

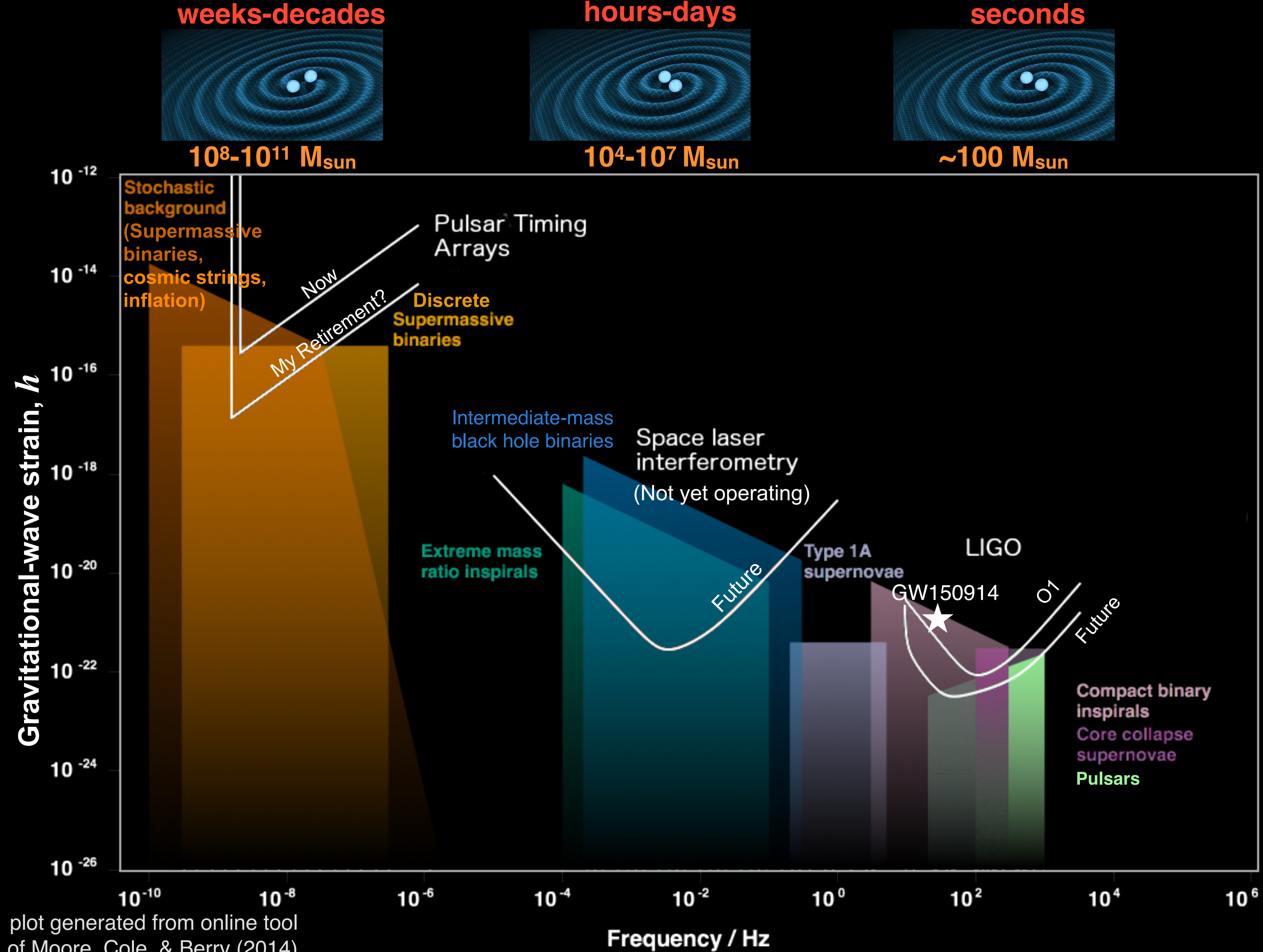
Long-Wavelength Multi-Messenger Astronomy at High Resolutions

Sarah Burke-Spolaor, WVU, AAS Splinter Session “The High Resolution Frontier”

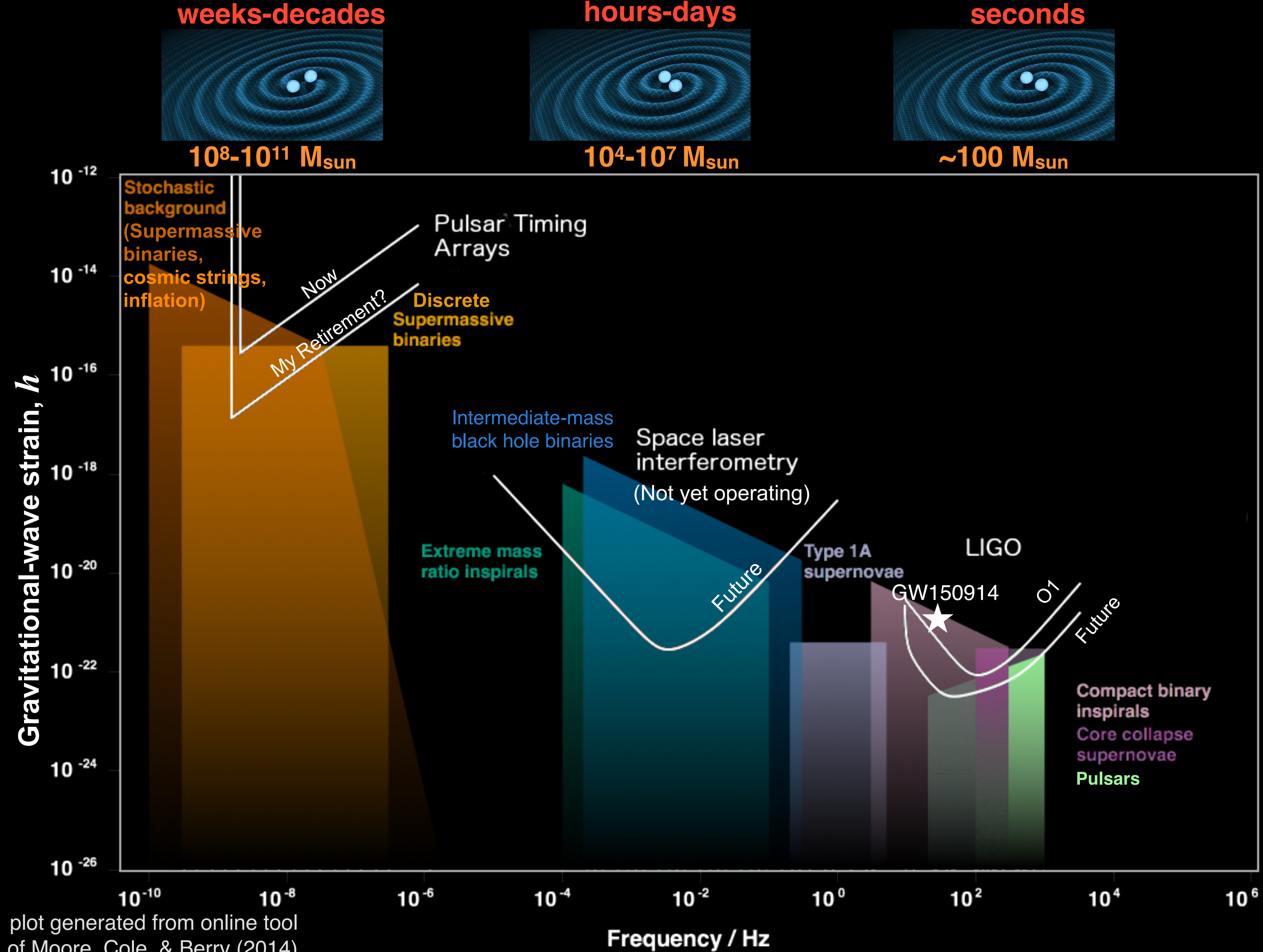
High-resolution radio
observation has an important
role to play in Massive Black
Hole Binary (MBHB)
identification and science.

(...especially in the MMA era!)



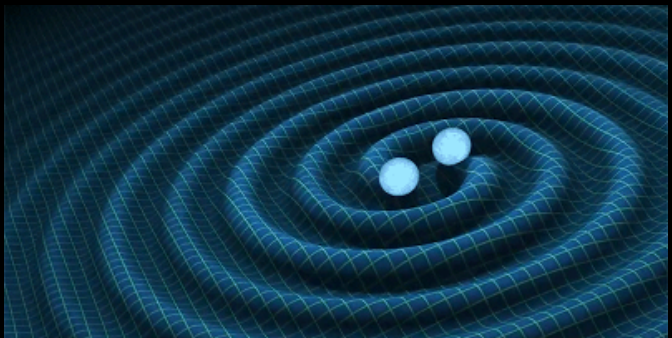


plot generated from online tool
of Moore, Cole, & Berry (2014)



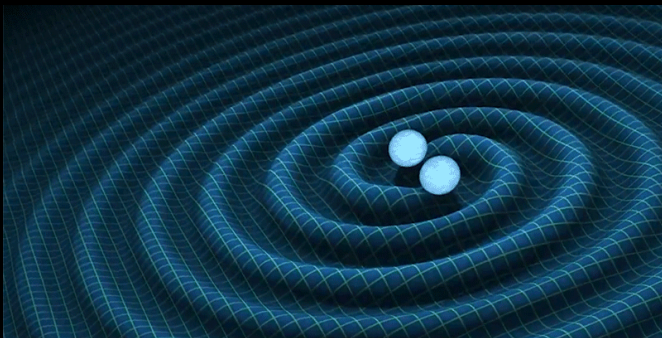
plot generated from online tool
of Moore, Cole, & Berry (2014)

weeks-decades



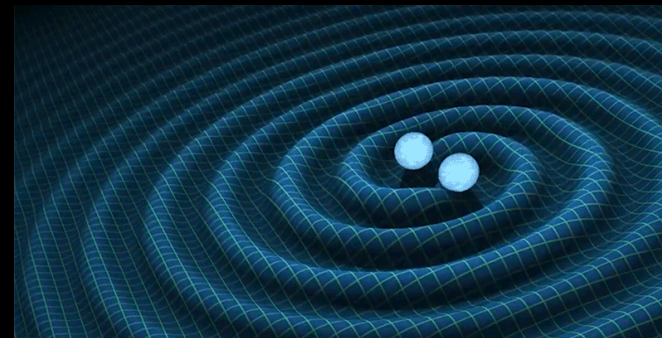
10^8 - $10^{11} M_{\text{sun}}$

hours-days

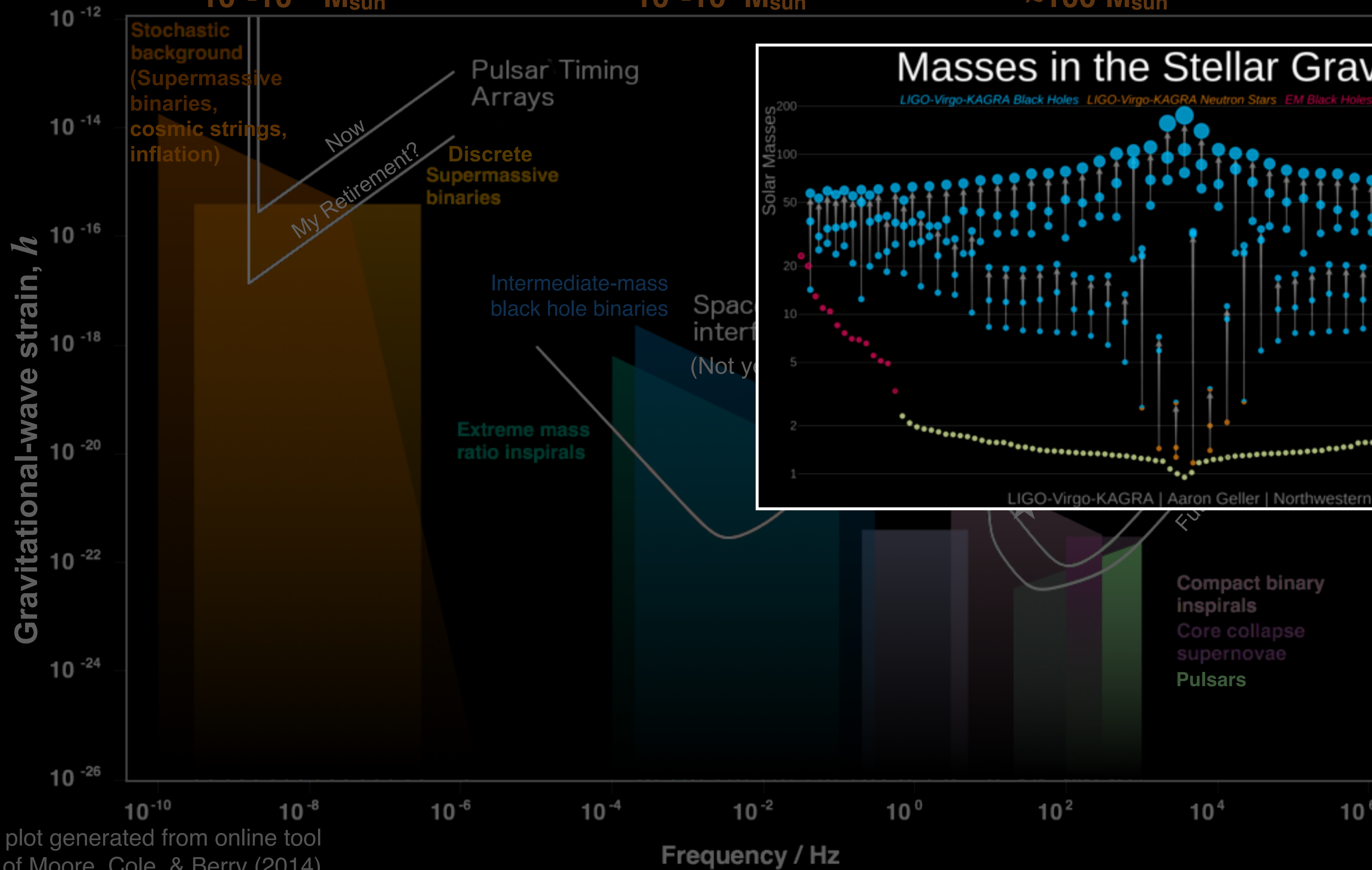


10^4 - $10^7 M_{\text{sun}}$

seconds

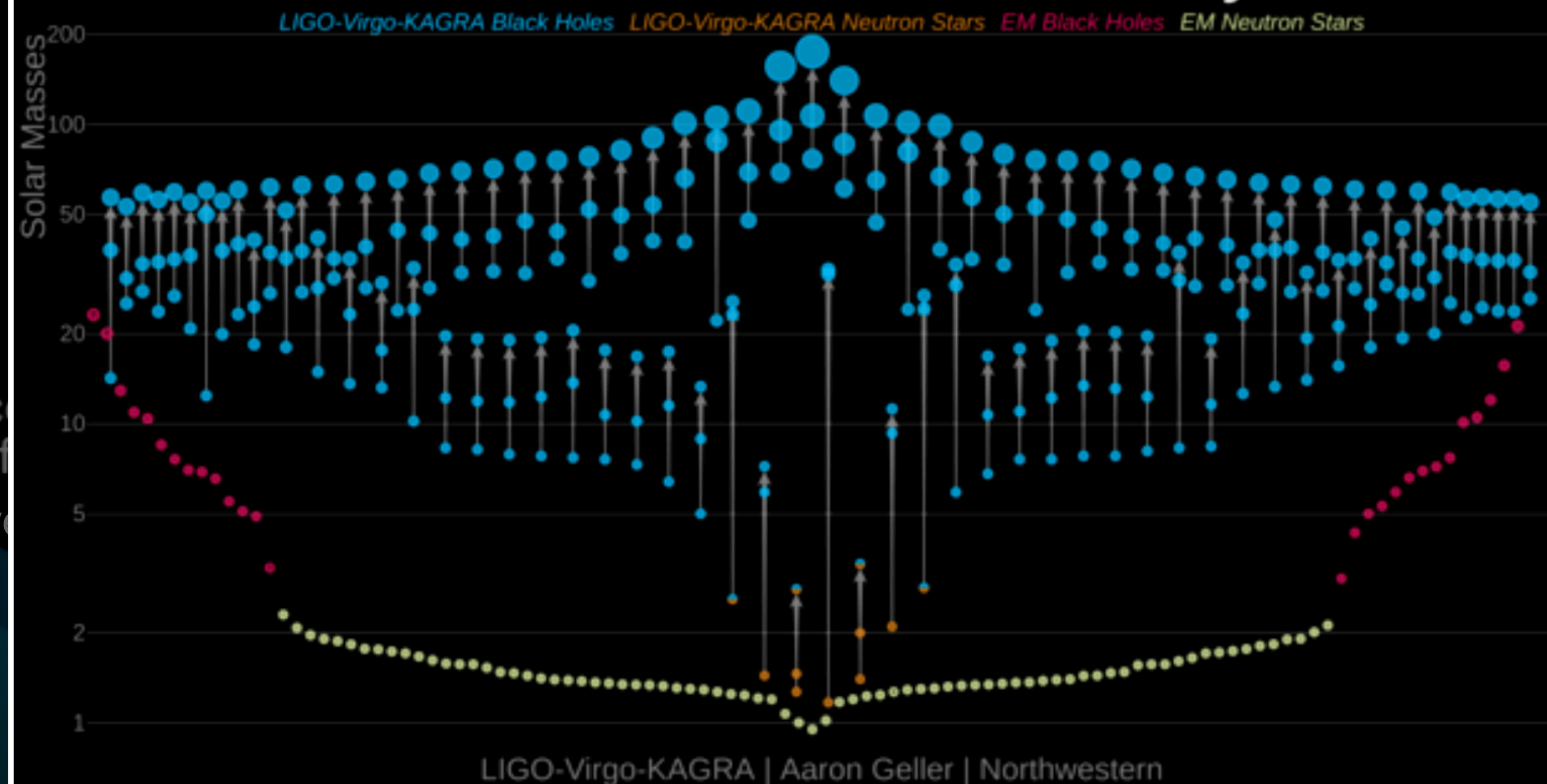


$\sim 100 M_{\text{sun}}$

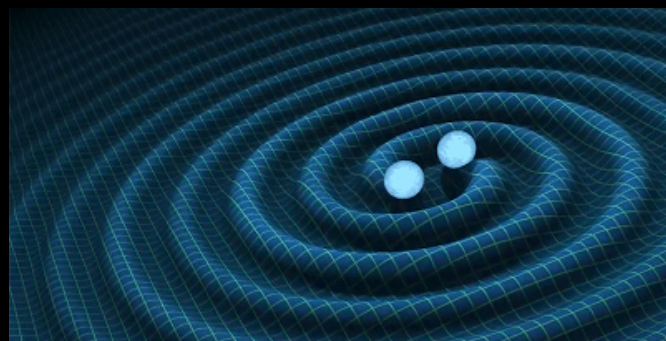


plot generated from online tool
of Moore, Cole, & Berry (2014)

Masses in the Stellar Graveyard

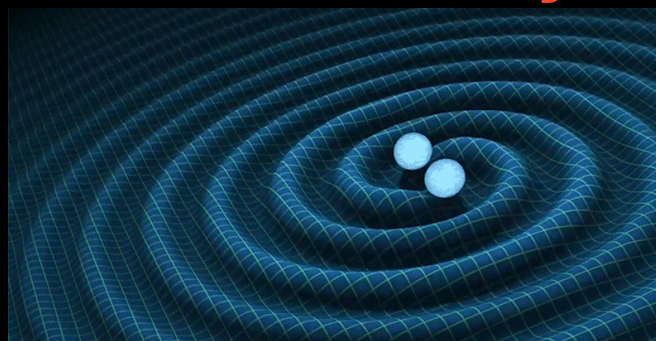


weeks-decades



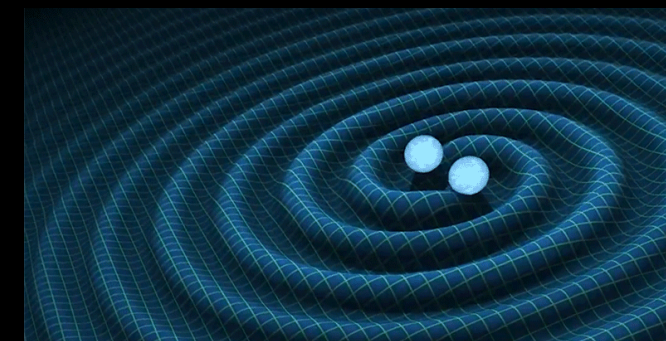
10^8 - $10^{11} M_{\text{sun}}$

hours-days

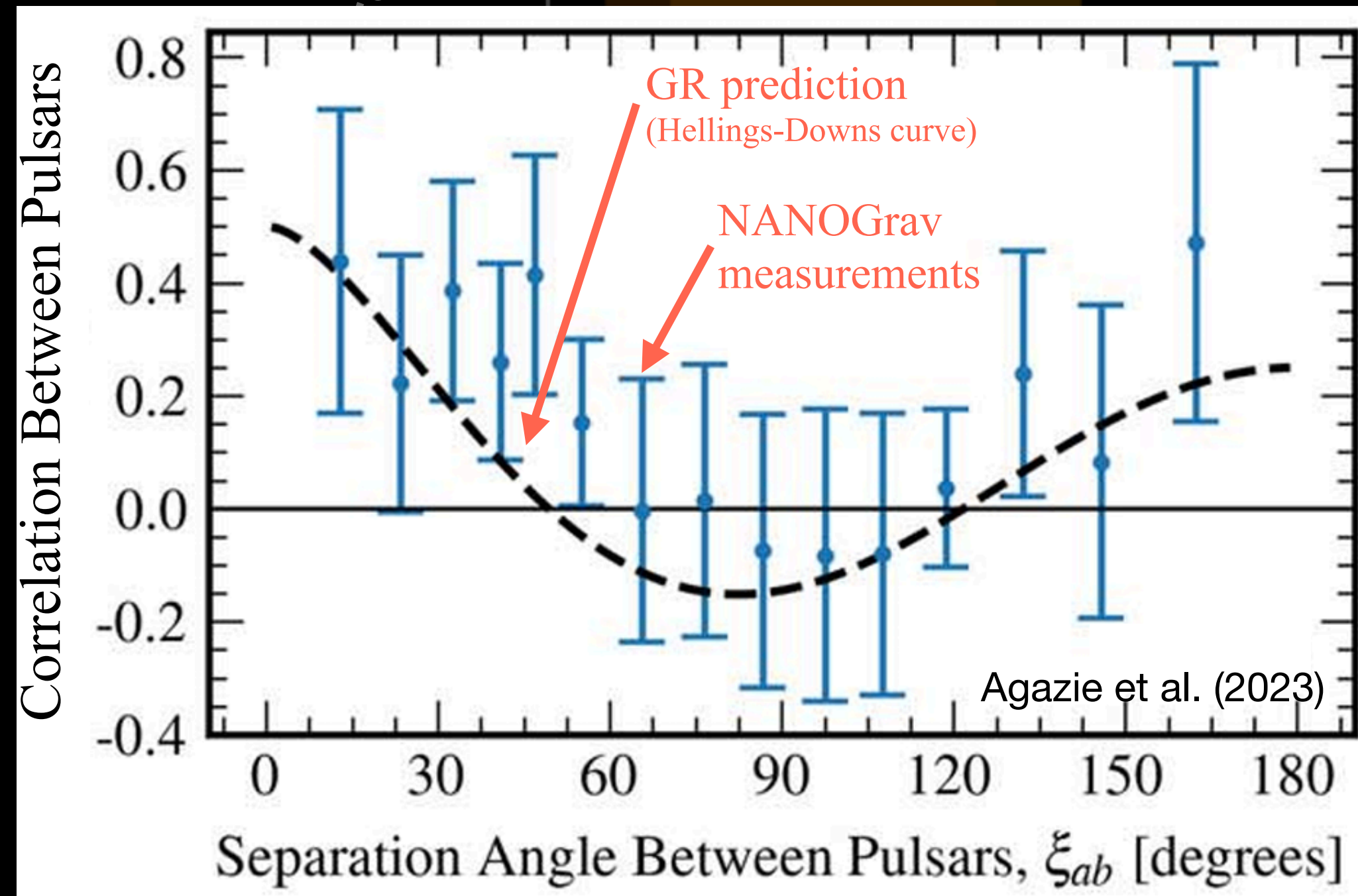
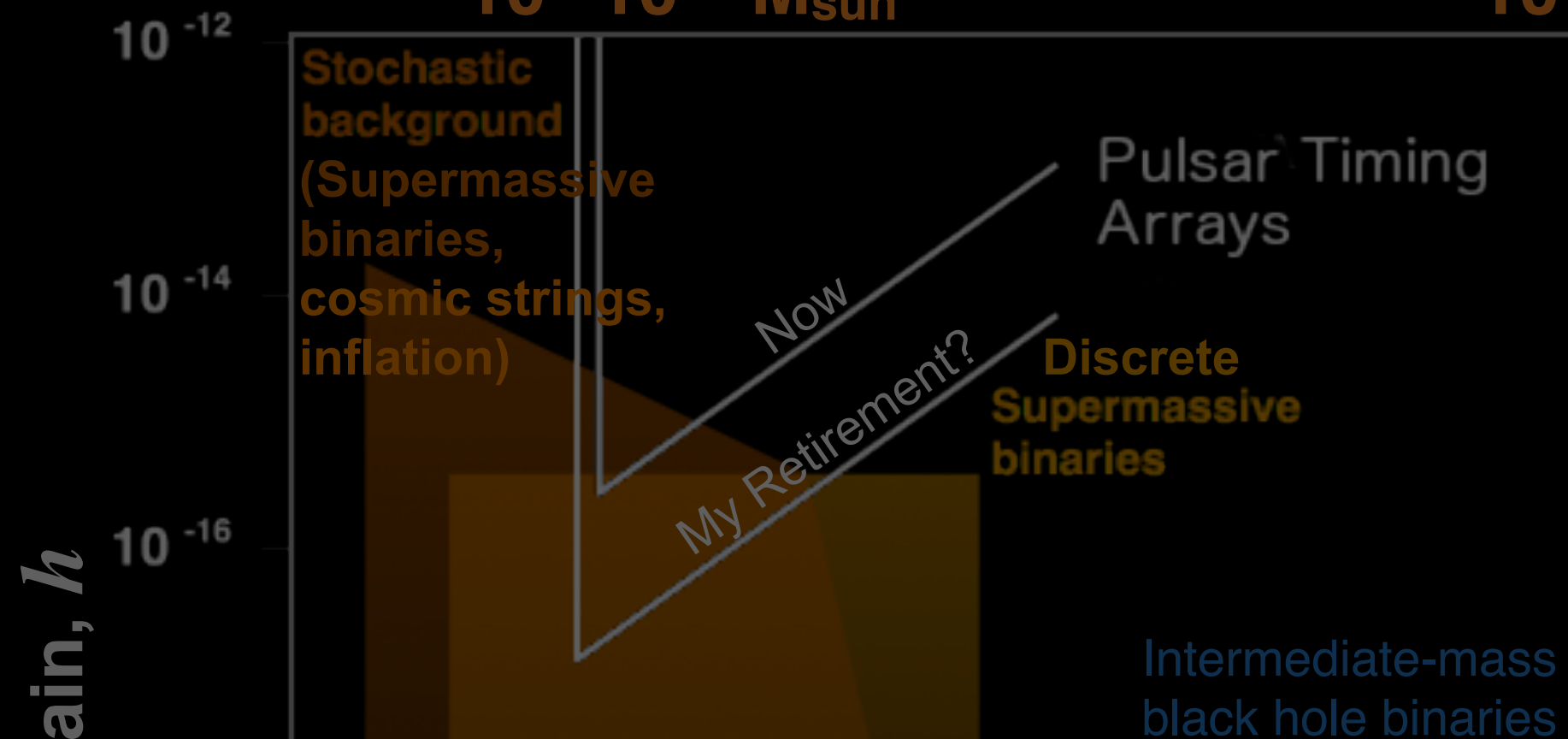


10^4 - $10^7 M_{\text{sun}}$

seconds



$\sim 100 M_{\text{sun}}$



plot generated from online tool
of Moore, Cole, & Berry (2014)

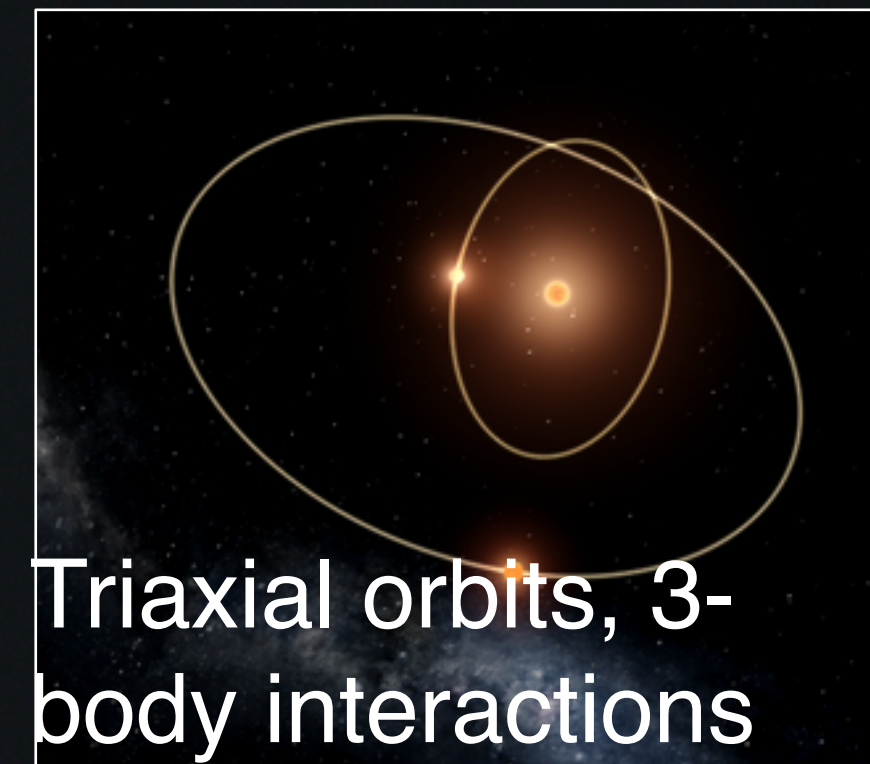
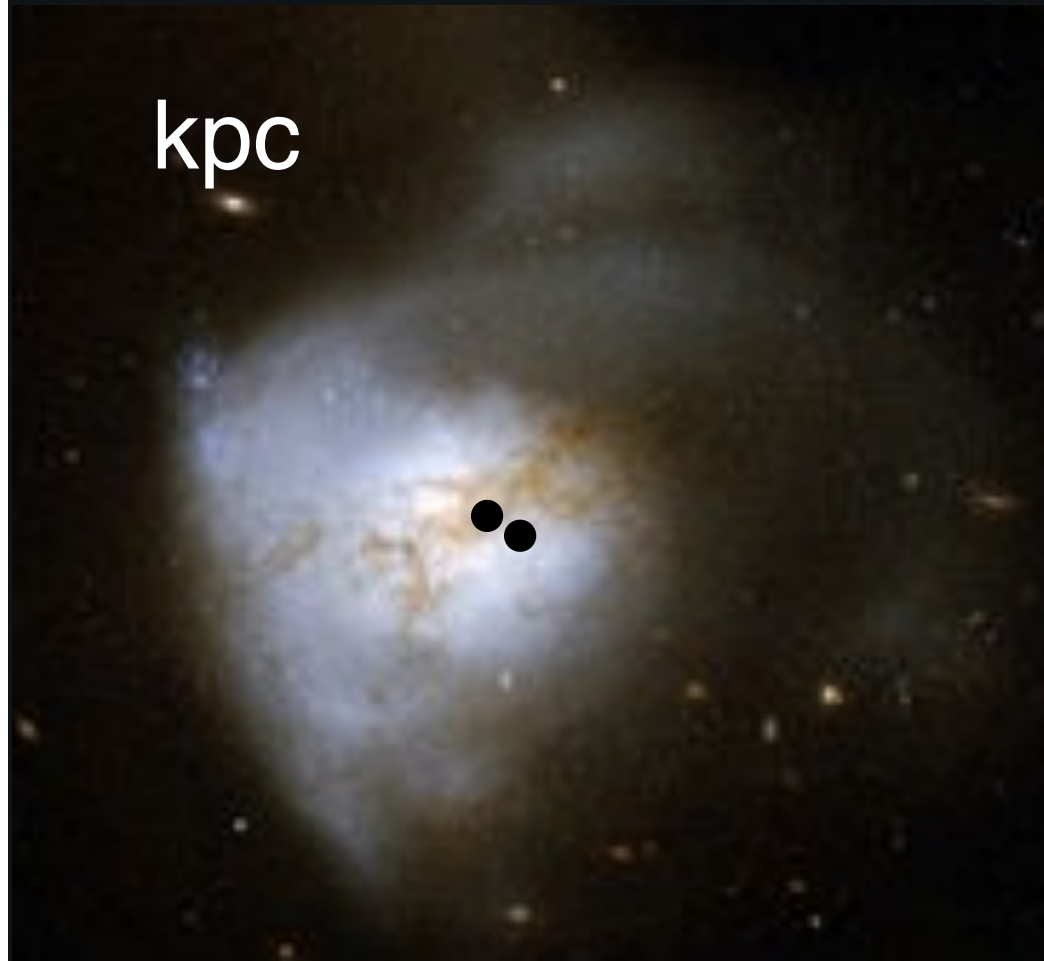
Frequency / Hz

How do MBHBs evolve?

And what do their hosts look like?

Something drives the binary's evolution here, but what?

kpc



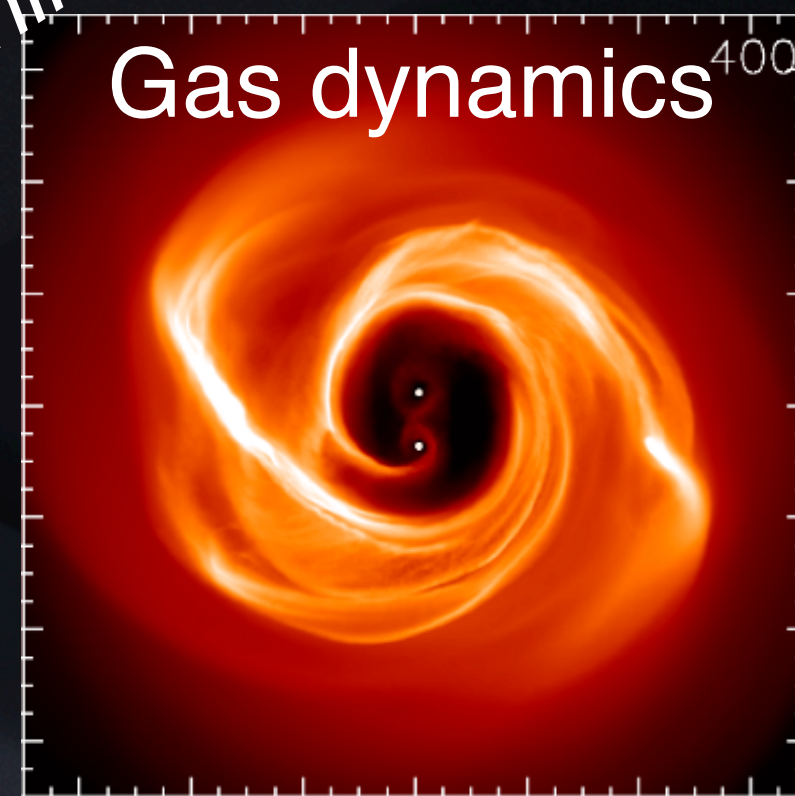
Triaxial orbits, 3-body interactions

e.g. , Khan et al, 2011;
Holley-Bockelmann &
Khan, 2015; Vasiliev et al,
2015; Pfister et al, 2017



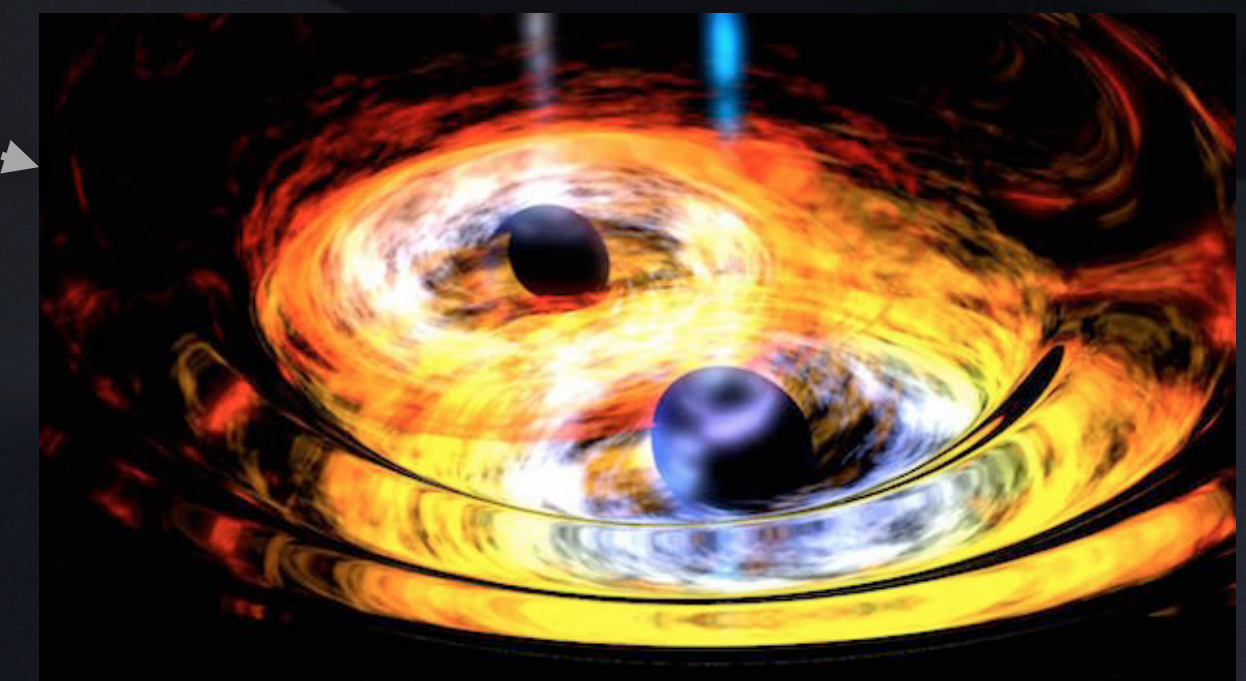
Subsequent
merger

e.g. Pfeifle et al. (2019),
Foord et al. (2021),
Bonetti et al. (2018)



Gas dynamics

e.g. Cuadra et al. (2009), Chapon et
al. (2013), Franchini et al (2021)

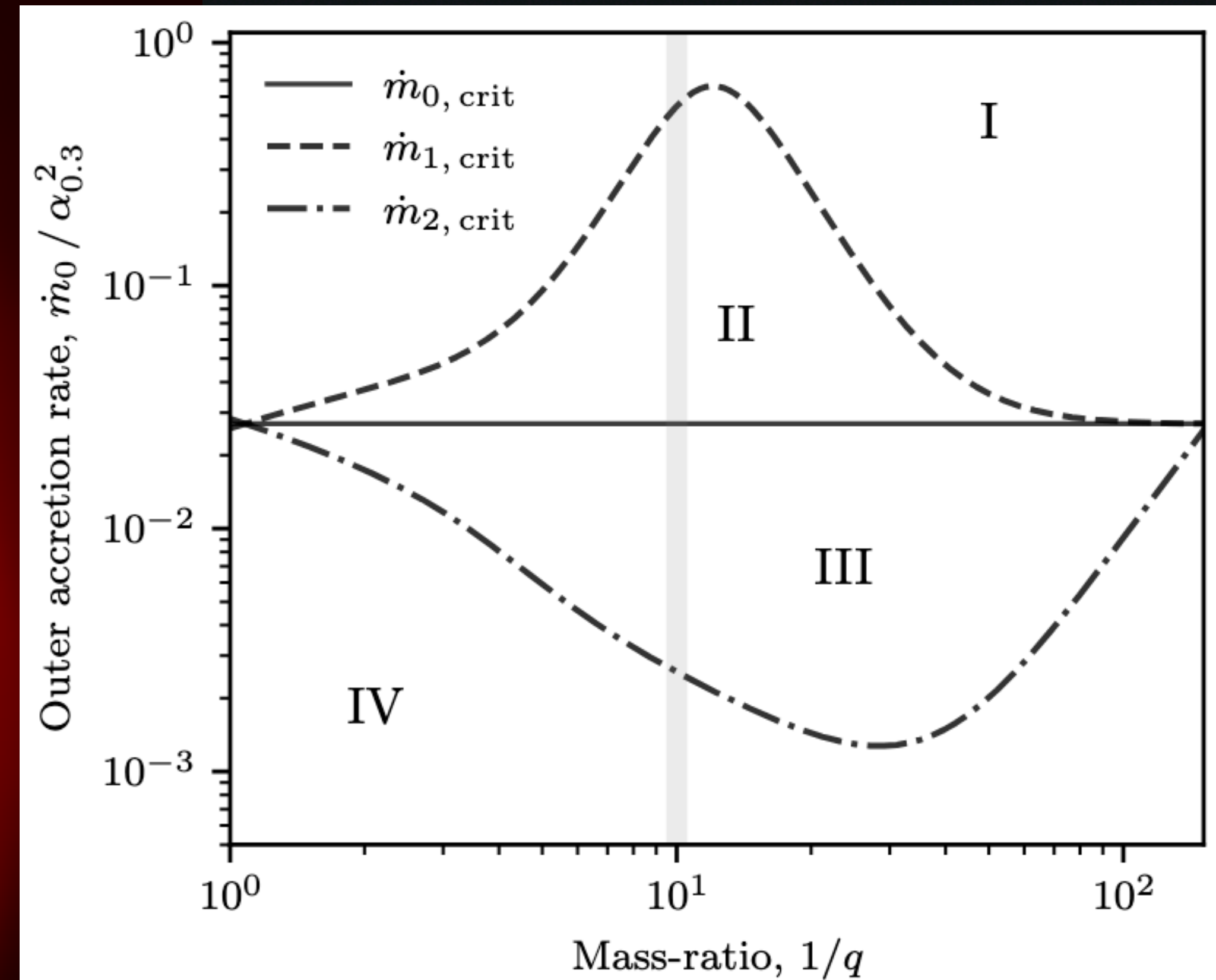


$\ll 0.1$ pc

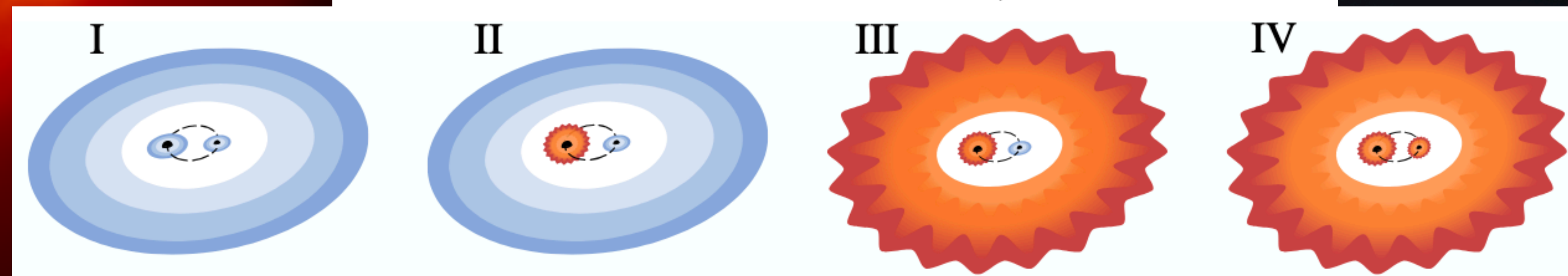
AGN, as we know, are *messy*.

Tiede & D'Orazio (2024)

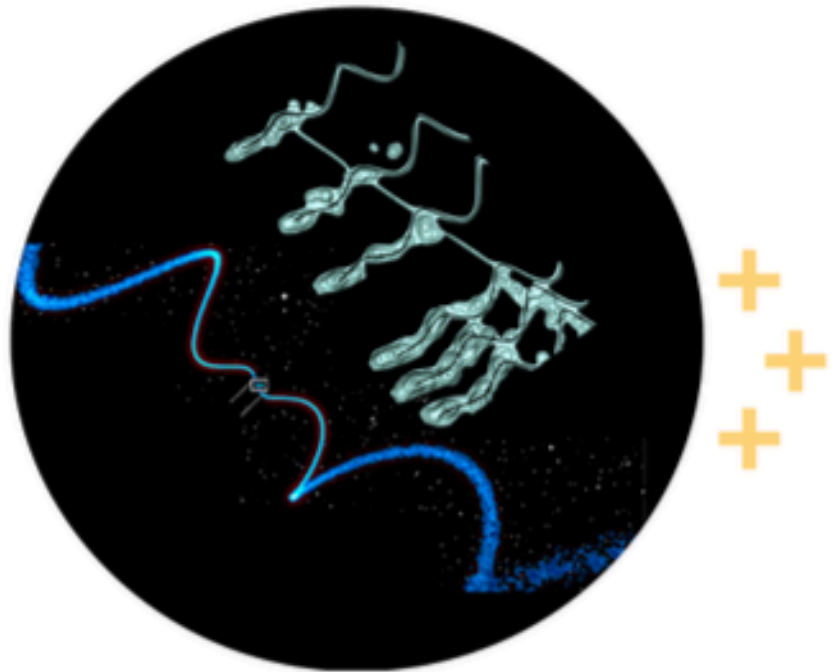
Two black holes = trouble²



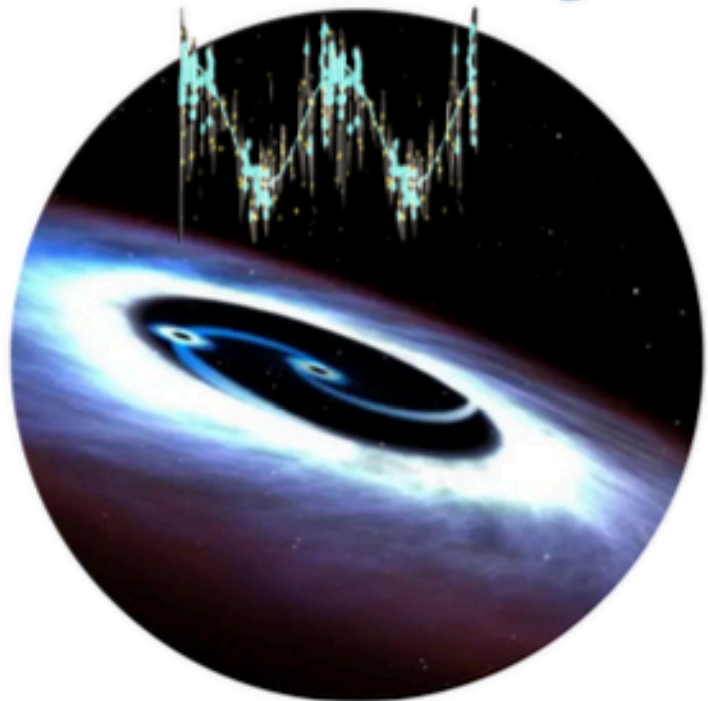
Cuadra et al. (2009)



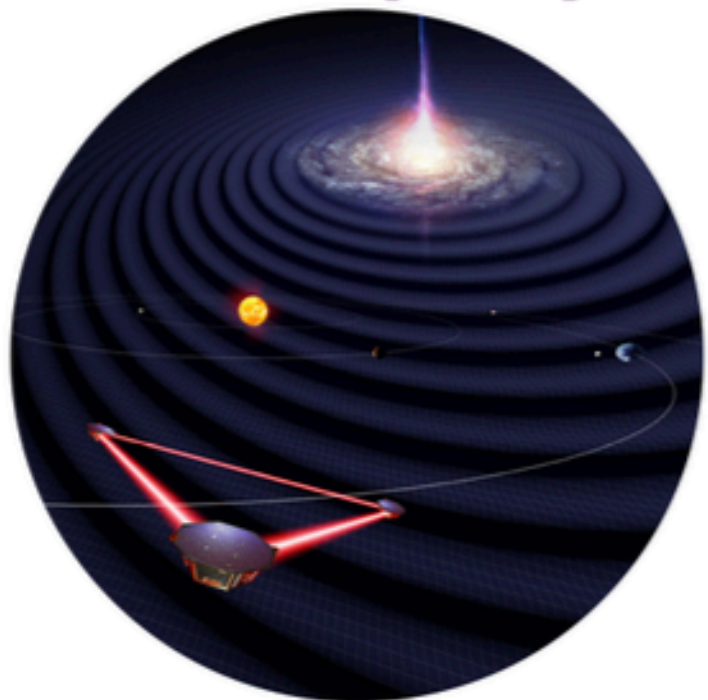
Helical Jets



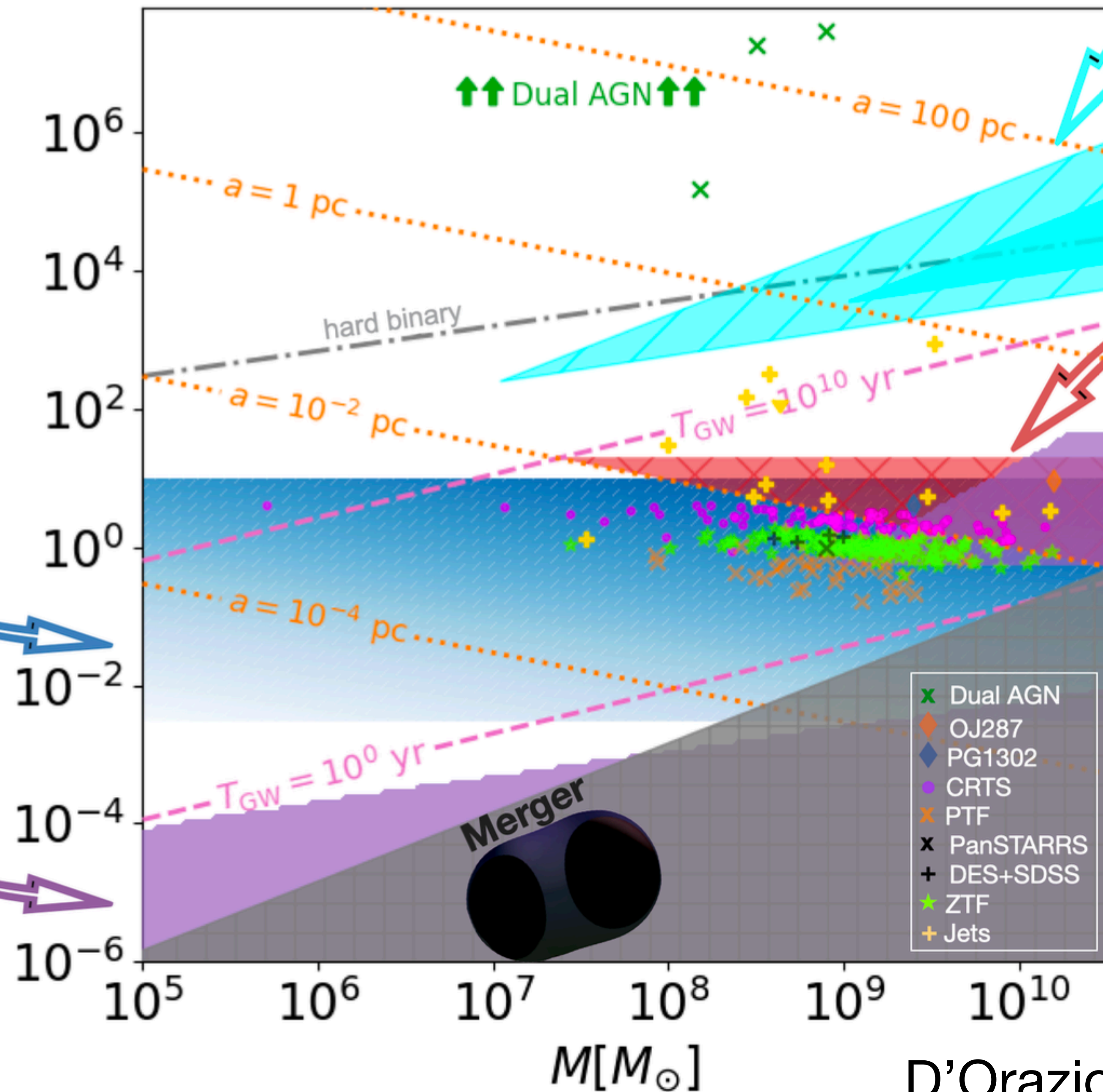
X, γ , radio, optical
Periodicity



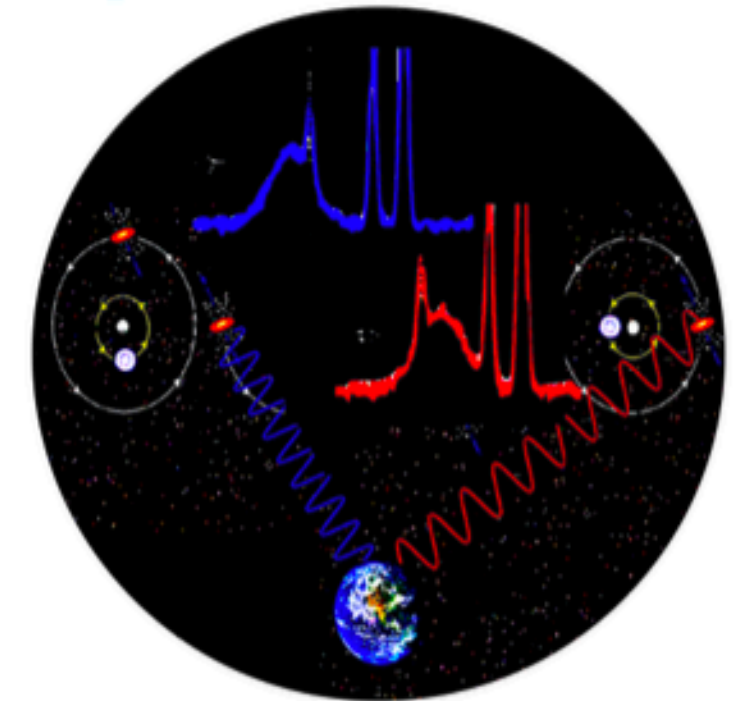
LISA ($z=1$)



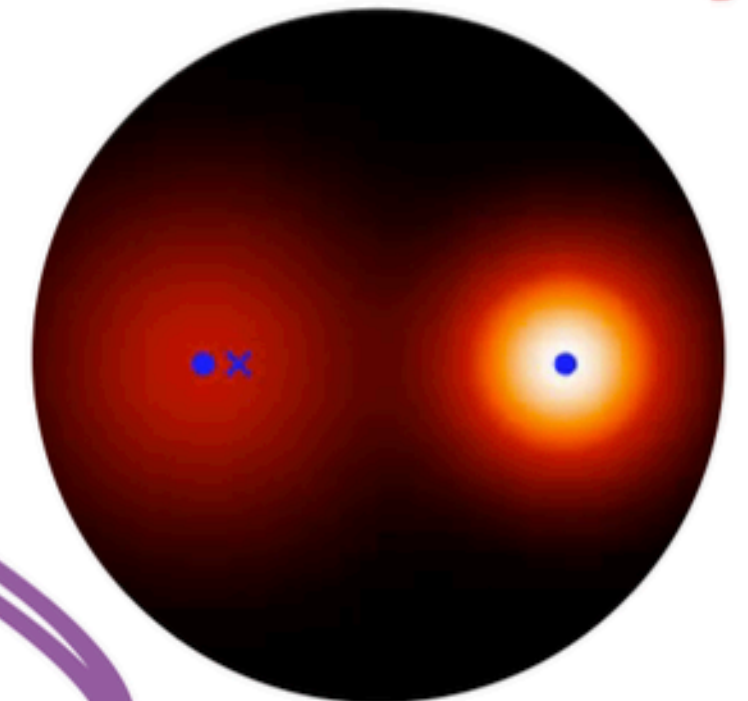
$P_{\text{rest}}[\text{yr}]$



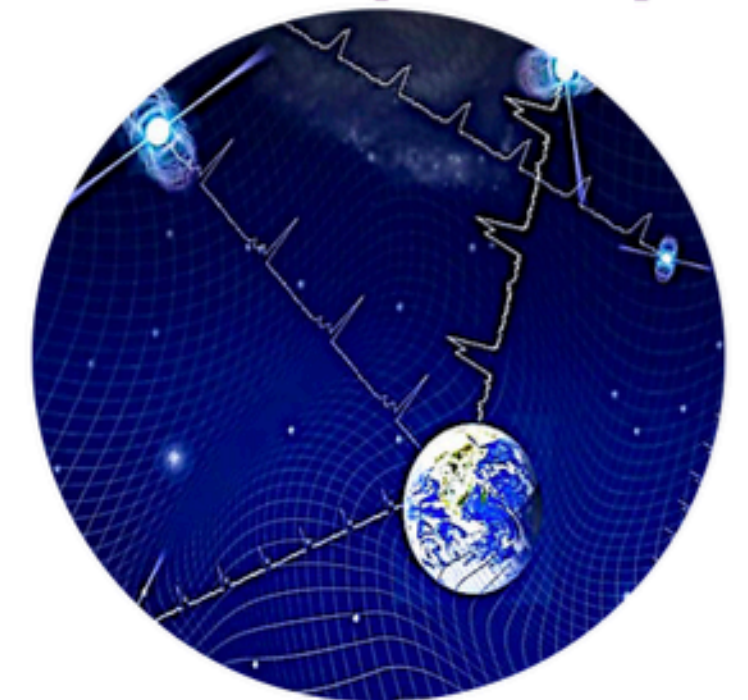
Spectral shifts



VLBI astrometry

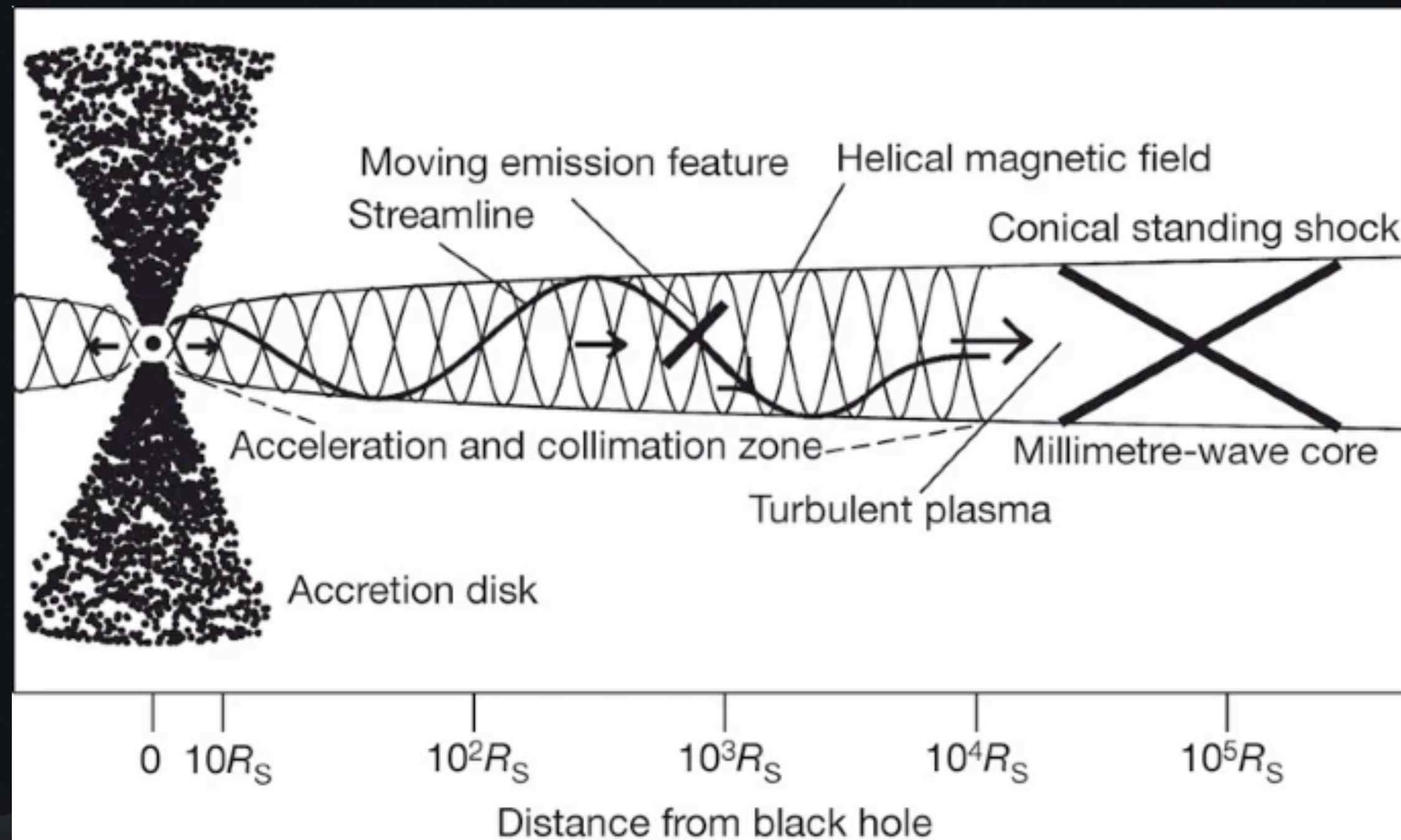


PTAs ($z=0.3$)

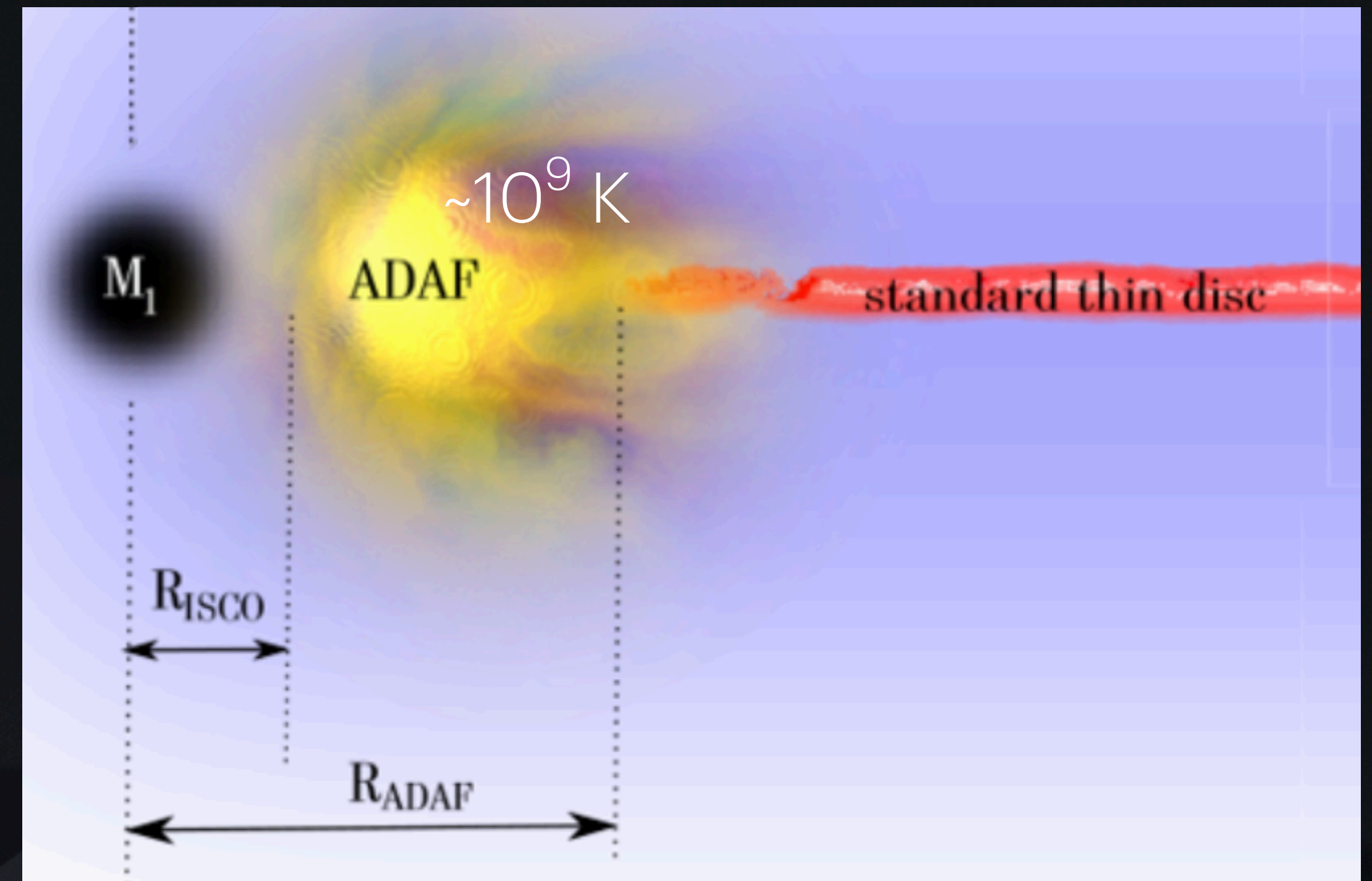


D'Orazio & Charisi (2025)

Flat-spectrum Imaging: Cores and Accretion Flows



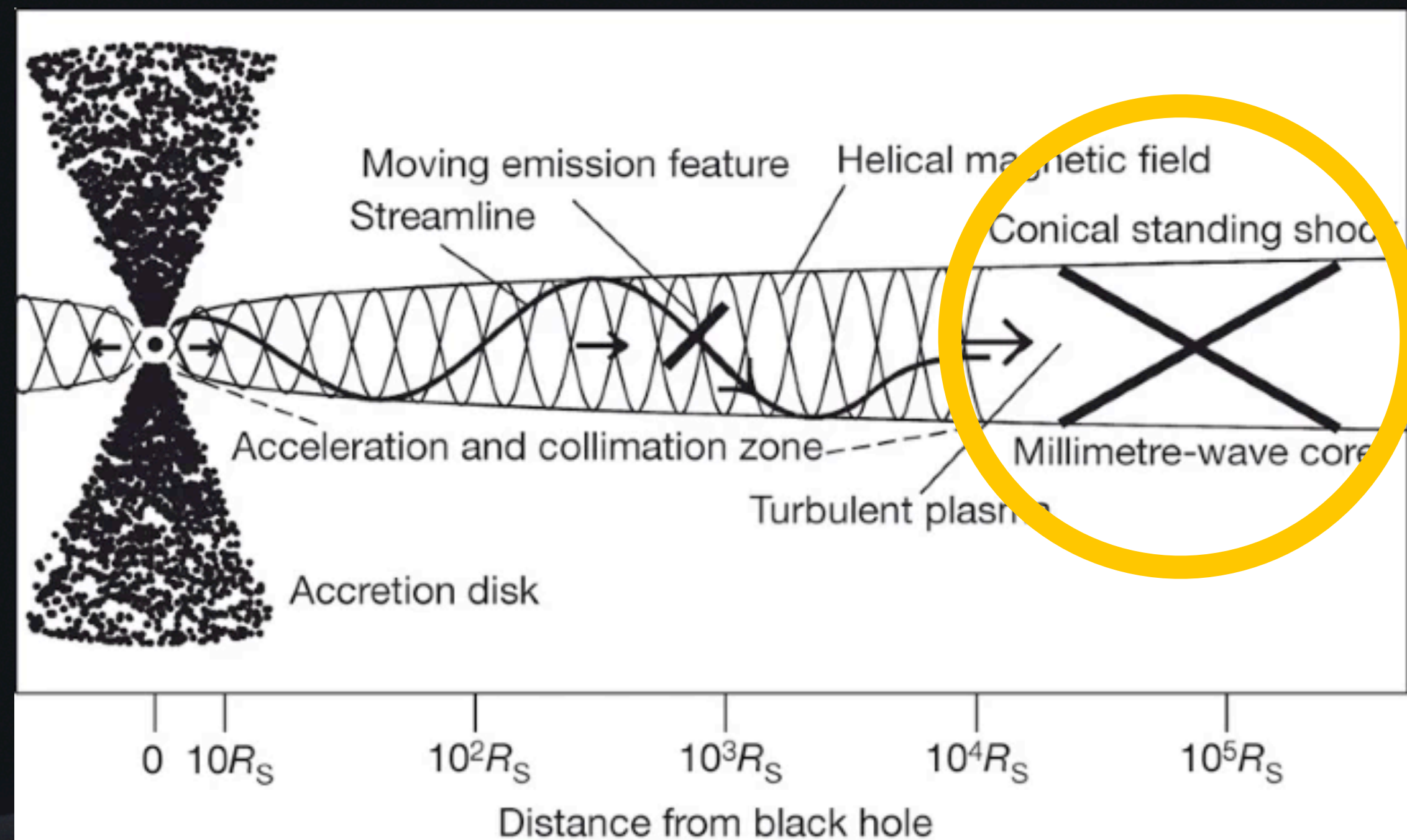
Marscher et al. (2008)



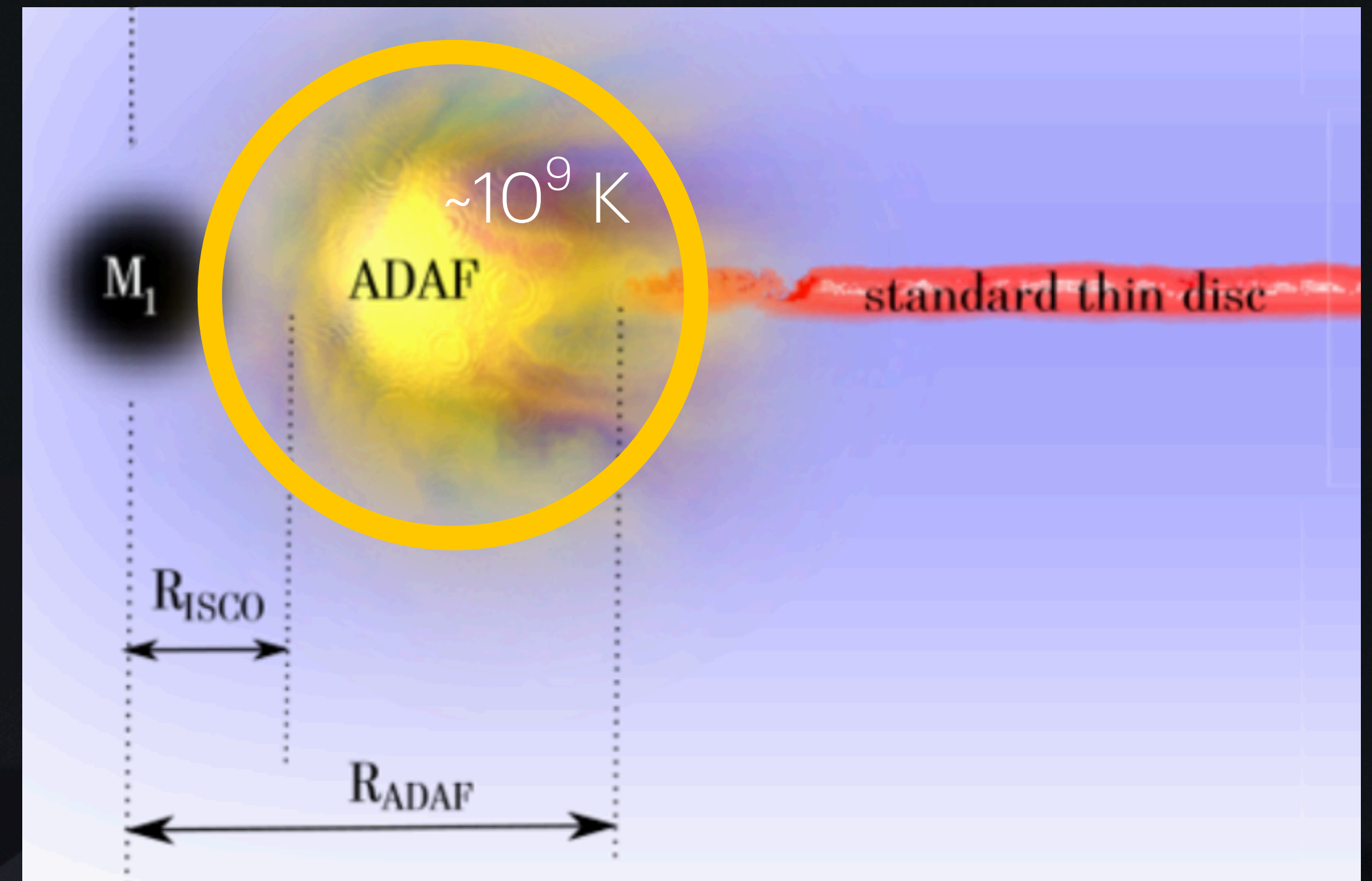
Zajacek et al. (2024)

Flat-spectrum Imaging: Cores and Accretion Flows

Both
Self-Absorbed Synchrotron



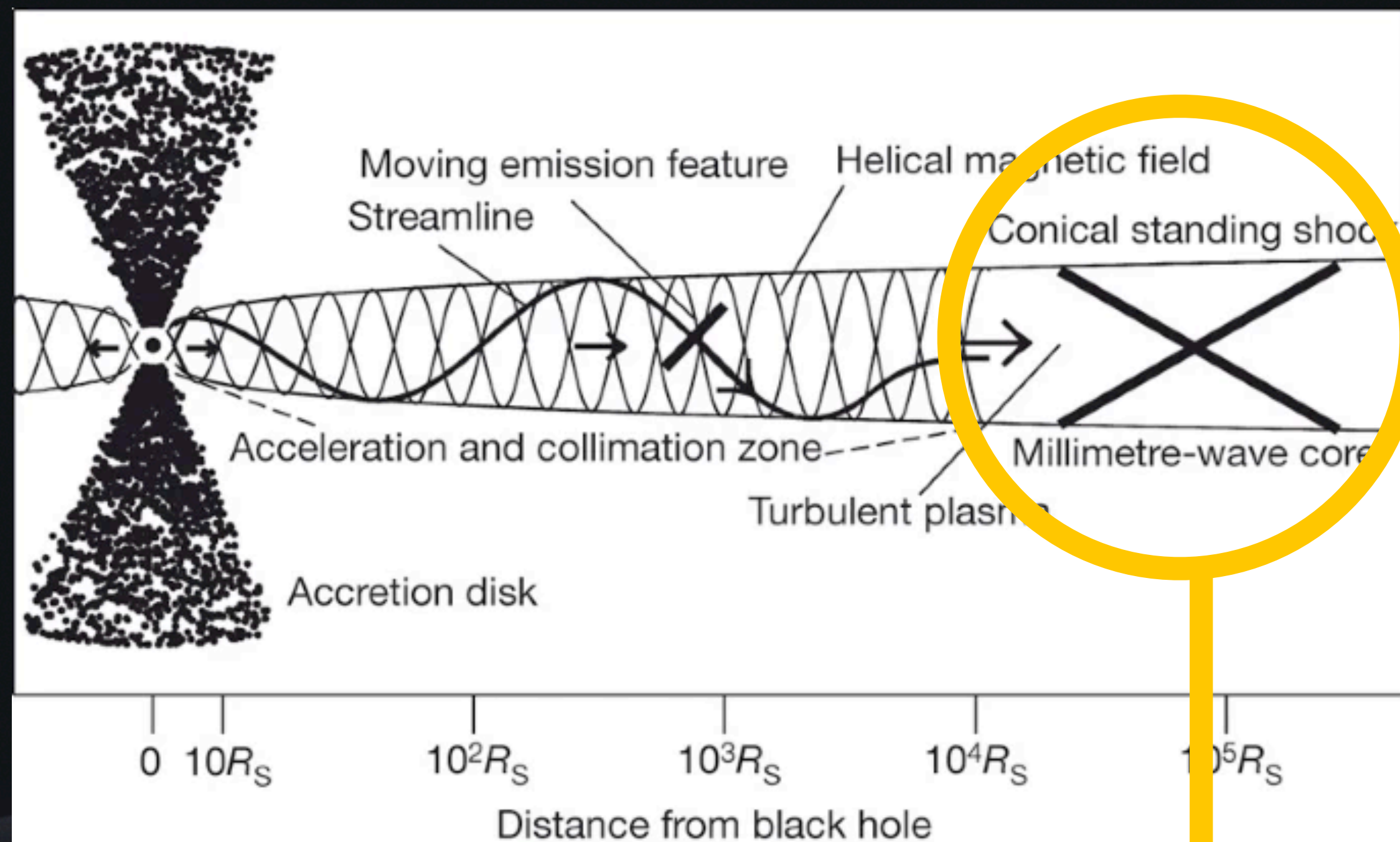
Marscher et al. (2008)



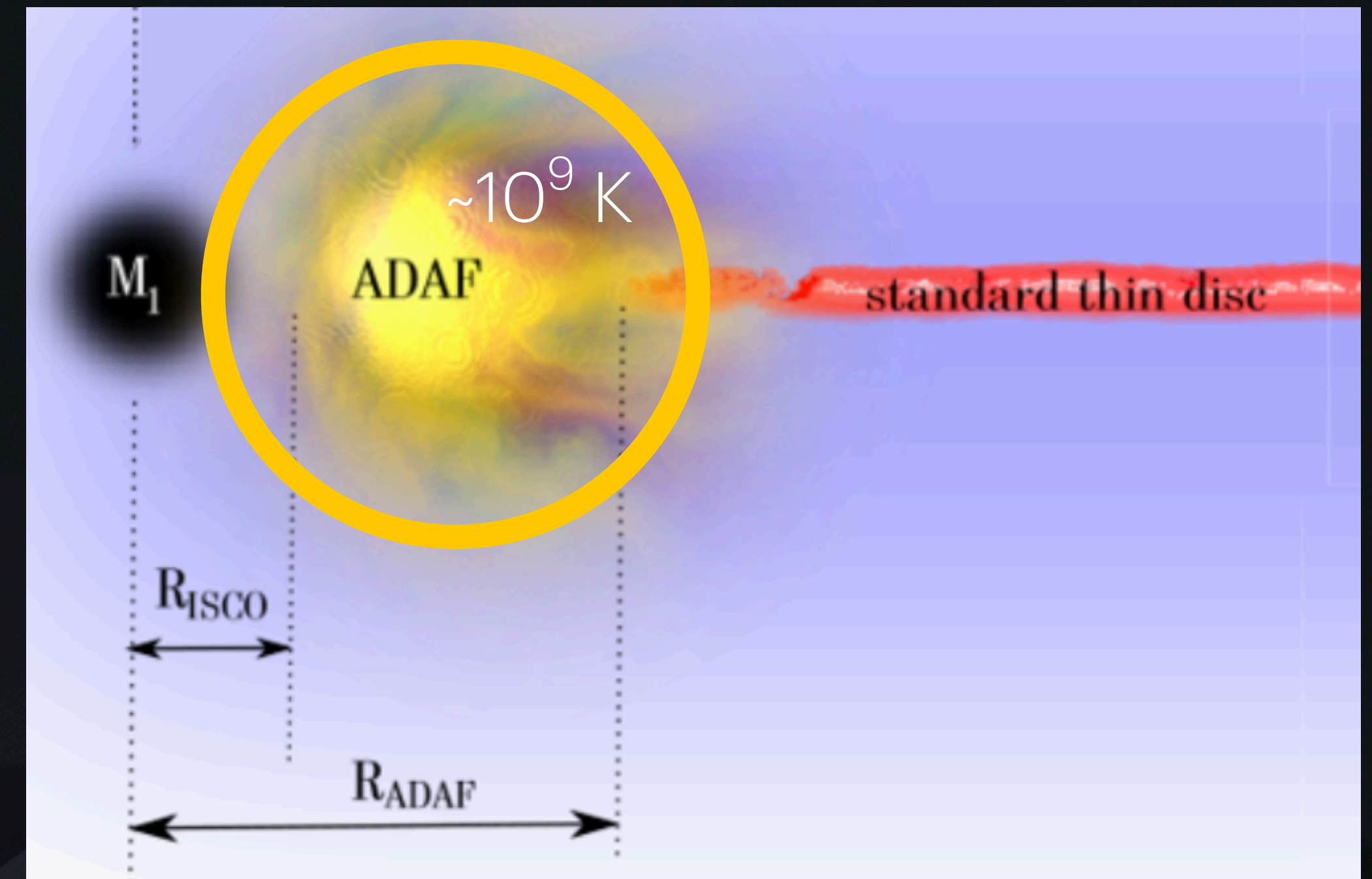
Zajacek et al. (2024)

Flat-spectrum Imaging: Cores and Accretion Flows

Both
Self-Absorbed Synchrotron



Marscher et al. (2008)

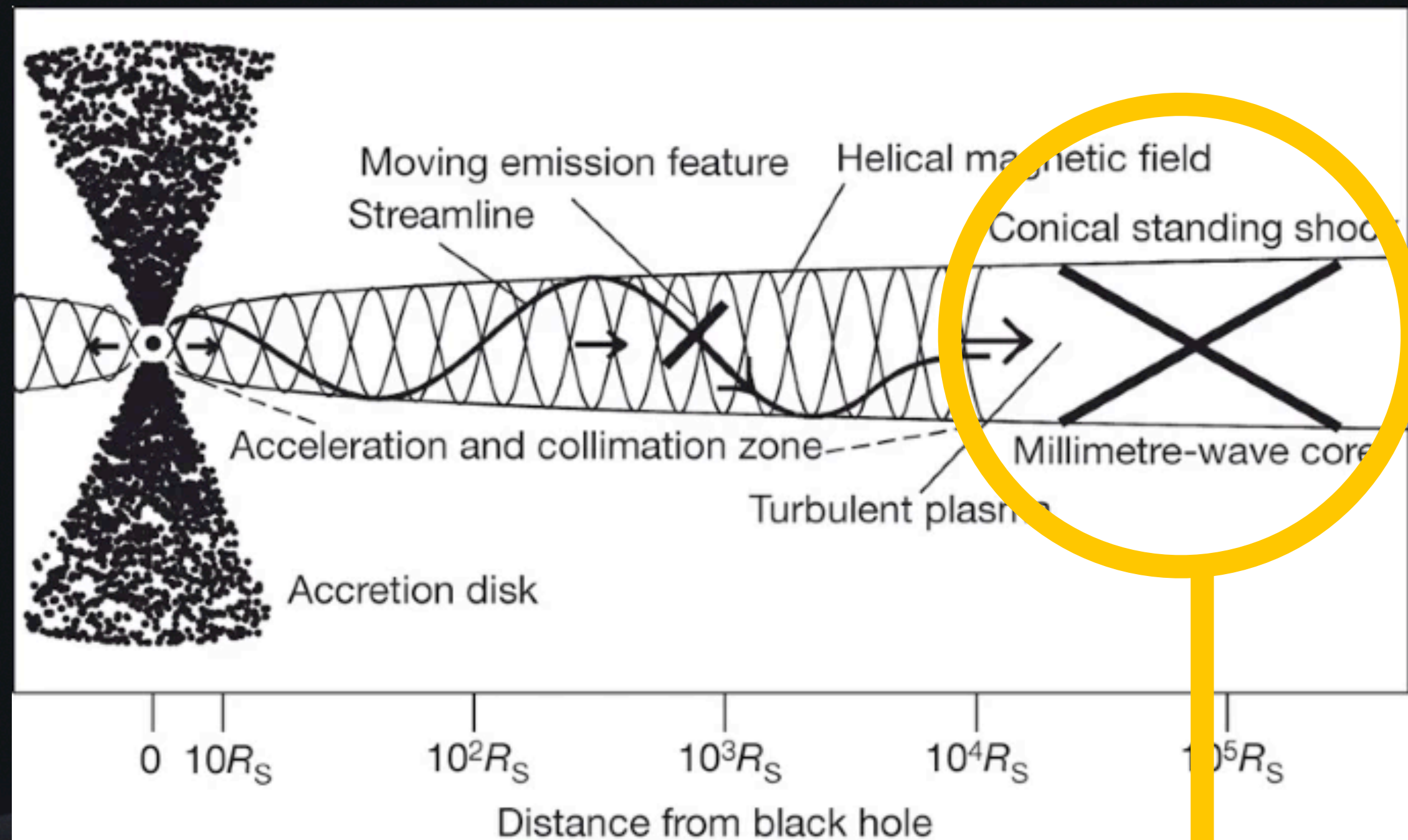


Zajacek et al. (2024)

Peaks cm to mm

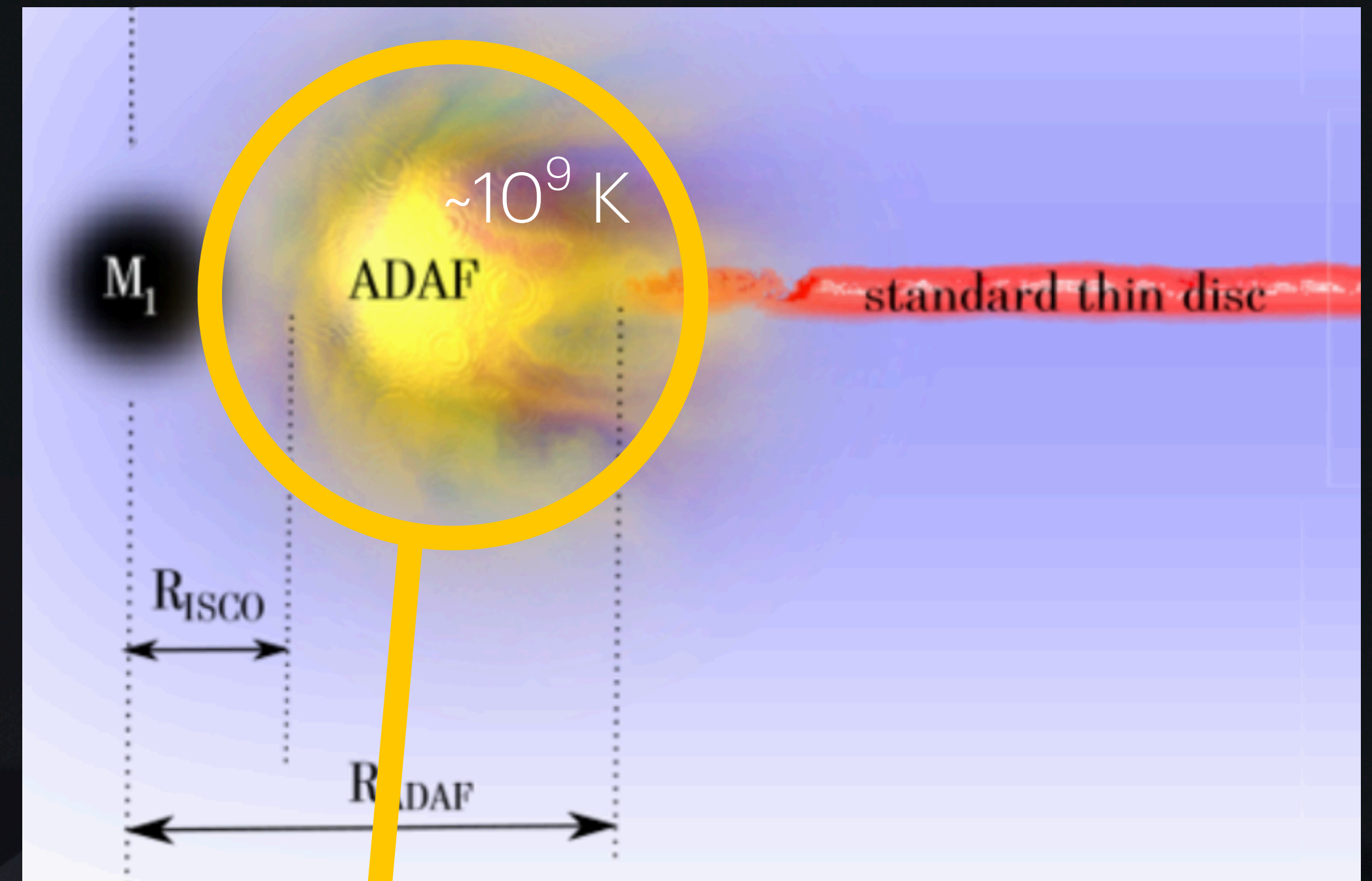
Flat-spectrum Imaging: Cores and Accretion Flows

Both
Self-Absorbed Synchrotron



Marscher et al. (2008)

Peaks cm to mm



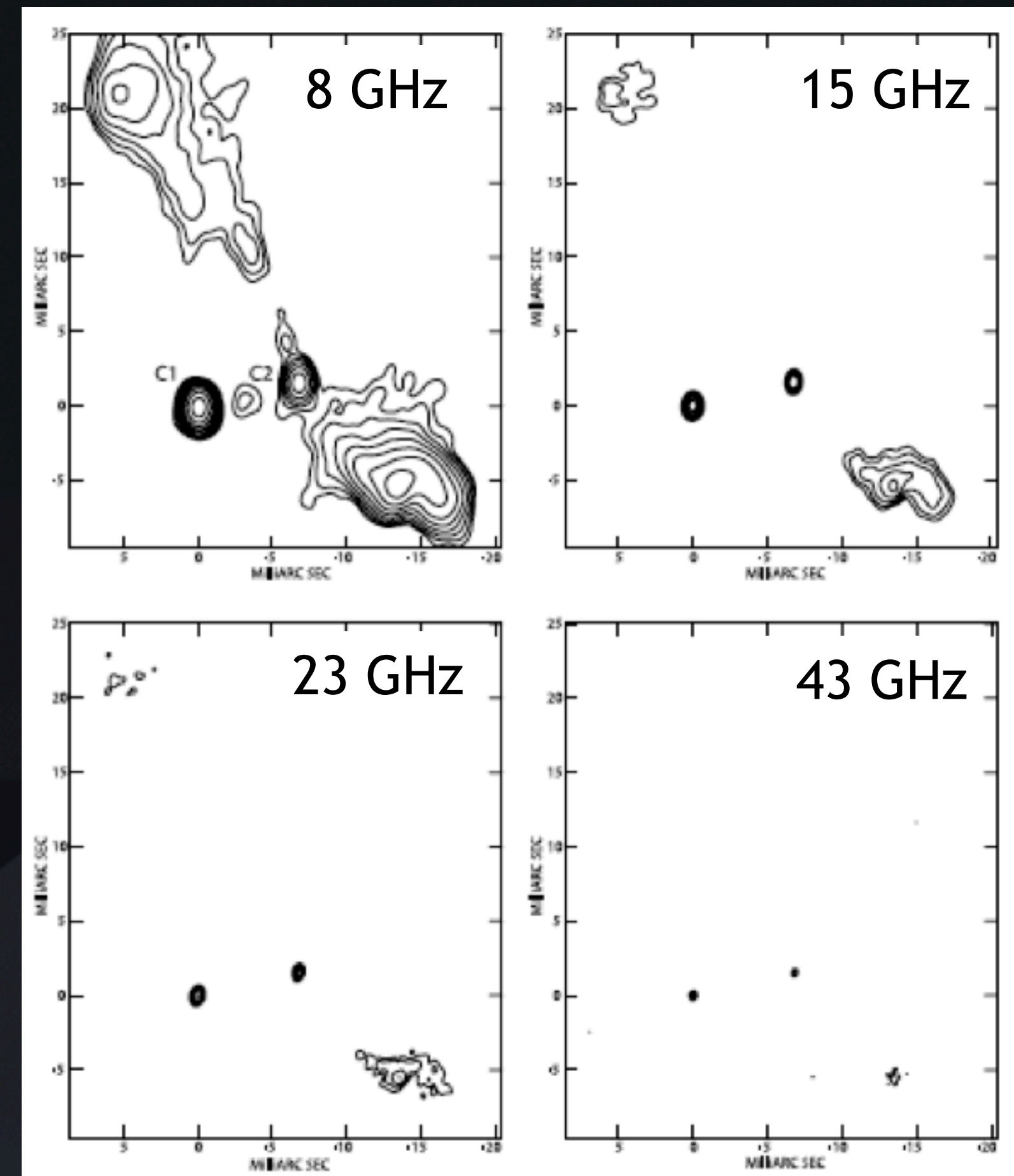
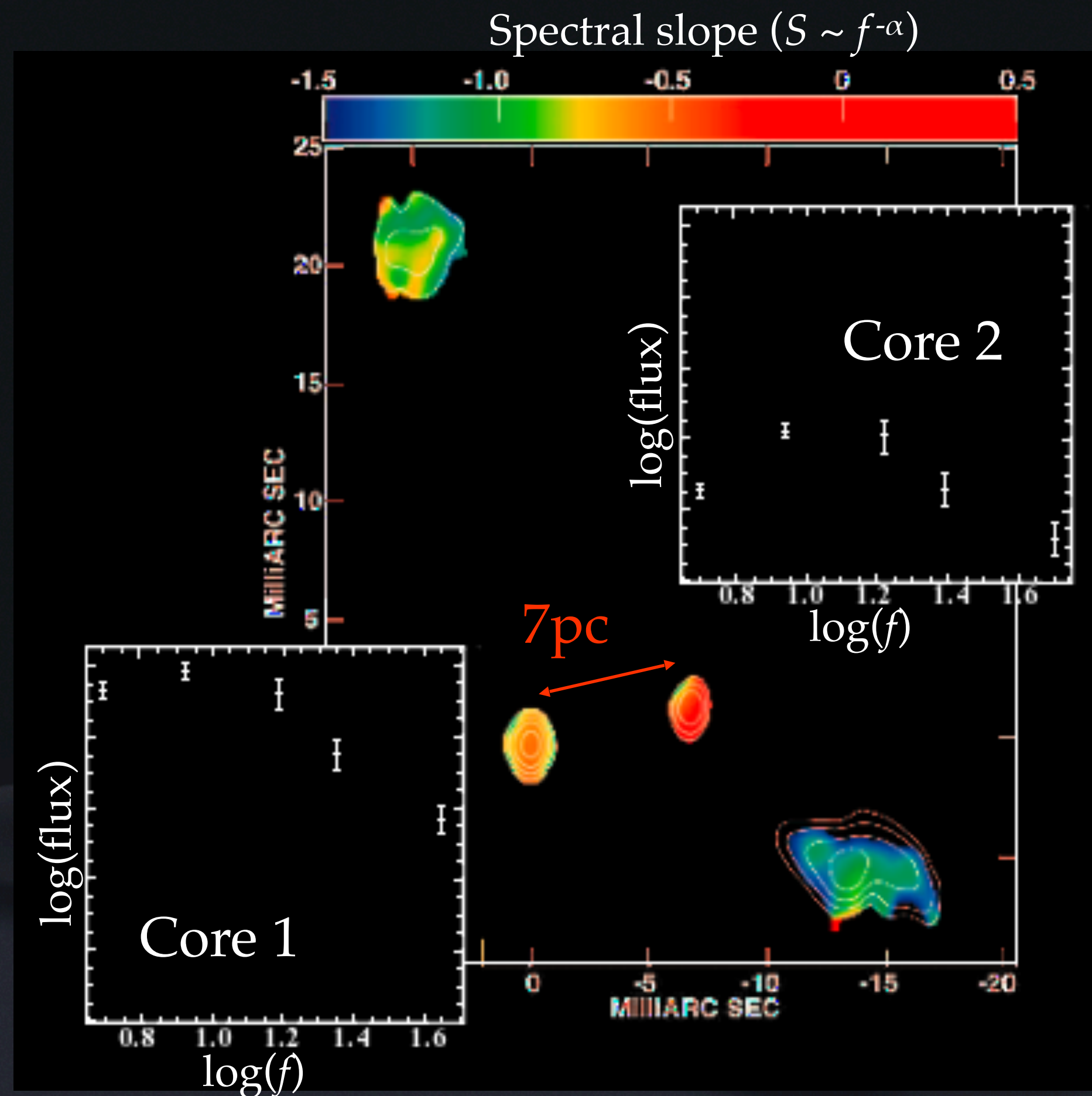
Zajacek et al. (2024)

Peaks ~mm

Directly Resolving MBHB

0402+379: The VLBA's own Gold Standard!

$P_{\text{orbit}} \sim 10^4$ years!



Rodriguez et al. (2006); Burke-Spolaor (2011); Bansal et al. (2017)

Direct Astrometry

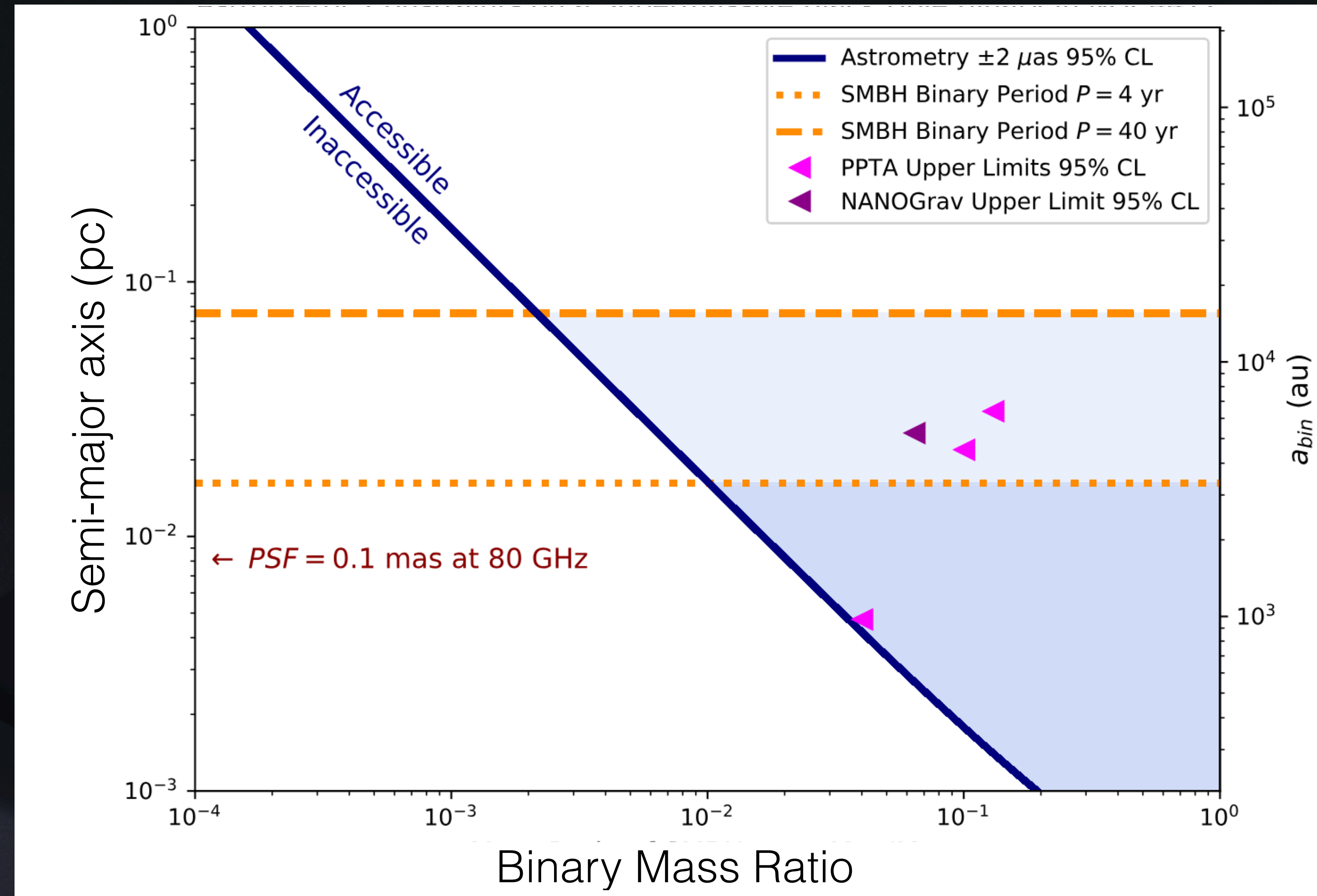
Track primary MBH reflex action with ngVLA,
multiple phase calibrators,
 $2\,\mu\text{as}$ localization



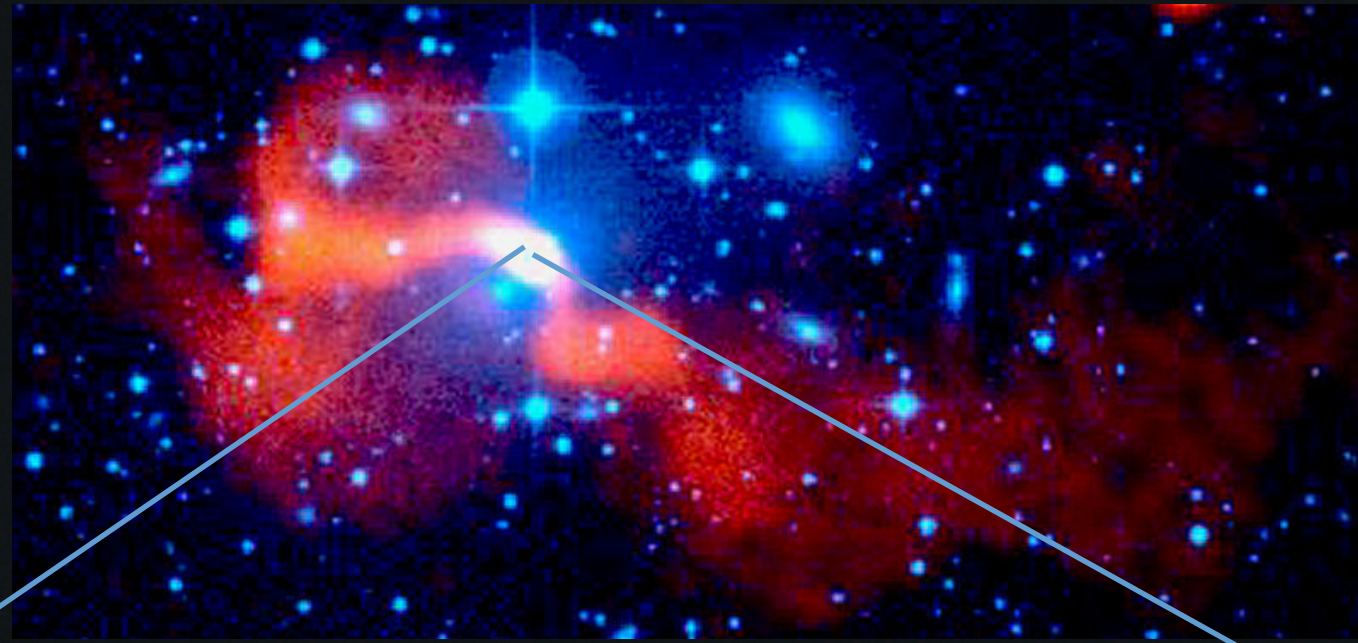
NGC4472:

$$M_{\text{tot}} = 2.4 \times 10^9 M_{\odot}$$

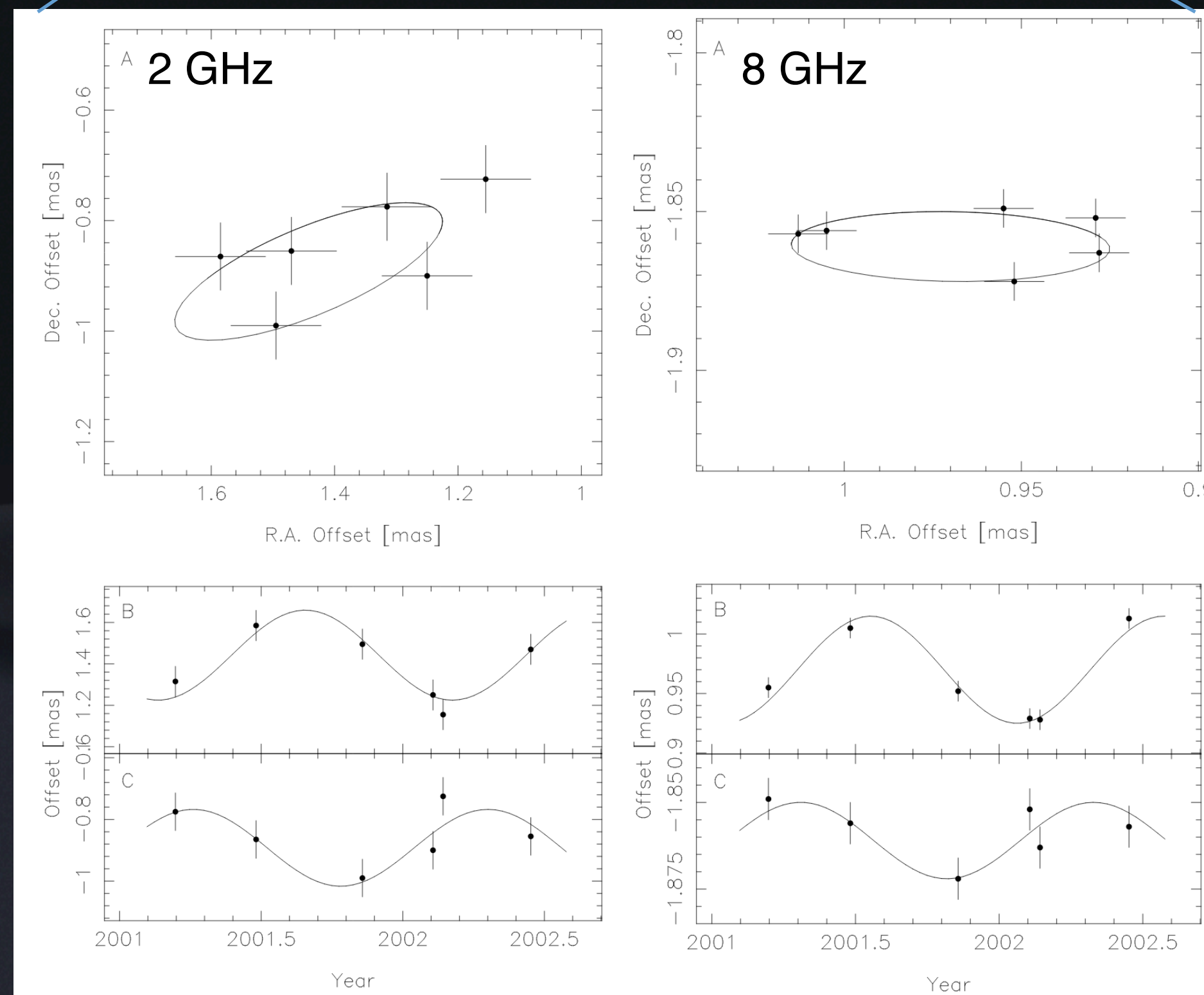
$$D = 16.7 \text{ Mpc}$$



Direct Astrometry

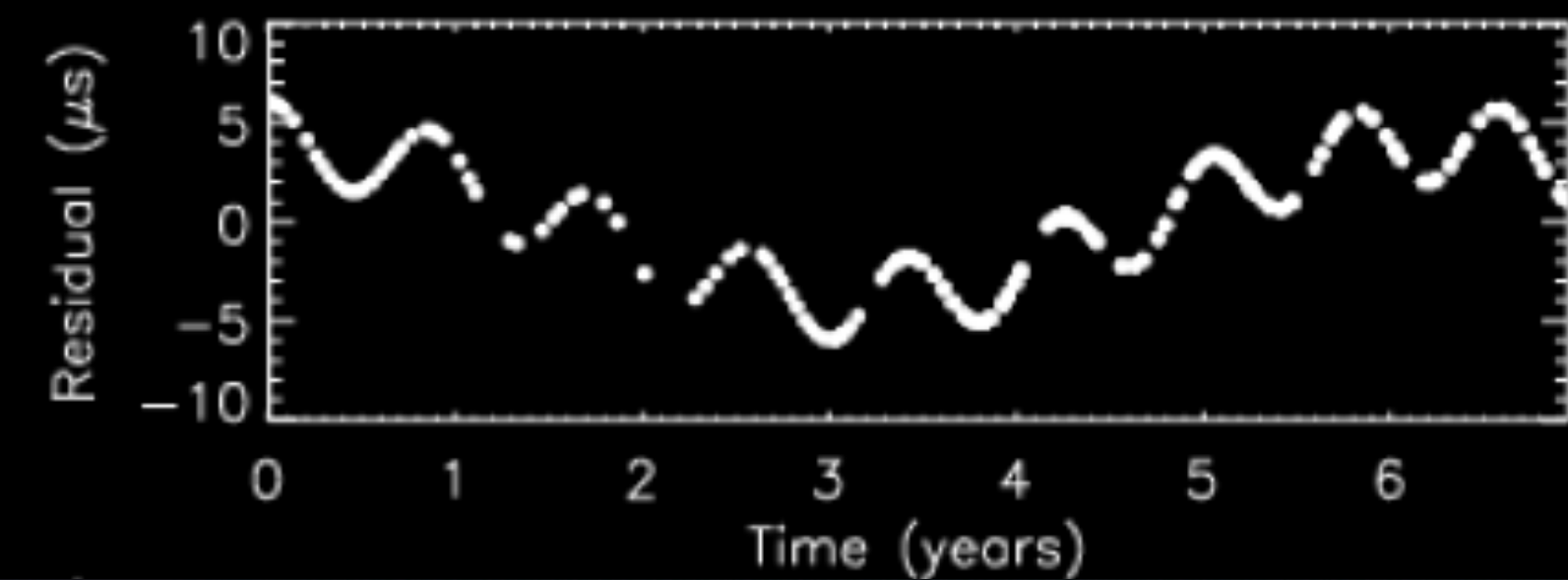


VLBA:

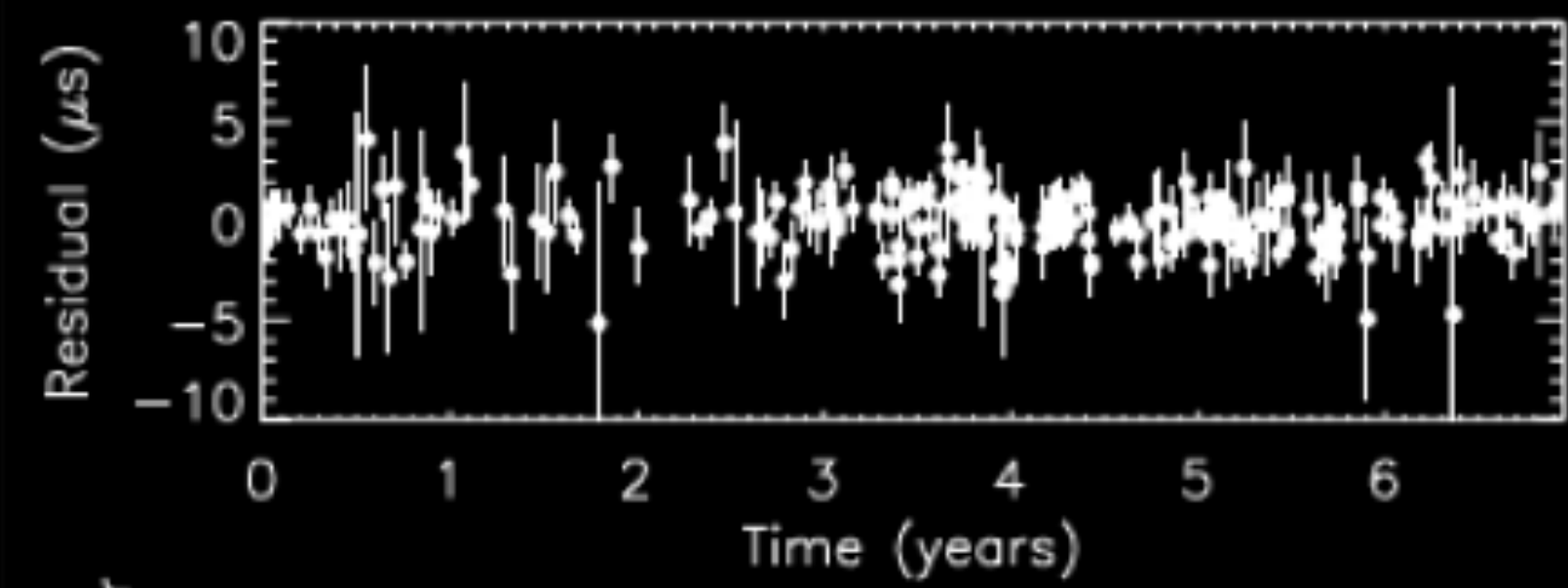


Jenet et al. (2004)

Original binary model: should see GWs...



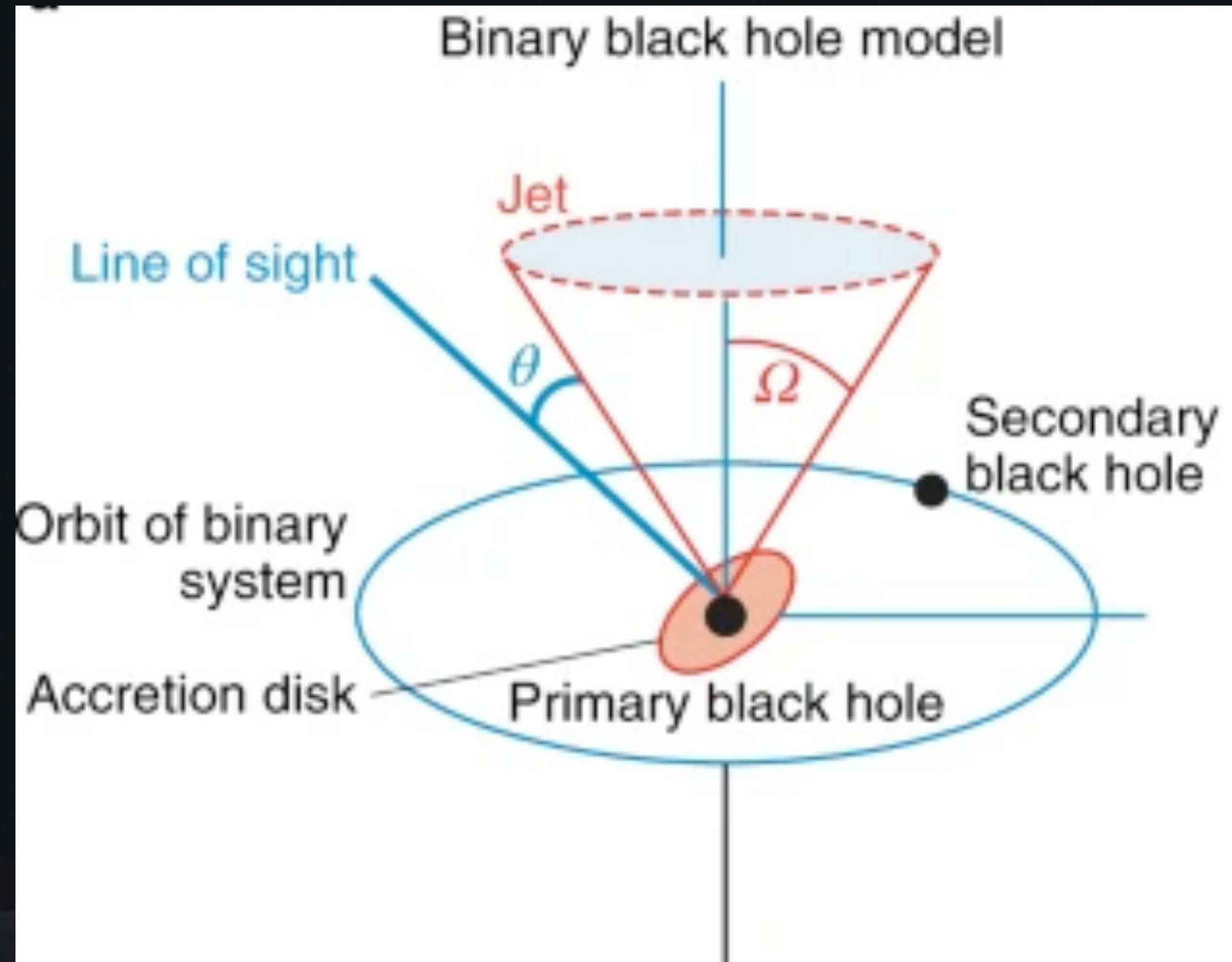
Actually see...



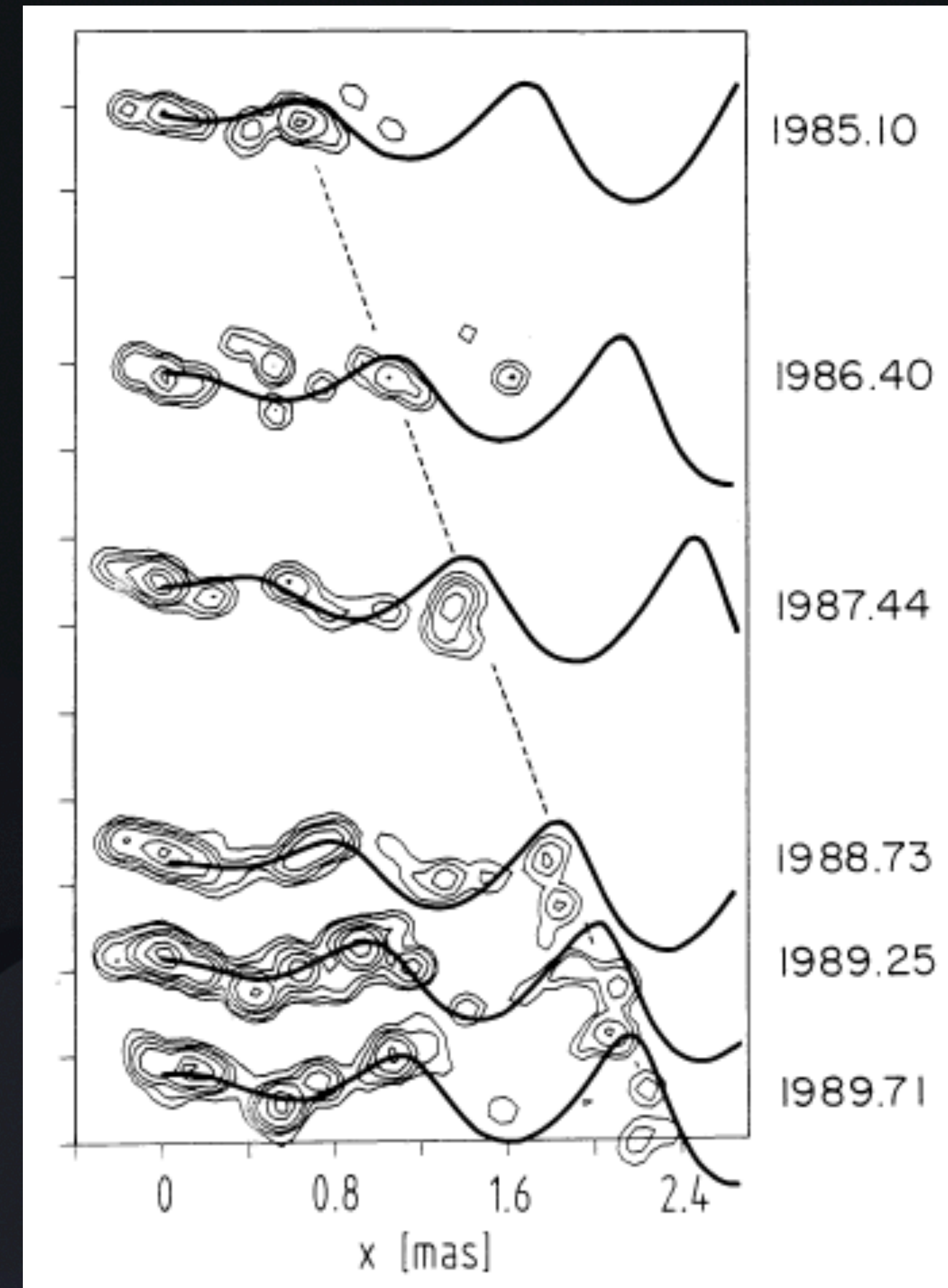
Sudou et al. (2003), Iguchi et al. (2010)

Helical, Periodic, or Precessing Jets

1928-738, $P = 2.9$ yr



Abraham (2018)

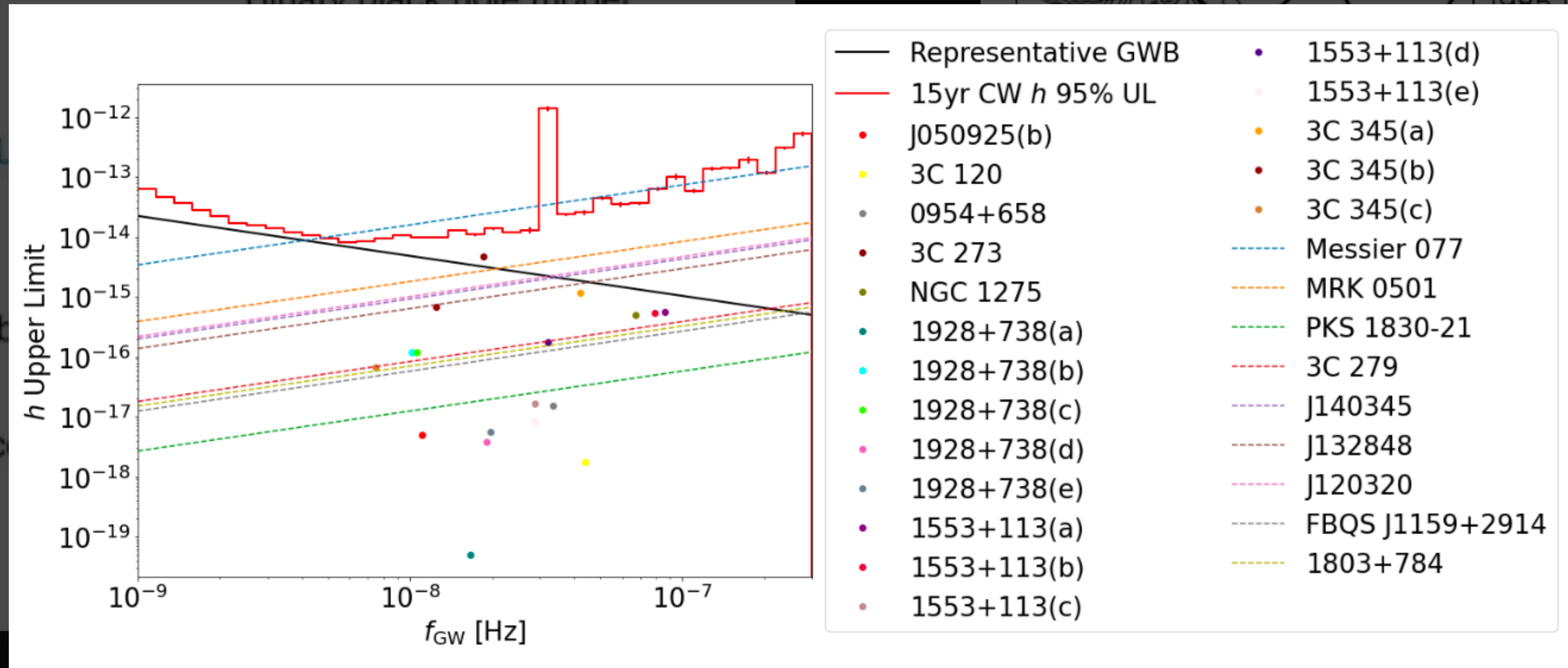


Roos et al. (1993)

See also Roland+08, Kun+14, Britzen+19, Hummel+22, Zhang+22, and others

Helical, Periodic, or Precessing Jets

1928-738, P = 2.9 yr



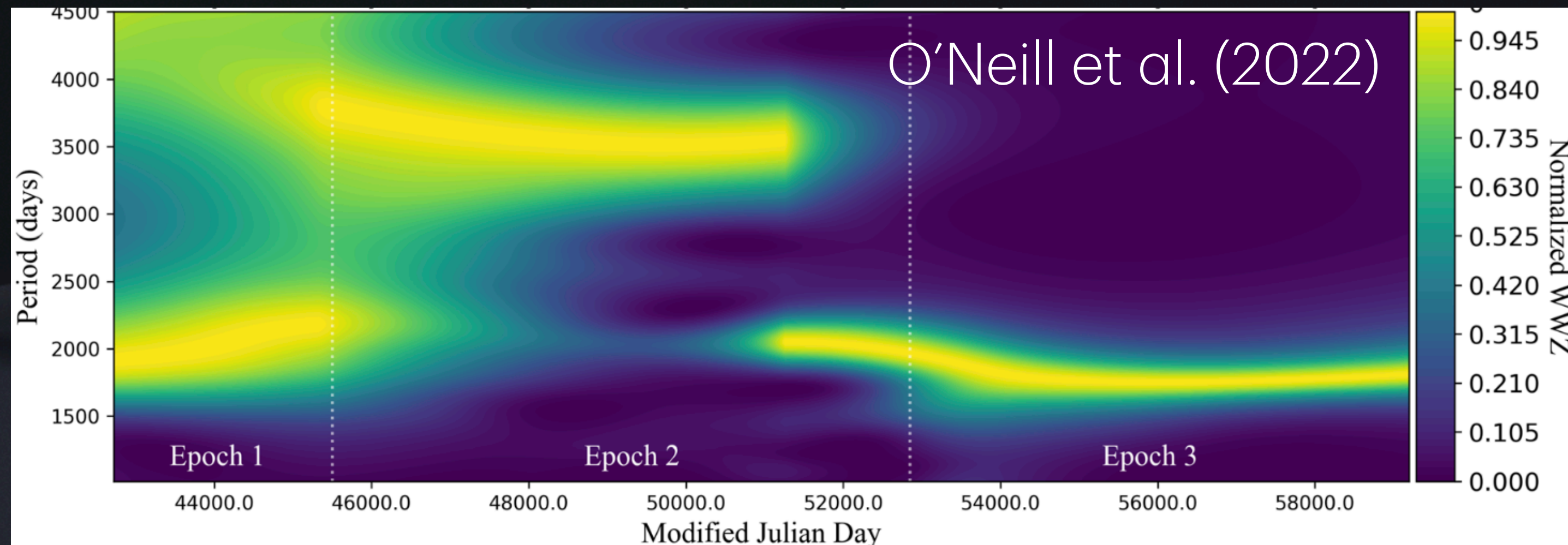
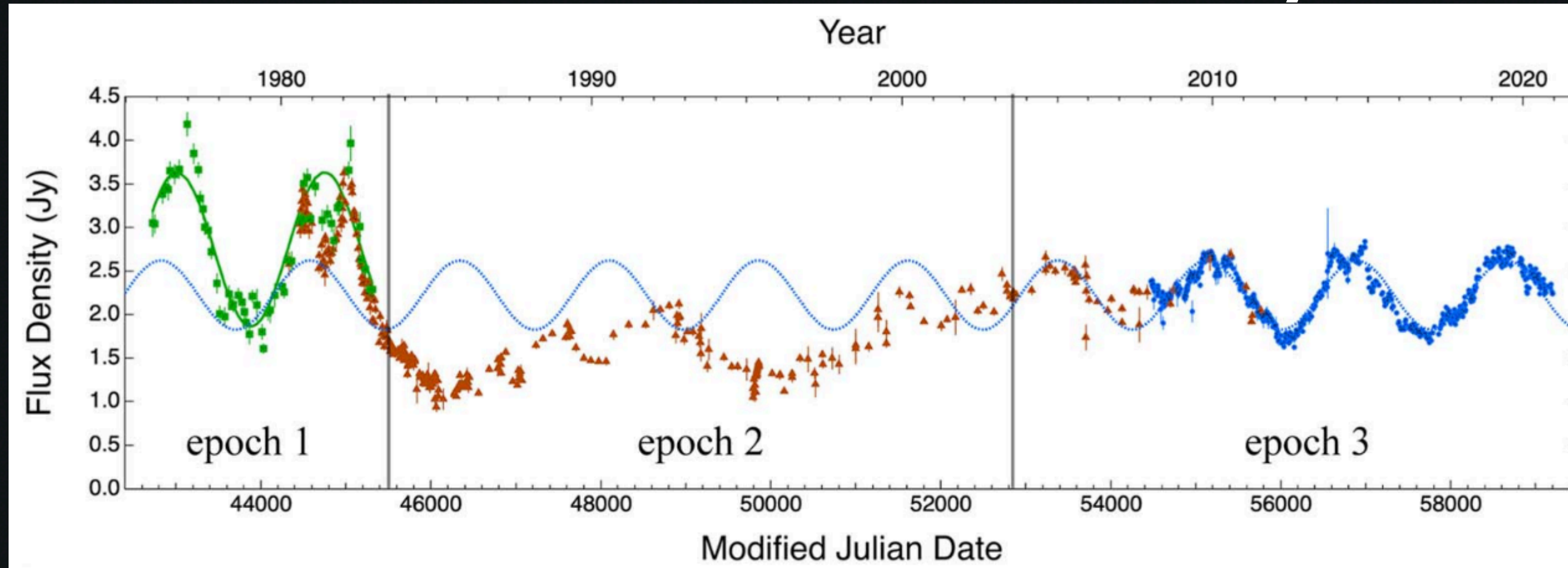
Targeted search upper limits by Sydnor (2025)/Sydnor & Burke-Spolaor (in prep.)

Roos et al. (1993)

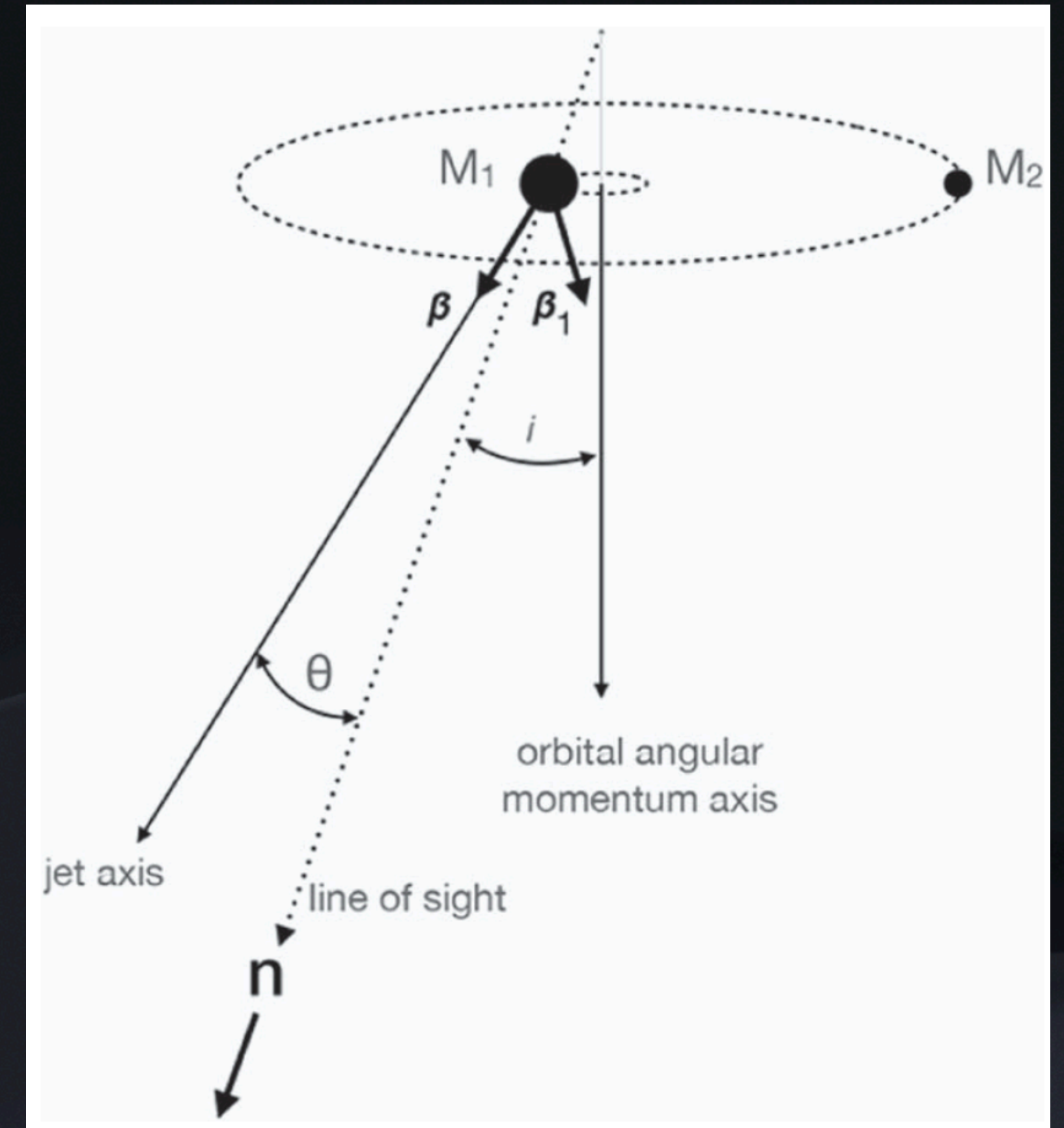
See also Roland+08, Kun+14, Britzen+19, Hummel+22, Zhang+22, and others

Helical, Periodic, or Precessing Jets

2131-021, $P = 2.082 \pm 0.003$ yr



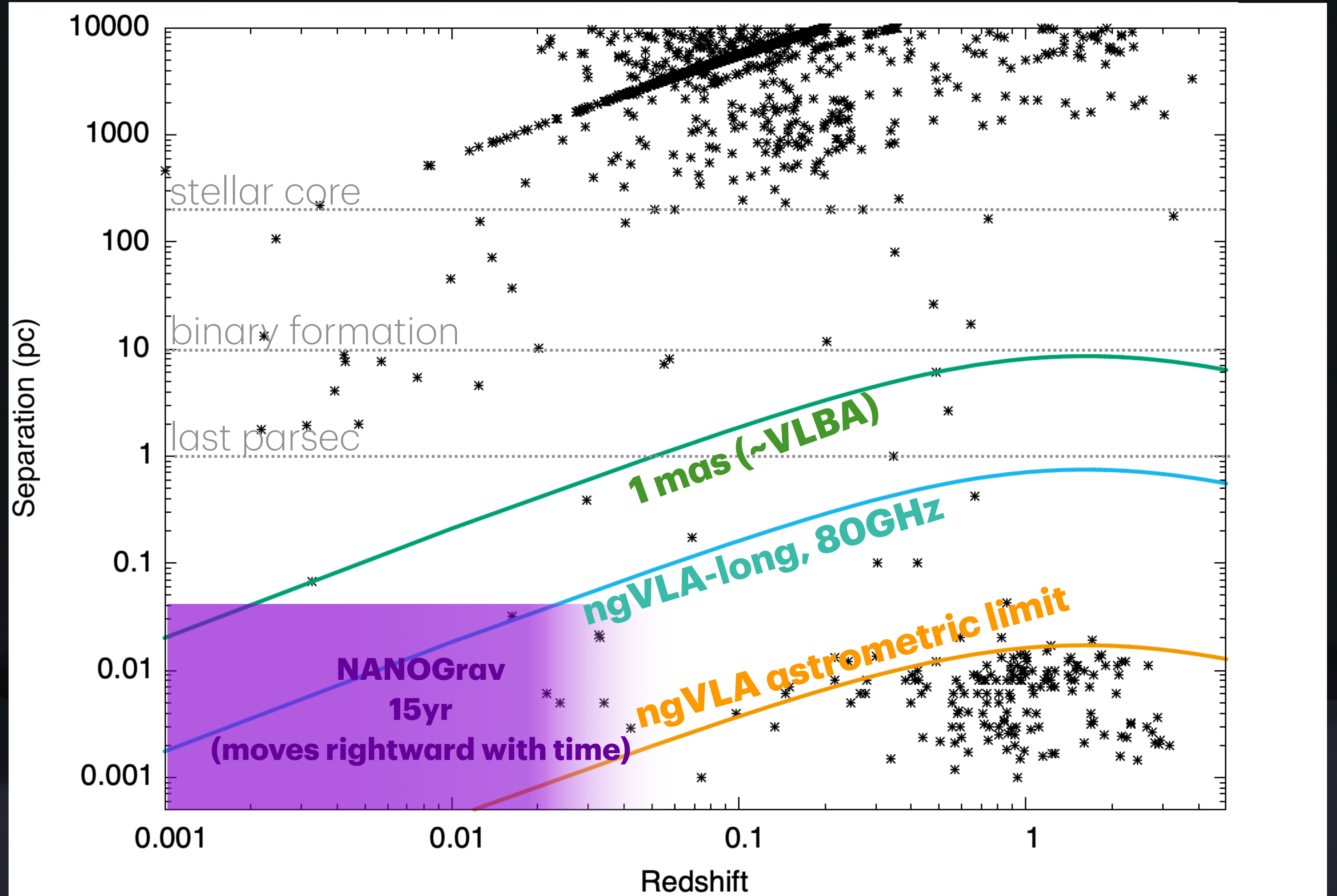
“Kinetic Orbital Model”:
Orbital speed doppler boosts jet flux



Targeted PTA limits pursued by Agarwal et al. (under review, led by C. Mingarelli)

Candidate MBHBs

Points from
BIGMAC (Pfeifle et al. 2025)
and
BOBCAT (Sydnor/Burke-
Spolaor in prep)



When ngVLA comes online,
there may be a hunt underway
for one or more continuous-
wave massive black hole
binary (MBHB) hosts.

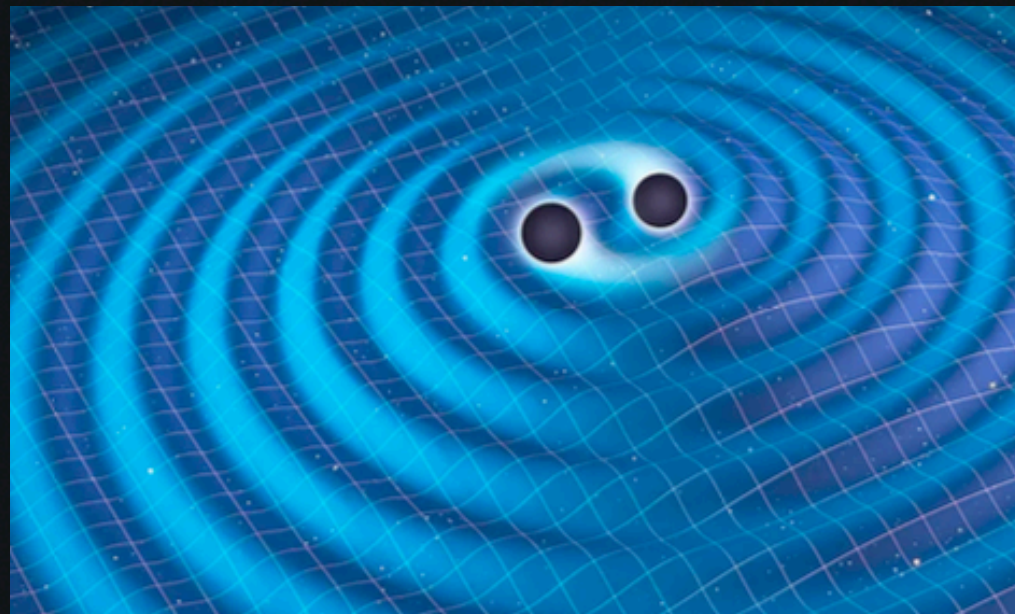


Check out a recent summary
of the road to MMA detection!



Lots of Science to Come

Highlights of some science applications in the MMA era - ask about these!



Discovery!

First definitive EM emission from MBHB.

Confirm MBHs as GWB origin.

First discovery of MBHB!



MBH Growth/Characterization

$M_{\text{BH}}-M_{\text{host}}$ relations.

Precise BH masses in merger environments.

Ellipticity measurements.

MBHB/Galaxy environmental coupling.

Binary dynamical evolution.



AGN Science

Are RLQ's linked to recent mergers?

Circumbinary disk / mini-disk dynamics.

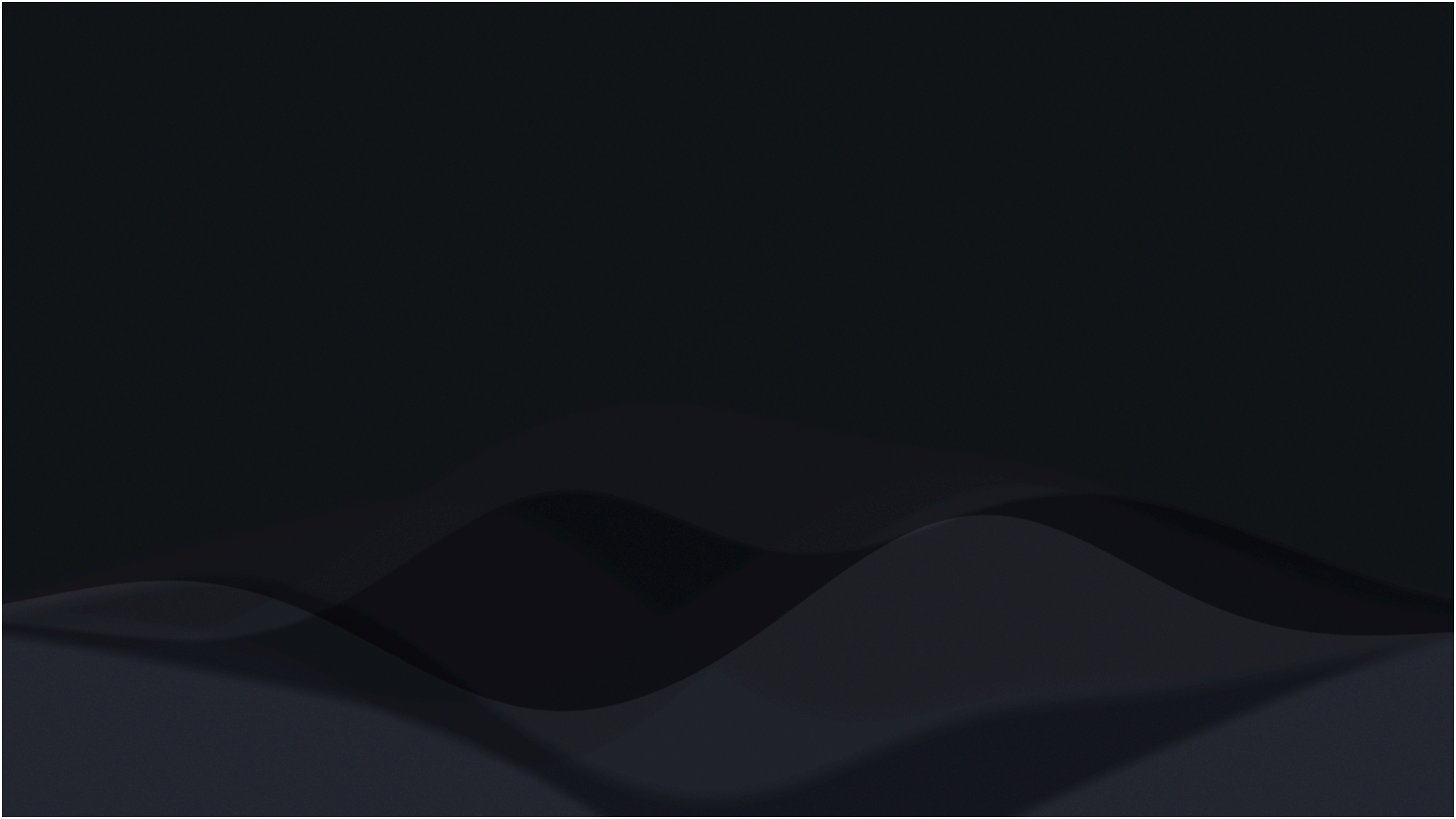
Jets vs. ADAFs in binaries?

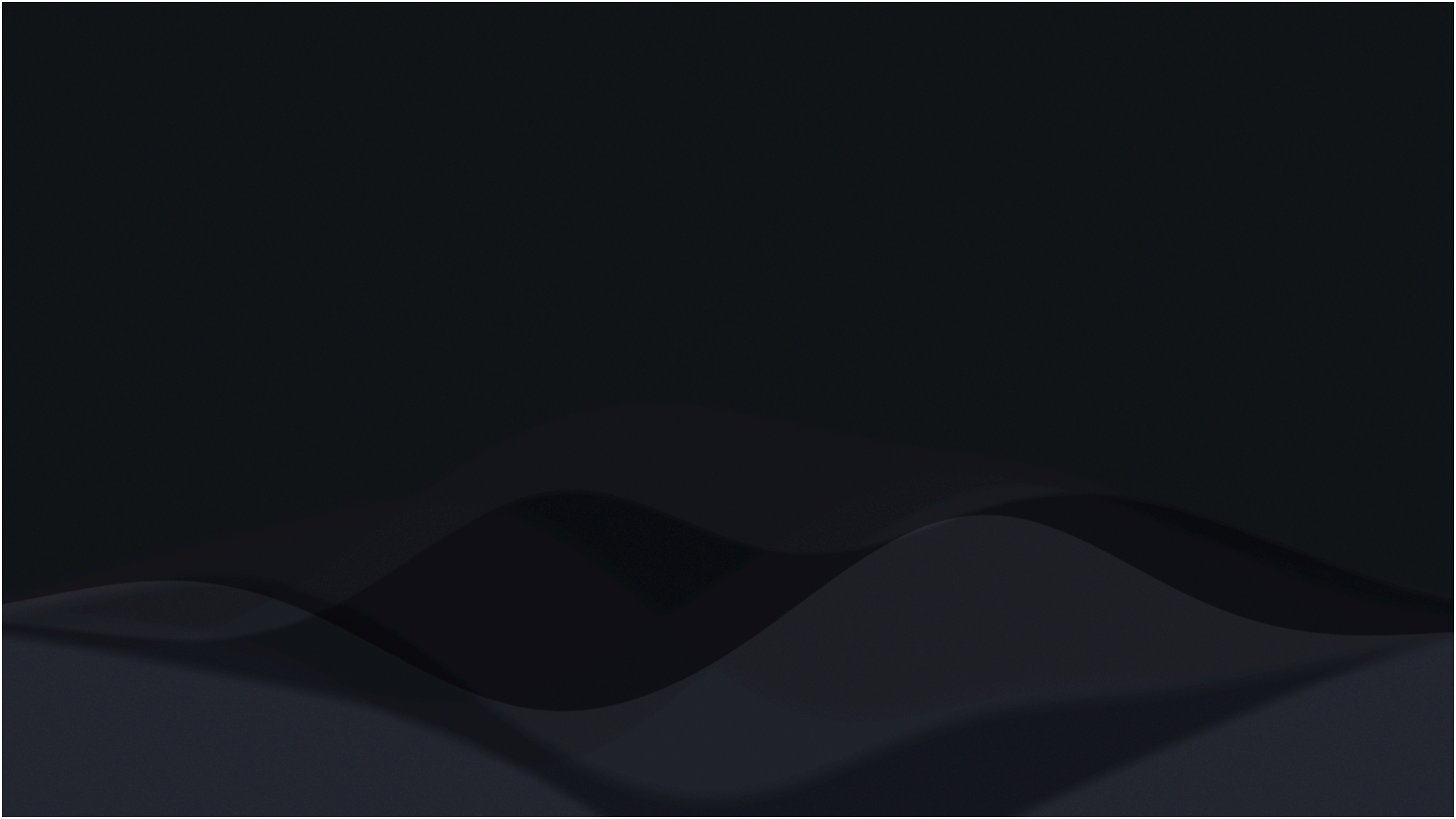
Binary-driven jet precession.

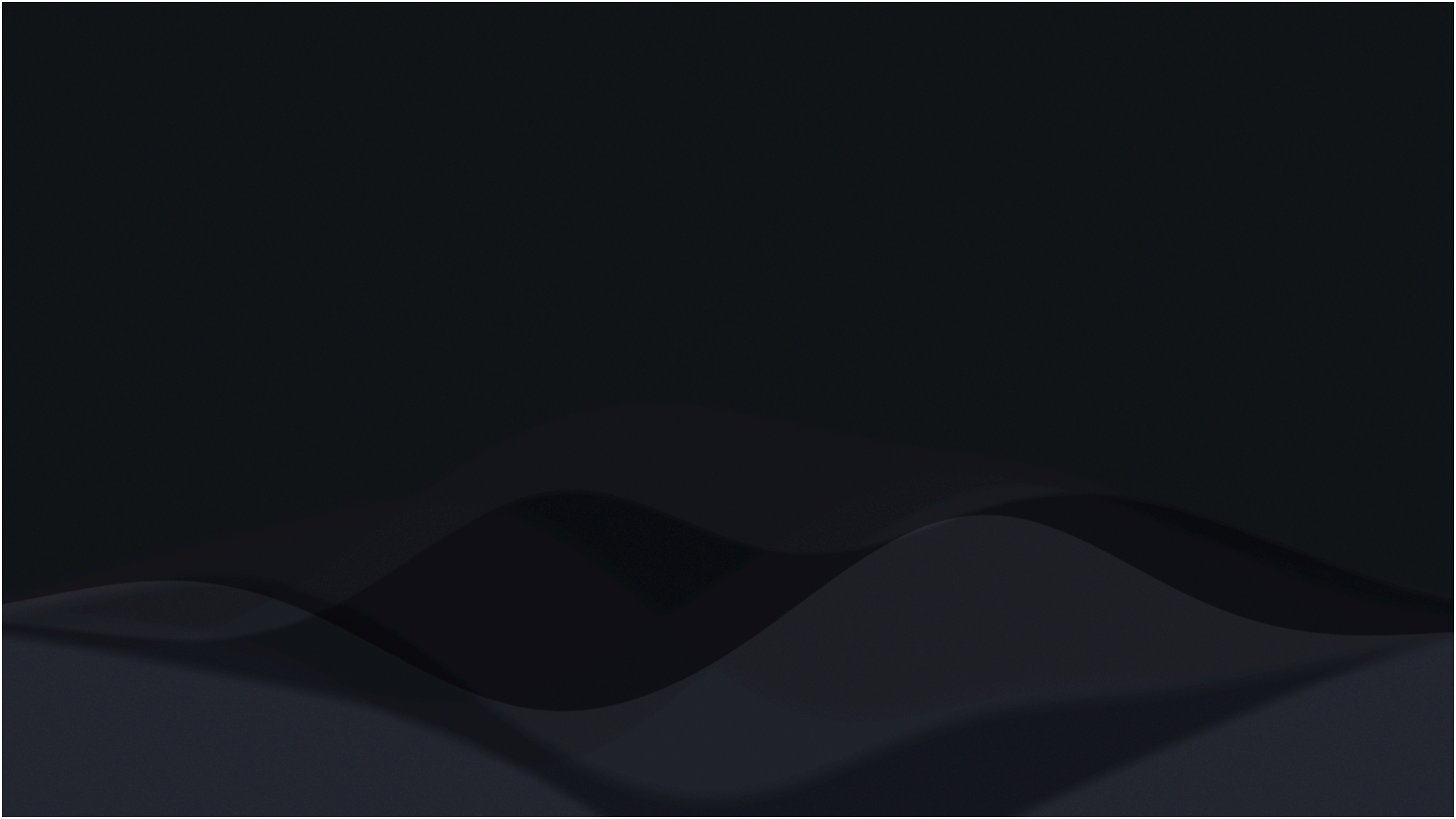
Coronal and jet geometries w.r.t BH spin and binary orbits.

Post-merger plasma dynamics.

Also standard rulers? (cool but maybe not high-impact given few sources, low redshift)



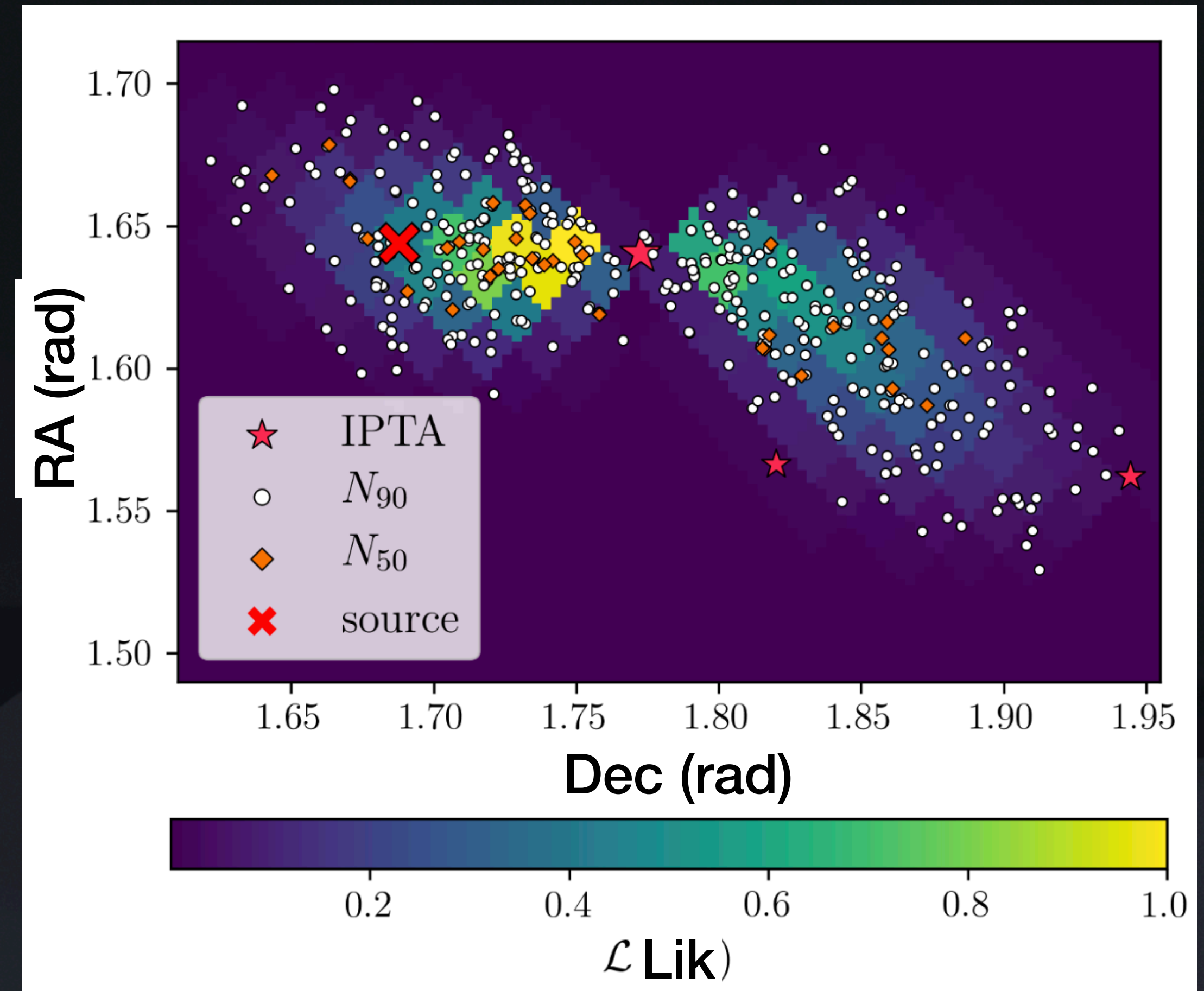
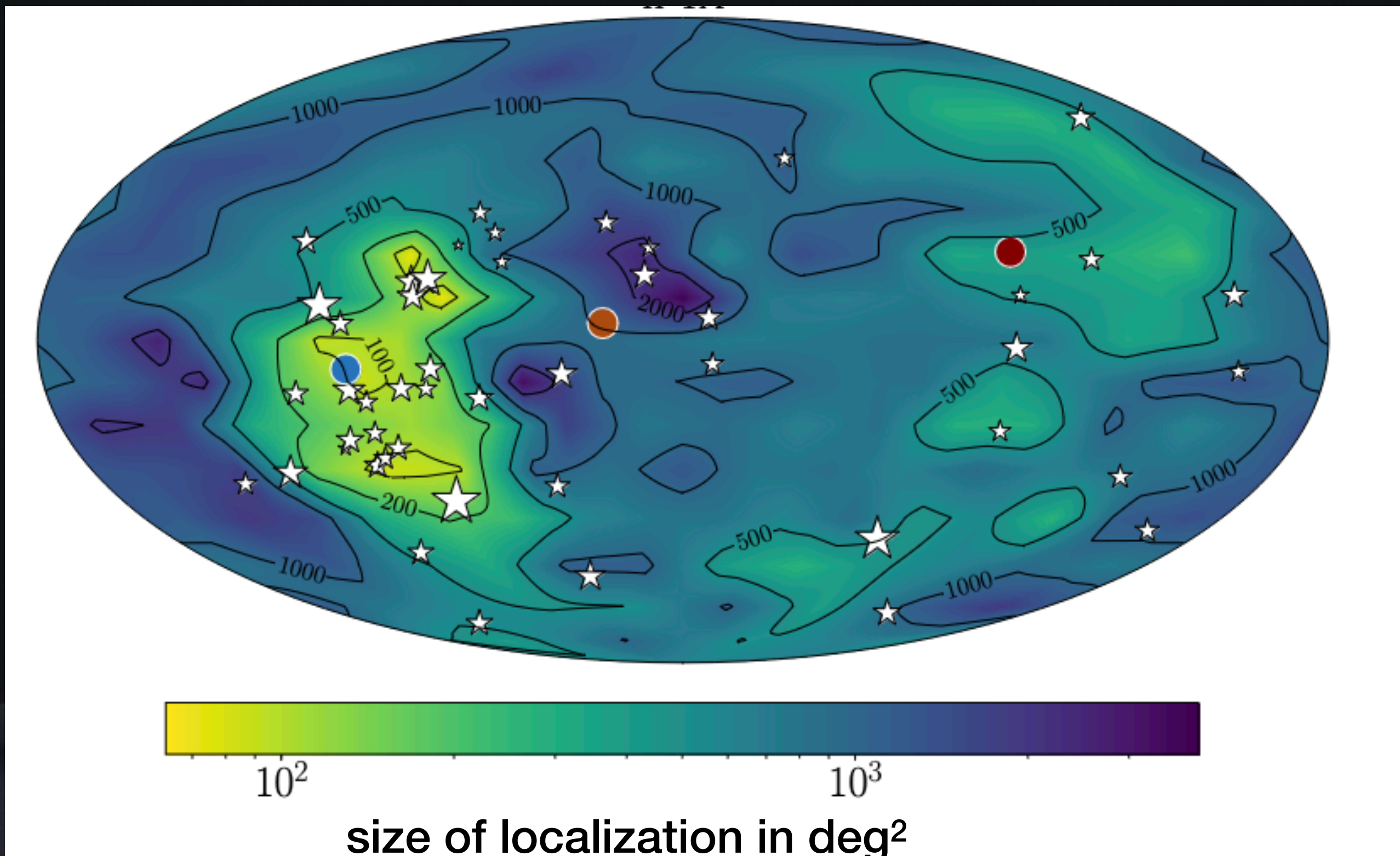




How well can we localize binaries?

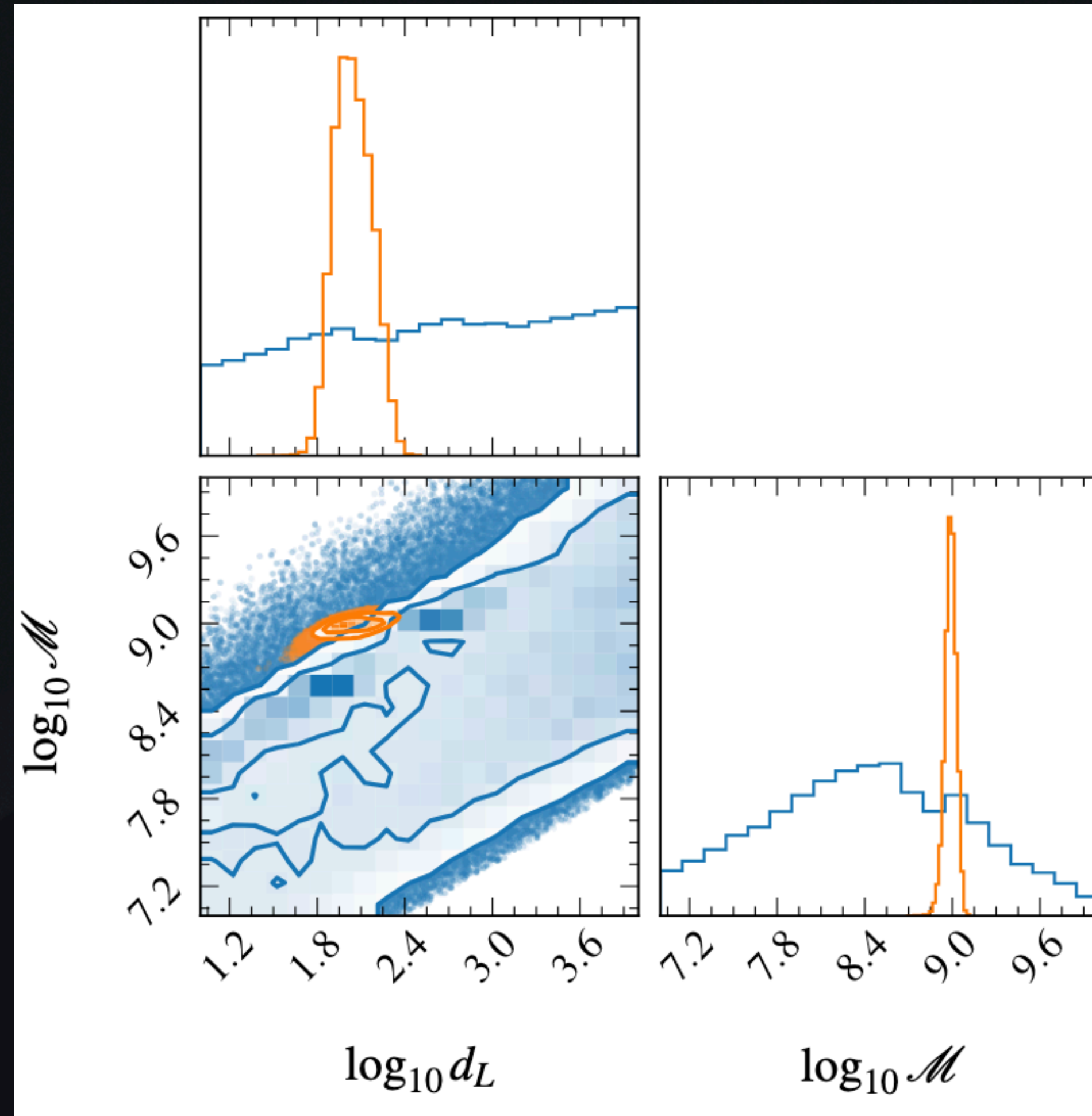
Localization capabilities of (simulated) IPTA

Likely hosts up to $z \lesssim 1.2$, $M_{\text{bulge}} \gtrsim 10^{11} M_{\odot}$



Goldstein et al. (2019)

BUT...

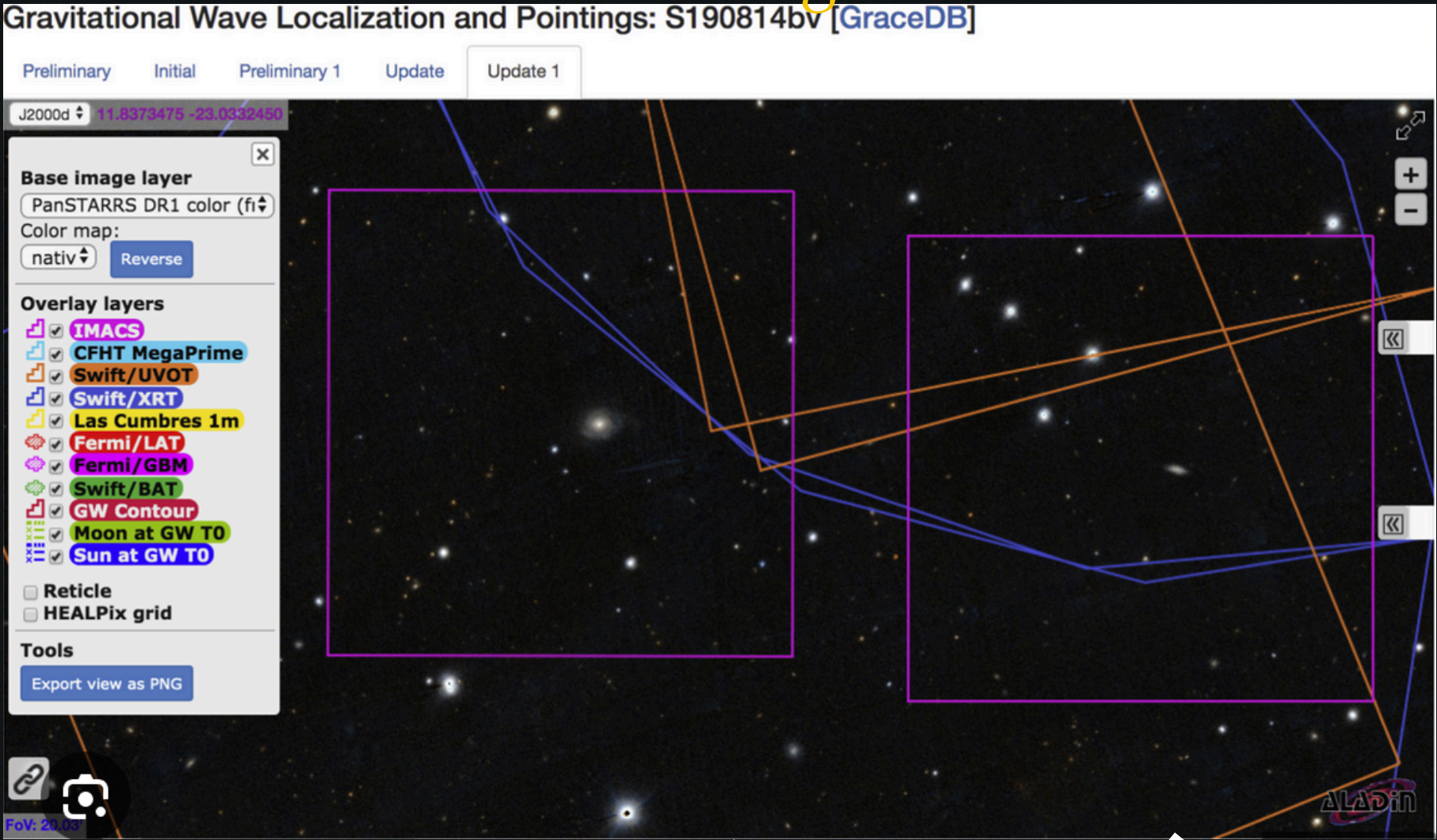
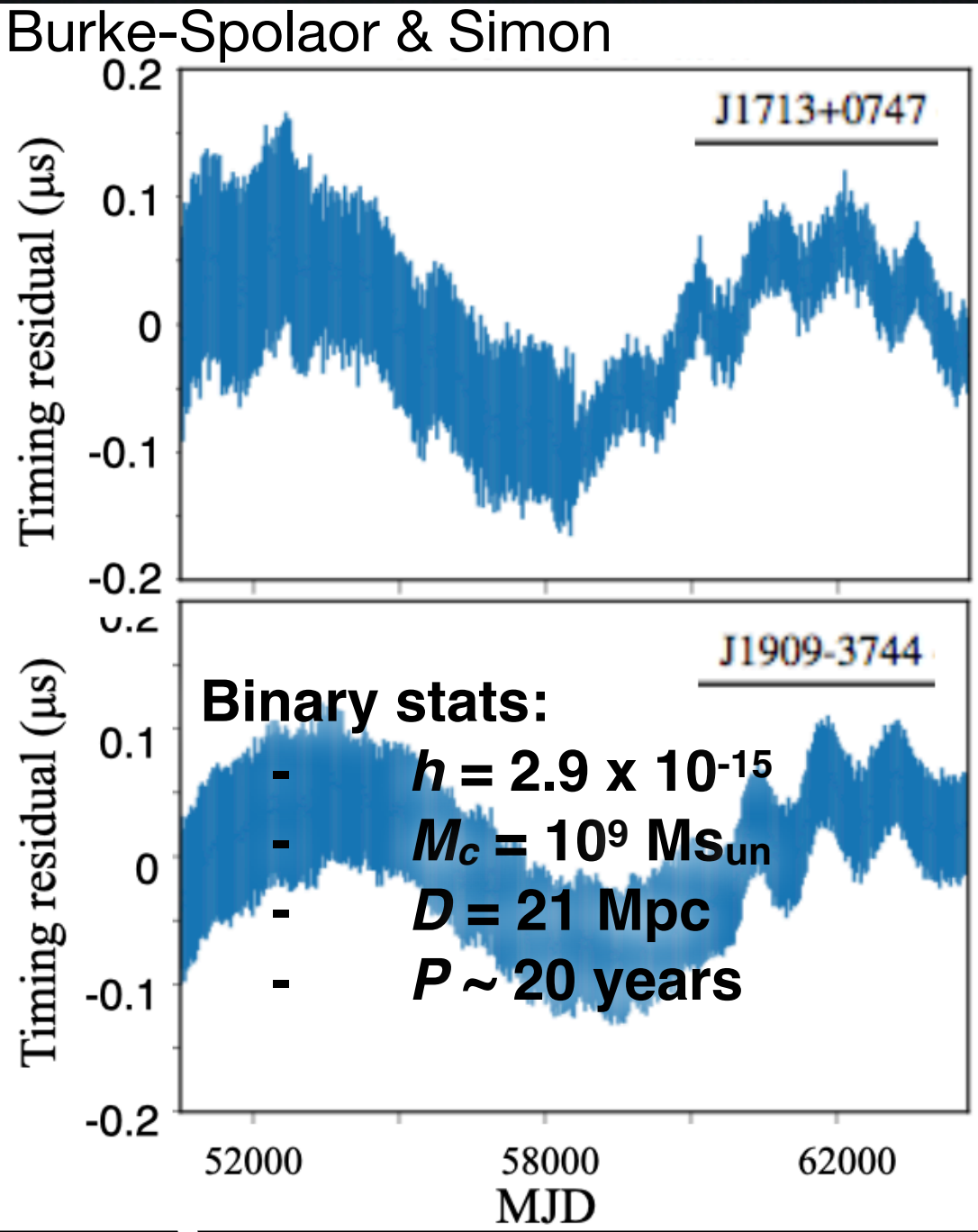


Plot by
P. Petrov

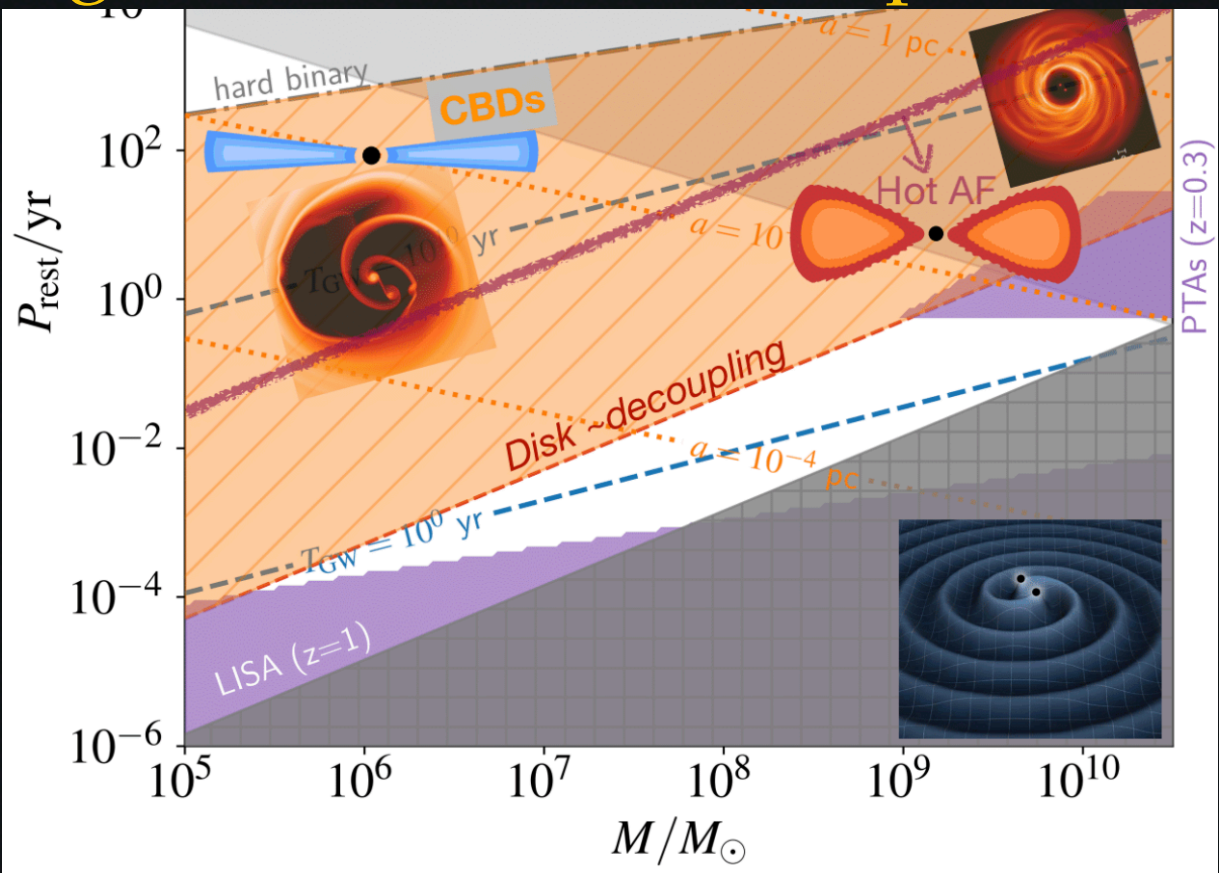
Burke-Spolaor et al. (2025)

A snapshot of early-mid 2030's, in just the right universe.

Coordinated multi-wavelength searches

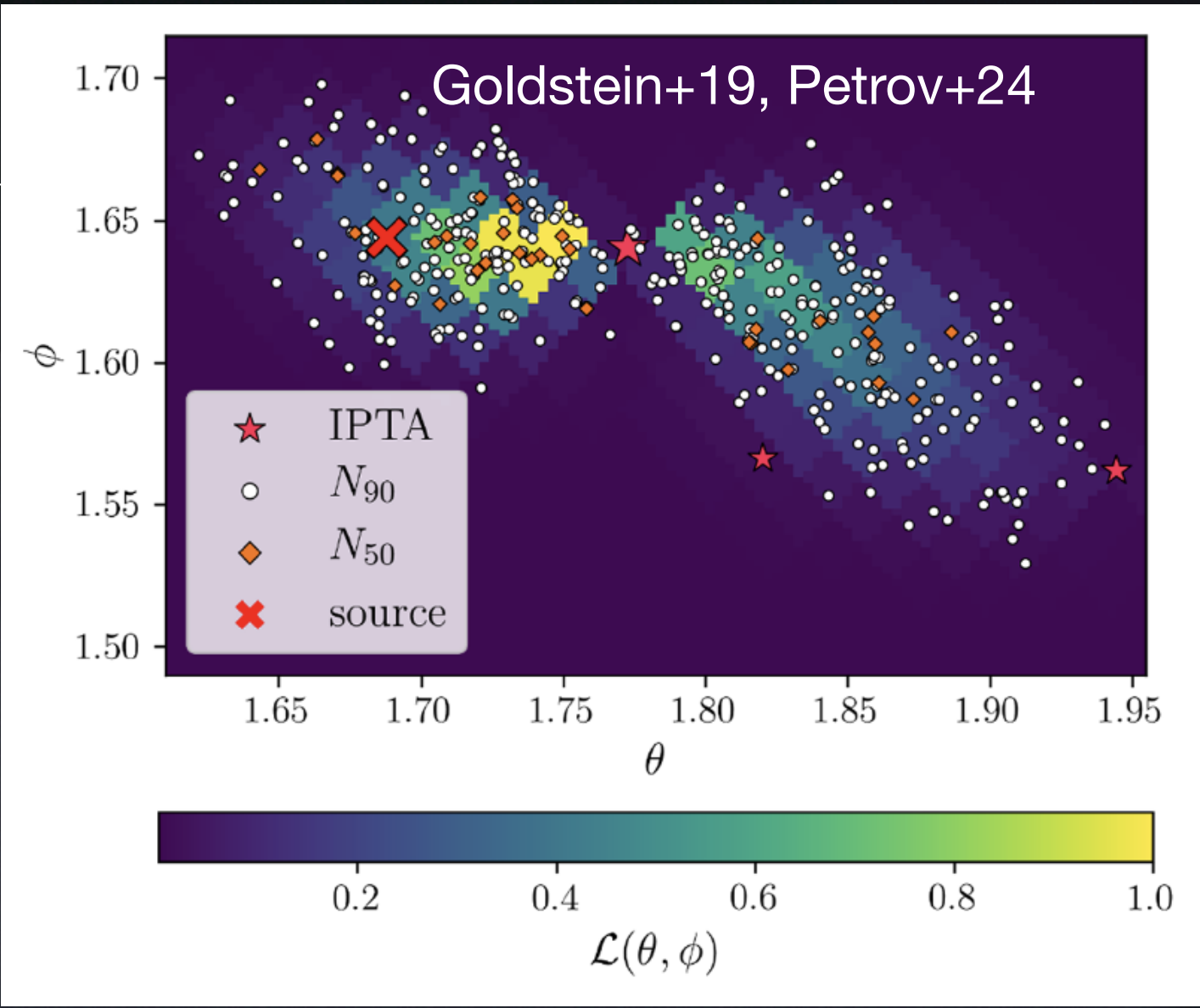


Theoretical model suites/ results templates to guide, rank, and interpret observations



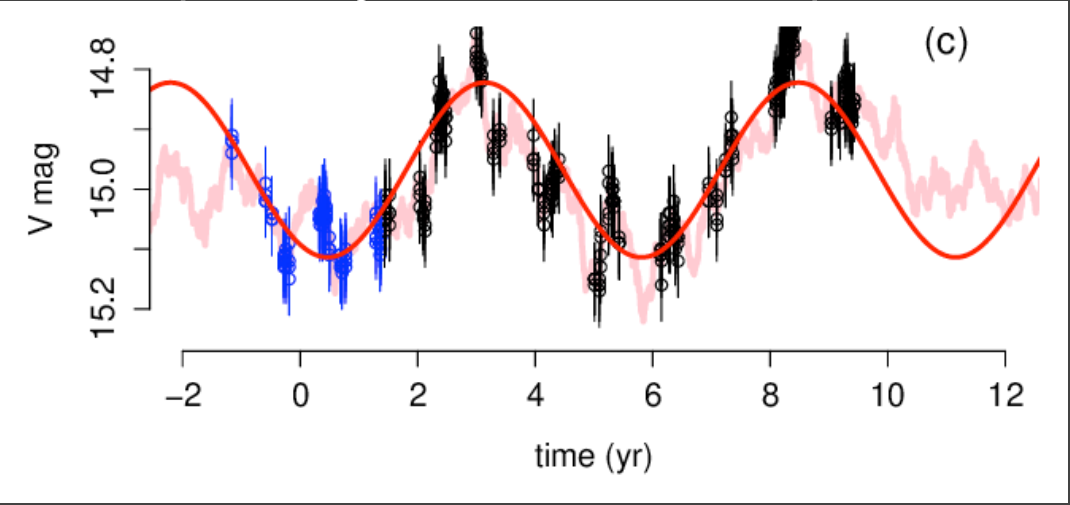
D'Orazio

Ranking based on photometric and spectroscopic galaxy catalogs

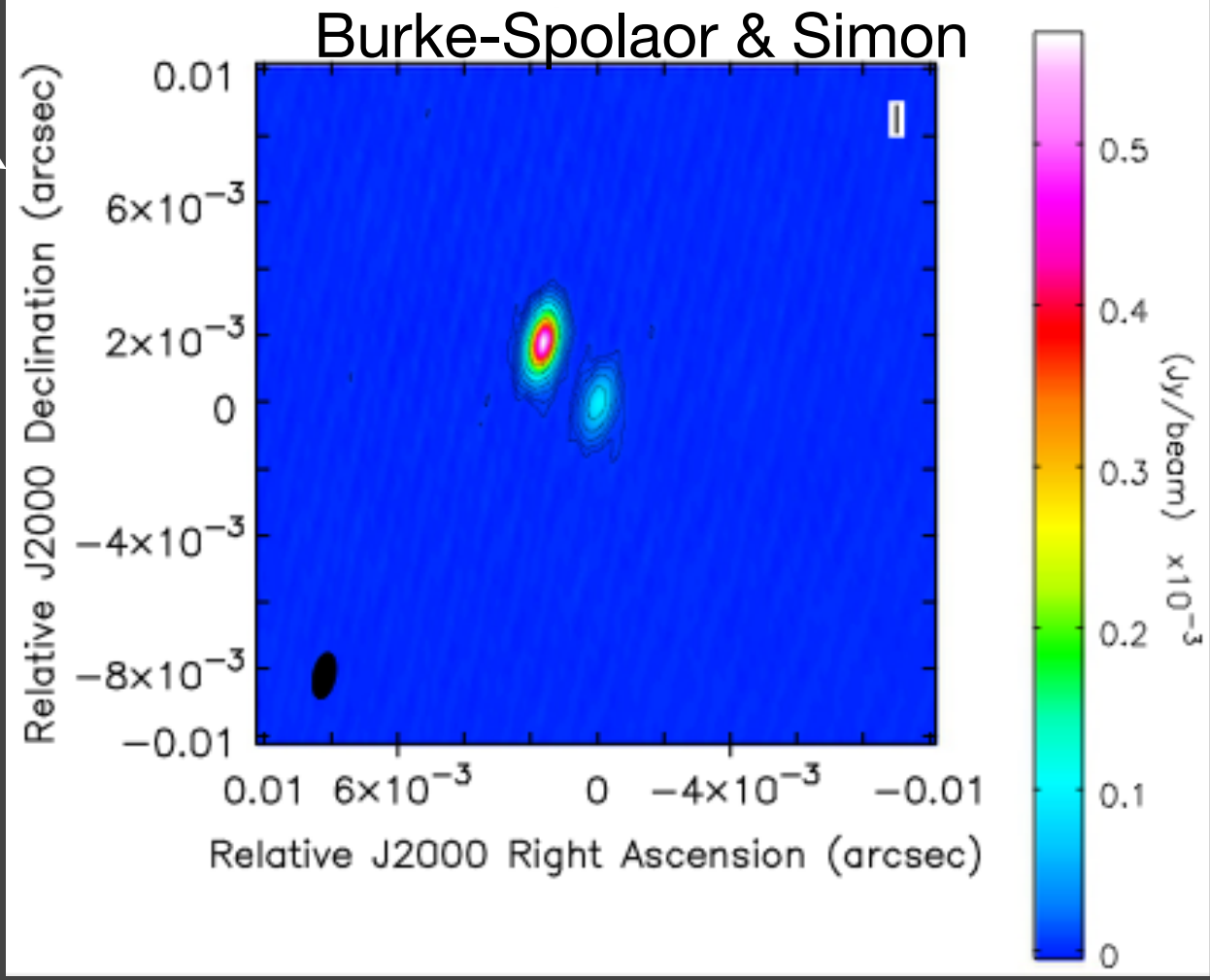


Candidate ranking based on multi-wavelength proof

Archival + new light curves (2-50 year baselines)

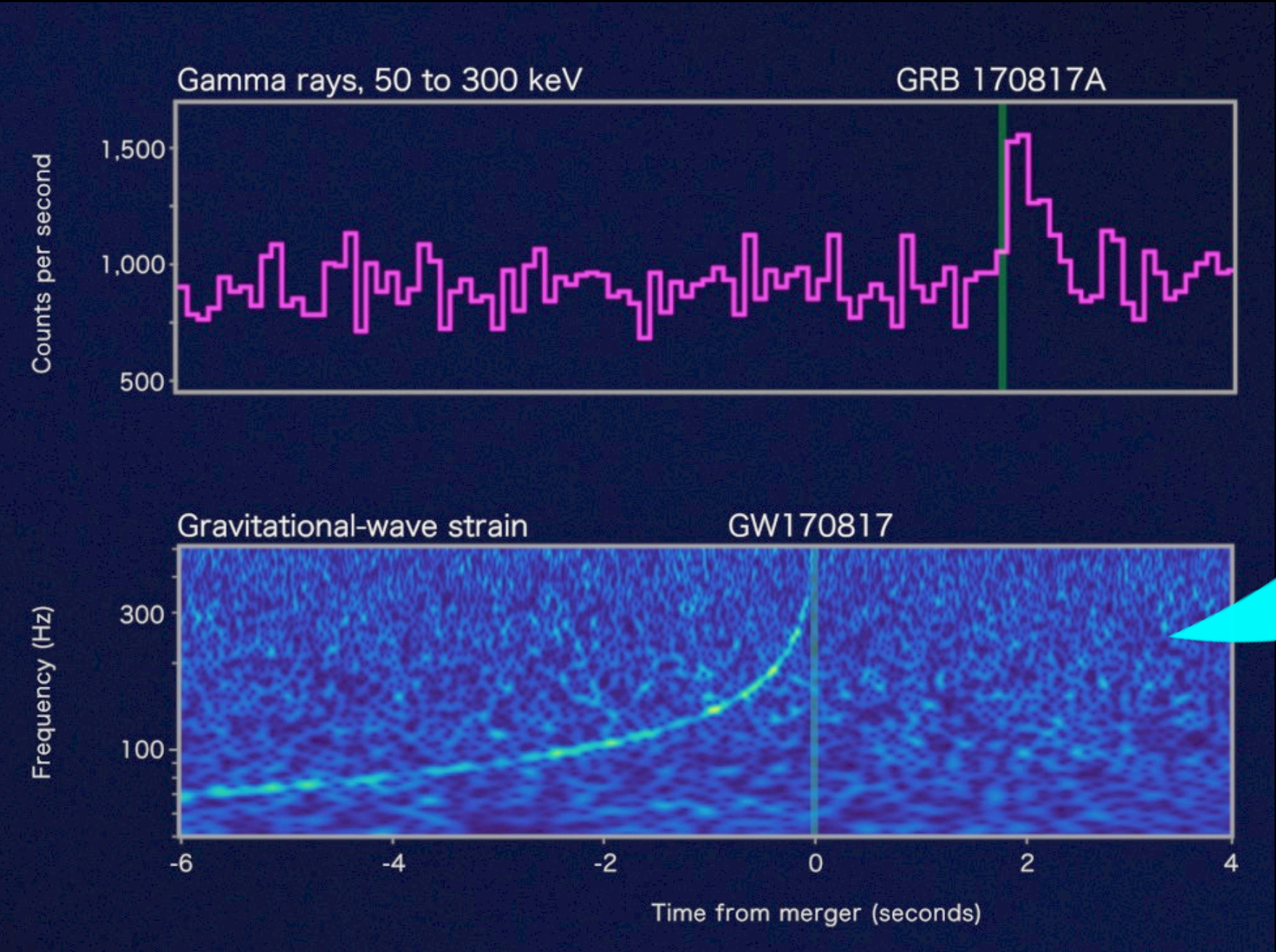


Simulated ngVLA Observation: 30GHz; Orbital period: 20 years



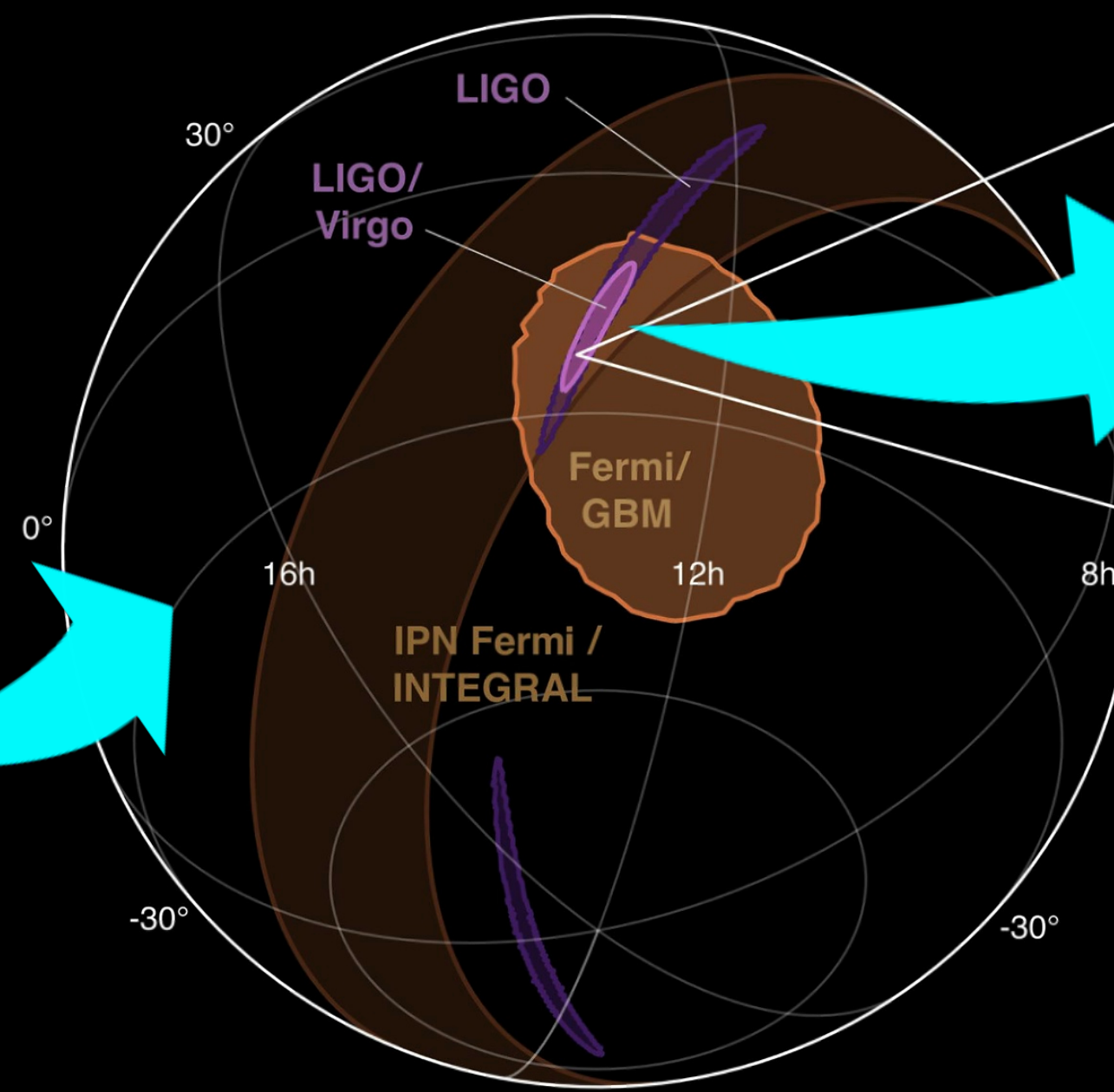
Beyond GW discovery: Enabling MMA

Goldstein et al 2017 ApJL 848 L14

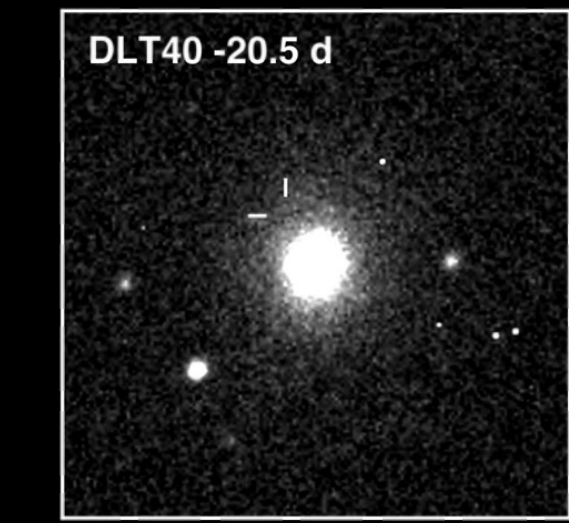
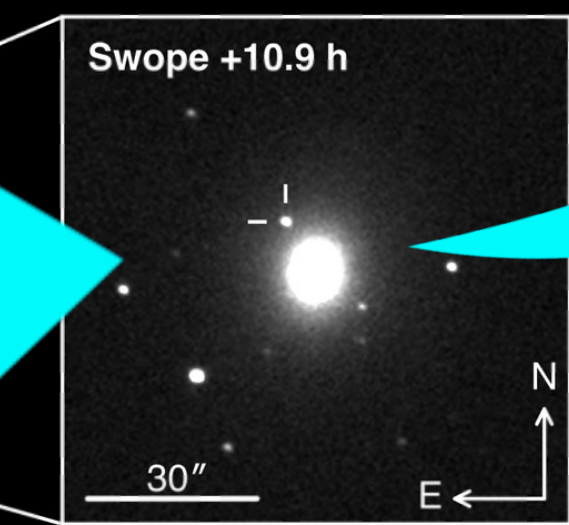


LIGO/Virgo; Fermi; NASA/DOE; NSF; EGO.

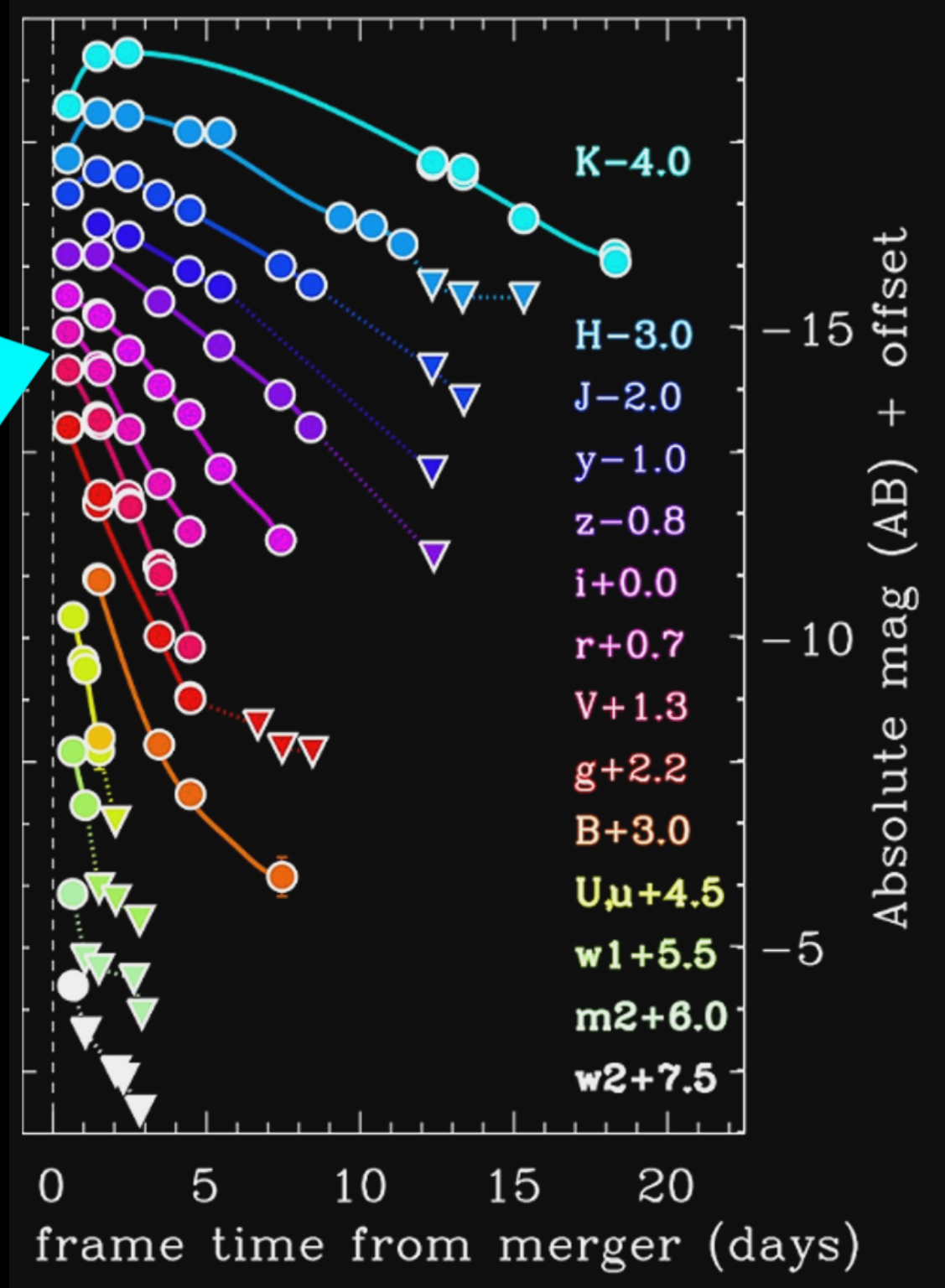
Abbott et al. 2017, ApJL, 848 L12



Coulter et al., Science, 358, 1556



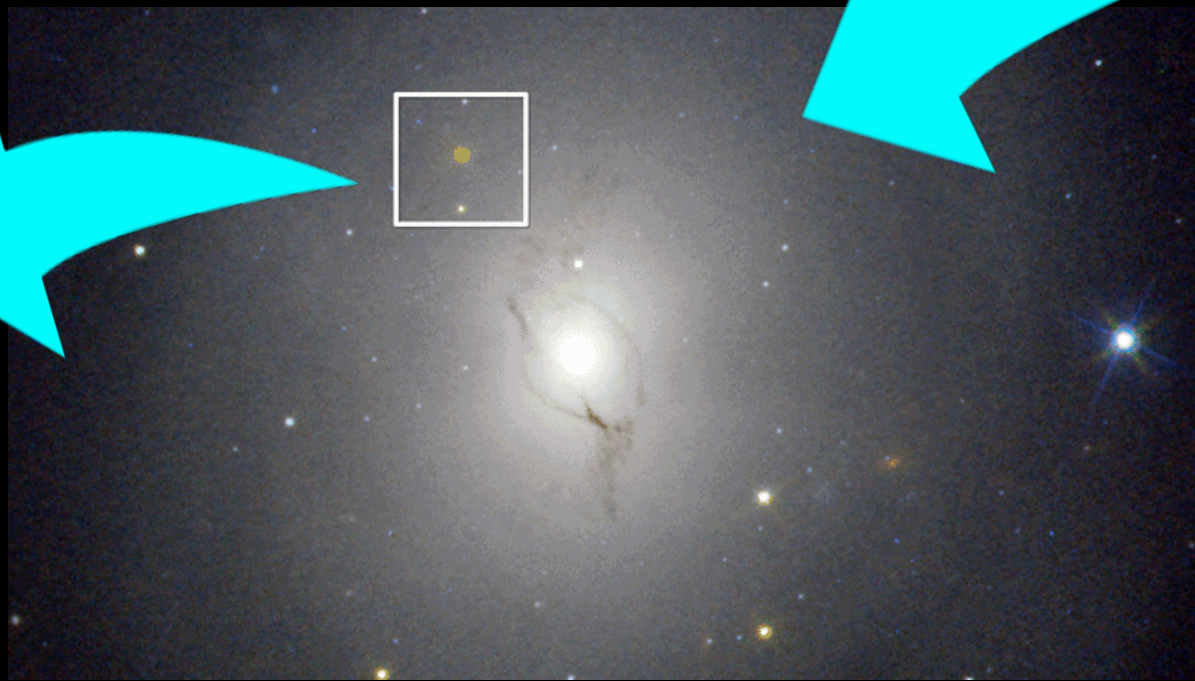
Valenti et al., ApJL, 848, L24,



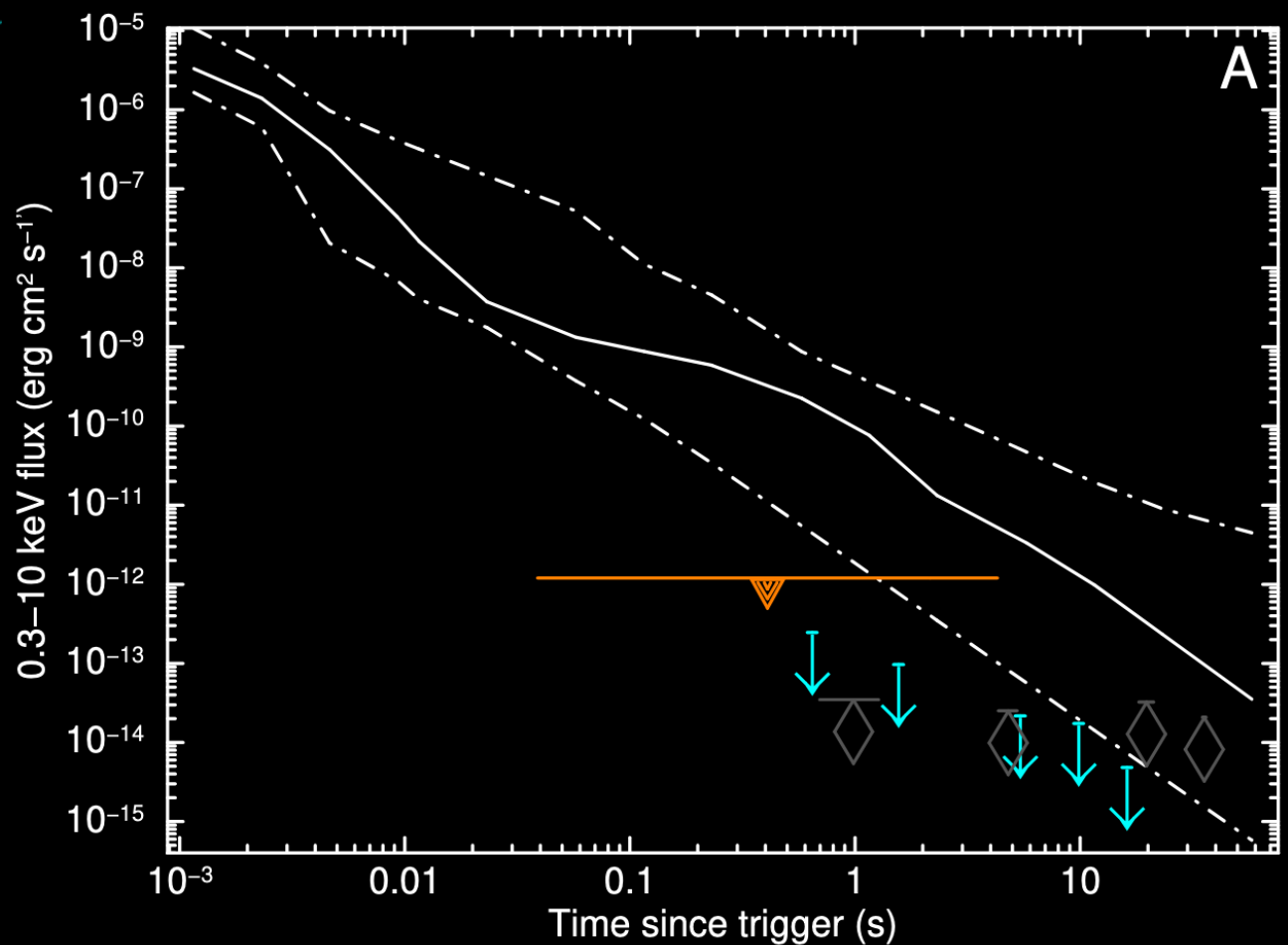
Drout et al. 2017, Science, 358, 1570

Hallinan, Corsi et al. 2017, Science, 358, 1579

VLA Observation September 1, 2017



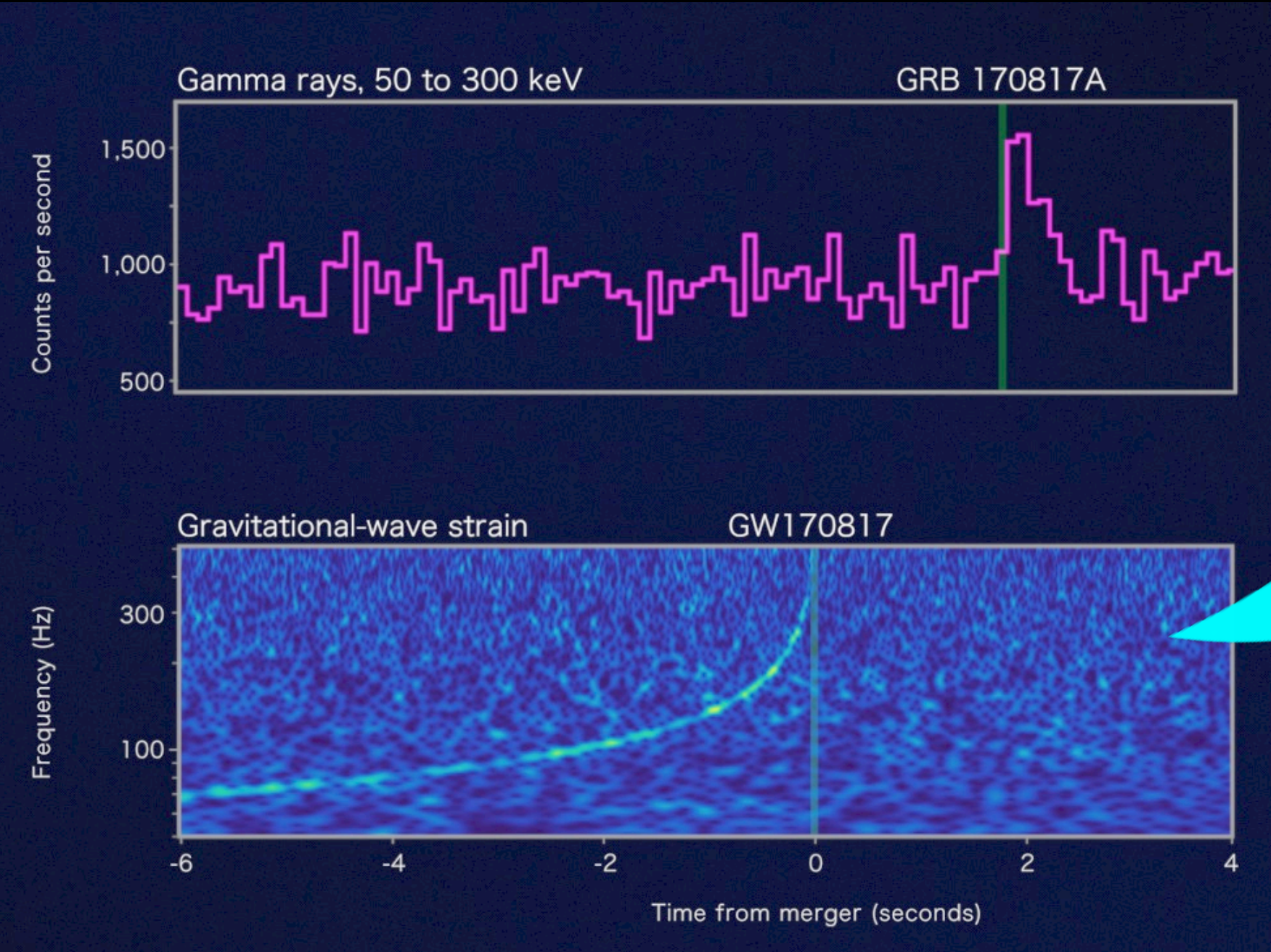
Troja et al. 2017, Nature, 551, 71



Evans et al. 2017, Science, 358, 1565

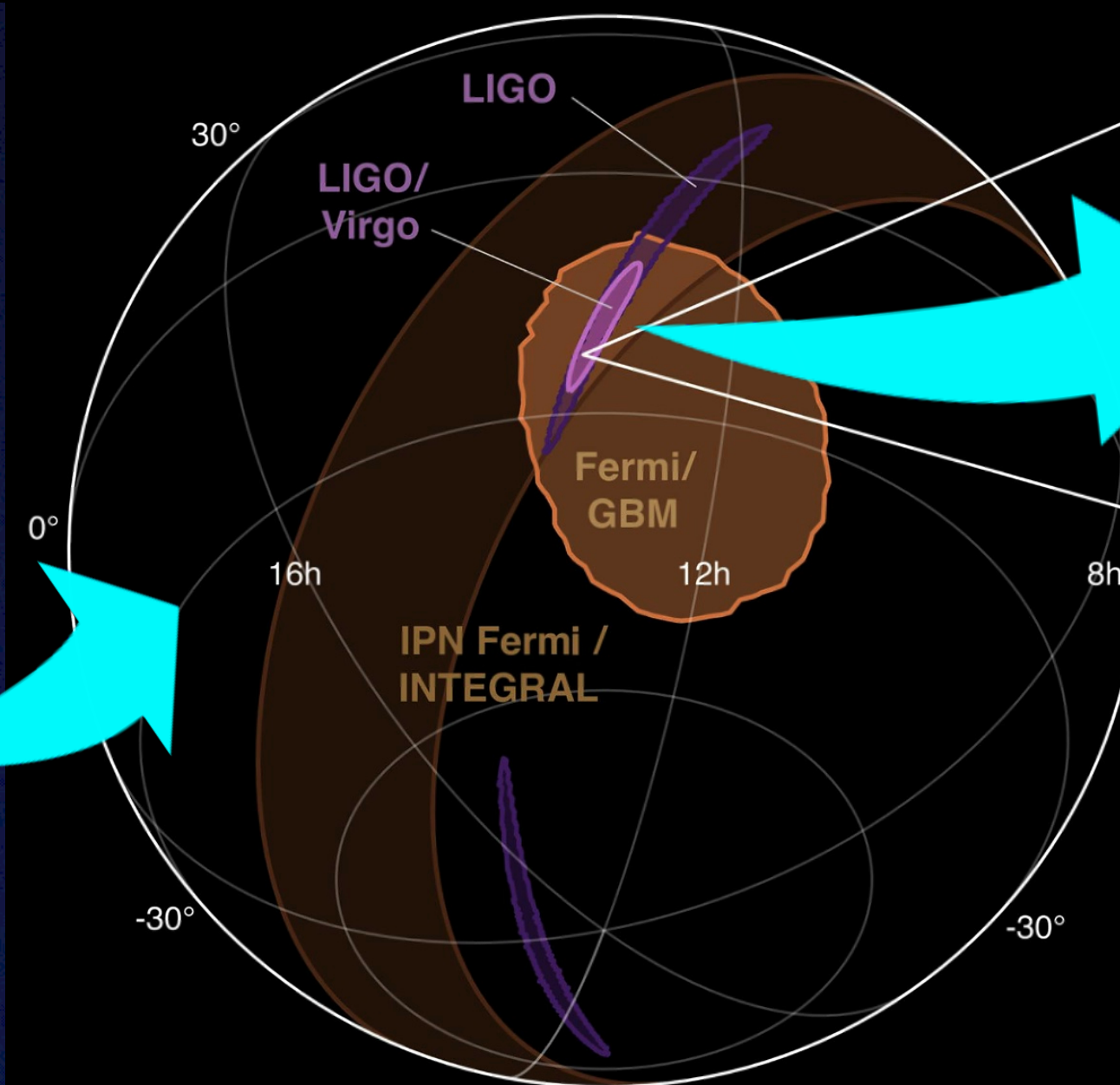
Beyond GW discovery: Enabling MMA

Goldstein et al 2017 ApJL 848 L14

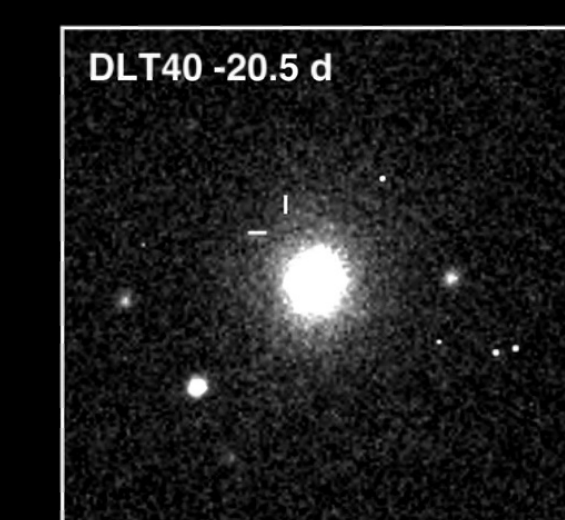
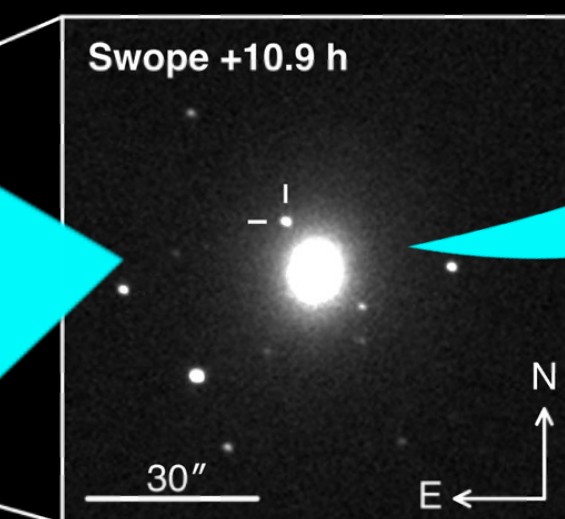


LIGO/Virgo; Fermi; NASA/DOE;
NSF; EGO.

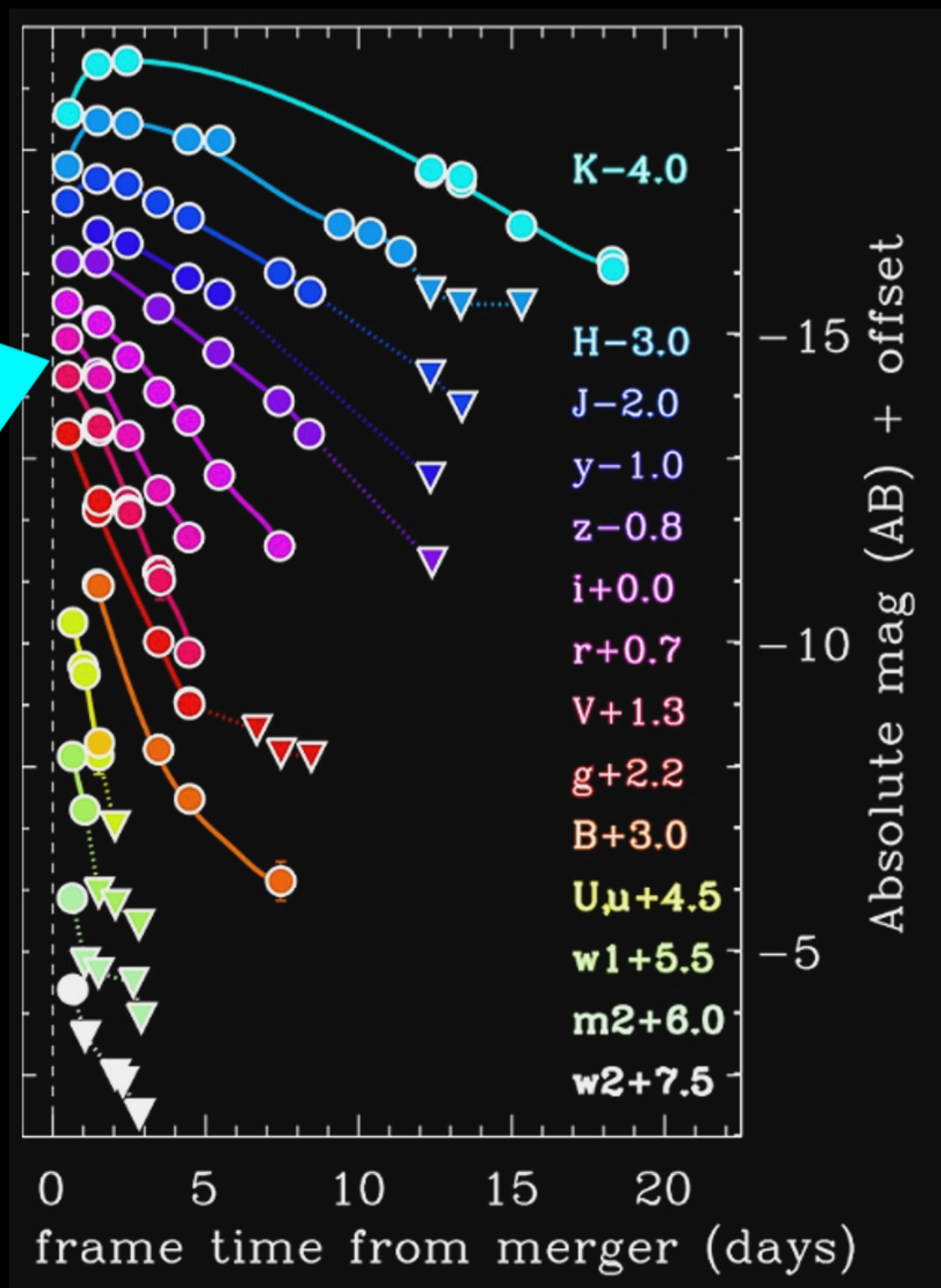
Abbott et al. 2017, ApJL, 848 L12



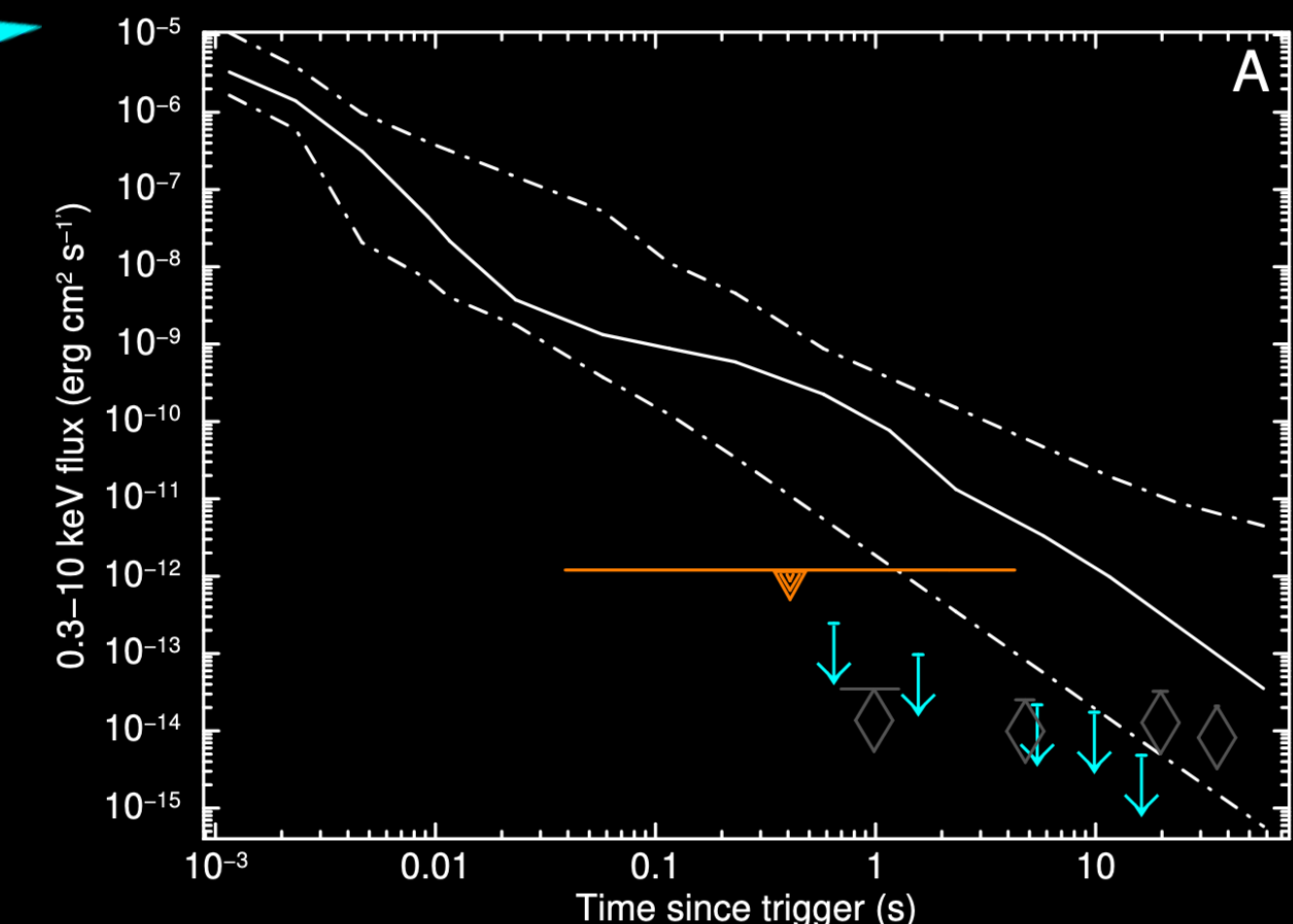
Coulter et al.,
Science, 358, 1556



Valenti et al.,
ApJL, 848, L24,



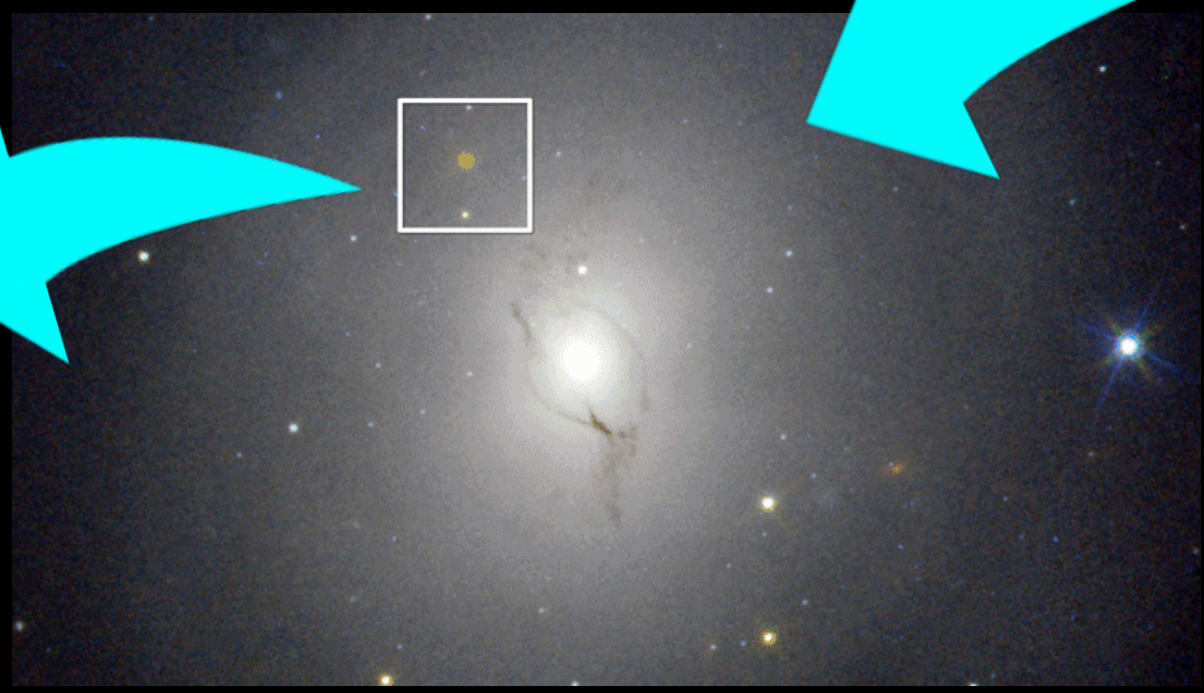
Drout et al. 2017,
Science, 358, 1570



Evans et al. 2017,
Science, 358, 1565

Hallinan, Corsi et
al. 2017,
Science, 358,
1579

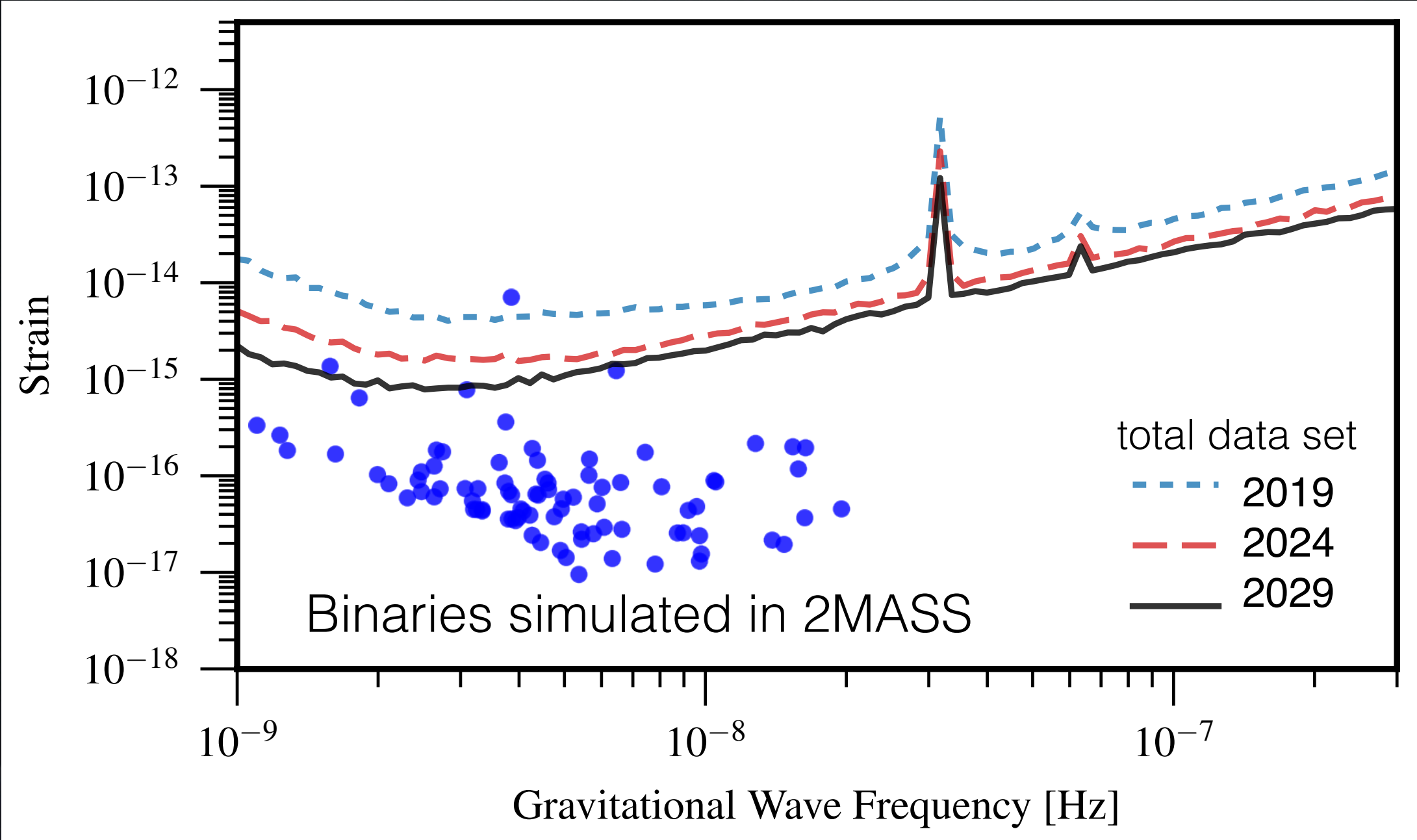
VLA Observation September 1, 2017



Troja et al. 2017, Nature, 551, 71

Binary Black Holes Timeline

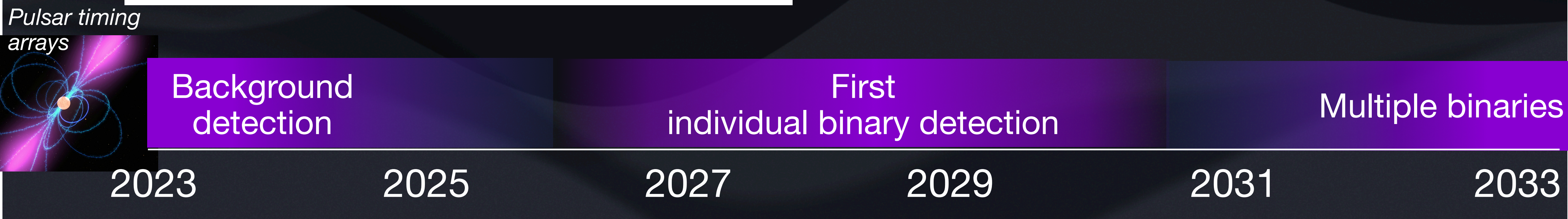
Mingarelli et al. (2017), Xin et al. (2021)



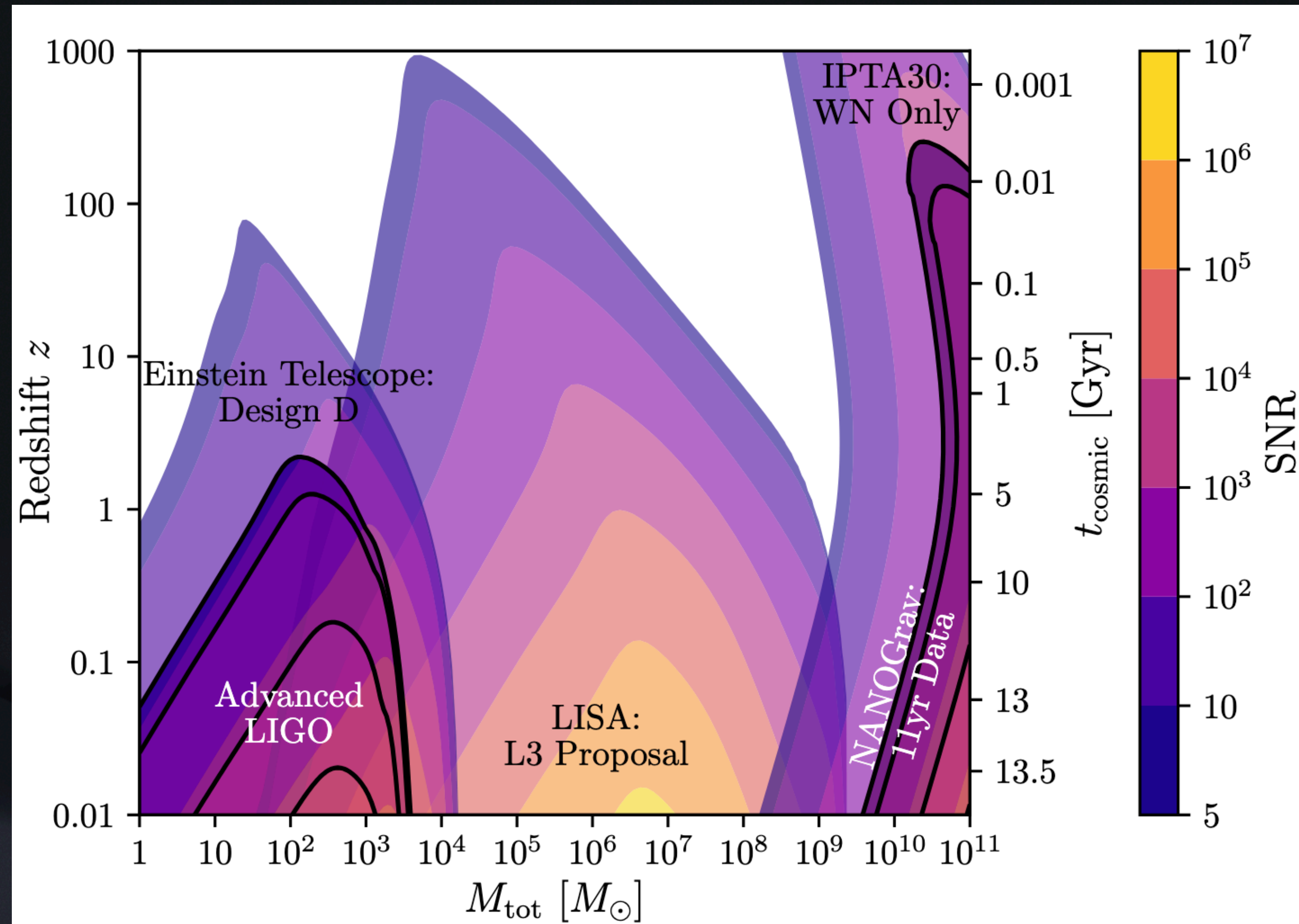
Modelled from local galaxy mergers, merger rates:

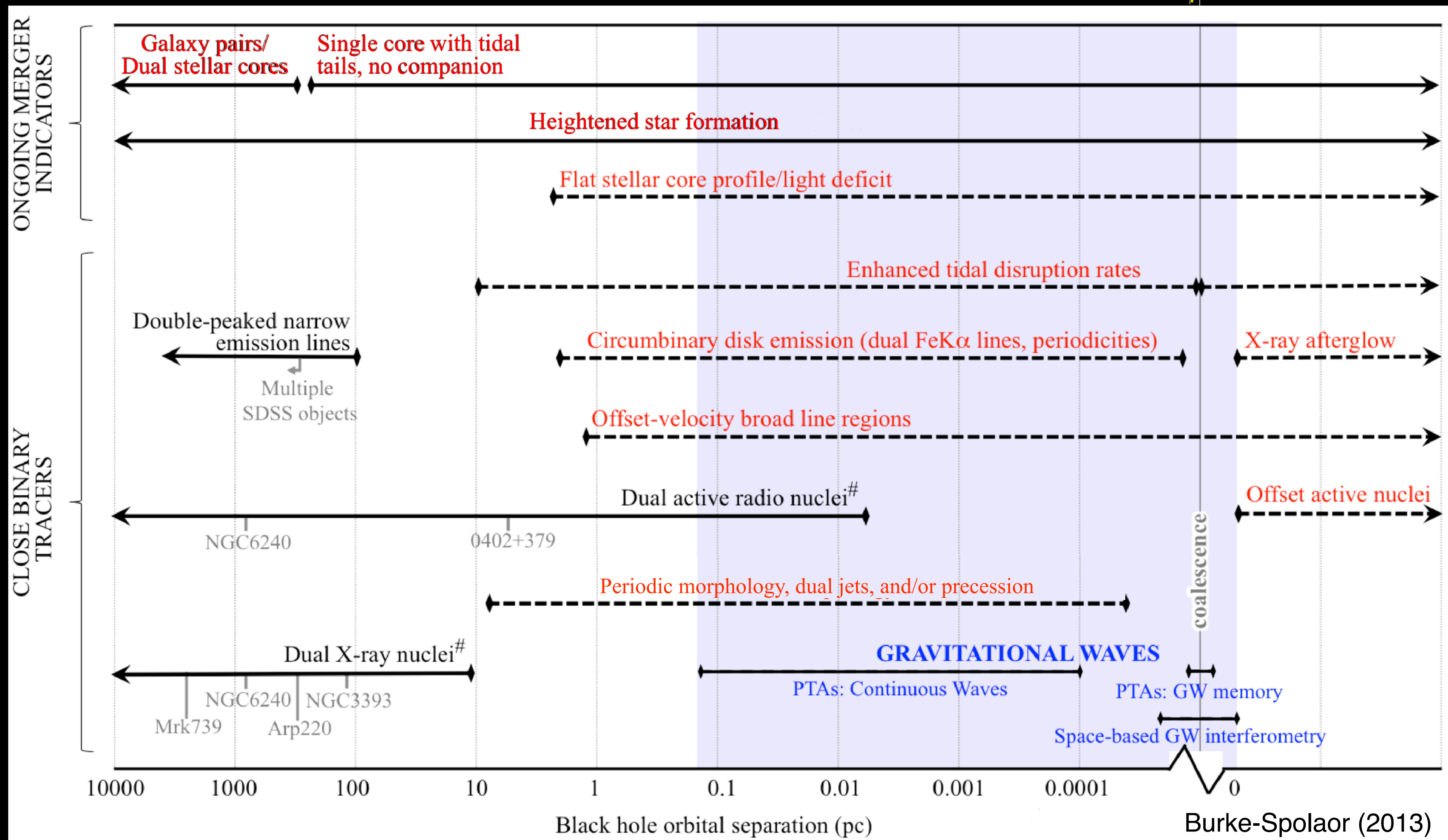
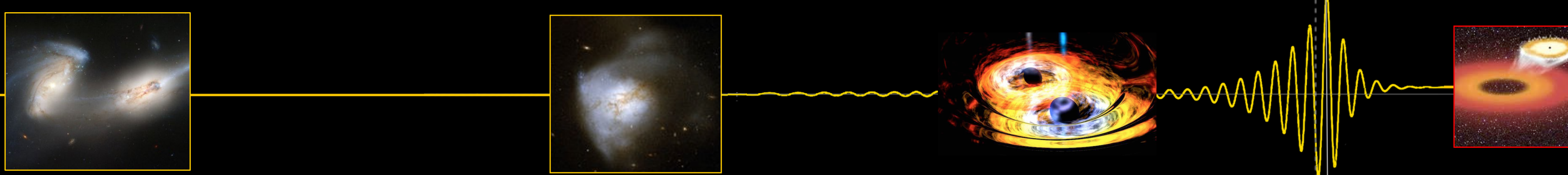
Detection Confidence	2019	2024	2029
2 σ	8%	96%	100%
3 σ	2%	36%	100%
4 σ	1%	16%	100%

Likely detection of *at least one* individual binary by 2029



Resolving Massive Black Hole Binaries





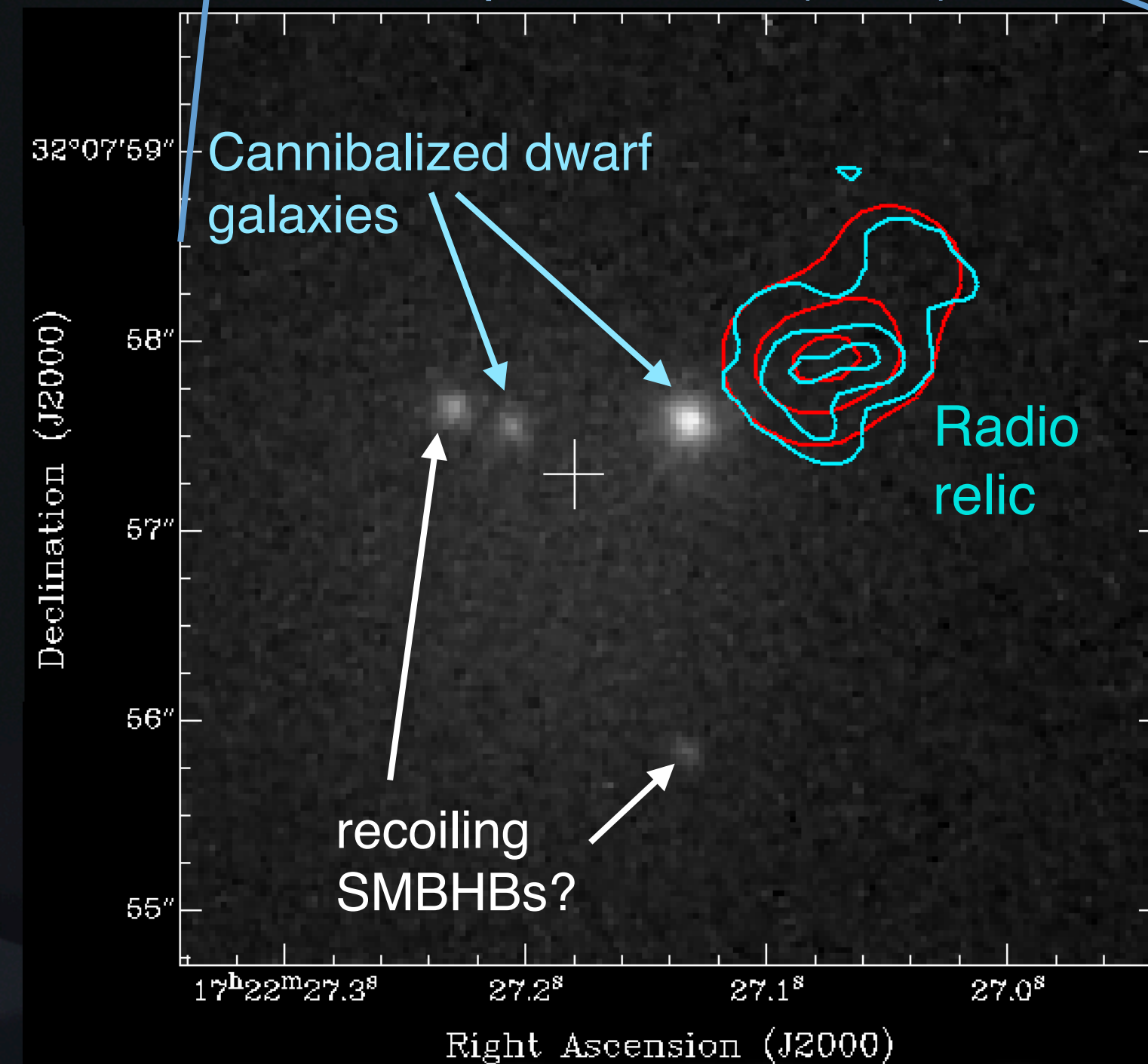
Red:
secondary or tertiary indicator

Theories & Observations: Gower82, Komossa+03, Graham04, Milosavljevic+Phinney05, Volonteri+08, Comerford+09, Liu+10, Burke-Spolaor11, Shen+11, Fabbiano+11, Sesana+11, Eracleous+11, Tanaka+12, Liu+14, Graham+15, Liu+15, Liao+20, Chen+20, and 800 more

Radio Black-hole Hunting

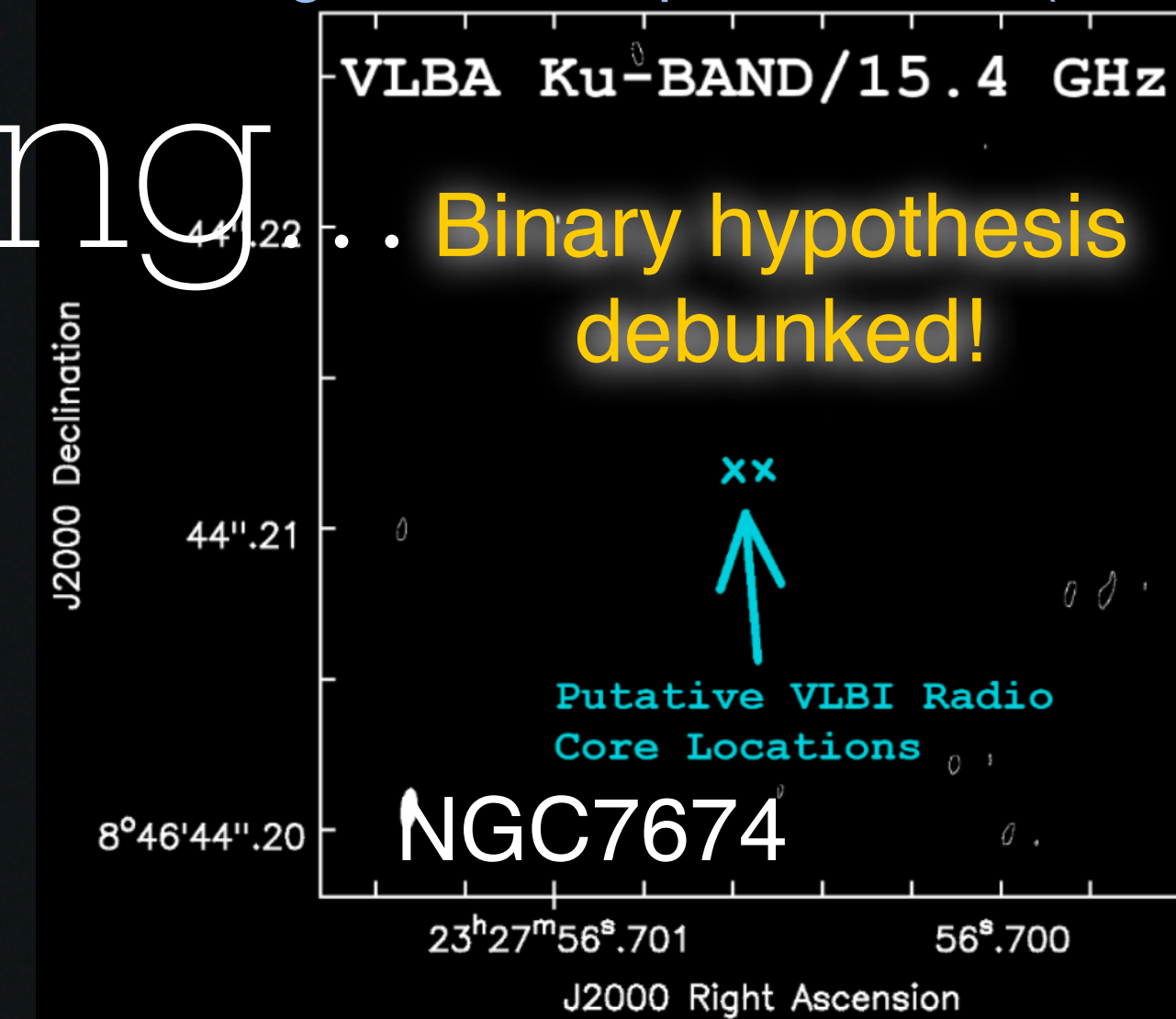


Burke-Spolaor et al. (2017)

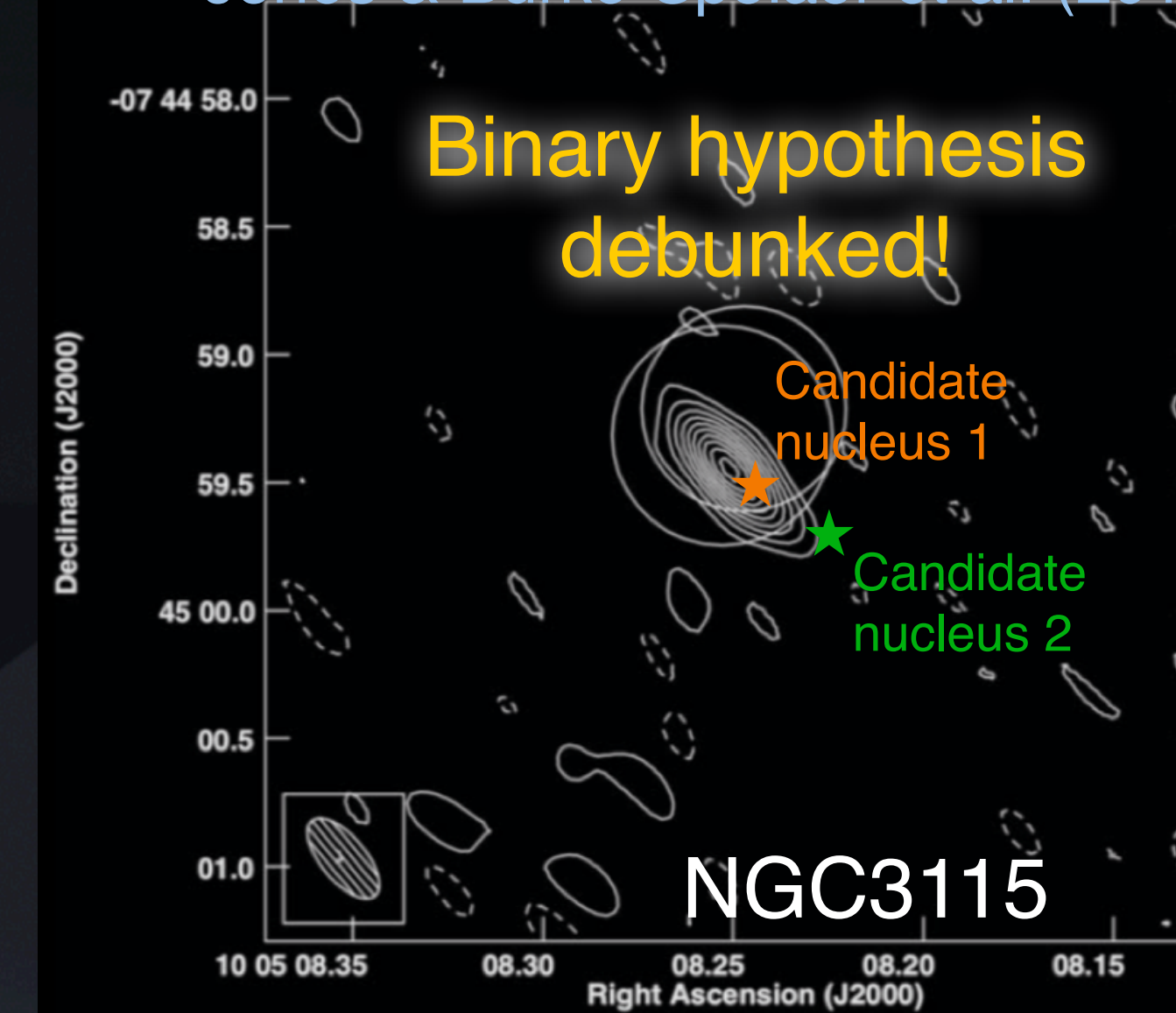


Investigating “Cored” Cluster Galaxy
[verdict: still candidate; needs JWST]

Breiding & Burke-Spolaor et al. (2021a)

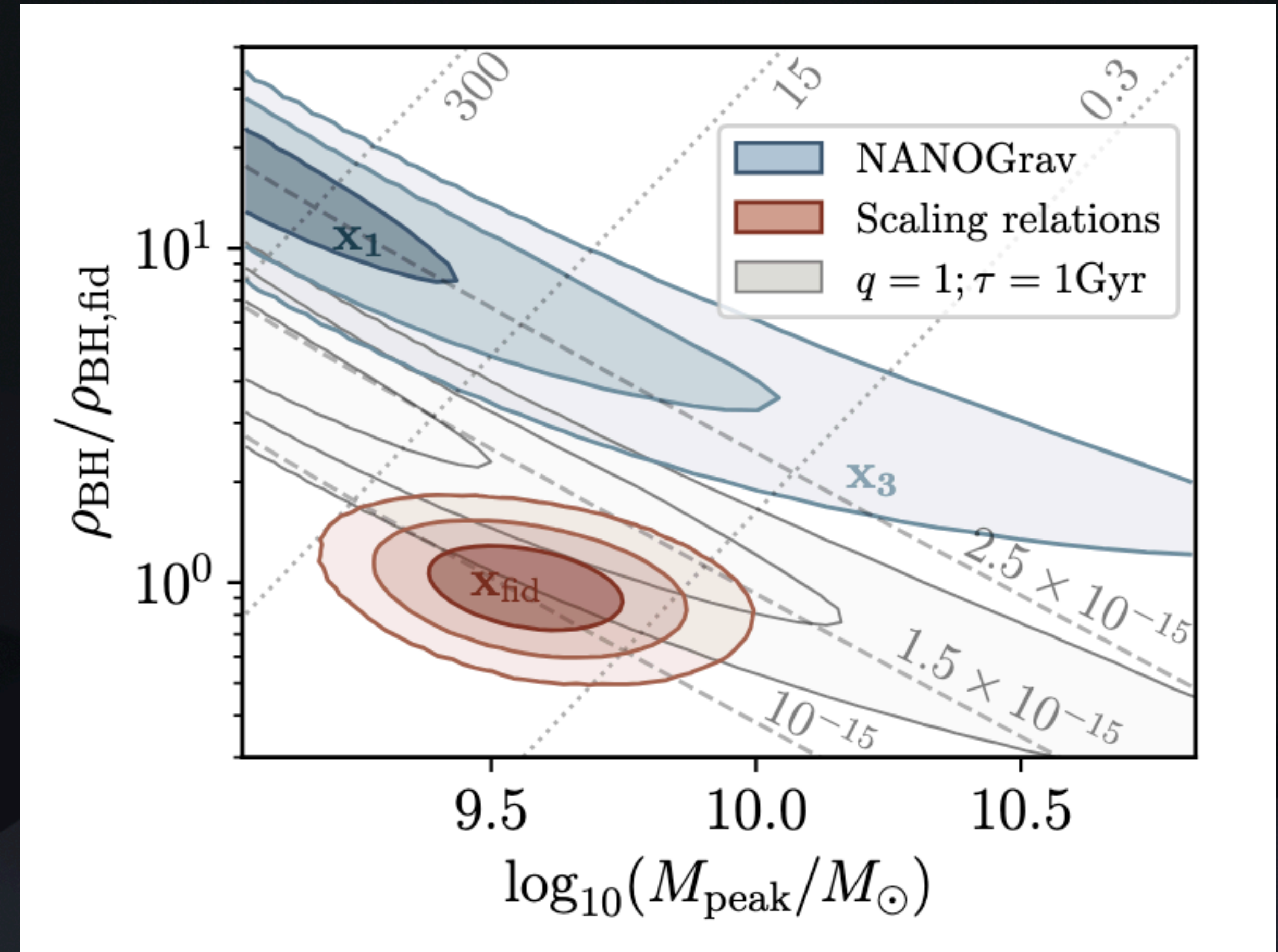
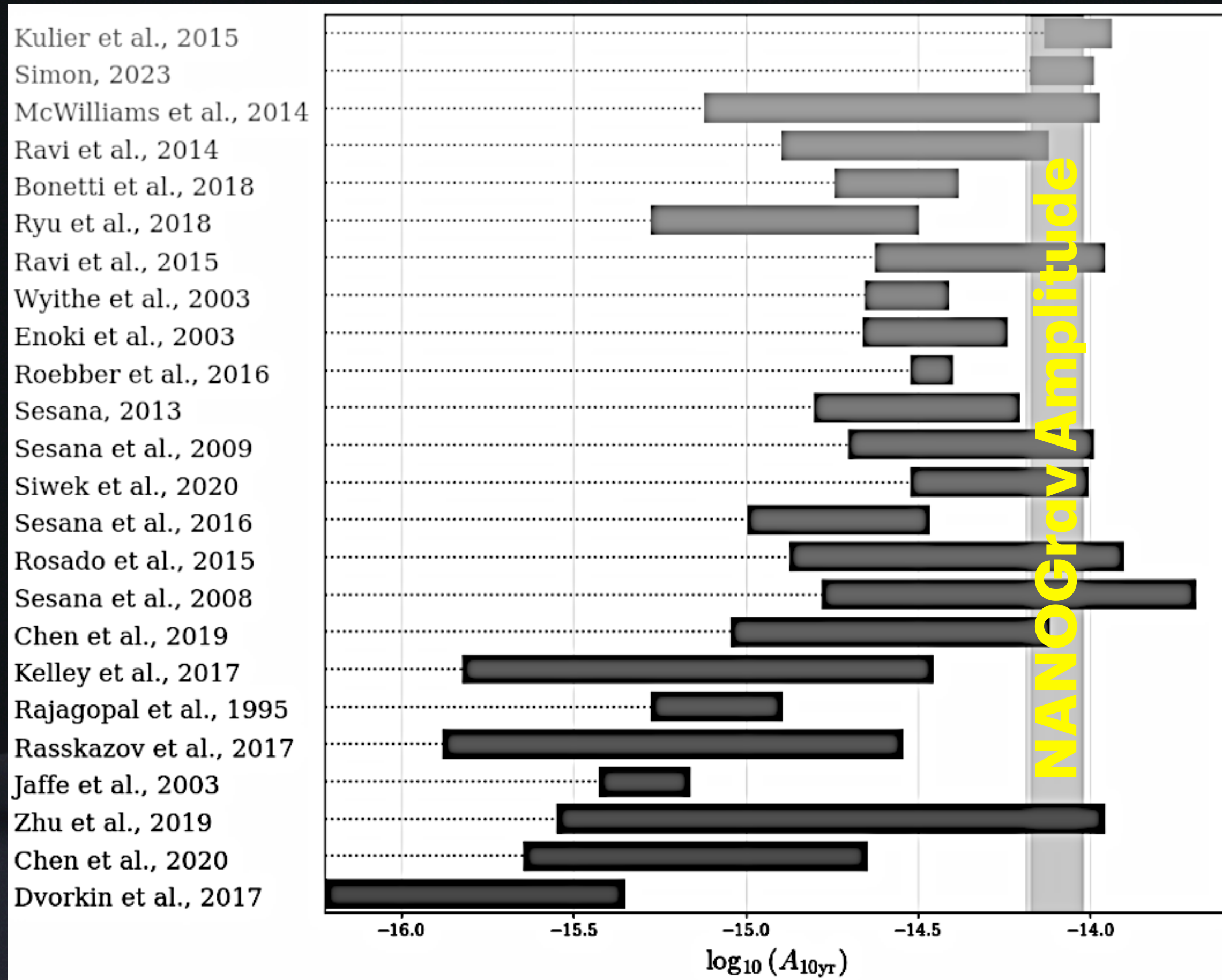


Jones & Burke-Spolaor et al. (2019)

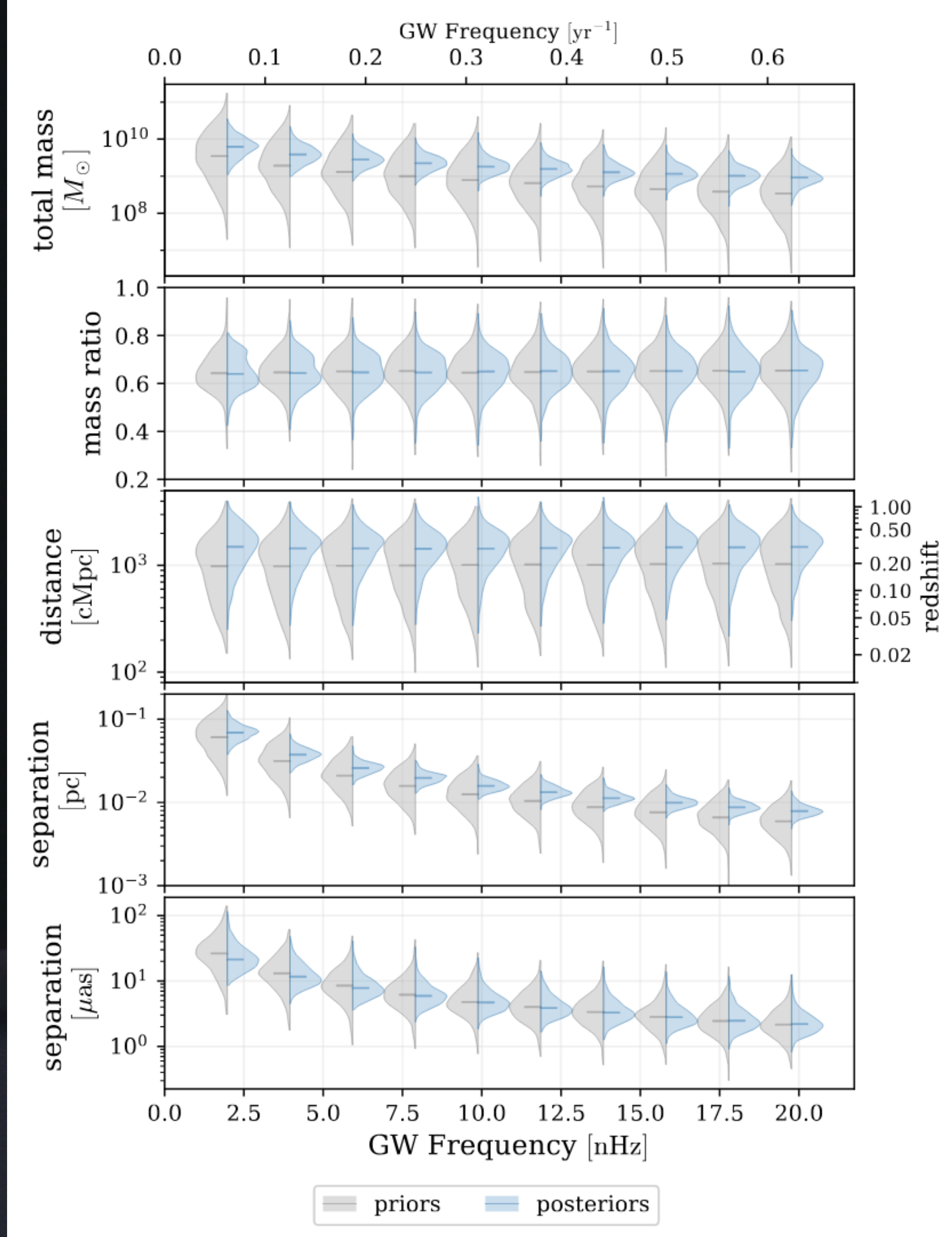


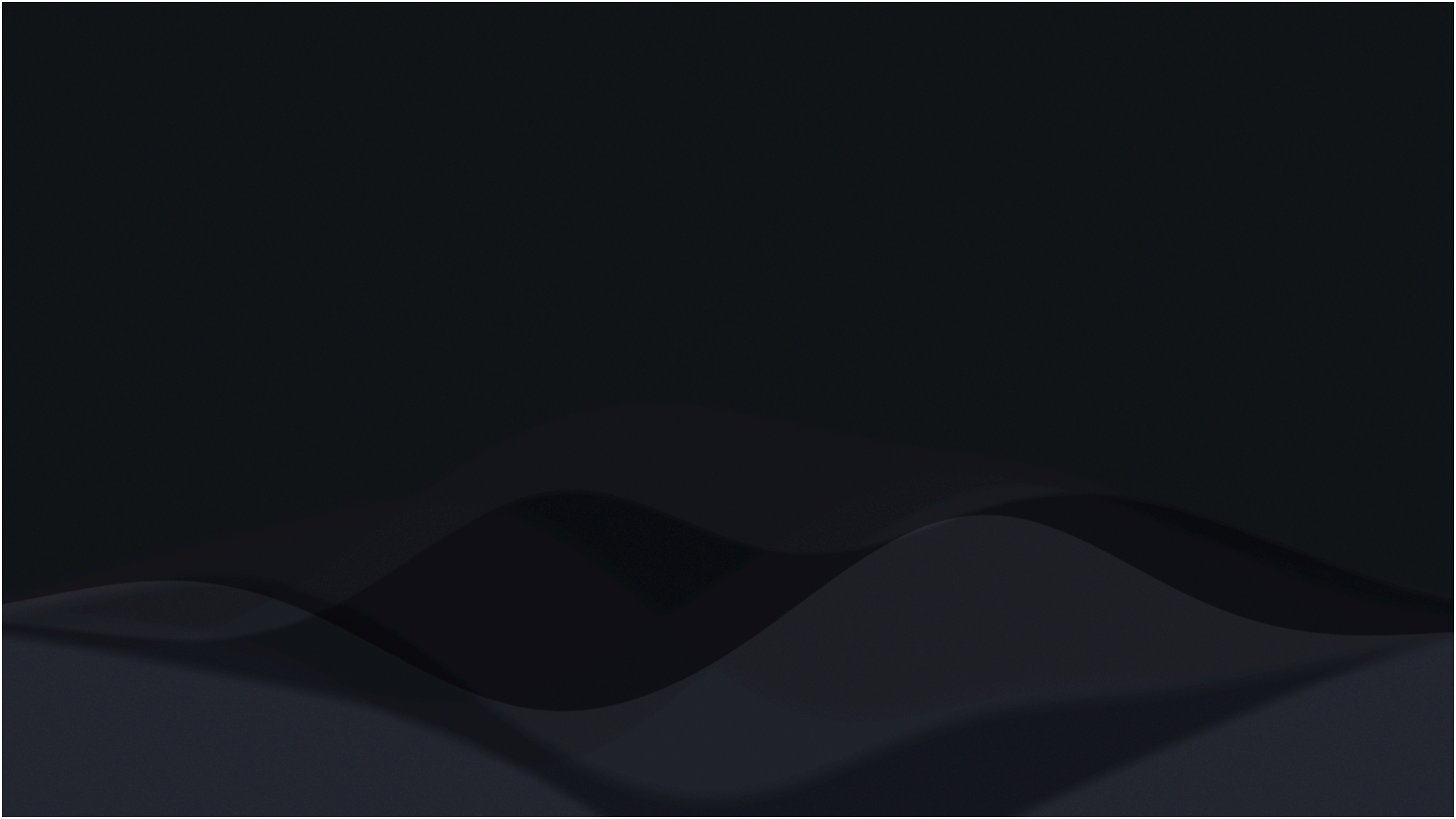
Also: Burke-Spolaor (2011); Godfrey et al. (2012); Burke-Spolaor (2013); Burke-Spolaor et al. (2014); Burke-Spolaor et al. (2018); Blecha et al. (2018), Gültekin & Burke-Spolaor et al. (2020), Breiding & Burke-Spolaor et al. (2021b)

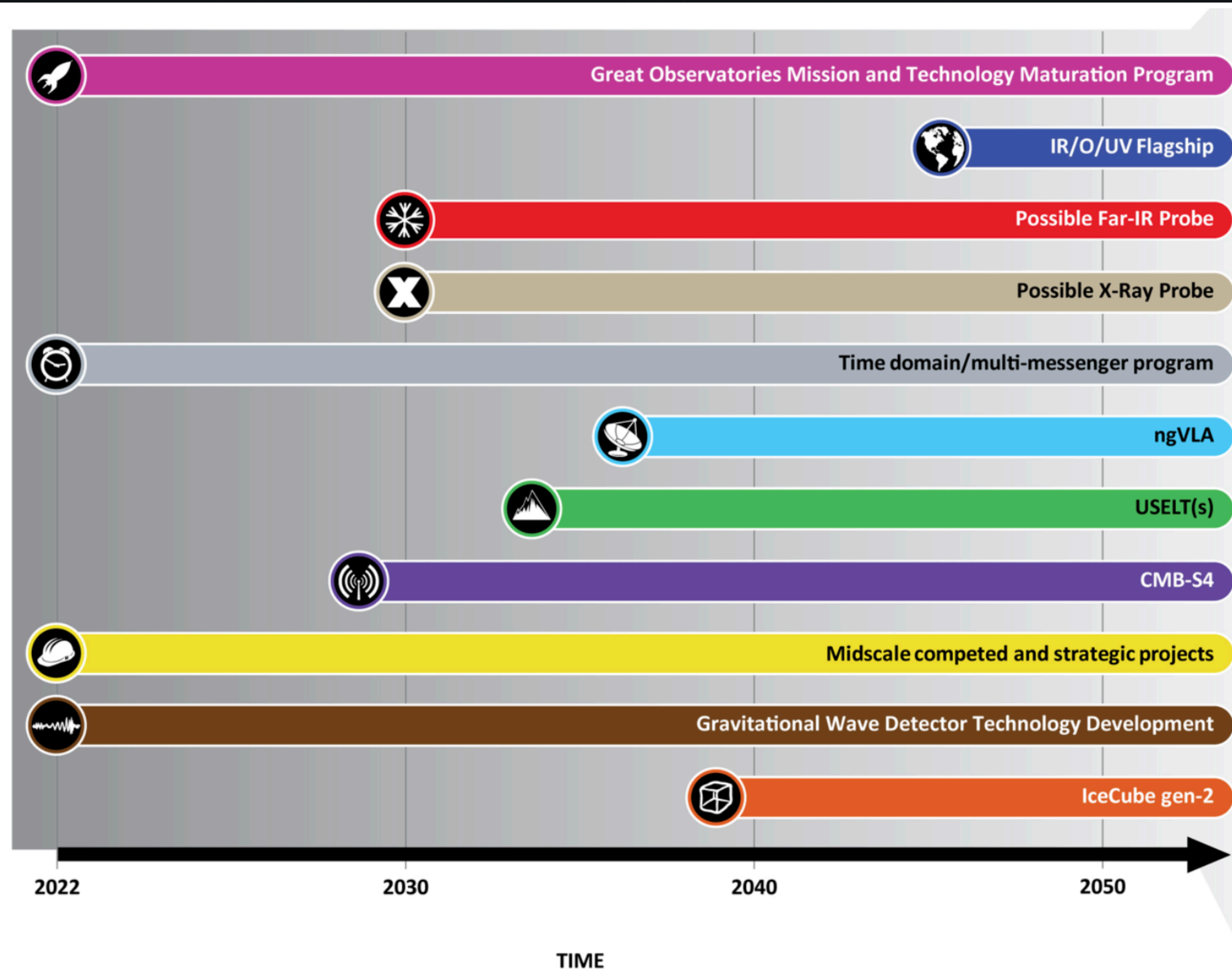
Is the GWB consistent with MBHBs?



Dominant GWB contributors





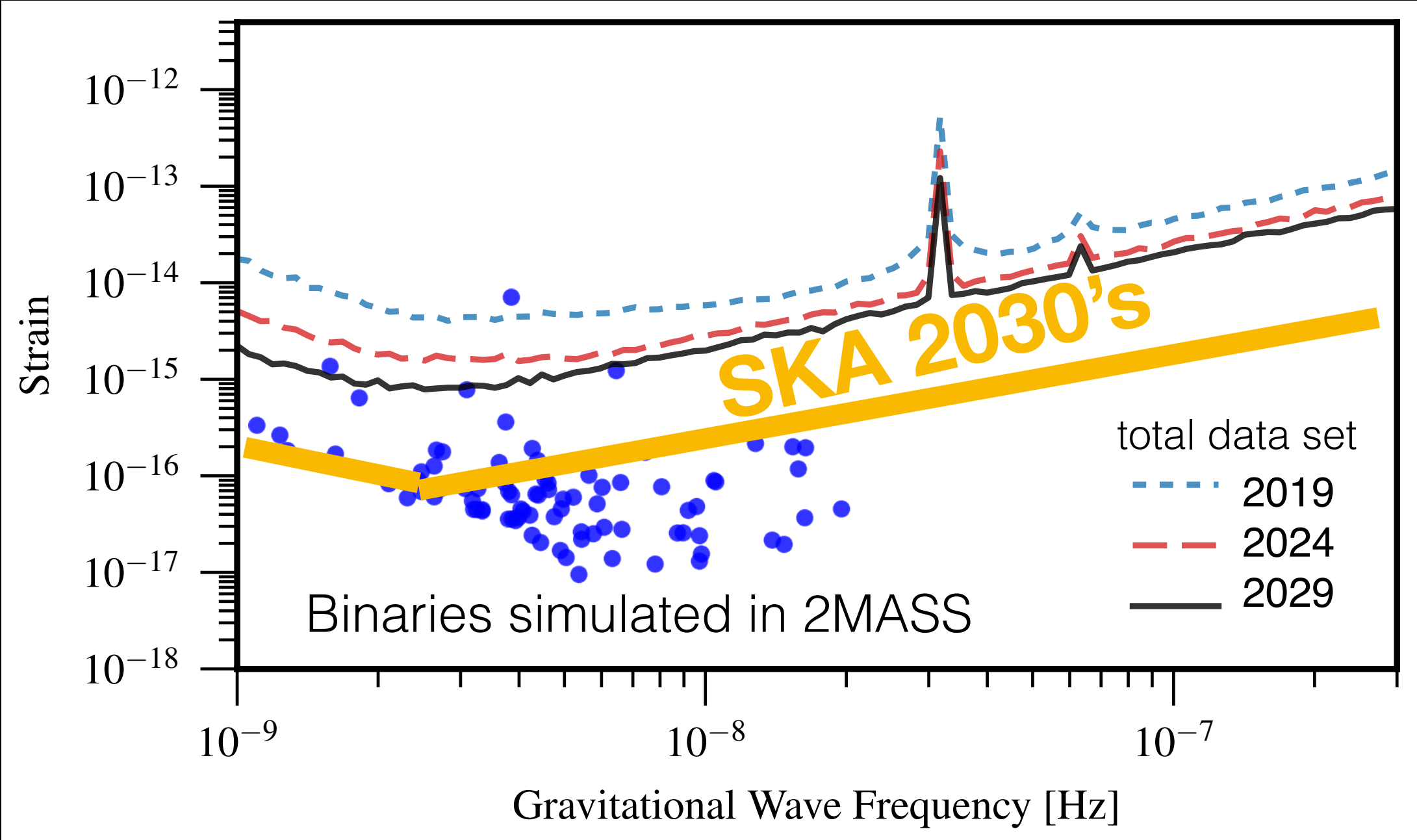


**The start date depicted is the start date of the program or the start of science operations for a particular mission.*

Credit: Astro
2020 report
(NAS)

Binary Black Holes Timeline

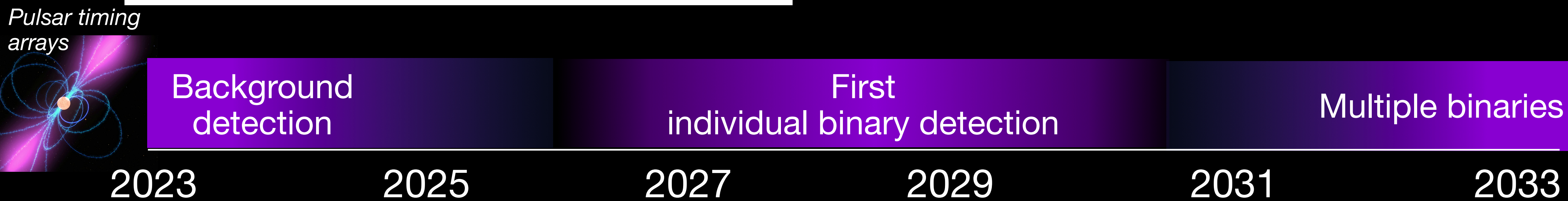
Mingarelli et al. (2017), Xin et al. (2021)



Modelled from local galaxy mergers, merger rates:

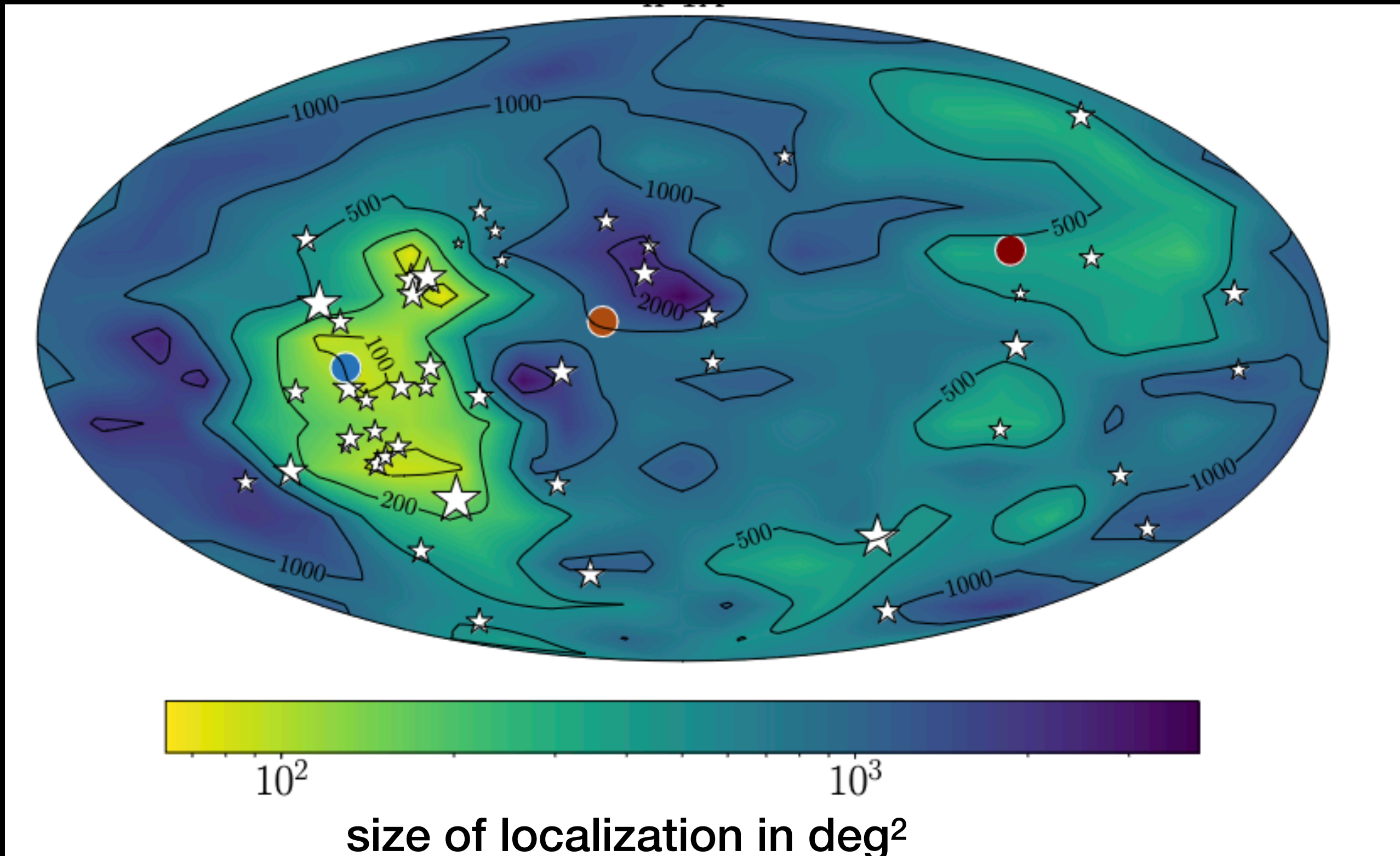
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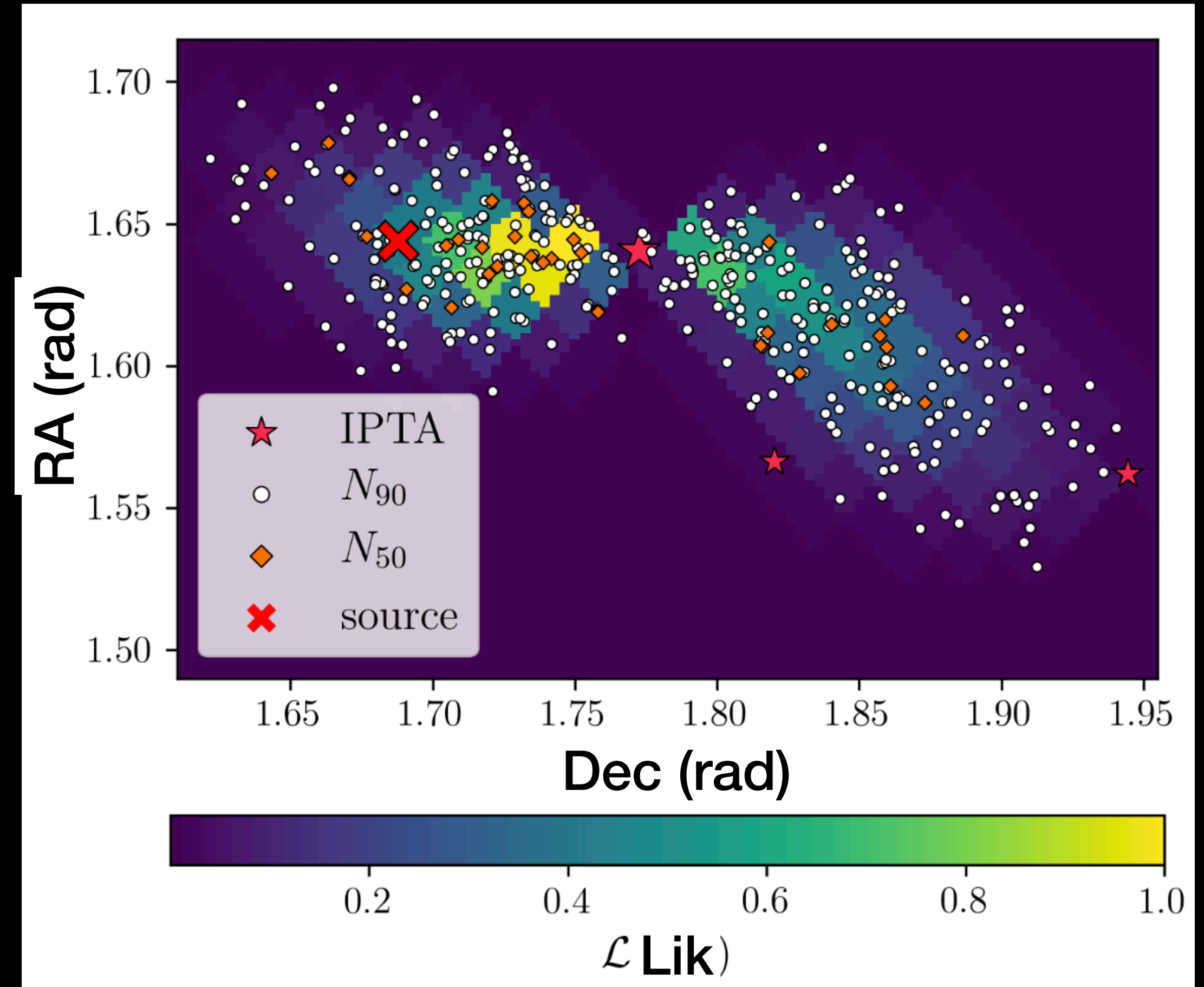


How well can we localize binaries?

Localization capabilities of (simulated) IPTA



Likely hosts up to $z \lesssim 1.2$, $M_{\text{bulge}} \gtrsim 10^{11} M_{\odot}$



Goldstein et al. (2019)

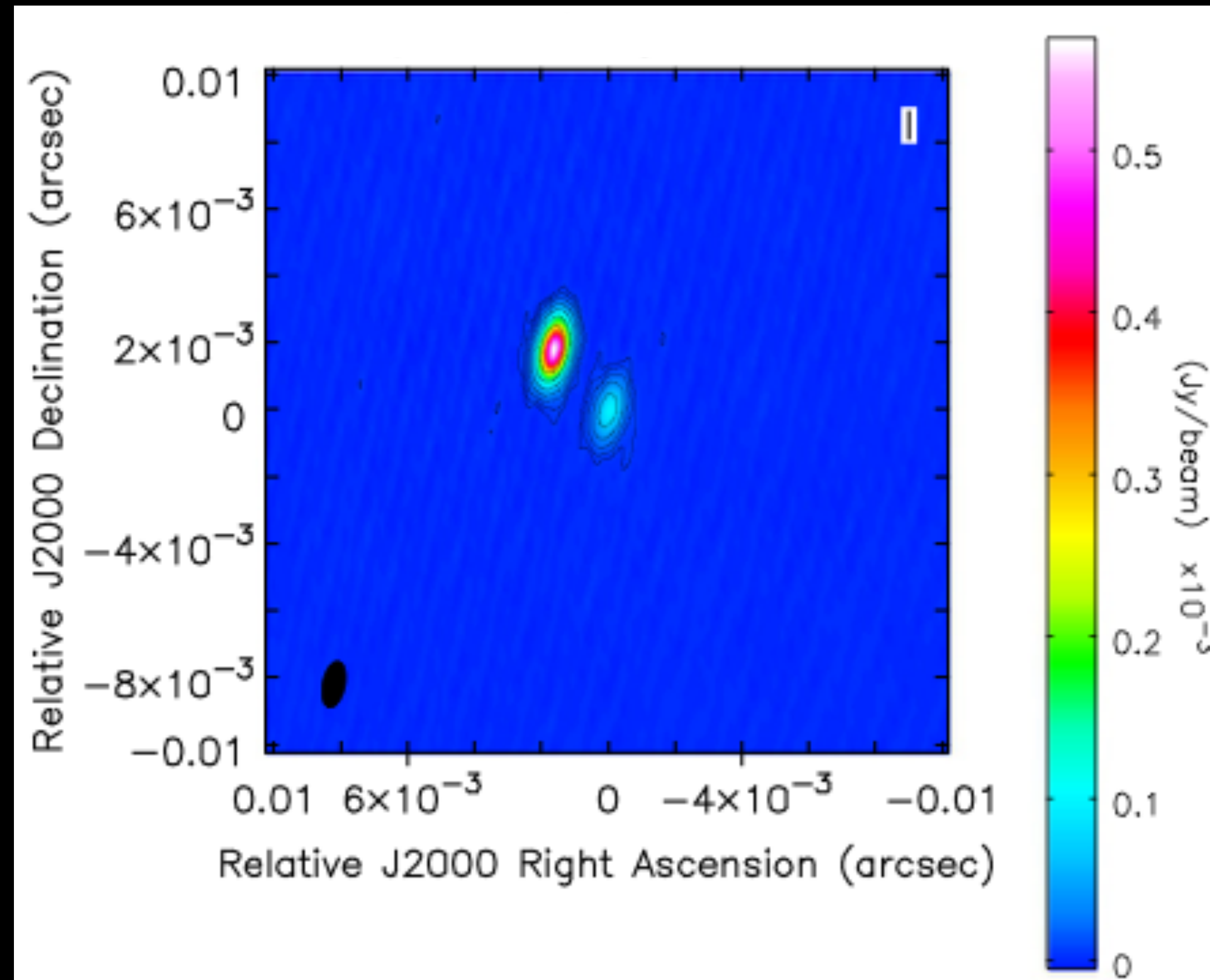
The Roles of SKAO and ngVLA

A snapshot of mid-2030's, in just the right universe.

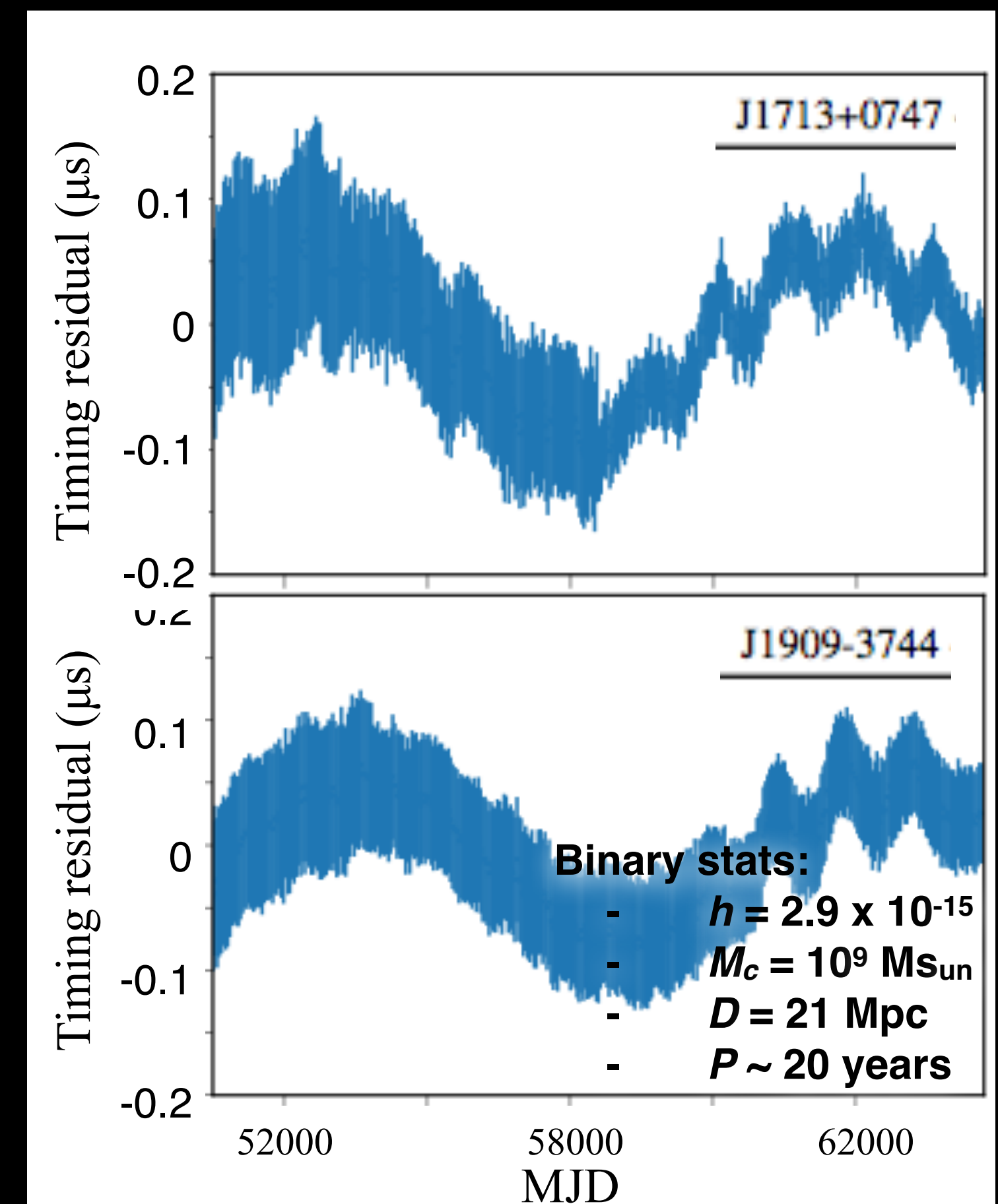
Simulated Binary SMBH ngVLA Observation: 30GHz

214x18m Main Array plus

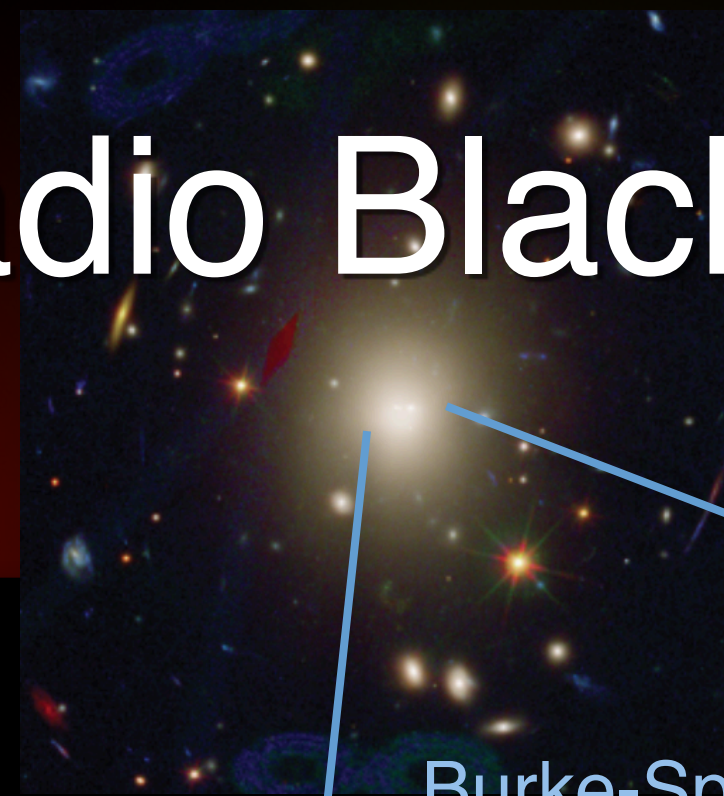
11 Continental-scale antennae (VLBA + 5x18m at GBO)



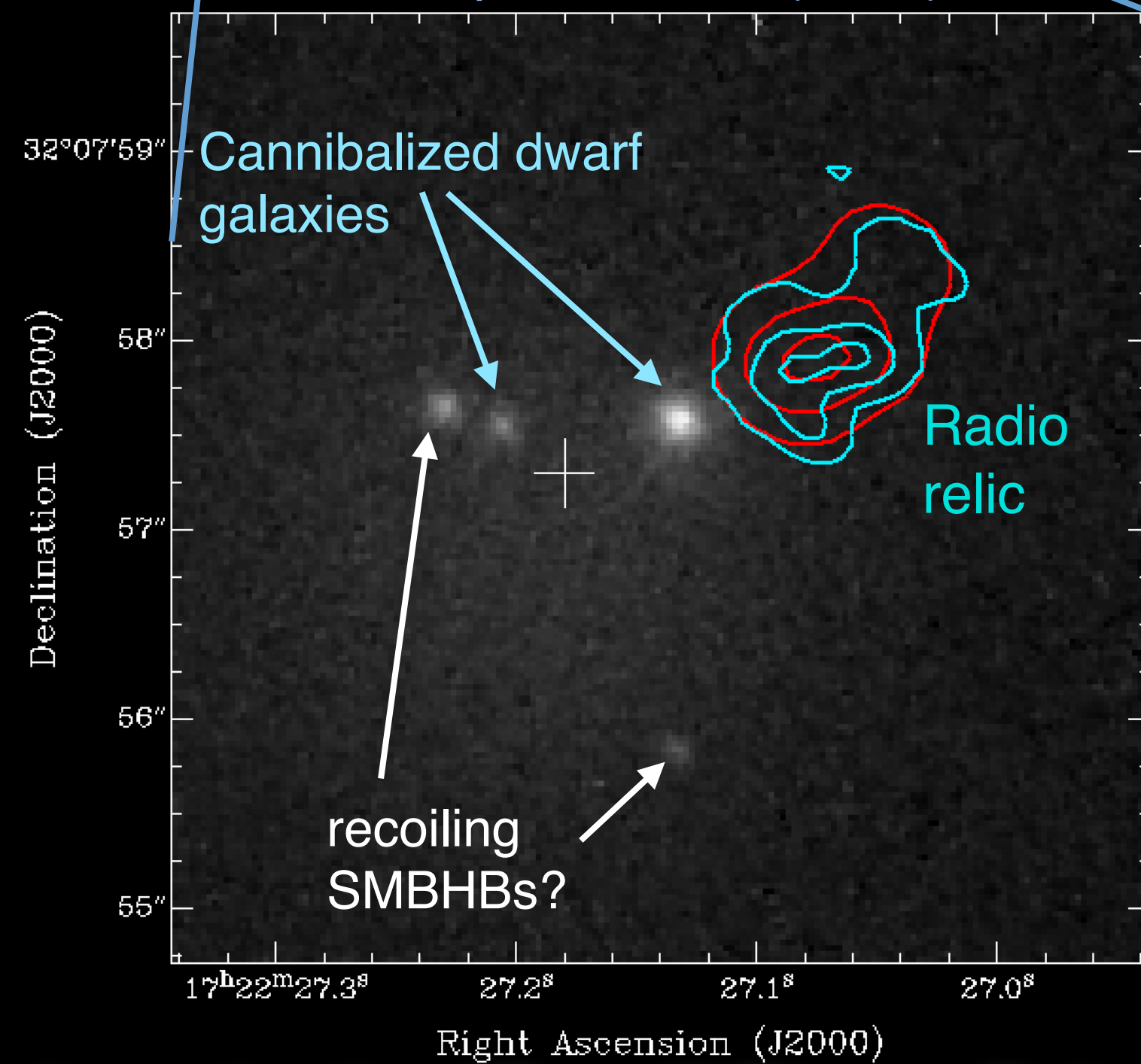
PTA Observation: SKA+IPTA



Radio Black-hole Hunting...

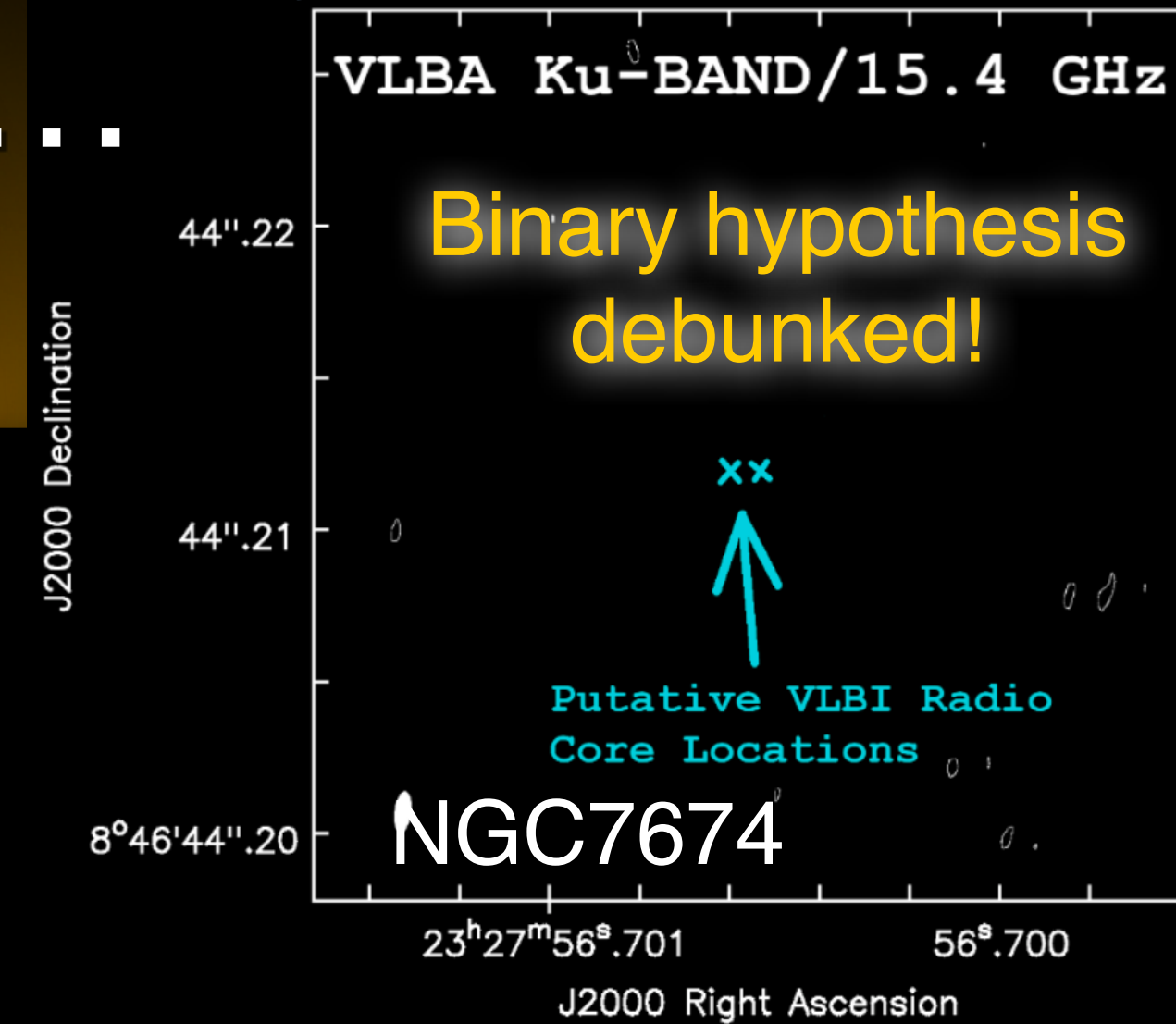


Burke-Spolaor et al. (2017)

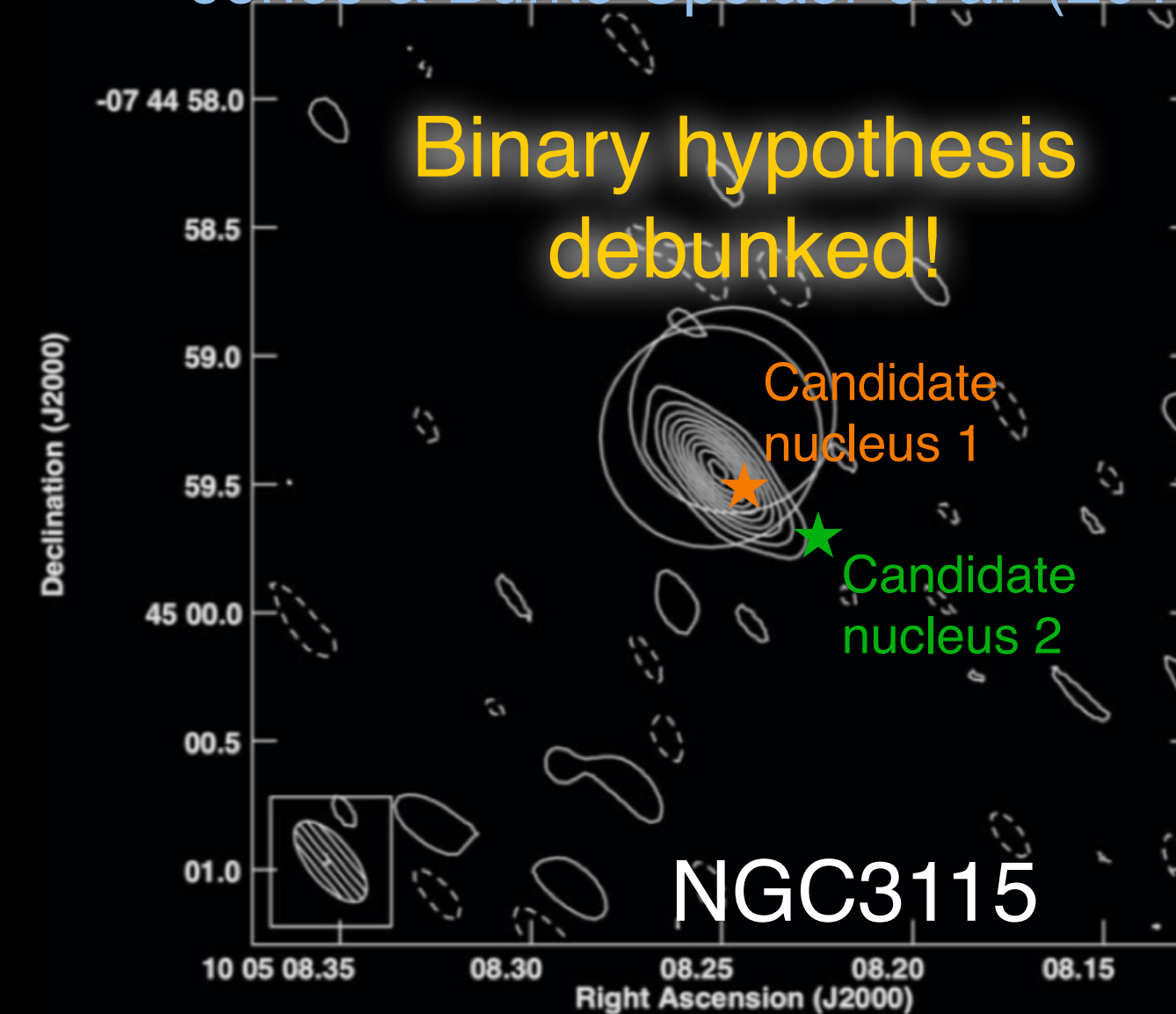


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Breiding & Burke-Spolaor et al. (2021a)



Jones & Burke-Spolaor et al. (2019)

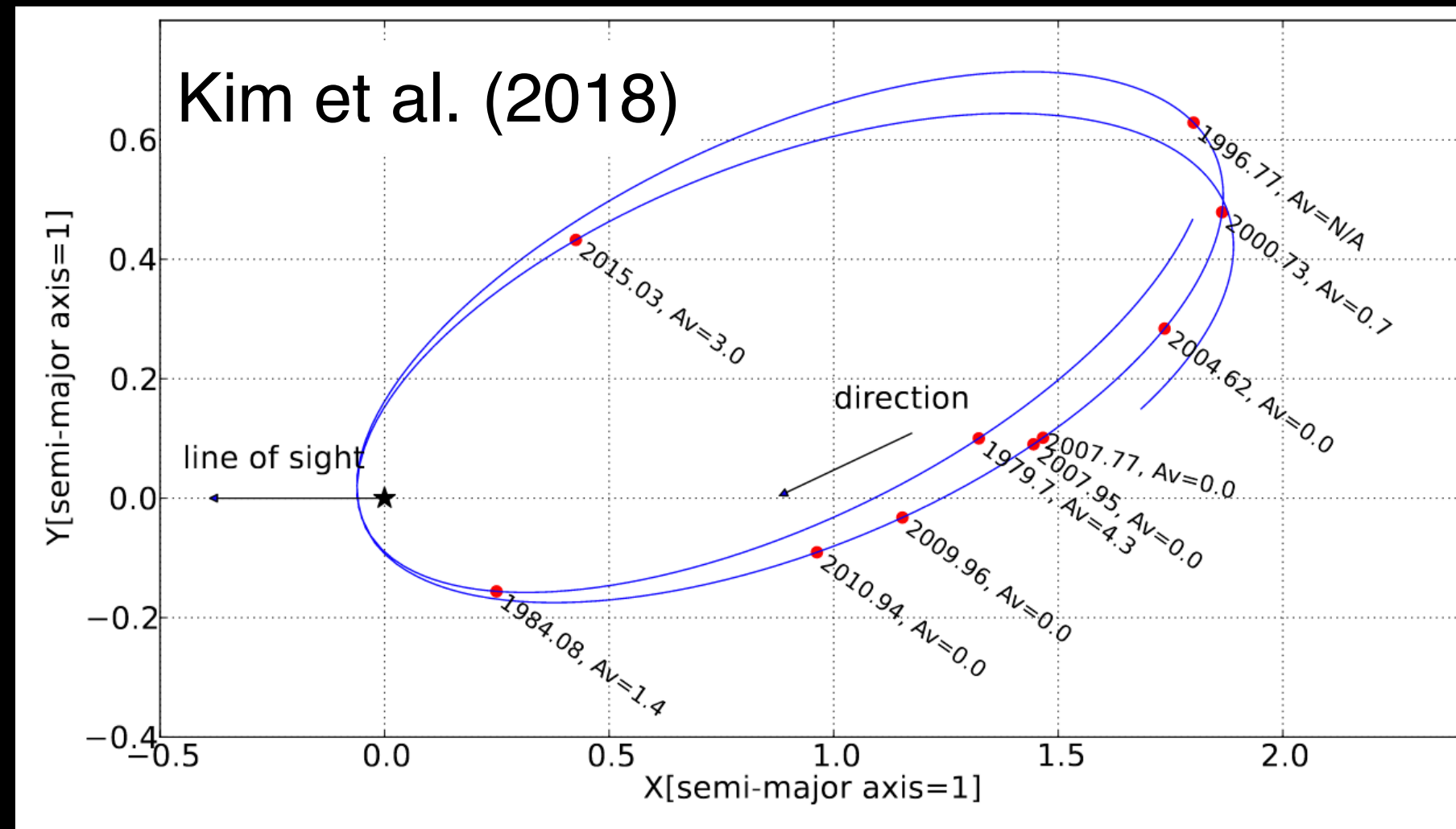


Also: Burke-Spolaor (2011); Godfrey et al. (2012); Burke-Spolaor (2013); Burke-Spolaor et al. (2014); Burke-Spolaor et al. (2018); Blecha et al. (2018), Gültekin & Burke-Spolaor et al. (2020), Breiding & Burke-Spolaor et al. (2021b)

Highlight: Galaxy 0206-0017



29-year apparent doppler motion about galaxy central potential well



*Model depends strongly on inclination.

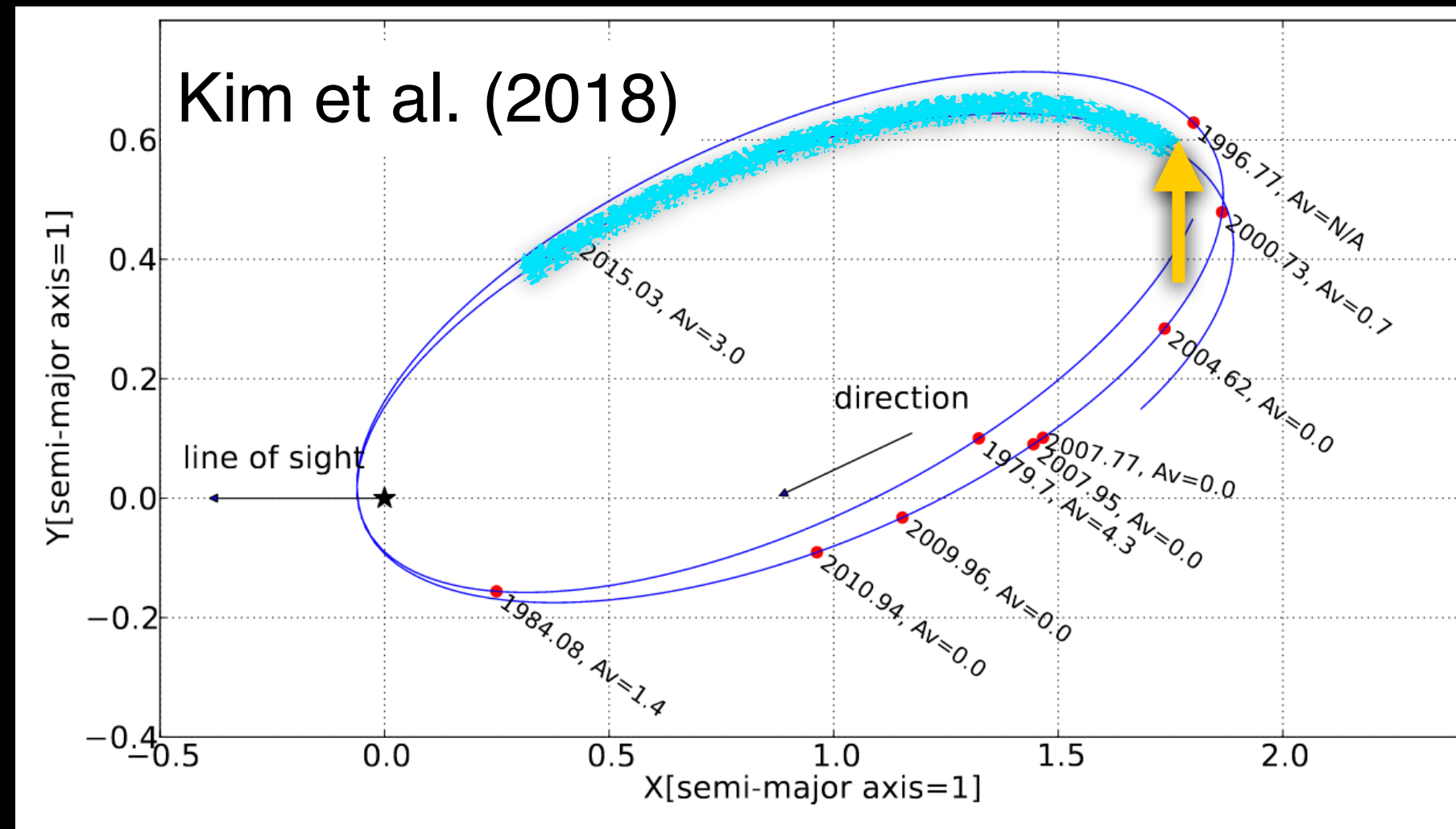


Greg Walsh

Highlight: Galaxy 0206-0017



29-year apparent doppler motion about galaxy central potential well

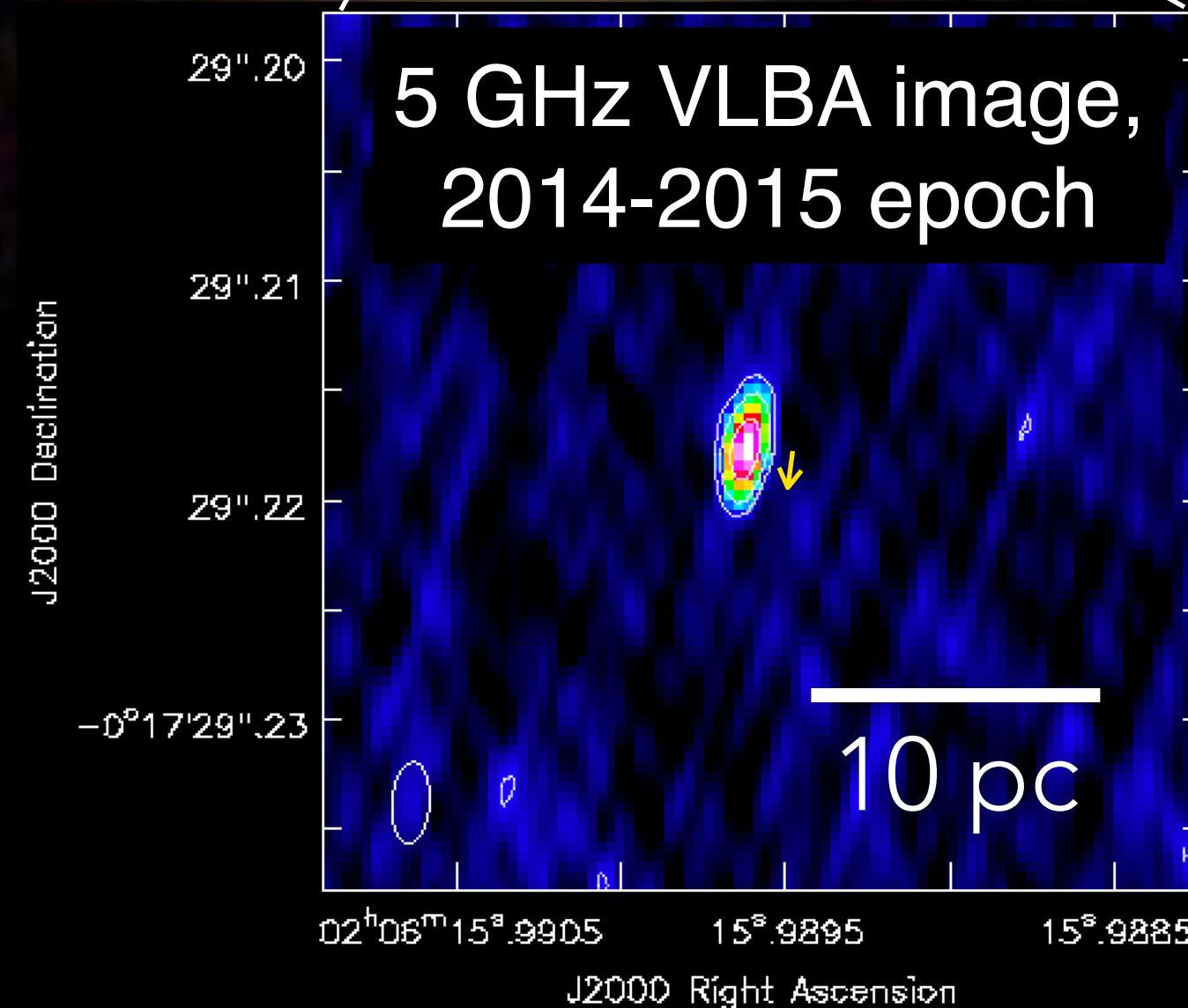


*Model depends strongly on inclination.



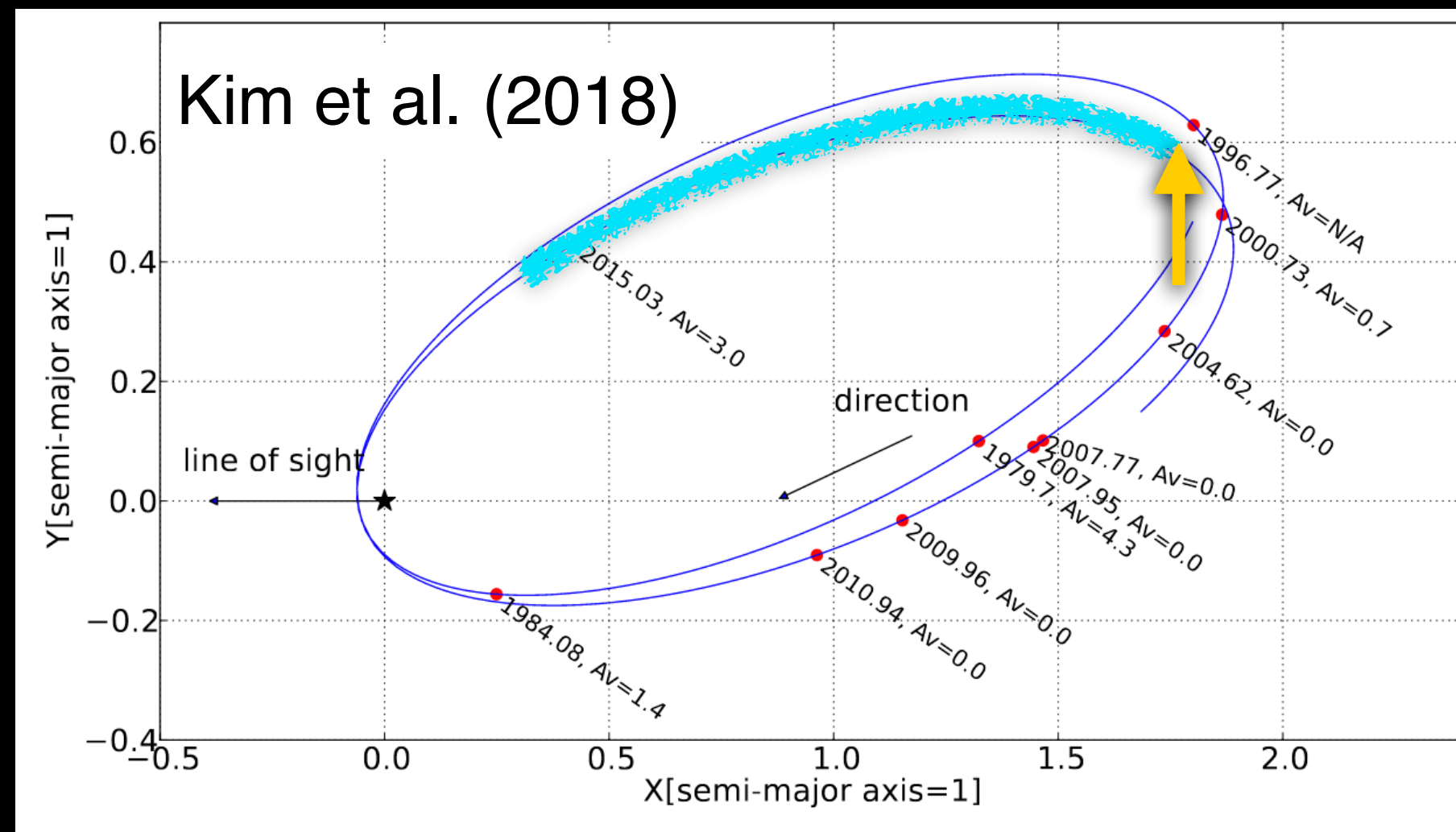
Greg Walsh

Highlight: Galaxy 0206-0017



Greg Walsh

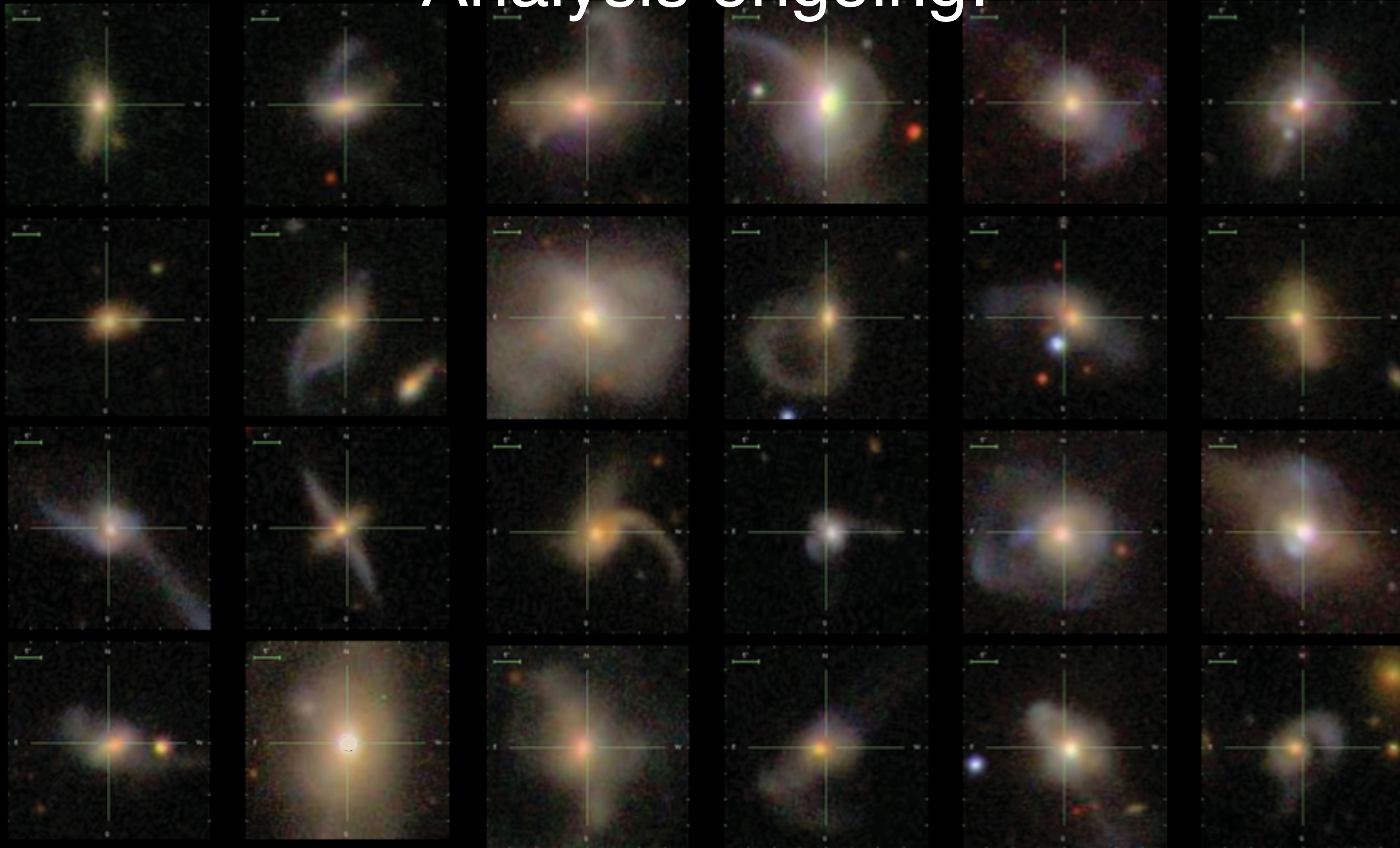
29-year apparent doppler motion about galaxy central potential well



*Model depends strongly on inclination.

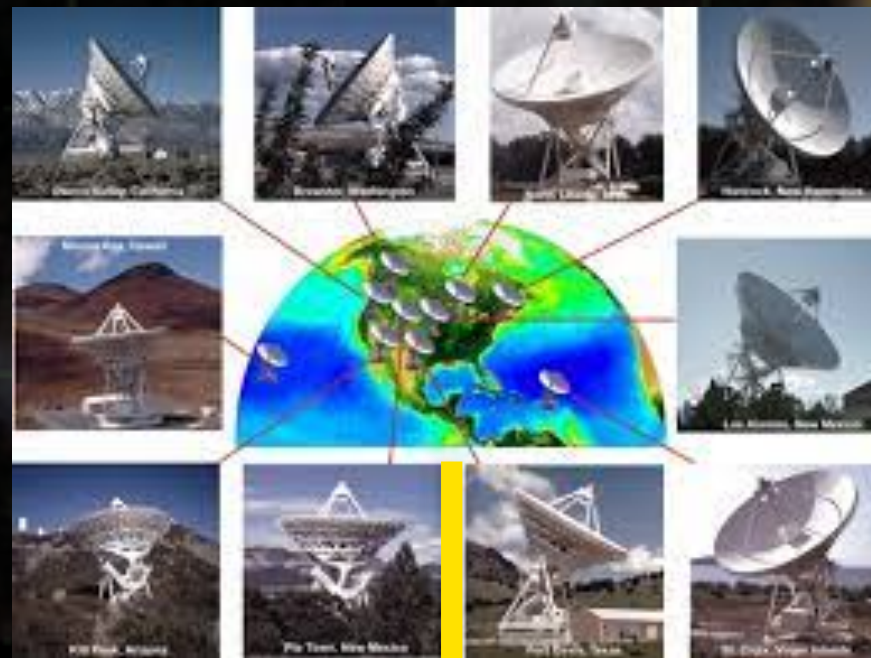
Marginal (2σ)
proper motion vector
(0.1 pc over 2014 - 2021)

Analysis ongoing!



Analysis ongoing!

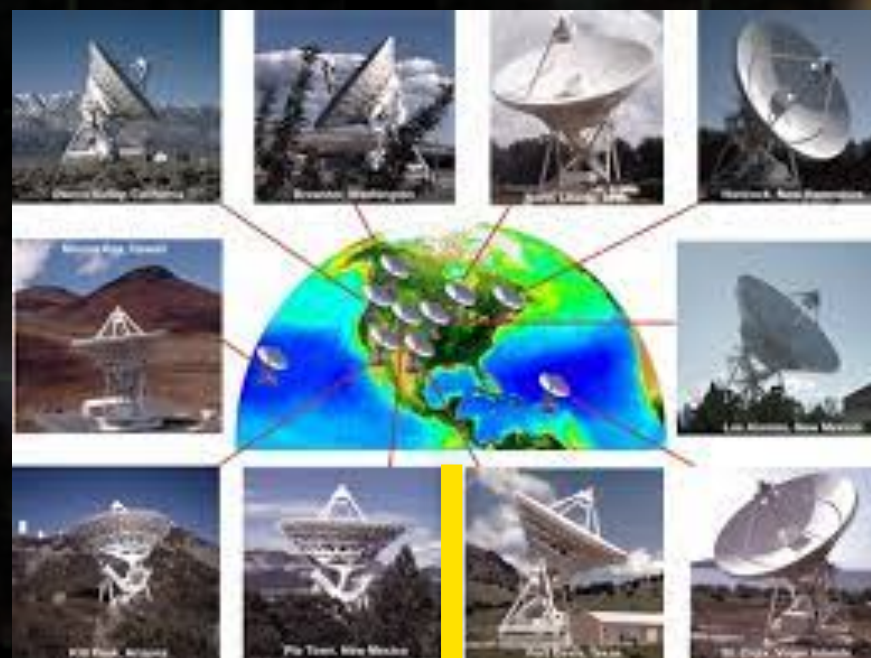
Long-baseline interferometry:
last-parsec pairs and recoils



Observations complete
Spring 2022

Analysis ongoing!

Long-baseline interferometry:
last-parsec pairs and recoils



Observations complete
Spring 2022

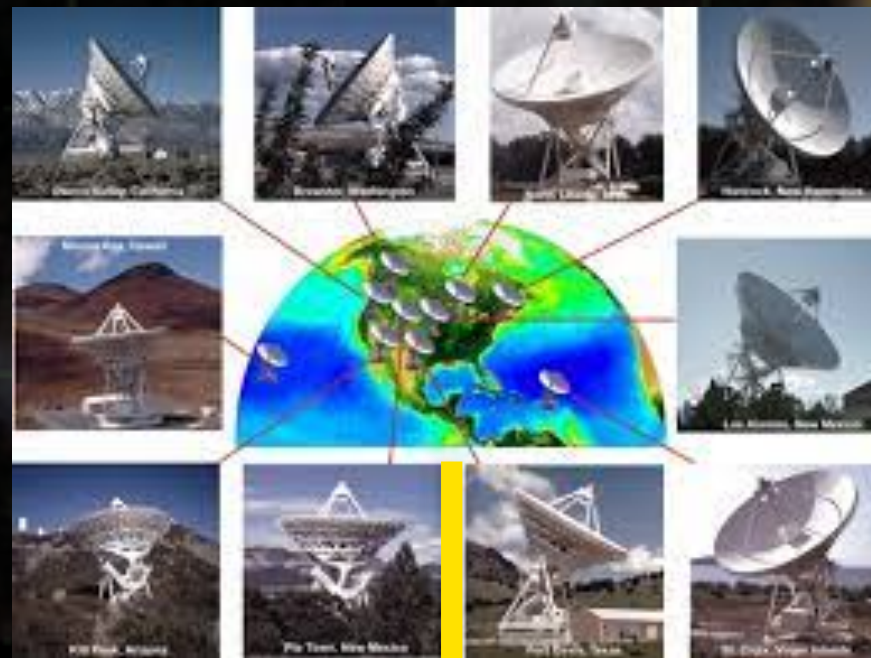
VLA (Radio), Keck and
Gemini (Optical):
Galaxy dynamics and history



VLA survey:
Test for general compact
objects in sample
Fall 2022
Optical: Ongoing

Analysis ongoing!

Long-baseline interferometry:
last-parsec pairs and recoils



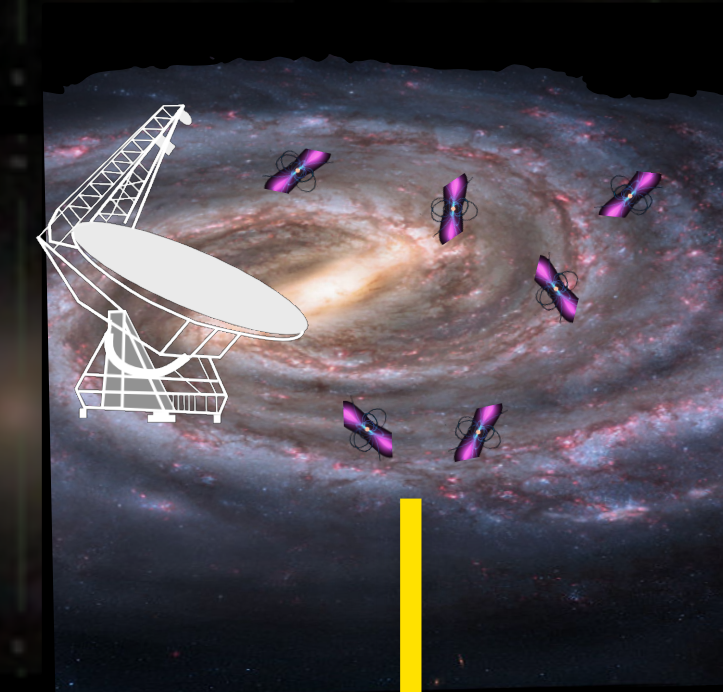
Observations complete
Spring 2022

VLA (Radio), Keck and
Gemini (Optical):
Galaxy dynamics and history



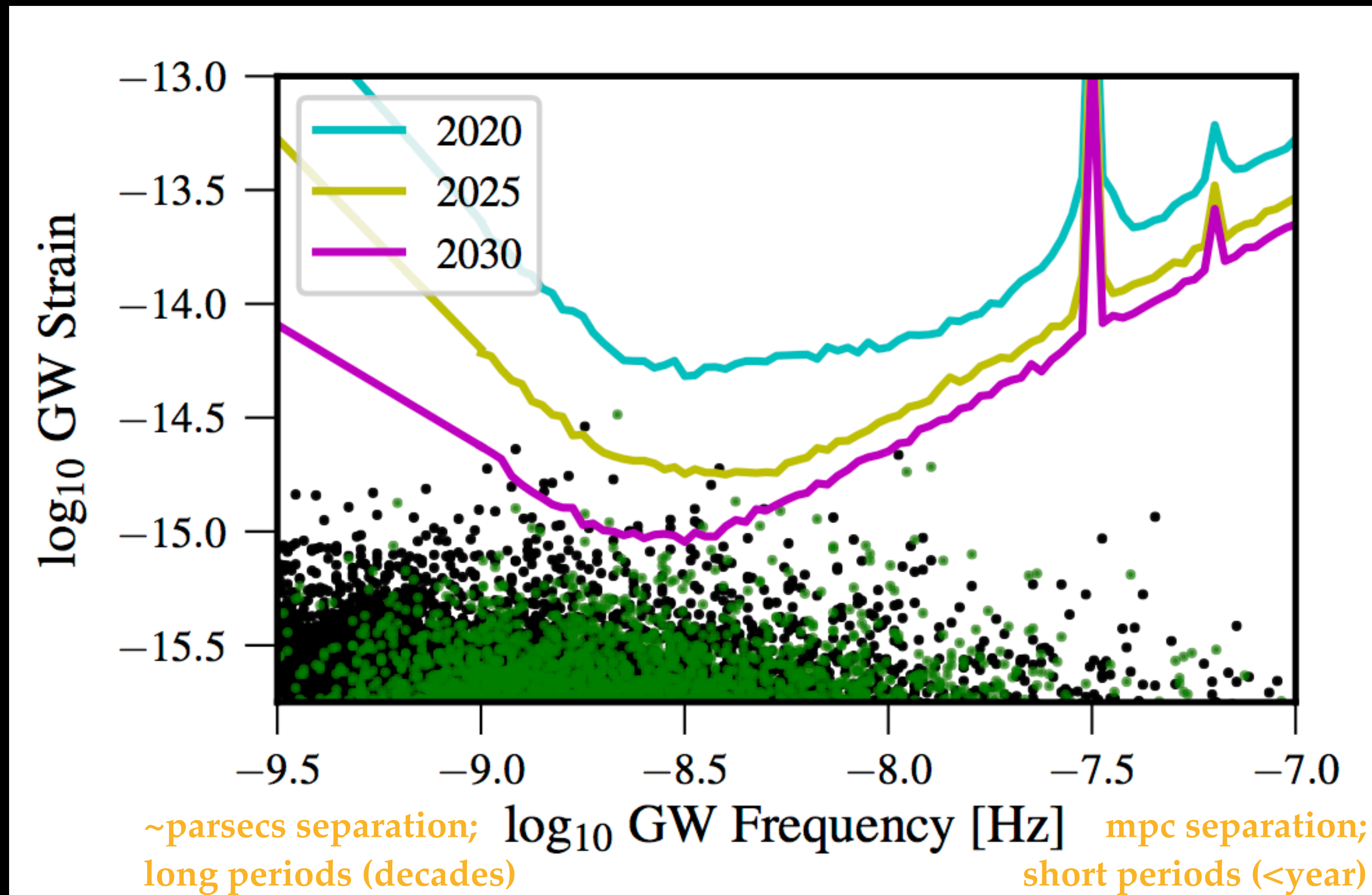
VLA survey:
Test for general compact
objects in sample
Fall 2022
Optical: Ongoing

Pulsar timing:
inspiraling binaries



Upcoming
NANOGrav data
release

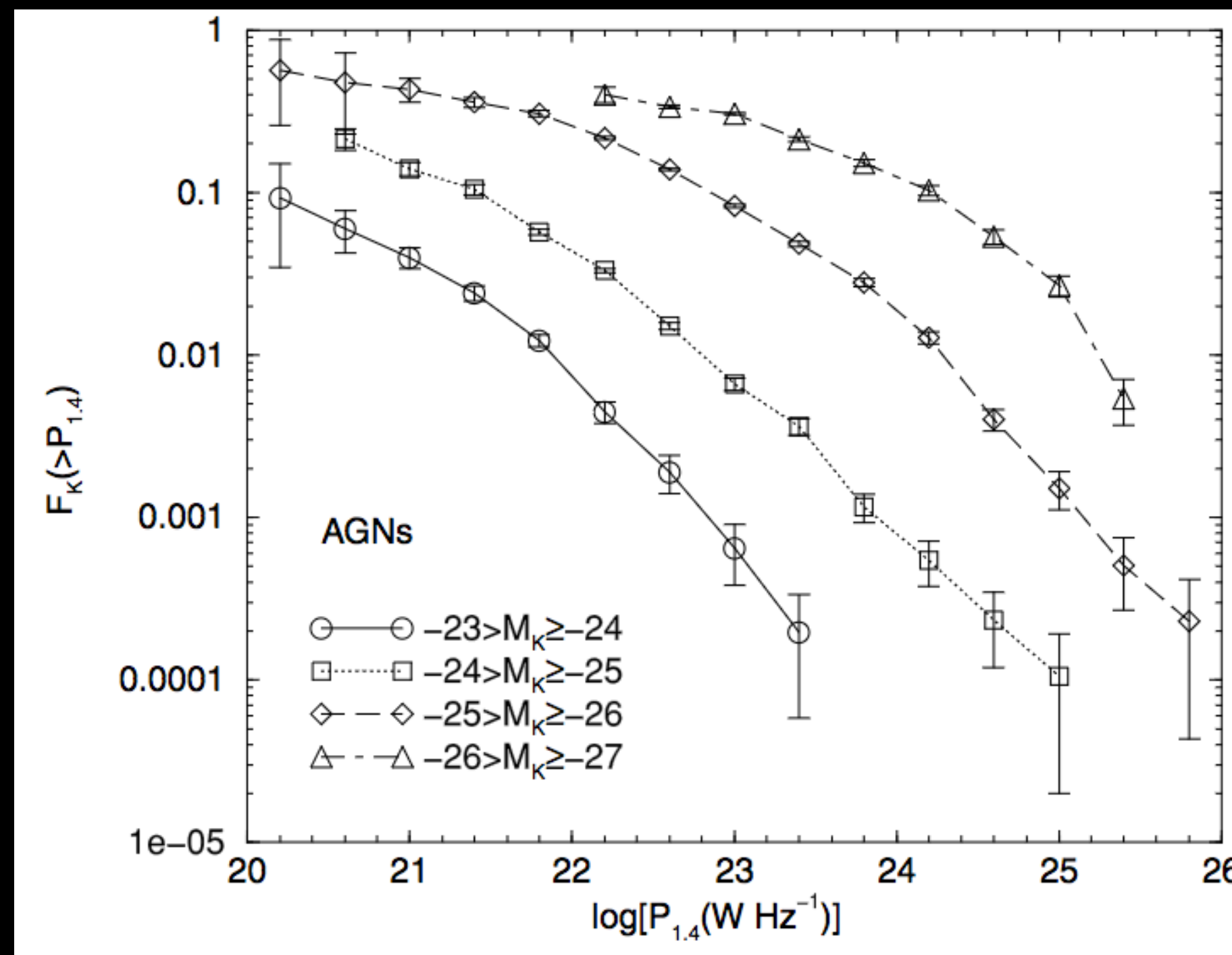
Binary SMBH Simulations



cf. Simon & Burke-Spolaor (2016)

Binary SMBH Simulations + EM

Seeding SMBHs with radio AGN:
Bivariate radio luminosity function.

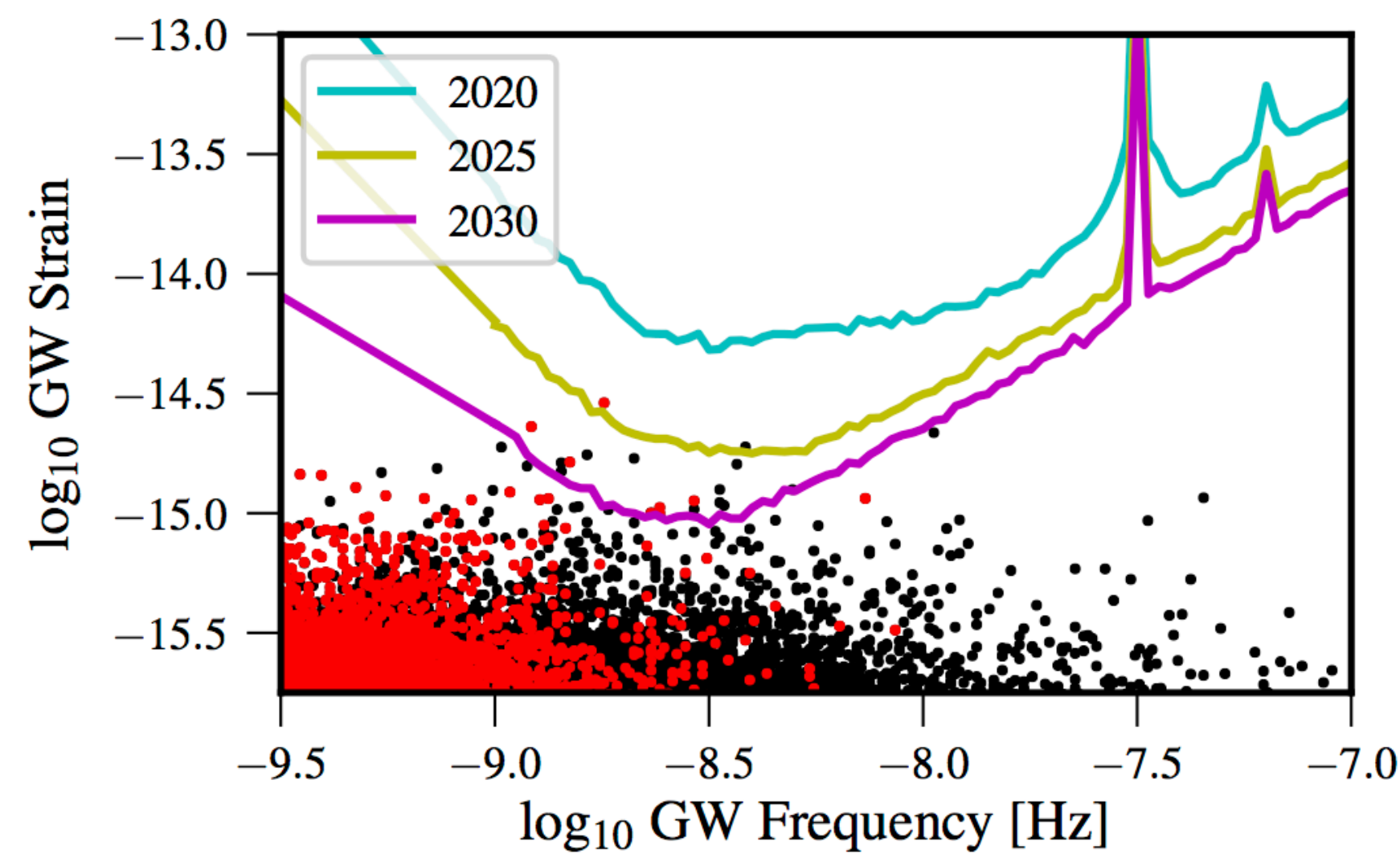


Also: seeding
10% of galaxies
with emission-
line systems.

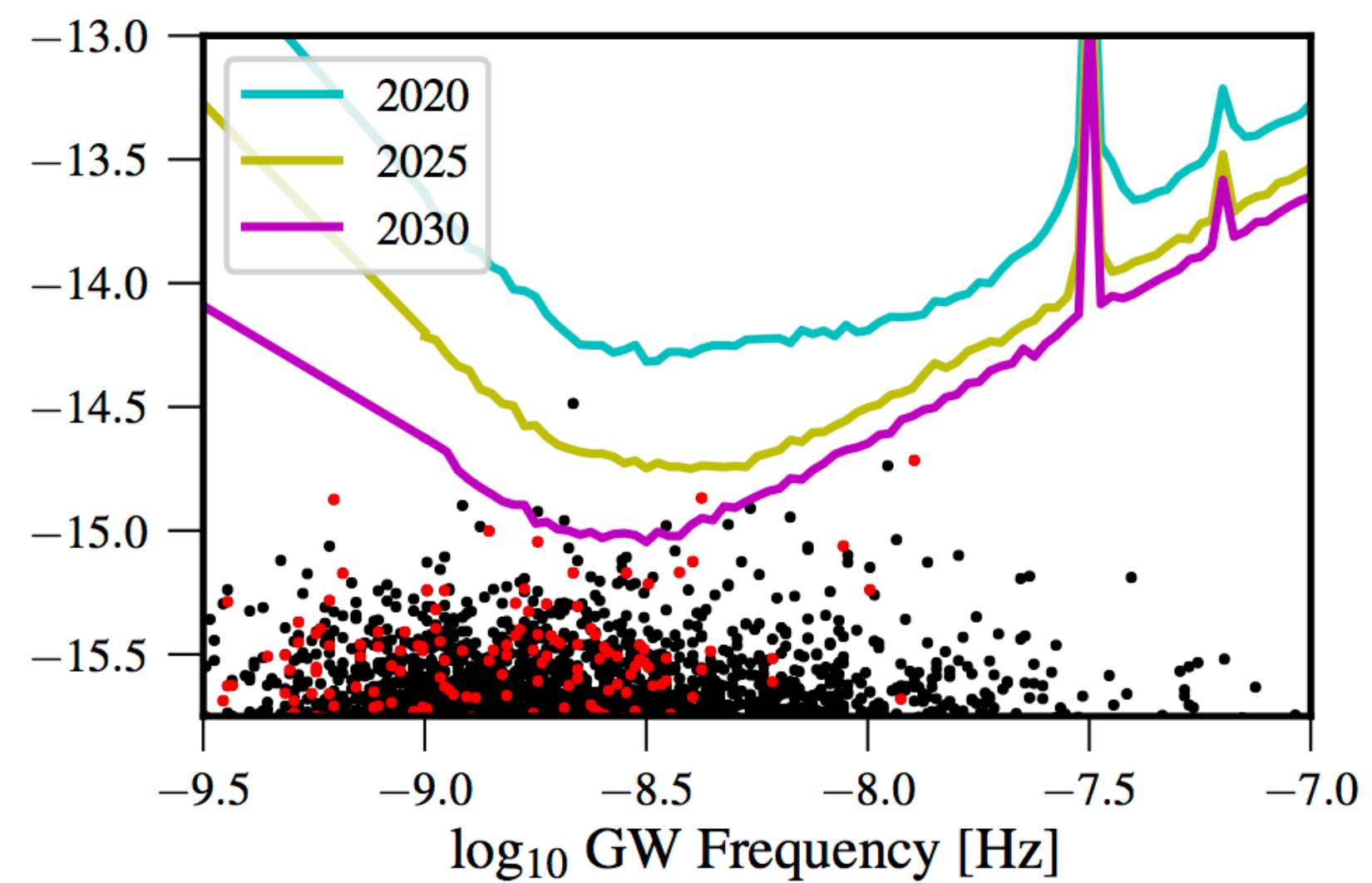
Mauch & Sadler (2007)

Binary SMBH Simulations

Weak Environmental Interaction



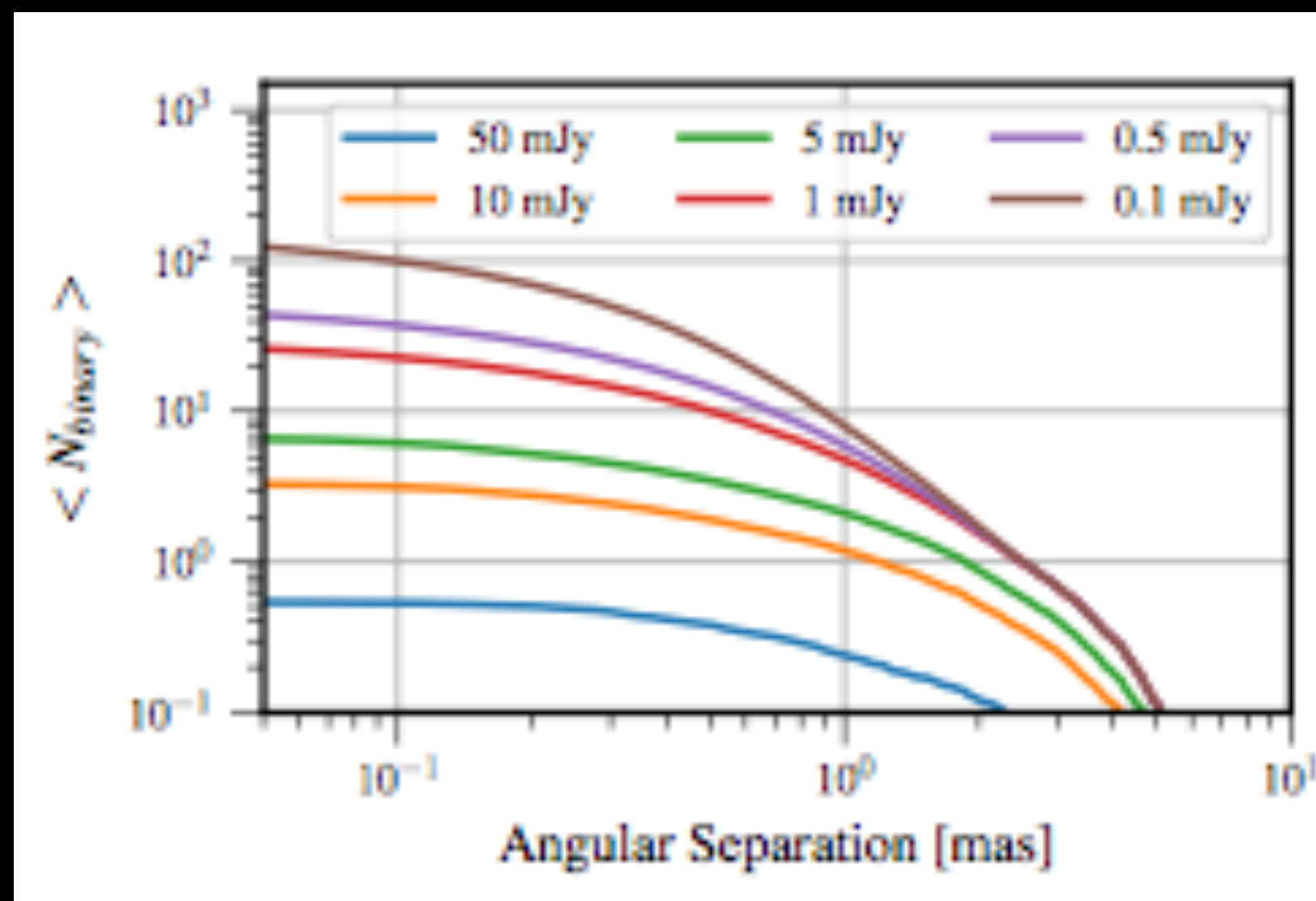
Strong Environmental Interaction



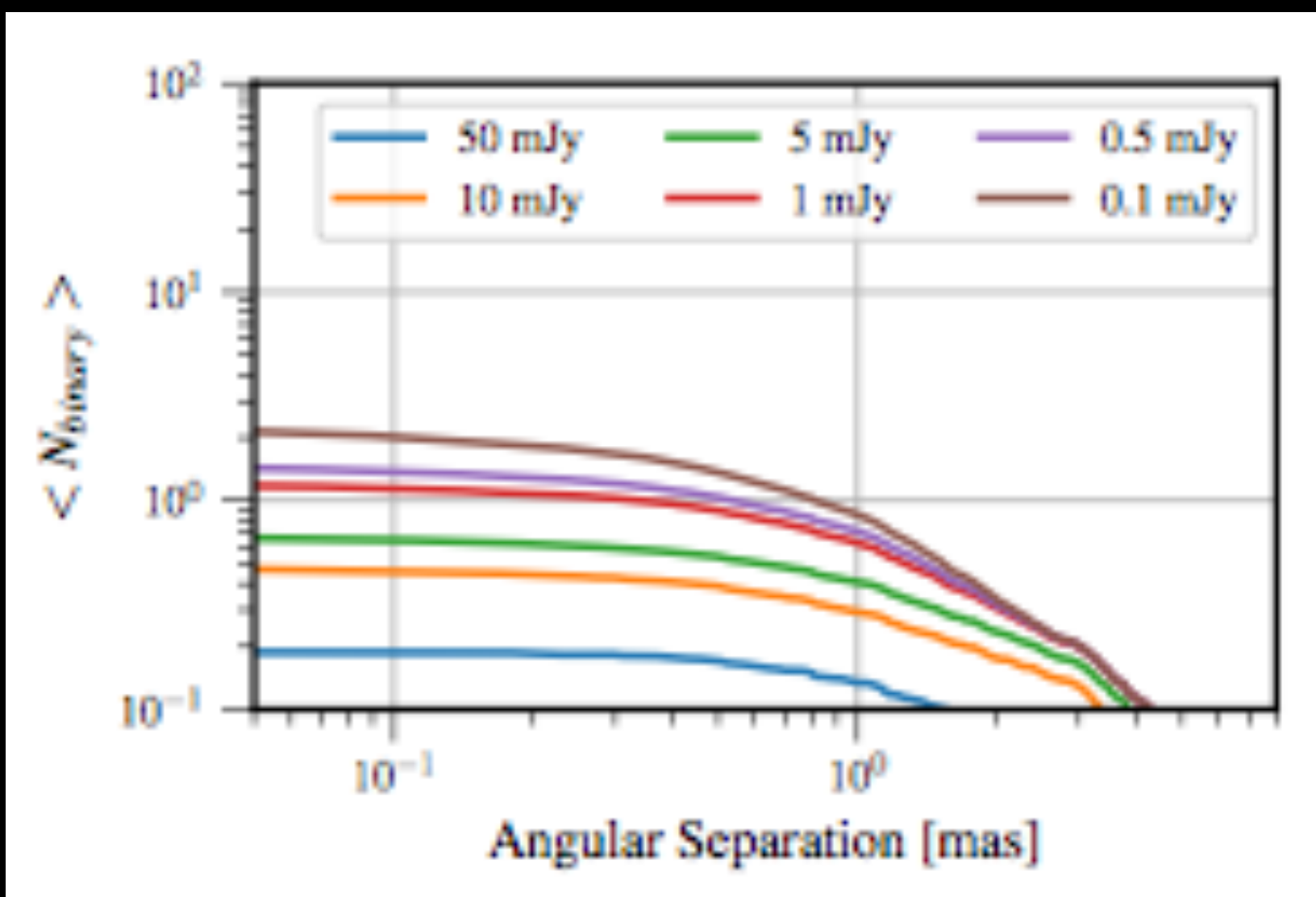
- Dual radio AGN
- GW Sources

Statistics of MM detection

Majorly Contributing Sources



Multi-Messenger Sources

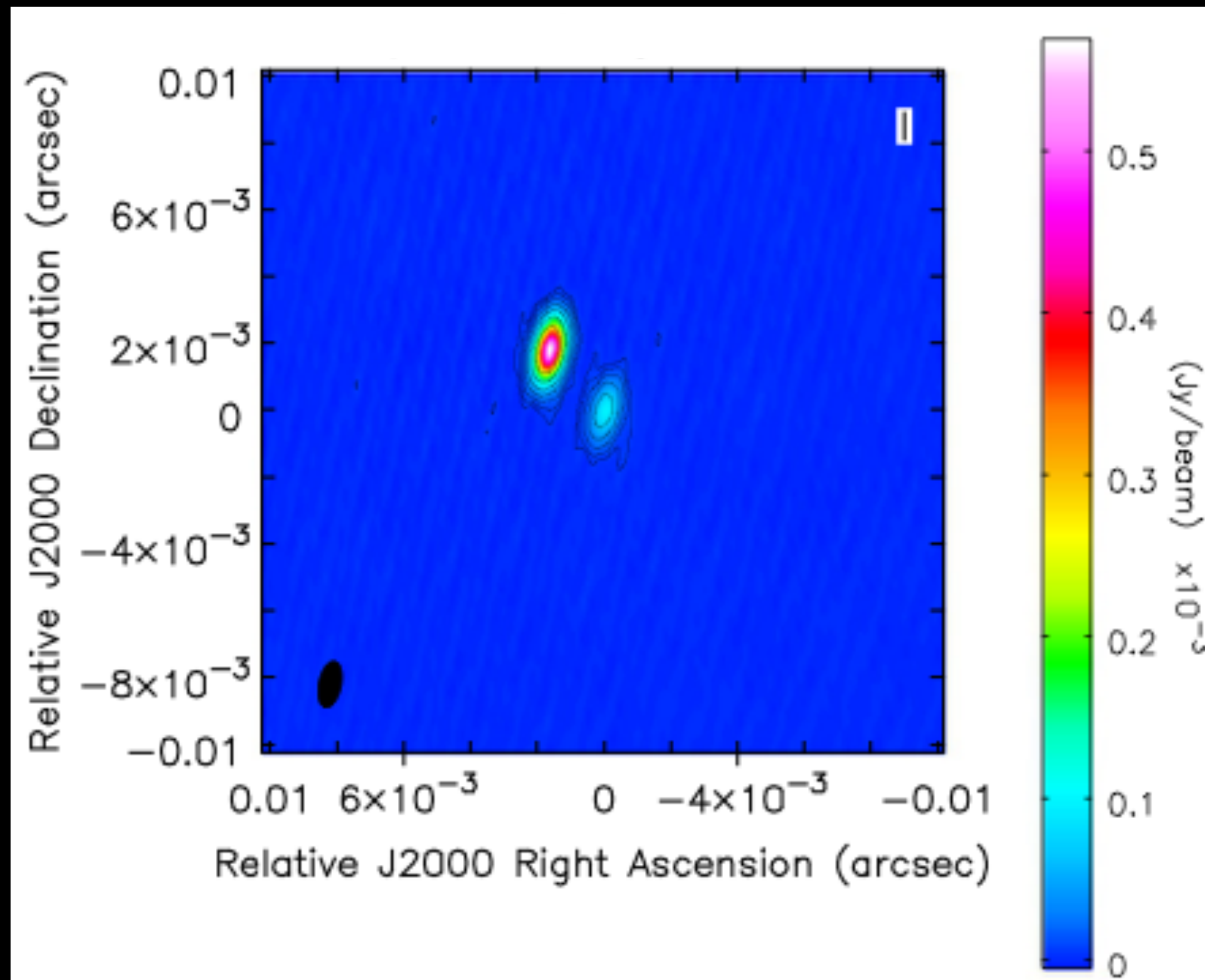


Example MM System

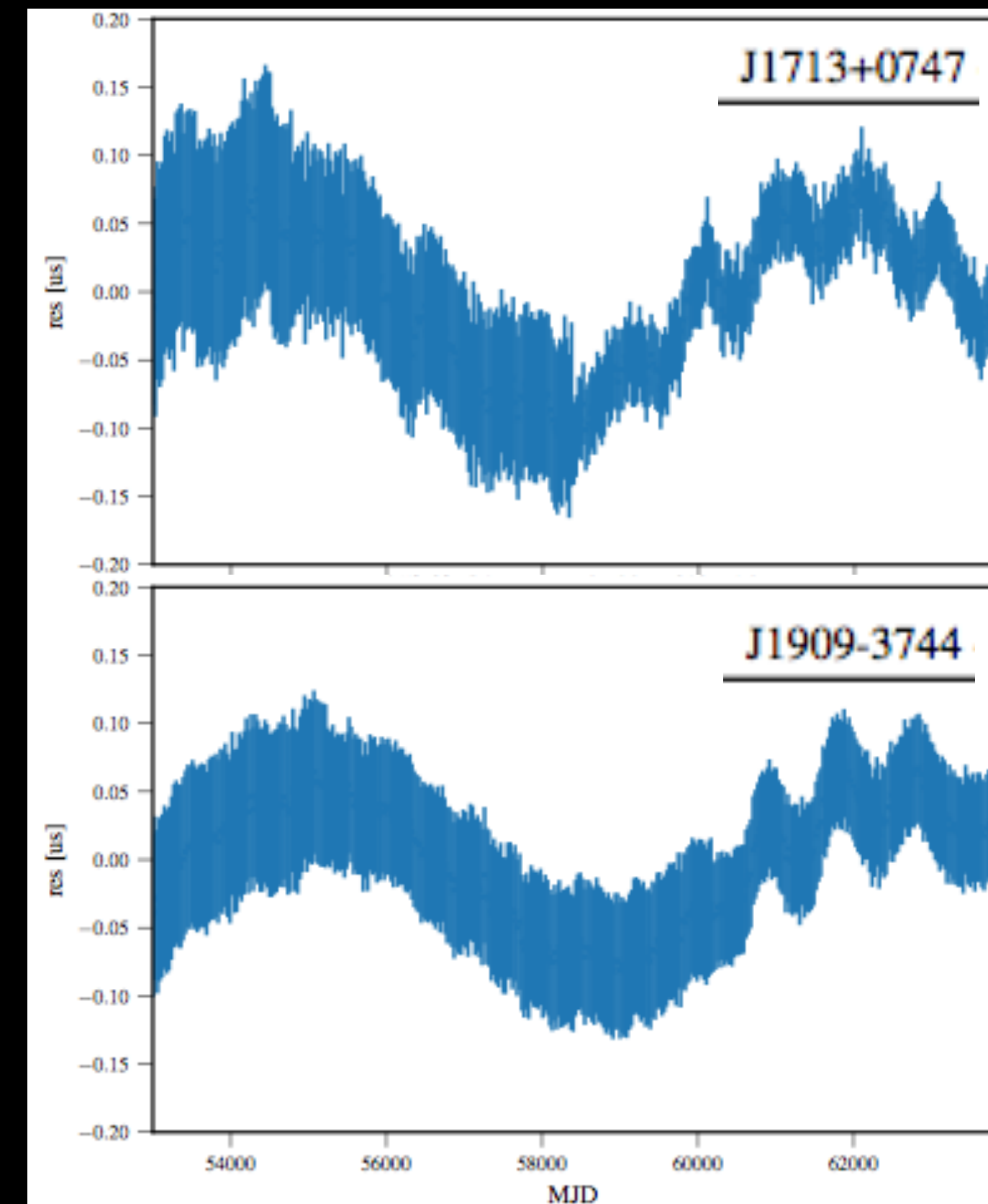
Simulated Binary SMBH ngVLA Observation: 30GHz

214x18m Main Array plus

11 Continental-scale antennae (VLBA + 5x18m at GBO)



PTA Observation



Properties of MM Systems

