

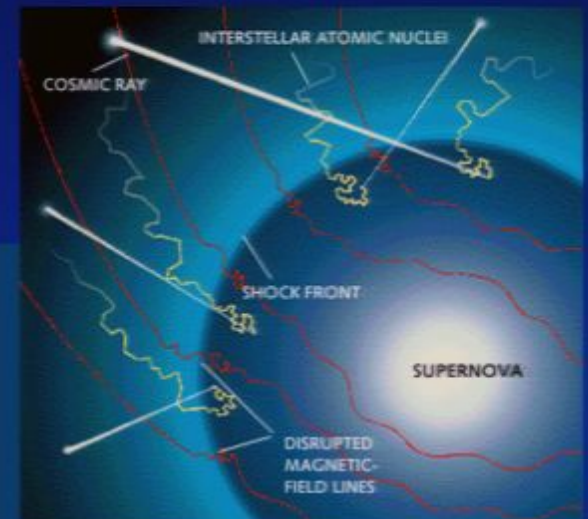
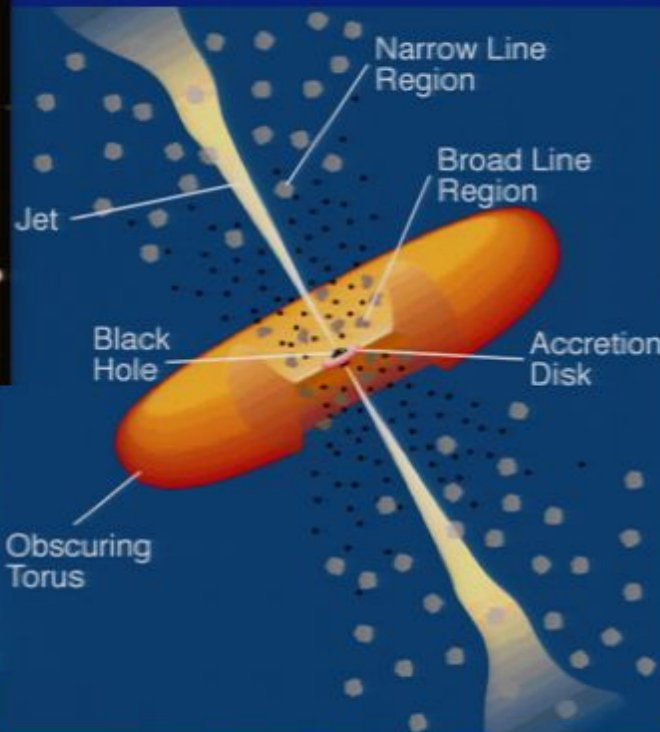
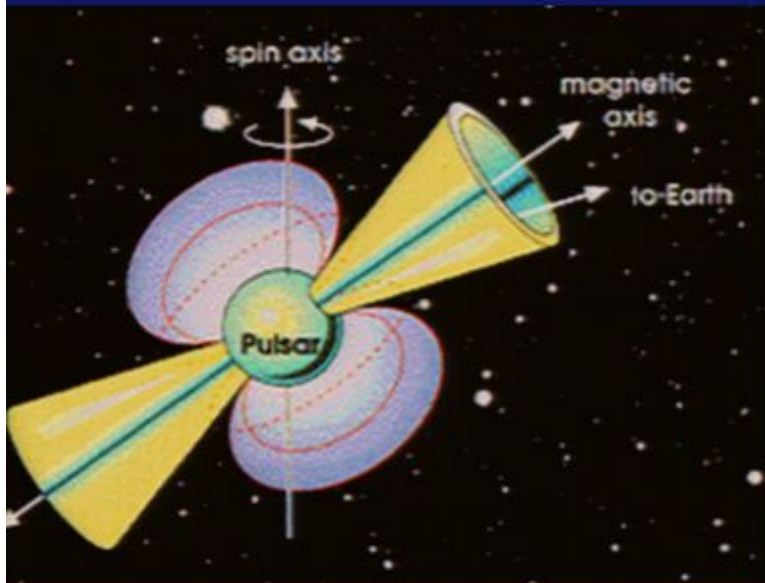
Title: Heavy Light: TeV gamma ray astrophysics

Date: Feb 15, 2006 02:00 PM

URL: <http://pirsa.org/06020030>

Abstract: The TeV energy range is a privileged part of the EM spectrum for astrophysical observations, allowing a view of some of the most energetic processes in the Universe, in objects as diverse as supernova remnants and black-hole driven Active Galactic Nuclei. Driven by new instruments, TeV gamma-rays astrophysics has made enormous strides in recent years with the discovery of many new sources, including new classes of sources such as galactic micro-quasars. This talk will give an overview of the state of TeV gamma-ray astrophysics, including the air Cherenkov technique used by ground-based TeV gamma ray detectors, the new instruments in operation or coming on line soon, and some of the results already obtained.

Gamma-ray Astrophysics at the TeV energy scale



K.J. Ragan
McGill University

Outline

- Introduction: information from the cosmos
- Science questions of high-energy astrophysics
- Detecting VHE gamma-rays
- Latest results: HESS telescope array
- Future projects: VERITAS, GLAST

We learn about the Universe through a very limited number of 'messengers':

- | | | |
|-----------------|---------|---------------------------------|
| • photons: | neutral | since antiquity |
| • cosmic rays: | charged | known for $\sim 10^2$ yrs |
| • neutrinos: | neutral | known for few $\times 10^1$ yrs |
| • gravity waves | neutral | no direct detection |
| • ? | | |

Sidereus Nuncius ("starry messenger")
Galileo, 1610



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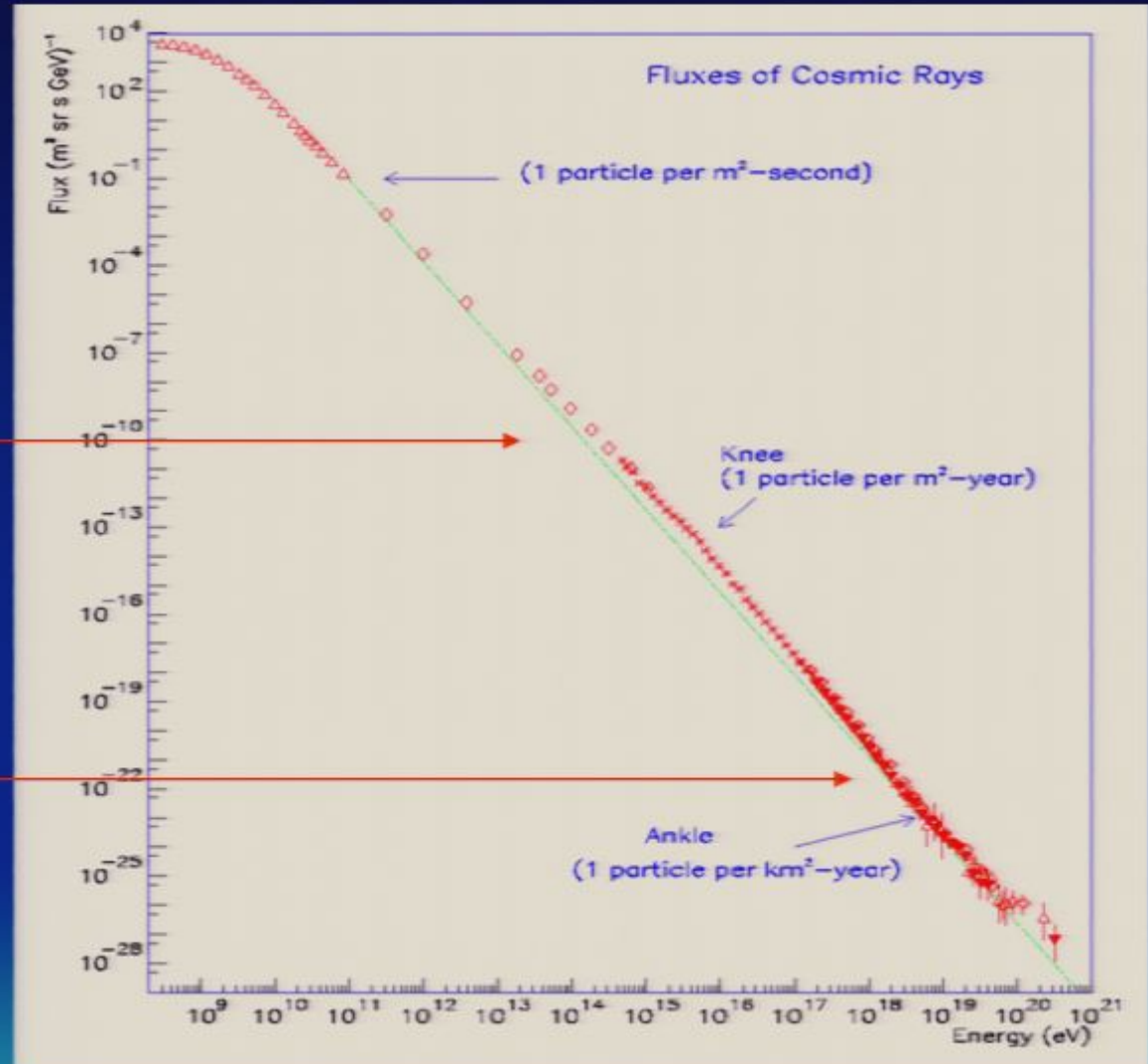


Intro

Cosmic ray energies extend to $> 10^{20}$ eV with power-law spectrum

galactic

Extra-galactic ?



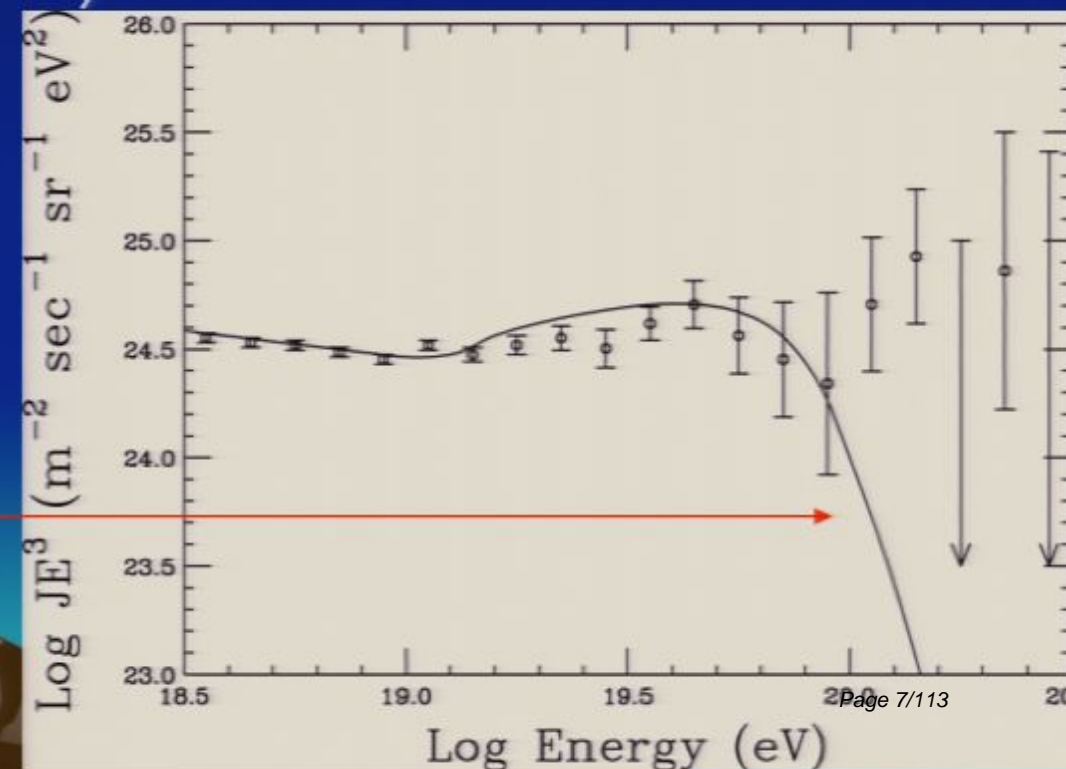
Total diffuse CR spectrum

Origin of cosmic rays $>10^{20}$ eV is mysterious:

- acceleration processes unknown
- scattering off CMB photons leads to absorption (GZK (Greisen-Zatsepin-Kuz'min) limit) -- Universe becomes opaque at ~ 50 Mpc



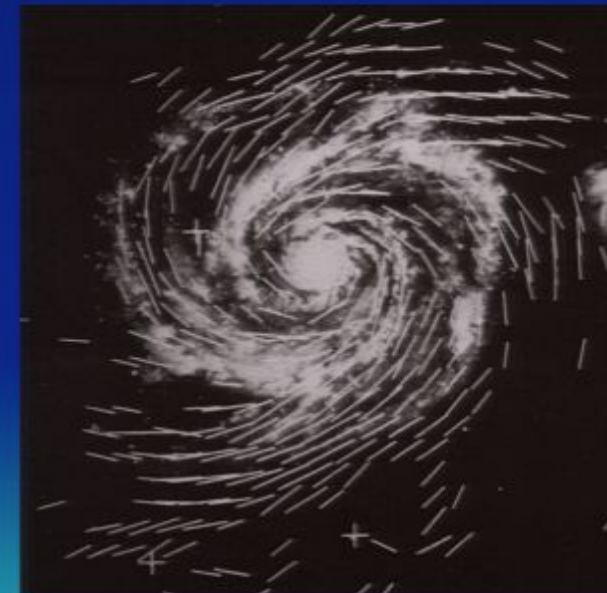
GZK limit



Cosmic rays are charged particles (p , α) subject to magnetic fields:

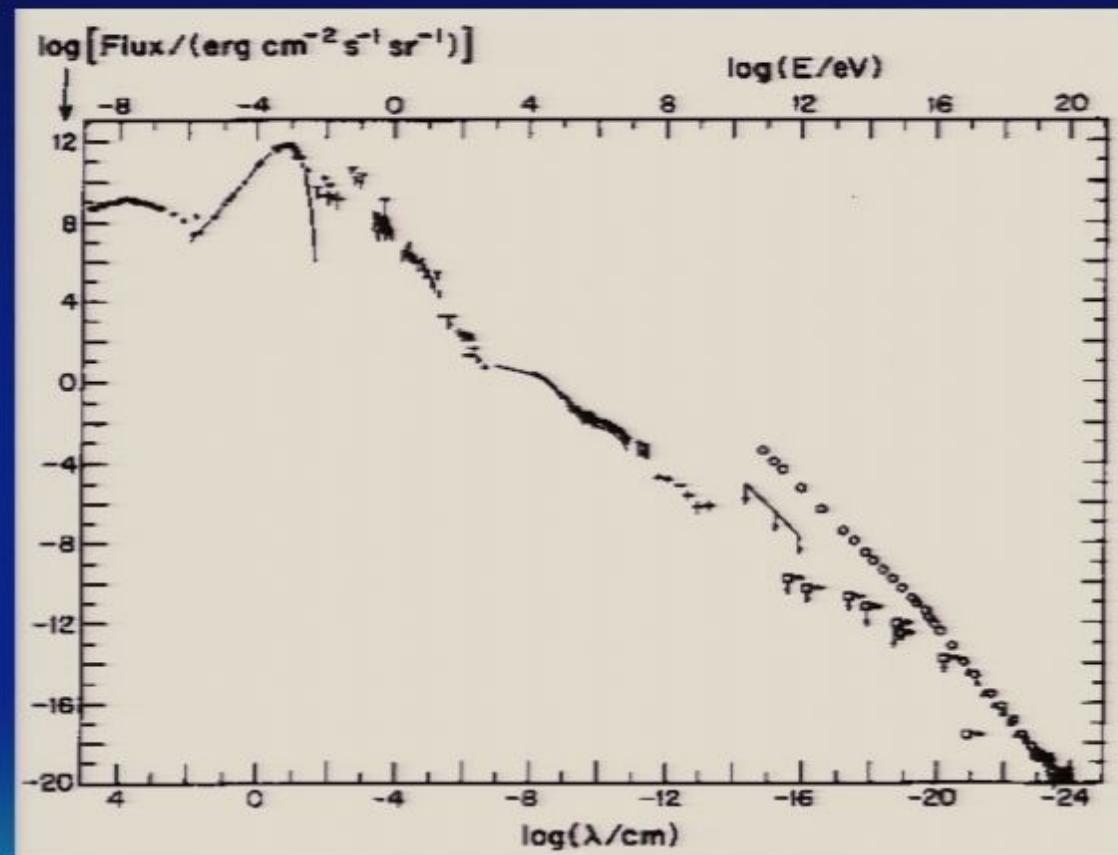
- Galaxies have $\sim \mu\text{G}$ fields; Larmor radius $r = E/cB$
 - $B = \mu\text{G}$, $E = 10^{20} \text{ eV}$
 $\rightarrow r \sim 30 \text{ kpc}$ (approx. size of Galaxy)
- Intergalactic fields may also be significant at least locally (eg Coma cluster has $B \sim 0.1 - 1 \mu\text{G}$ in filaments)

We need neutral particles to do astronomy!



M51 magnetic field

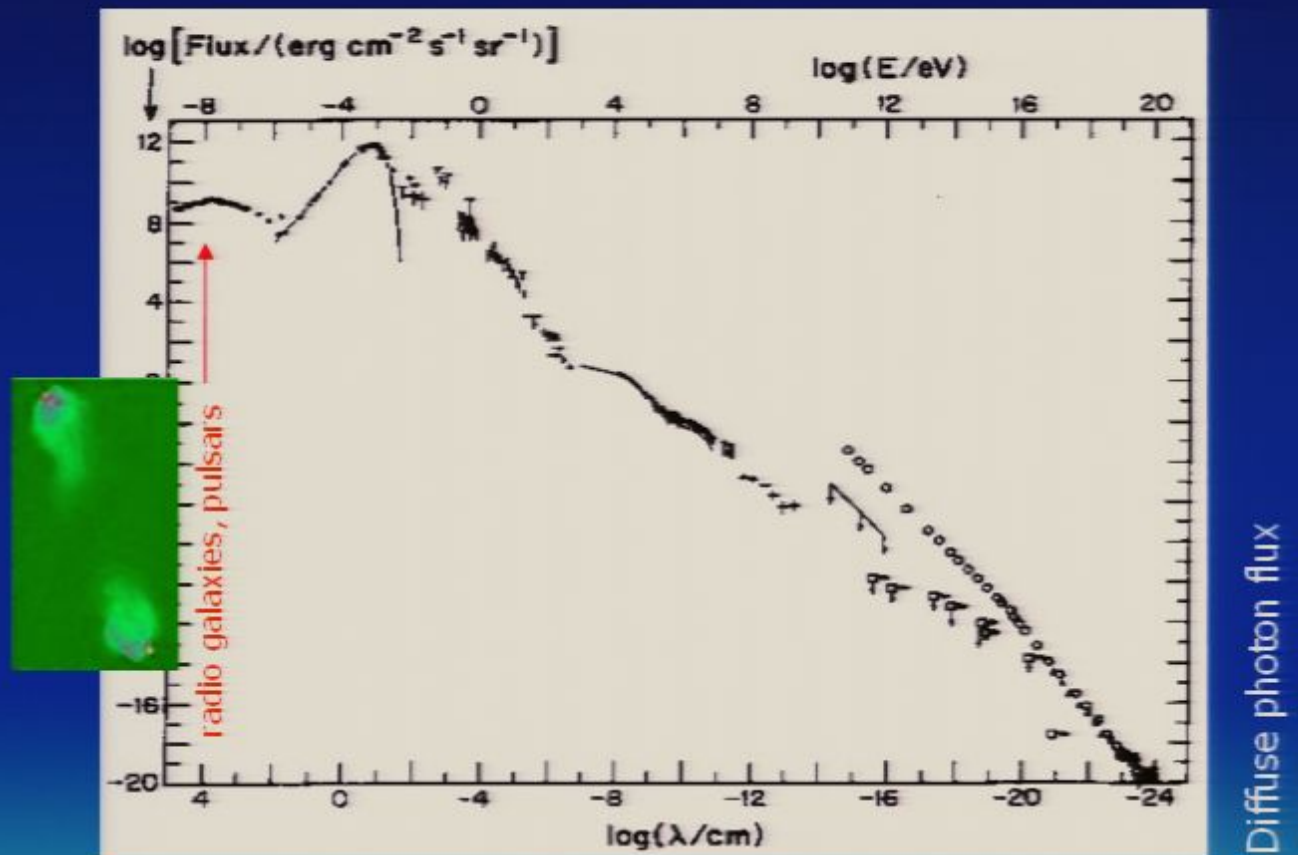
Turning to photon spectrum...



Diffuse photon flux

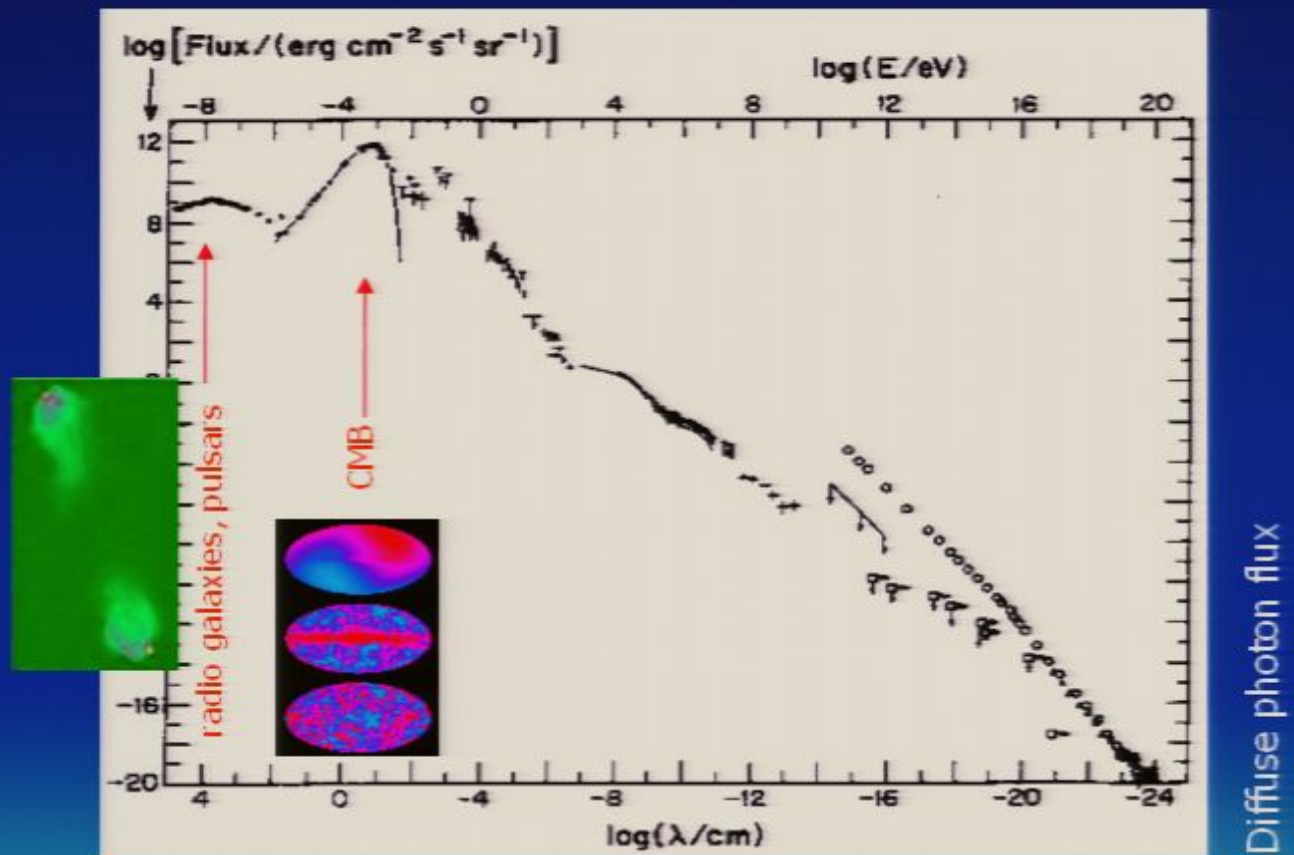
Revolutionary discoveries have occurred at each
new wavelength !

Turning to photon spectrum...



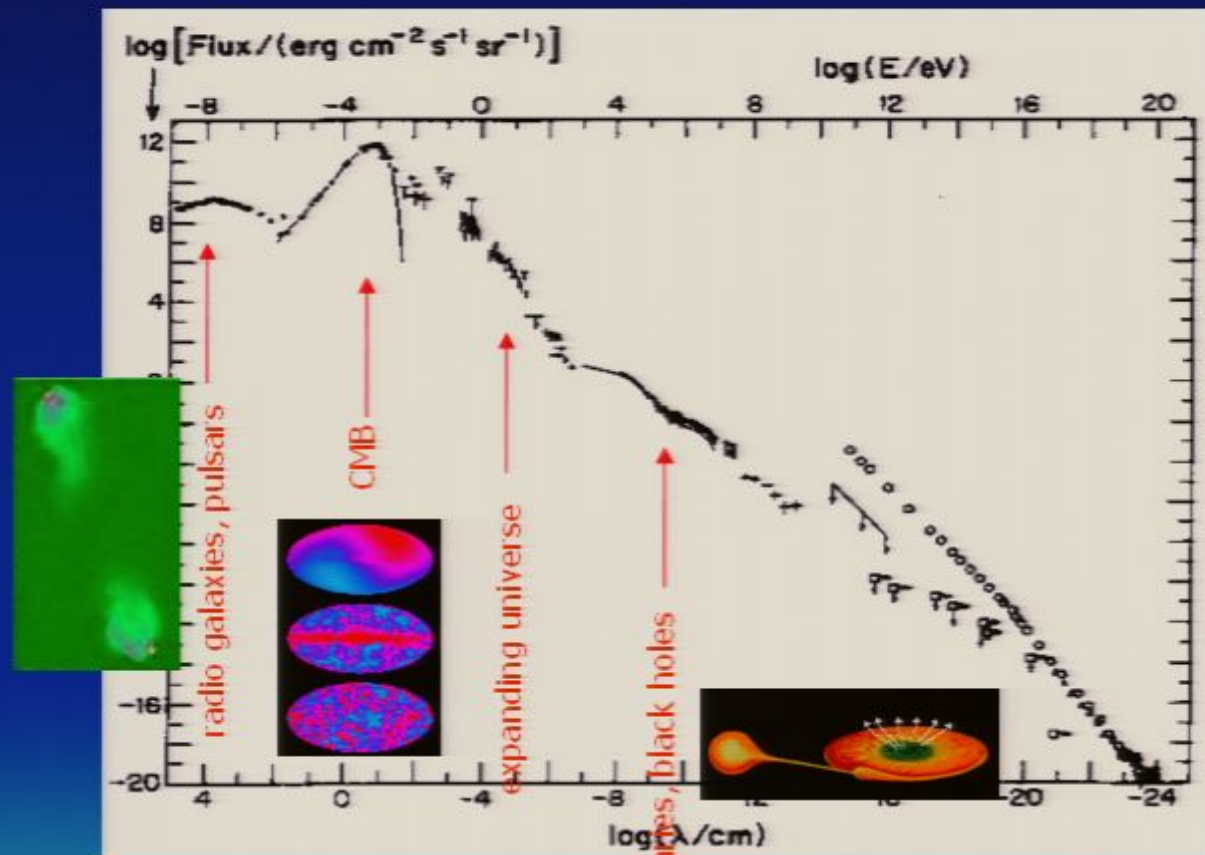
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Turning to photon spectrum...



Revolutionary discoveries have occurred at each
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Turning to photon spectrum...

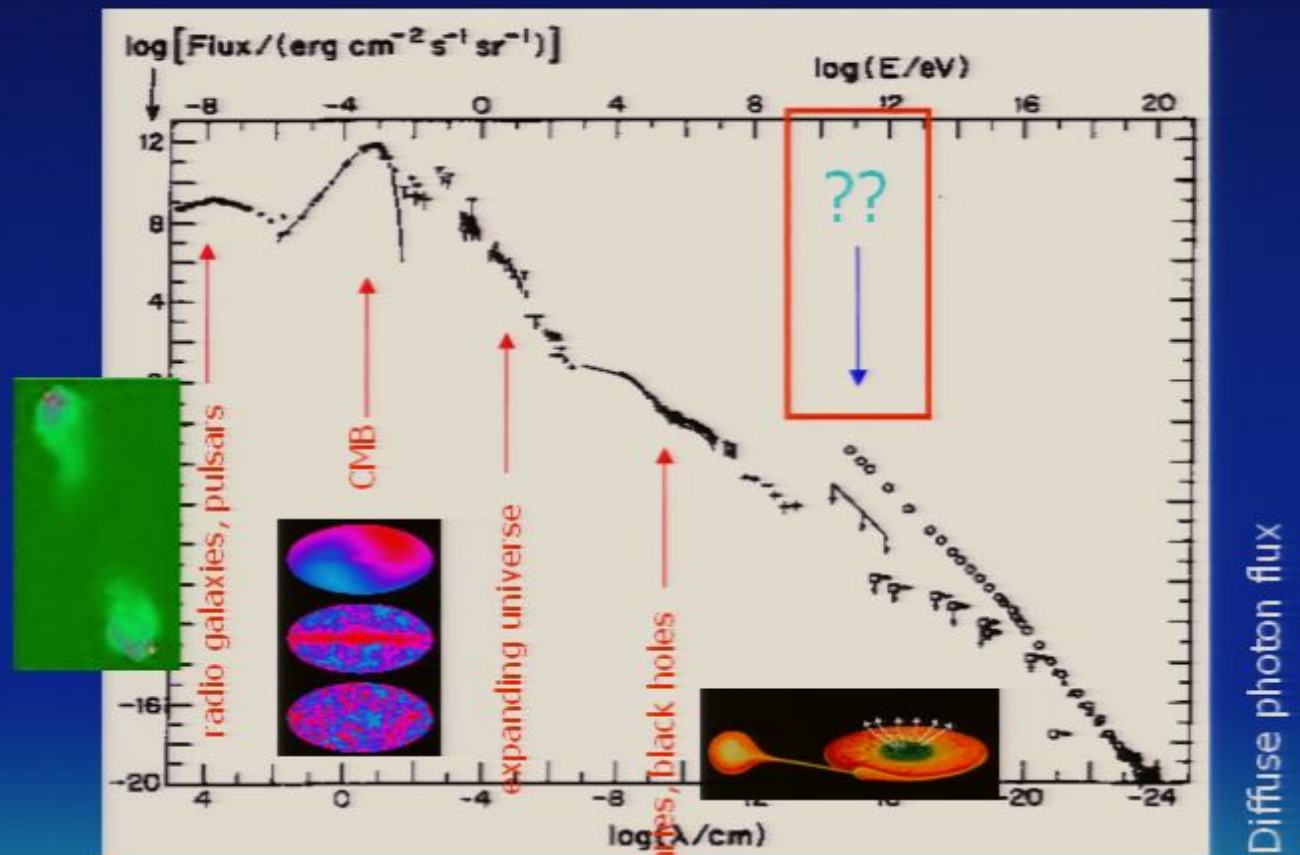


Diffuse photon flux

Revolutionary discoveries have occurred at each
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Turning to photon spectrum...

GeV-TeV energies

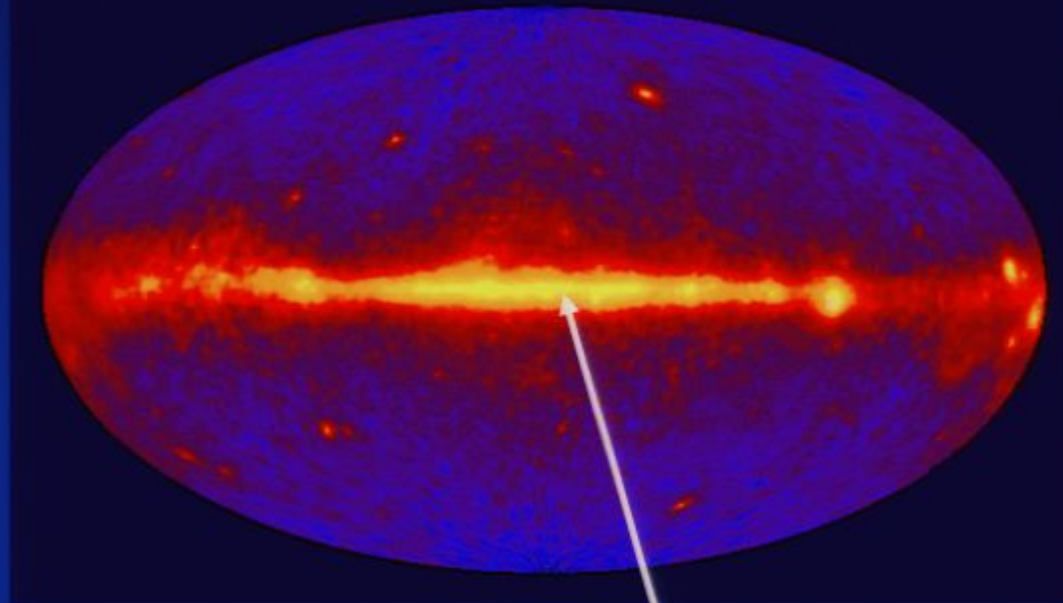


Revolutionary discoveries have occurred at each
new wavelength !



Science

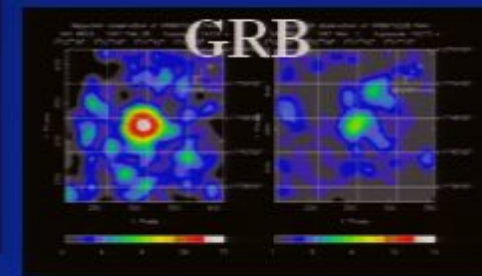
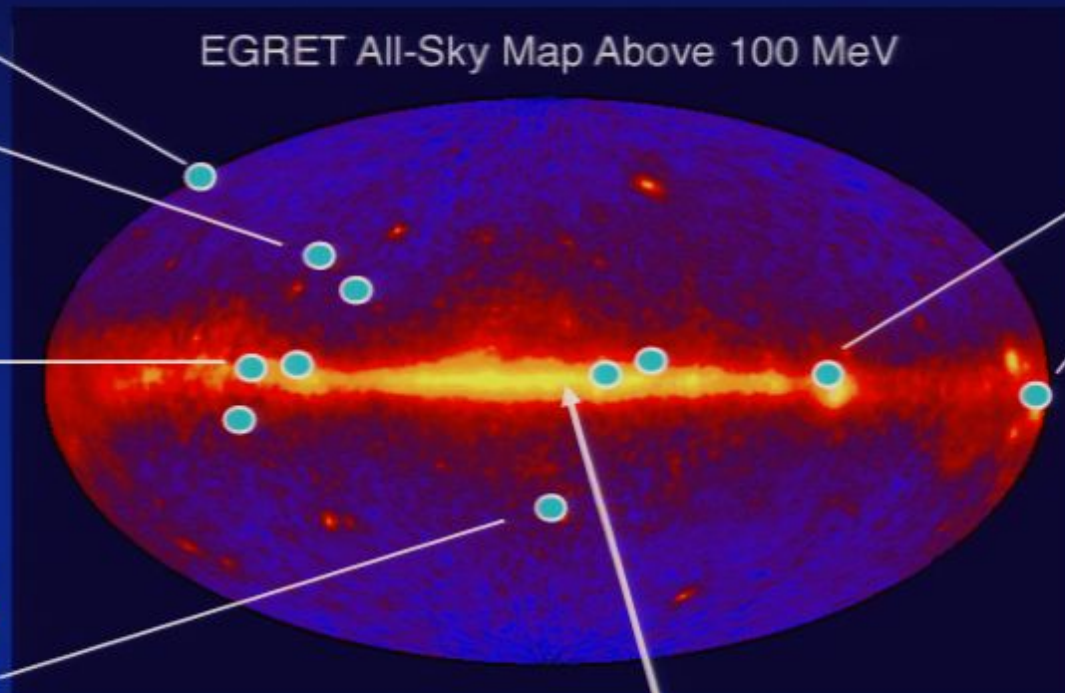
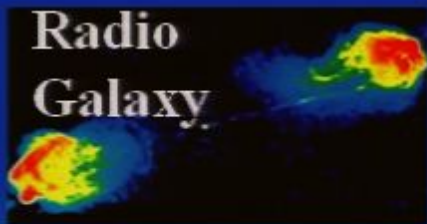
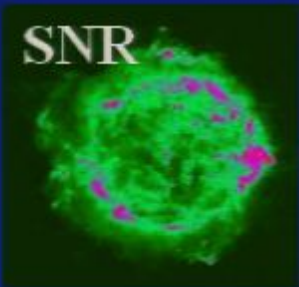
EGRET All-Sky Map Above 100 MeV



Cosmic Rays !



Science

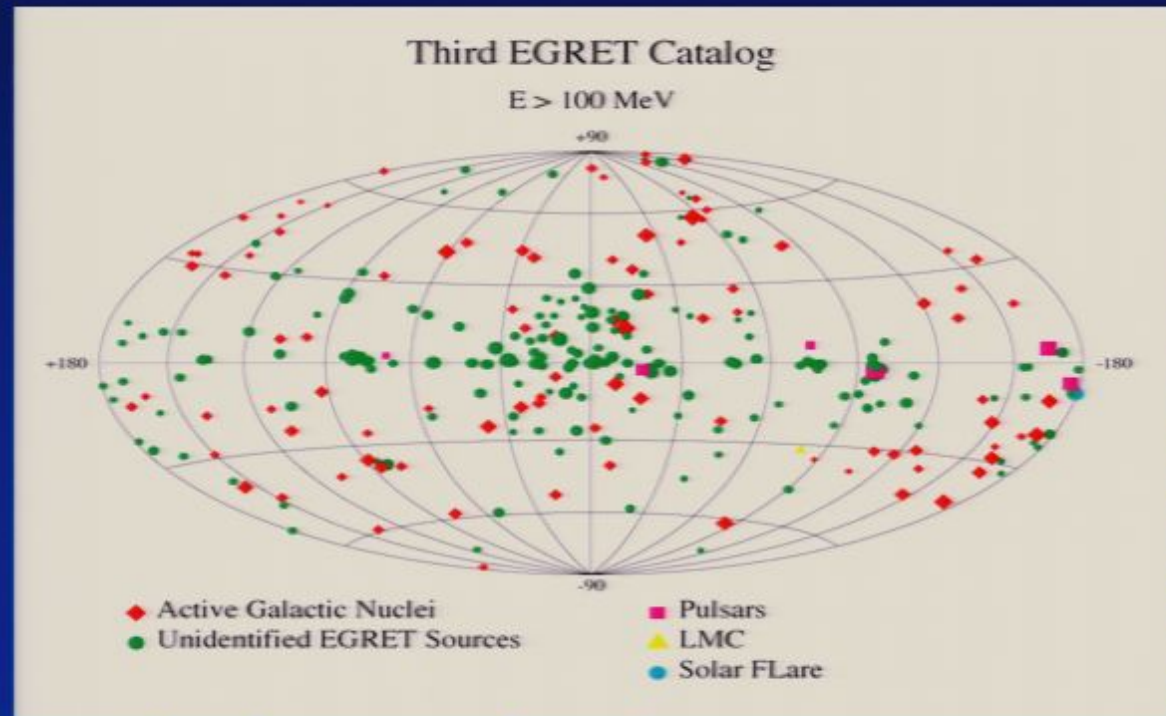


Cosmic Rays !



Science

At $< \text{GeV}$ γ energies, satellite detectors show that the Universe is a busy place:



CGRO/EGRET, circa 1995

- ~300 point sources, in three major classes:
- supernova remnants (SNR)
 - active galactic nuclei (AGN)
 - unidentified sources



Two very different power sources involved:

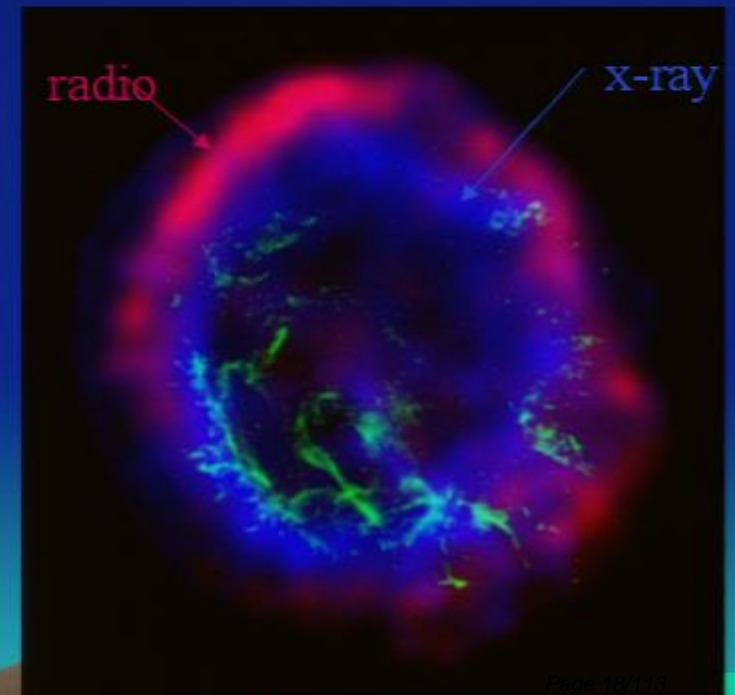
- Electromagnetic:
eg. rotating highly magnetized objects – pulsars
- Gravitational
 - Accretion onto a compact object:
Active Galactic Nuclei, microquasars, etc
 - Core collapse of massive star
Supernova remnants

Details sketchy !



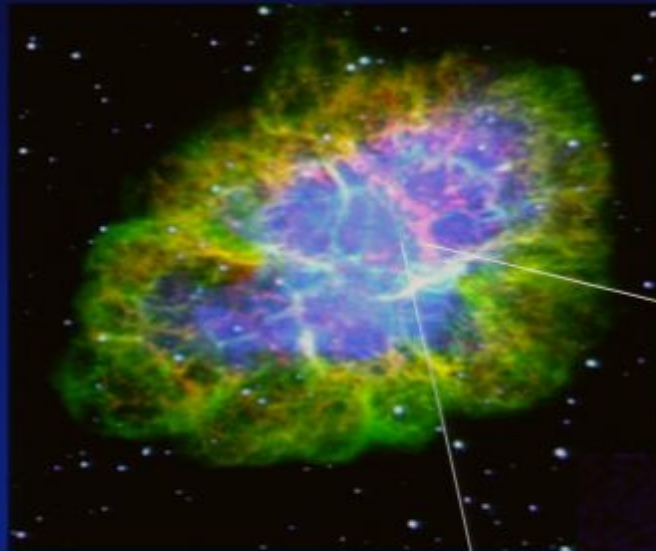
SNR:

- remnant of collapse of massive star
- outer layers ejected at $1-2 \times 10^4$ km/s
- shell expands, shock front forms as ISM swept up
- particle acceleration via canonical Fermi process
- blast wave starts to decelerate after $\sim 10^4$ yrs
- believed to be source of CR

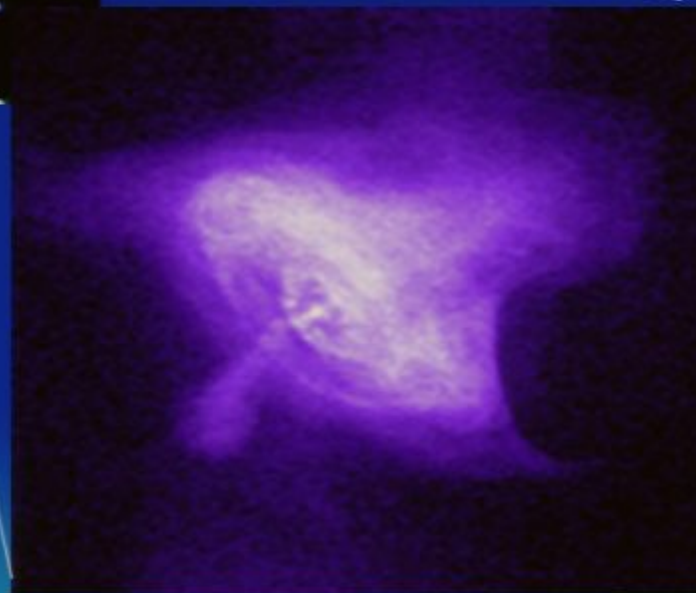
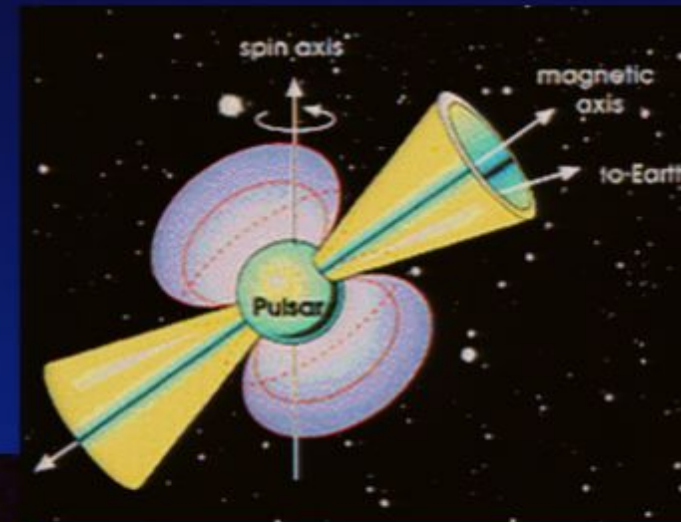




Archetypical SNR is the Crab Nebula, seen at *all* wavelengths:



Palomar, optical



Chandra, X-ray

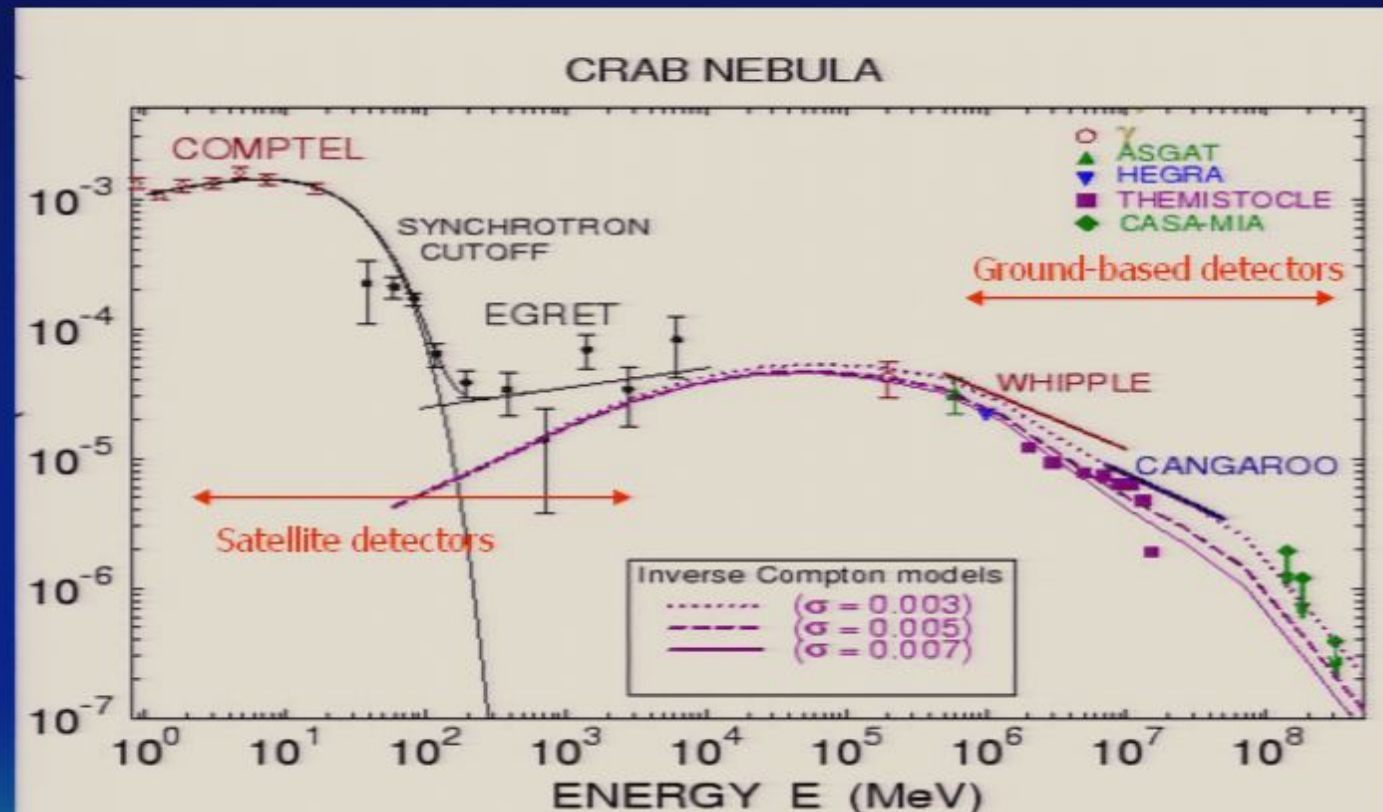
Result of Type II SN explosion in 1054 AD, resulting in
neutron star (pulsar)



Science

Crab provides:

- a 'standard candle' for γ detectors
- a success for model builders !

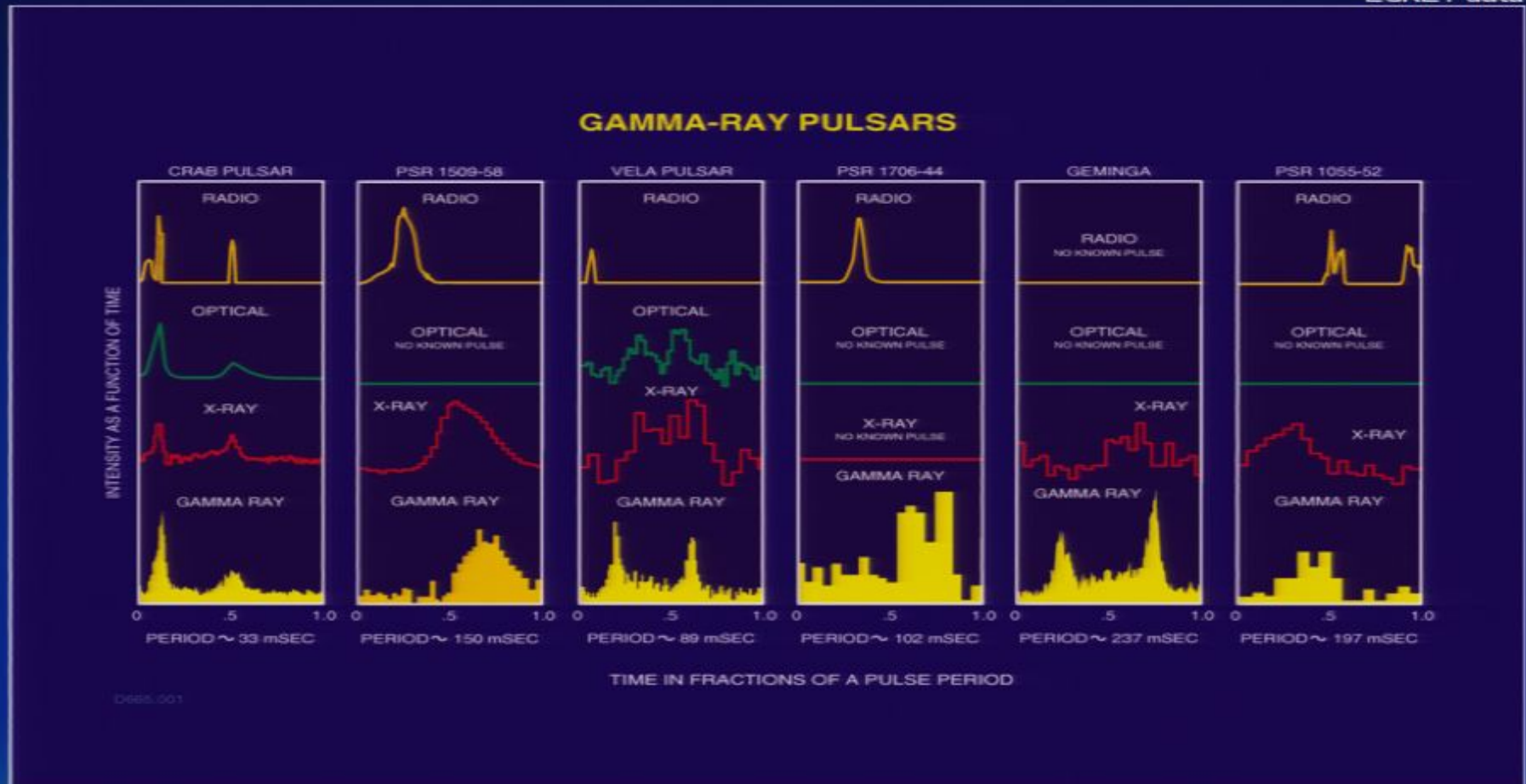


Nebula is powered by pulsar, γ arise through inverse Compton scattering of synchrotron emission (SSC)



Pulsar itself is also a γ source at $< \text{GeV}$ energies:

EGRET data

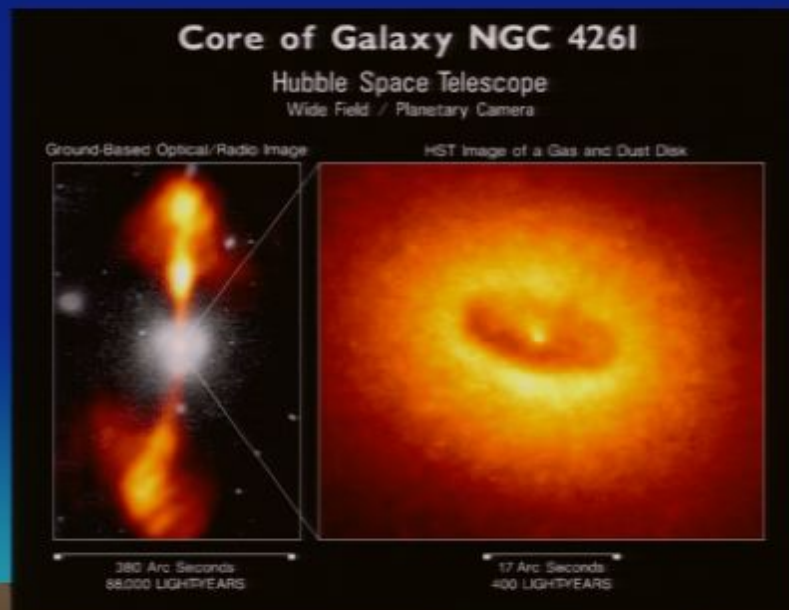


Competing models predict this emission to cut off anywhere from $\sim 10 \text{ GeV}$ to $> 50 \text{ GeV}$

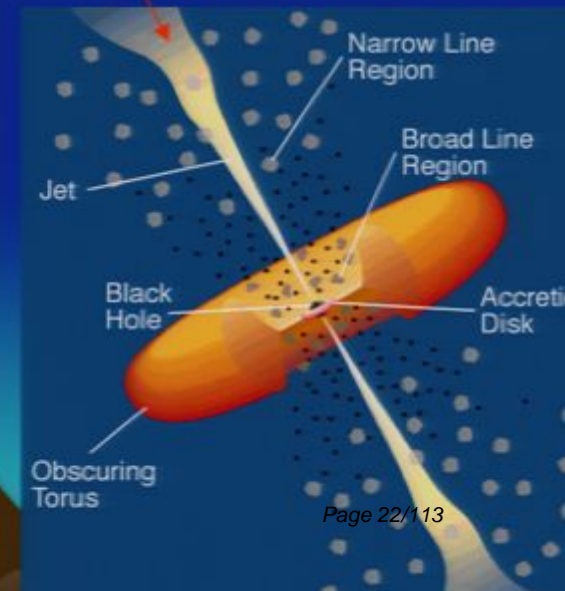


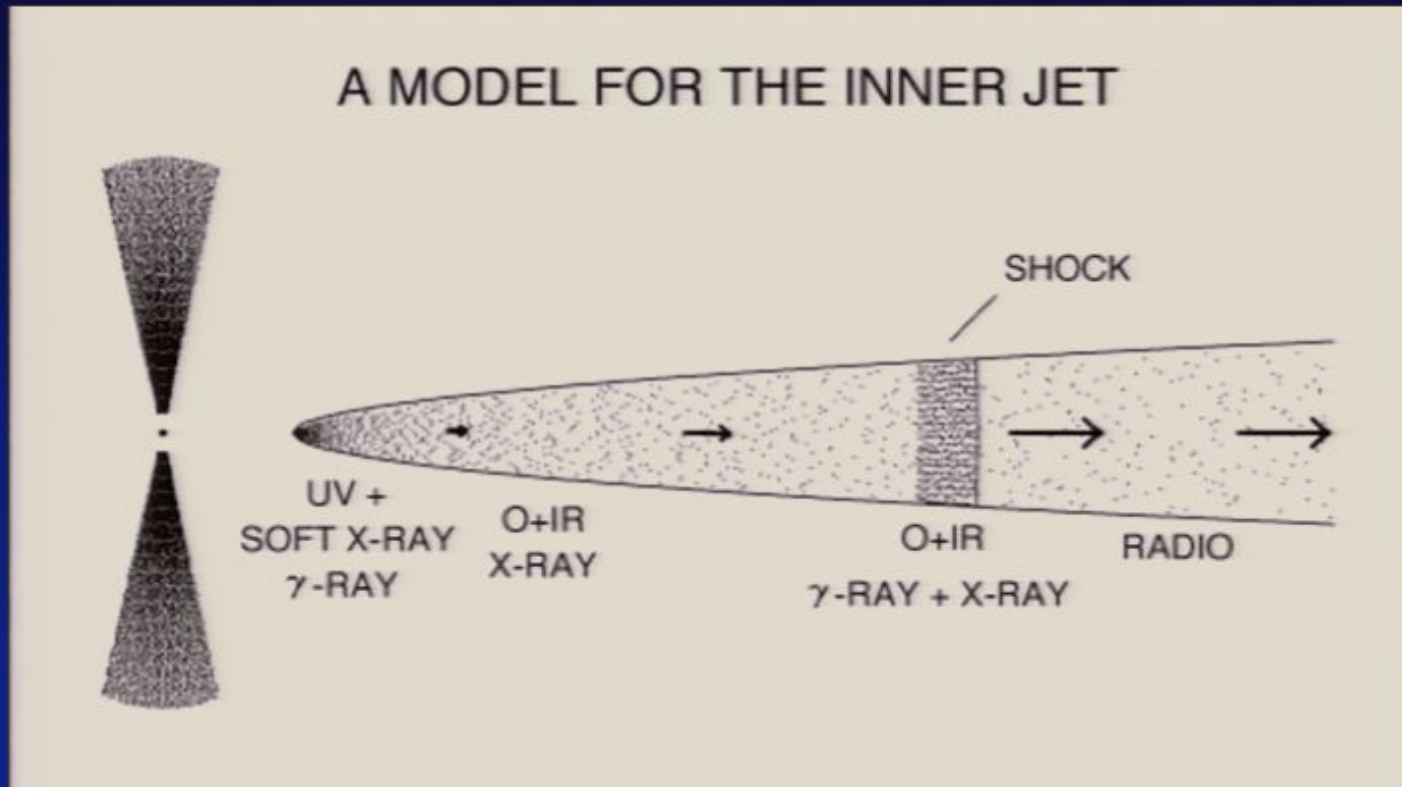
Active galactic nuclei (AGN):

- very luminous galaxies
- bright central core
- likely powered by accretion onto $\sim 10^9$ solar mass black hole, surrounded by accretion disk
- accretion energy powers jets with relativistic outflow

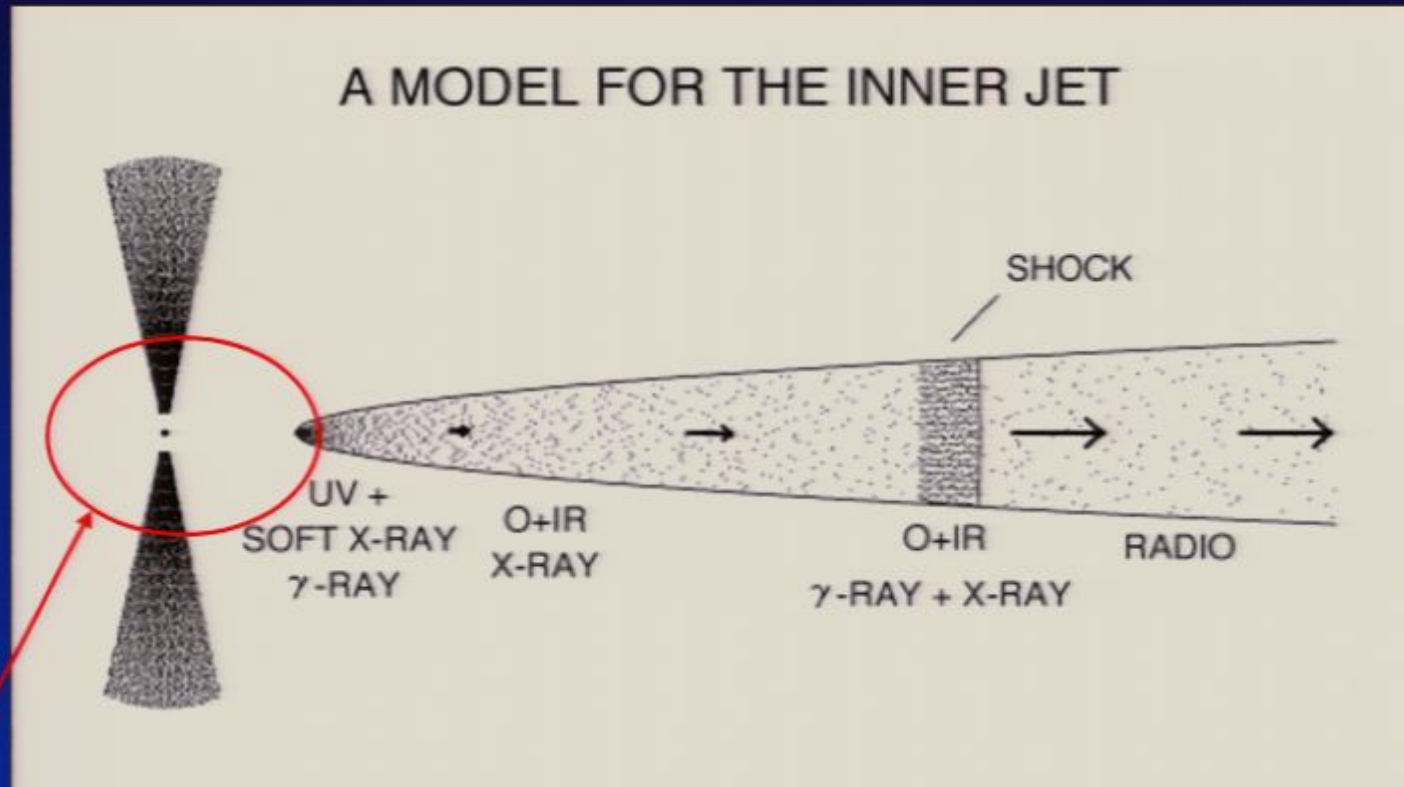


Blazar view

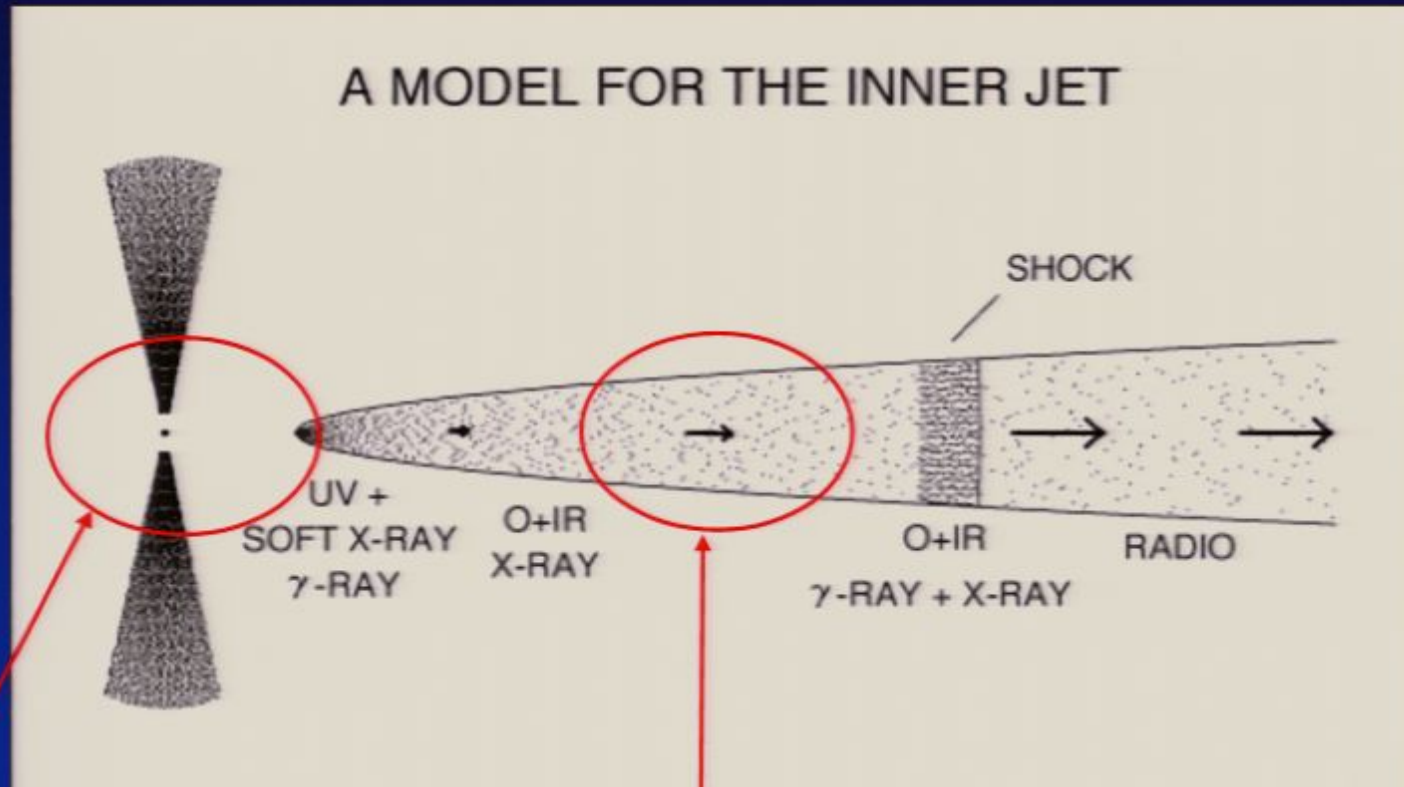




→ Earth



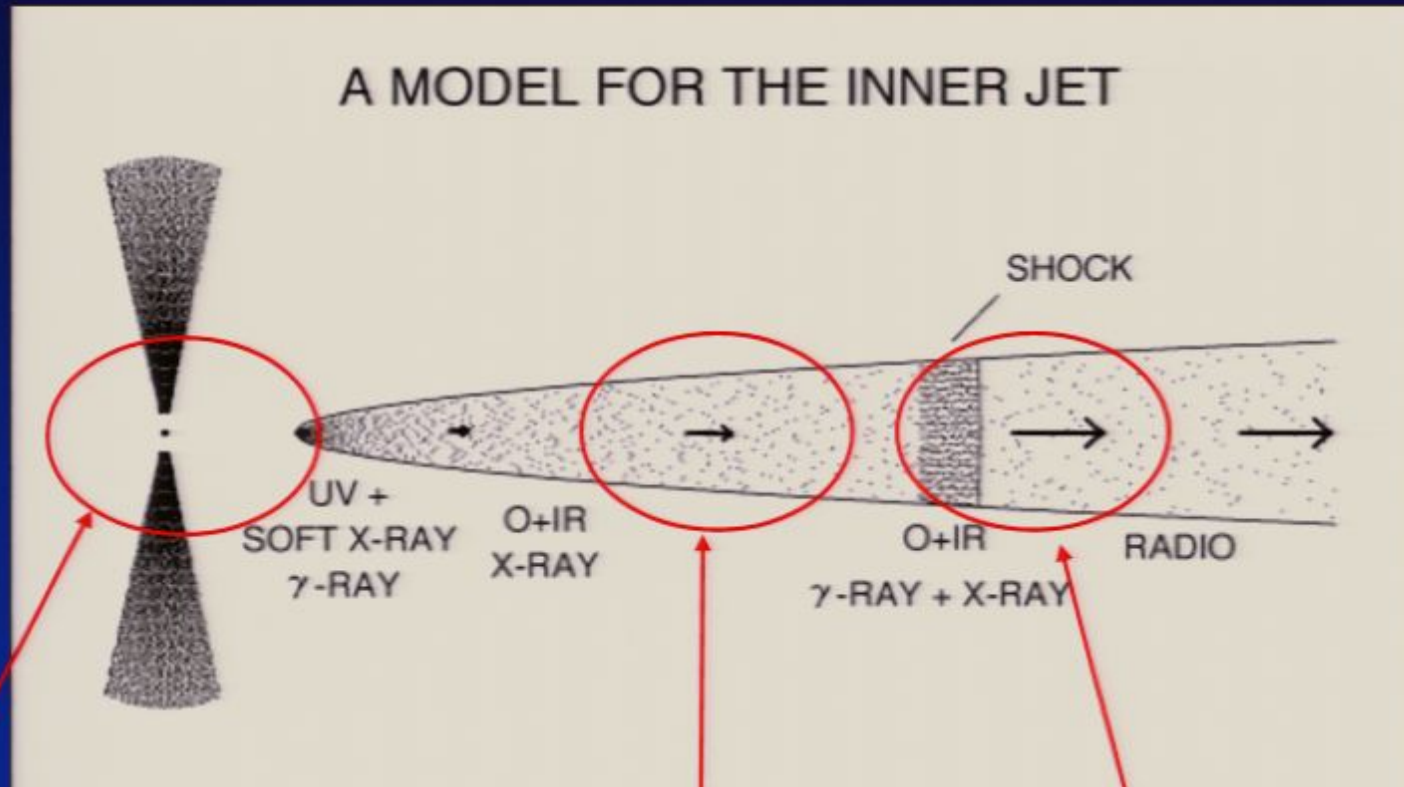
How do Jets form
& what powers them?



→ Earth

How do Jets form
& what powers them?

Nature of beam:
energetics Γ
particle type: e or p
field strengths B, γ



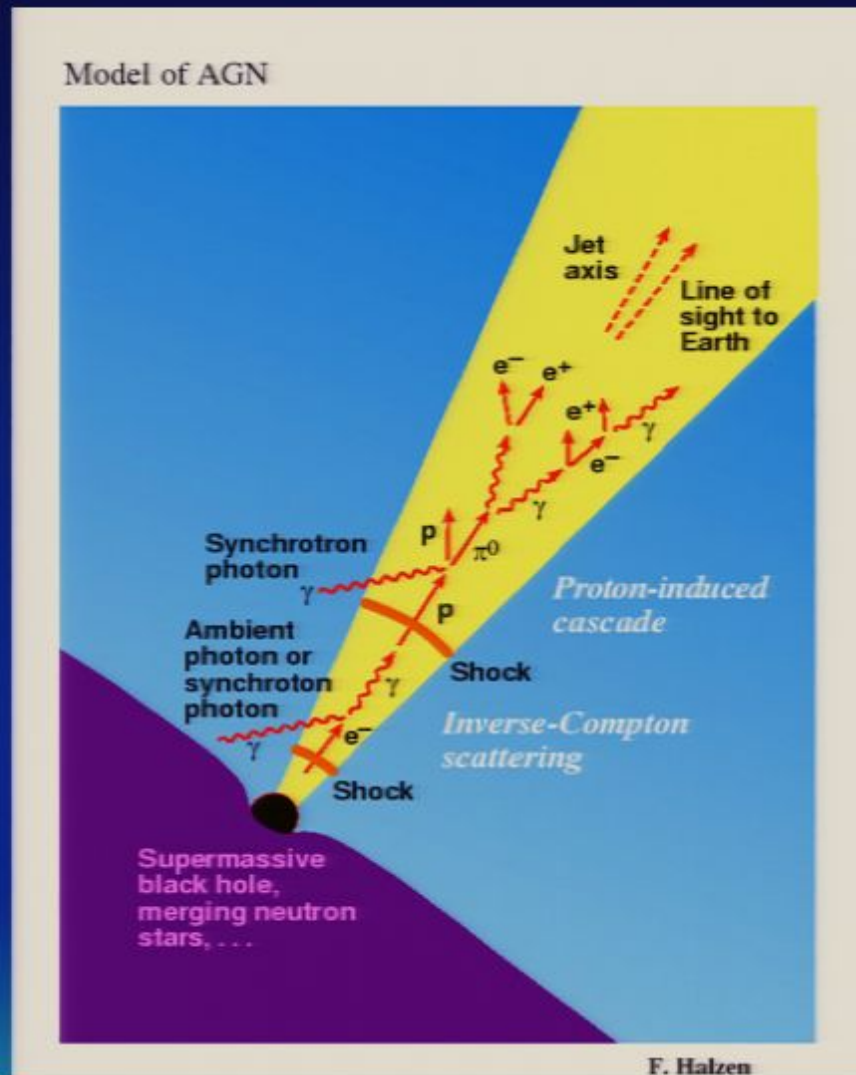
How do Jets form
& what powers them?

Nature of beam:
energetics Γ
particle type: e or p
field strengths B, γ

Geometry & External:
emission zones
source of soft photons

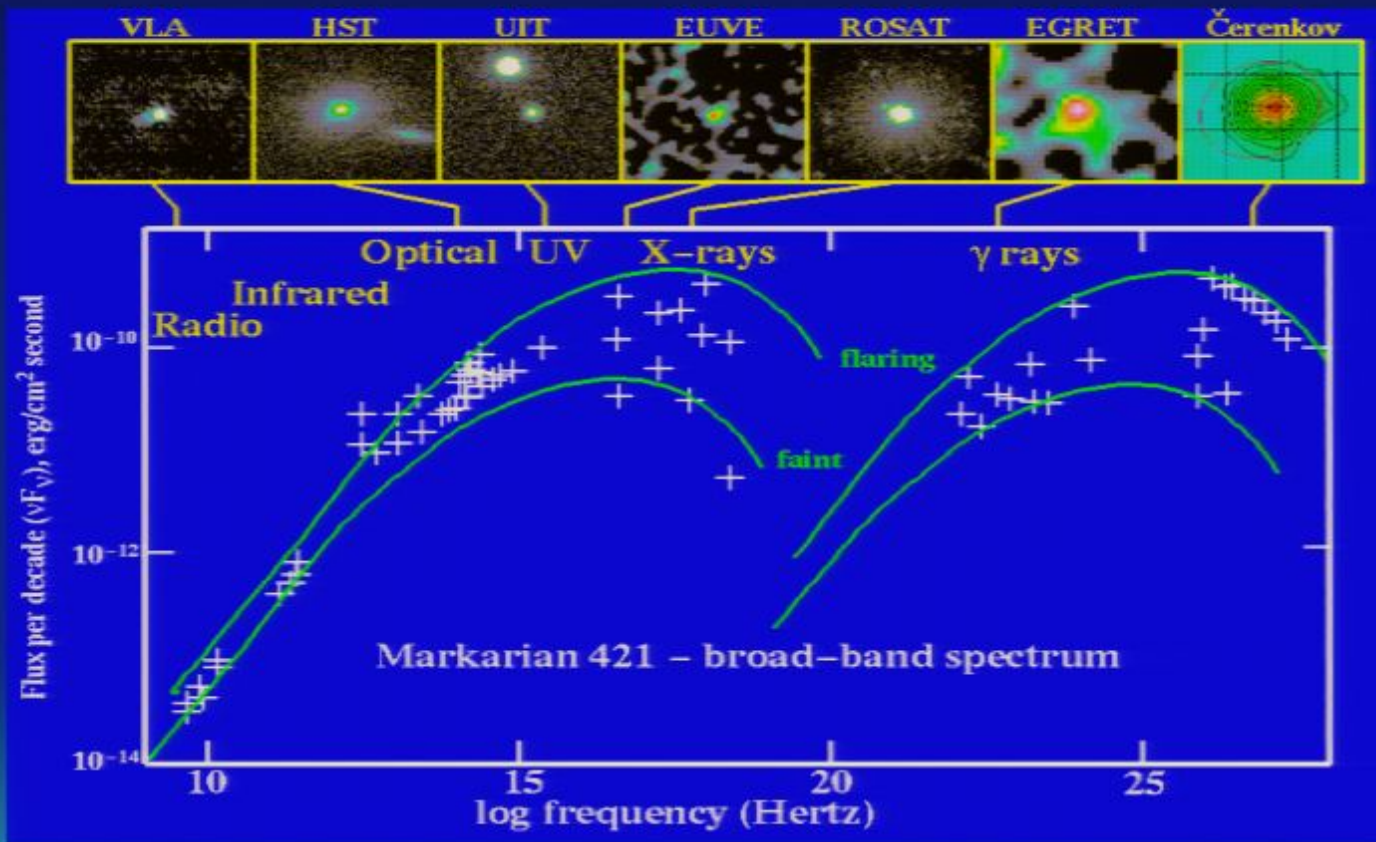


'Acceleration' to
VHE energies
requires extreme
particle physics;
elucidation of
mechanism needs
multi-wavelength
(multi-messenger)
studies





Emission mechanism not understood in detail, but extends up to > 10 TeV in at least *some* objects:



Structure most naturally explained in synchrotron-IC scenario: same electron population

Observations starting to constrain Γ , time scales, emission zones, photon density, etc...



New physics might also give rise to VHE gammas:

- Particle physics at higher mass scales
 - Eg. SUSY (dark matter?)
 - Top-down sources (GUT scale particles)
- Relics from early Universe
 - Primordial black holes
 - Decaying heavy neutrinos

Very speculative, of course...

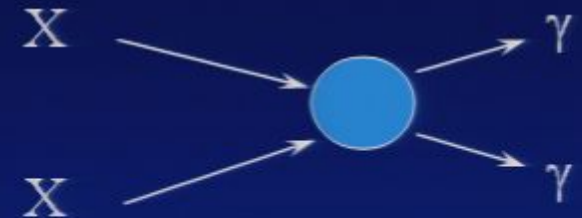


Dark matter & SUSY:

Neutralinos might have enhanced density in GC, annihilate to give GeV and TeV γ -rays

Generally expect broad bump in γ -ray spectra

Neutralino
Annihilation



$$\text{Flux} \sim (\rho_x / M_x)^2 \sigma v$$



Galactic Center

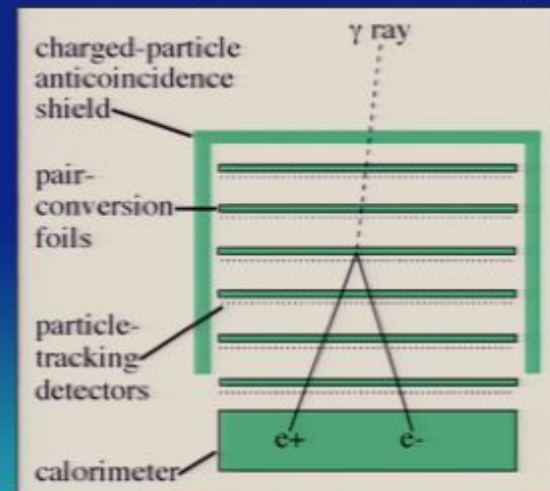
Detection

γ -ray astronomy pioneered by space-borne instruments,
most notably the Compton Gamma-ray Observatory



Flew 1991-2000
4 instruments
EGRET detected ~ 300 point sources

EGRET (30 MeV – 20 GeV)

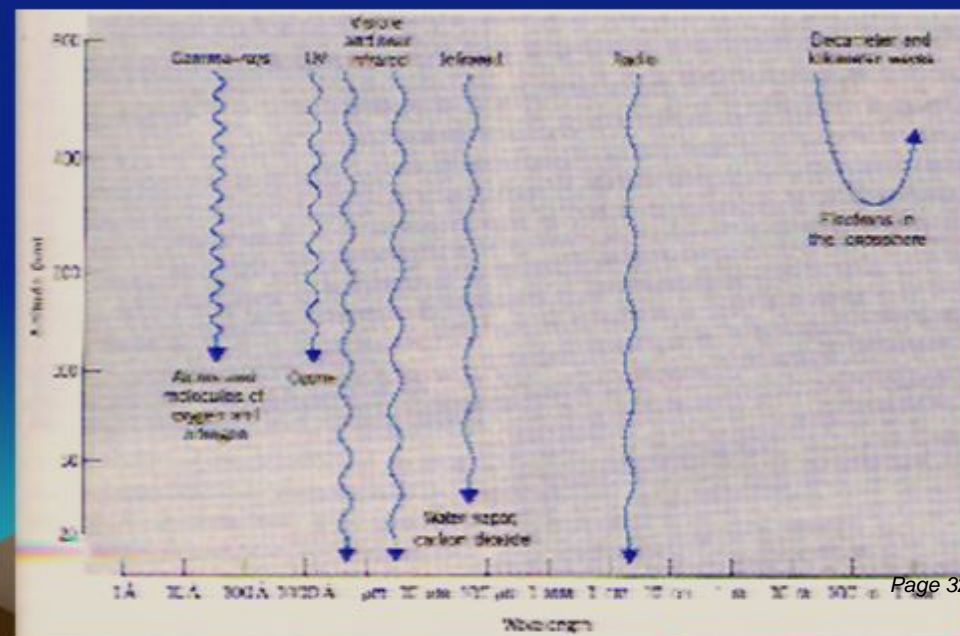


Detection

Satellite observations above ~ 10 GeV are difficult:

- costly
- long lead times
- low fluxes - Crab ($E > 10$ GeV): $\sim 100 \gamma/\text{yr}/\text{m}$

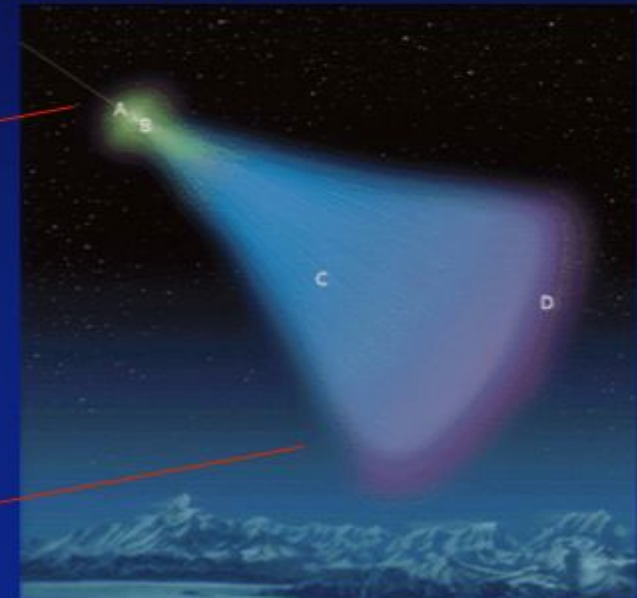
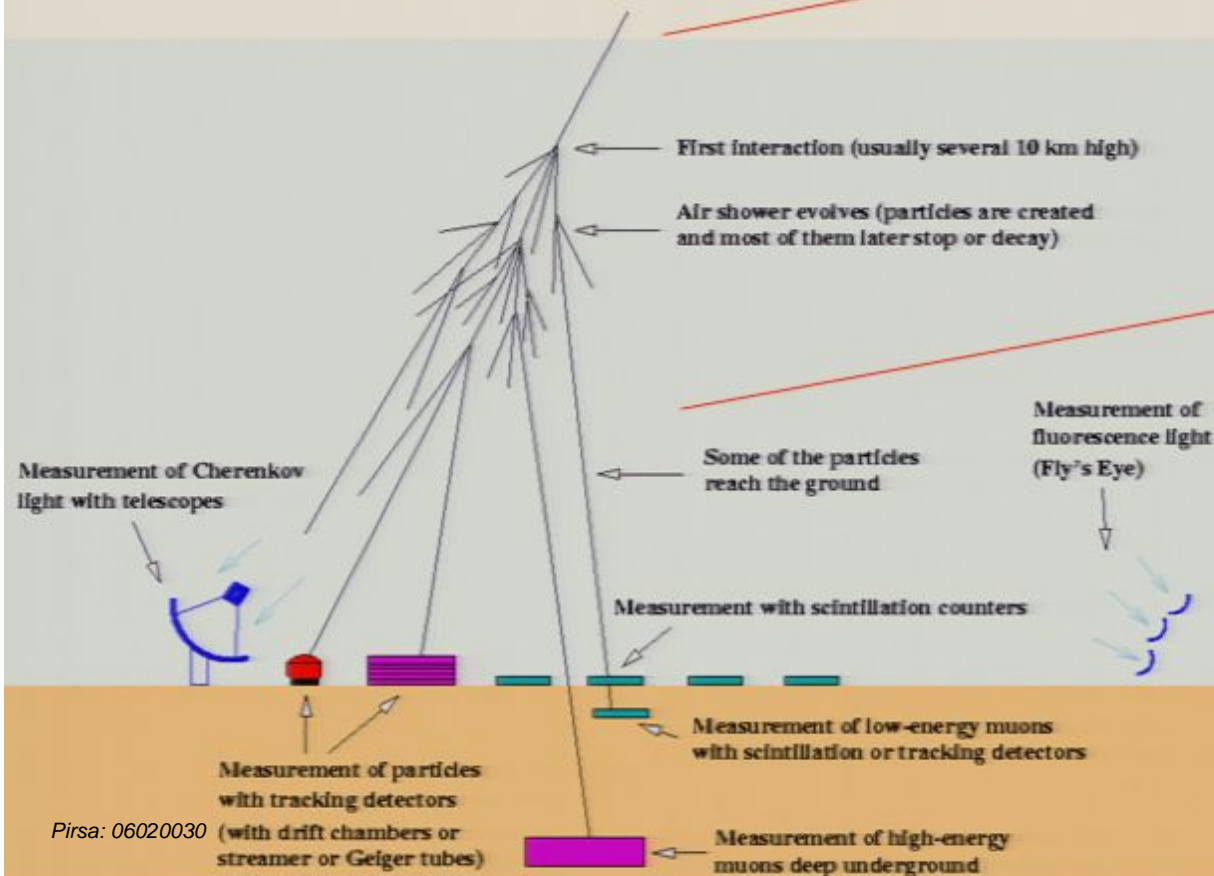
Ground-based observations are hindered by atmospheric absorption:



Detection

Solution: use the atmosphere as part of the detector - detect high energy showers created by energetic primaries

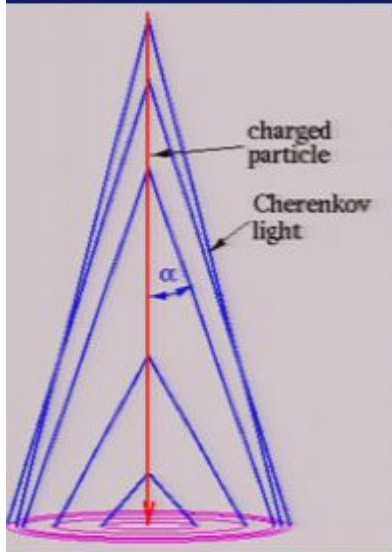
Measuring cosmic-ray and gamma-ray air showers



- A - interaction
- B - start of shower
- C - Cherenkov light cone
- D - charged particle 'wavefront'

Detection

Use of Cherenkov signal - fast, directional, approx. linear response with E - turns the atmosphere into a calorimeter !



First proposed by Blackett (40's) & Jelley (50's); first experimental work in 60's

Pirsa: 06020030

Perimeter Institute, Feb '06

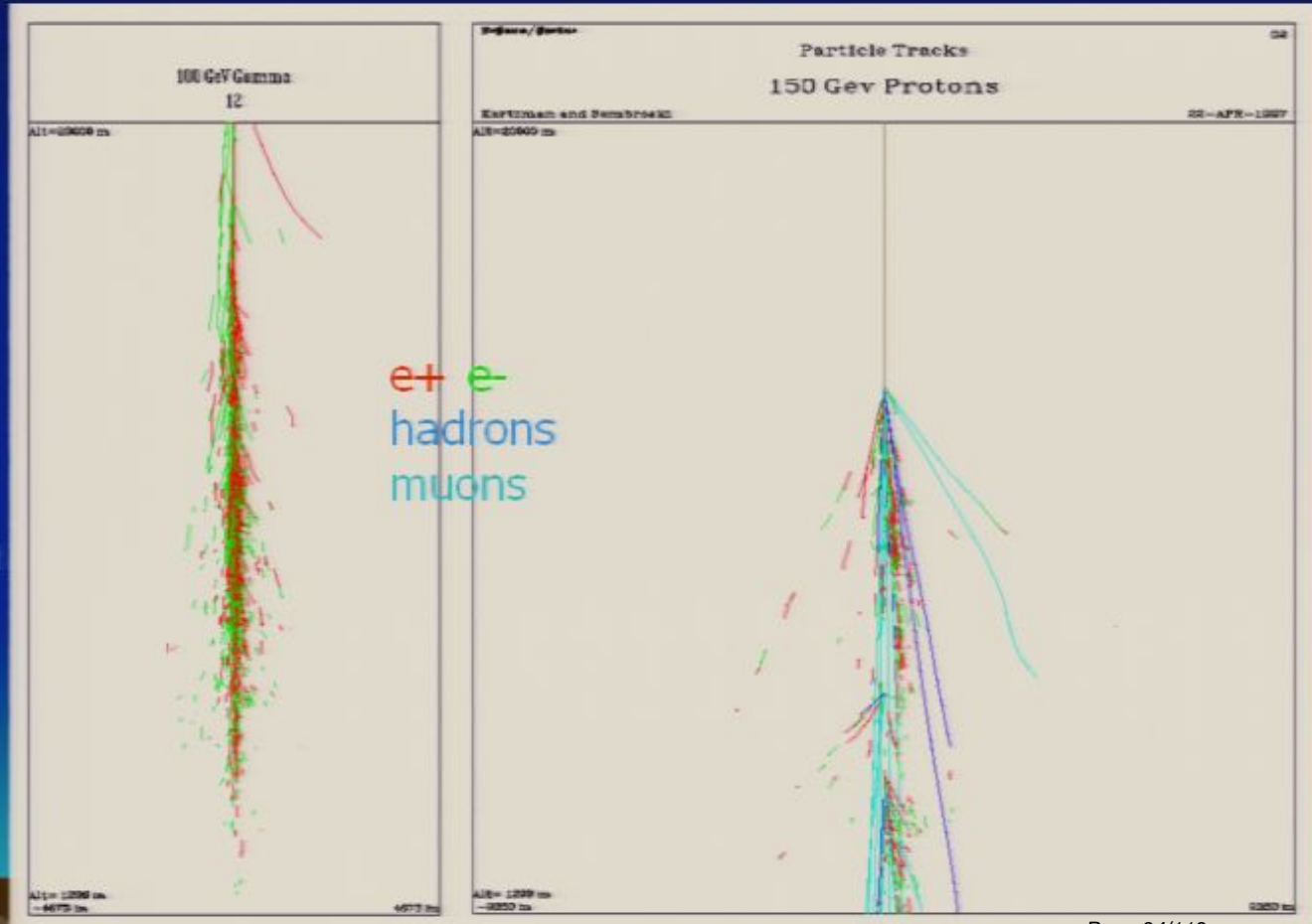
signal

background

20 km

$\beta=1$

ground



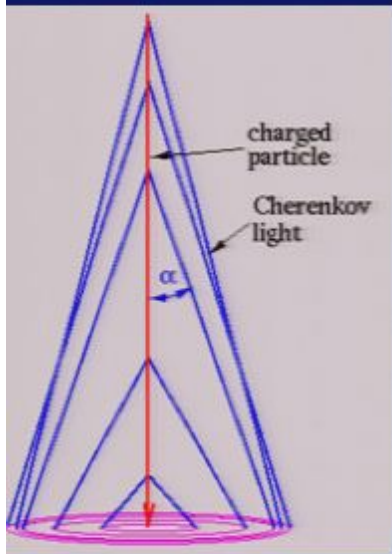
100 GeV gamma

150 GeV proton

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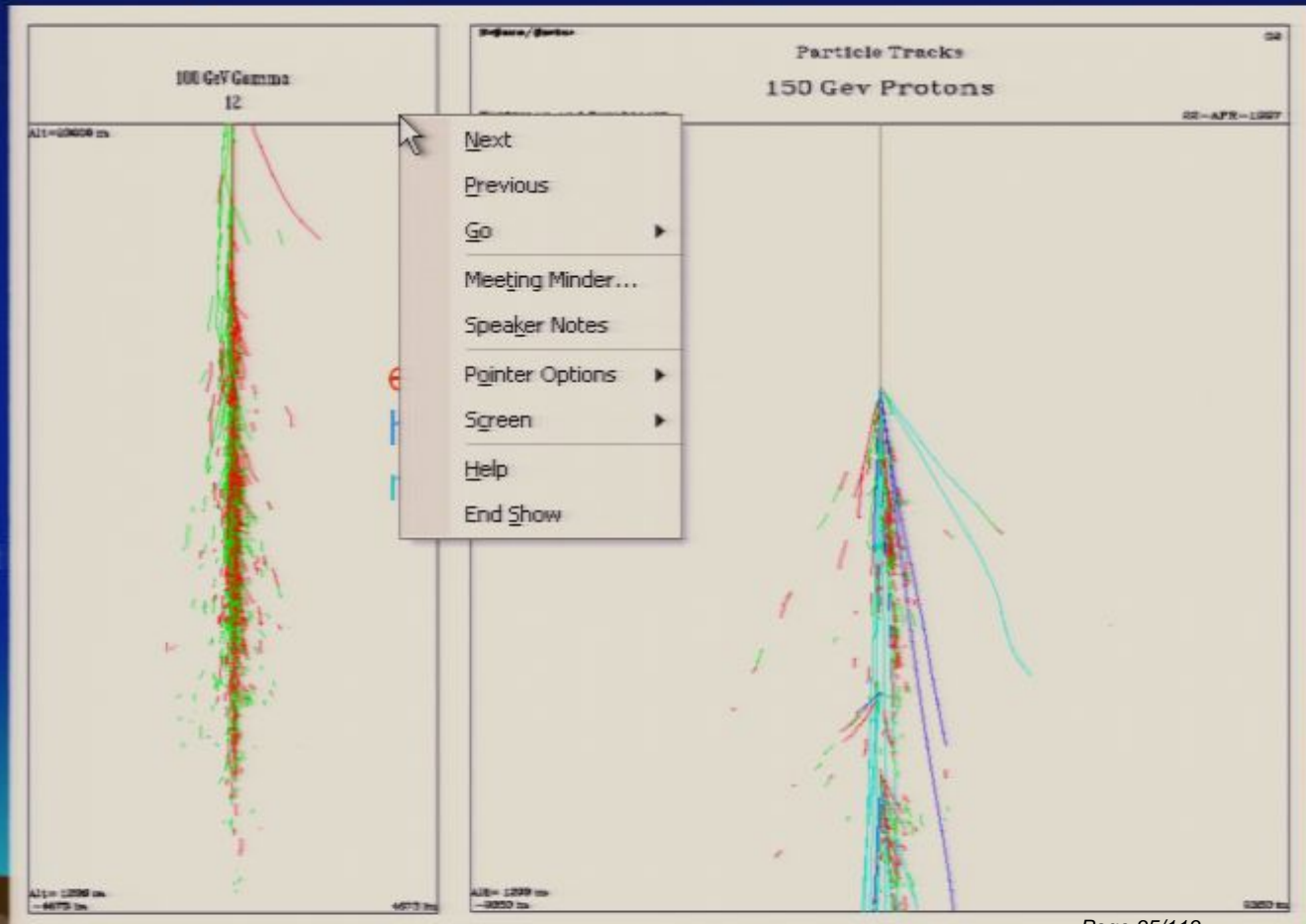
signal

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20 km

$\beta = 1$

ground



100 GeV gamma

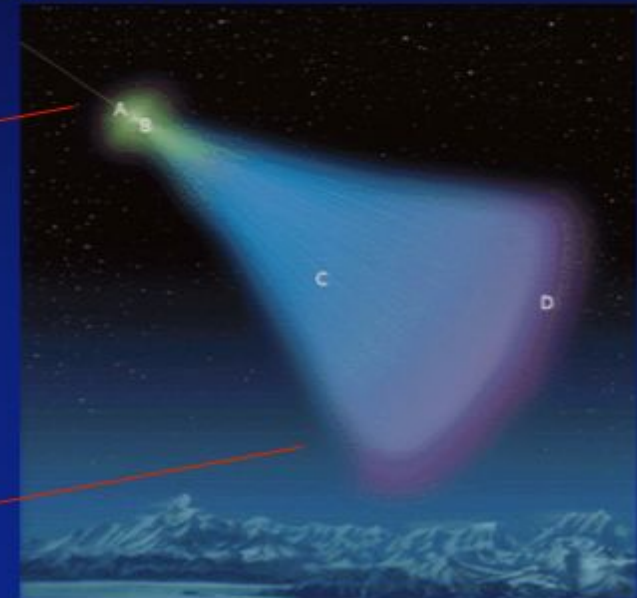
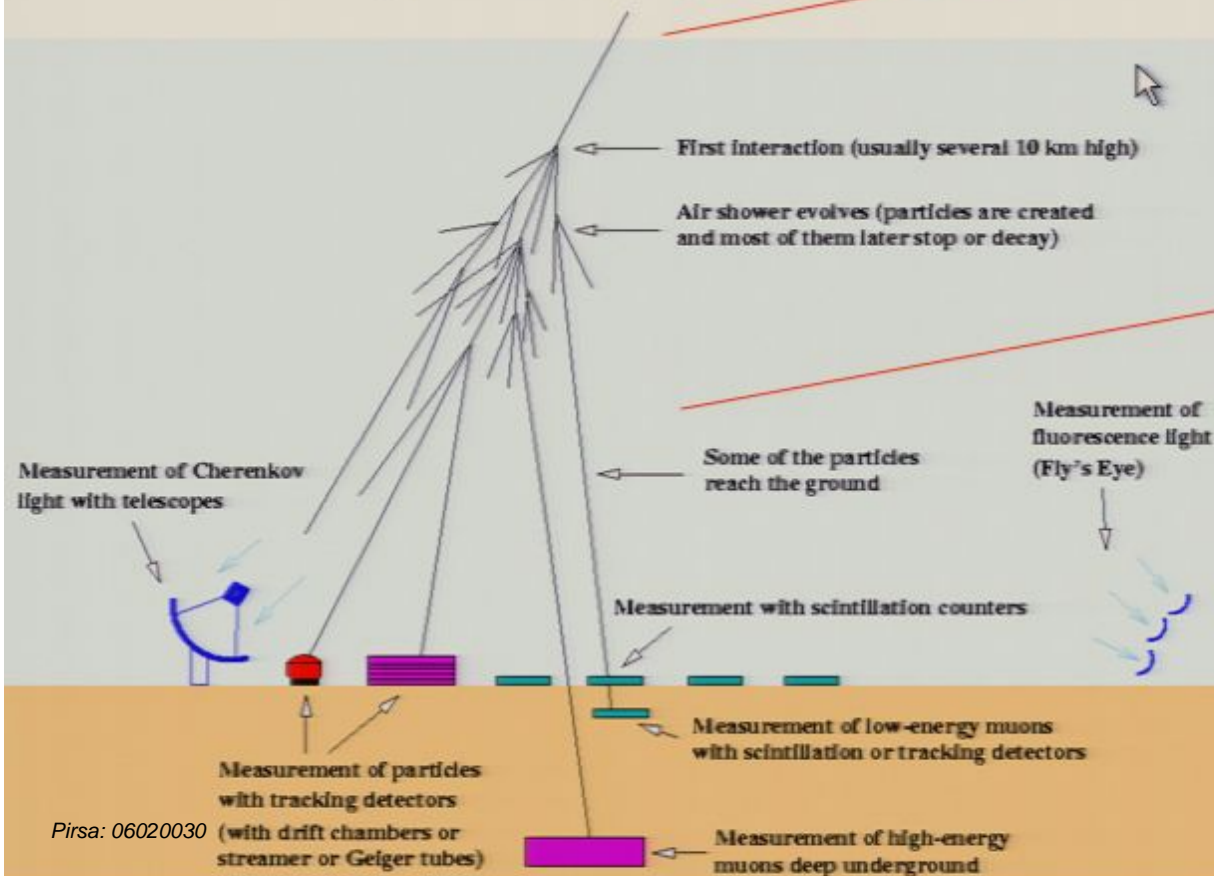
150 GeV proton

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Detection

Solution: use the atmosphere as part of the detector - detect high energy showers created by energetic primaries

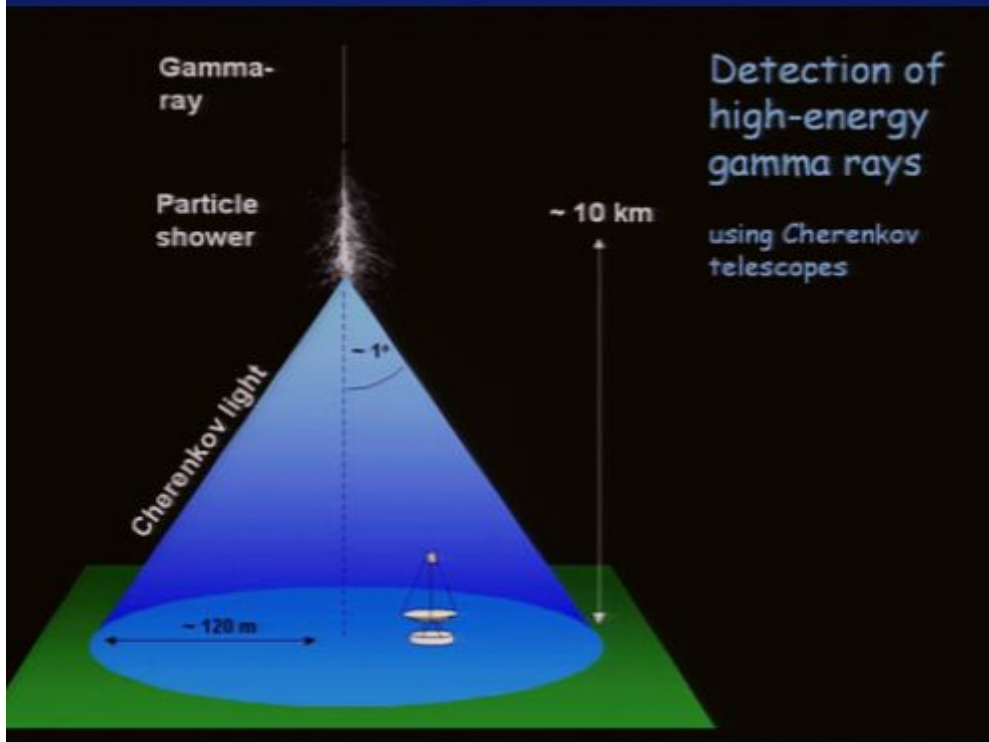
Measuring cosmic-ray and gamma-ray air showers



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Detection

First successful application of technique Whipple group (SAO) in late 1980's using imaging telescope and highly pixellated camera



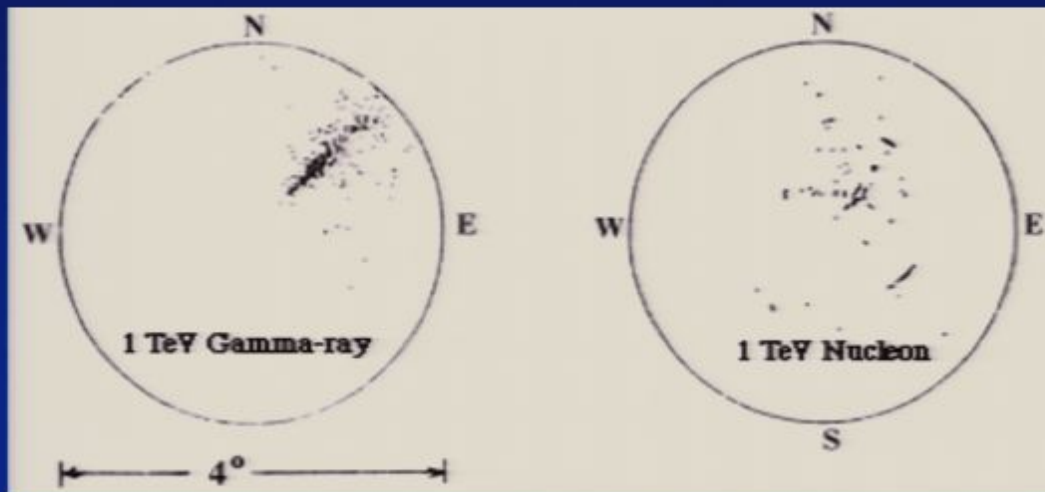
Whipple 10m, Mount Hopkins, AZ



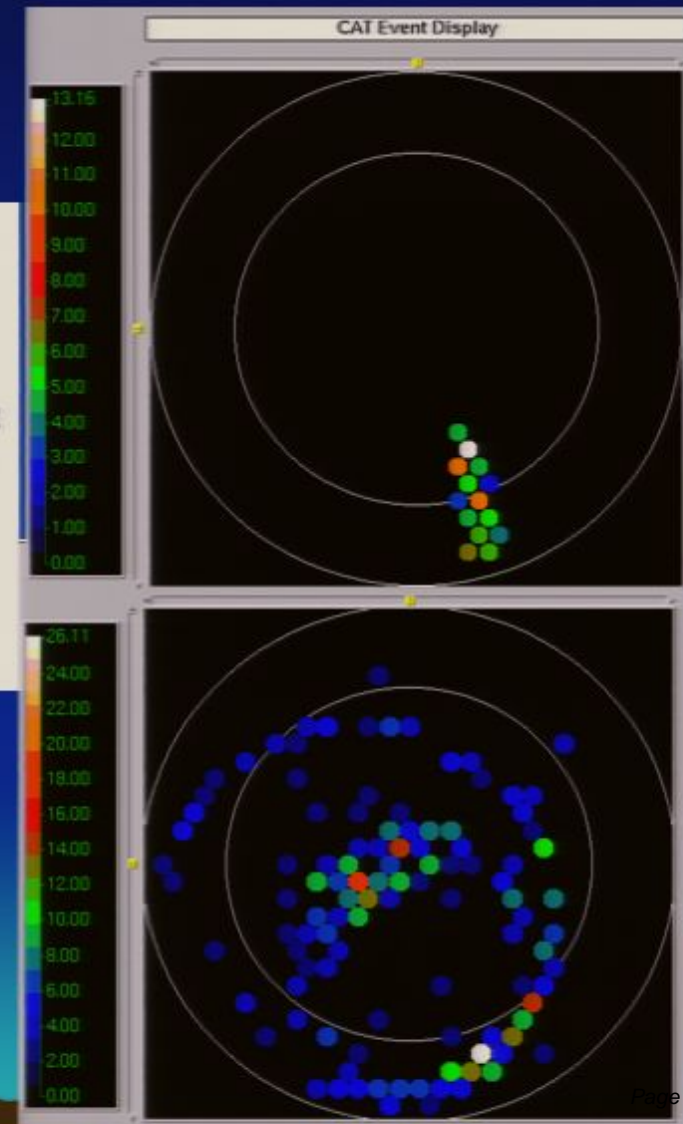
Phototube-camera

Detection

Cherenkov shower is imaged in focal plane; technique's power resides in image analysis



Simulated focal plane images

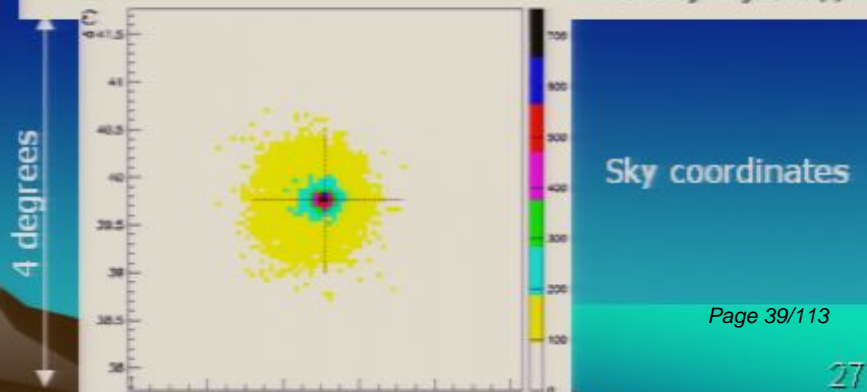
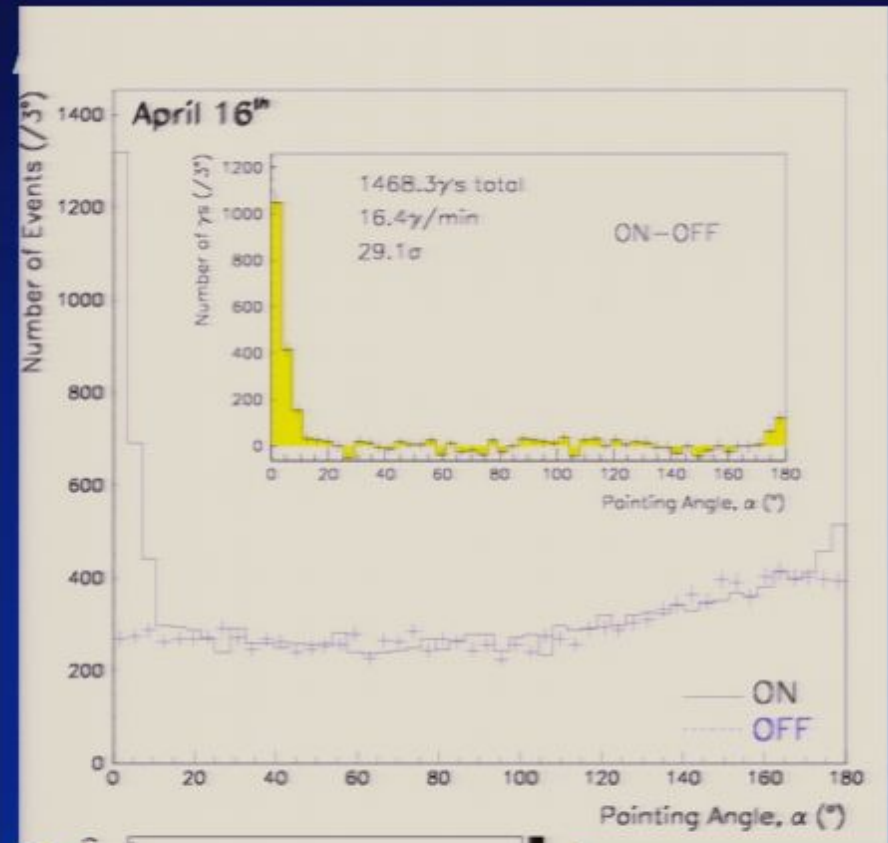
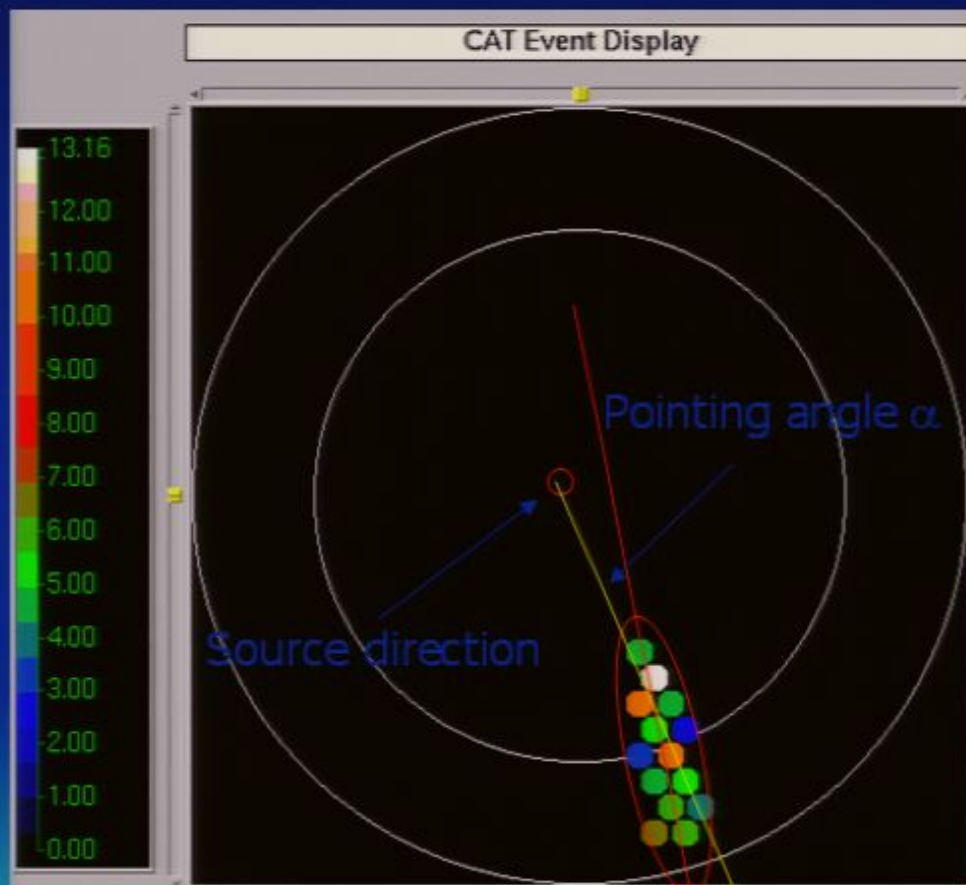


gamma?

hadron
+ muons

Detection

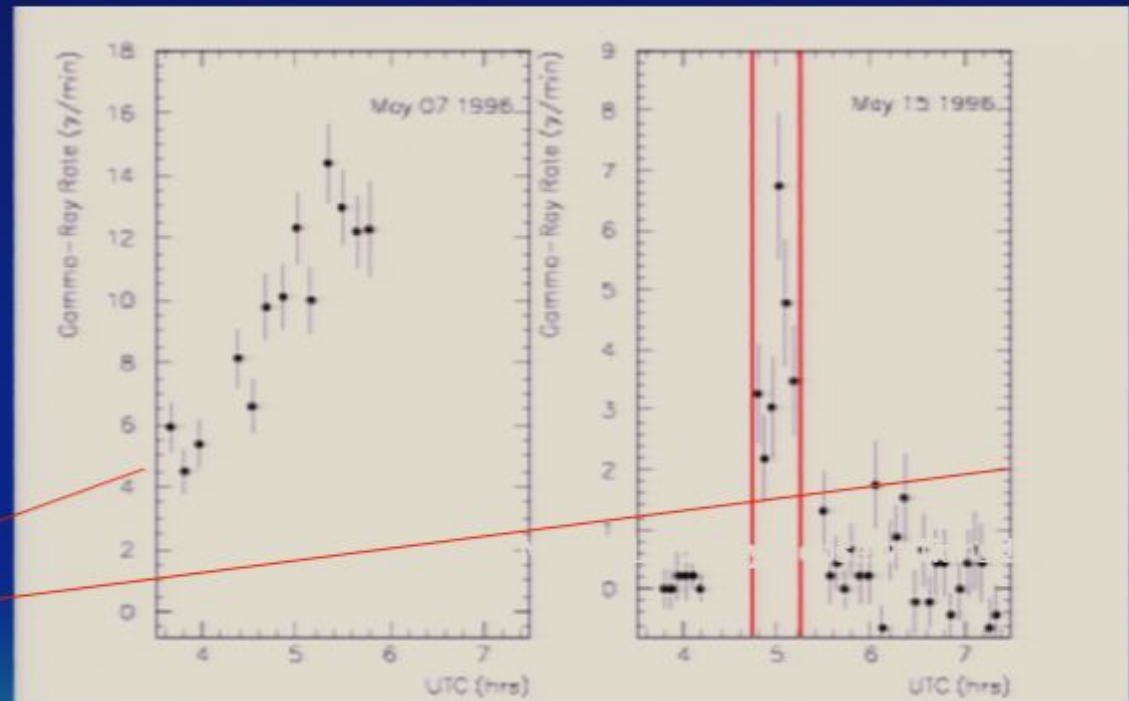
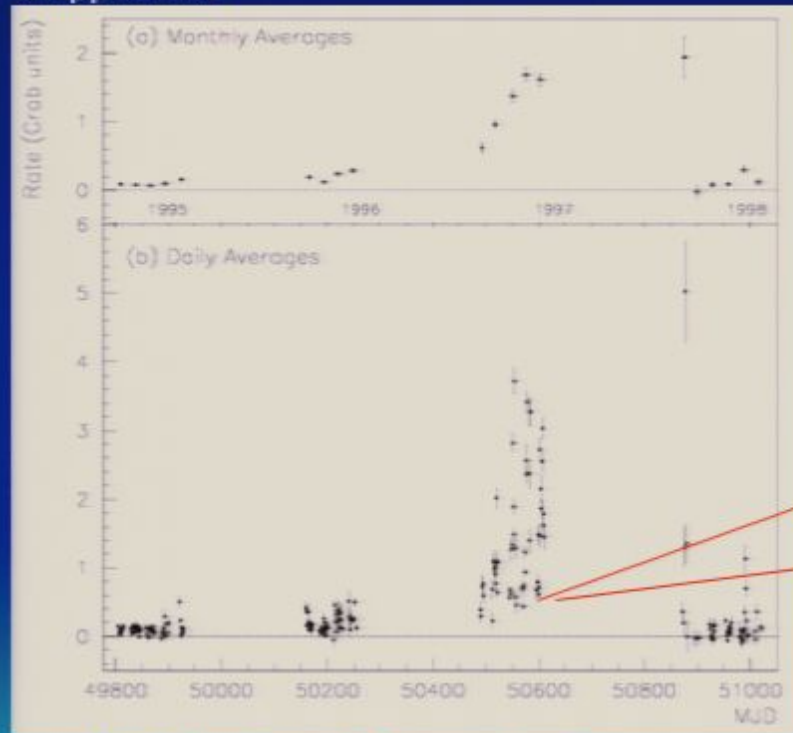
Each gamma candidate allows computation of direction (angular origin) from image



Detection

With these techniques, second generation imaging ACT telescopes achieved sensitivities to fluxes of \sim Crab on hour timescales - critical for variability studies

Whipple data



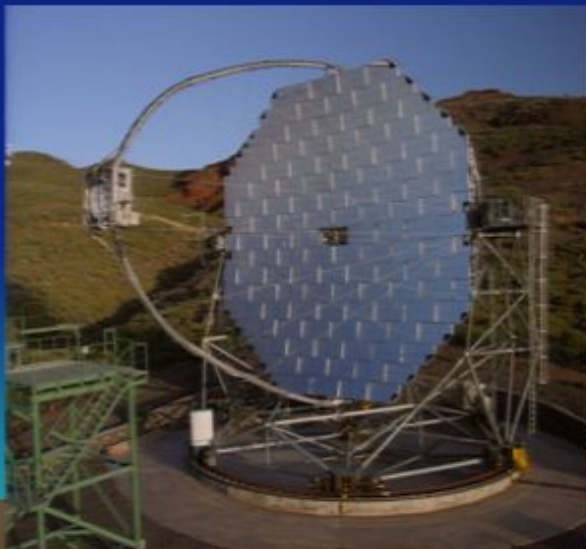
Mrk 421 - 3 year's observations



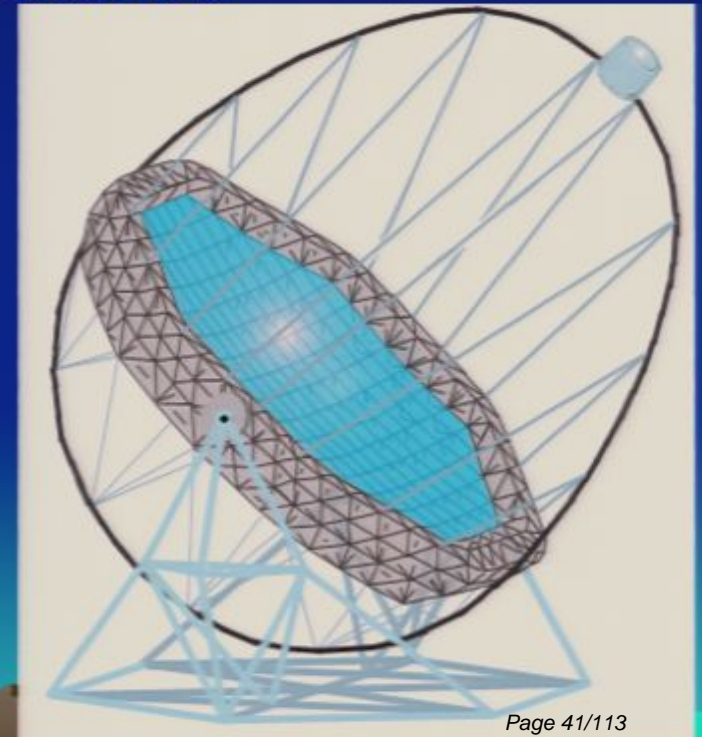
Detection

Technological limit of **single imager** pushed by German-Spanish *MAGIC*:

- 17 m diamond milled mirror (900 facets)
- active optics; state-of-the-art carbon fibre mirror mount
- optical fibre transport of signal to electronics
- fast slewing for GRB studies



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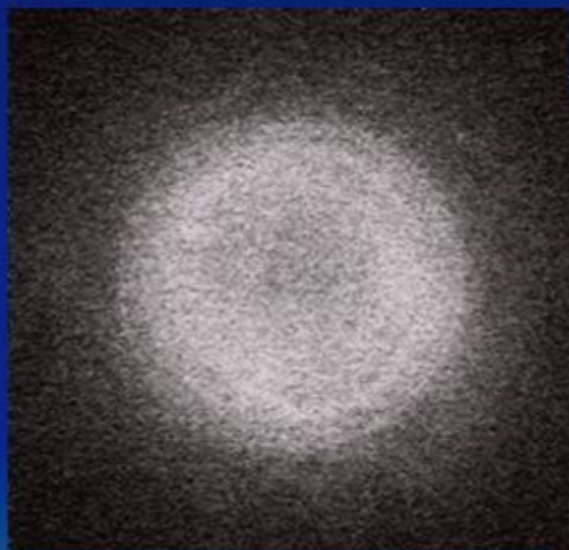


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Detection

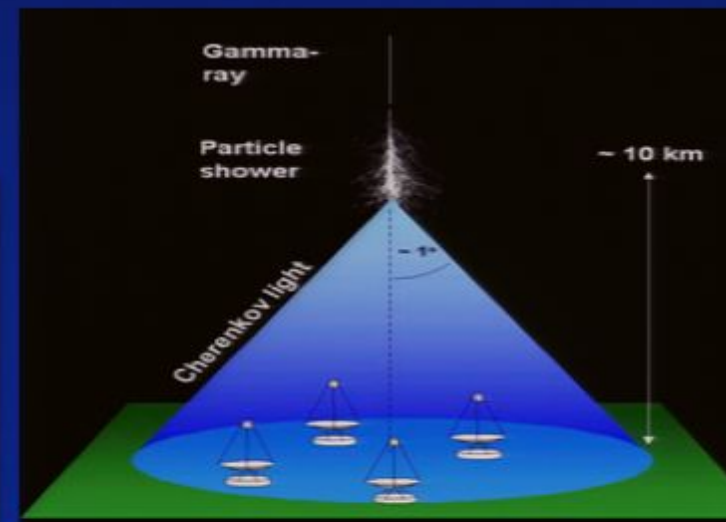
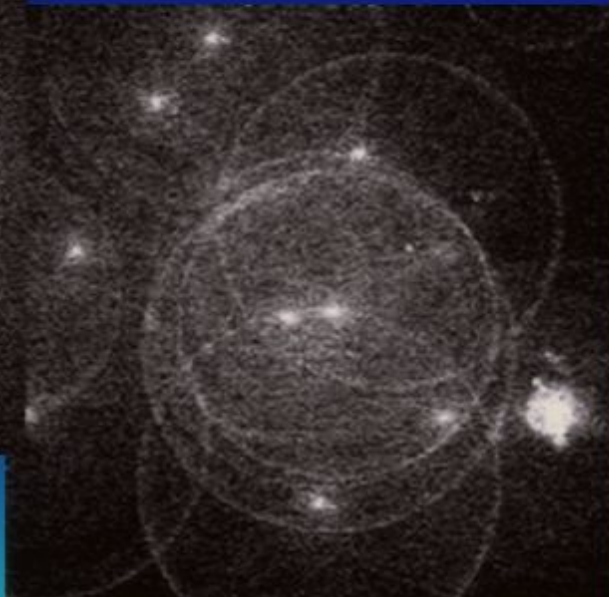
Another approach: an array of imaging telescopes, separated by $<$ size of Cherenkov light pool (~ 100 m).

Backgrounds (cosmic rays) are (partially) independent while signal (gamma rays) is correlated



300 GeV gamma

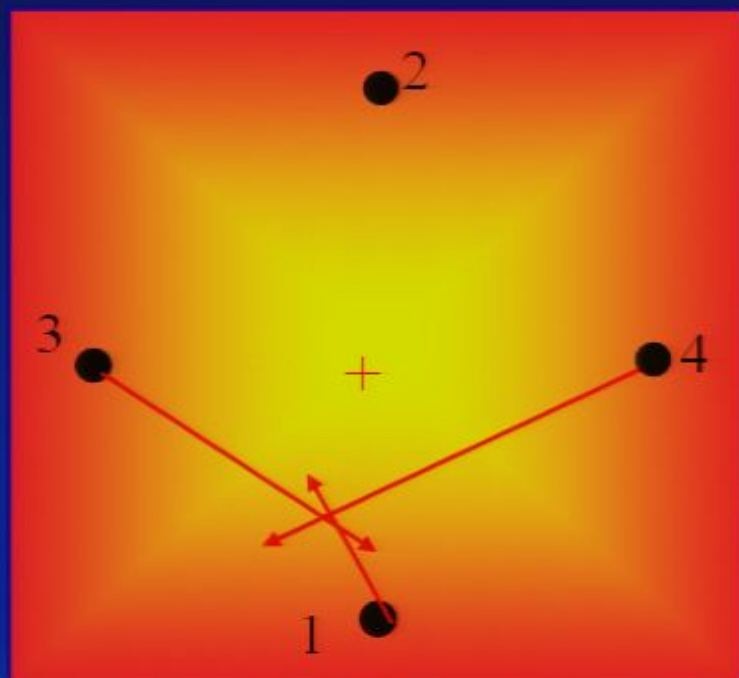
TeV proton showers



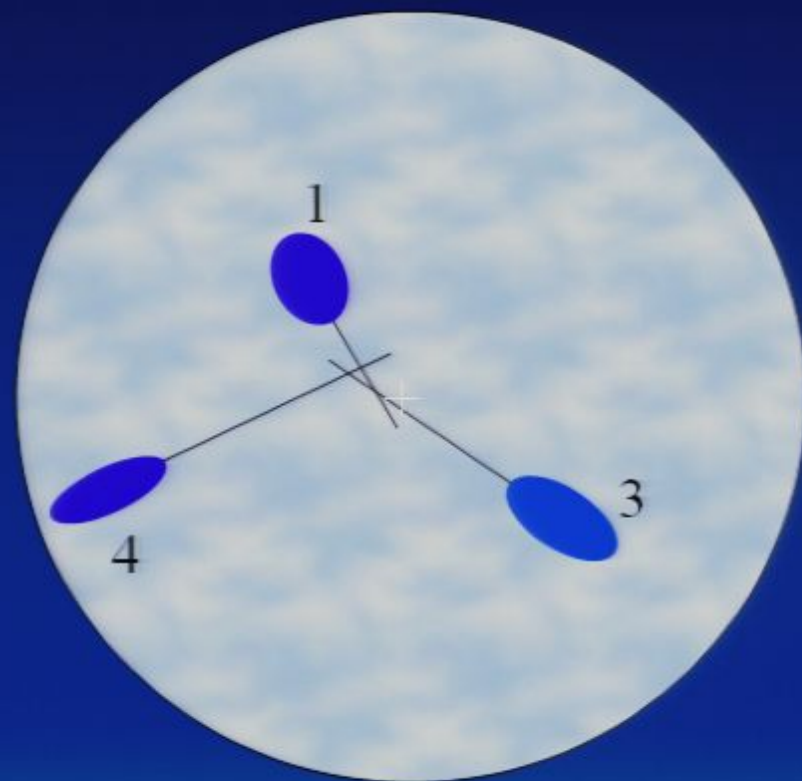


Detection

Multiple views allow improved directional and energy reconstruction



**Telescopes on
Ground**



Field of View

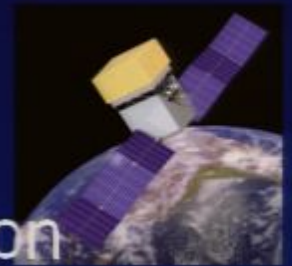


Detection

Worldwide network of arrays now entering operation



Detection

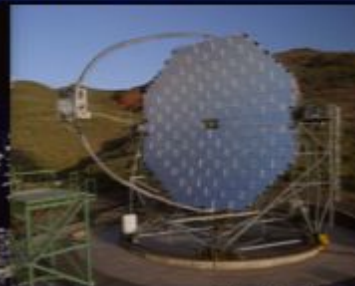


Worldwide network of arrays now entering operation

GLAST (2007)

MAGIC

MAGIC



VERITAS

VERITAS



HESS

HESS

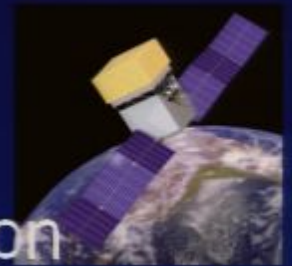


CANGAROO III

CANGAROO



Detection



Worldwide network of arrays now entering operation

GLAST (2007)

MAGIC

MAGIC

VERITAS

VERITAS

HESS

HESS

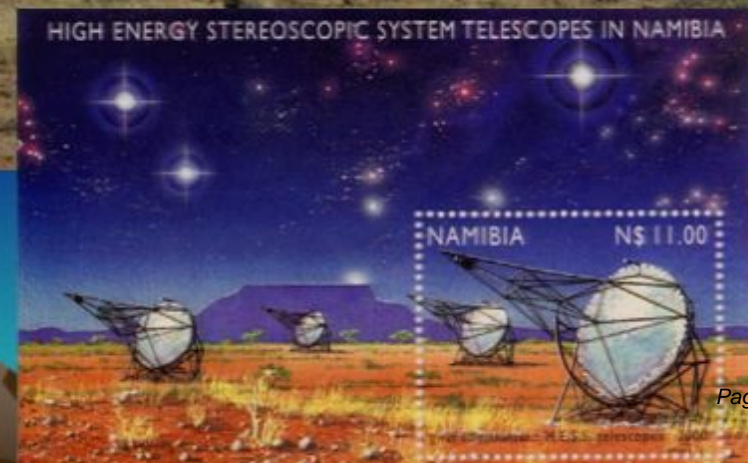
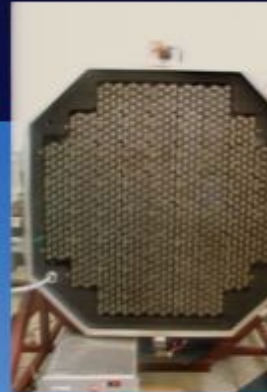
CANGAROO III

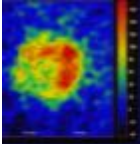
CANGAROO

Detection

HESS:

- Franco-German project
- 4 x 12m telescopes
- 5 degree field of view
- threshold < 150 GeV
- located in the Gamsberg (Namibia)
- first light early 2002



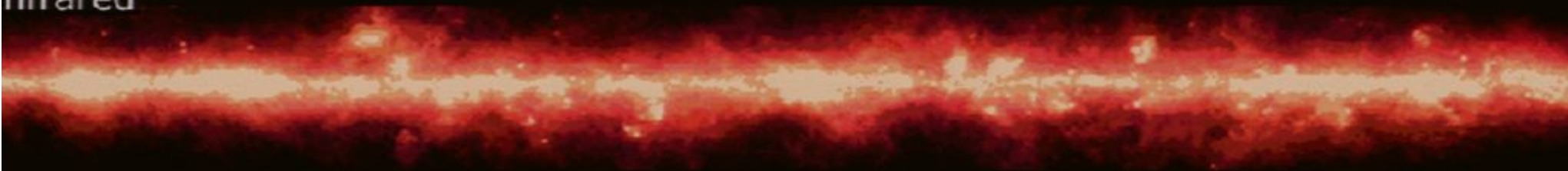


Results

HESS can see the galactic centre (visible best from the southern hemisphere) and has observed it extensively:

The multi-wavelength Milky Way up to VHE gammas:

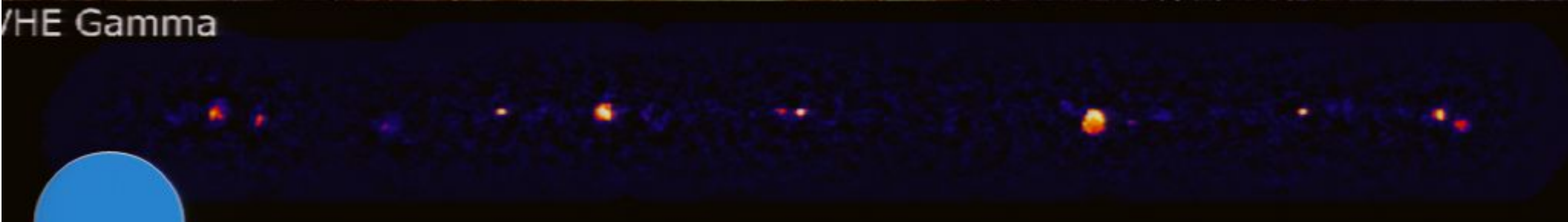
Infrared



Optical



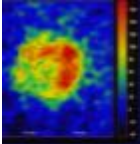
VHE Gamma



Pirsa: 06020030

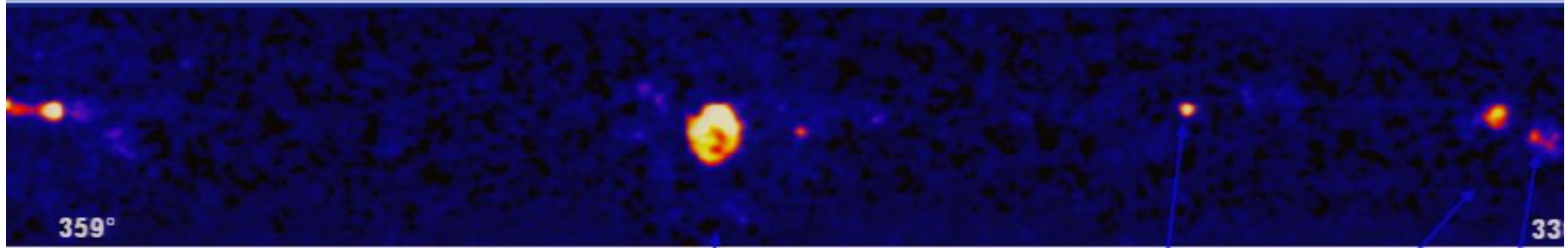
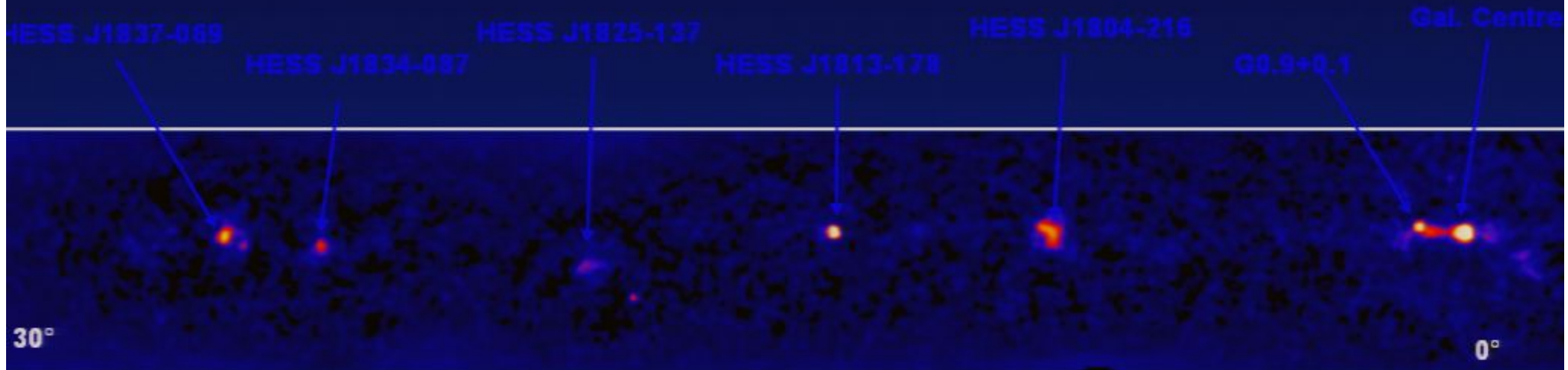
Approximate HESS field of view (5°)

Perimeter Institute, Feb '06



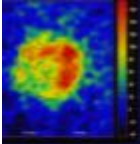
Results

HESS Galactic Survey



Sources > 6 sigma (9 new, 11 total)

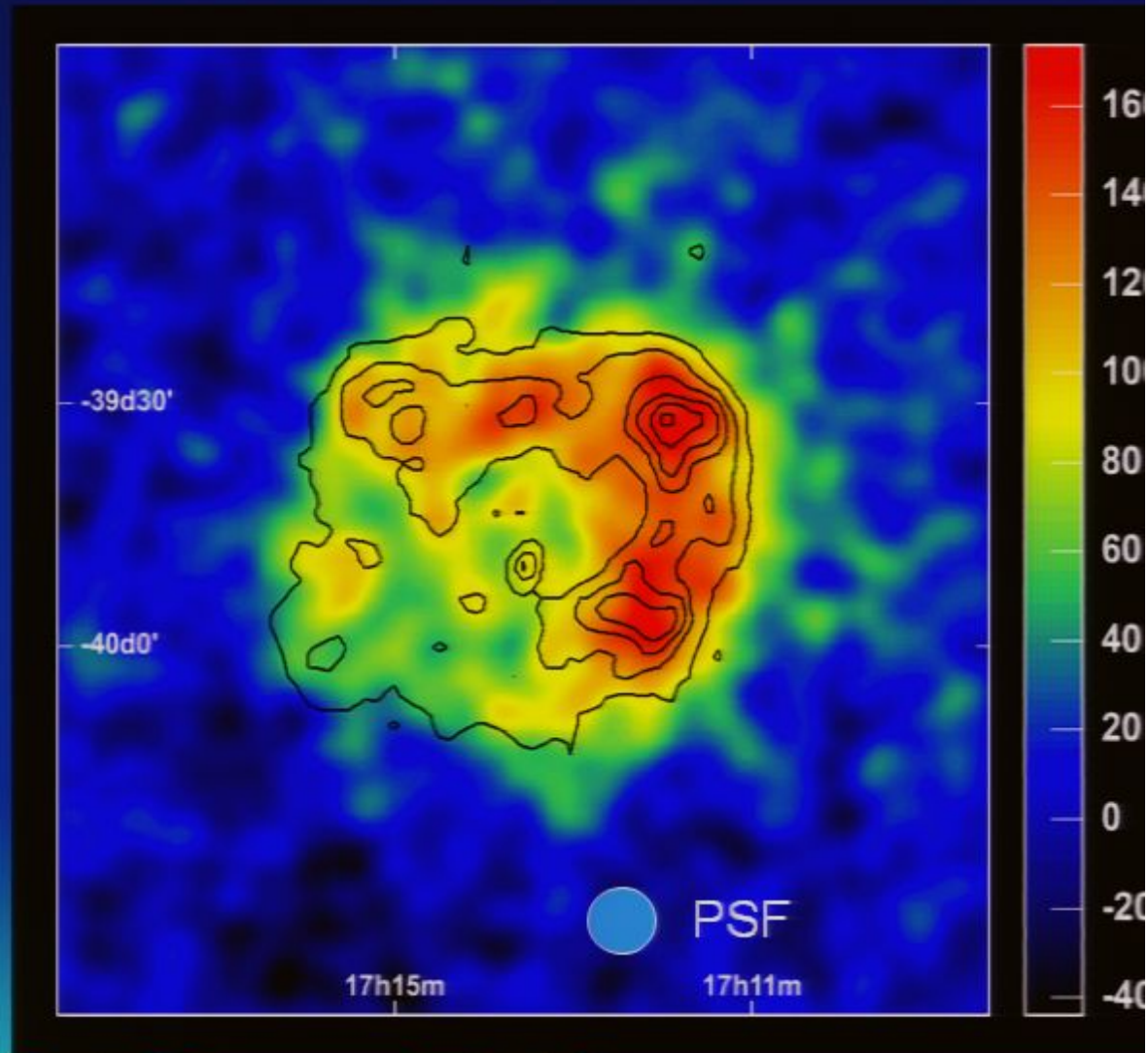


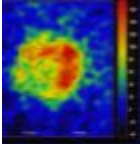


Results

RXJ 1713:

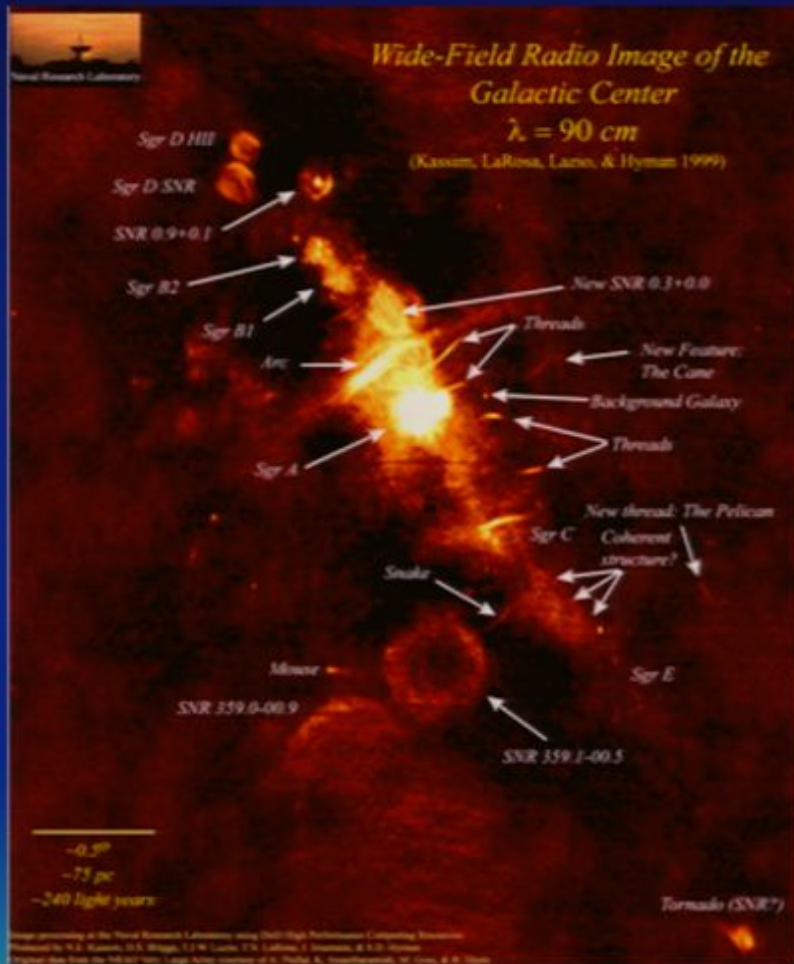
- First definitive SNR detection
- Extended γ -ray source
- Spectrally resolved image
- Good correlation with X-ray image
- Will help test CR origin



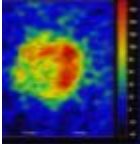


Results

Galactic Center:

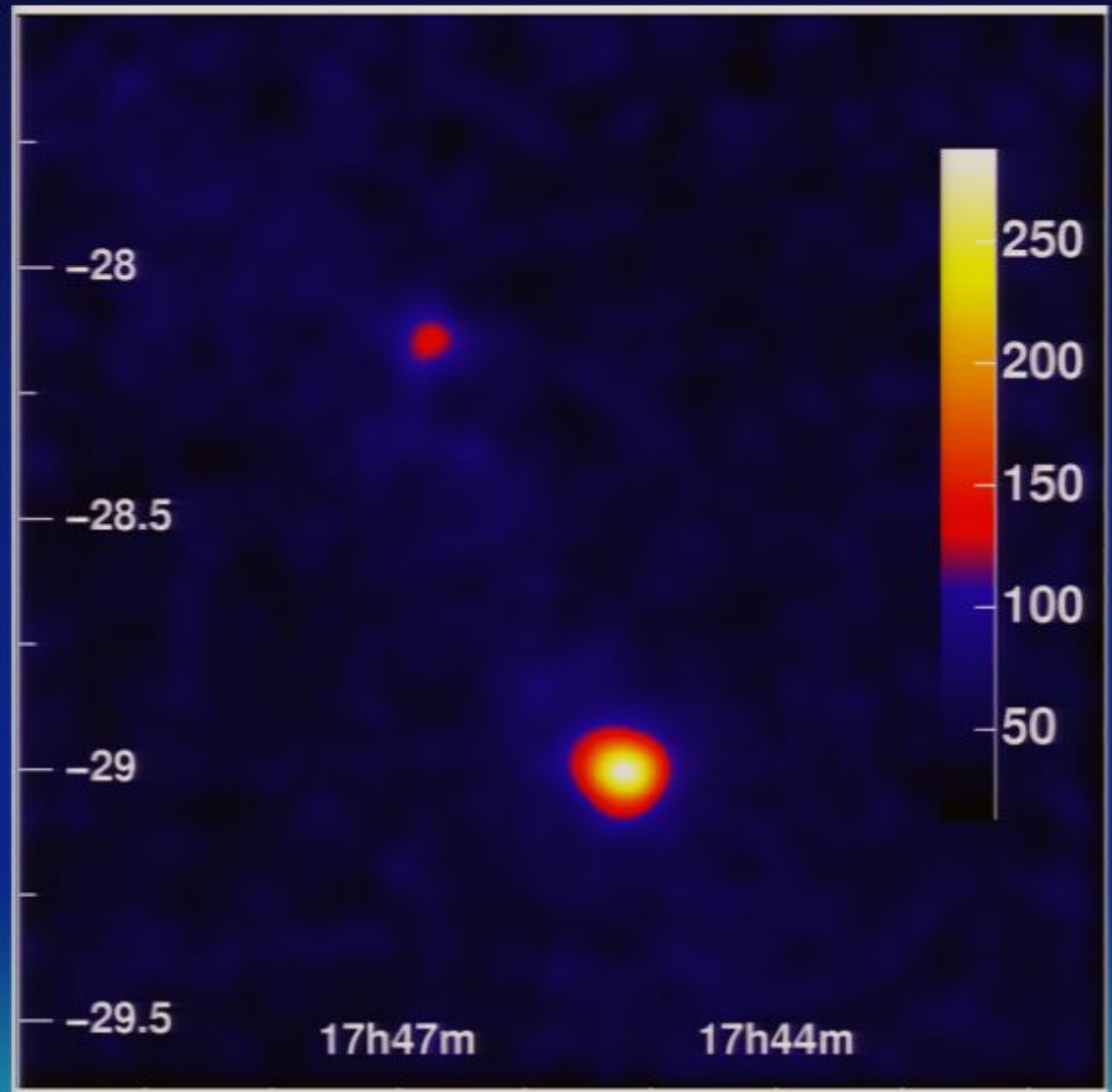
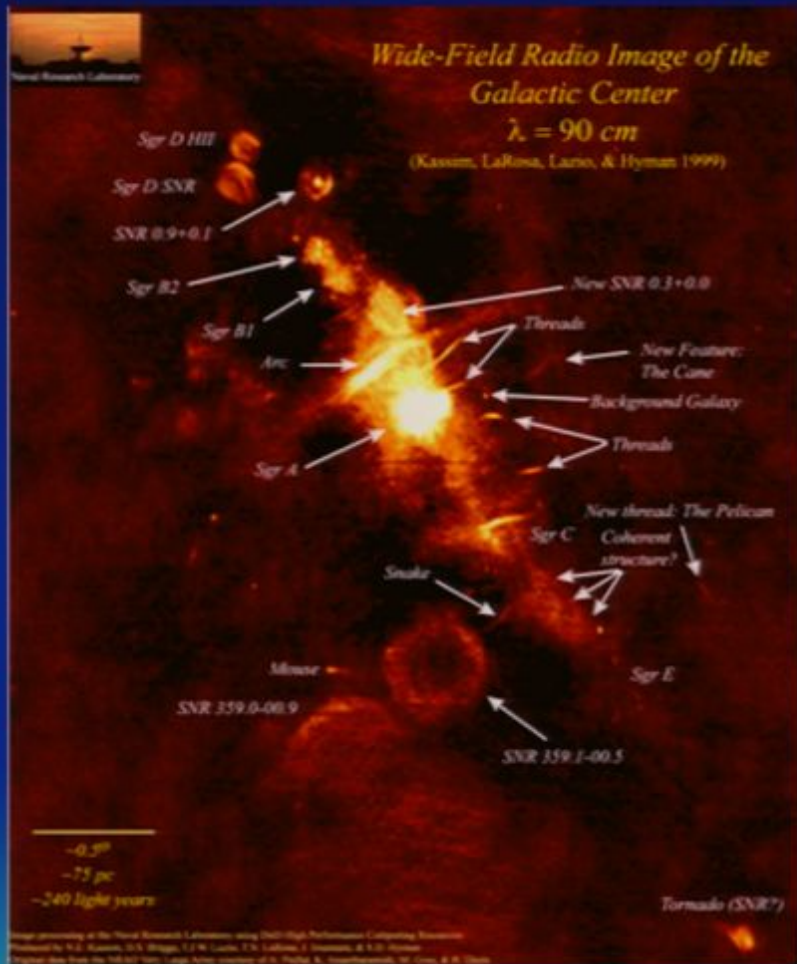


Radio

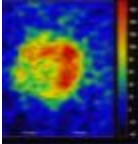


Results

Galactic Center:

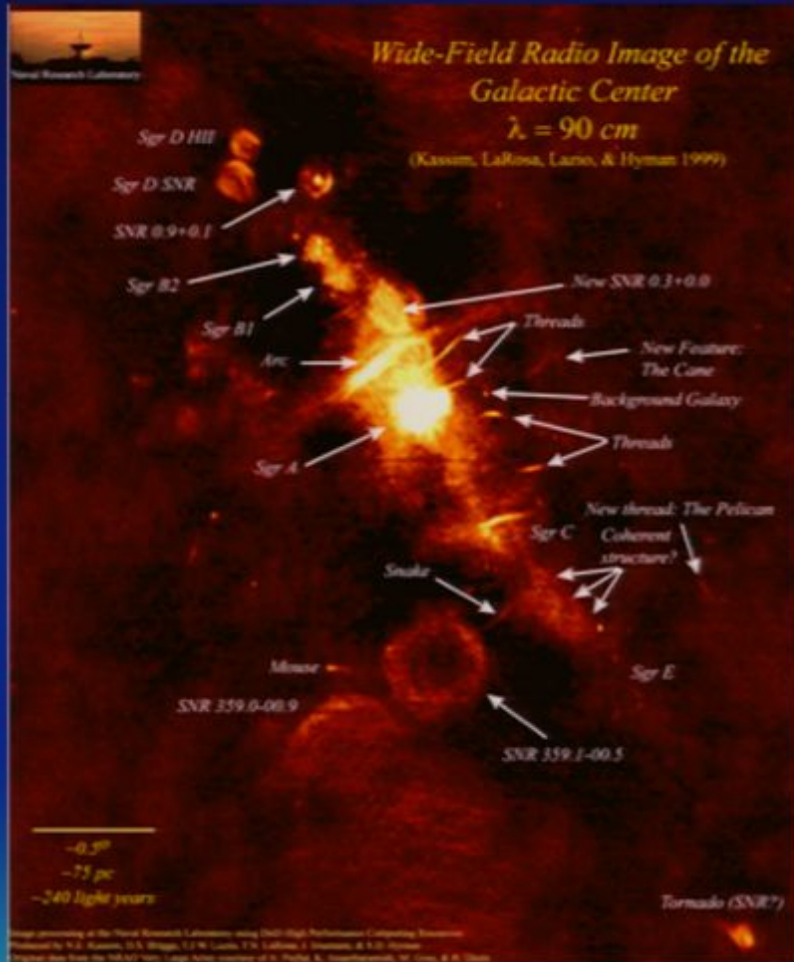


Radio

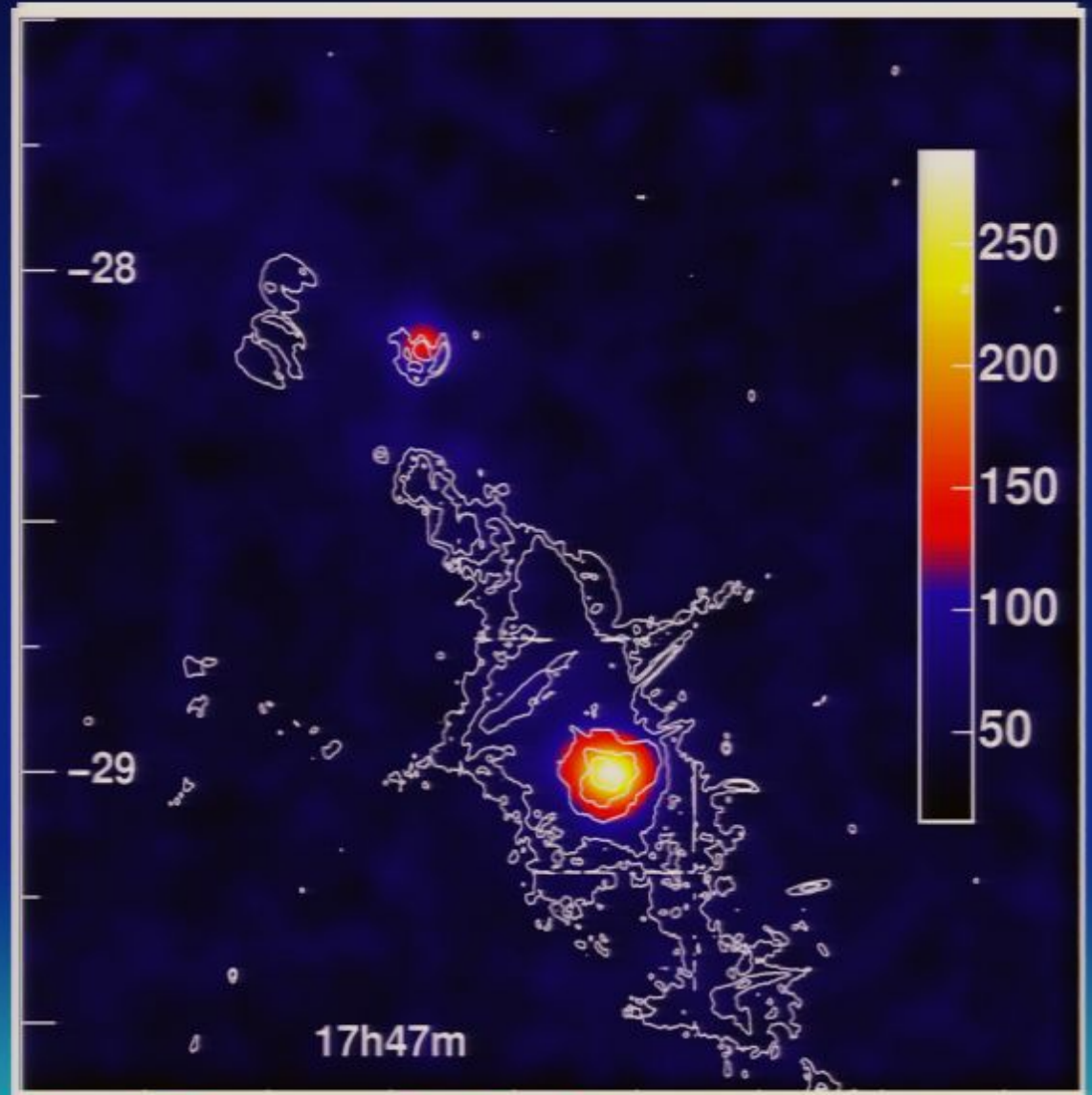


Results

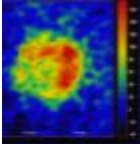
Galactic Center:



Radio

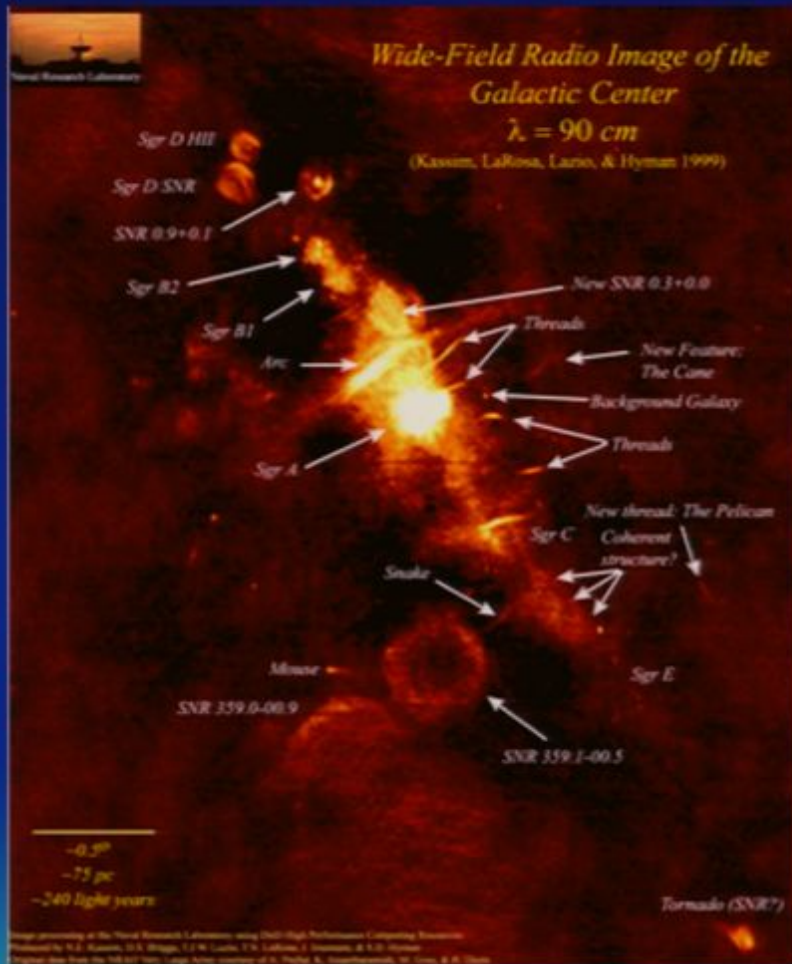


HESS

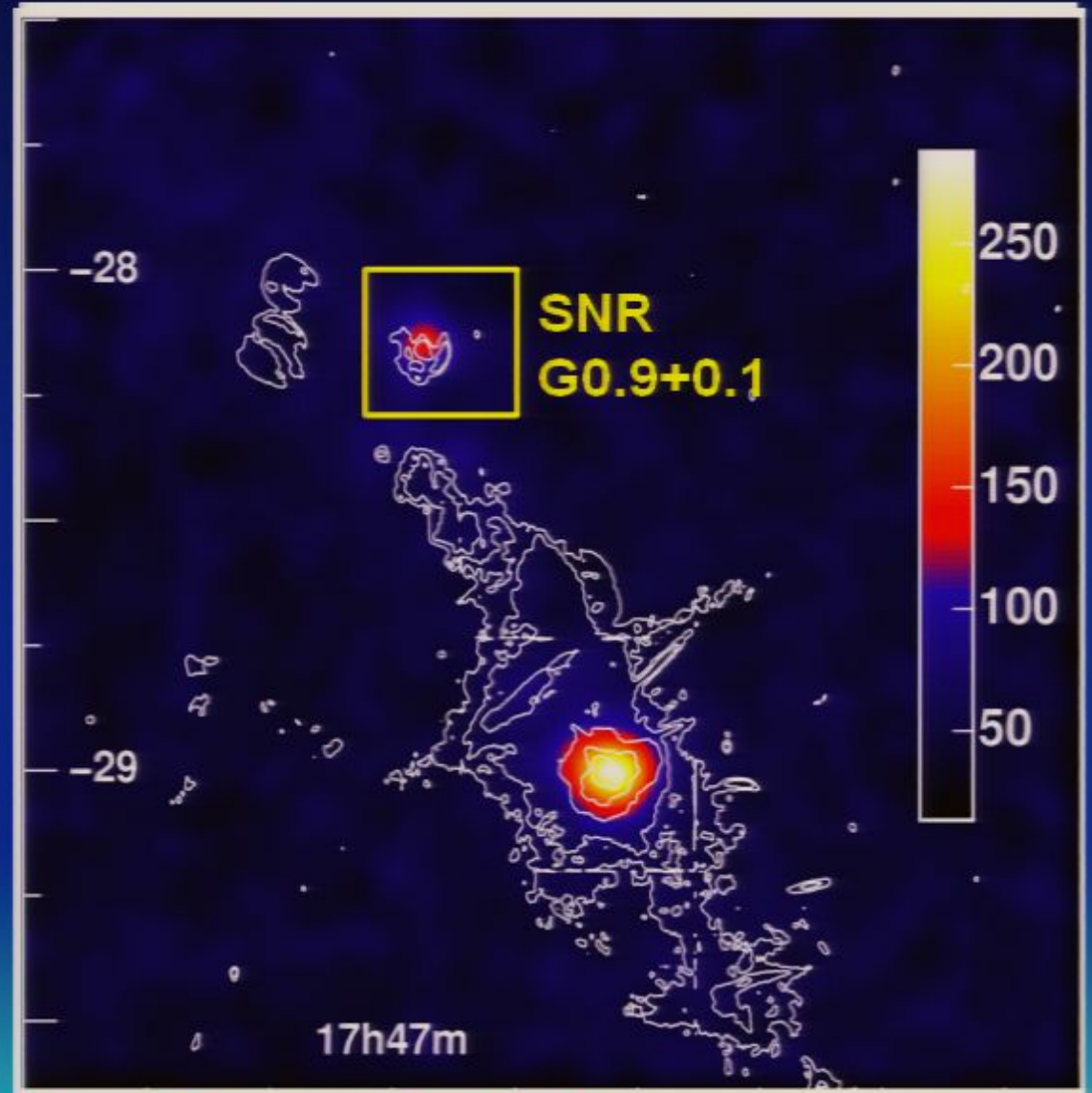


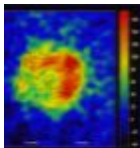
Results

Galactic Center:



Radio





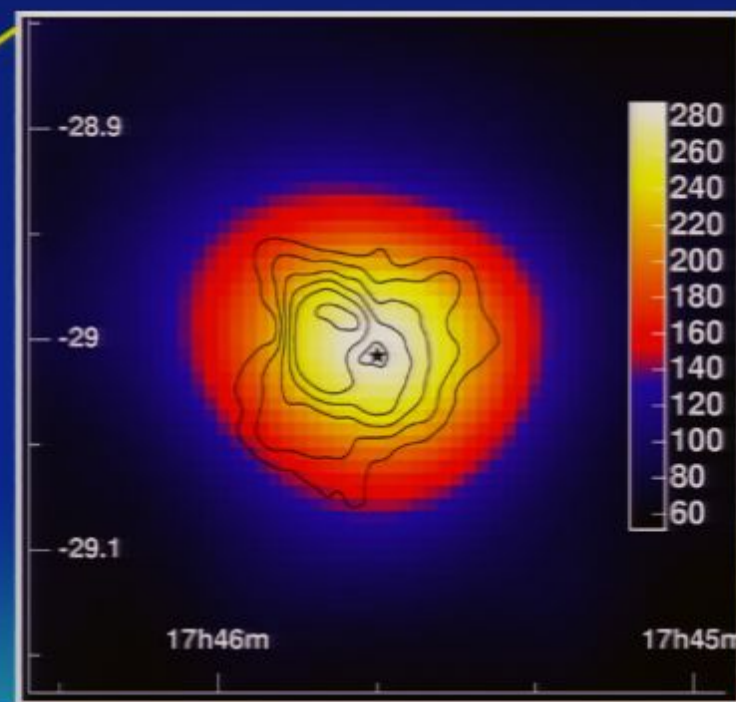
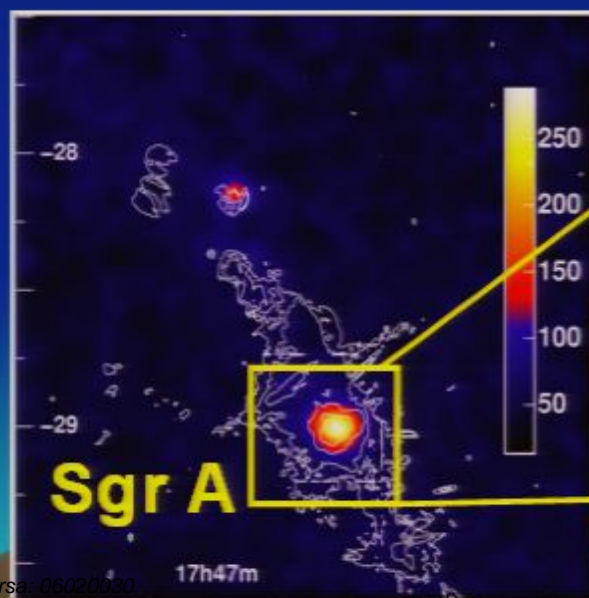
Results

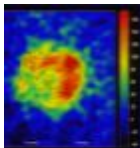
Galactic Center:

- $>4\sigma$ detection
- Almost a point source
- Hard, flat spectrum

Not previously observed in γ ;
no idea how to generate this
 γ -ray flux.

Speculation on dark matter !



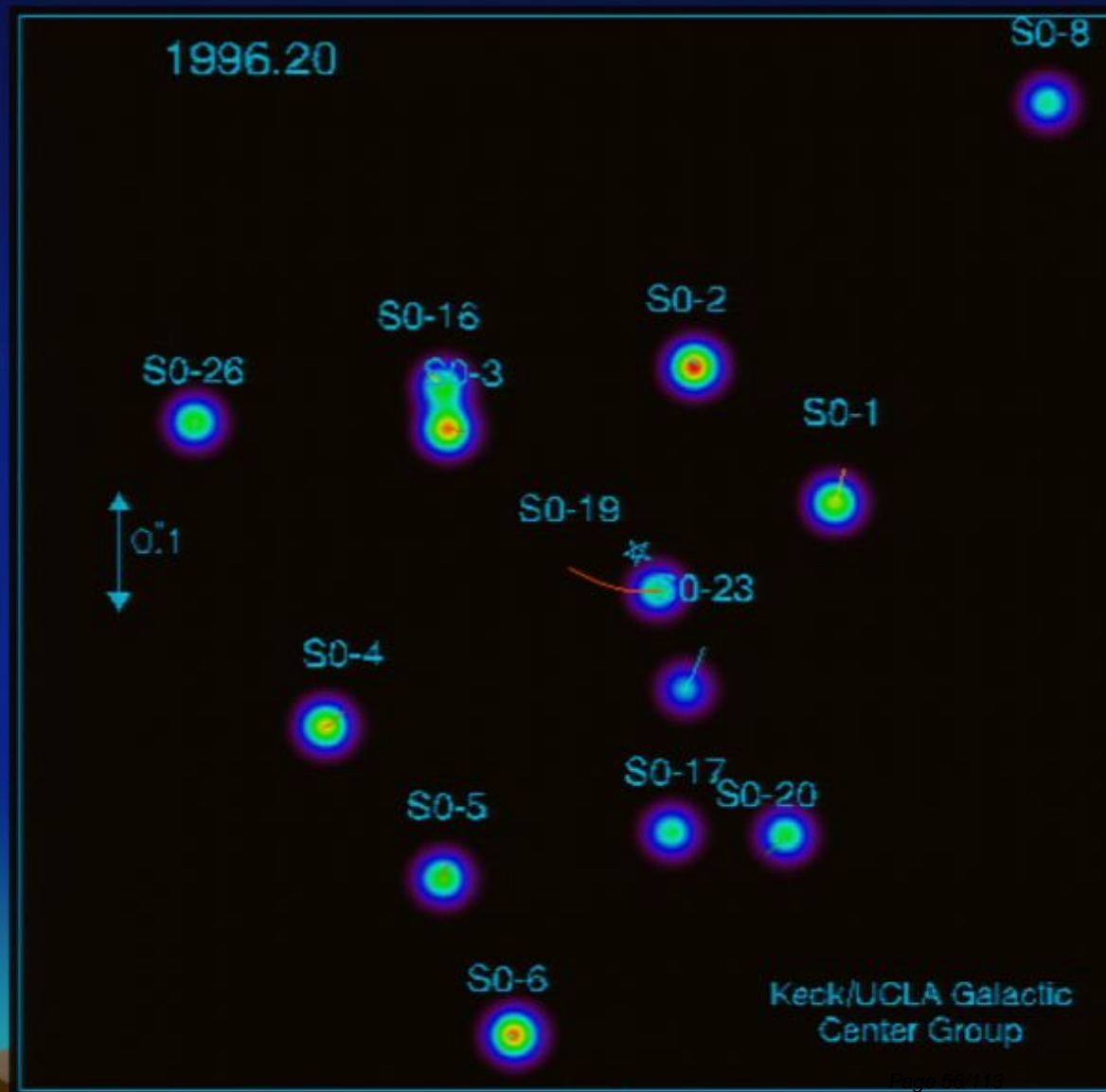


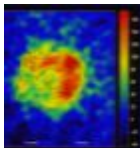
Results

Galactic Center:

No idea how to generate this γ -ray flux.

Stars seen down to $\sim 20 r_s$
-- no appreciable concentration
of luminous material



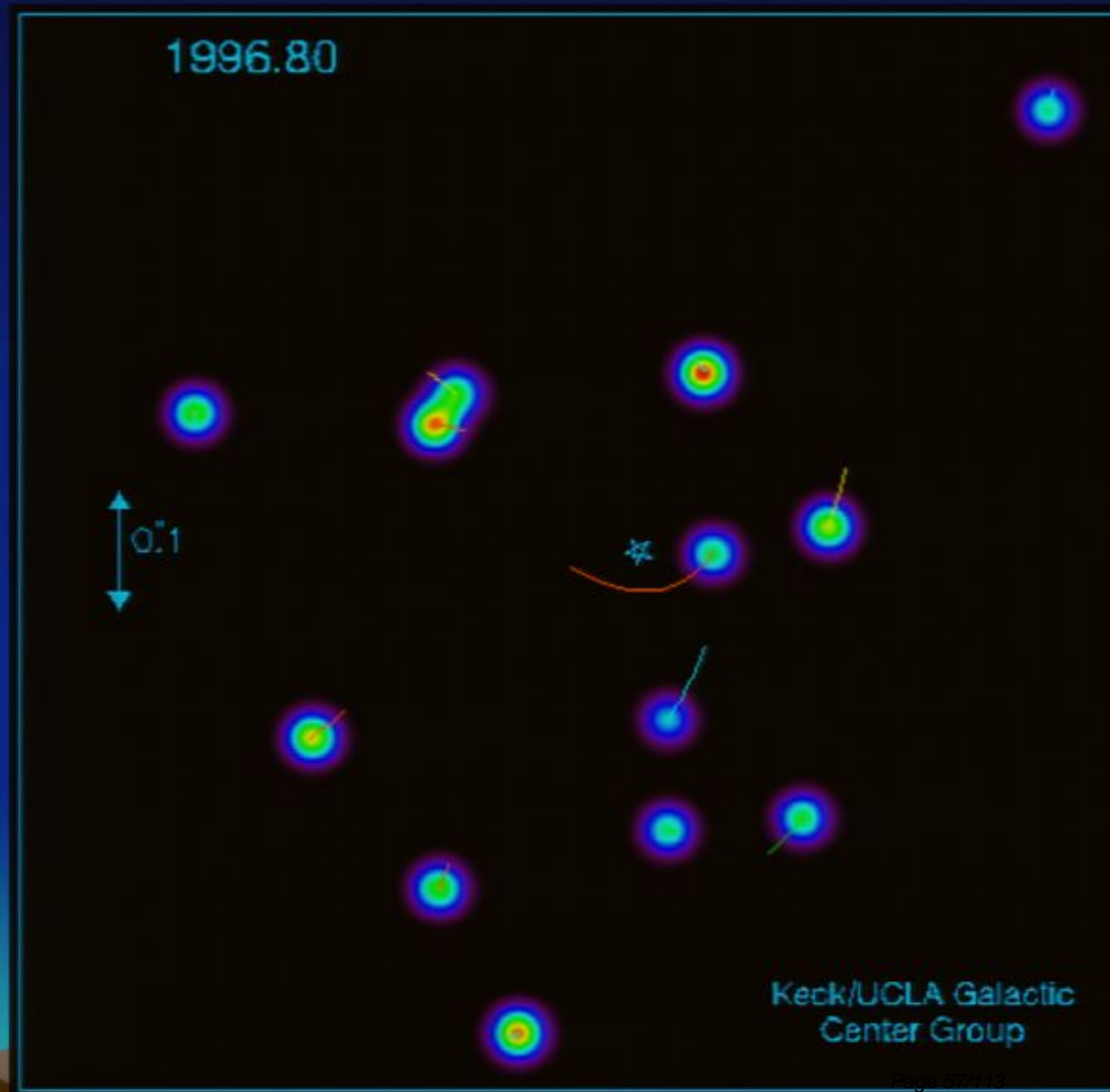


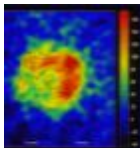
Results

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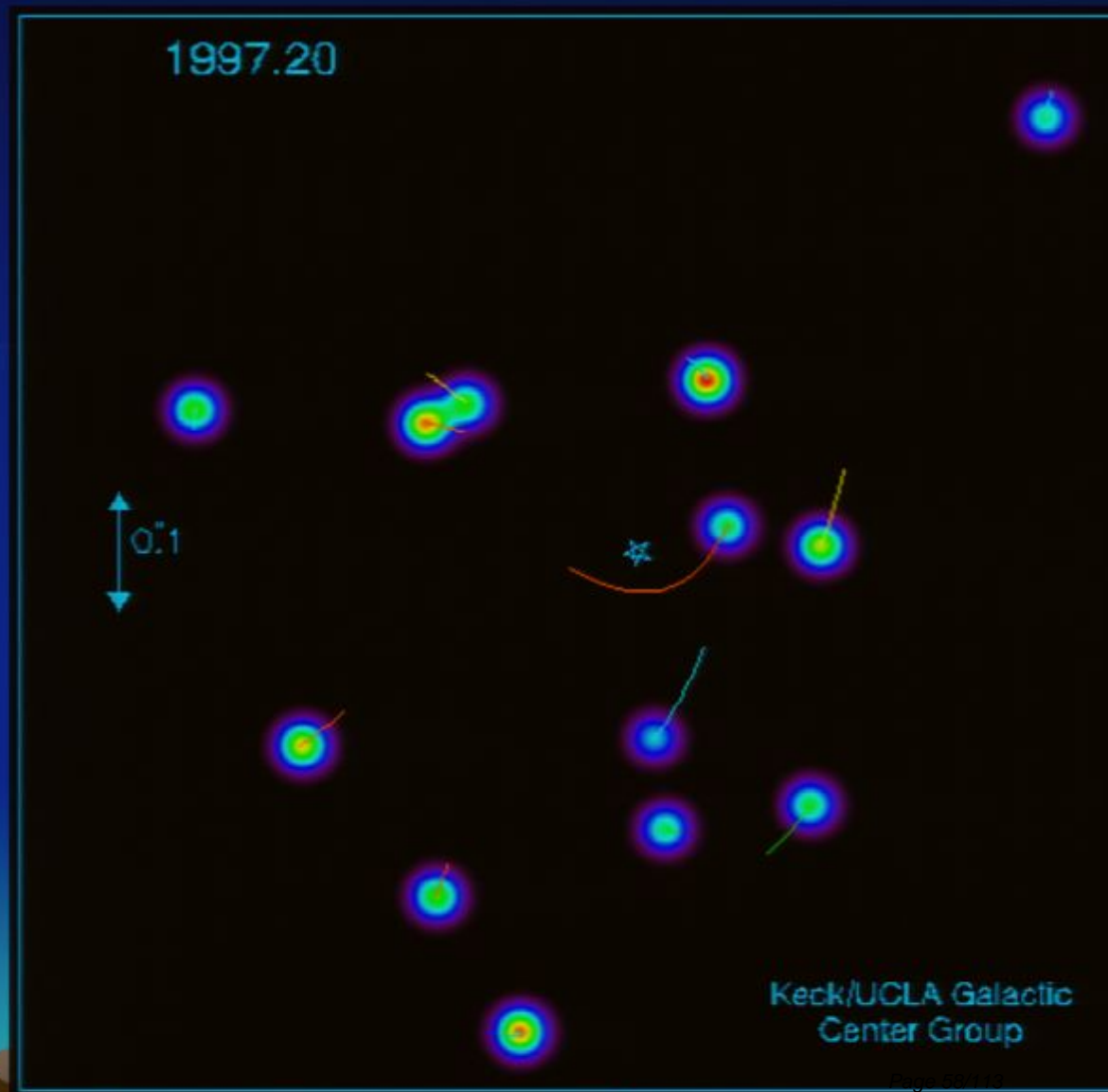


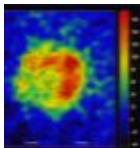
Results

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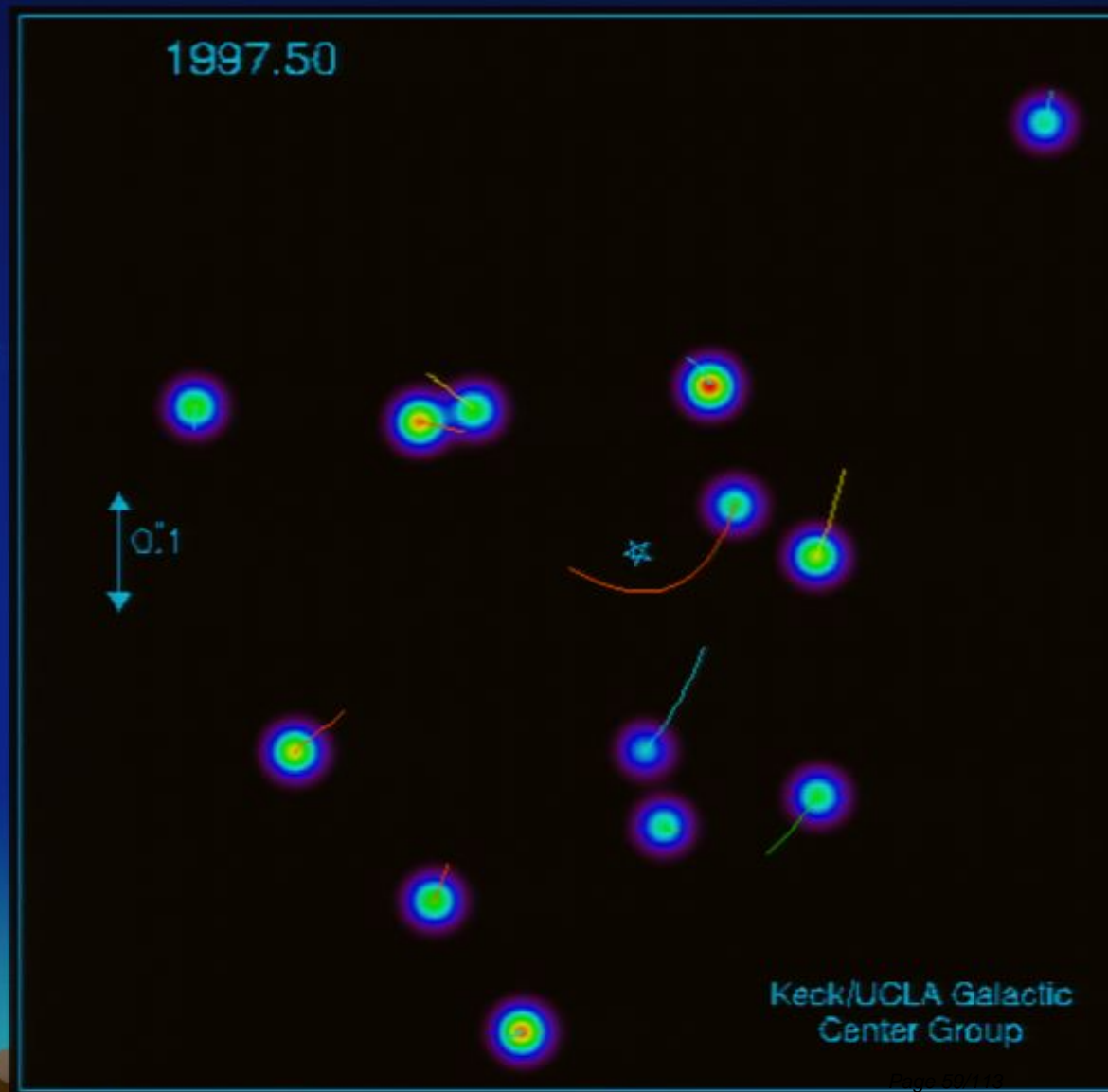


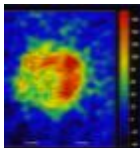
Results

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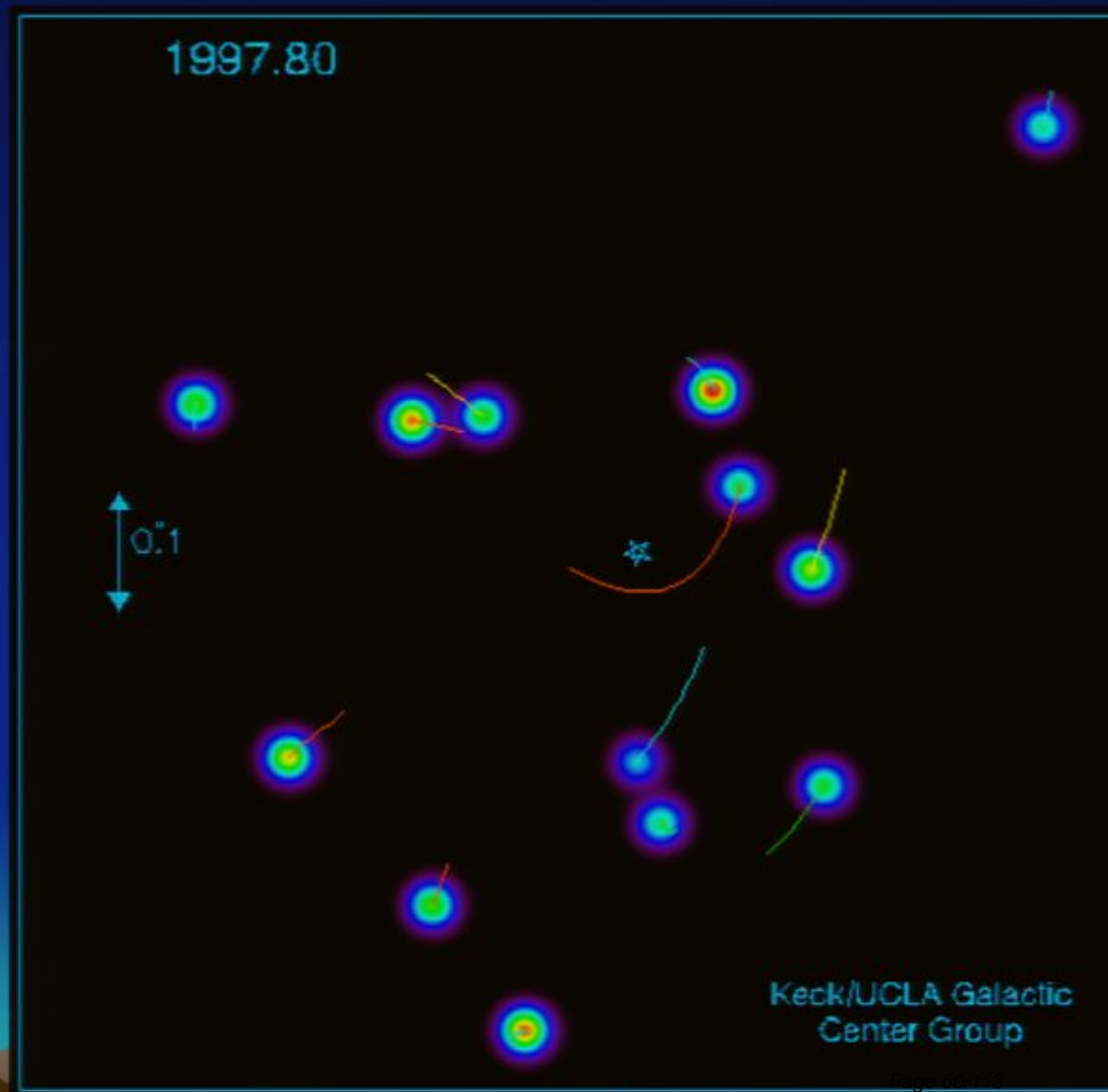


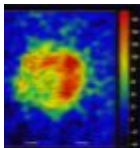
Results

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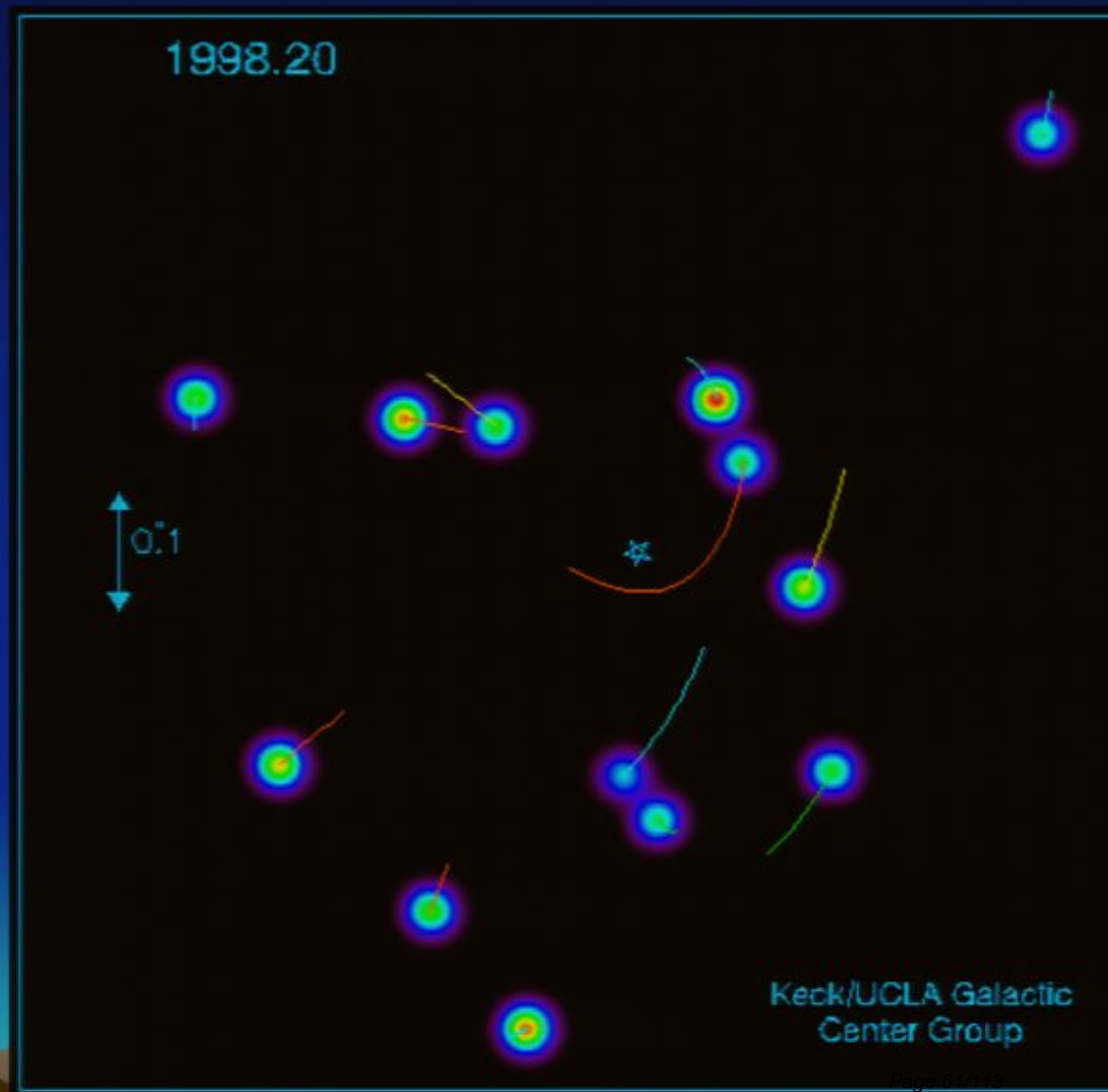


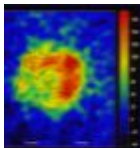
Results

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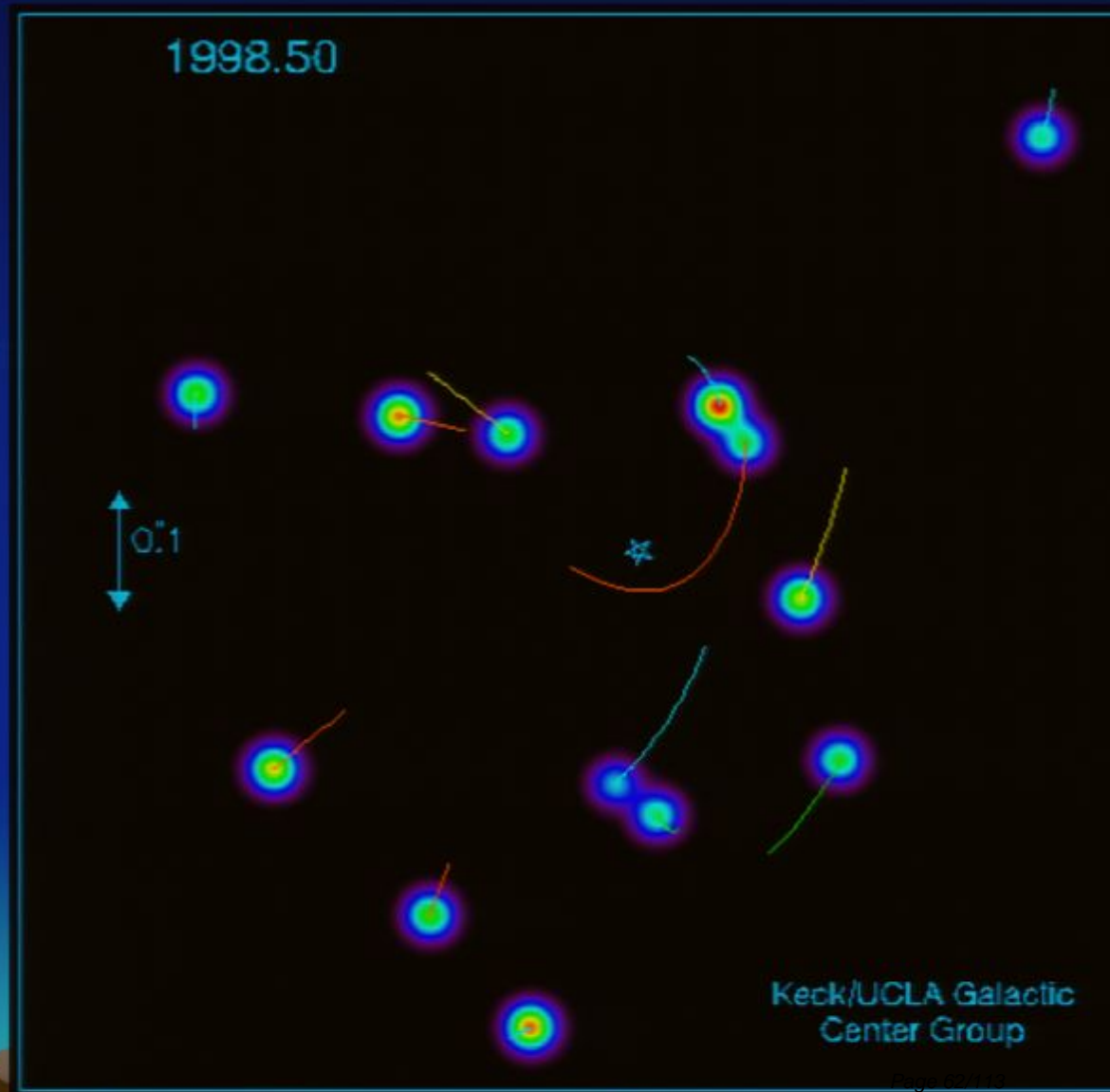


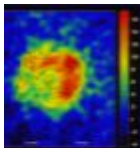
Results

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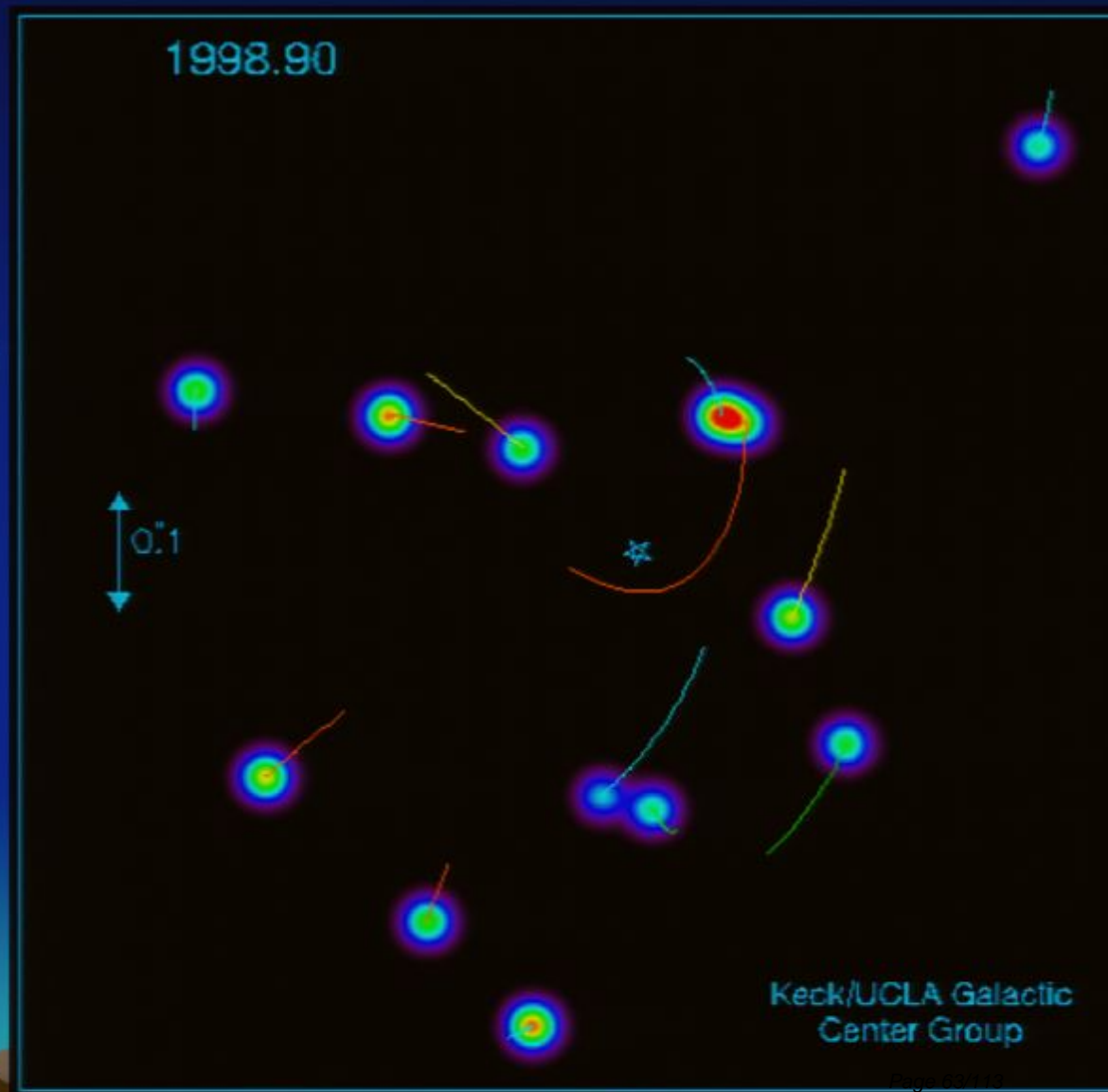


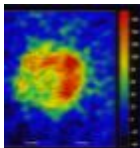
Results

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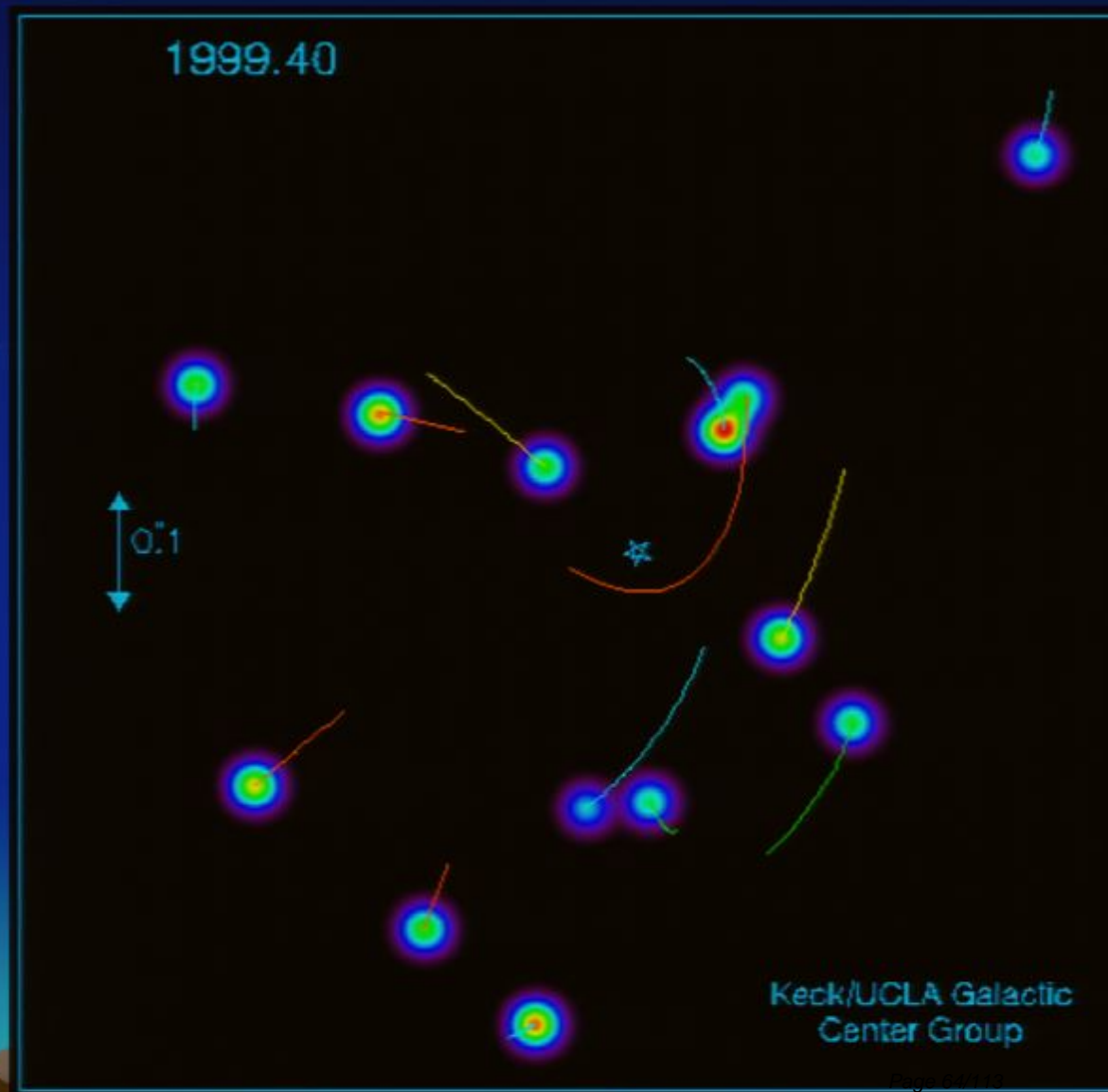


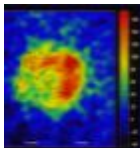
Results

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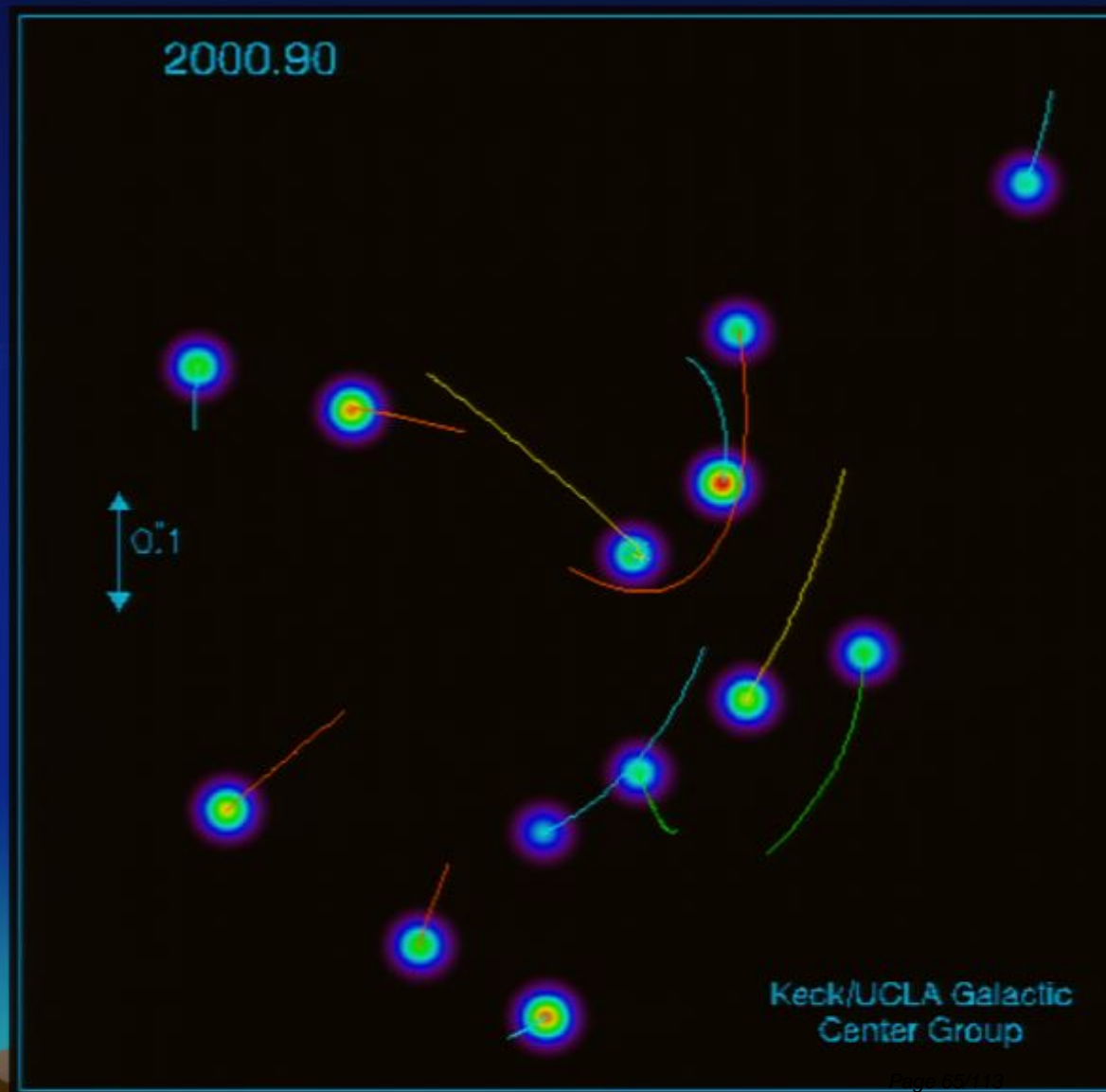


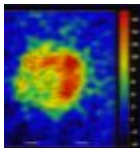
Results

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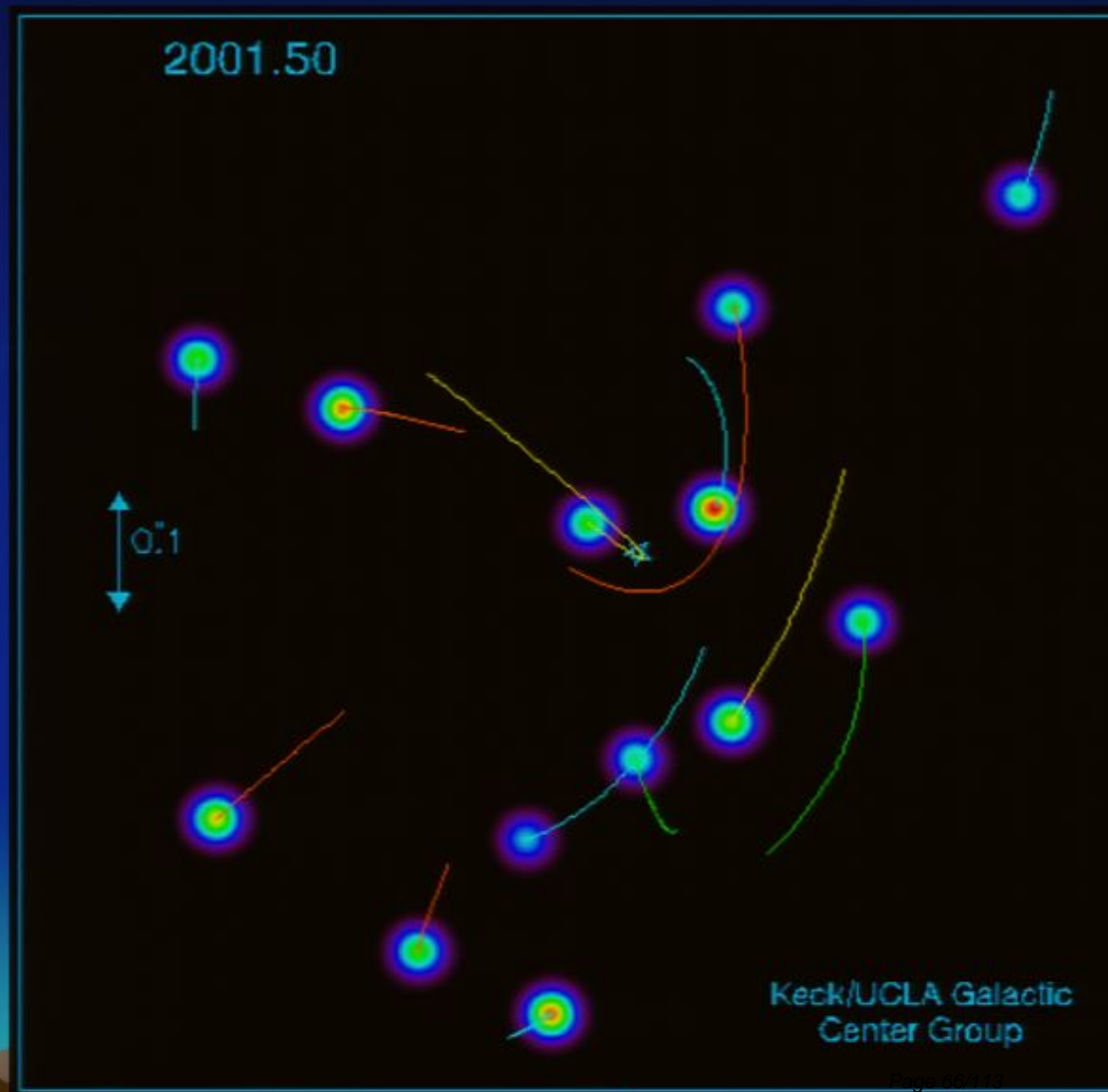


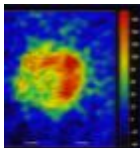
Results

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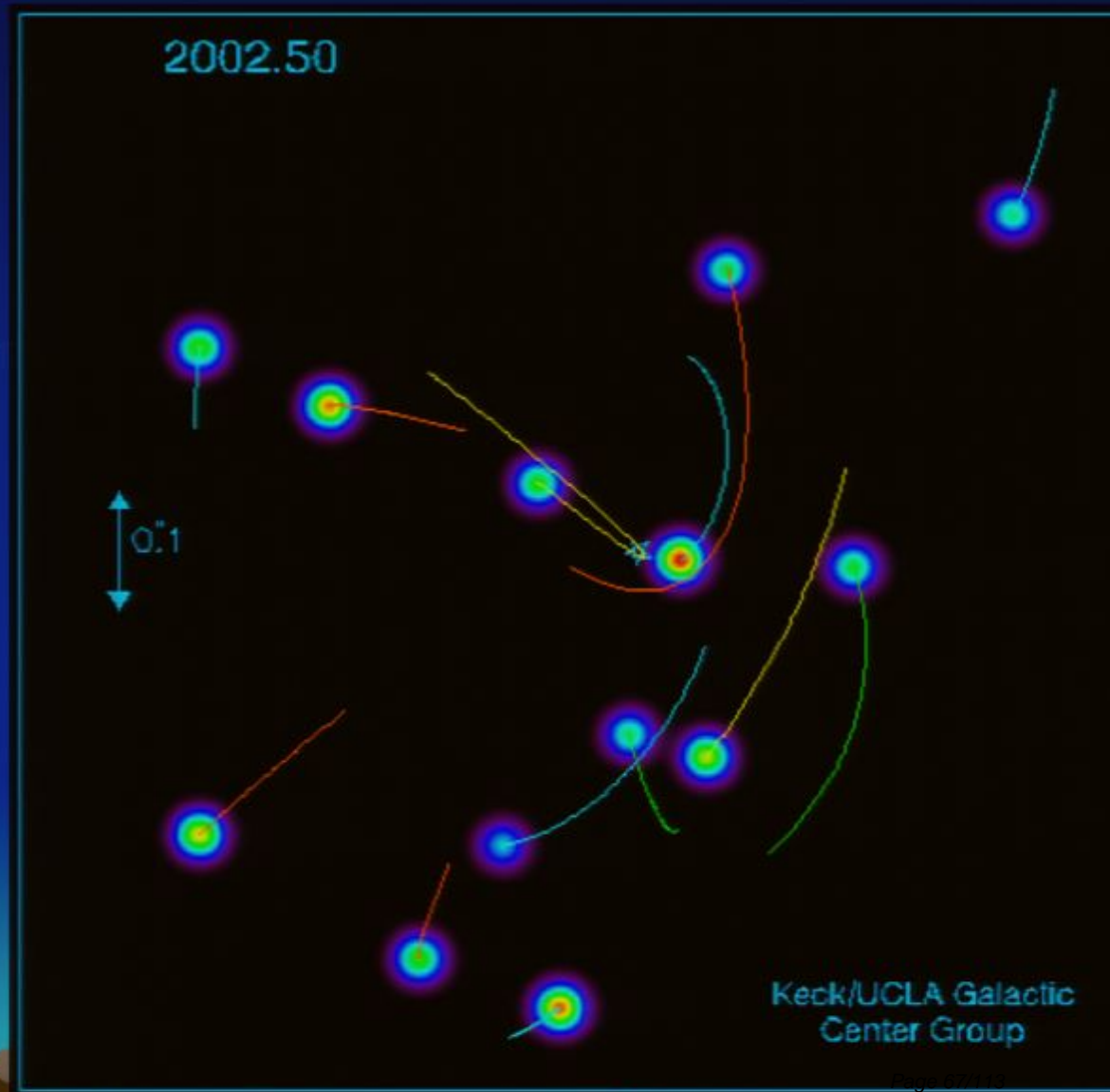


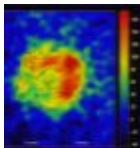
Results

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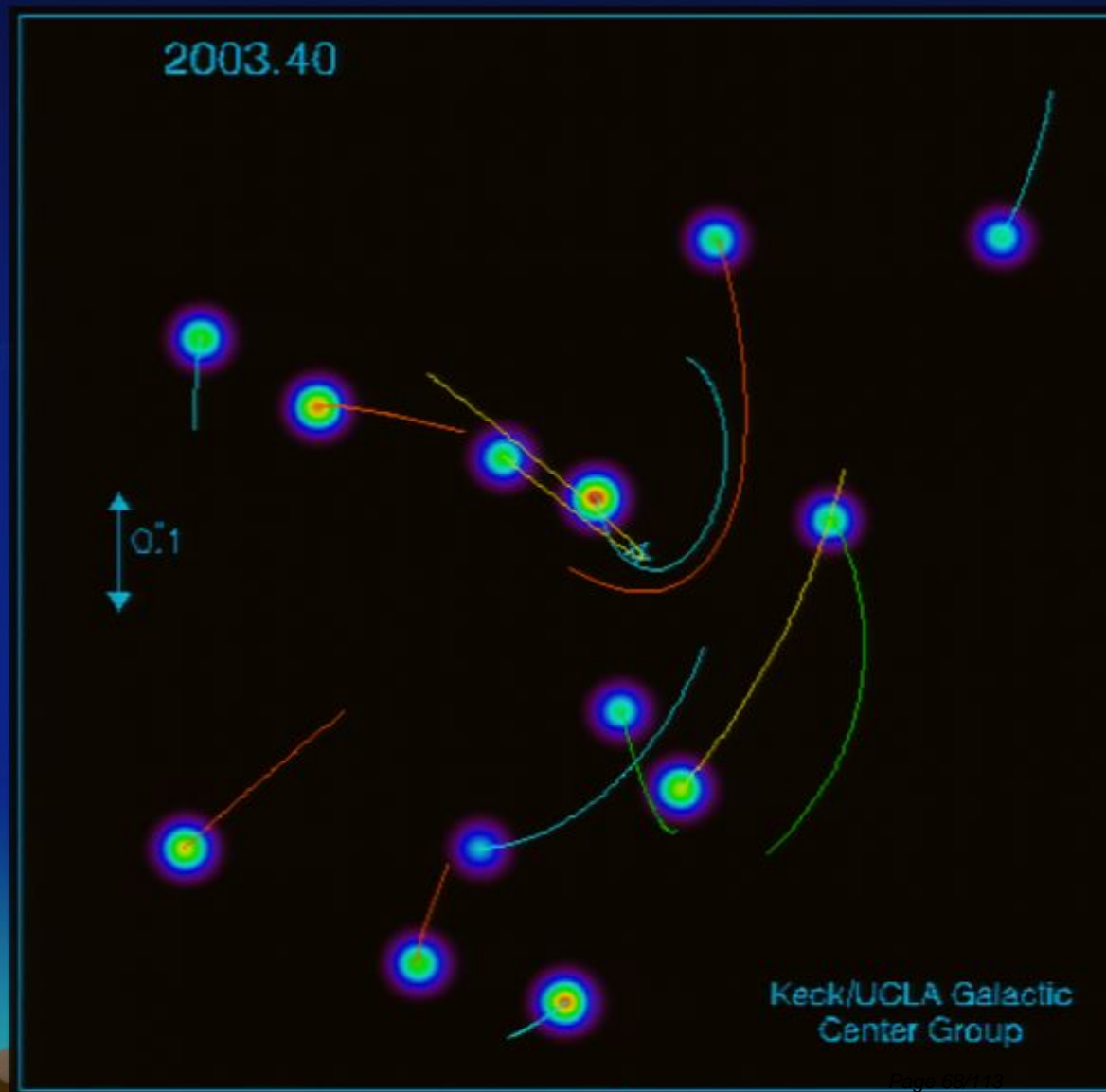


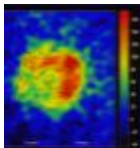
Results

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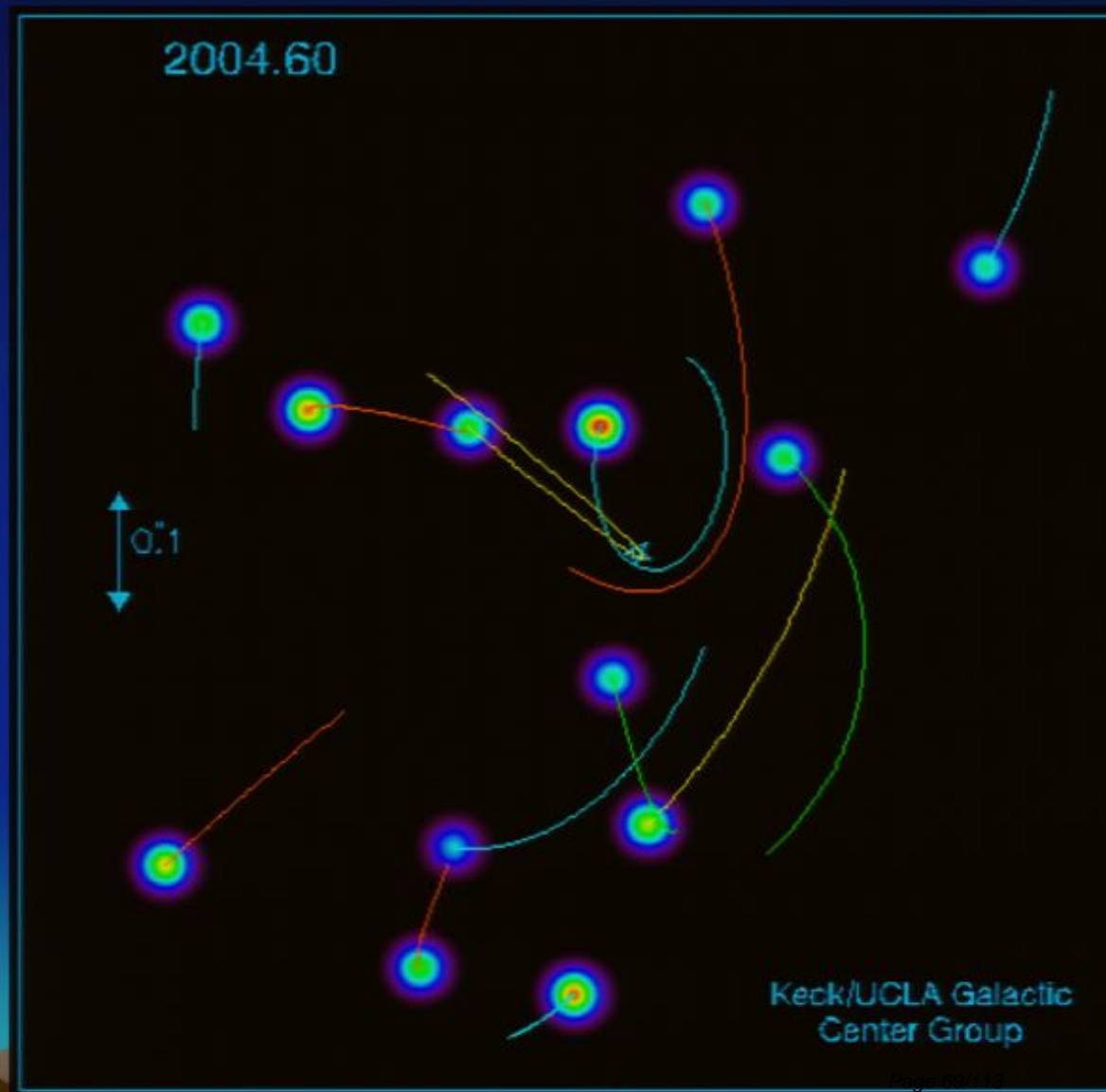


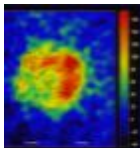
Results

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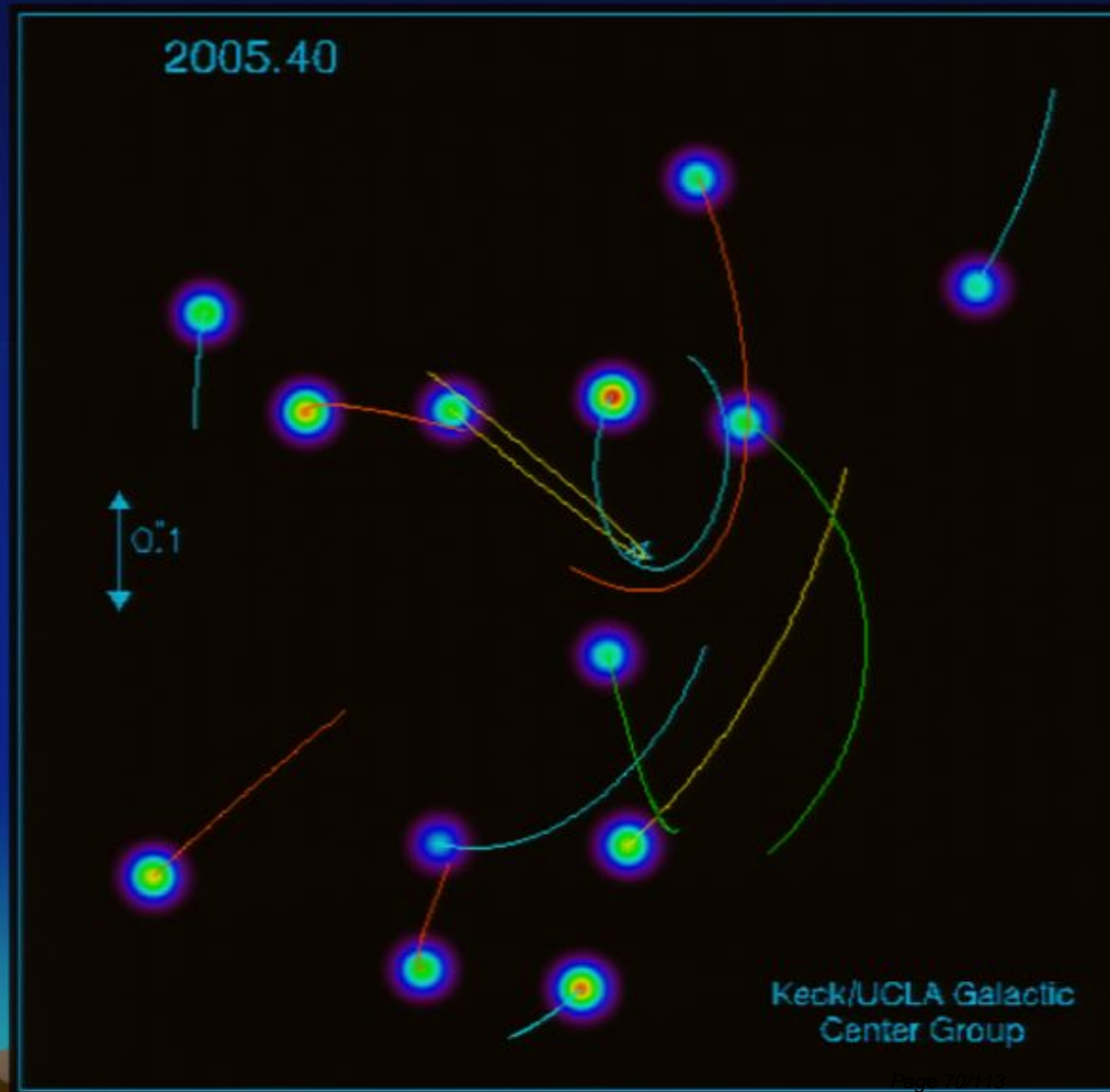


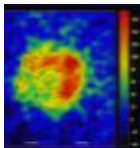
Results

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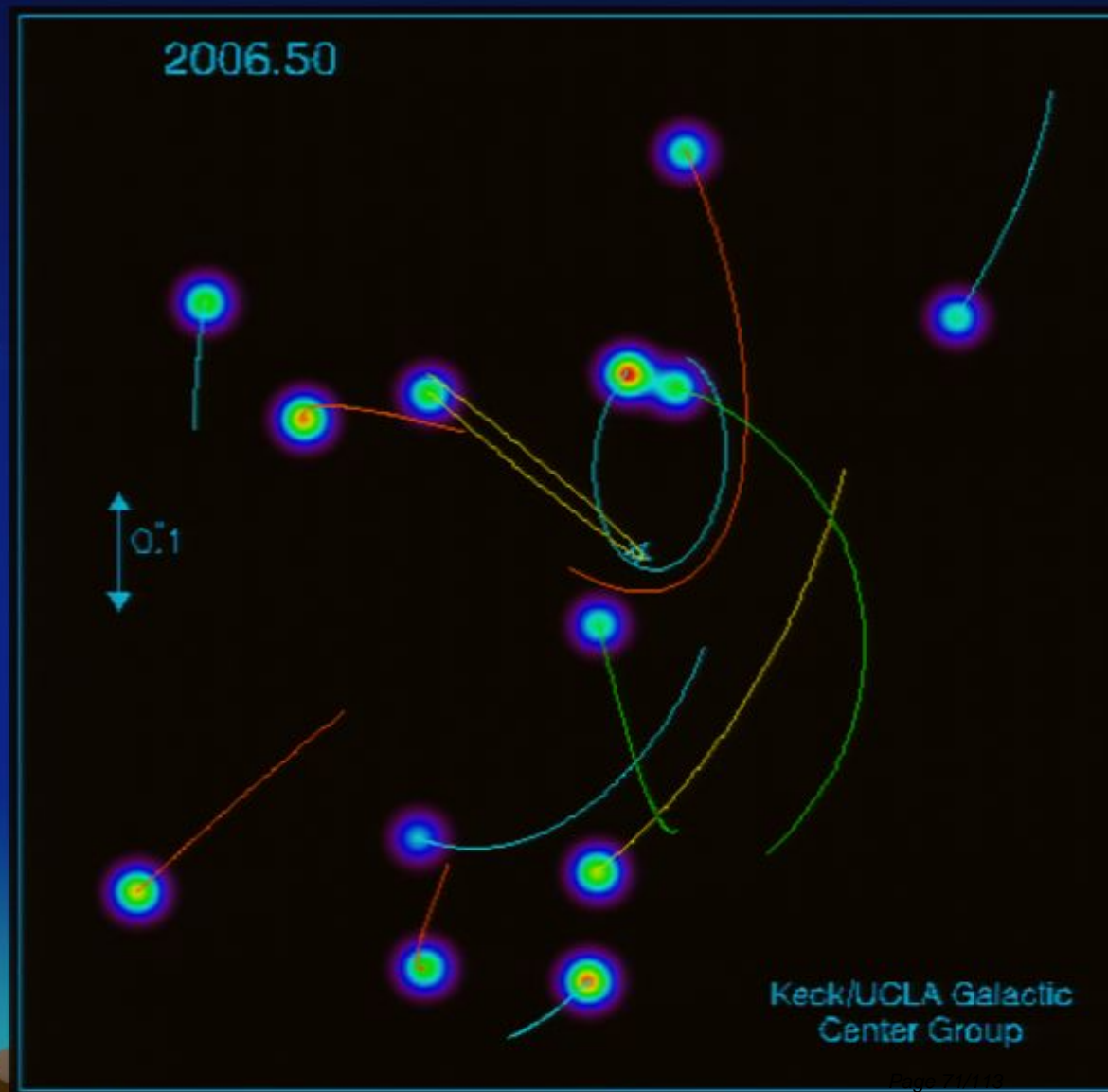


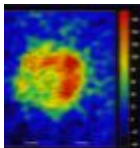
Results

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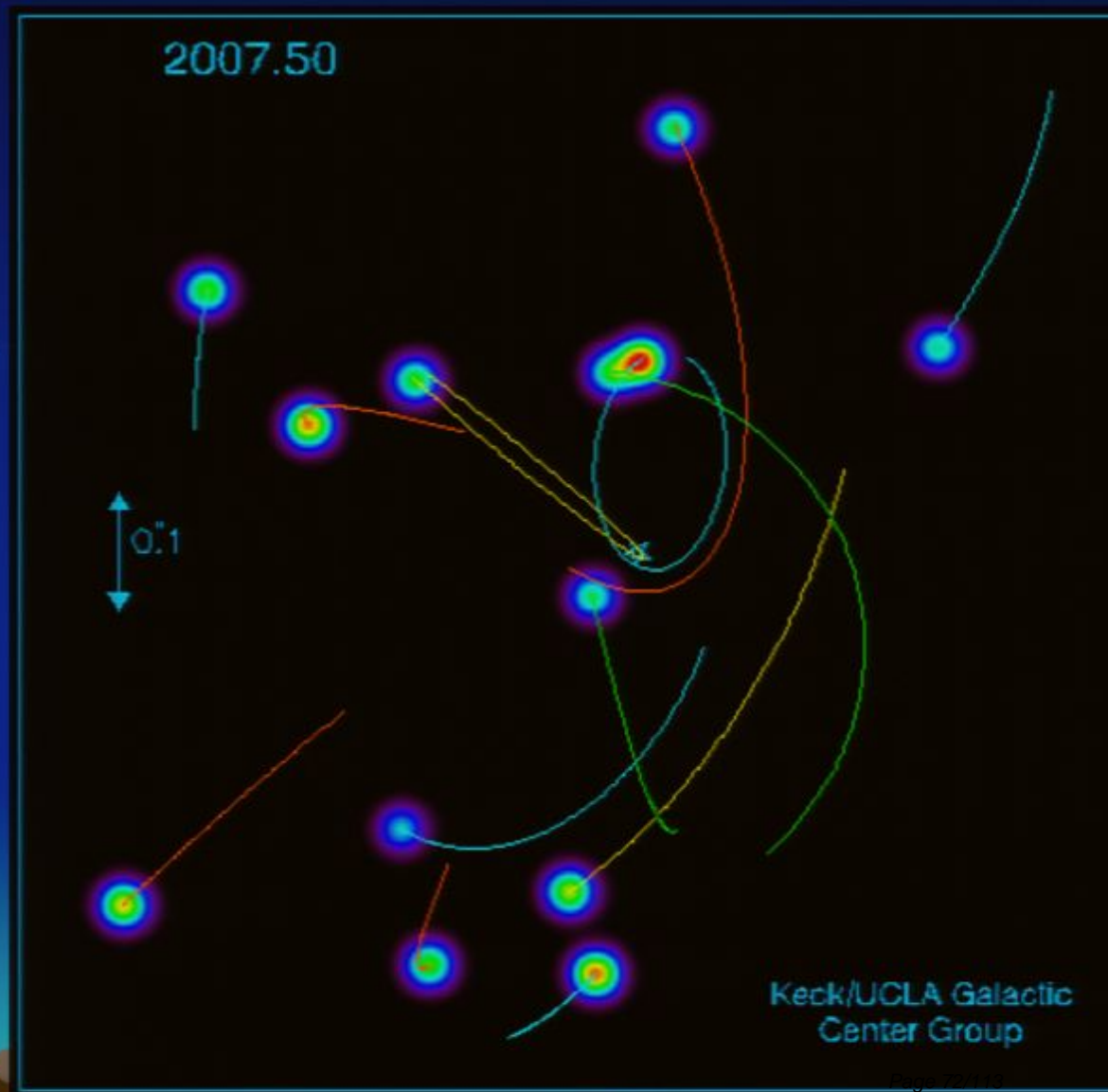


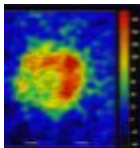
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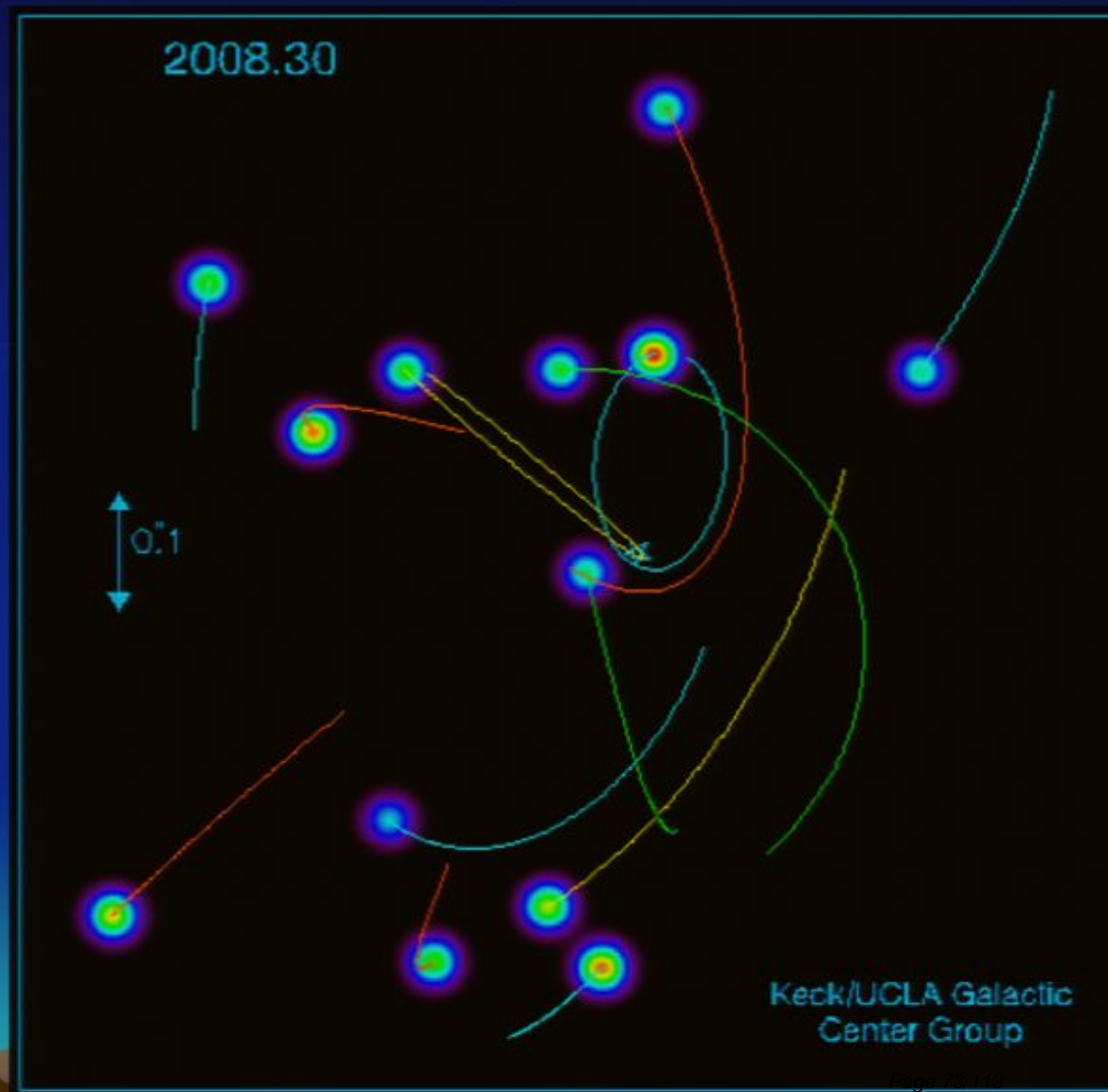


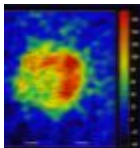
Results

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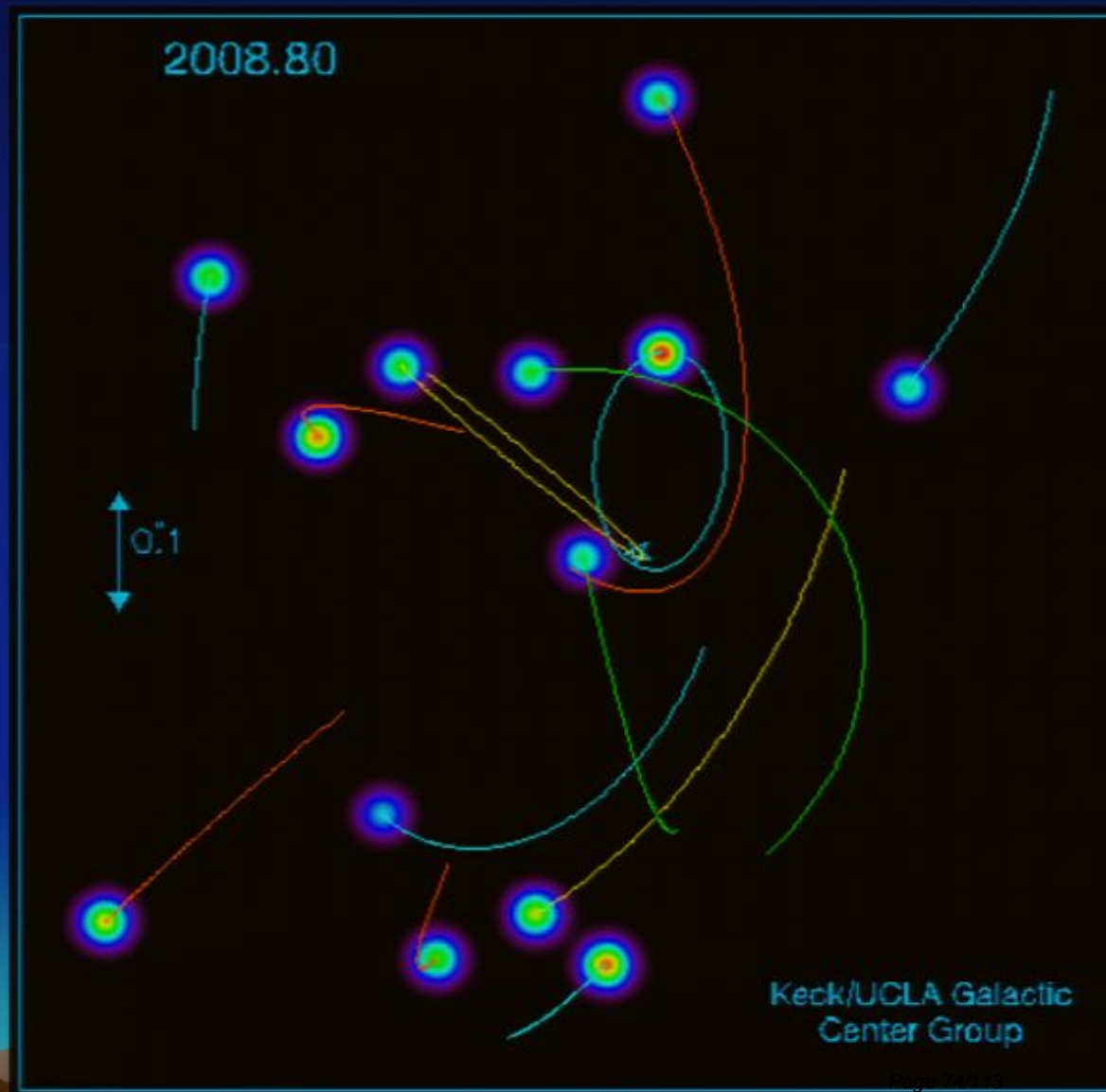


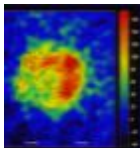
Results

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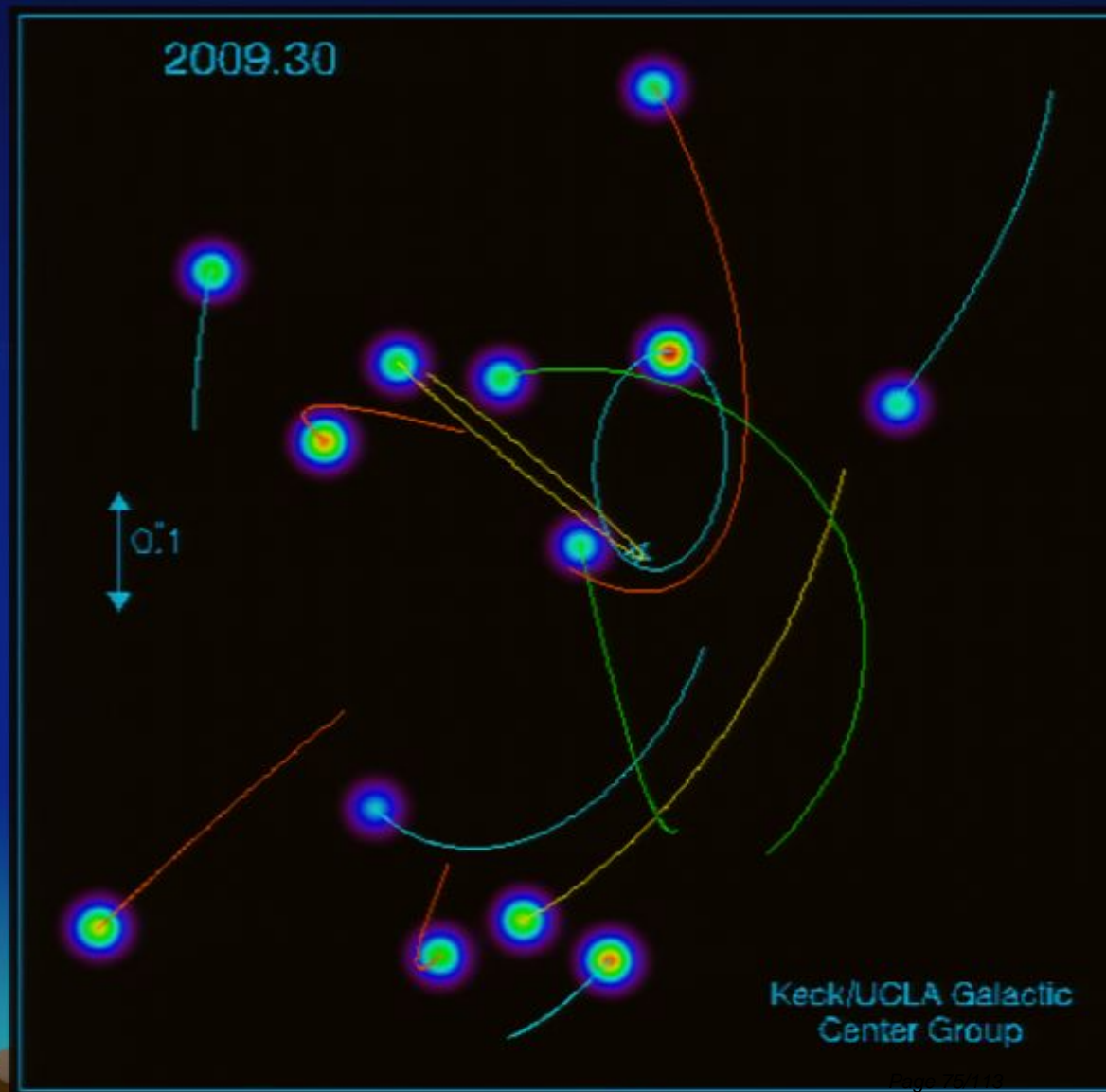


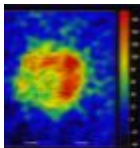
Results

Galactic Center:

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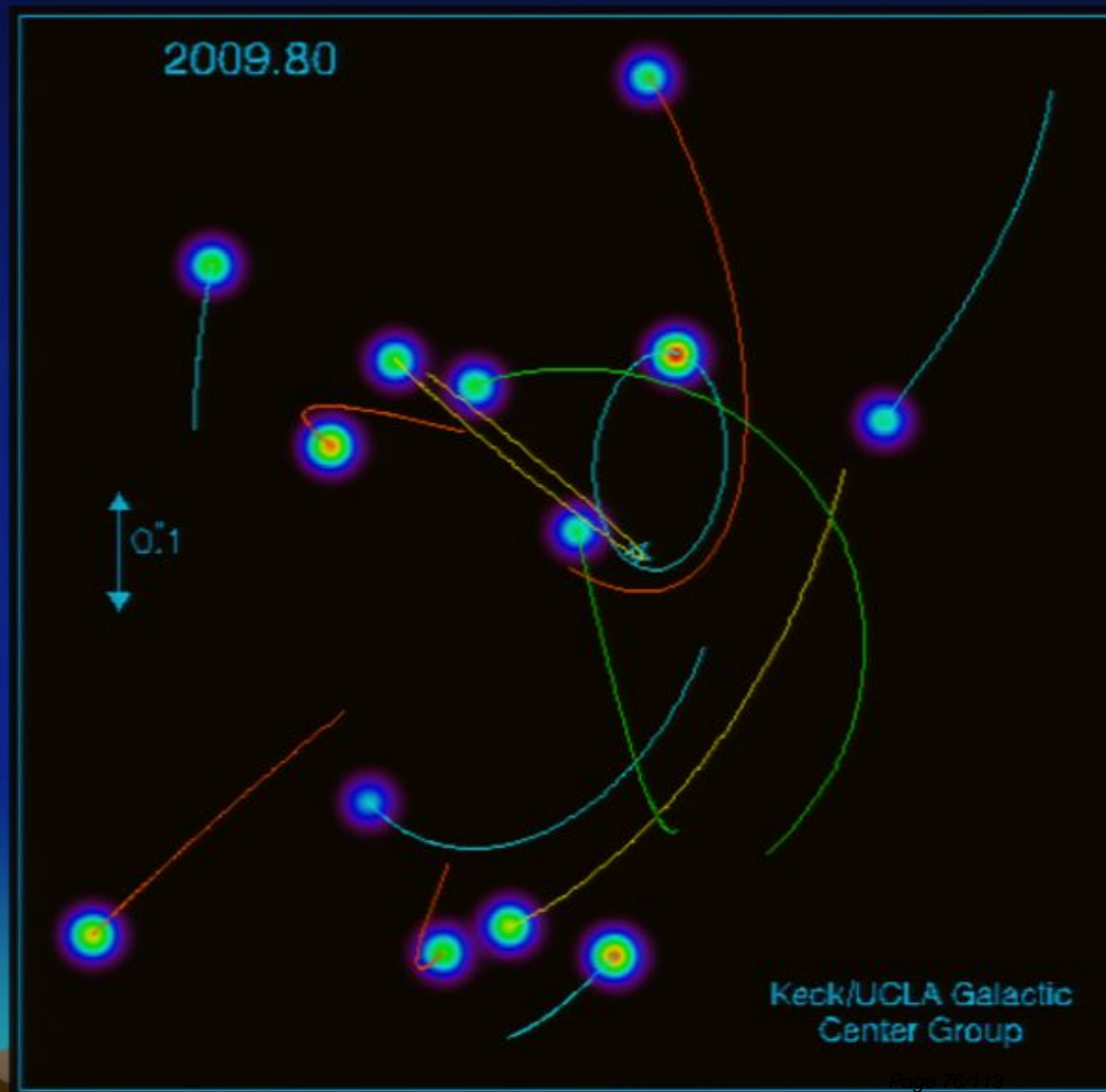


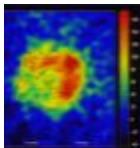
Results

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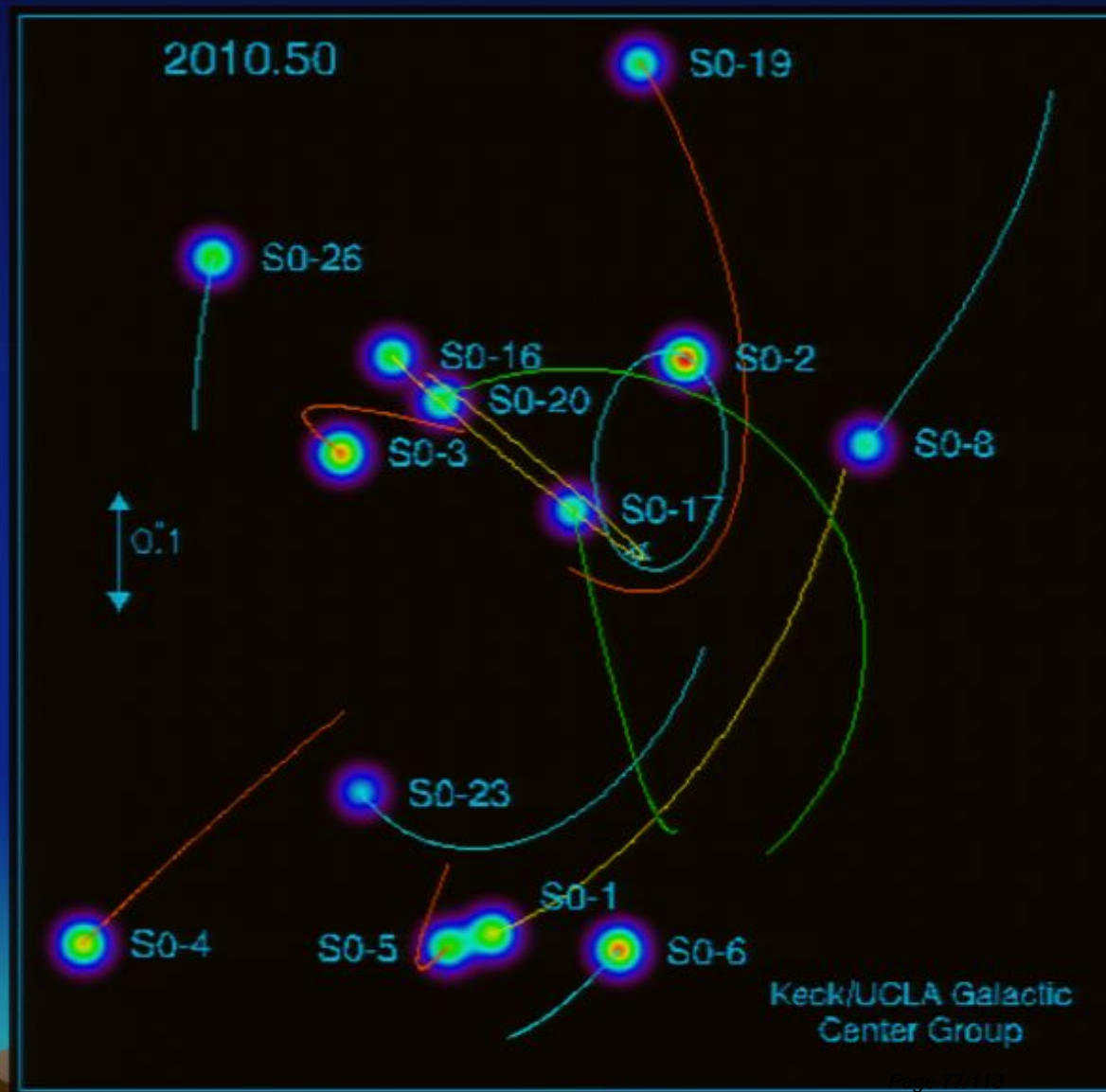


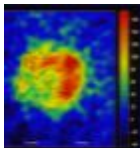
Results

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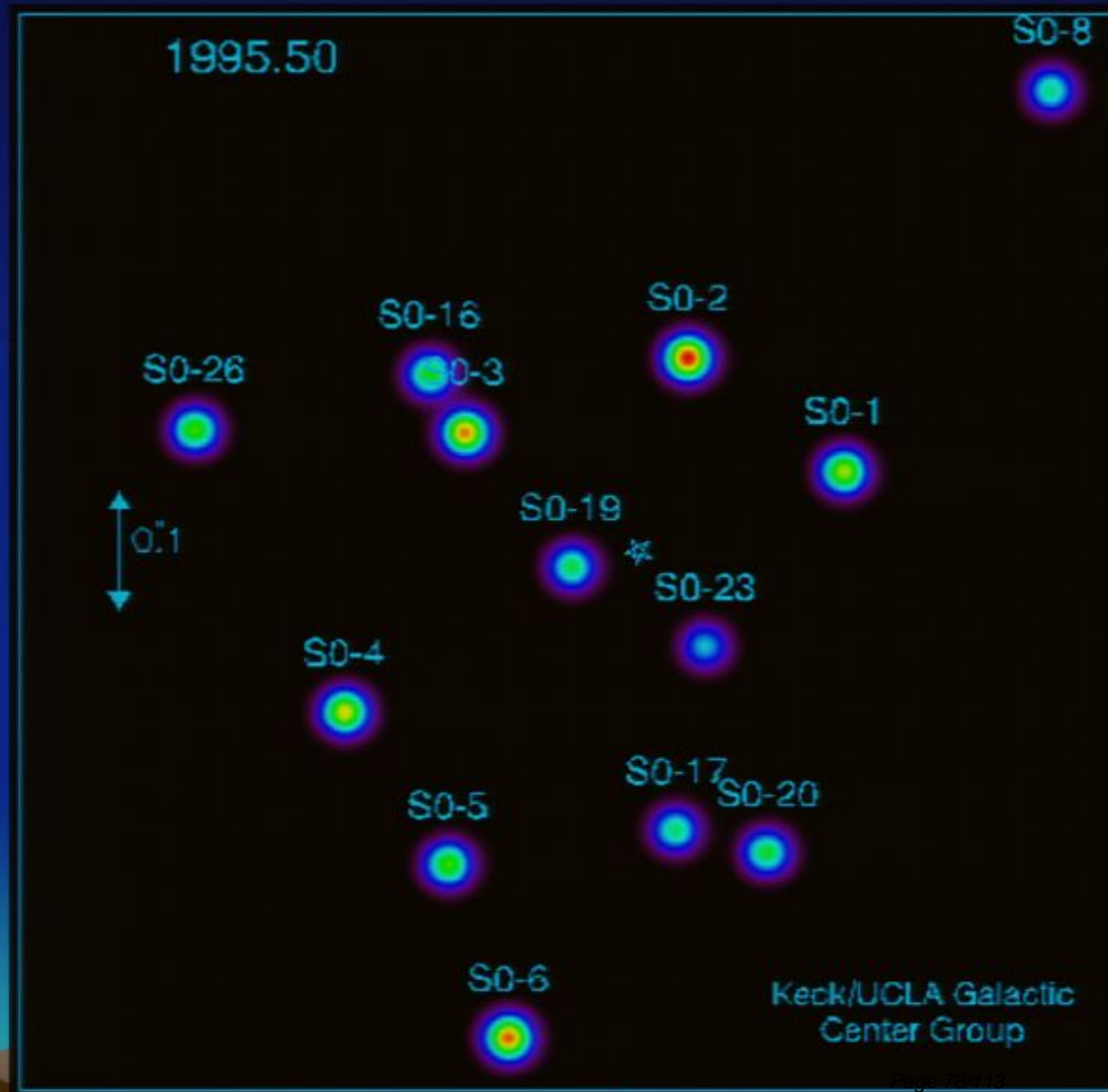


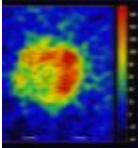
Results

Galactic Center:

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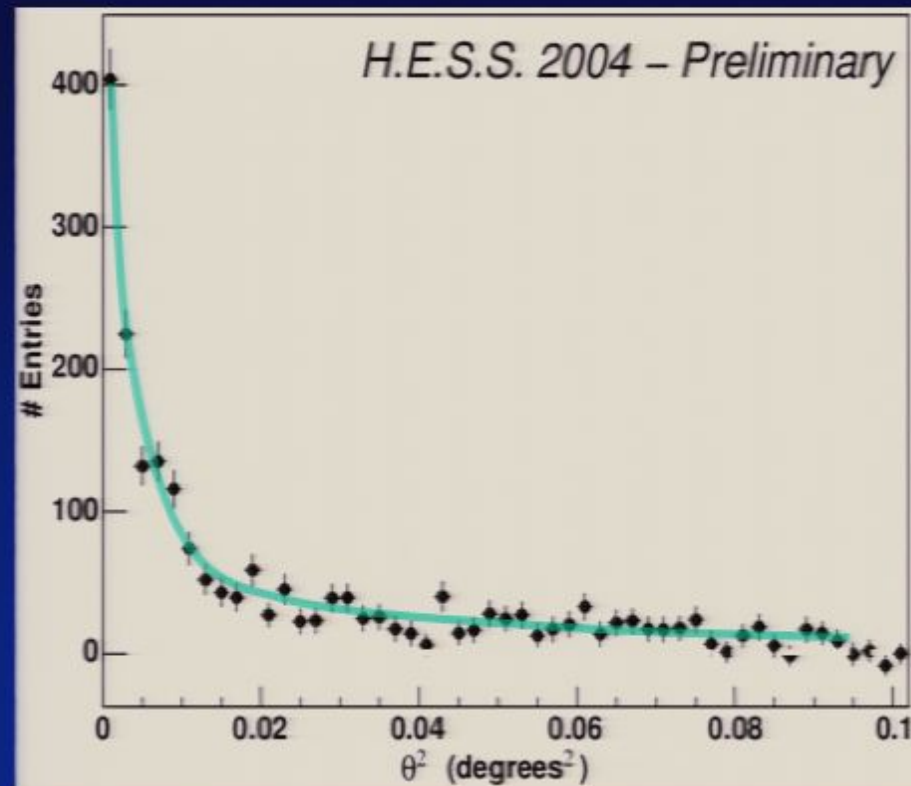
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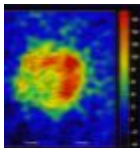
Results

Galactic Center:



Consistent with SGR A* to 6'' and slightly extended.

Position consistent with SgrA*

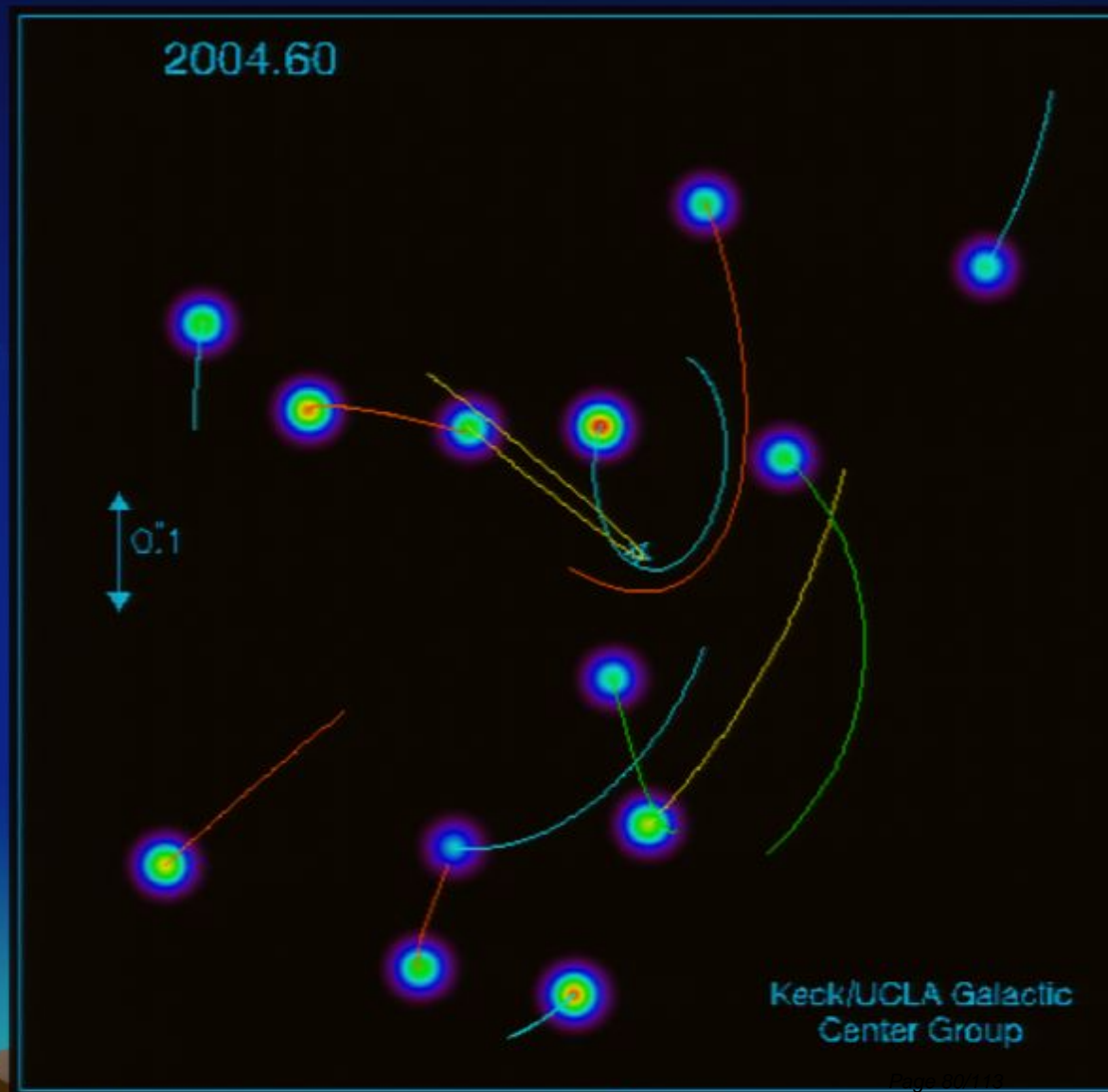


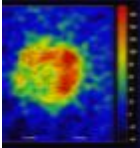
Results

Galactic Center:

No idea how to generate this γ -ray flux.

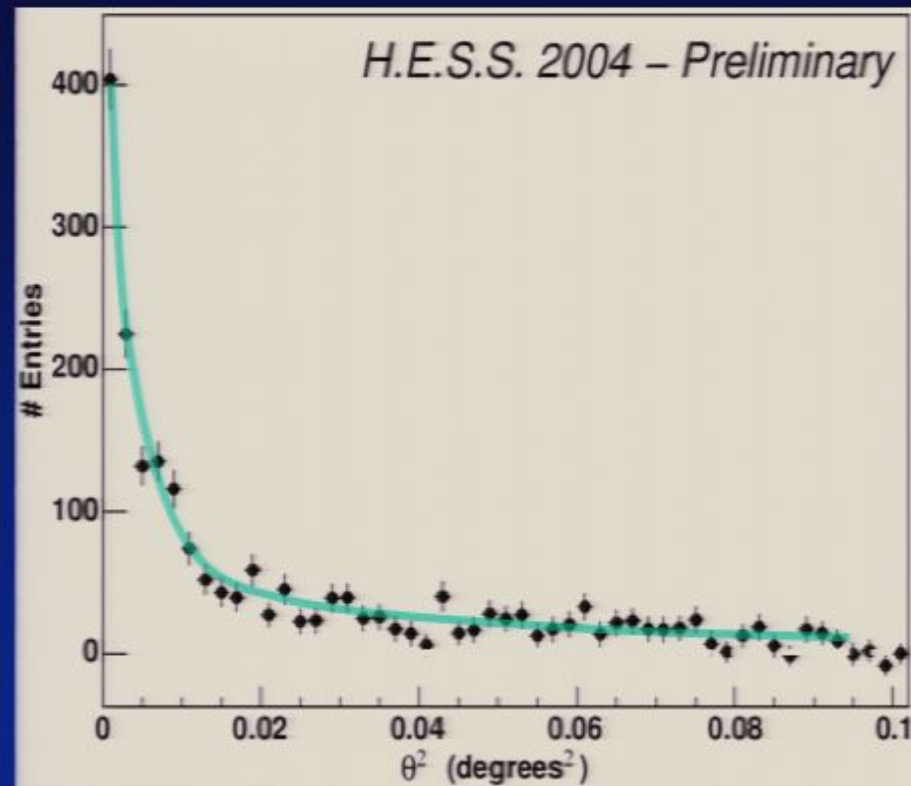
Stars seen down to $\sim 20 r_s$
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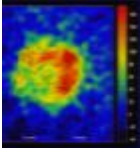
Results

Galactic Center:



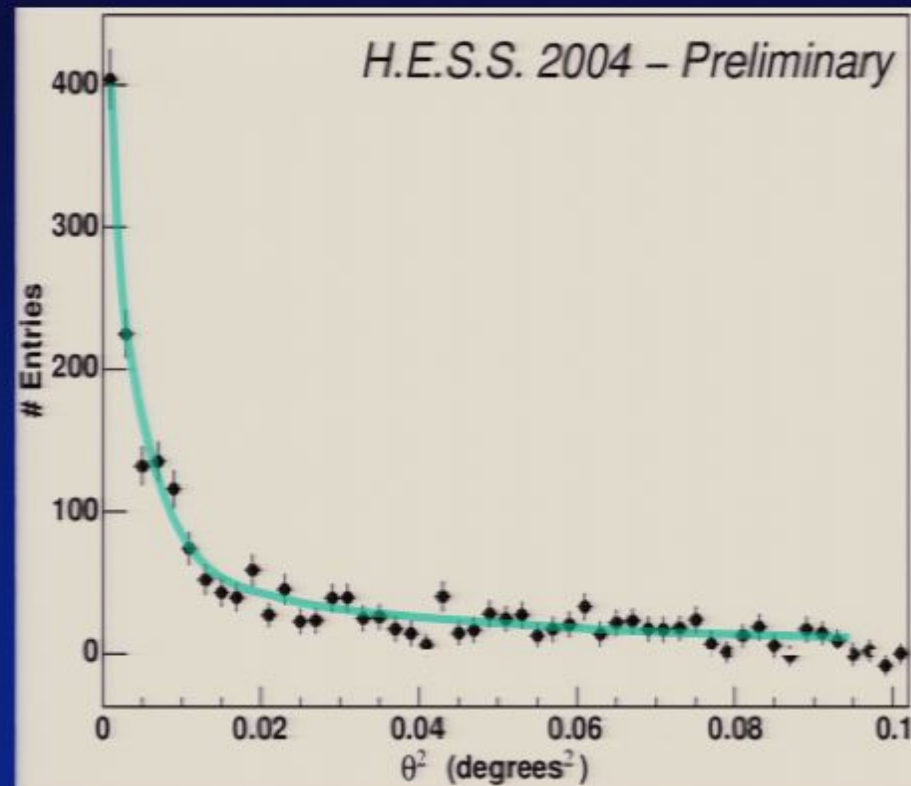
Consistent with SGR A* to 6'' and slightly extended.

Position consistent with SgrA*



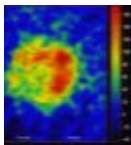
Results

Galactic Center:



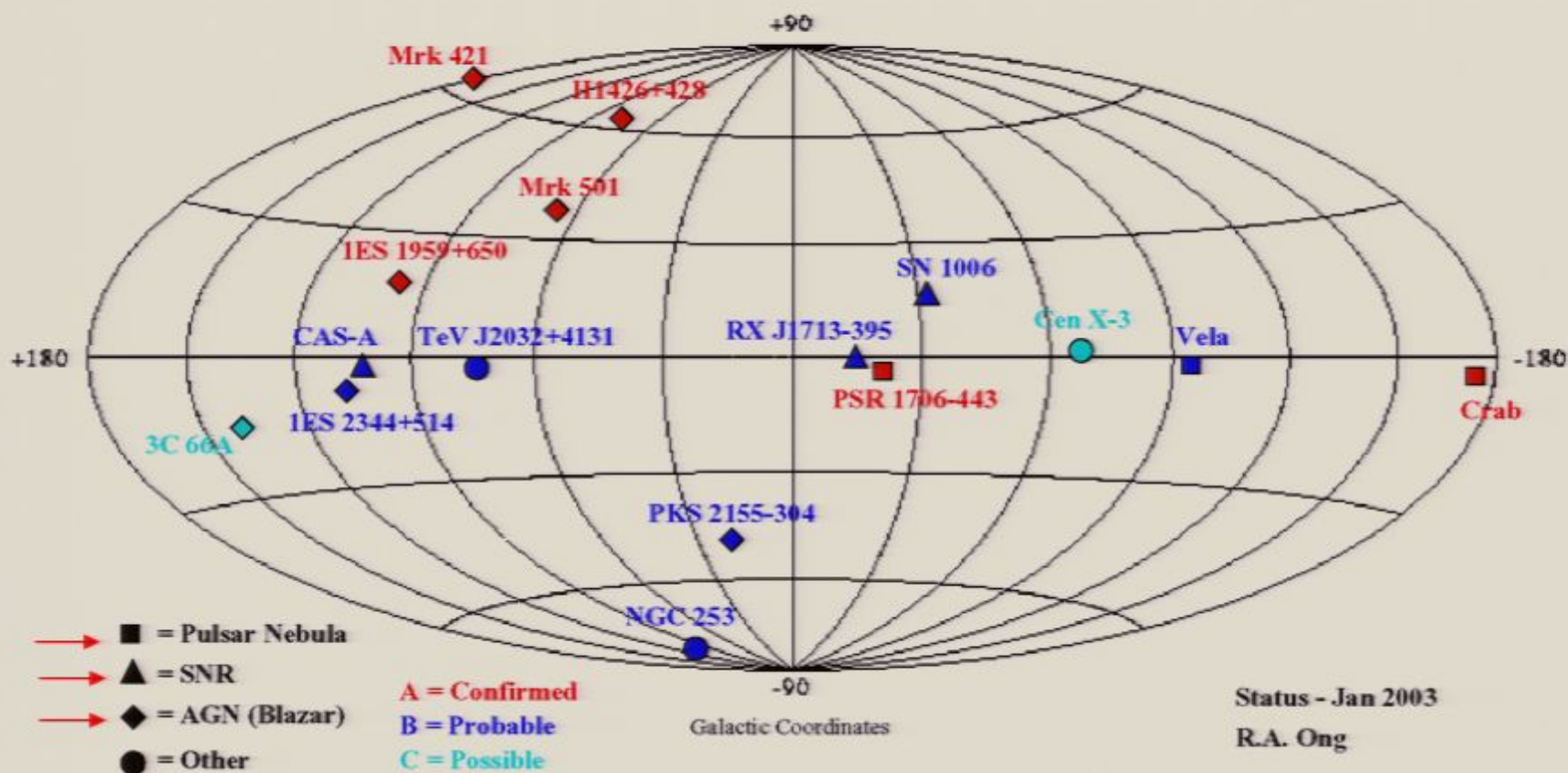
Consistent with SGR A* to 6'' and slightly extended.

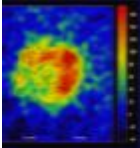
Position consistent with SgrA*



Results

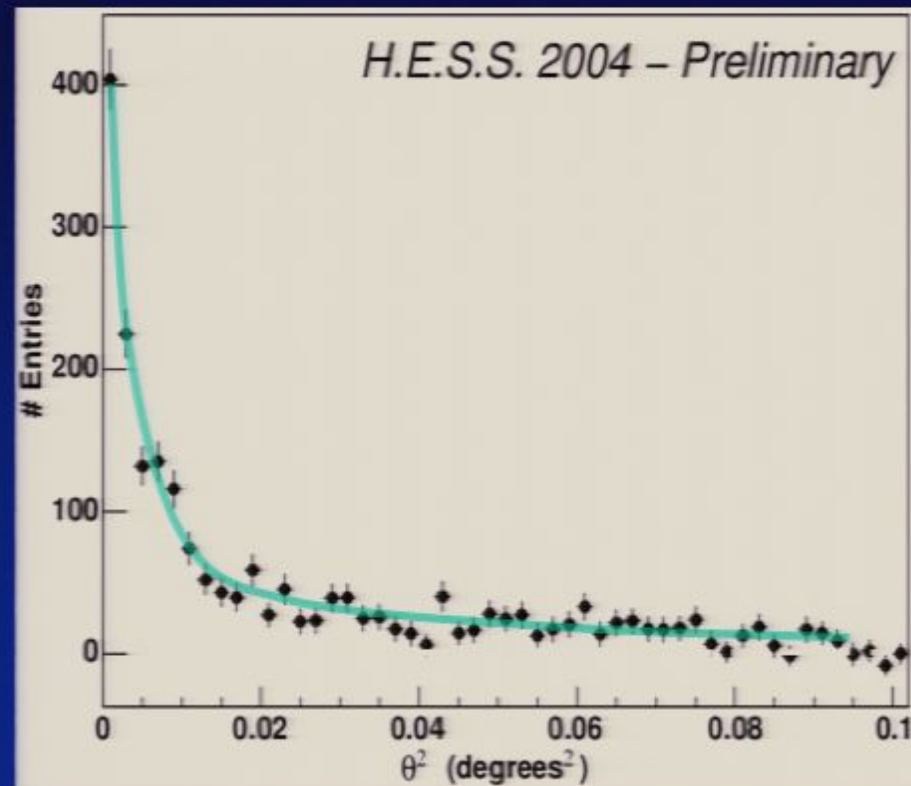
TeV γ -ray Sky ~2003:





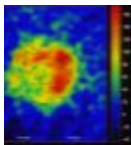
Results

Galactic Center:



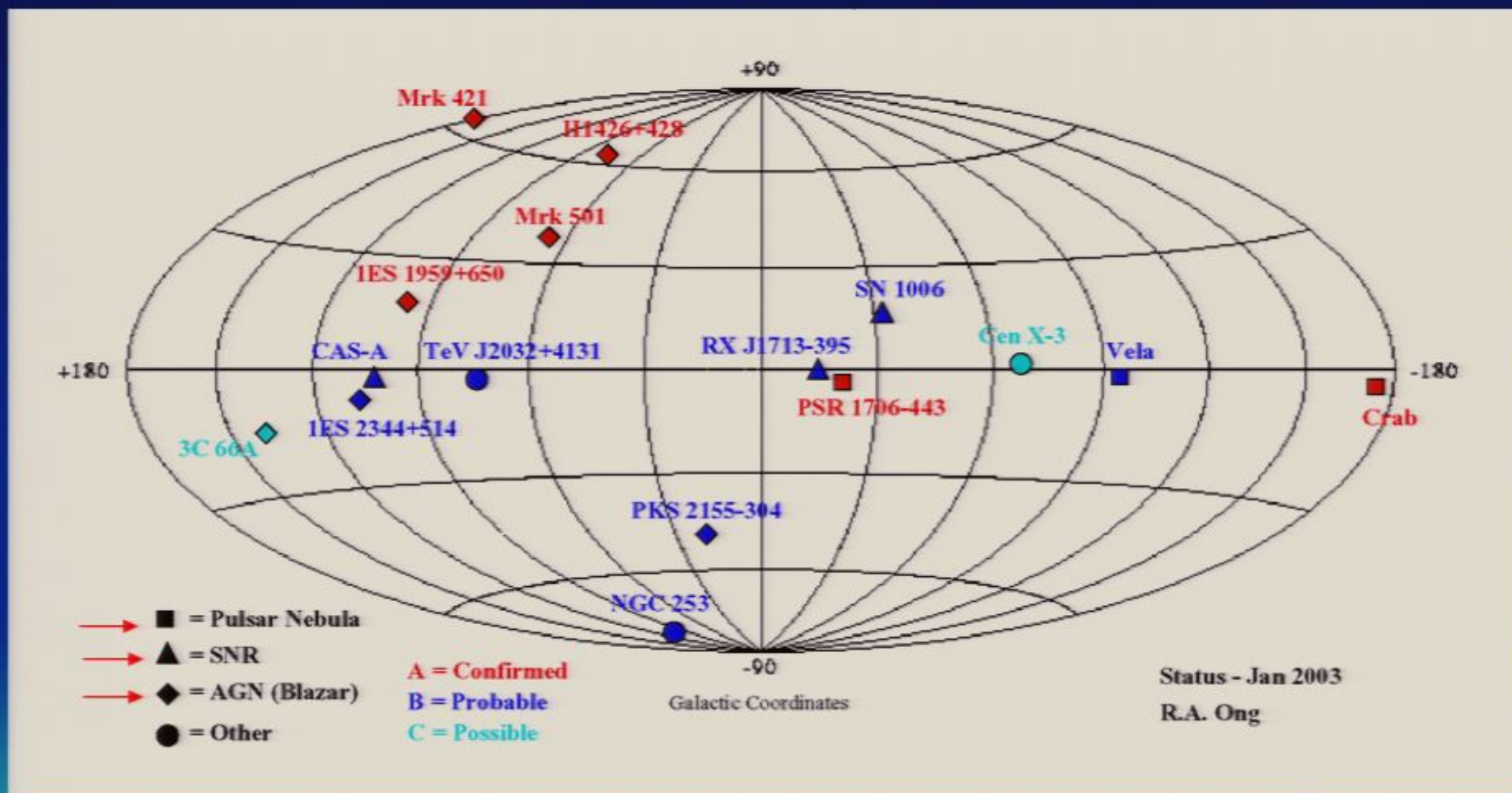
Consistent with SGR A* to 6'' and slightly extended.

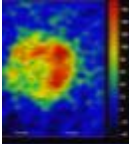
Position consistent with SgrA*



Results

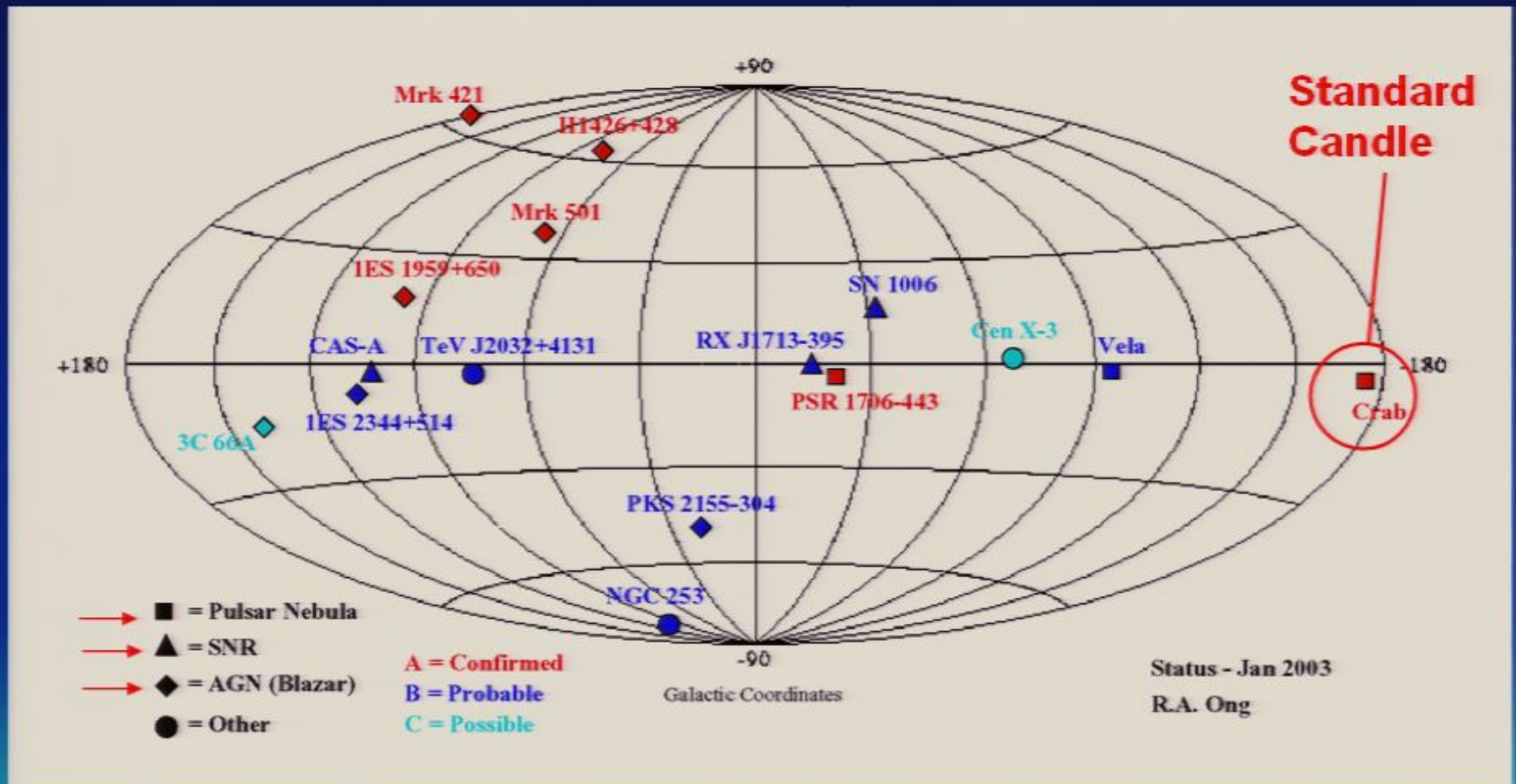
TeV γ -ray Sky ~2003:

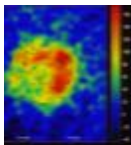




Results

TeV γ -ray Sky ~2003:

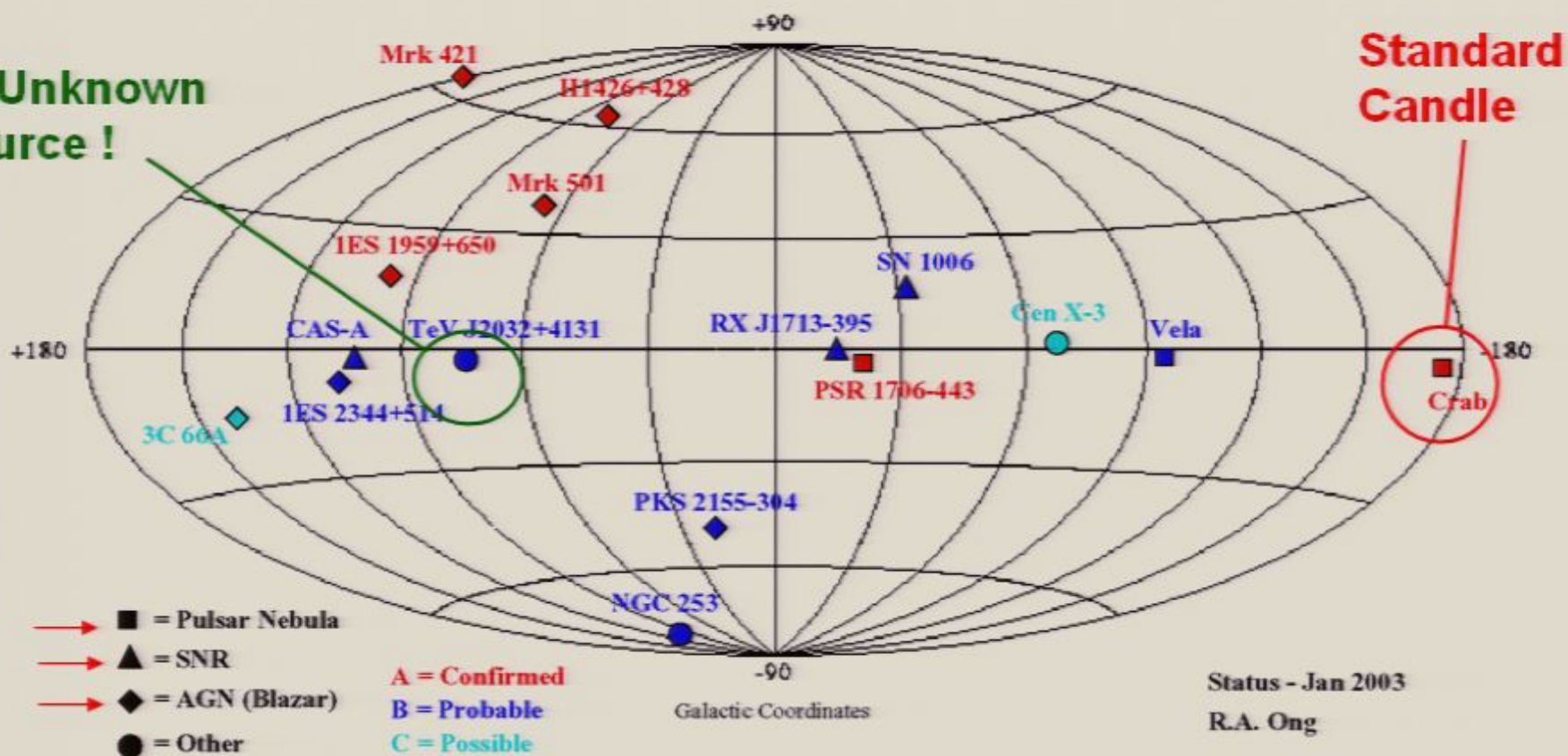


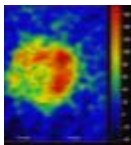


Results

TeV γ -ray Sky ~2003:

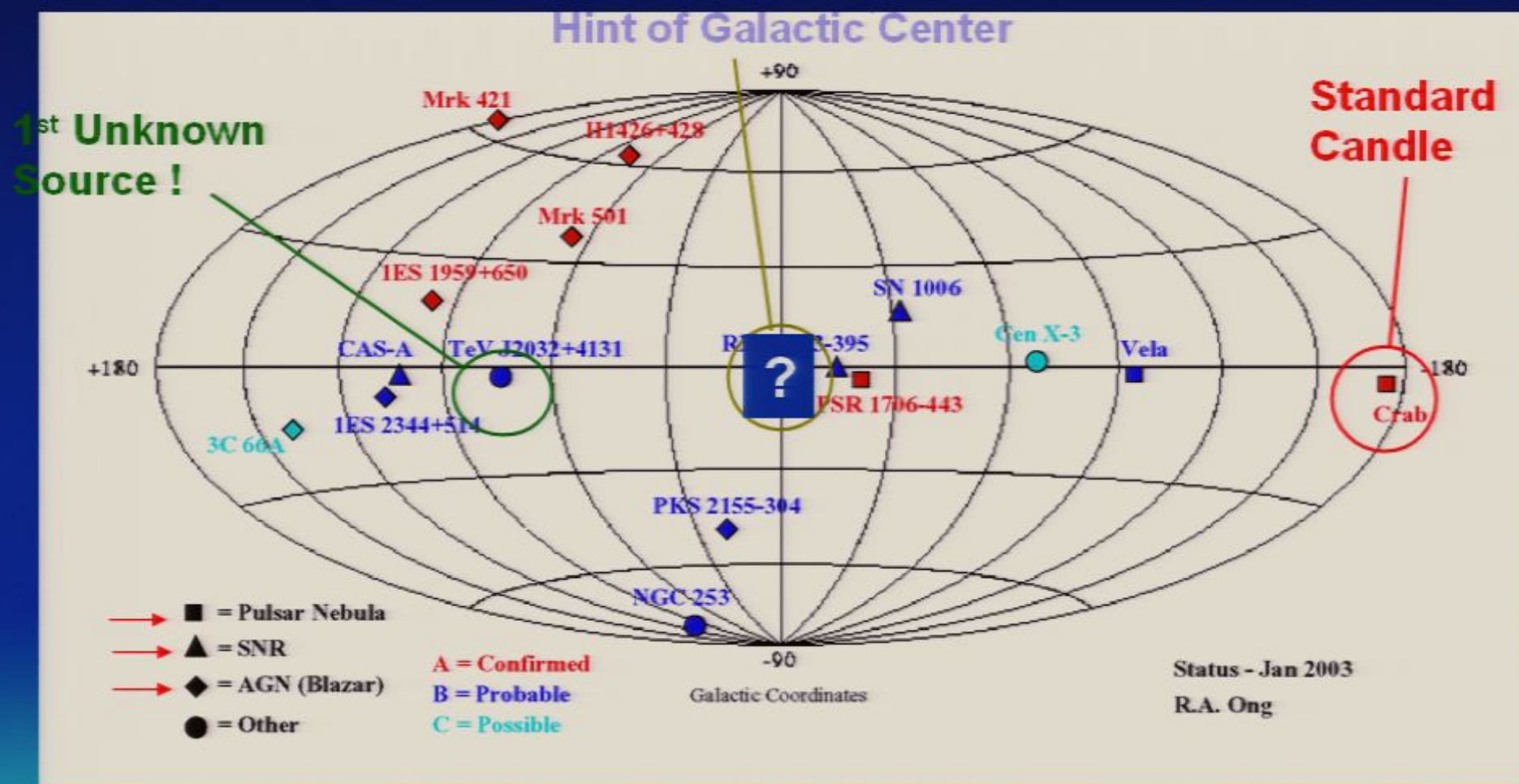
1st Unknown Source !

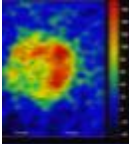




Results

TeV γ -ray Sky ~2003:






Results

Source Counts

Source Type*	2003	2005
Pulsar Wind Nebula (e.g. Crab, MSH 15-52 ...)	3	6
Supernova Remnants (e.g. Cas-A, RXJ 1713 ...)	2	6
Binary Pulsar (B1259-63)	0	1
Micro-quasar (LS 5039)	0	1
Diffuse (Cygnus region)	0	1
AGN (e.g. Mkn 421, PKS 2155 ...)	6	11
Unidentified	2	6
TOTAL	13	32

* Includes likely associations of HESS un-ID sources.

→ **Explosion in the number of VHE sources.**



Future

Future: VERITAS & GLAST

VERITAS is North American analog to HESS:

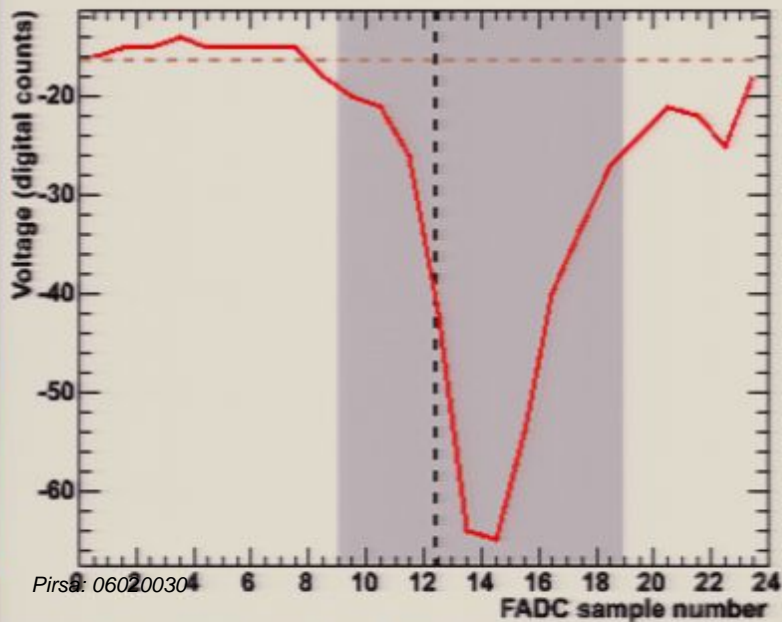
- 4 x 12 m telescopes
- Expansion of successful Whipple collaboration:
 - ~ 80 scientists from US/UK/Ireland/Canada
- 499-PMT cameras
- 3.5° field of view
- ~ 100 GeV threshold
- ~ 4' angular resolution
- Crab detection in 20 s



Future

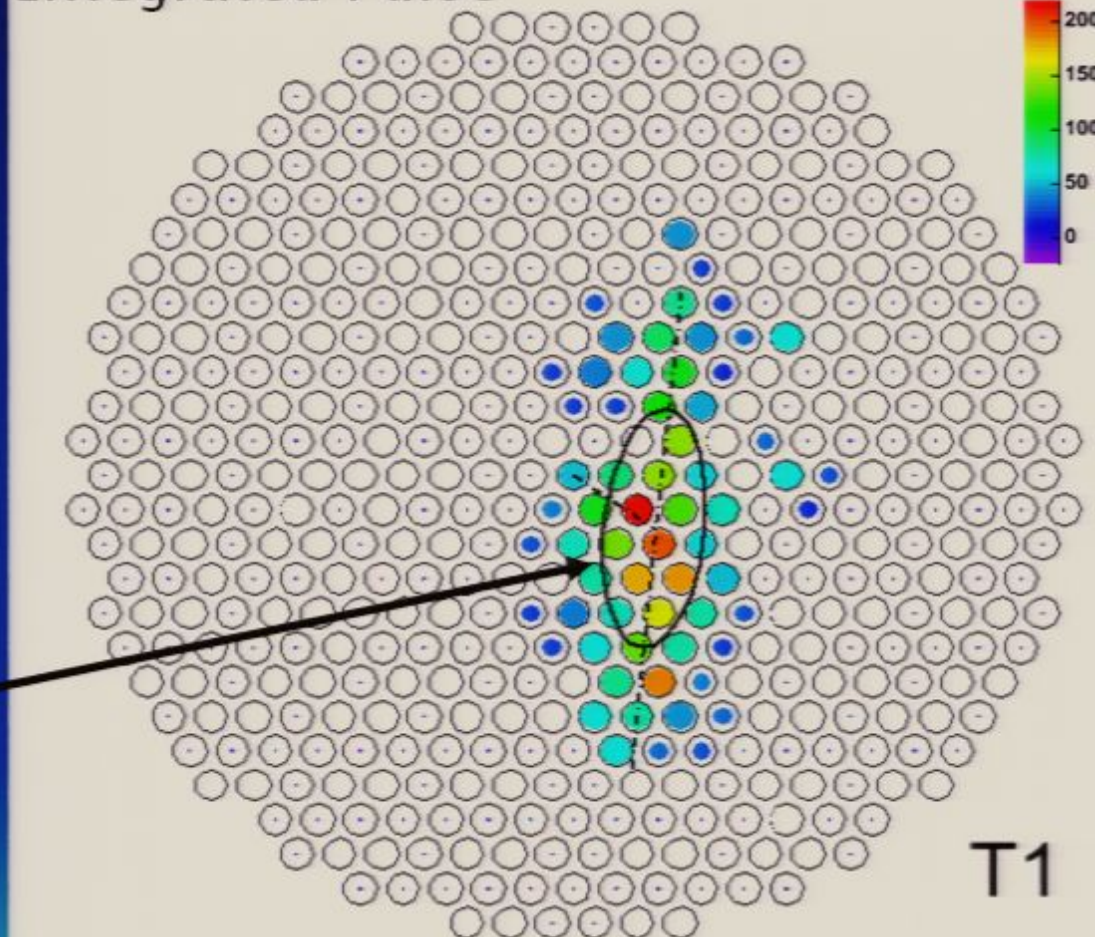
VERITAS Data Acquisition

- PMTs digitized with 500 MHz sampling FADCs
 - 24 samples/channel.
 - <4% deadtime @ 150 Hz.



Pirsa: 060200304

Integrated Pulse



Future

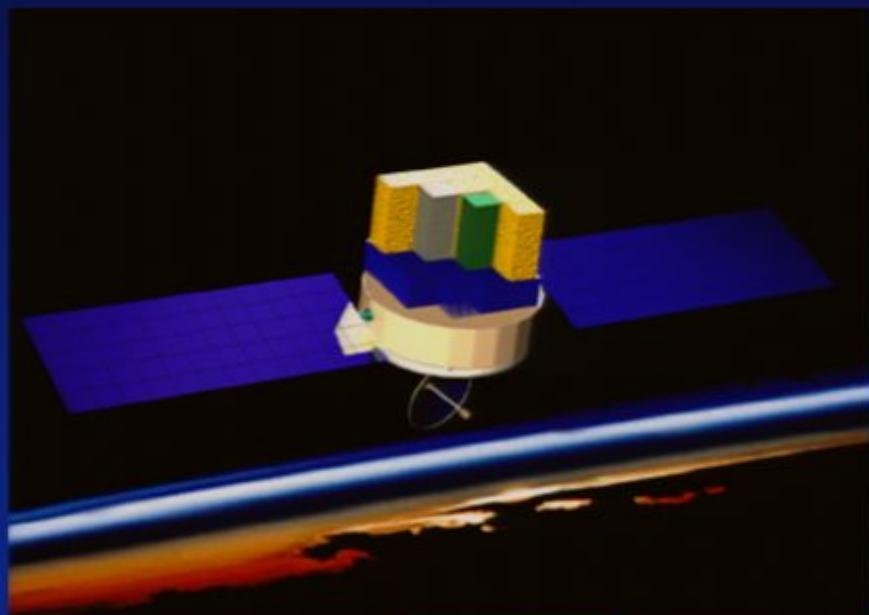
First two telescopes now
operations at Mt.
Hopkins (Arizona);
routine operations
starting

Assembly of next two
telescopes will be
completed during 2006



Future

GLAST – Satellite Telescope



GLAST LAT Instrument:

- **Si-strip tracker**
- **CsI calorimeter**
- **Anti-coincidence veto**

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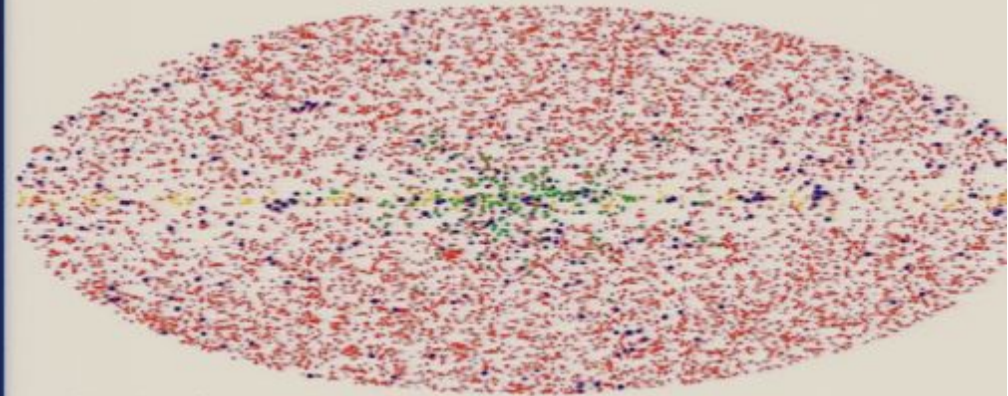


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Extensive LAT Catalog

5 σ Sources from Simulated
One Year All-sky Survey



Results of one-year
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(Total: 9900 sources)

● AGN ● Galactic Halo
● 3EG Catalog ● Galactic Plane

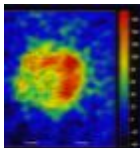
Simulated sky map from 1 year survey

Launch in 2007 (?)

Conclusions

The future of ground-based gamma-ray astrophysics seems bright indeed!

- VHE γ -rays probe astrophysics in regimes not yet fully explored
- at TeV energies most of the sky is still unexplored
- new generation of instruments: HESS, VERITAS, GLAST are powerful and complementary in coverage
- significant potential for discovery of 'new physics'

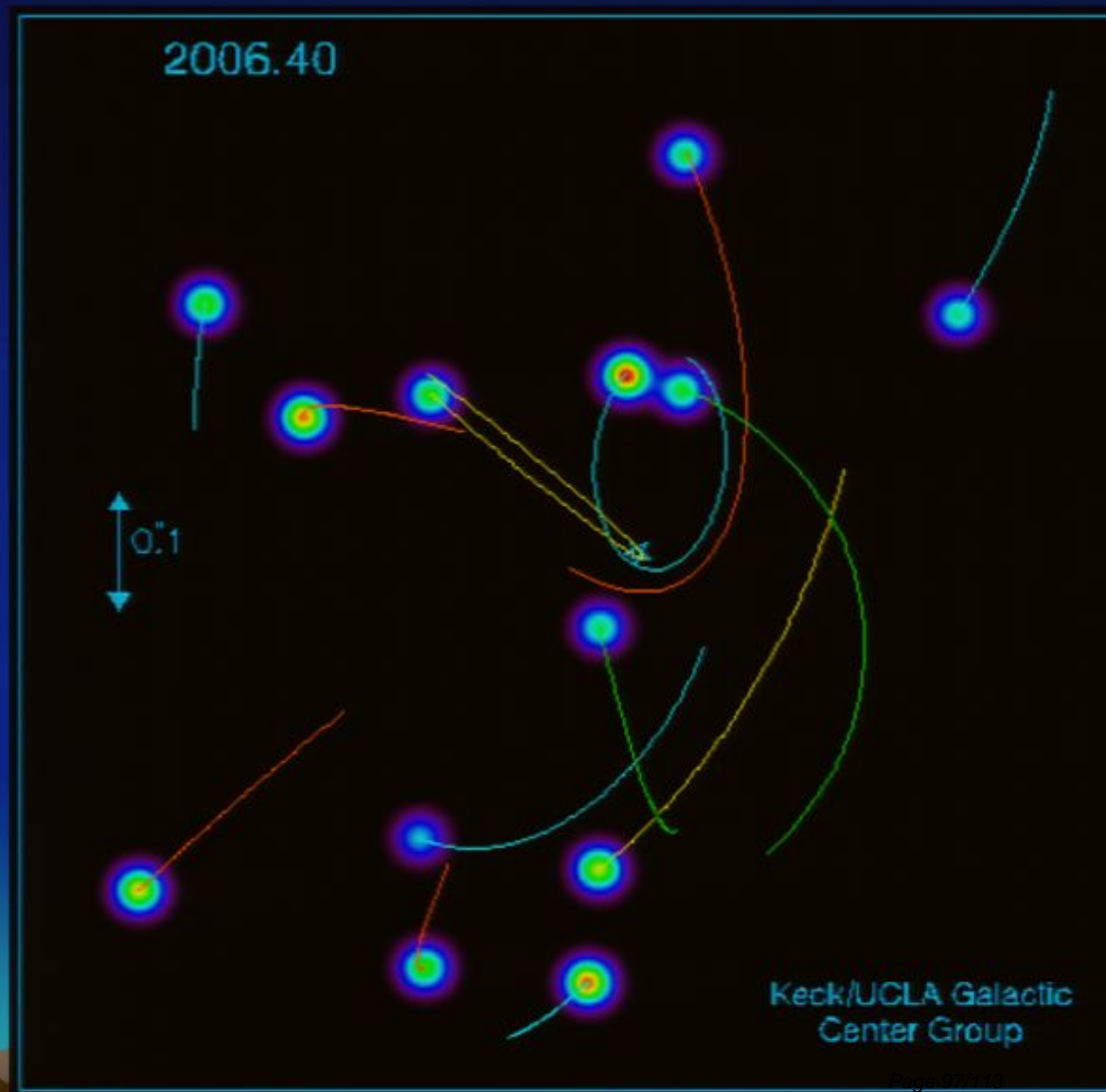


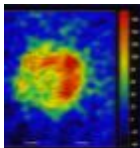
Results

Galactic Center:

No idea how to generate this γ -ray flux.

Stars seen down to $\sim 20 r_s$
-- no appreciable concentration of luminous material



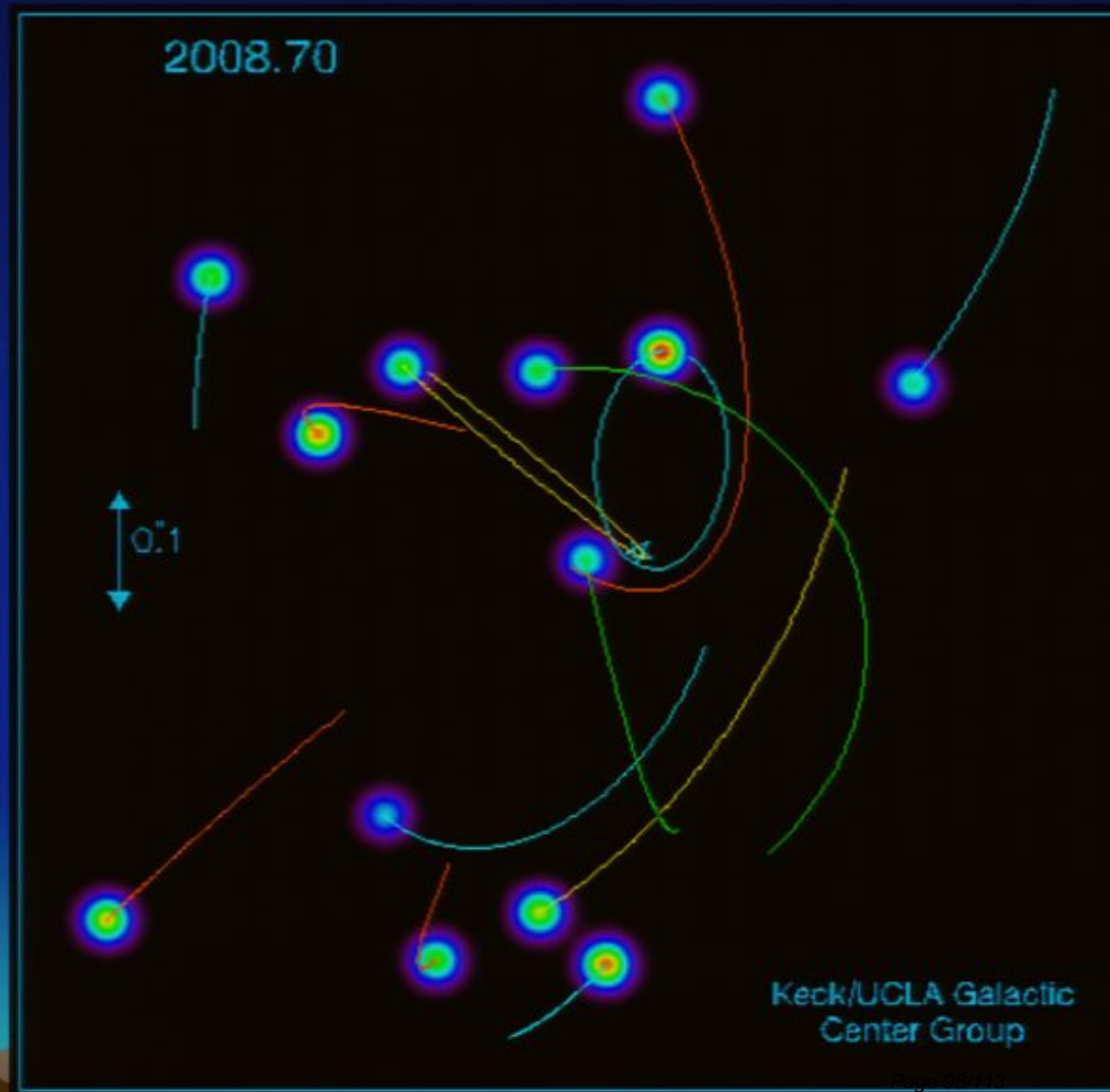


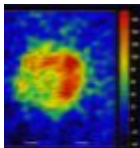
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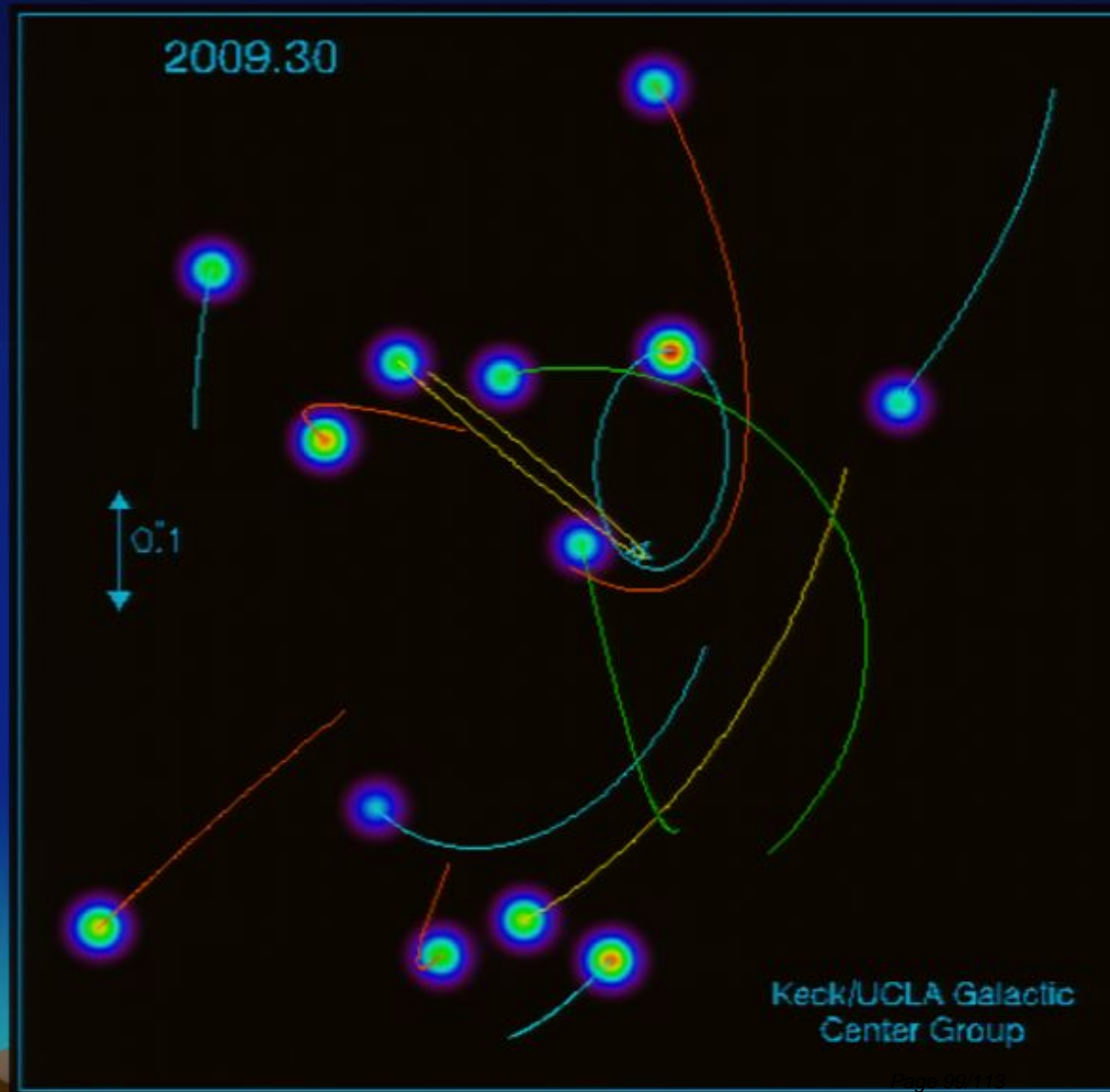


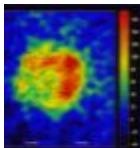
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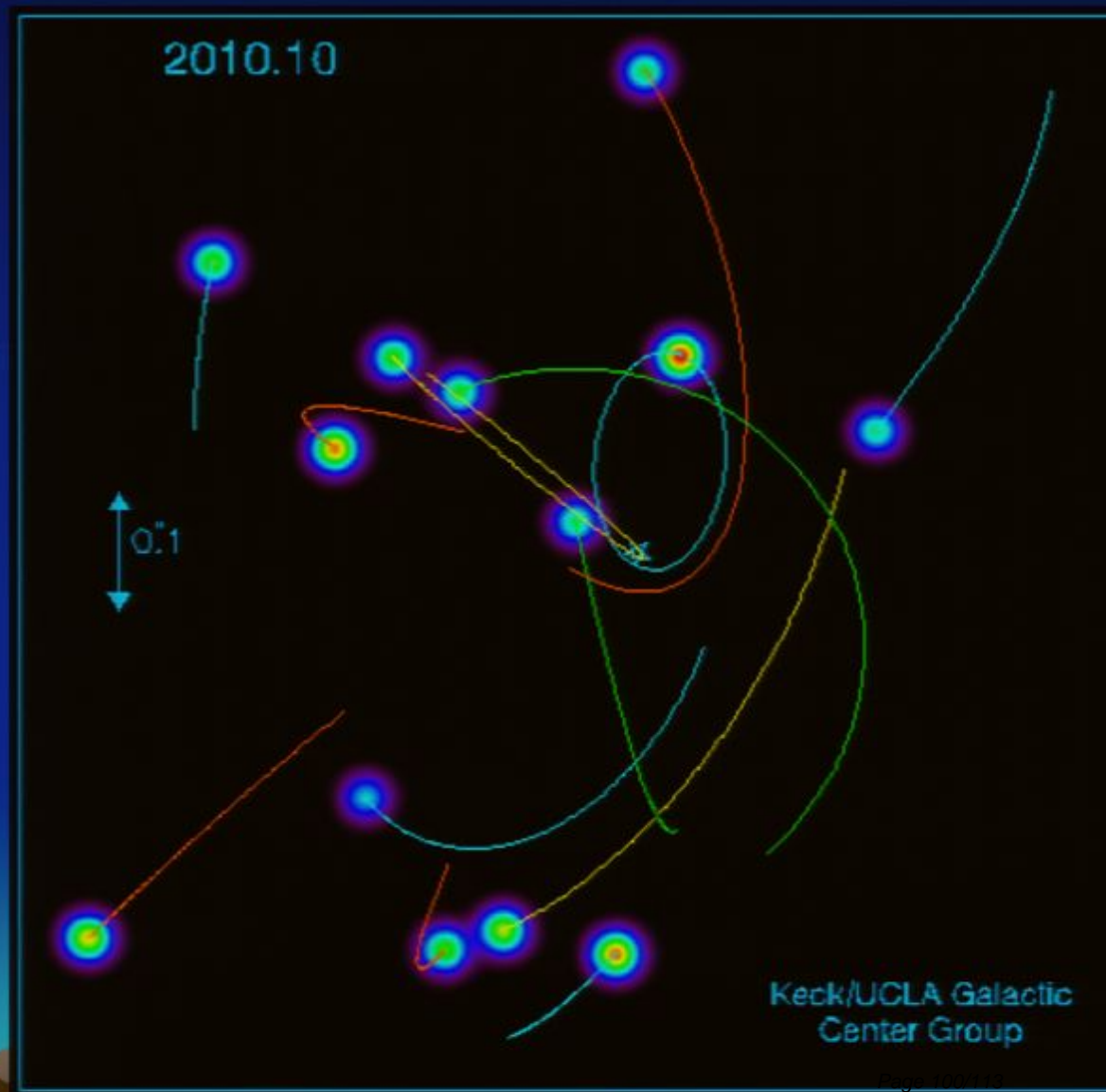


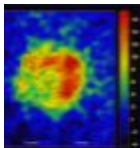
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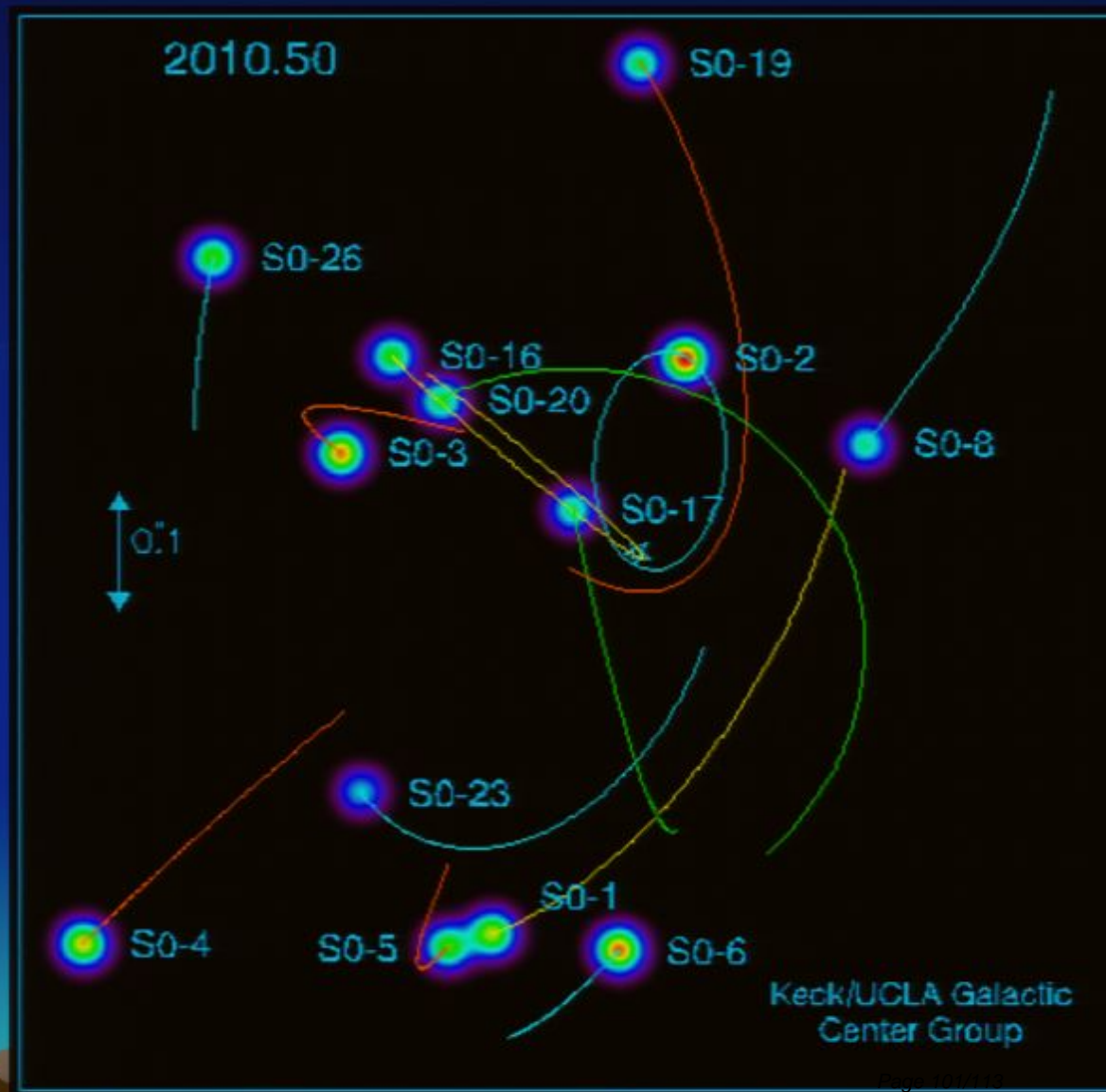


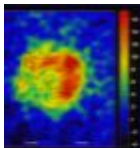
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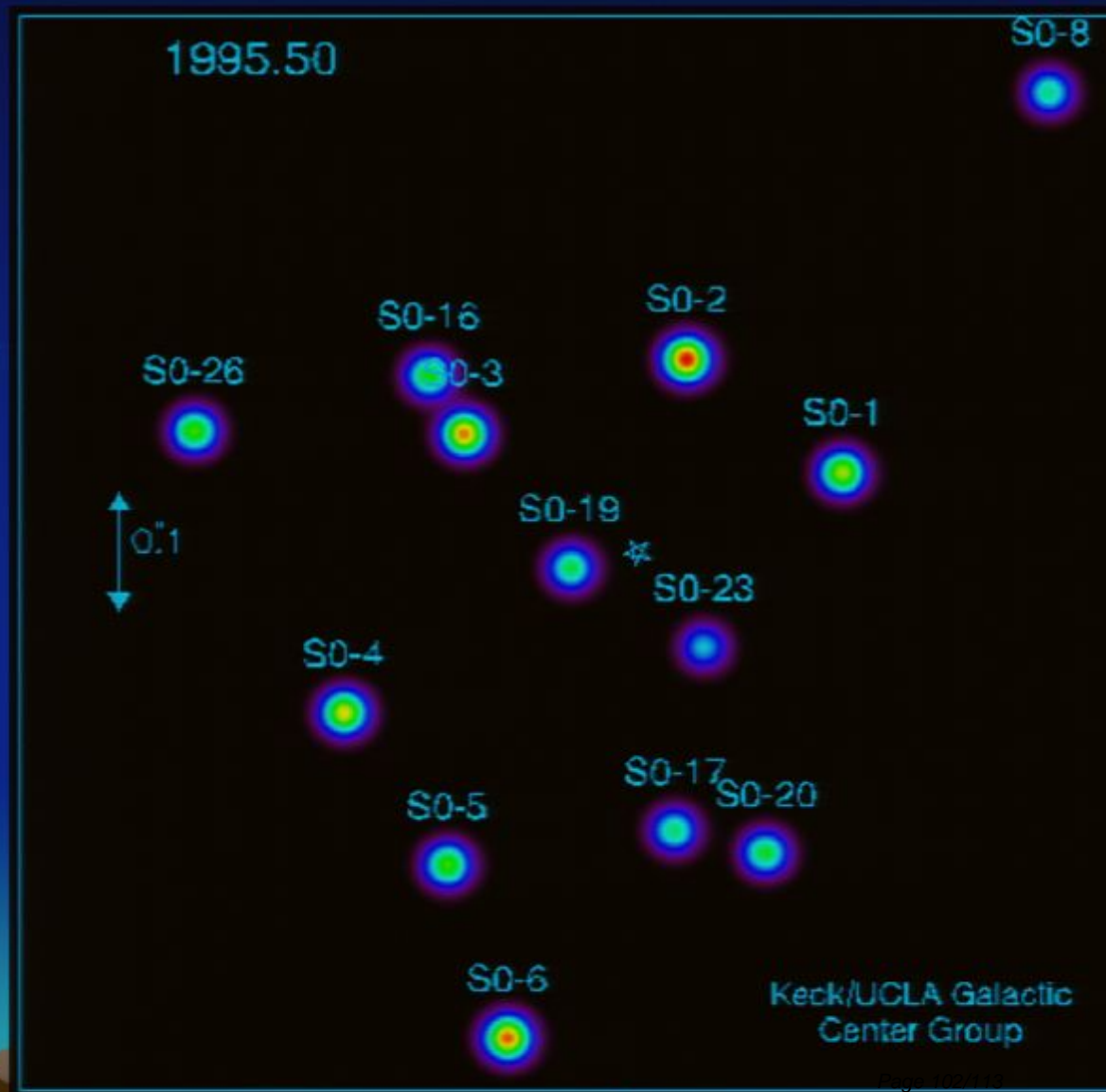


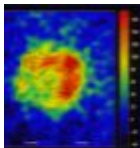
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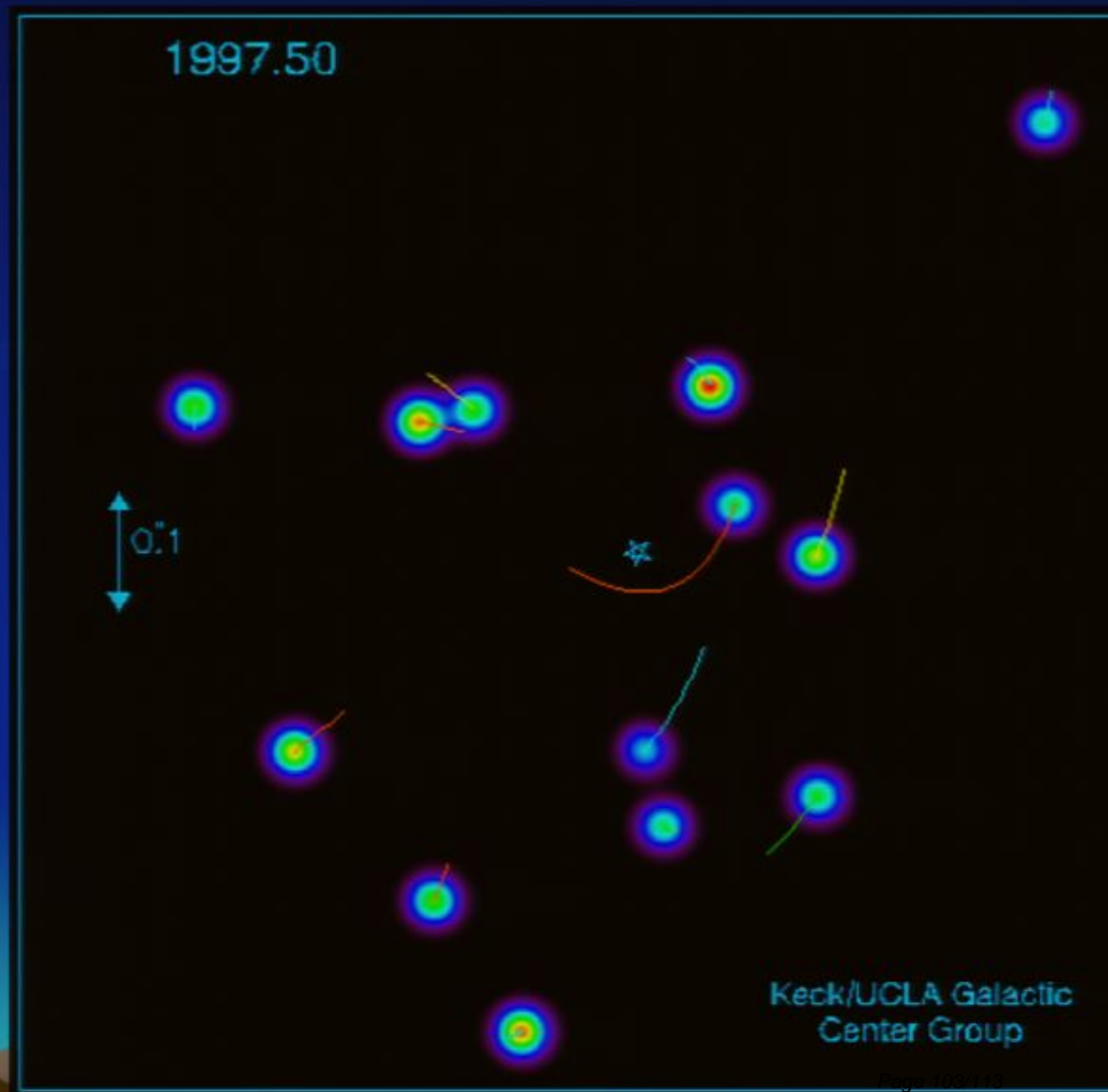


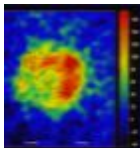
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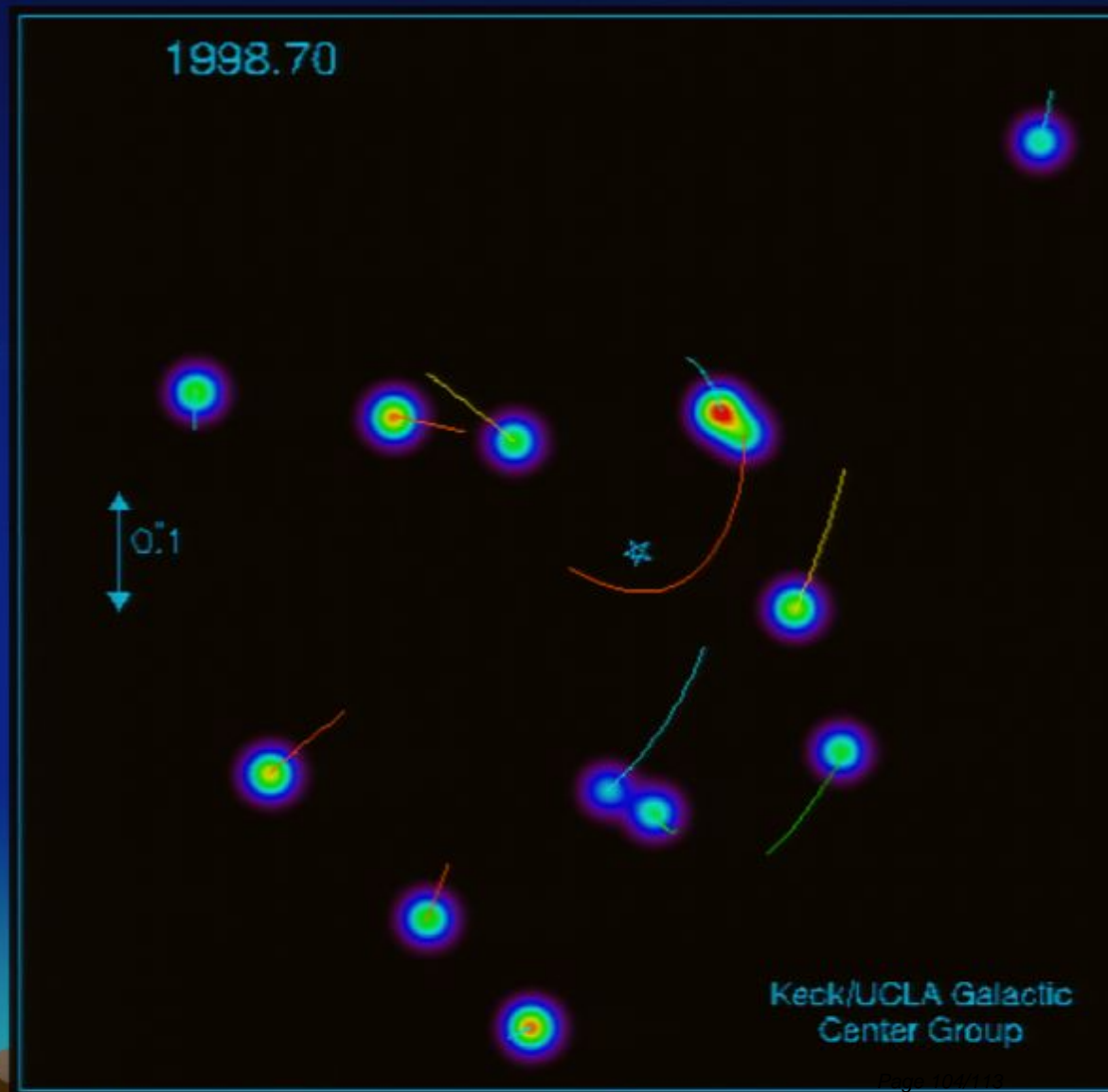


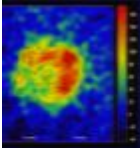
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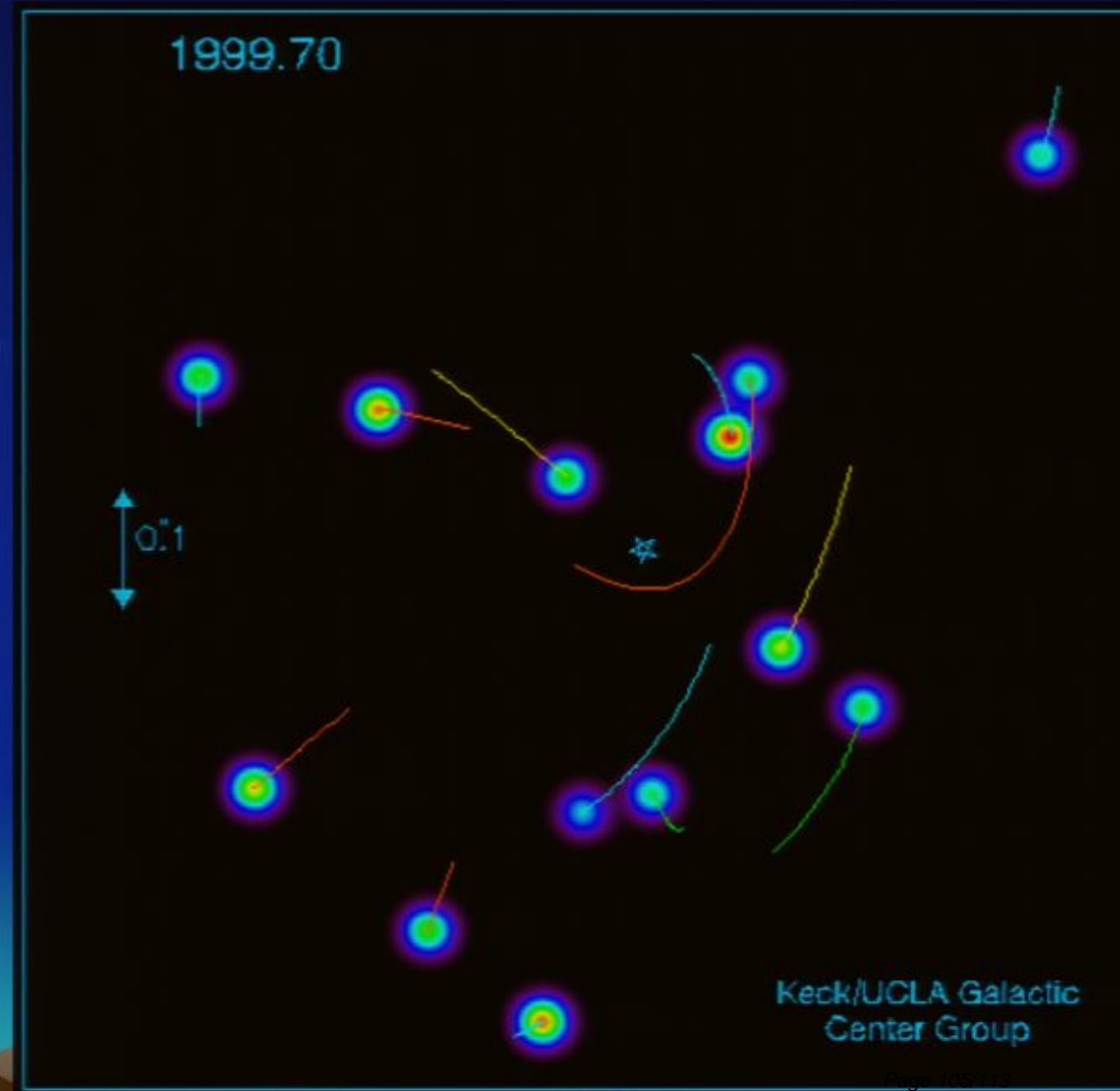


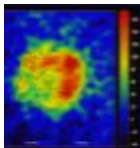
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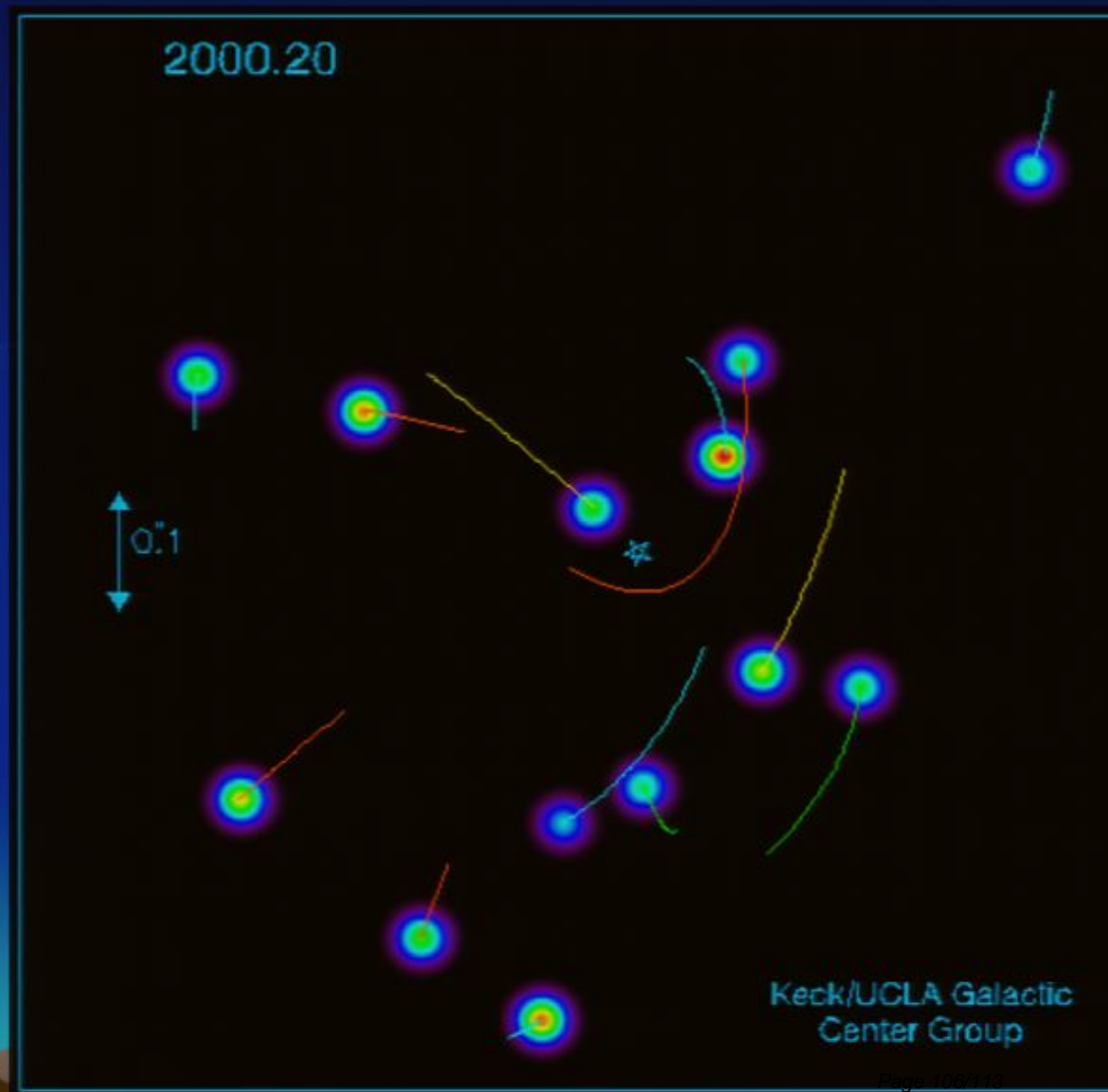


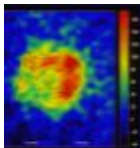
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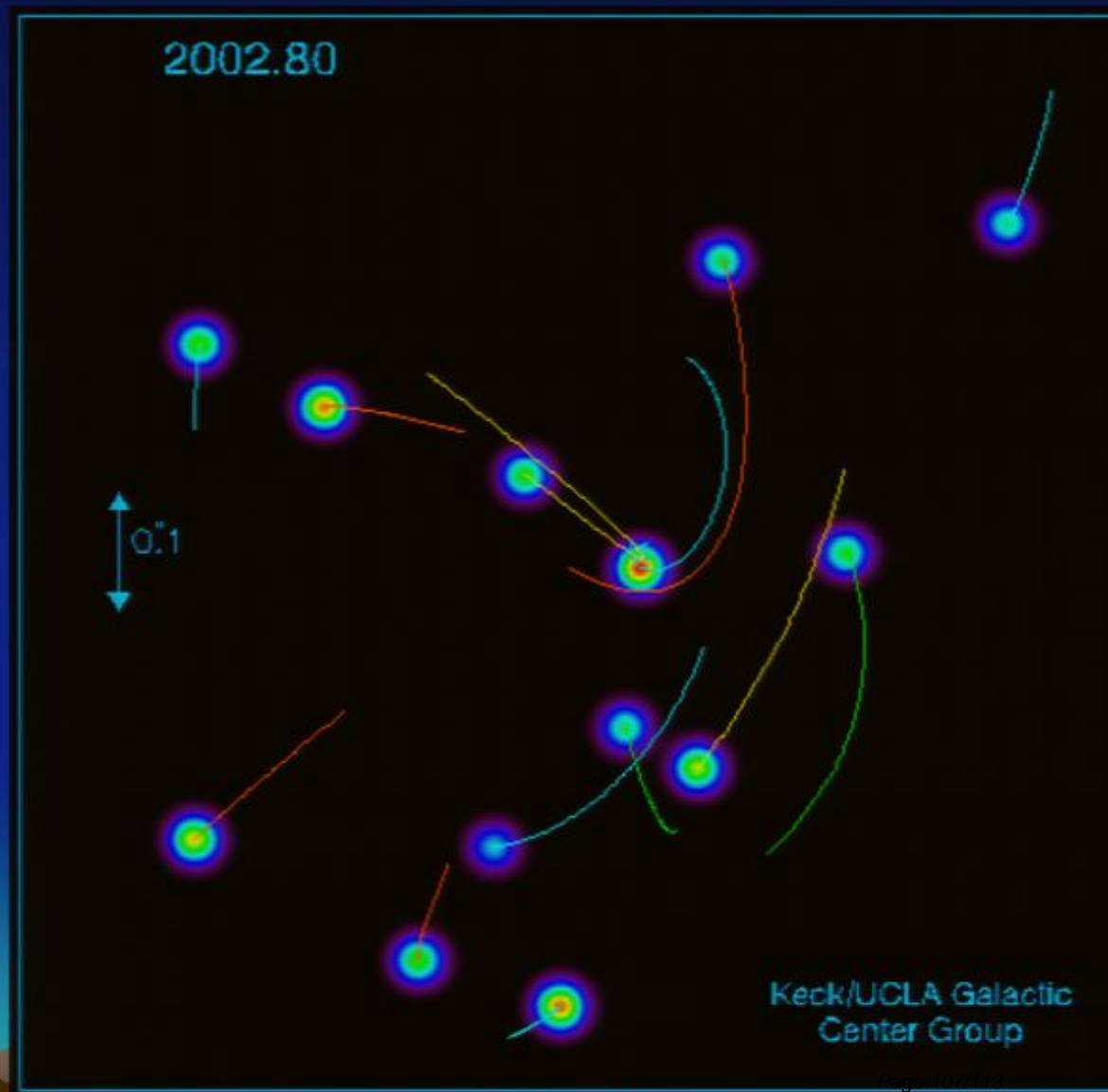



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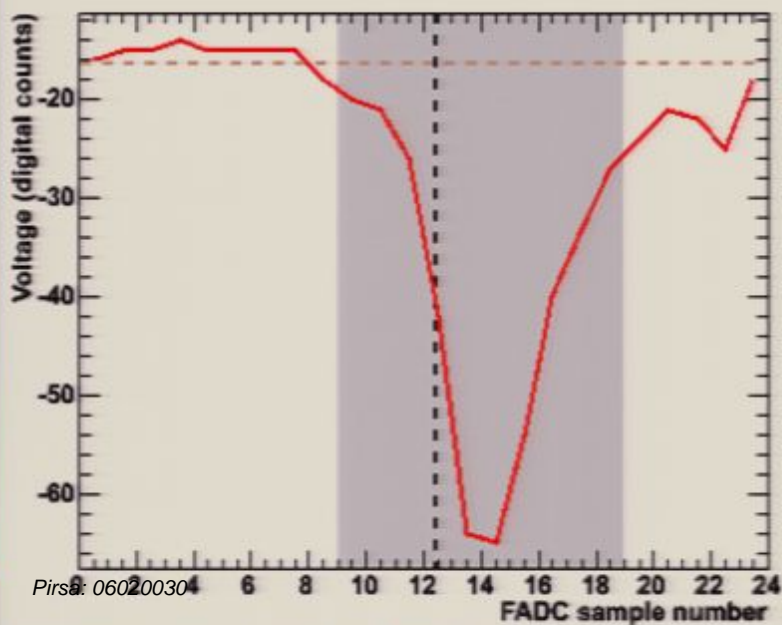
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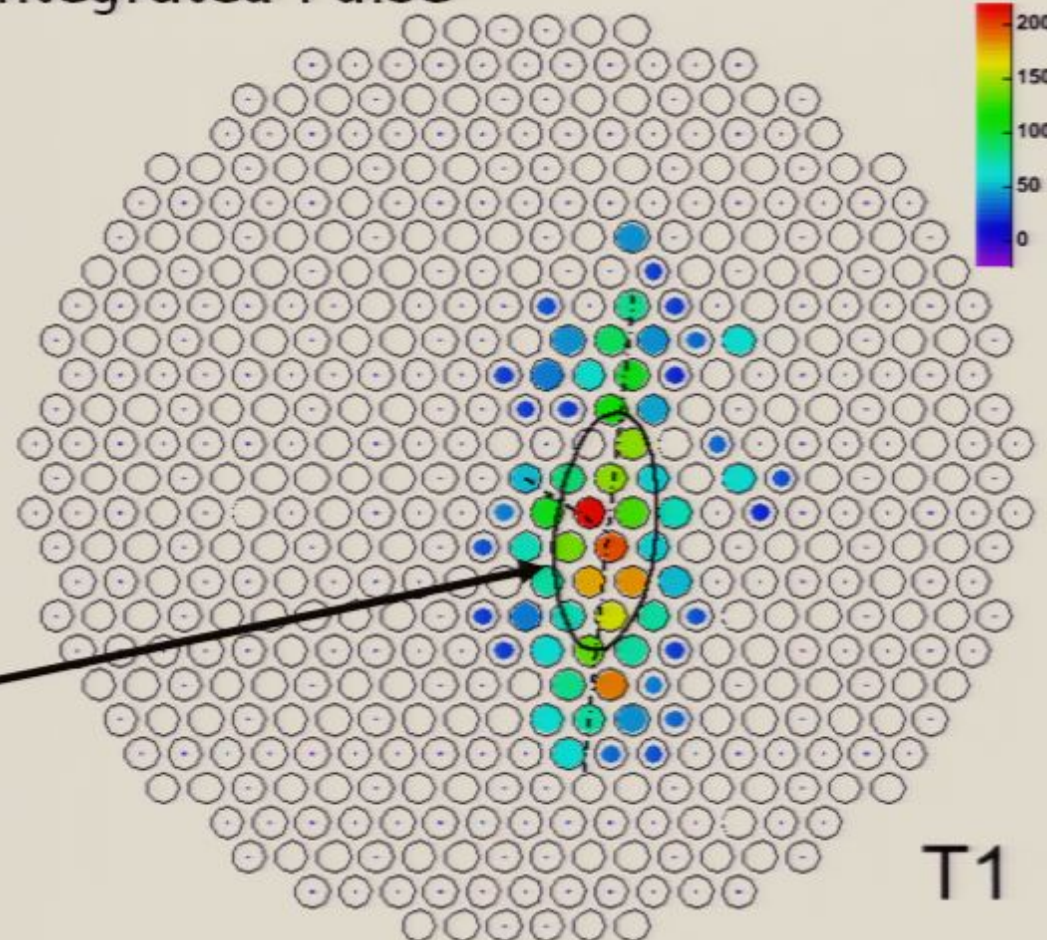
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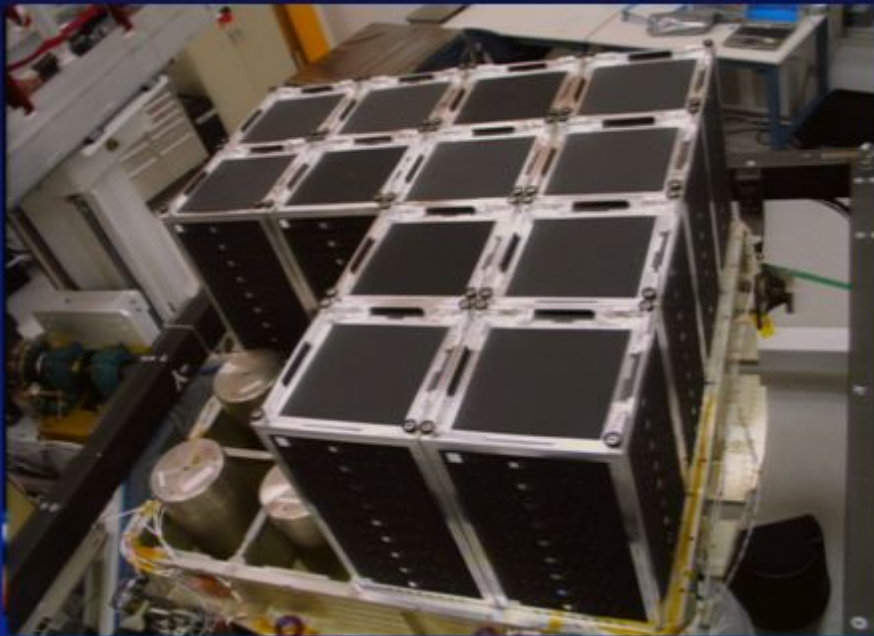


Integrated Pulse



Future

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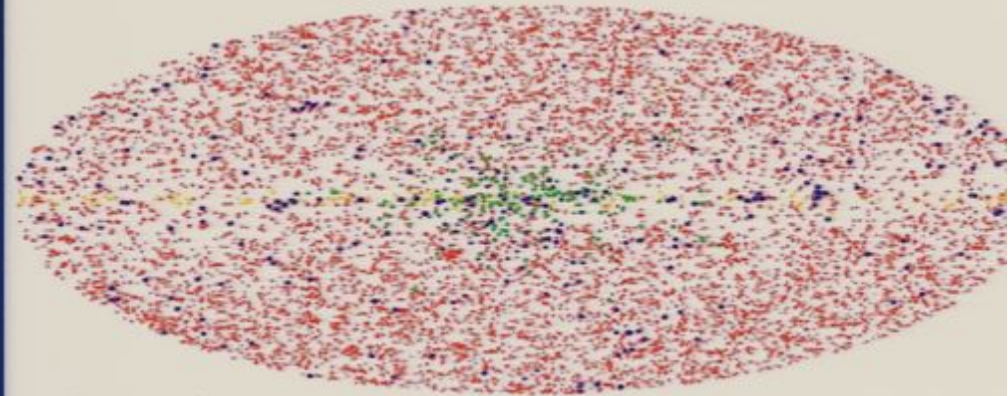


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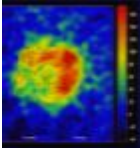


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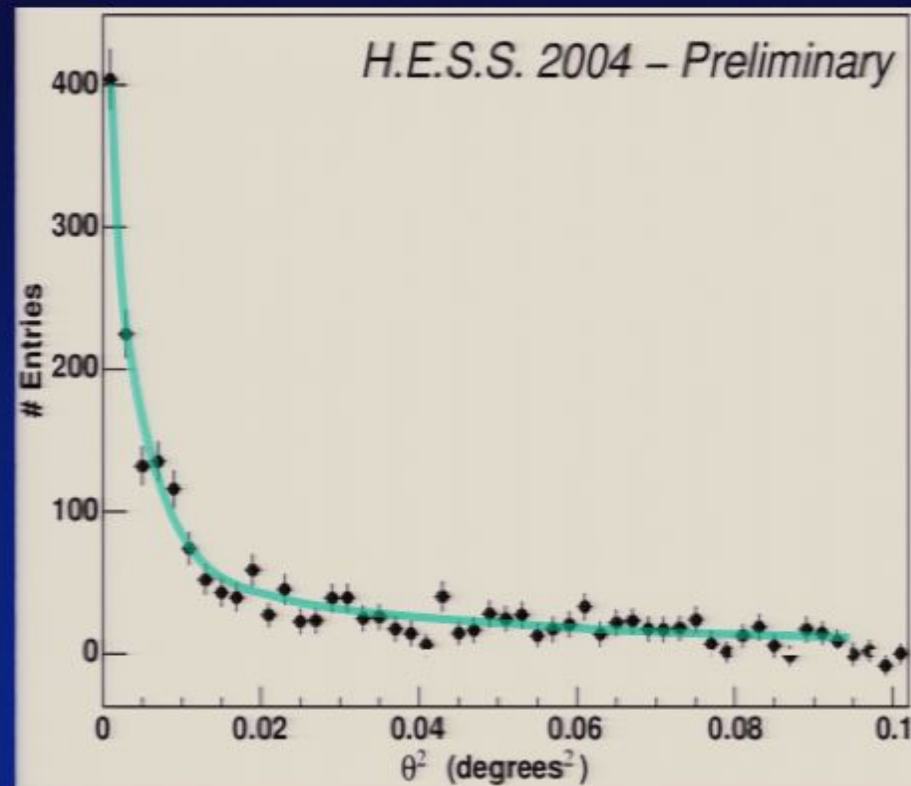
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Launch in 2007 (?)



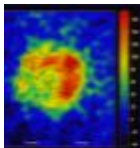
Results

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Consistent with SGR A* to 6'' and slightly extended.

Position consistent with SgrA*

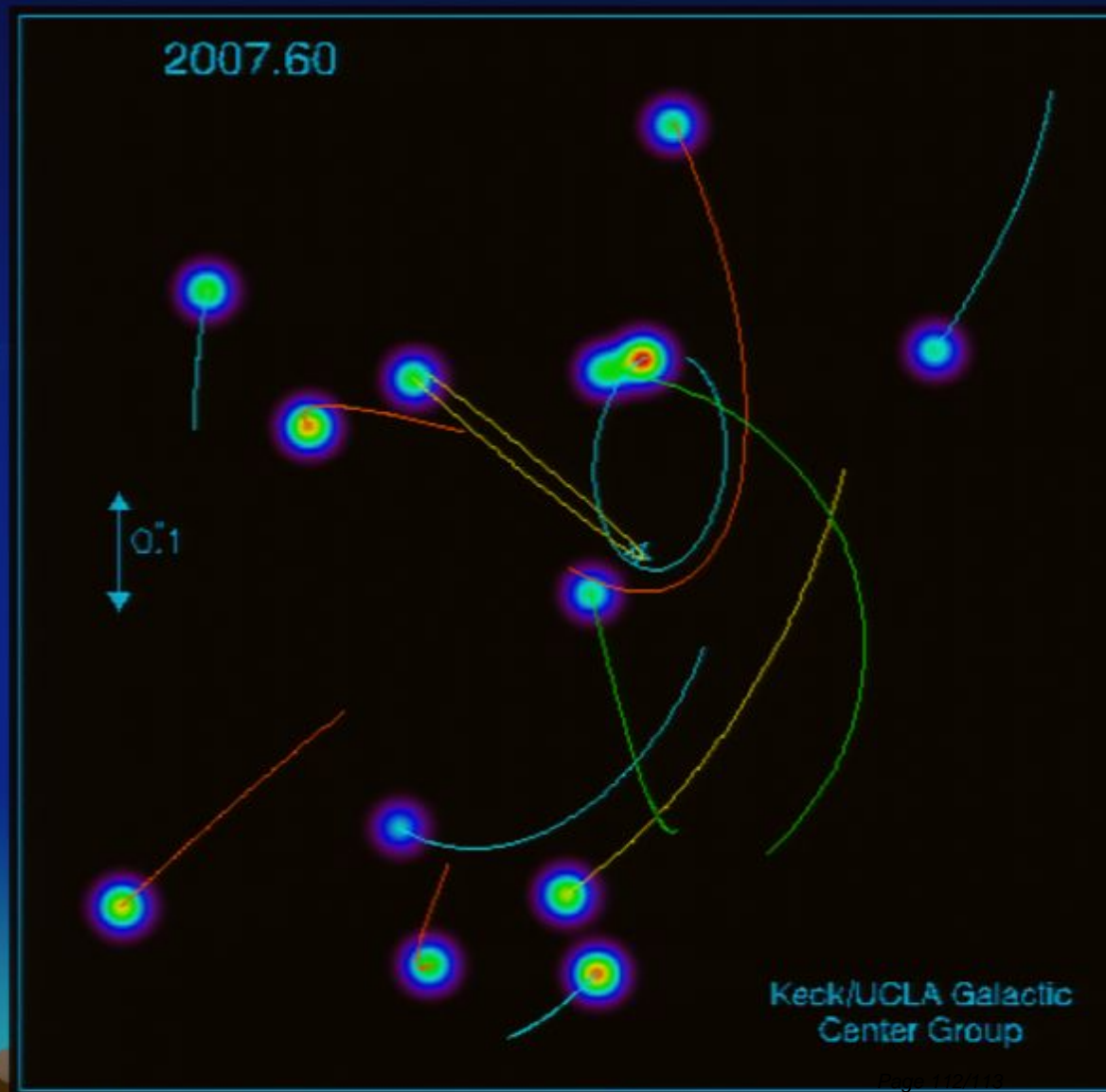


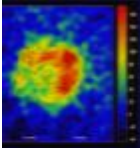
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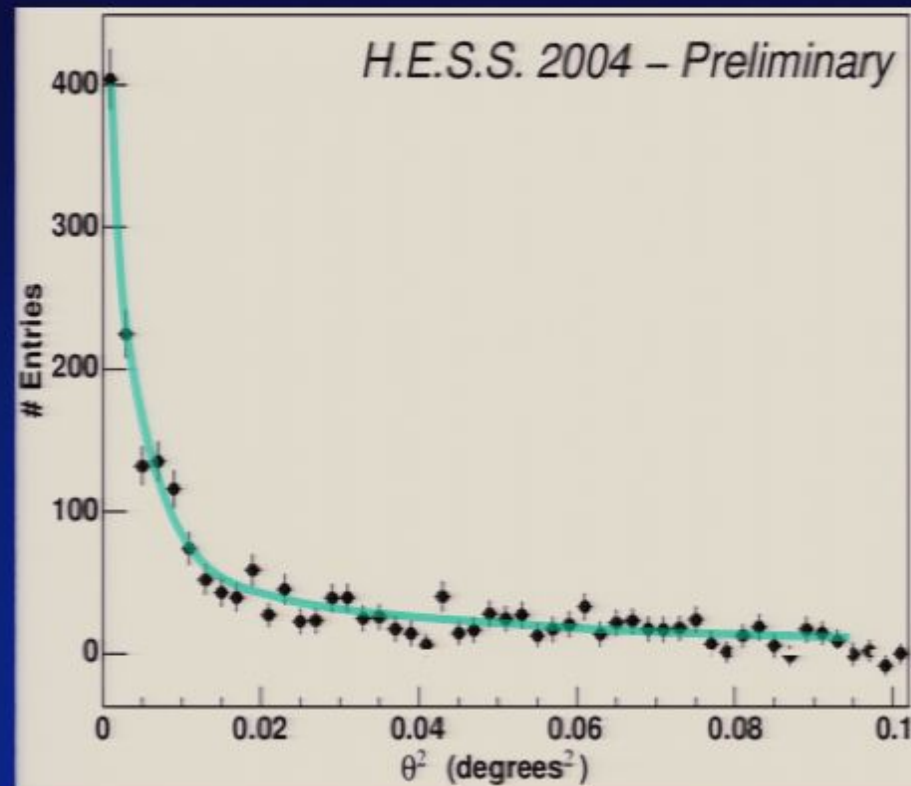
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