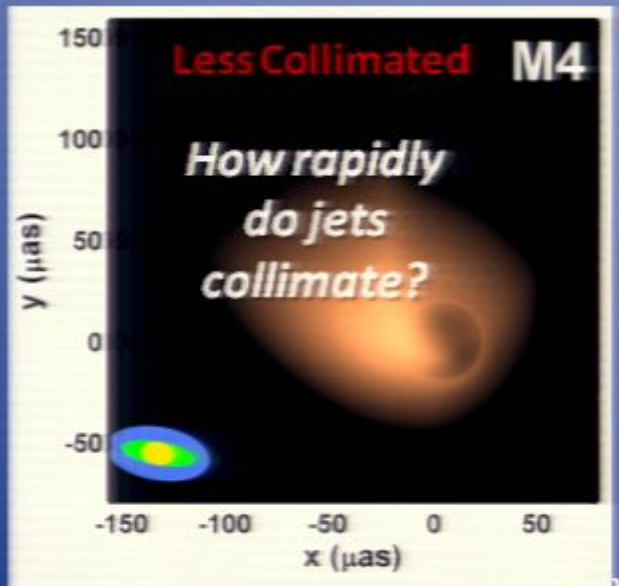
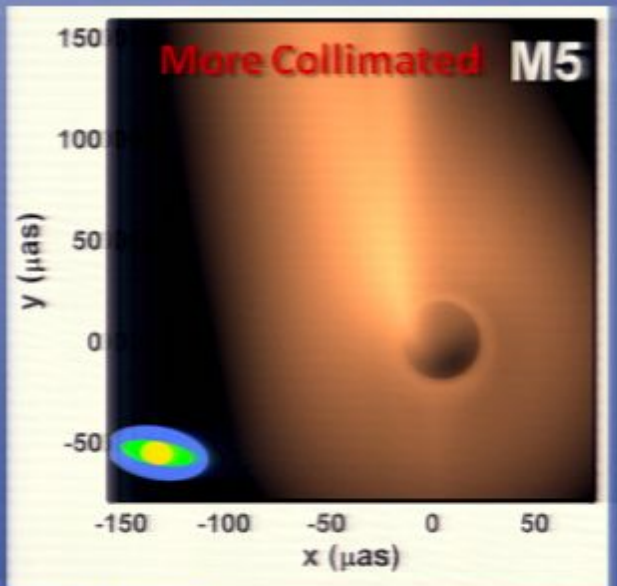










AEB & Loeb (2009)

Jets

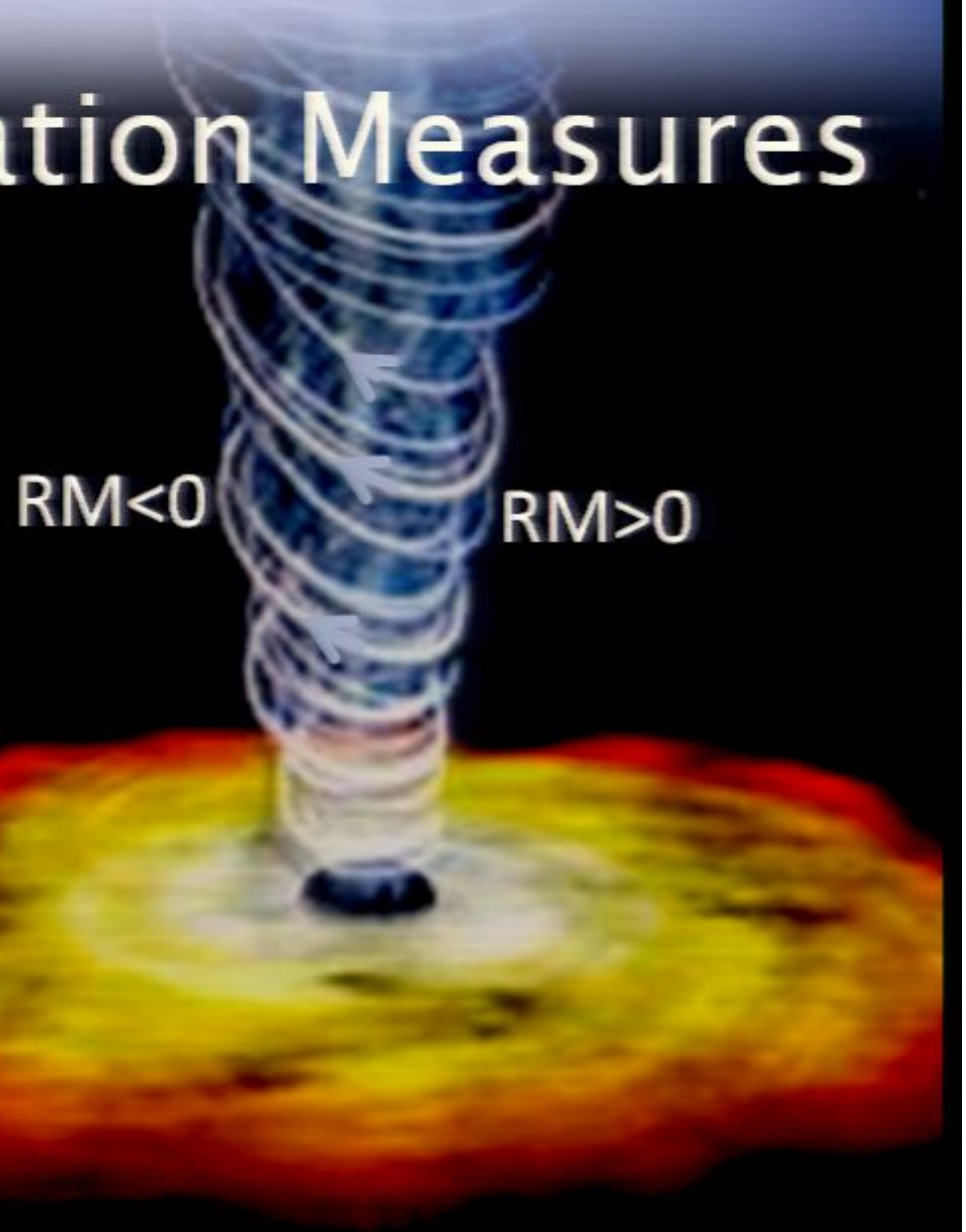
pc-scale Jet Rotation Measures

- Polarization effect due to magnetized plasma

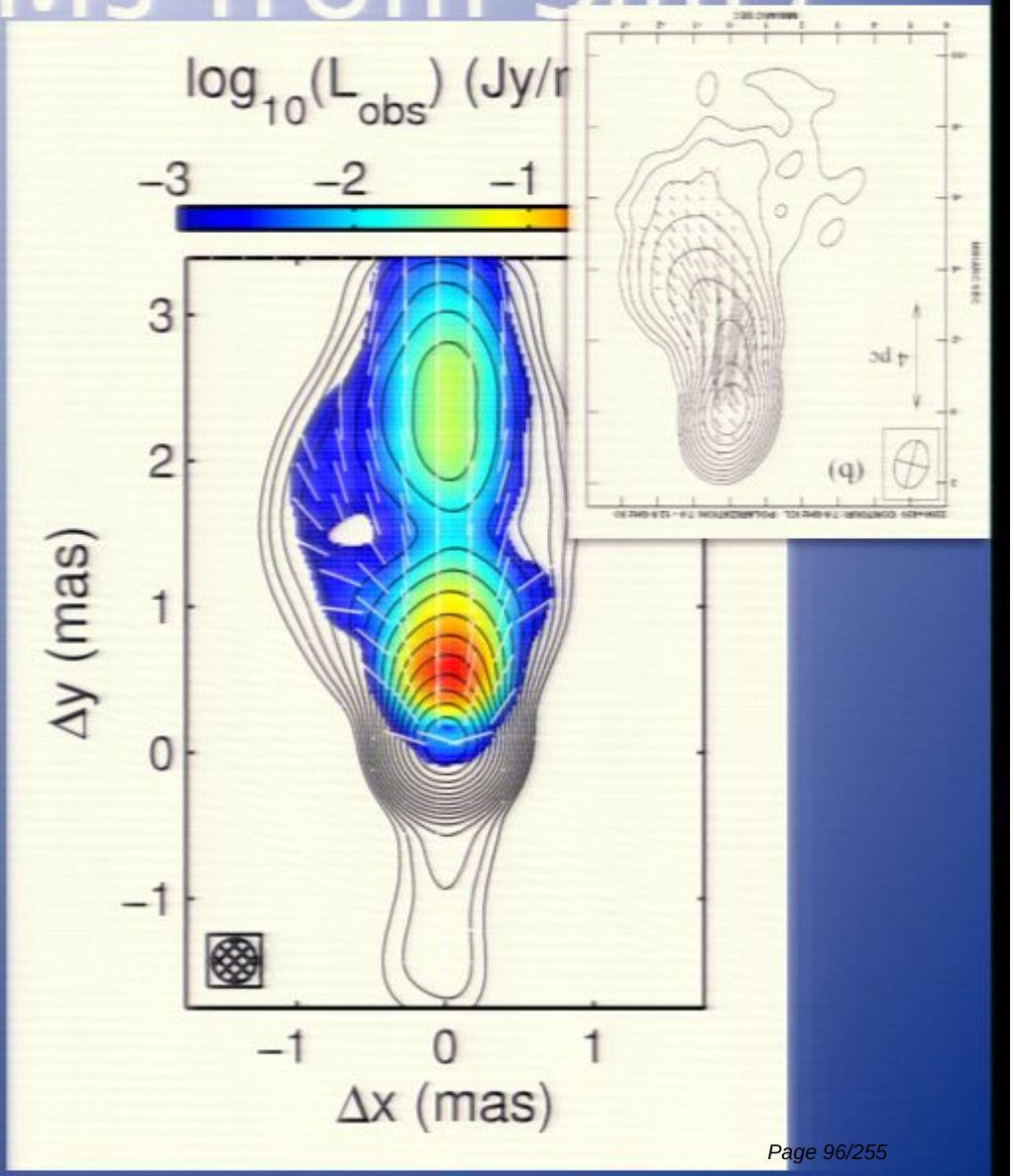
$$\Delta\Psi \approx \lambda^2 \int n\,\mathbf{B}\cdot\mathbf{dl}$$

- Probes line-of-sight magnetic field (sort of)

- Toroidal fields in jets
  → transverse gradients in jet RM maps!



pc-scale Jet RMs from Sims



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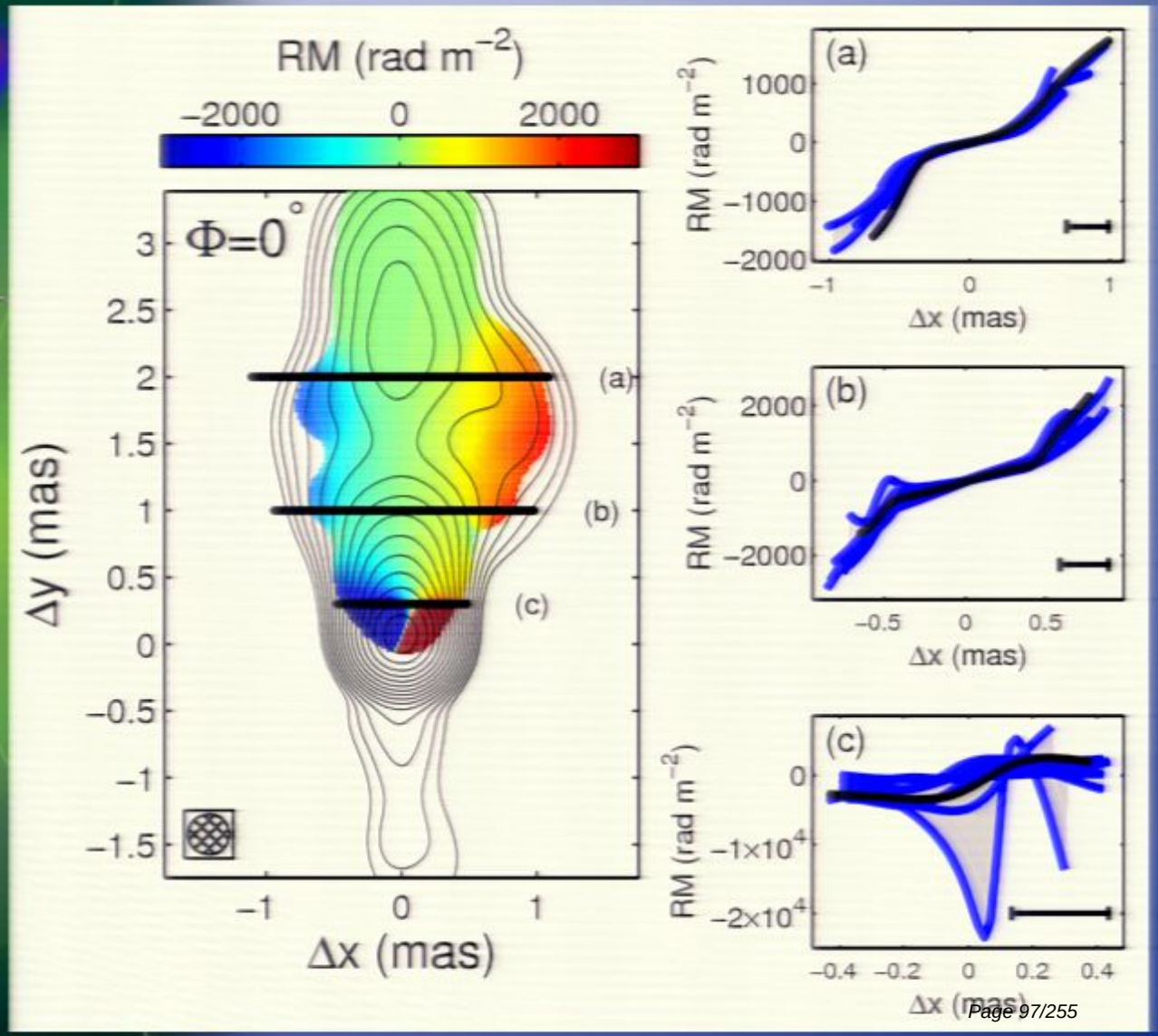

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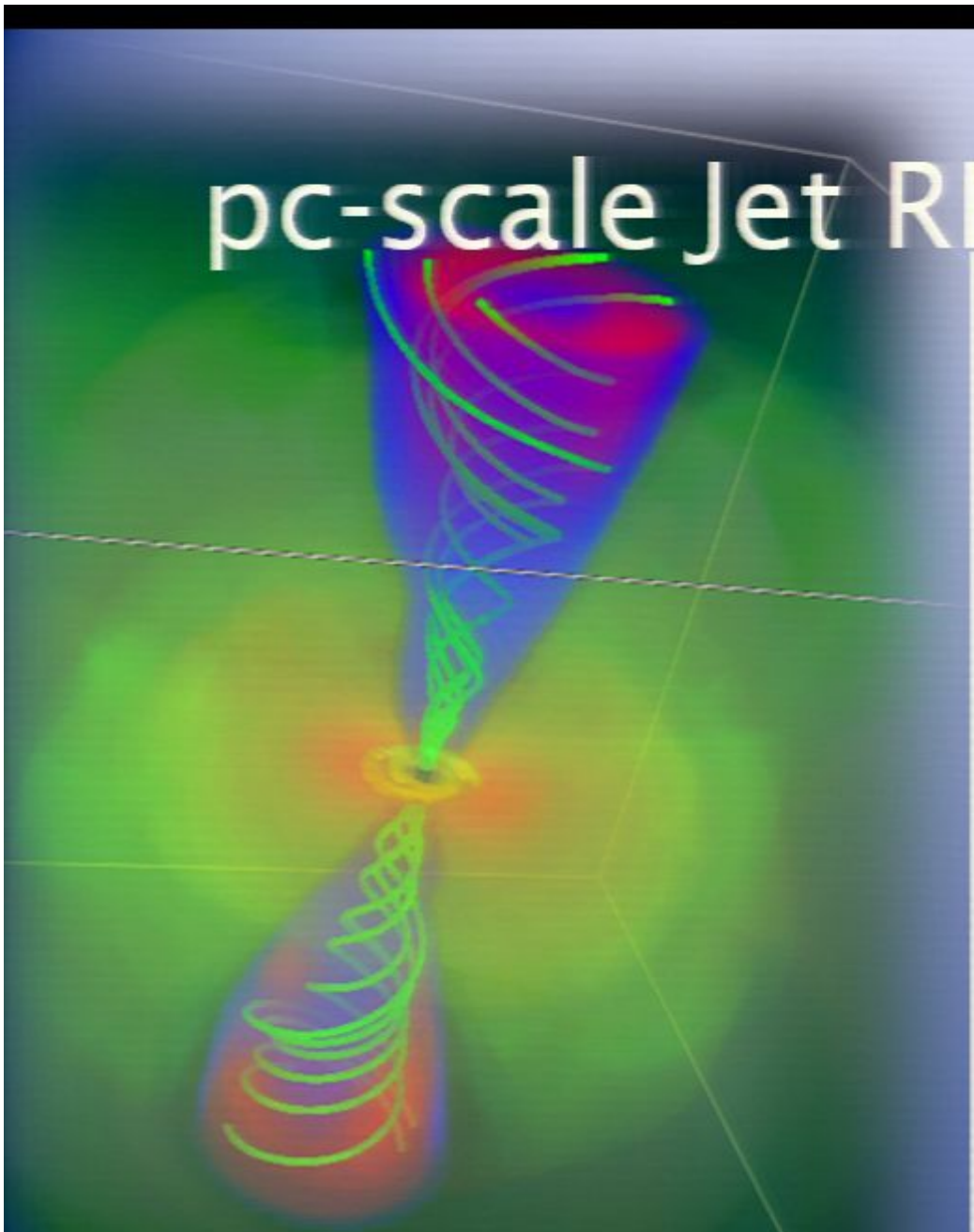

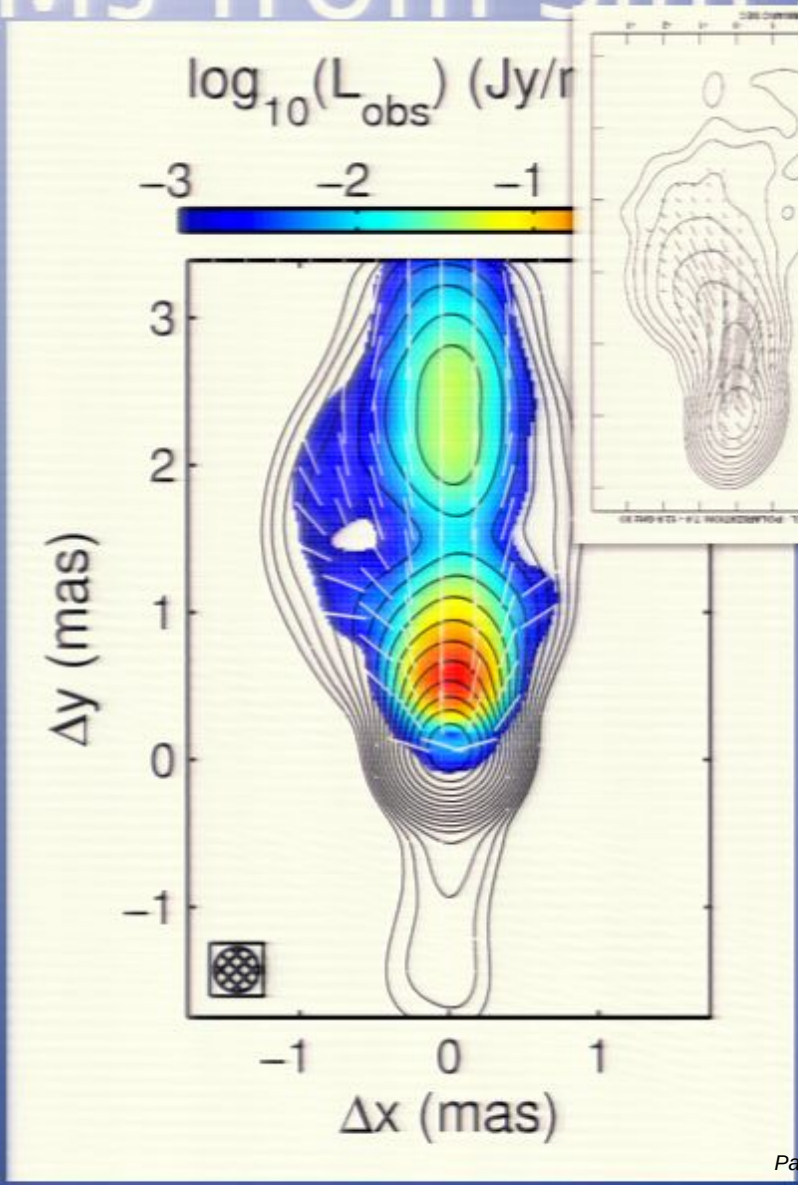

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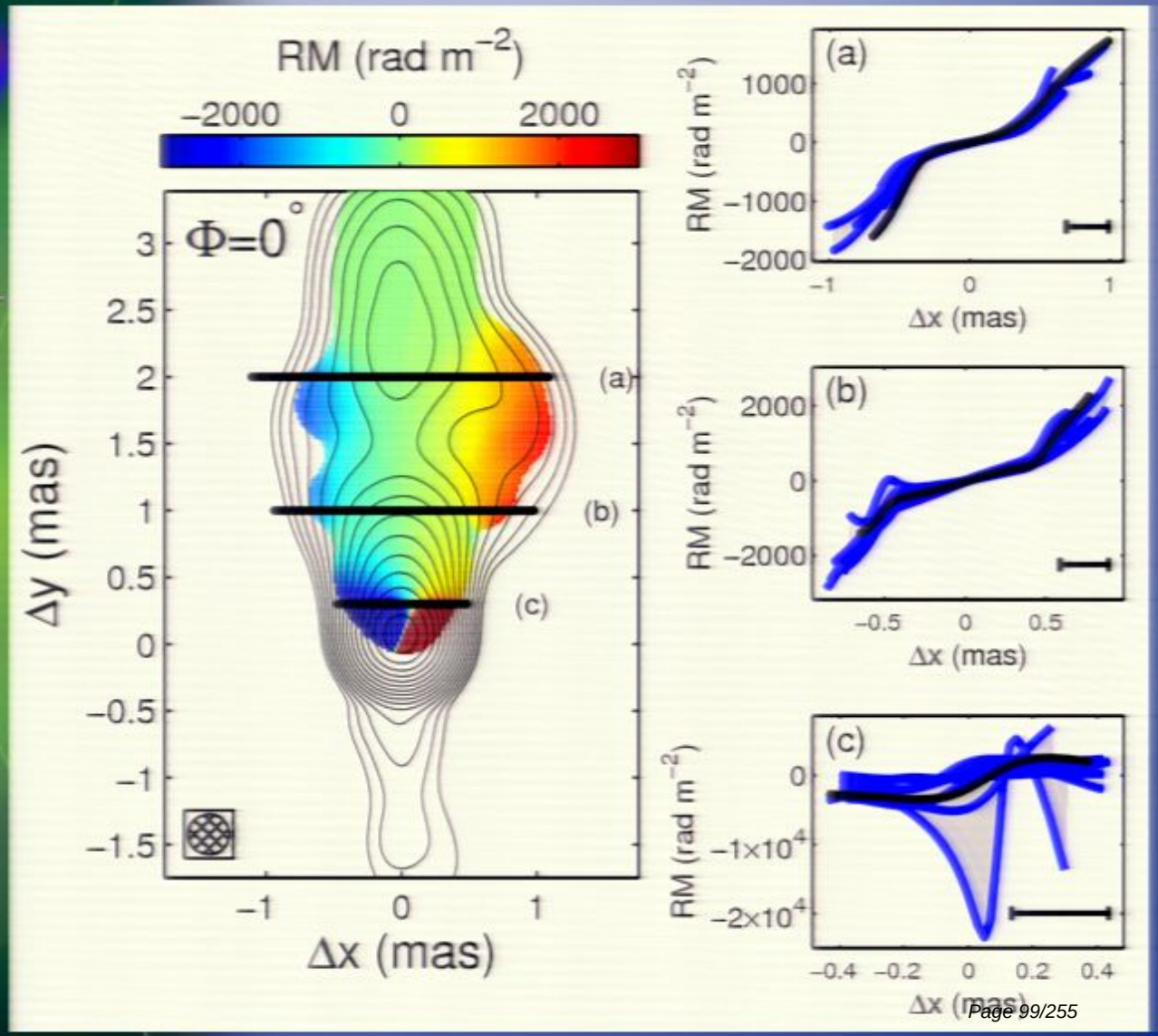

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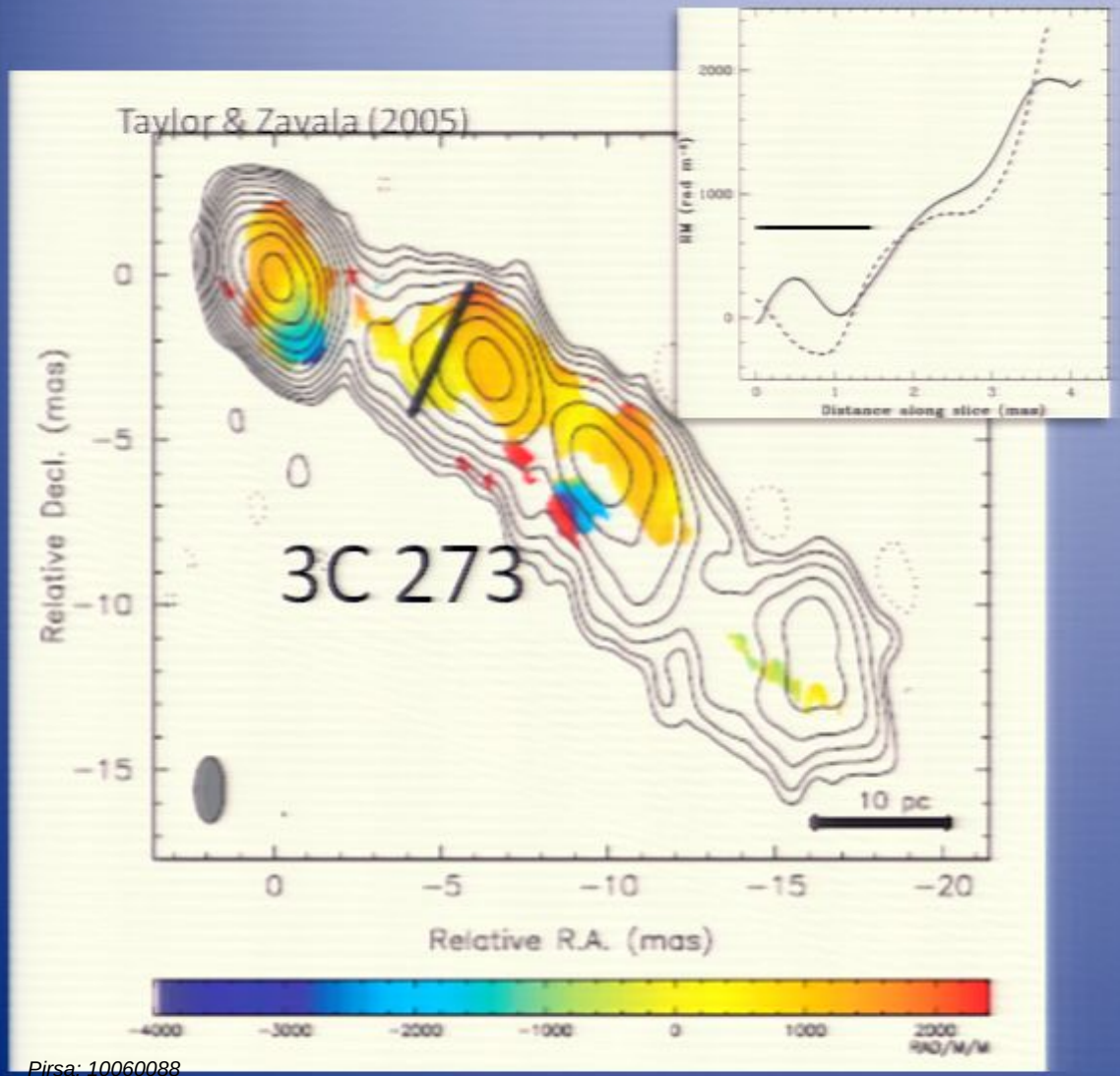

Jets

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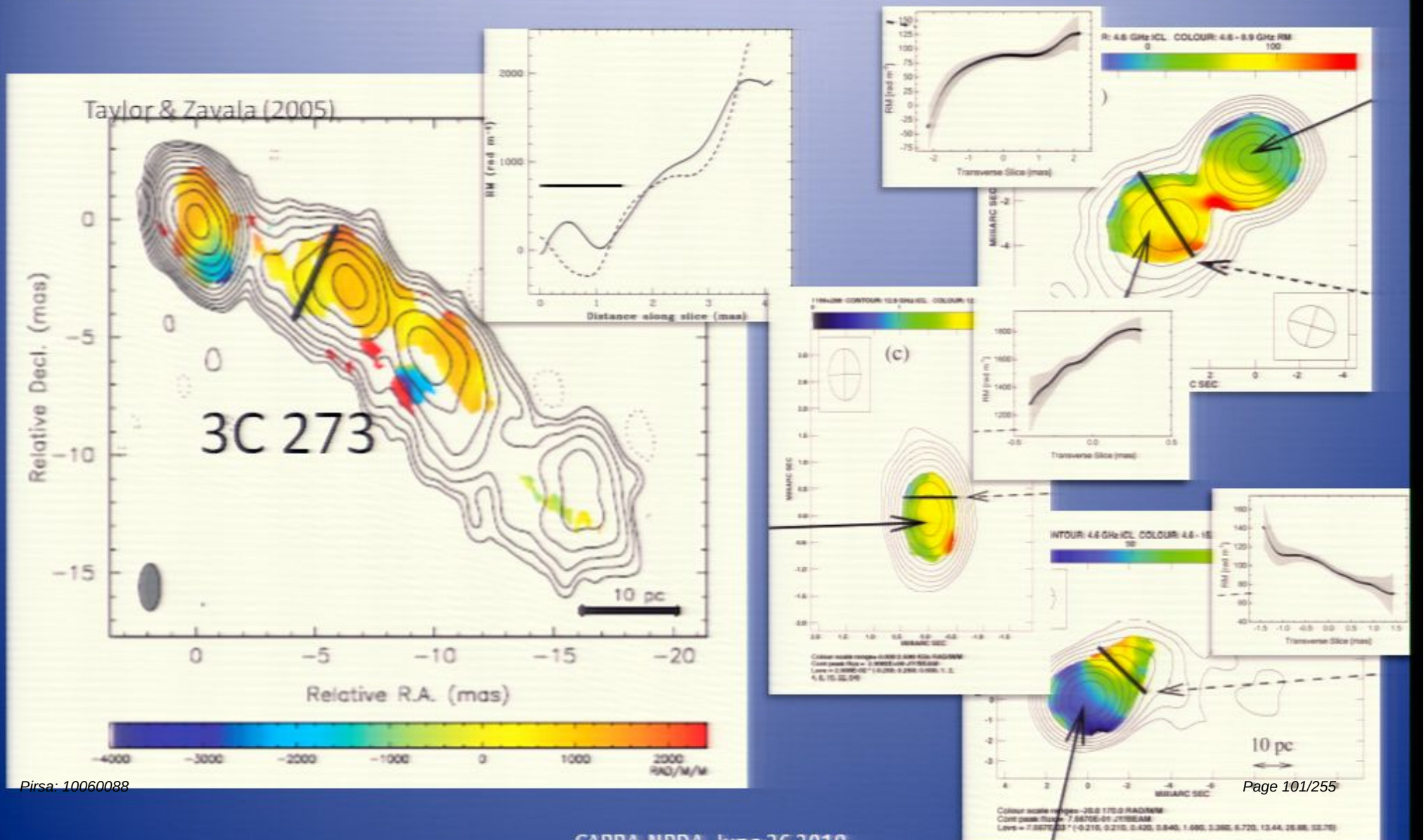
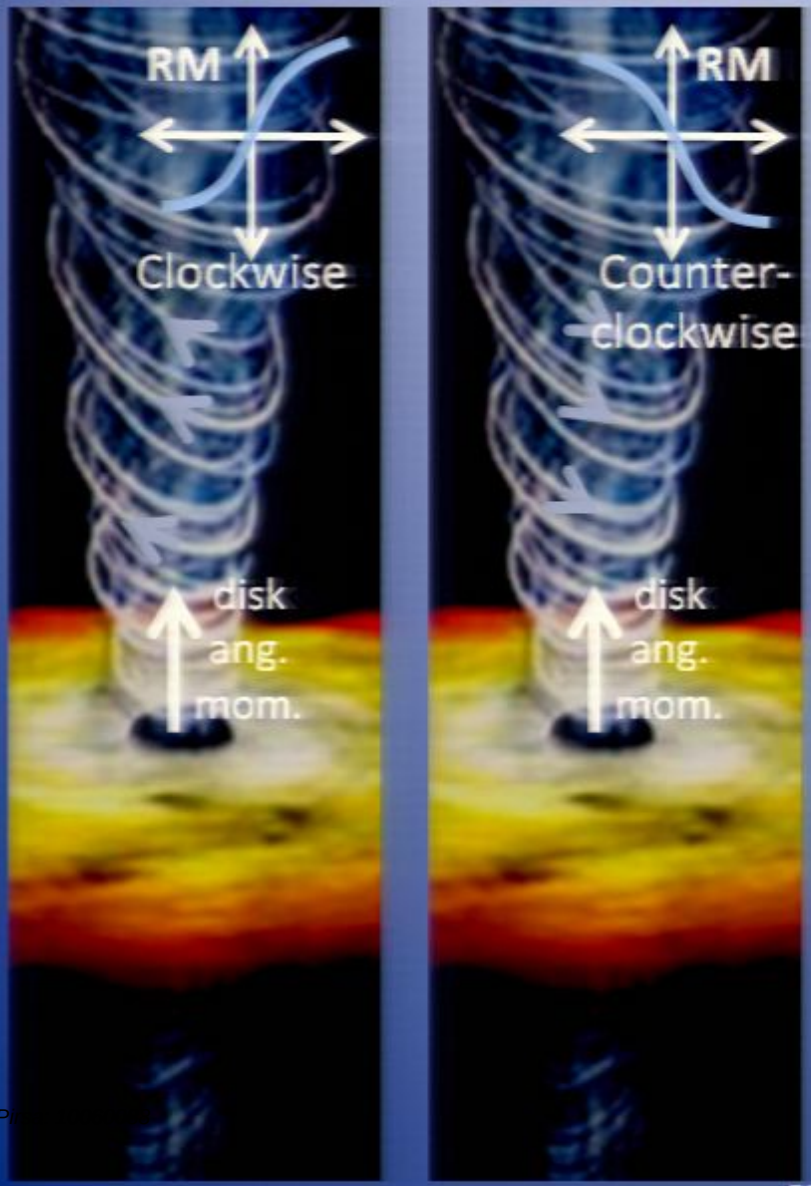


pc-scale Jet RM Asymmetry?



- MHD: +RM as likely as –RM

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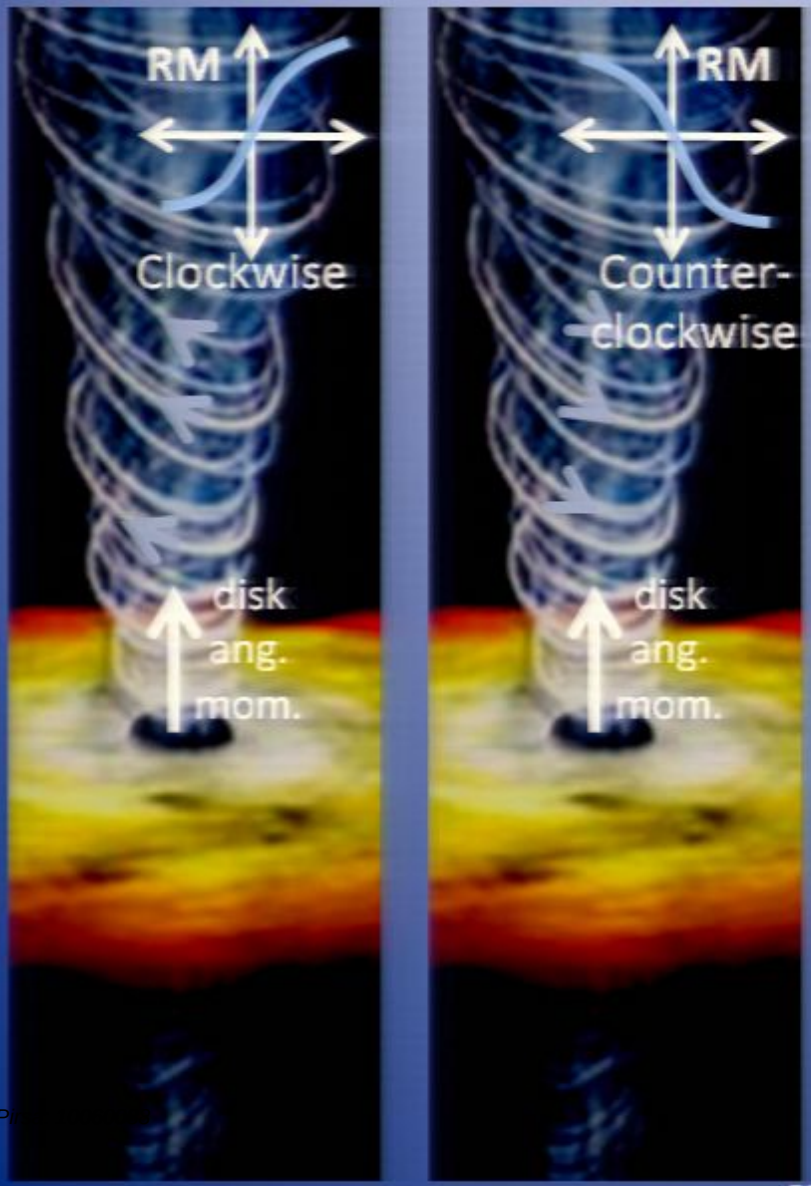

- MHD: +RM as likely as –RM
- BUT, 22 of 29 show Clockwise gradients:
  - $2\sigma \rightarrow$ so what?

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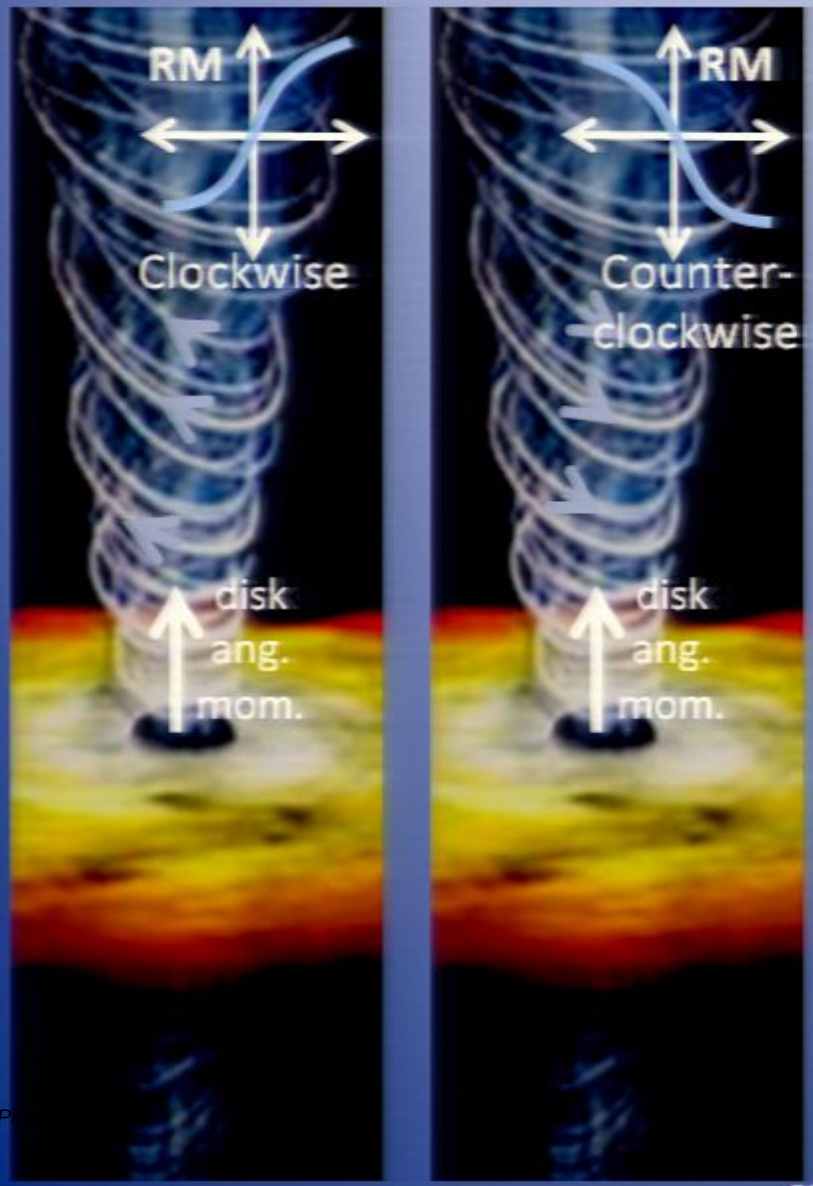
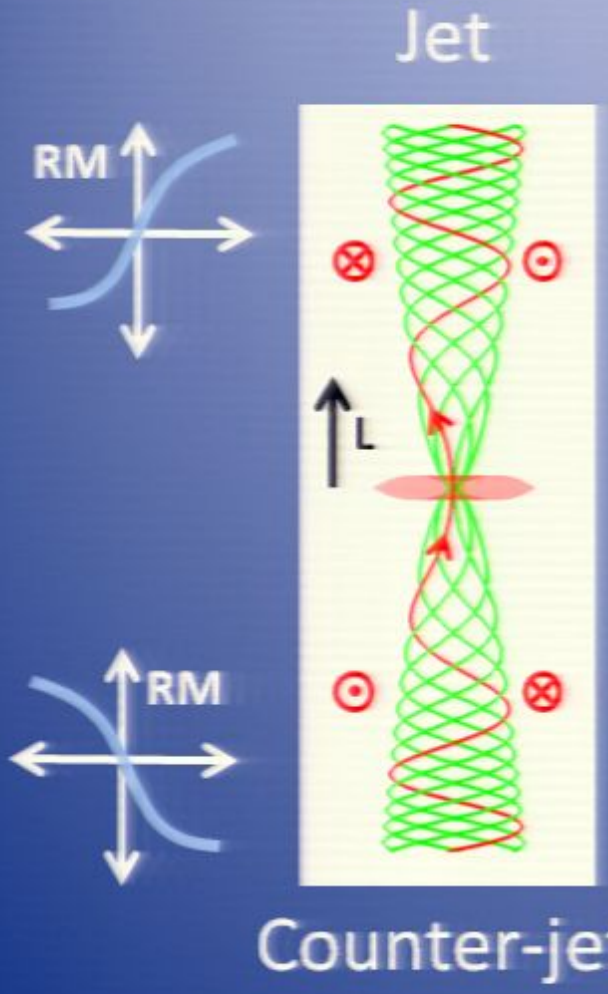


- MHD: +RM as likely as –RM
- BUT, 22 of 29 show Clockwise gradients:
  - 2 σ → so what?
  - 29 is still small, 0.4% prob.! (so more like 3σ effect)
- How?

pc-scale Jet RM biases



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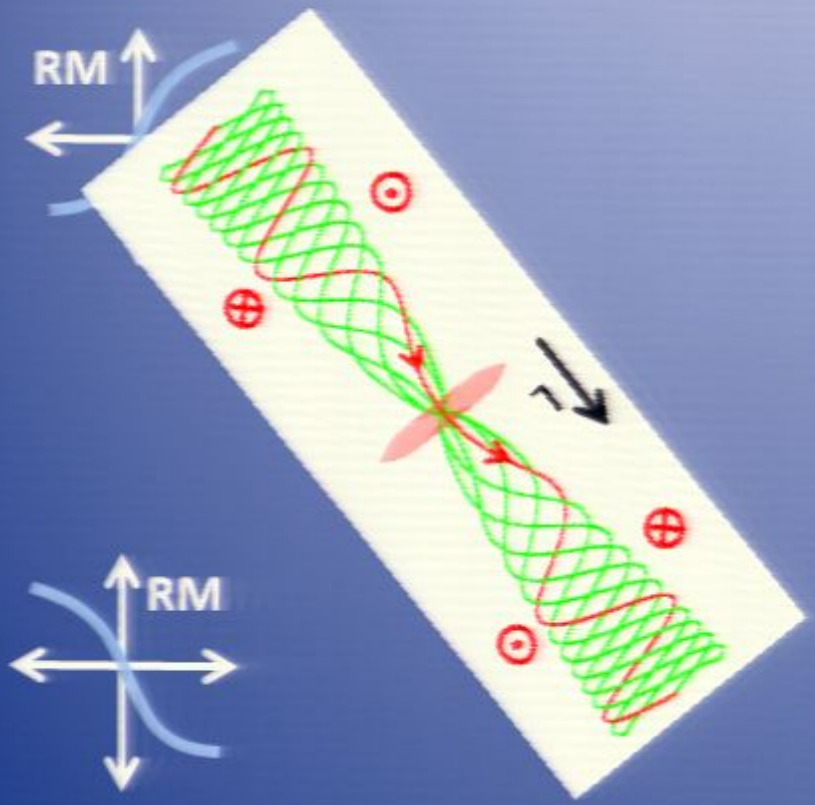

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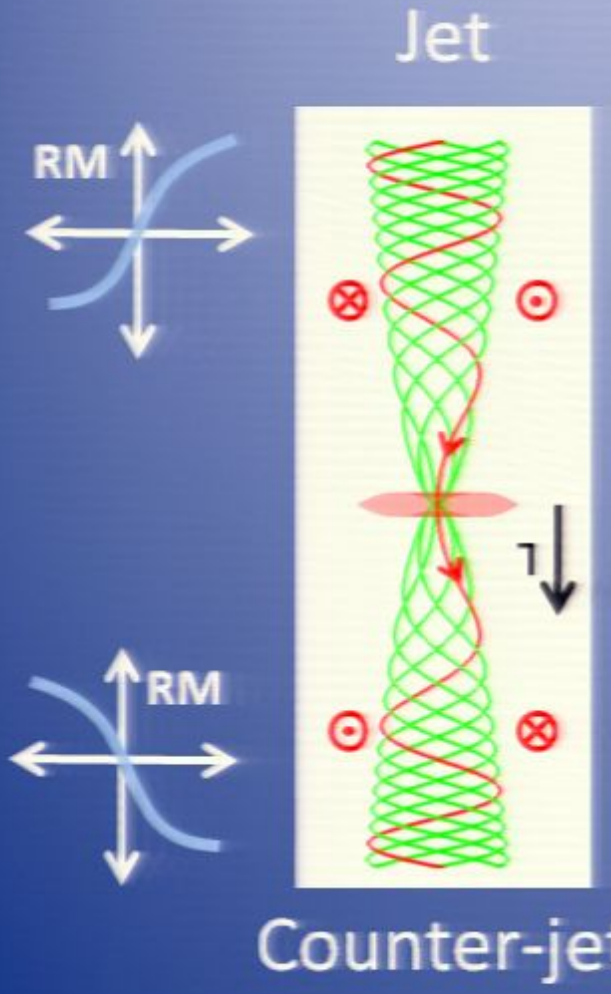

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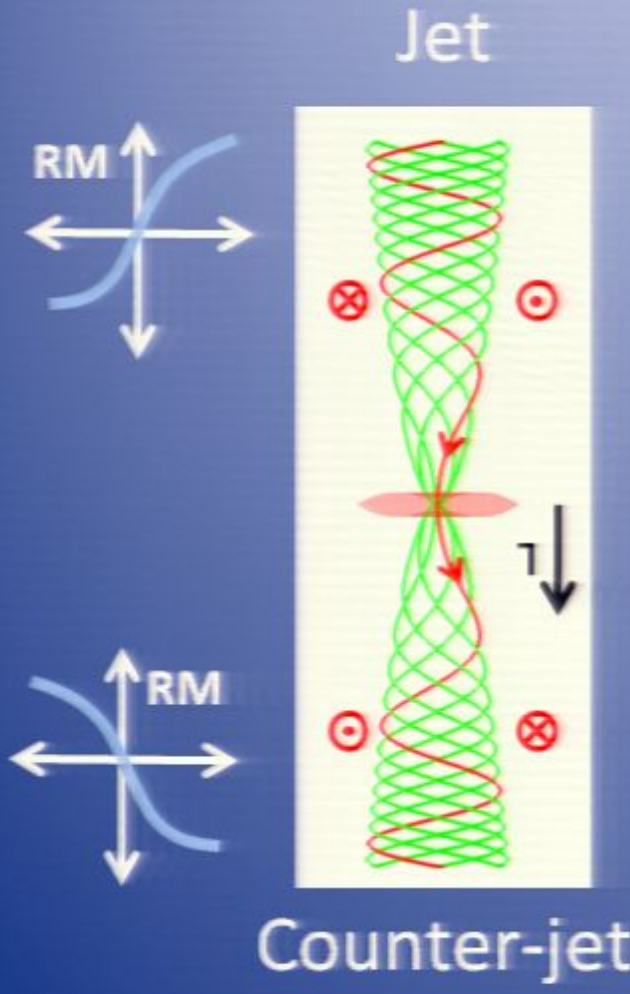
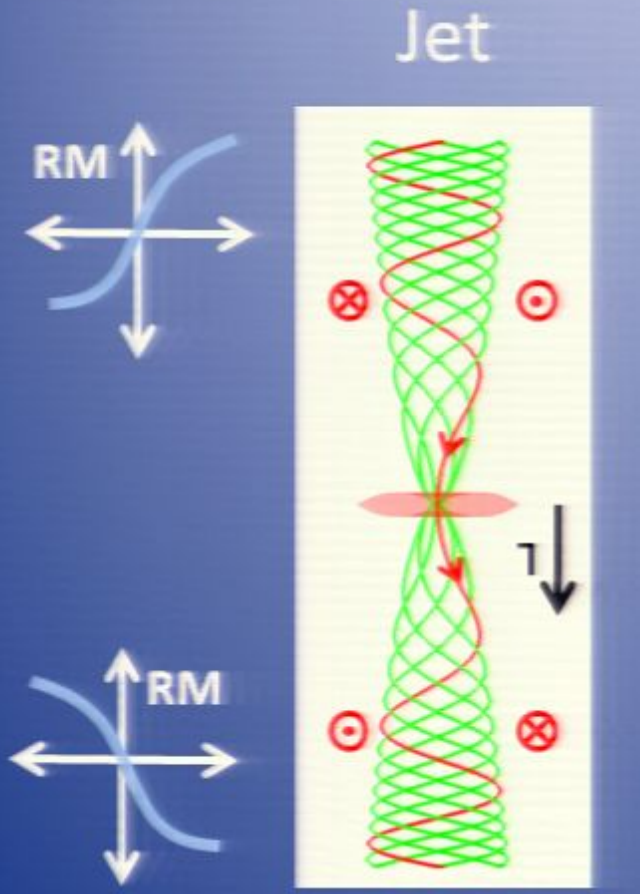


- A possible solution: correlation between B^P & a
- Poynting-Robertson Battery
  - Feeds off of m_e vs. m_p
  - Naturally gets B^P || a

pc-scale Jet RM biases



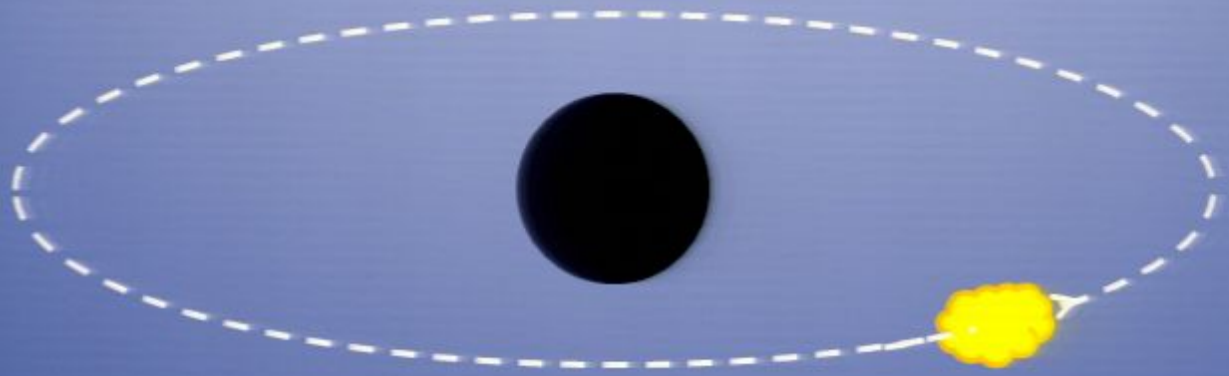
- A possible solution: correlation between B^P & a
- Poynting-Robertson Battery
  - Feeds off of m_e vs. m_p
  - Naturally gets B^P || a
  - Takes 10^5 yrs!
- Q & BH magnetic moments?

$$\mu = \frac{QJ}{M}$$

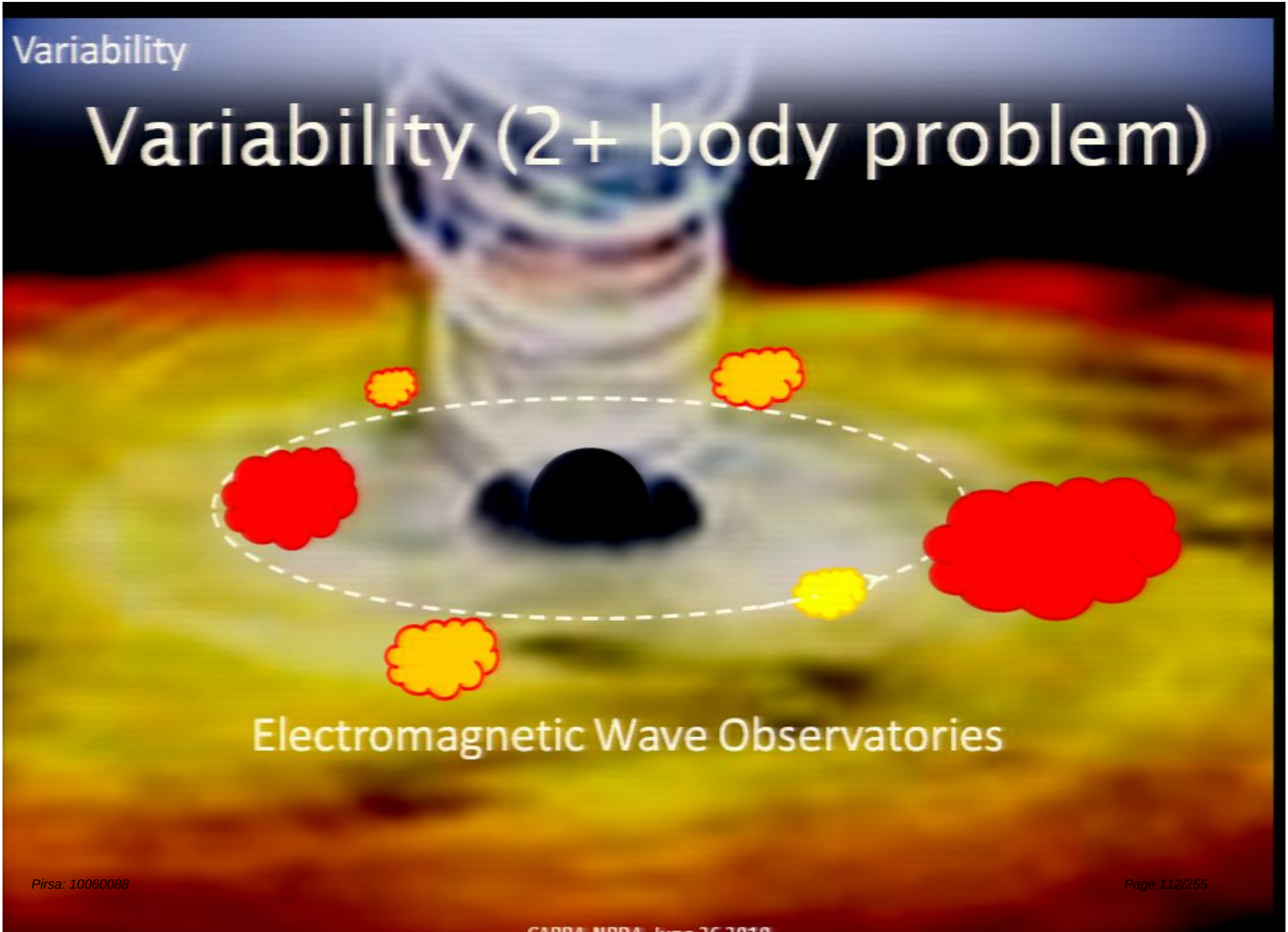
Variability (2+ body problem)

Gravitational Wave Observatories
→ Detection problem

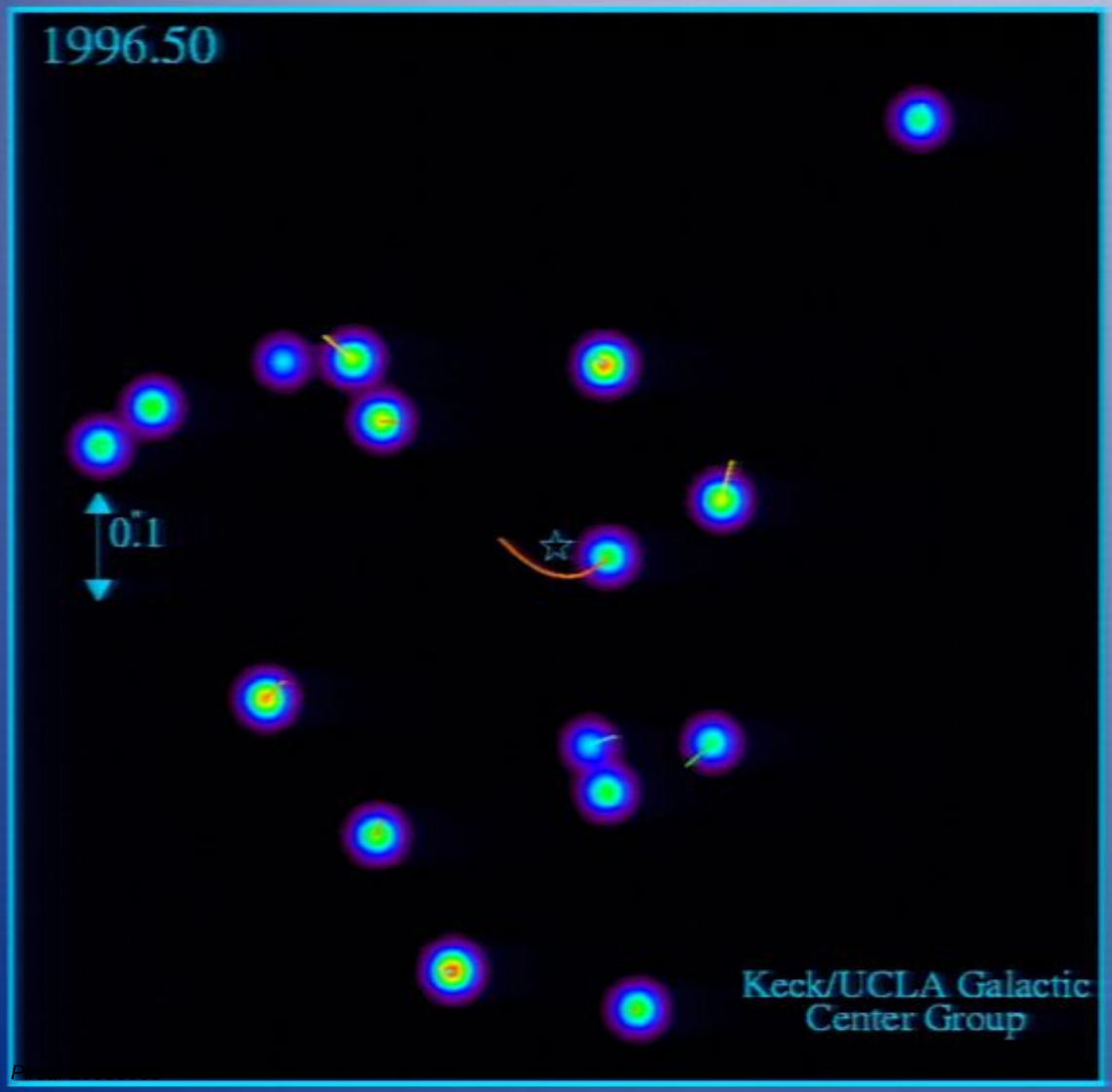
Variability (2+ body problem)



Electromagnetic Wave Observatories


Variability
Variability (2+ body problem)
Electromagnetic Wave Observatories

Best BH Mass Known



- Stars as test particles
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- New generation of telescopes should probe spin-effects! (TMT, ELT,GMT)

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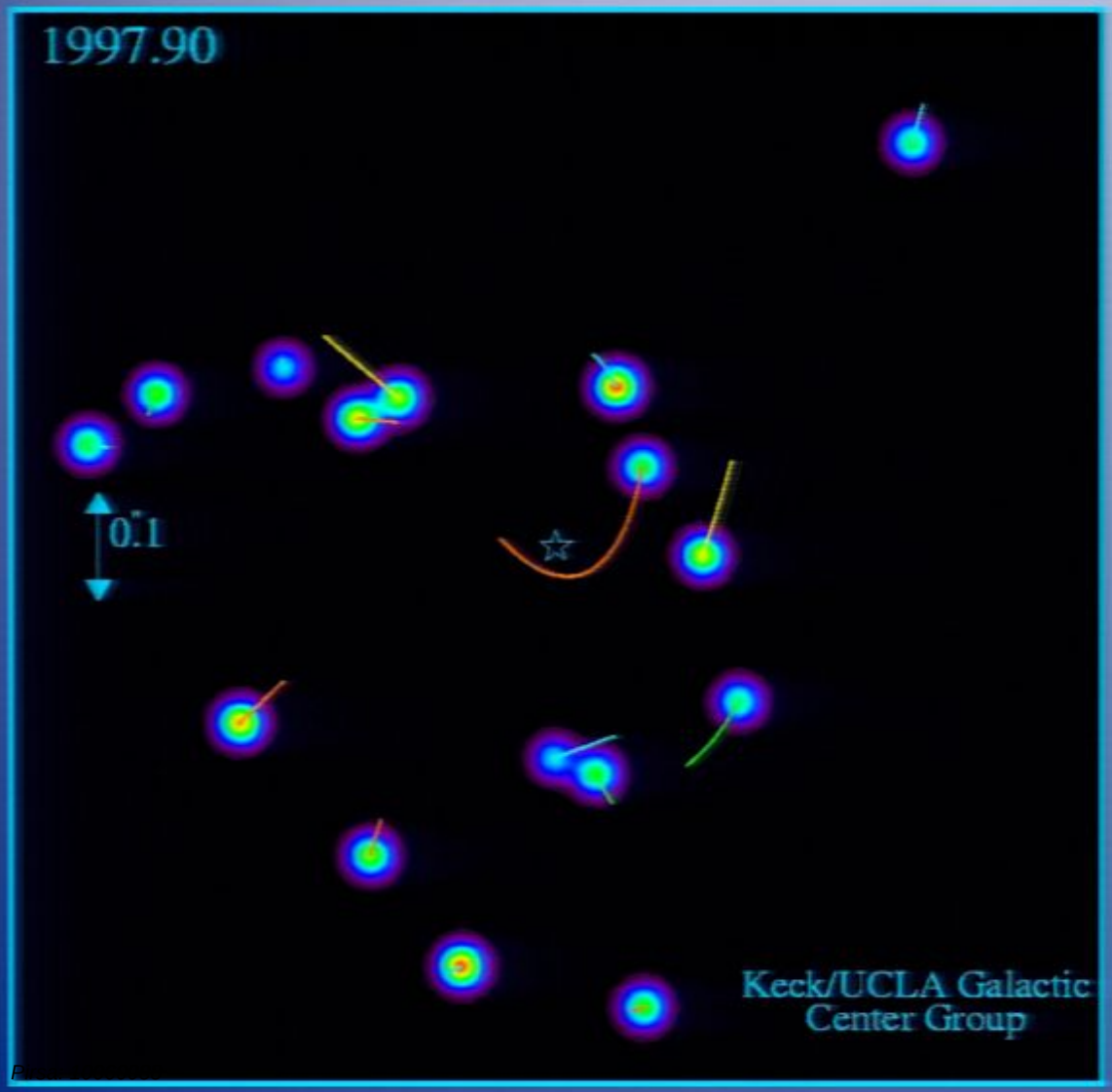

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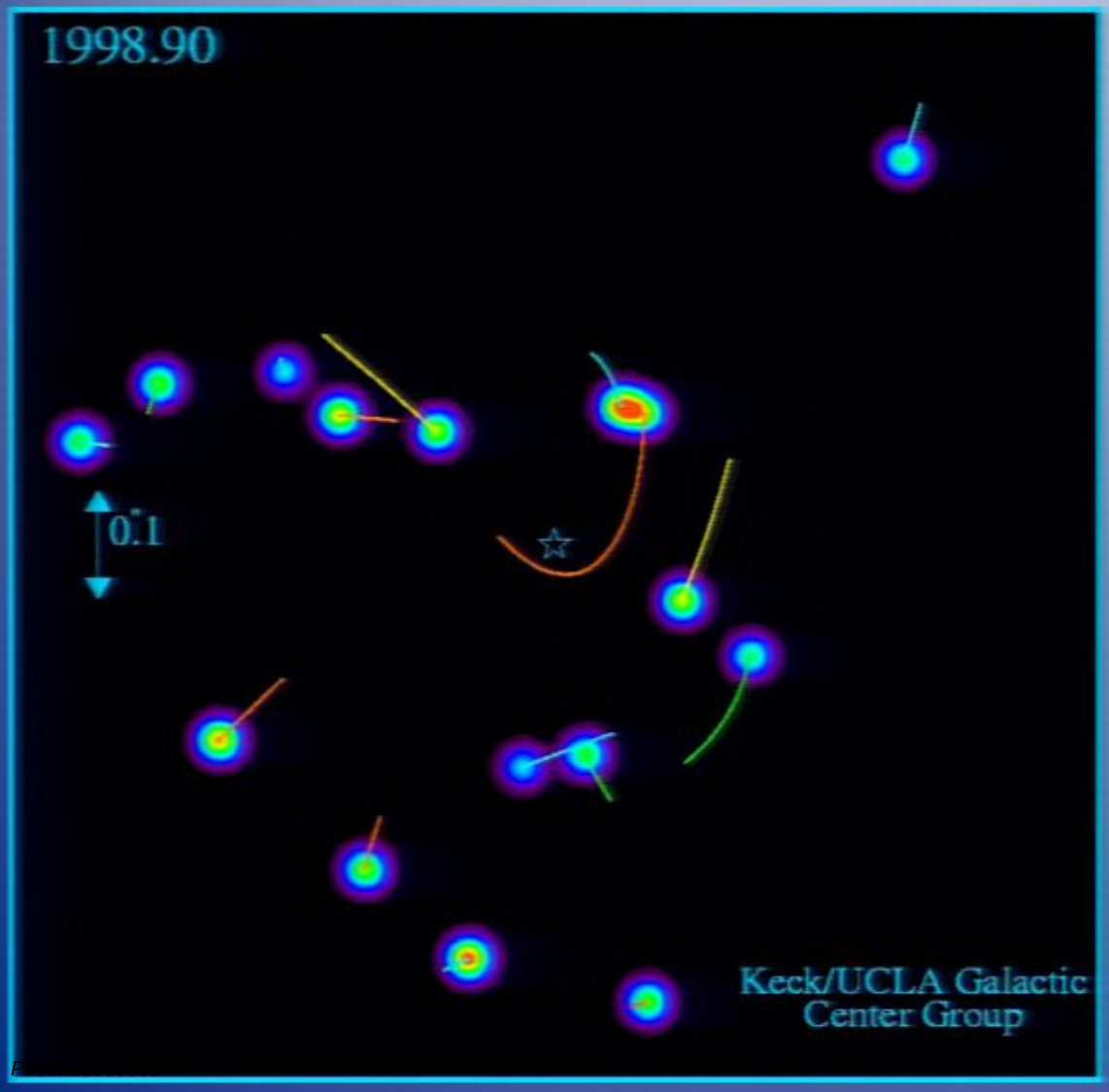

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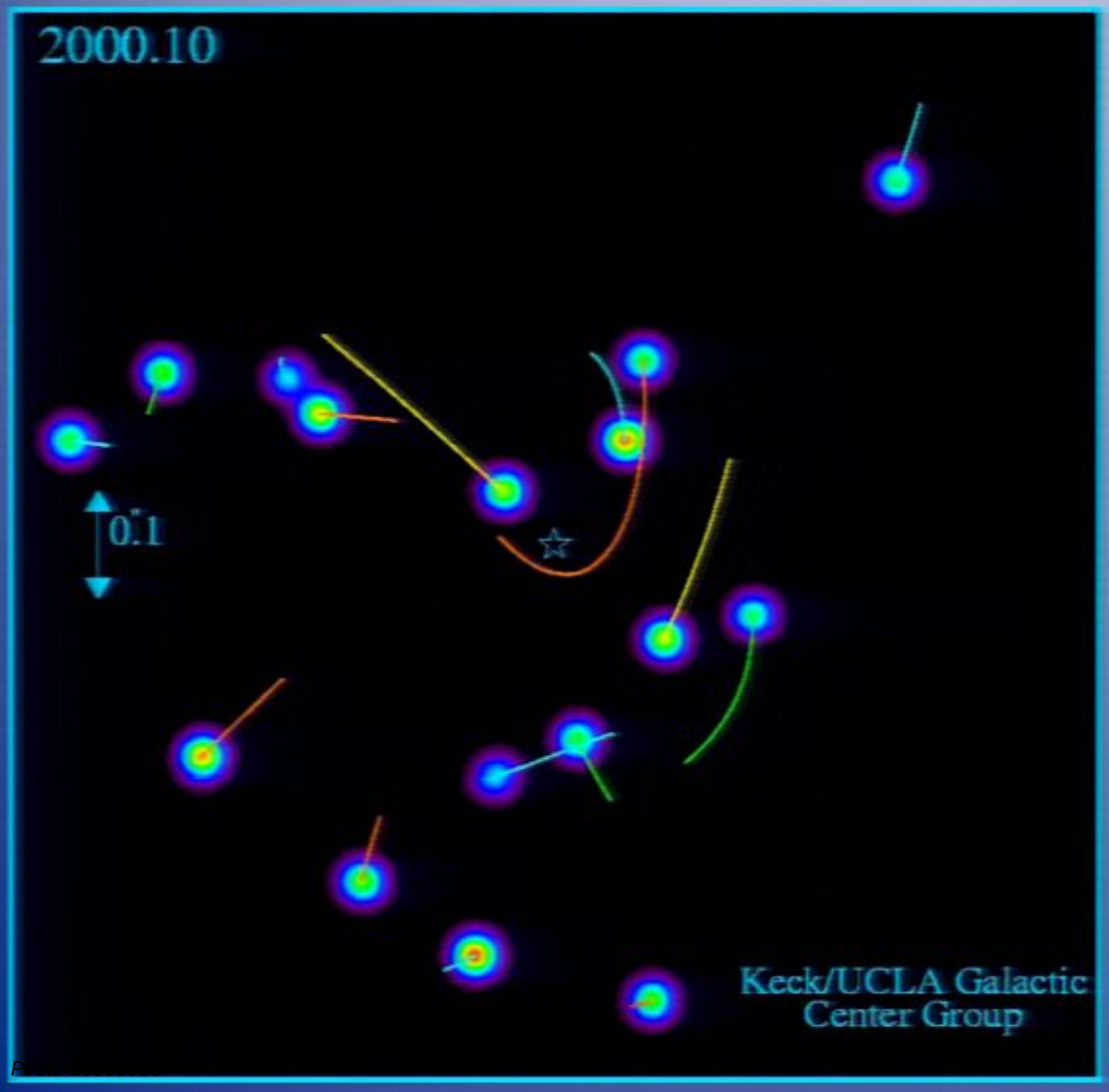

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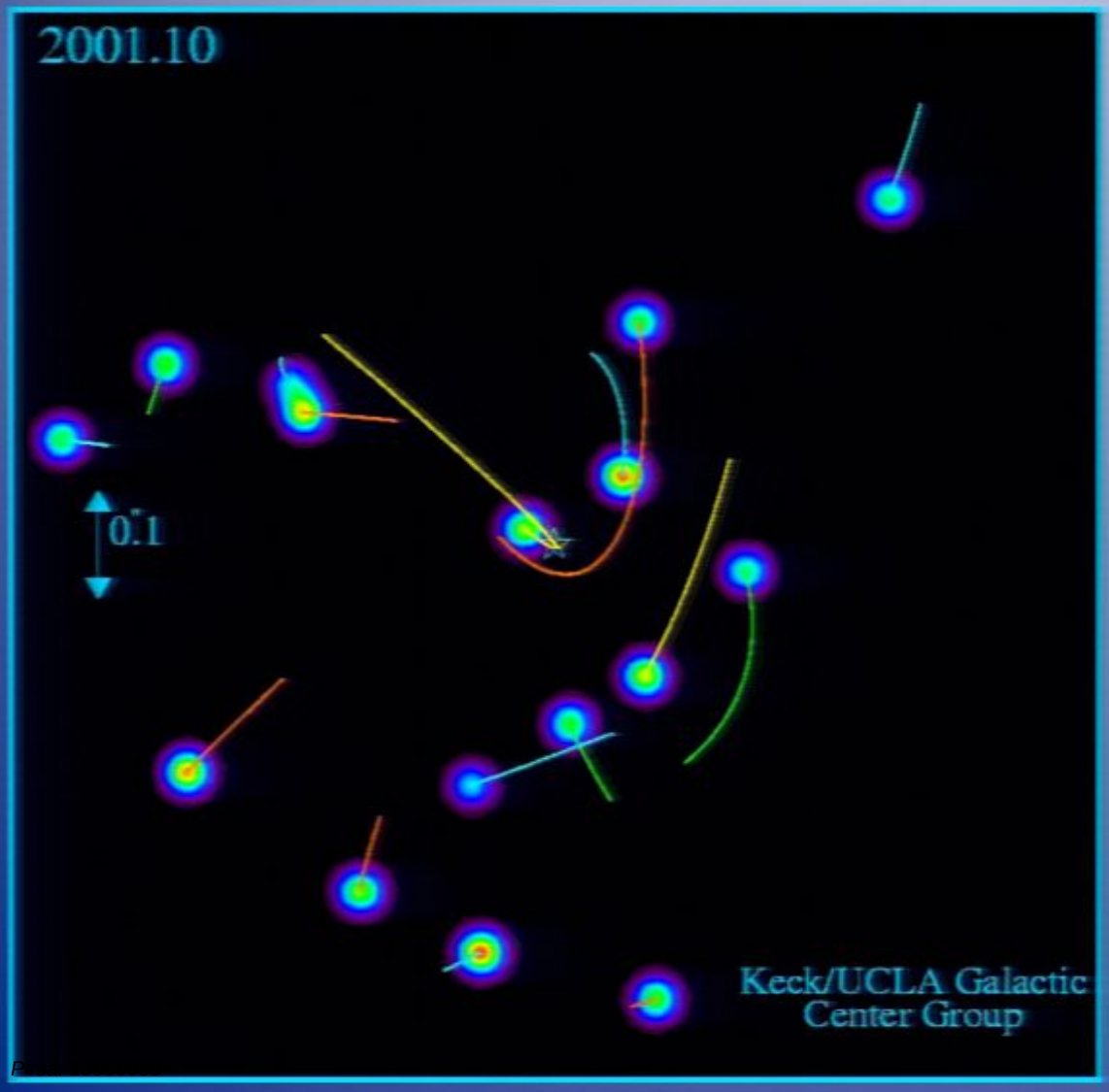

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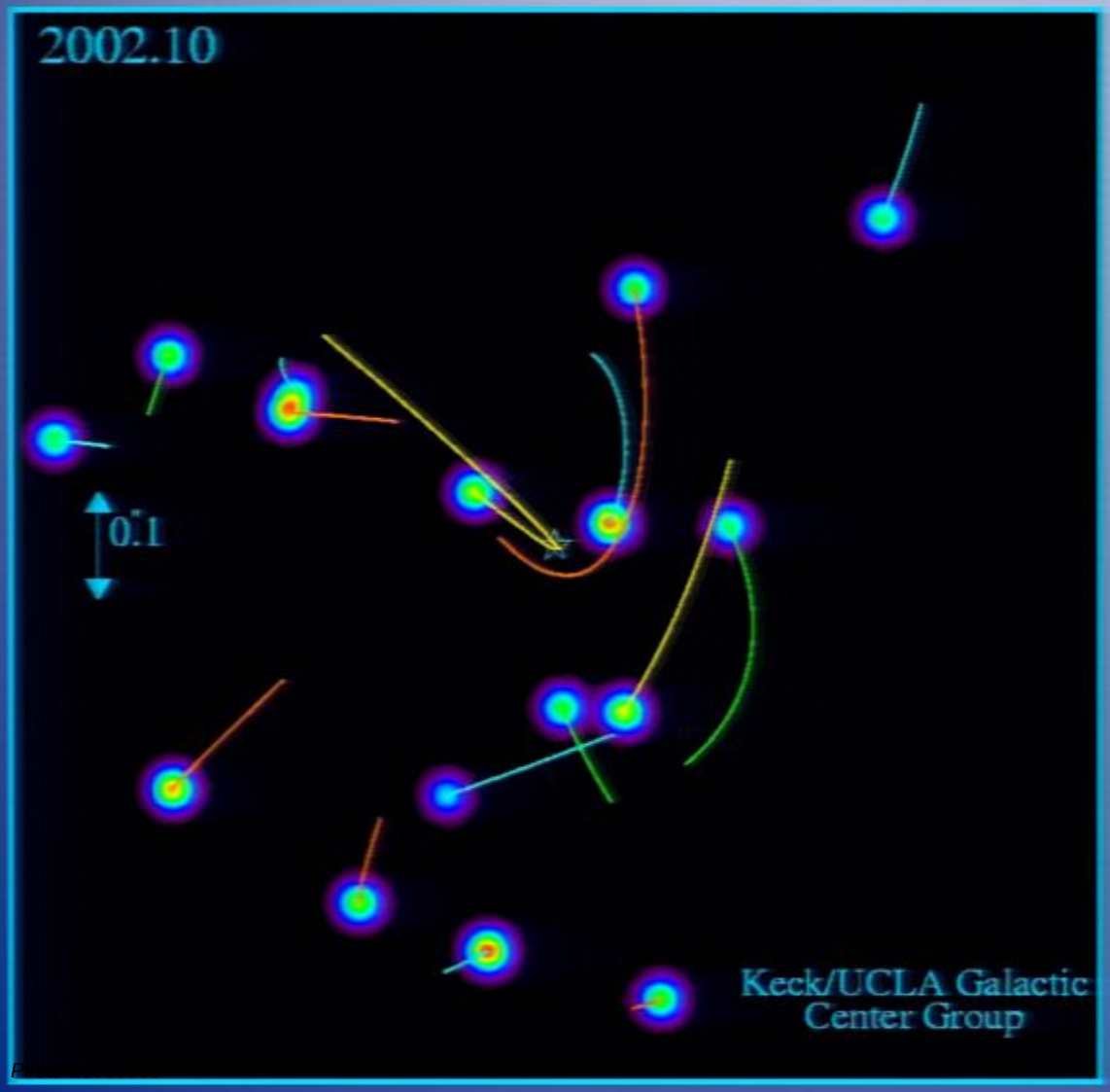

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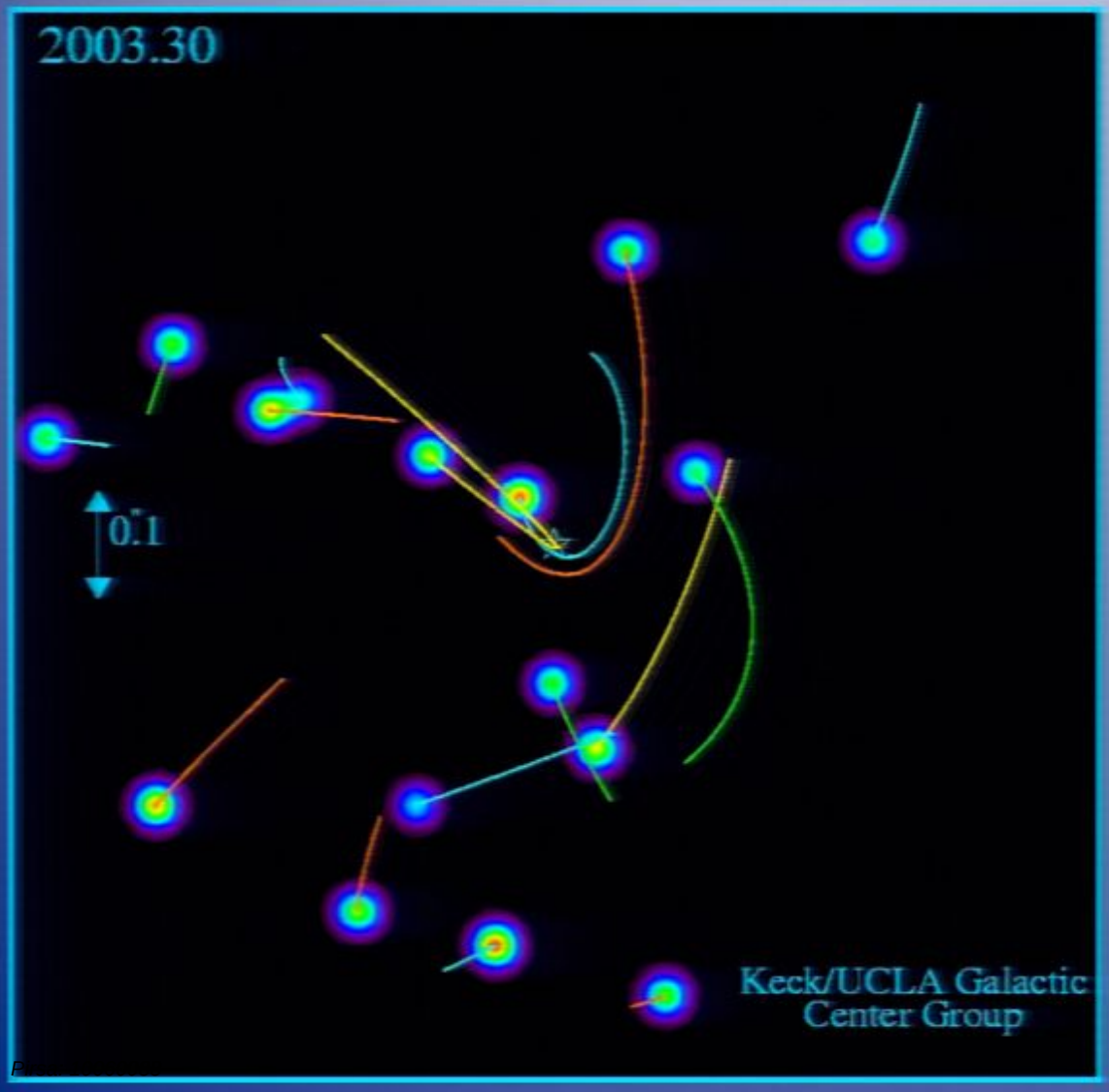

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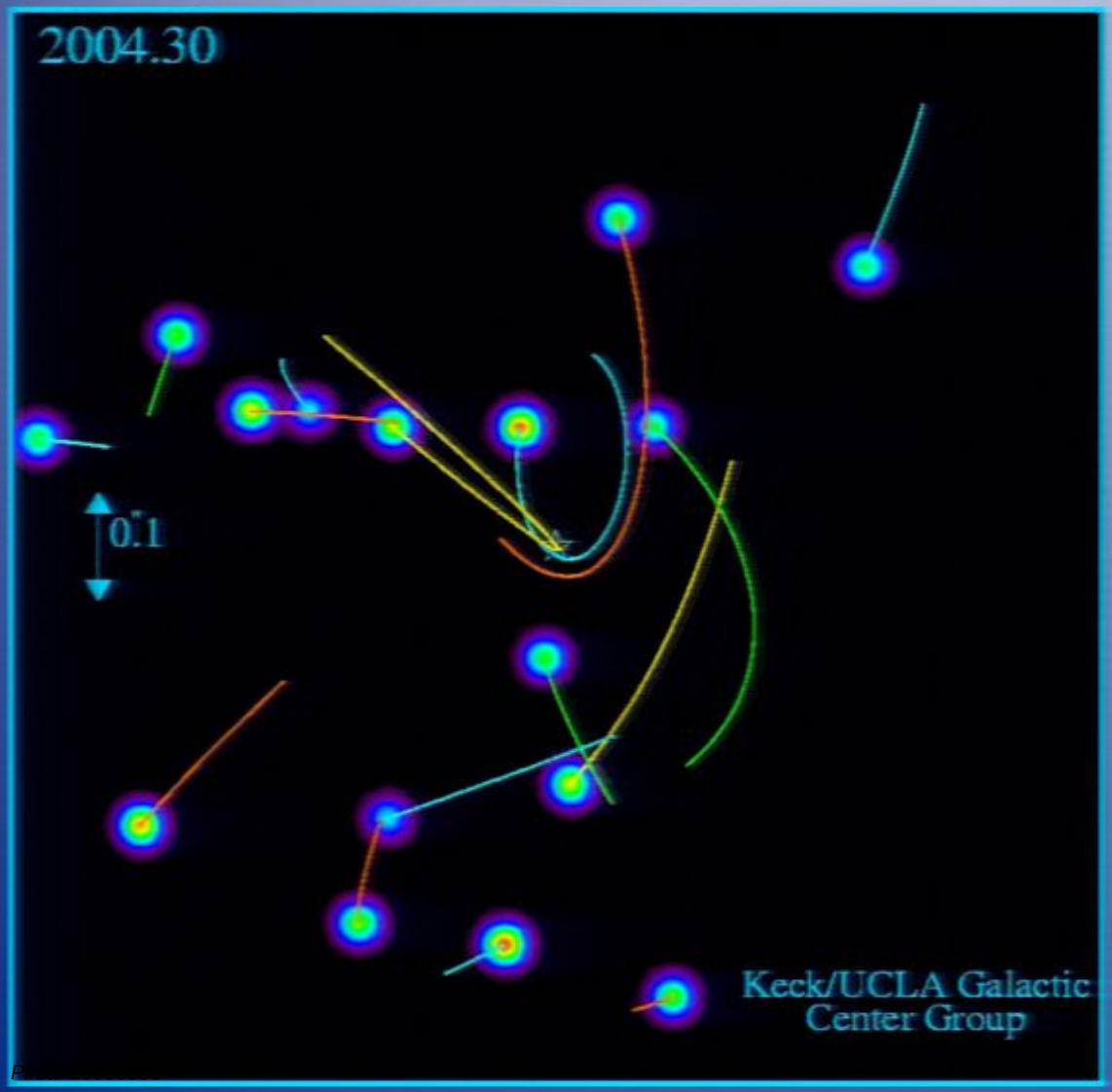

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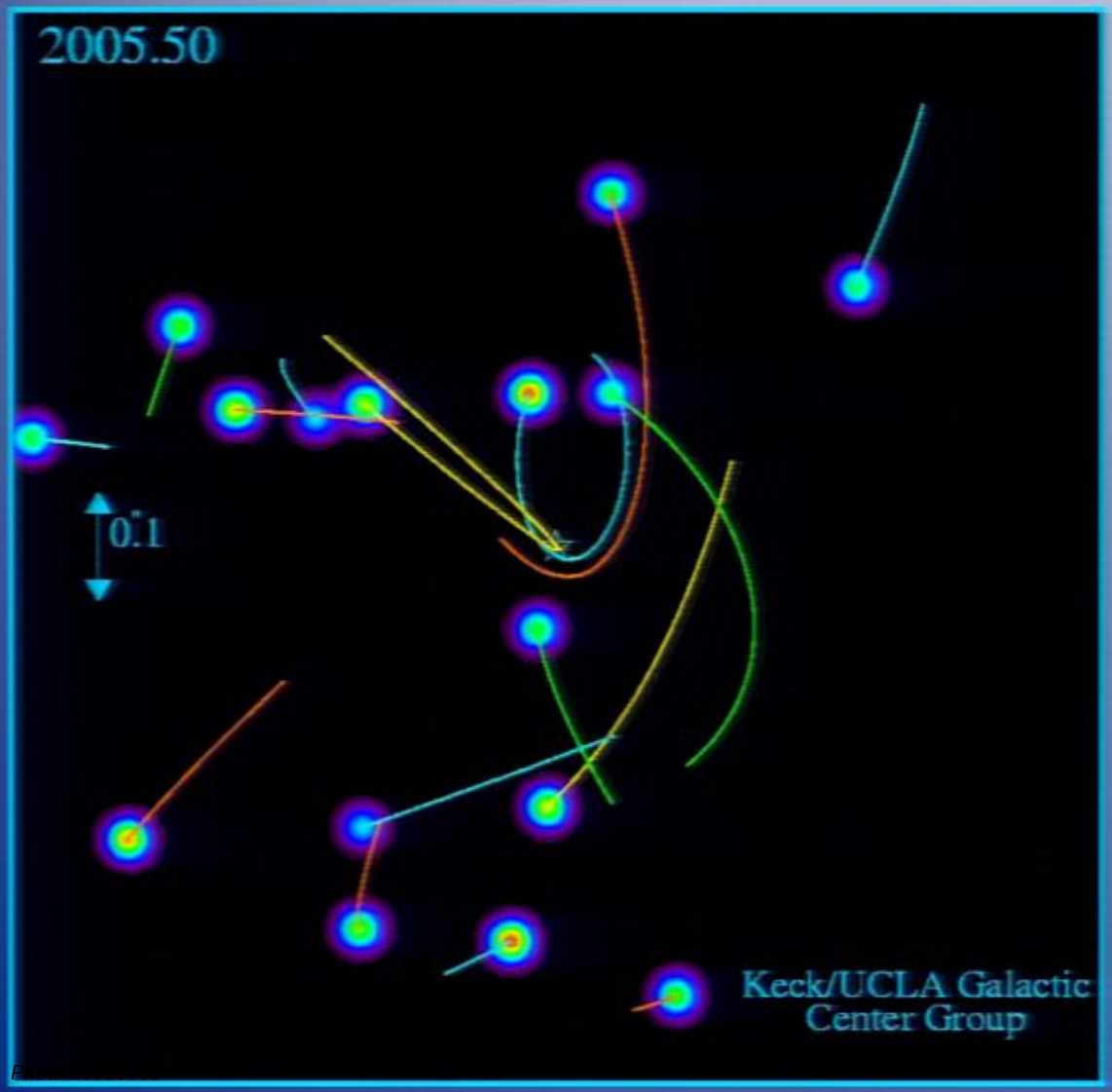

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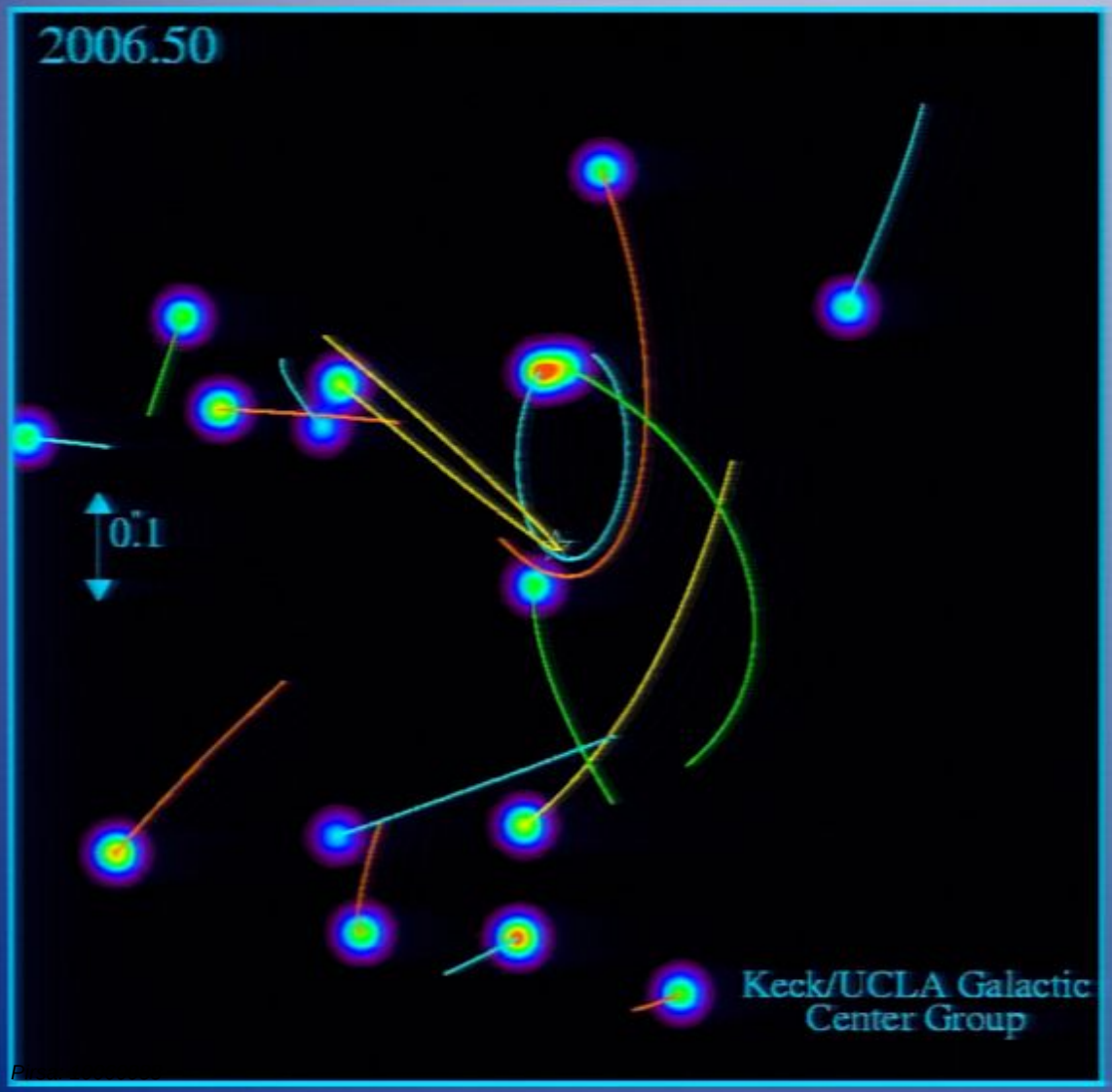

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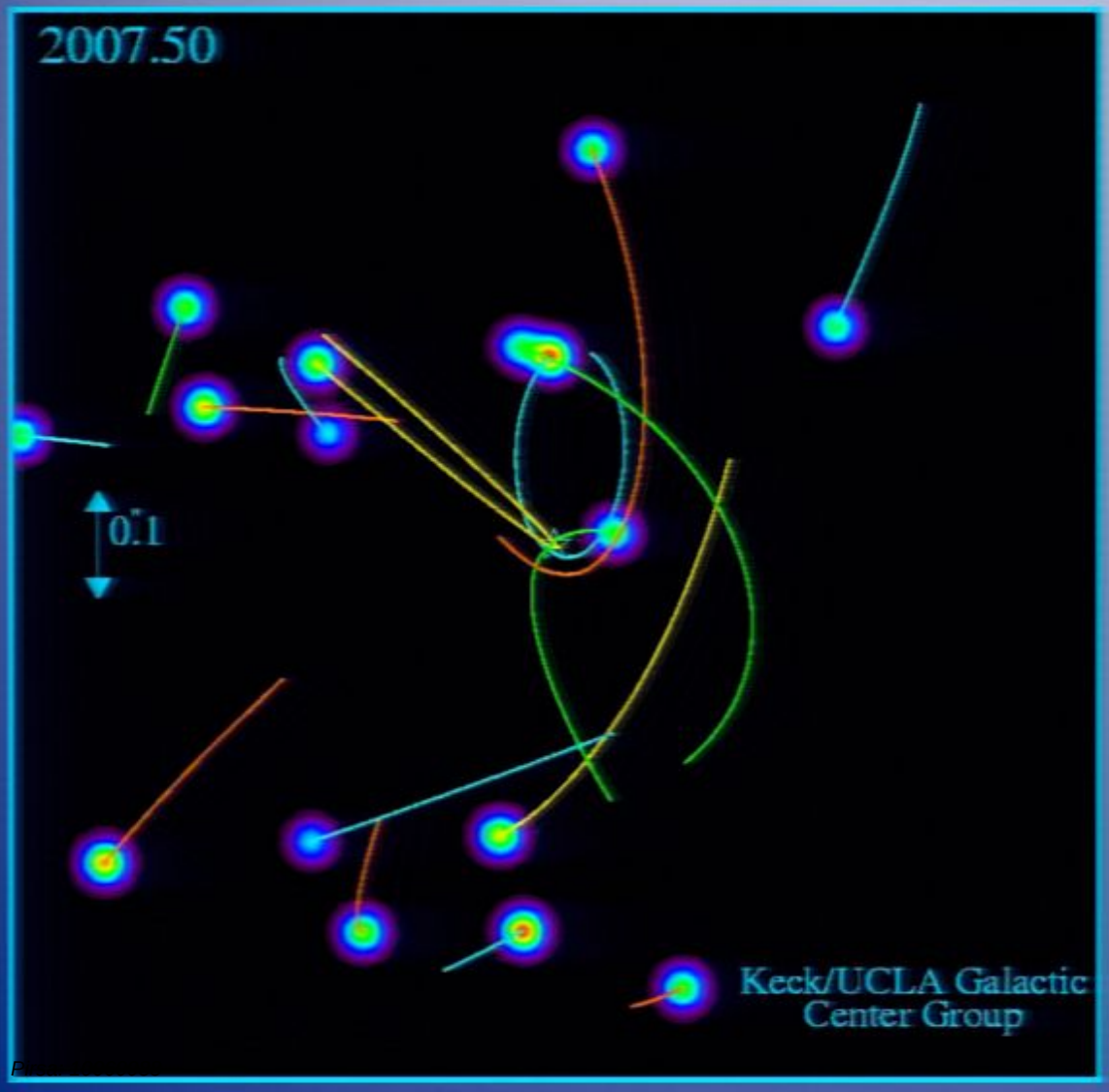

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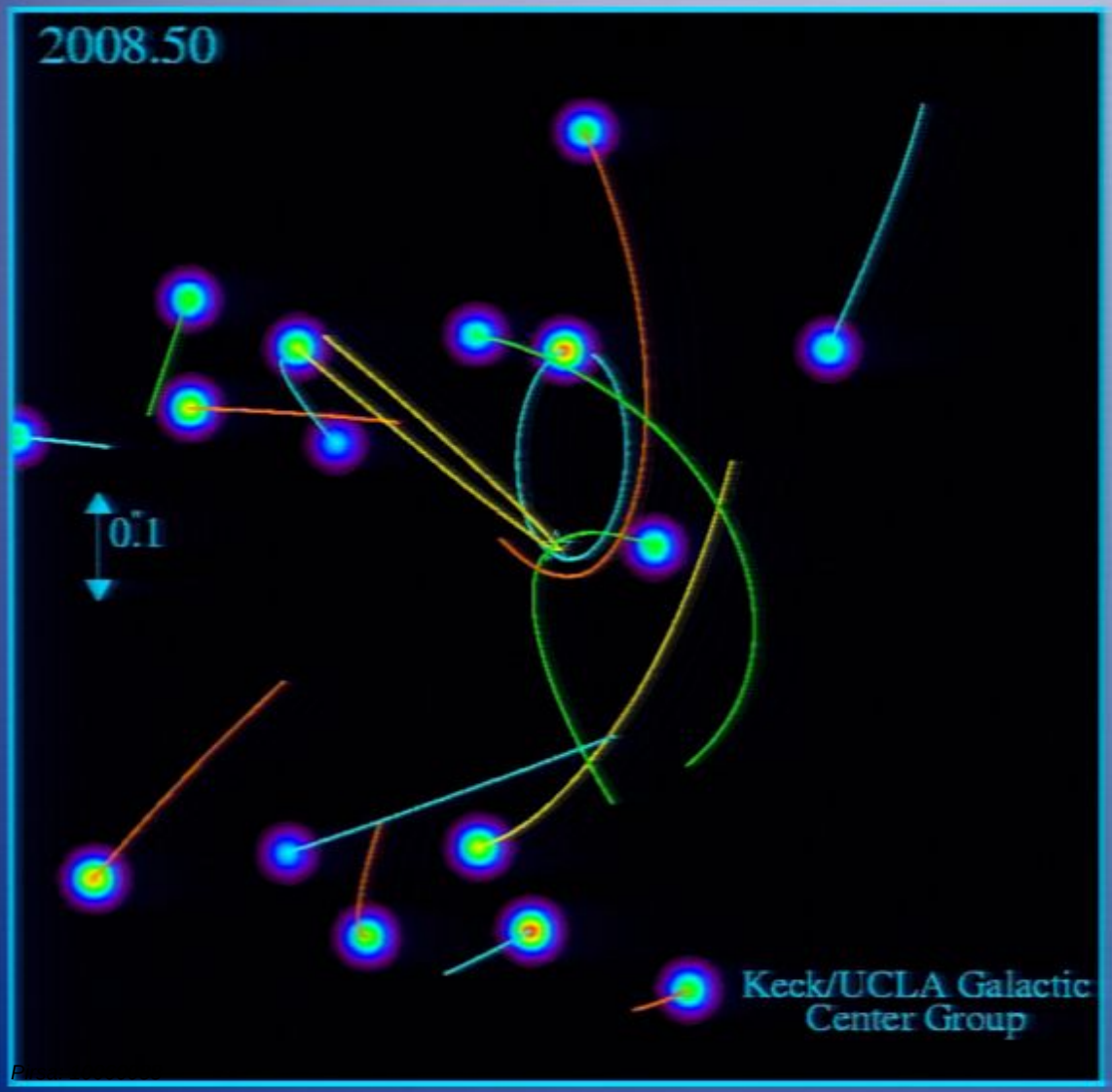

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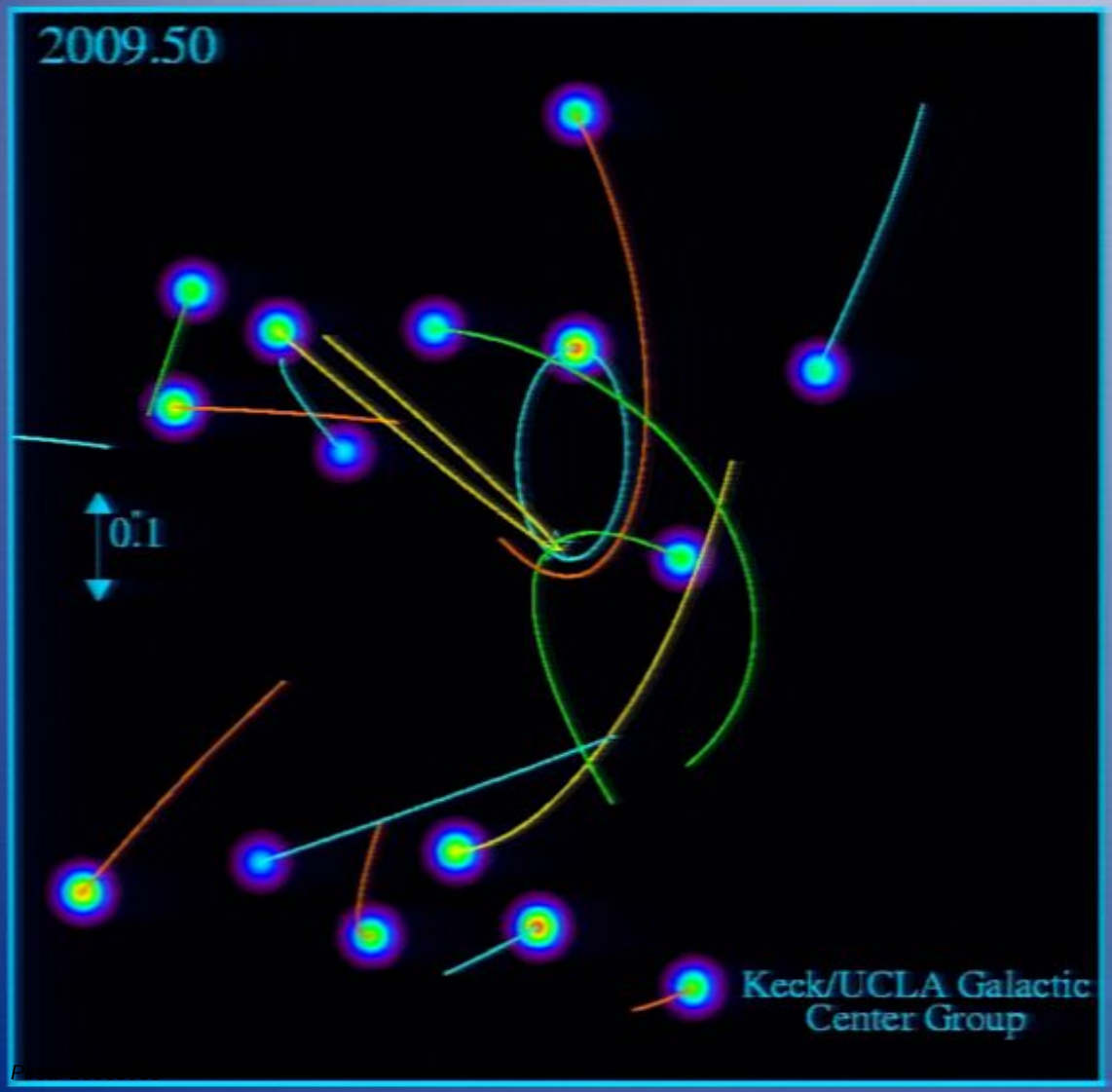

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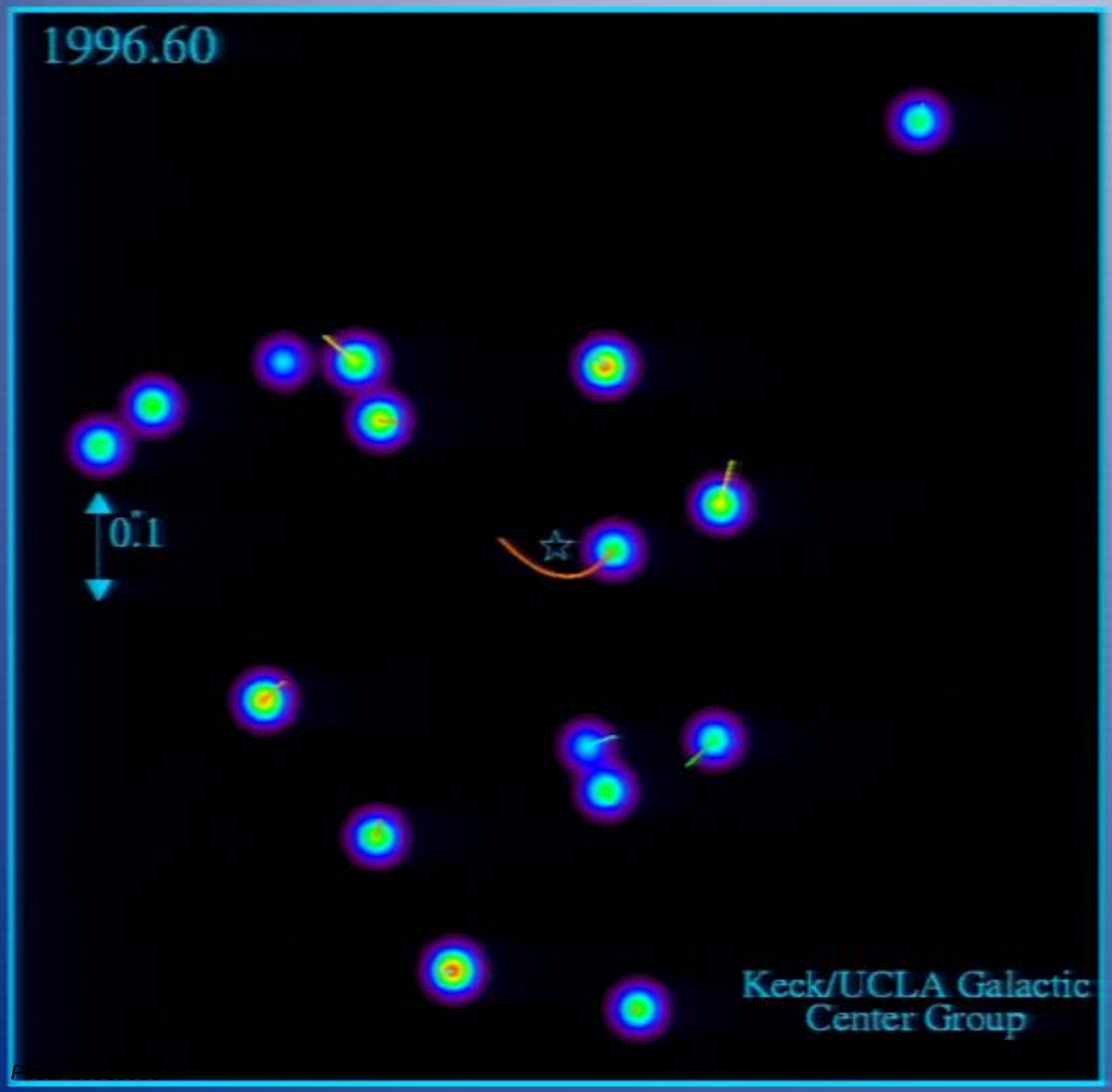

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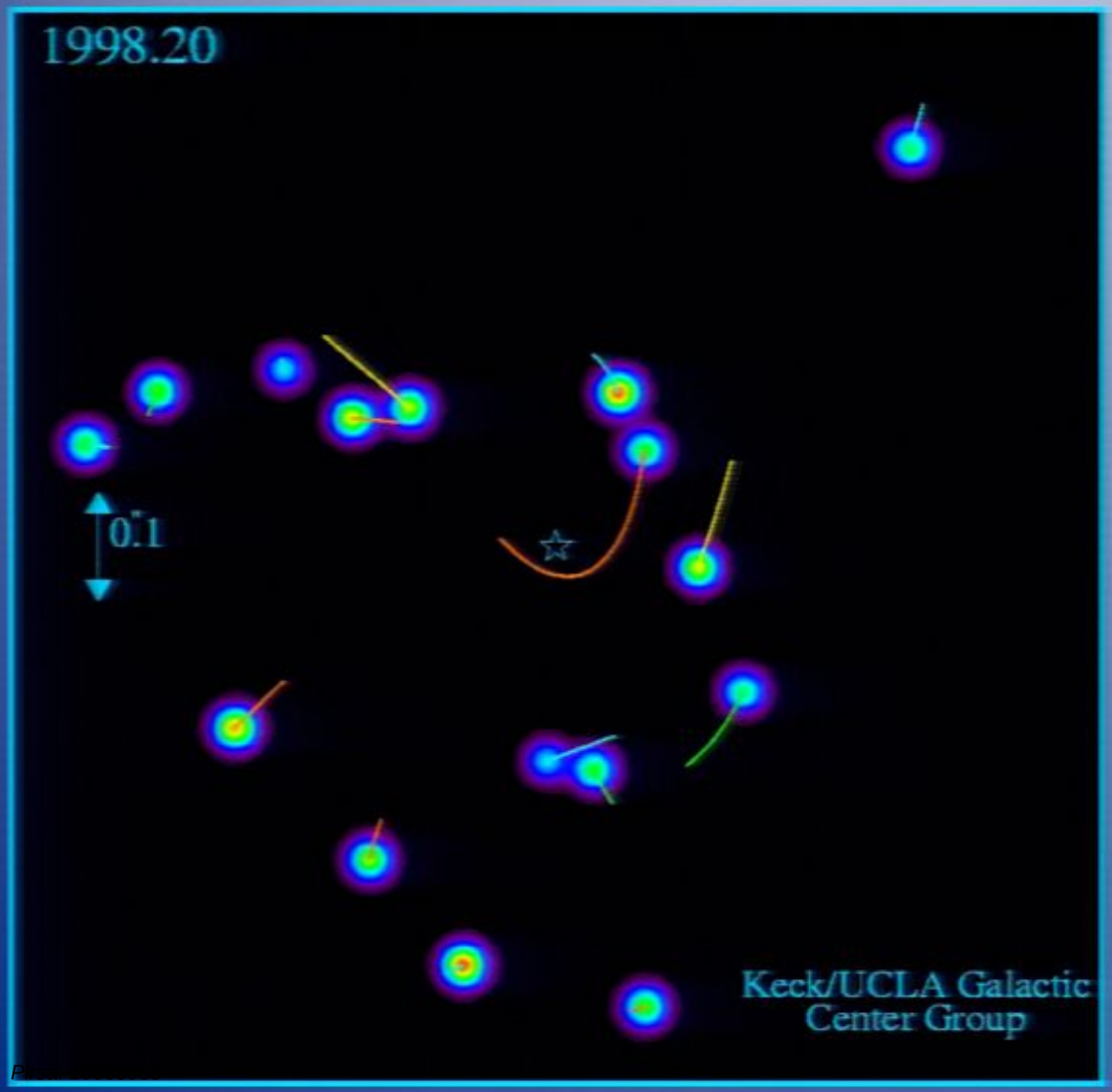

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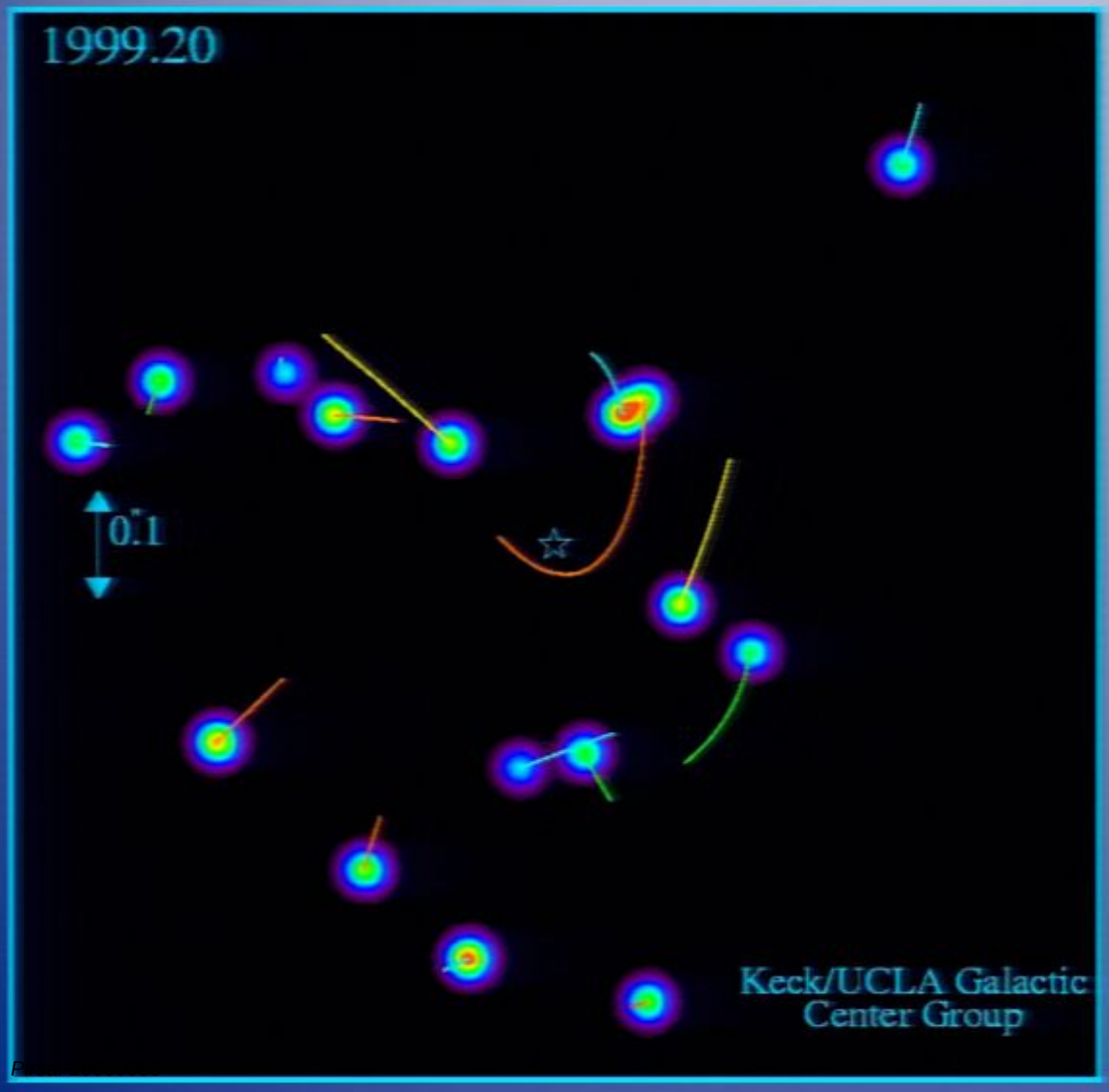

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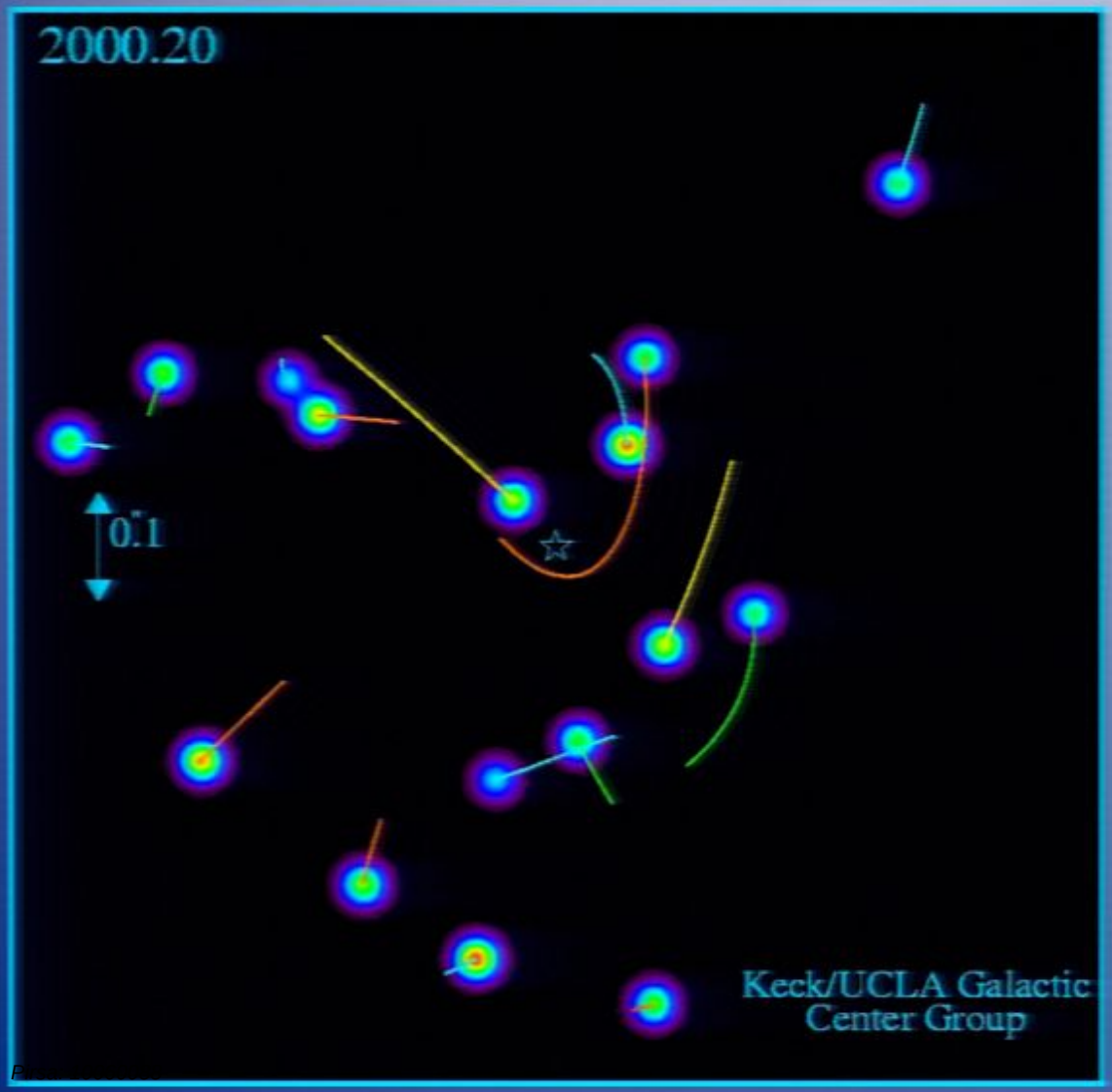

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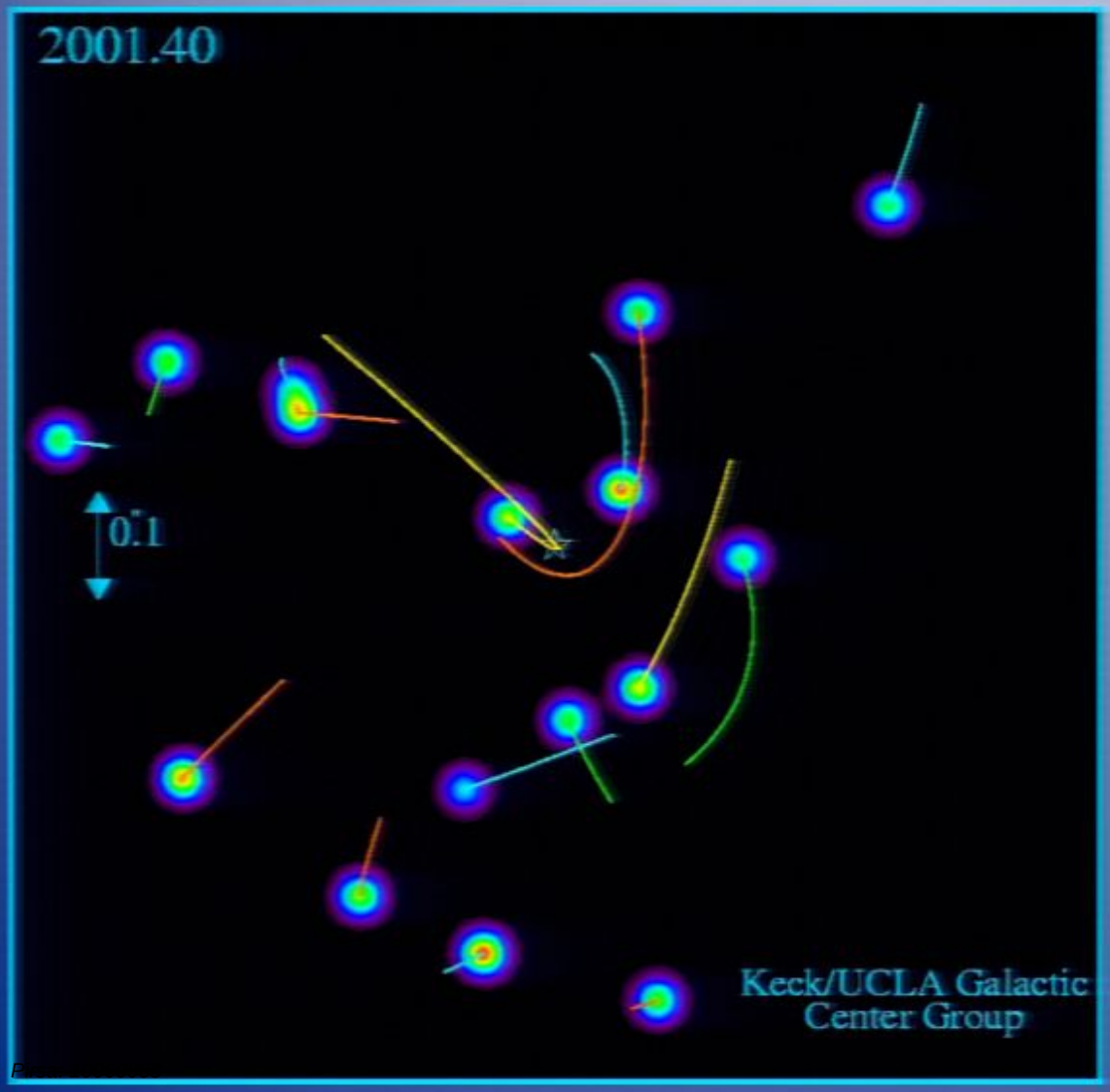

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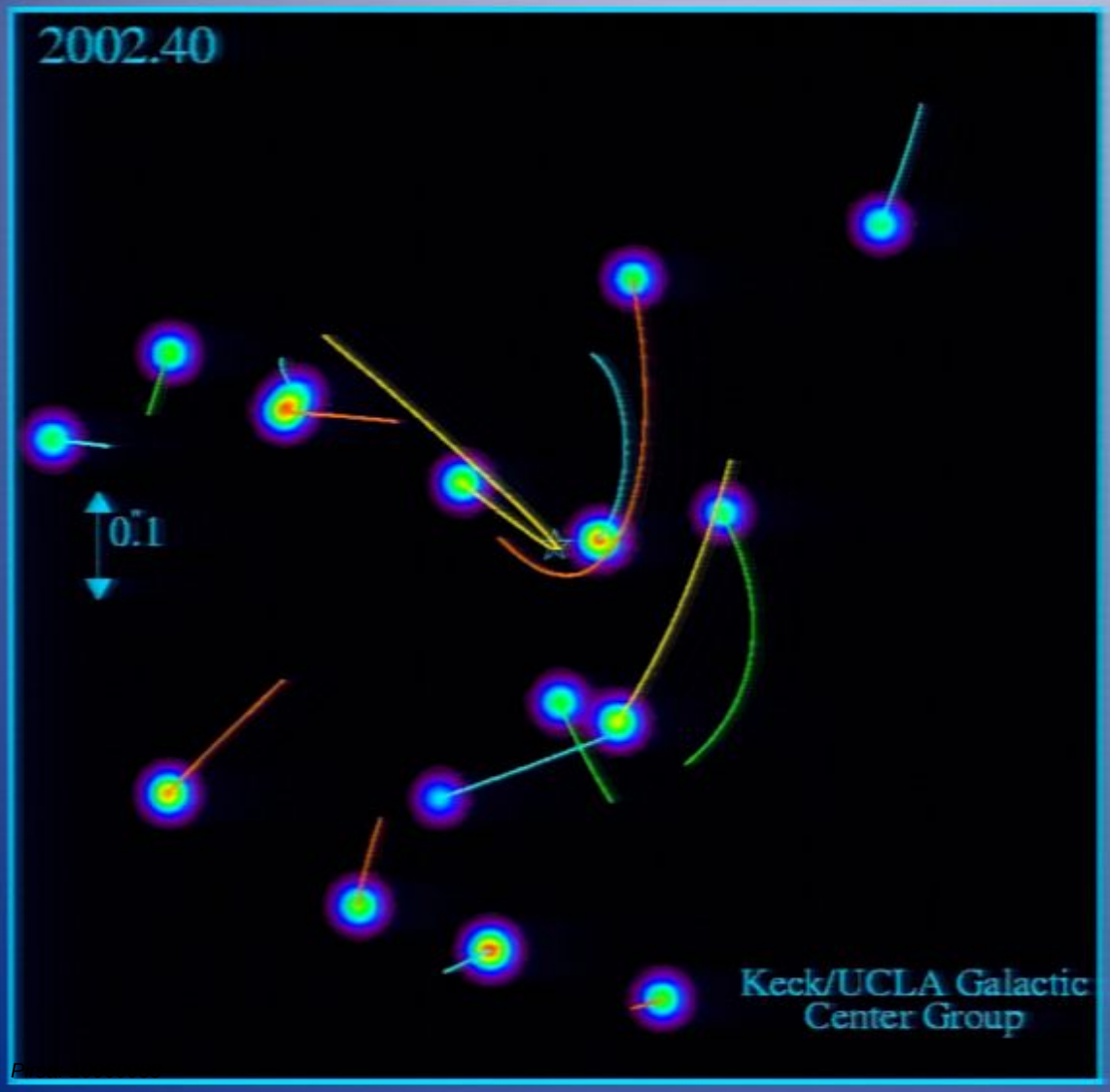

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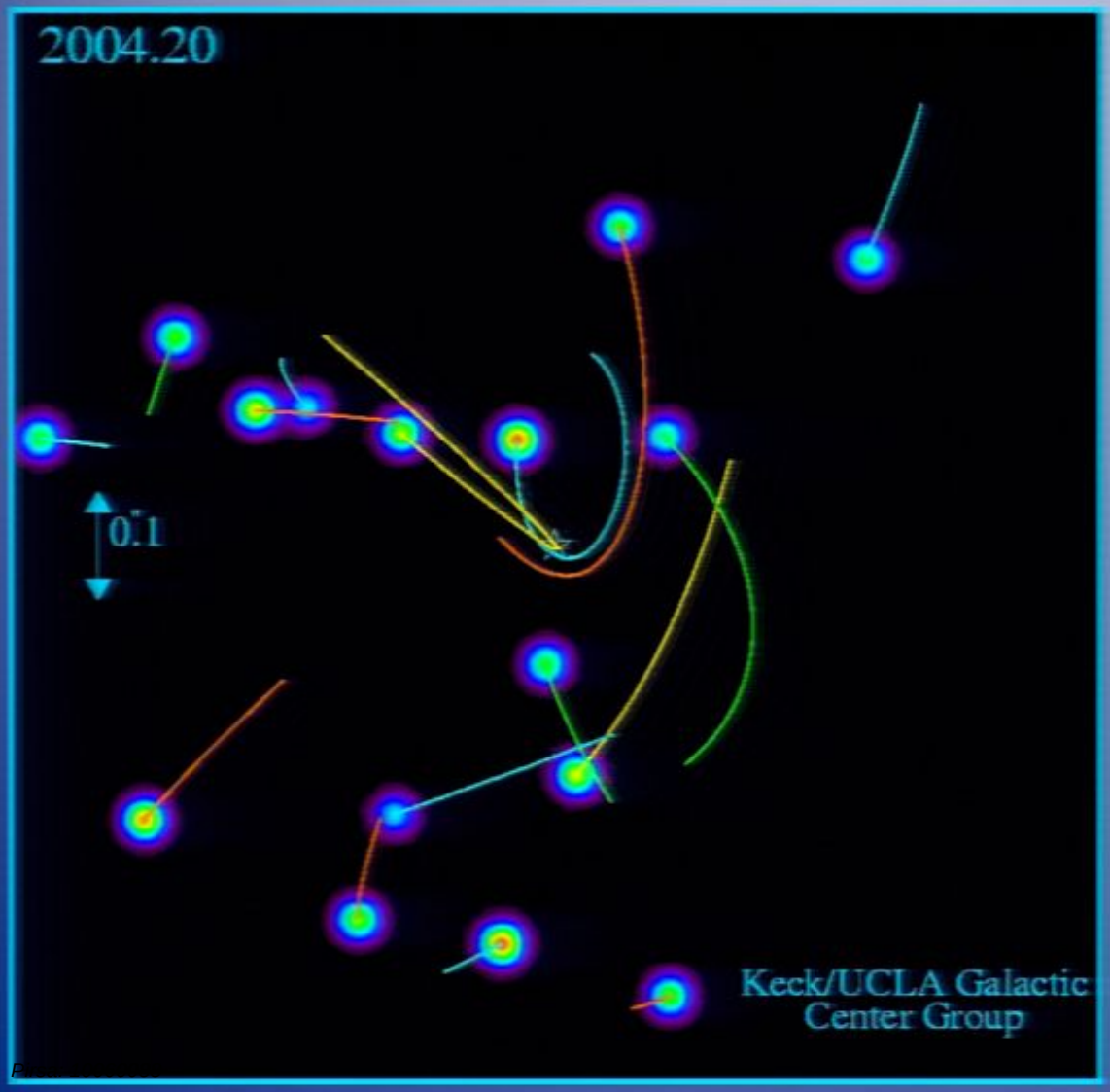

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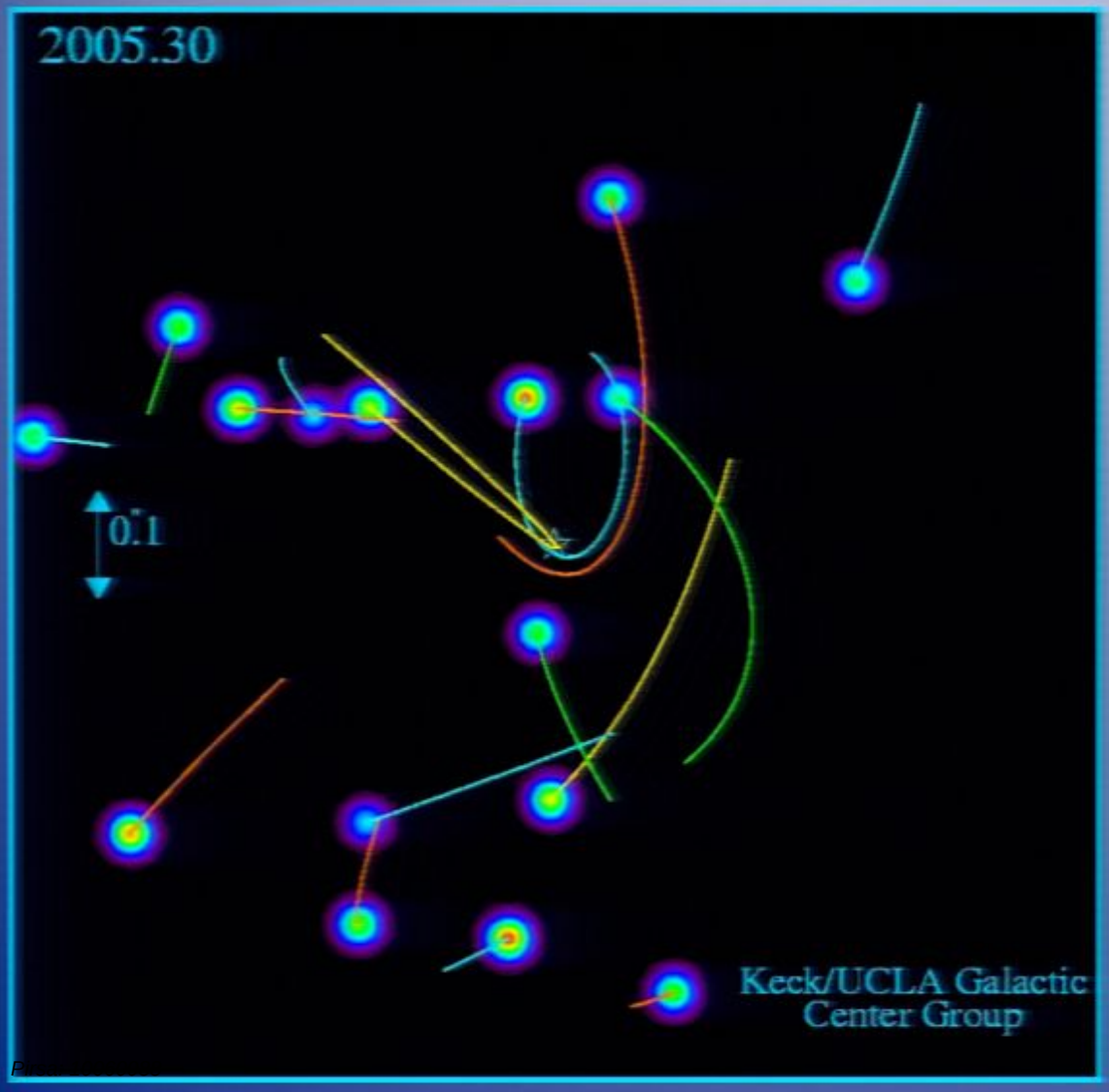

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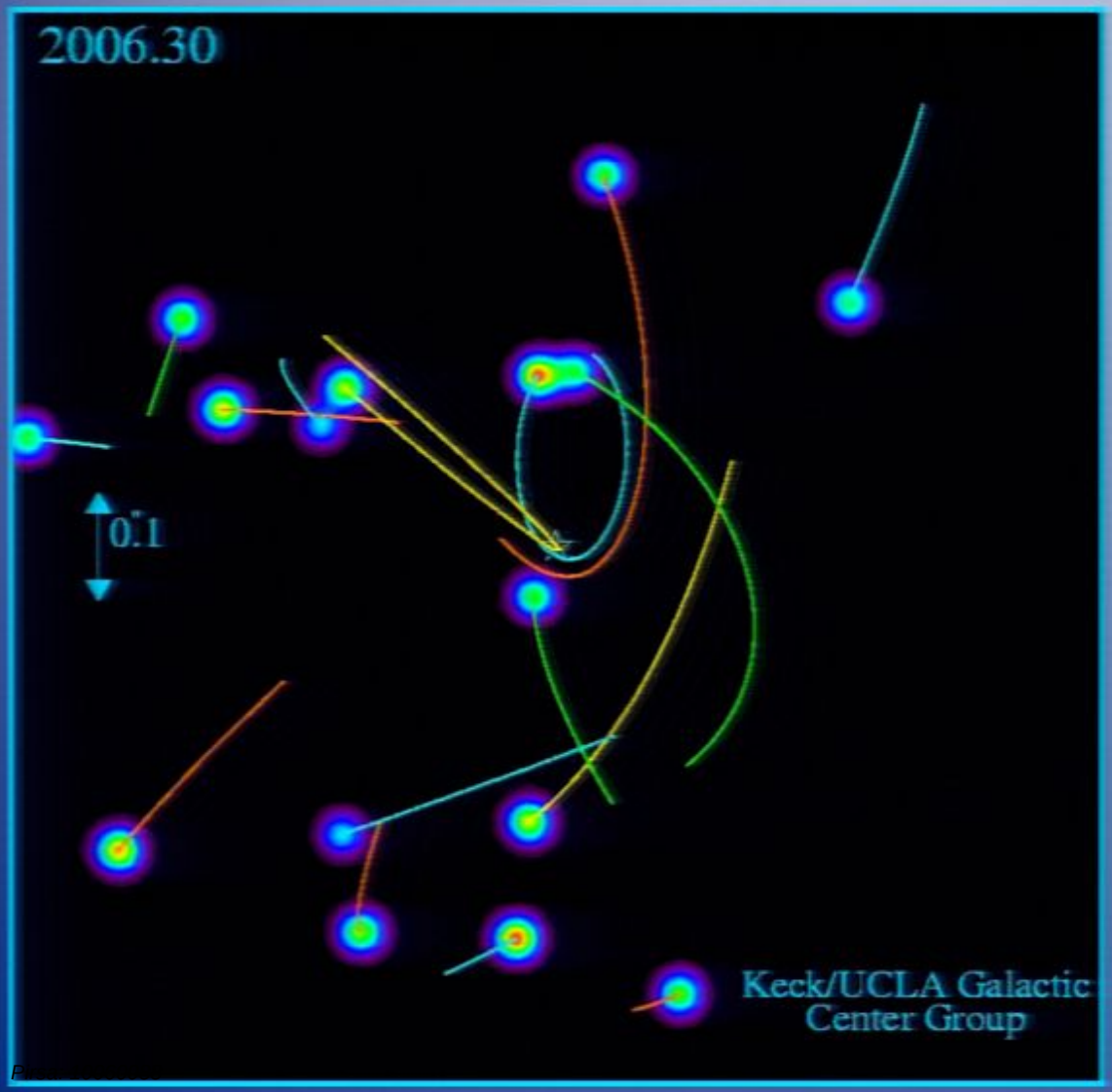

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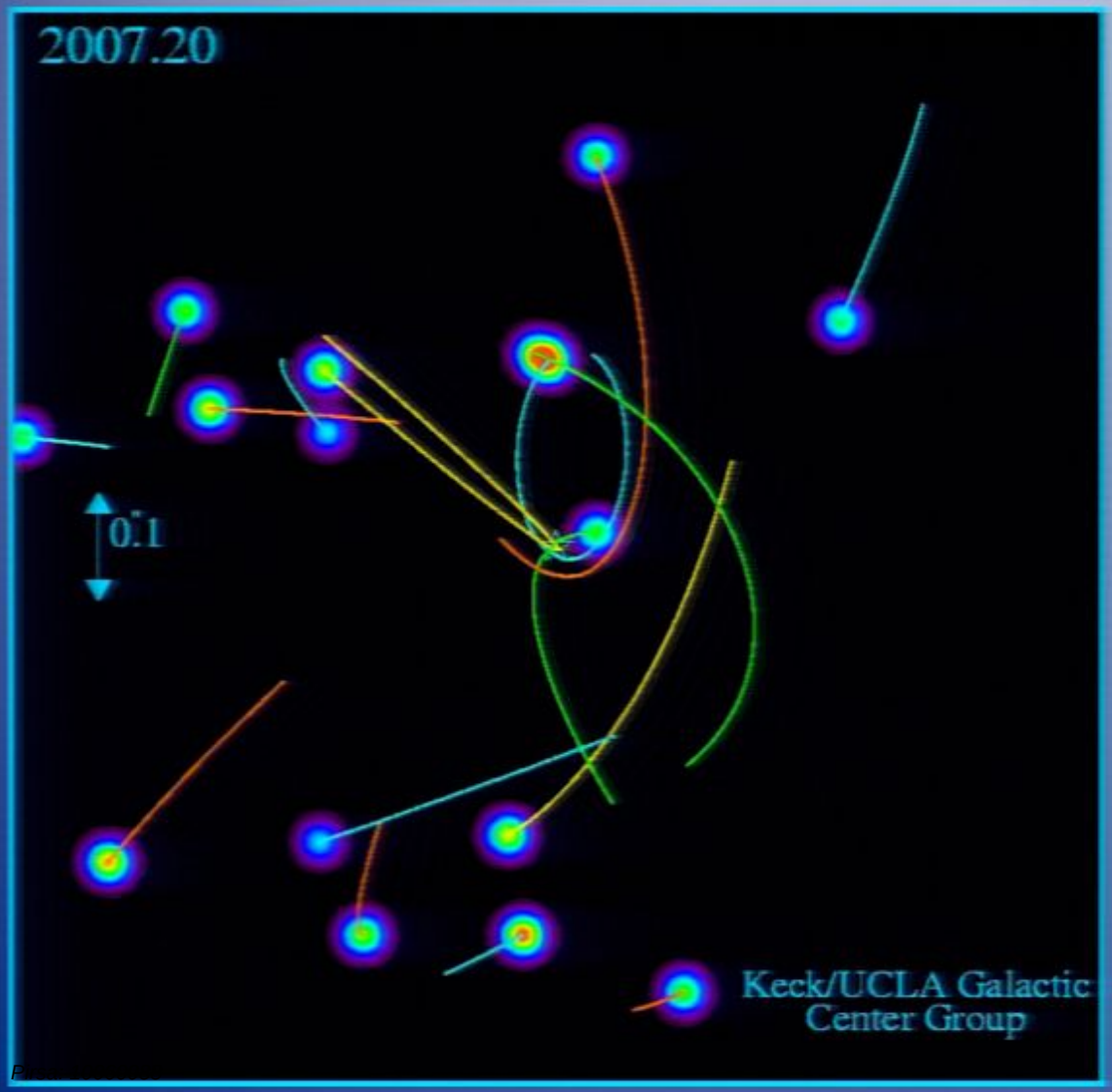

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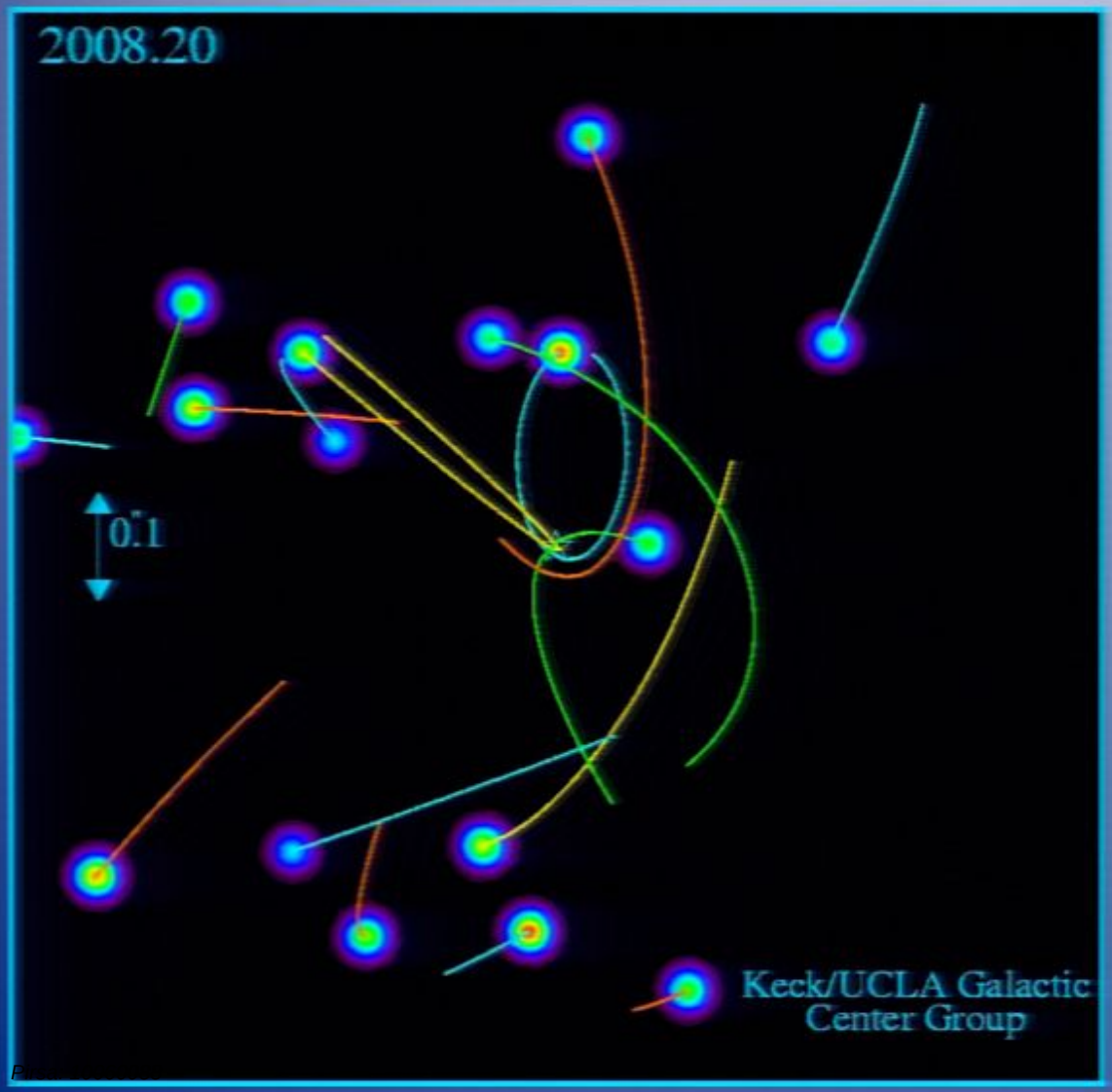

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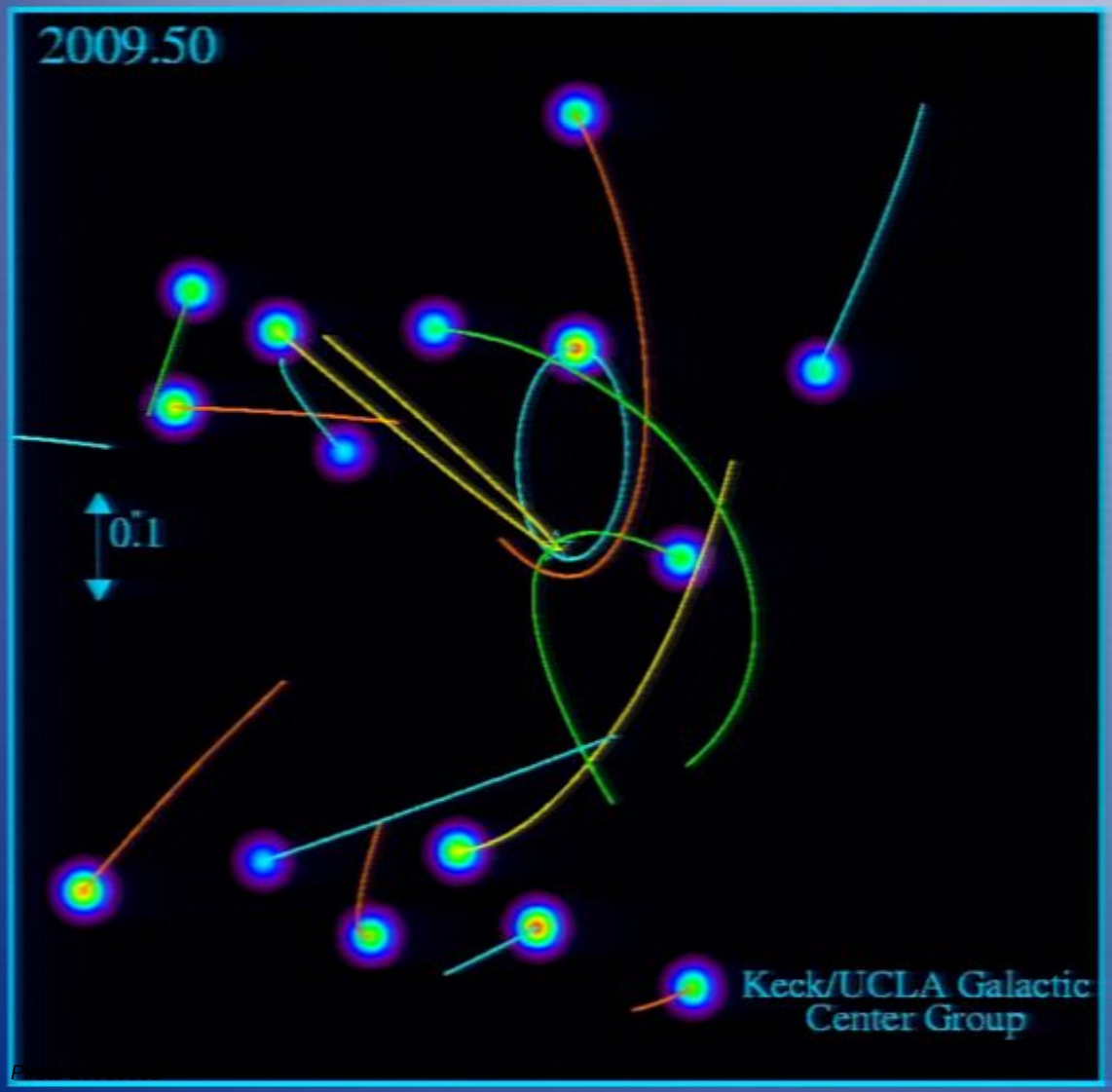

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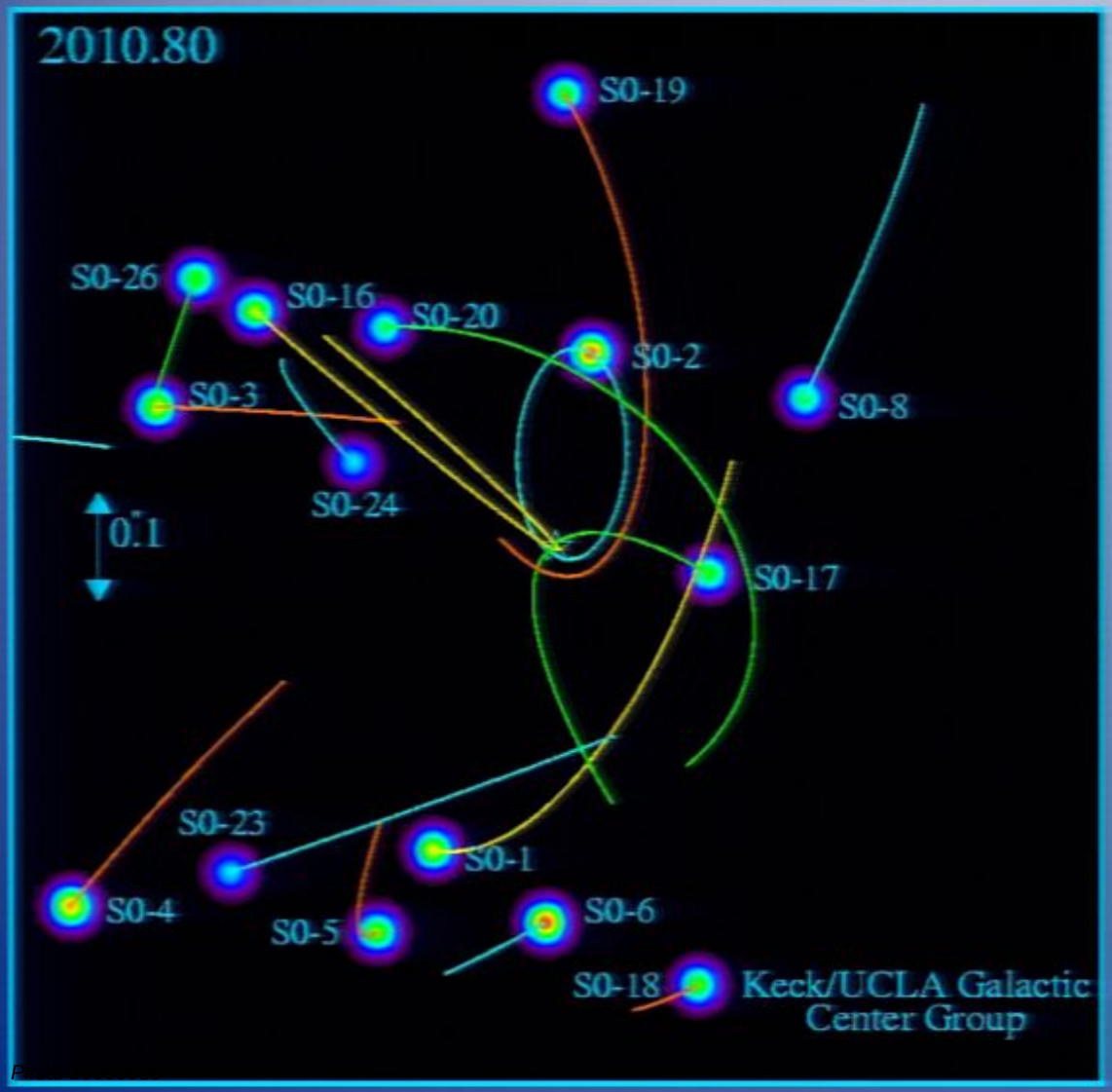

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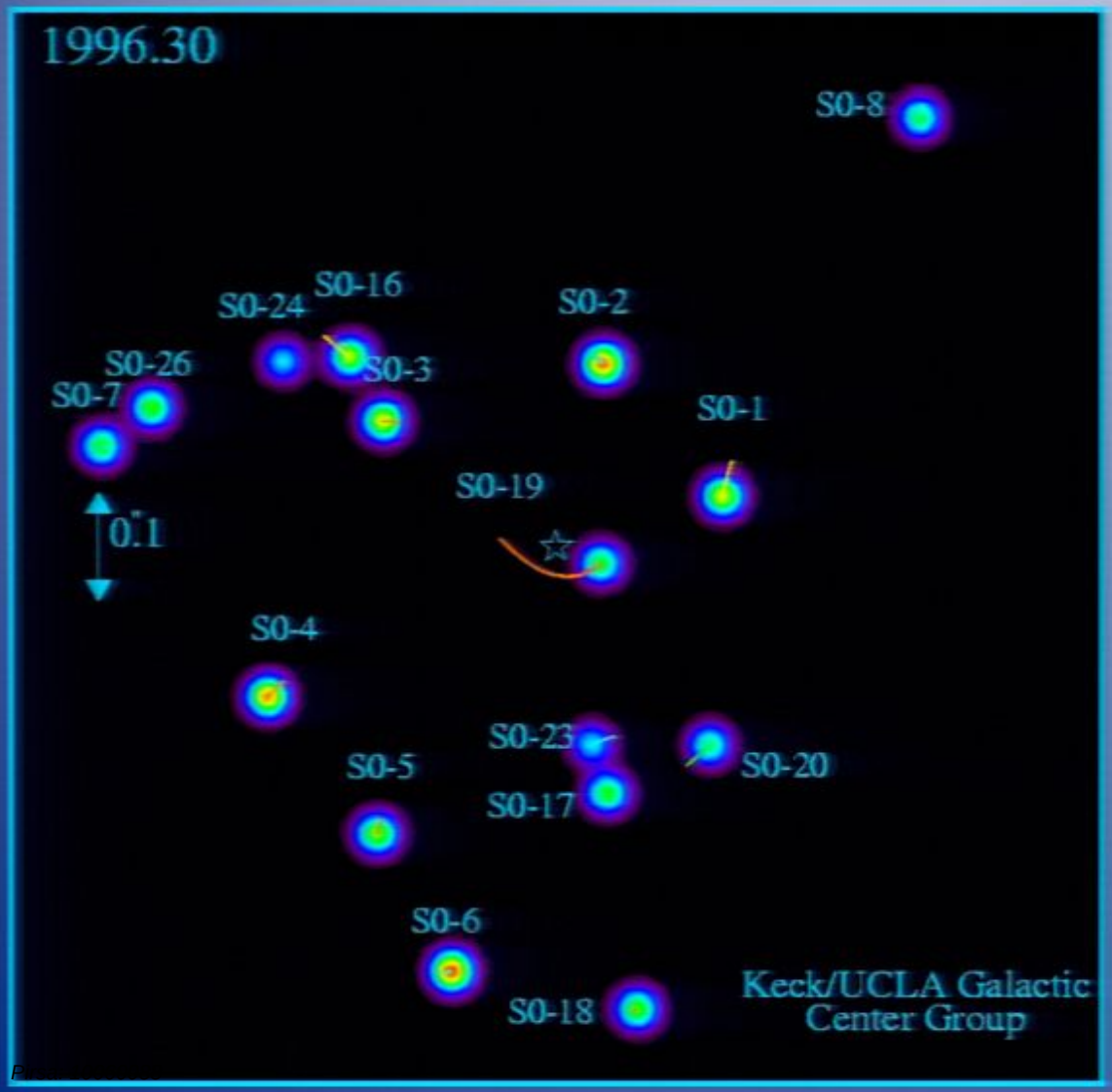

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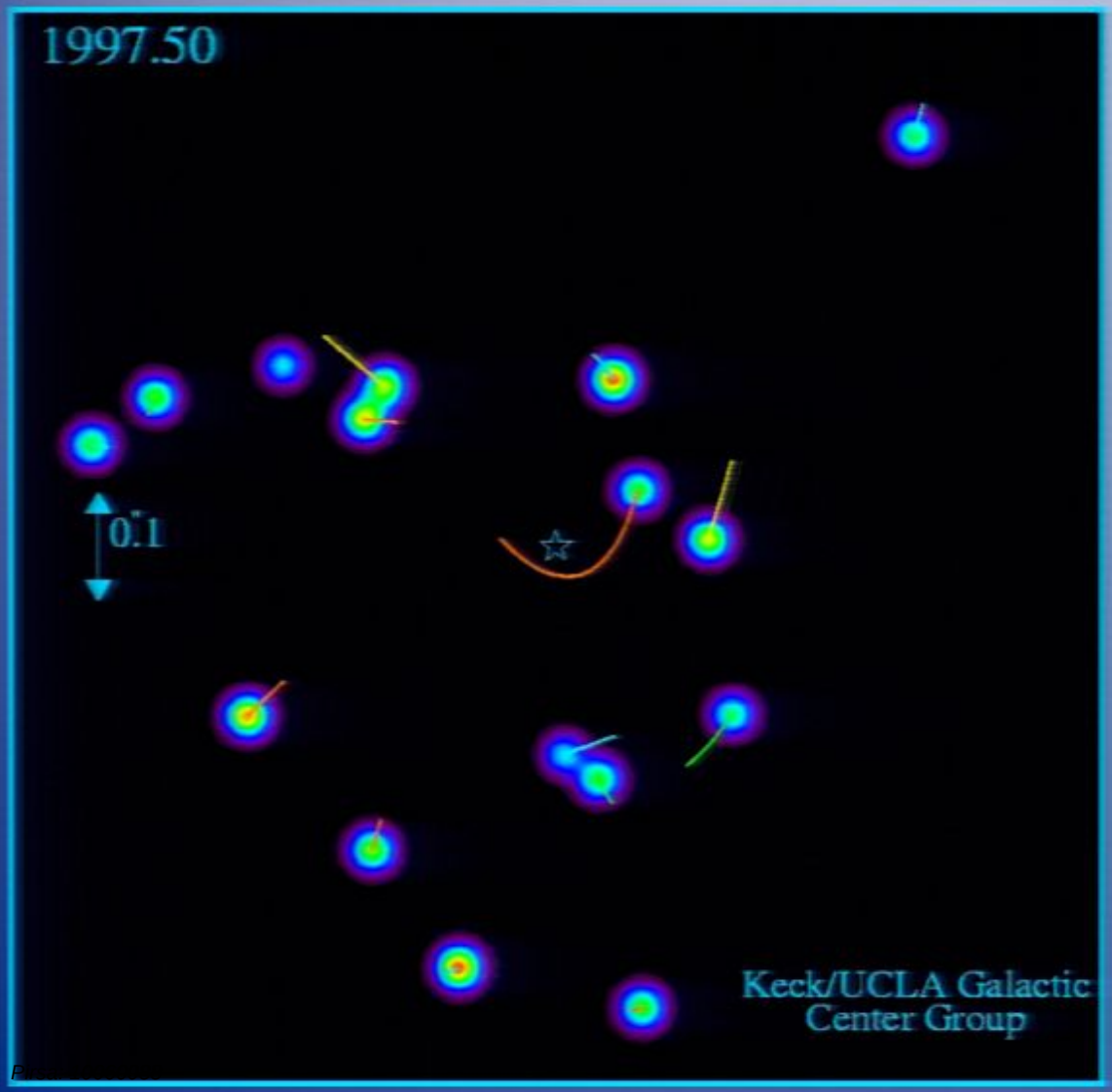

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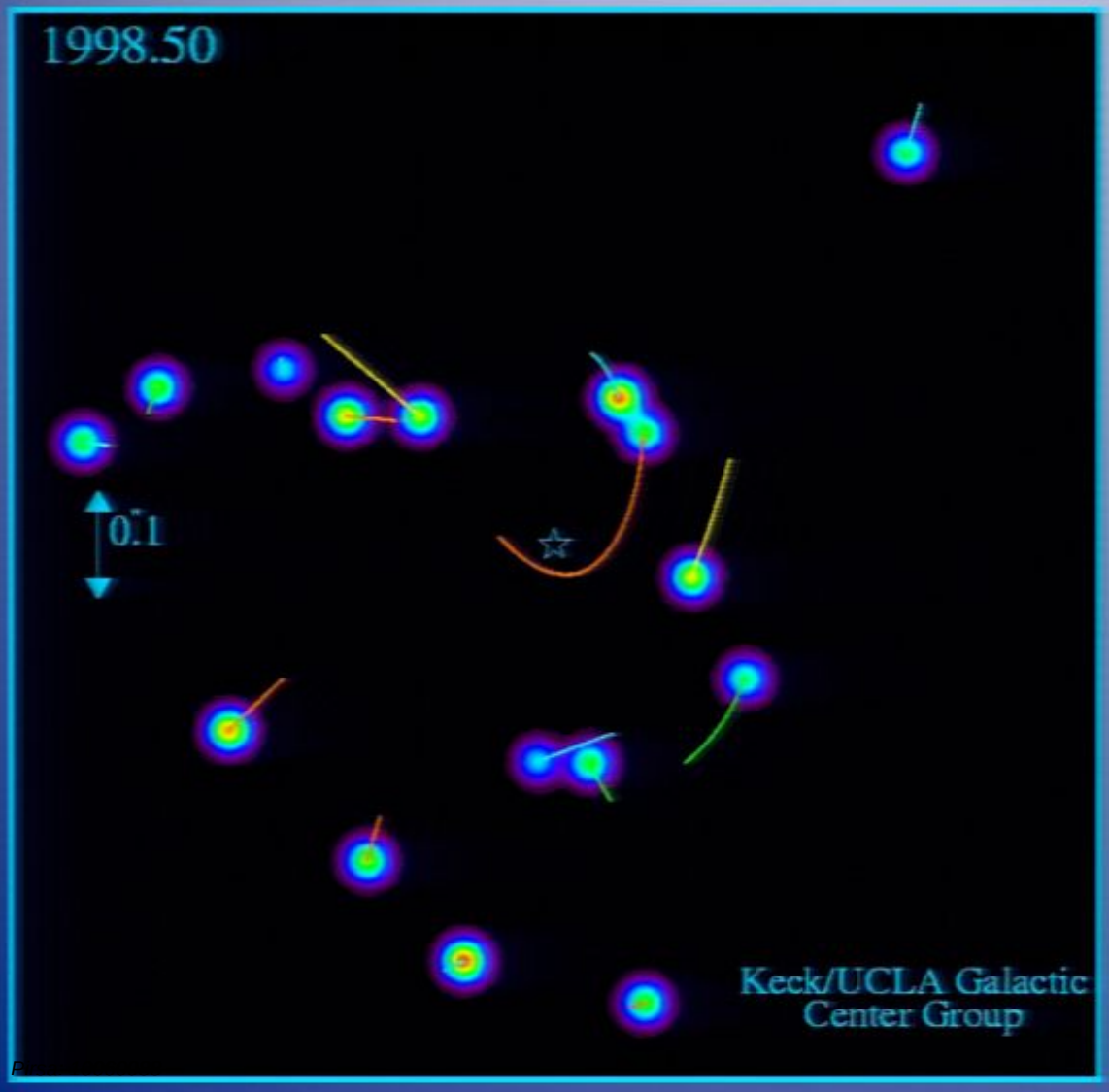

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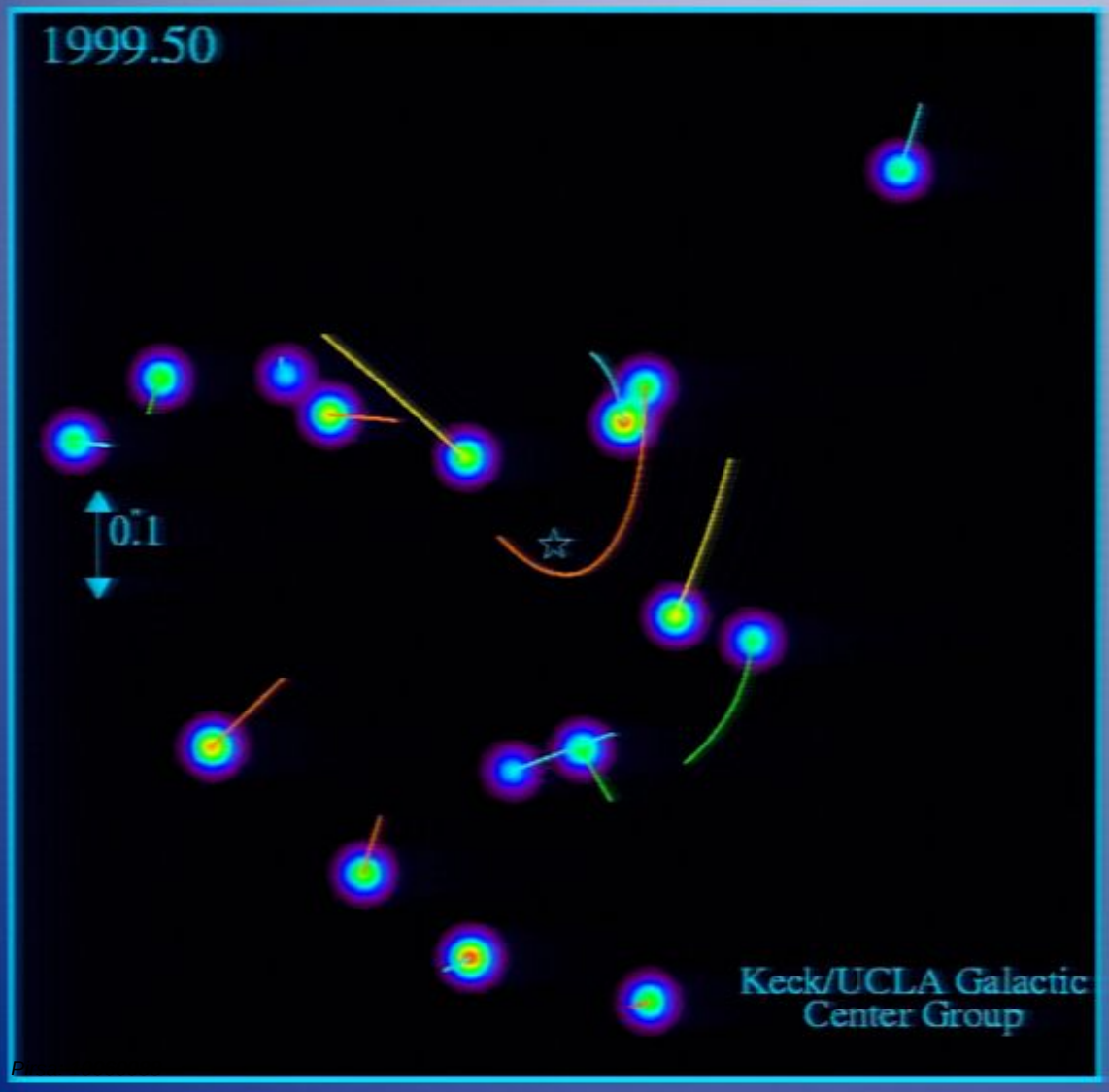

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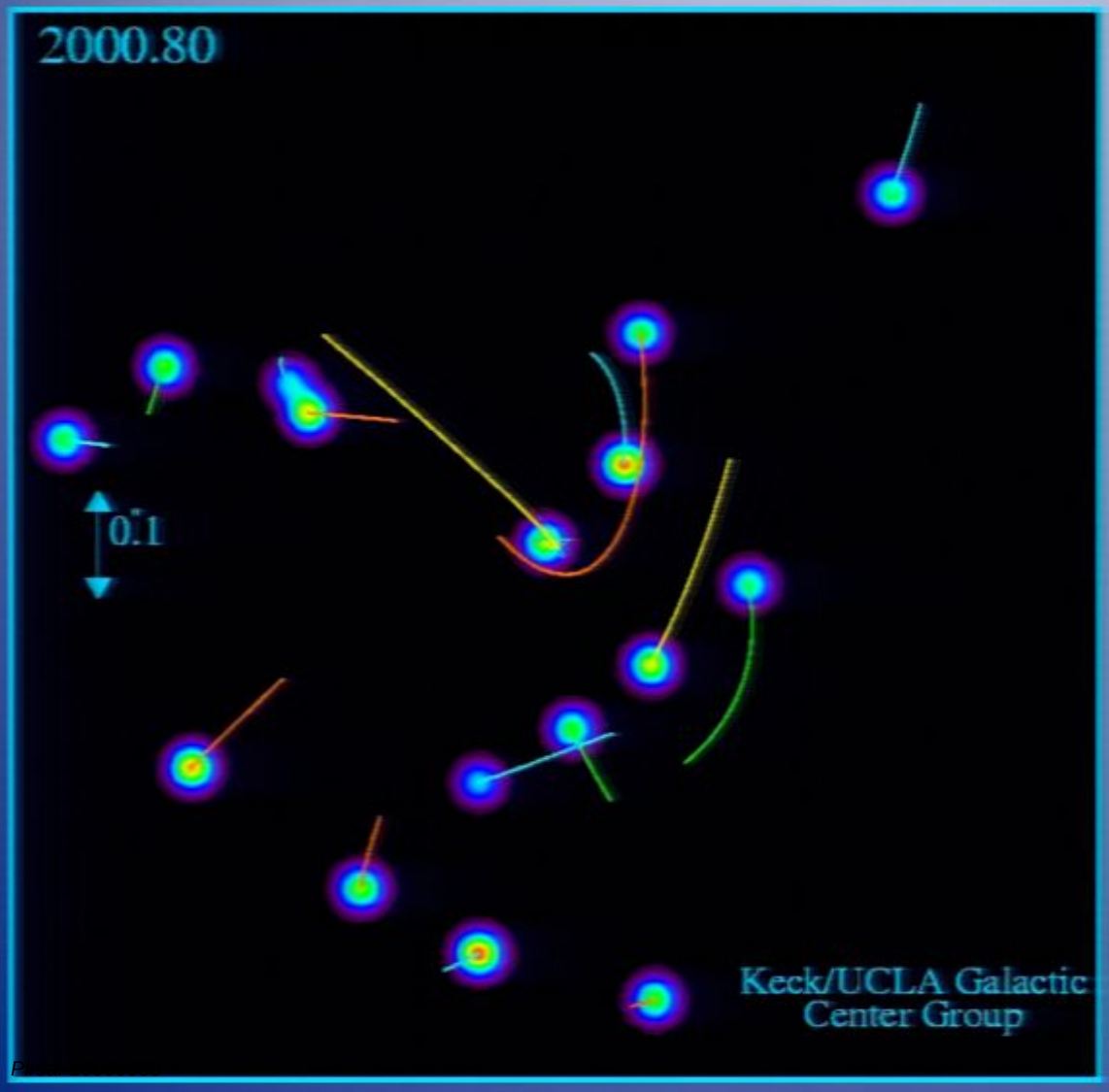

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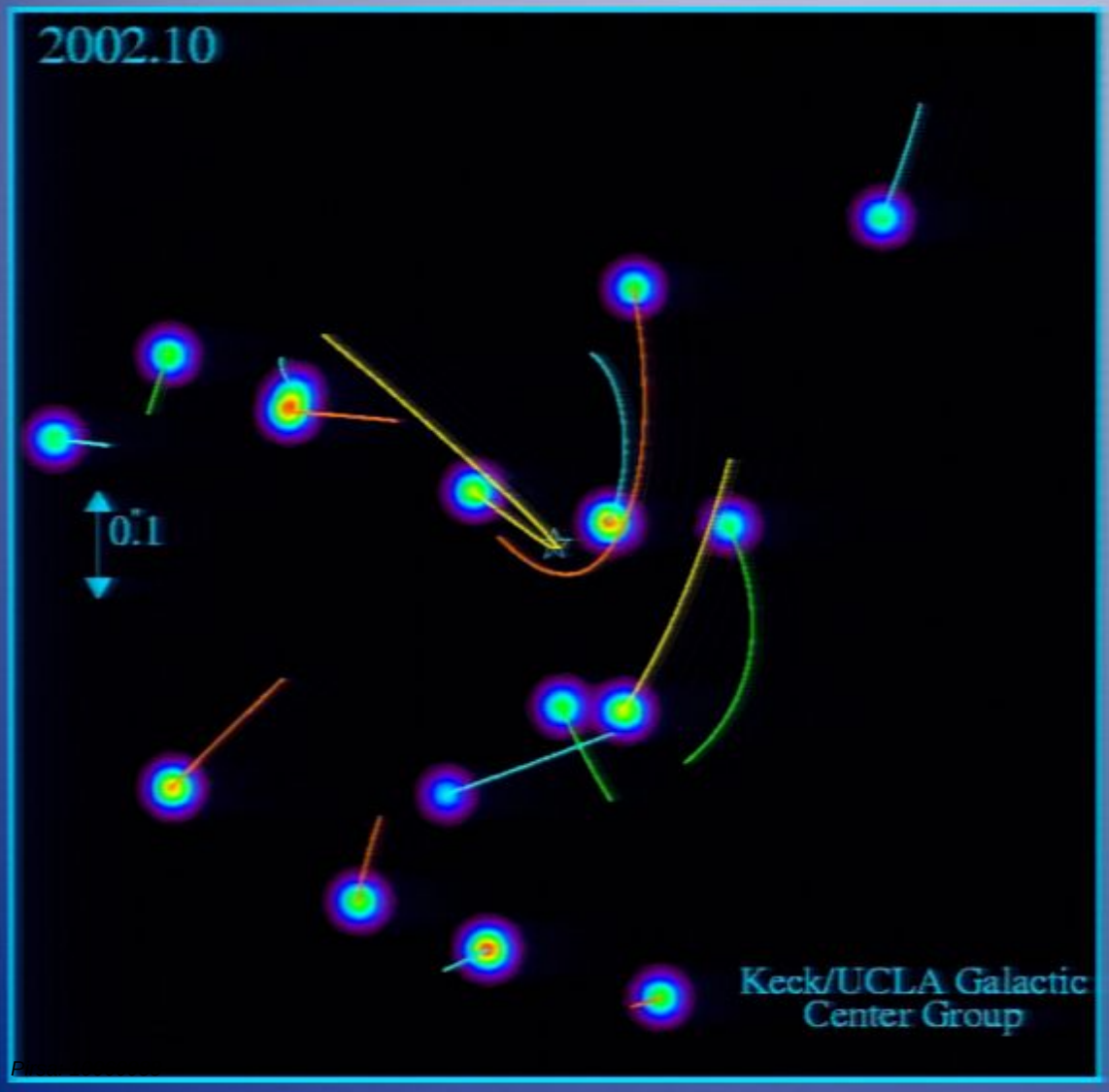

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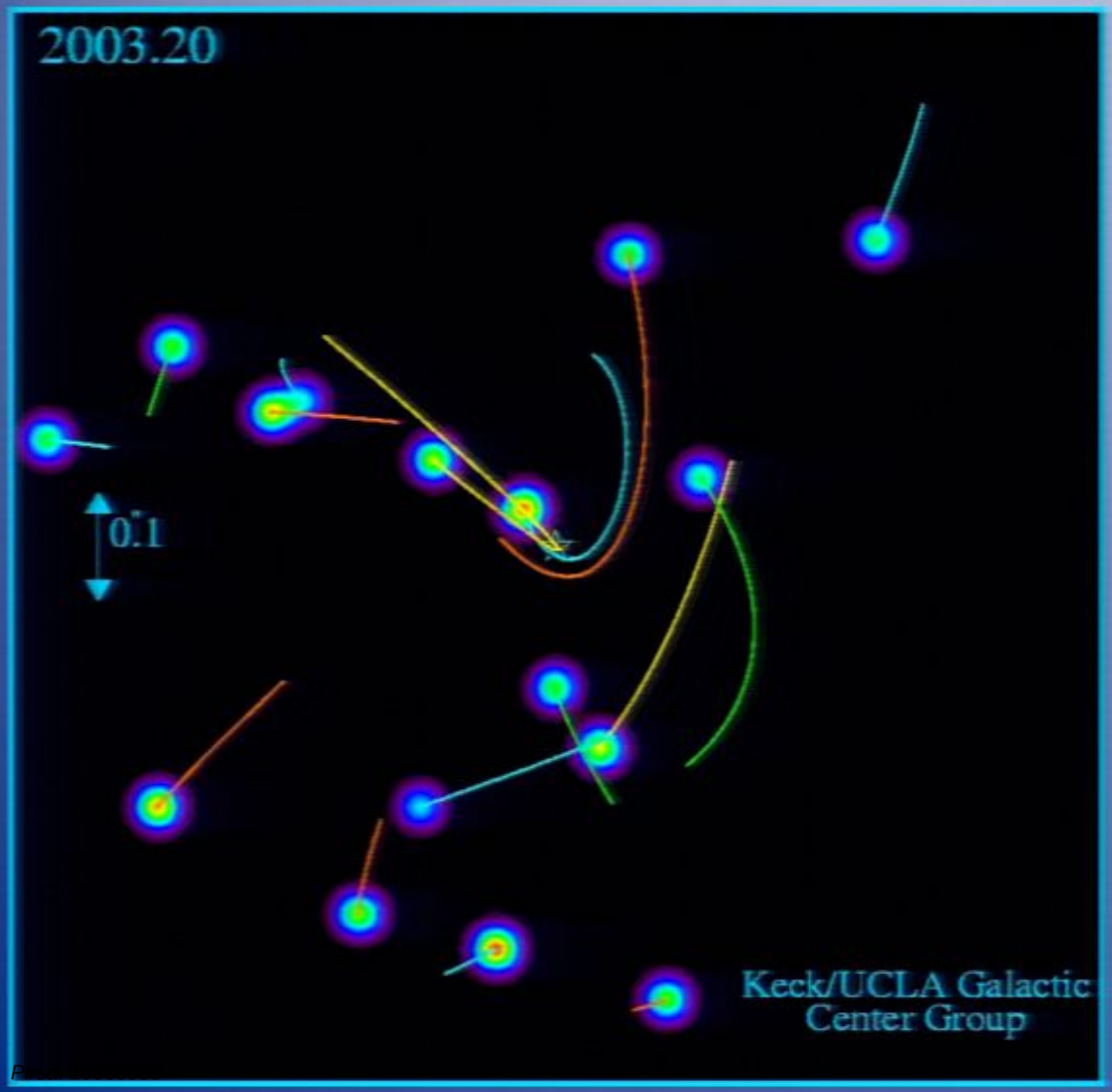

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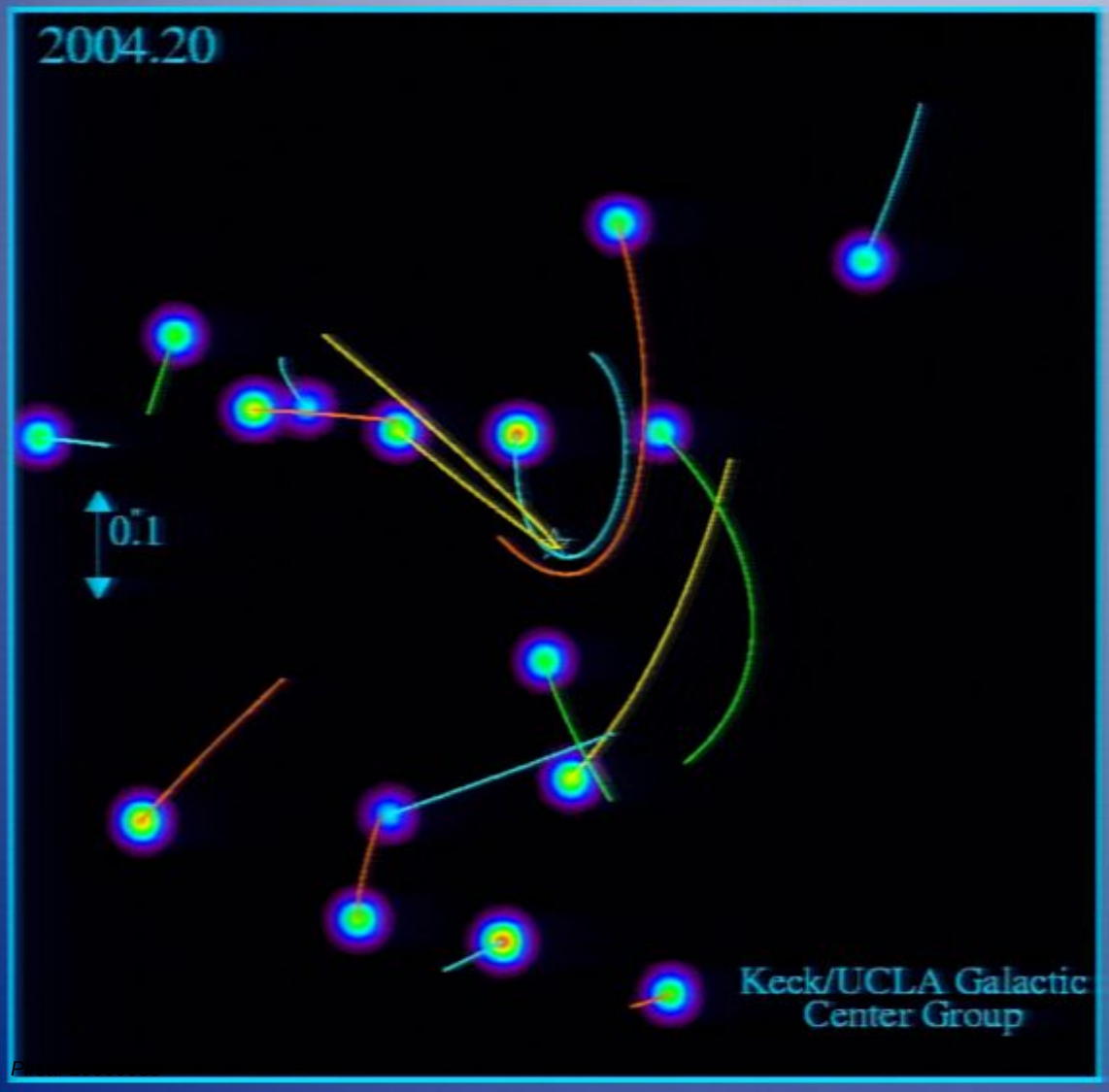

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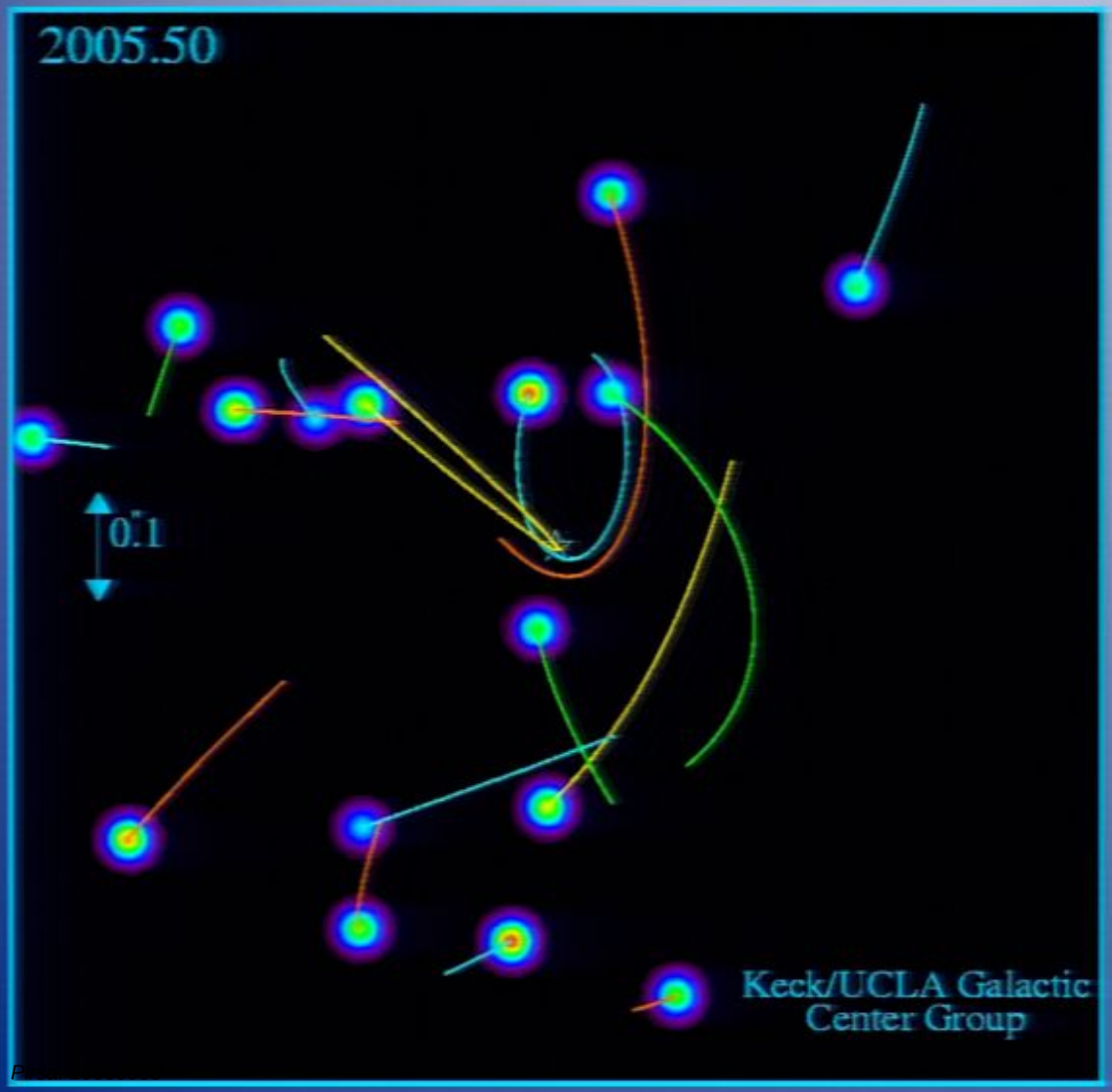

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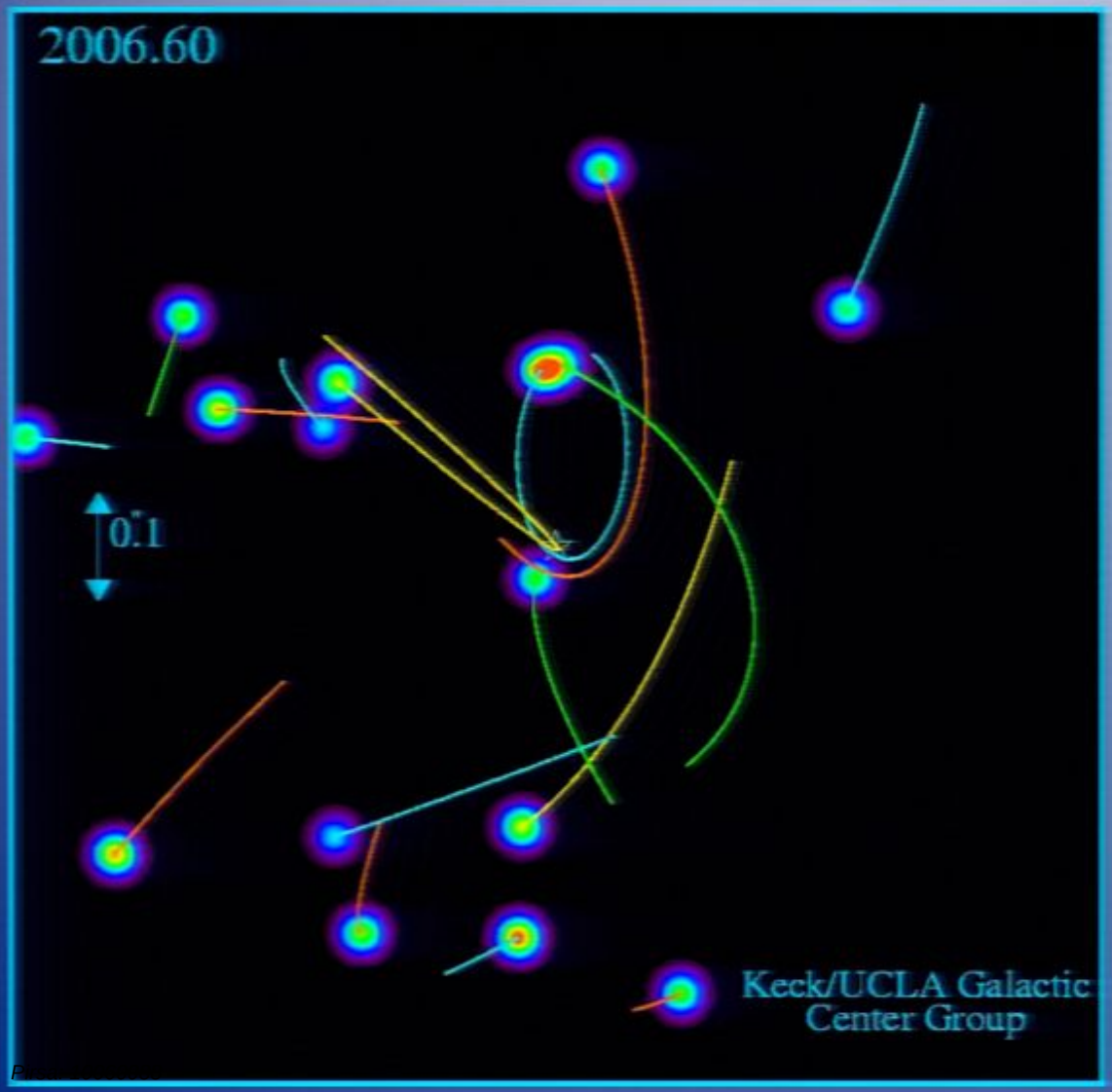

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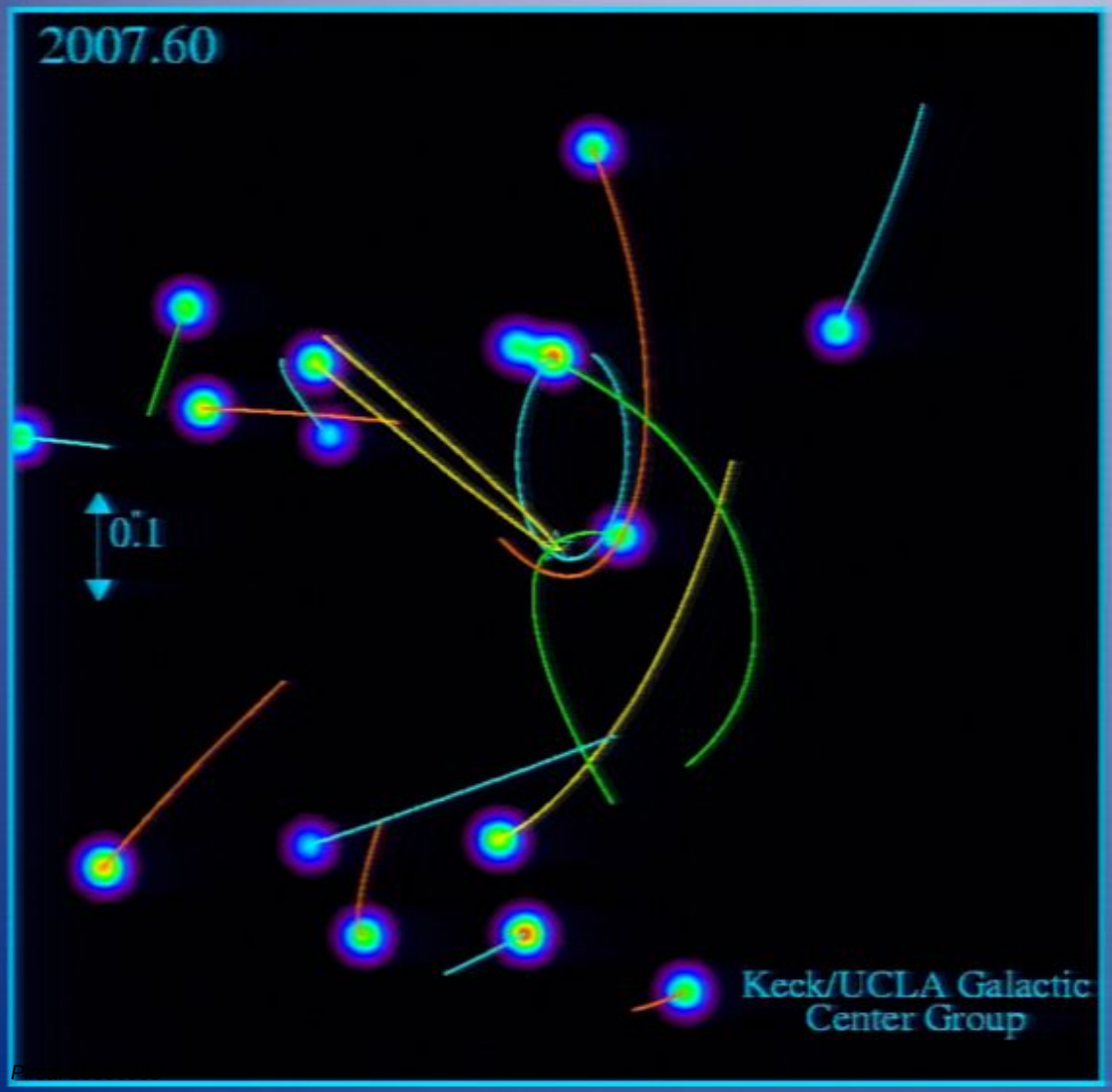

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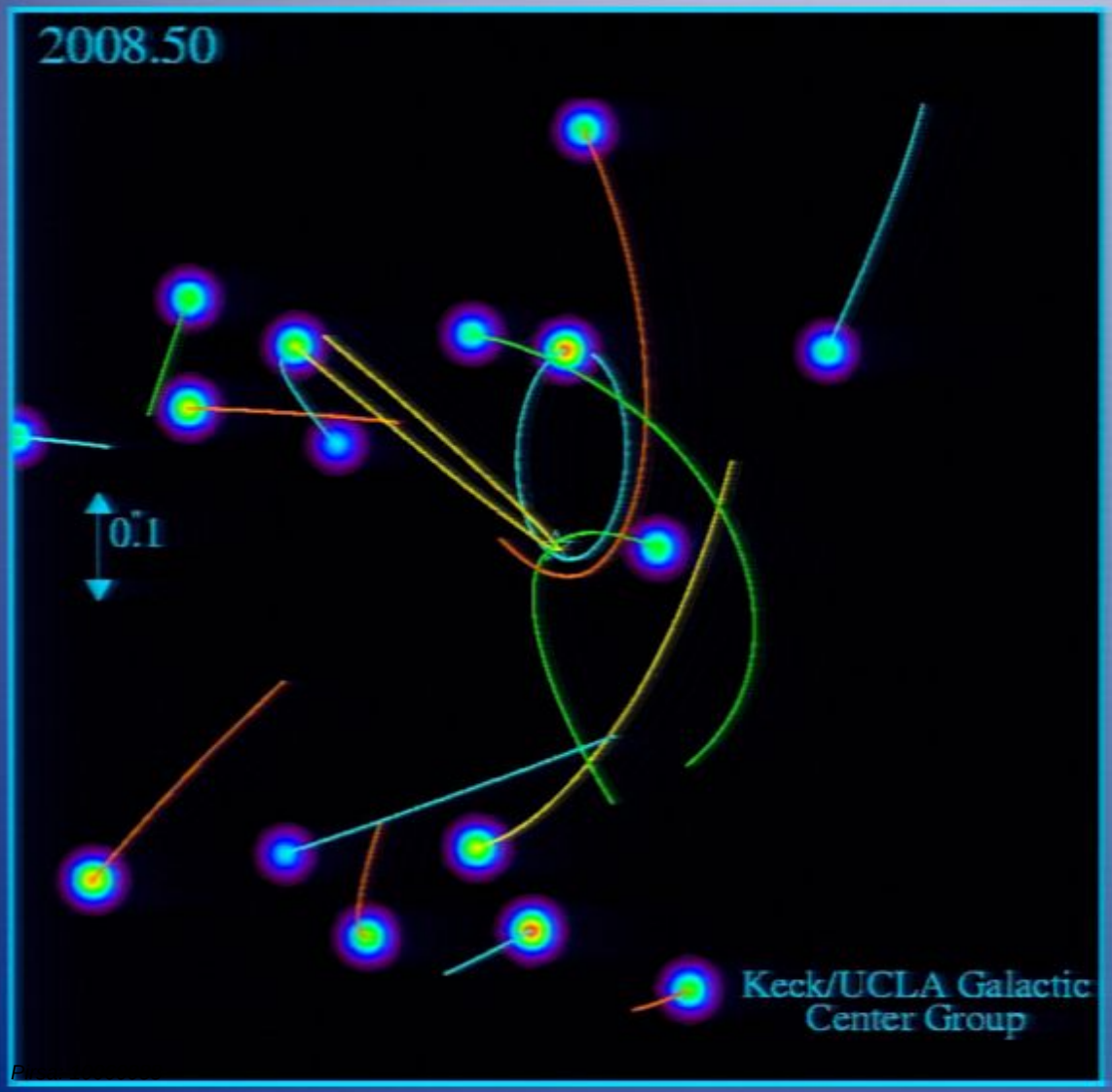

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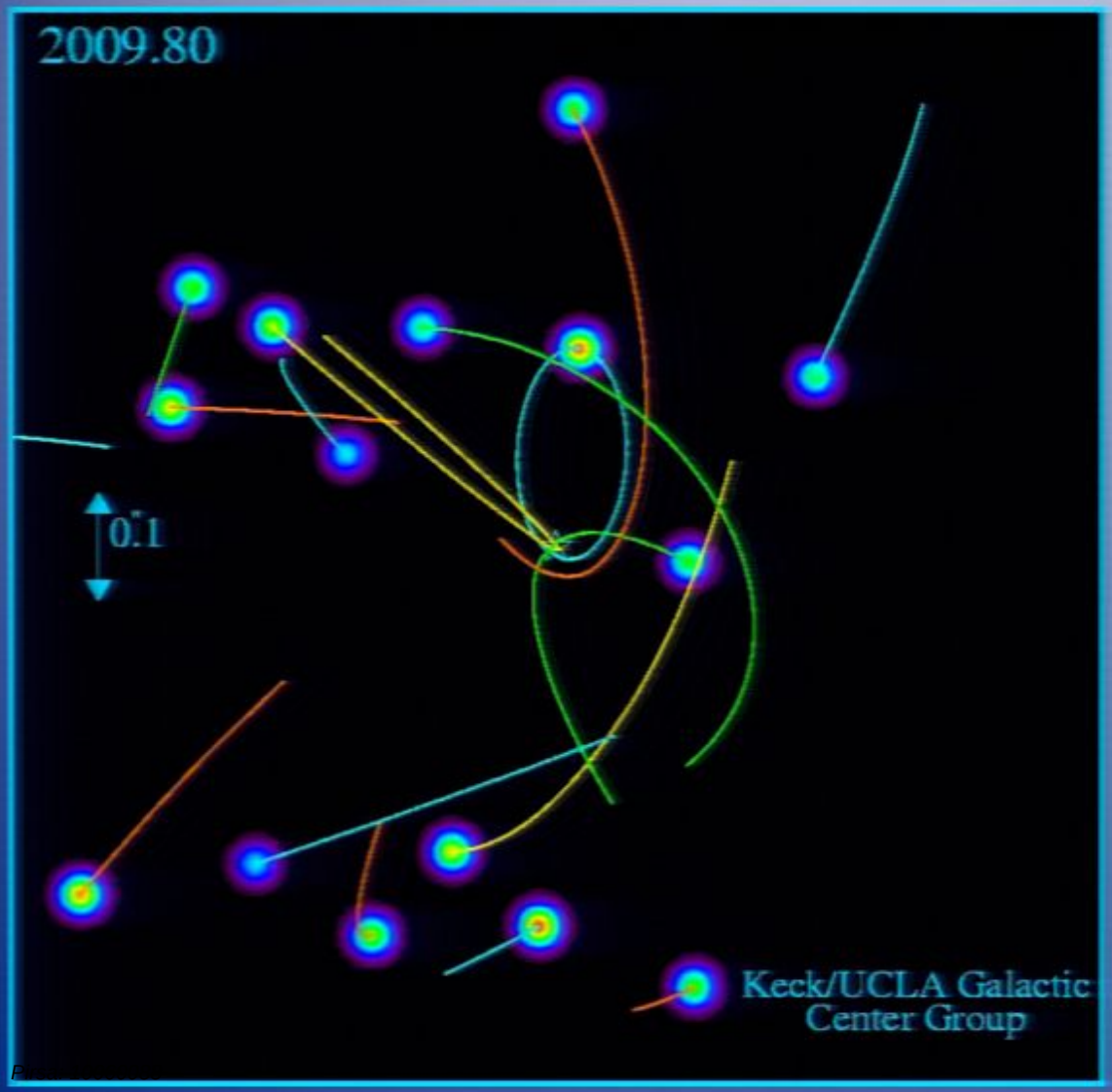

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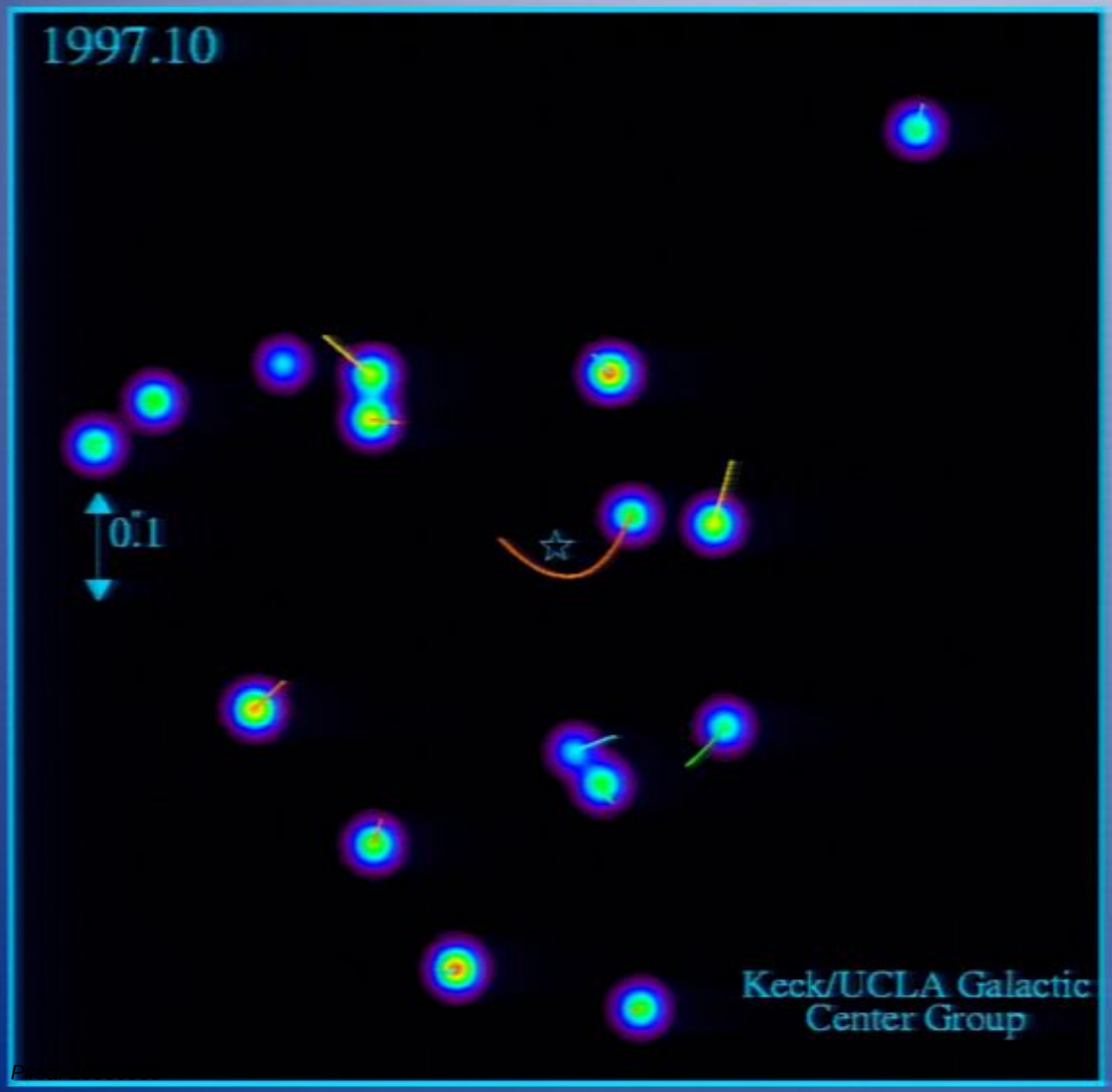

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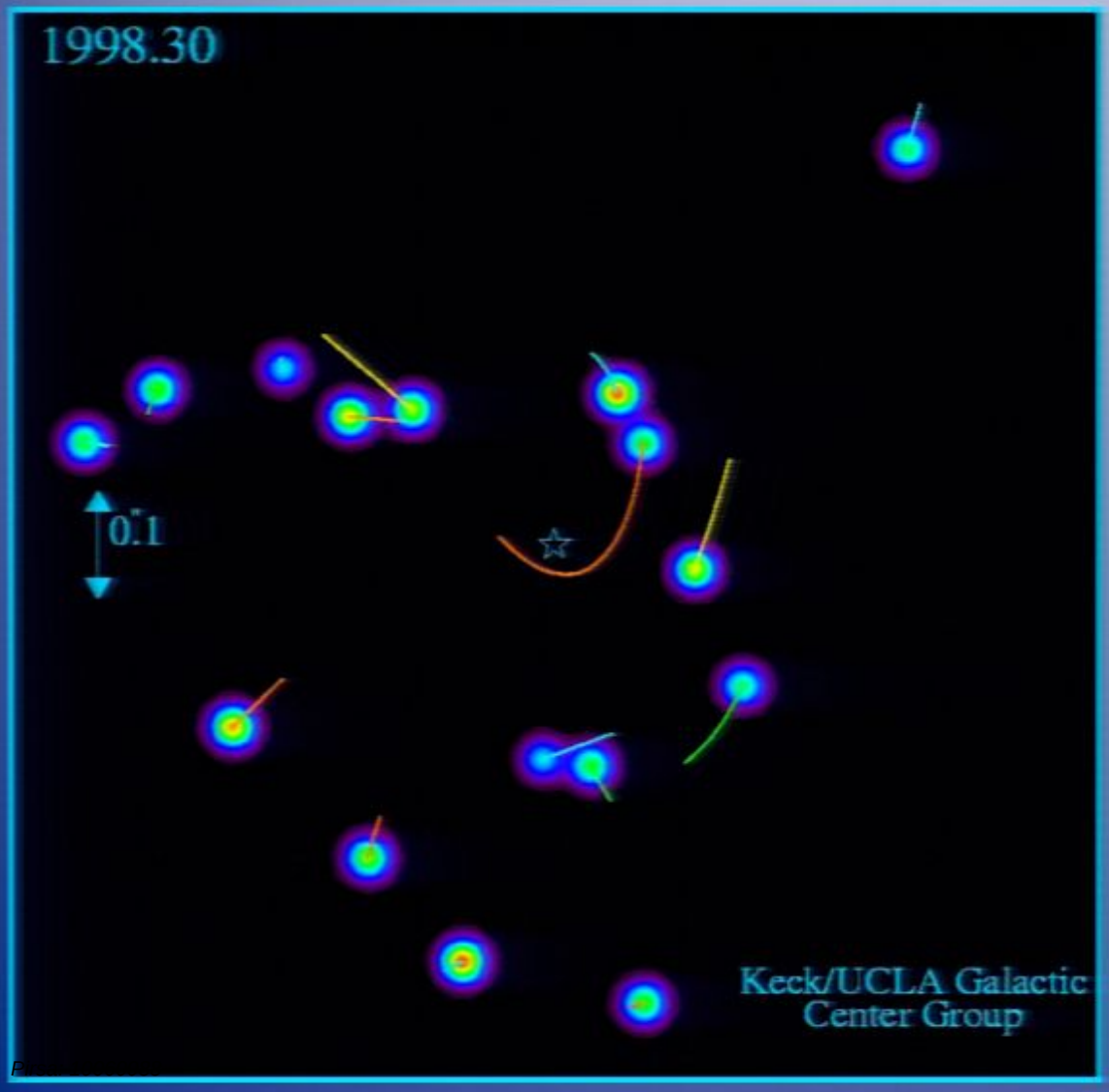

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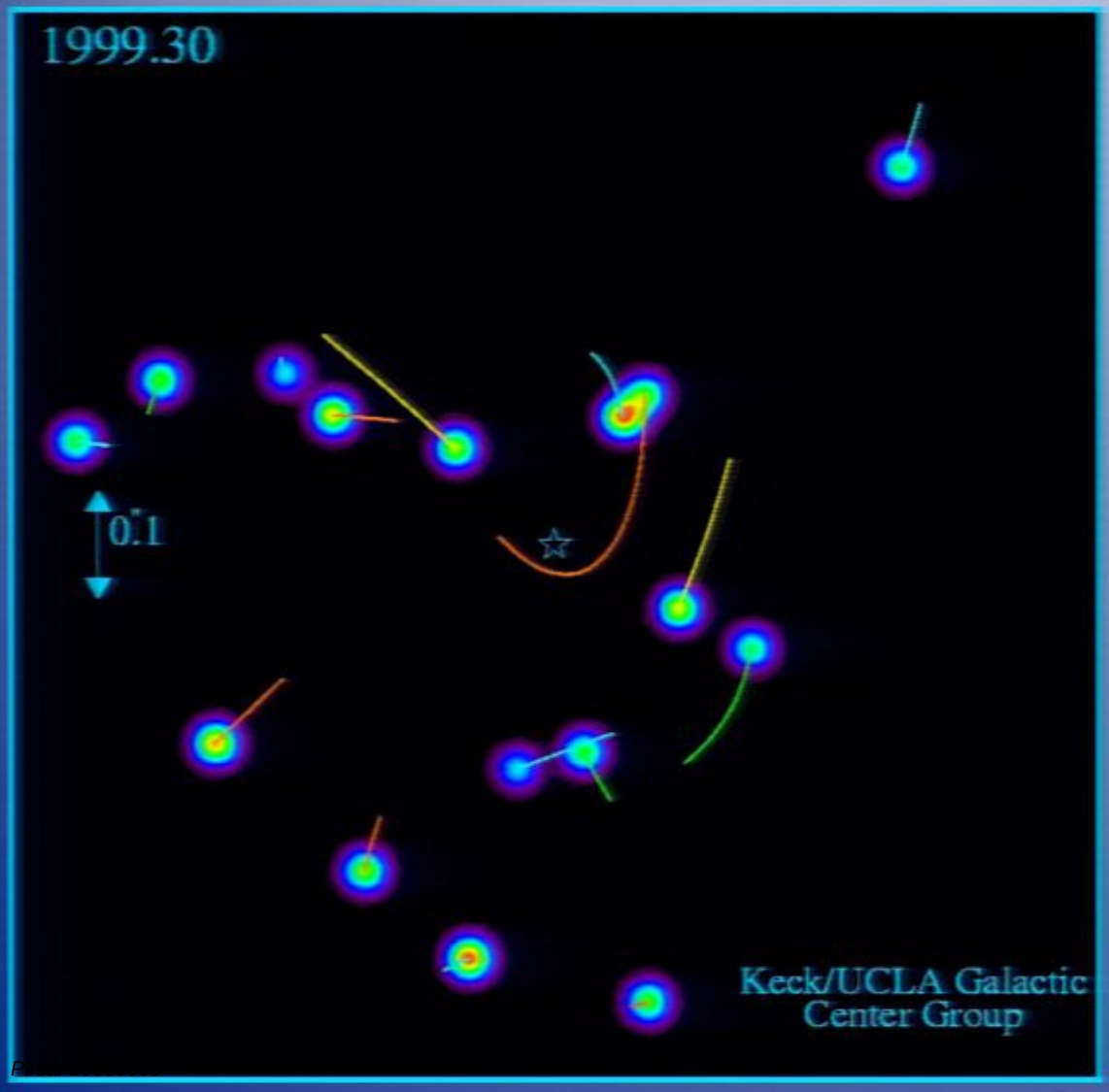

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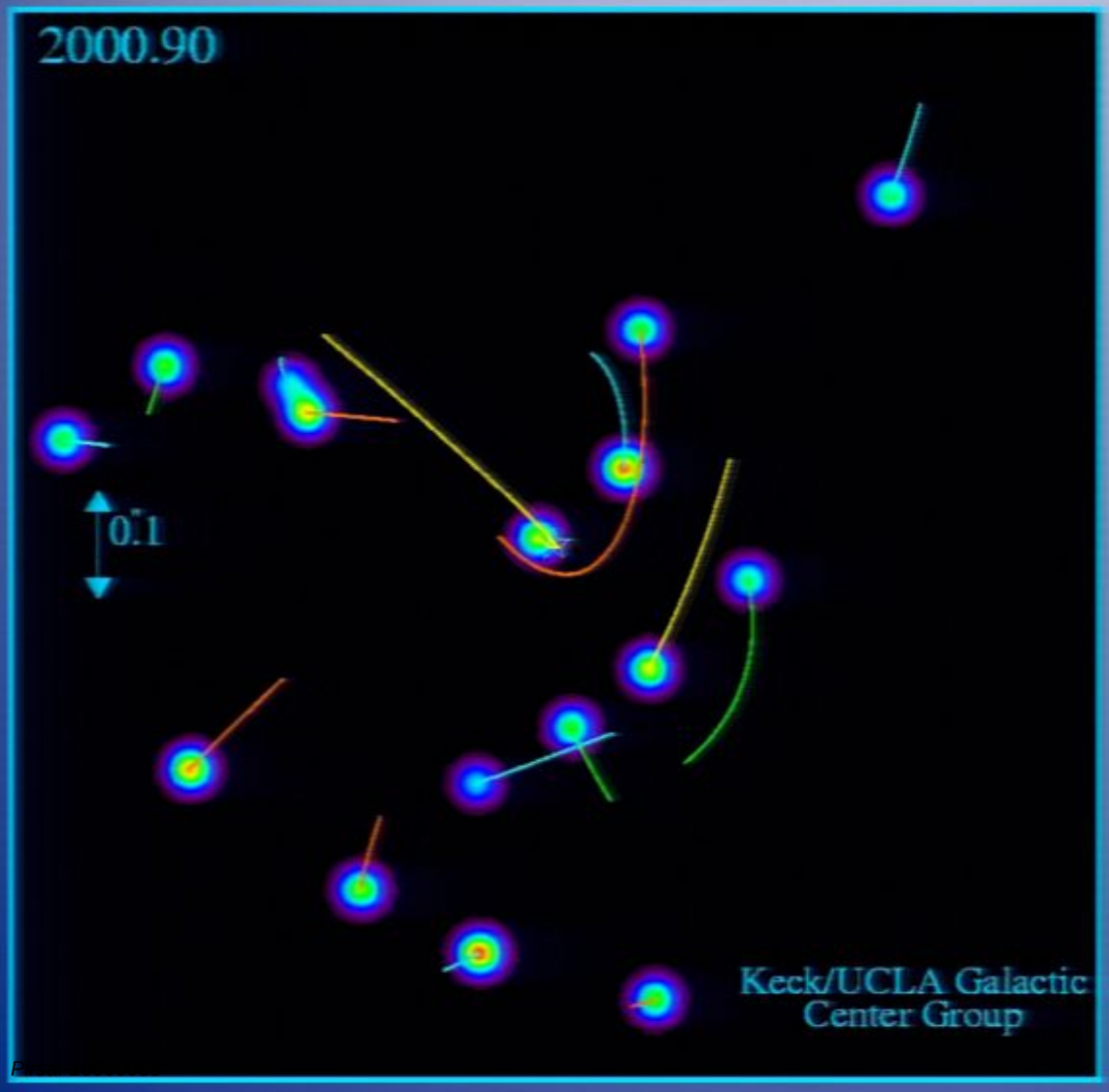

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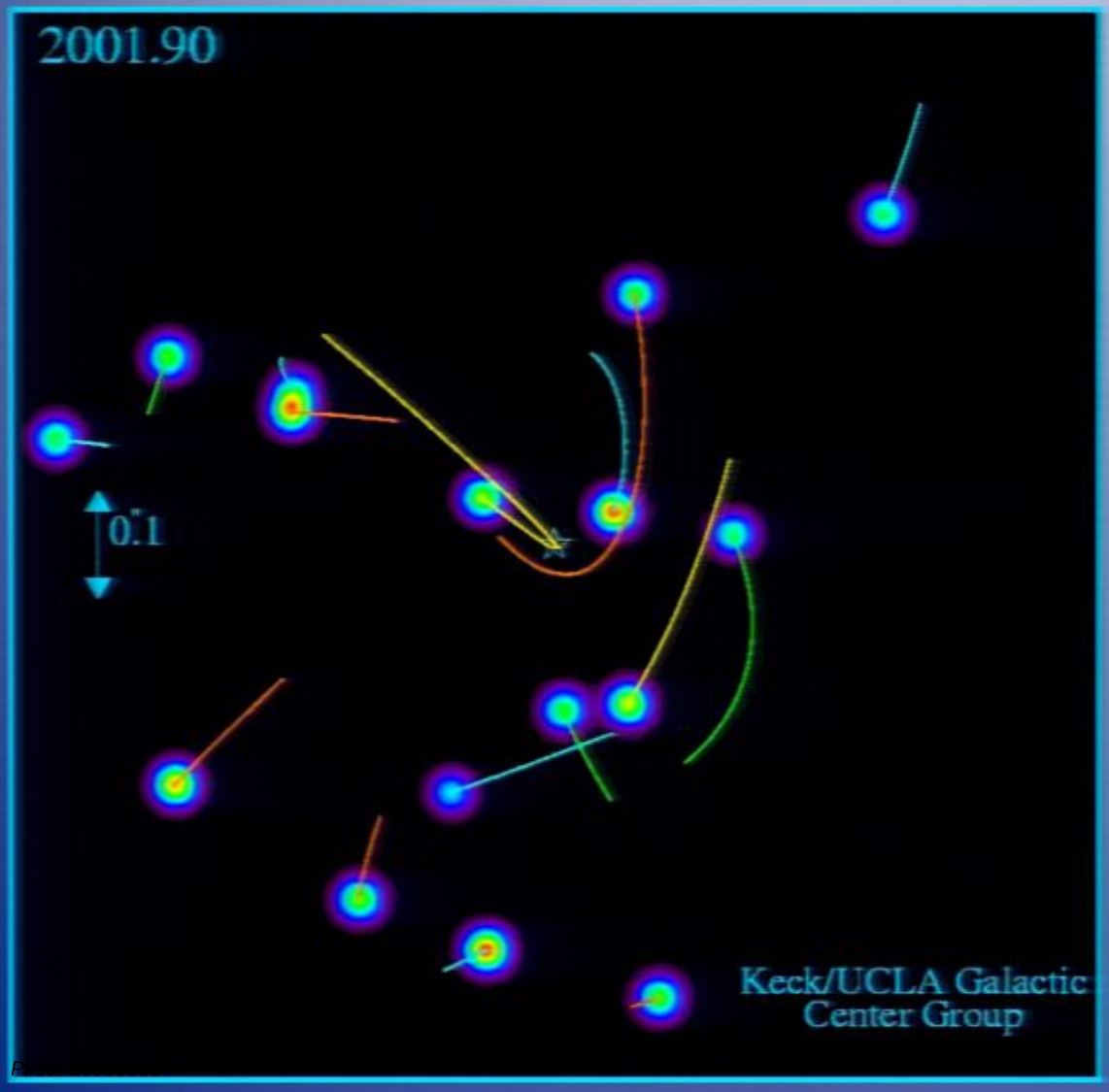

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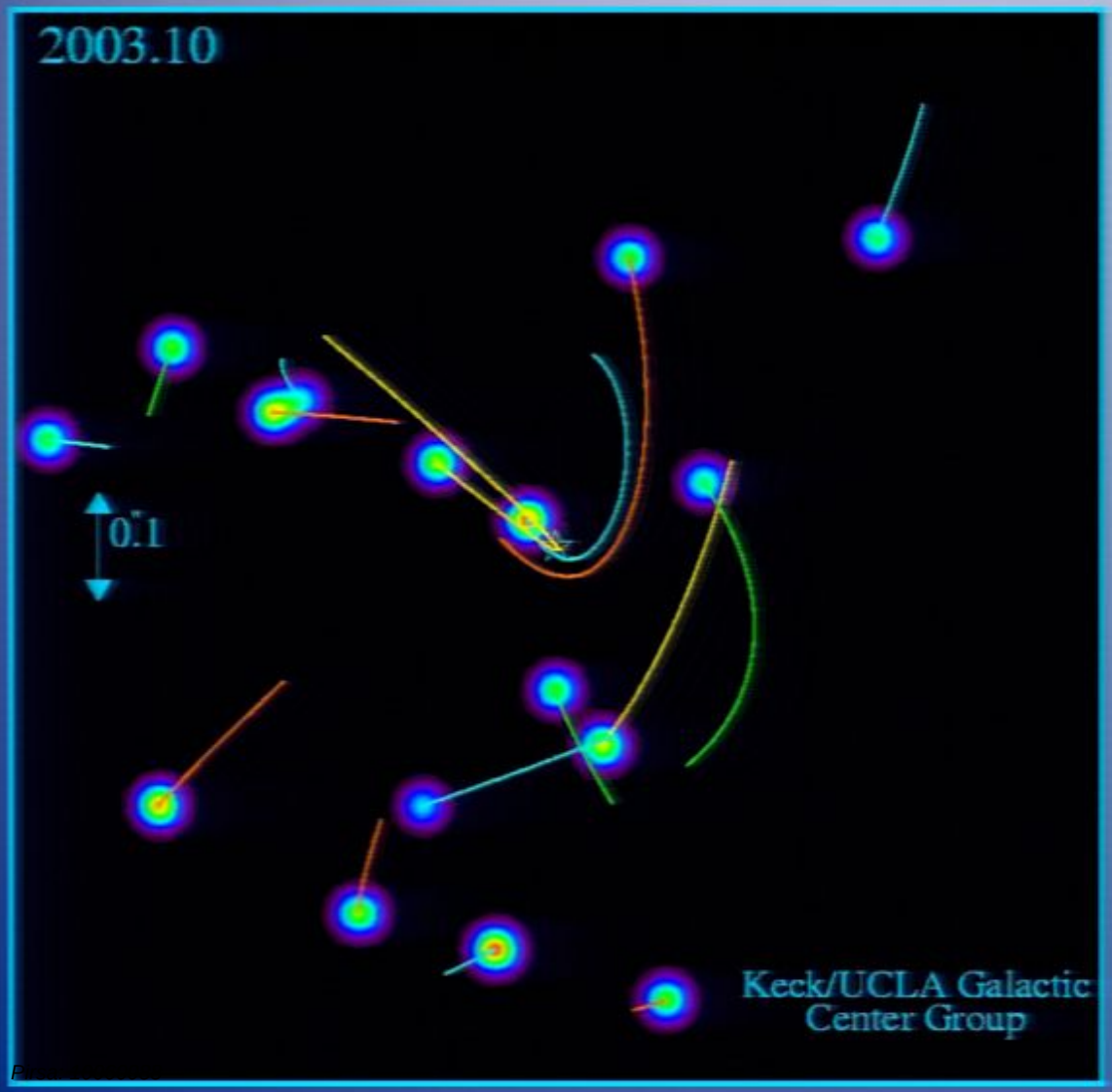

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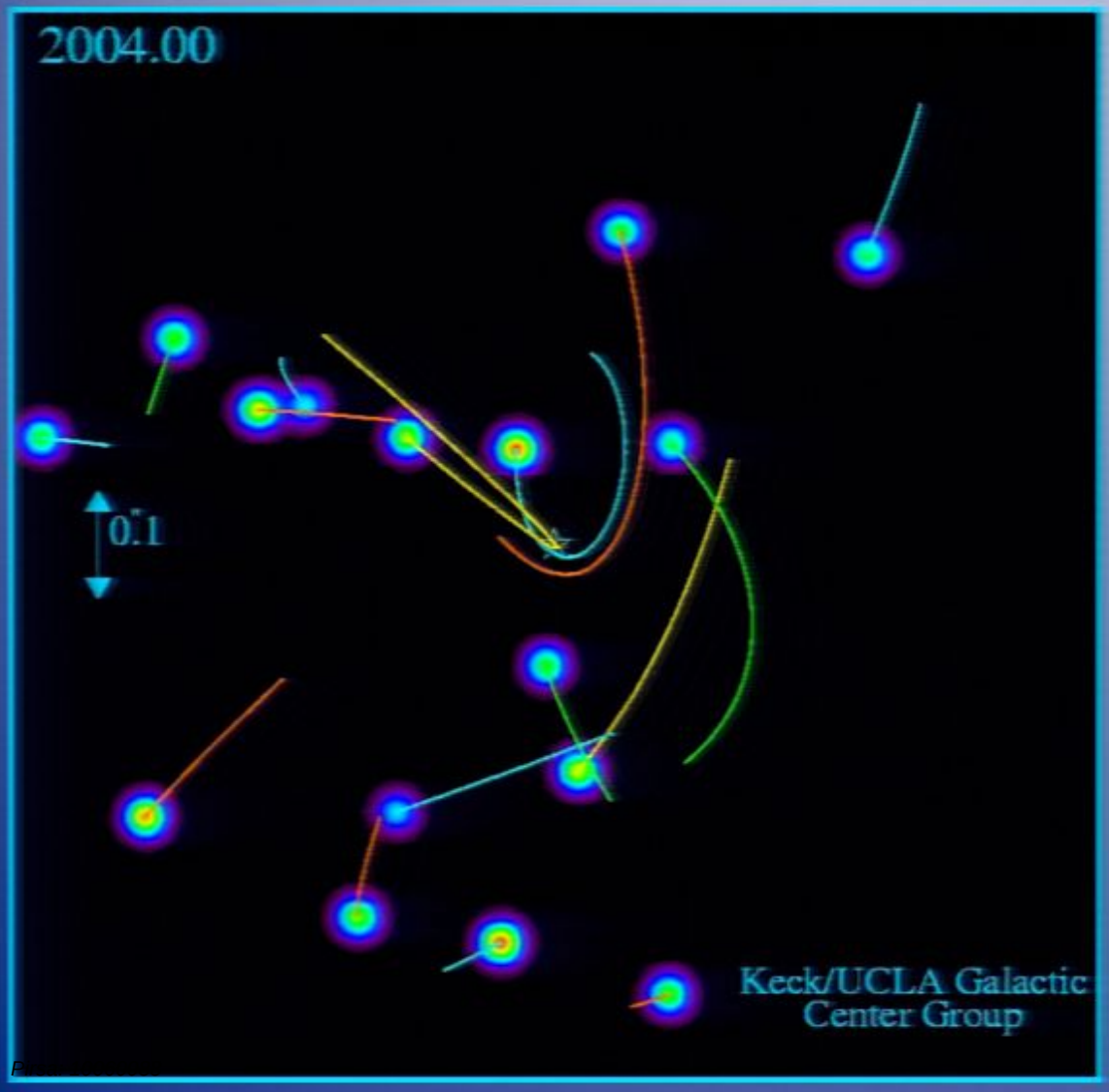

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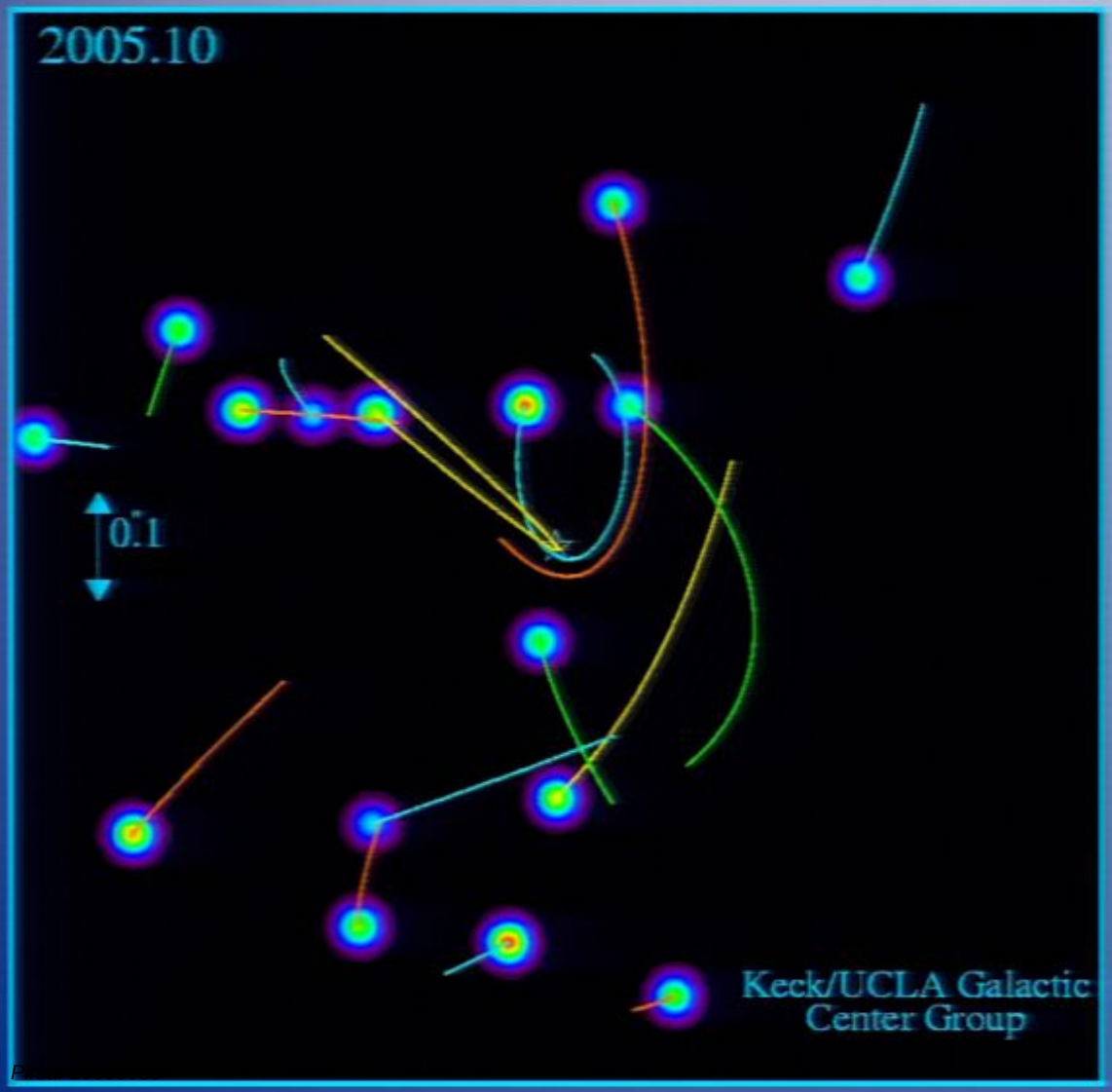

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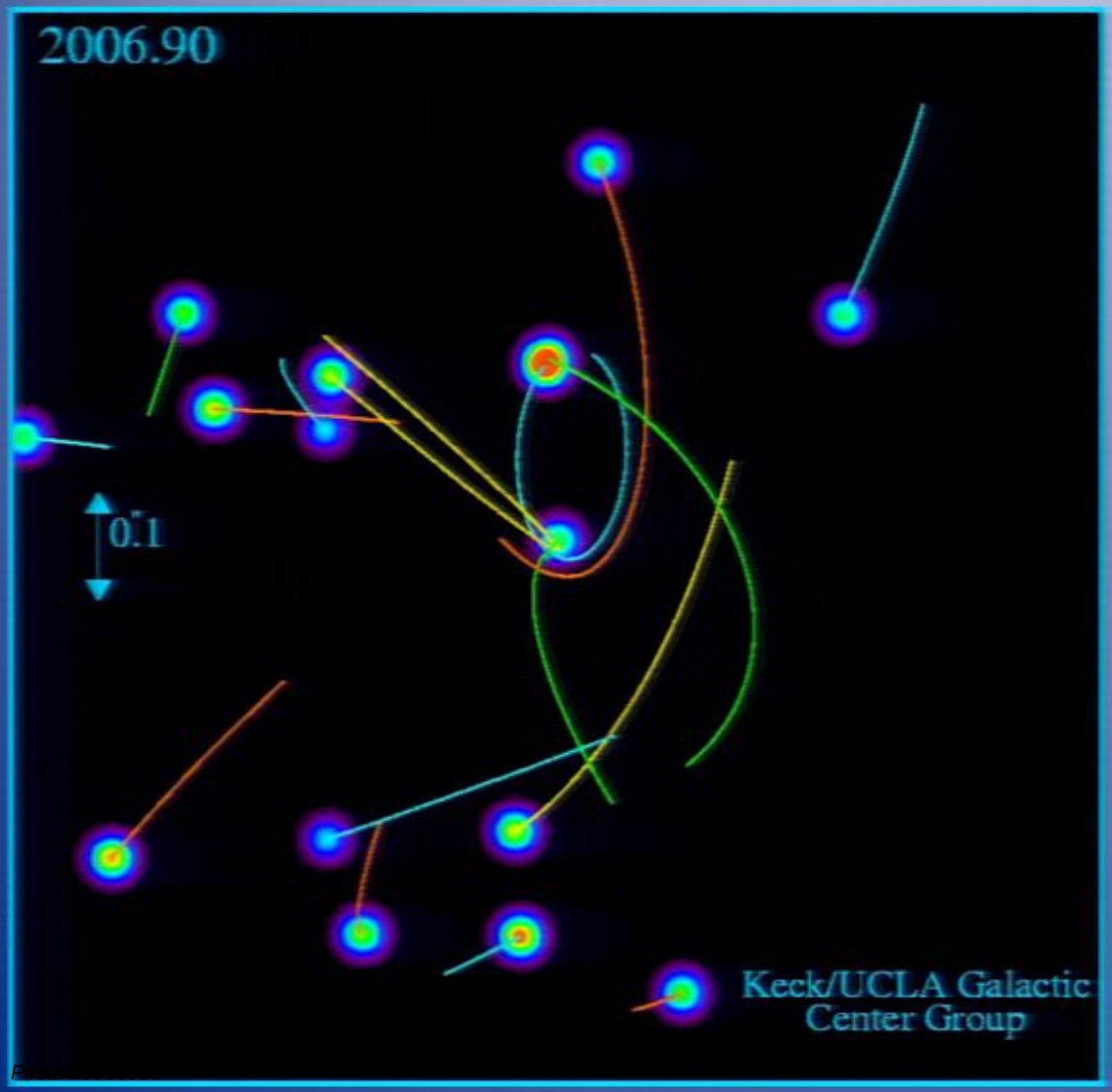

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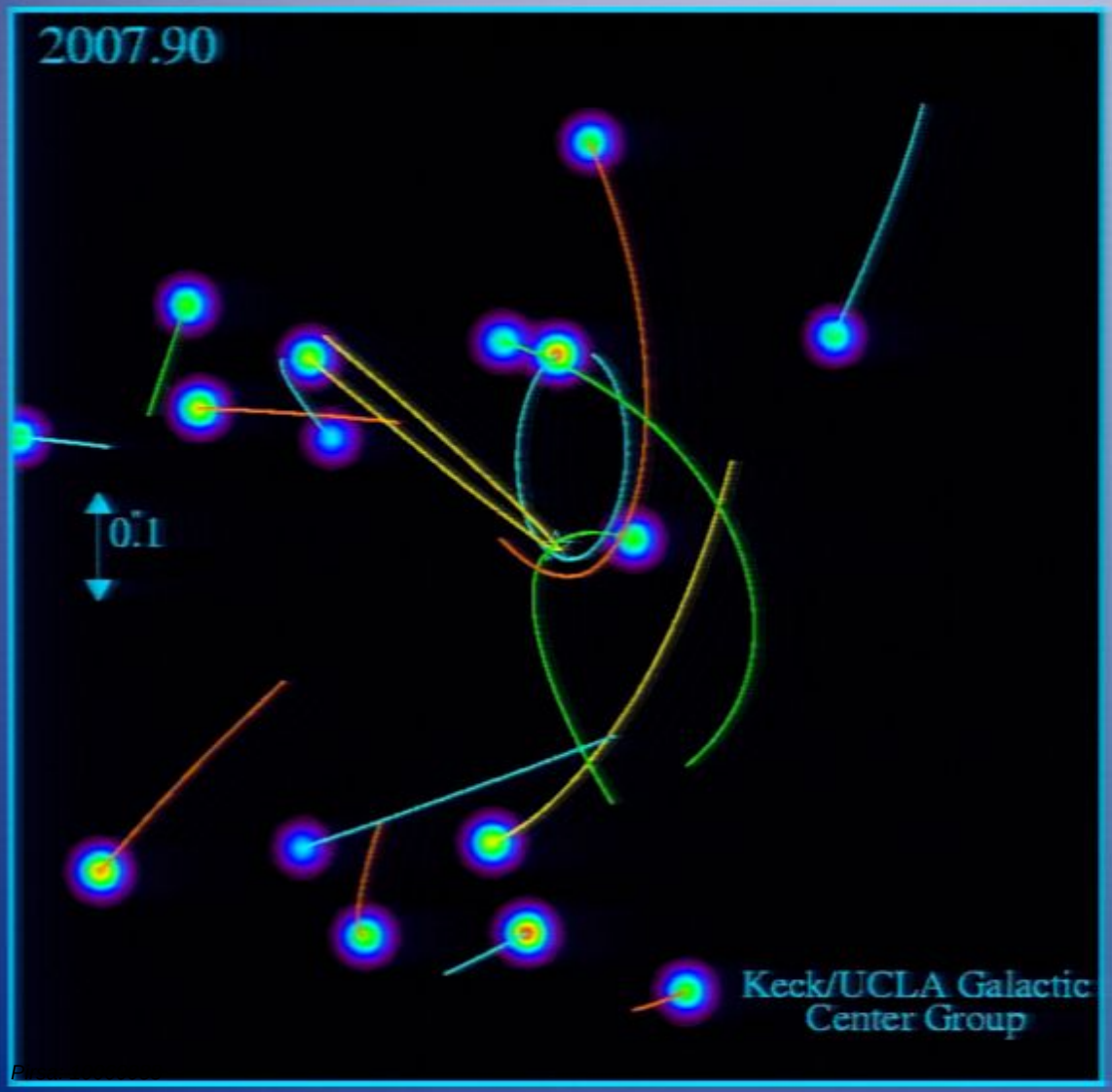

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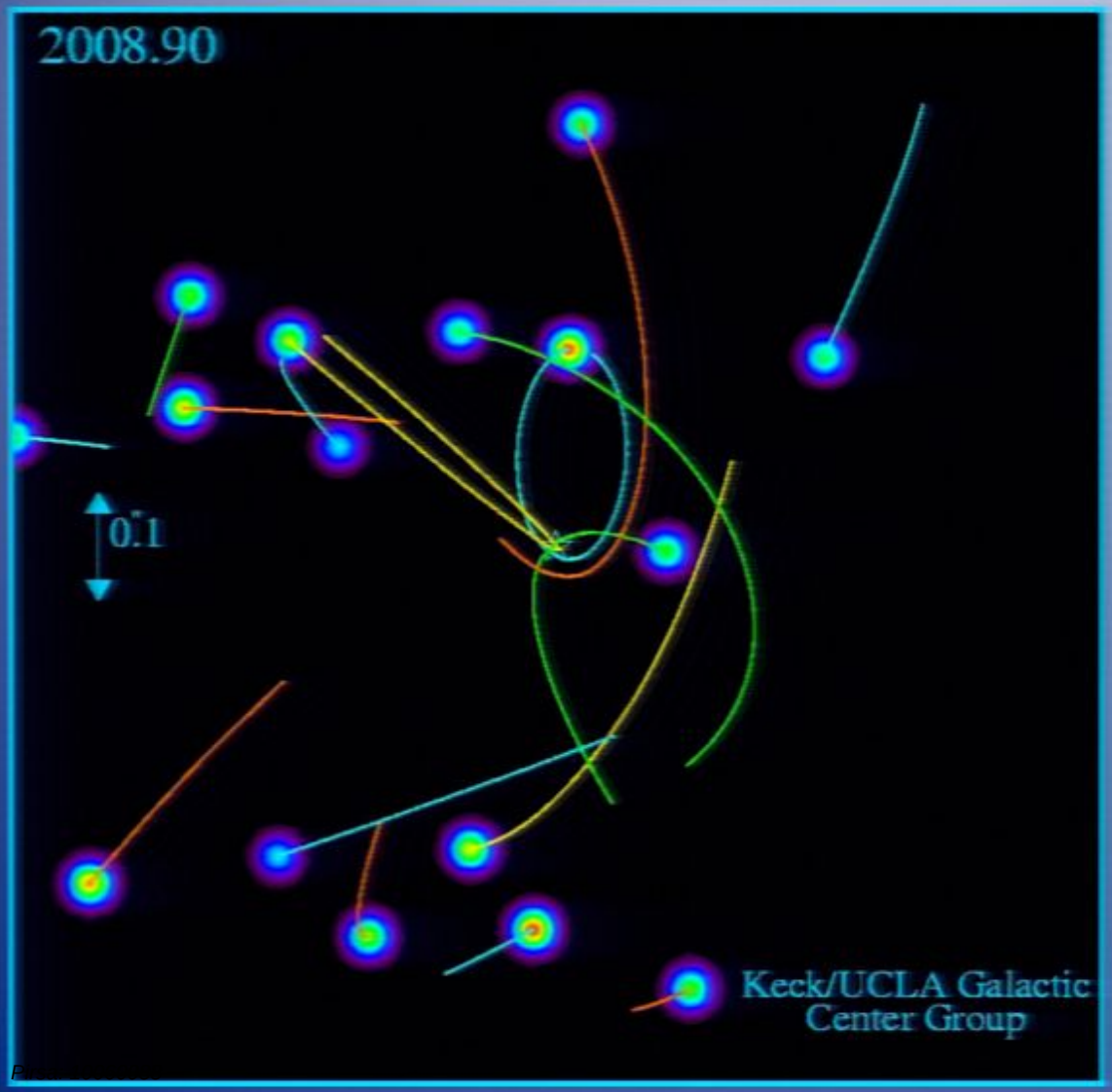

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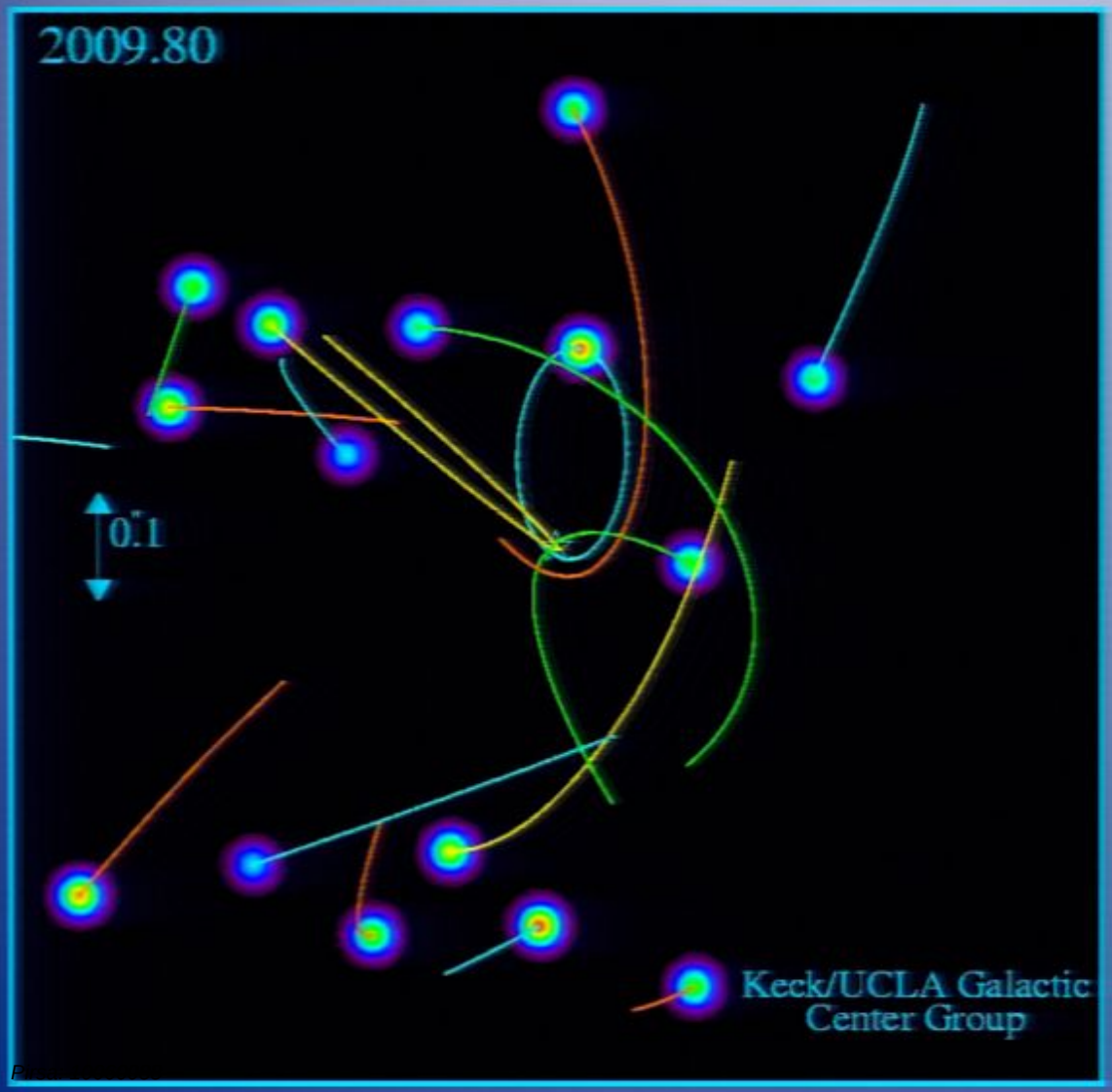

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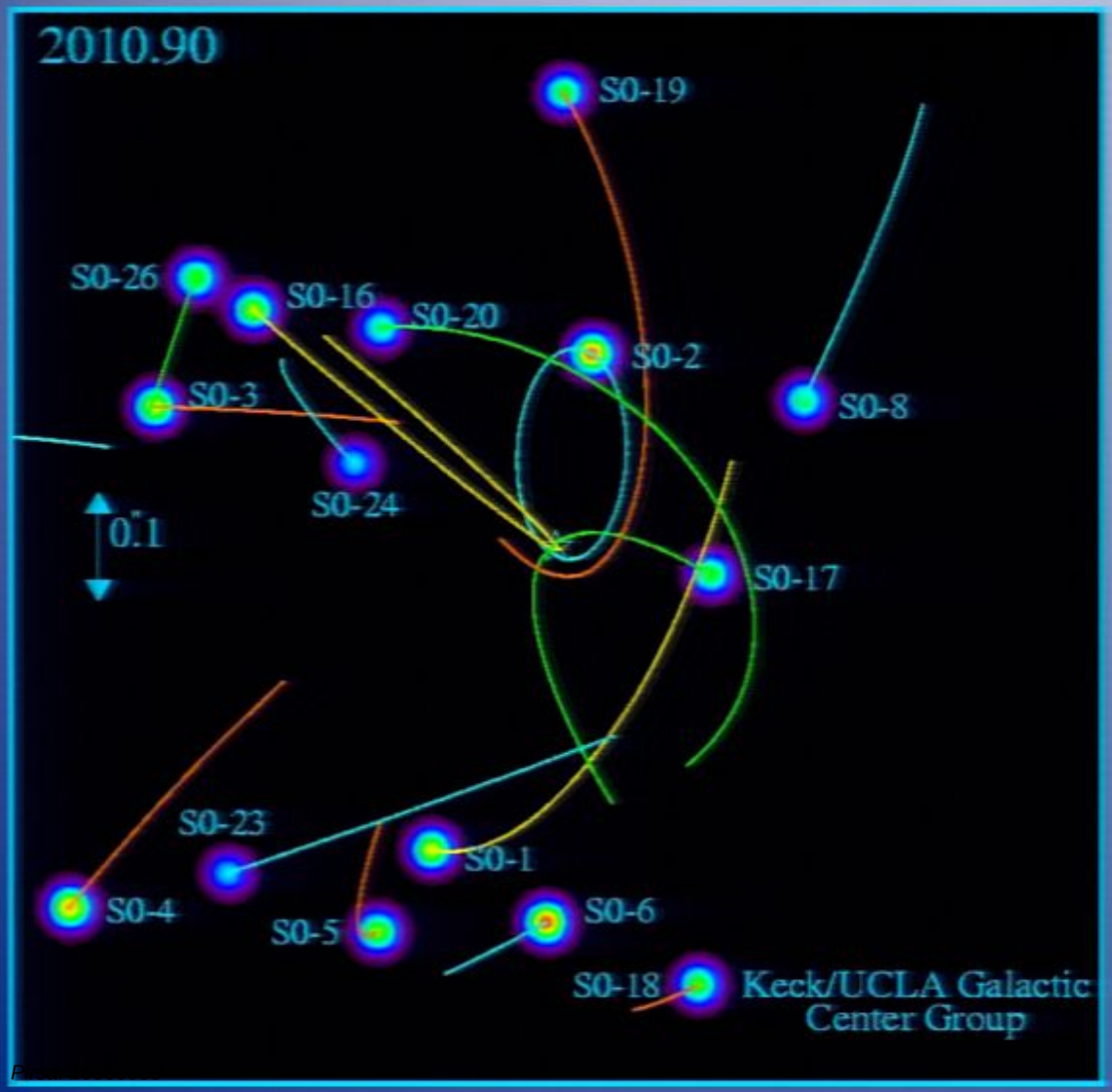

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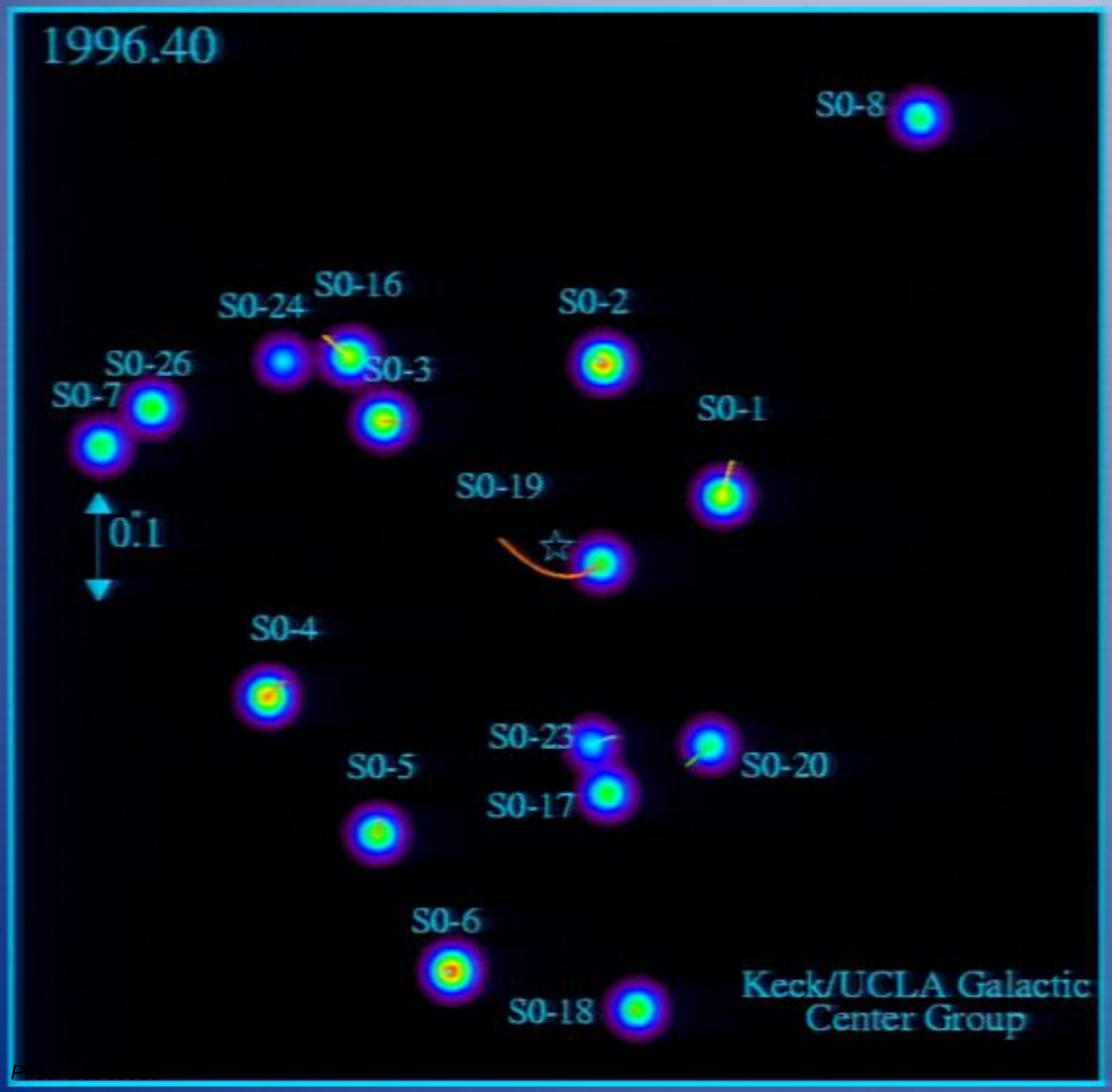

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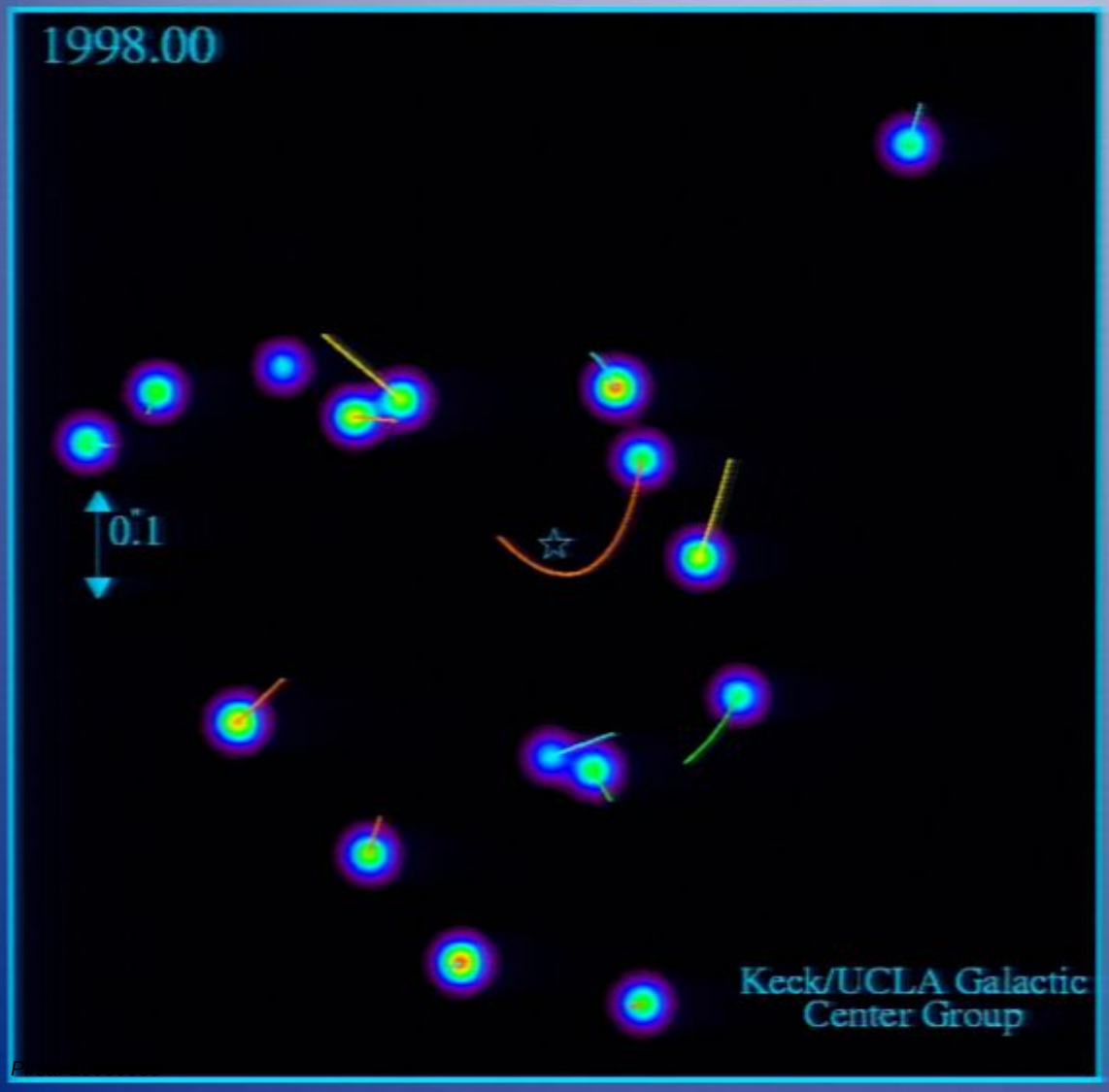

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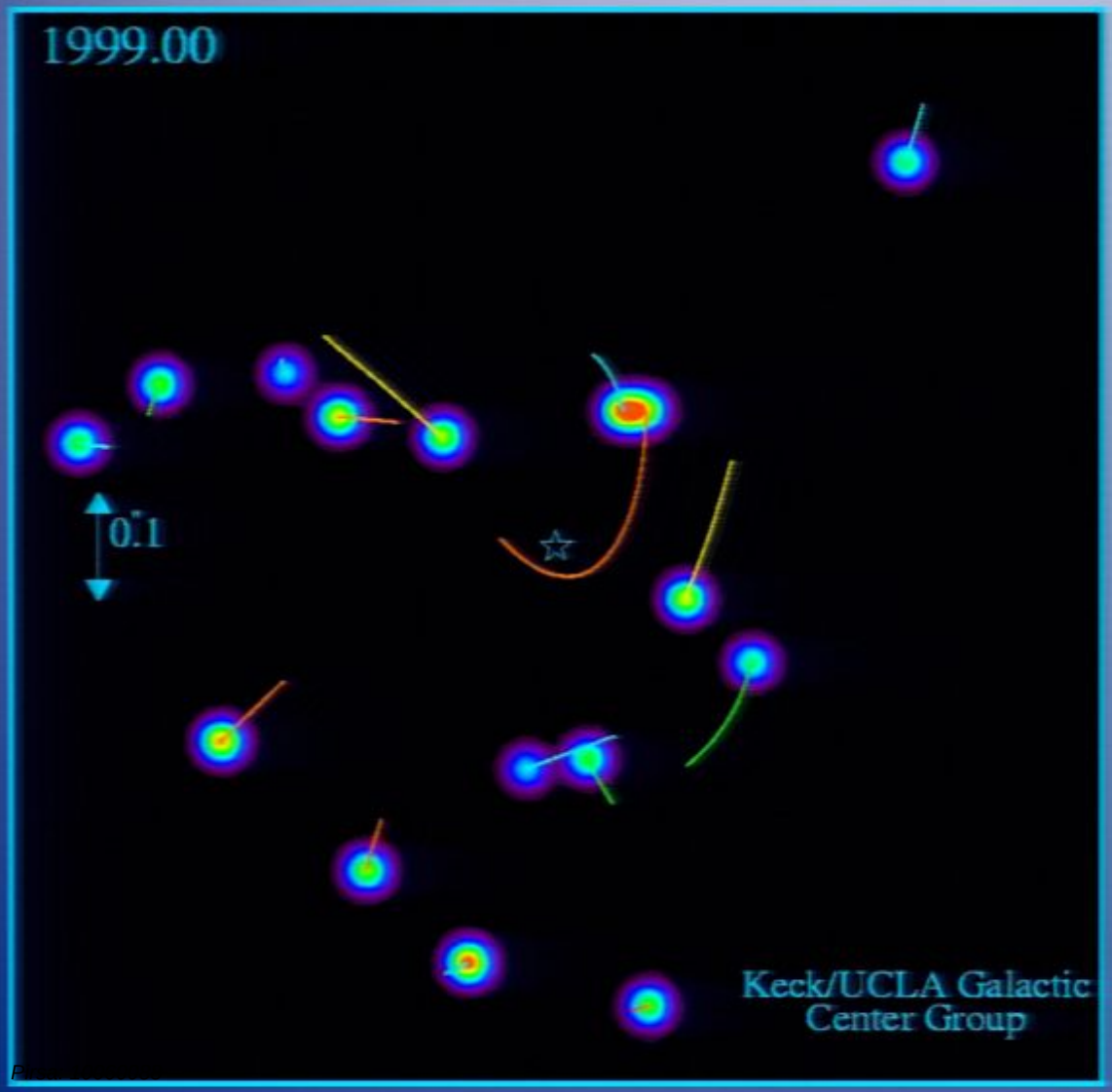

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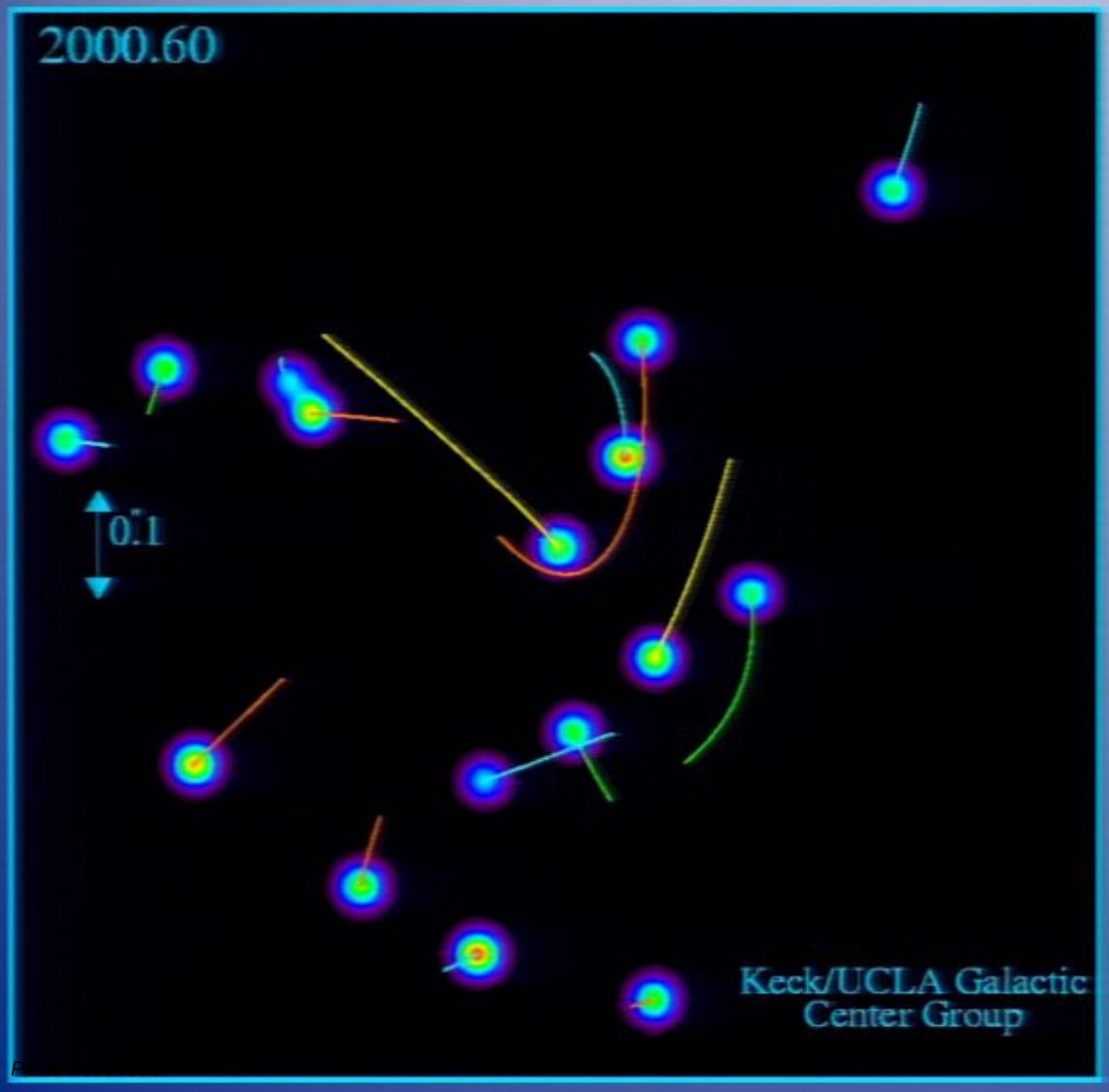

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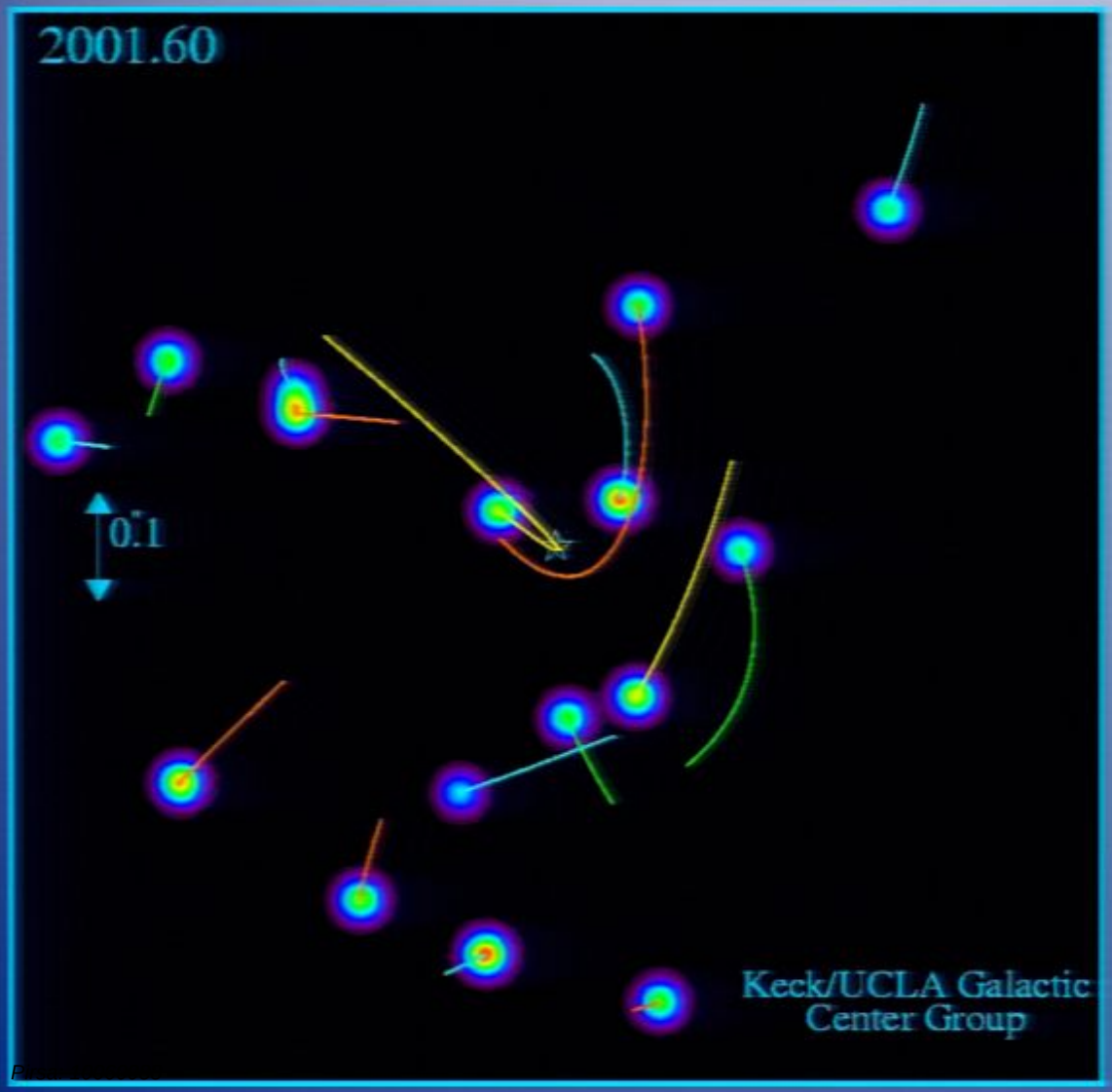

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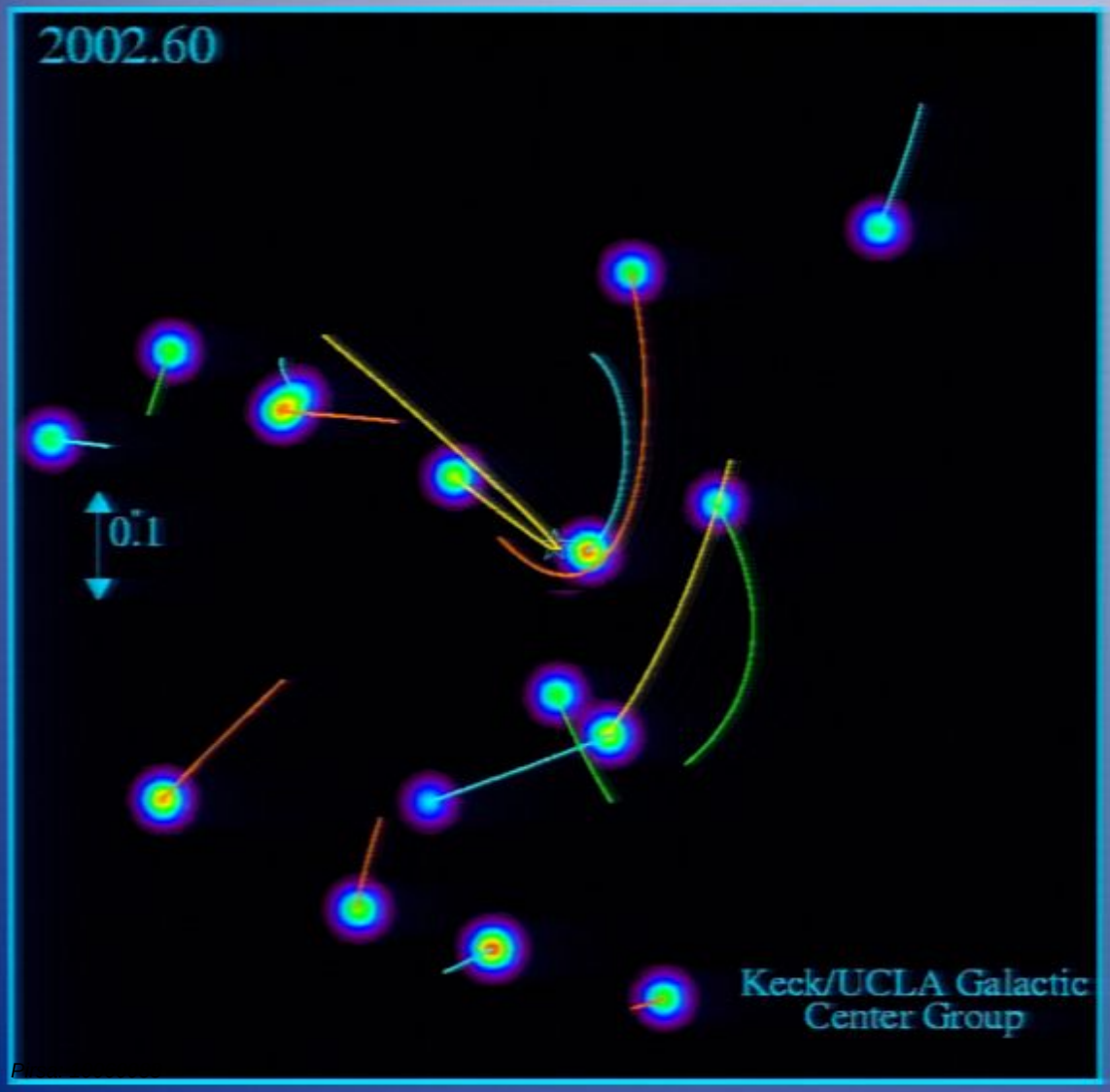

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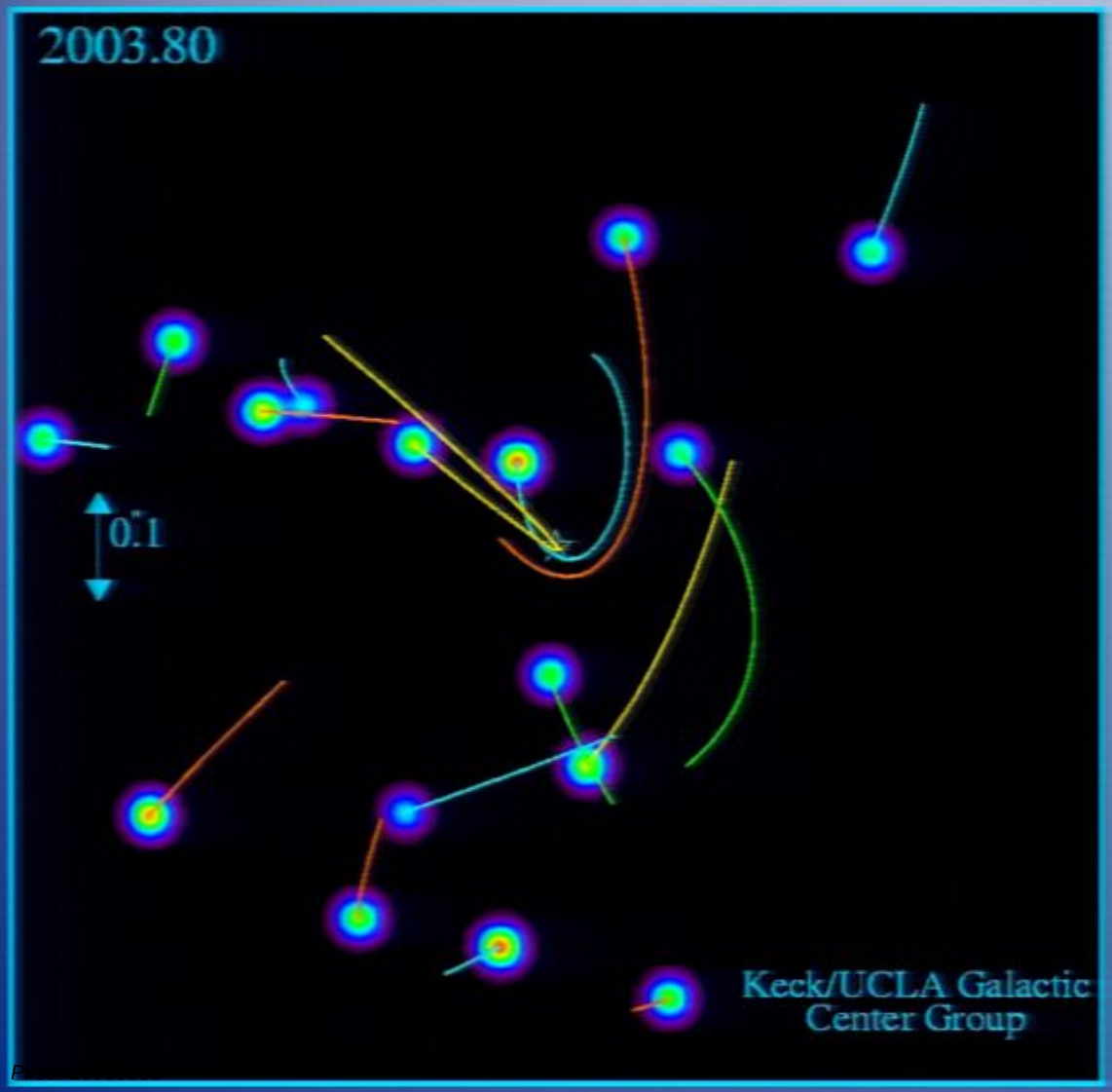

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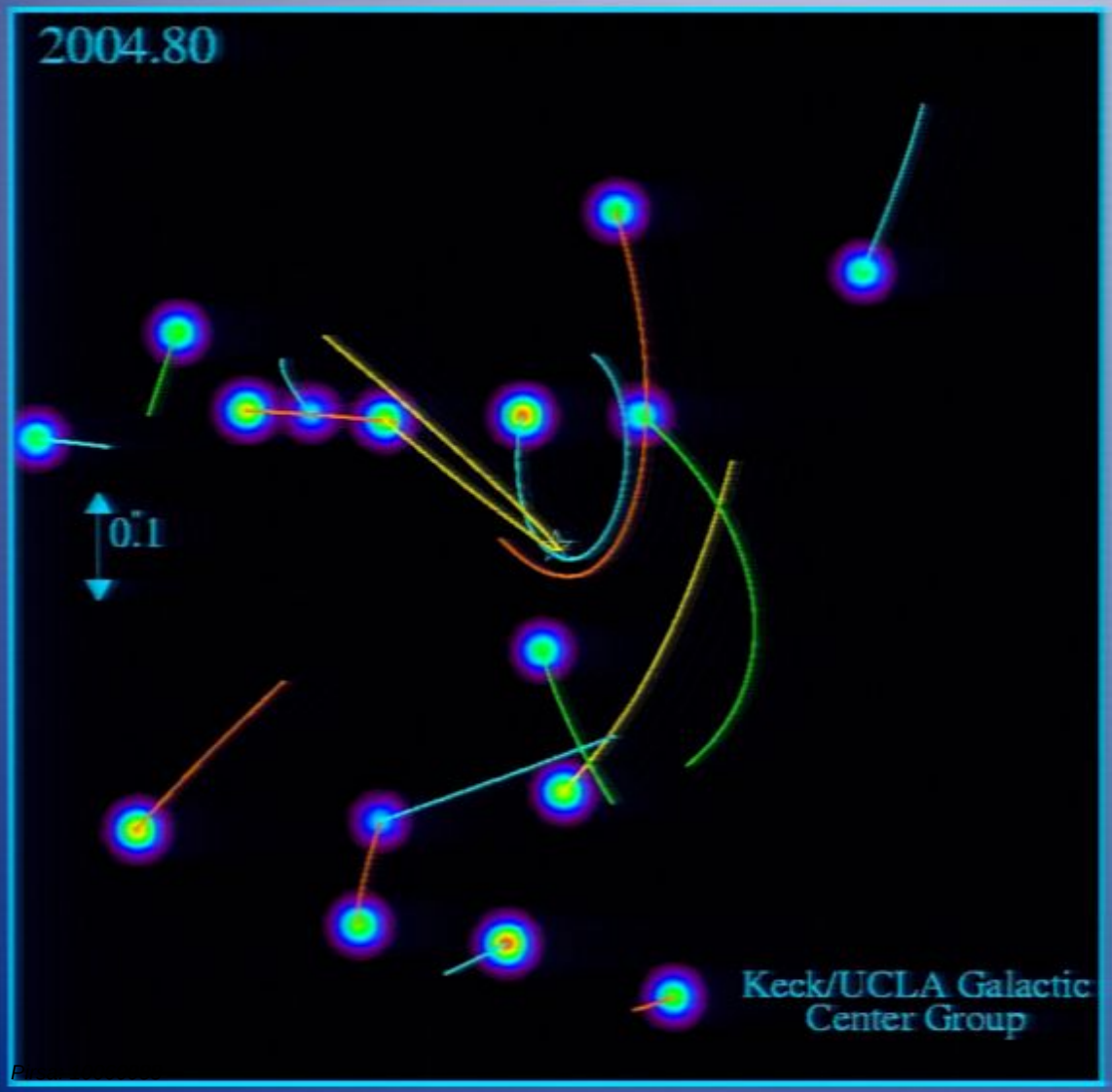

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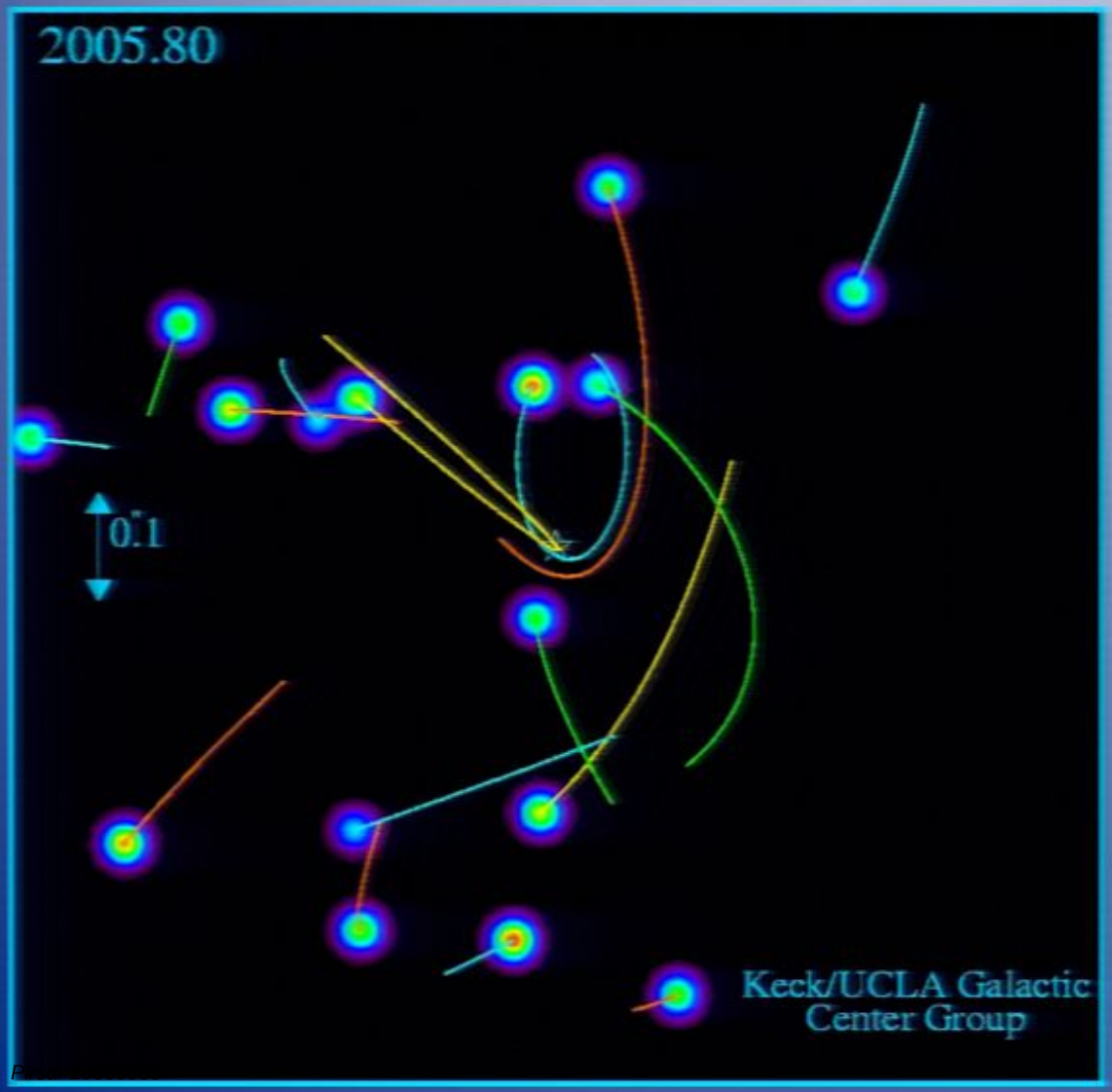

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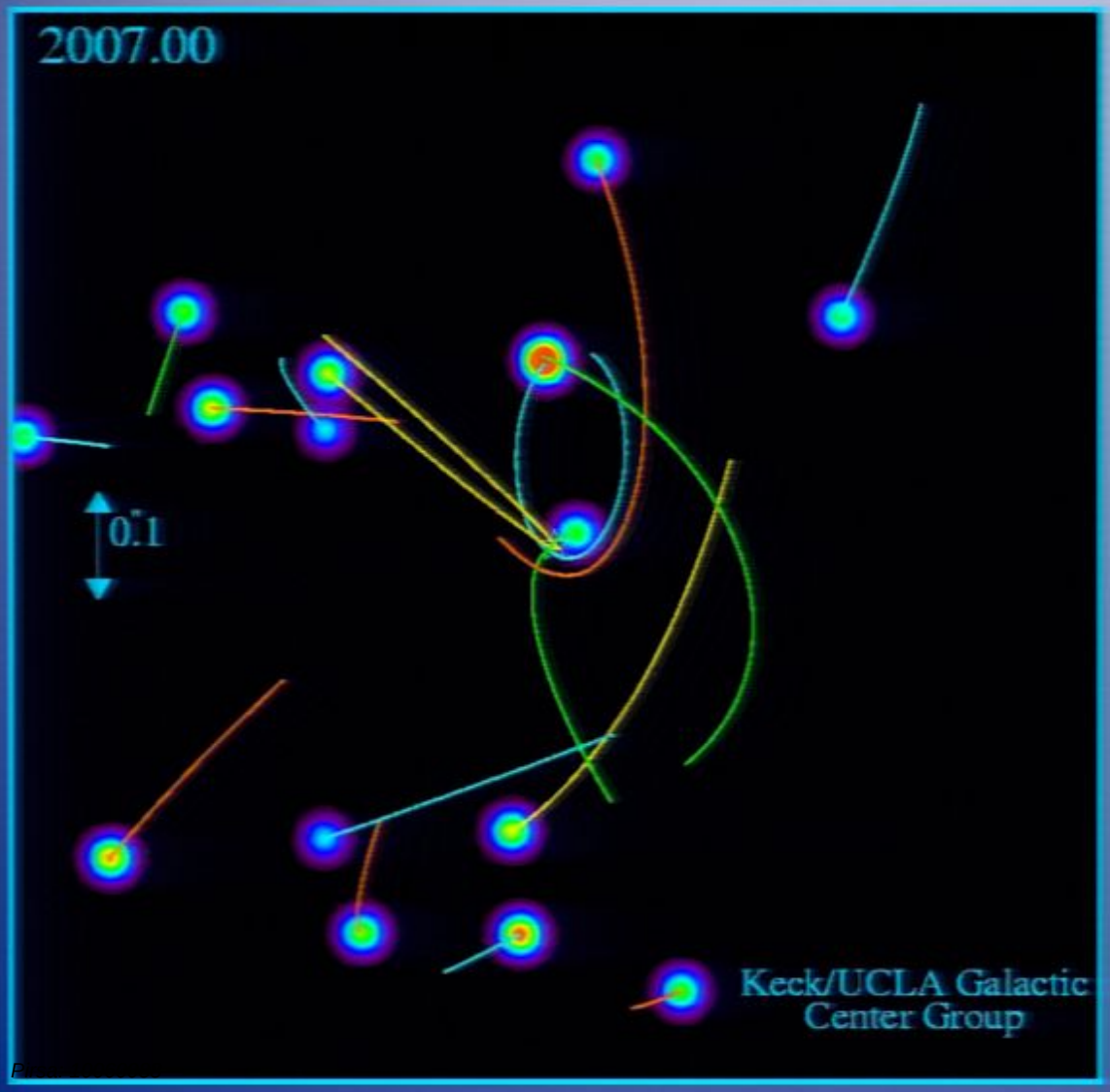

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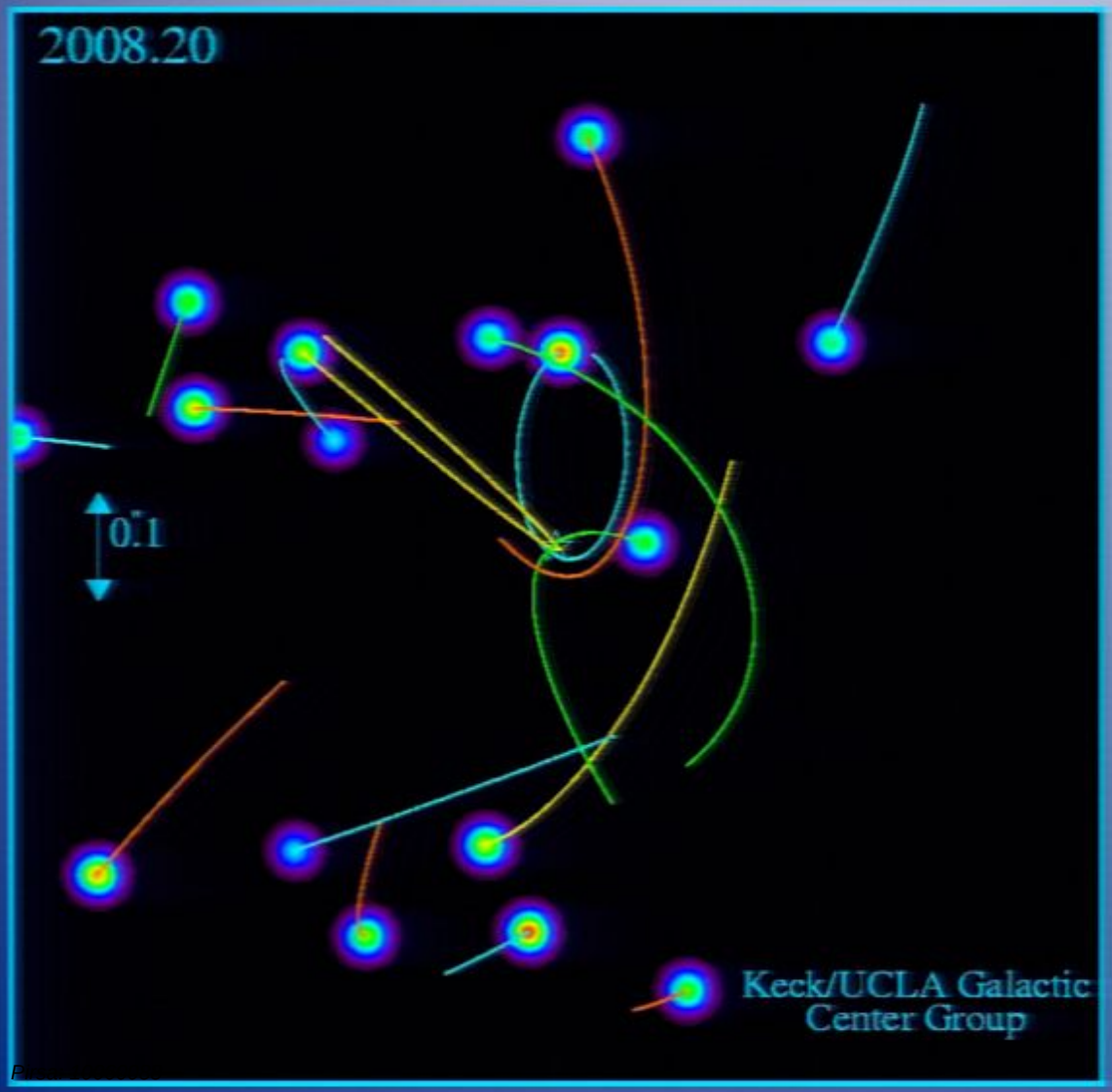

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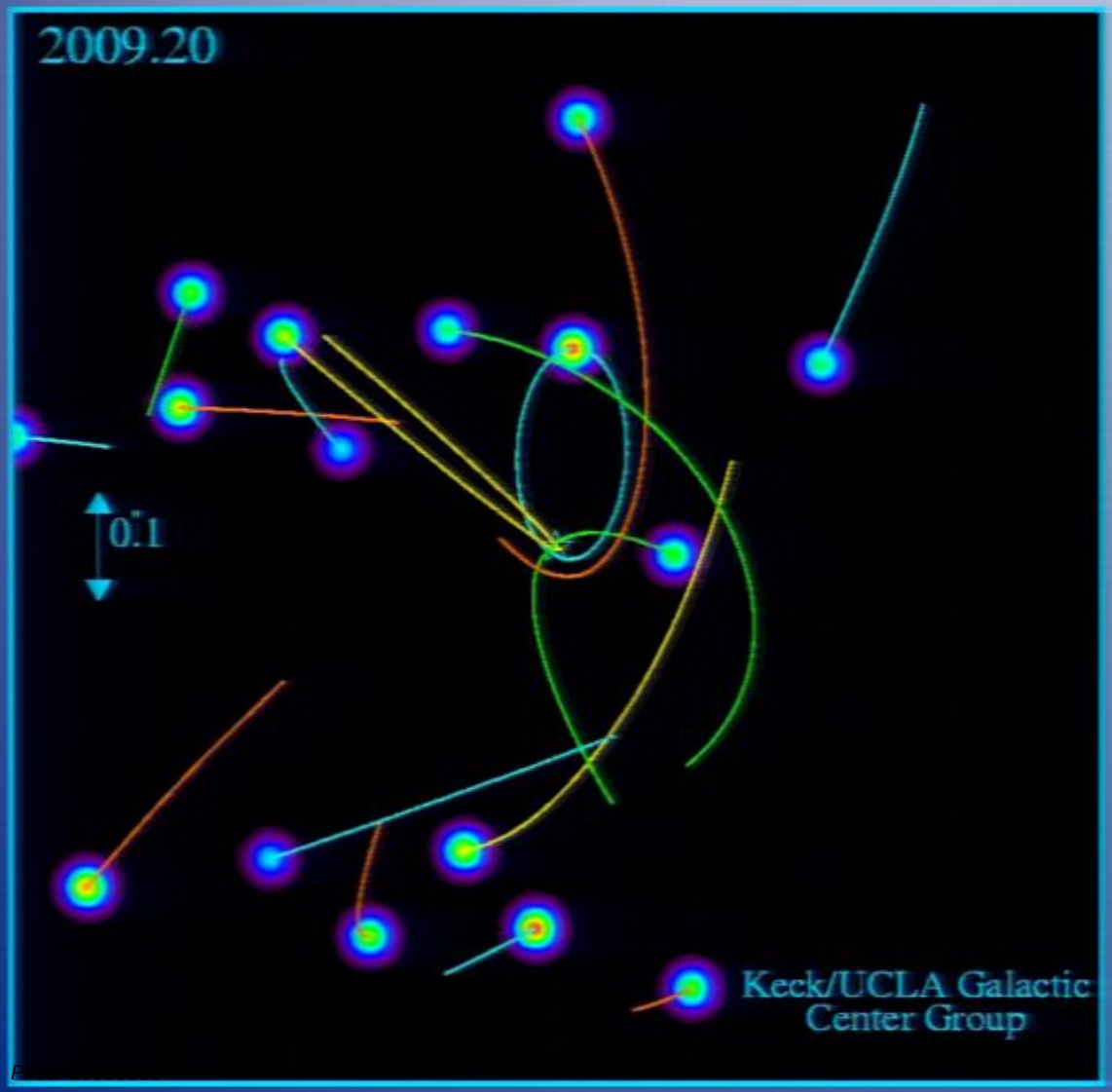

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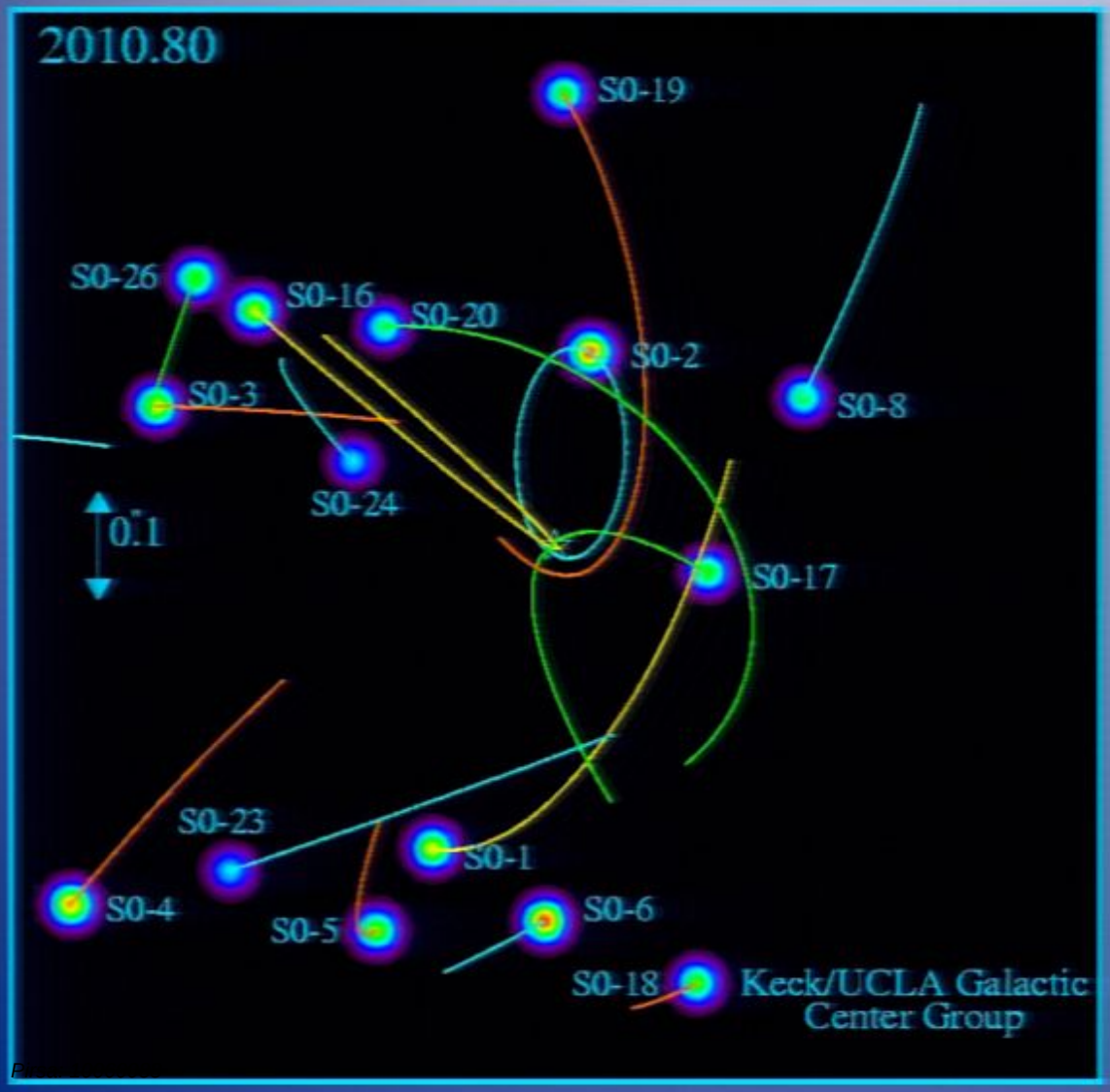

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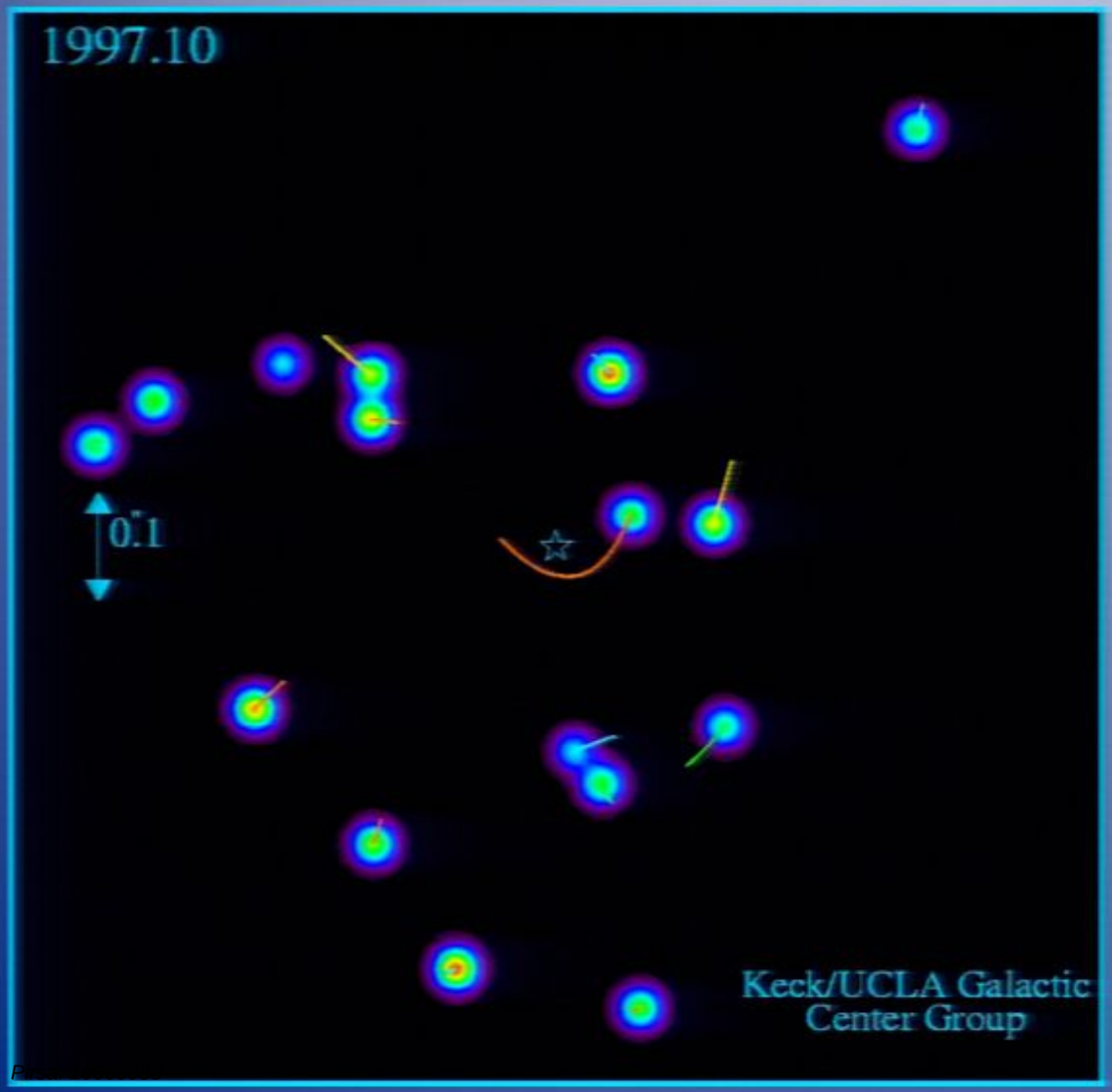

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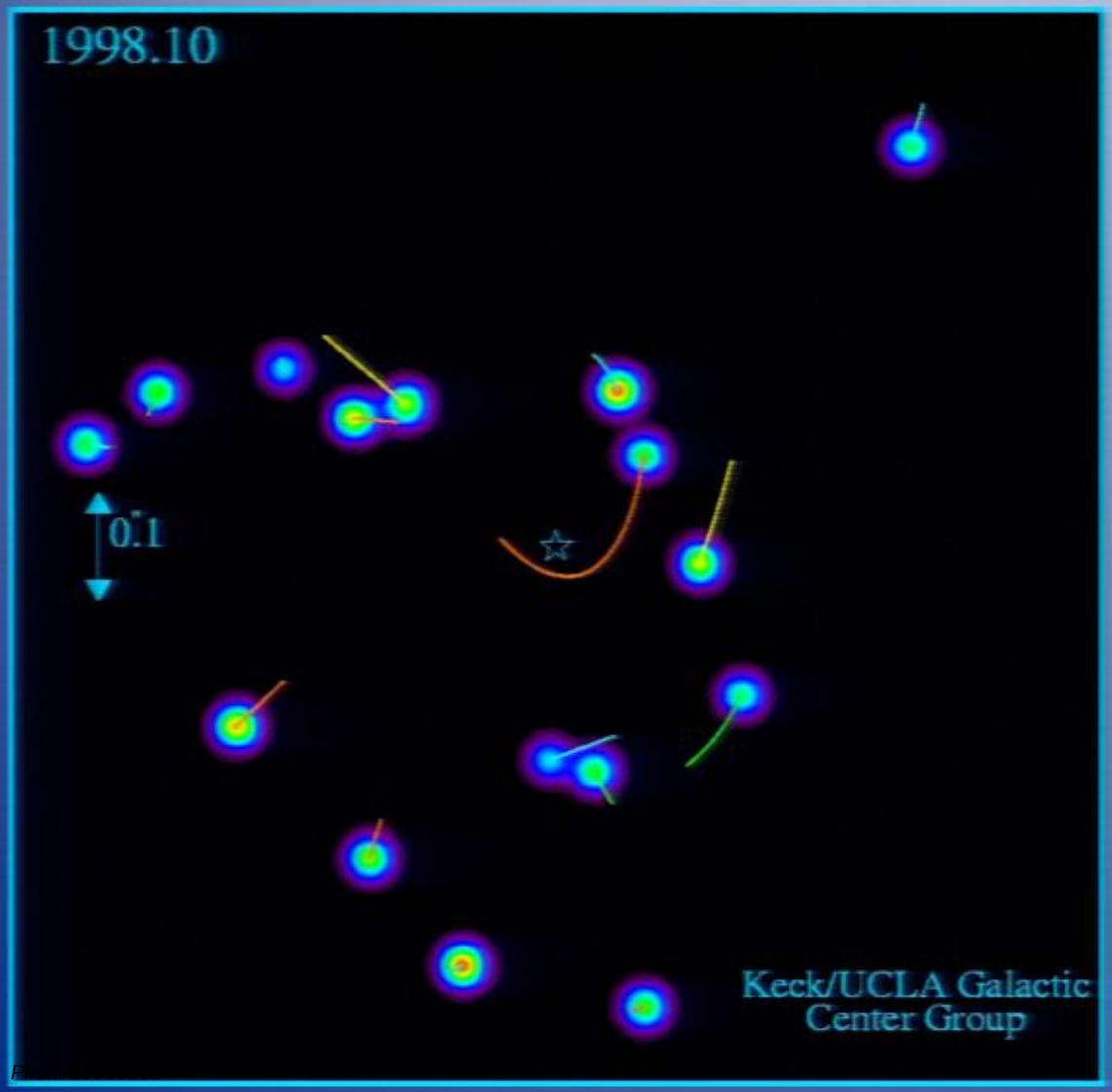

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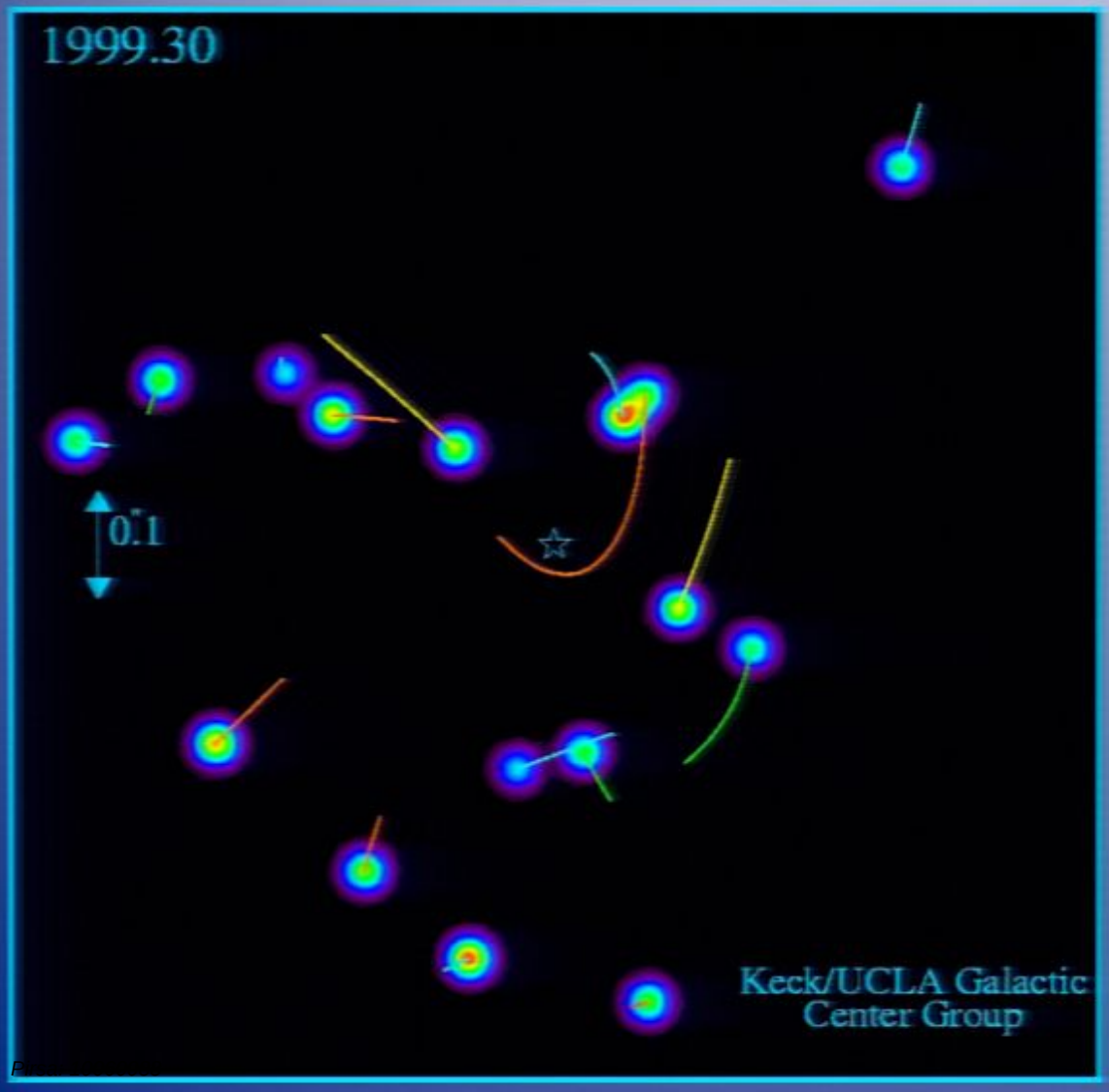

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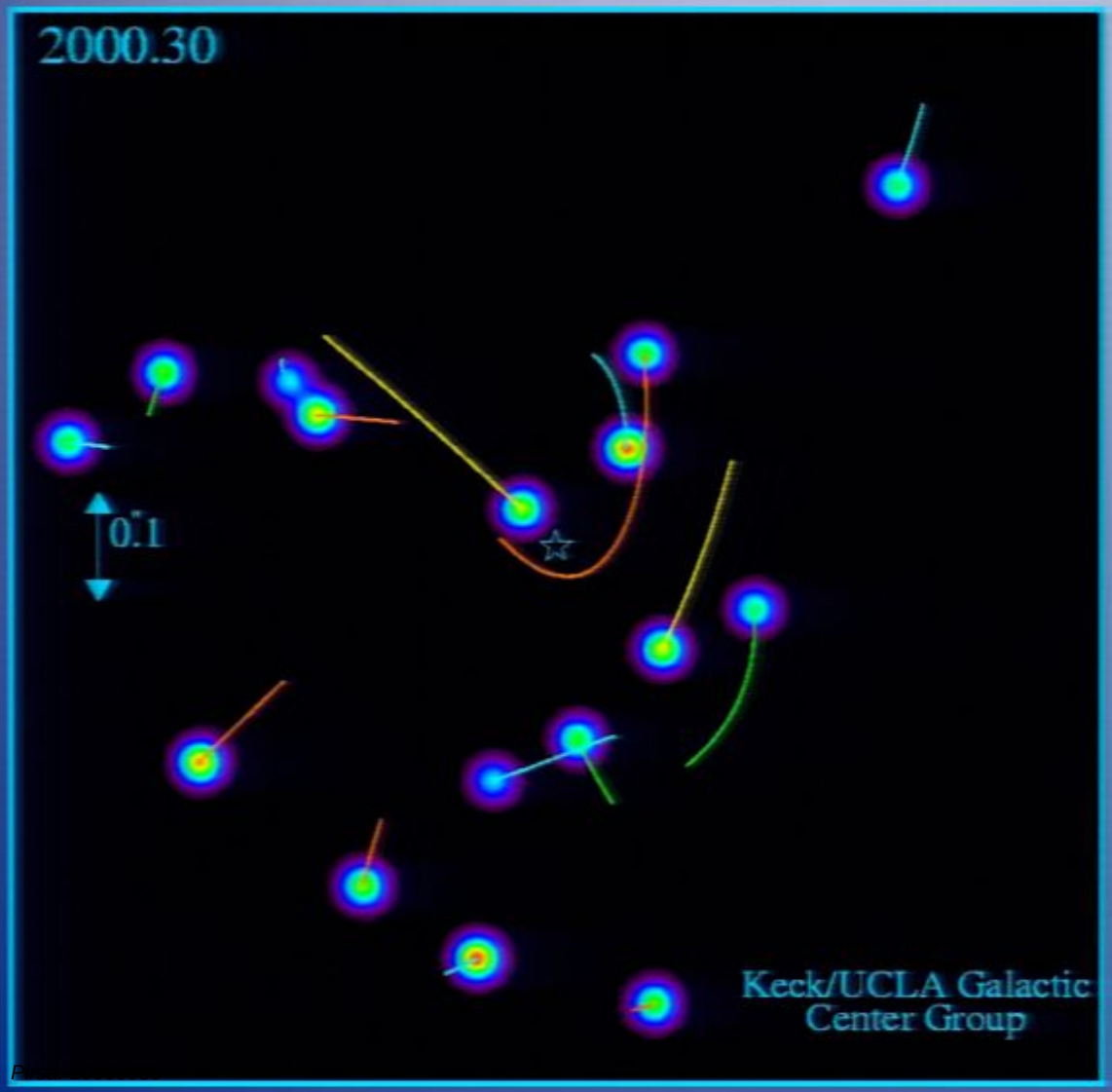

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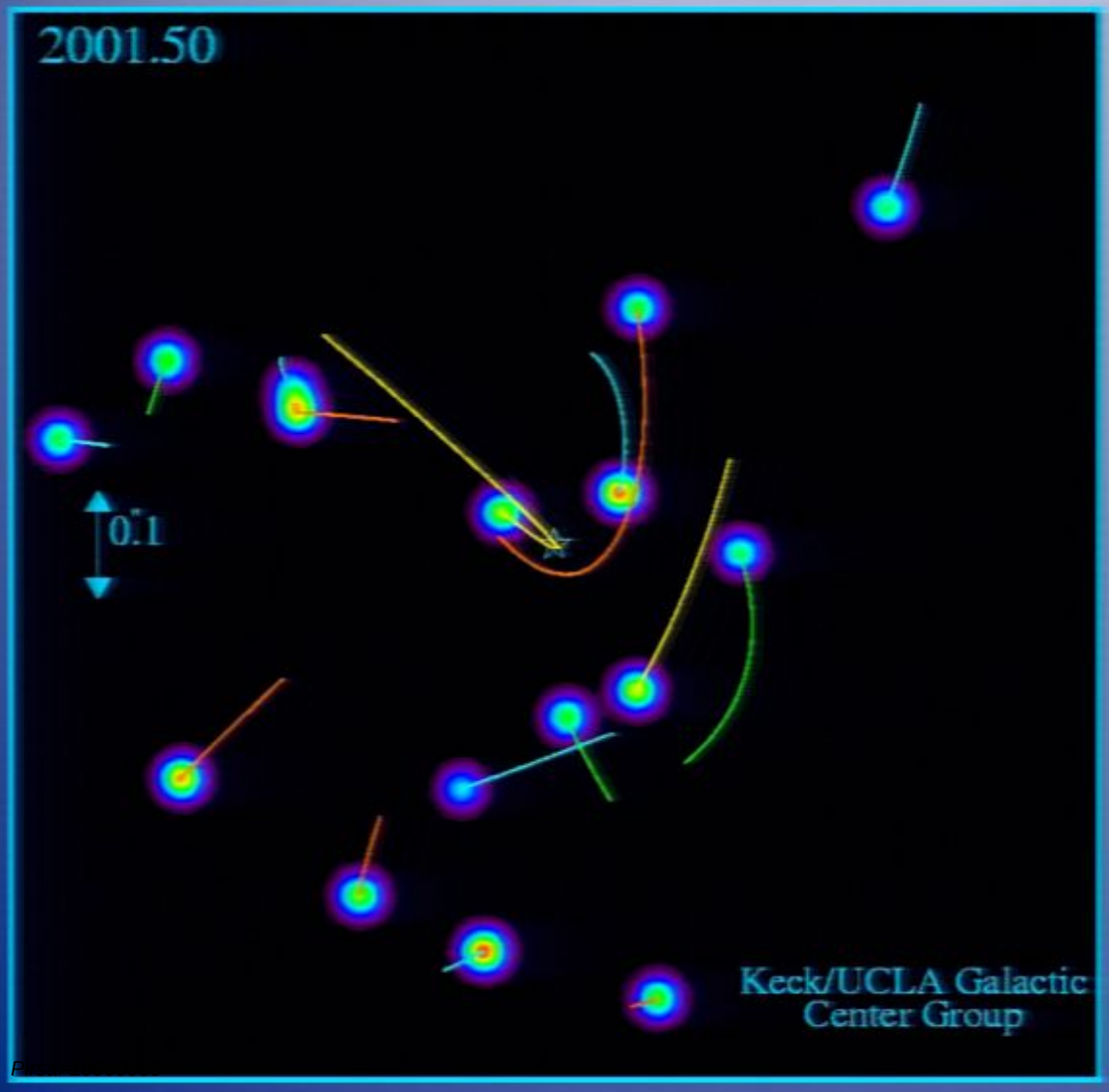

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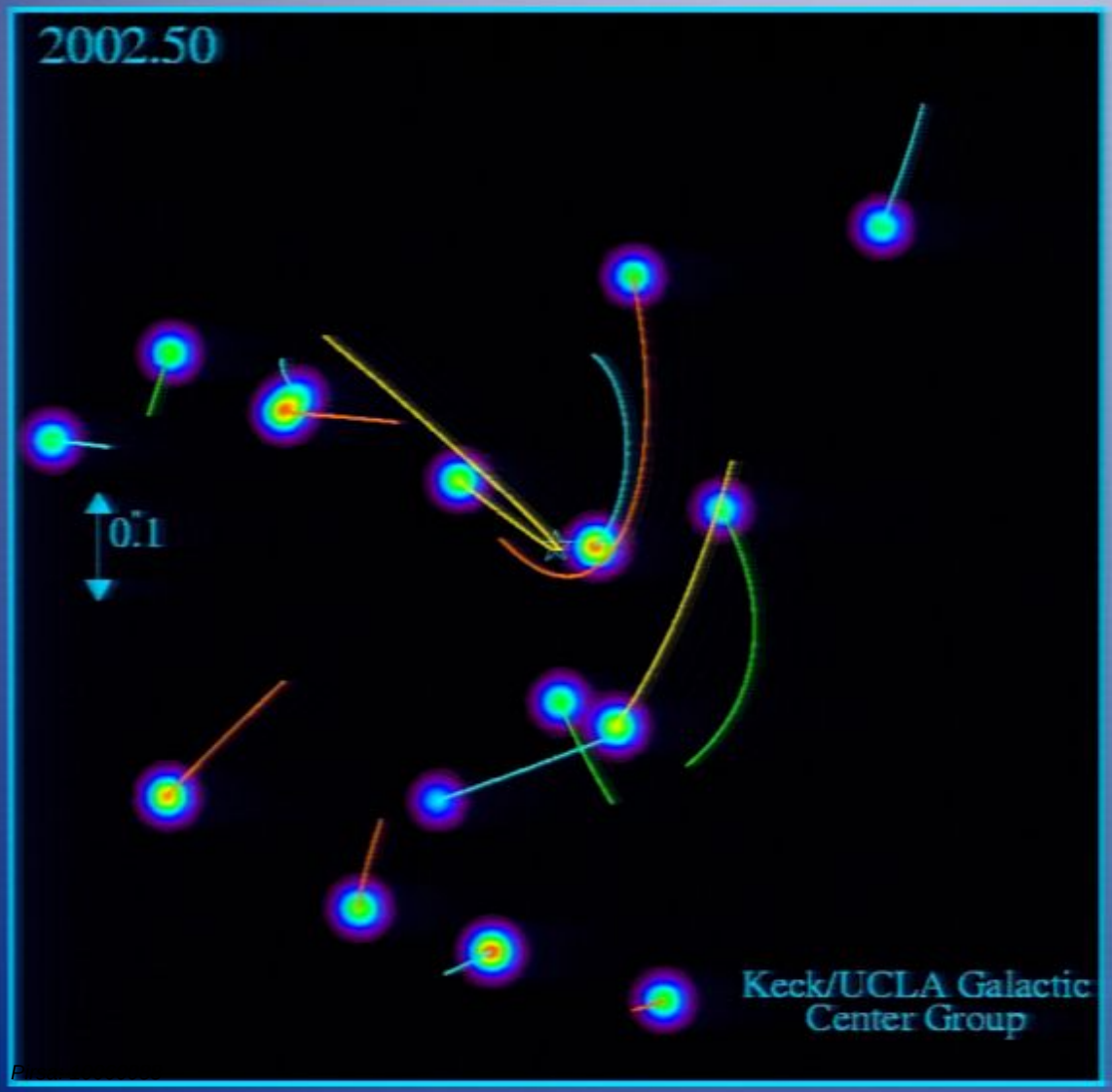

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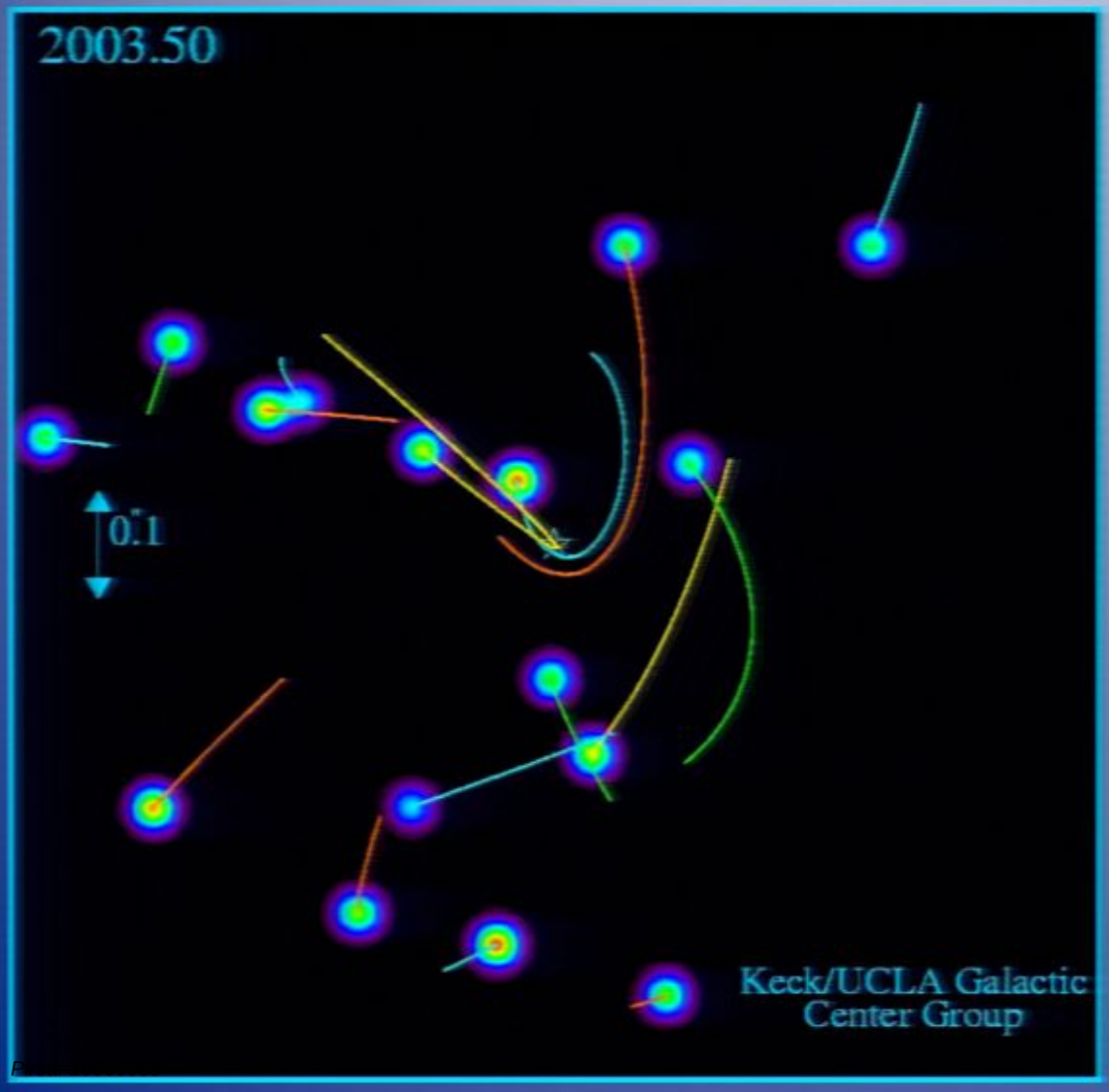

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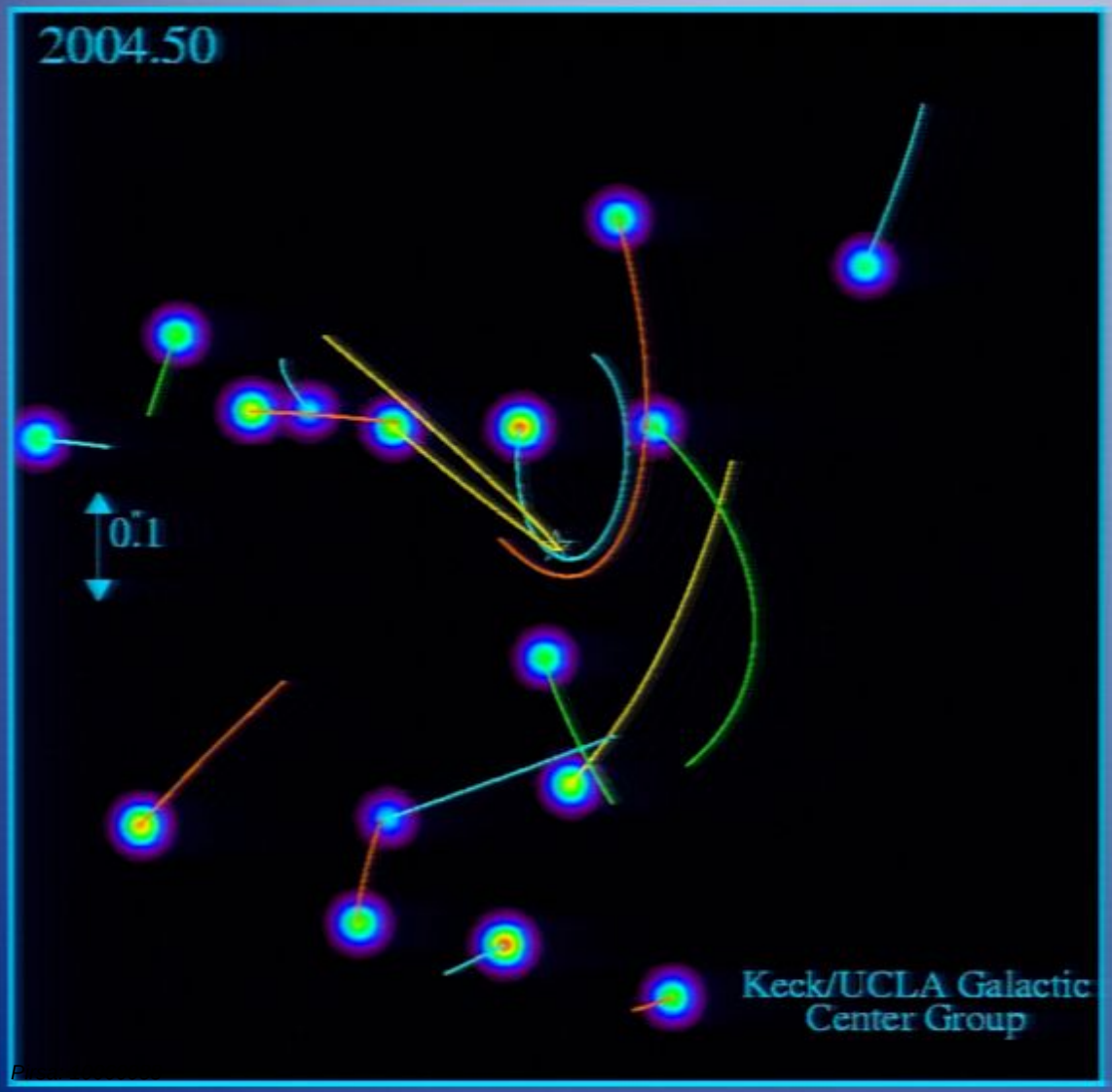

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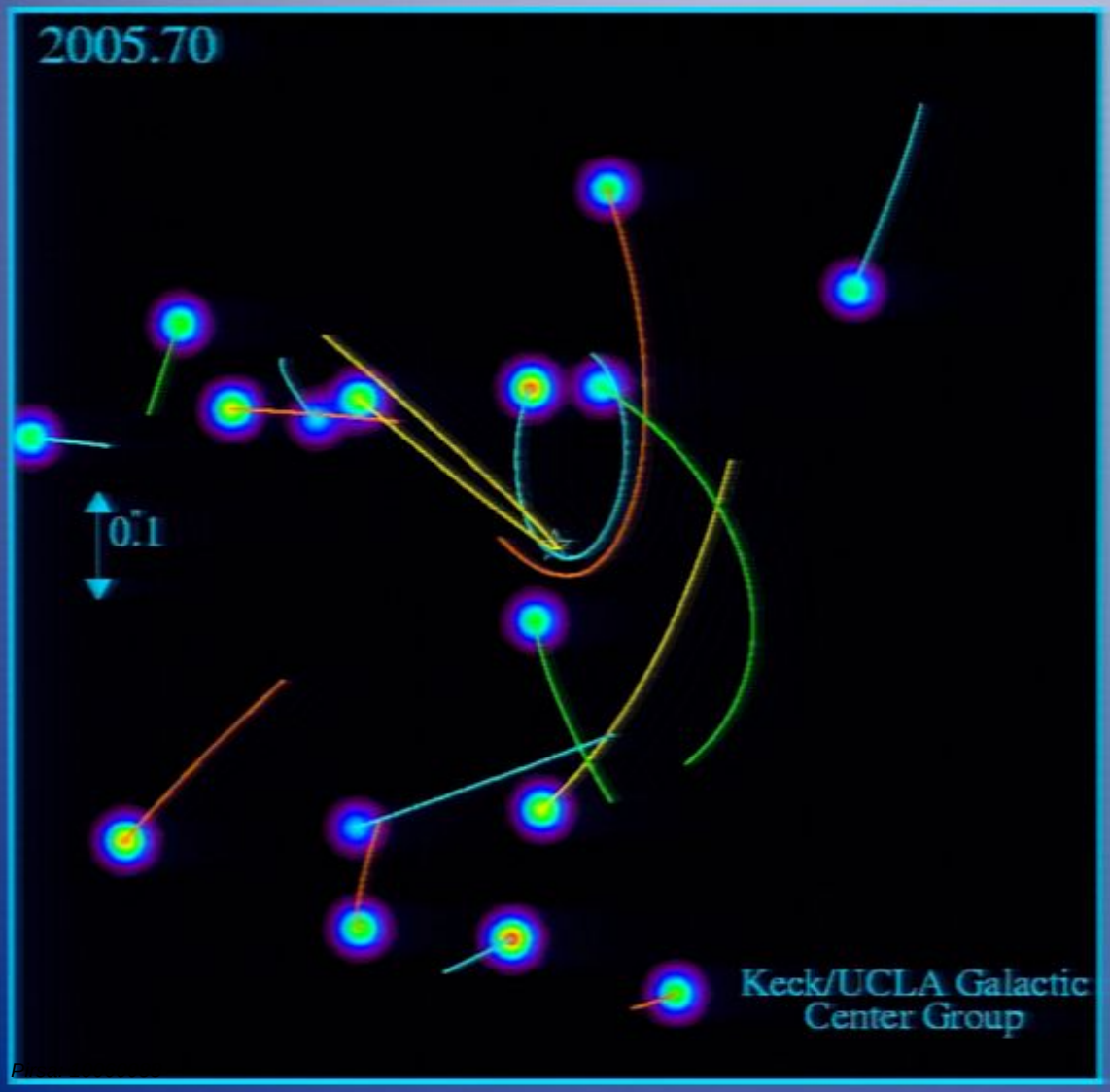

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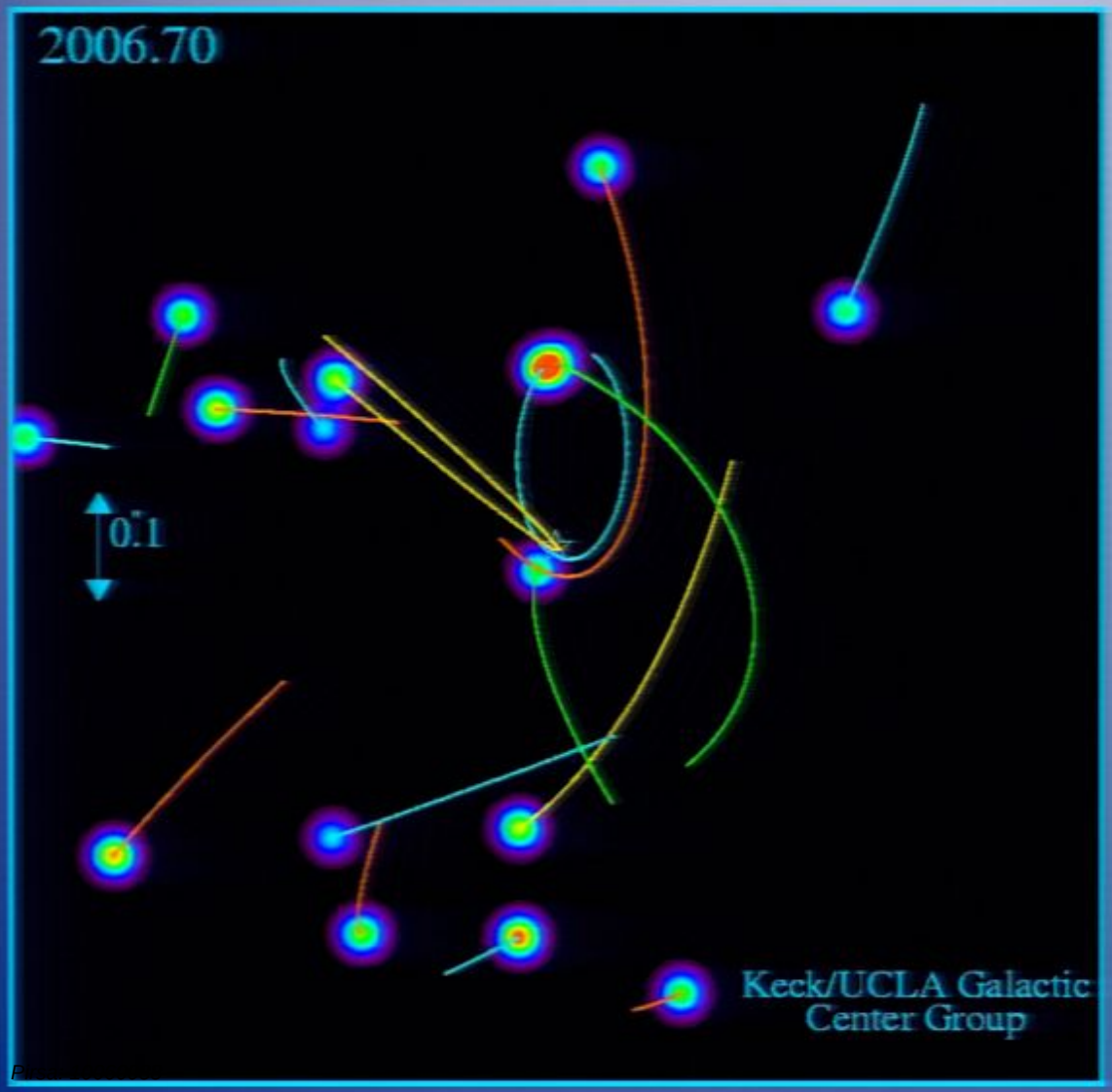

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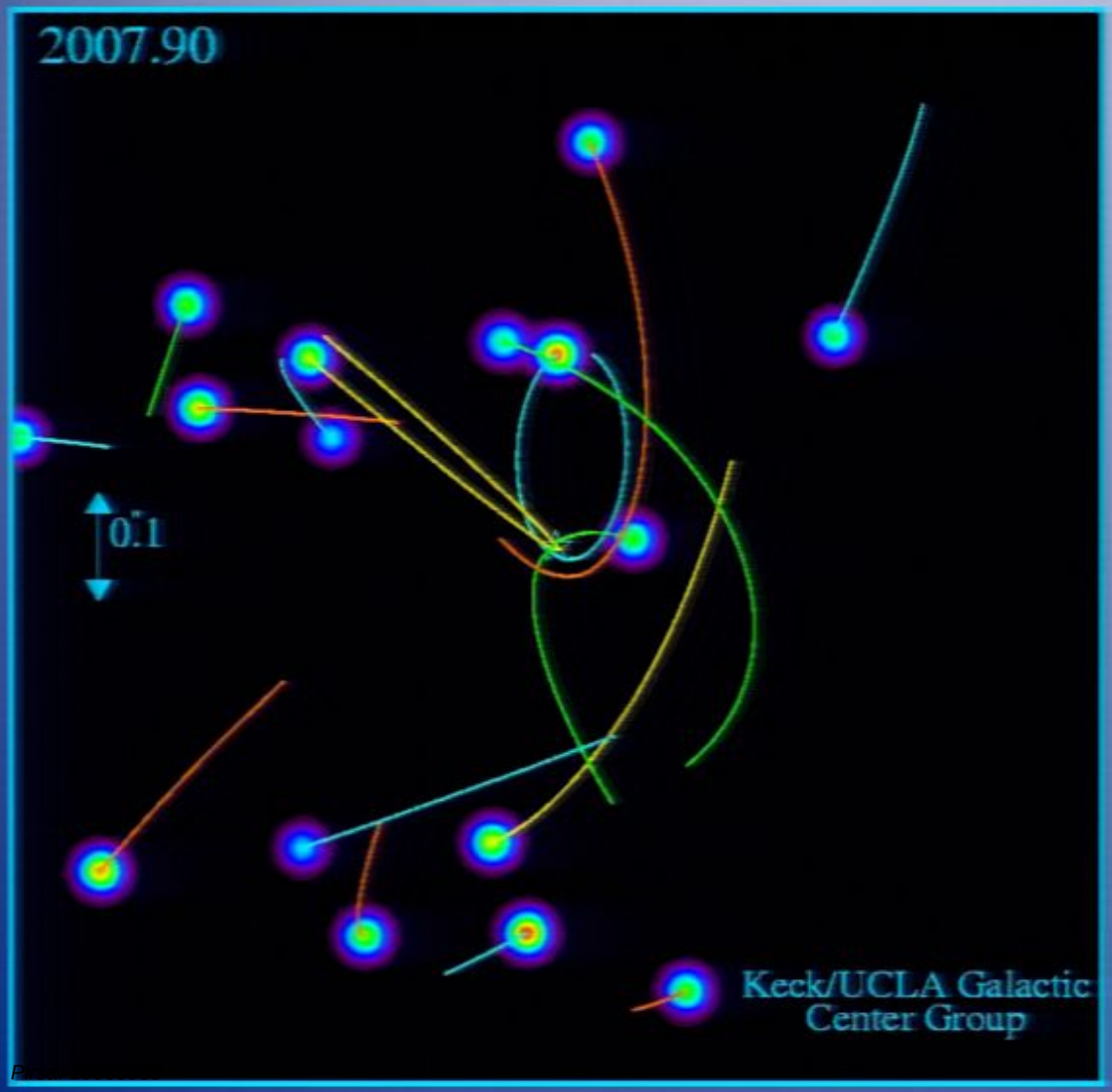

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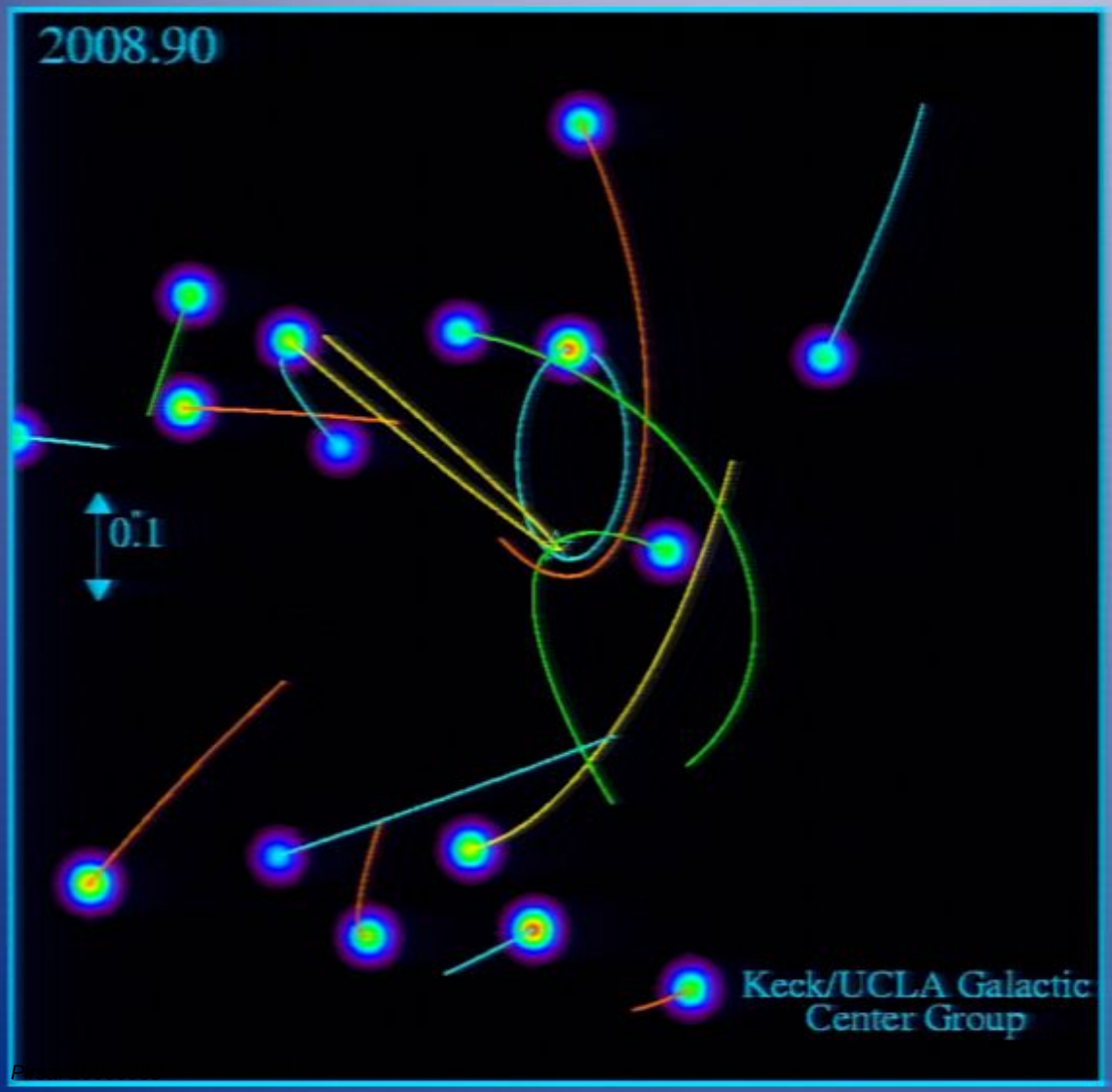

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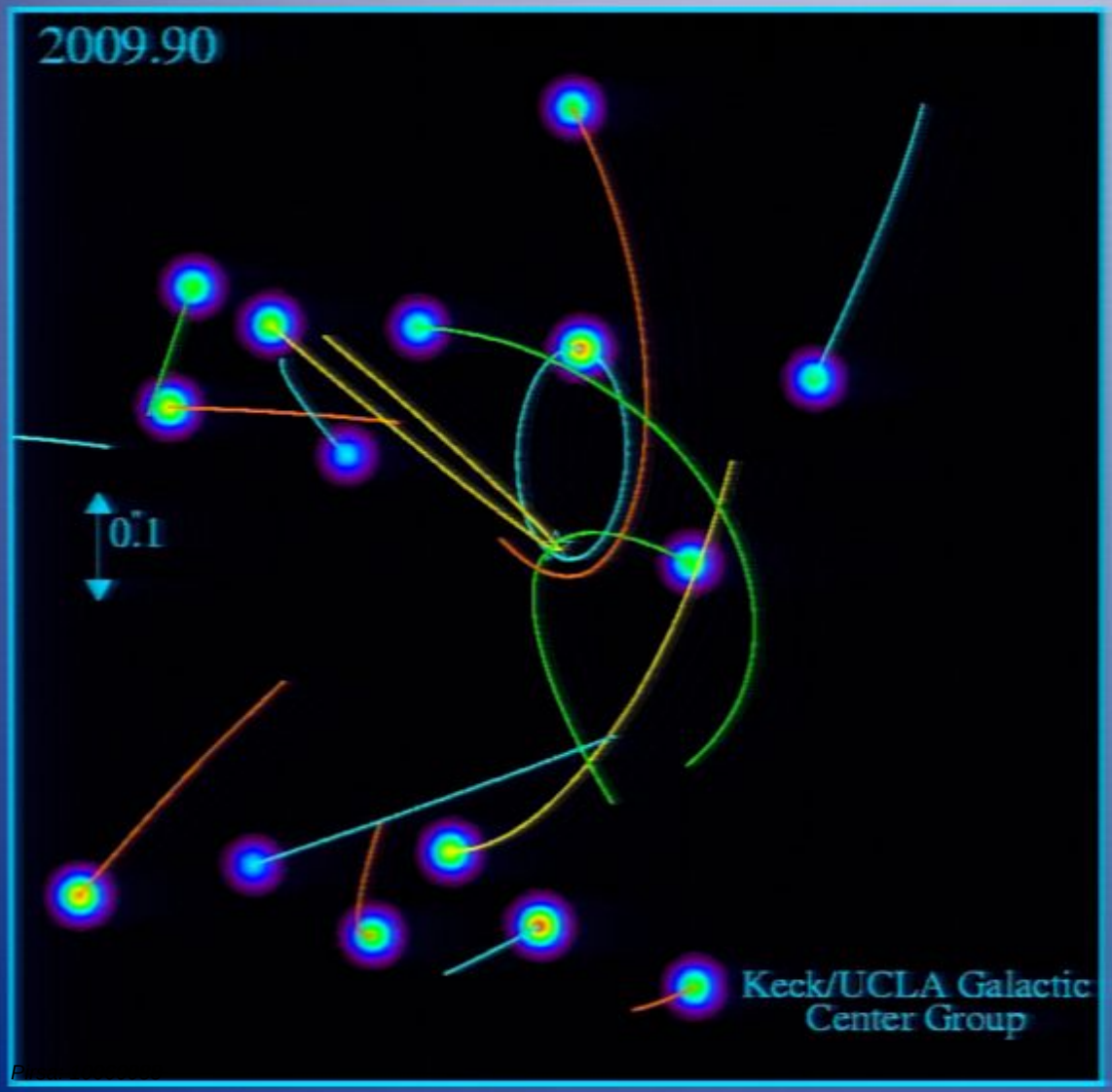

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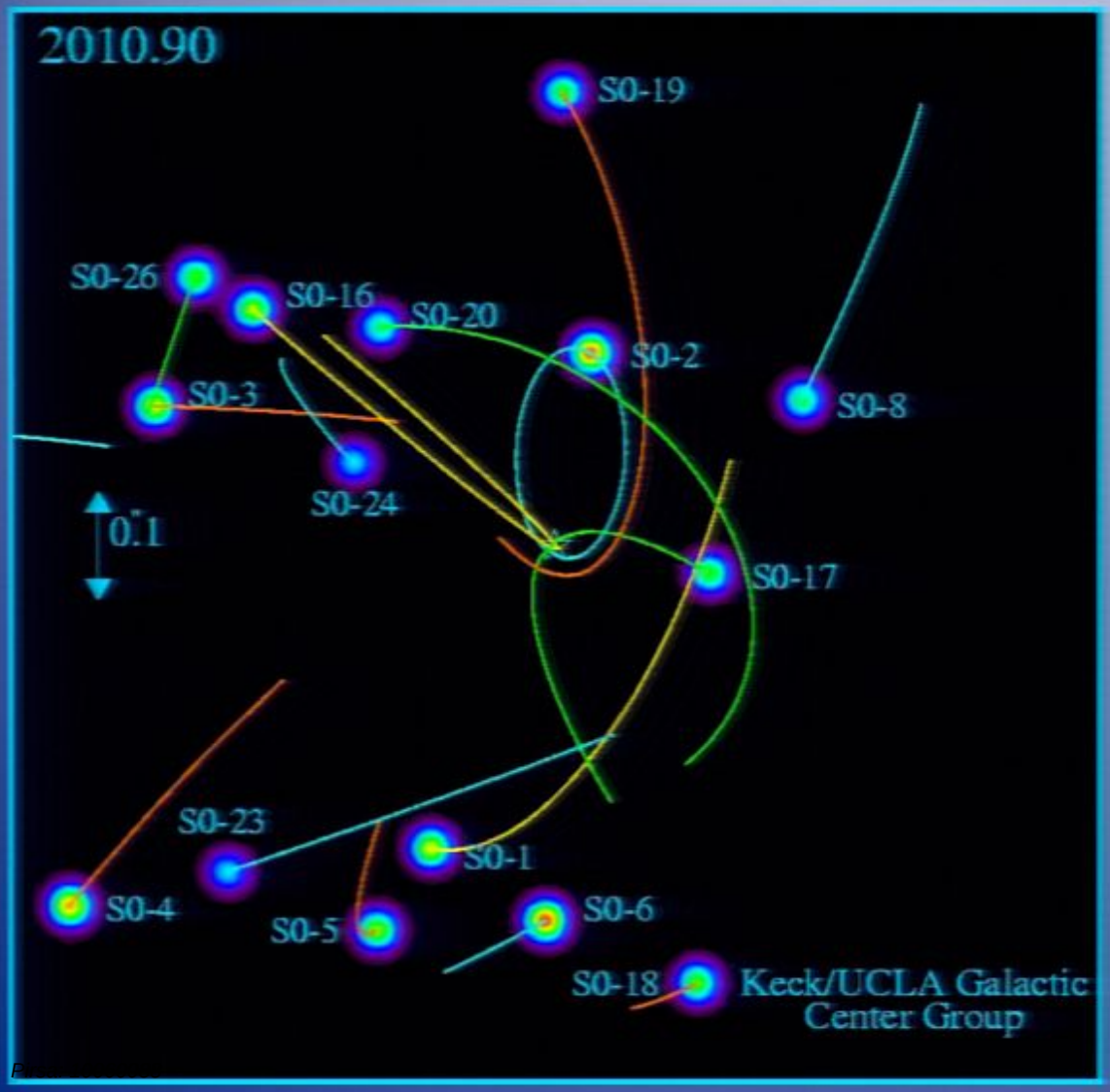

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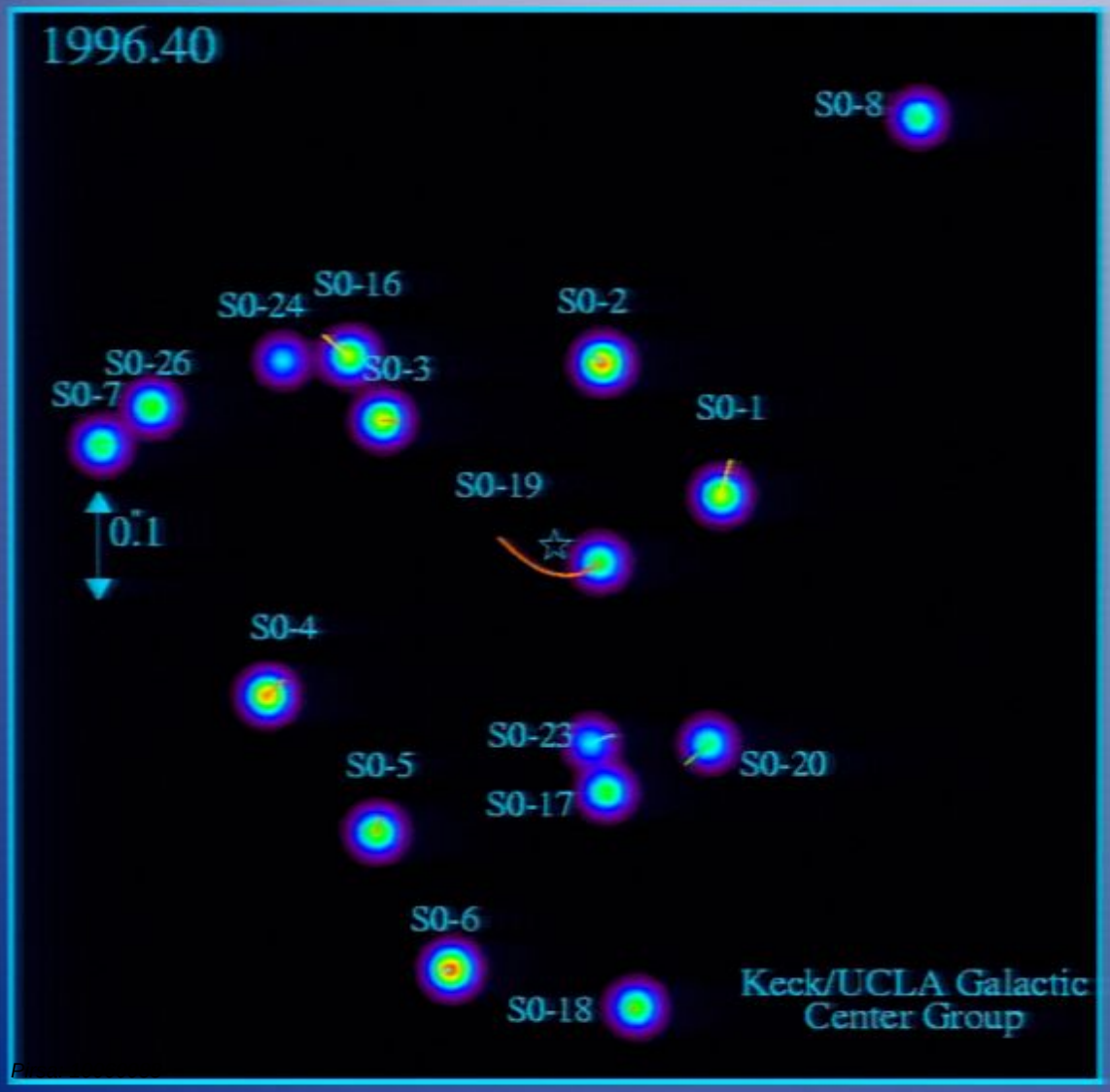

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Variability

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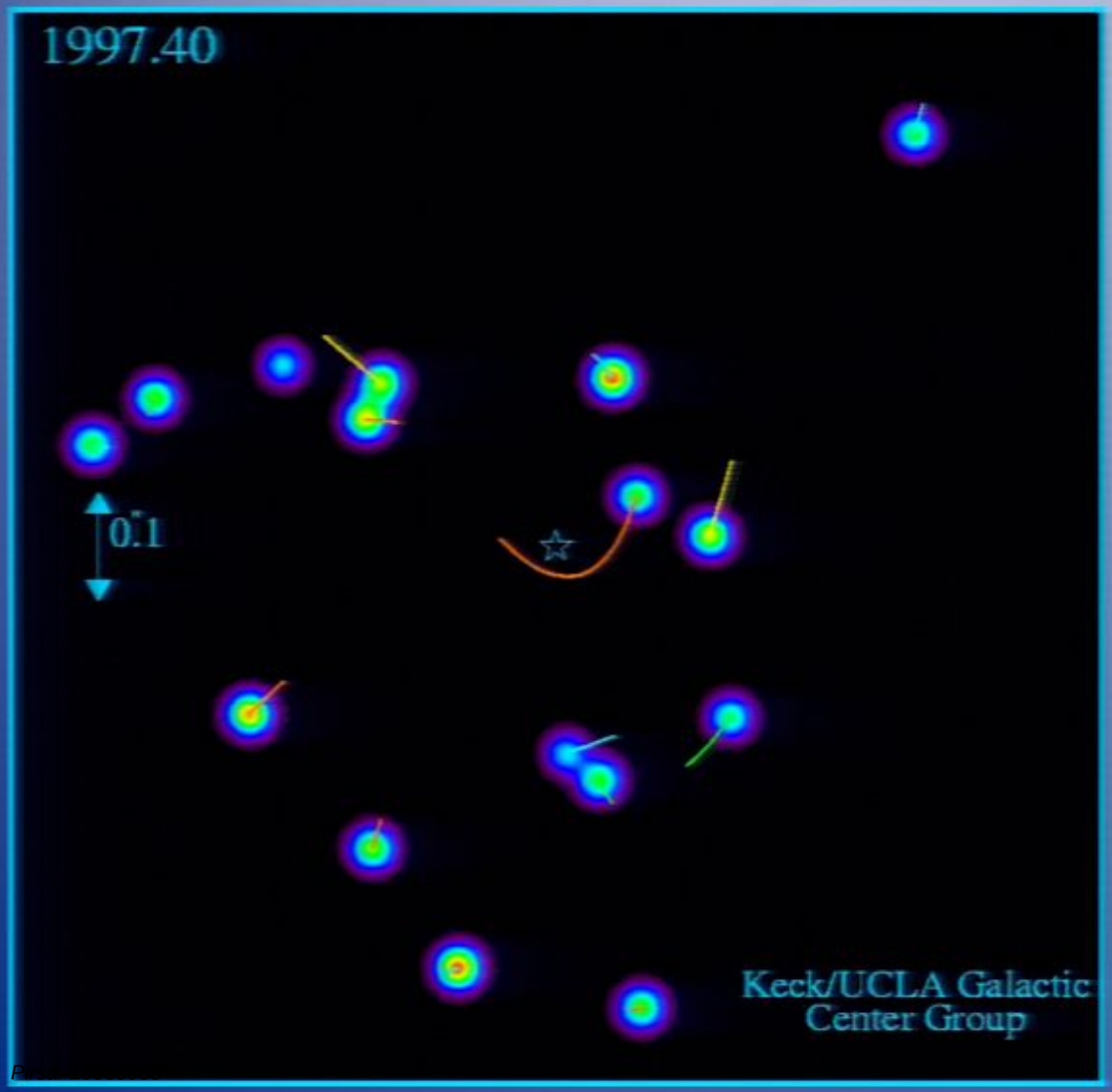

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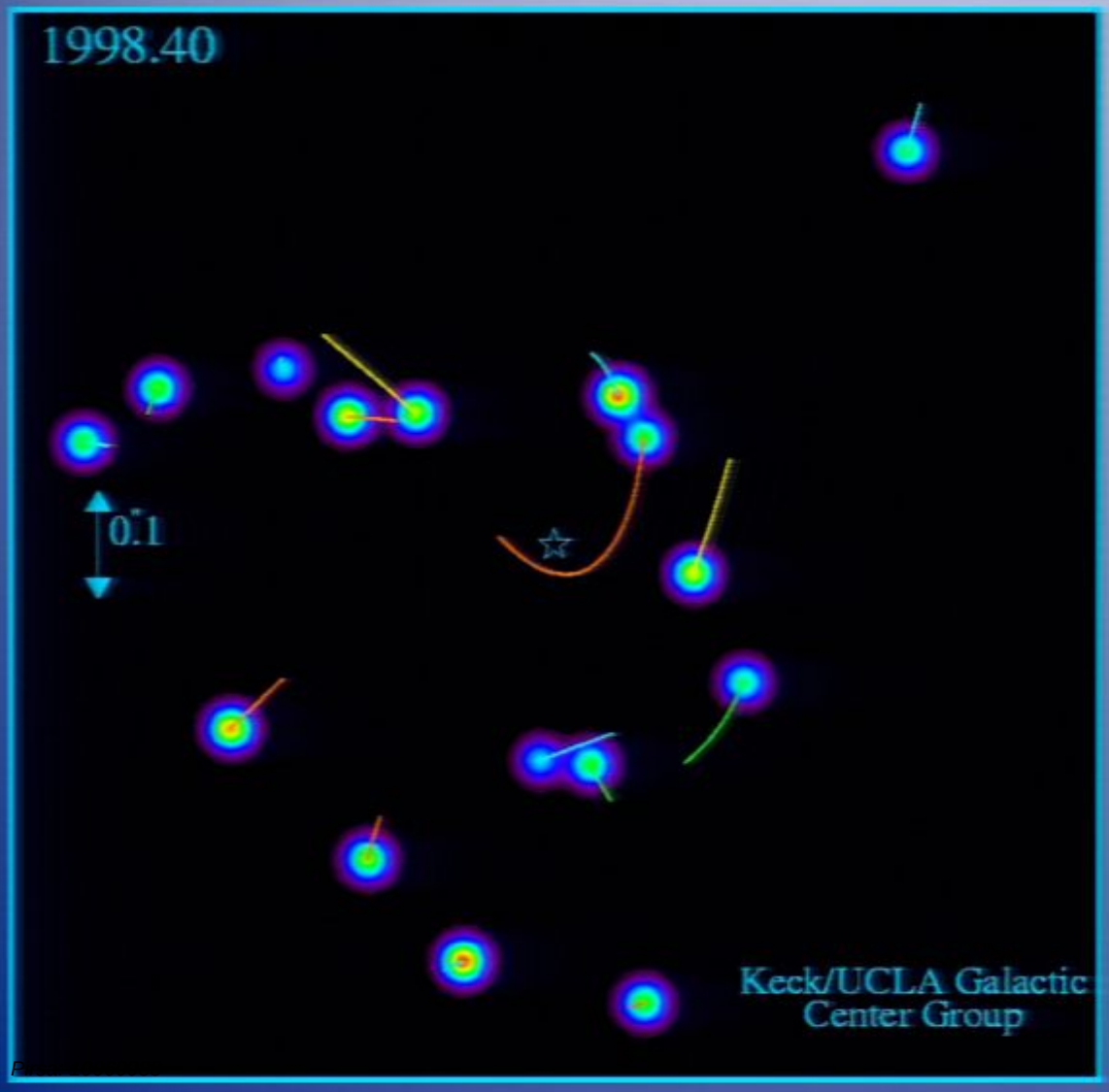

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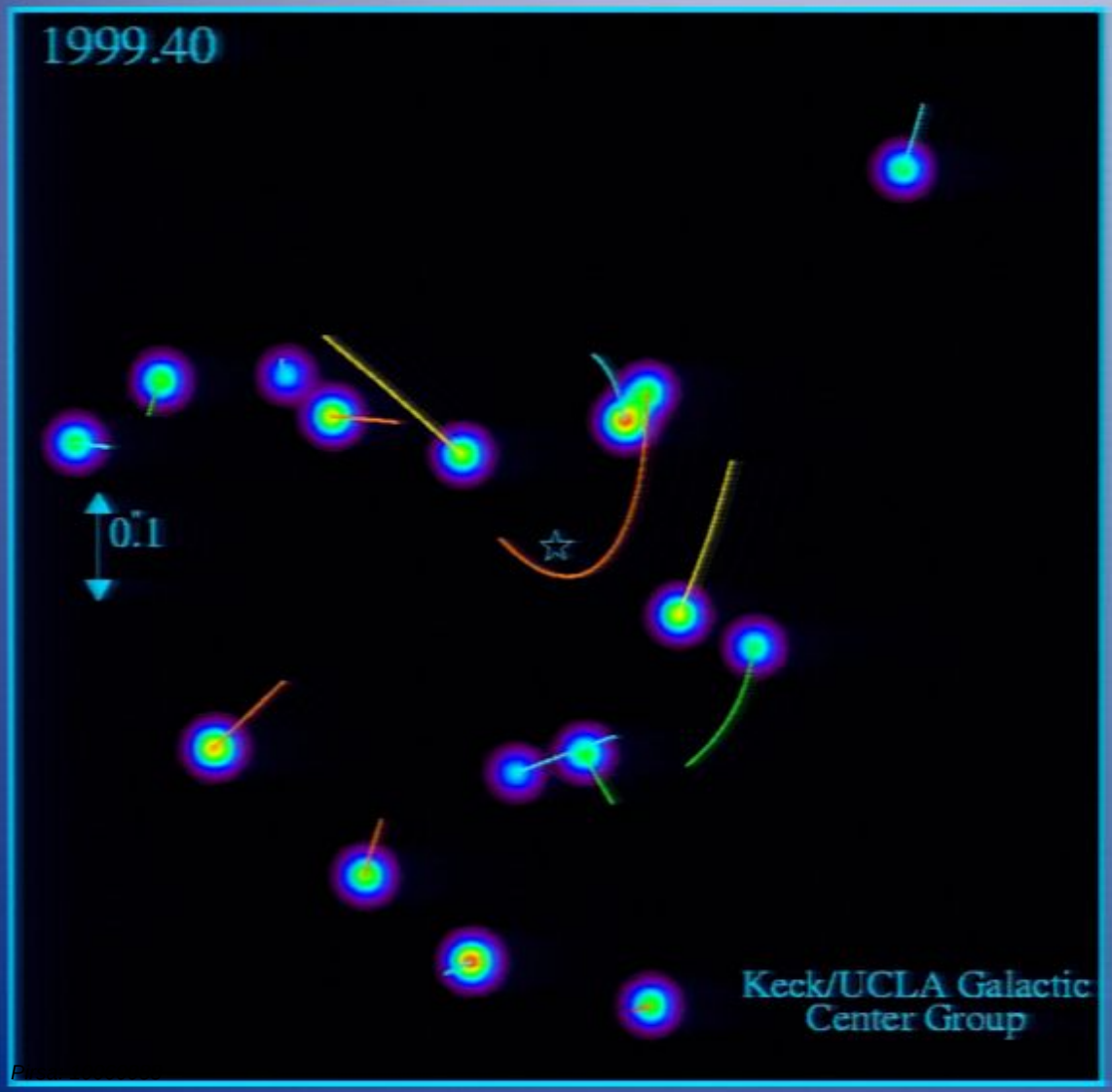

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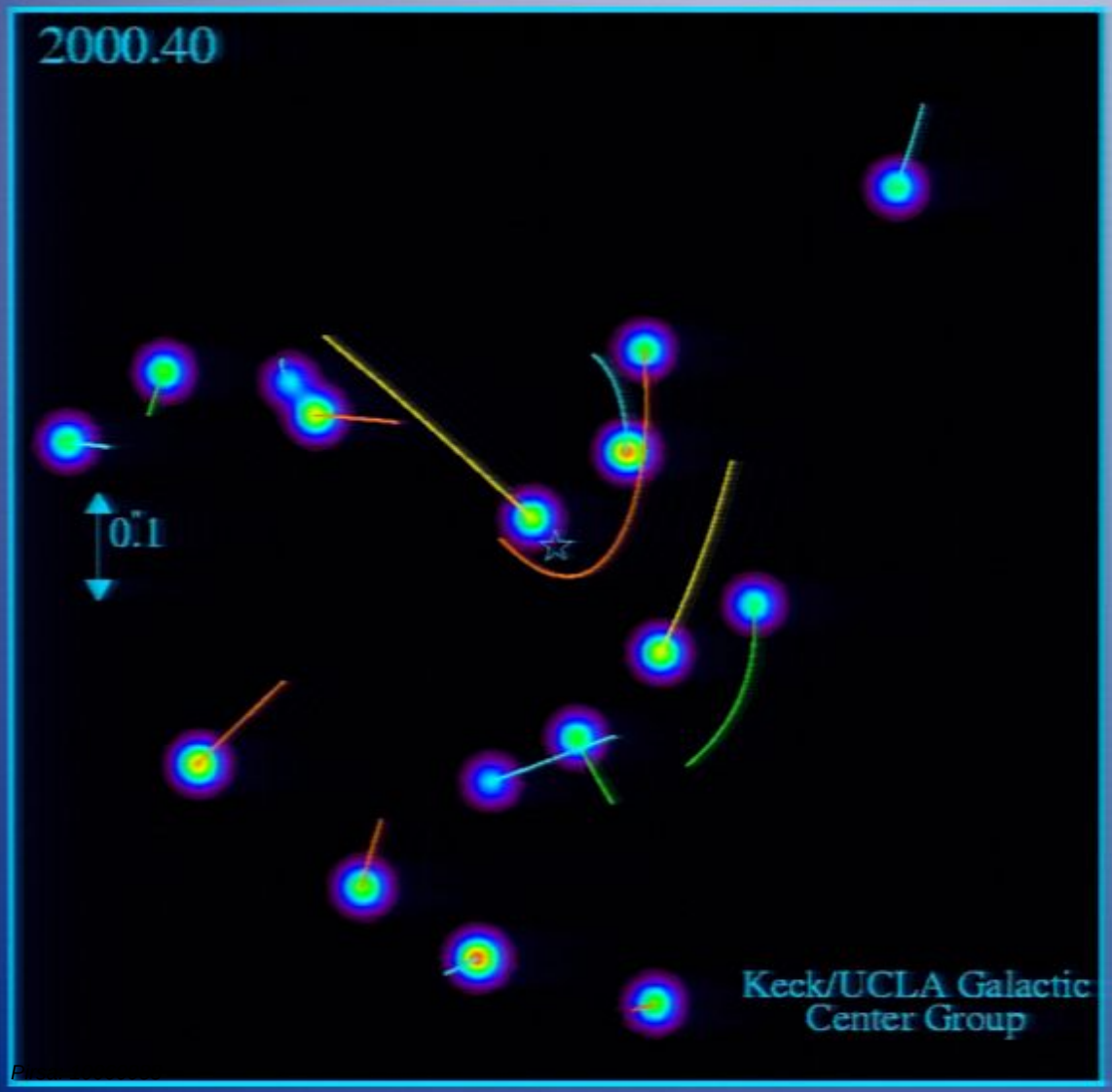

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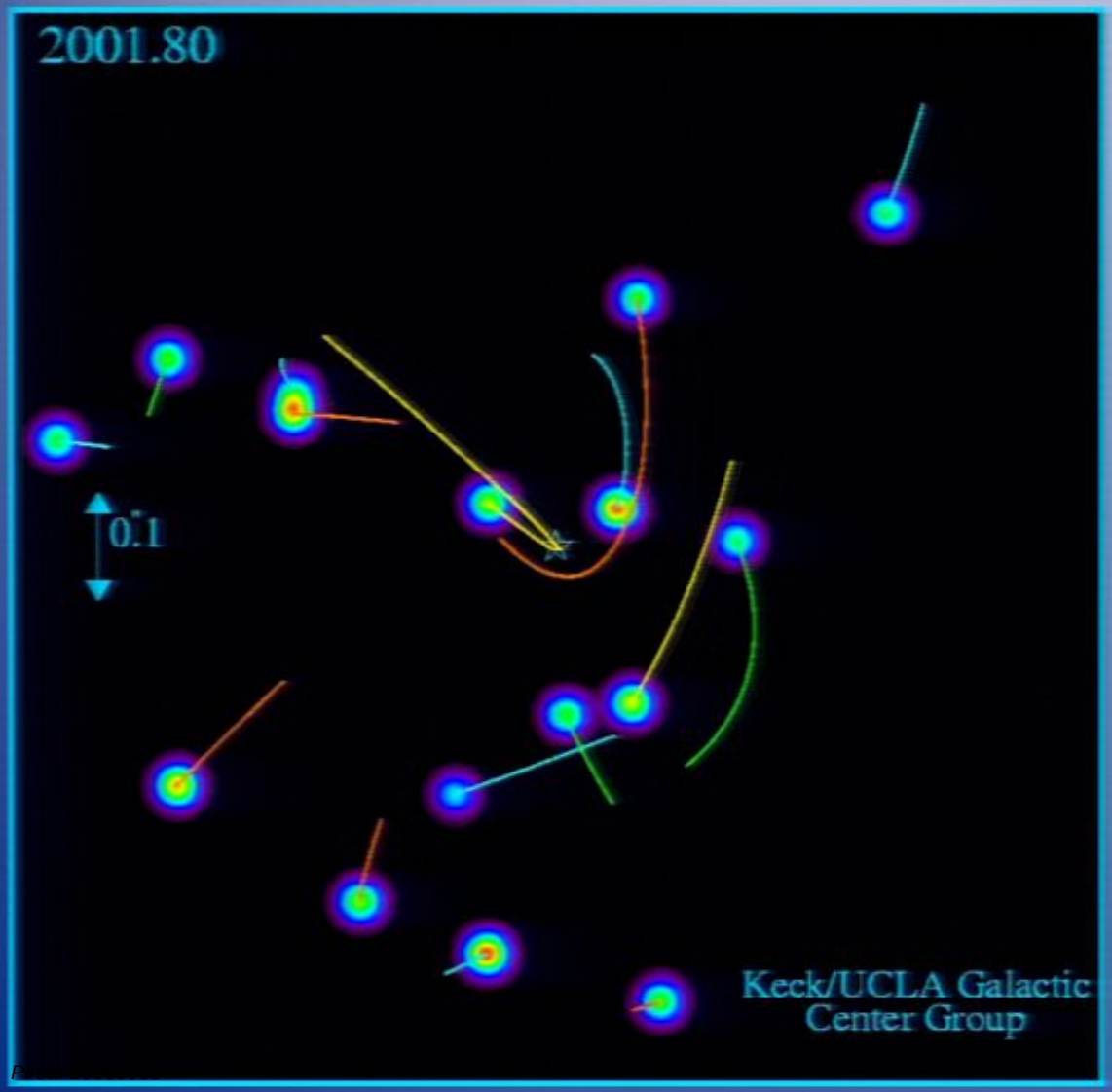

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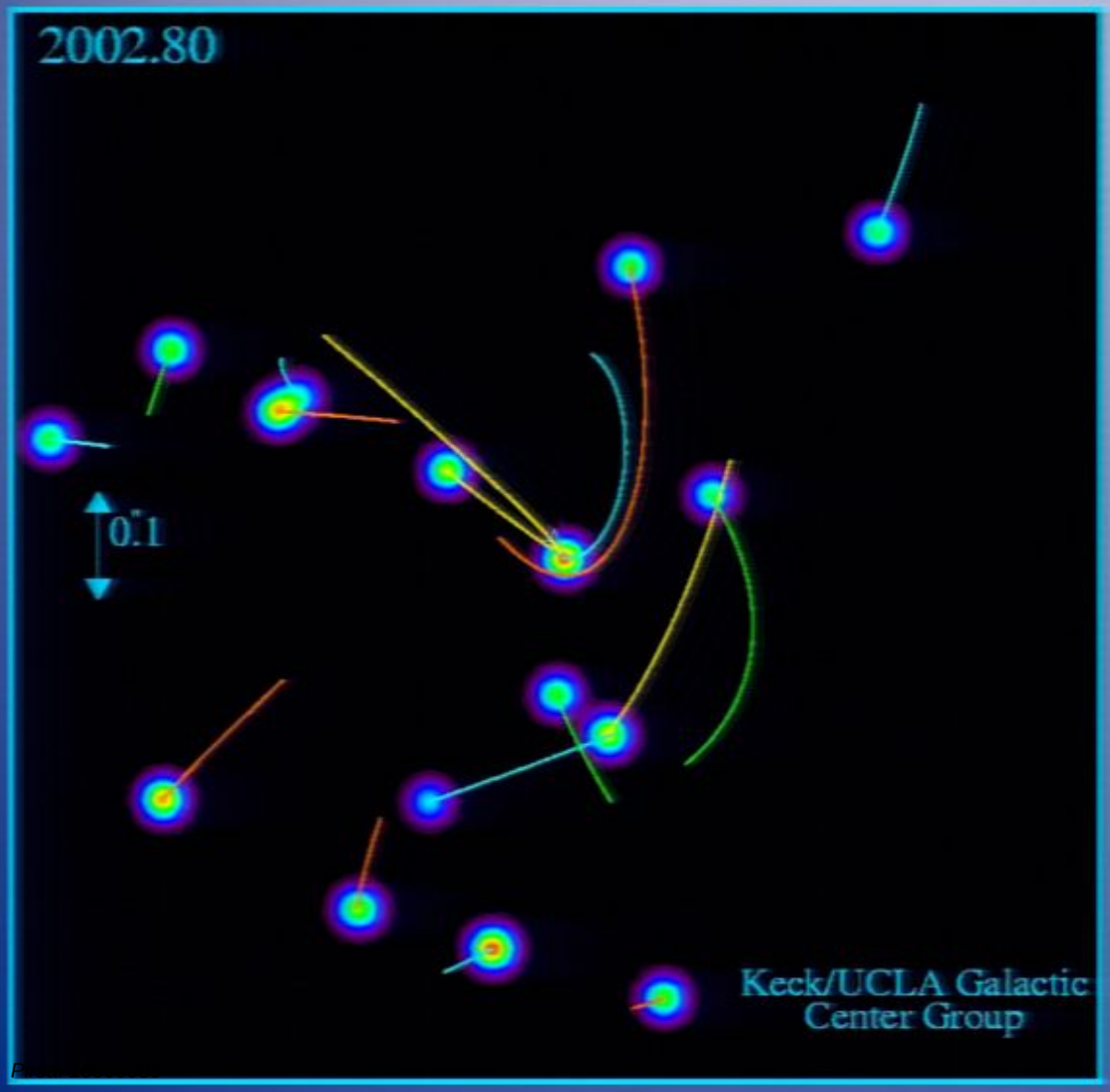

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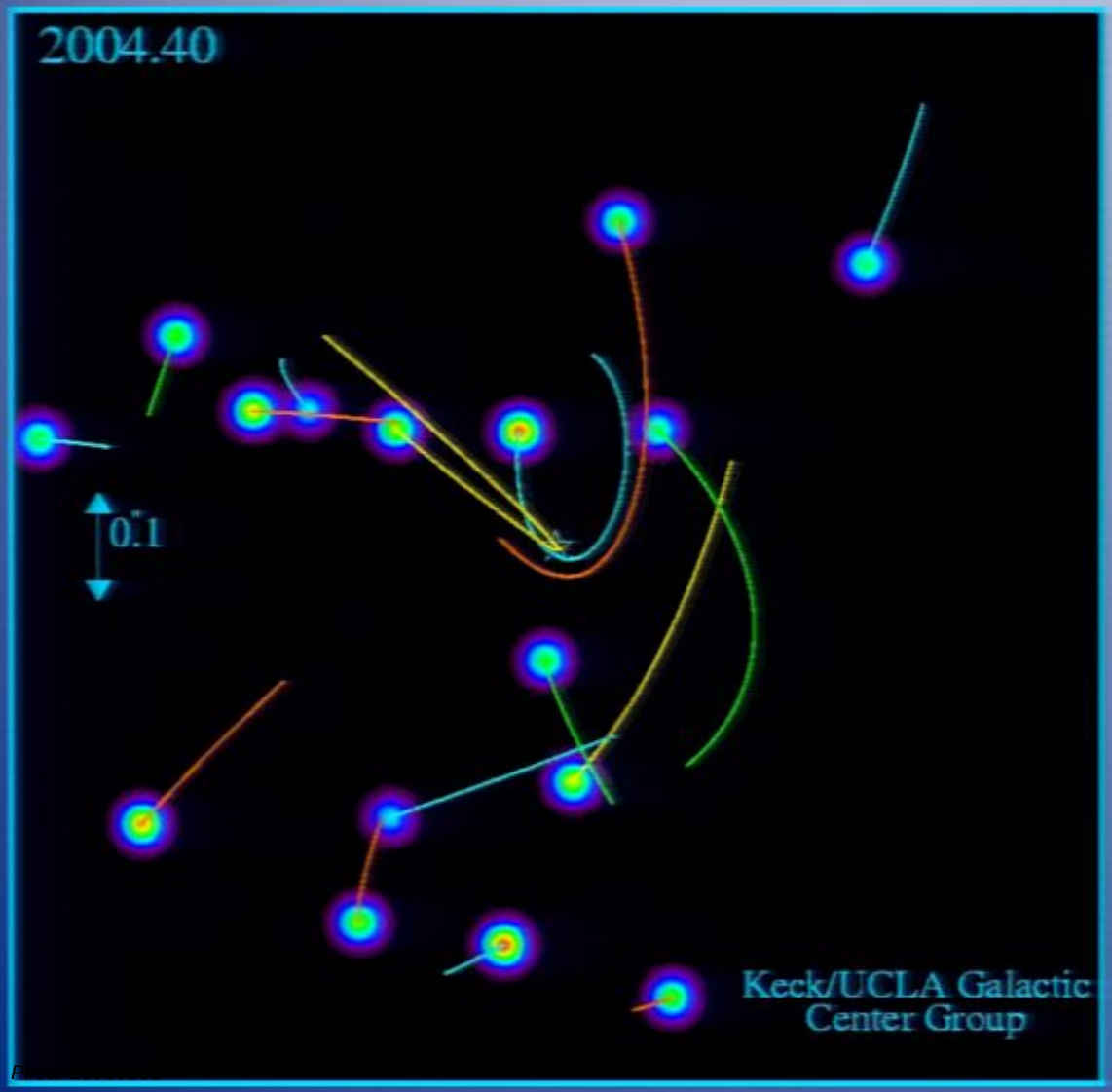

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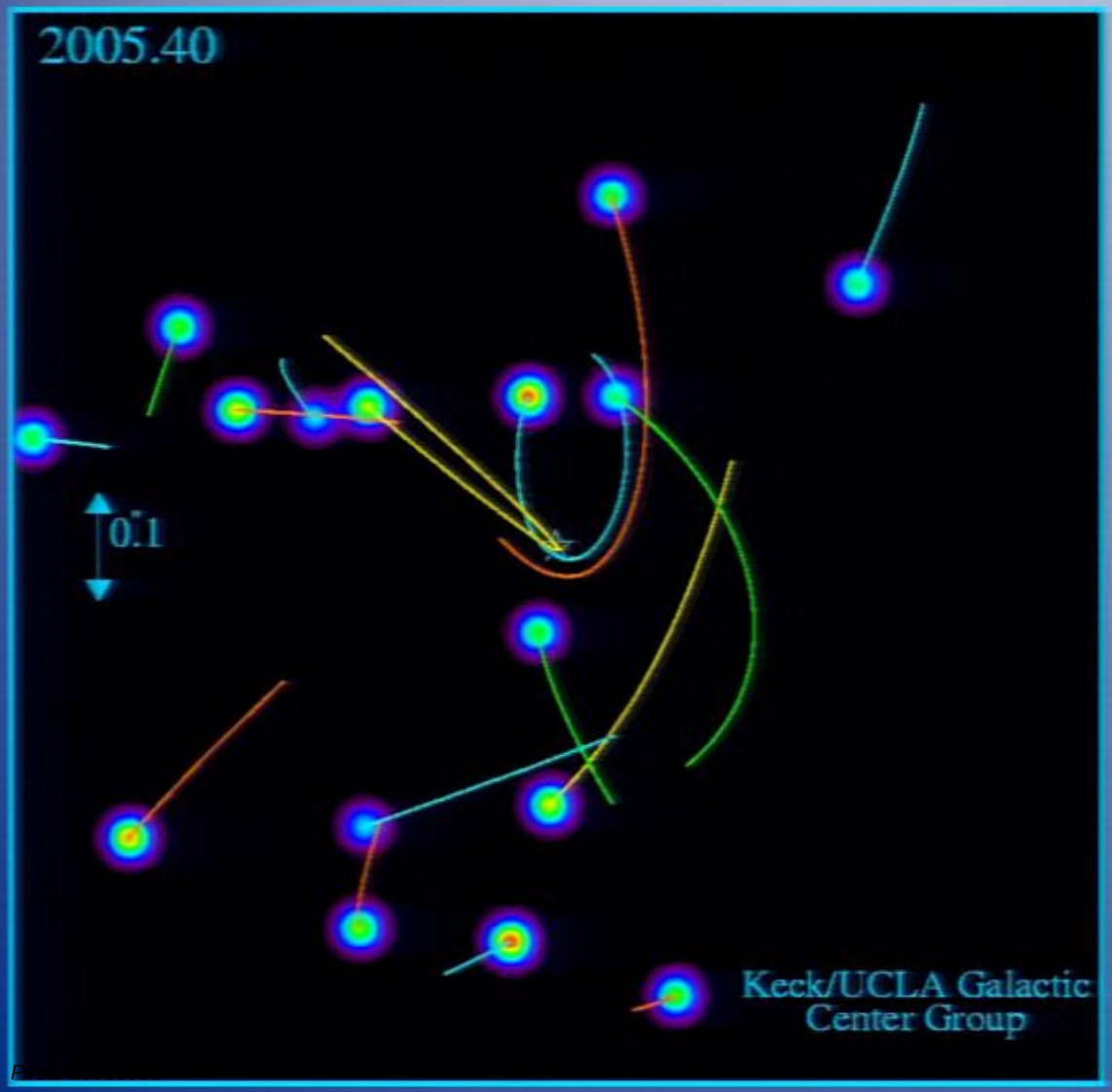

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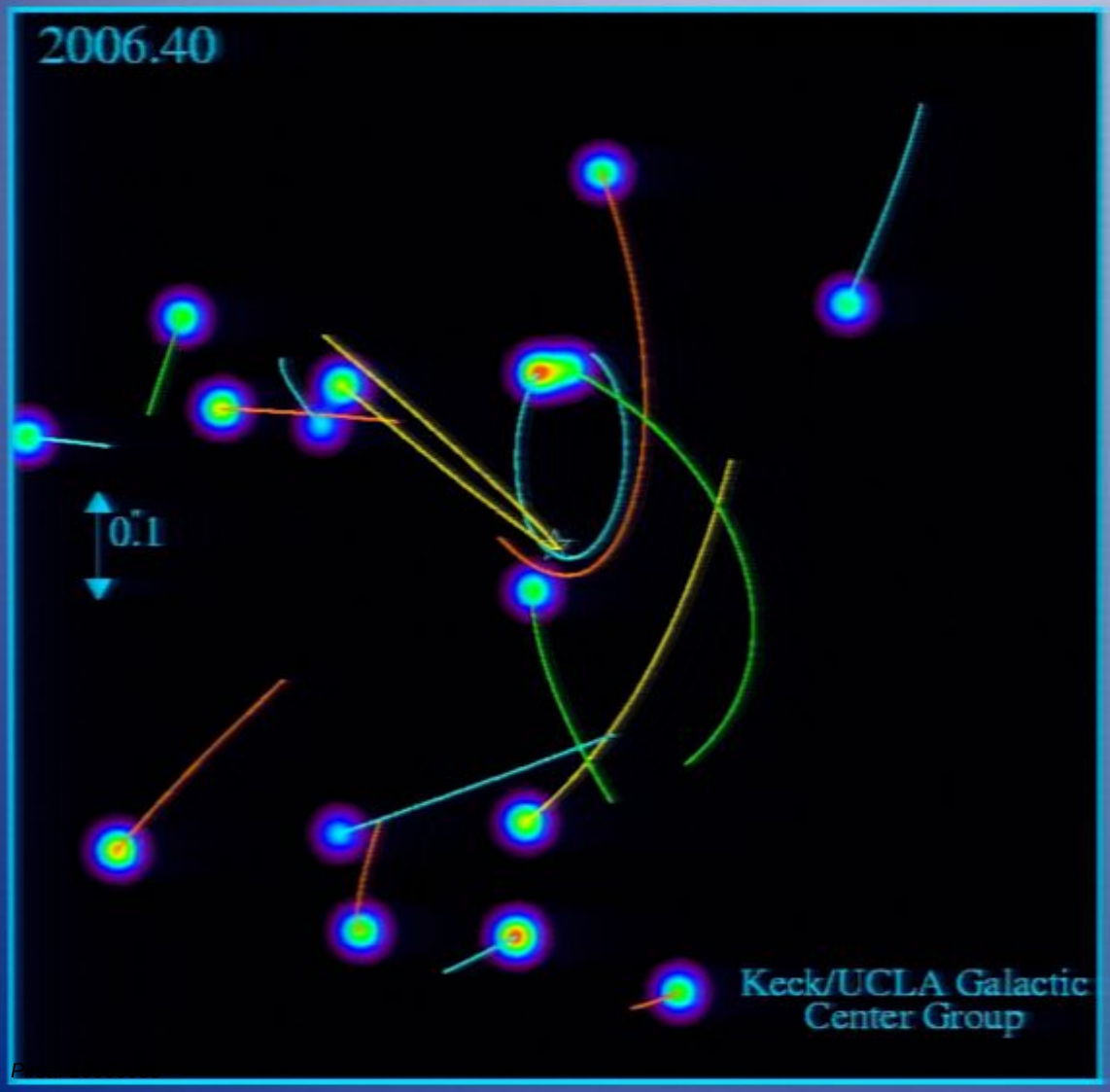

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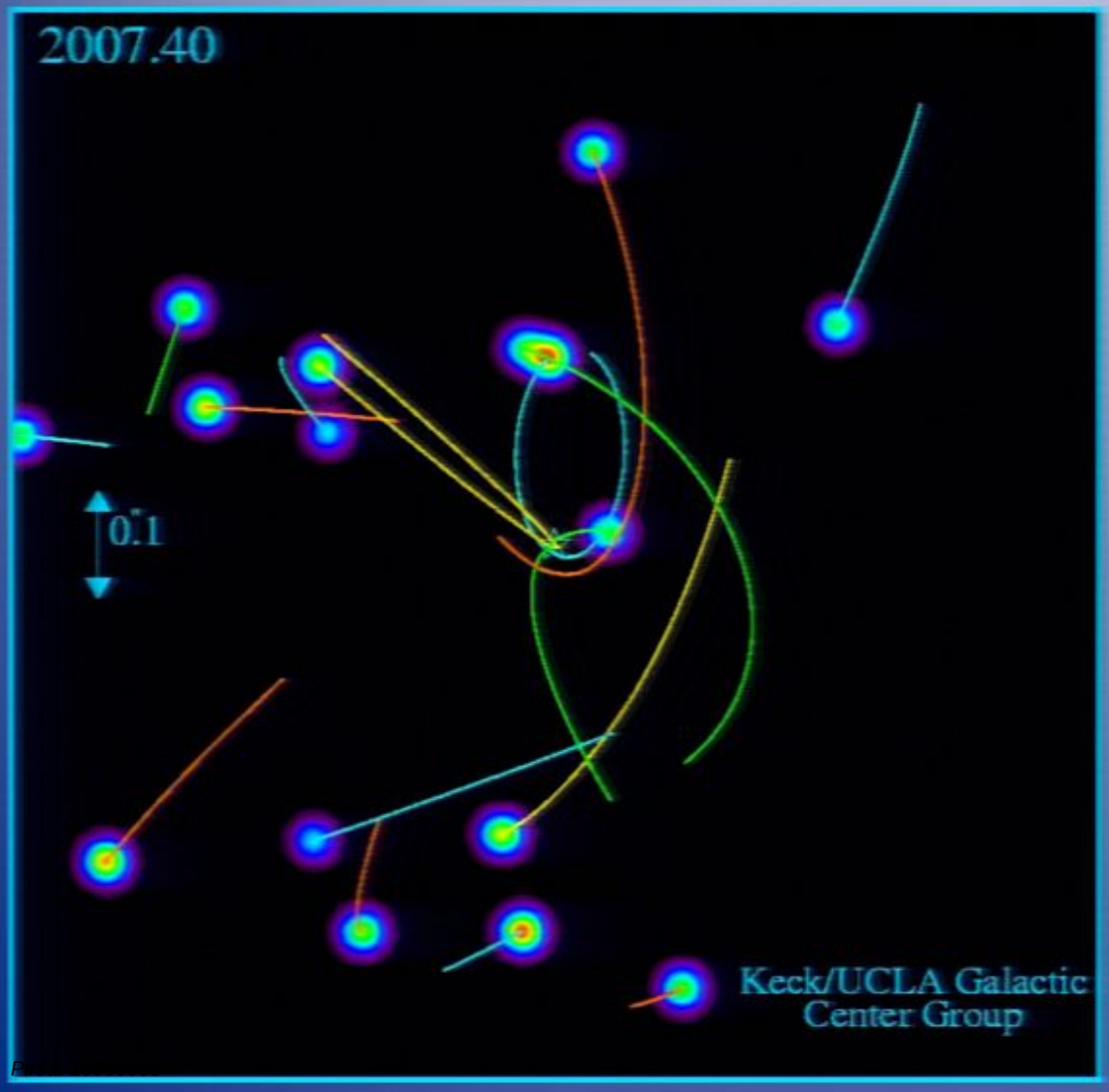

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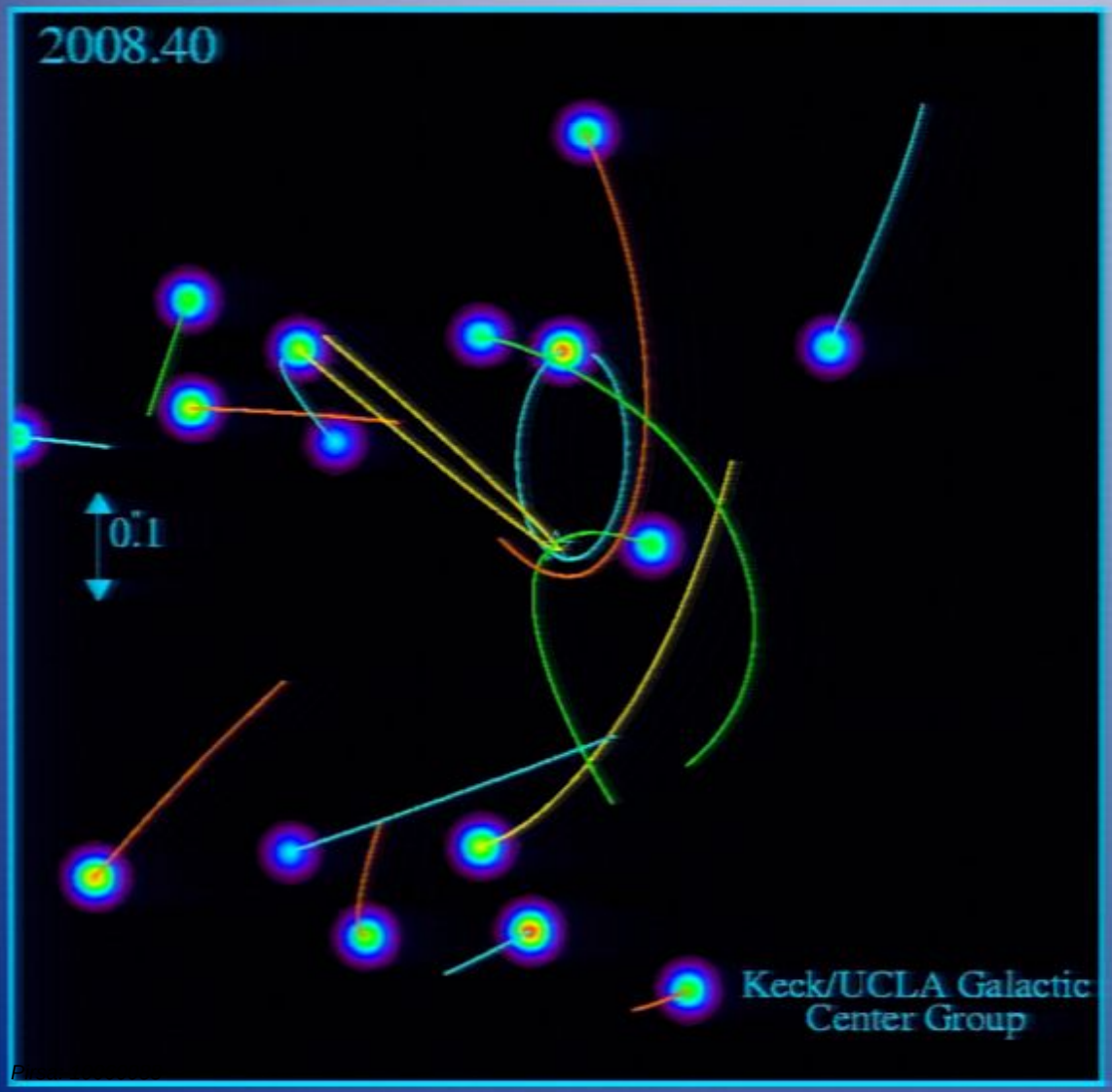

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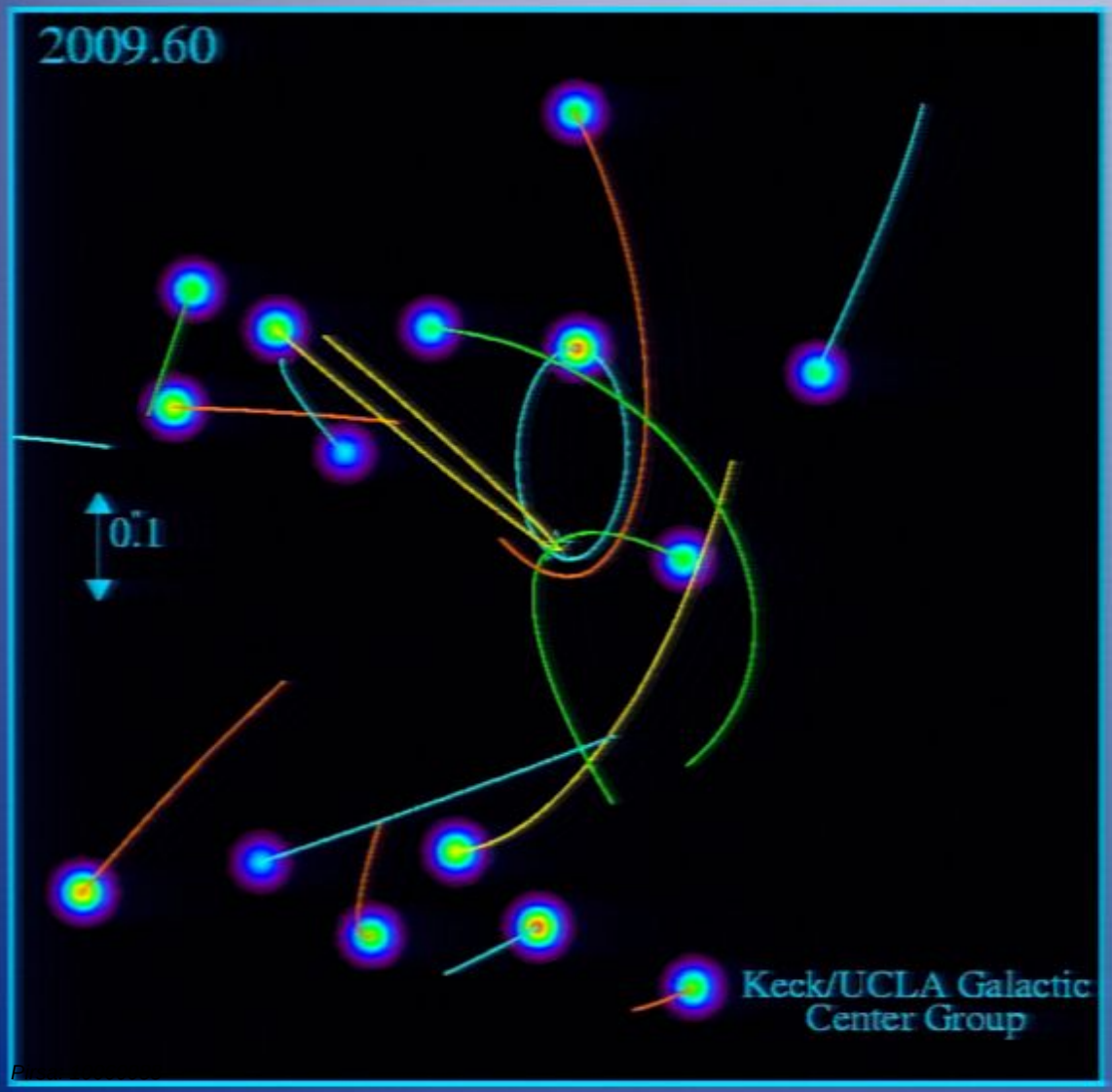

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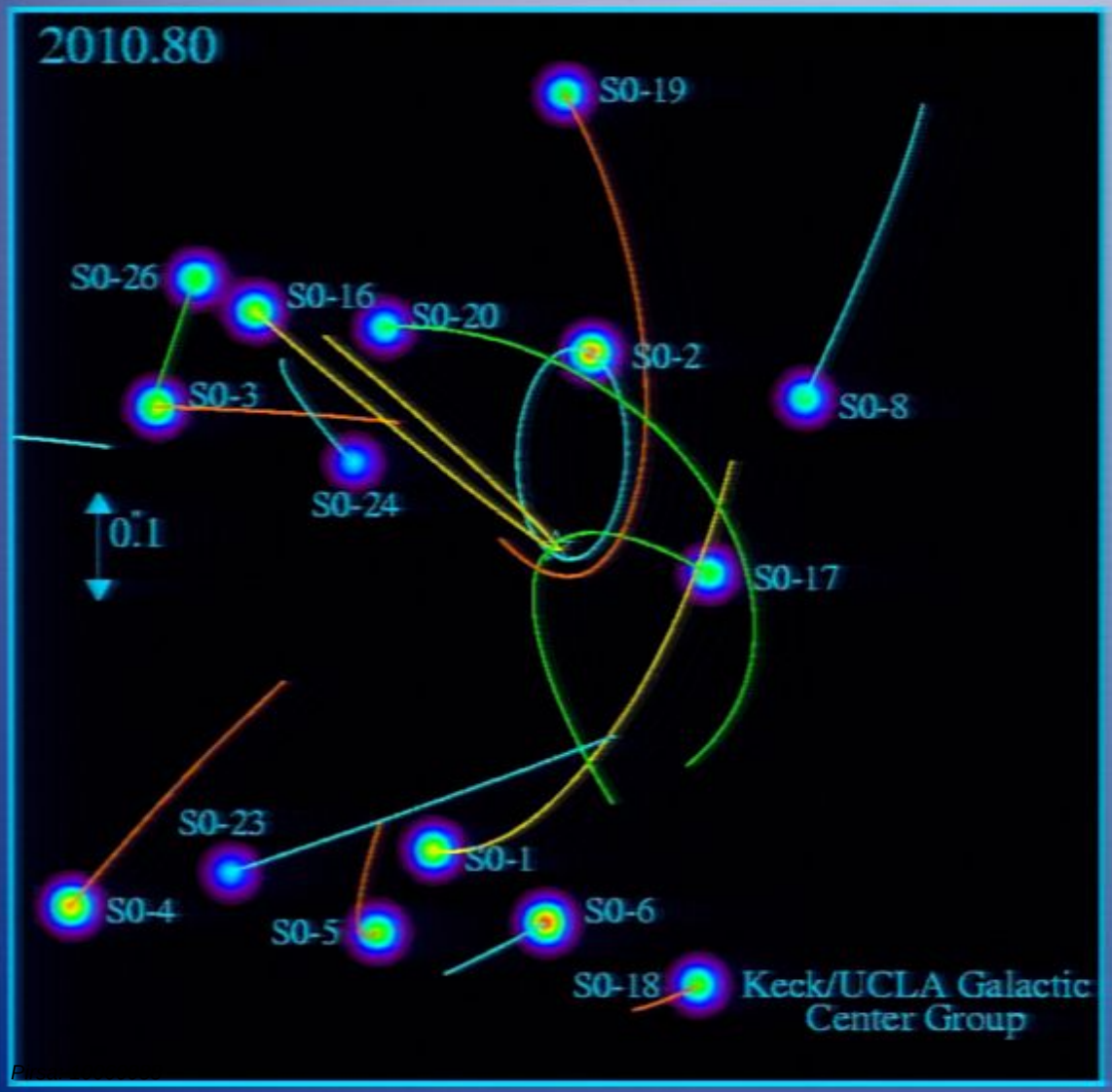

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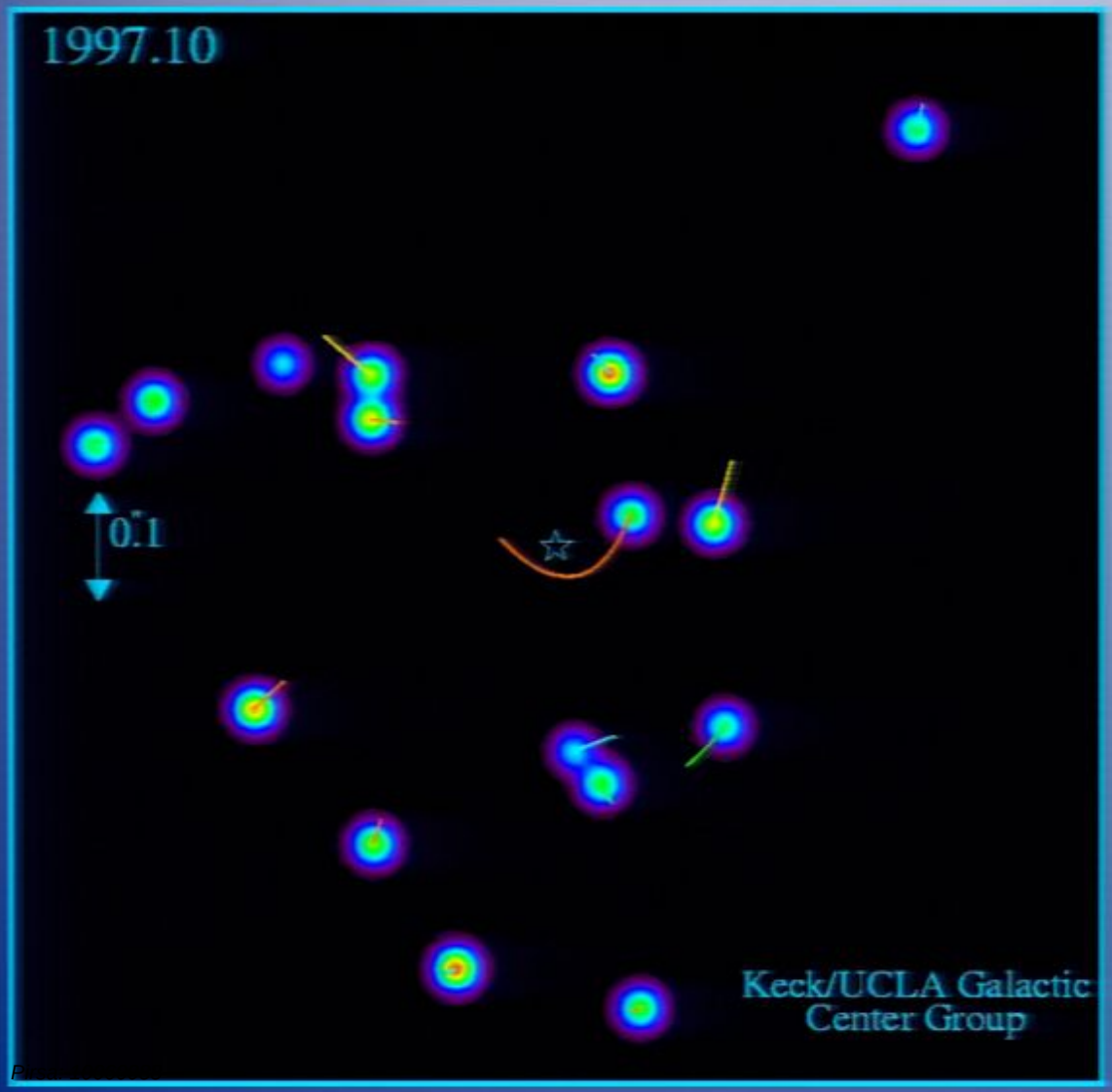

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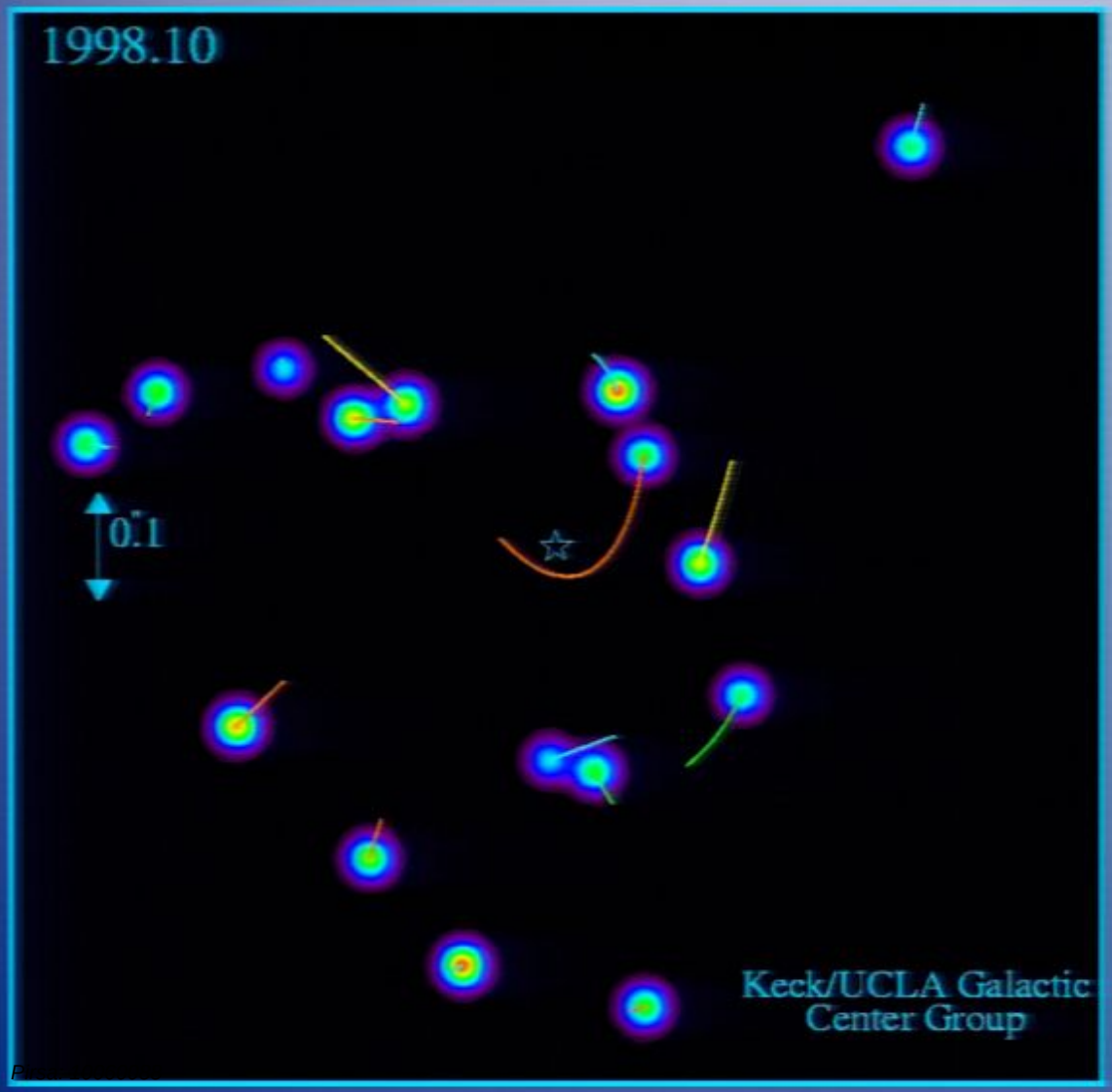

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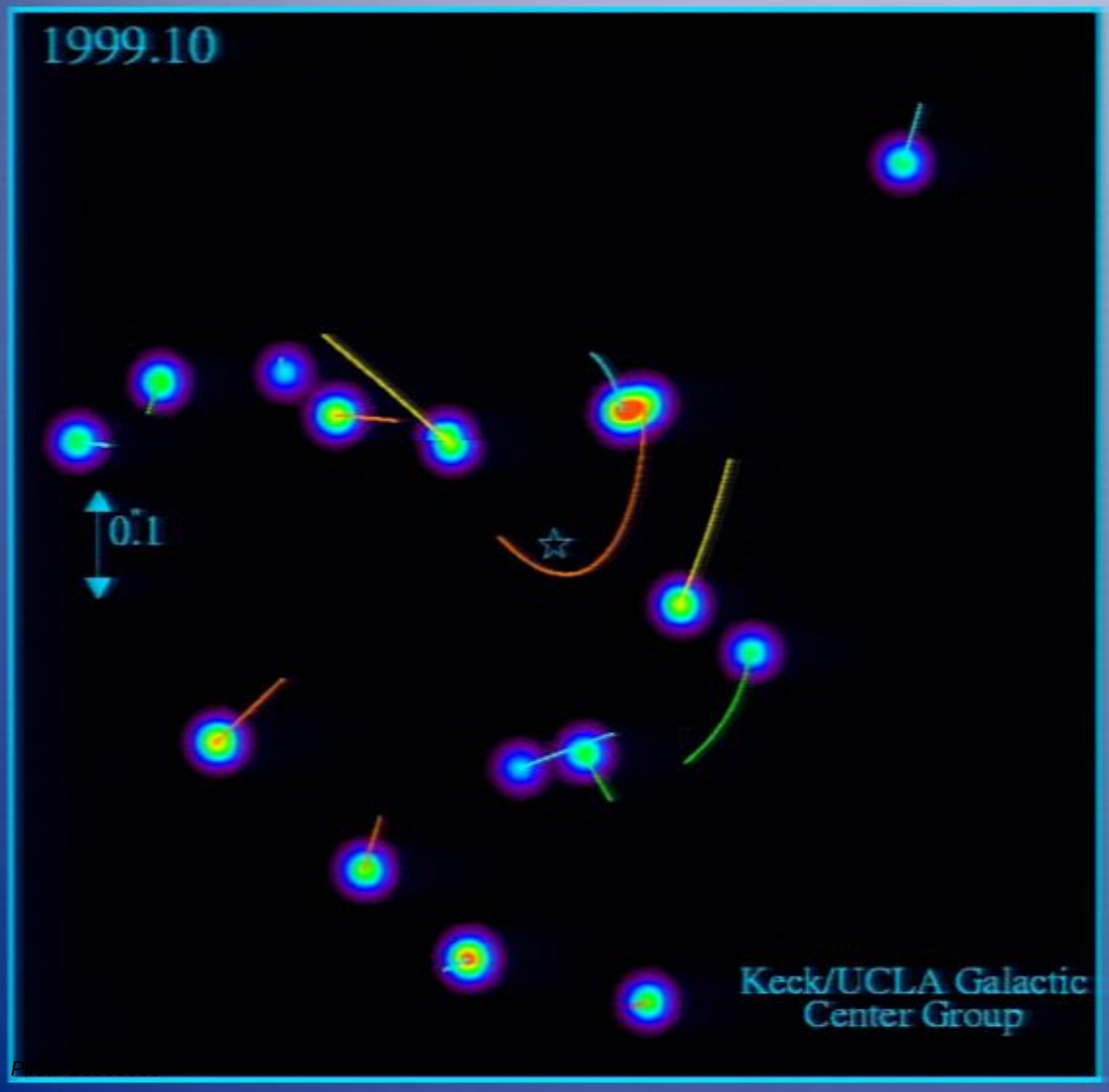

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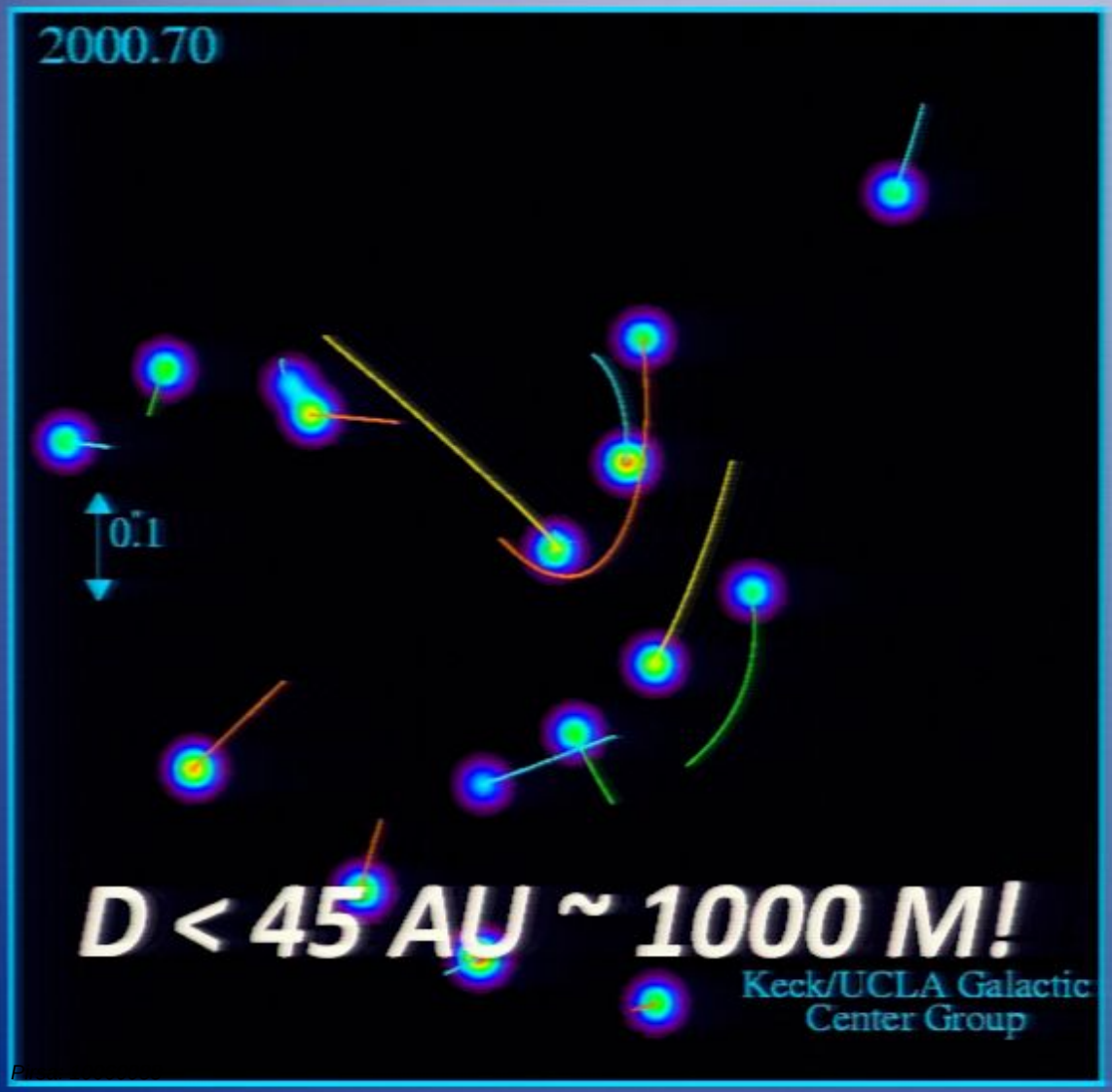

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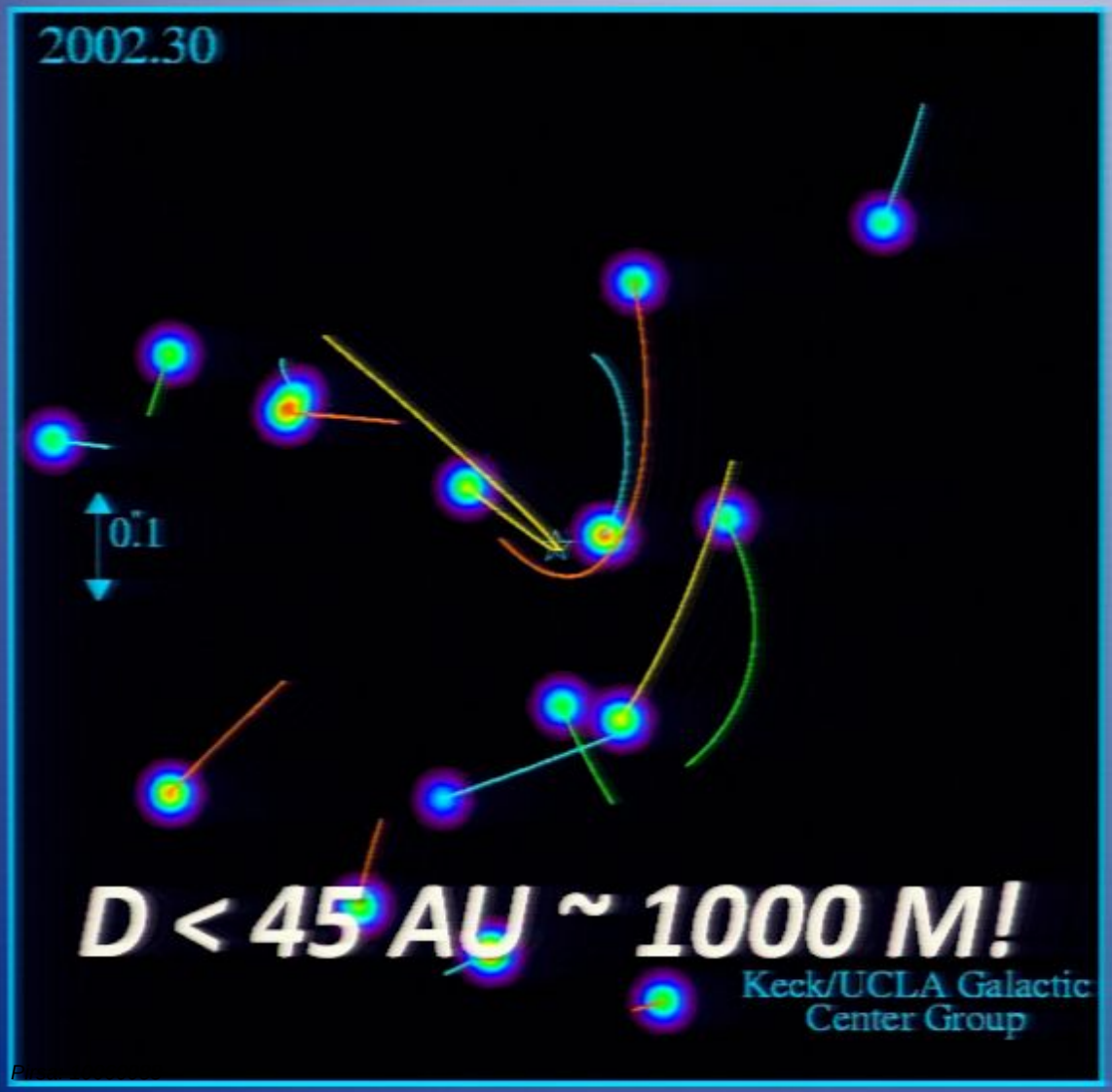

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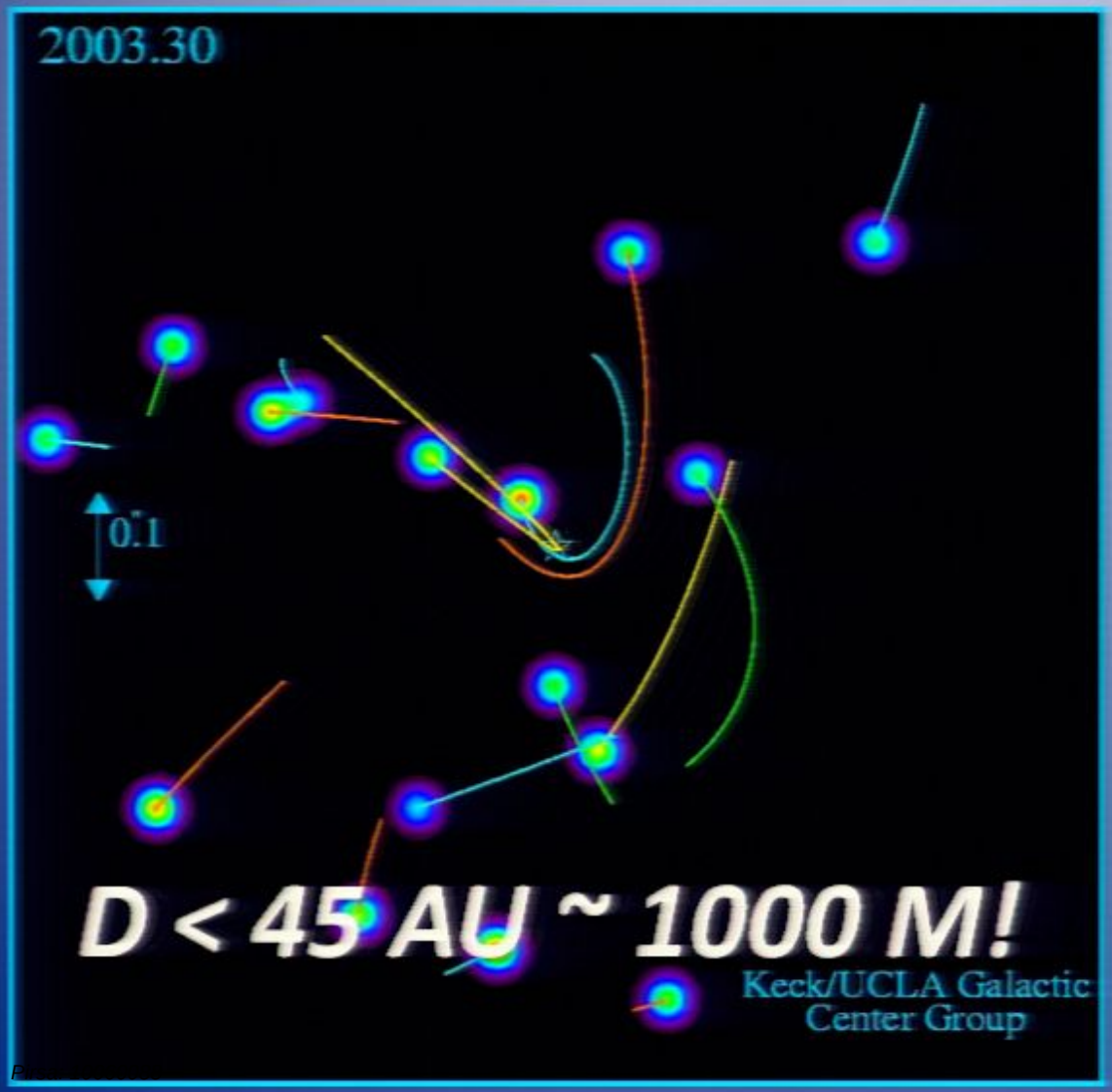

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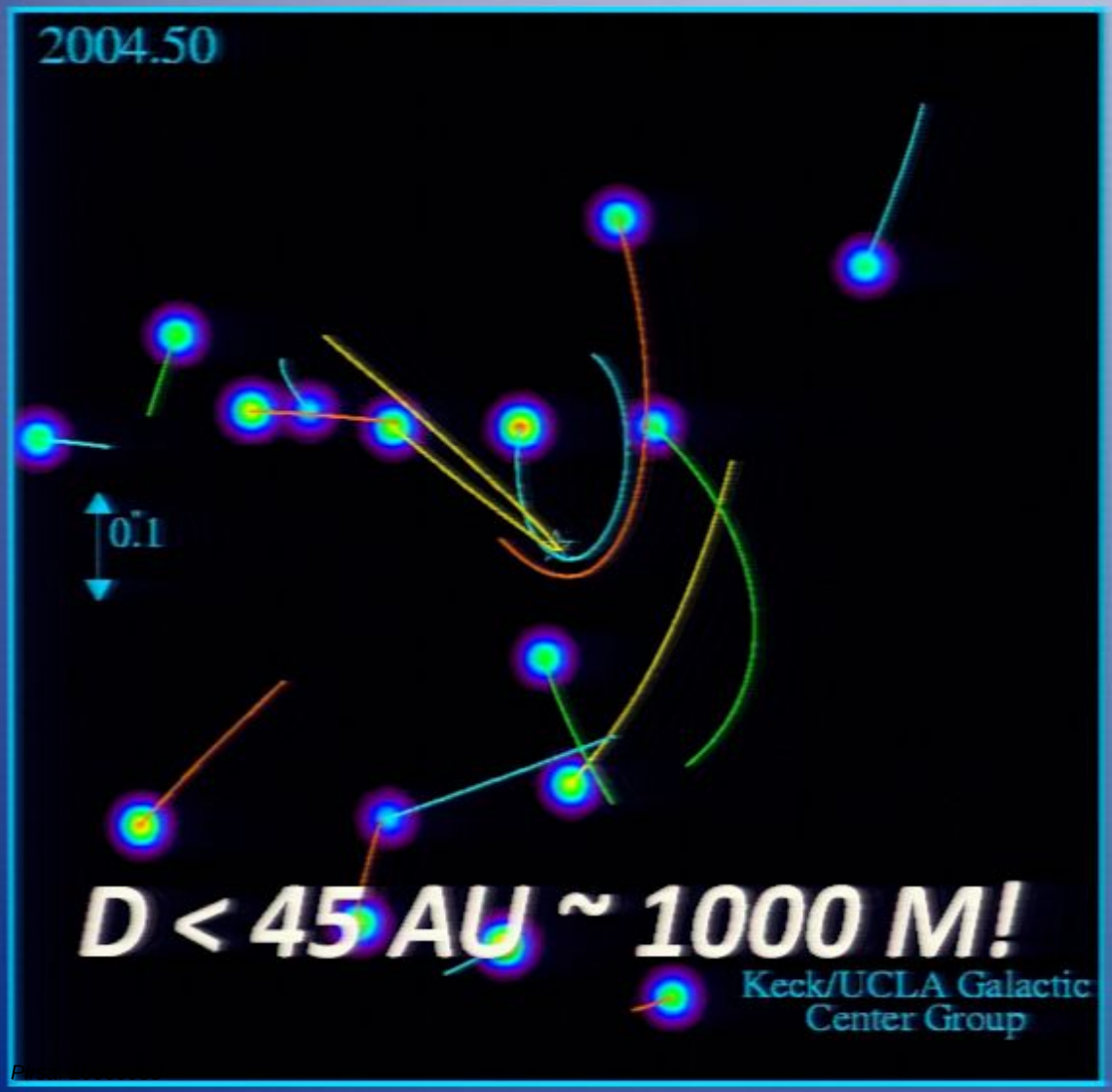

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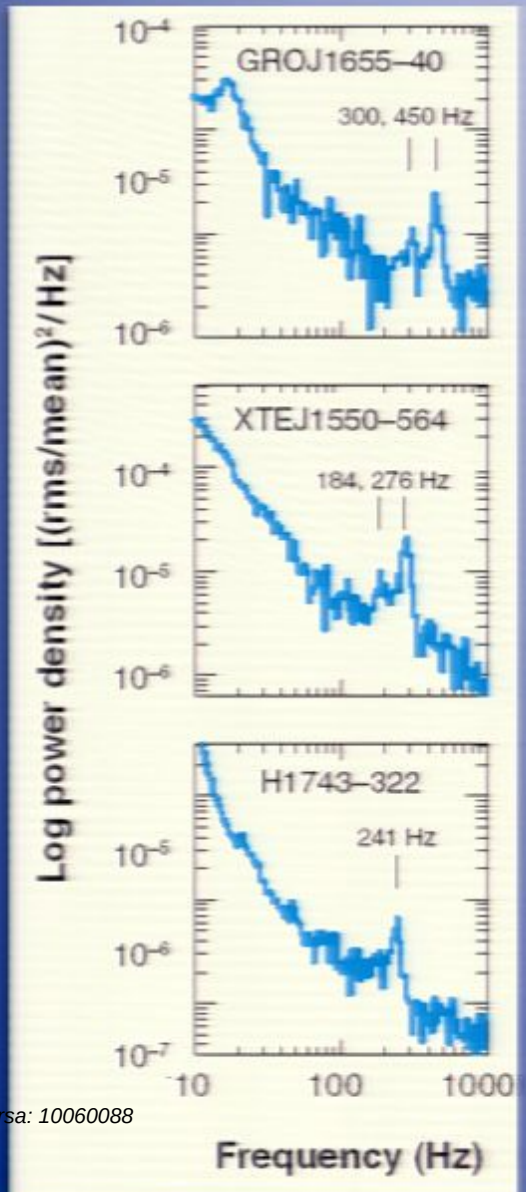
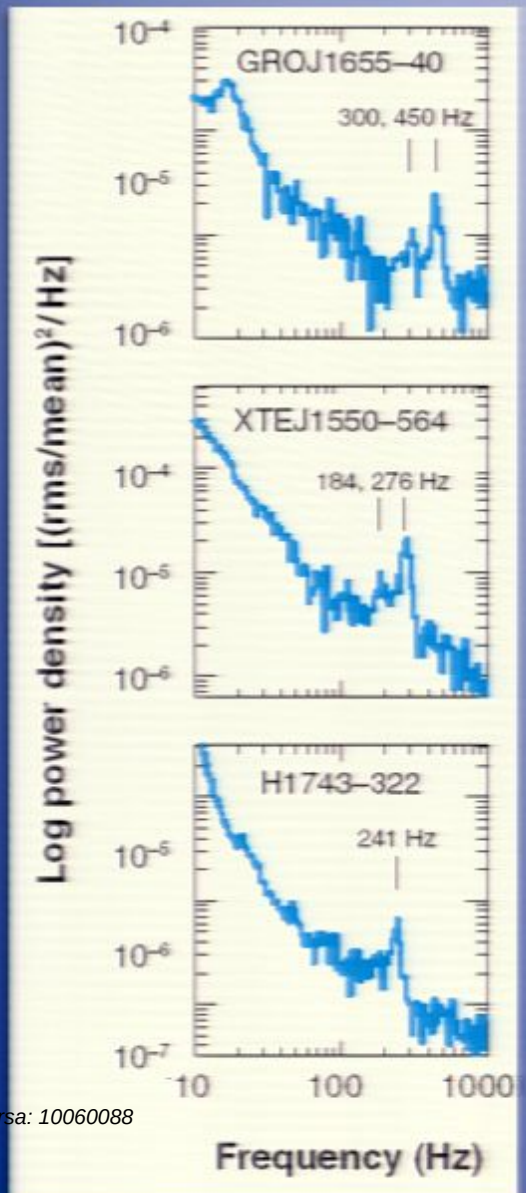
Quasi-Periodic Oscillations



- BH QPOs:
  - ~300 Hz ~ $\nu^{\phi}(6M)$
  - 3:2 ratios → resonant phenomena?
  - Epicycles

Variability

Quasi-Periodic Oscillations



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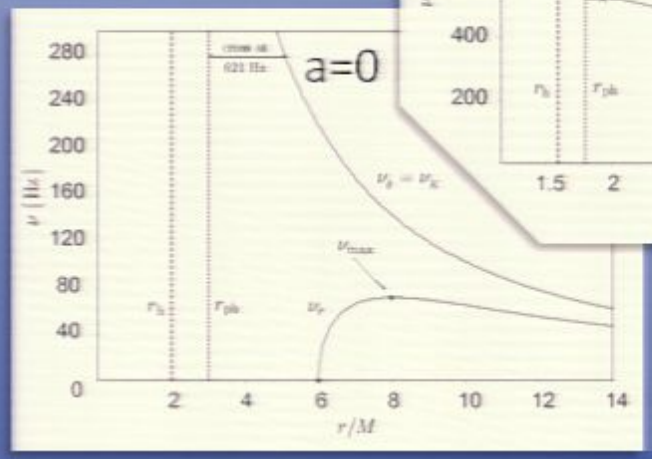

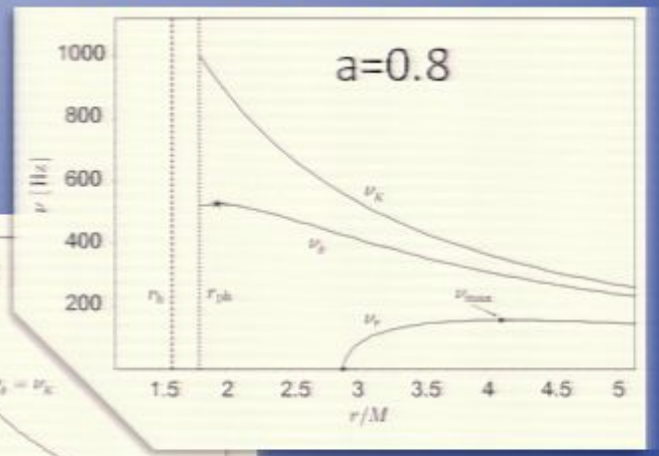

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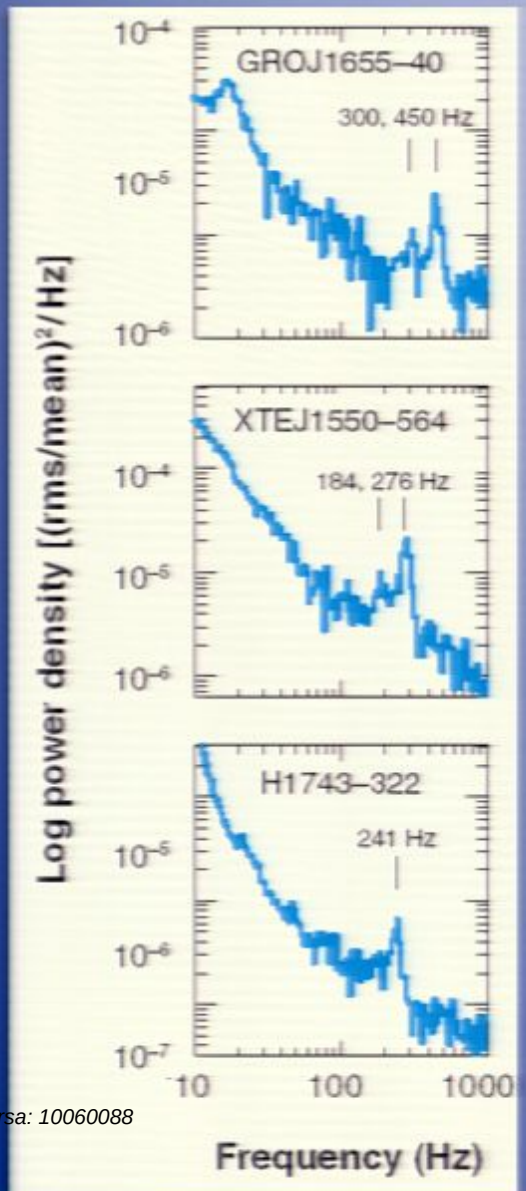

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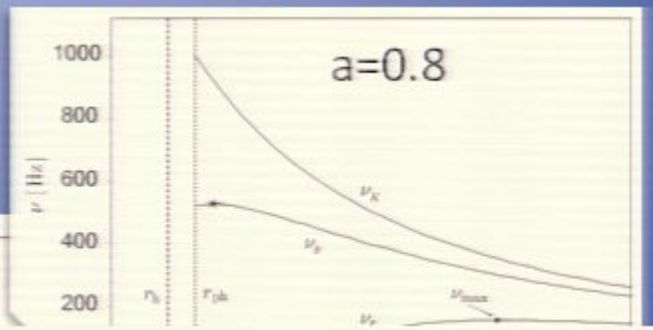

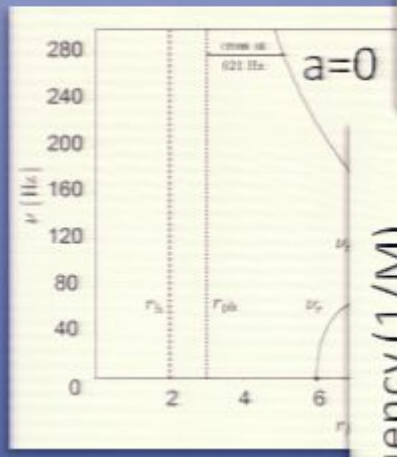

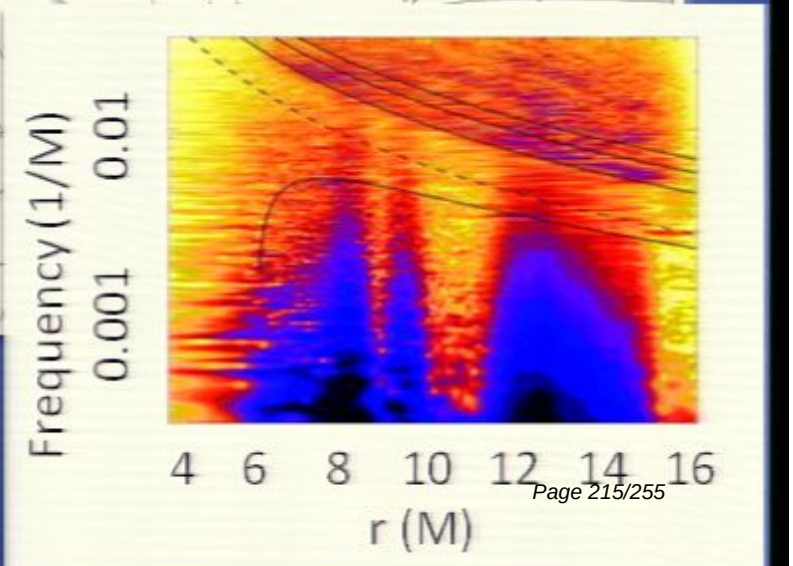

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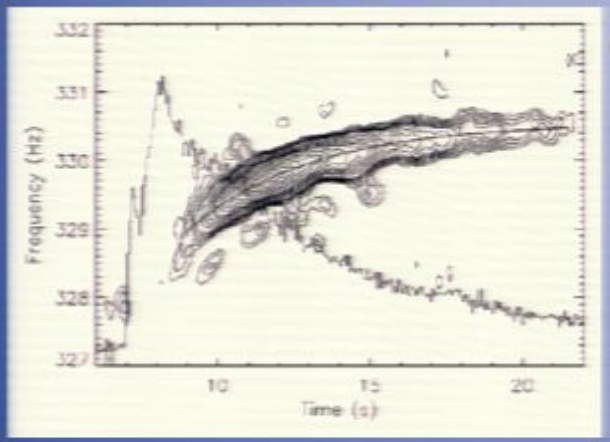

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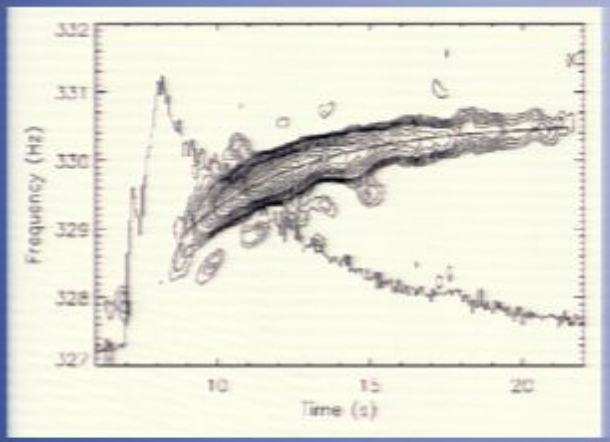
- NS QPOs:
  - Type-I X-ray burst QPOs → spin

Quasi-Periodic Oscillations



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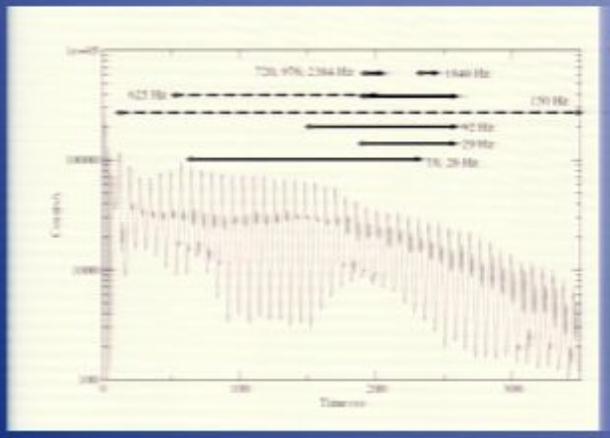

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Quasi-Periodic Oscillations

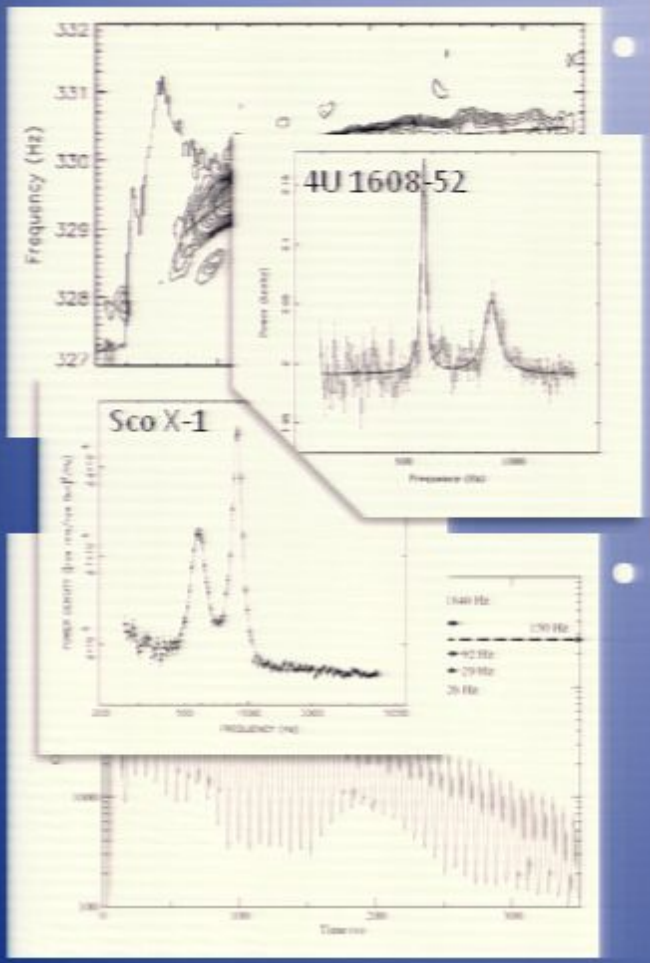

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TABLE 4 Commensurability of kHz QPO and burst oscillation frequencies

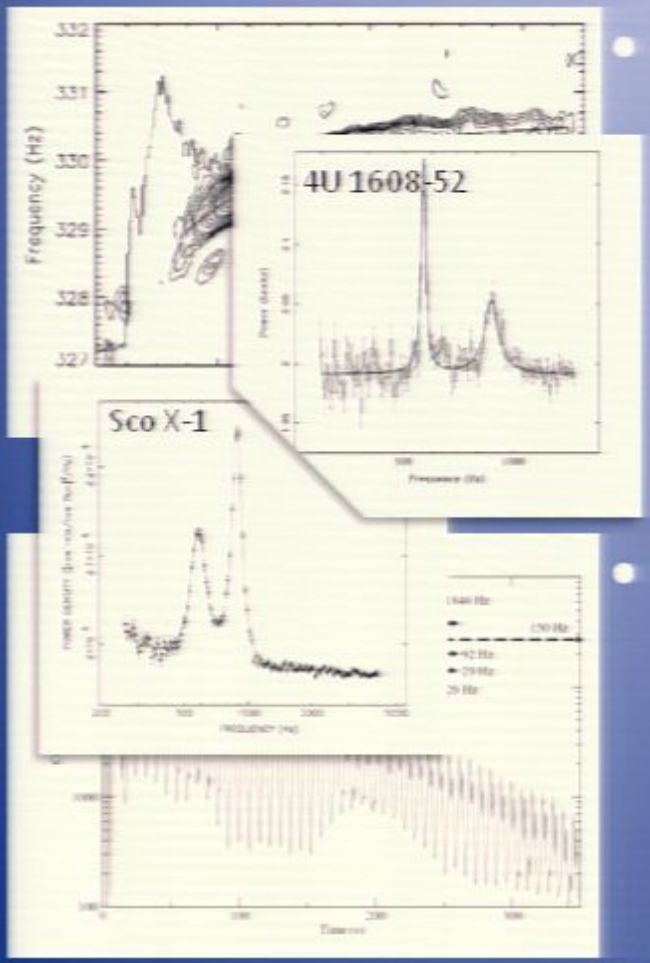
Source	Highest ν_{NS} (Hz)	Highest $\Delta\nu$ (Hz)	Ratio ($\nu_{NS}/\Delta\nu$)	Discrepancy (%)	References
4U 1702–43	330.55 ± 0.02	344 ± 7	0.96 ± 0.02	-4 ± 2	1
4U 1728–34	364.23 ± 0.05	349.3 ± 1.7	1.043 ± 0.005	$+4.3 \pm 0.5$	2
KS 1731–260	525.08 ± 0.18	260 ± 10	2.020 ± 0.078	$+1.0 \pm 3.8$	3, 6
Aql X-1	548.9	241 ± 9[1]	2.28 ± 0.09[1]	$+14 \pm 5$[1]	4
4U 1636–53	581.75 ± 0.13	254 ± 5	2.29 ± 0.04	$+15 \pm 2$	5

[1]Based on a marginal detection (see Table 3). References: (1) Markwardt et al 1999a; (2) Méndez & van der Klis 1999; (3) Wijnands & van der Klis 1997; (4) M Méndez et al 1999, in preparation; (5) Méndez et al 1998c; (6) Mumo et al 2000.

- NS QPOs: van der Klis (2000)
  - Type-I X-ray burst QPOs → spin
  - Giant Flare QPOs → crustal modes?
  - kHz QPOs → similar to BHs?

Variability

Quasi-Periodic Oscillations



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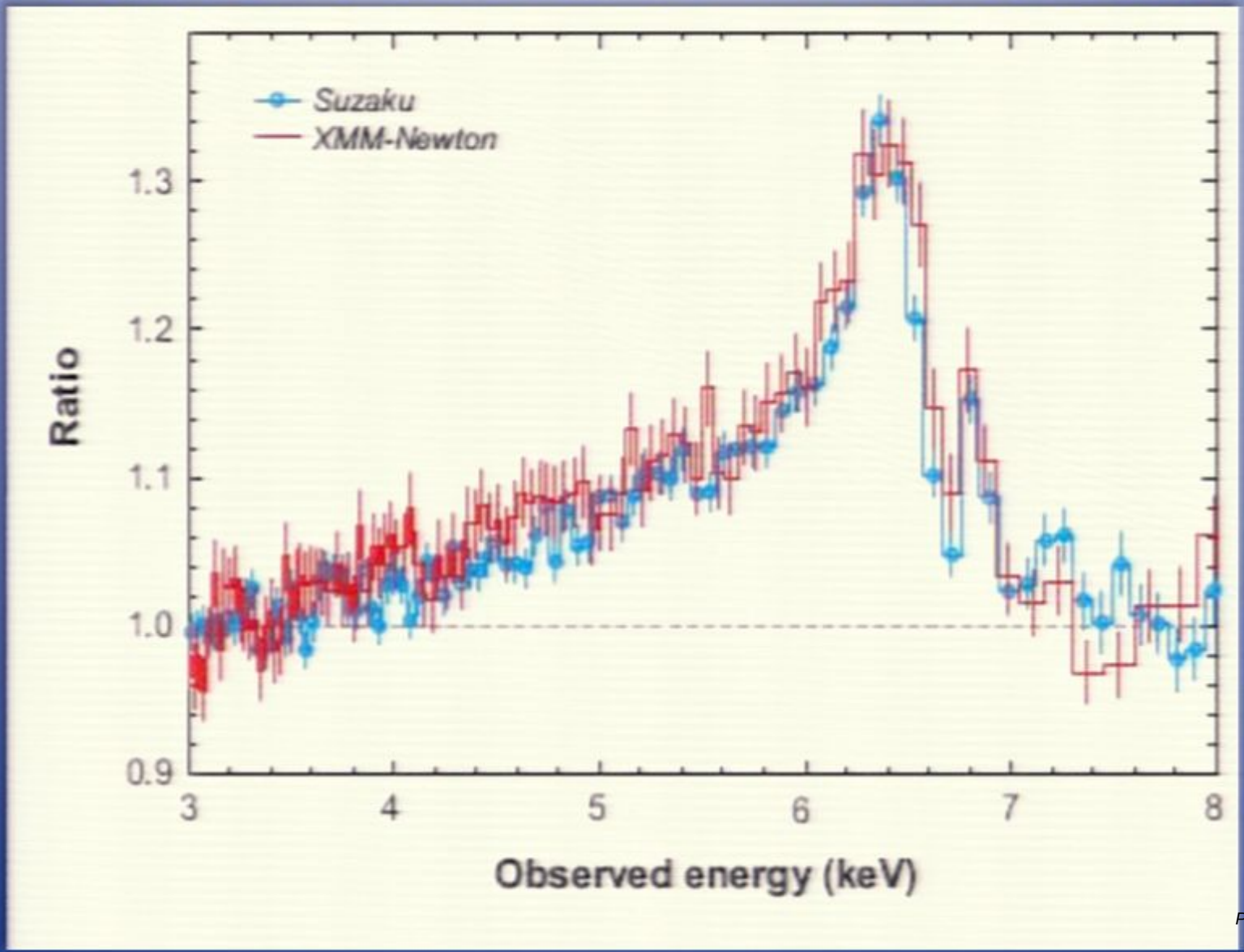
  - kHz QPOs → similar to BHs?
- Rapidly rotating NSs are macroscopic manifestations of spin-½ spinors!

Time Variable Iron lines



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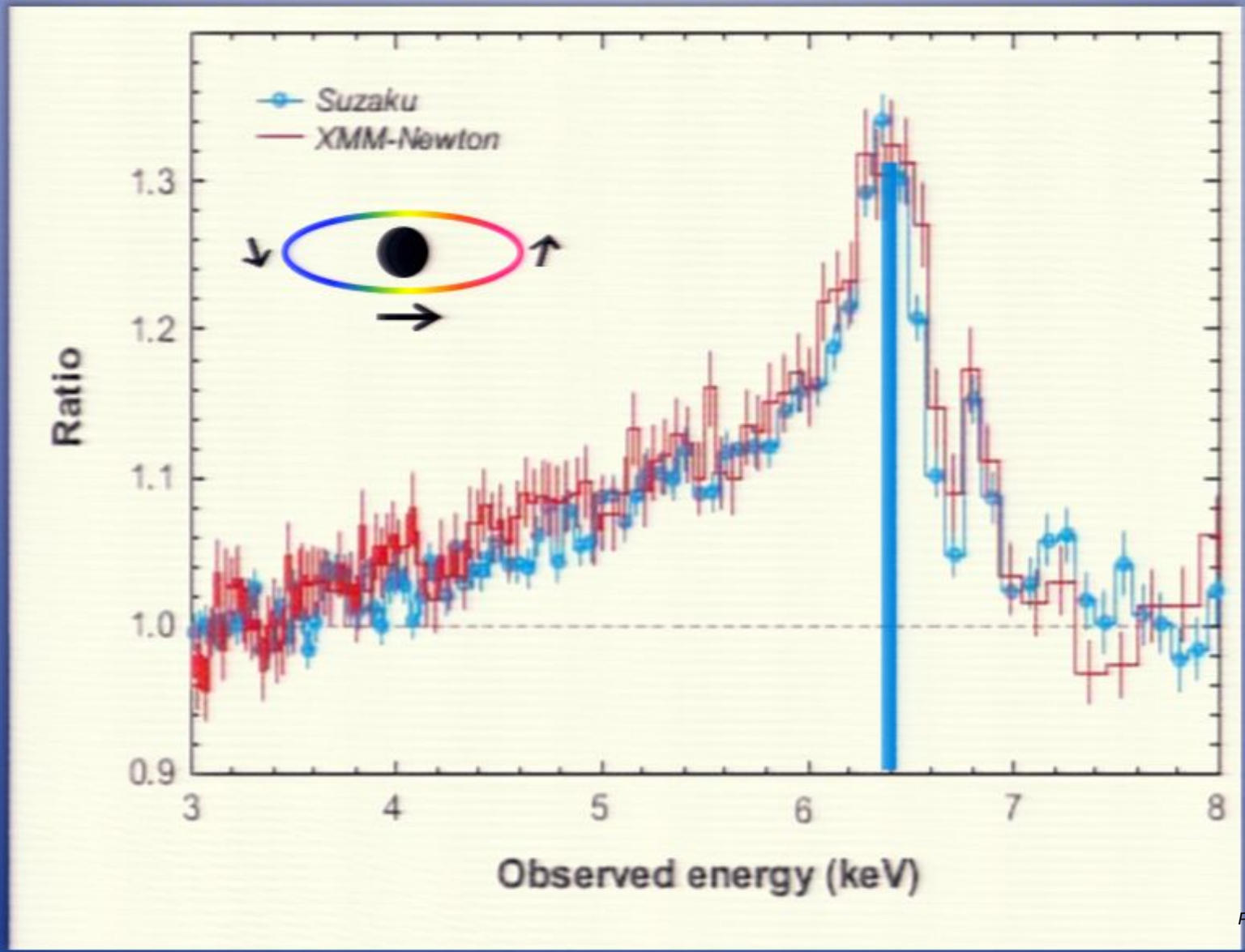

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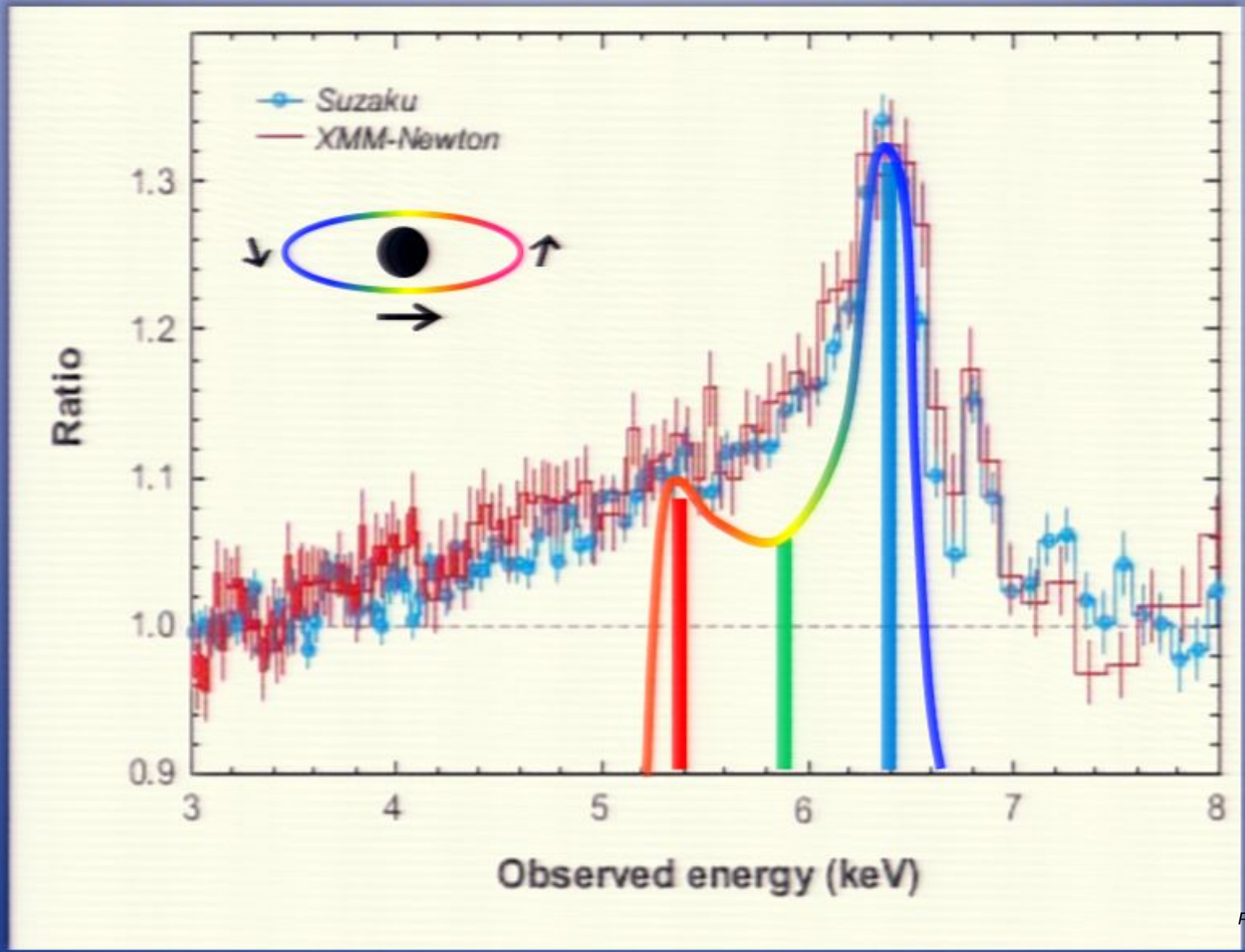
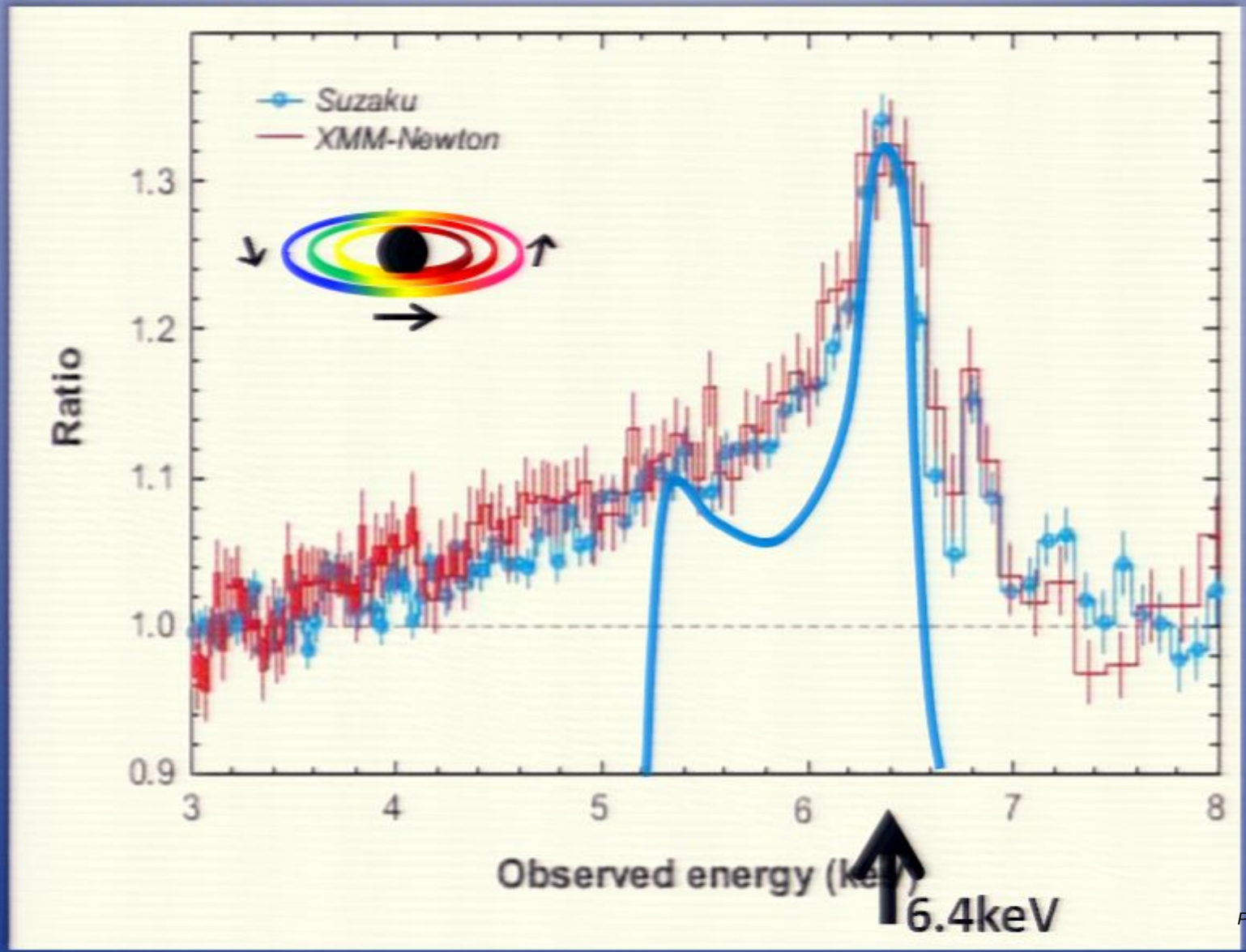
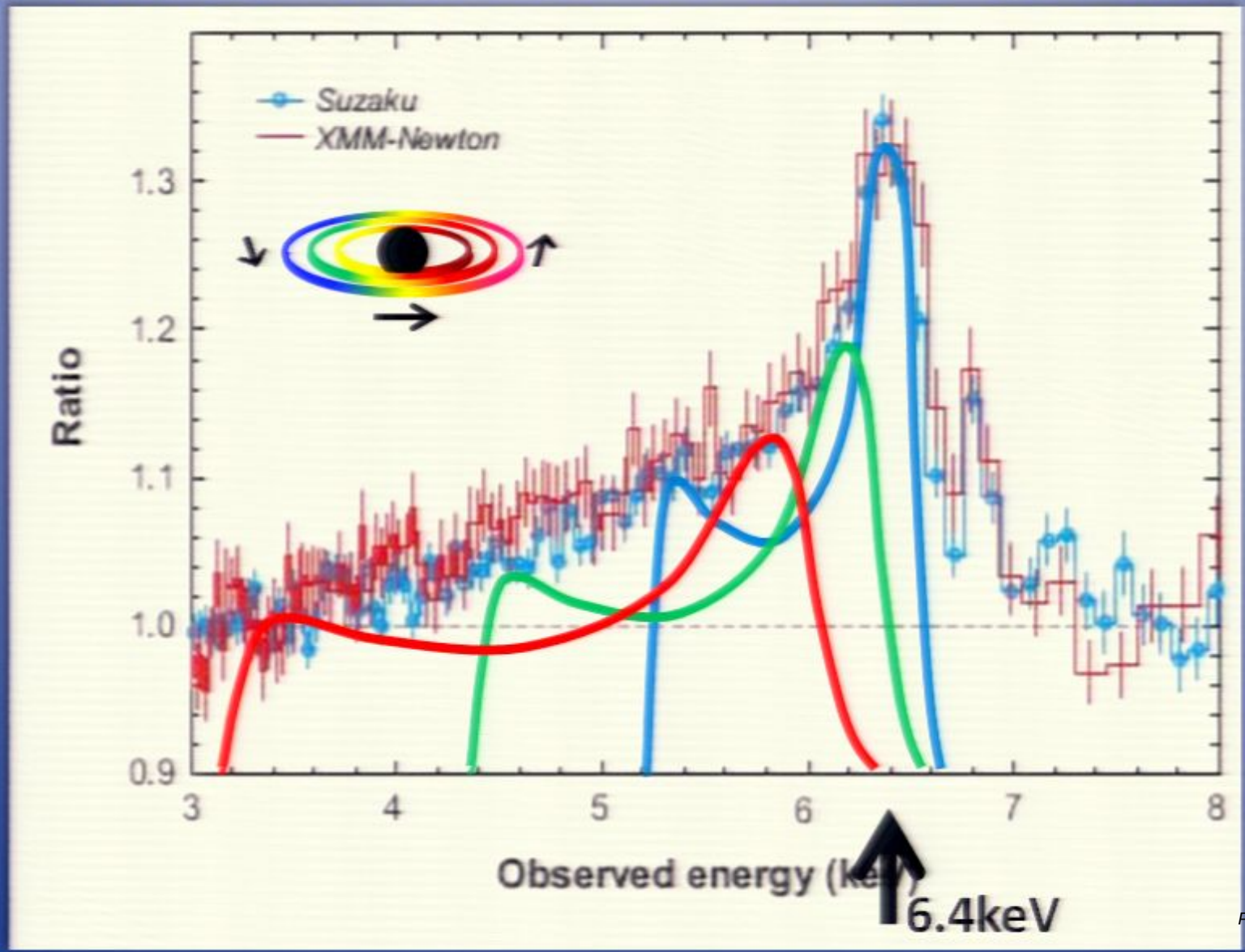


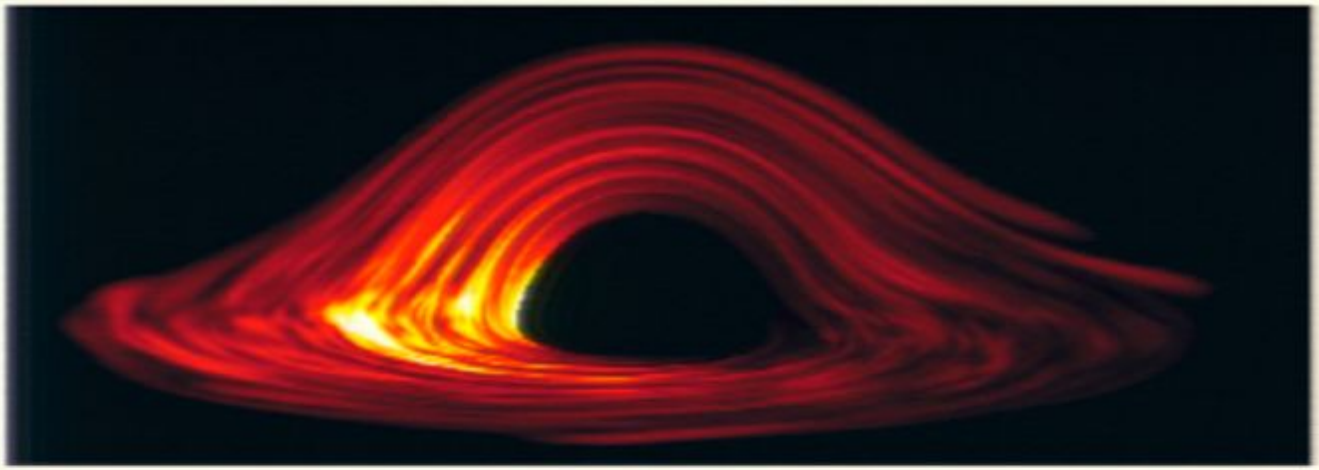
Time Variable Iron lines

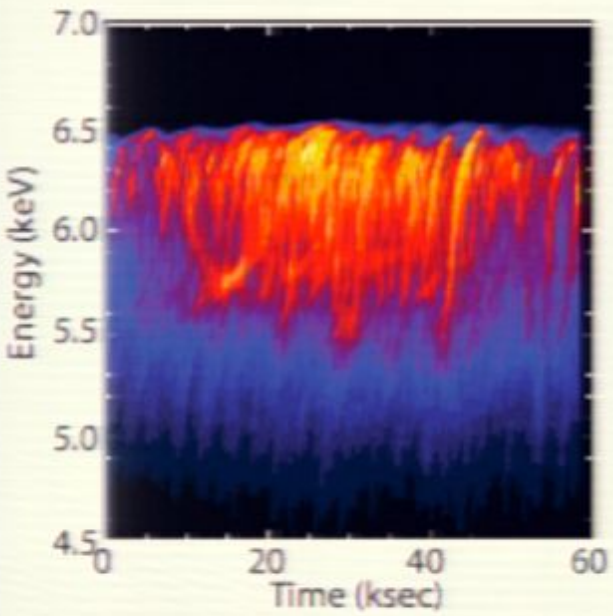


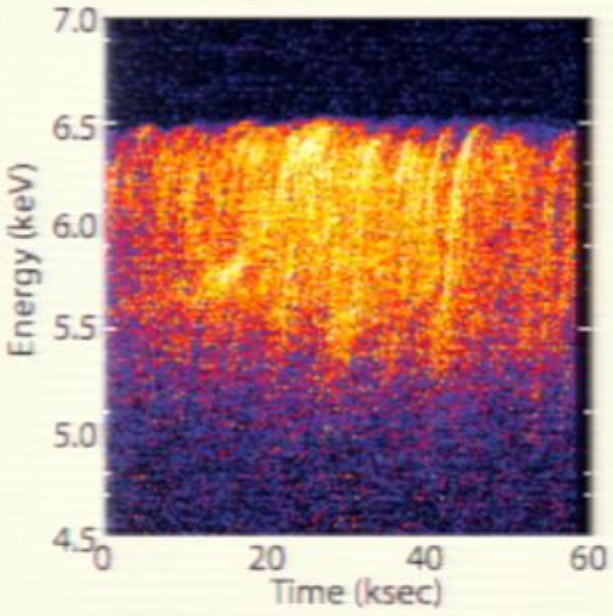
Time Variable Iron lines



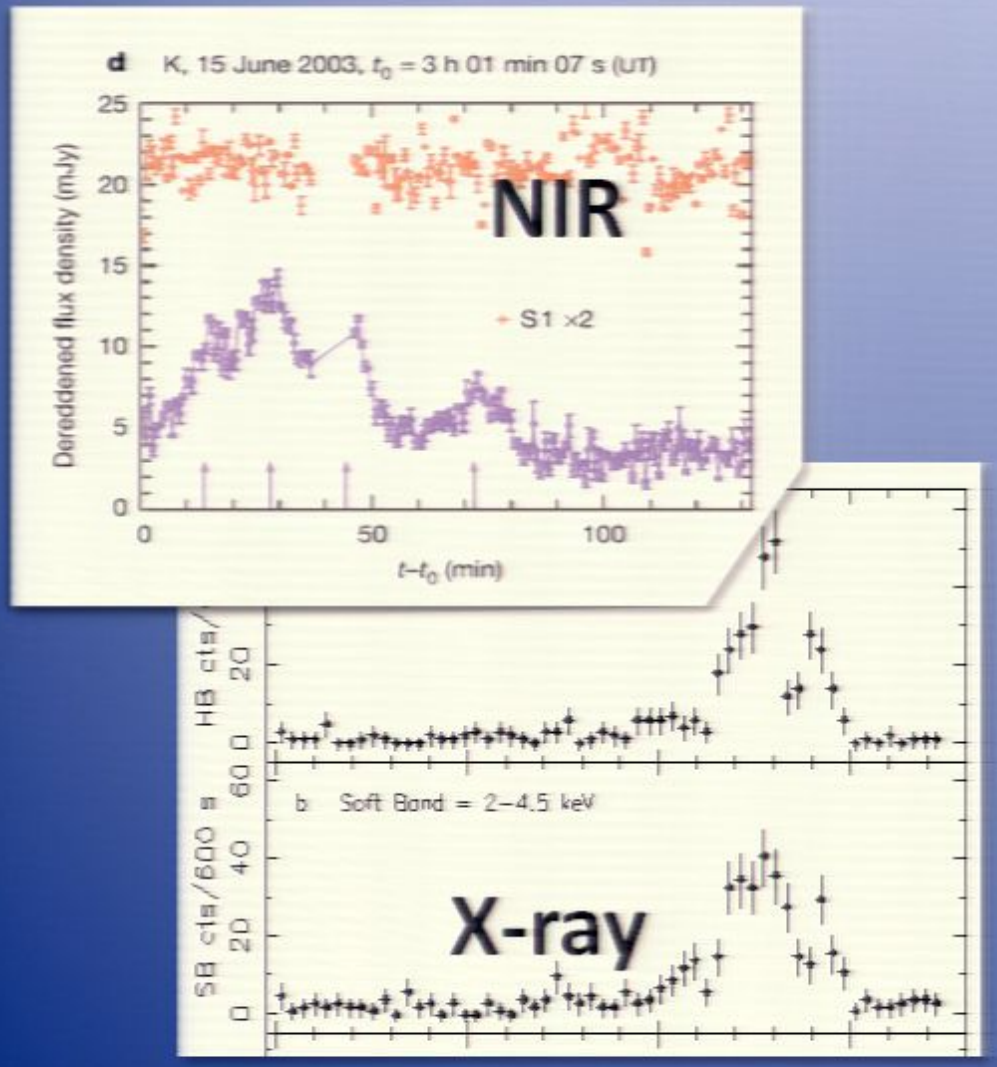
Time Variable Iron lines





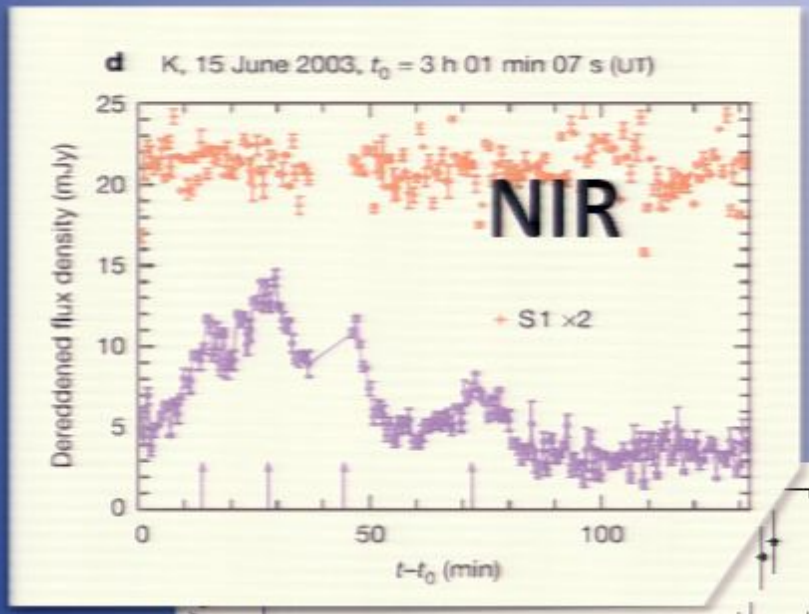


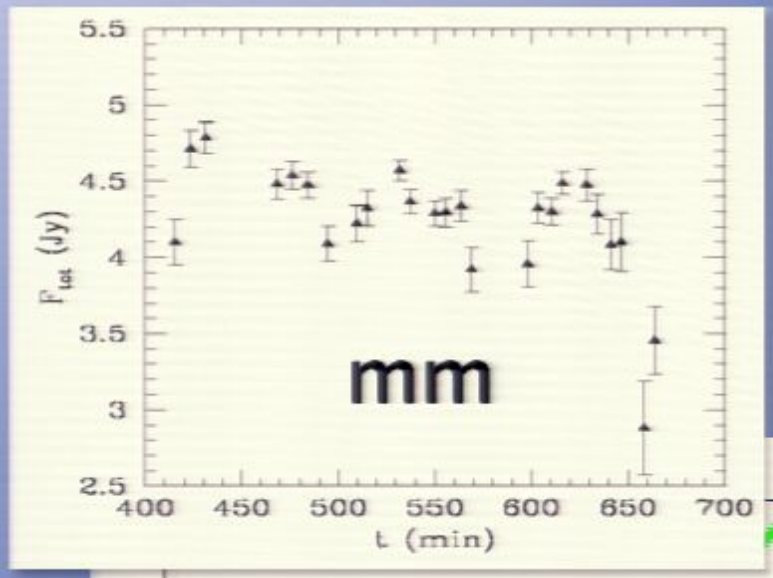
"QPOs" in Sgr A*

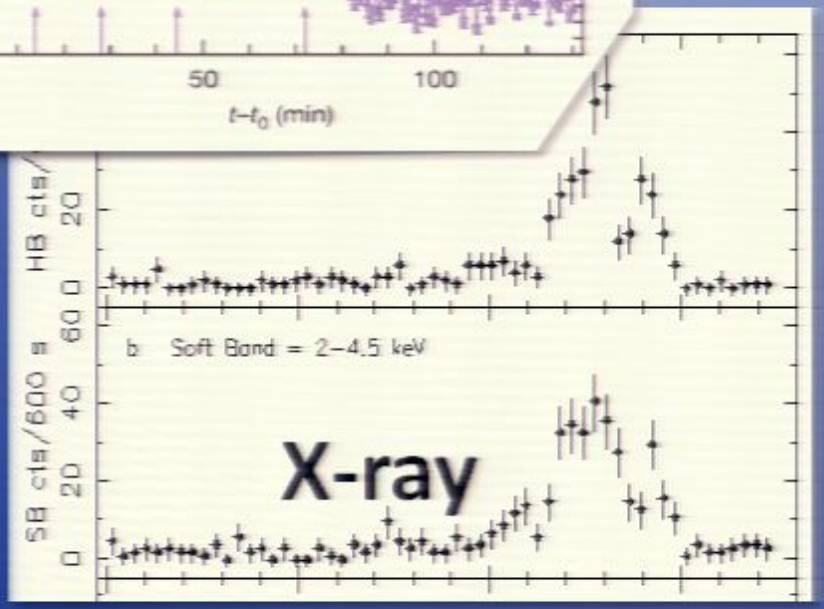

d
K, 15 June 2003, t_0 = 3 h 01 min 07 s (UT)
Dereddened flux density (mJy)
25
20
15
10
5
0
0
50
100
$t-t_0$ (min)
NIR
S1 ×2
HB cts/
20
0
b Soft Band = 2–4.5 keV
SB cts/600 s
60
40
20
0
X-ray

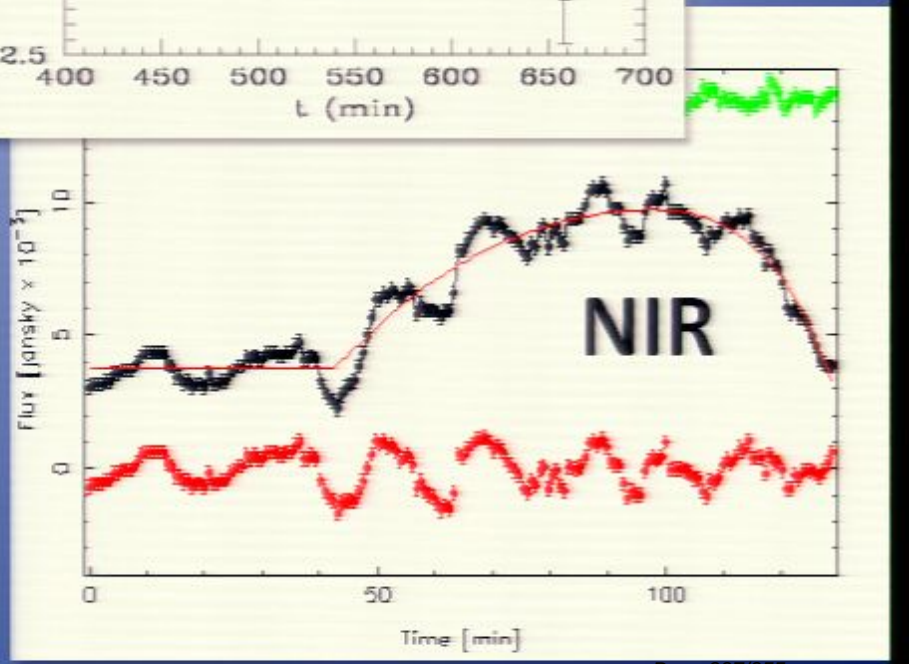
Variability

"QPOs" in Sgr A*



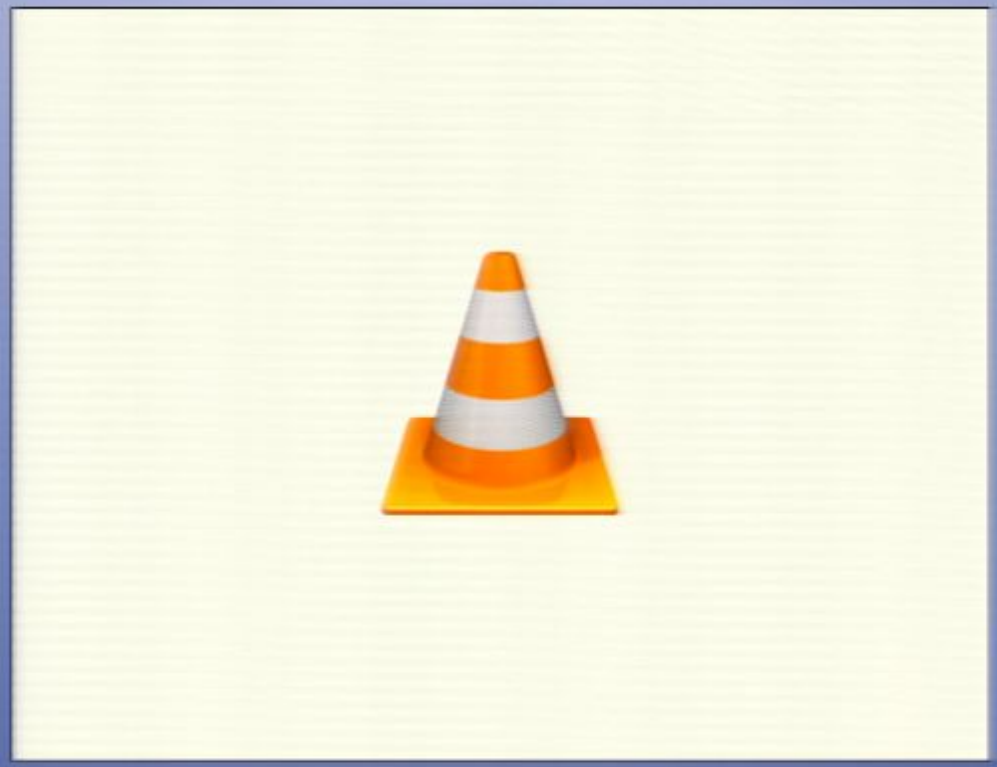






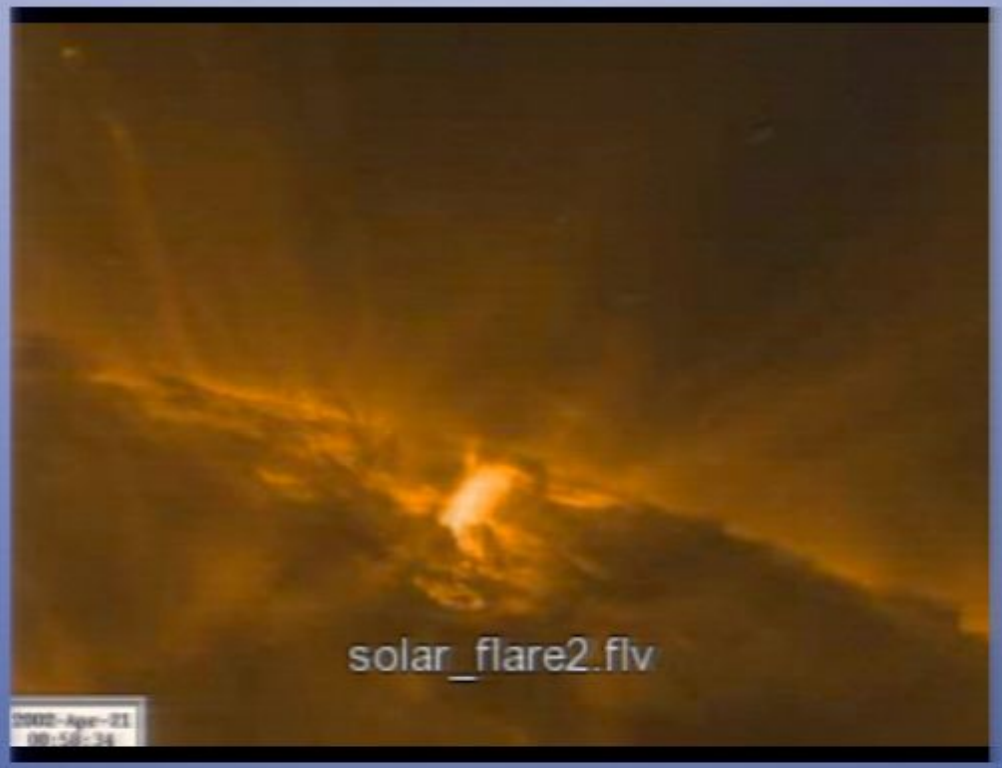
Variability

Wagging the Sun



- Rapid magnetic → nonthermal e^- conversion
- Trapped on magnetic field lines

Wagging the Sun



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Variability

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Variability

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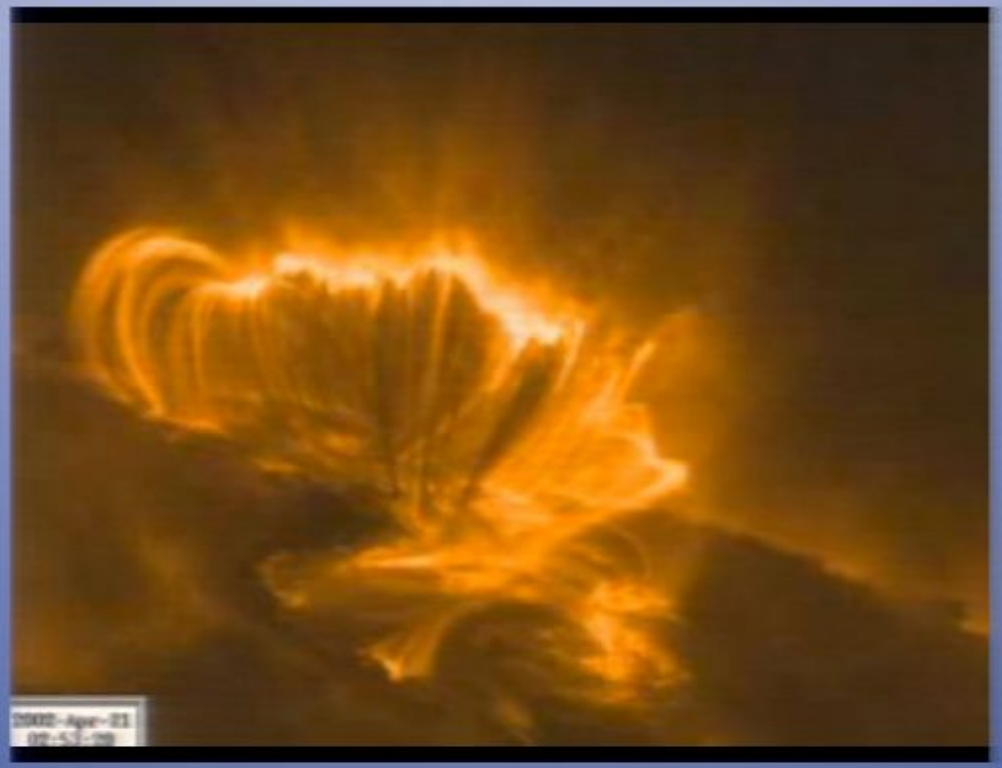

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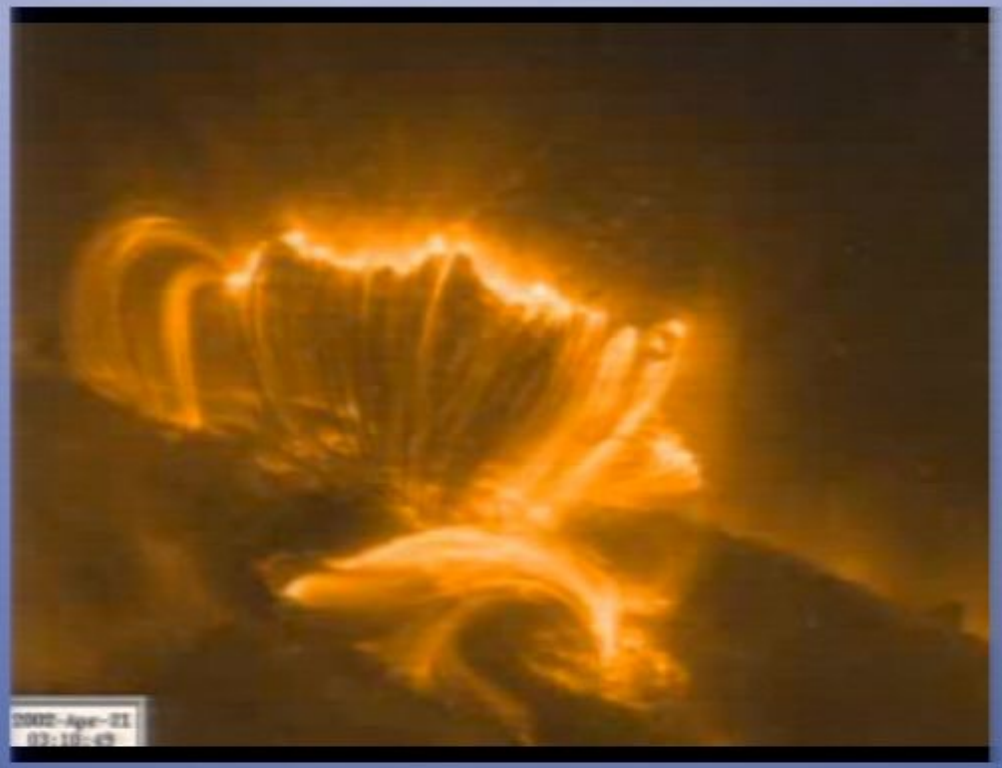
Variability

Wagging the Sun



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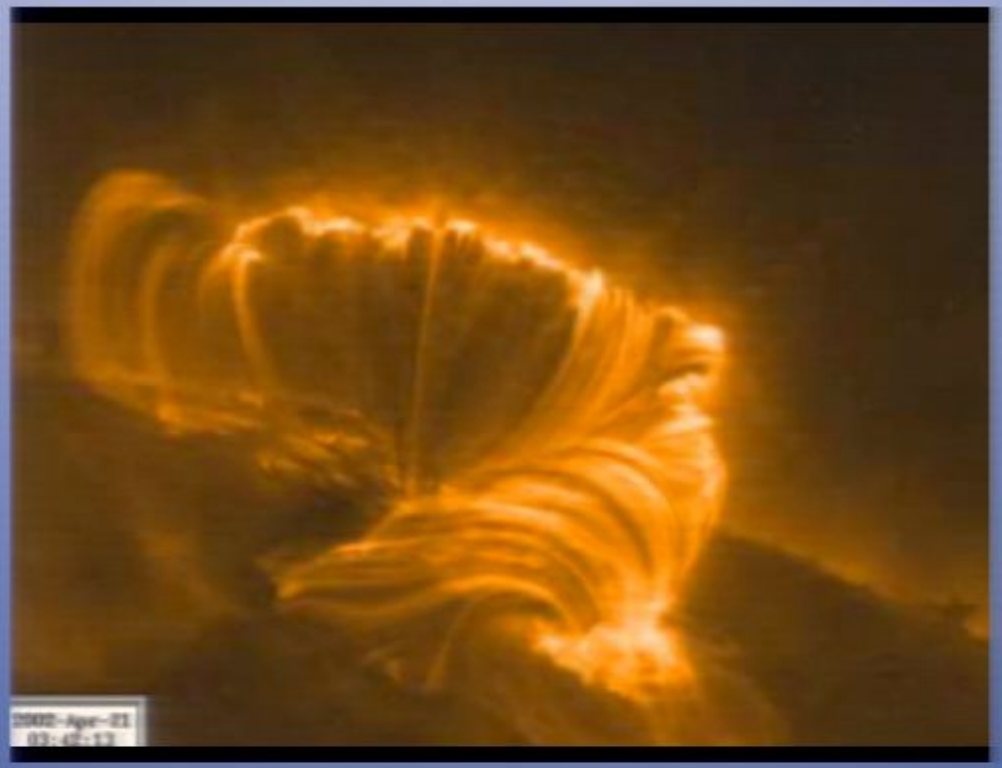
Variability

Wagging the Sun



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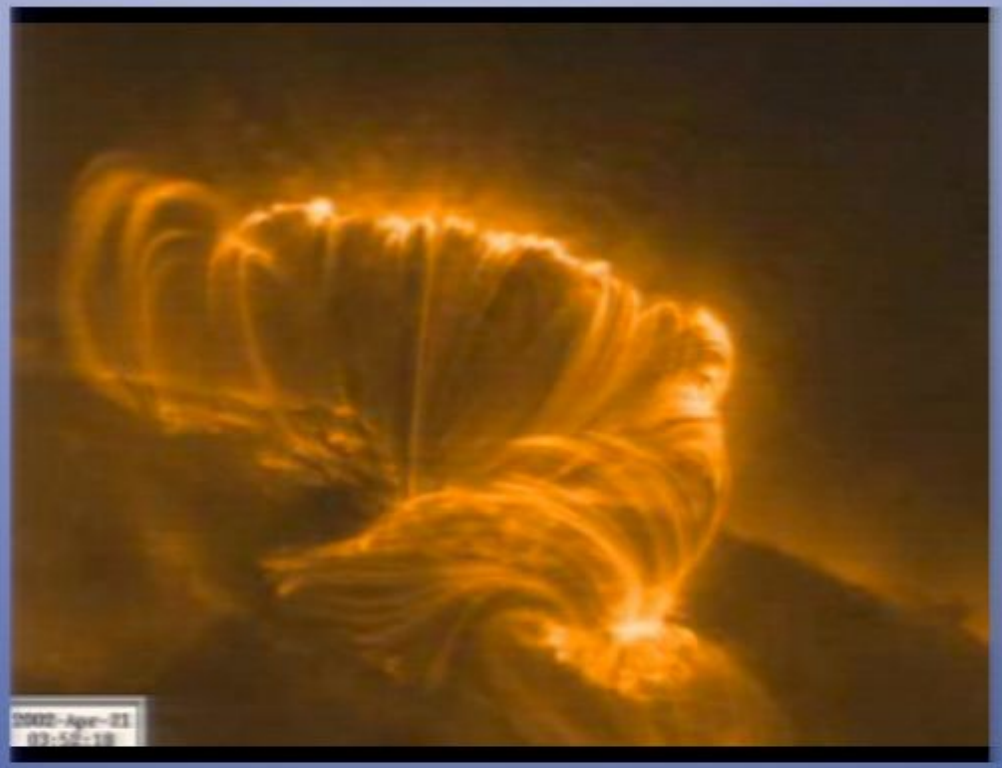

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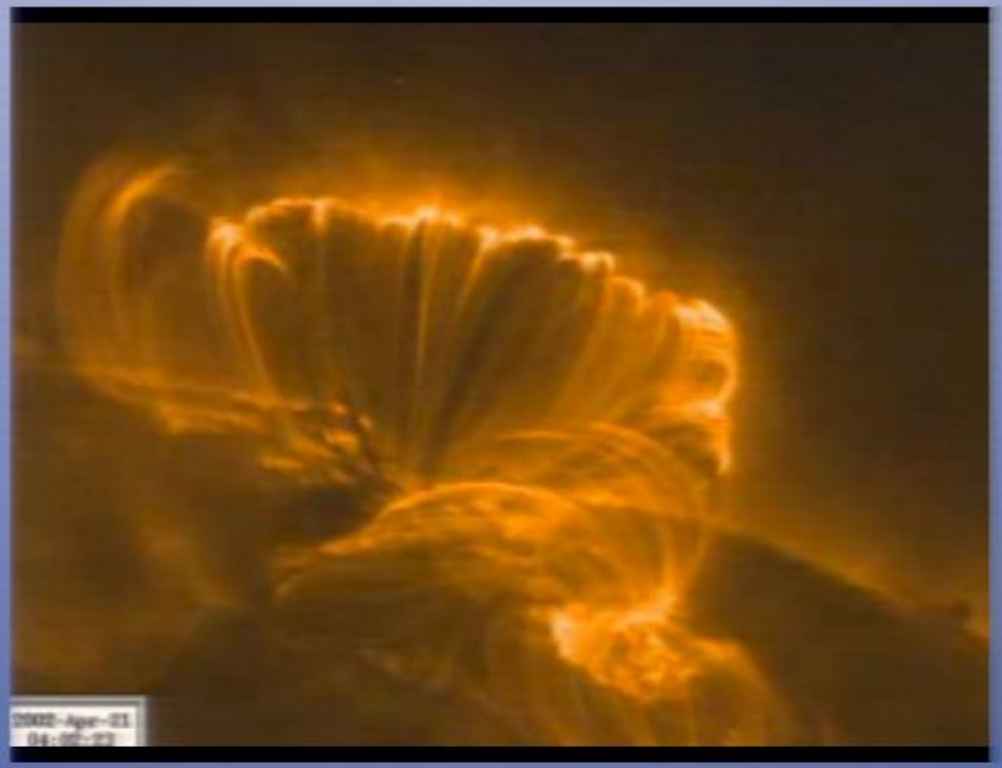
Wagging the Sun



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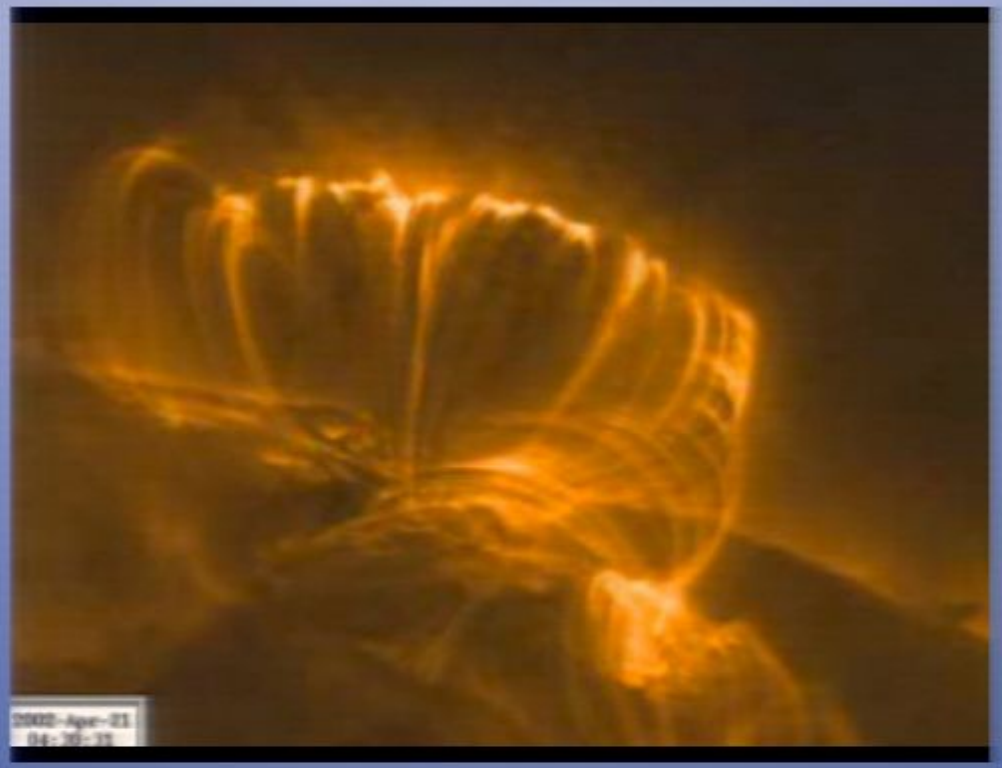
Wagging the Sun



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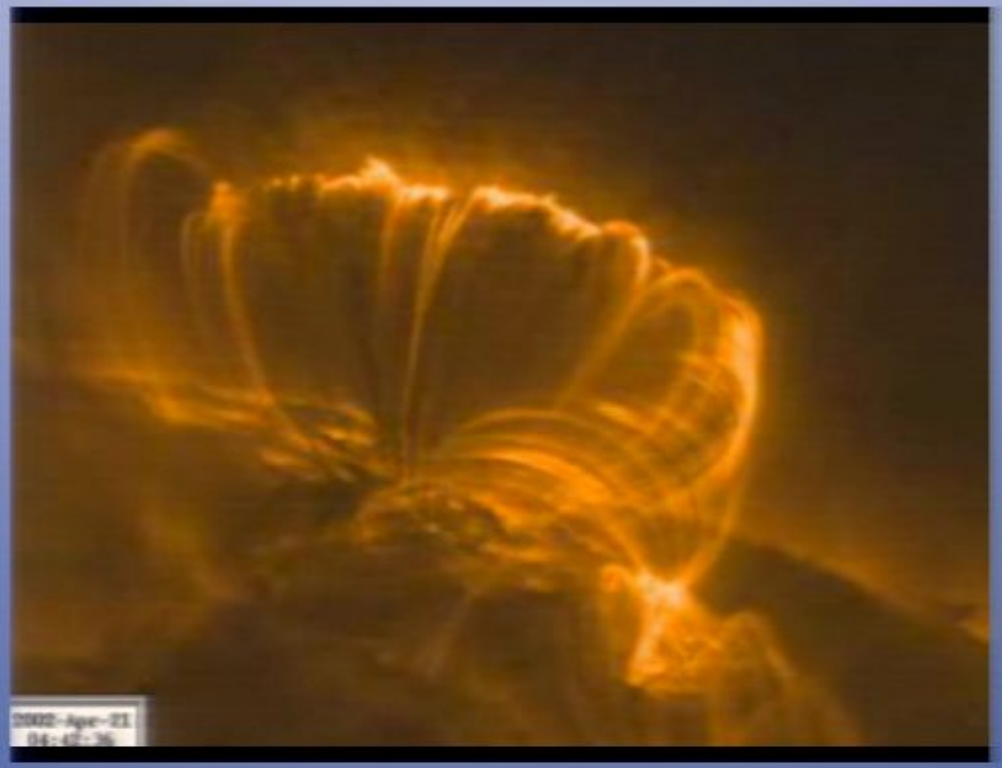
Variability

Wagging the Sun



- Rapid magnetic → nonthermal e^- conversion
- Trapped on magnetic field lines

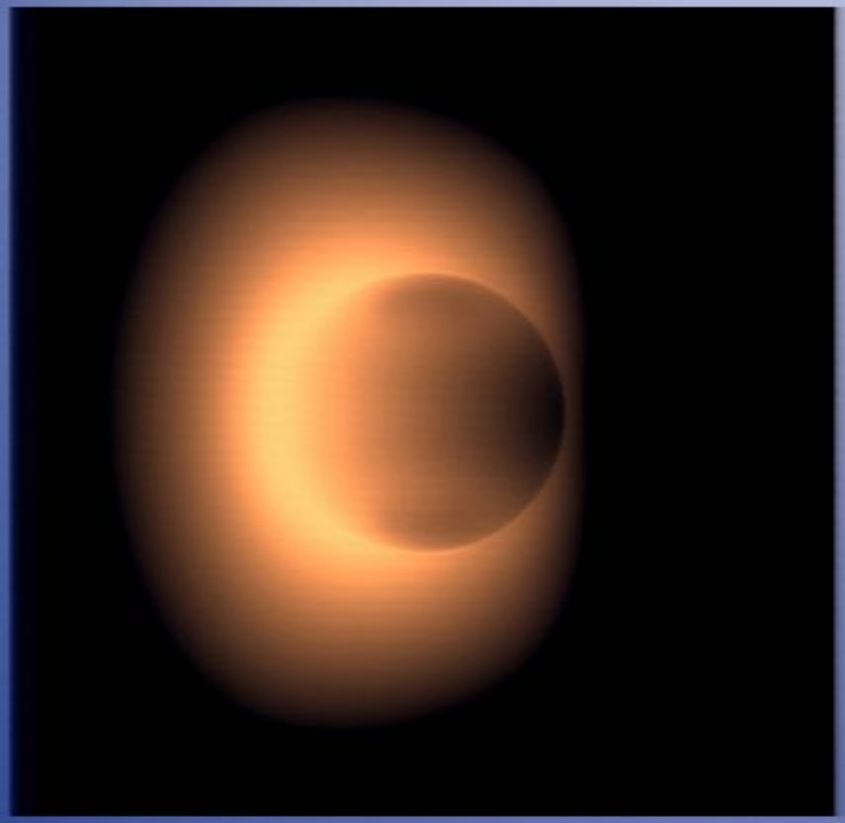
Variability

Wagging Sgr A*

- Electrons are subdominant → localized
- Electrons radiate rapidly → bright
- Small spots are long lived

Variability

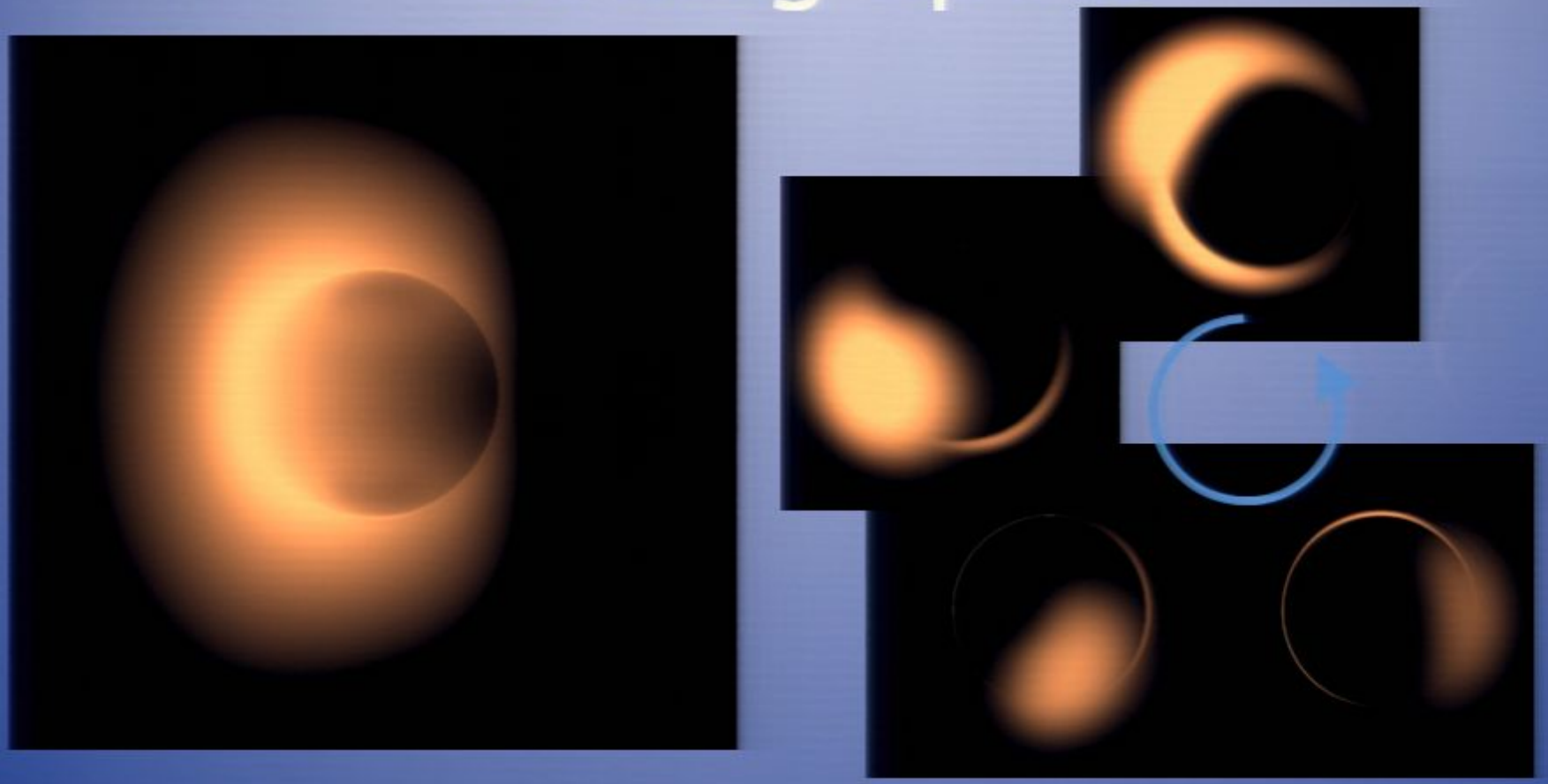
Seeing Spots



- Degenerate vs. Temporally separated

Variability

Seeing Spots



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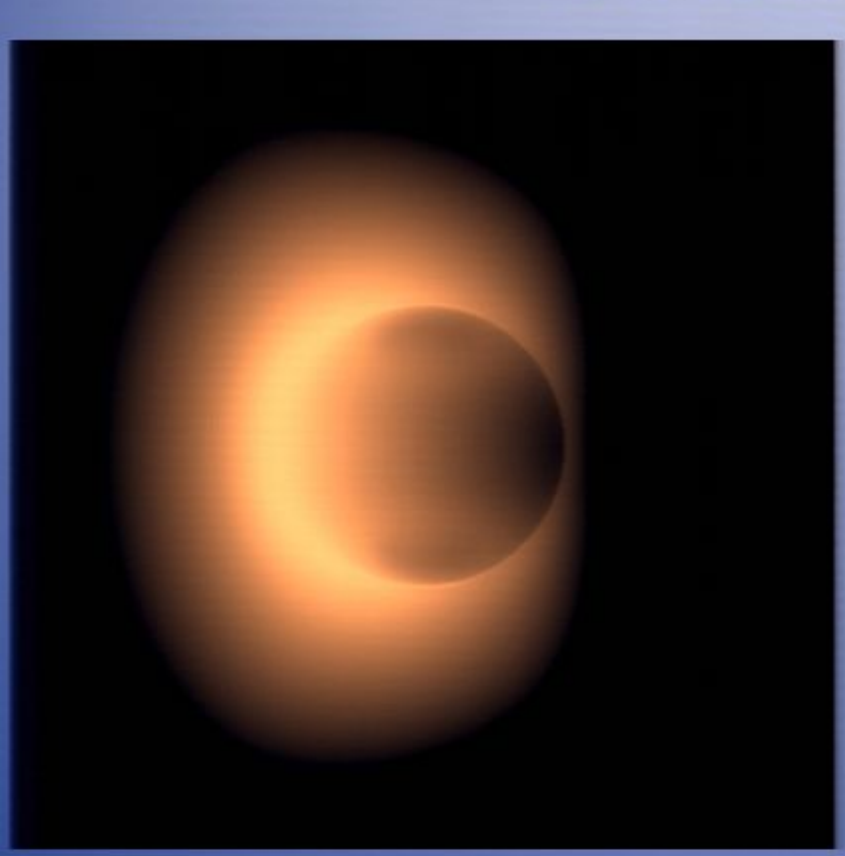
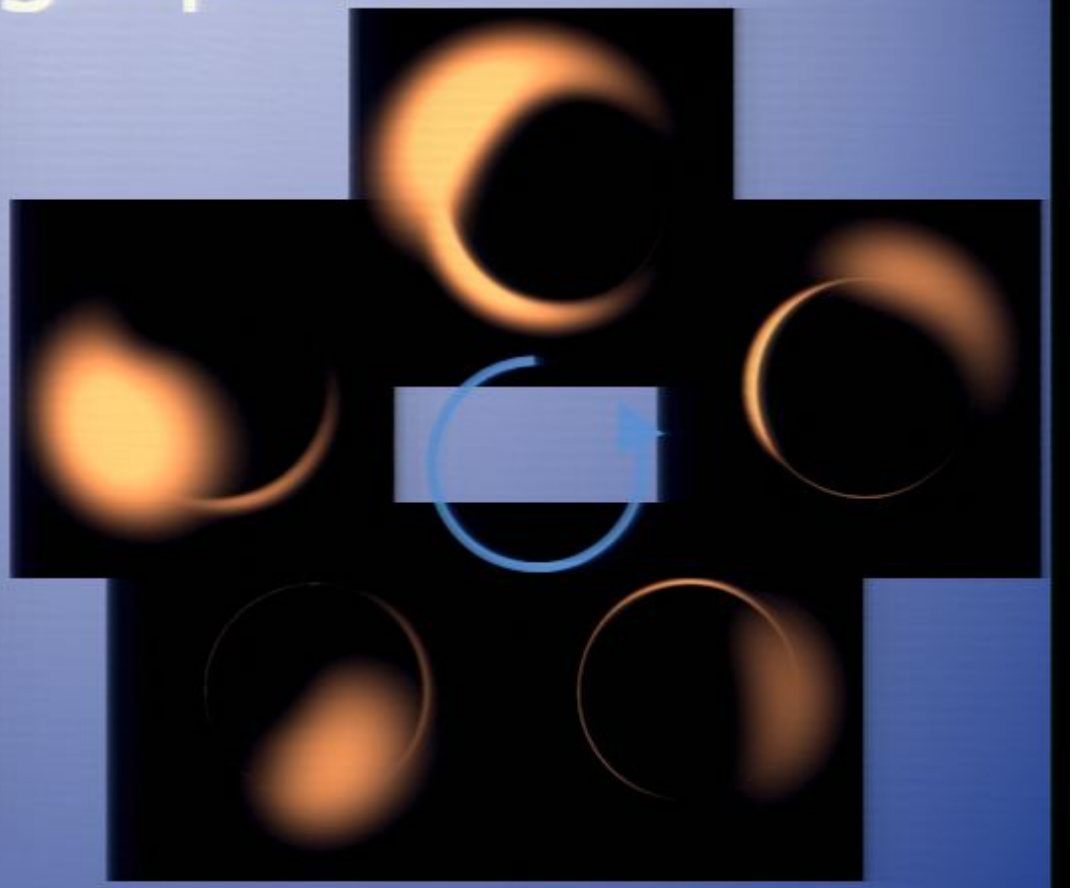
Variability

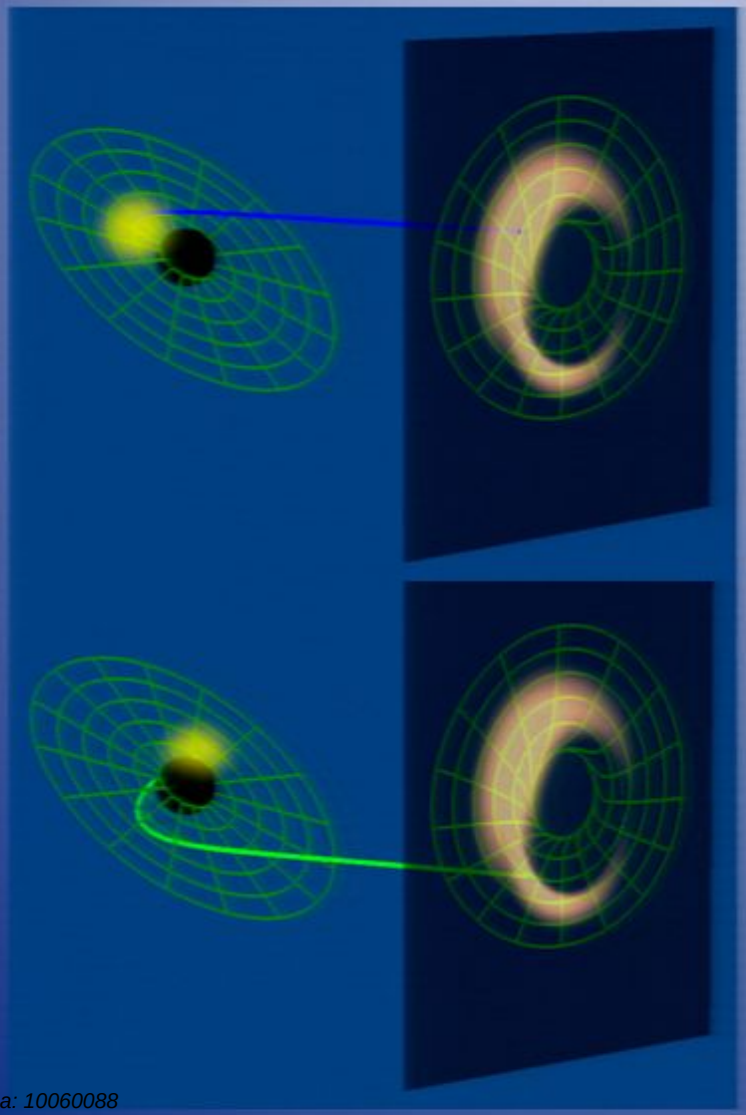
Seeing Spots





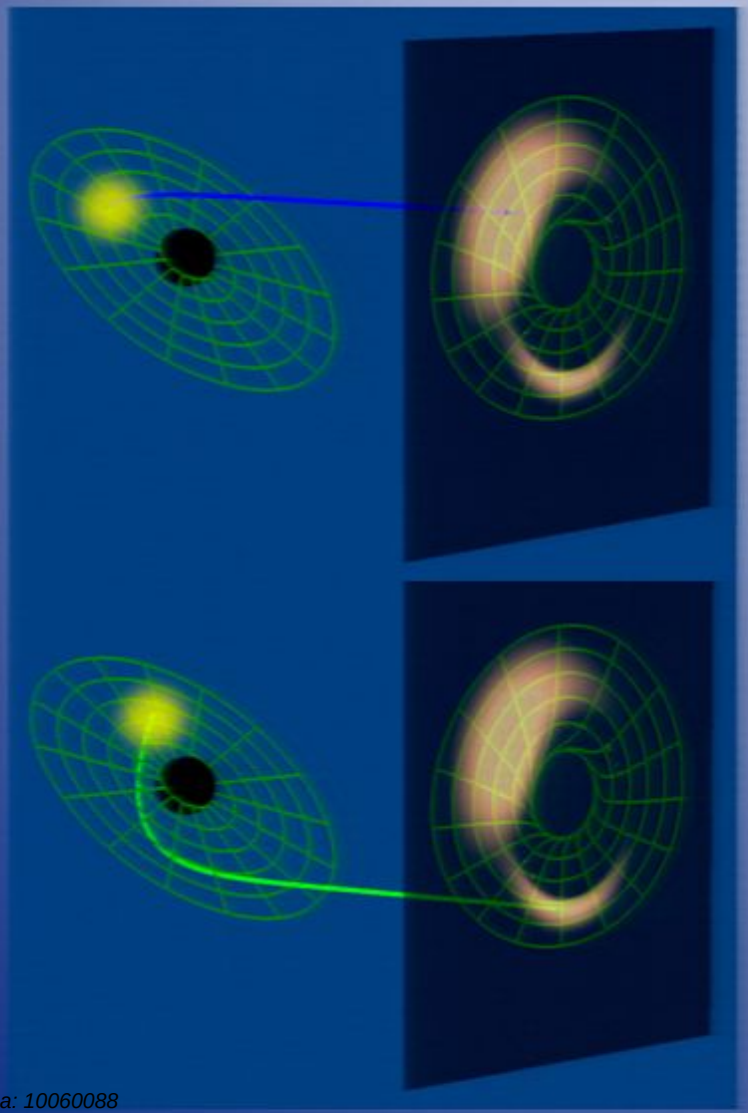
- Degenerate vs. Temporally separated

Multiple Spots as EMRIs



- Different spots probe different regions.
- Comparing many images → Test no hair + Kerr

Multiple Spots as EMRIs



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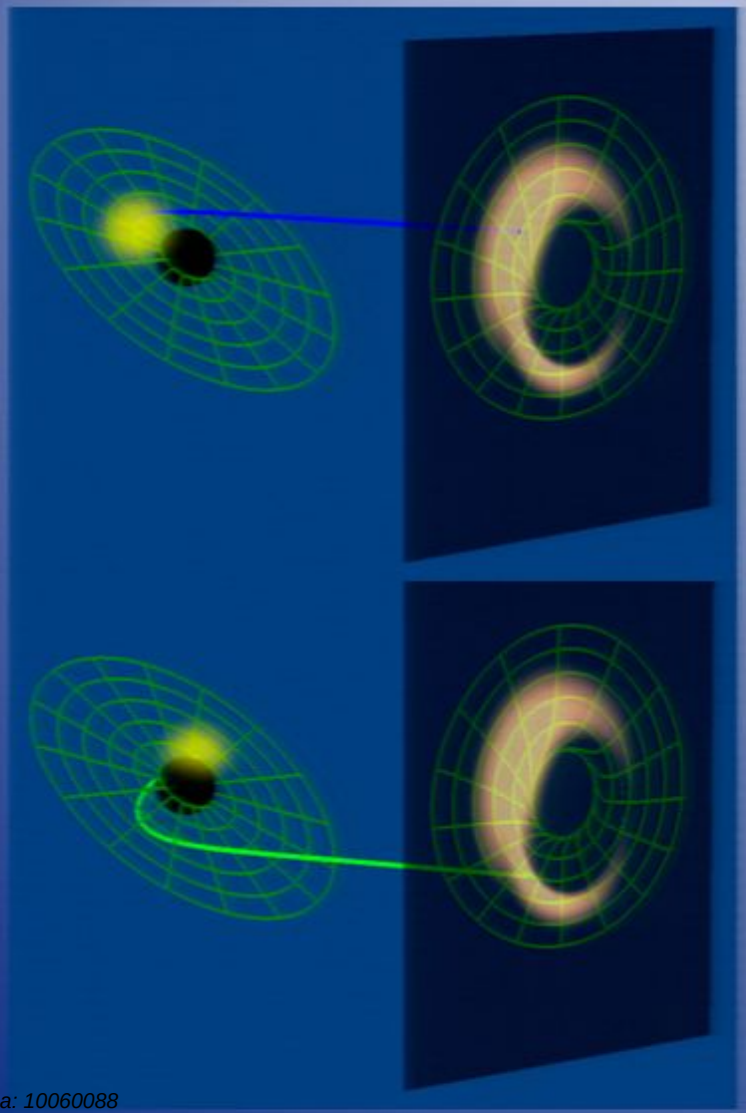

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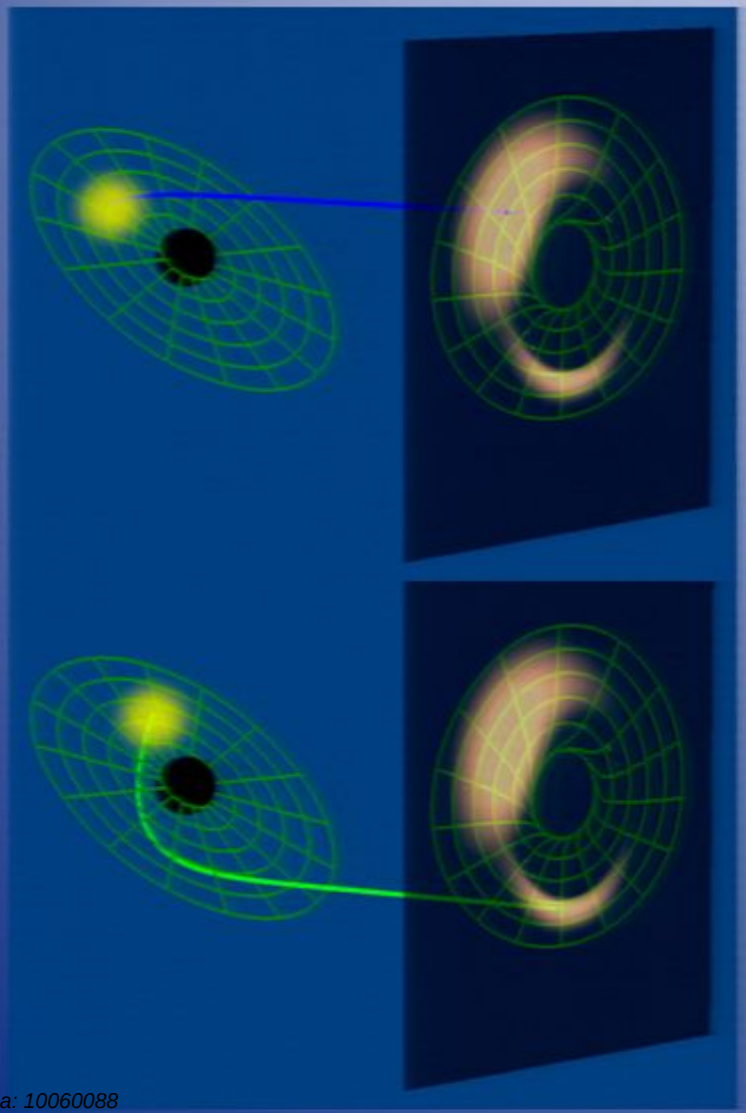
Multiple Spots as EMRIs



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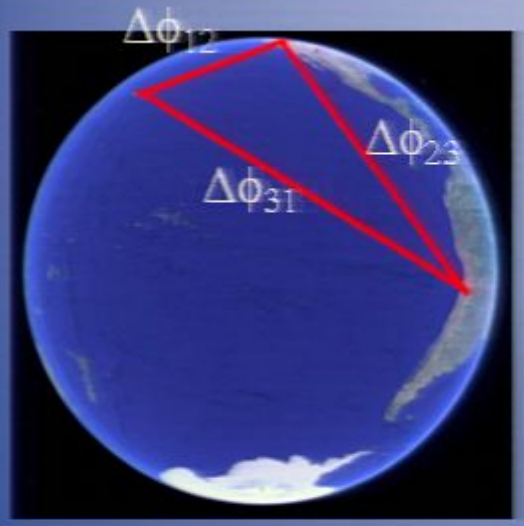
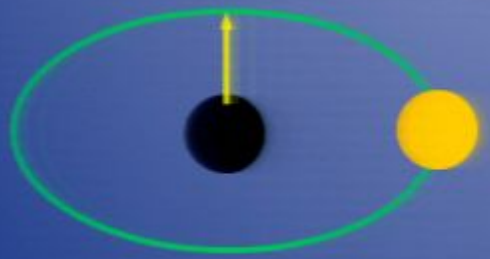
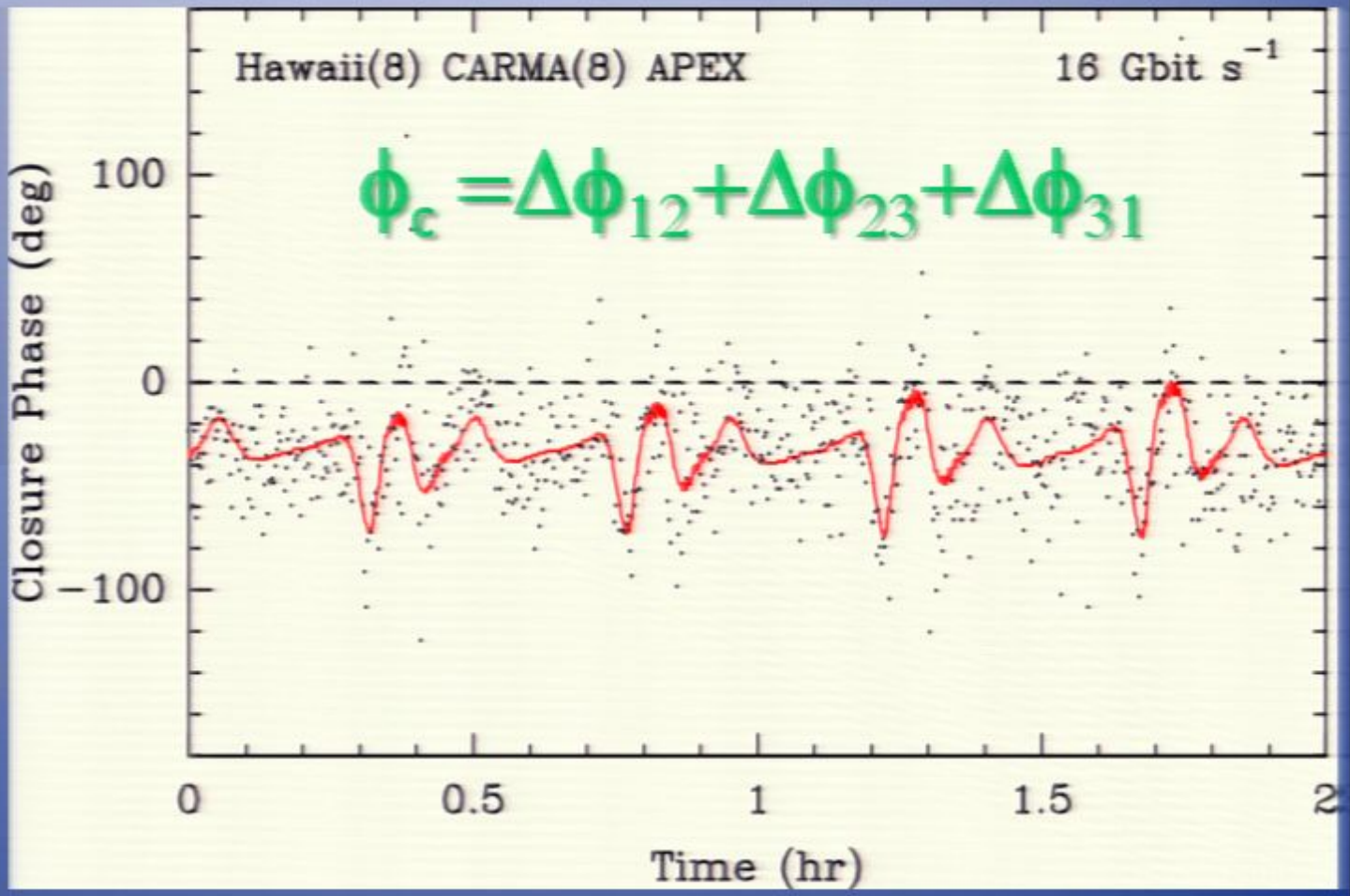
Detecting Spots

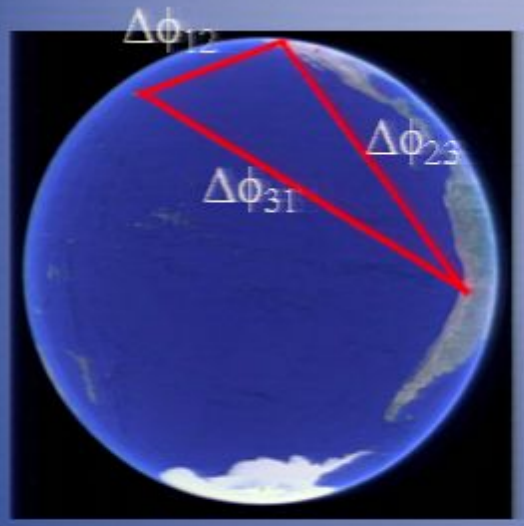


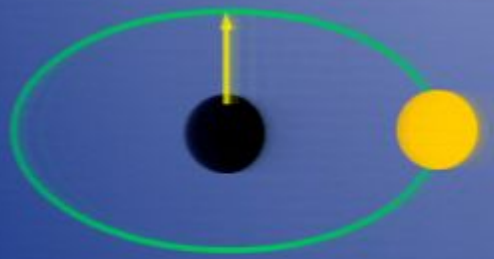


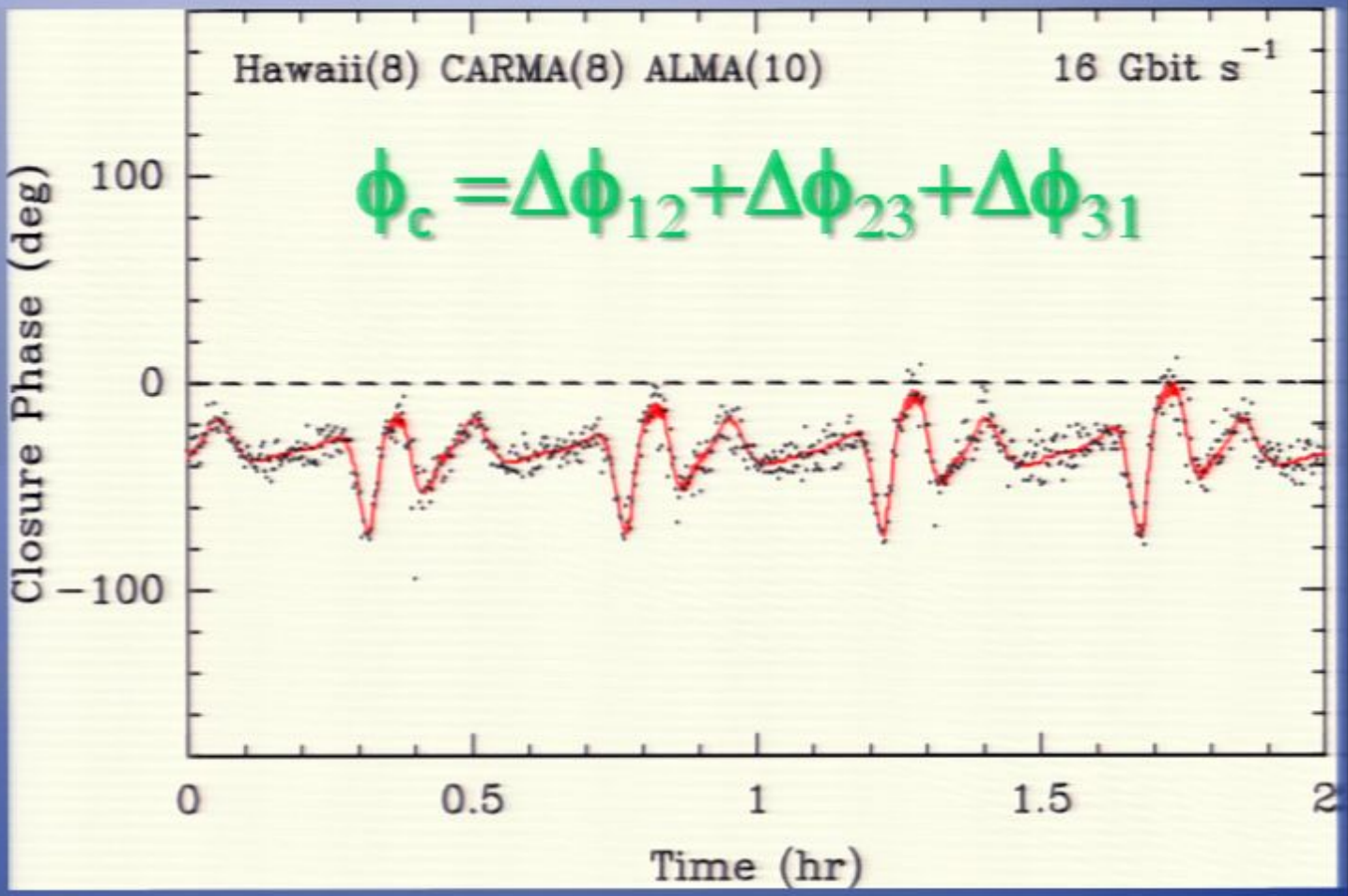


Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

Detecting Spots

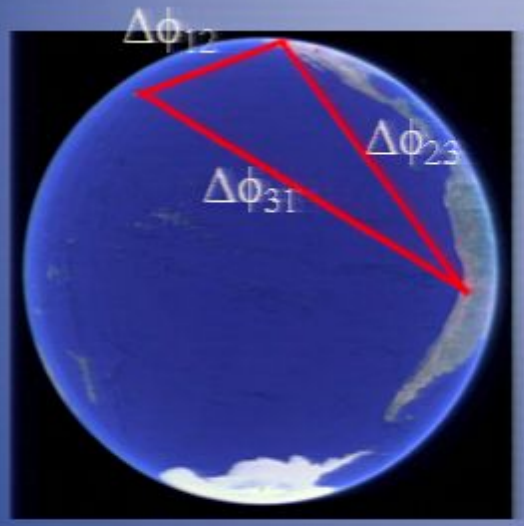


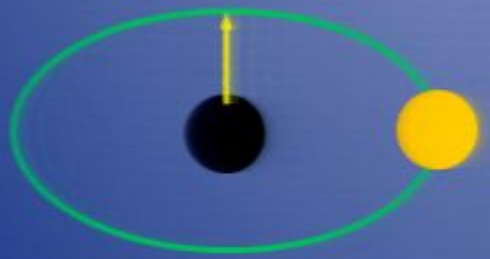


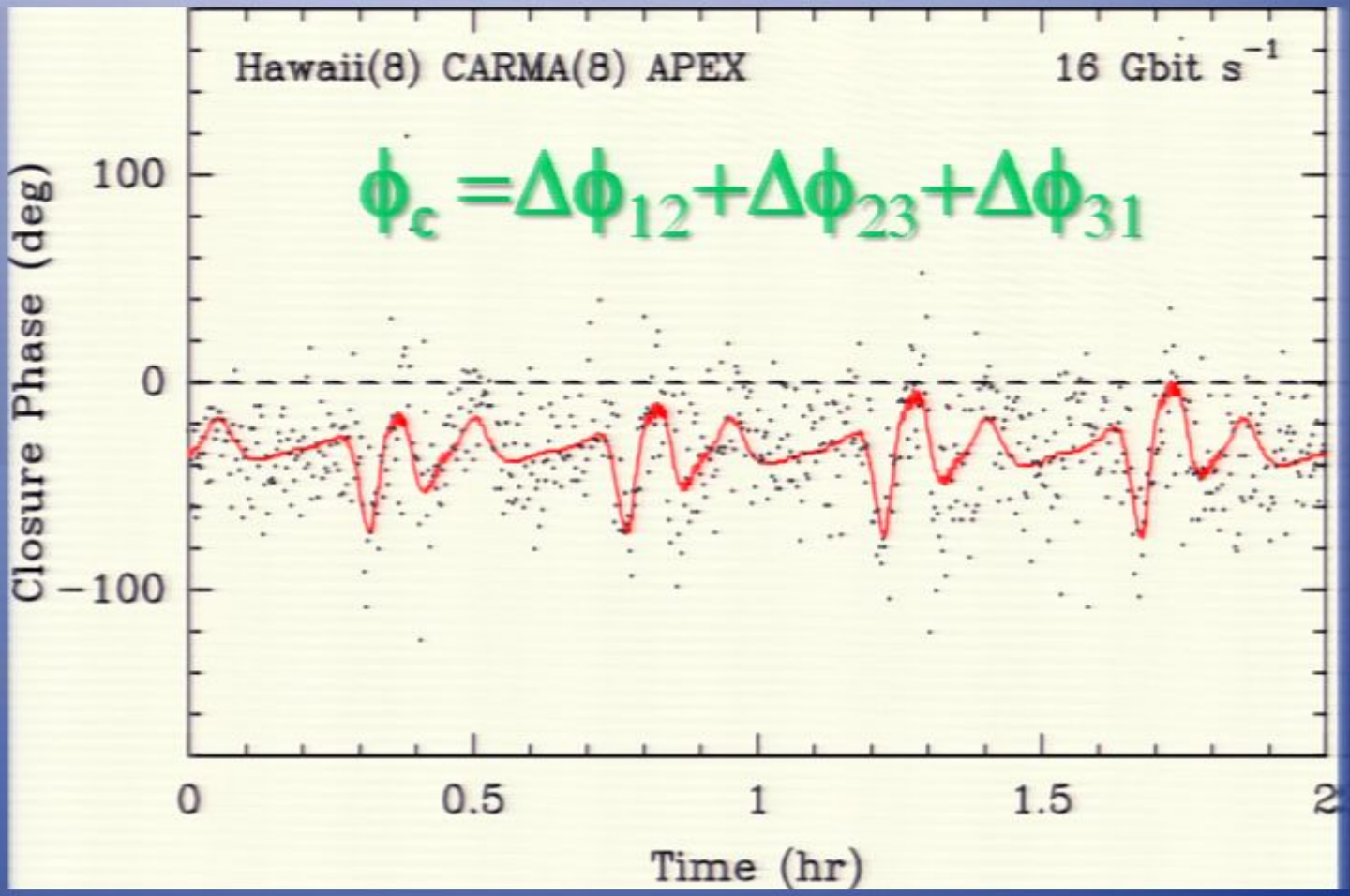


Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

Detecting Spots

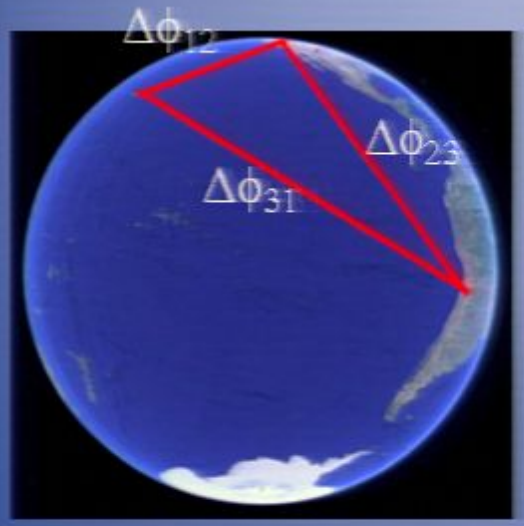


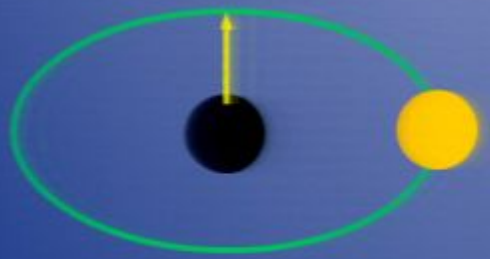


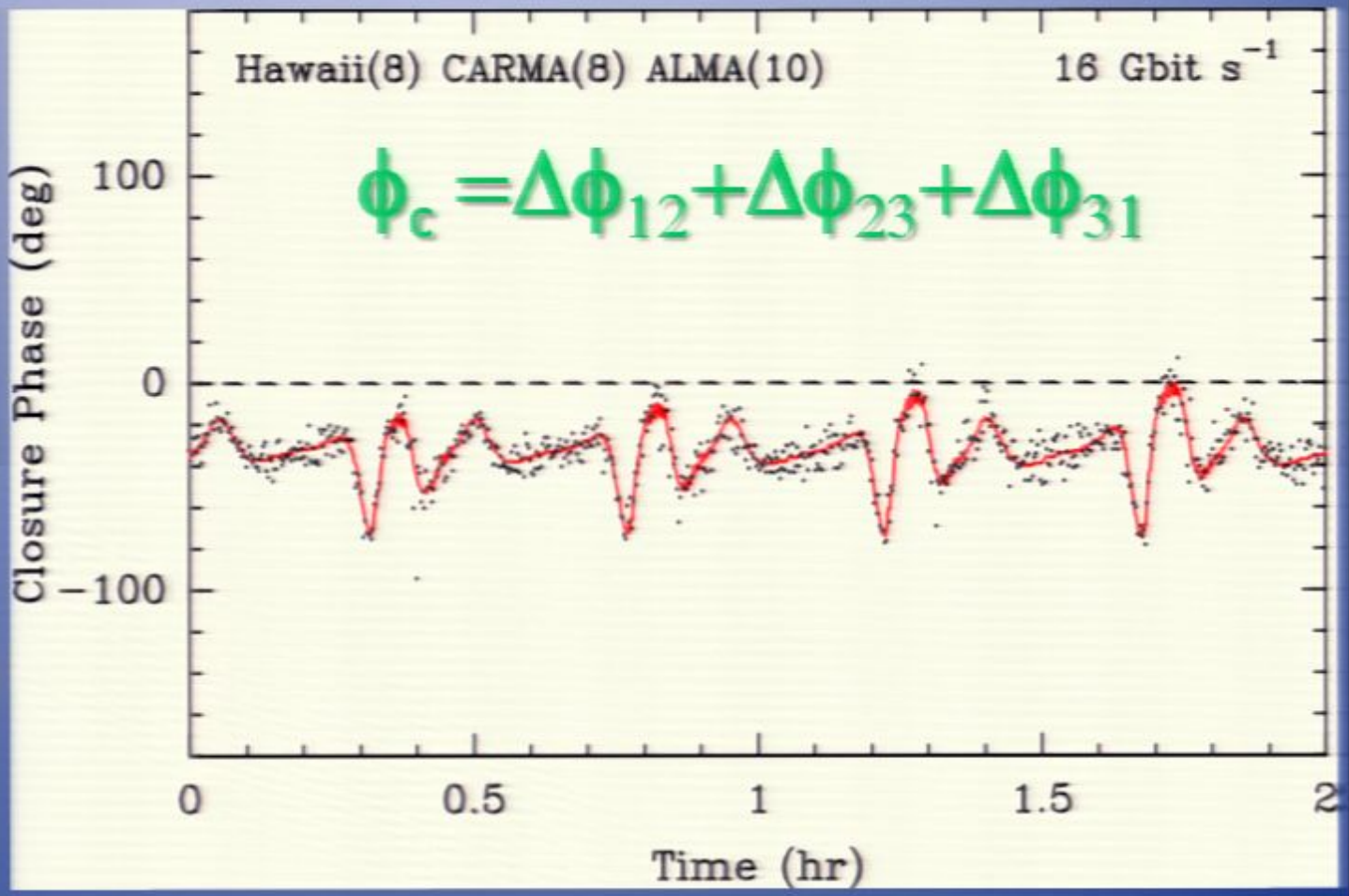


Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

Detecting Spots







Doeleman, Fish, A.E.B., Loeb & Rogers (2009)

Where We Are Today

- Already we know quite a bit about fundamental gravity
- Spin are being measured
- Lots of phenomenology to exploit
- New capabilities are already on the horizon.
- Messy astrophysics makes for happy astrophysicists!

Stellar Mass Black Hole Spins

System	a	Reference
GRO J1655-40	0.65 - 0.75	Shafee et al. 2006
	~0.7	Davis et al. 2006
4U 1543-47	0.75 - 0.85	Shafee et al. 2006
LMC X-3	< 0.26	Davis et al. 2006
	TBD	Steiner et al.
XTE J1550-564	0-0.7	Davis et al. 2006
	TBD	Steiner et al.
GRS 1915+105	0.98 - 1	McClintock et al. 2006
	~0.8	Middleton et al. 2006
M33 X-7	0.77 ± 0.05	Liu et al. 2007
LMC X-1	0.92 (+0.05, -0.07)	Gou et al. 2009
A0620--00	0.12 (+0.18, -0.20)	Gou et al. 2010
Cygnus X-1	TBD	Gou et al.