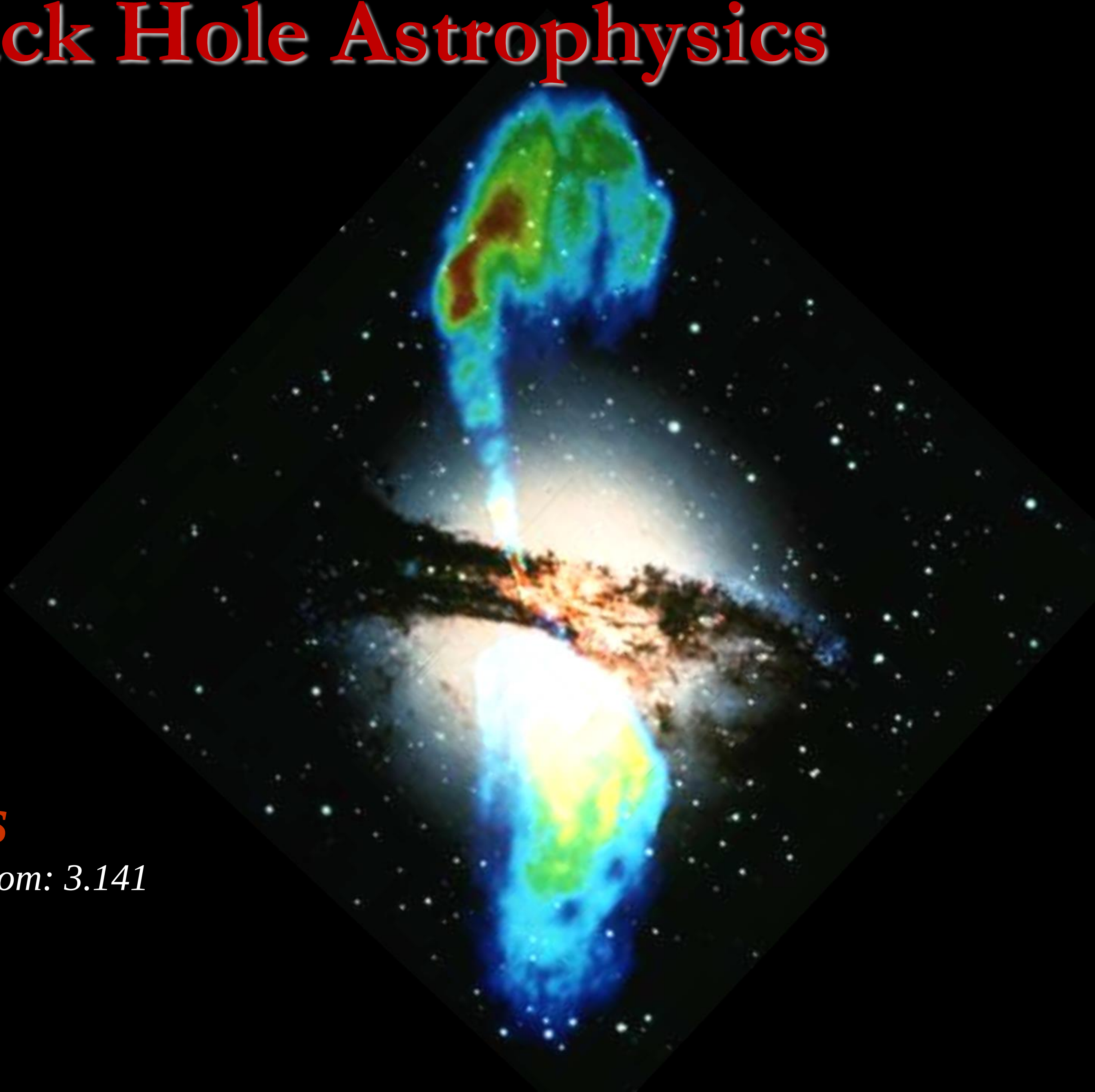
Black Hole Astrophysics



Bence Kocsis

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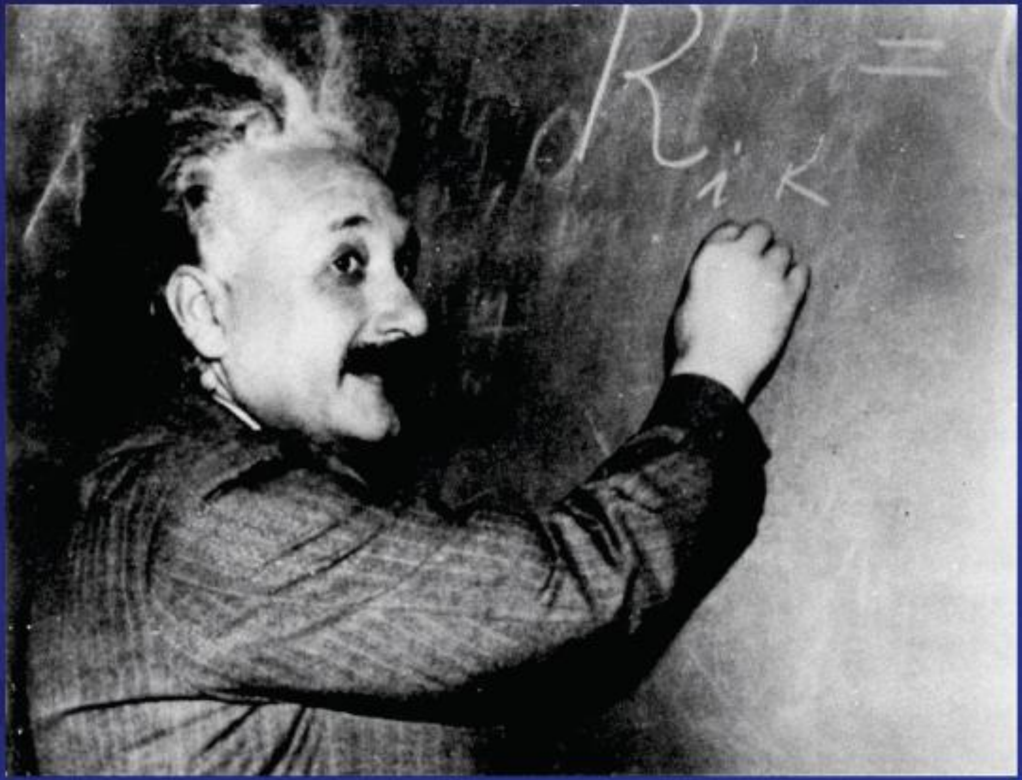
Syllabus

1. Introduction
   - black hole types,
   - blackhole imaging,
   - microlensing,
   - gravitational wave sources
   - supermassive black hole binaries
2. Black holes and general relativity
   - Schwarzschild metric
   - Black hole horizon
   - Motion around a black hole
   - Extended black hole spacetime
3. Spherical accretion onto black holes
   - Eddington limit
   - Bondi accretion
4. Black hole disk accretion
   - Shakura-Sunyaev alpha-disk model
   - Radiatively inefficient accretion flow
5. Stellar mass black holes
   - Formation b. X-ray binaries
   - Black hole accretion states
   - Black hole spin
6. Supermassive black holes
   - Formation
   - Soltan's argument
   - Mass function
7. Active galactic nuclei
   - Electromagnetic observables
   - Spectrum: continuum, broad and narrow spectral lines
   - Unified model of AGN
   - Mass measurement, reverberation technique
8. Supermassive black hole correlations and their physical interpretation
9. Gravitational wave astrophysics
   - LIGO/VIRGO observations
   - Astrophysical channels to form merging black hole binaries

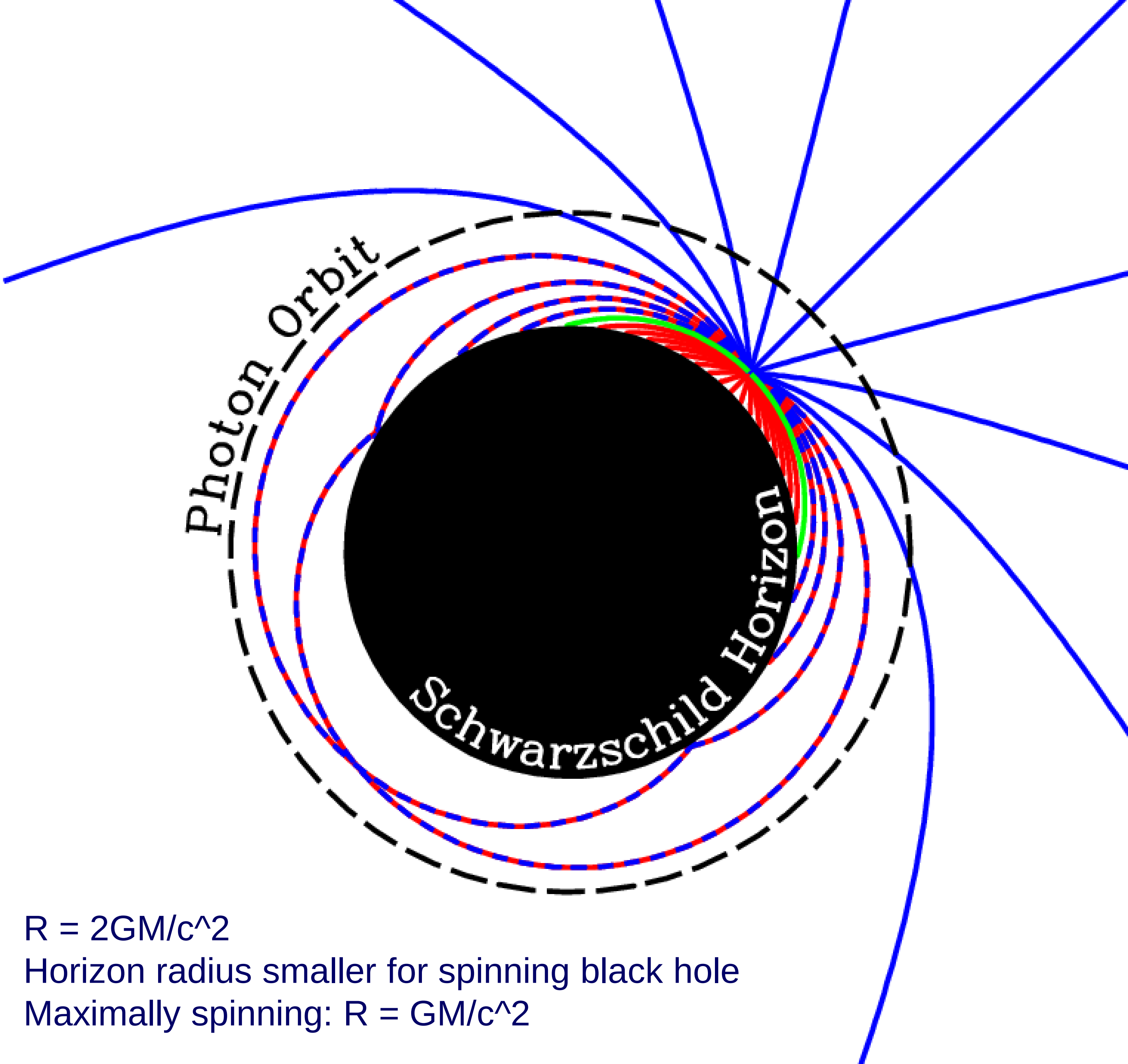
100 years ago…



Albert Einstein

Karl Schwarzschild

In working out the full consequences of a theory for an extended period of time, one is better off being a pacifist!



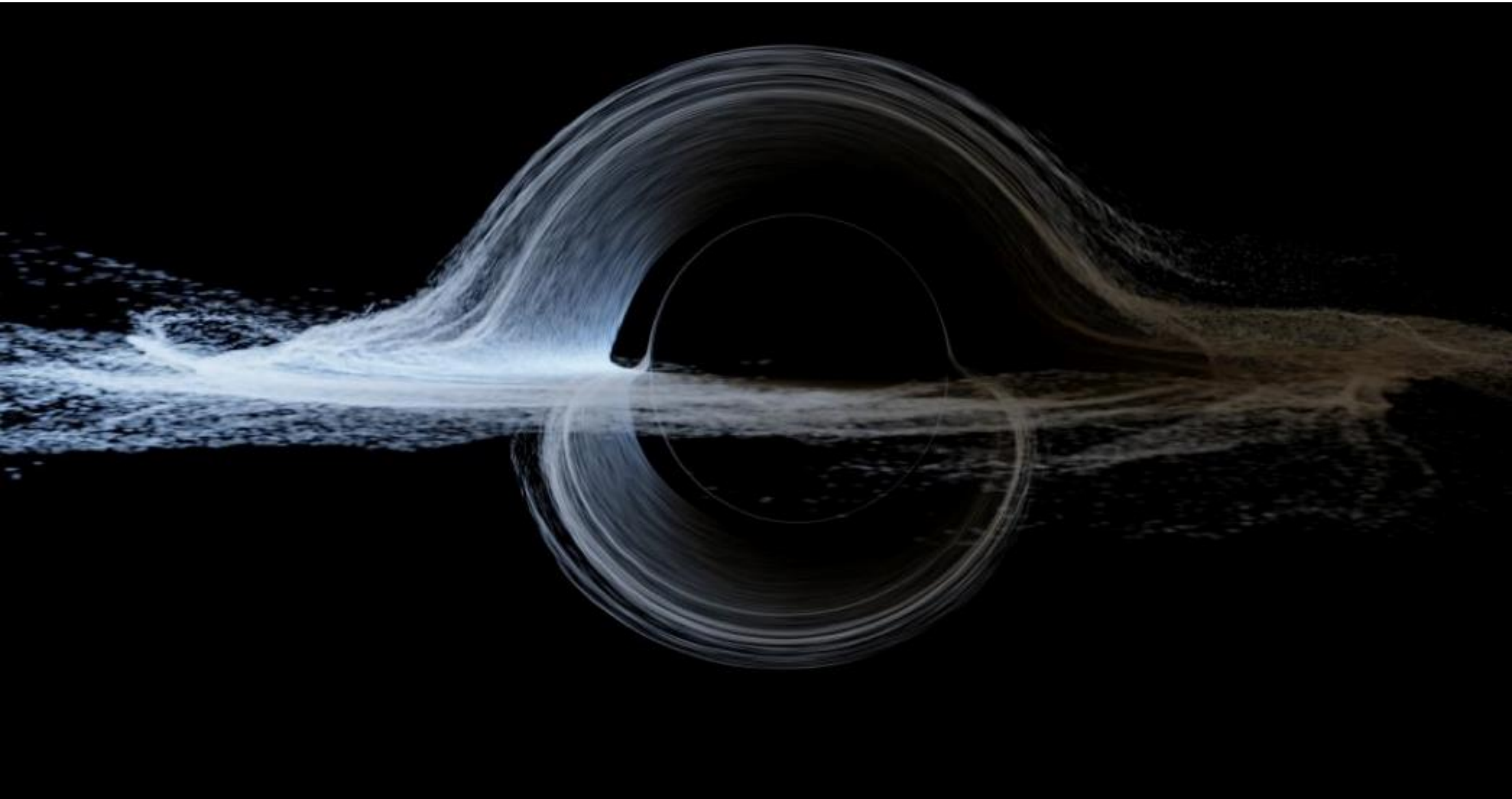
R = 2GM/c^2

Horizon radius smaller for spinning black hole

Maximally spinning: R = GM/c^2

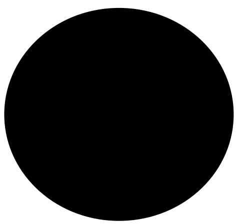
Gravitational Lensing by Spinning Black Holes in Astrophysics, and in the Movie *Interstellar*

Oliver James[1], Eugénie von Tunzelmann[1], Paul Franklin[1] and Kip S Thorne[2] arXiv:1502.03808



Why study black holes?

- Theory of everything
  - Last step: gravity + quantum physics
- Important in astrophysics
  - Galaxy evolution
  - Most powerful phenomena
  - New frontier: gravitational waves
- Fascinating science
  - curved spacetime
  - time travel?



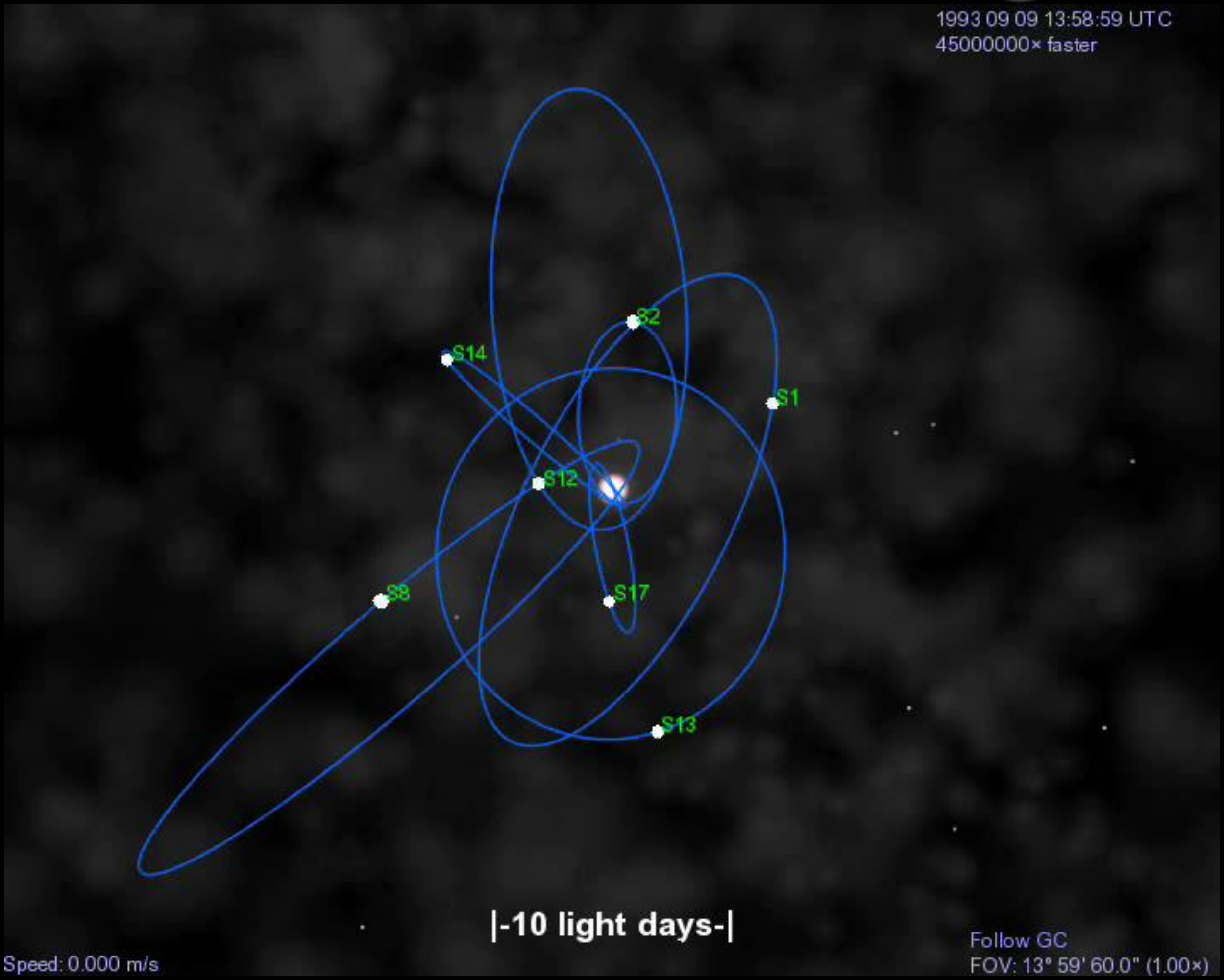
"The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time."– S. Chandrasekhar

"In all cultures studied, the single most important criterion of human beauty and attractiveness to the opposite sex is symmetry of the facial features." – Jones et al, *Nature* 2003

Black hole types in astrophysics

- Supermassive black hole (10^5 – 10^{10} M_{sun})
  - Forms in the early universe from the collapse of low metallicity clouds
  - Grows by gas accretion
  - 1 in each galaxy
- Stellar mass black hole (5 – 50 M_{sun})
  - Forms from stars of mass 25 – 130 M_{sun}
  - 10 million in a typical galaxy
- Intermediate mass black hole?
  - expected to form from repeated mergers or gas accretion by stellar mass black holes

Stellar Orbits Around SgrA*

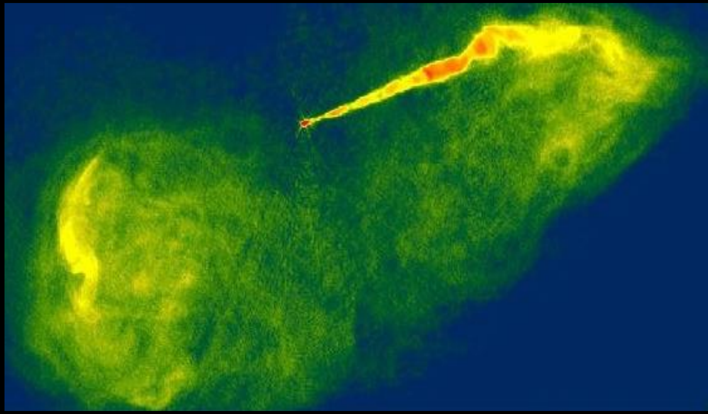


$$M_{\rm BH} = (4.5 \pm 0.4) \times 10^6 M_\odot$$

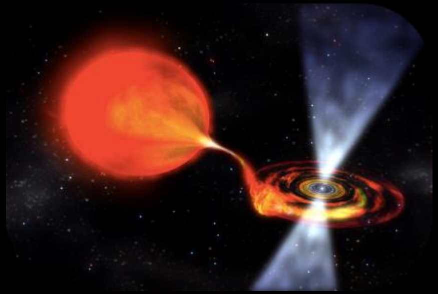
Ghez et al. 2008; Genzel et al. 2008

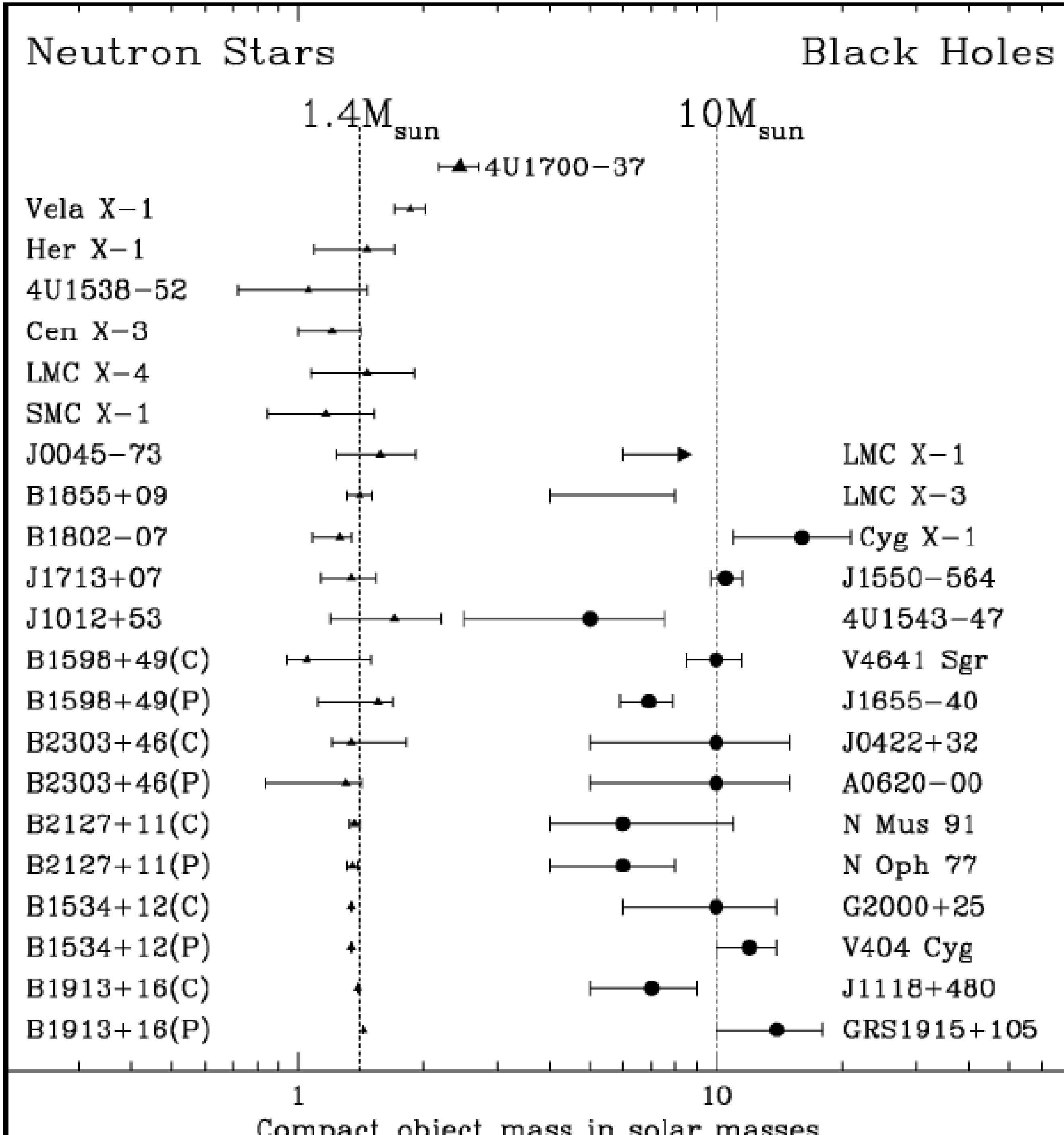
Further evidence

- Active galactic nuclei (every 100th galaxy)
  - Very small region (< light year) outshines galaxy
  - Varies over month timescale
  - Relativistic jets 0.999c
  - Gas orbiting the center at 0.1c



- Stellar mass black hole binaries
  - Binary: star + black hole
  - Highly variable X-rays



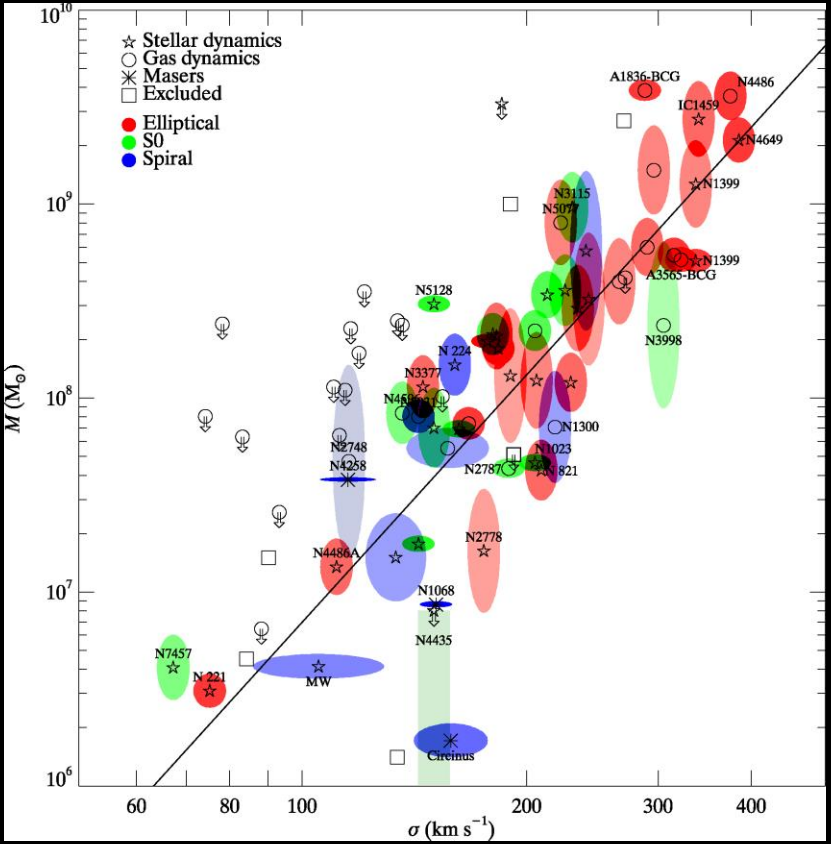


About 20 binaries in our galaxy where the compact object seems to be too massive to be a neutron star

Supermassive black holes and host galaxies

0.2% of galactic bulge mass = SMBH mass

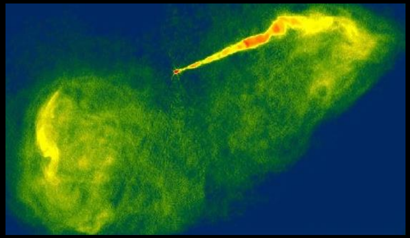
Black hole mass



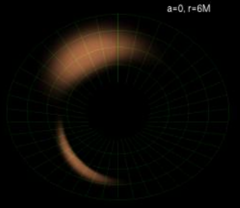
Random velocities of stars

Imaging Black Holes

- **Testing theory of gas accretion:**
  accretion disks, winds, and jets



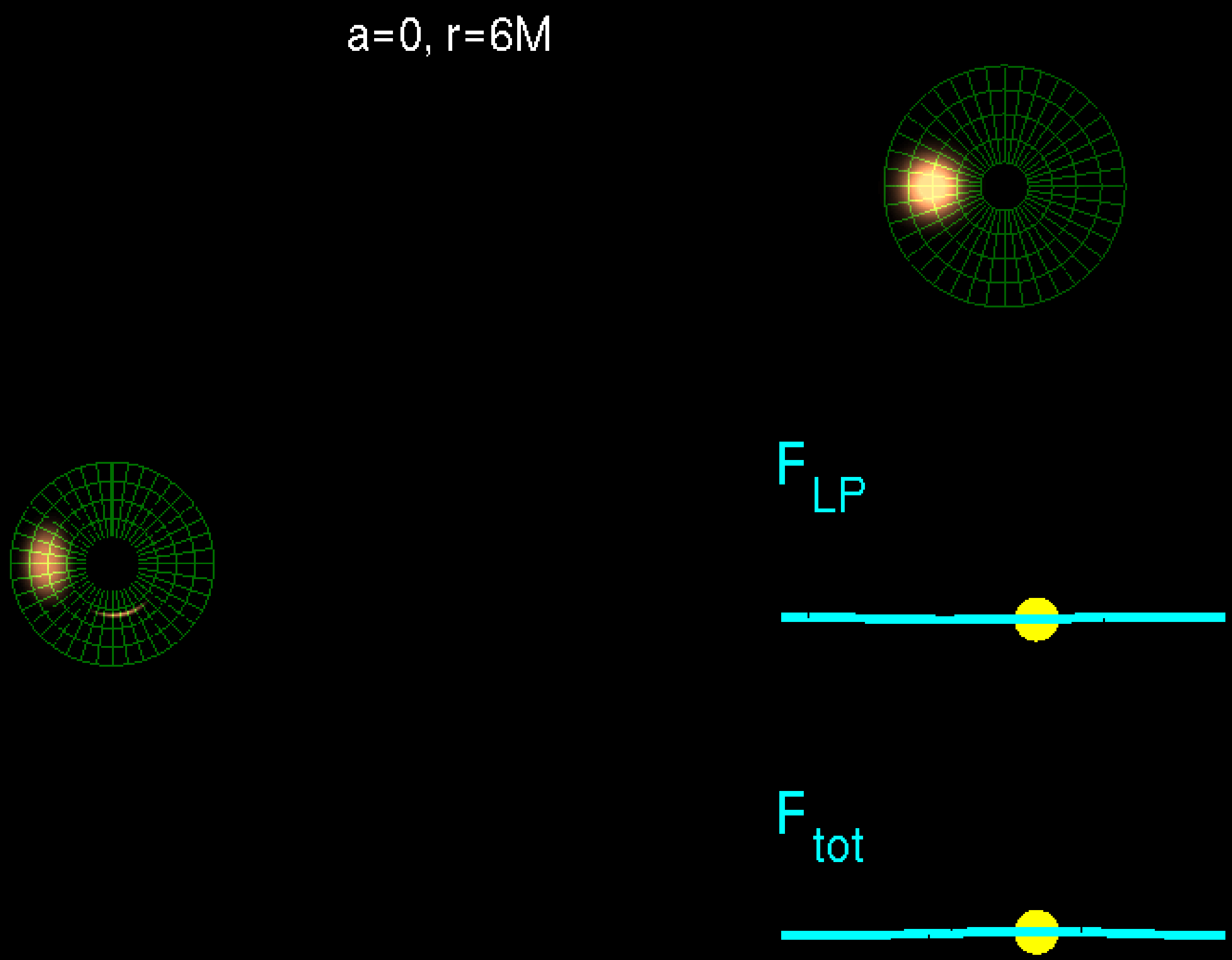
- **Testing General Relativity:**
  strong field gravity, existence of event horizon



Quantum effects near horizon (firewalls?)

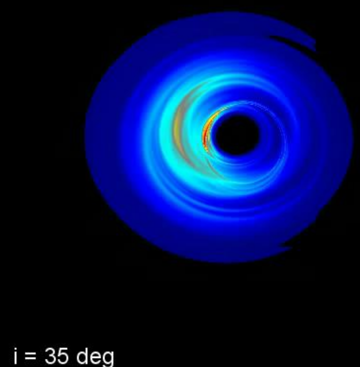
Breakdown of GR at the singularity

Physics + Astrophysics: Imaging Black Holes

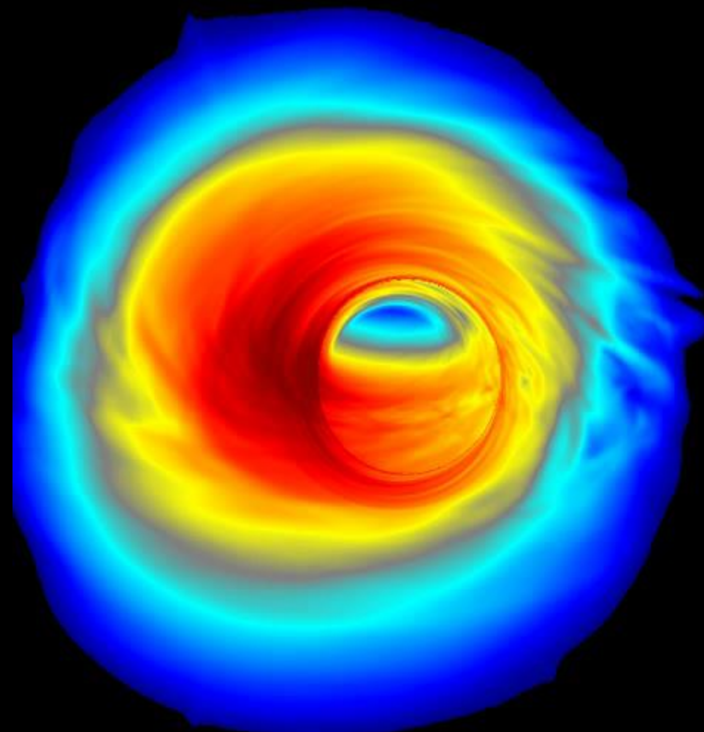


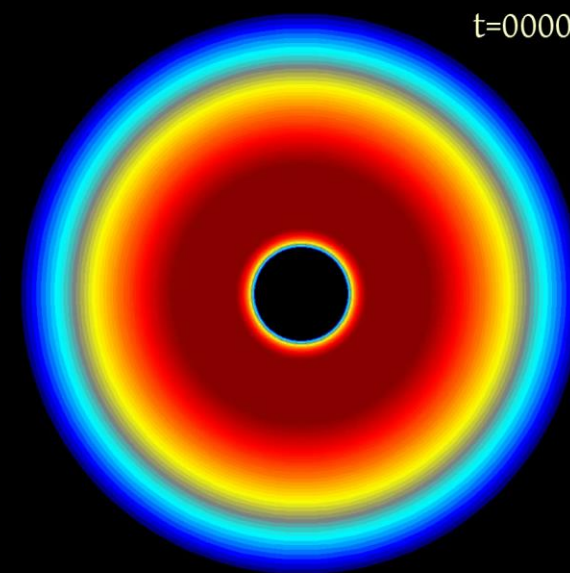
Broderick & Loeb, 2006, MNRAS, 367, 905

Numerical Simulations (GRMHD)

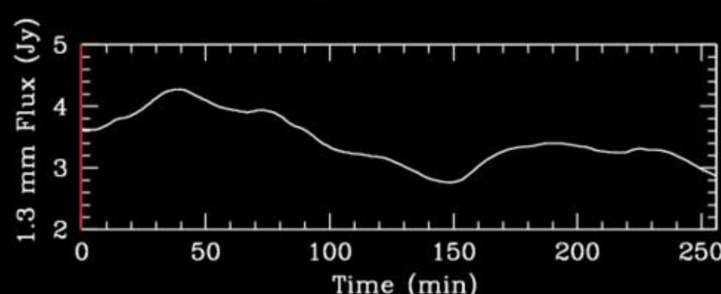


inclination



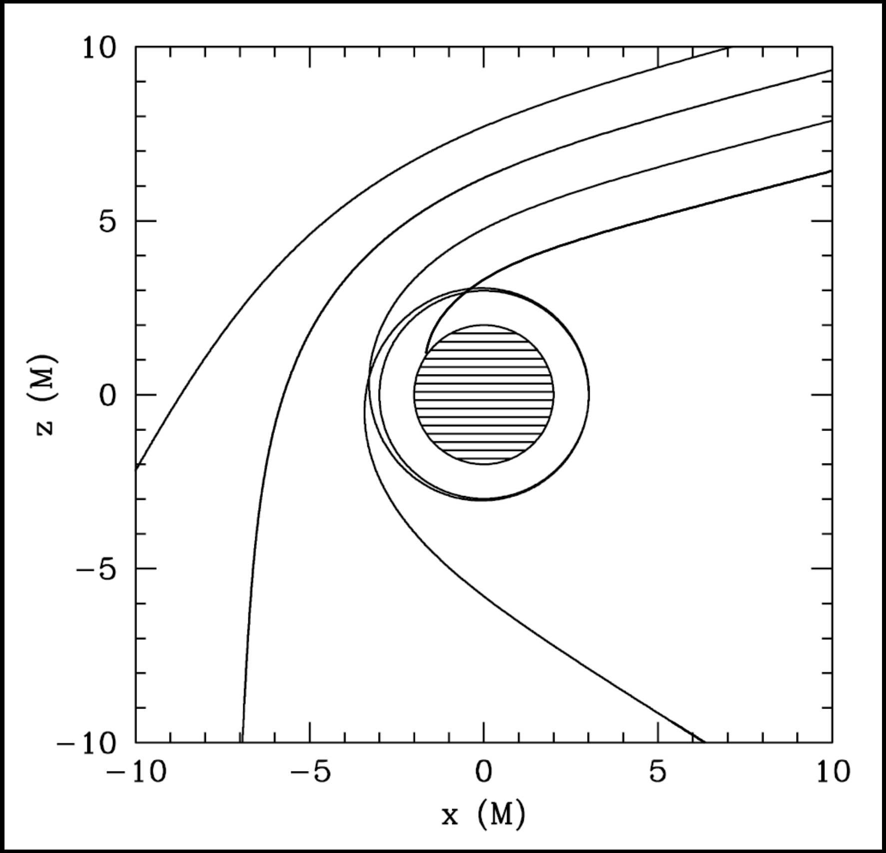


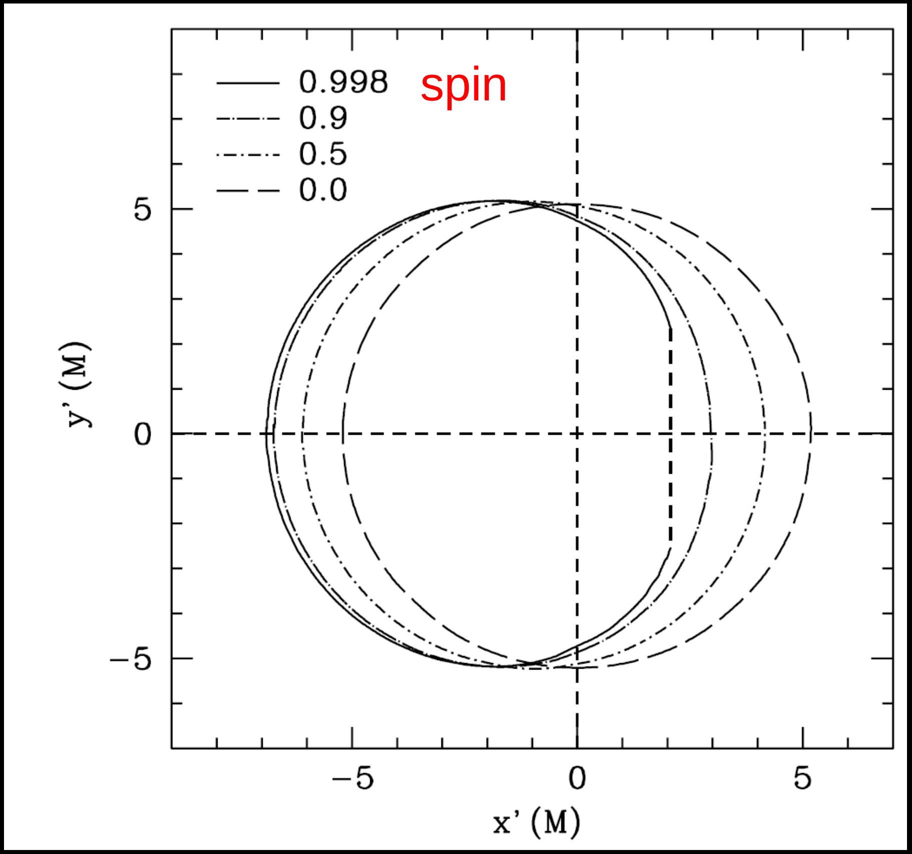
setup



***C. Gammie**, J. Dolence, M. Moscibrodzka, H. Shiokawa, P. Leung (2009)*

The black hole shadow



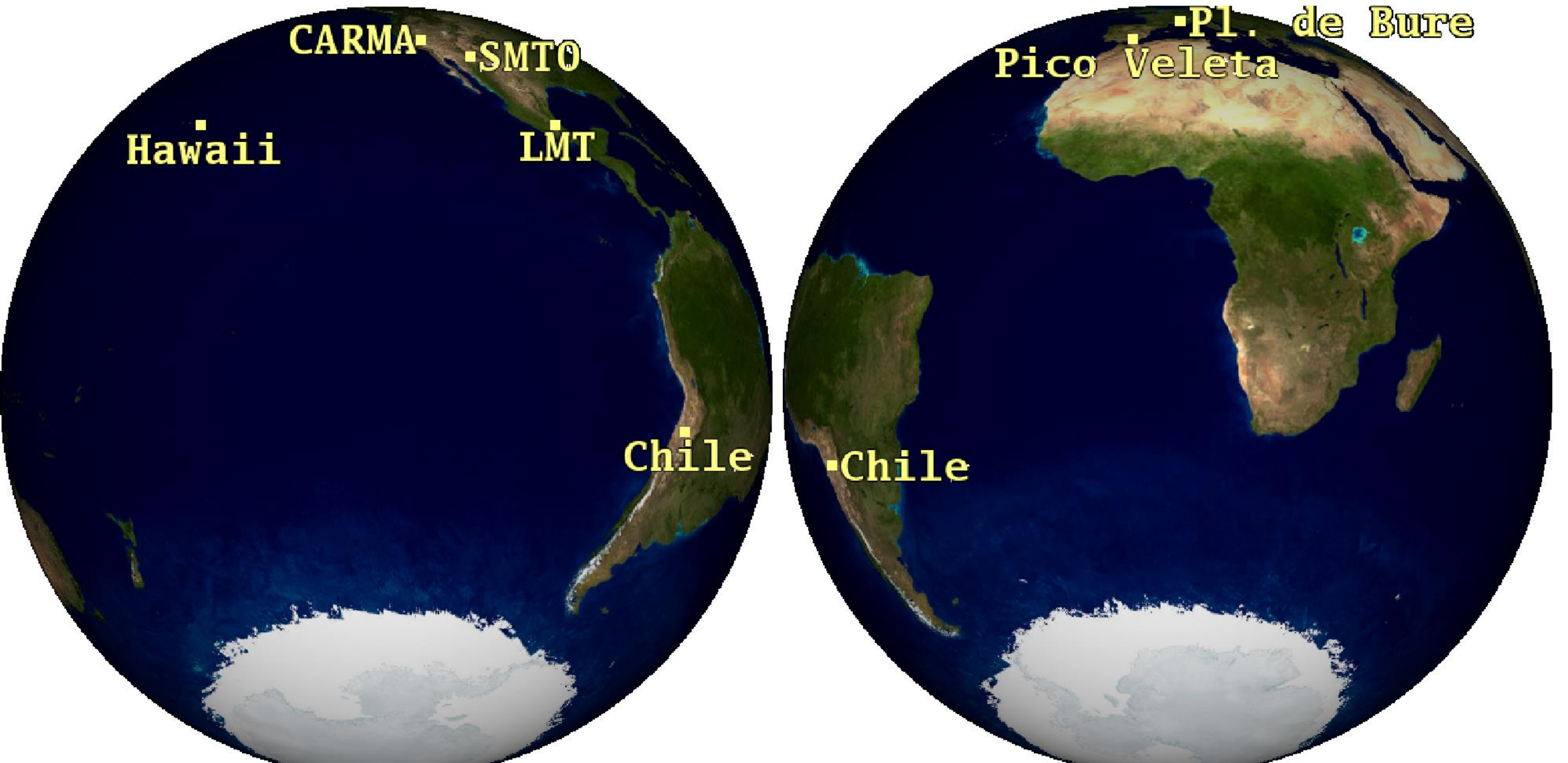


Johannsen & Psaltis, 2010, ApJ, 718, 446

Very Long Baseline Interferometry (VLBI) at sub-millimeter wavelengths

Earth-sized "dish"
(11 μas) x (λ / 0.9 mm)

Sgr A* **10 μas** [4x10^6 M$_{sun}$ @ 26k lyr]



SgrA is the largest black hole on the sky*

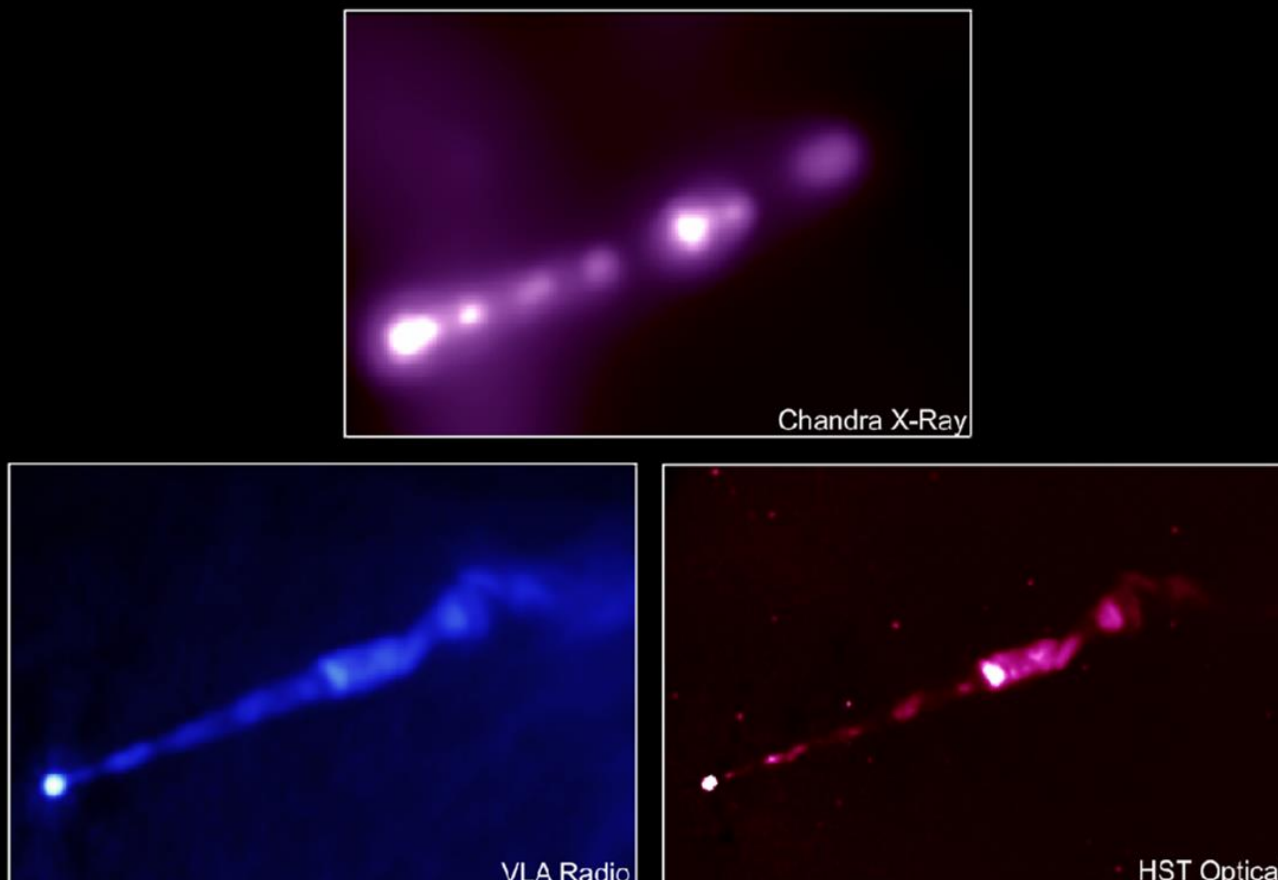
10 μas [4 million solar masses @ 26,000 lyr]

M87

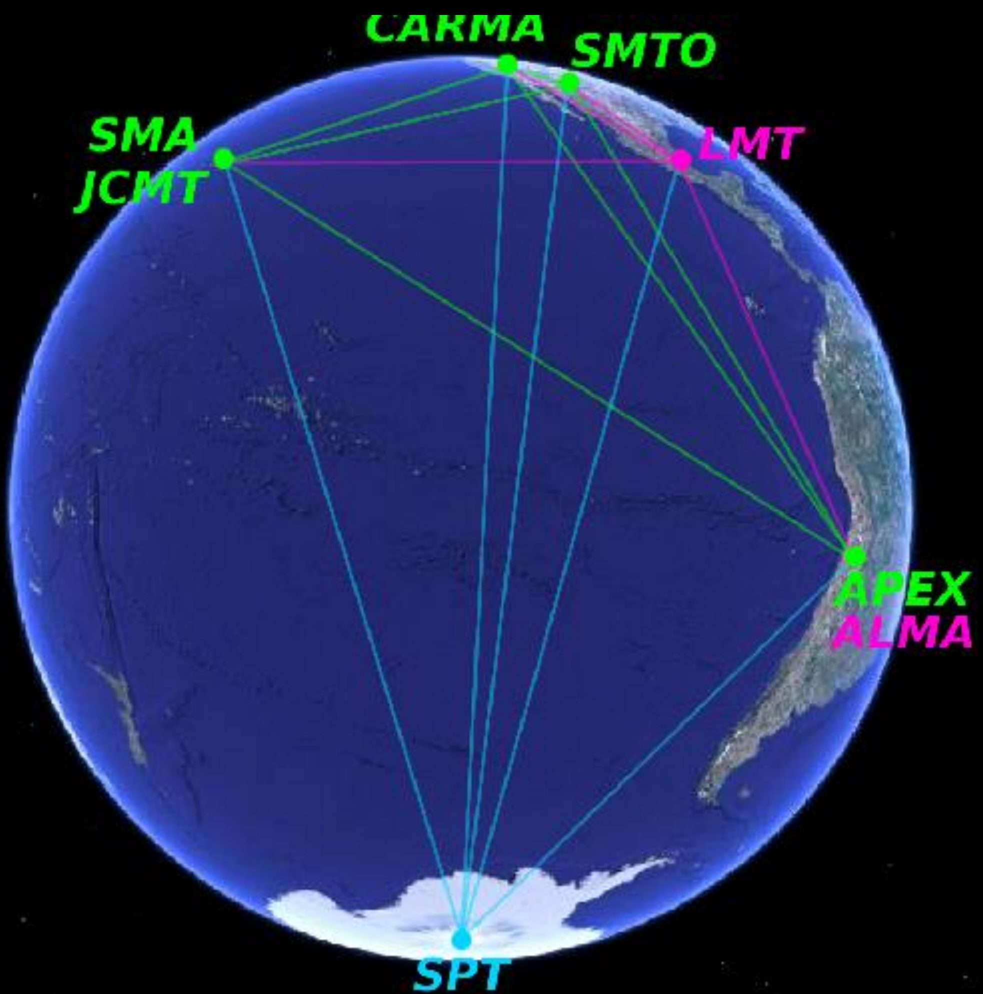
$$M_{\rm BH} = 6.4 \times 10^9 M_\odot$$

1400 times more massive than SgrA*

But 2000 times farther than SgrA*



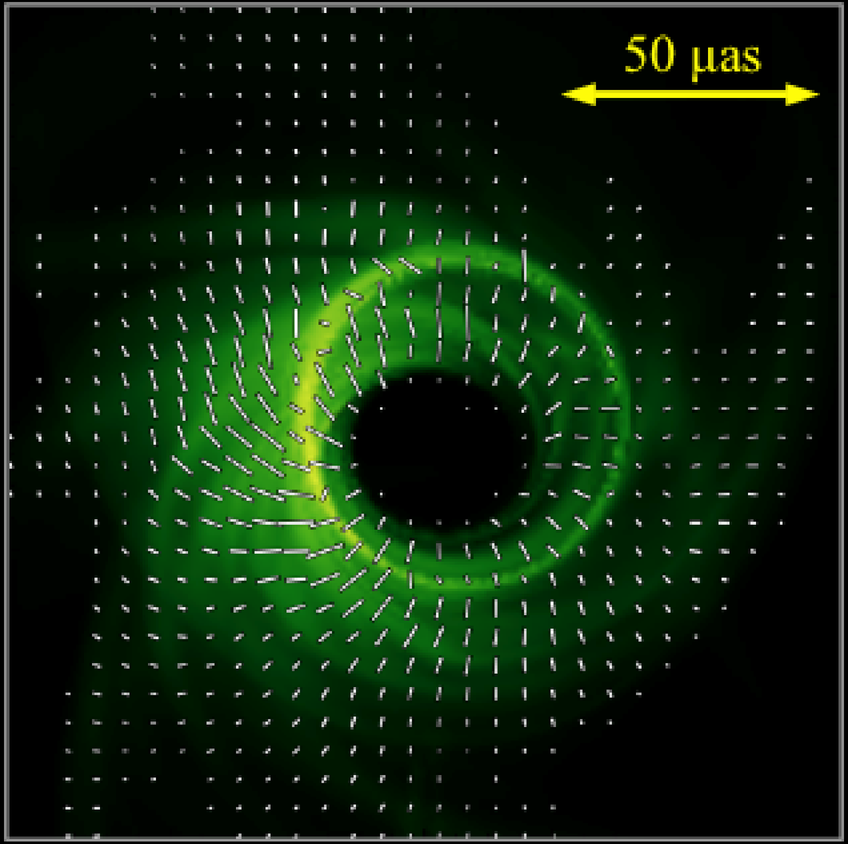
Very Long Baseline Interferometry (VLBI) at sub-millimeter wavelengths



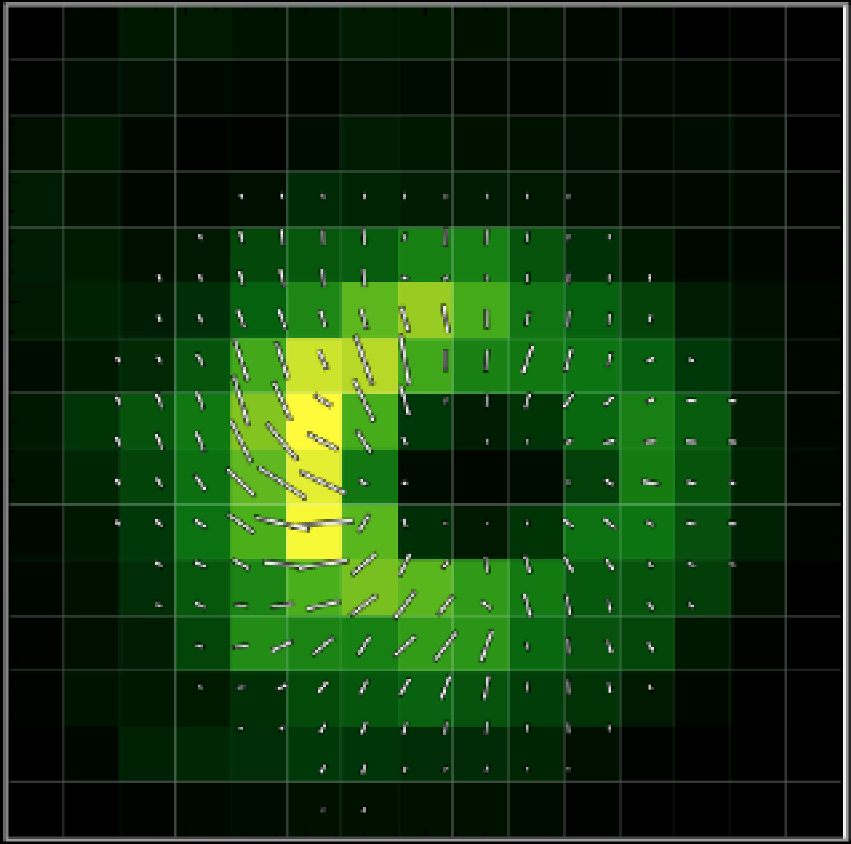
Polarimetric Imaging

What can we hope to learn with the full EHT?

Simulated Image

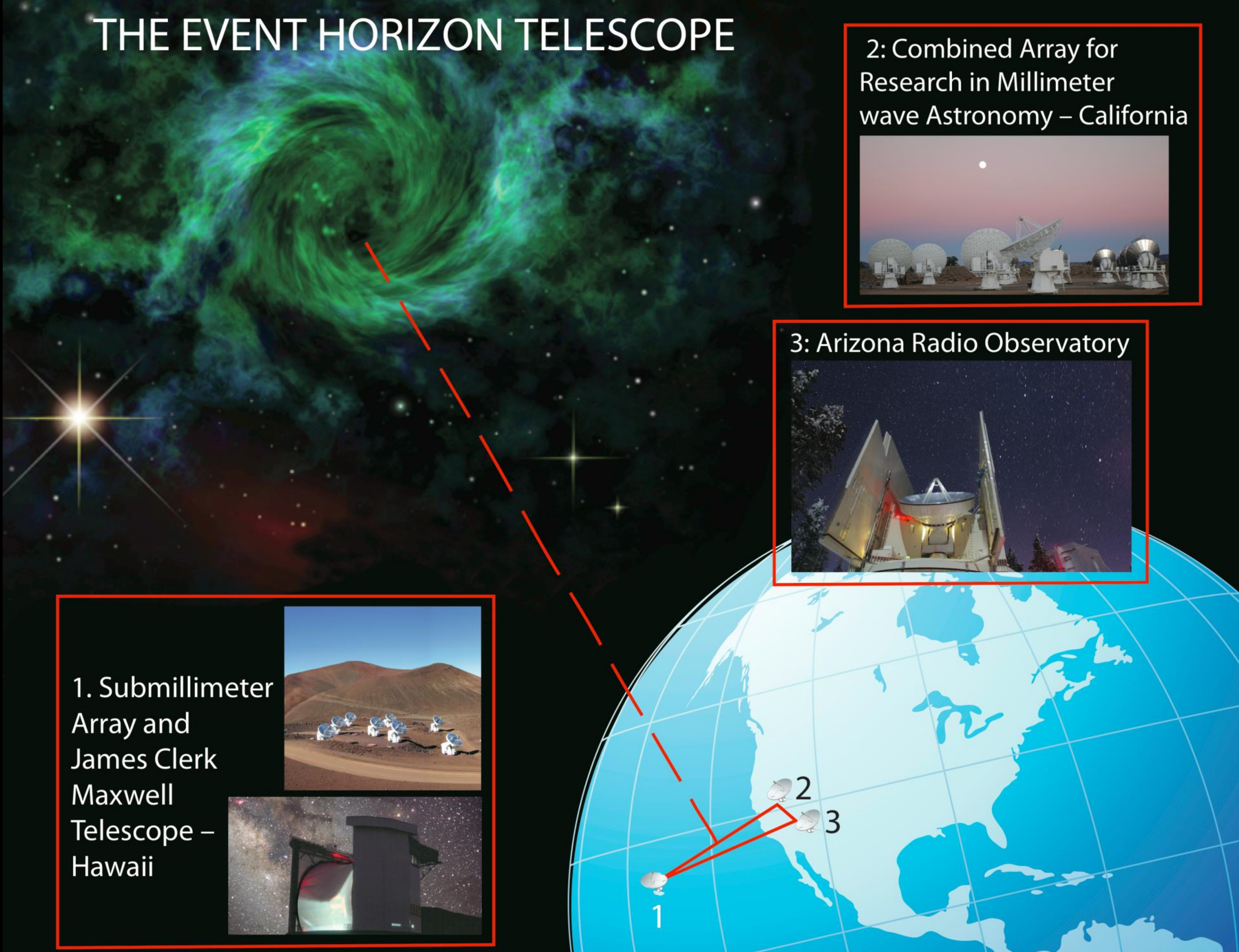


Reconstructed Image



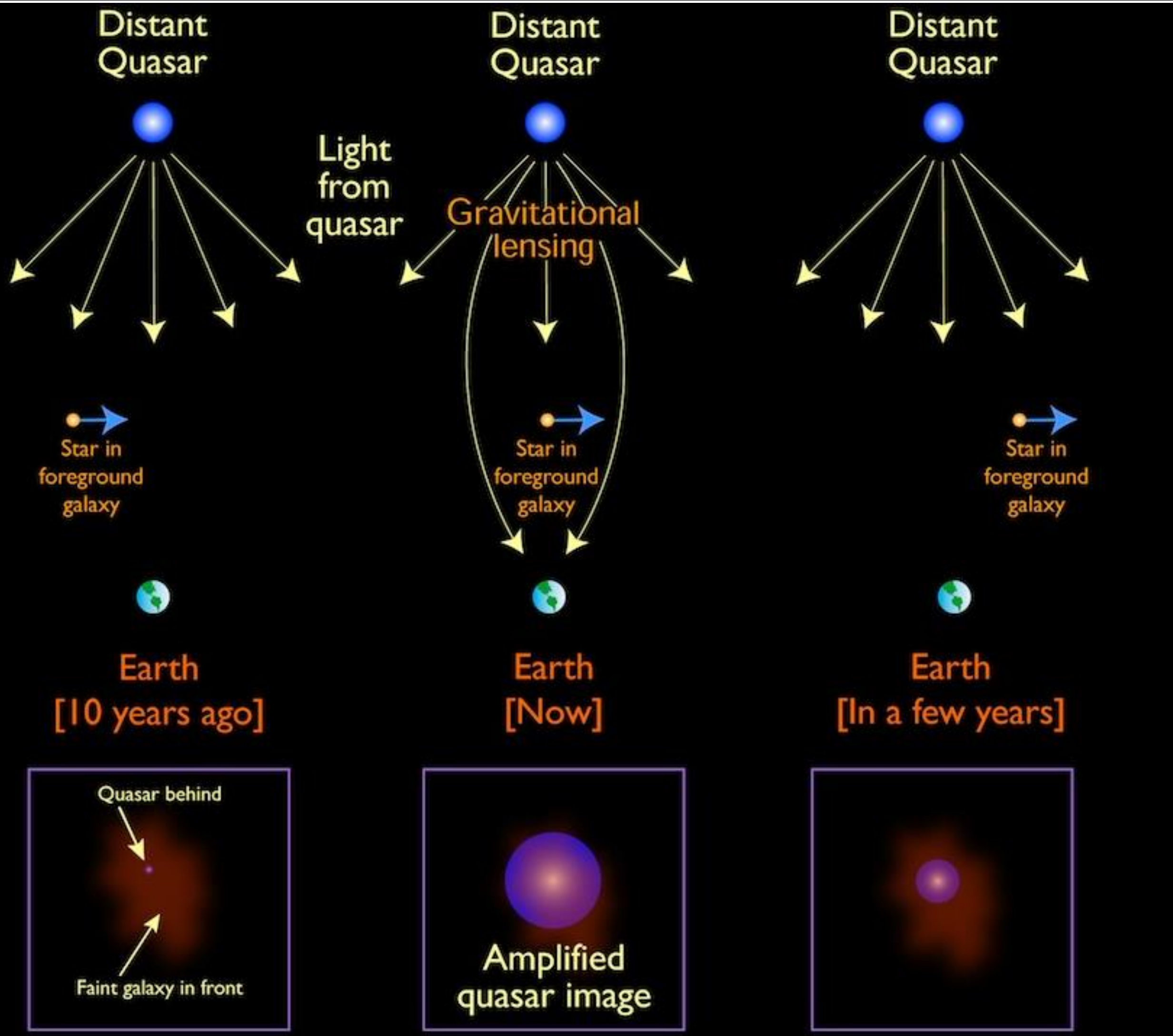
Michael Johnson, et al. (2015)

Simulated Data: Jason Dexter
Polarimetric Imaging: Andrew Chael

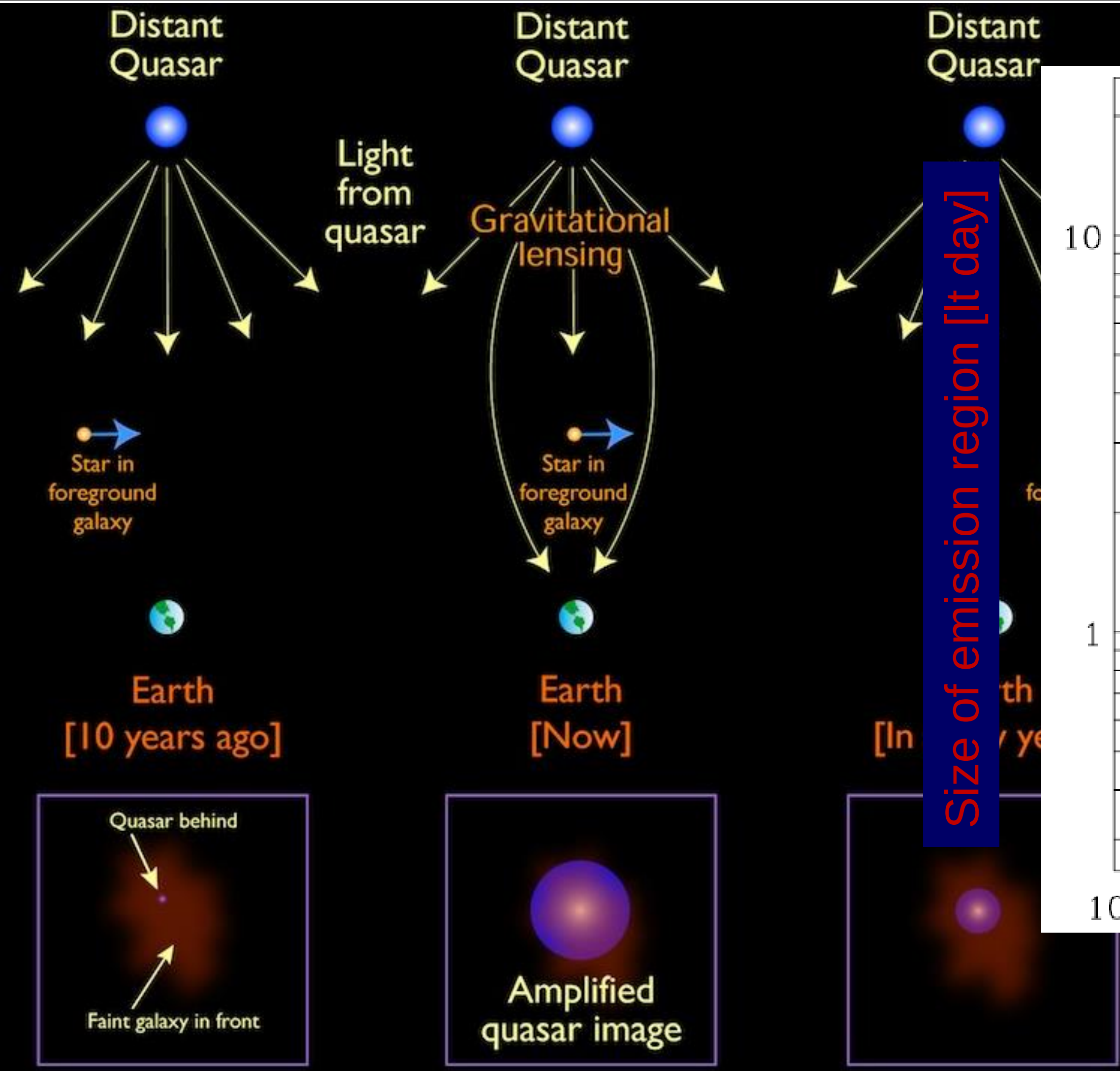

THE EVENT HORIZON TELESCOPE
2: Combined Array for Research in Millimeter wave Astronomy – California
3: Arizona Radio Observatory
1. Submillimeter Array and James Clerk Maxwell Telescope – Hawaii
2
3
1

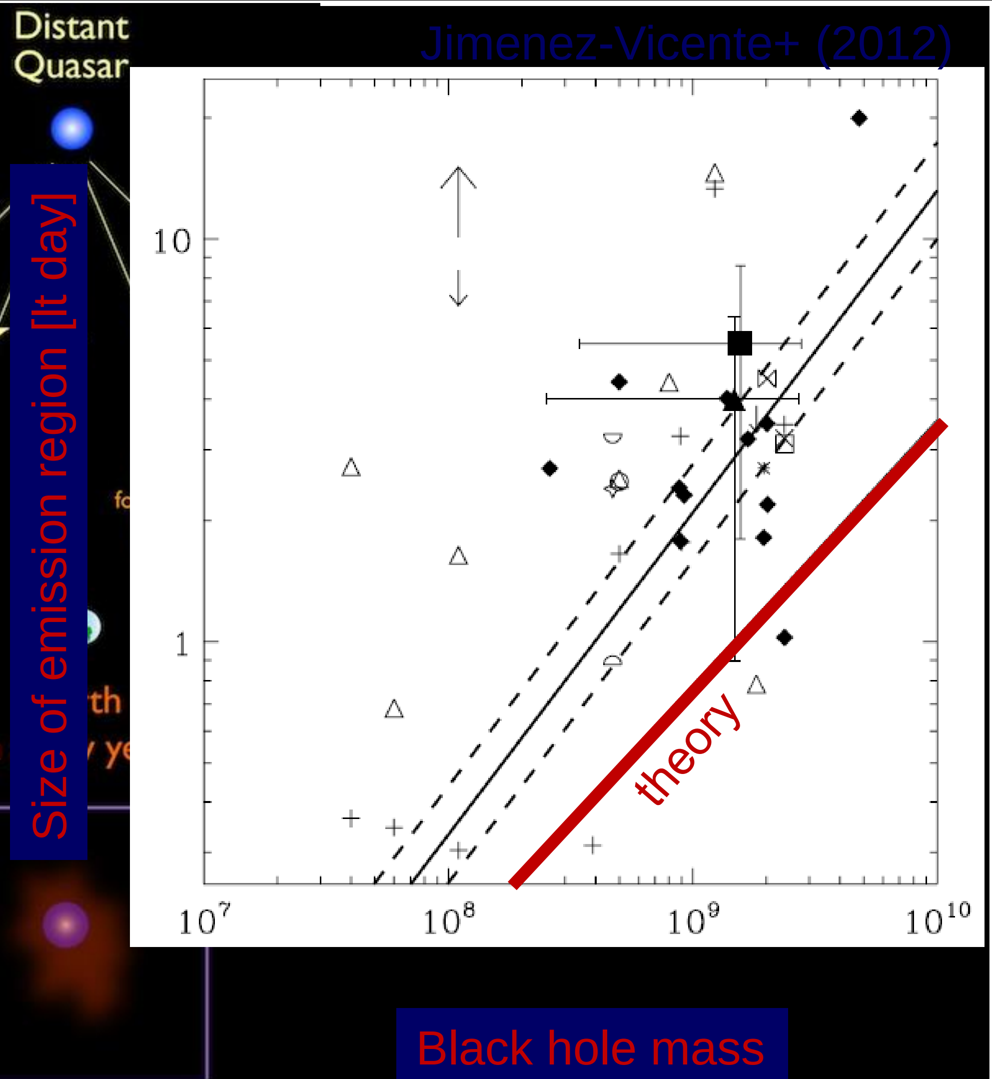
Gas disk around black hole in M87 (2019)

Imaging BHs II. – microlensing

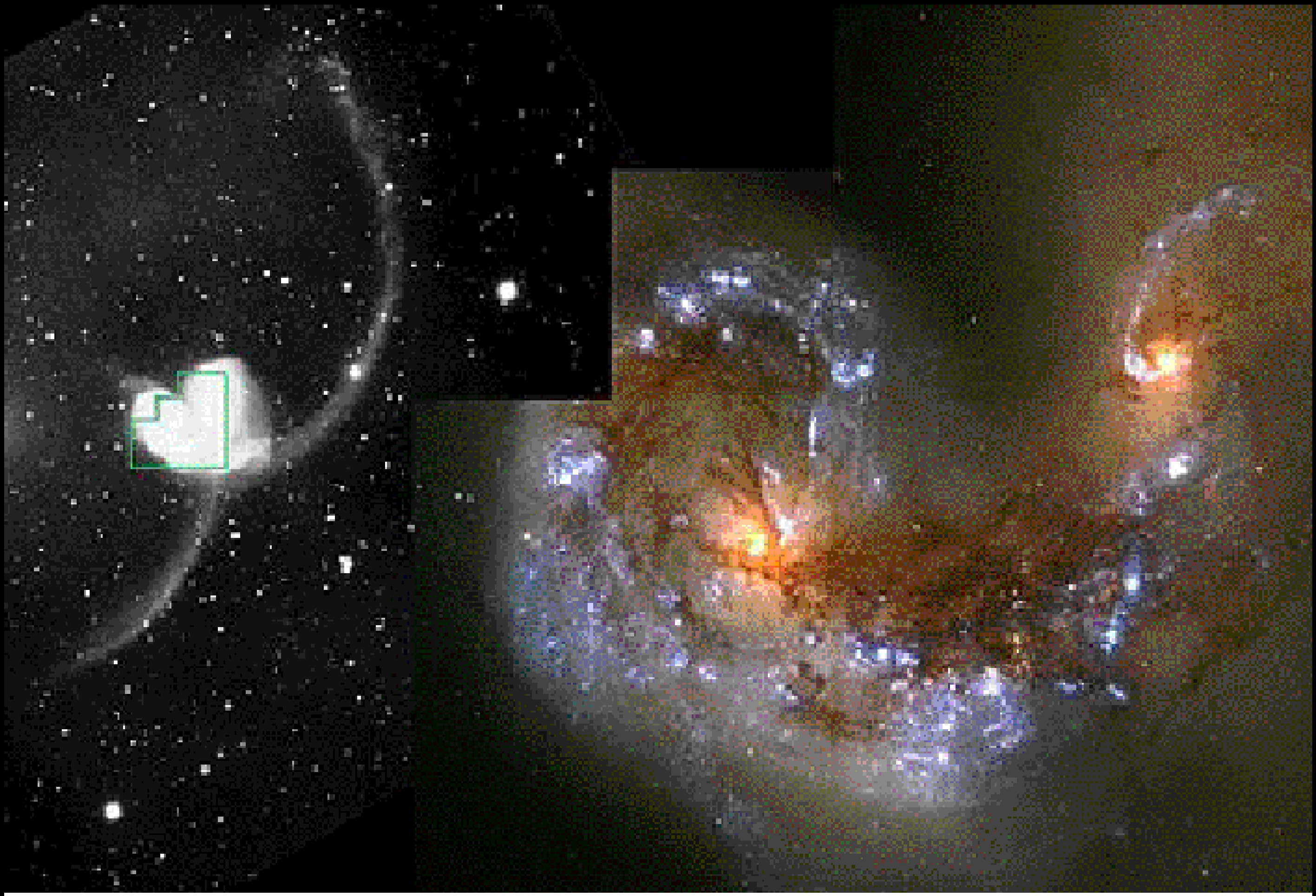


Imaging BHs II. – microlensing





Black Hole Binaries due to Galaxy Mergers



B. Whitmore (STScI), F. Schweizer (Carnegie Institute),

Binary AGN with 1-10kpc separation at z<0.3

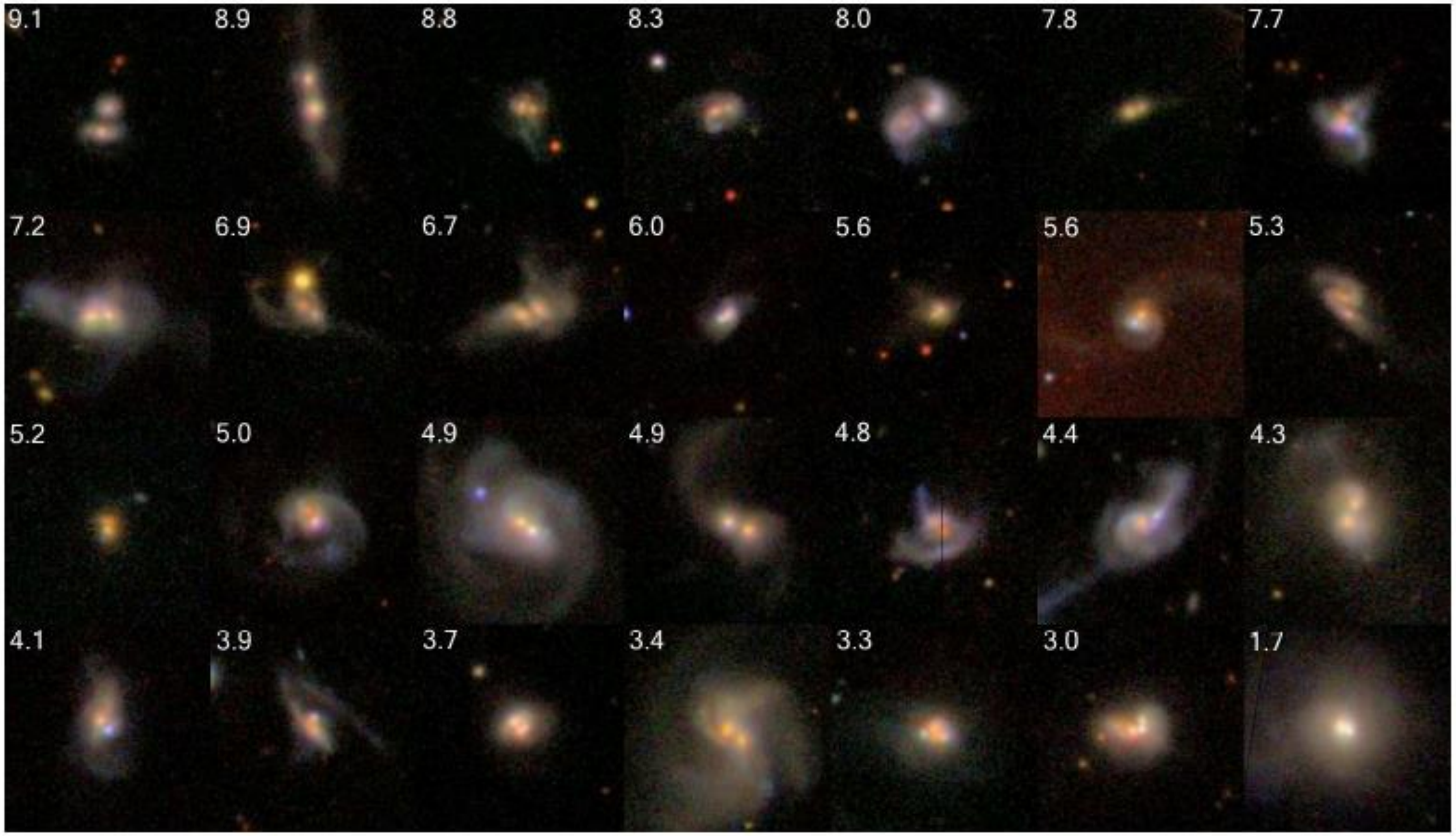
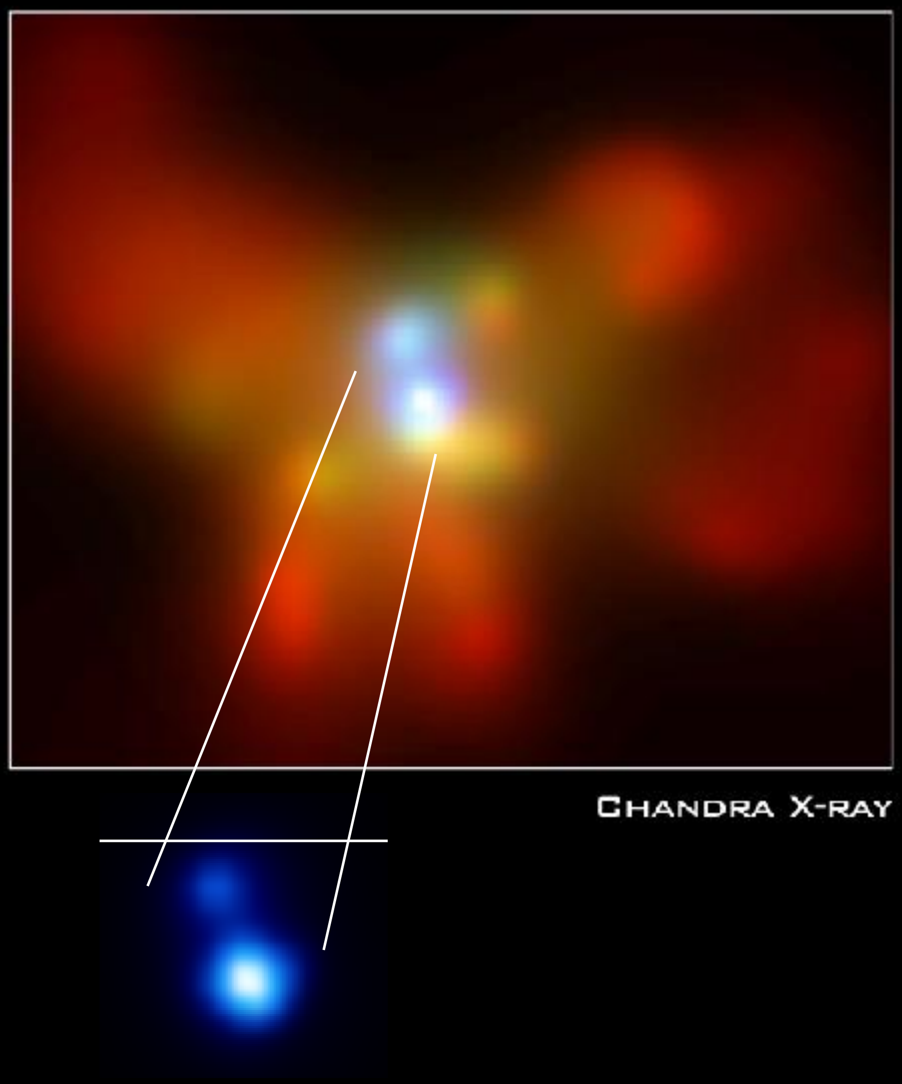


Figure 1: SDSS *gri*-color composite images of some binary AGNs selected from SDSS. North is up and east is to the left. Each panel is 50 × 50". We order the targets with decreasing projected separation r_p, ranging from $r_p = 9.1$ kpc to 1.7 kpc as labeled on each panel.

Shen et al. (2011)

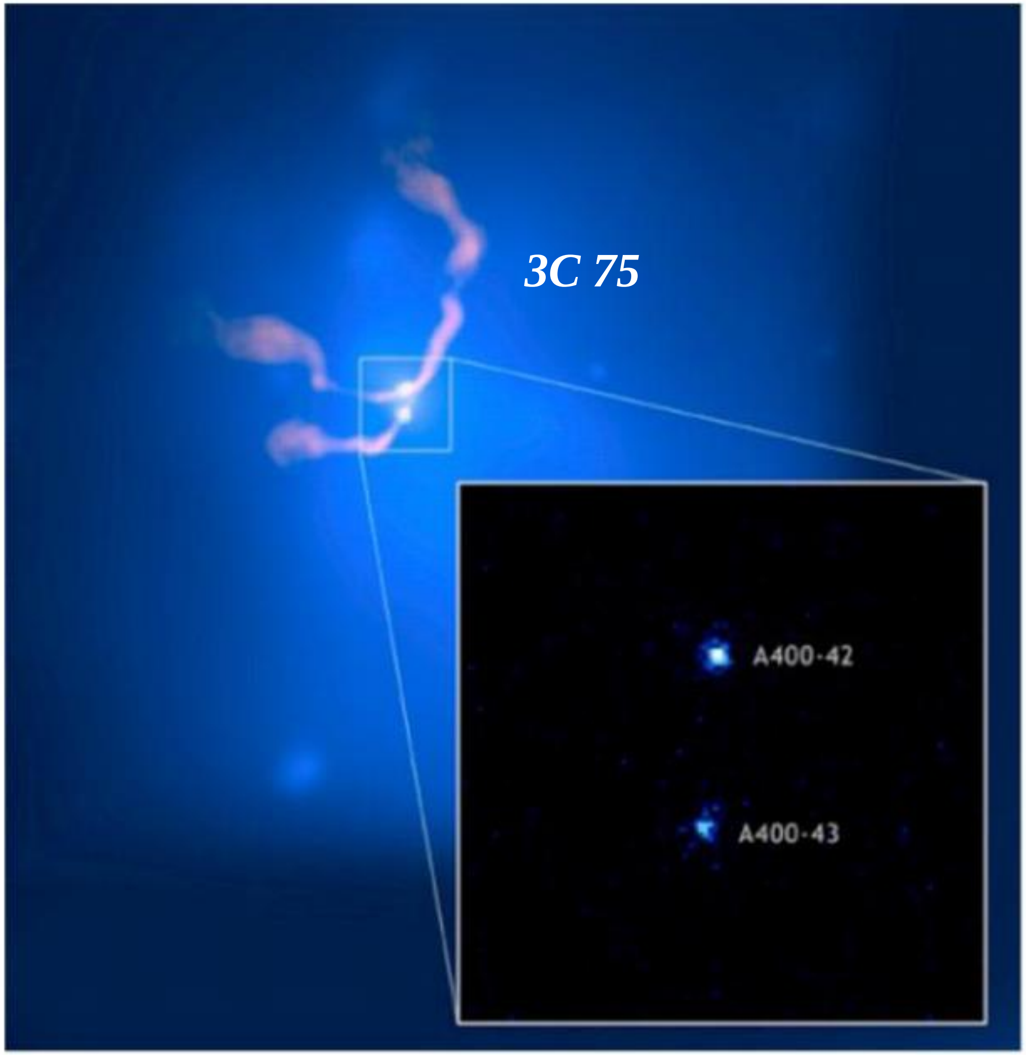
X-ray Image of a binary black hole system in NGC 6240

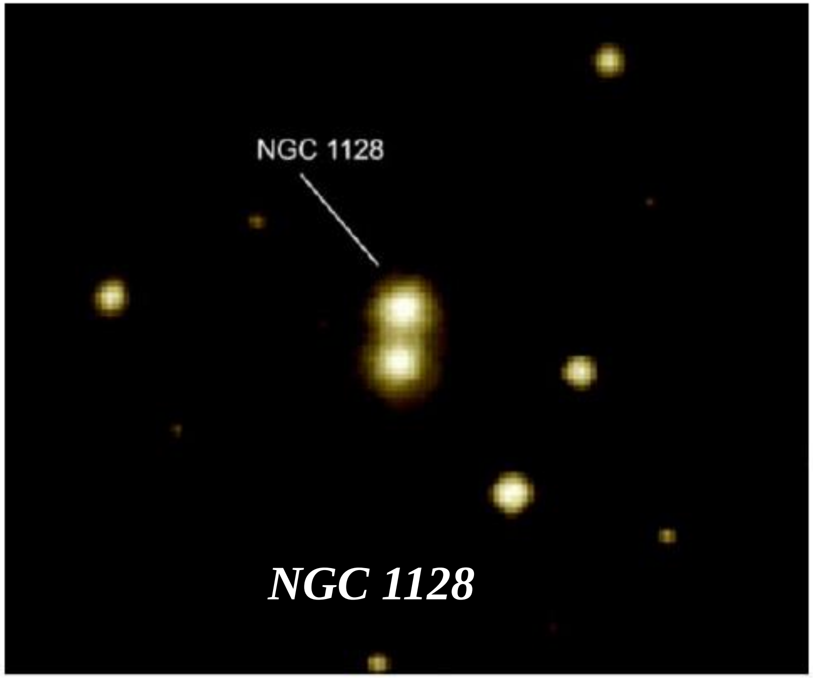


z=0.025

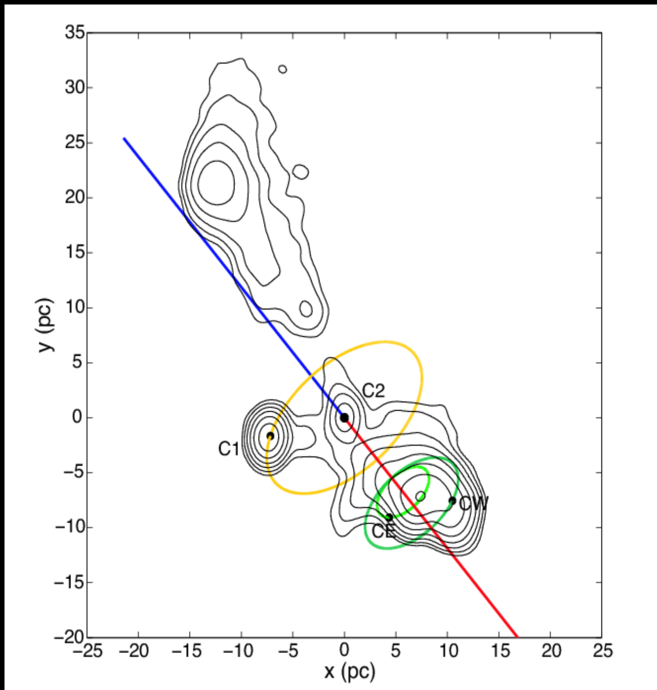
Komossa et al. 2002

X-ray Cluster Abell 400

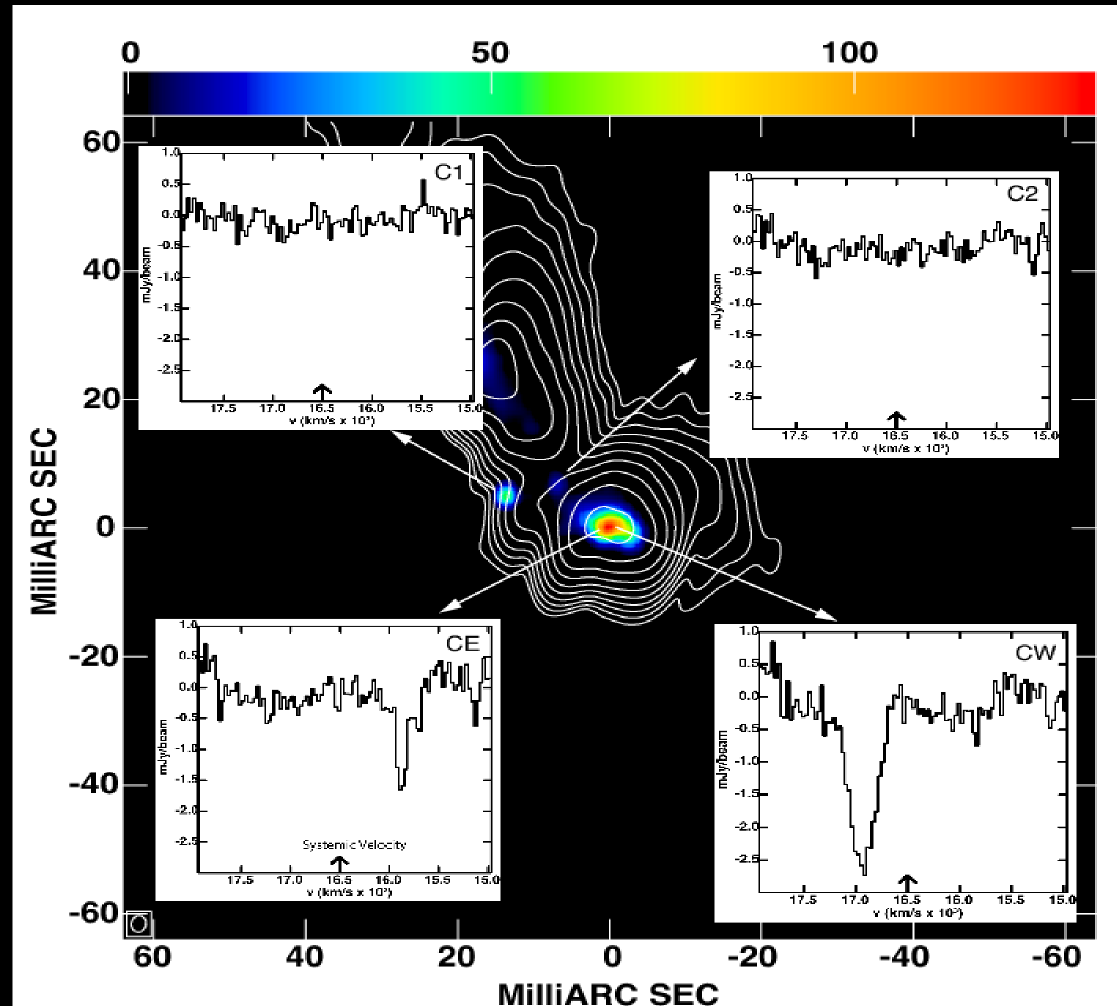




0402+379 (Rodriguez et al. 2006-9)

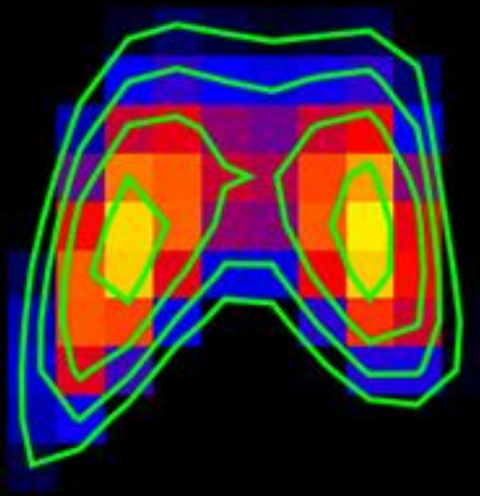


VLBI at 1.35 GHz



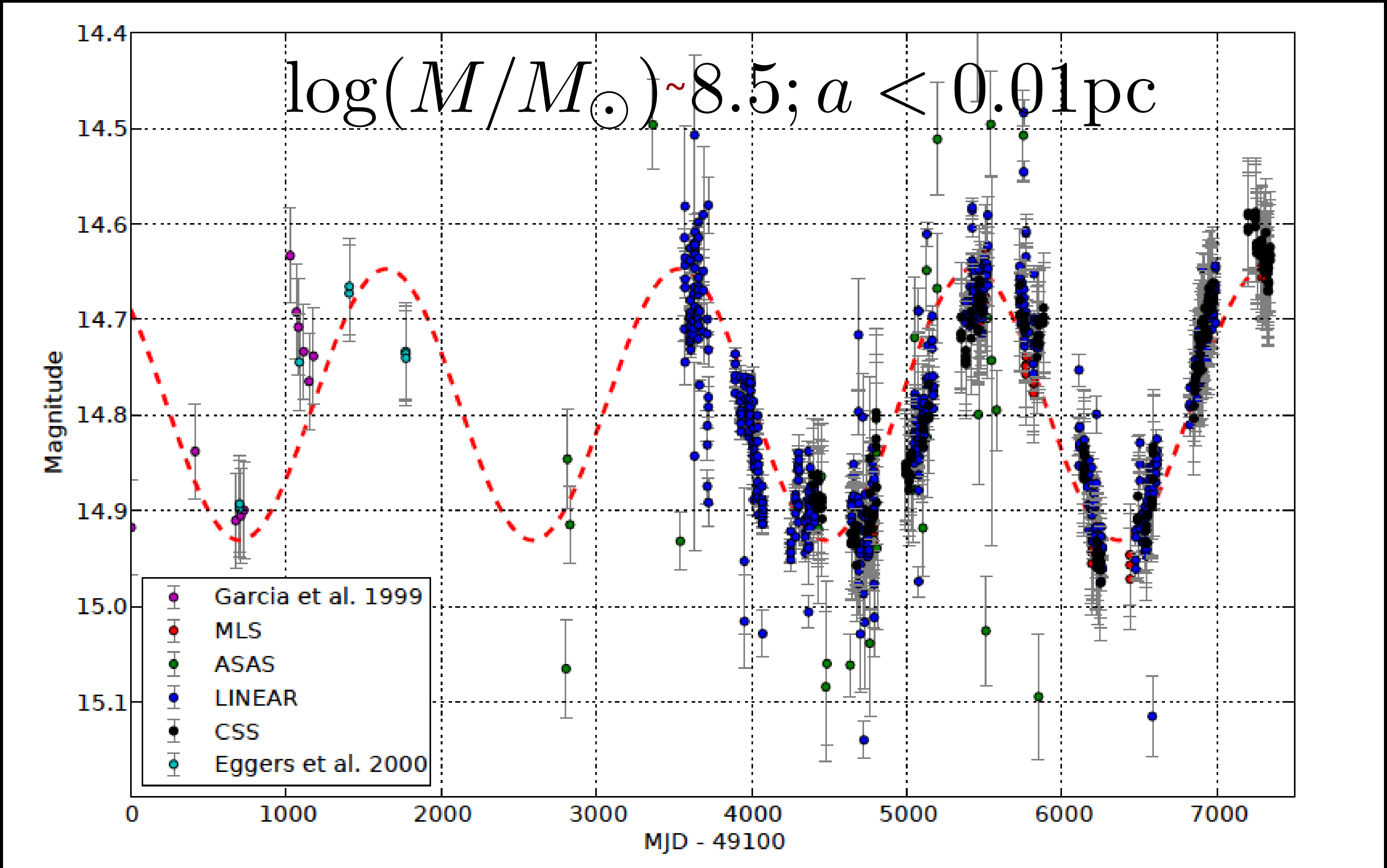
- Projected separation: 7.3 pc,
- Estimated total mass: $\sim 10^9 M_\odot$

Subparsec binary



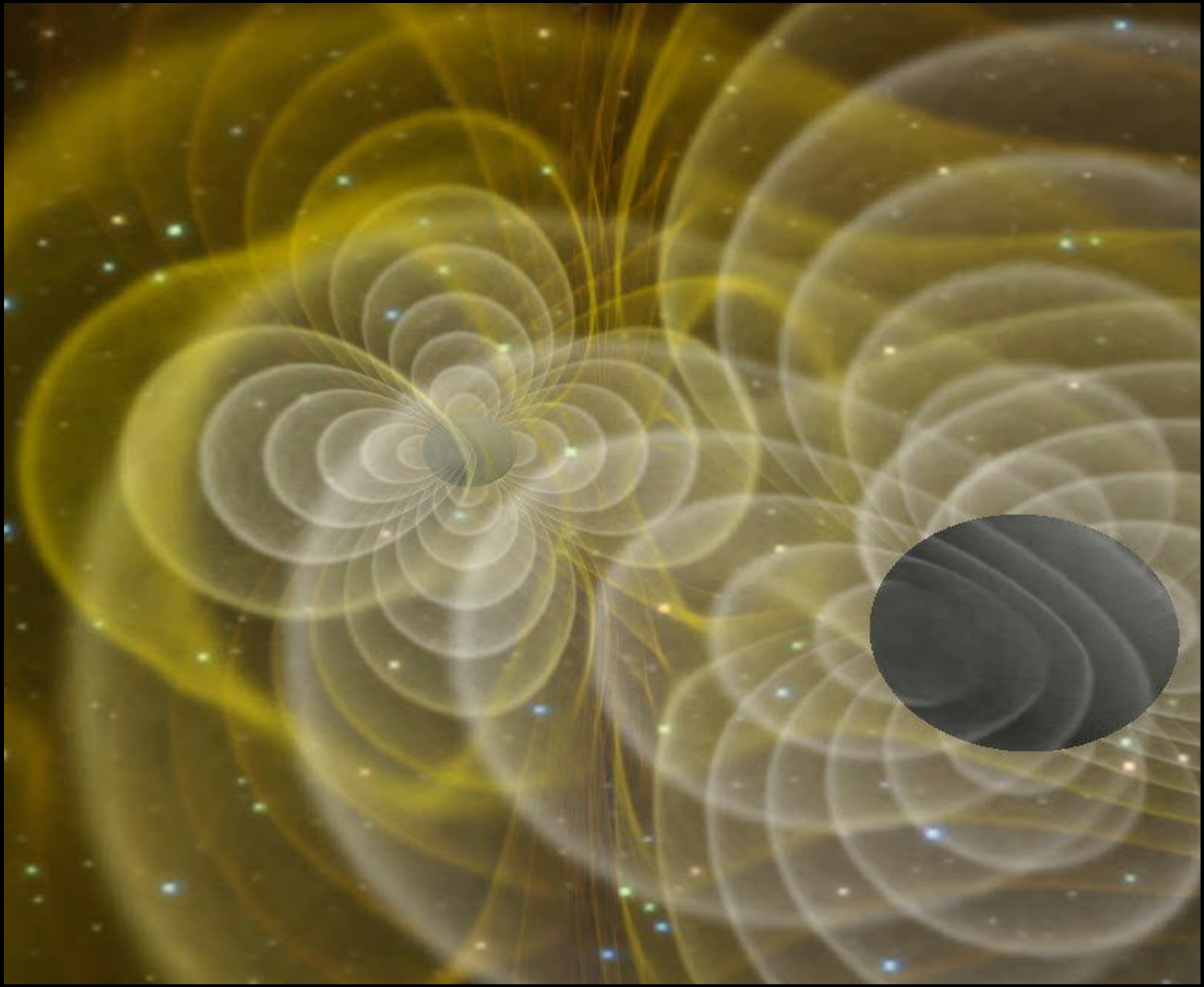
- Projected separation: 0.35 pc,
- Nature September 19, 2017

PG 1302-102: periodicity at 5.2 years



Graham et al. arXiv: 1501.013

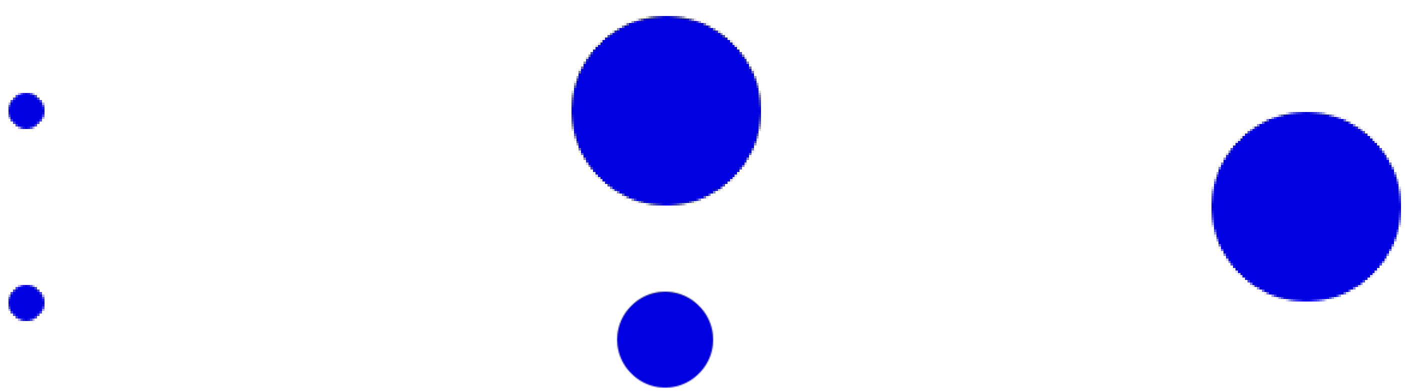
Gravitational waves



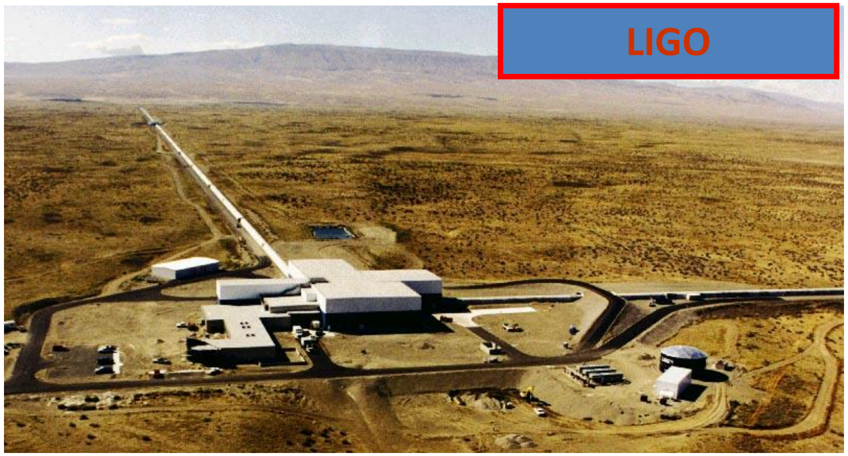
(Centrella et al. 2007)

Gravitational waves

- Gravitational waves = spacetime distortion
- Propagate with the speed of light
- Relative distortion
- Scales with 1/r with distance
- Two polarizations

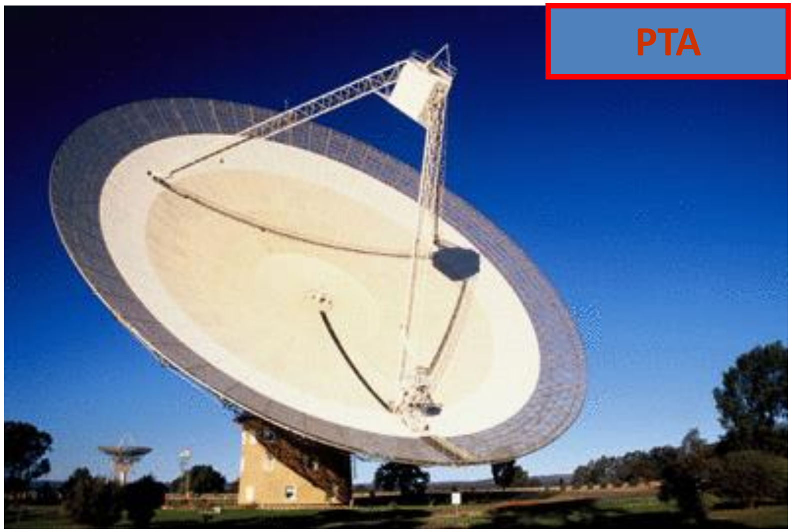


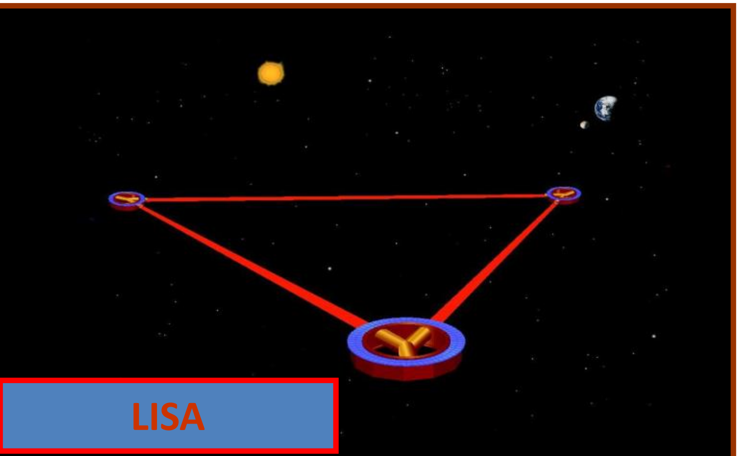
Gravitational wave detectors

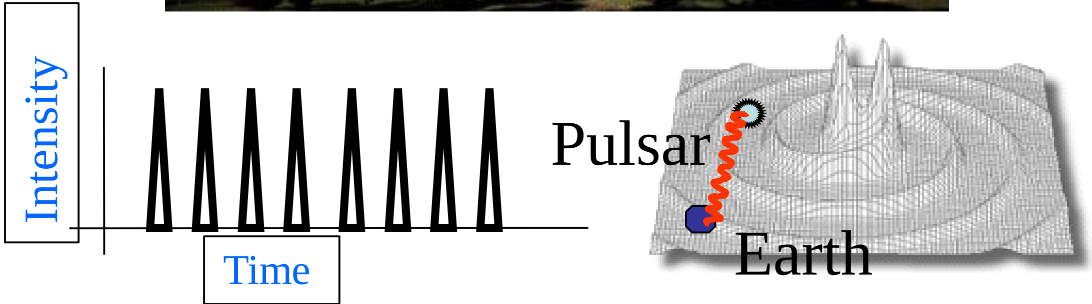


Laser Interferometric Gravitational wave Obs.

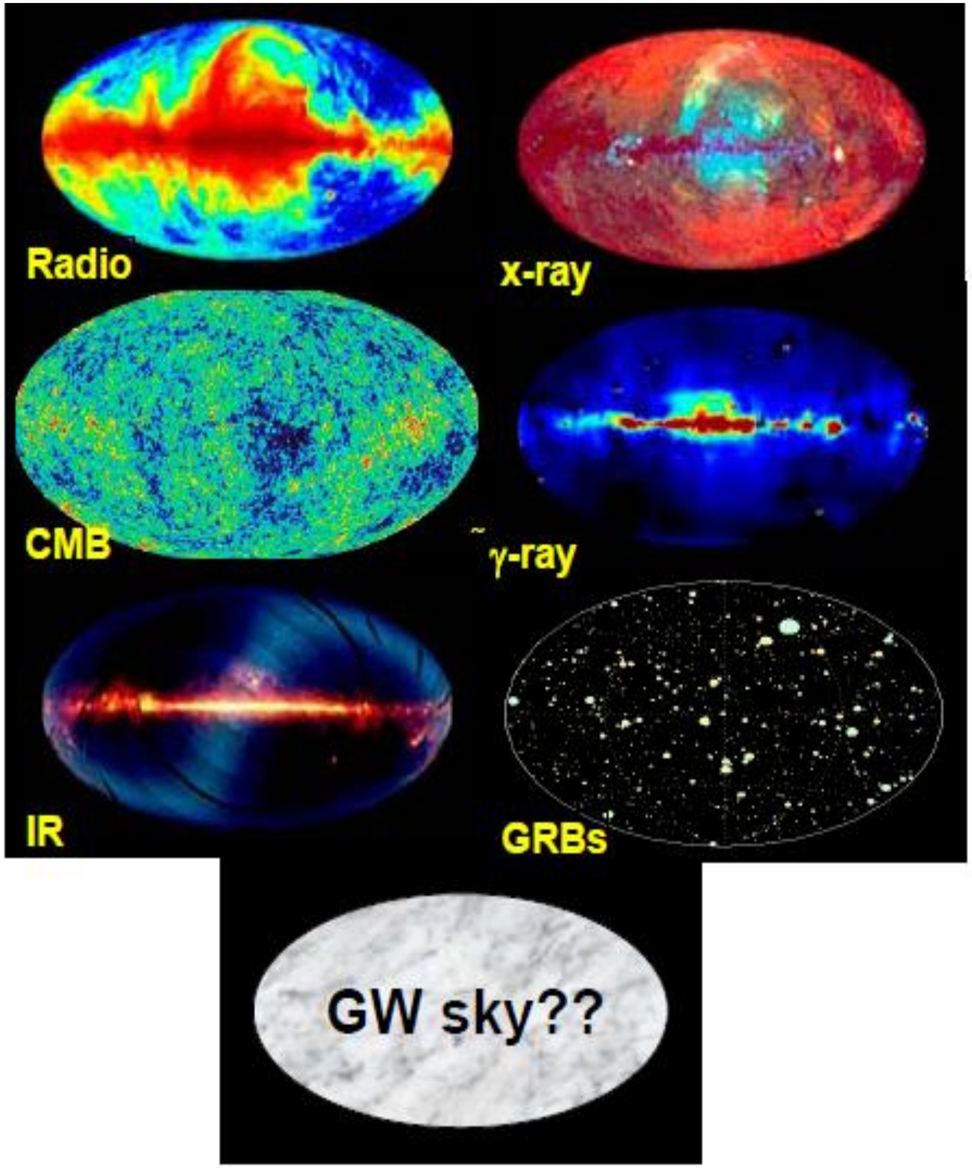
Pulsar Timing Arrays







A new window on the Universe



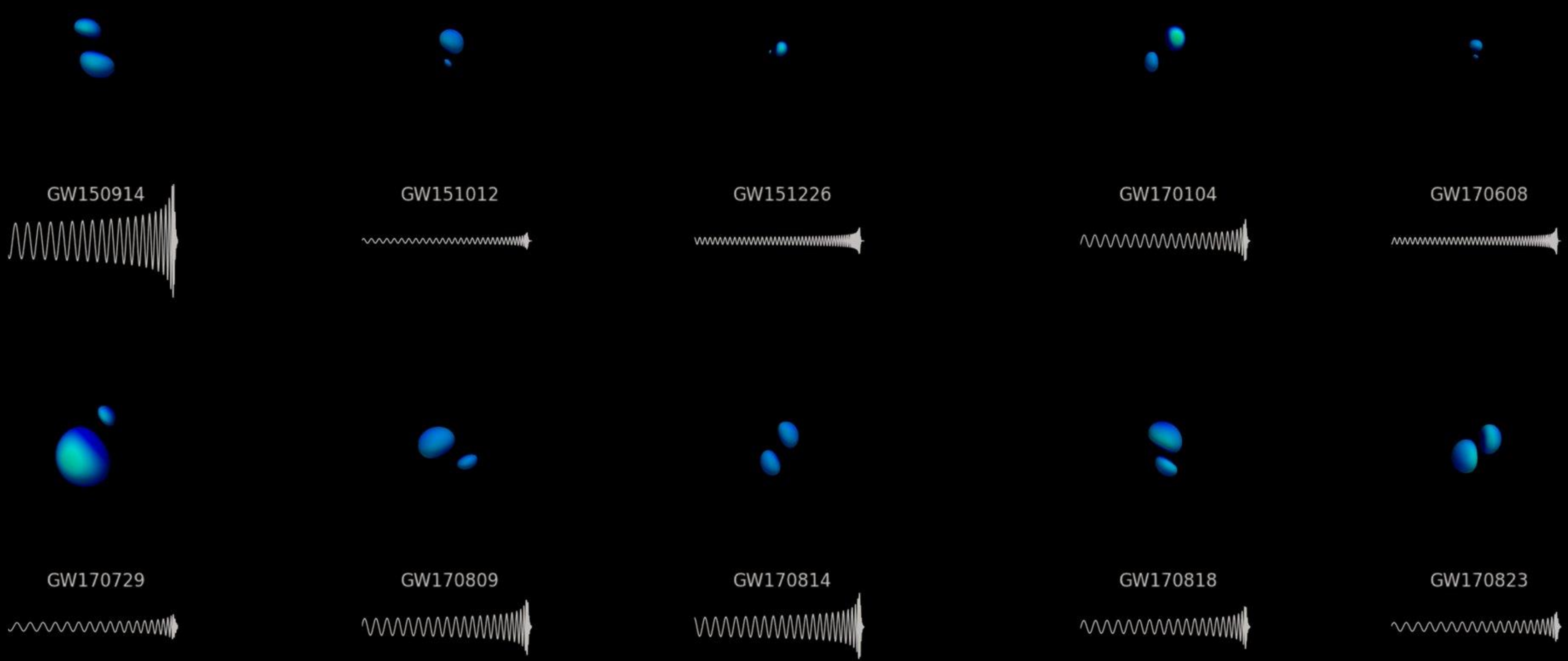
- EXPECT THE UNEXPECTED!

Known sources

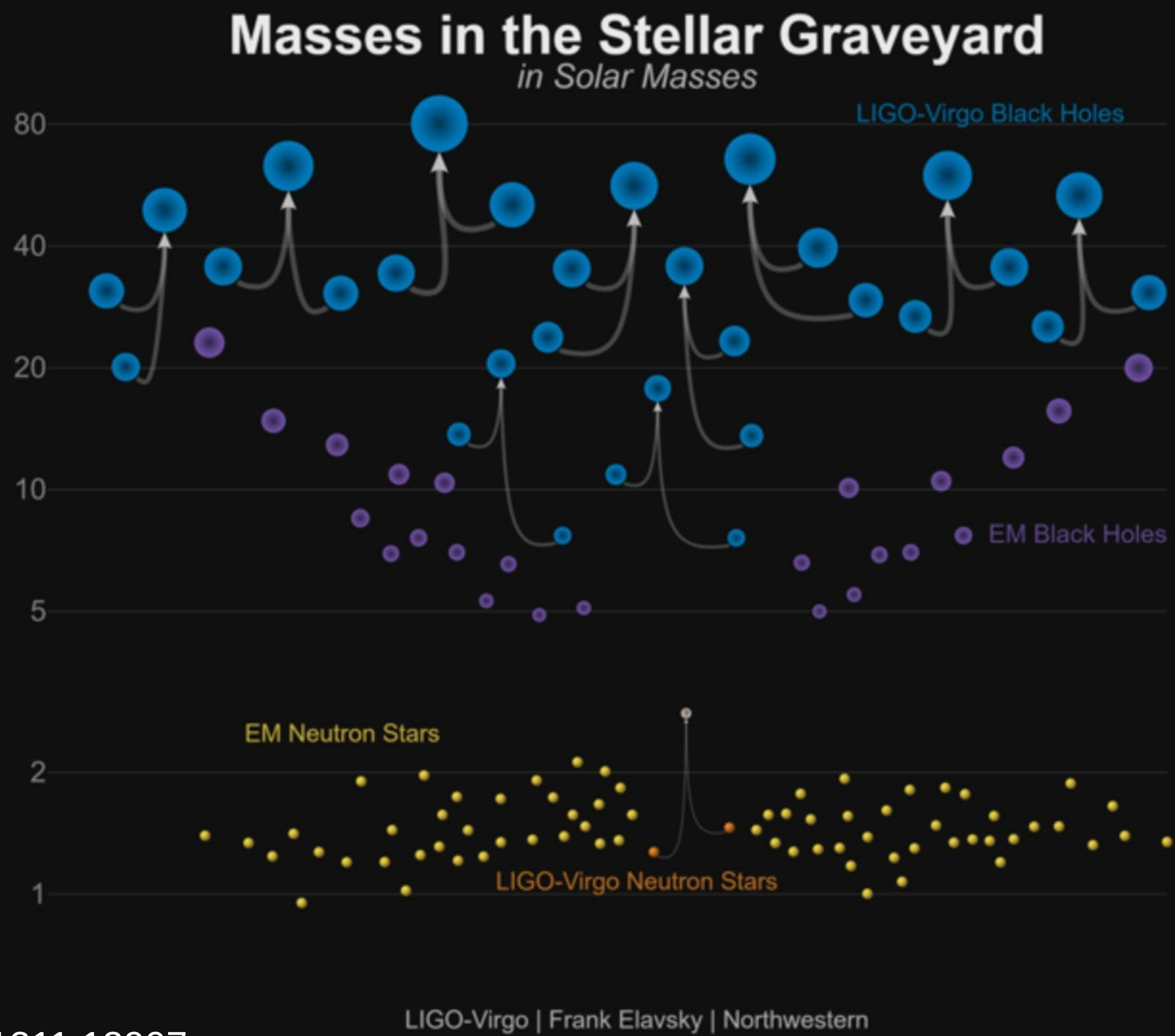
- Advanced LIGO fobserving run
  - O1: 12 September 2015 –19 January 2016
  - O2: December 2016 – August 2017
  - O3: February 2019 –
- 11 secure detections in O1,O2 (10 BH-BH, 1NS-NS)
  - **GW150914**: 14 Sept. 2015
  - > 5.3 sigma

LSC+Virgo, PRL 116, 061102 (2016); LSC+Virgo, PRL 116, 241103 (2016); LSC+Virgo, PRL 116, arxiv:1606.04856

Gravitational wave detections



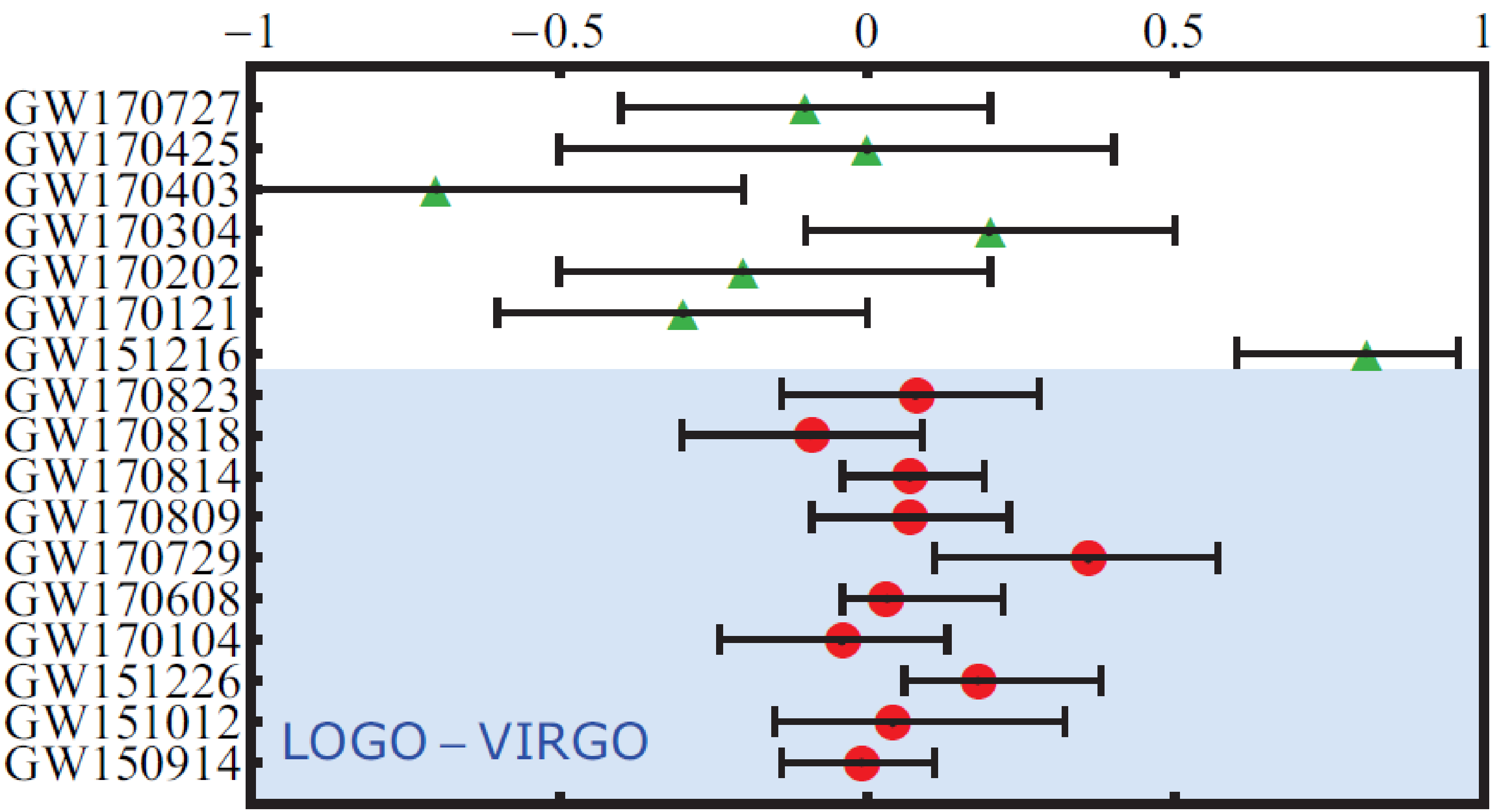
arxiv:1211.12907



arxiv:1211.12907

Spins

$$\chi_{\rm eff} = \frac{(m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2)}{M}$$



LIGO/VIRGO Collaboration 2018; Zackay+ 2019, Venumadhav+ 2019

Rate of BBH coalescence

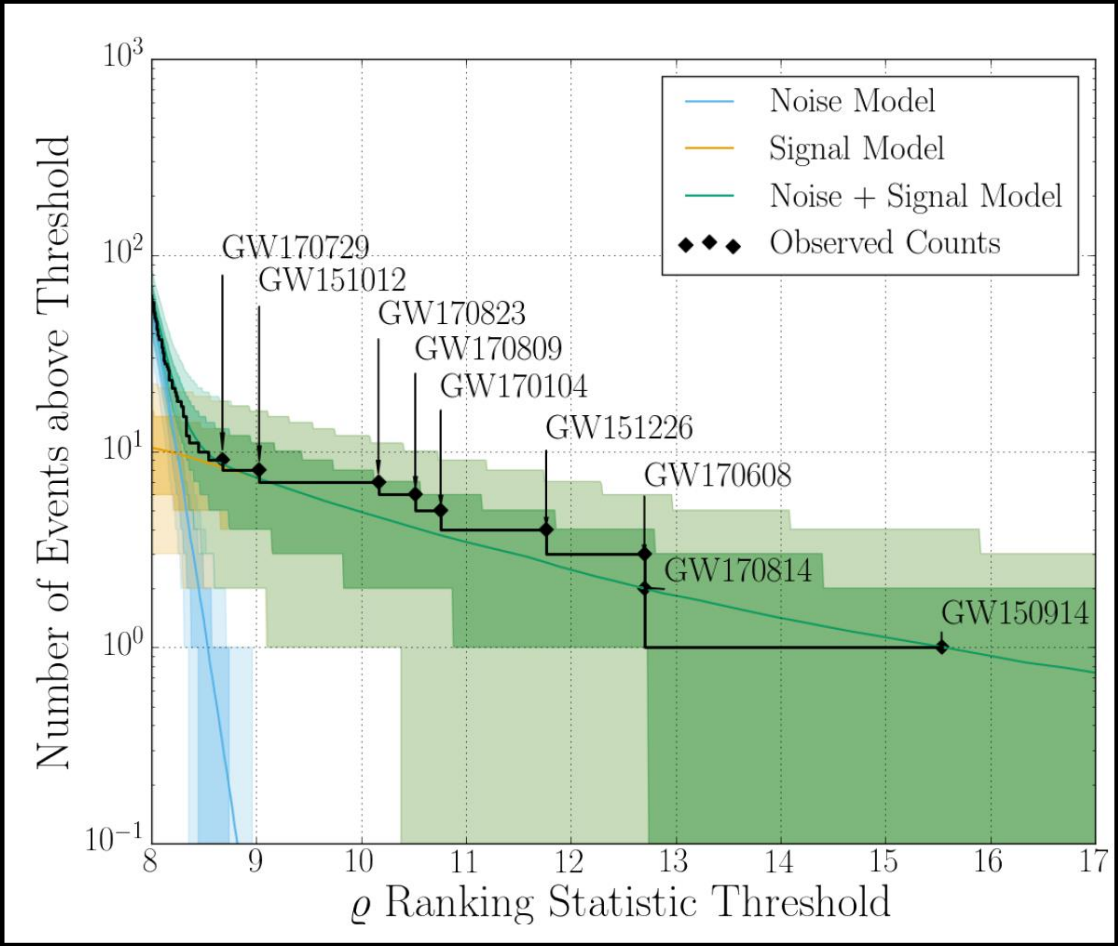
GW150914+LVT151012:
$2 – 600\ Gpc^{-3}\ yr^{-1}$

+GW151226:
$9 – 240\ Gpc^{-3}\ yr^{-1}$

+GW170104:
$12 – 213\ Gpc^{-3}\ yr^{-1}$

+7 new BH/BH detections:
$29 – 100\ Gpc^{-3}\ yr^{-1}$

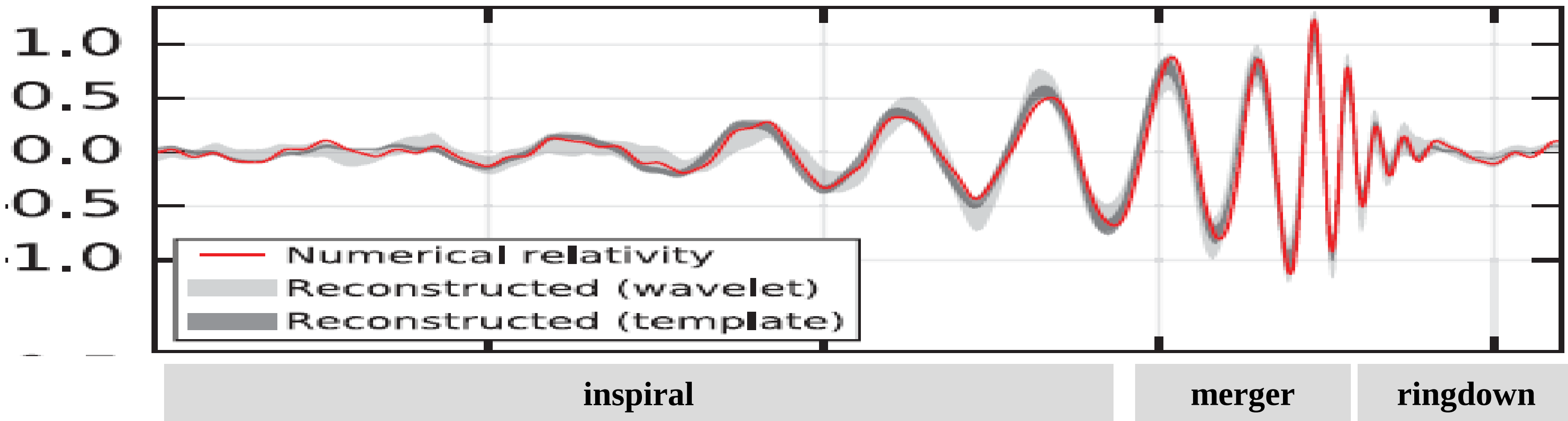
Rate of NS coalescence
GW170608:
$300 – 4700\ Gpc^{-3}\ yr^{-1}$



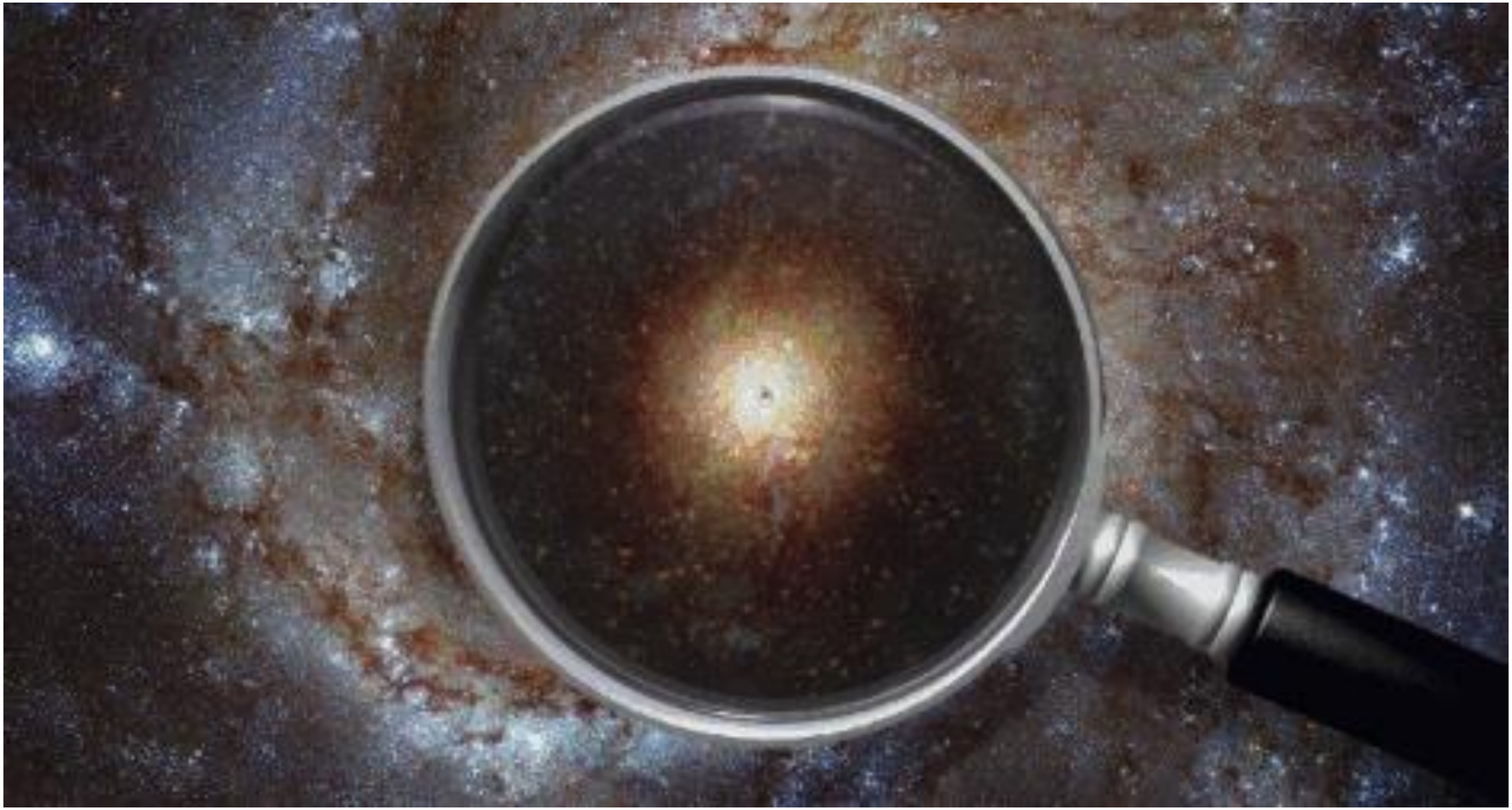
arxiv:1211.12907

LIGO/VIRGO Collaboration 2018

What have we learned so far?



- Black holes exist!
  - Have horizons (at least light ring)
  - Theory of relativity is confirmed in strong and time dependent gravity
  - mass of graviton consistent with zero (< 10^{-22} eV), Compton wavelength > 1 light year
- Stellar black holes may be more massive than previously thought!
  - 30 solar mass possible!
- Black hole – black hole binaries exist
- collisions are frequent > 30-100/Gpc^3/yr
- Big surprise:
  - Electromagnetic gamma ray burst within 0.4 seconds of GW150914 – but controversial

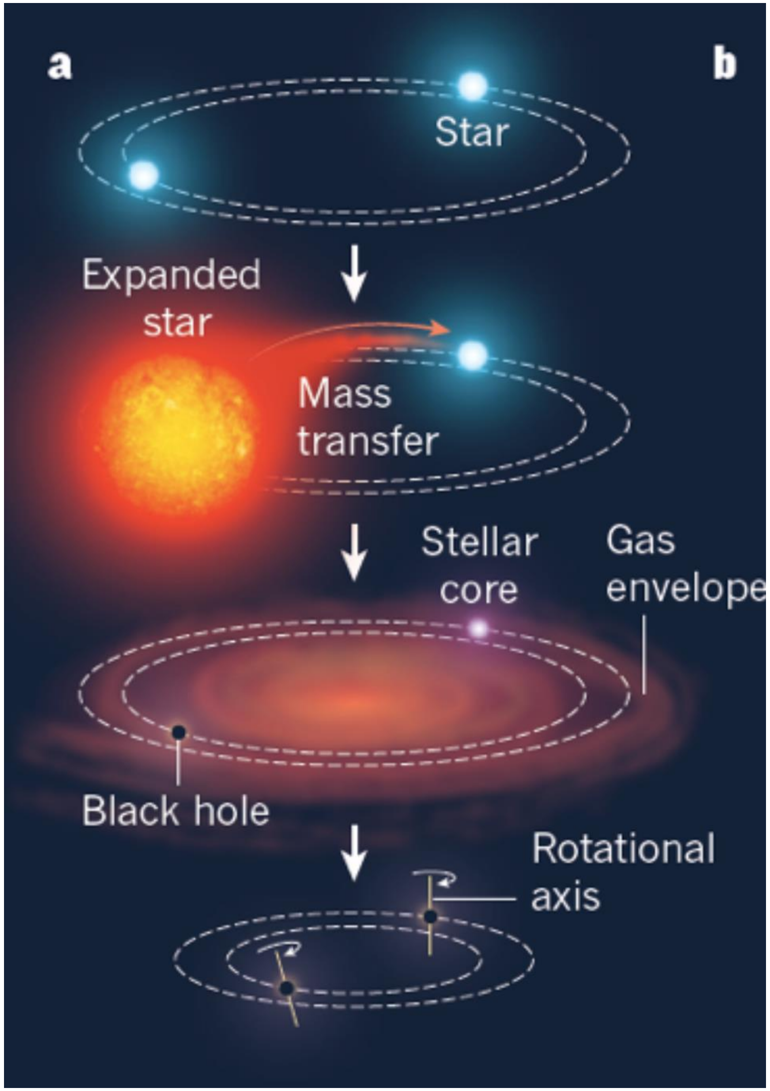


Astrophysical origin of mergers

Option 1: stellar binary evolution

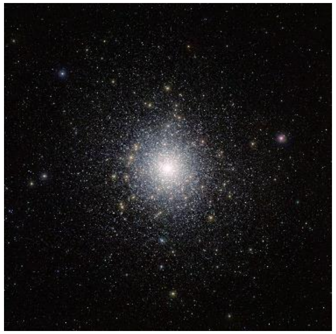
Galactic binaries

- 10^11.5 stars in a Milky Way type galaxy
- 10^{7-8} stellar mass black holes
- Most massive stars are in binaries
  - 25% in triples



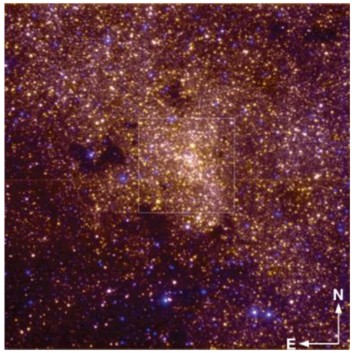
Option 2: Dynamical environments

Globular clusters

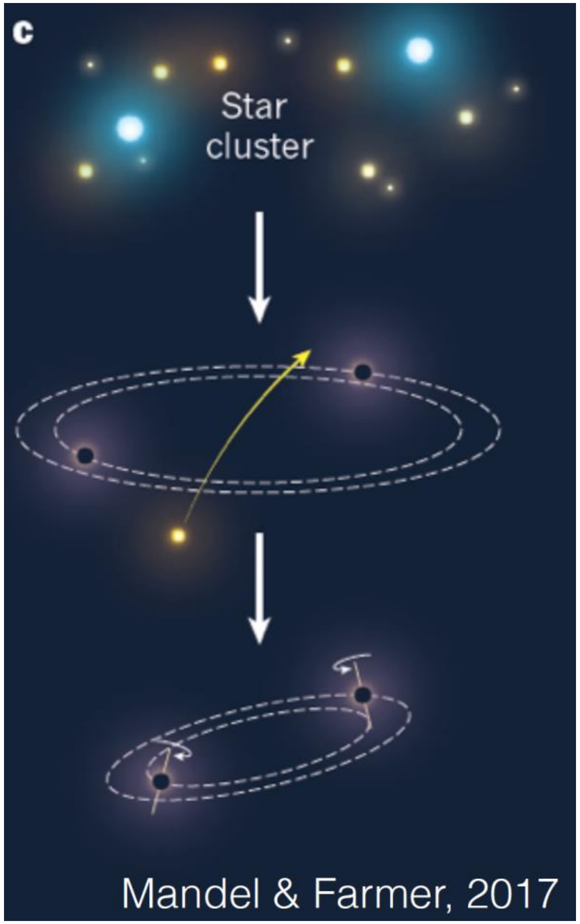


- 200 in a Milky Way type galaxy
- 10^{2-3} stellar mass black holes
- Size: 1 pc – 10 pc
- Density 10^3—10^5 x higher

Galactic nuclei



- 10^{6-7} M_{sun} supermassive black hole
- 10^{4-5} stellar mass black holes
- Size: 1 pc – 10pc
- Density 10^6 – 10^10 x higher



encounter rate ~ density^2

$$\frac{d}{d\ln r}\Gamma = (4\pi r^3) n_\bullet^2 \sigma_{cs} v$$

Option 3: Dark matter halo

Dark matter halo

- 10x more mass than in stars
- 10^{10} primordial mass black holes?

- Rates match if
  - 100% of dark matter is in 30 Msun **single BHs** (Bird et al 2016)
    - RULED OUT BY OBSERVATION OF a GLOBULAR CLUSTER IN A DWARF GALAXY (Brandt et al. 2017)
    - Newer studies: 1% of dark matter in BHs is sufficient (Ali-Haimud et al 2017)
  - 0.1% of dark matter is in primordial **binary BHs** after inflation (Sasaki et al 2016)

- 30 Msun primordial BHs form when T ~ 30 MeV (Carr 1975)
  - standard model does not have any phase transitions at this temperature

Are there intermediate mass black holes?

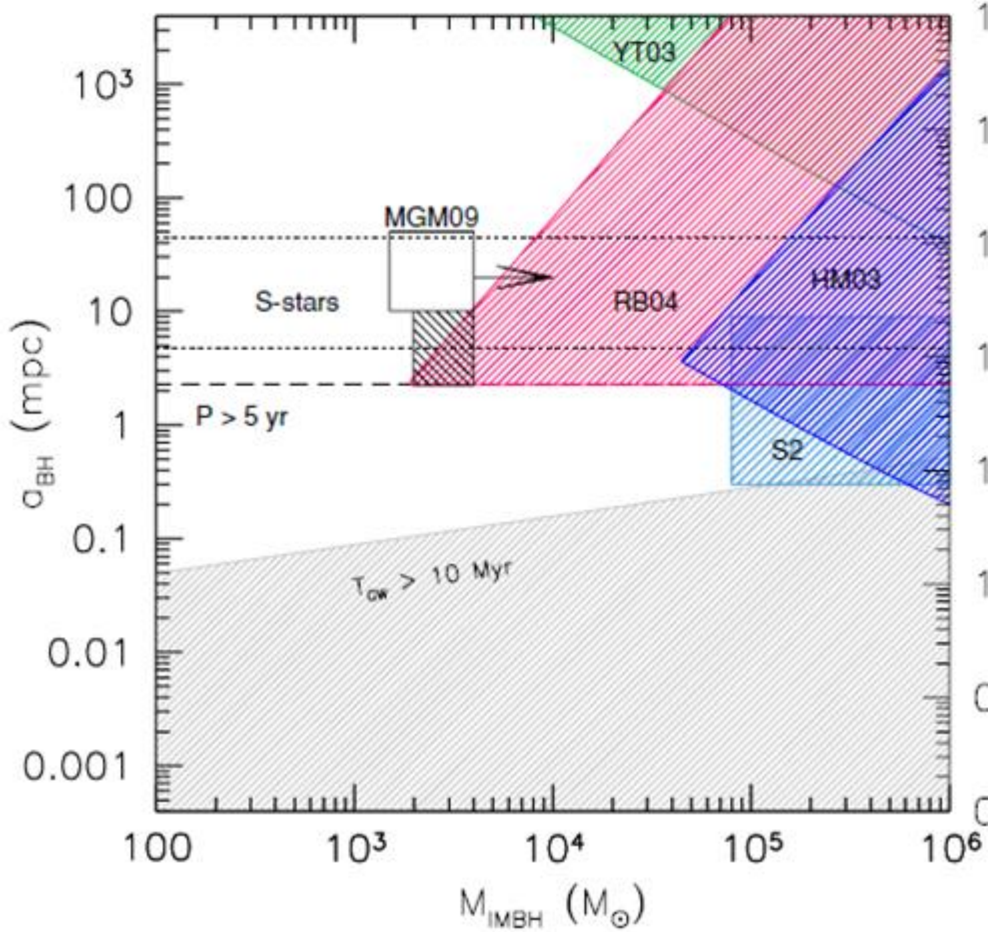
Theory

Formation

- Early universe:
  - collapse of the first stars
- Globular clusters
  - runaway collisions
  - mergers of stellar mass black holes
  - dynamical friction
    - → IMBH deposited in the galactic center
- In accretion disk

~ 50 IMBHs within 10 pc

Observational constraints



Gualandris & Merritt ‘09

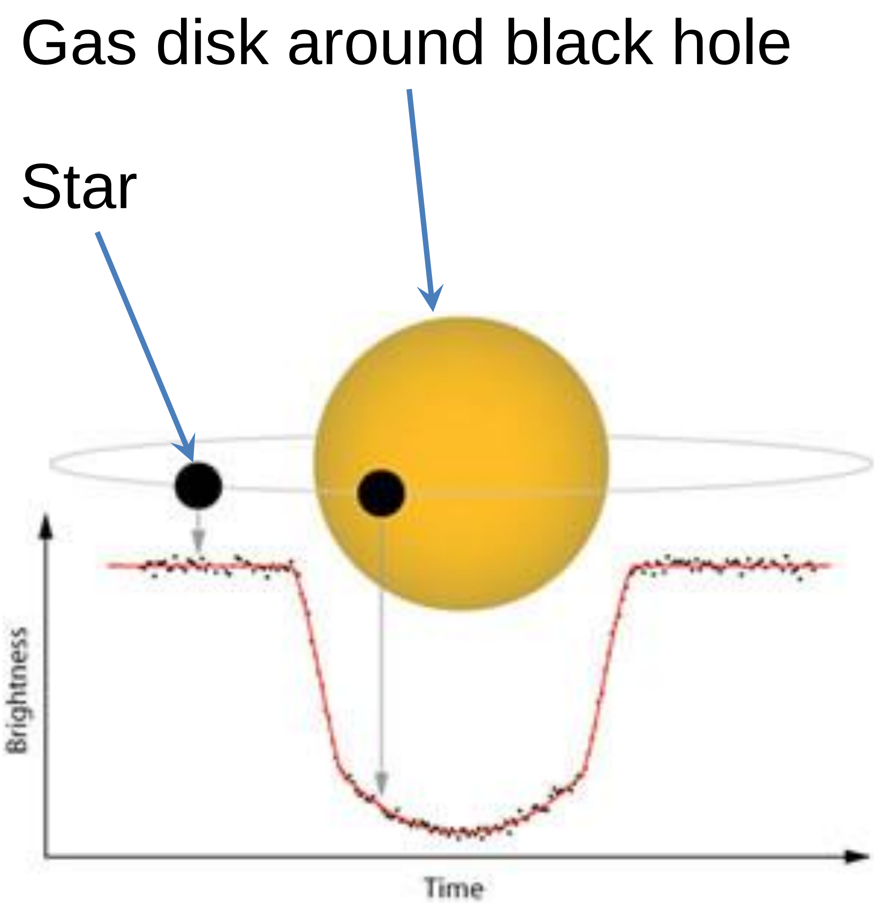
Big questions

- How did they form?
  - collapse of gas or first stars, runaway collisions in dense star clusters?
- How do they grow?
  - Gas accretion, collisions, or eating stars?
- How do they influence their environment?
- How do they launch jets? flares?
- Why/where do they merge so often?
- Are they really black holes?

Summary

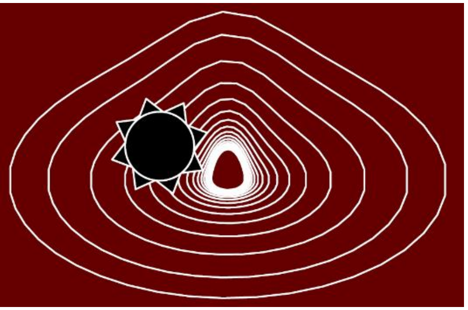
- Black holes exist
- Supermassive black holes are at the center of galaxies
- Supermassive black holes are engines of extremely bright emission
- Black hole shadows may be resolved
- Gravitational waves are an important new window on the Universe
- Many open questions

Imaging BHs III. – stellar transit

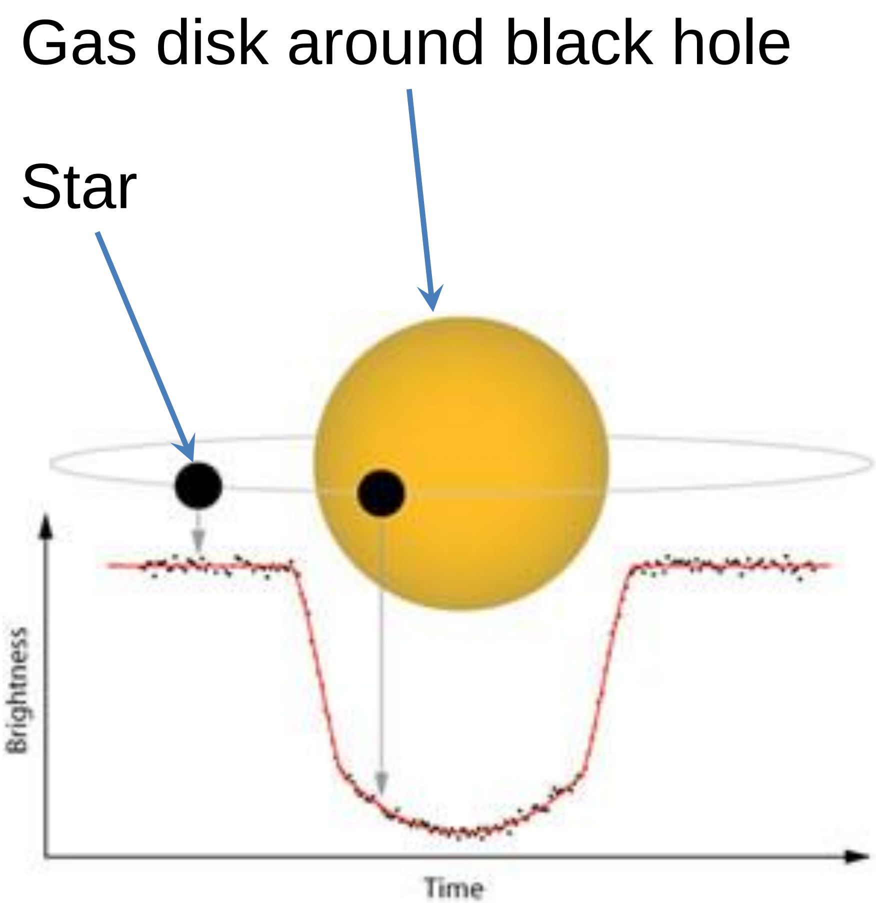


Lucky coincidences:

- Many stars are orbiting around supermassive black holes
- The size of supermassive black hole horizon is comparable to the size of a star



Imaging BHs III. – stellar transit



Lucky coincidences:

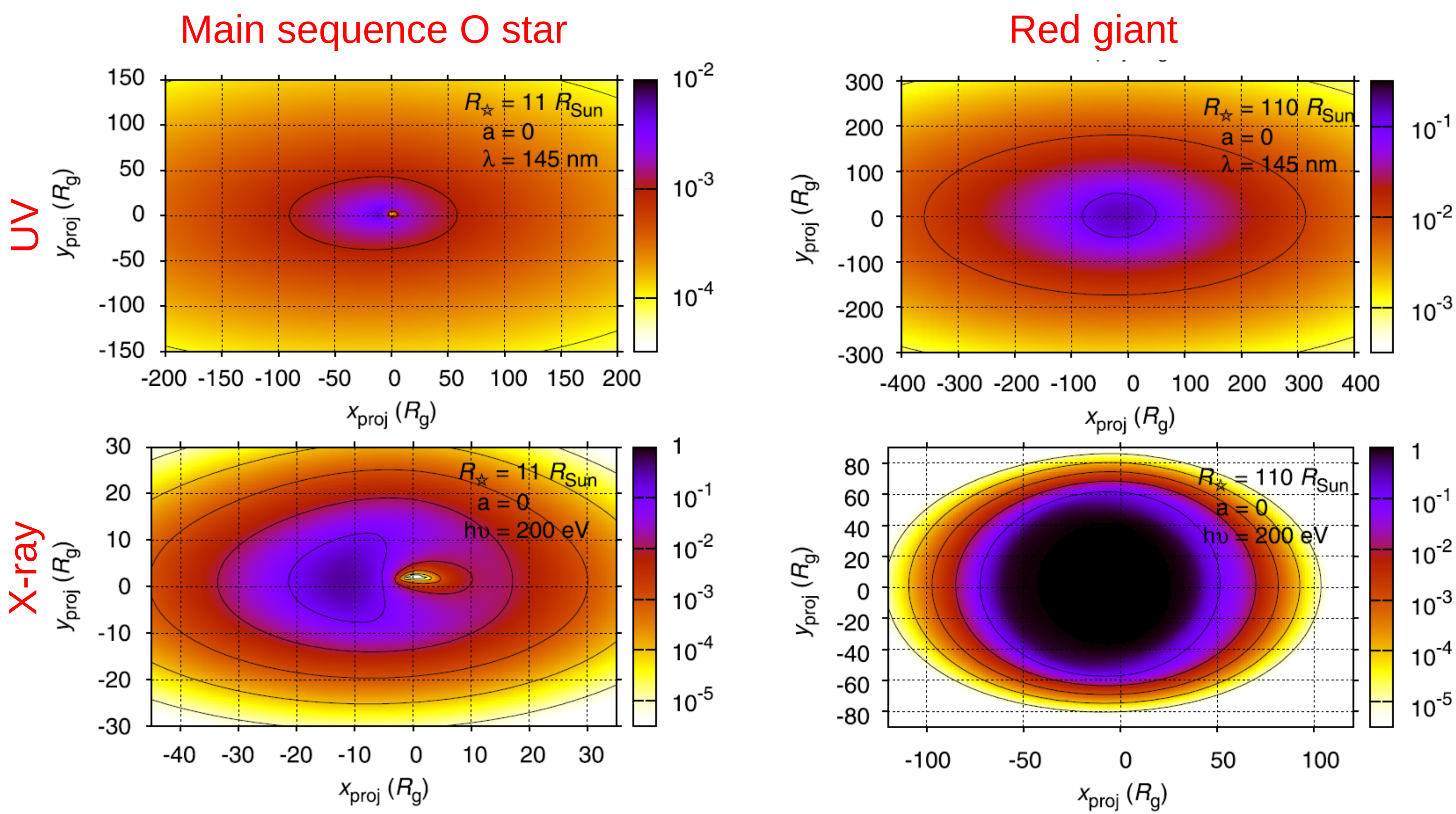
- Many stars are orbiting around supermassive black holes
- The size of supermassive black hole horizon is comparable to the size of a star

Prediction:

- transit duration hours – week
- probability 10^{-4}
- transit depth 10^{-3} to 1

Bence Beky & Bence Kocsis (2013)

Imaging BHs III. – stellar transit



Bence Beky and Bence Kocsis (2013)