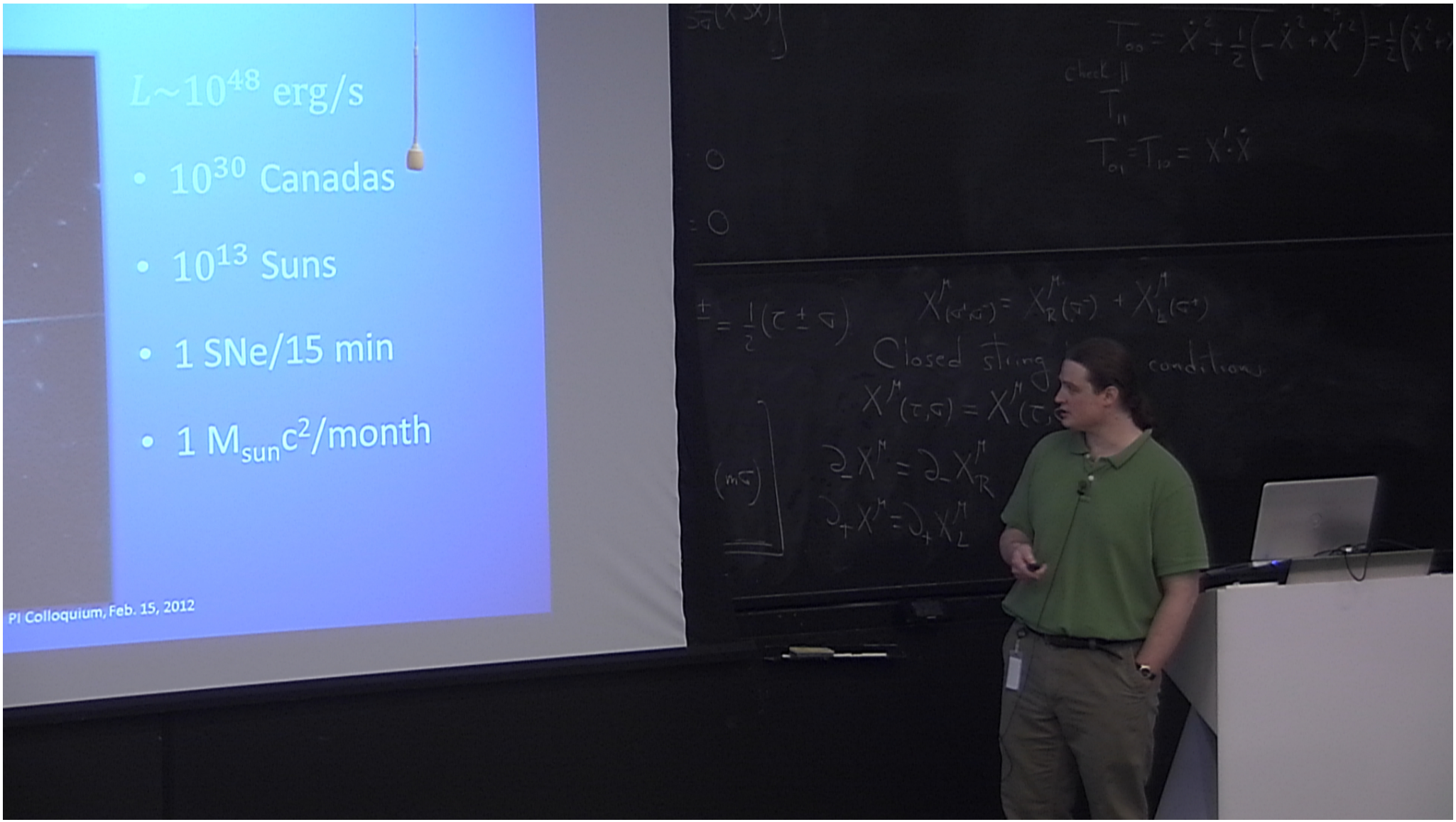
Title: The Other 99%: The Life and Times of the Black Hole Next Door

Date: Feb 15, 2012 02:00 PM

URL: http://pirsa.org/12020127

Abstract: Black holes lead a double life, simultaneously the dark, enigmatic, hairless consequence of general relativity and the powerful engines lurking at the hearts of galaxies with cosmological consequences.


$L \sim 10^{48}$ erg/s
• 10^{30} Canadas
• 10^{13} Suns
• 1 SNe/15 min
• 1 $M_{sun}c^2$/month
Pi Colloquium, Feb. 15, 2012

The Other 99%: The Life and Times of the Black Hole Next Door

Avery E Broderick

Sheperd Doeleman (MIT Haystack)
Vincent Fish (MIT Haystack)
Alan Rogers (MIT Haystack)
Dimitrios Psaltis (Arizona)
Tim Johannsen (Arizona)
Avi Loeb (Harvard)
Ramesh Narayan (Harvard)
Jonathan Bittner (Harvard)
Mark Reid (Smithsonian)
Mareki Honma (NAOJ)

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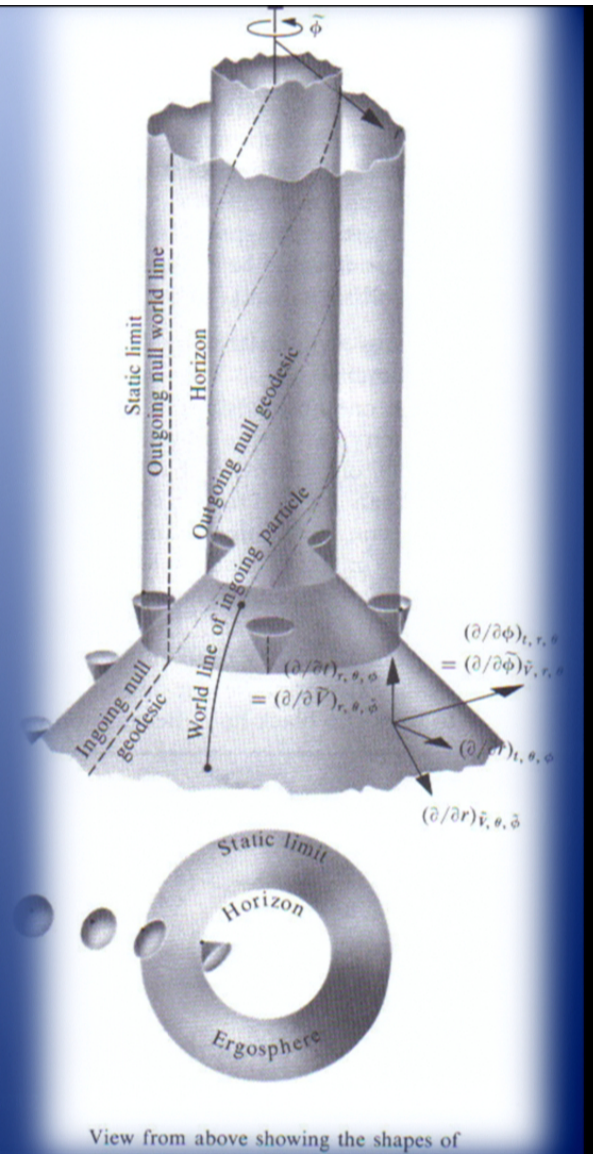
Black Holes

$$R_{\mu\nu} = 0$$

$$g_{\mu\nu}(M, a, Q)$$

$$r_+,\ r_e$$
$$r_\gamma,\ r_{ISCO}$$



View from above showing the shapes of

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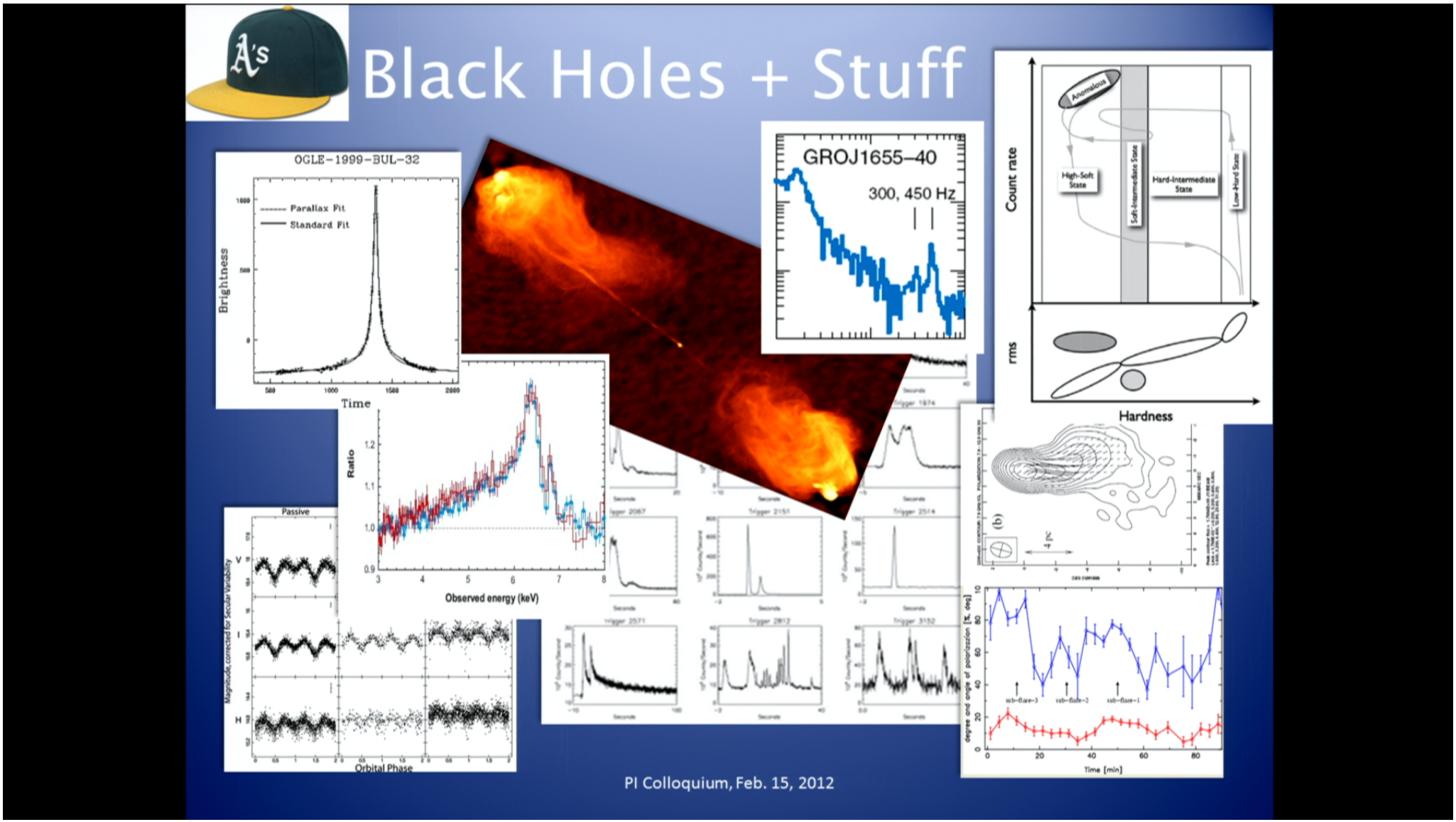
Black Holes + Stuff
OGLE-1999-BUL-32
Parallax Fit
Standard Fit
Brightness
Time
GROJ1655-40
300, 450 Hz
Count rate
rms
Hardness
Anomalous
High-Soft State
Soft-Intermediate State
Hard-Intermediate State
Low-Hard State
Ratio
Observed energy (keV)
Passive
Magnitude, corrected for Secular Variability
Orbital Phase
Time [min]
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Black Holes as Engines

$L \sim 10^{47}$ erg/s

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Black Holes as Engines

$L \sim 10^{48}$ erg/s

- 10^{30} Canadas

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$L \sim 10^{48}$ erg/s

- 10^{30} Canadas
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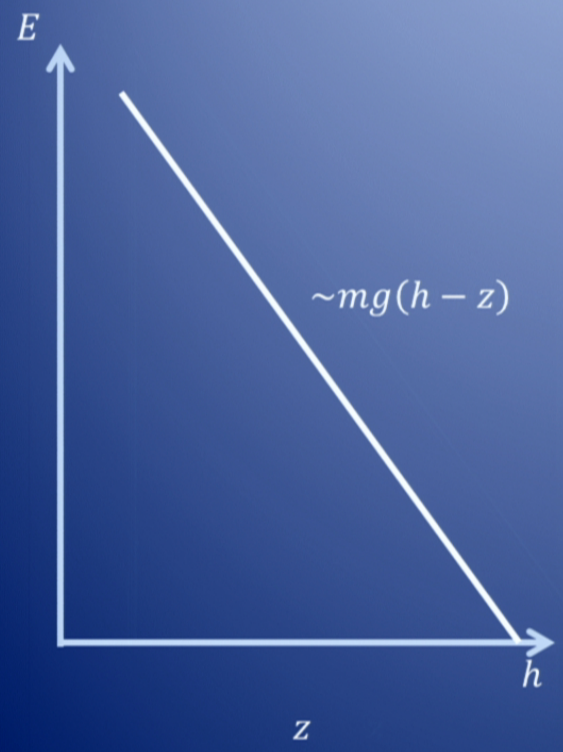
The Story: Accretion Power



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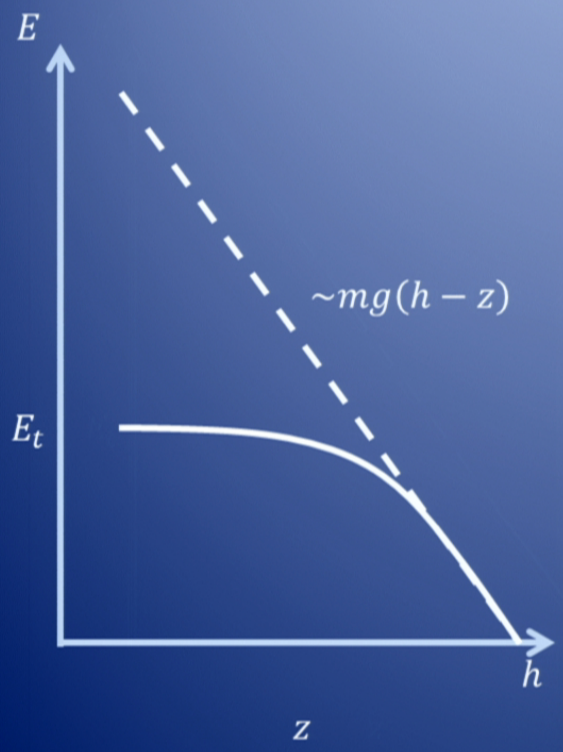

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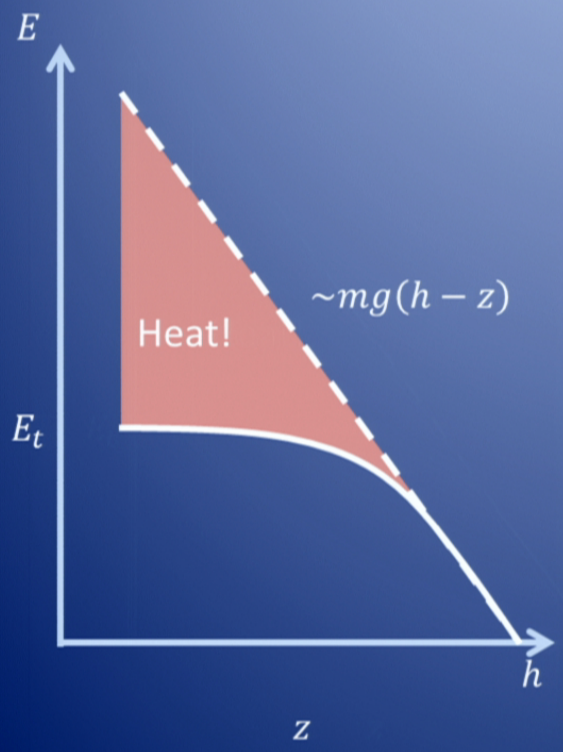

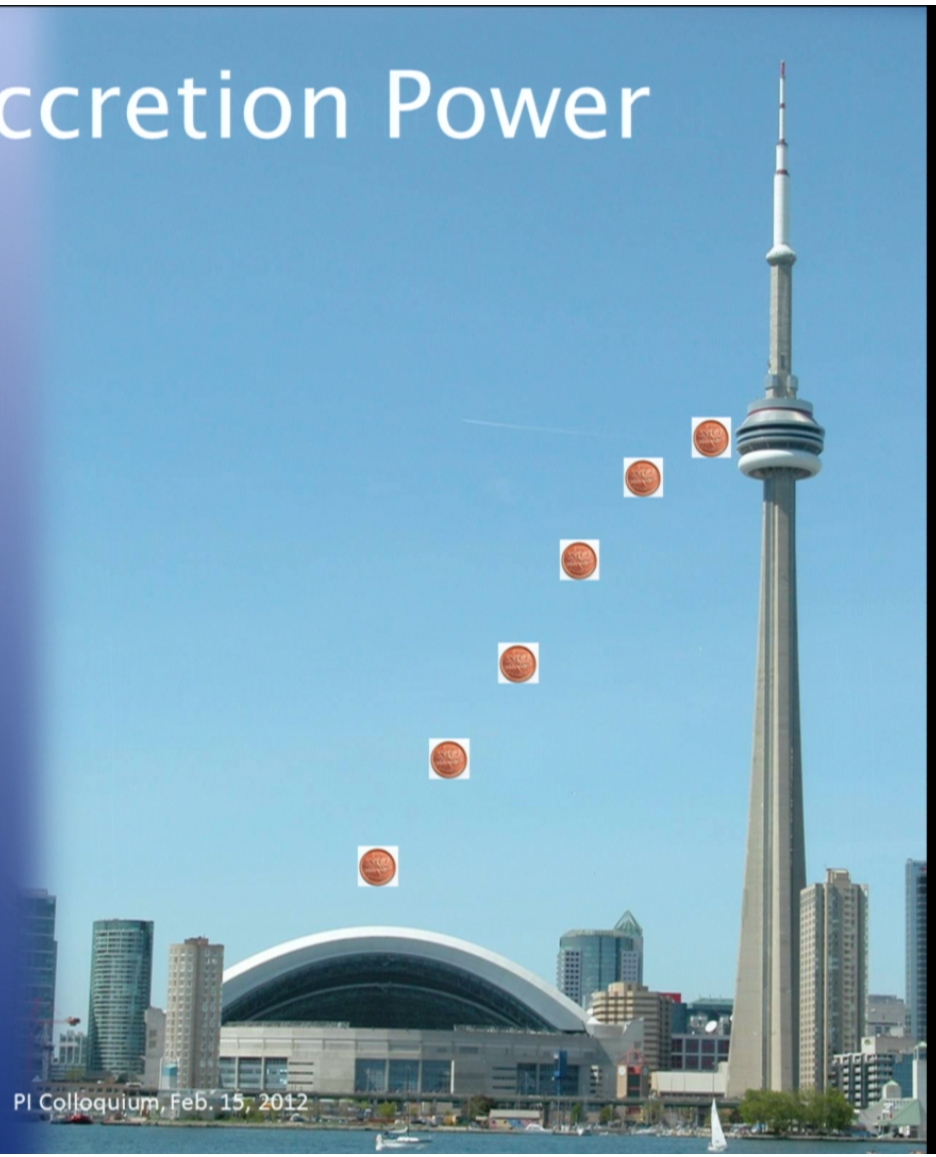

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The Story: Accretion Power

$$E_M \sim \frac{GM_E m}{R_E} \sim 10^{-9} mc^2$$

$$E_M \sim \frac{GMm}{R_{BH}} \sim \frac{GMm}{(GM/c^2)} \sim mc^2$$

$$\rightarrow L \sim \dot{M}c^2$$

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How Bright can BHs Get?

$T \rightarrow c_s \sim T^{1/2}$

1. Bondi Accretion:

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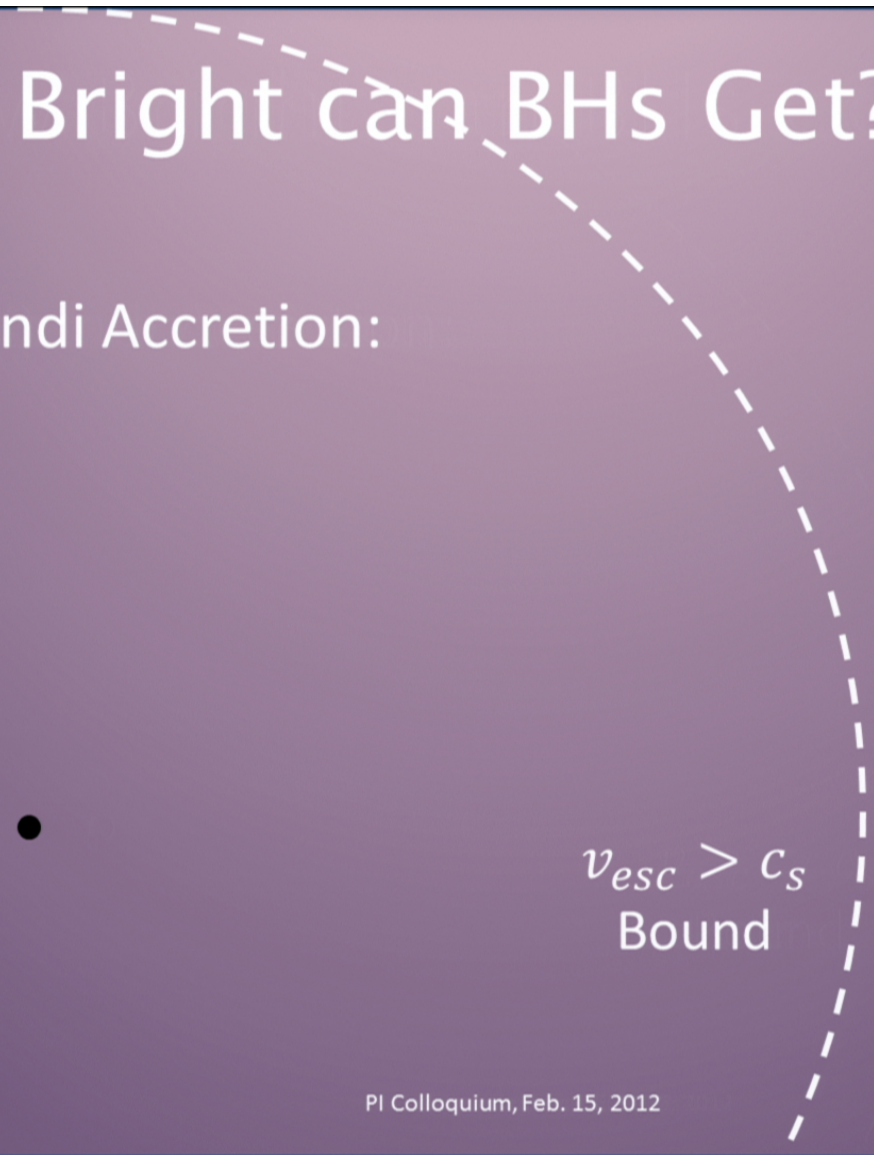

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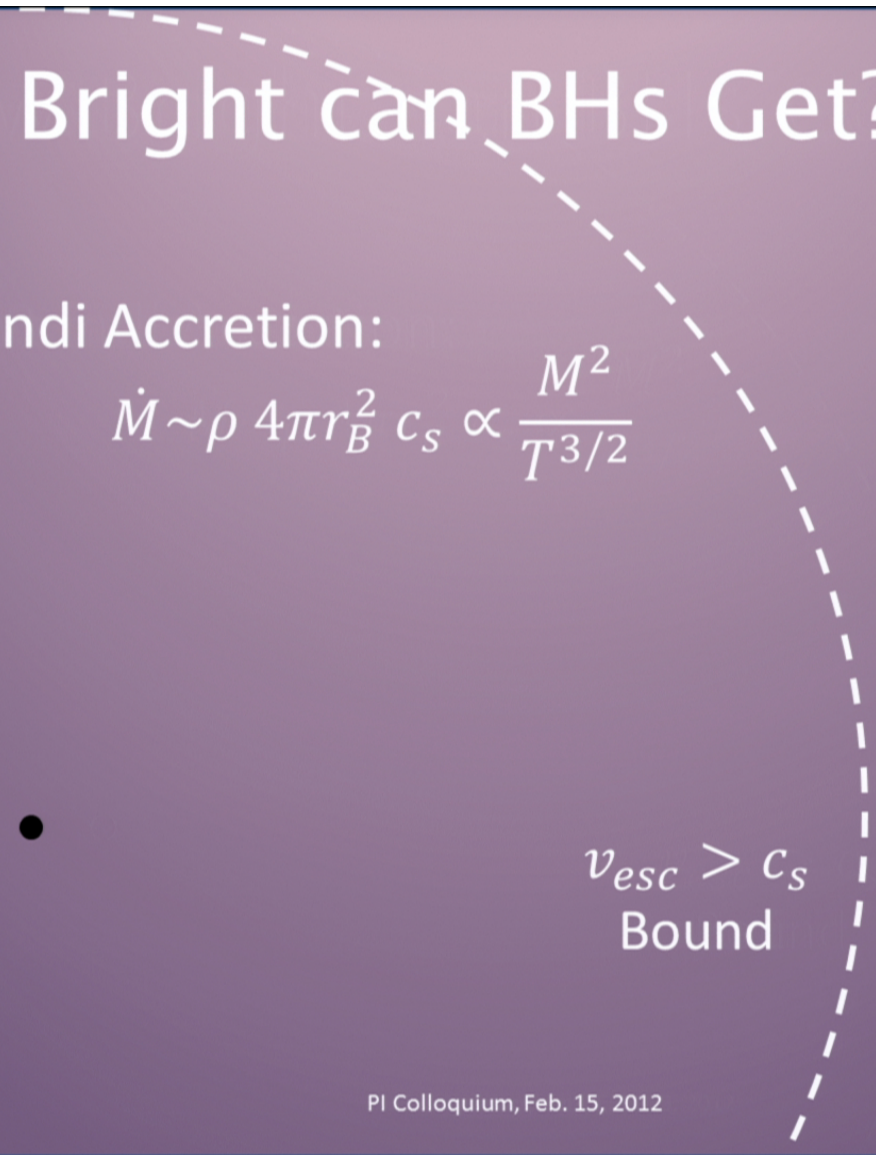

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$$f \sim \frac{L\sigma}{4\pi r^2 c}$$

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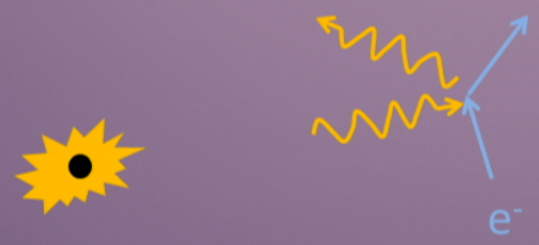

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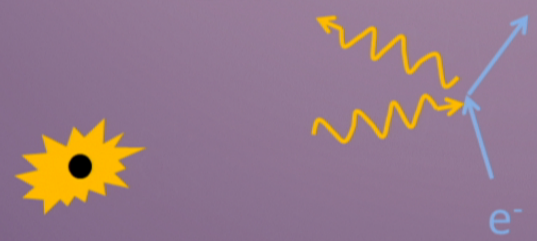

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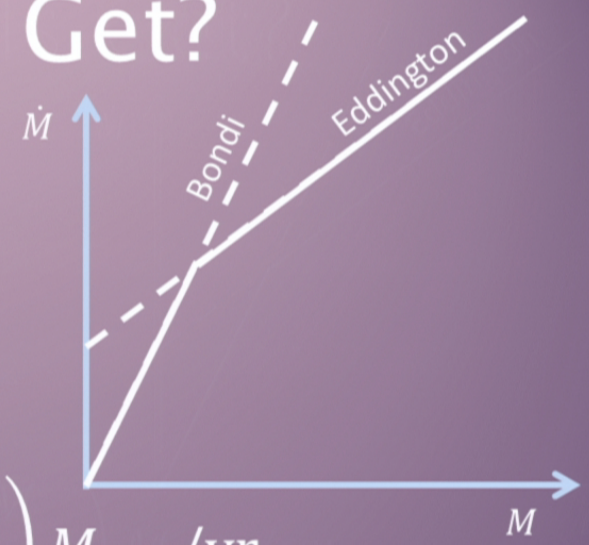

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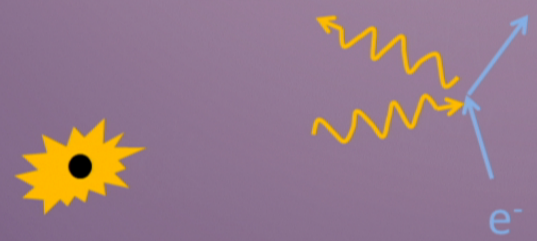

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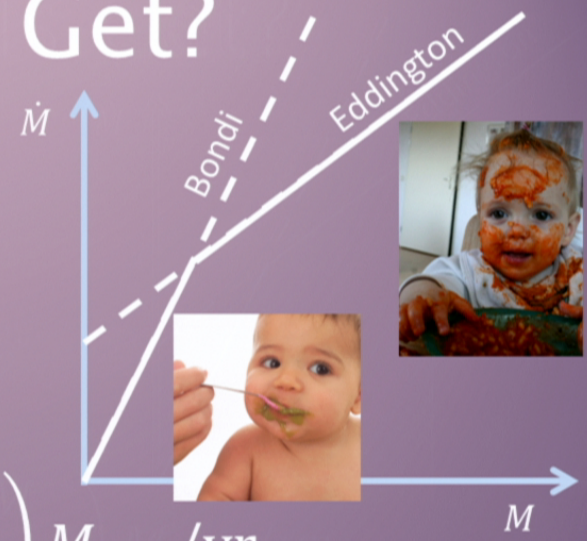

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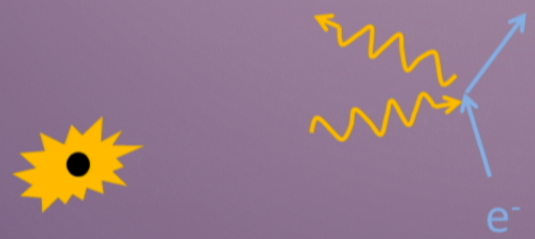

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3. Angular Momentum:

$$\frac{GM}{c^2} \sim 10^{11} - 10^{15}\ \mathrm{cm} \ll R_{\mathrm{gas}} \sim 1\ \mathrm{pc} \sim 3 \times 10^{18}\mathrm{cm}$$

$$l = \sqrt{GMr} \rightarrow \frac{l_i}{l_f} \sim 10^2 - 10^4!$$

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Astrophysical "Viscosity"

- Molecular viscosity (Spitzer viscosity) much too small to drive observed luminosities
- Parameterized ignorance: $\nu = \alpha h c_s \rightarrow v^r \simeq \alpha v_k$

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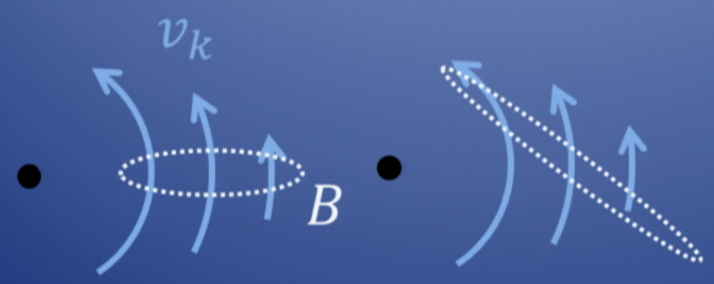

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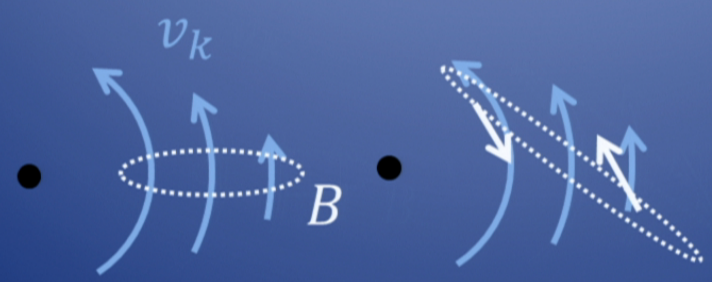

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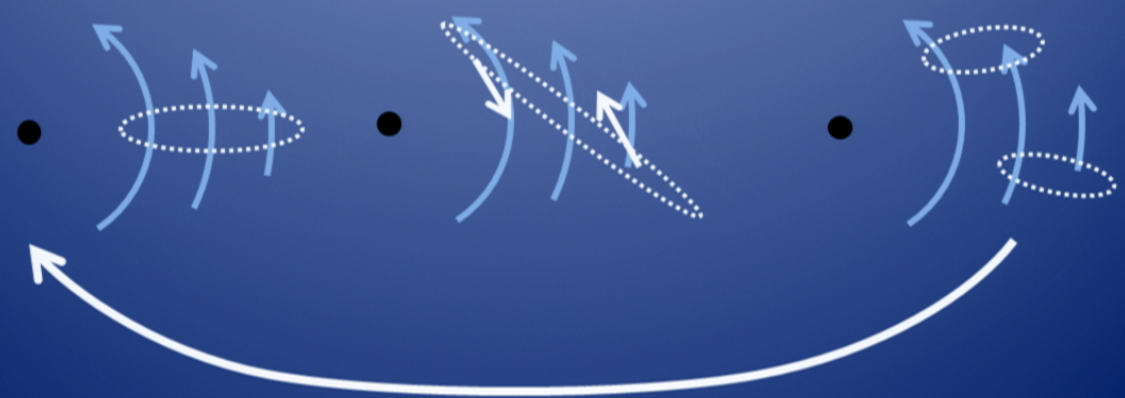

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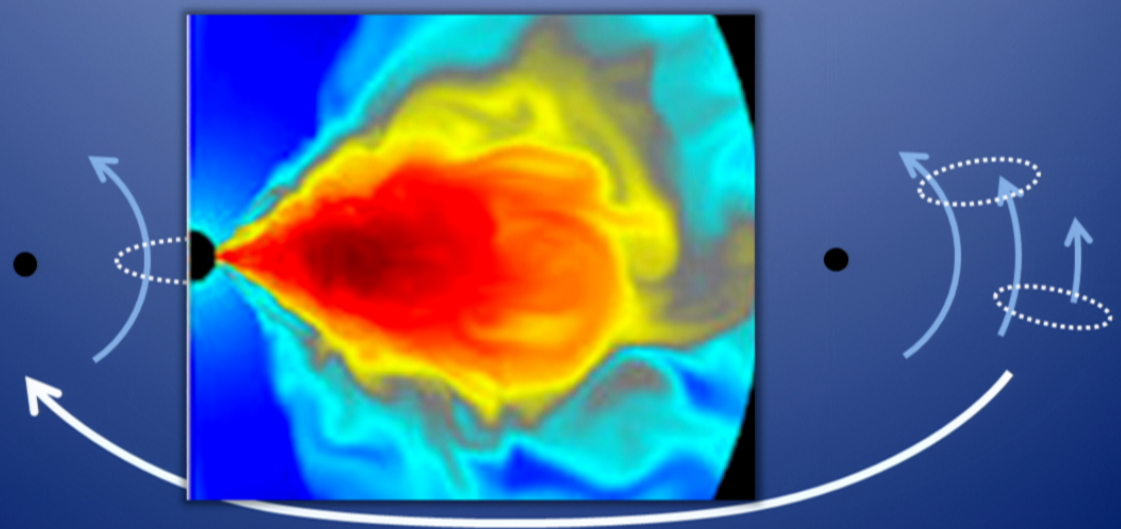

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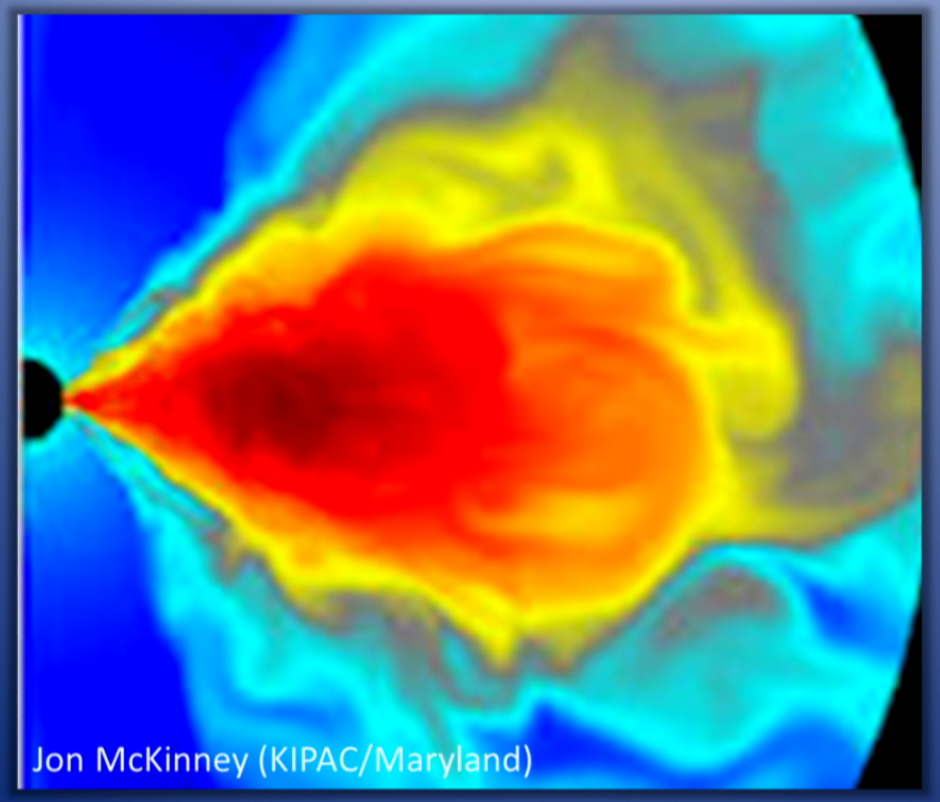
Disks in the Other Dimension!



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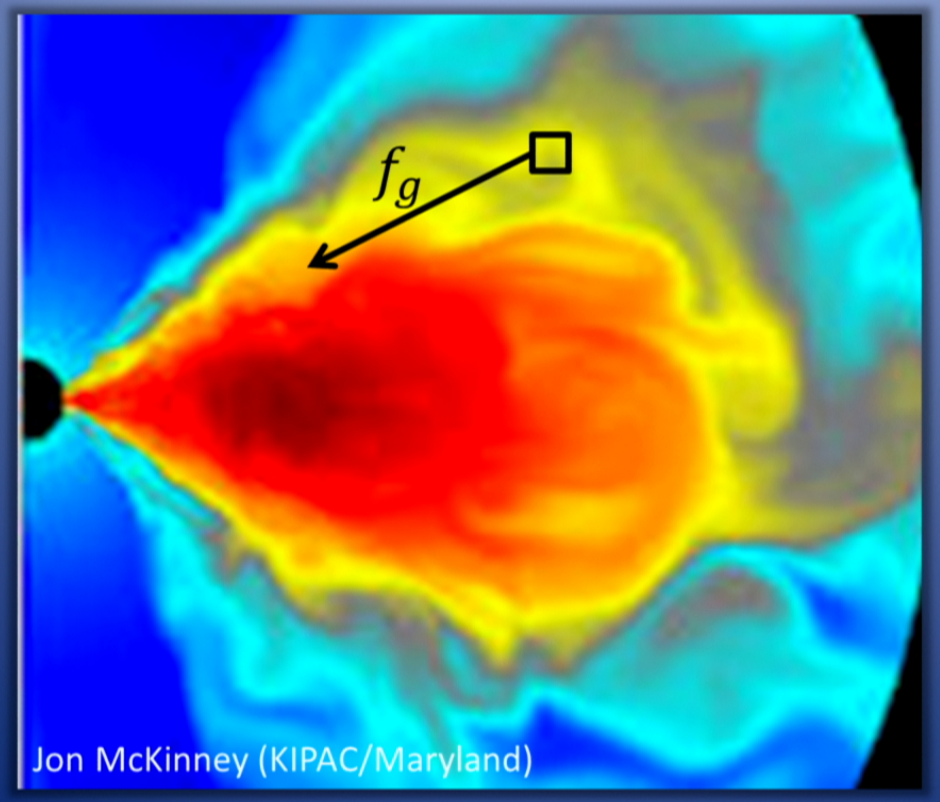

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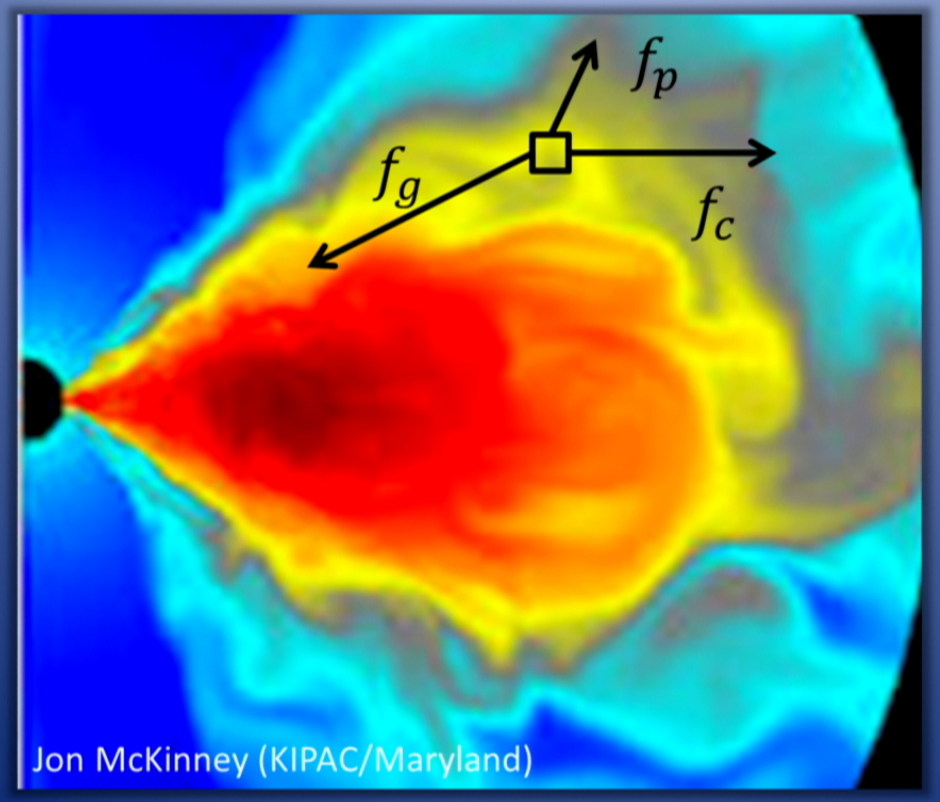

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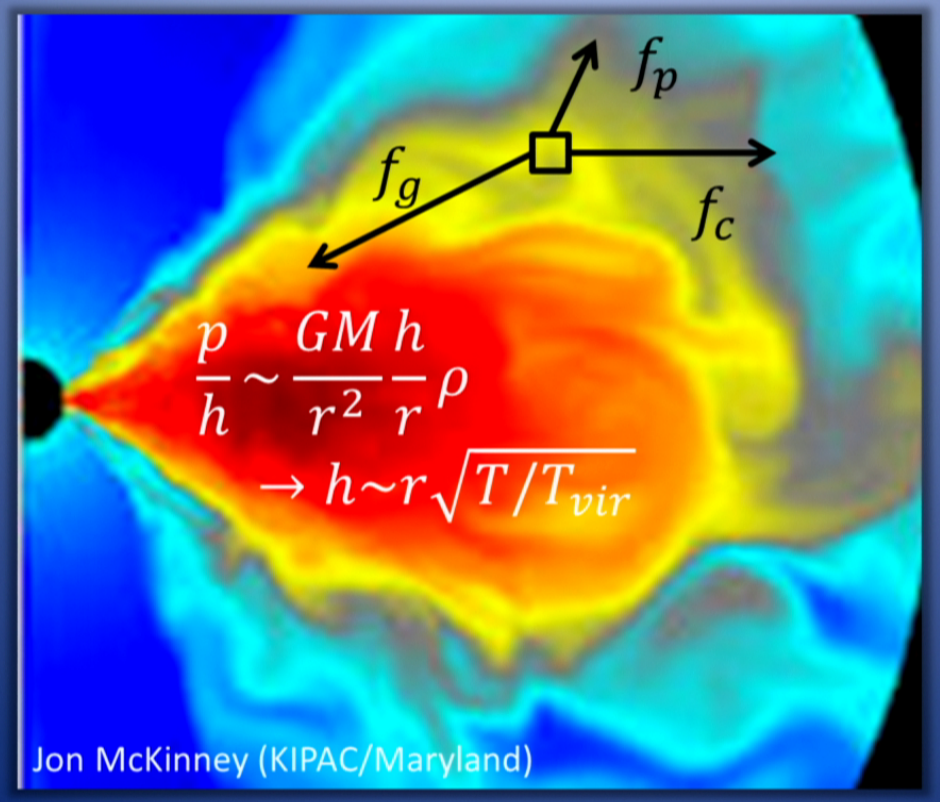

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Efficient Radiators ($T \ll T_{vir}$)

Shakura-Sunyaev Disks (α-disks)

$h \ll r$ $\qquad$ $v^{\phi} \simeq v_k, v^r \simeq \alpha v_k \ll v_k$

$L \sim 0.1\, \dot{M} c^2$ (independent of α!)

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→ Energy in ions → Energy in leptons → Radiation → Thin Disk

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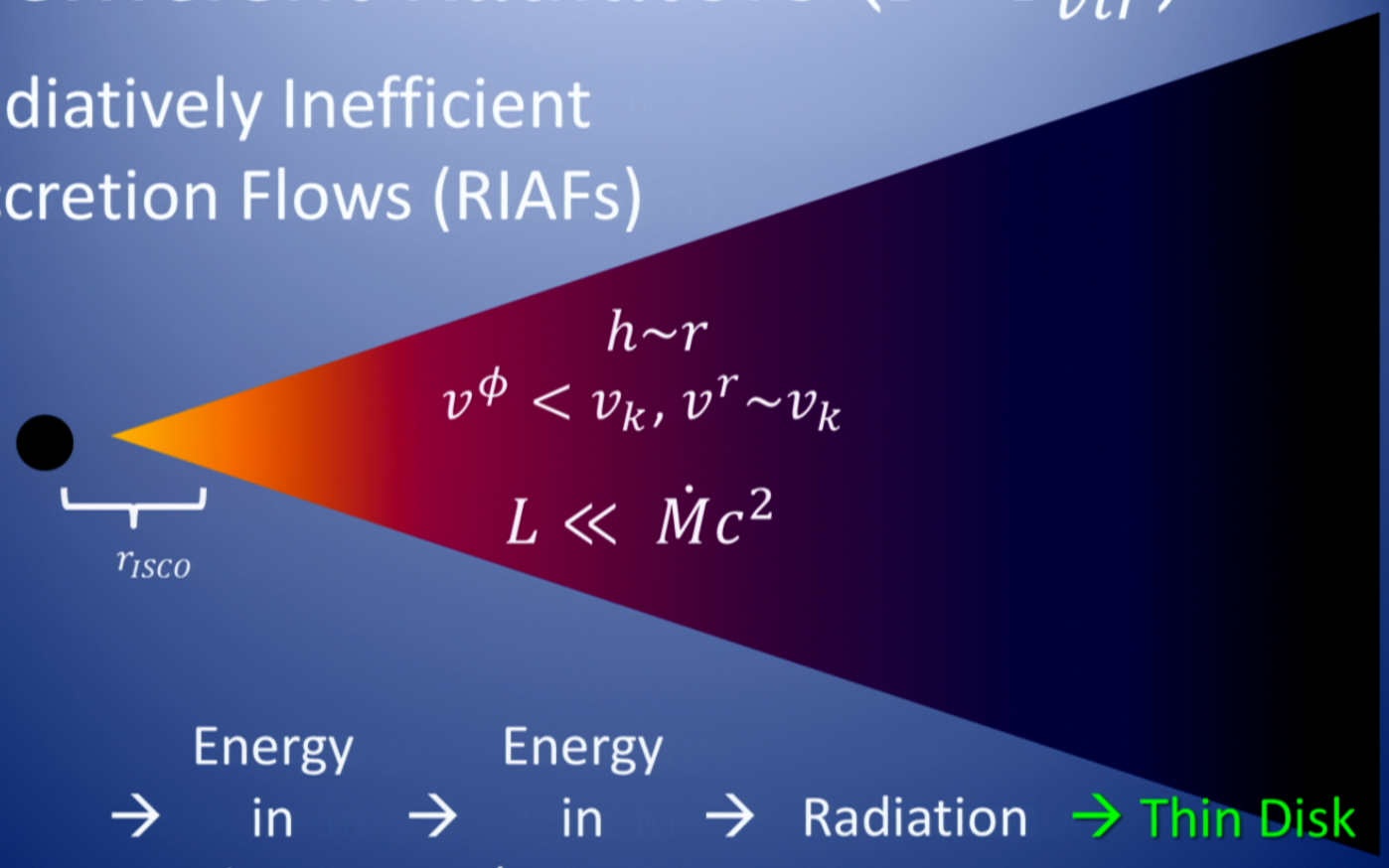
Inefficient Radiators ($T \sim T_{vir}$)

Radiatively Inefficient Accretion Flows (RIAFs)



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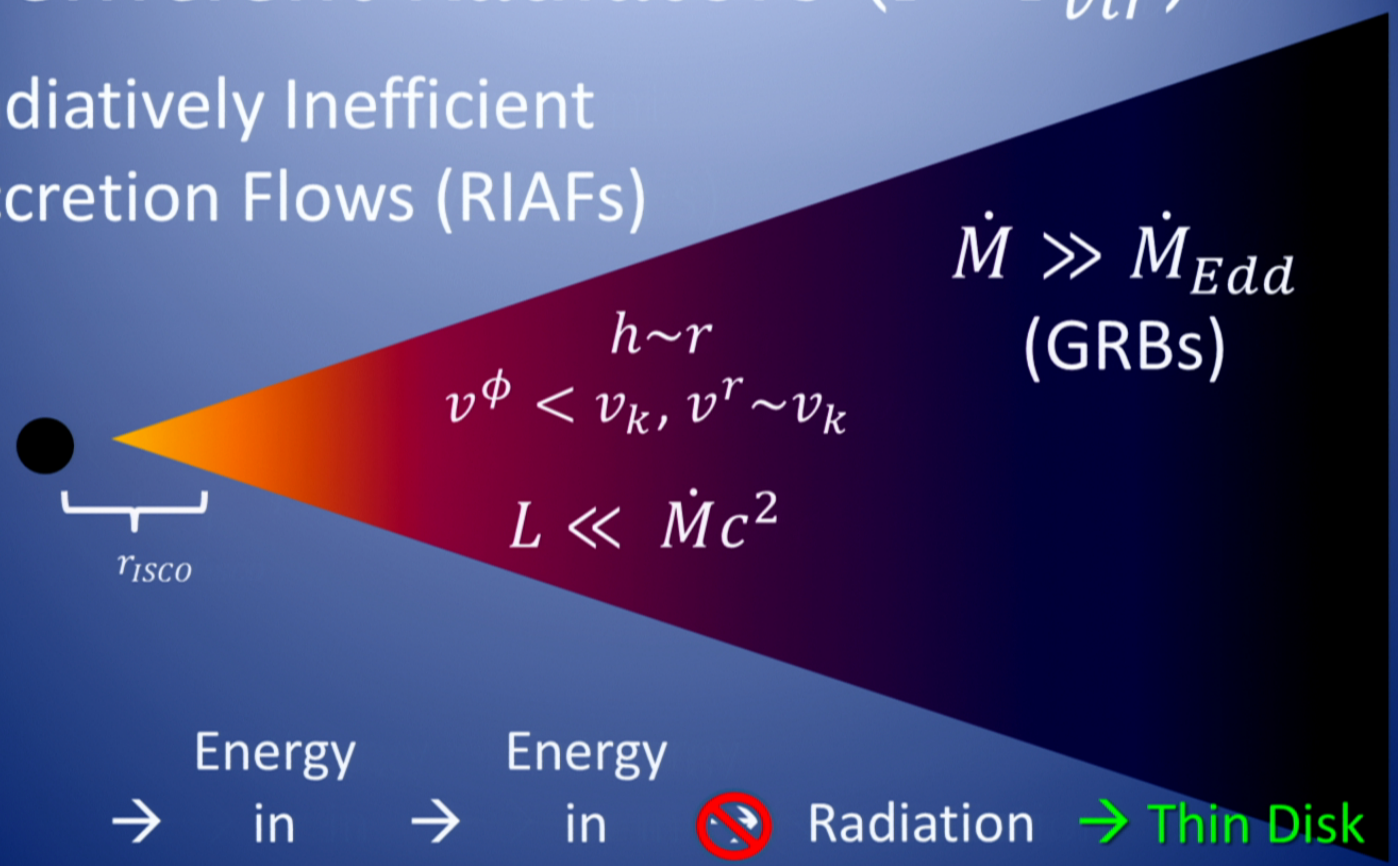

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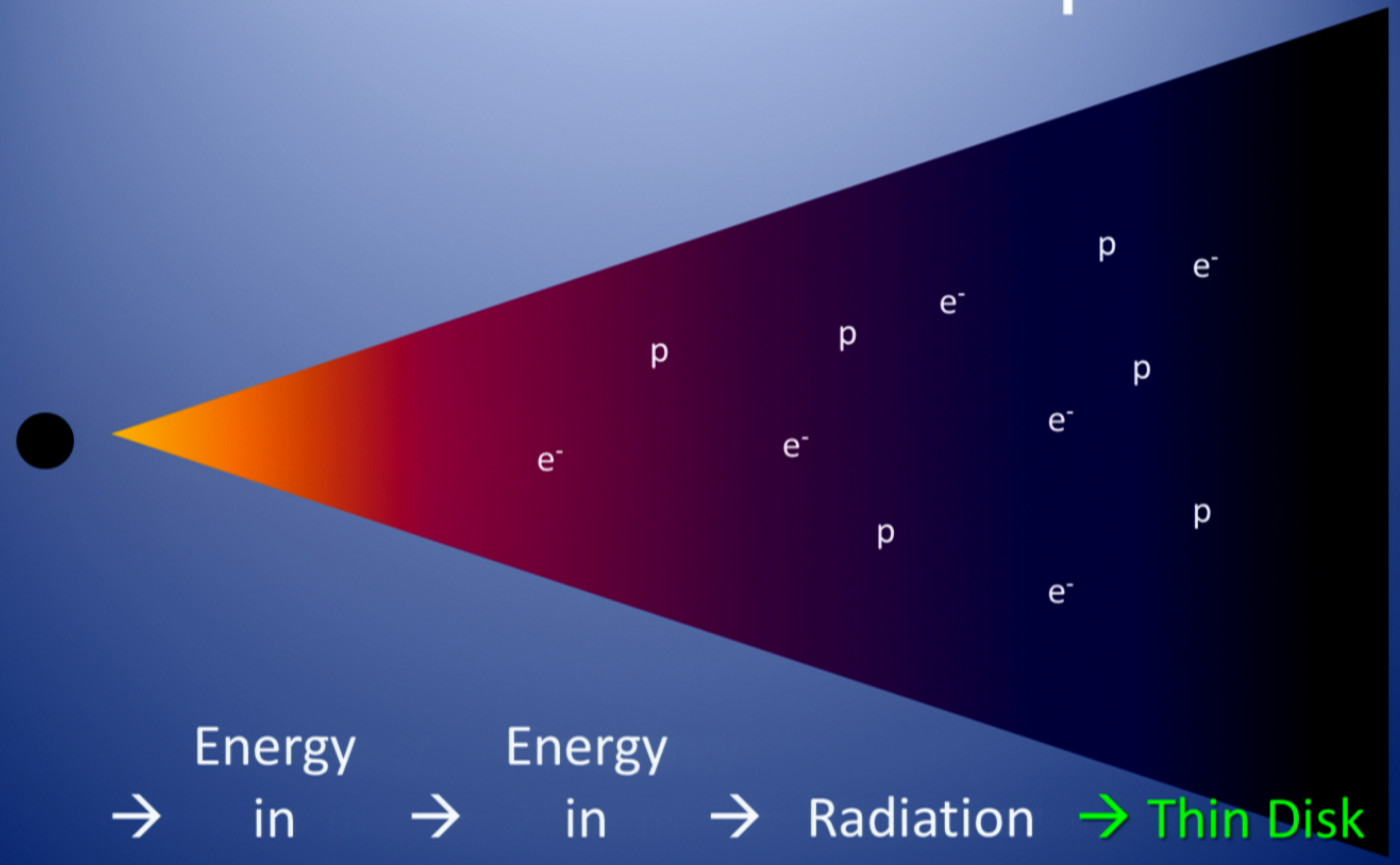
RIAFs at low $\dot{M}$: Two-Temp flows



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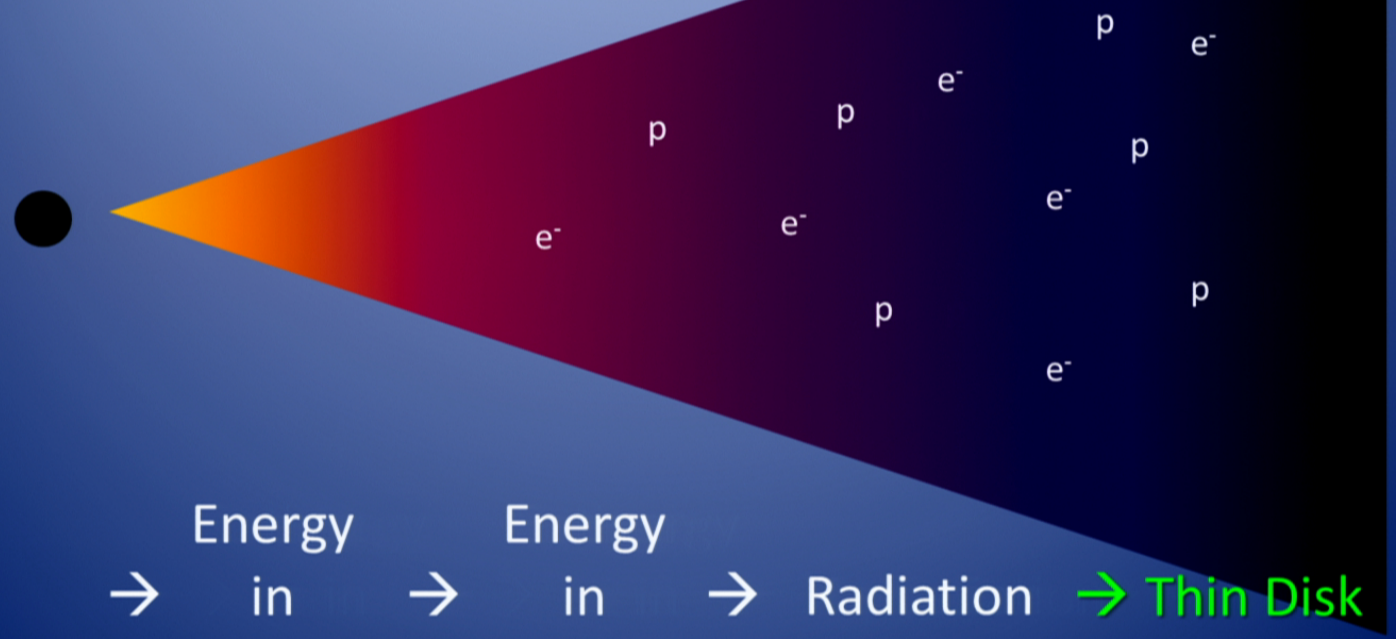
RIAFs at low $\dot{M}$: Two-Temp flows

$$t_{ee} \propto \frac{1}{n},\ t_{pp} \propto \frac{1}{n}\left(\frac{m_p}{m_e}\right)^{1/2},\ t_{ep} \propto \frac{1}{n}\left(\frac{m_p}{m_e}\right)$$



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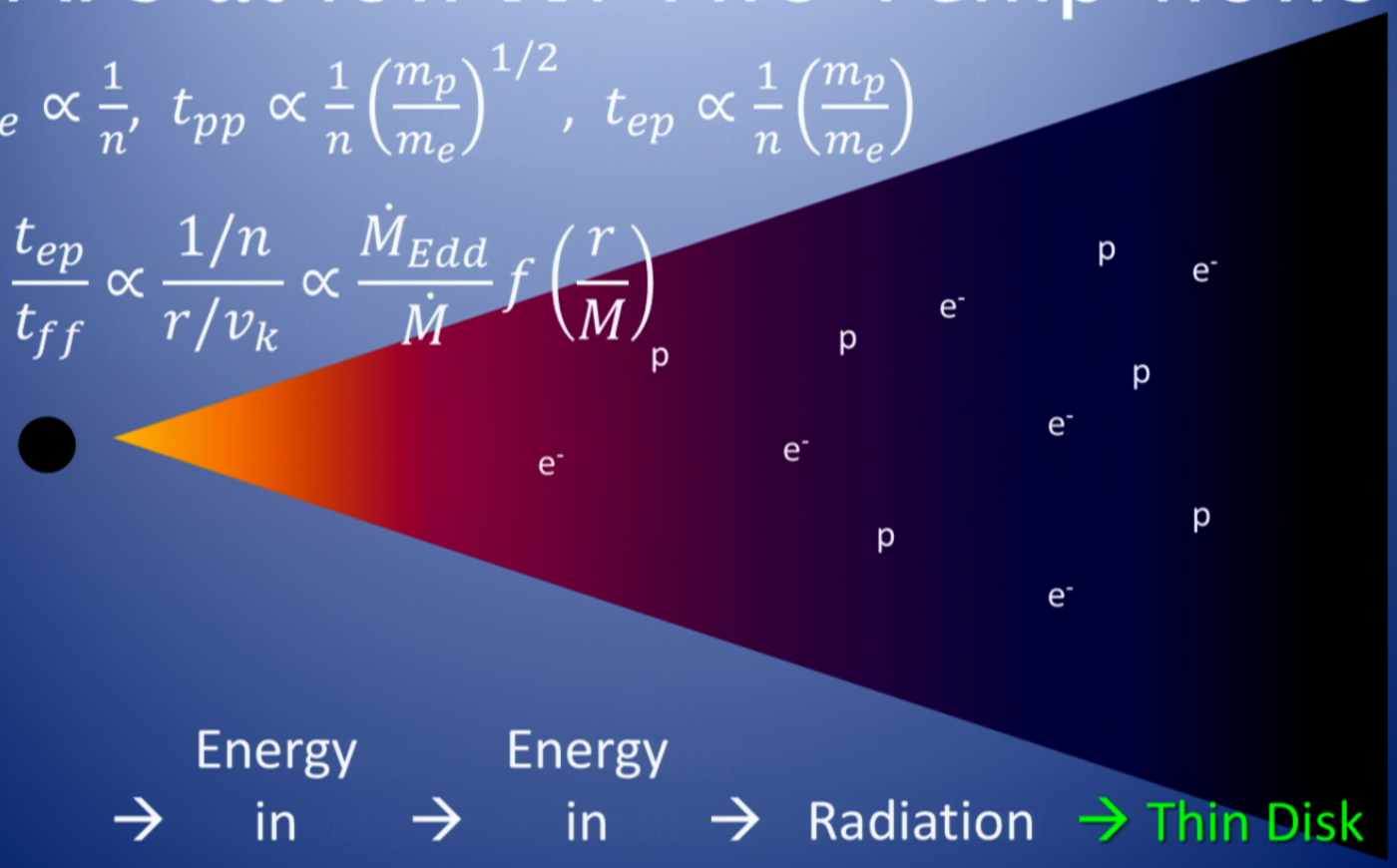

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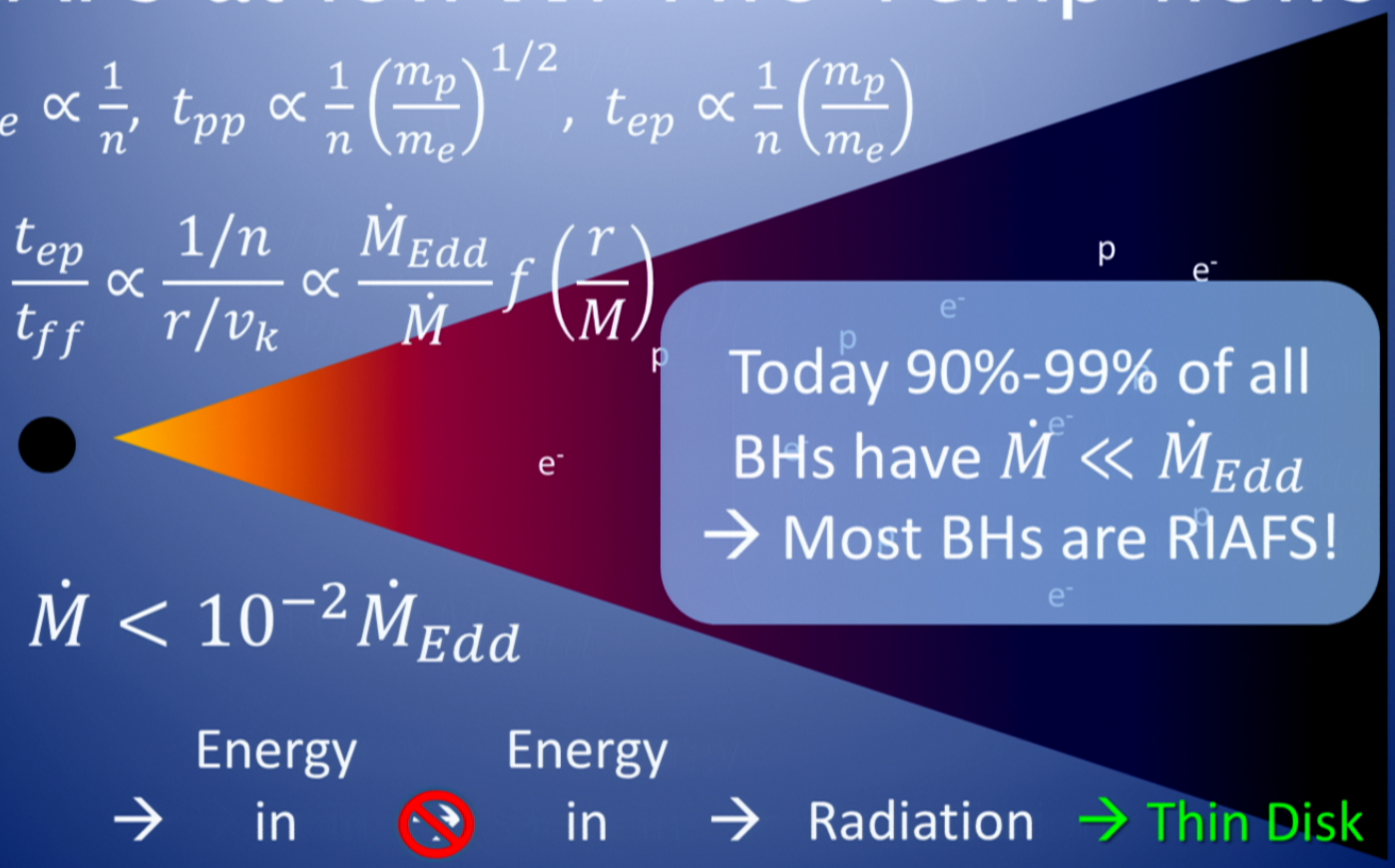

Today 90%-99% of all BHs have $\dot{M} \ll \dot{M}_{Edd}$
→ Most BHs are RIAFS!

$$\dot{M} < 10^{-2}\dot{M}_{Edd}$$

→ Energy in ions ≠ Energy in leptons → Radiation → Thin Disk

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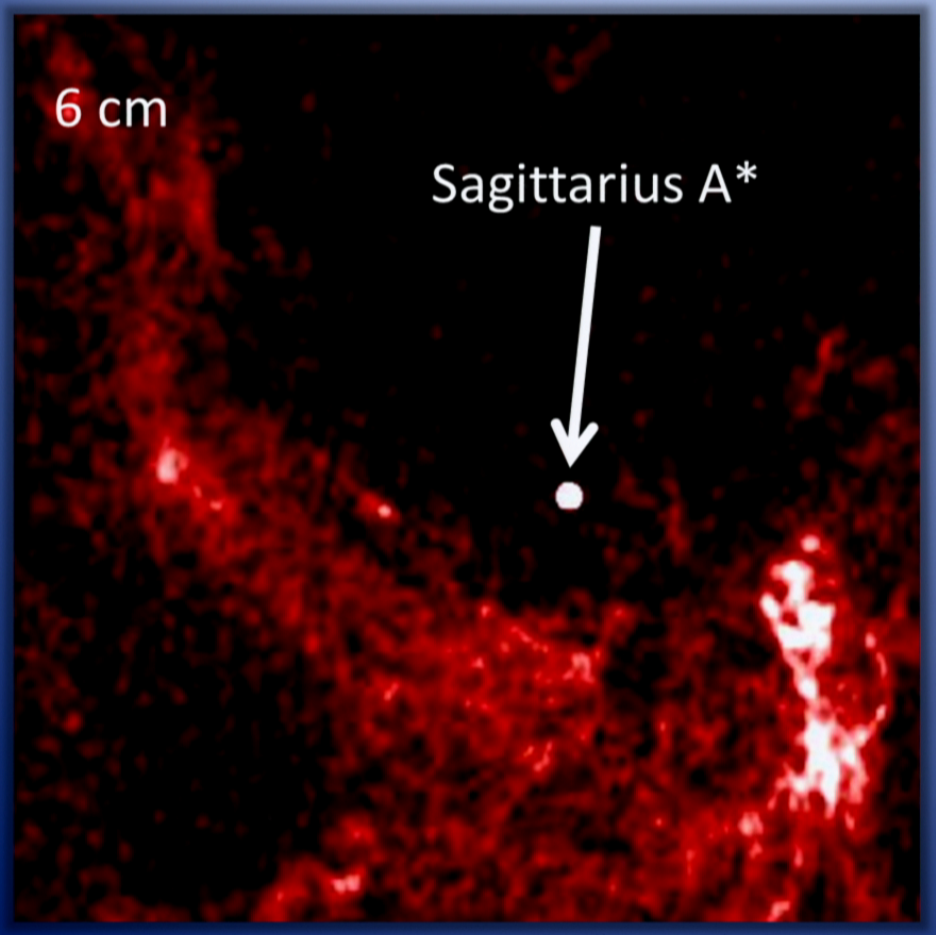
Sagittarius A*: Neighborhood RIAF



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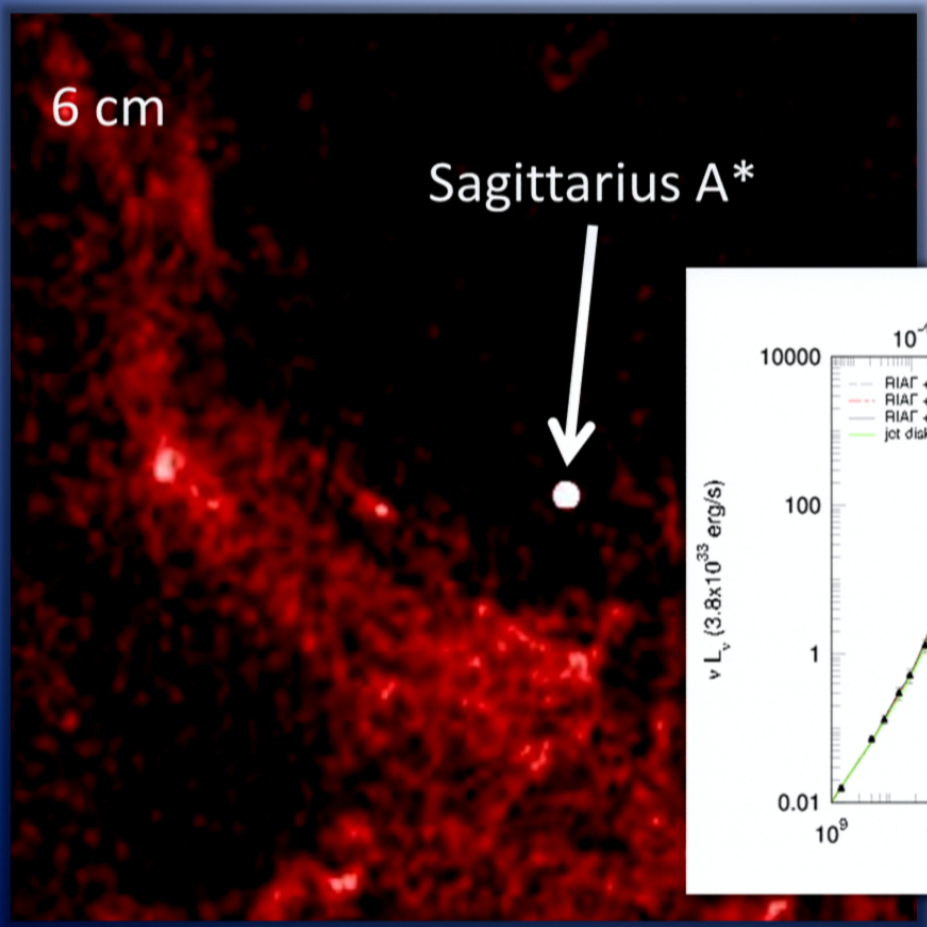

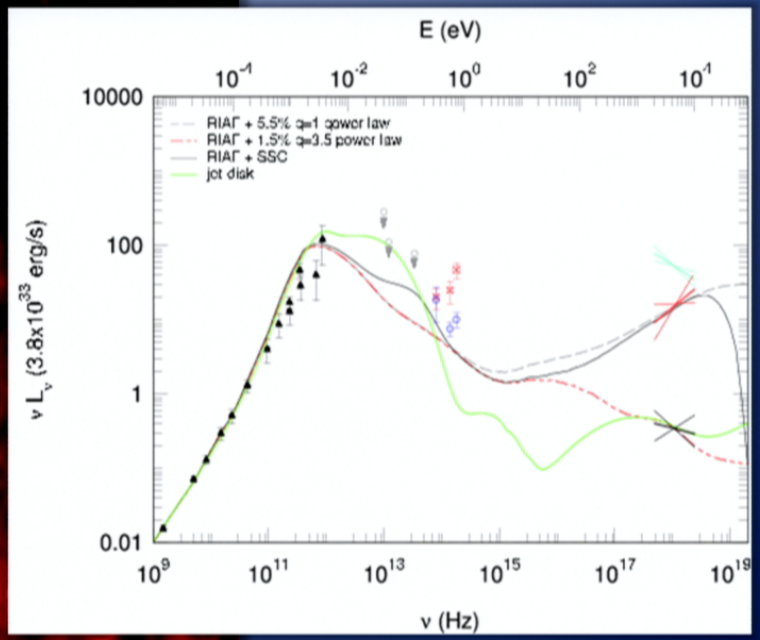

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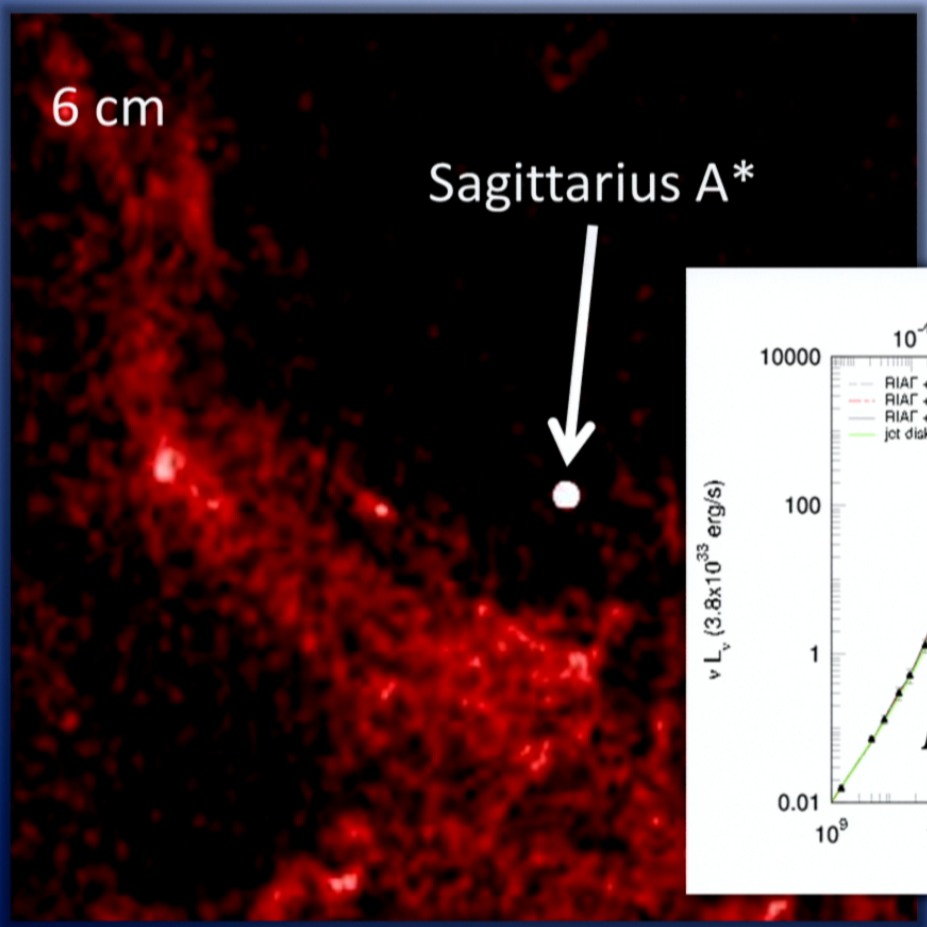
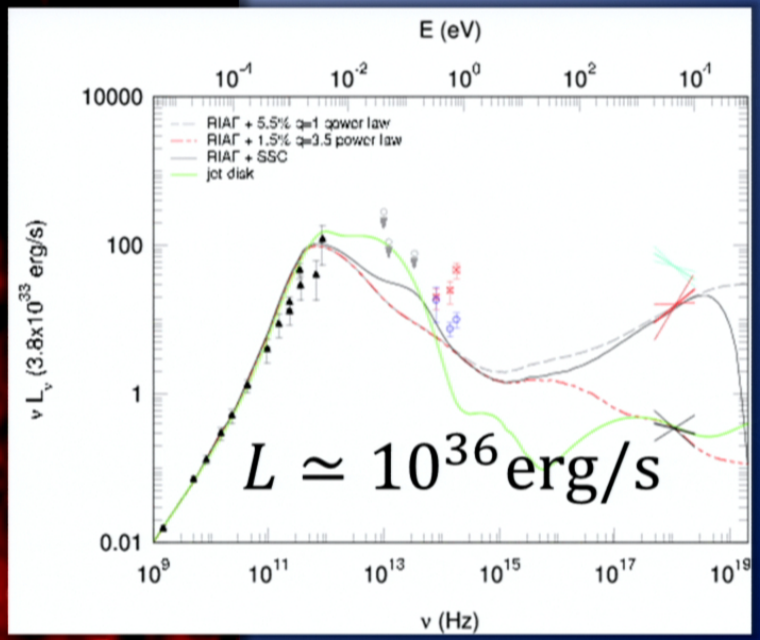
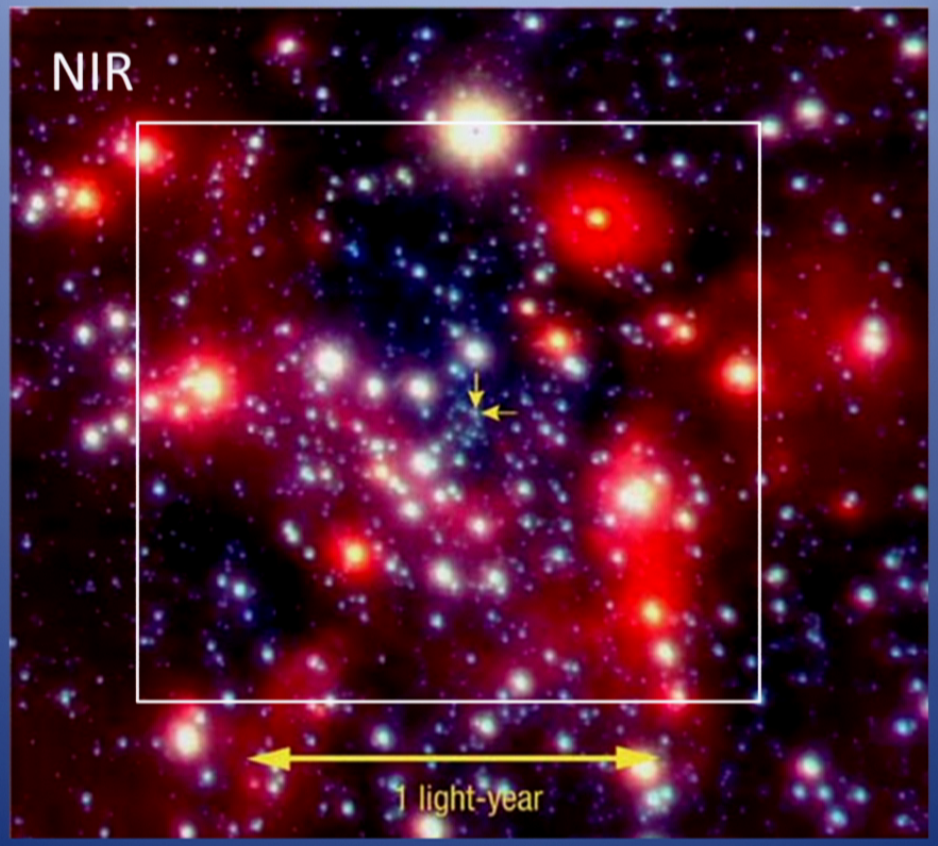
Sagittarius A*: Neighborhood RIAF





PI Colloquium, Feb. 15, 2012

Sgr A*'s disappearing act!



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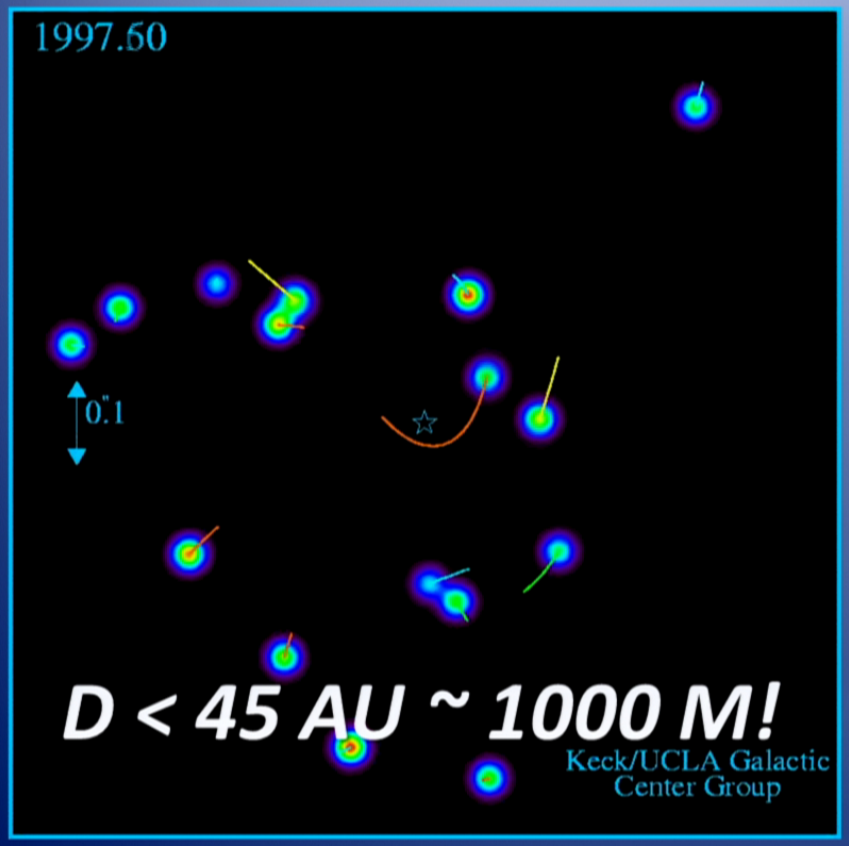
Mass and Just How Dim?



- $M = 4 \times 10^6 M_{sun}$

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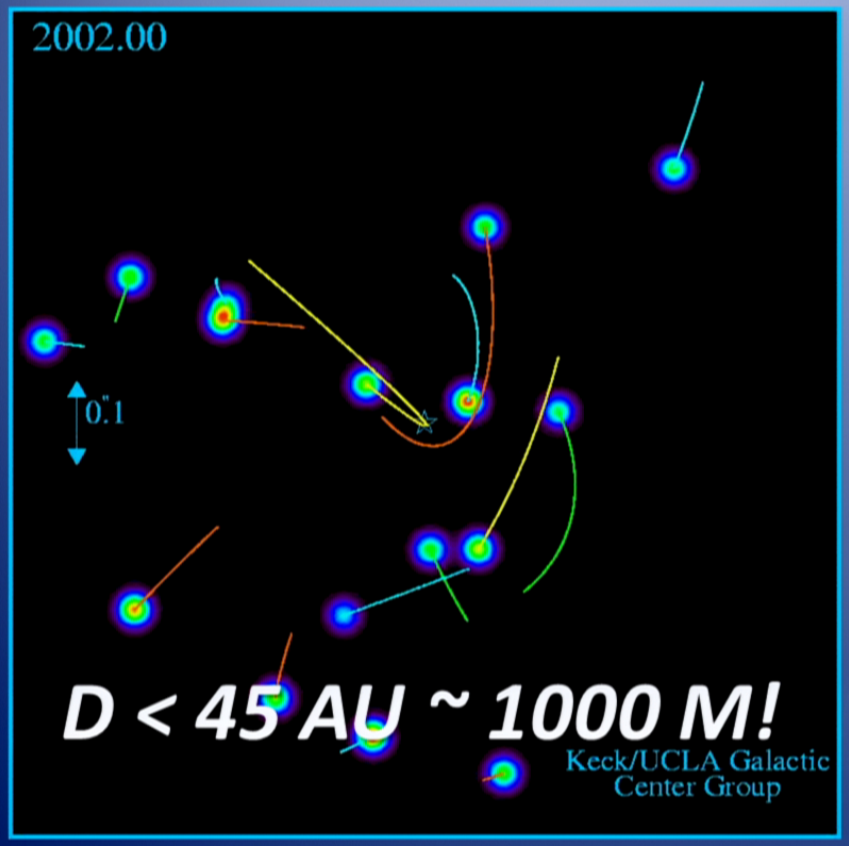

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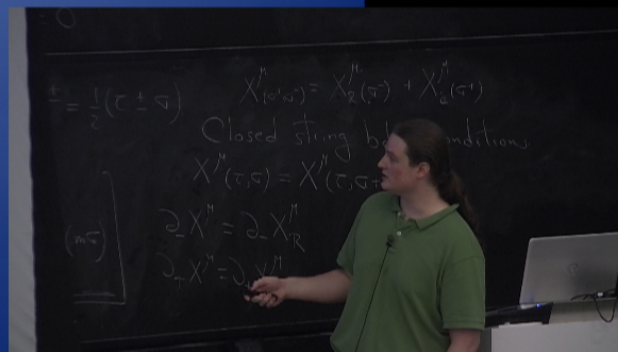

PI Colloquium, Feb. 15, 2012

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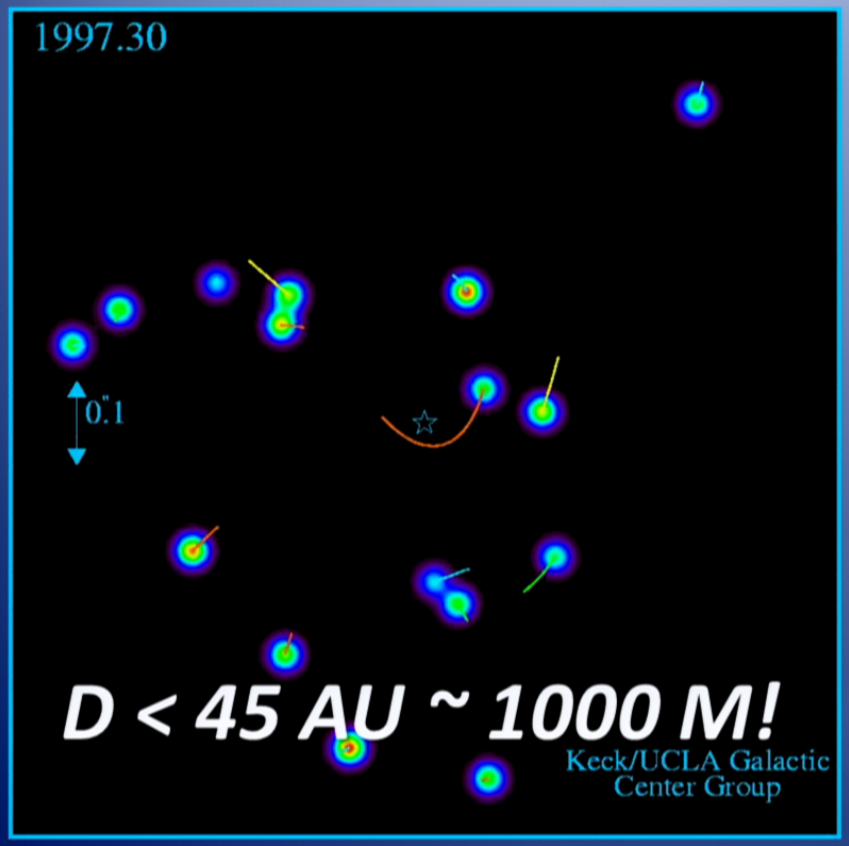

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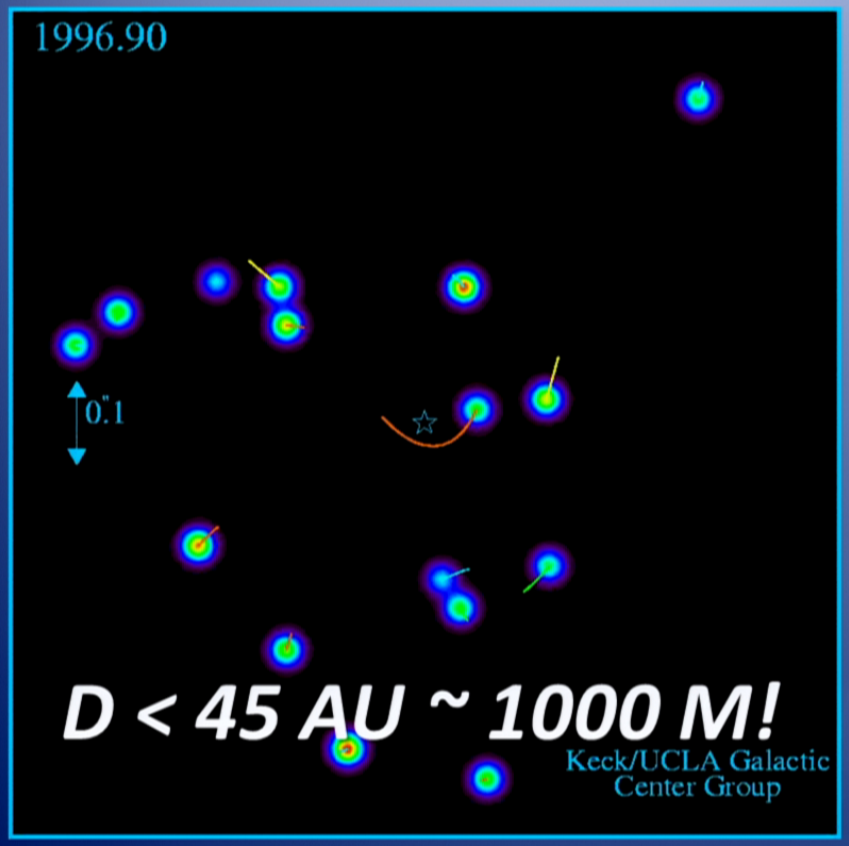

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PI Colloquium, Feb. 15, 2012

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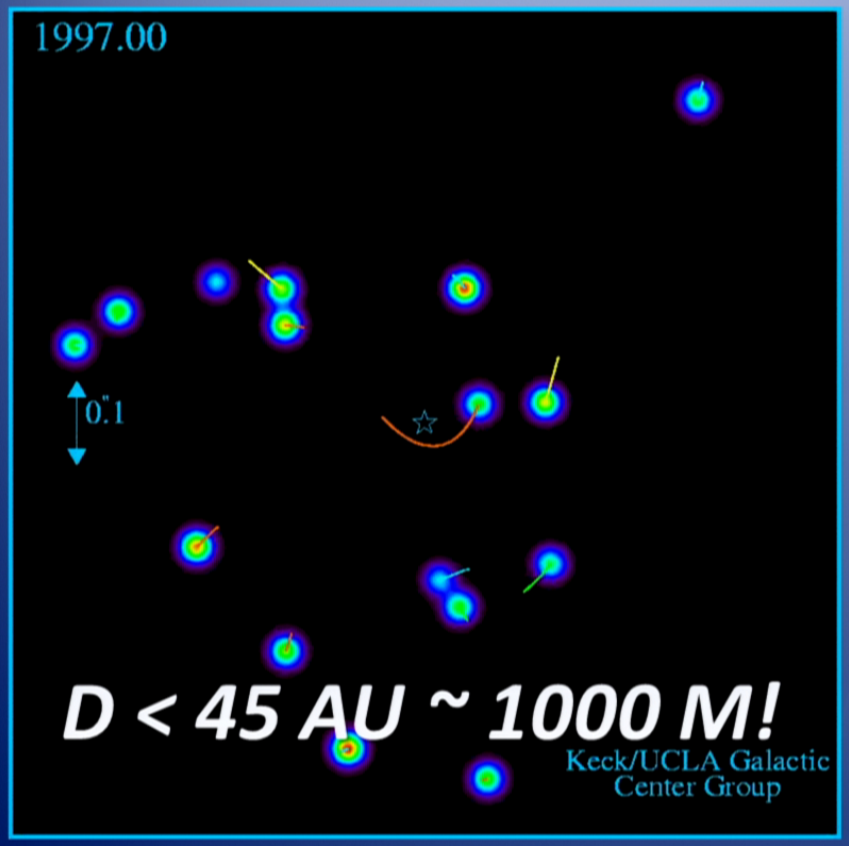

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PI Colloquium, Feb. 15, 2012

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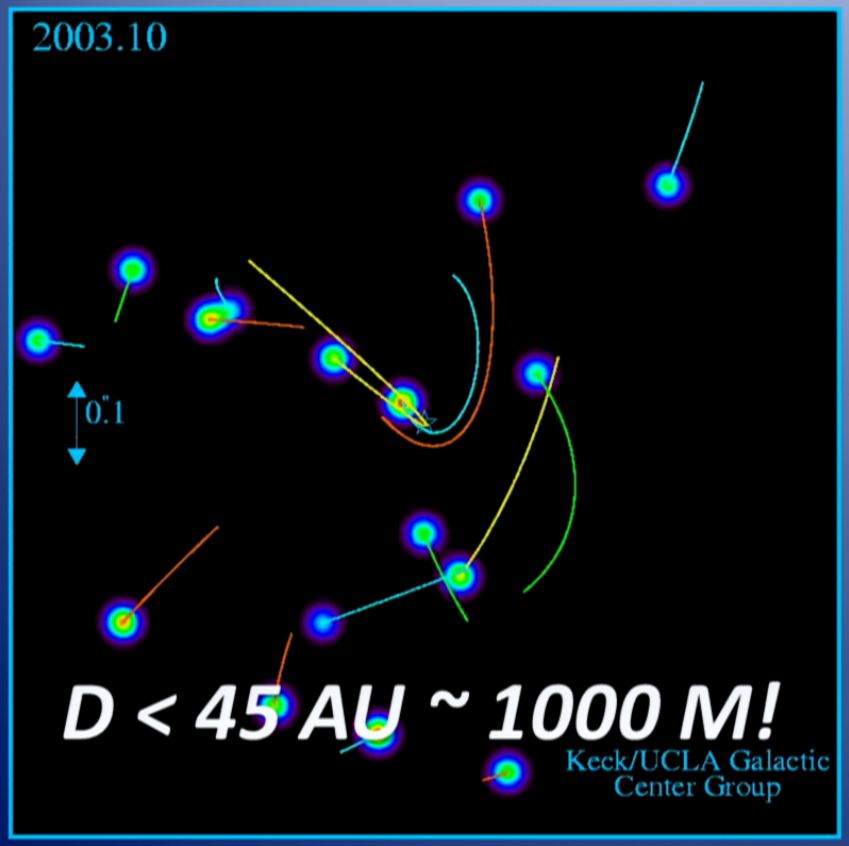

- $M = 4 \times 10^6 M_{sun}$
- $L_{Edd} \simeq 10^{45} \mathrm{erg/s}$
- $L \sim 10^{-9} L_{Edd}$!

PI Colloquium, Feb. 15, 2012

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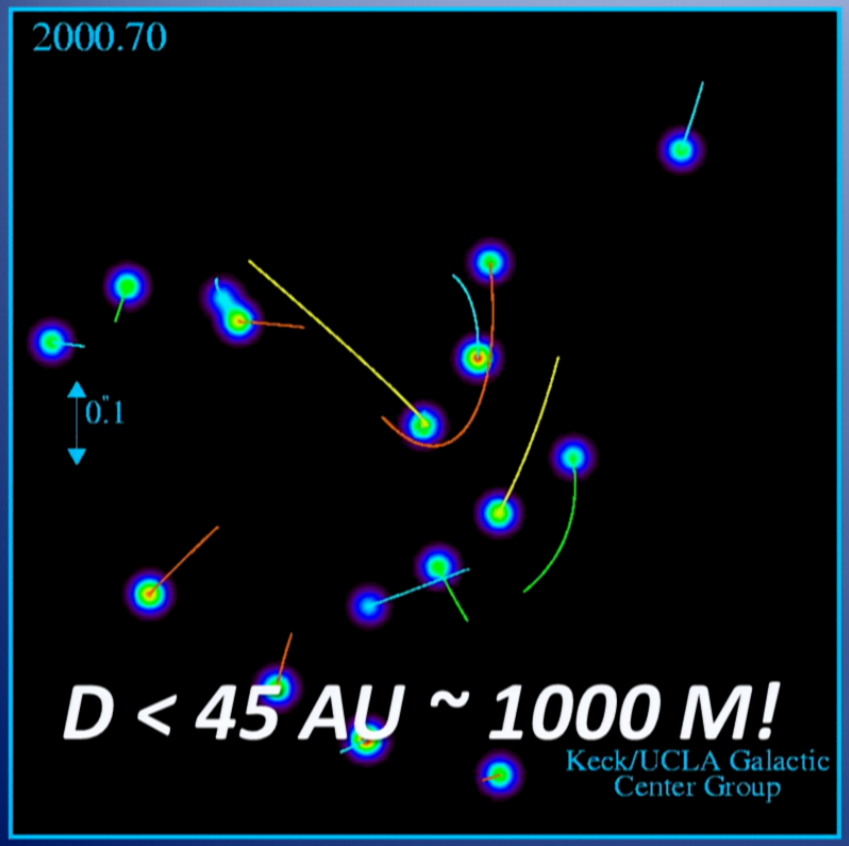

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- $L \sim 10^{-9} L_{Edd}$!
- $\dot{M} \sim 10^{-9}\ \dot{M}_{Edd}$

(if at 10% efficiency!)

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Is $\dot{M}$ really that low?

$\dot{M}_{Bondi} \sim 10^{-5}\, M_{sun}/\mathrm{yr}$

$\sim 10^{-4}\, \dot{M}_{Edd}$

$\gg 10^{-9} \dot{M}_{Edd}$!

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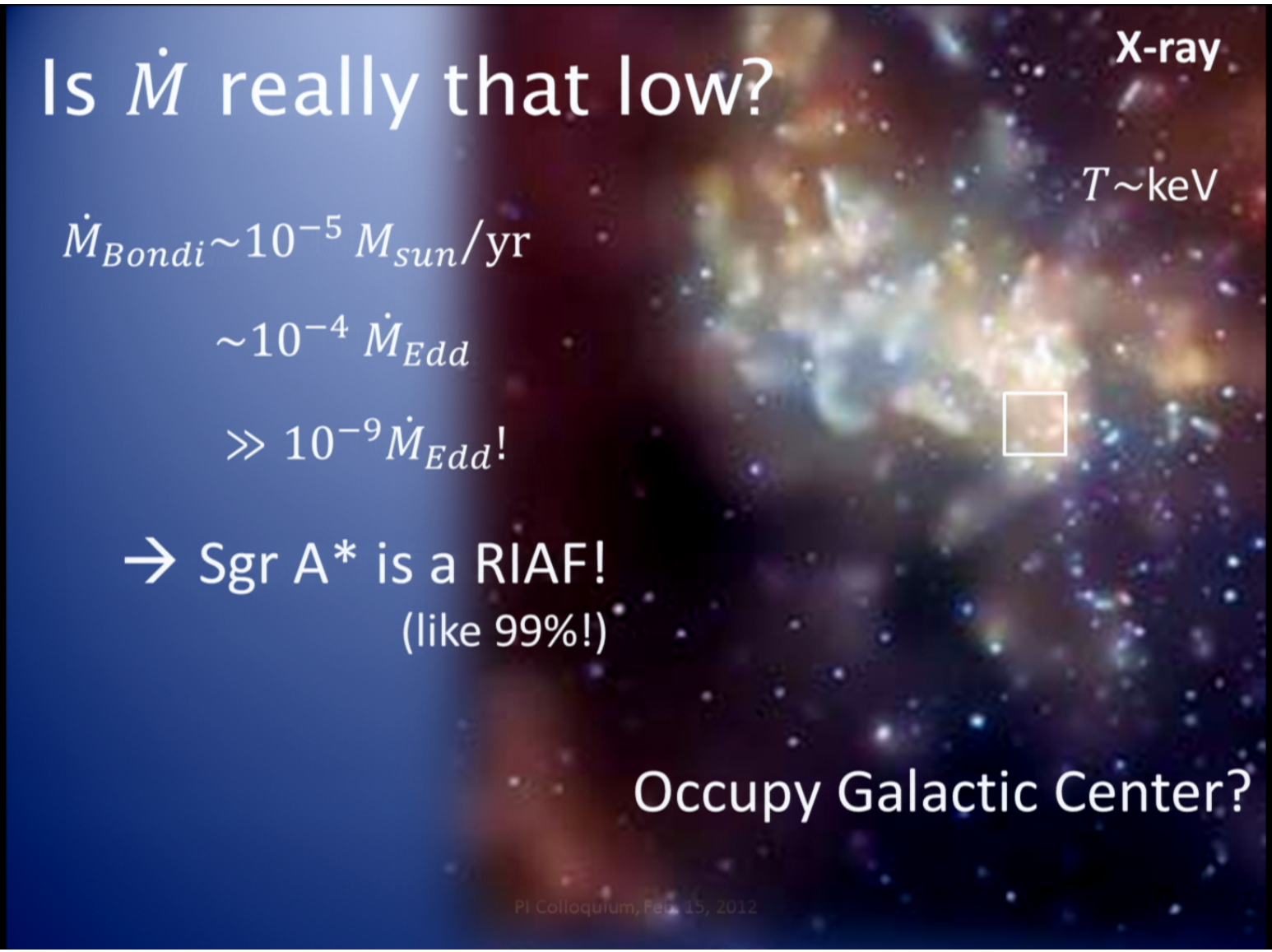
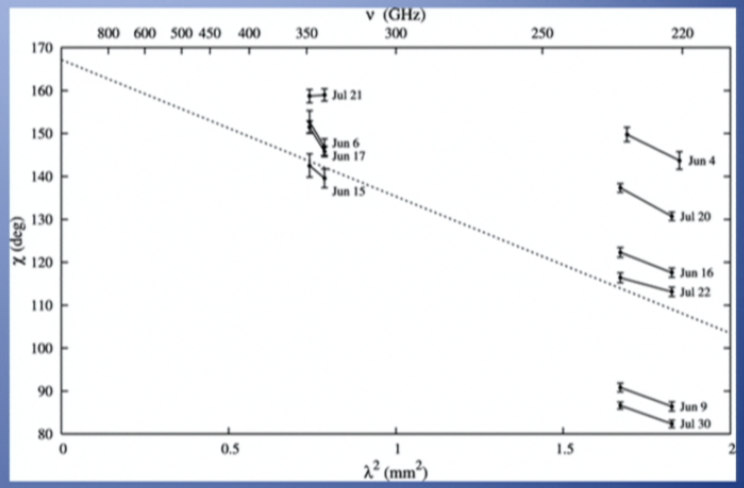


Loose Threads …

- Polarization:

Dan Marrone



$$RM \equiv \frac{d\chi}{d\lambda^2} \sim 10^6 \text{ rad/m}^2 \propto nBR$$

$$\rightarrow \dot{M} \sim 10^{-8}\, M_{sun}/\text{yr}$$

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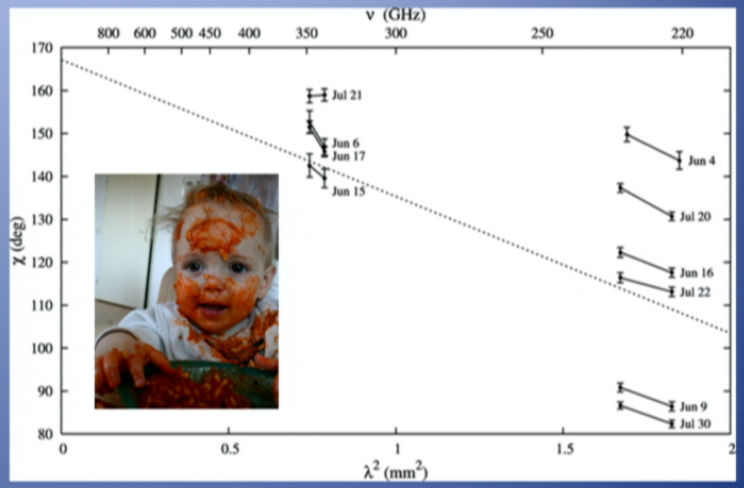

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PI Colloquium, Feb. 15, 2012

Loose Threads …

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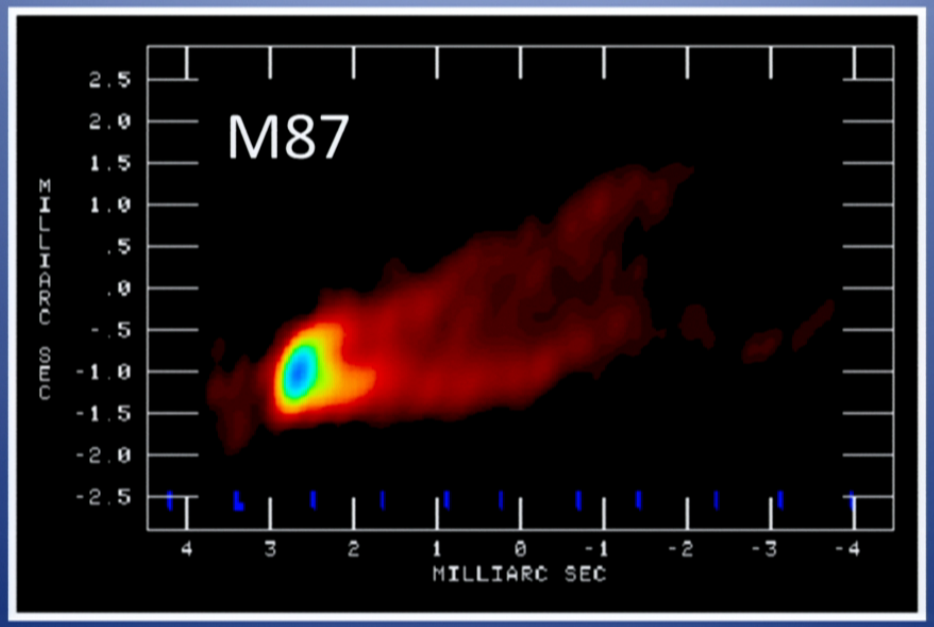
- Accretion vs. Jet Power



Craig Walker

PI Colloquium, Feb. 15, 2012

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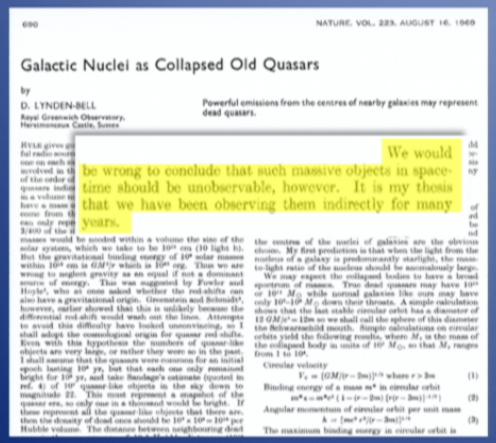
- Accretion vs. Jet Power
- Accretion power vs. something else?



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.

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.

- Power Density
- Inevitability

PI Colloquium, Feb. 15, 2012

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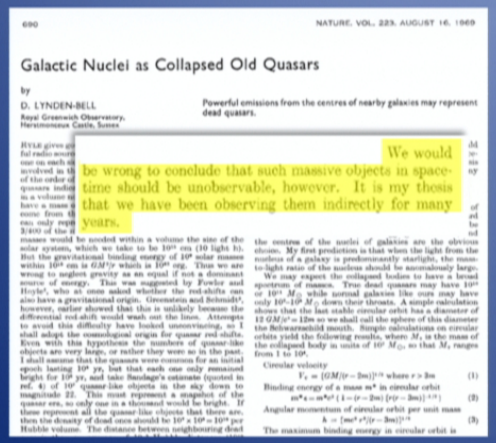

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*"**That some form of the meteoric theory is certainly the true and complete explanation of solar heat can scarcely be doubted**, when the following reasons are considered: (1) No other natural explanation, except by chemical action, can be conceived. (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

- Power Density
- Inevitability

PI Colloquium, Feb. 15, 2012

Loose Threads …

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- How does ang. mom. transfer really work?

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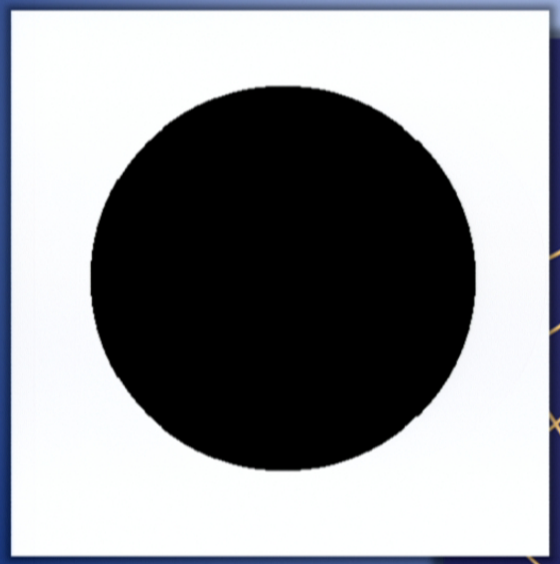
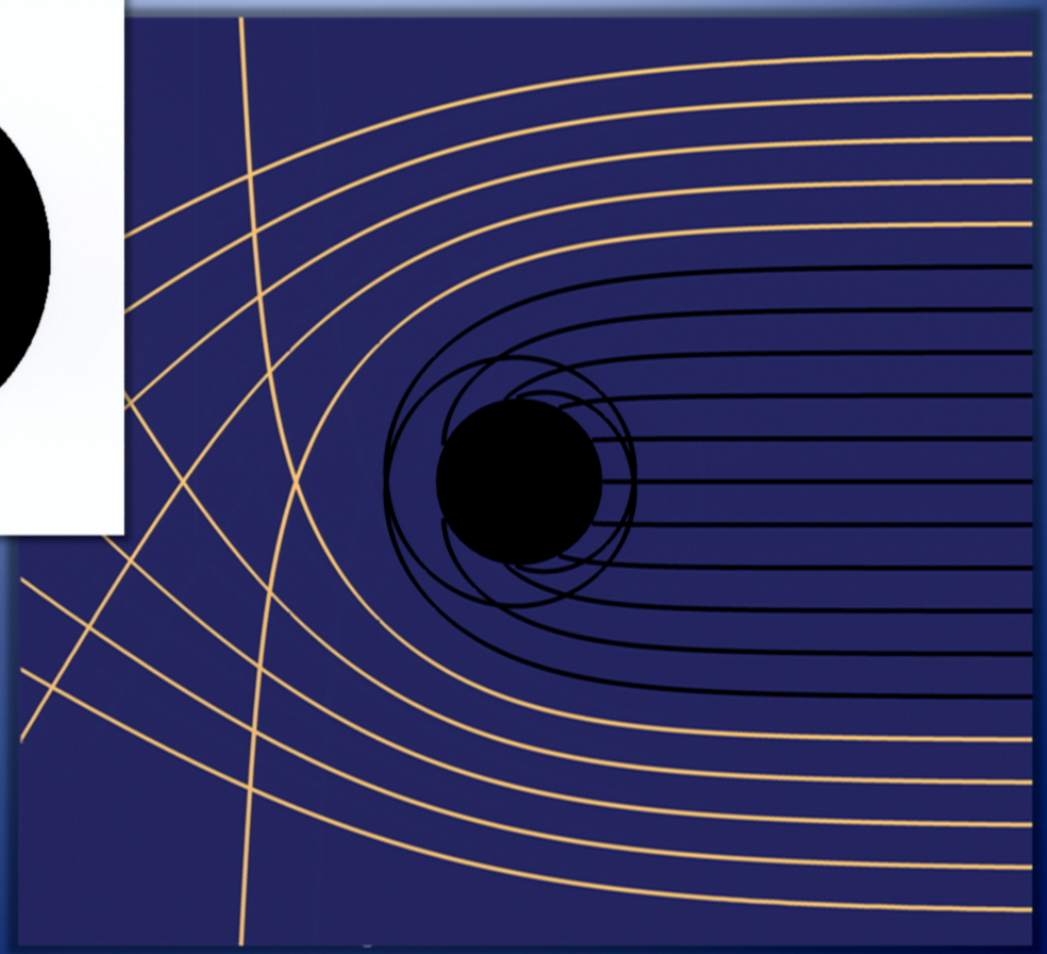
- How does ang. mom. transfer really work?
- What are the consequences of strong gravity?

PI Colloquium, Feb. 15, 2012

Advantages of being next door!





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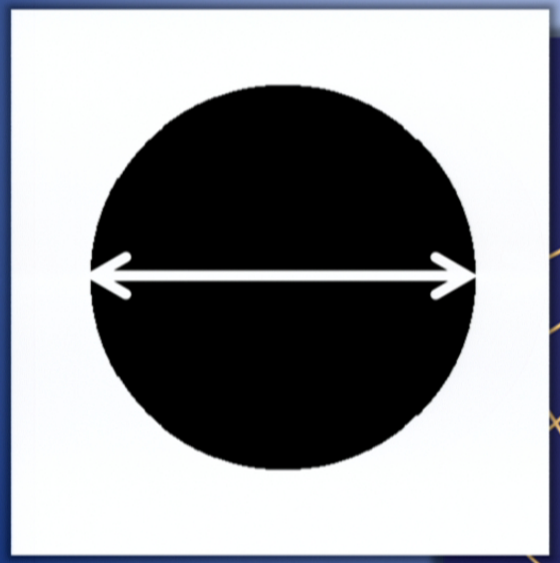

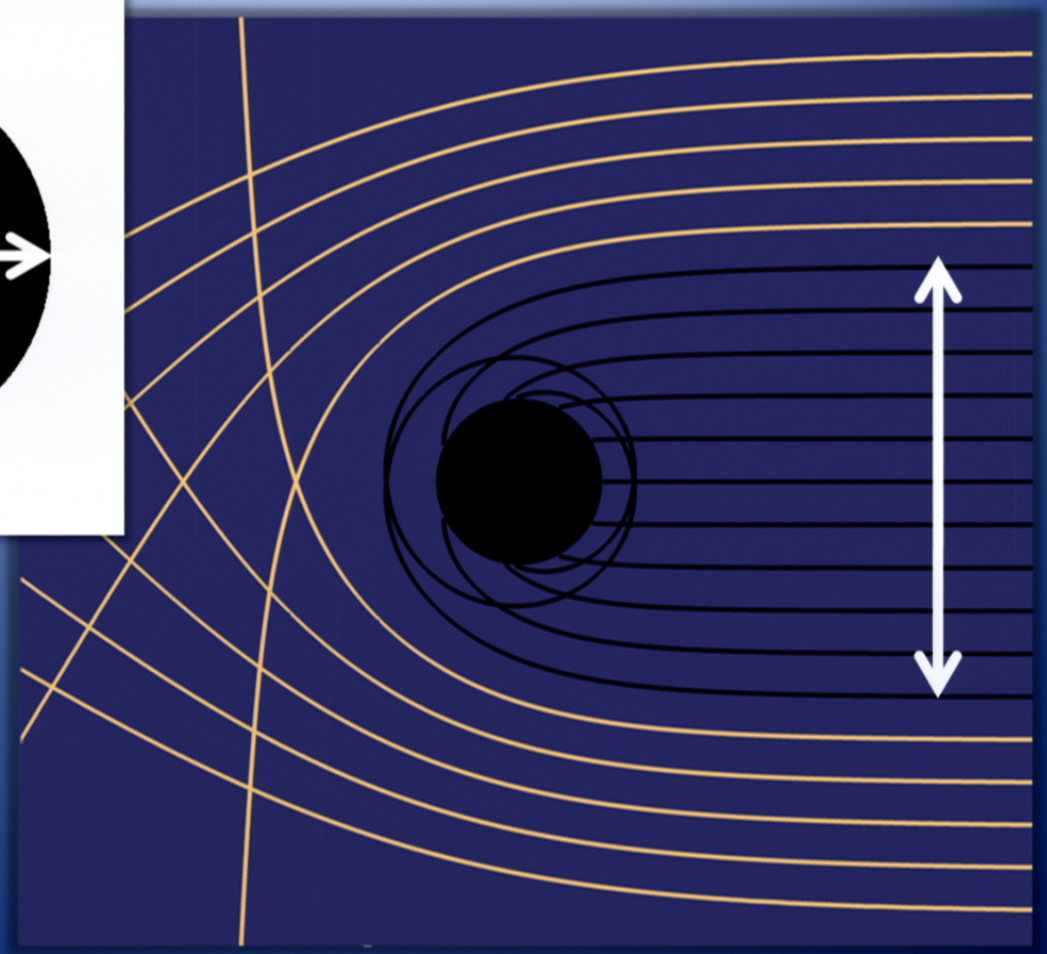

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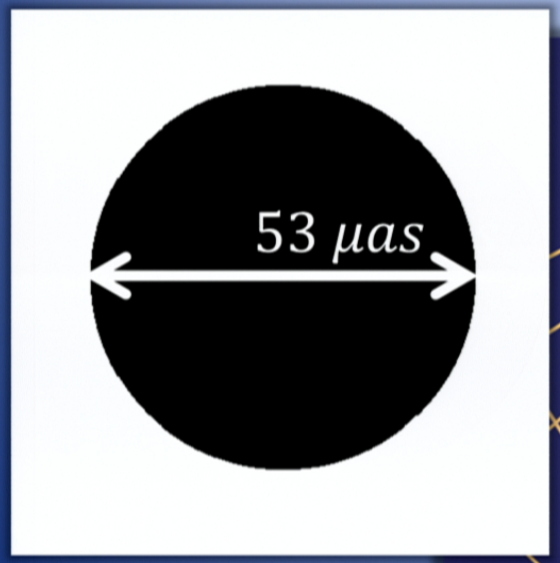
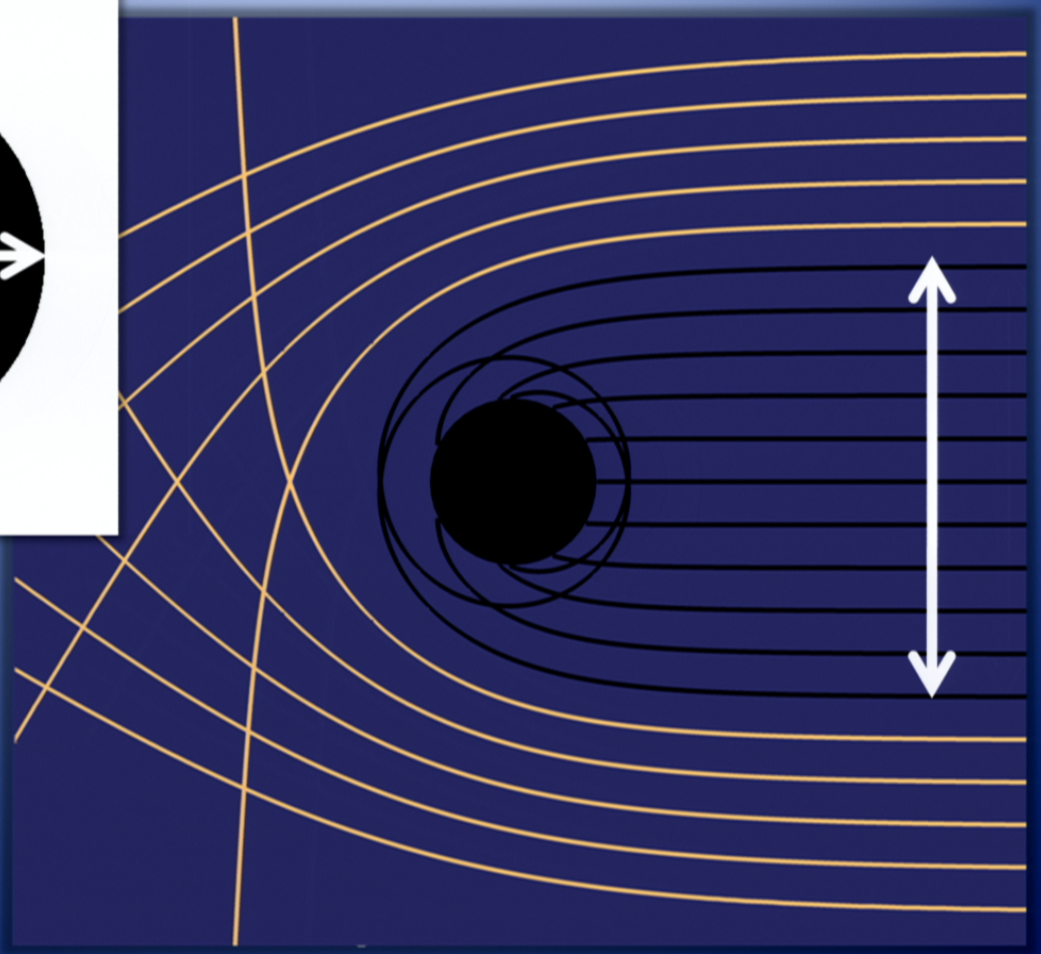
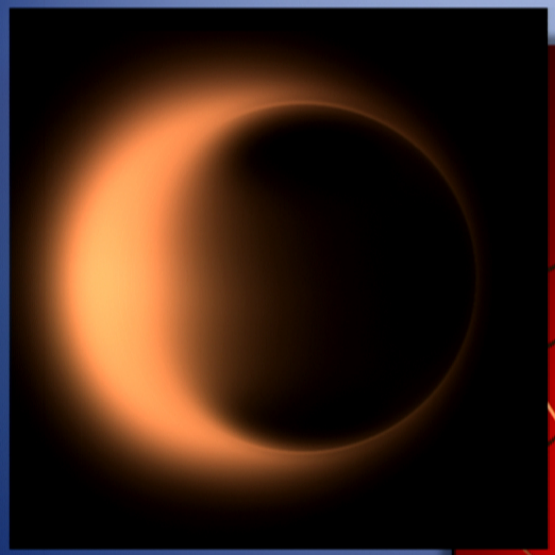
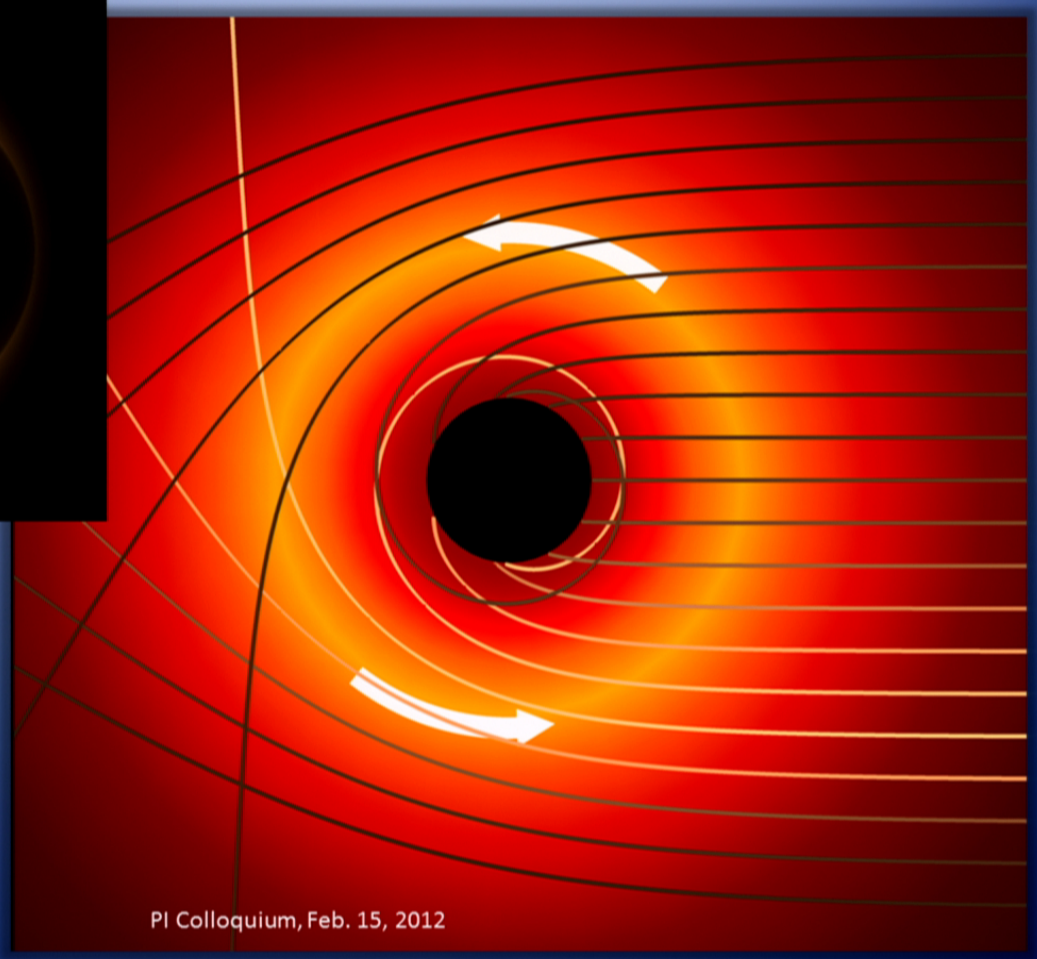




Accretion Flows Near the Horizon





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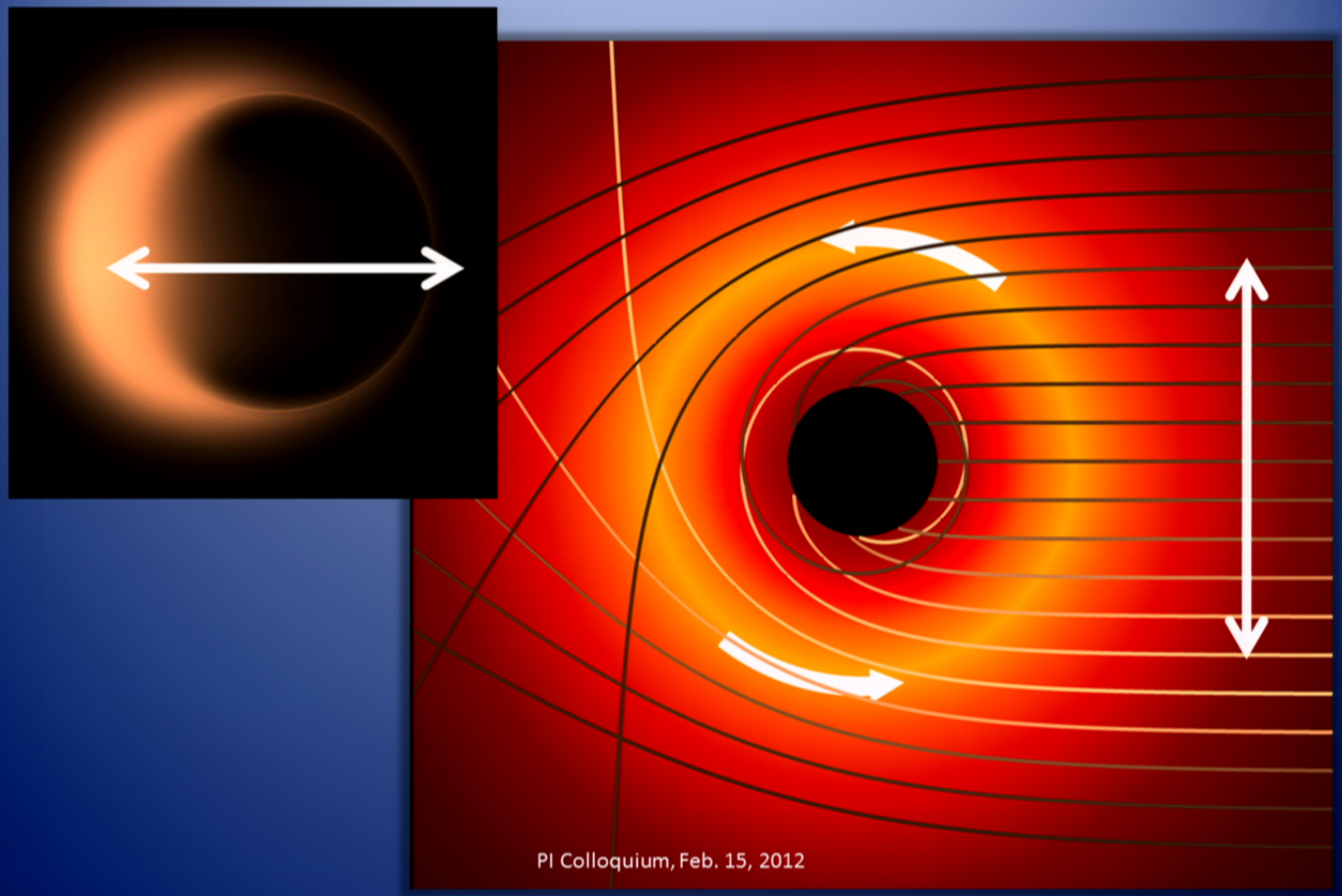

Diffraction Limited Telescopes

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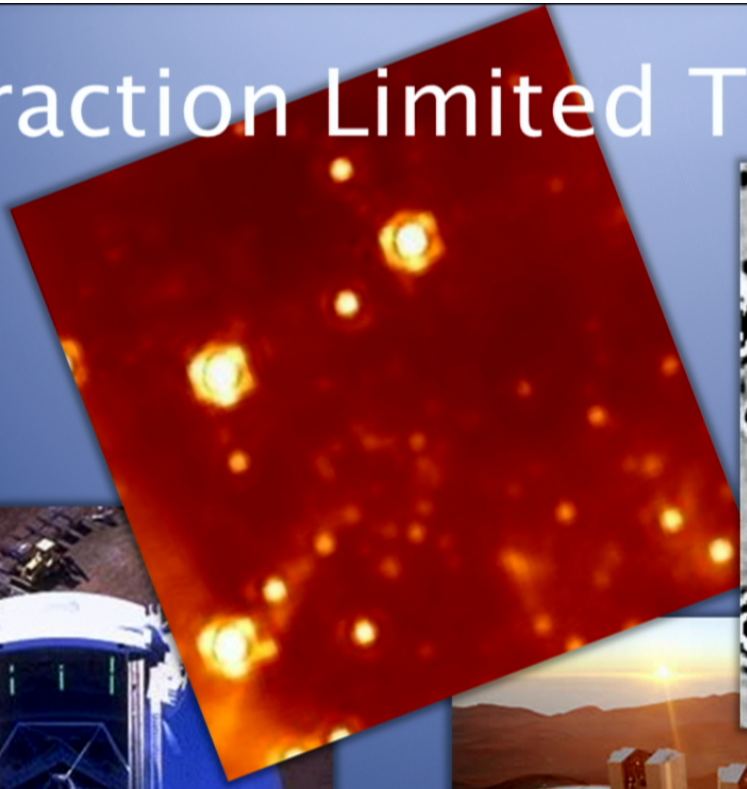
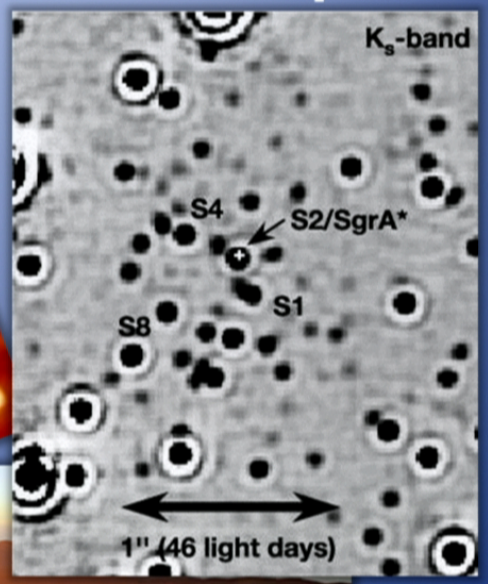
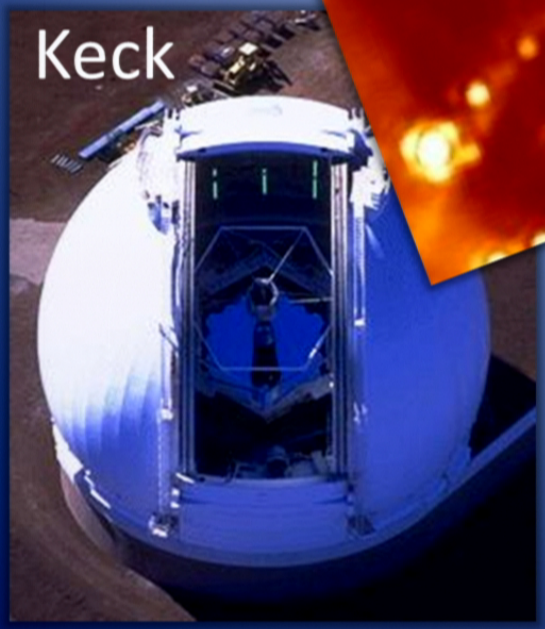
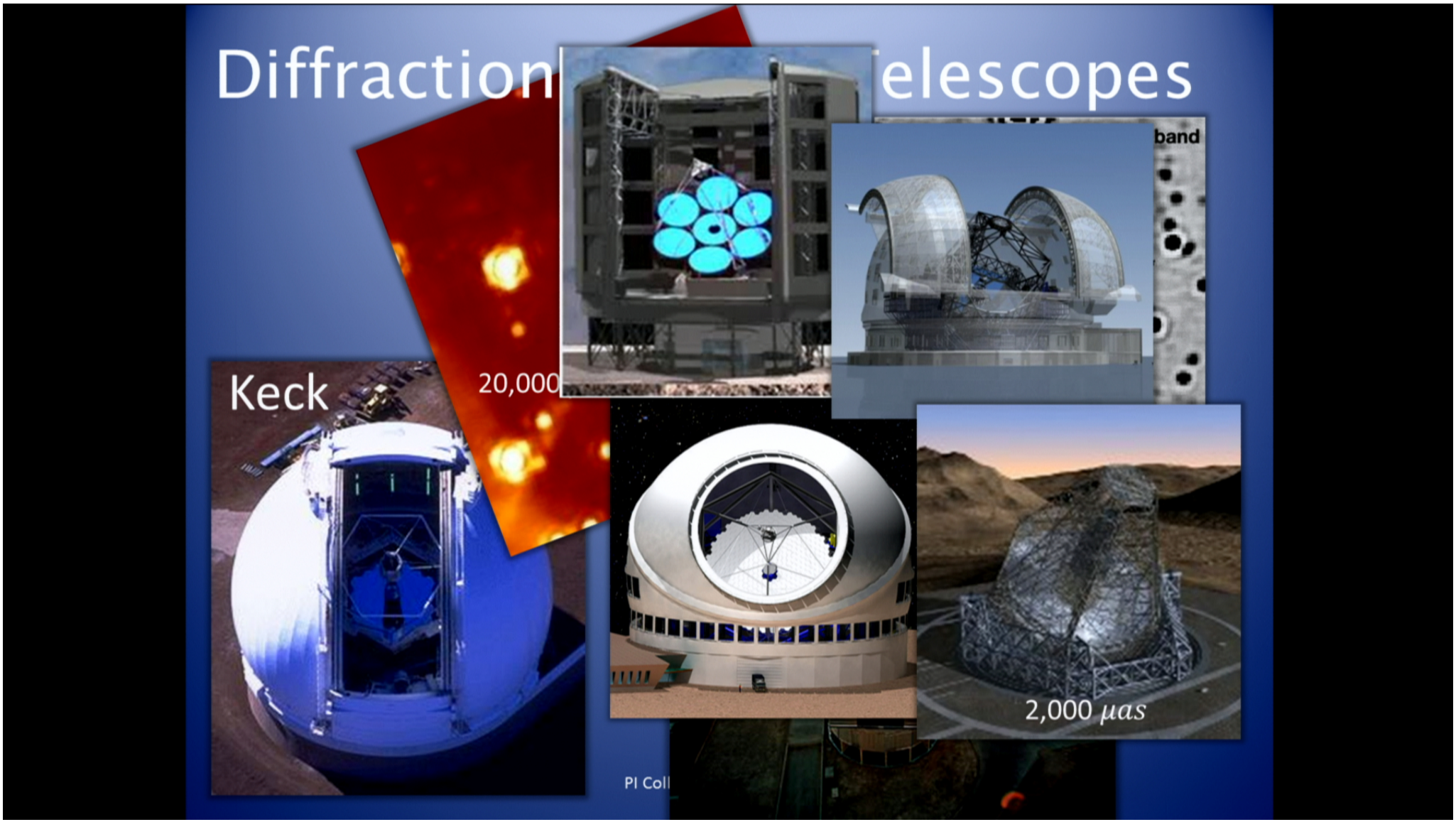






PI Coll


Diffraction
elescopes
band
Keck
20,000
2,000 μas
PI Coll

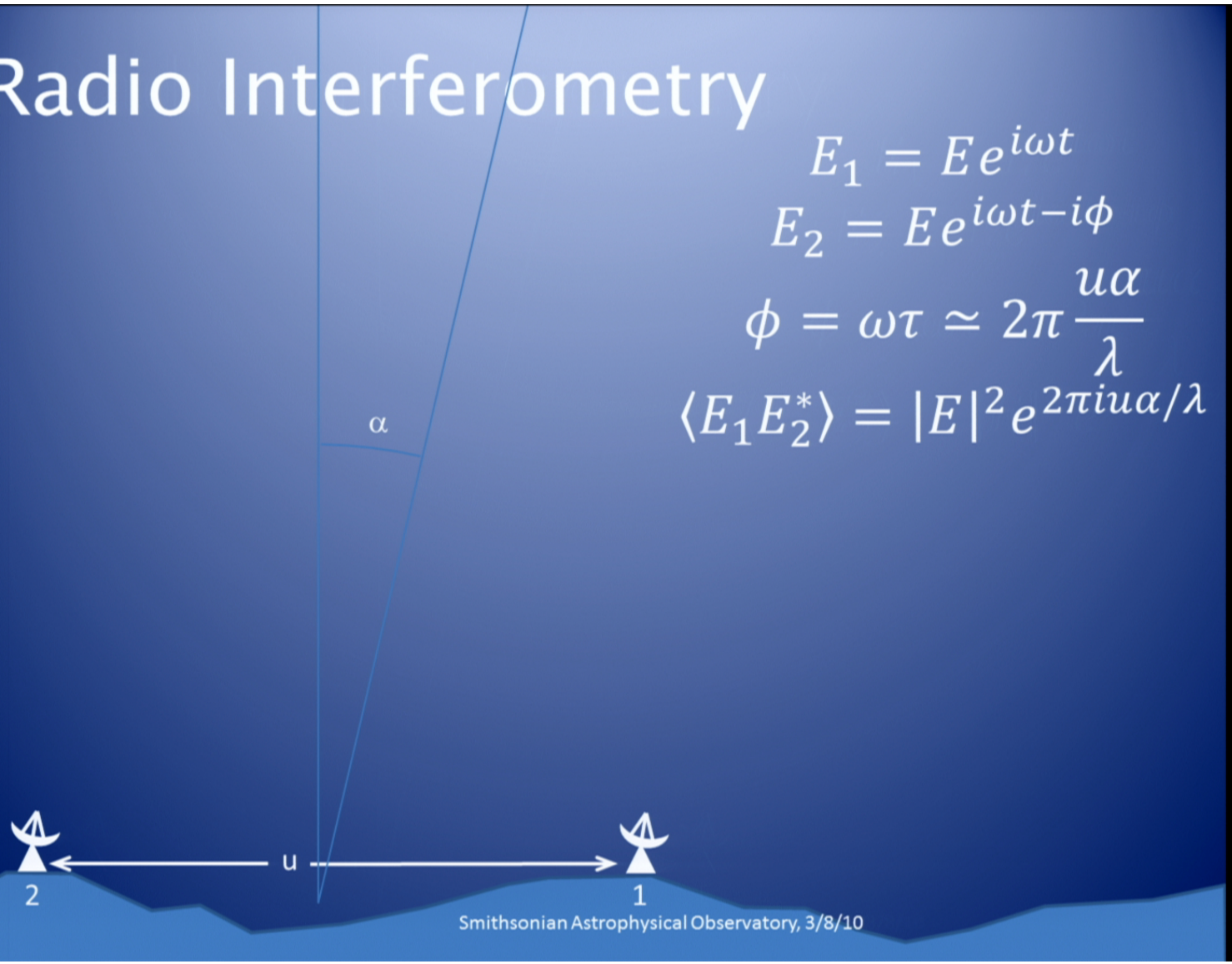
Radio Interferometry

$$E_1 = E e^{i\omega t}$$

$$E_2 = E e^{i\omega t - i\phi}$$

$$\phi = \omega\tau \simeq 2\pi \frac{u\alpha}{\lambda}$$

$$\langle E_1 E_2^* \rangle = |E|^2 e^{2\pi i u\alpha/\lambda}$$



Smithsonian Astrophysical Observatory, 3/8/10

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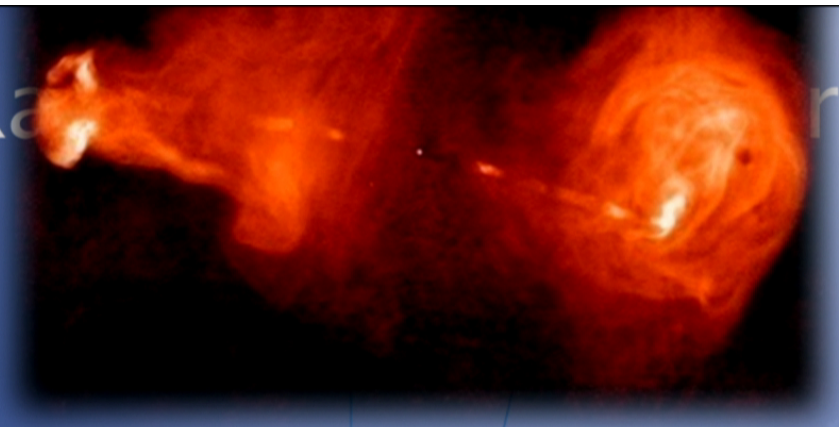

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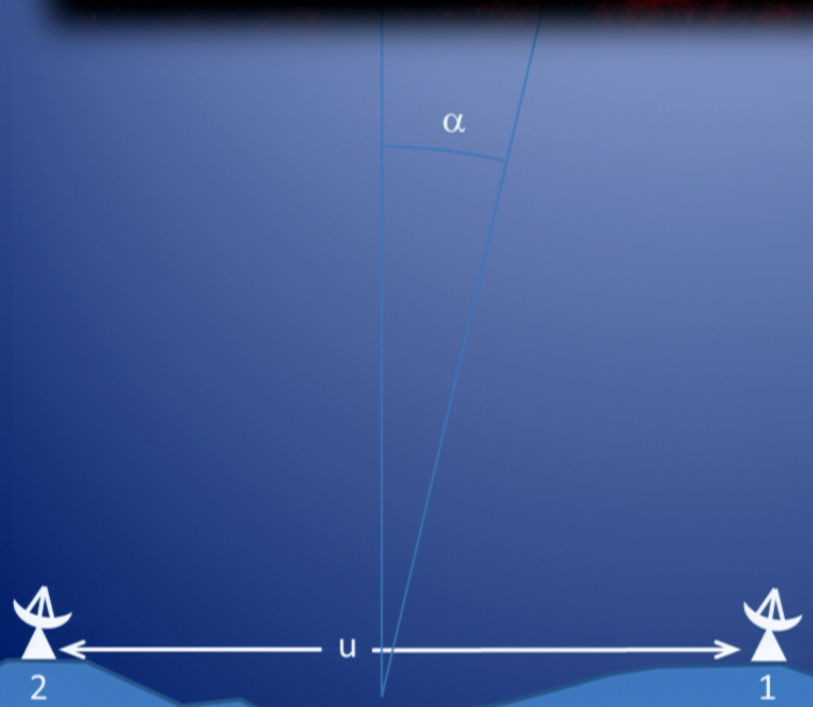

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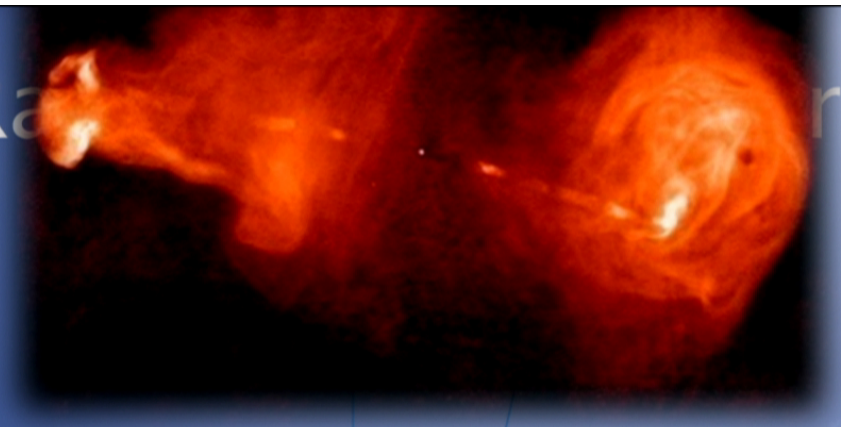

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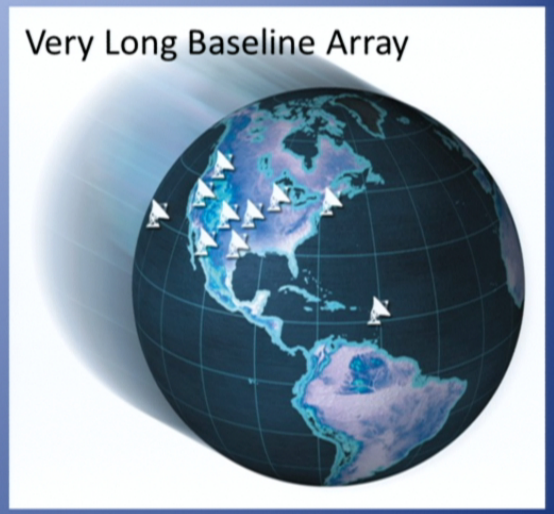
$$\rightarrow V_{12}(u) = \langle E_1 E_2^* \rangle = \int I(\alpha)\, e^{2\pi i u\alpha/\lambda} d\alpha$$

$$\Delta\theta \simeq \lambda/u$$

Smithsonian Astrophysical Observatory, 3/8/10

Very Long Baseline Interferometry

- The good: $\Delta\theta = \lambda/u$



PI Colloquium, Feb. 15, 2012

Very Long Baseline Interferometry

- The good: $\Delta\theta = \lambda/\mathbf{u}$
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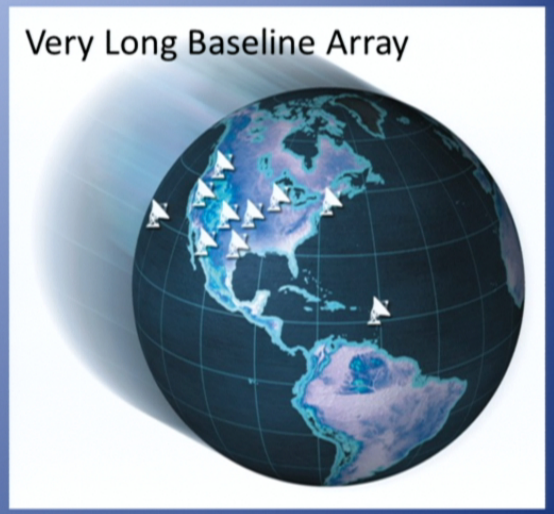
$$V_{ij} = \int I(\boldsymbol{\alpha}) e^{2\pi i \mathbf{u}_{ij} \cdot \boldsymbol{\alpha} / \lambda} d^2\alpha$$



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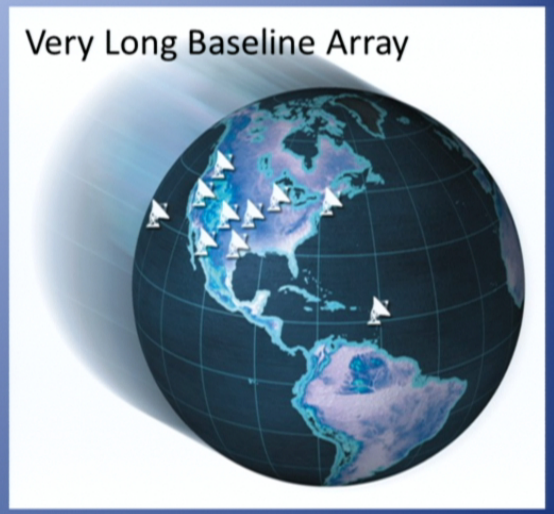

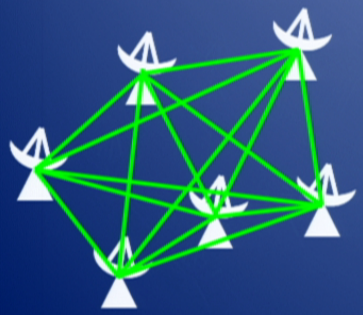

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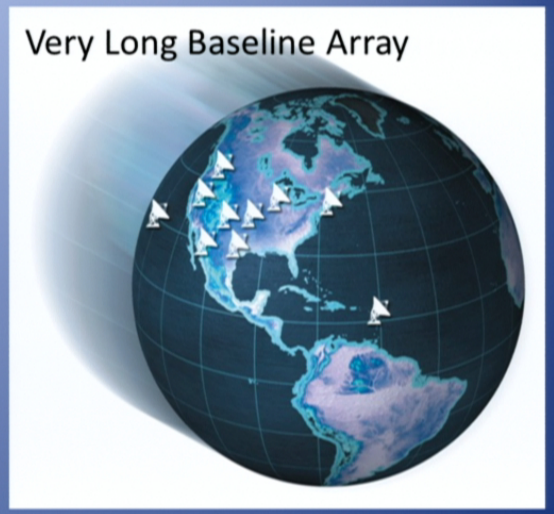

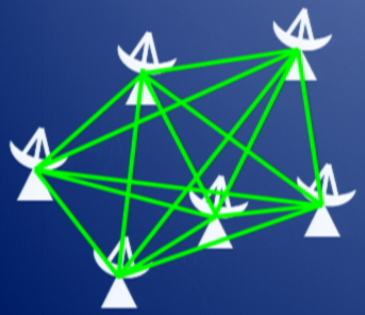

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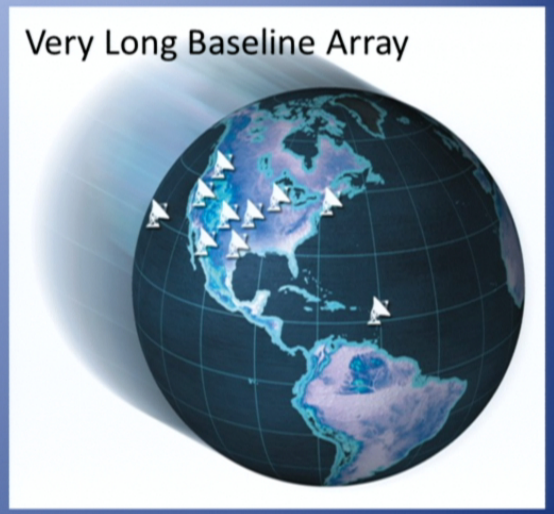

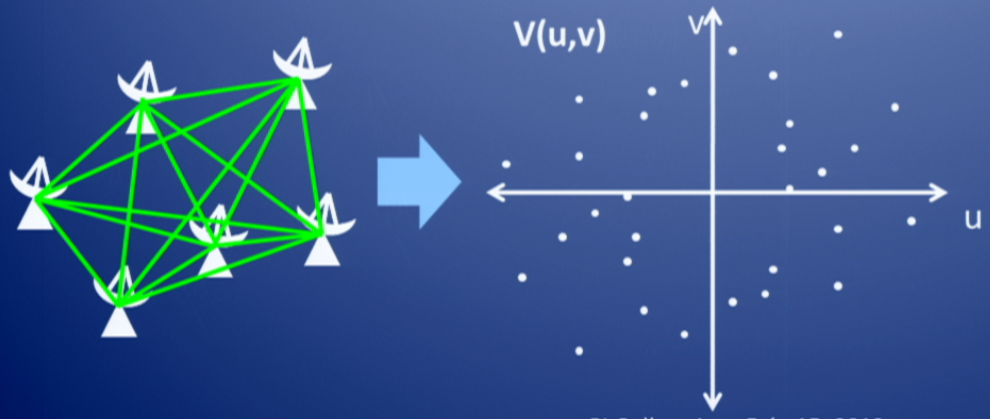

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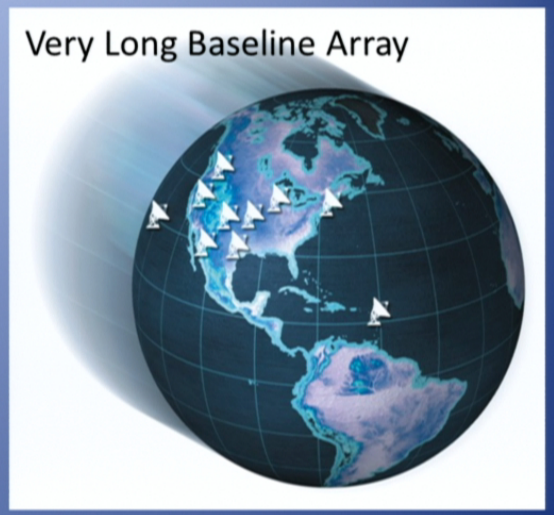

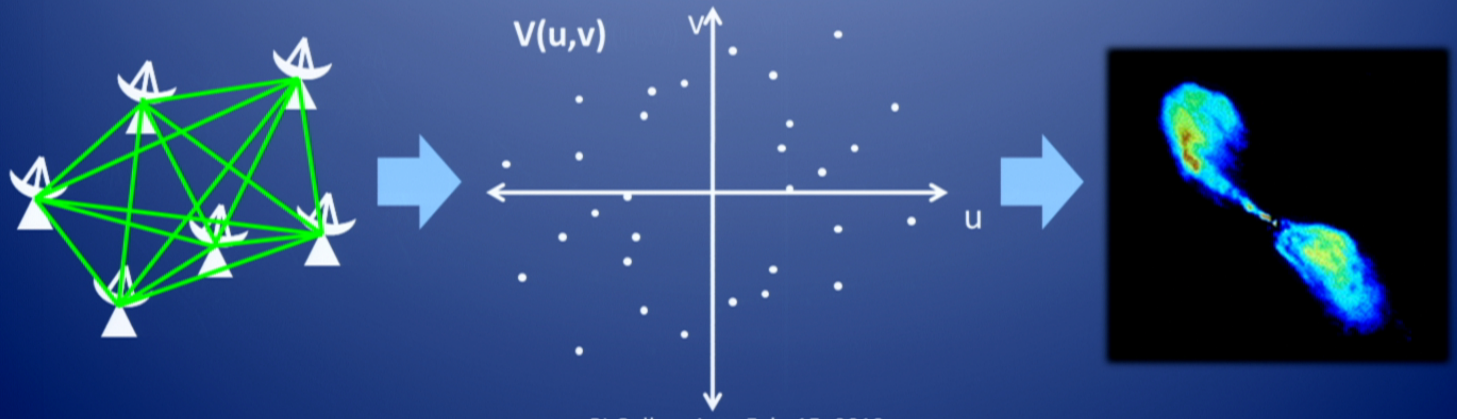

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Very Long Baseline Interferometry

- The good: $\Delta\theta = \lambda / \mathbf{u}$
- The bad: $V_{ij} = \int I(\boldsymbol{\alpha}) e^{2\pi i \mathbf{u}_{ij} \cdot \boldsymbol{\alpha} / \lambda} d^2\alpha$
- The ugly:
  - Sparse u-v coverage
  - Atmospheric phase errors

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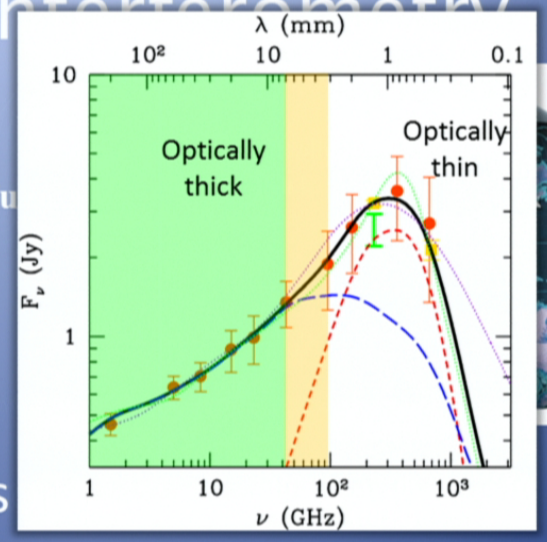

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  - Optically thick—thin transition

Very Long Baseline Interferometry

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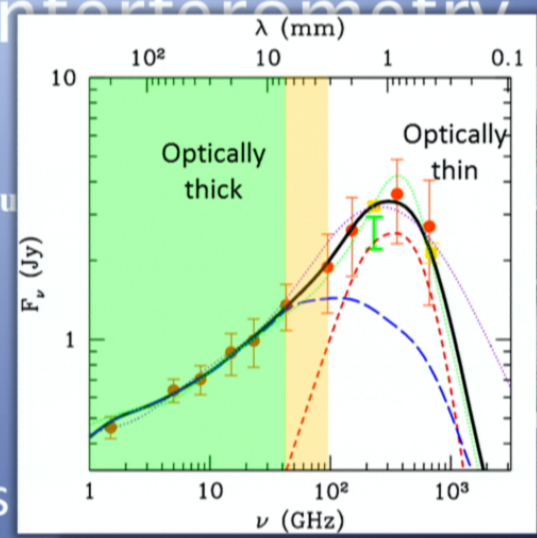

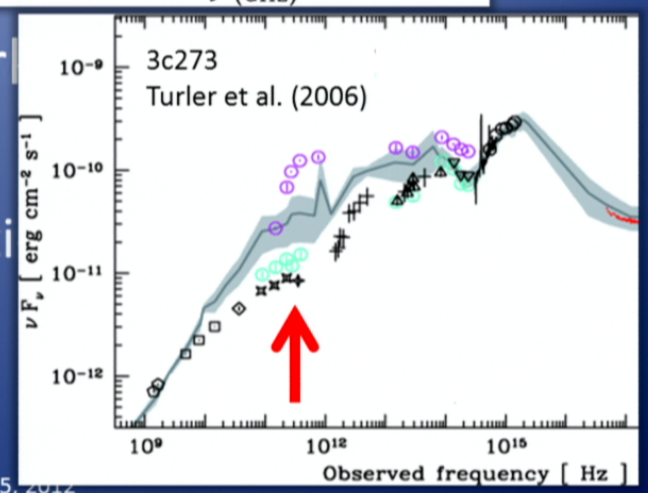

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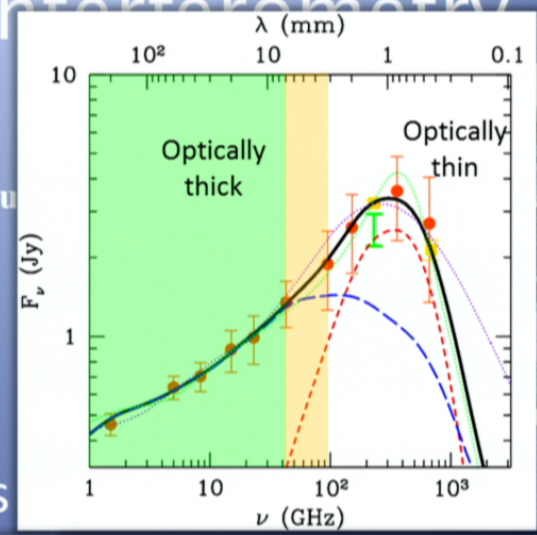

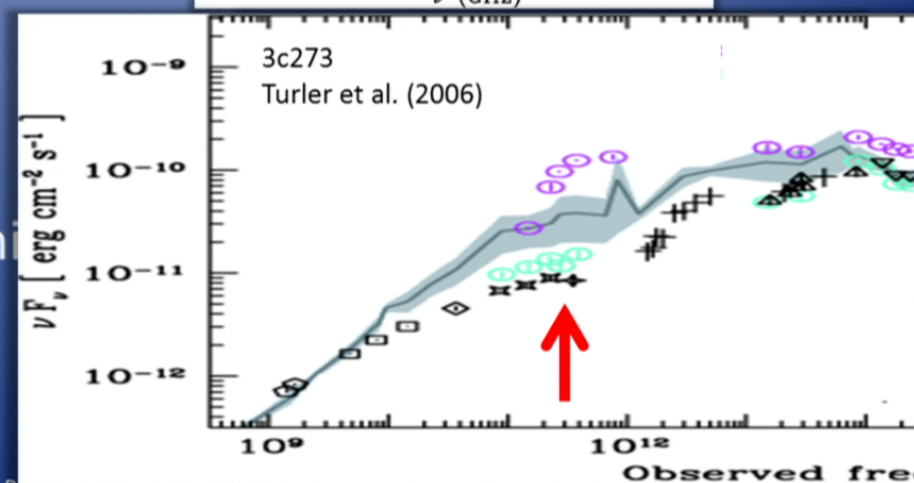

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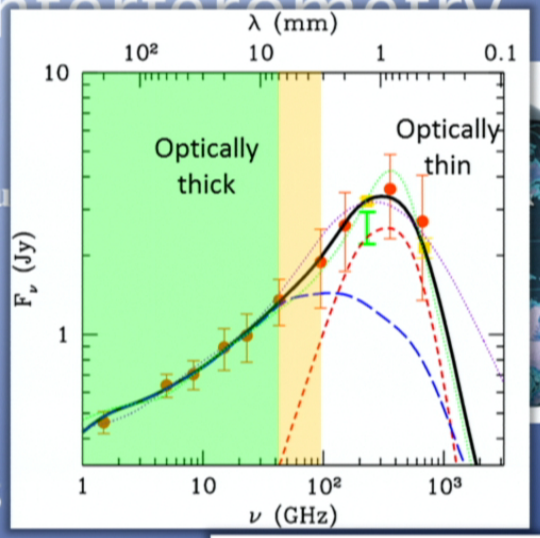

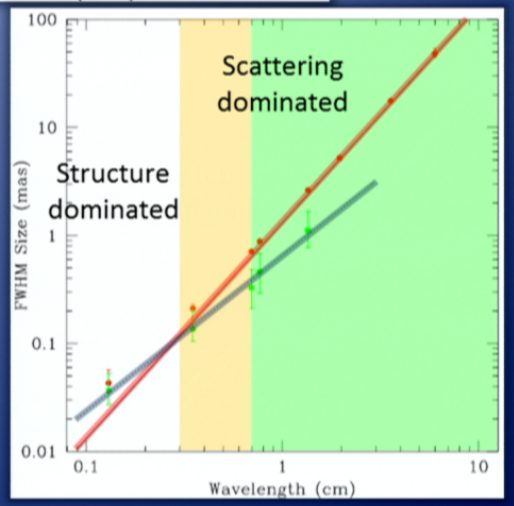

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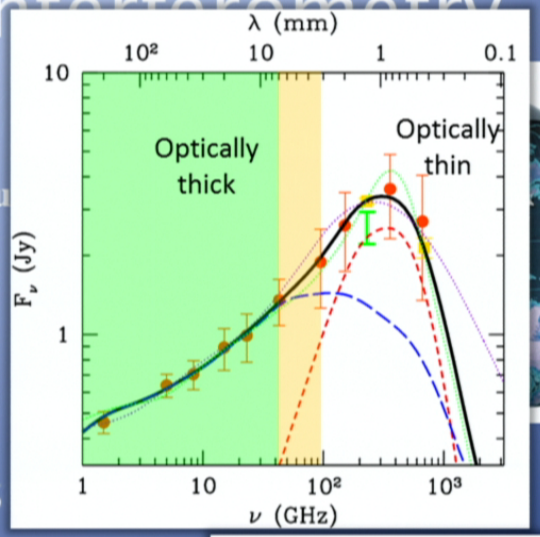
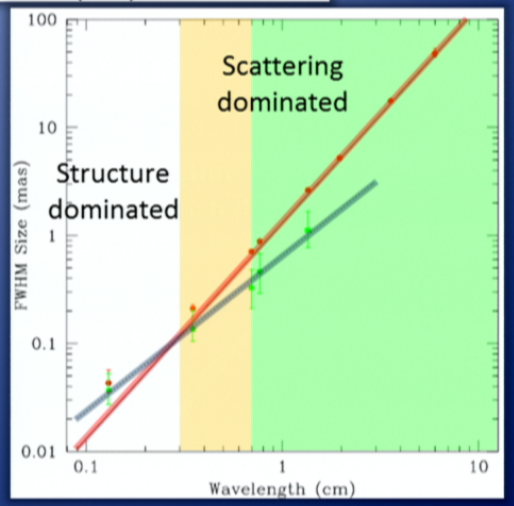
- But at 1 mm …





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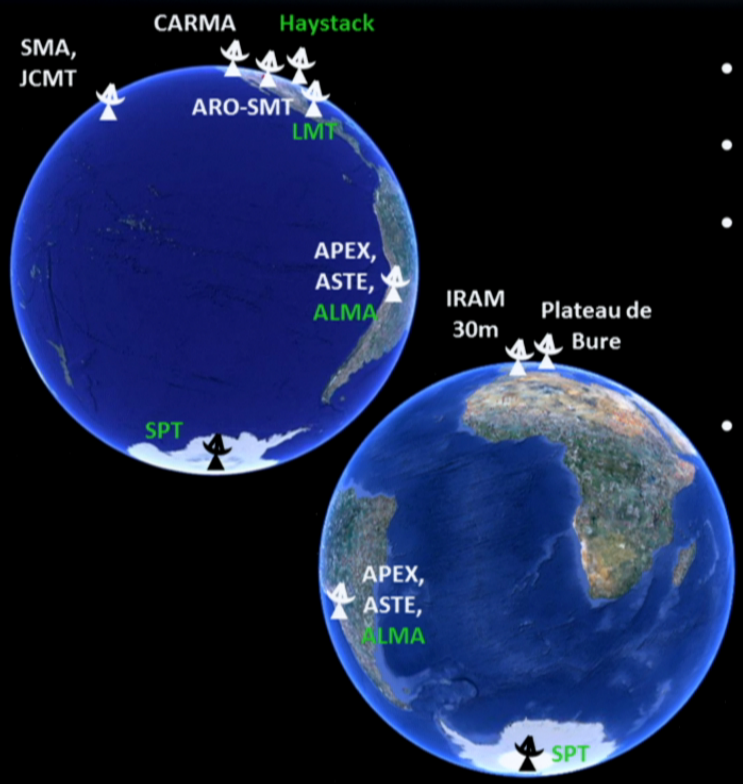
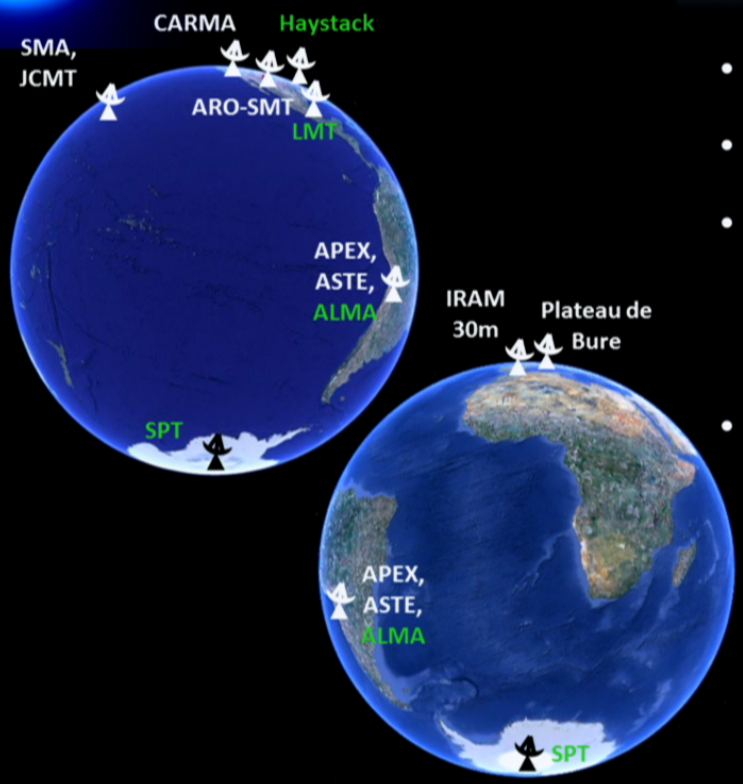
The *Event Horizon Telescope*



- Earth-sized mm/sub-mm VLBI array
- Existing and Planned telescopes.
- Accesses resolutions of ~10 μas,
  → Sufficient to resolve Sgr A*'s horizon!
- Why mm/sub-mm?
  - Optically thin transition (<3mm)
  - Interstellar scattering (<3mm)
  - Resolution from ground (<3mm)
  - "Standard" VLBI techniques (>0.1mm)
  - Good seeing at many sites (>0.5mm)

EventHorizonTelescope



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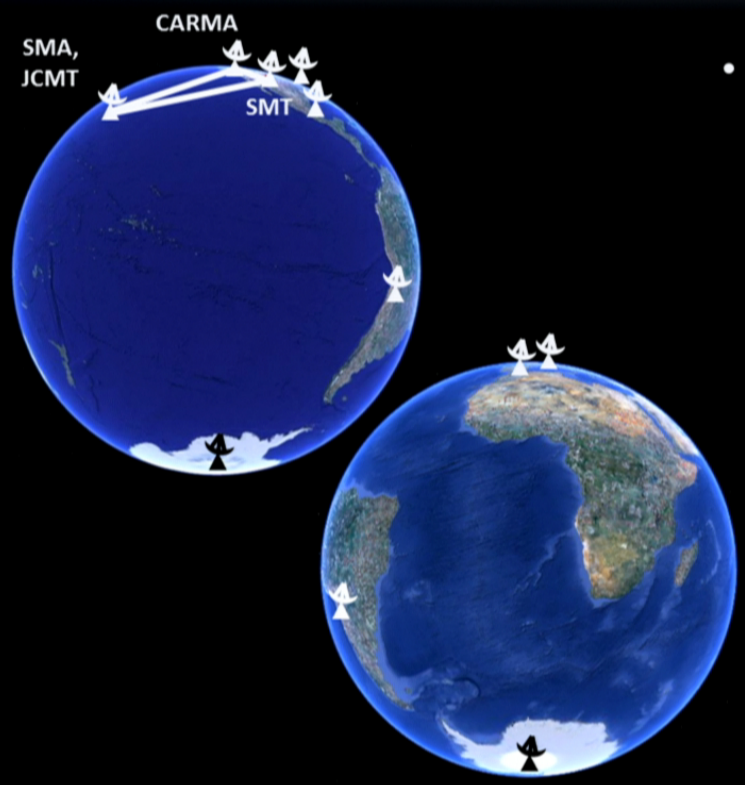
First Data from the EHT



- Data already exists on Hawaii-CARMA-SMT
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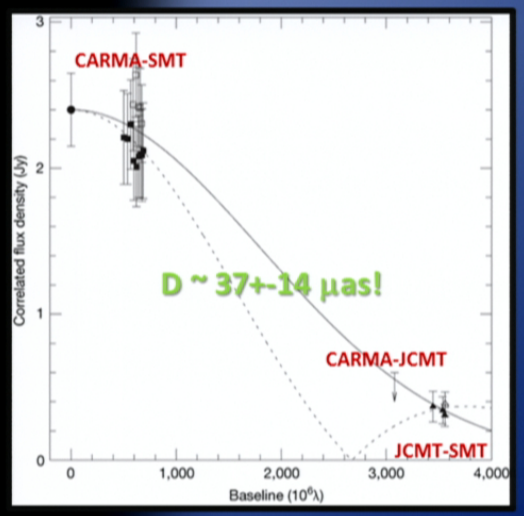

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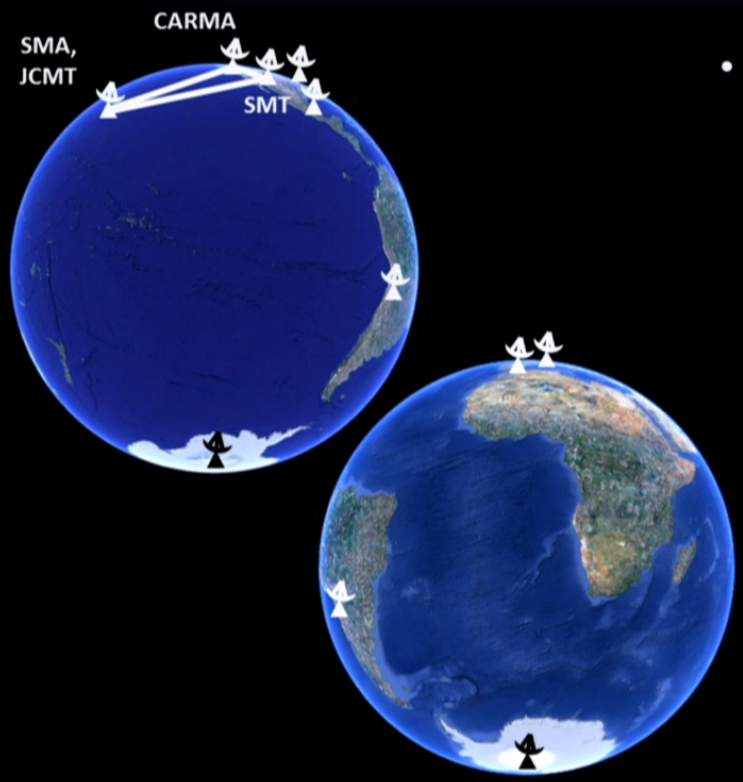

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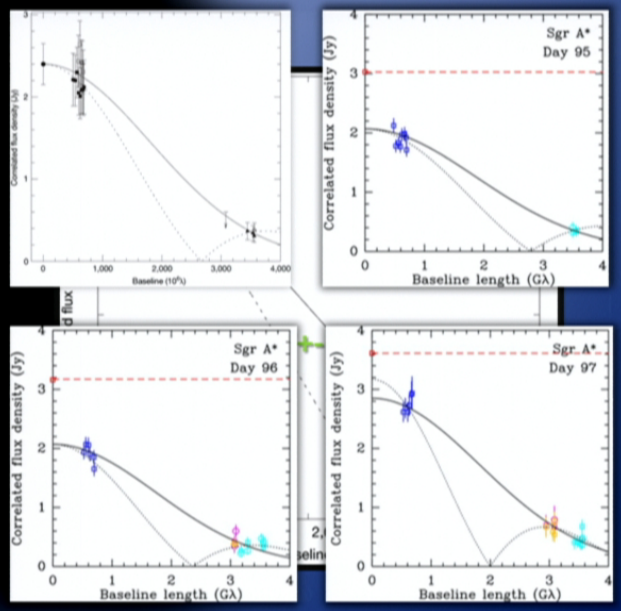

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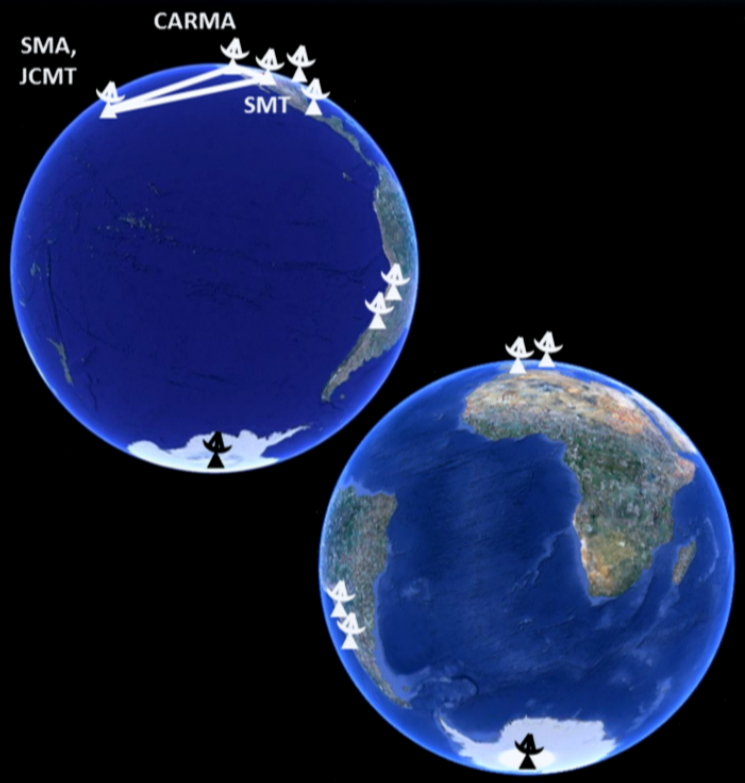
Future Growth of the EHT



- Increasing Sensitivity:
  - Phasing Arrays
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  - Expanding Bandwidth to 4GHz
  - Building New Receivers

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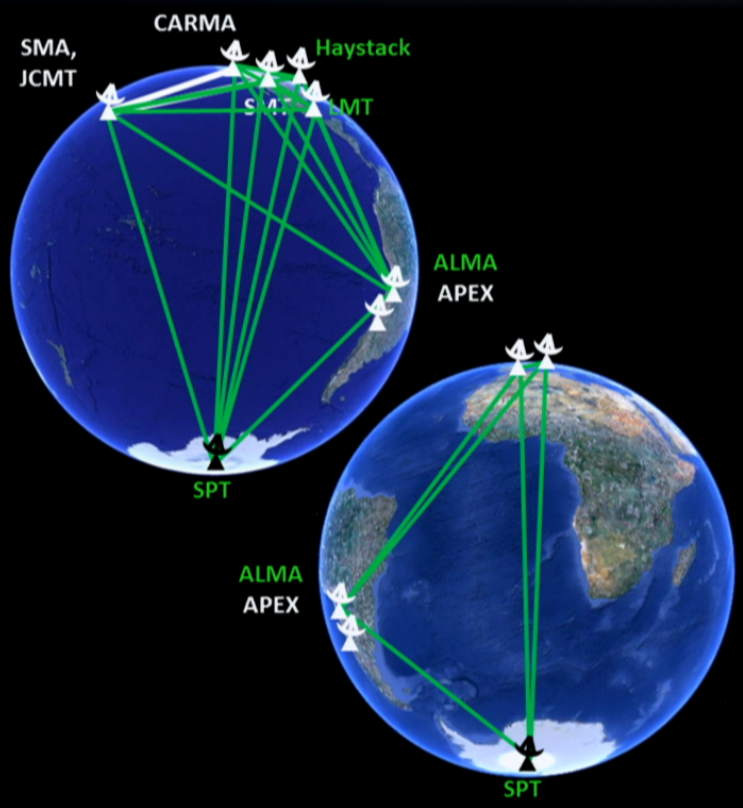

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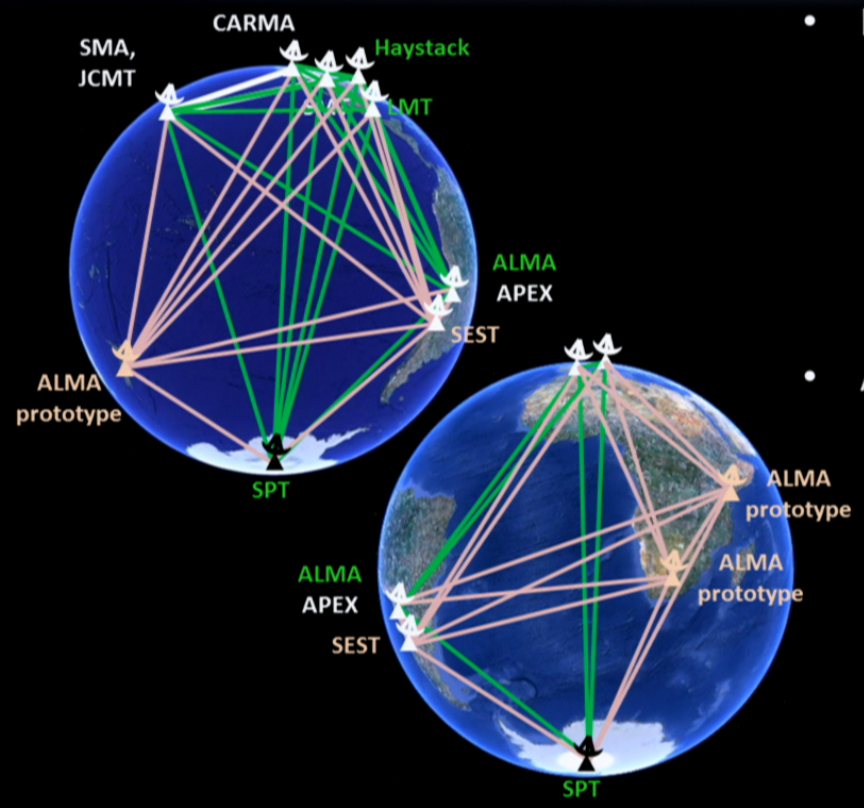

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  - New (ALMA prototype dishes)
    - New Zealand
    - Kilimanjaro
    - South Africa
    - SEST

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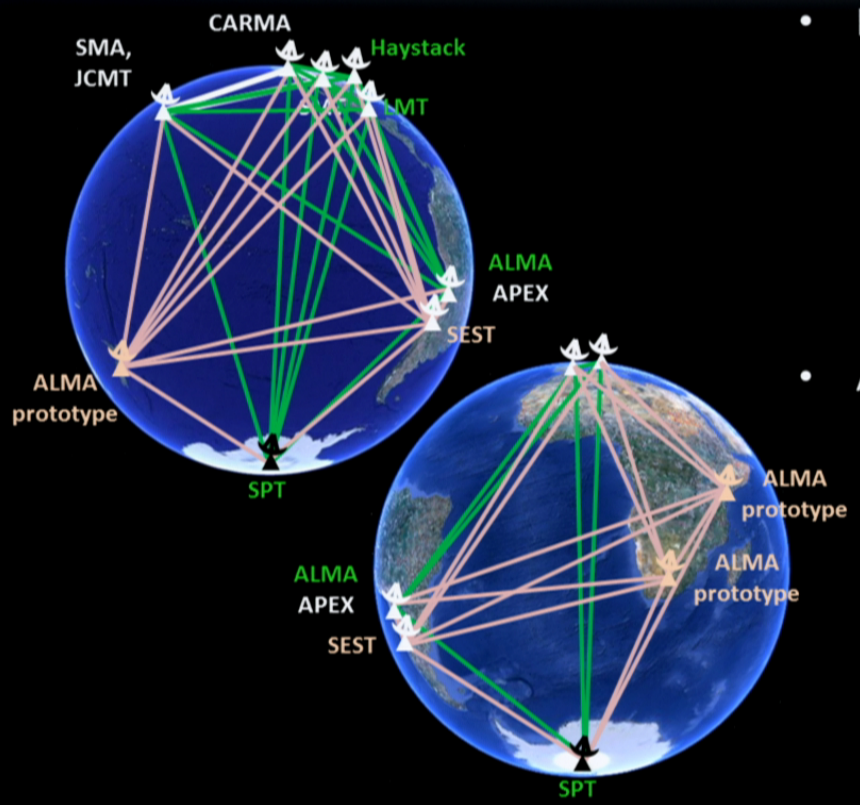
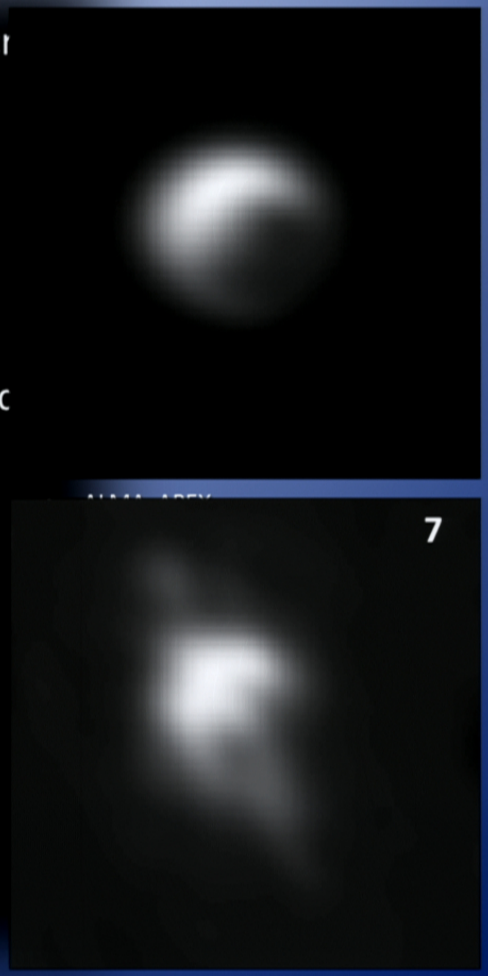
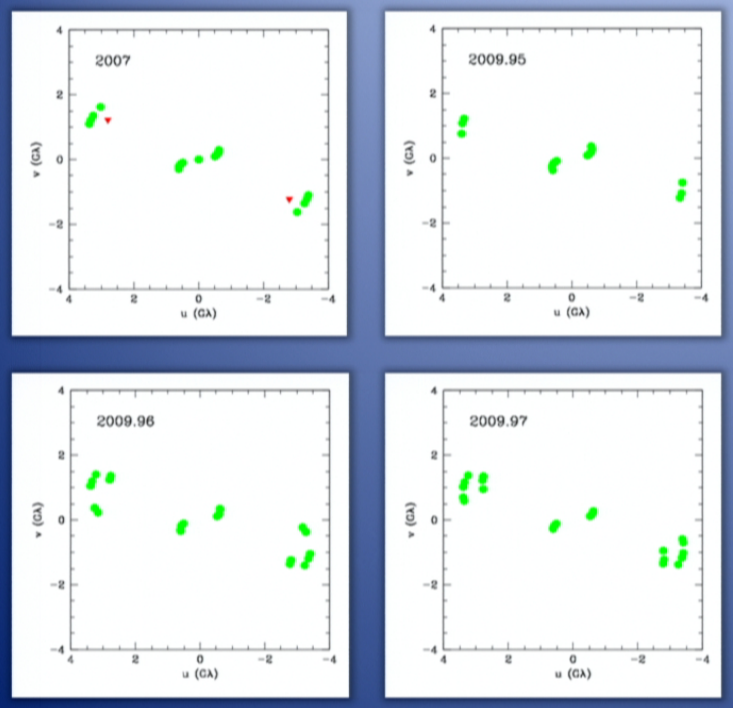


- Incr
  -
  -
  -
- Adc
  -
  -



EHT Data Today



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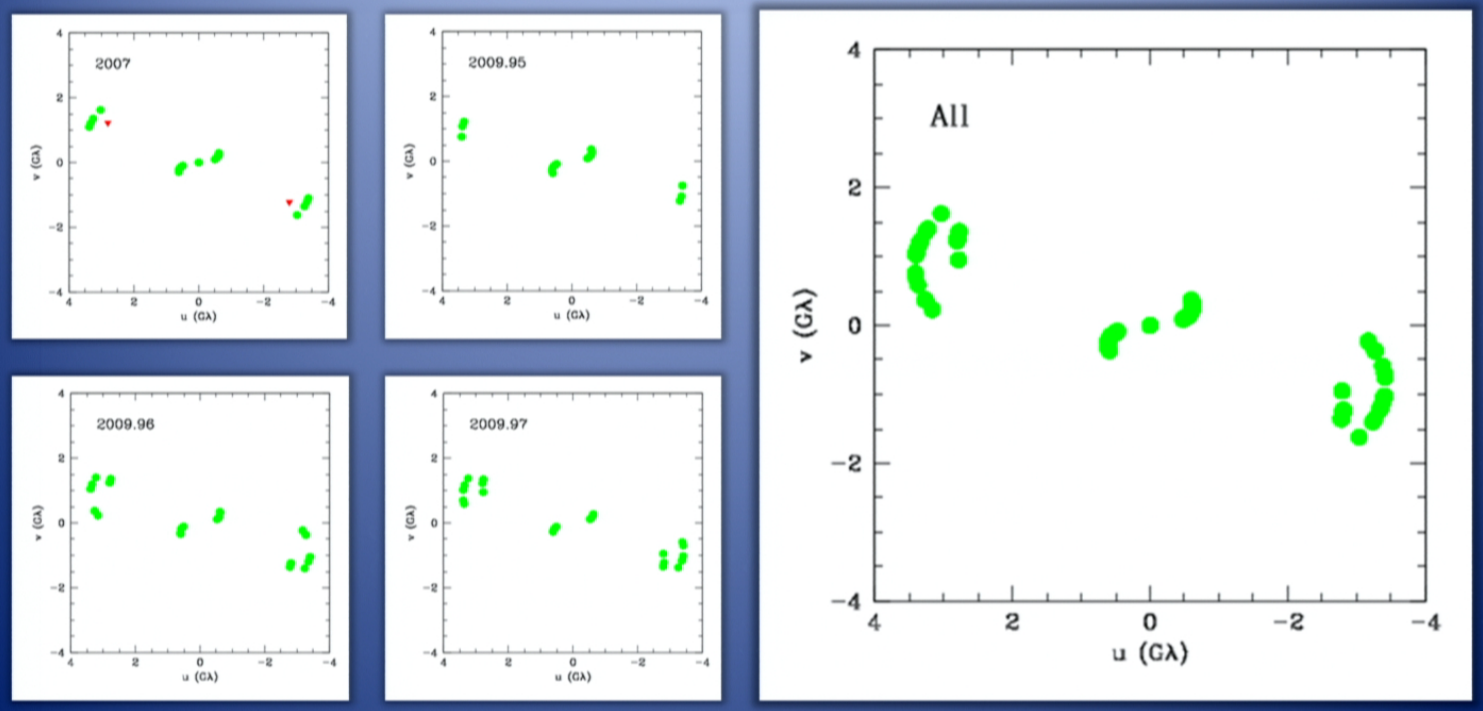

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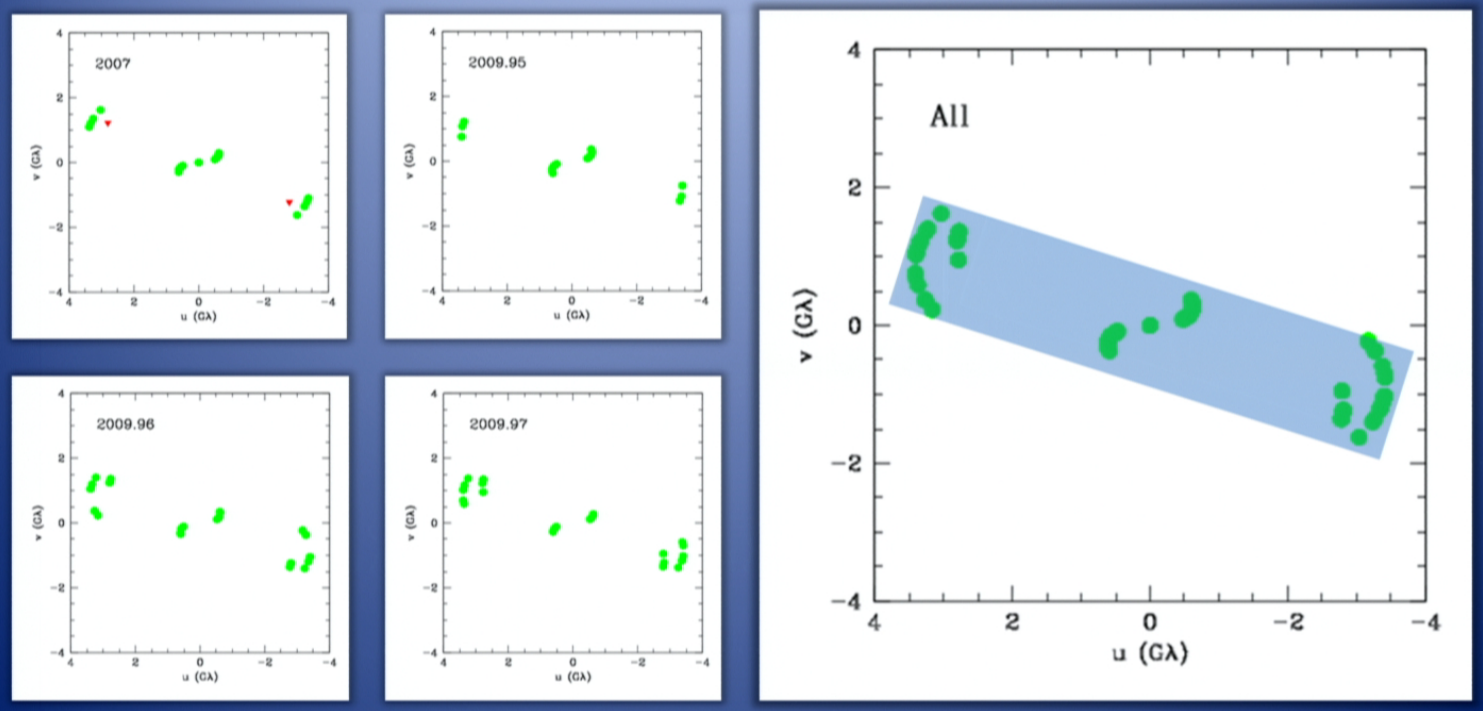

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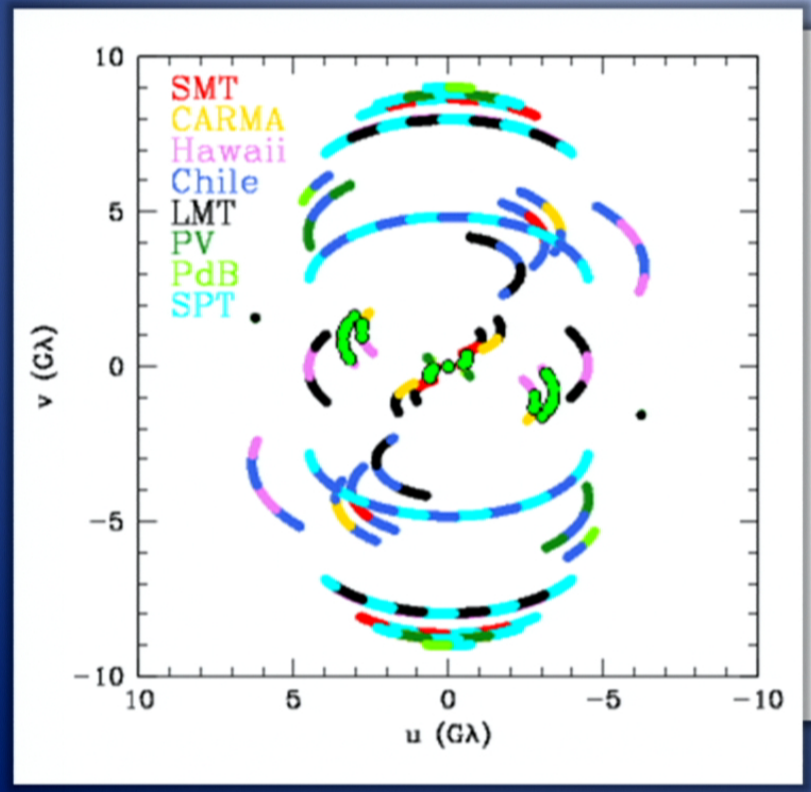

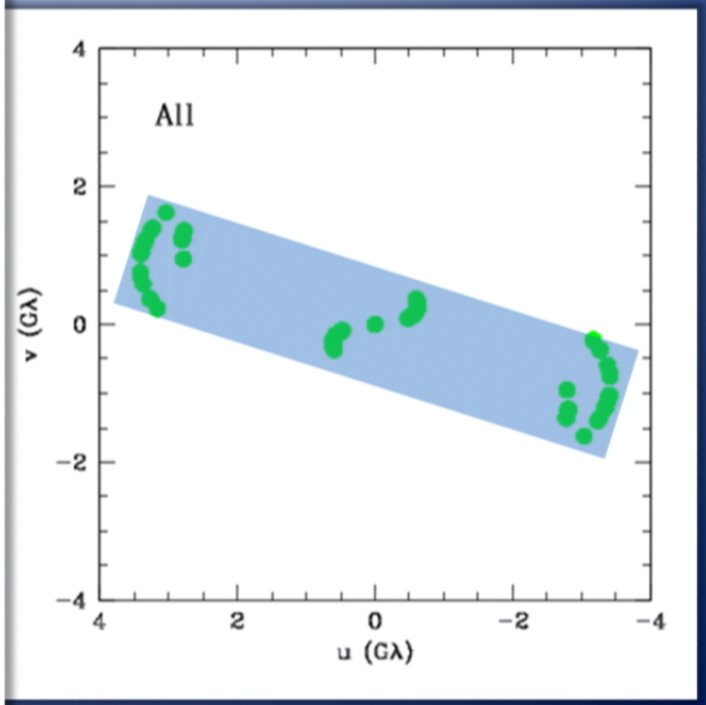

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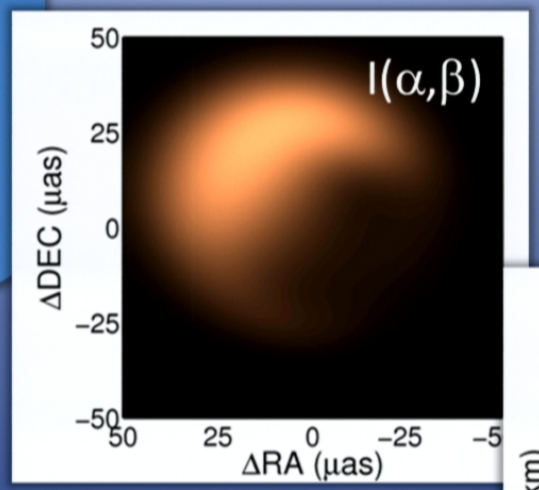
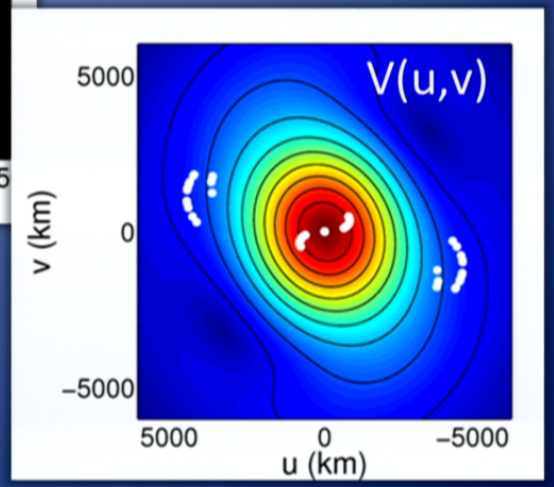
Filling gaps in data with theory

Model Input:

- Phenomenological (gaussian, annuli, etc.)
- Physical (α-disk, RIAF, jet, etc.)





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Measuring Fits and Models

- Quality of a fit:
  - Do good (high likelihood) fits exist? χ^2
  - What model parameters are preferred? $P(a|V)$
  - Are these consistent among different epochs? $P(a|V)$
- Quality of a model:
  - Bayesian Information Criterion: $BIC = \chi^2 + k \log N$
  - Akaike Information Criterion: $AIC = \chi^2 + 2k + \frac{2k(k+1)}{N-k-1}$
  - Relative significance: $w_{ij} = e^{-(IC_i - IC_j)/2}$
  - Occam's Razor?
  - Lies, damn lies, and statistics!

ΔIC	Conclusion
0	Negative
0-1	Not worth more than a bare mention
1-3	Positive
3-5	Strong
5-10	Very Strong
>10	Conclusive

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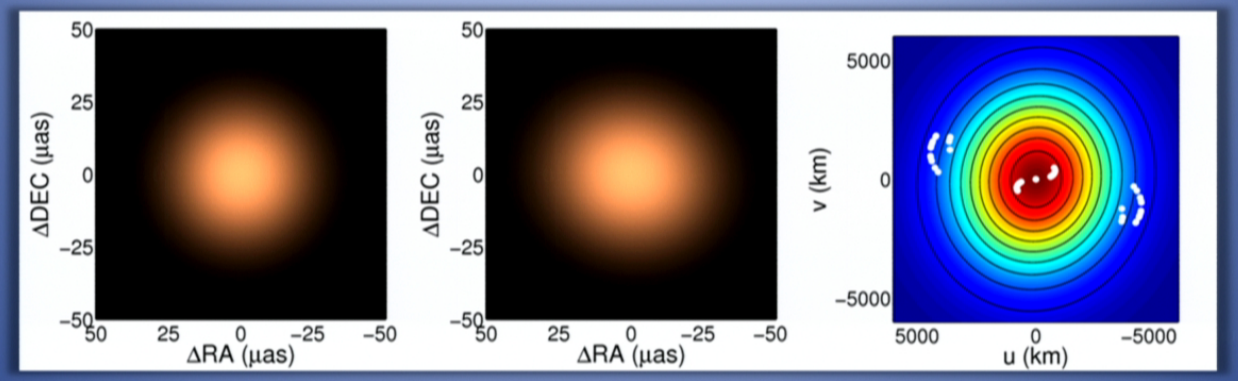
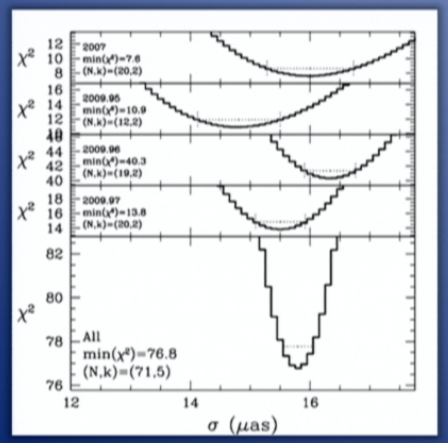
Toy Model: Symmetric Gaussian





σ=15.8+-0.2 μas

χ^2/DoF=1.16

BIC=98.1

AIC=87.7

AEB, Fish, Doeleman & Loeb, ApJ, 735, 110 (2011)

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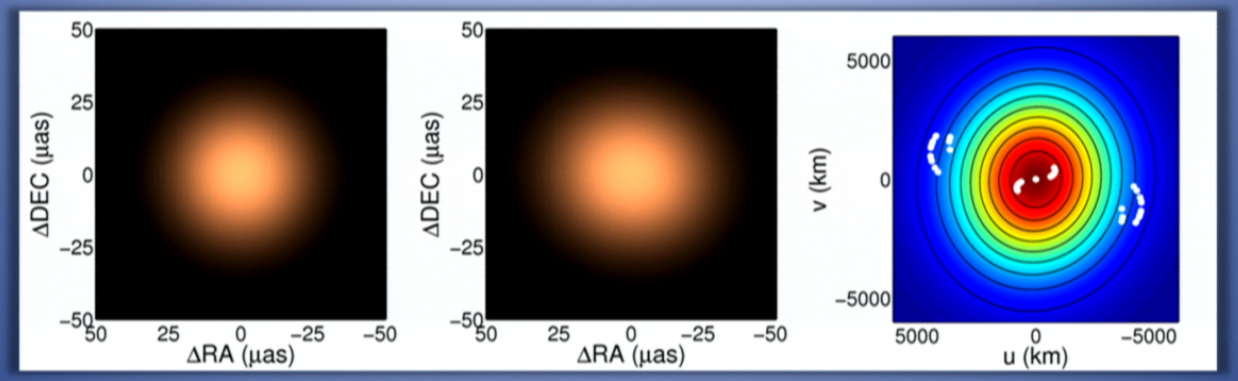

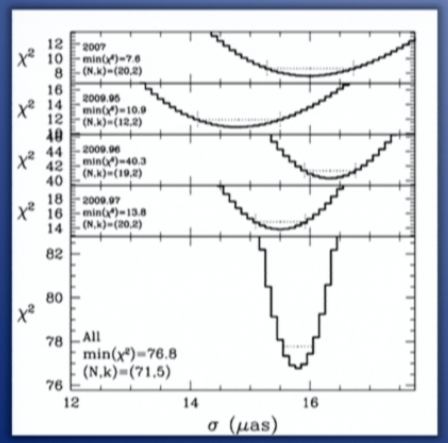

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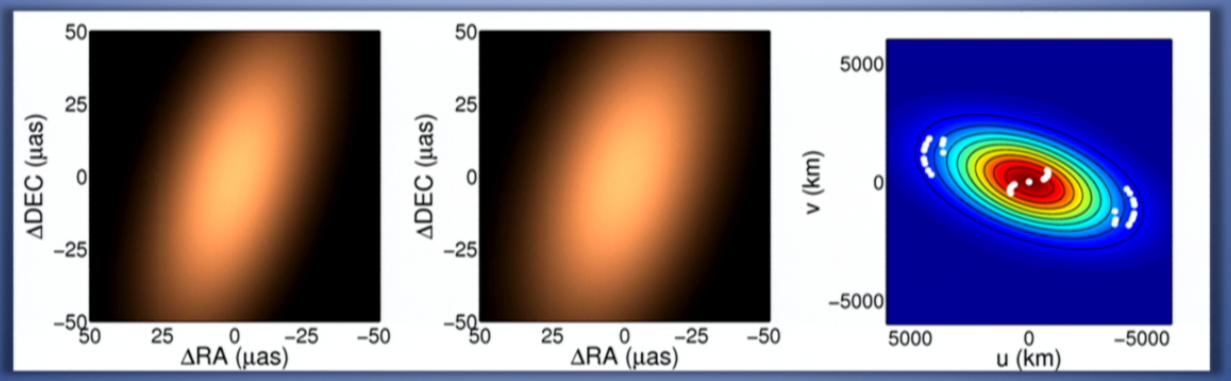
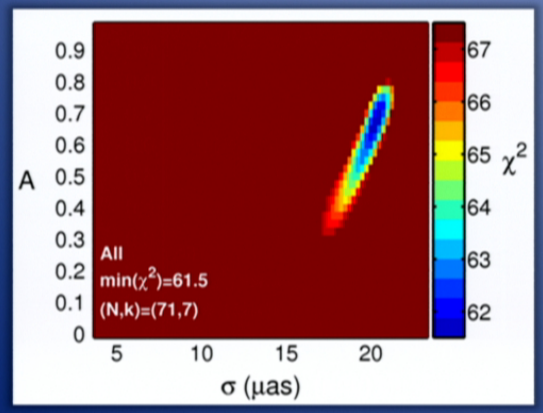
Toy Model: Asymmetric Gaussian





$$\sigma = \left[\frac{1}{2\sigma_m^2} + \frac{1}{2\sigma_M^2}\right]^{-1/2} = 20.5^{+0.3+0.5}_{-0.8-1.3}\ \mu\text{as}$$

$$A = \left[\frac{\sigma_M^2 - \sigma_m^2}{\sigma_M^2 + \sigma_m^2}\right]^{1/2} = 0.70^{+0.03+0.05}_{-0.1-0.18}$$

$$\xi = 19^{\circ\,+3^\circ+6^\circ}_{-1^\circ-2^\circ}$$

χ^2/DoF=0.961

BIC=91.3 (-6.9)

AIC=77.3 (-7.4)

AEB, Fish, Doeleman & Loeb, ApJ, 735, 110 (2011)

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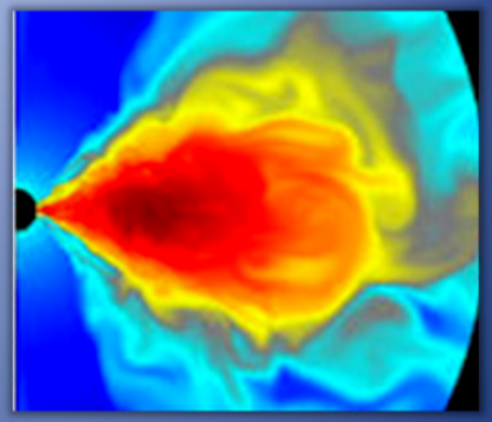
A Physical Model: RIAFs

- Thick, self-similar disk
- Keplerian beyond ISCO, ballistic inside
- Sub-equipartition magnetic field
- "Thermal" and power-law electron components
- Self-Absorbed Synchrotron
- Model defined by n_{th}, n_{nth}, T_e, and **a**



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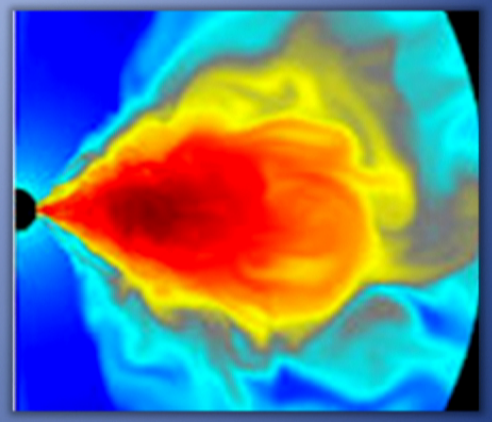

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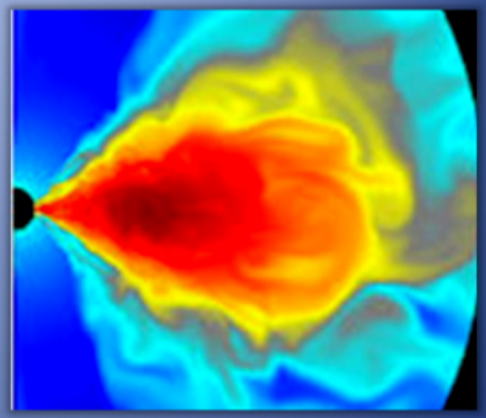
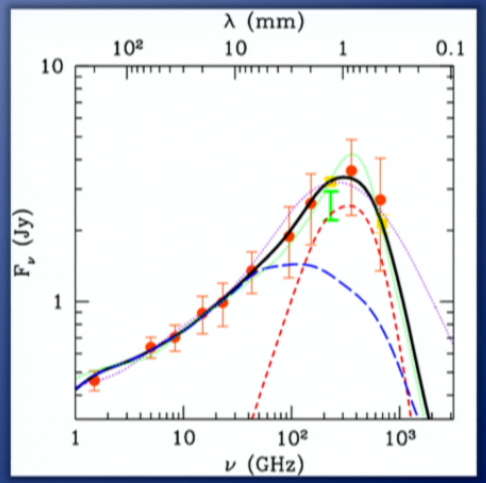
- Self-Absorbed Synchrotron
- Model defined by n_{th}, n_{nth}, T_e, and **a**
- Leverage existing spectra





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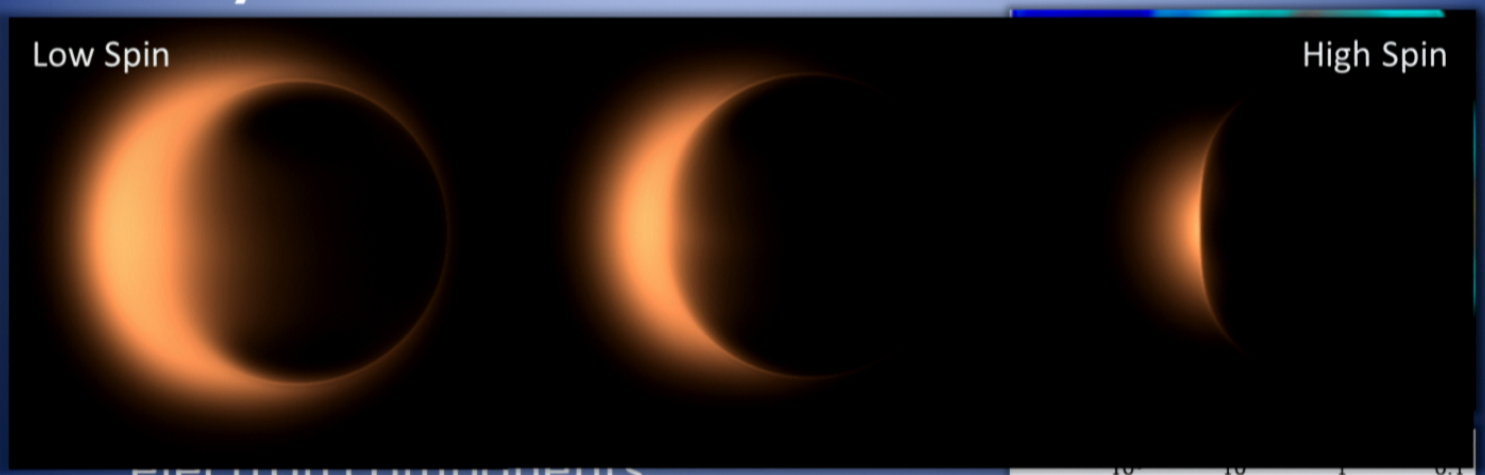
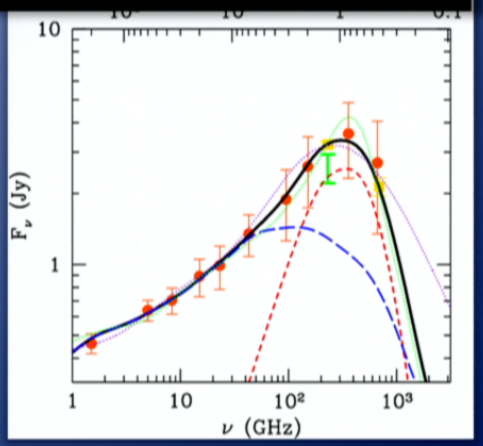
A Physical Model: RIAFs



electron components

- Self-Absorbed Synchrotron
- Model defined by n_{th}, n_{nth}, T_e, and **a**
- Leverage existing spectra



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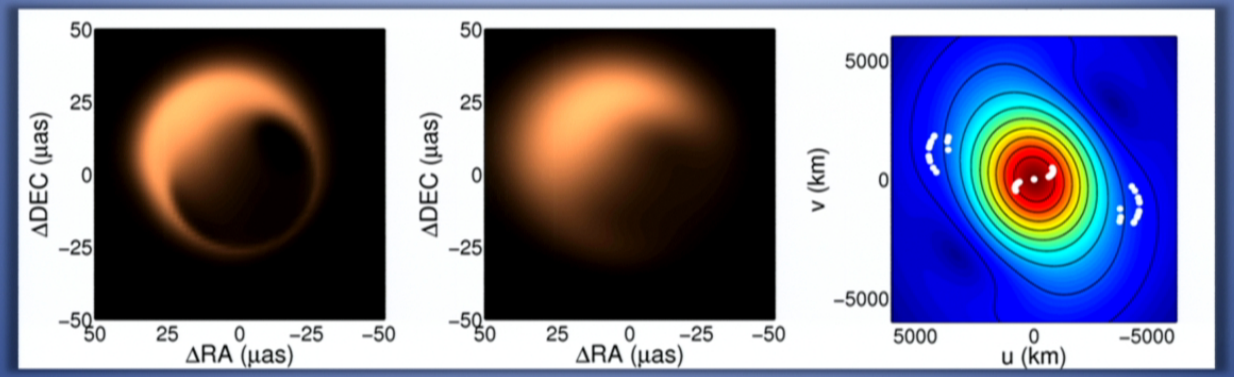
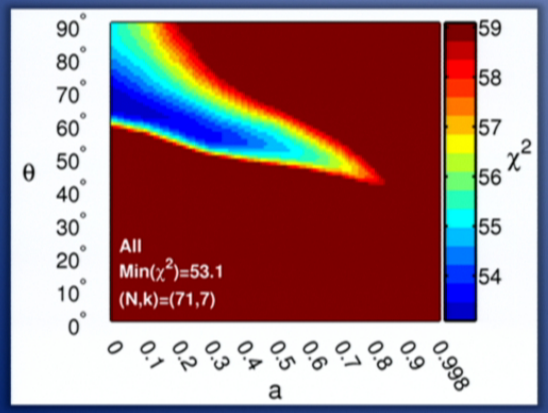
Radiatively inefficient accretion flow





χ^2/DoF=0.830

BIC=82.9 (-8.4, -15.3)

AIC=68.9 (-8.4, -15.8)

AEB, Fish, Doeleman & Loeb, ApJ, 735, 110 (2011)

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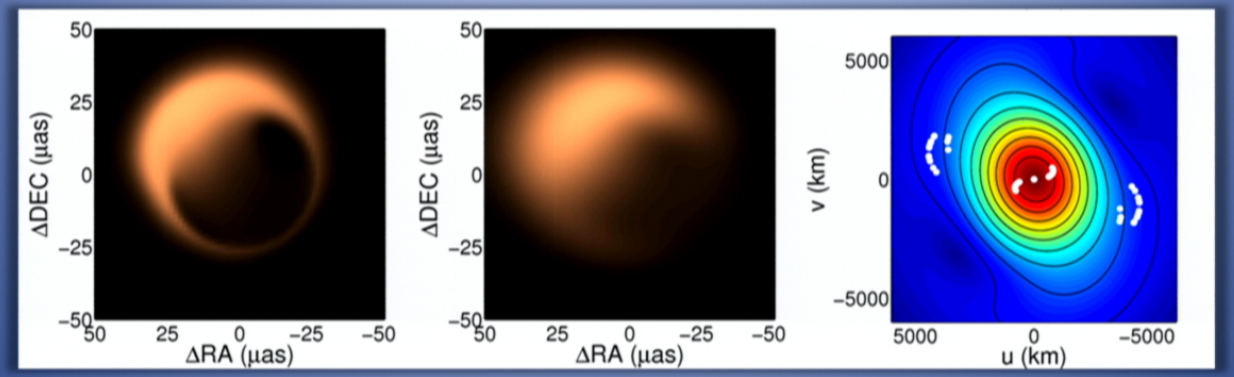

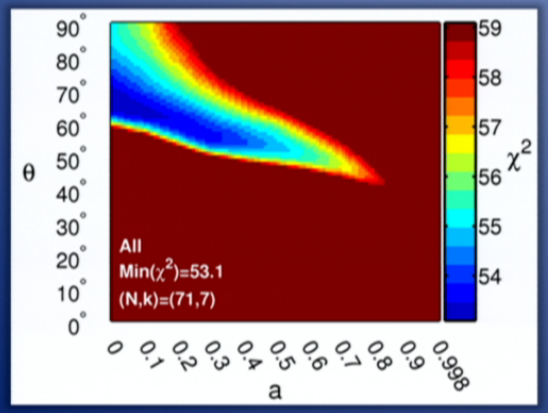

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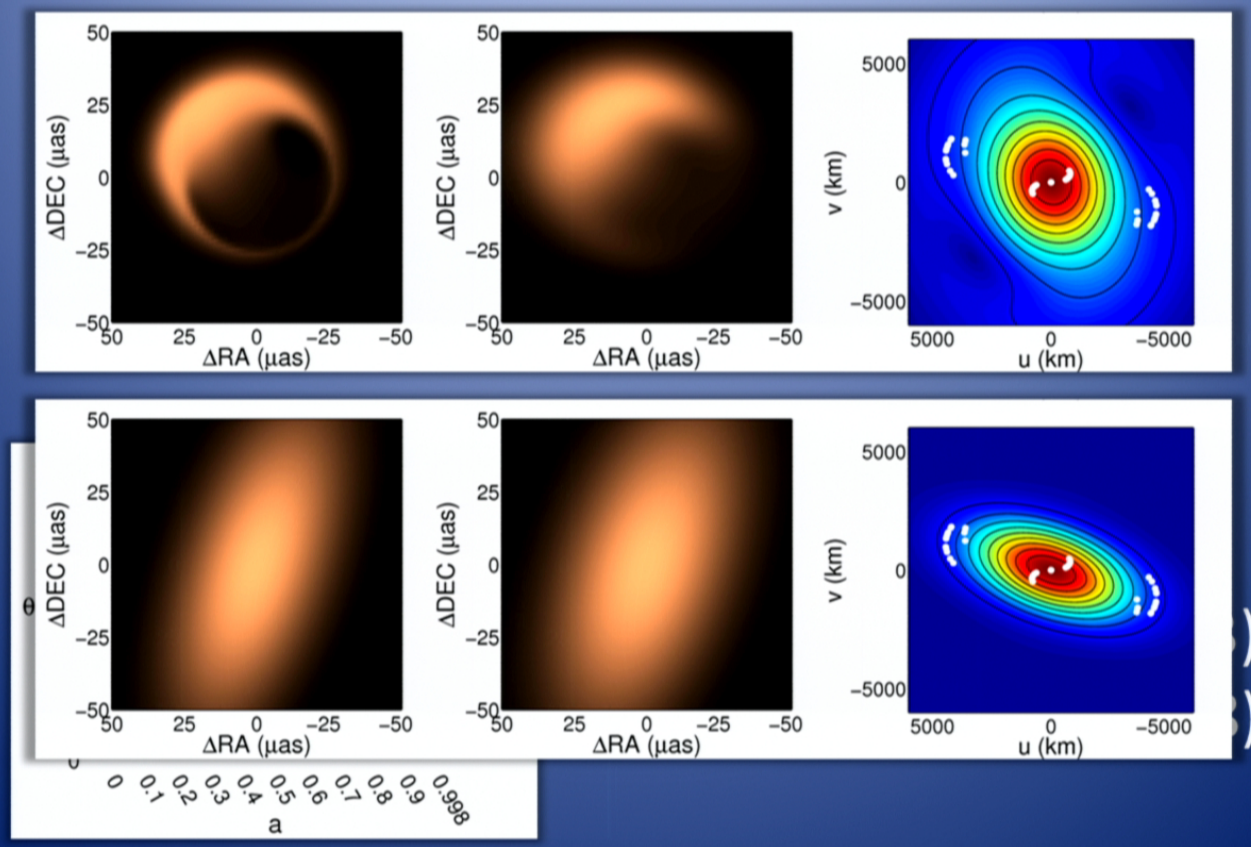

AEB, Fish, Doeleman & Loeb, ApJ, 735, 110 (2011)

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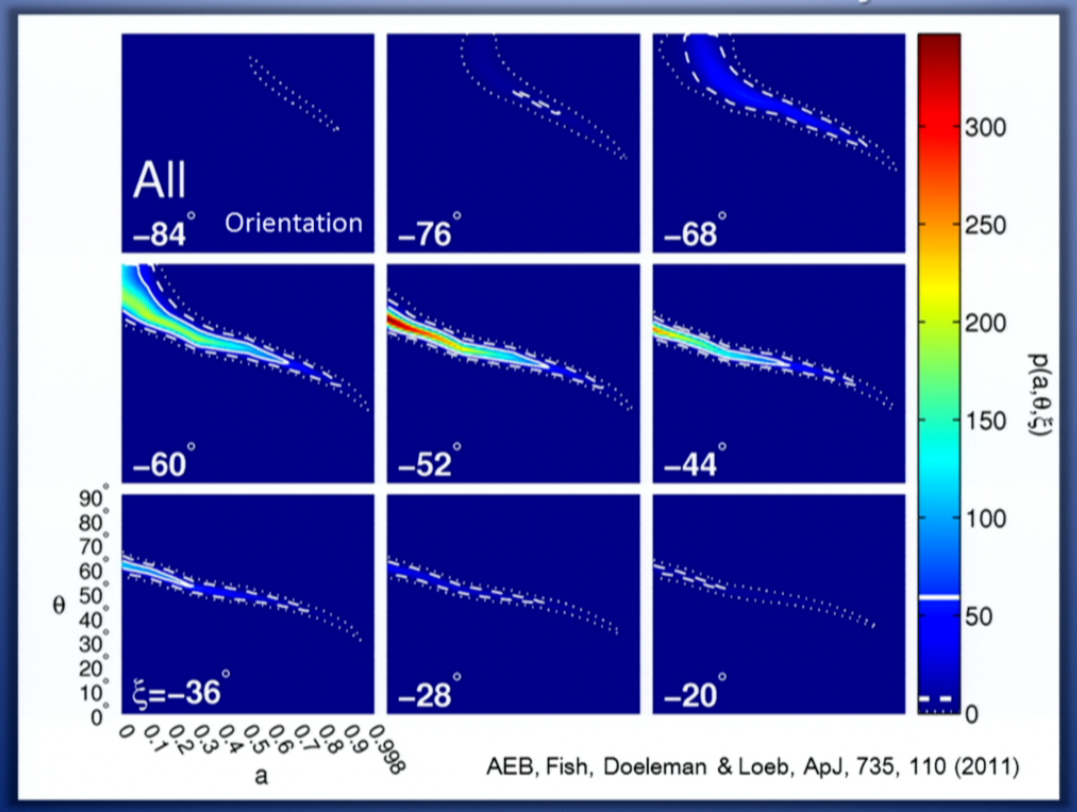
The Spin of Sgr A*

$a \sim 0^{+0.64+0.86}$

$\theta = 68^{+5+8}_{-20-28}$ deg.

$\xi = -52^{+17+33}_{-15-24}$ deg.



Inclination

Spin Magnitude

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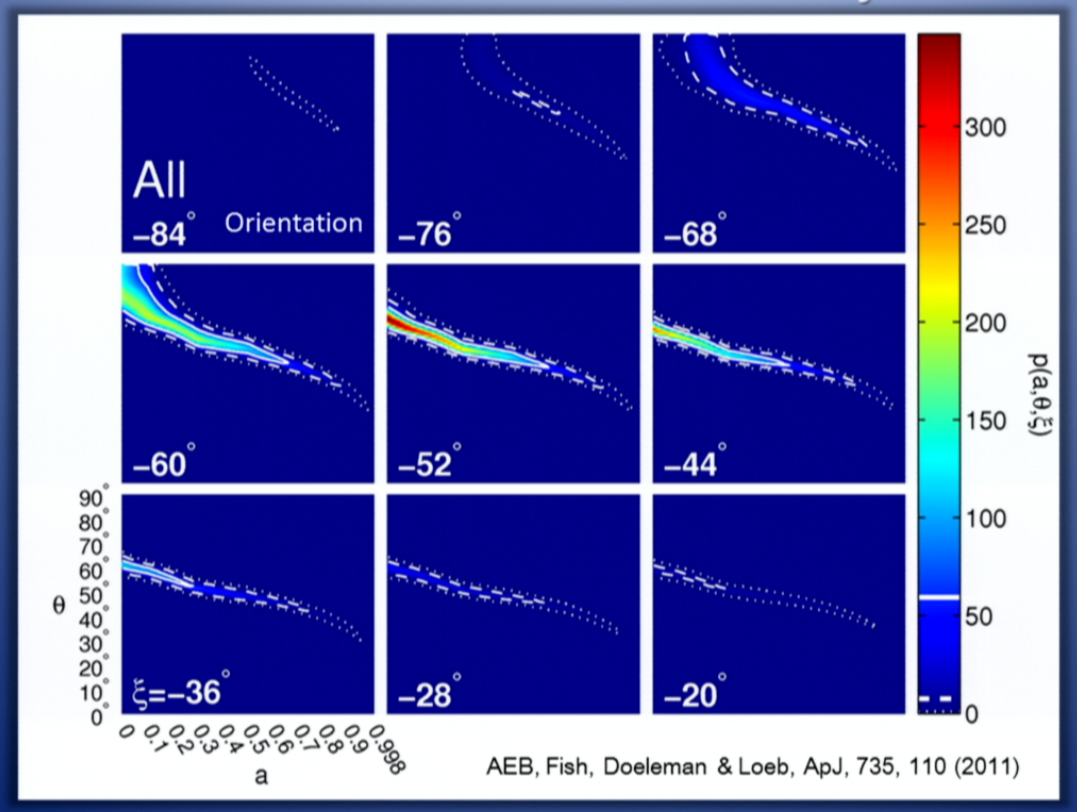

Spin Magnitude

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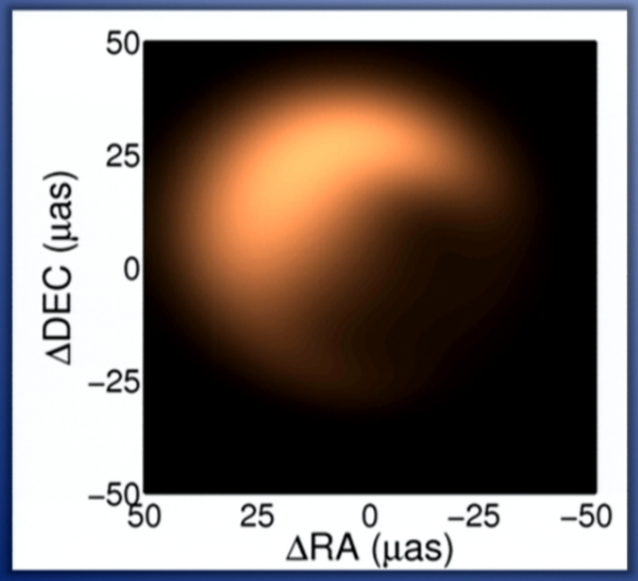
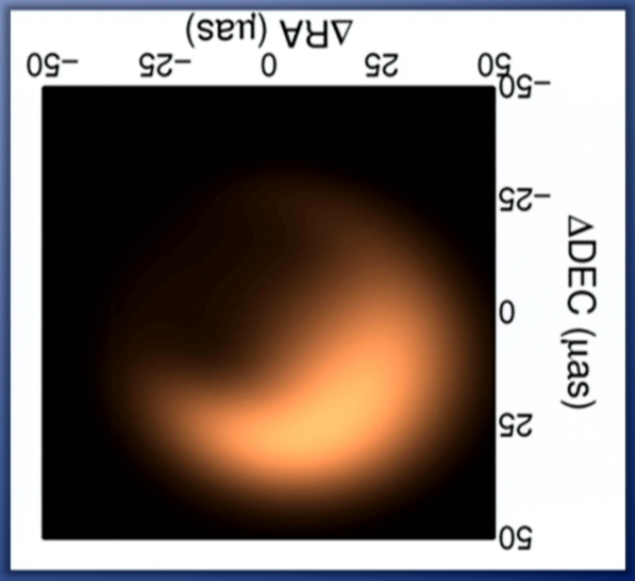
The Importance of Phase

- Lack of phase info gives $\xi \rightarrow \xi + 180^\circ$ degeneracy





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- Image structure strongly dependent upon phase

PI Colloquium, Feb. 15, 2012

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|V|

arg(V)

PI Colloquium, Feb. 15, 2012

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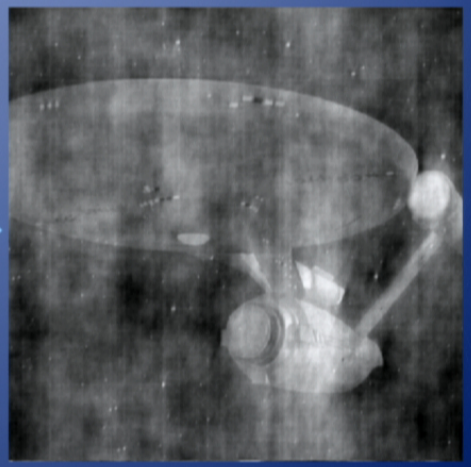

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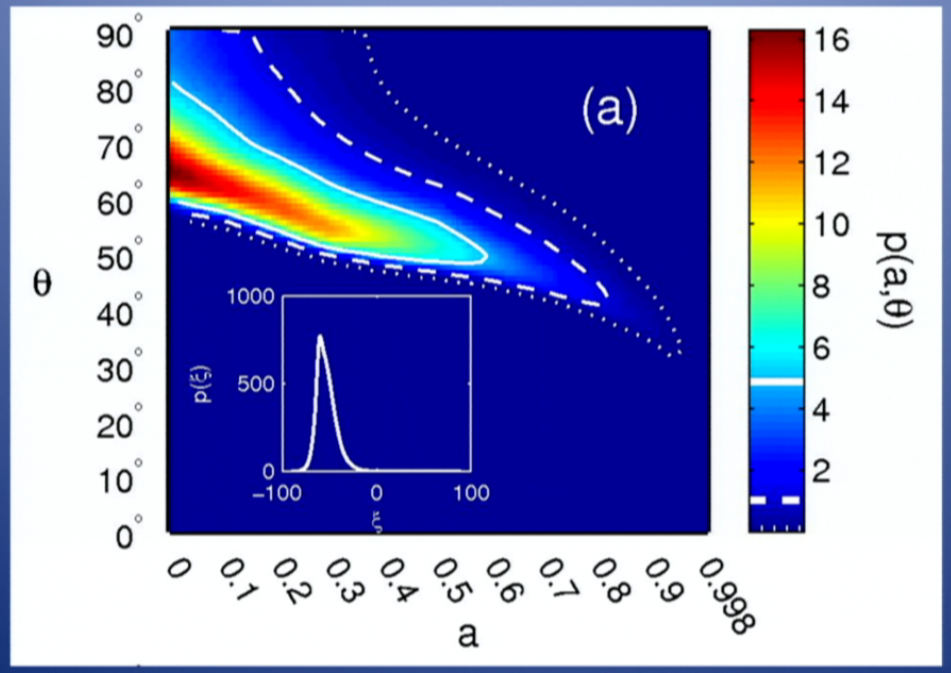
The Future with Closure Phases

|V| Only



AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)

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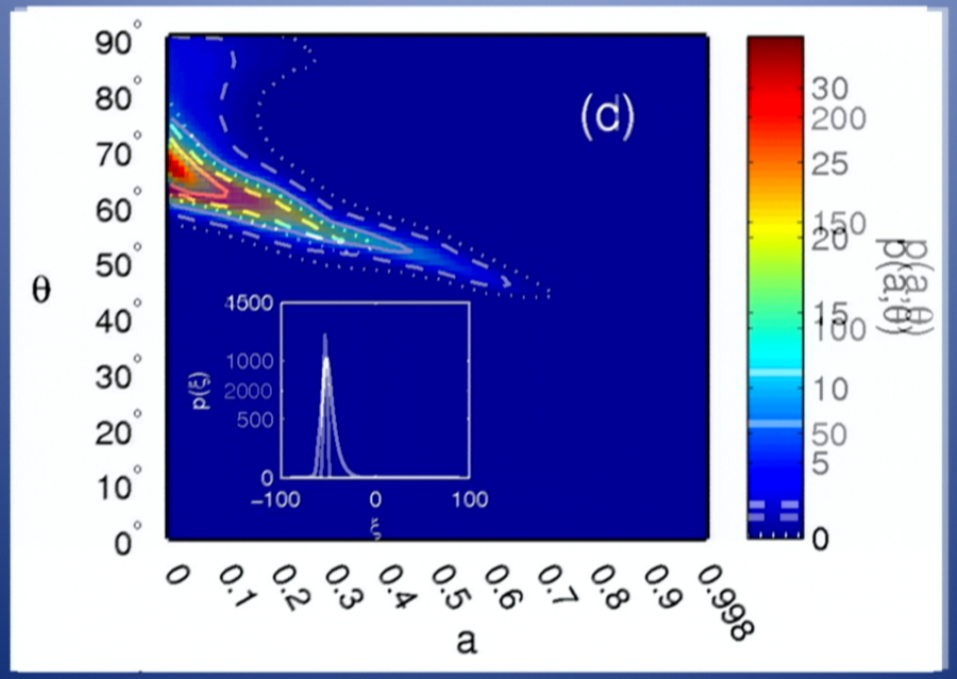
The Future with Closure Phases

|V| & Anticipated Precision on all triangles in an SMT-Hawaii-CARMA-APEX



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PI Colloquium, Feb. 15, 2012

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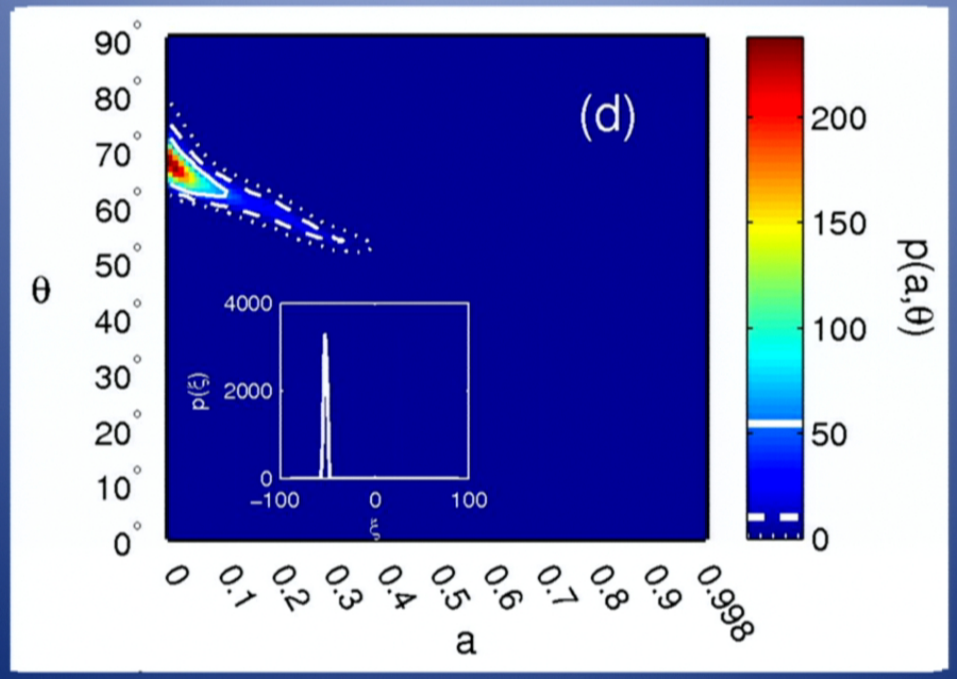

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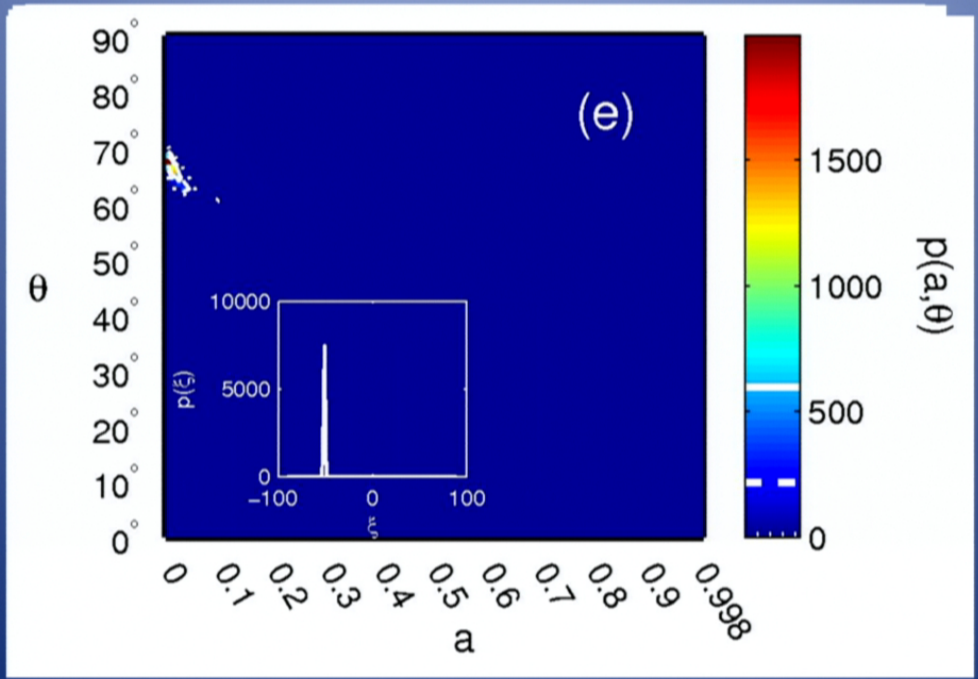
The Future with Closure Phases

|V| & Anticipated Precision on all triangles in an SMT-Hawaii-CARMA-ALMA10 array



AEB, Fish, Doeleman & Loeb, ApJ, 738, 38 (2011)

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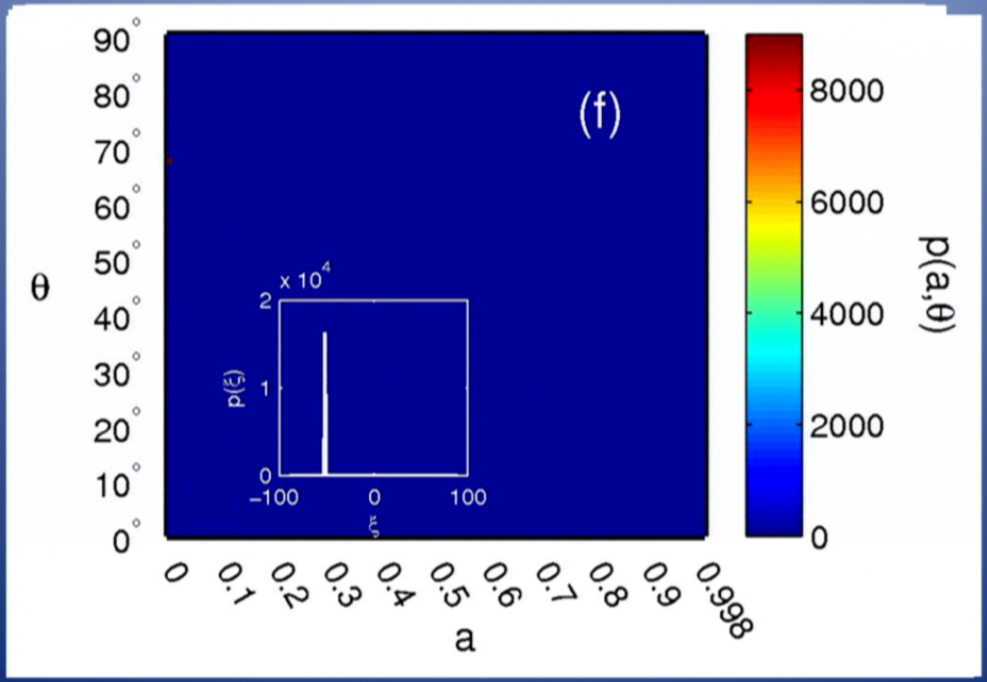
The Future with Closure Phases

|V| & Anticipated Precision on all triangles in an SMT-Hawaii-CARMA-ALMA10-LMT



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PI Colloquium, Feb. 15, 2012

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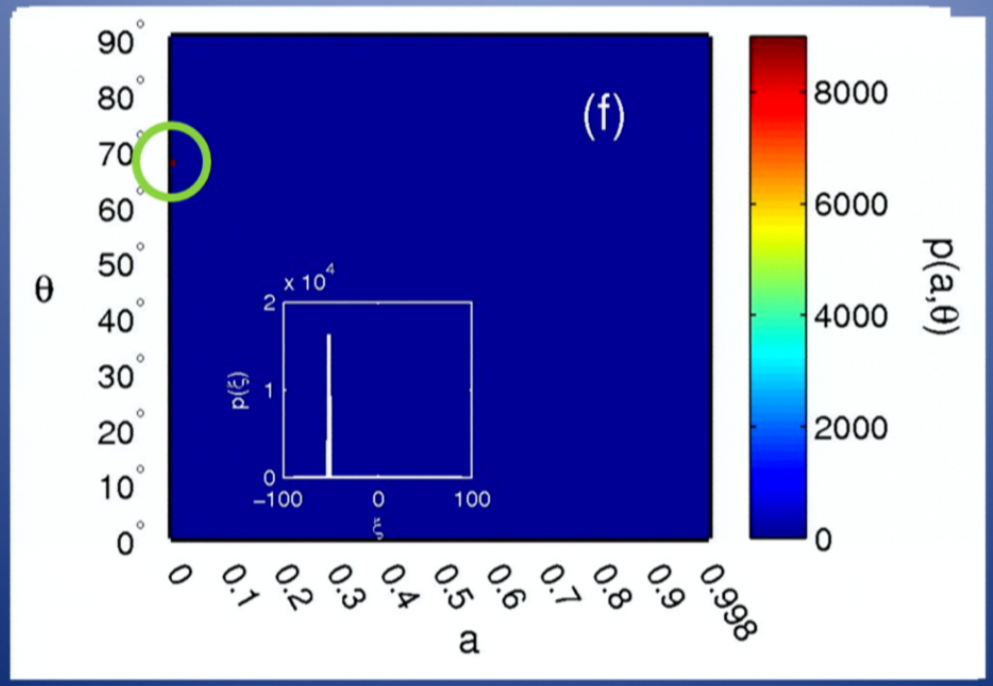

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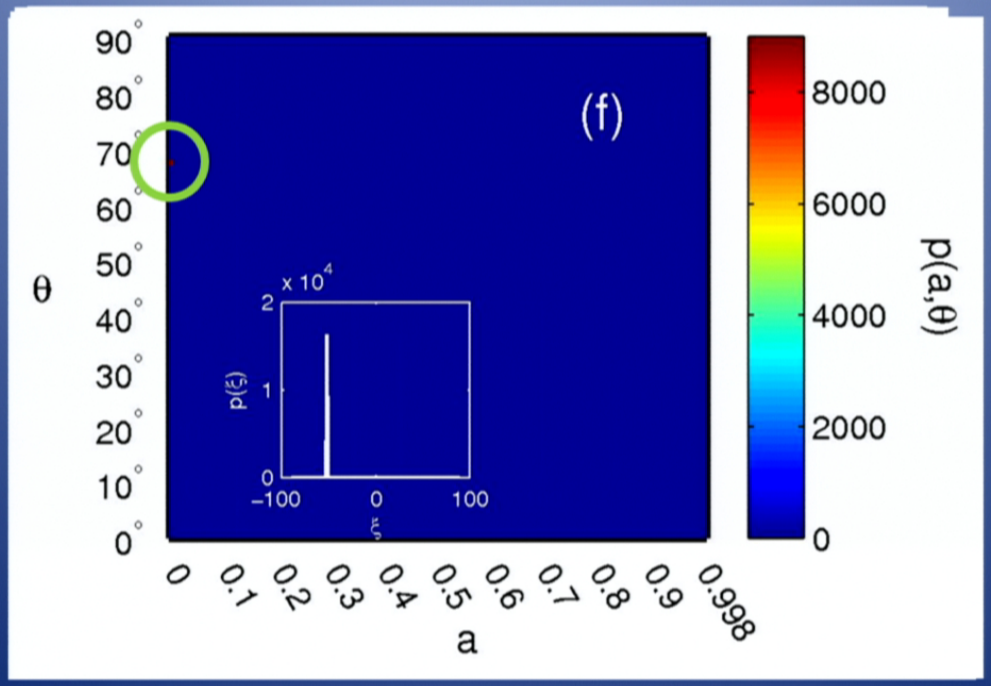

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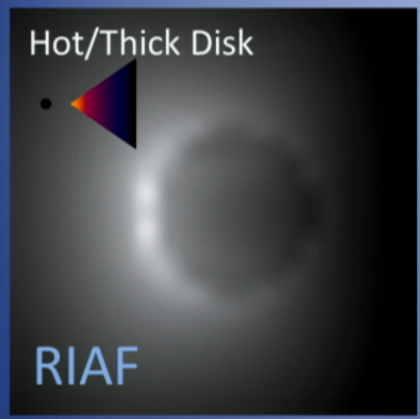
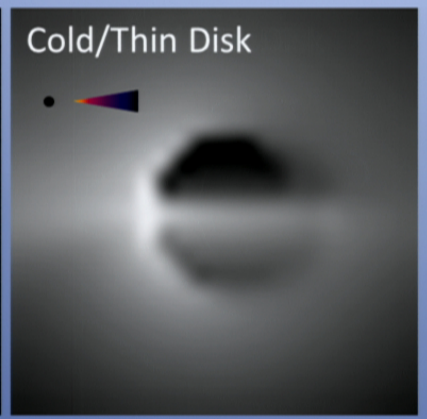
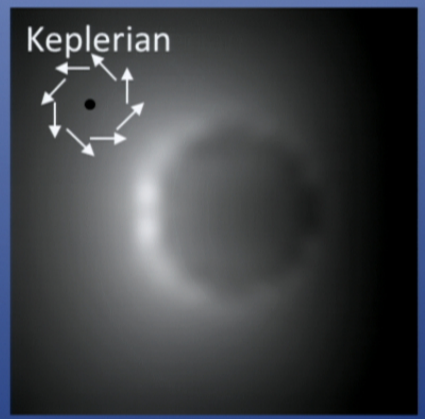
The Future: Is Sgr A* a RIAF?





→How inefficient is ion-electron coupling really? (Do RIAFs make sense?)

→ Angular momentum transport near horizon.



Bittner, AEB & Loeb (2012)

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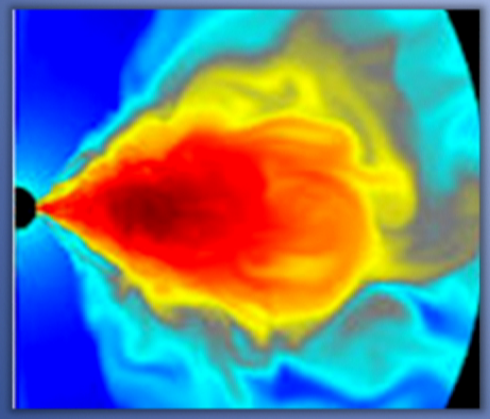
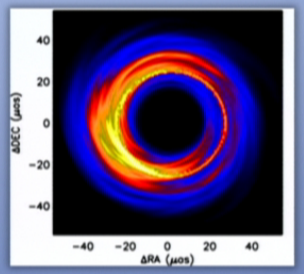
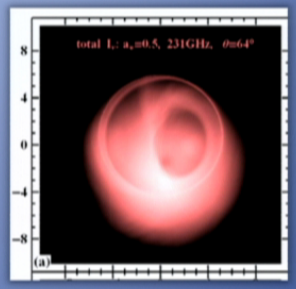
The Future: Does the MRI work?



Dexter, Agol & Fragile (2009)





Shcherbakov, Penna & McKinney (2011)

- Only fit smooth models thus far (though see Dexter, Agol & Fragile (2009),)
- Power from turbulence on small scales (large u)
- Measure turbulent spectrum:

$$\varepsilon_k \propto k^{-\gamma} \text{ and } j_\nu \propto \nu^{-\alpha} \rightarrow V(u) \propto u^{-\eta}$$

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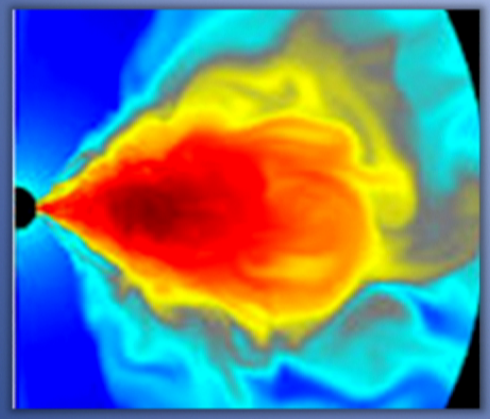

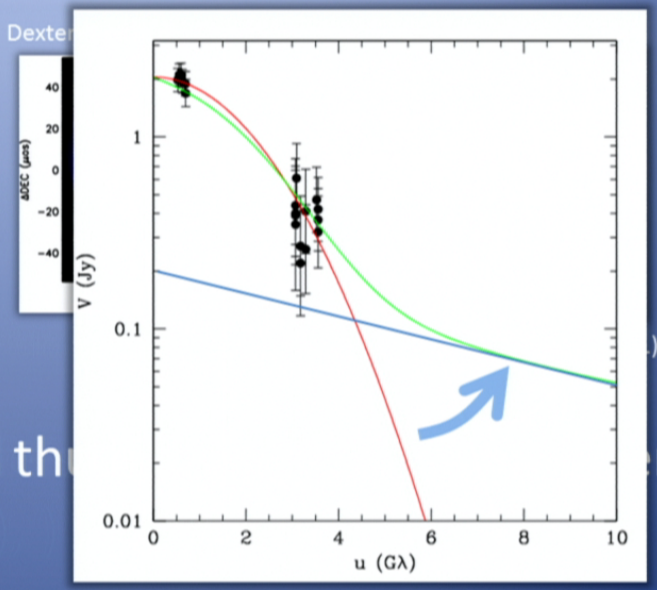

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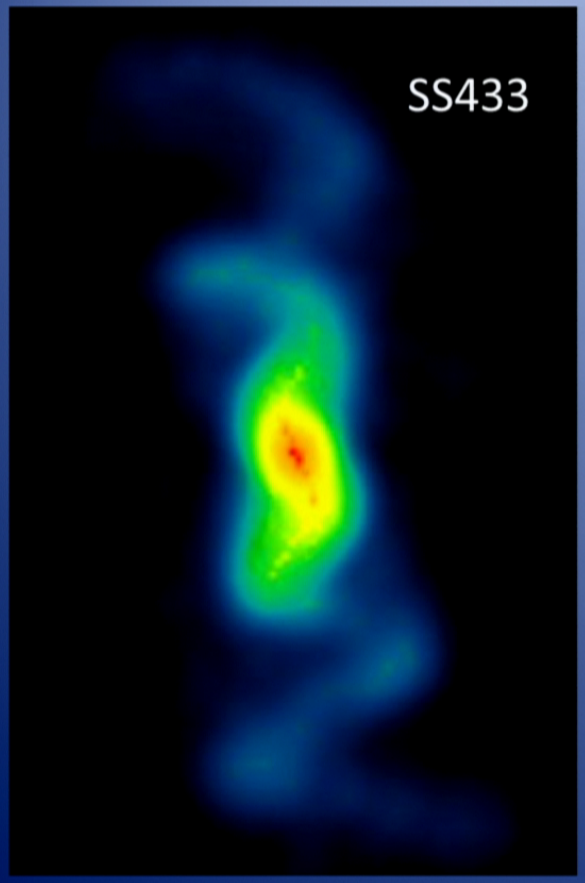
The Future: Is Sgr A* Static?



- Probed timescales from 10s – 2 yrs already
- Thick disks don't align
- Should precess due to:
  - Lense-Thirring
  - Local massive perturbers
  - Deviations from GR?
- Timescale

$$\sim \frac{L}{\tau} \sim a^{-1} \left(\frac{R}{10^3 GM/c^2} \right)^2 \text{yrs}$$

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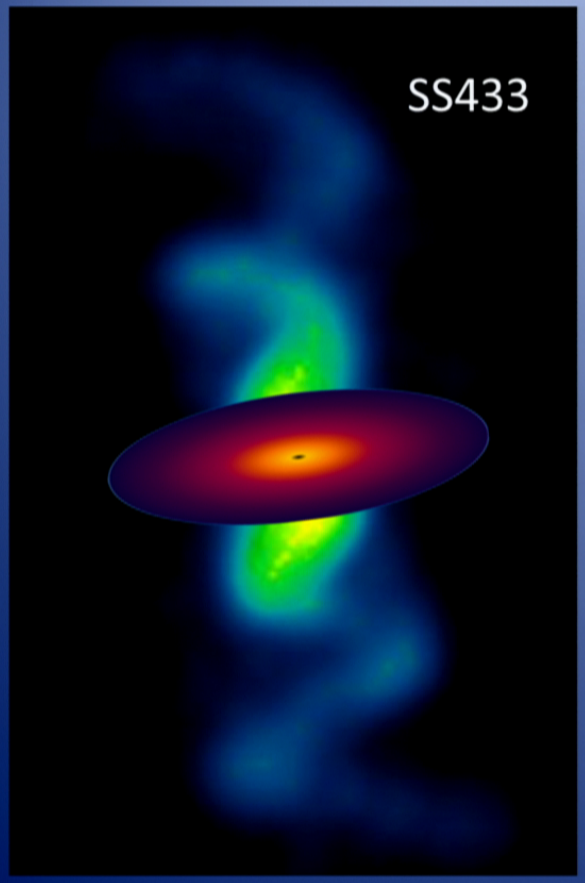

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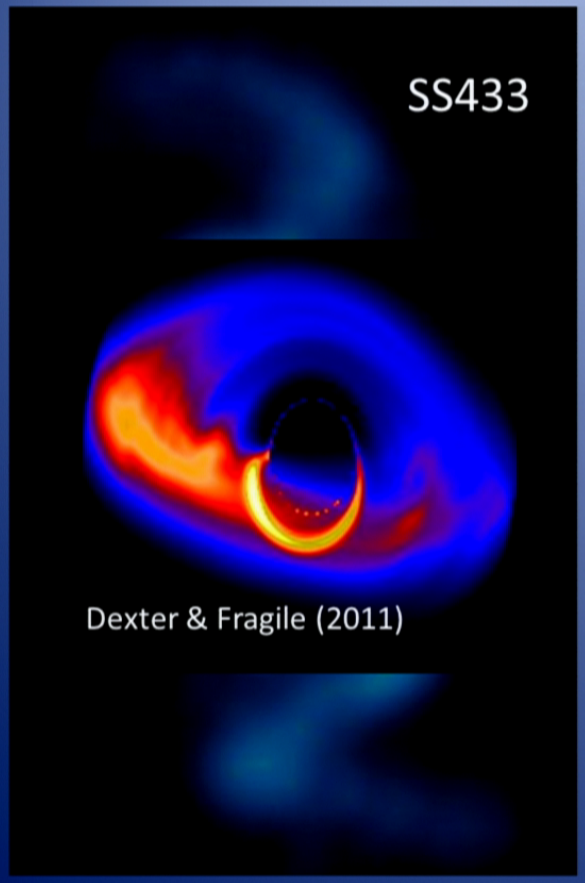

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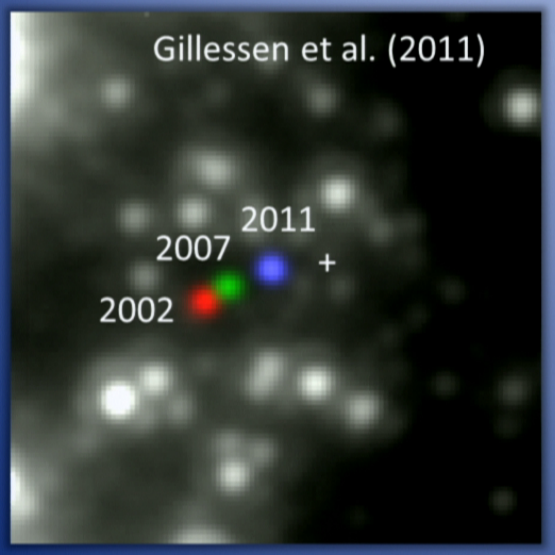
The future: Supply & Demand



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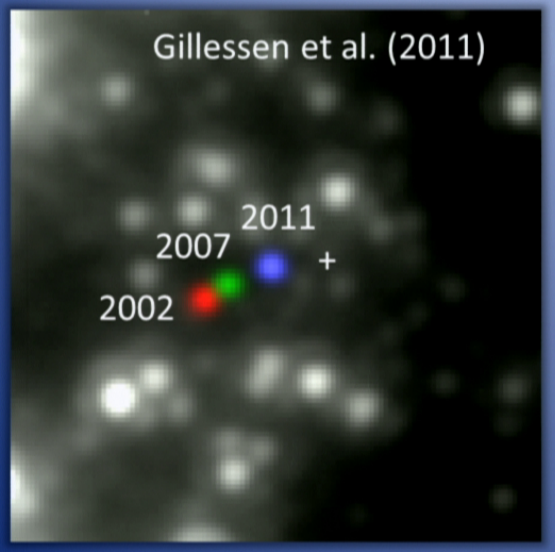

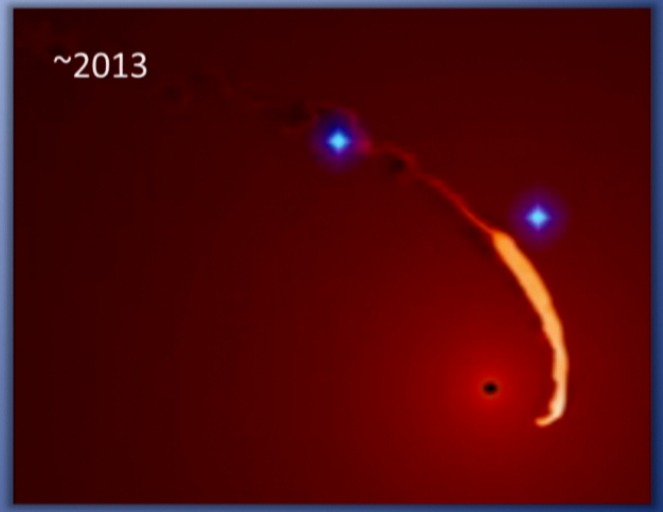

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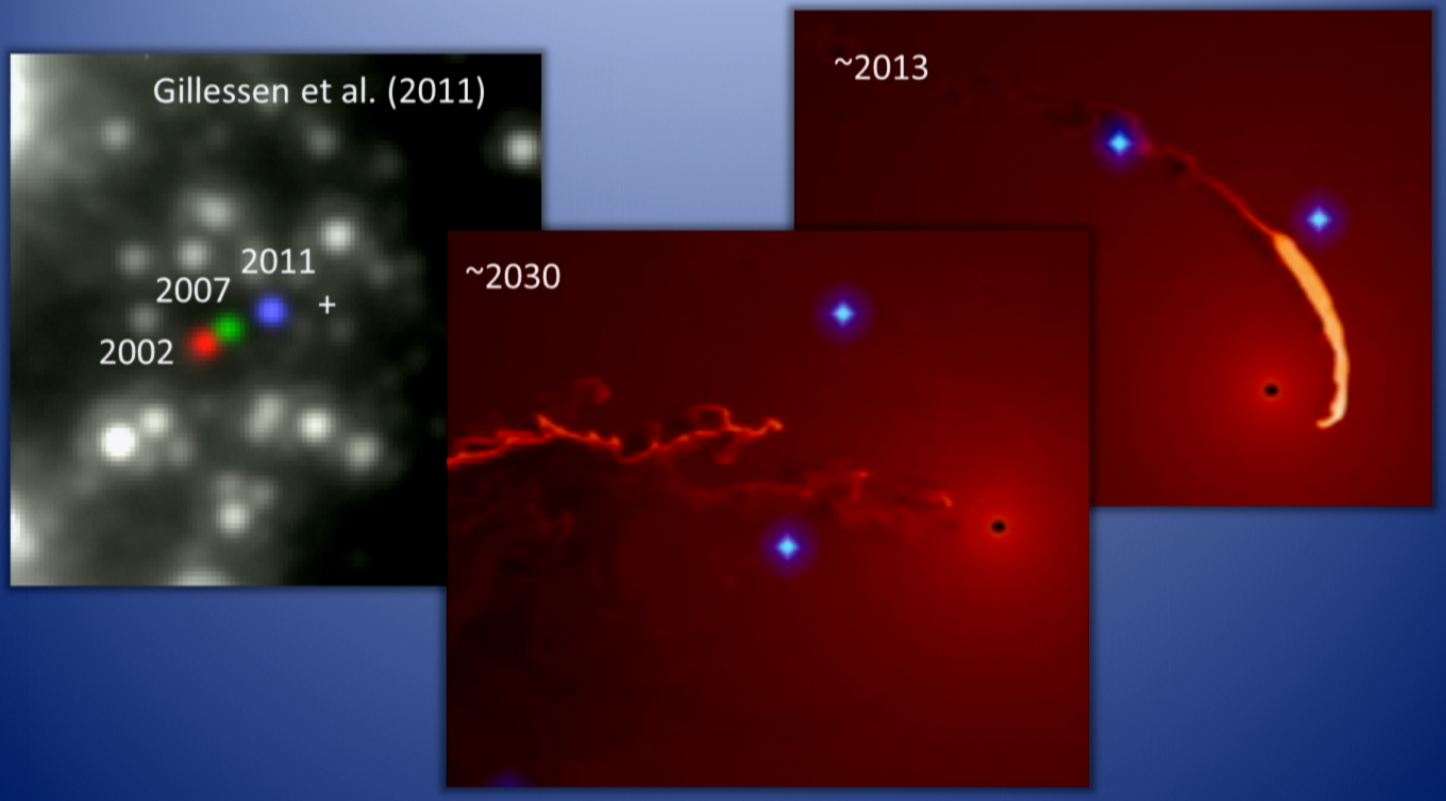

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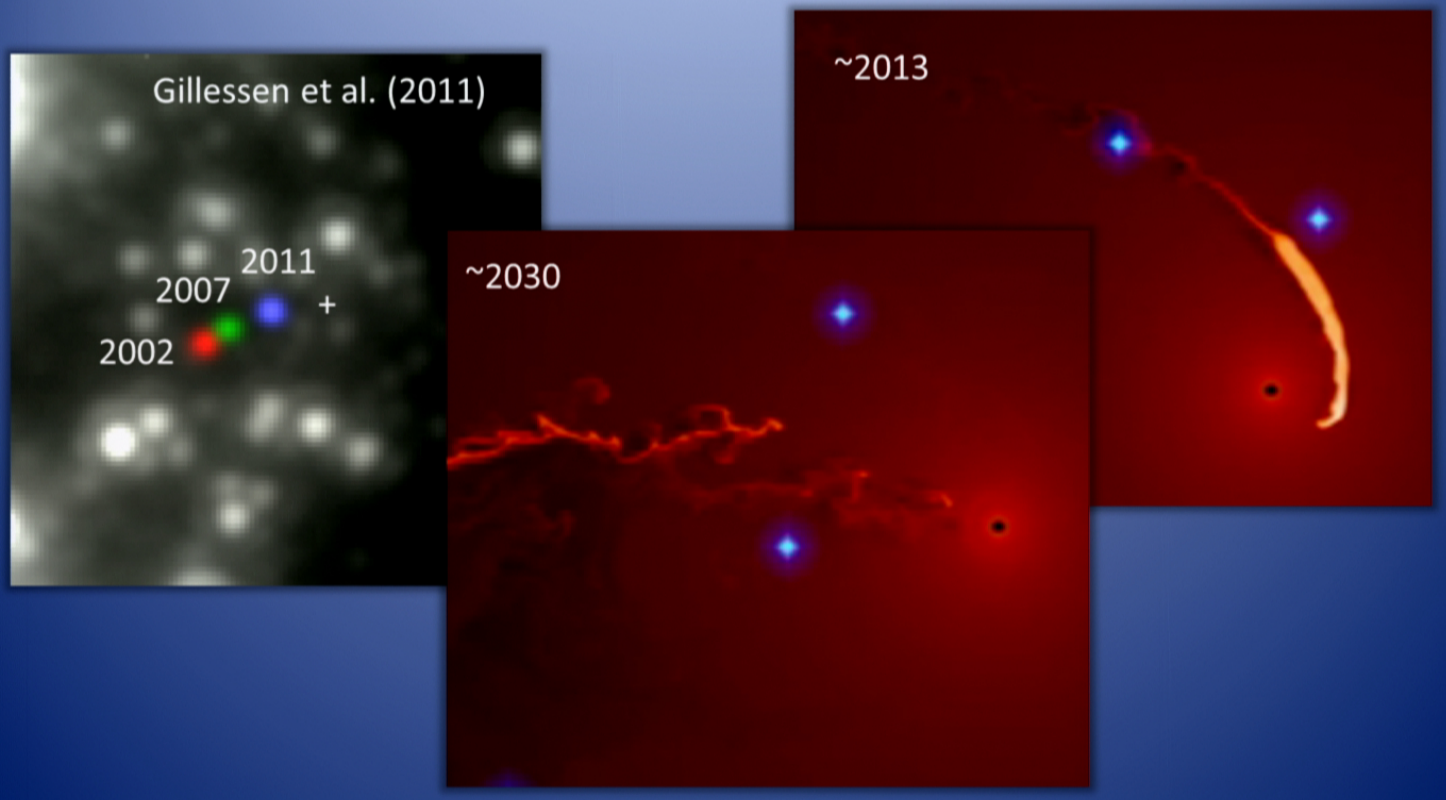

→ Increase in $\dot{M}$ by roughly 2 or so.

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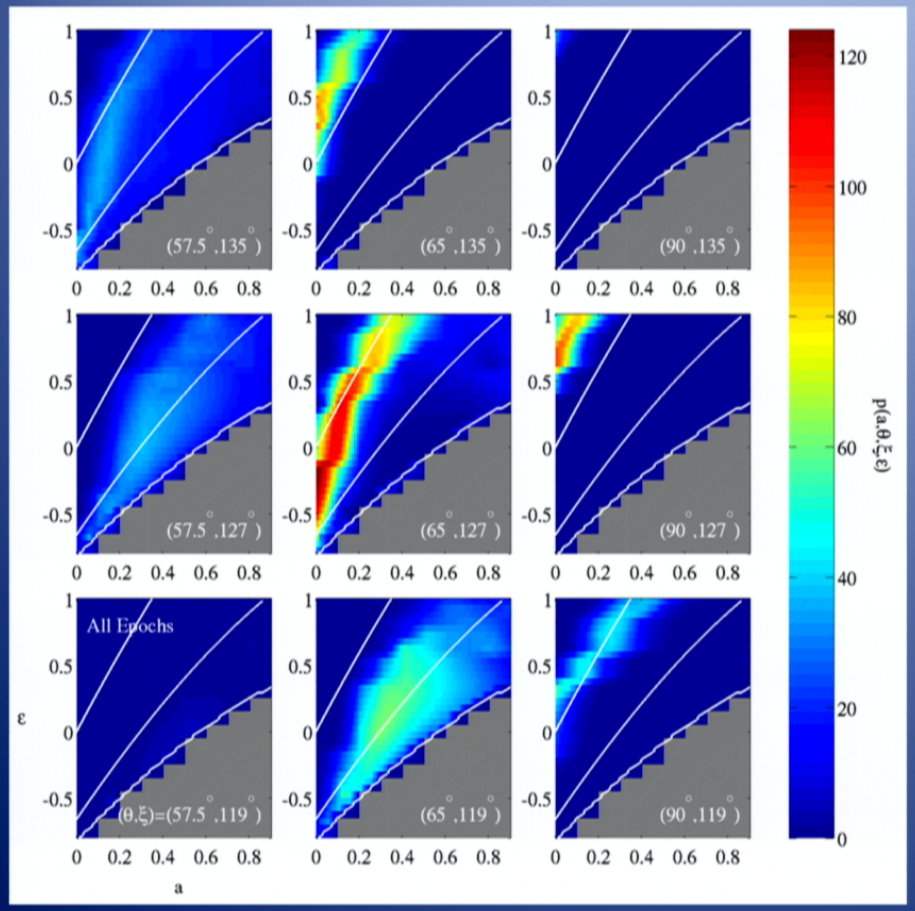
Testing GR with quasi-Kerr



- $g_{\mu\nu} = g_{\mu\nu}^{Kerr} + \varepsilon h_{\mu\nu}$
  $\rightarrow M, a, q = -(a^2 + \varepsilon)$
- Wrong quadrupole (meaured by ε)
- θ and ξ surprisingly insensitive to ε
  → robust direction
- Already best fit model clearly has nonzero ε!

Johannsen, AEB, Psaltis & Loeb (2011)

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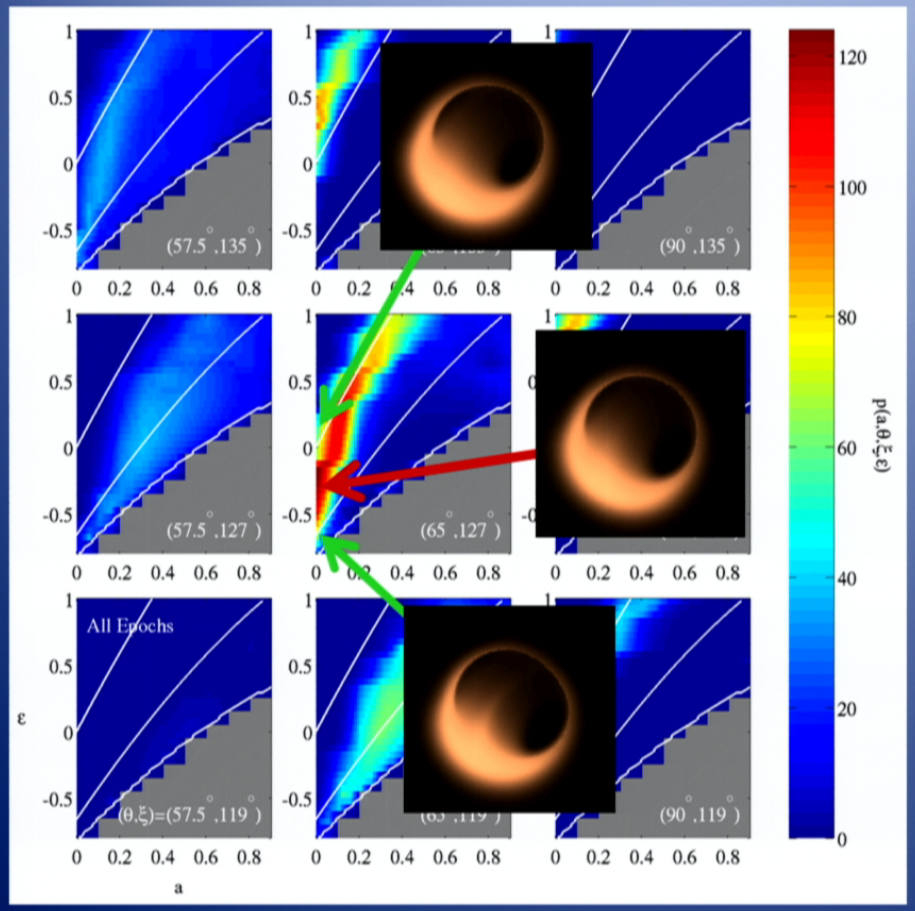

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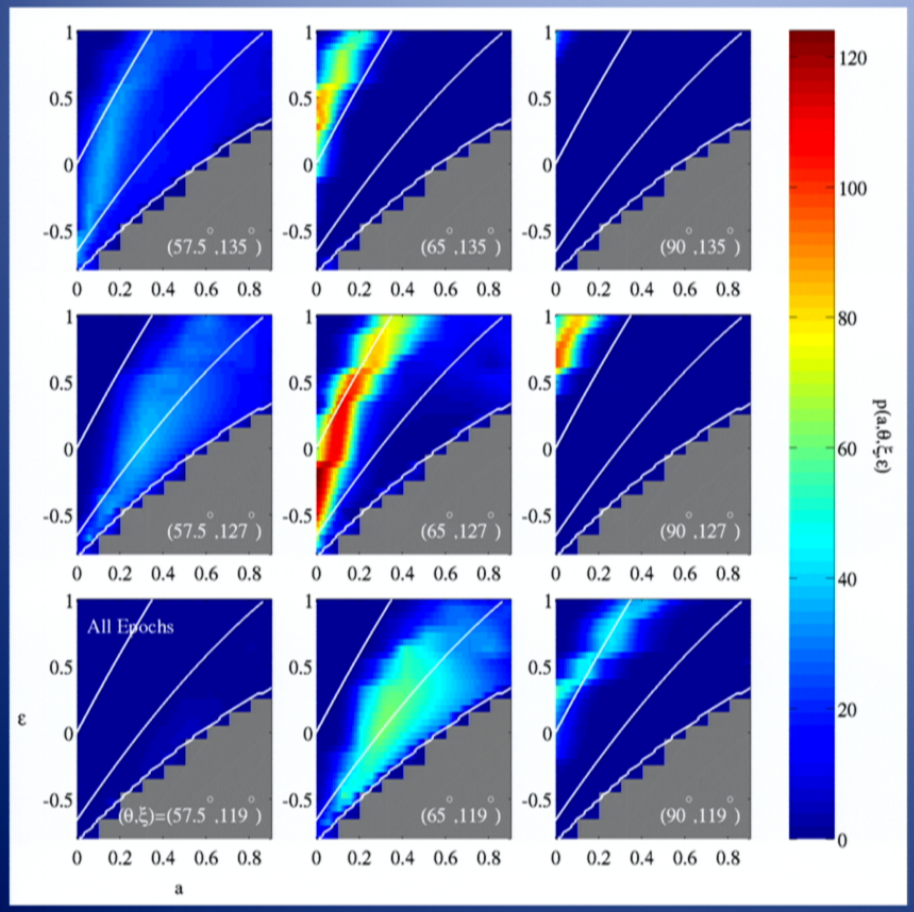
Non-Imaging Analysis: The Near Future!

Testing GR with quasi-Kerr



- Bandwidth: 1GHz
- Observatories
  - SMT
  - JCMT, SMA (LO)
  - CARMA (2 ind. dishes)
- |V| only

Johannsen, AEB, Psaltis & Loeb (2011)

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Non-Imaging Analysis: The Near Future!

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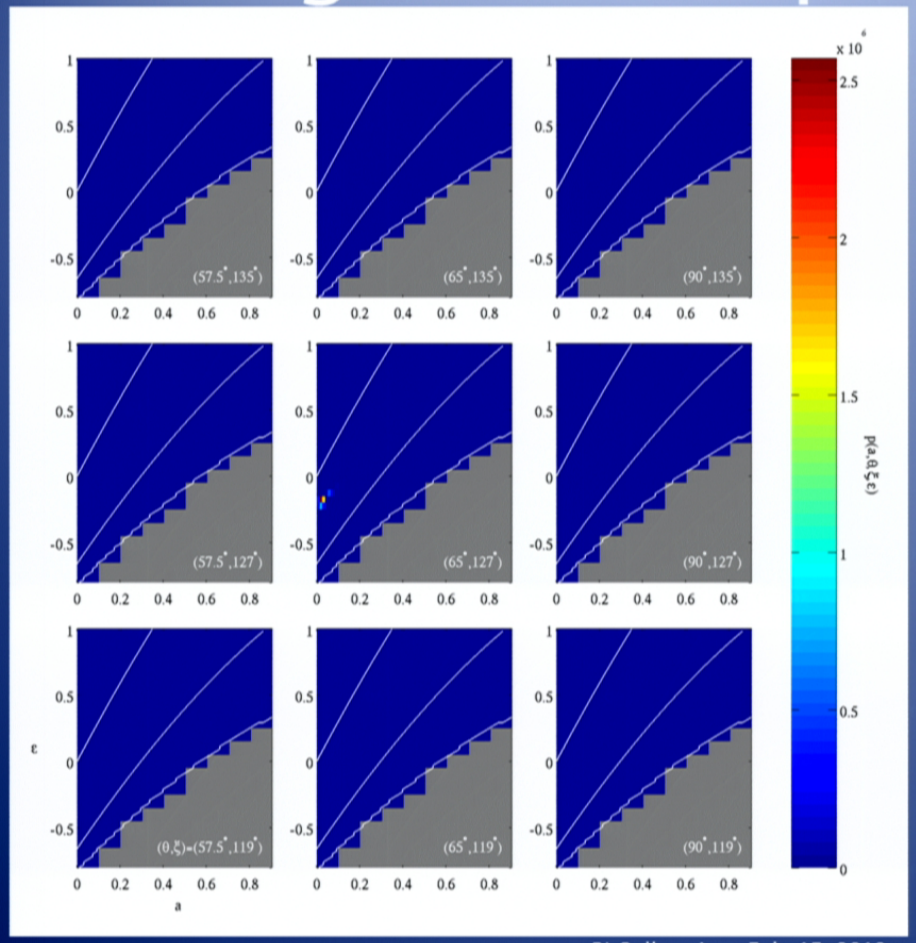

- Bandwidth: 4GHz
- Observatories
  - SMT
  - Phased Hawaii
  - Phased CARMA (8)
  - Phased ALMA (10)
- |V| only

Johannsen, AEB, Psaltis & Loeb (2011)

PI Colloquium, Feb. 15, 2012

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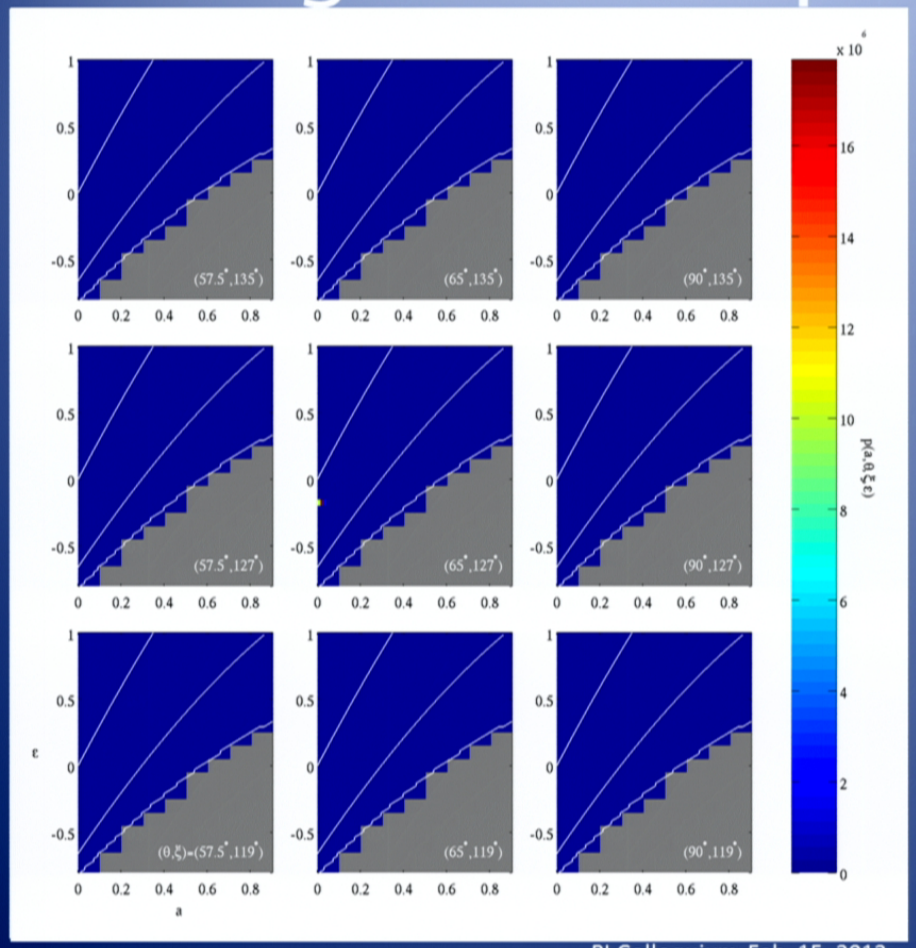

- Bandwidth: 4GHz
- Observatories
  - SMT
  - Phased Hawaii
  - Phased CARMA (8)
  - Phased ALMA (10)
- |V|
- ***+ Closure Phases***

Johannsen, AEB, Psaltis & Loeb (2011)

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Conclusions (so far…)

- Most black holes are "boring", i.e., $\dot{M} \ll \dot{M}_{Edd}$ → RIAFs are common.
- Lot's of reasons to believe Sgr A* is a RIAF (i.e., Copernicus strikes again!).
- Low $\dot{M}$ + proximity enables unique horizon resolving study of Sgr A* with the Event Horizon Telescope.
- Already finding that RIAFs work extremely well.
- In the near future we will begin to test:
  - Internal consistency of RIAFs specifically
  - Critical components of accretion models generally
  - Structure of the spacetime around Sgr A*

PI Colloquium, Feb. 15, 2012

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- Most black holes are "boring", i.e., $\dot{M} \ll \dot{M}_{Edd}$
  → RIAFs are common.
- Lot's of reasons to believe Sgr A* is a RIAF
  (i.e., Copernicus strikes again!).
- Low $\dot{M}$ + proximity enables unique horizon resolving study of Sgr A* with the EventHorizonTelescope
- Already finding that RIAFs work extremely well.
- In the near future we will begin to test:
  - Internal consistency of RIAFs specifically
  - Critical components of accretion models generally
  - Structure of the spacetime around Sgr A*

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