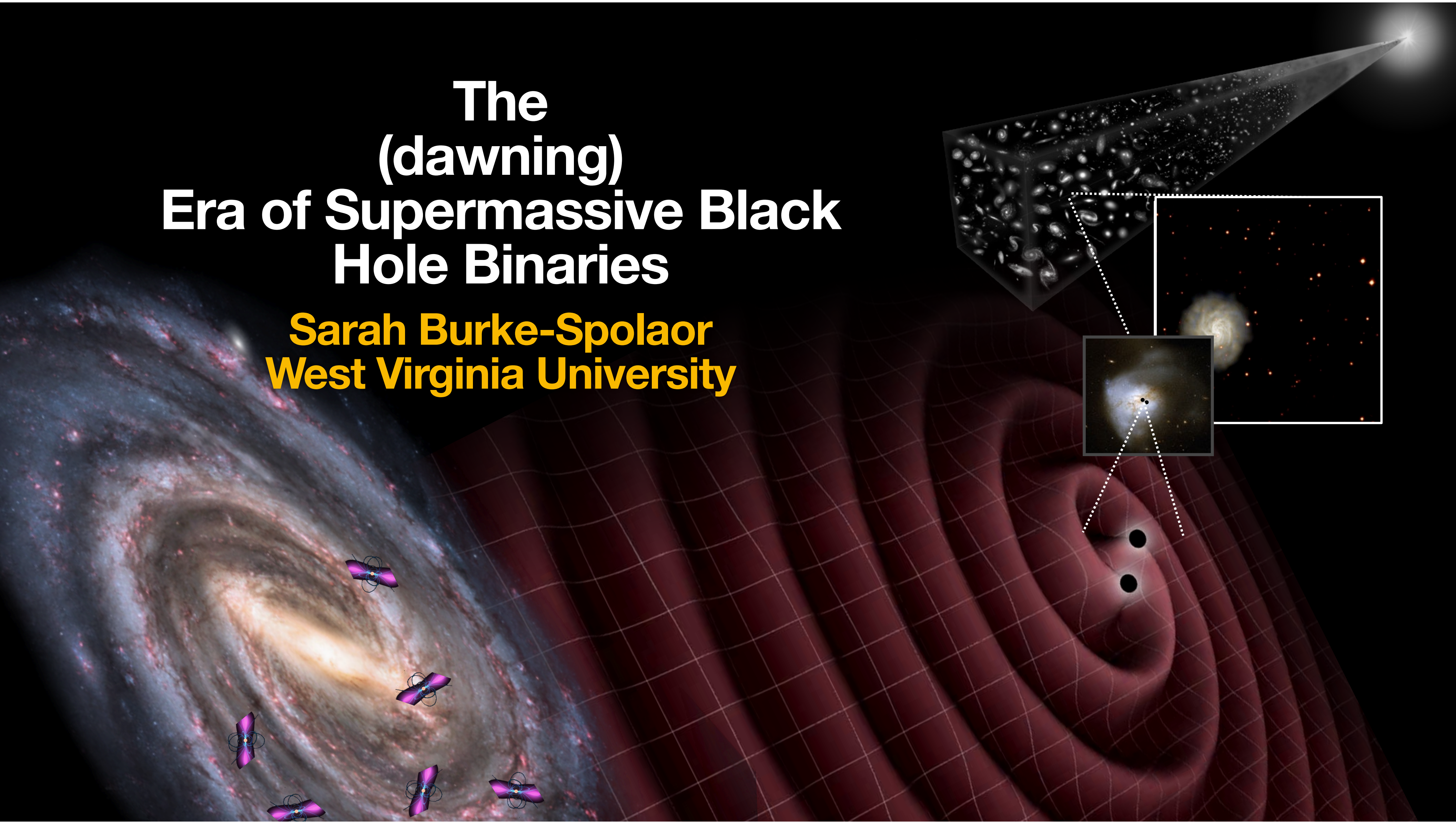
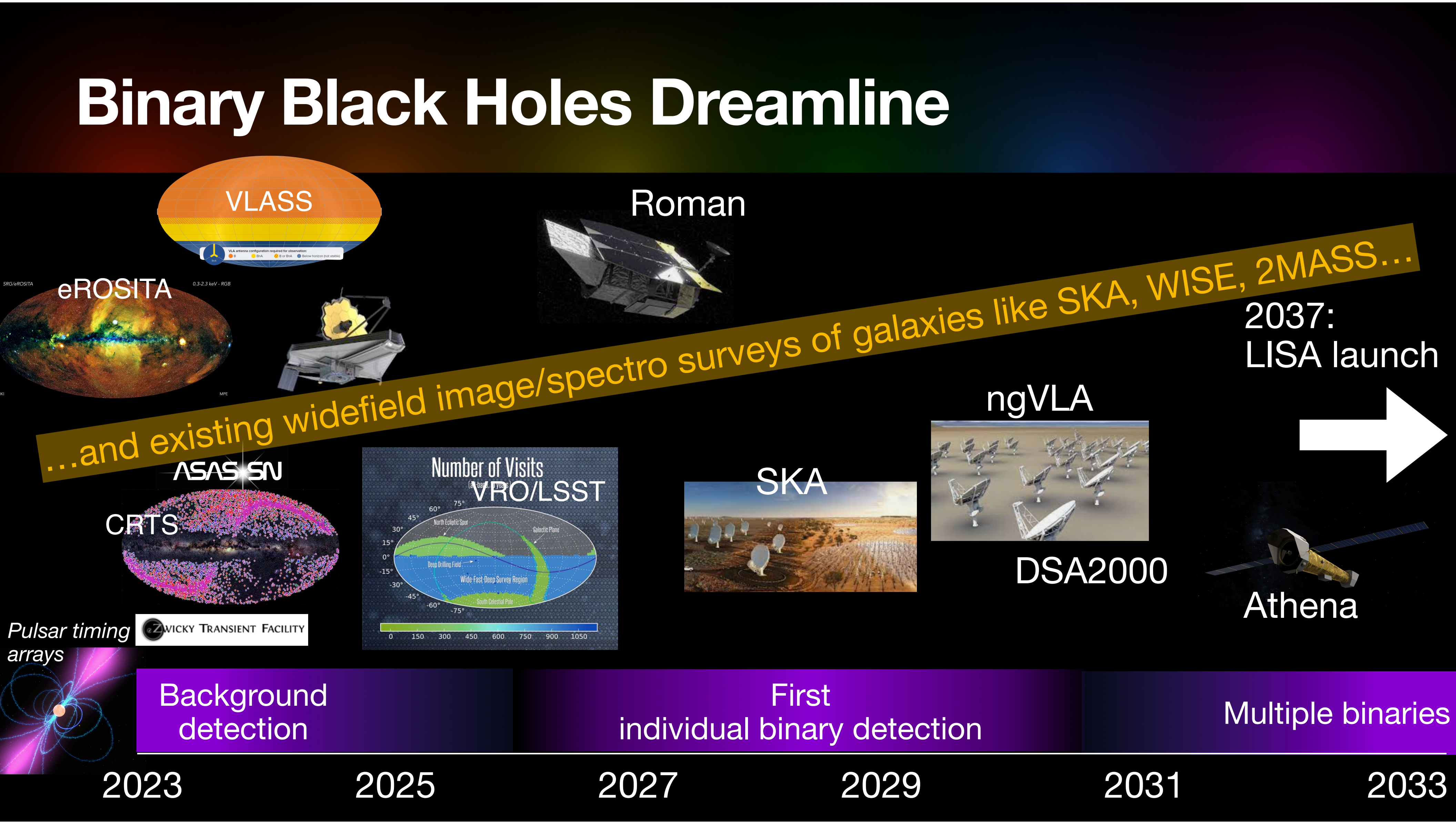
The (dawning) Era of Supermassive Black Hole Binaries

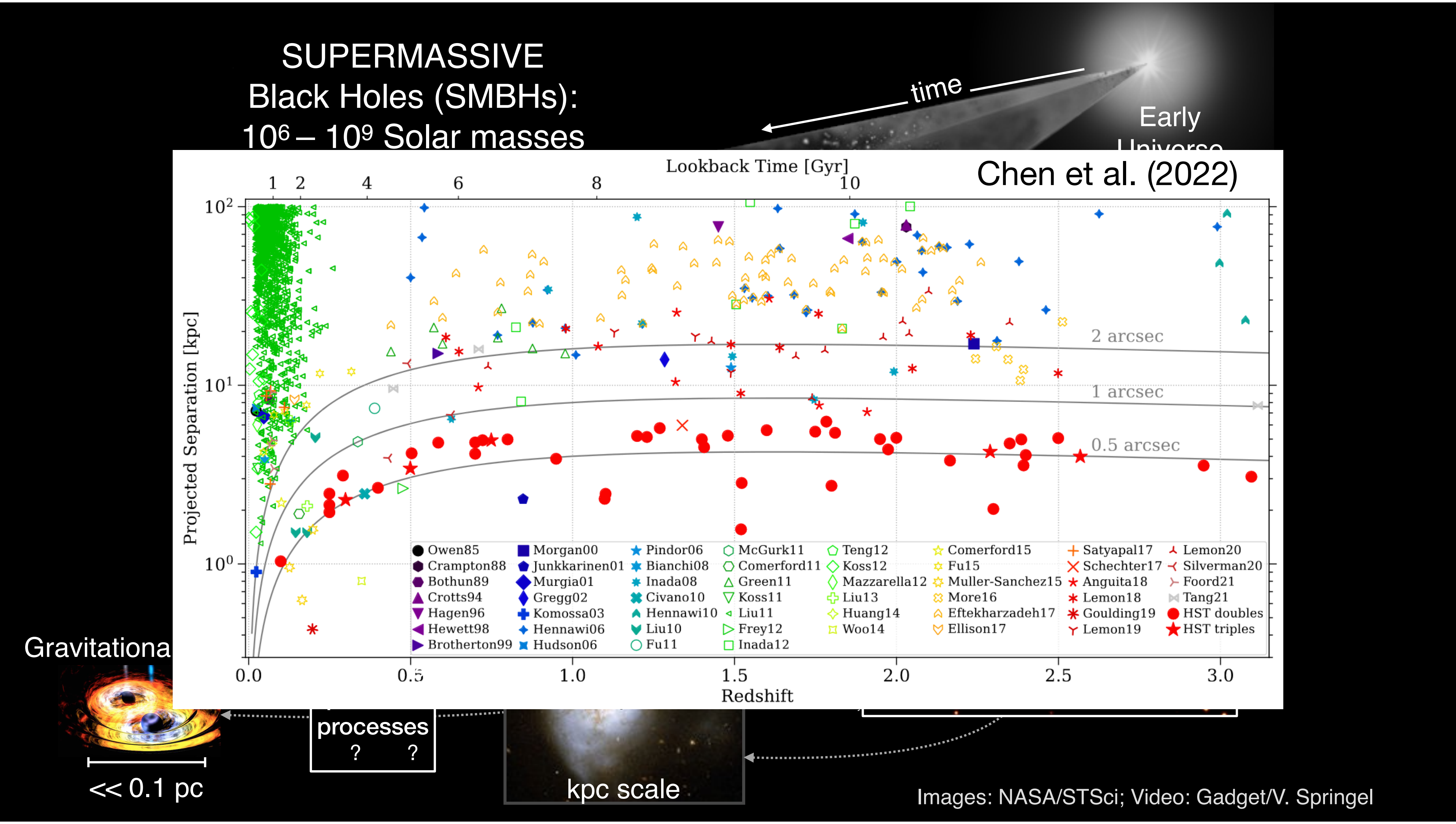
Sarah Burke-Spolaor
West Virginia University




Binary Black Holes Dreamline
VLASS
eROSITA
Roman
…and existing widefield image/spectro surveys of galaxies like SKA, WISE, 2MASS…
2037:
LISA launch
ngVLA
ASAS-SN
Number of Visits
VRO/LSST
CRTS
SKA
DSA2000
Athena
Pulsar timing arrays
Zwicky Transient Facility
Background detection
First individual binary detection
Multiple binaries
2023
2025
2027
2029
2031
2033

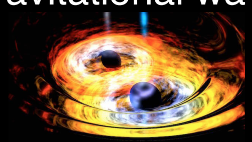
Binary SMBHs:
We haven’t really found any yet!*

* ”Actually, there are around 300 publications currently exist reporting binary/dual SMBH candidates.”


SUPERMASSIVE
Black Holes (SMBHs):
10^6 – 10^9 Solar masses
time
Early
Chen et al. (2022)
Lookback Time [Gyr]
1 2 4 6 8 10
Projected Separation [kpc]
10^2
10^1
10^0
2 arcsec
1 arcsec
0.5 arcsec
0.0 0.5 1.0 1.5 2.0 2.5 3.0
Redshift
Owen85
Crampton88
Bothun89
Crotts94
Hagen96
Hewett98
Brotherton99
Morgan00
Junkkarinen01
Murgia01
Gregg02
Komossa03
Hennawi06
Hudson06
Pindor06
Bianchi08
Inada08
Civano10
Hennawi10
Liu10
Fu11
McGurk11
Comerford11
Green11
Koss11
Liu11
Frey12
Inada12
Teng12
Koss12
Mazzarella12
Liu13
Huang14
Woo14
Comerford15
Fu15
Muller-Sanchez15
More16
Eftekharzadeh17
Ellison17
Satyapal17
Schechter17
Anguita18
Lemon18
Goulding19
Lemon19
Lemon20
Silverman20
Foord21
Tang21
HST doubles
HST triples
Gravitationa
processes
? ?
<< 0.1 pc
kpc scale
Images: NASA/STSci; Video: Gadget/V. Springel

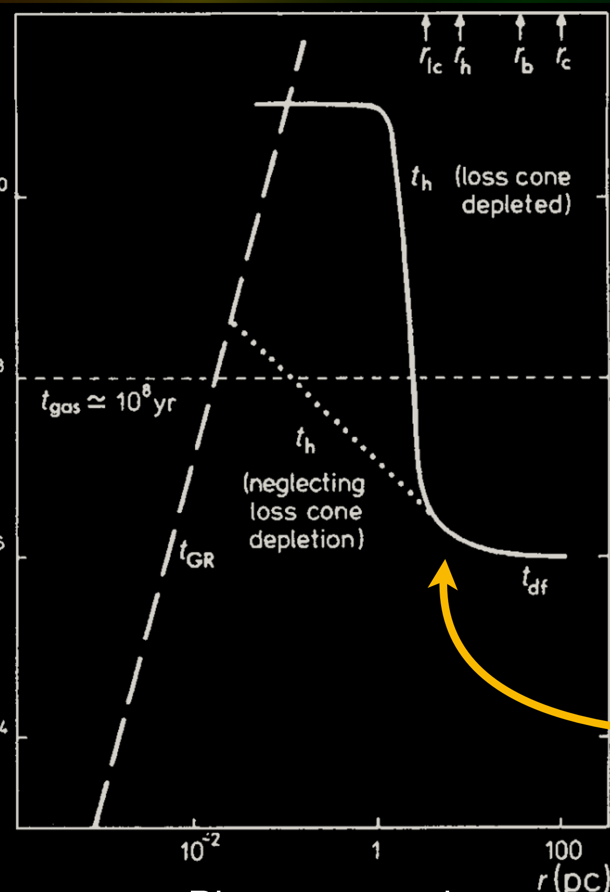
Interactions in the "Final Parsec"

Gravitational waves

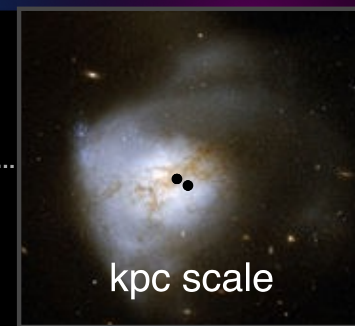


< 0.1 pc

Binary inspiral timescale



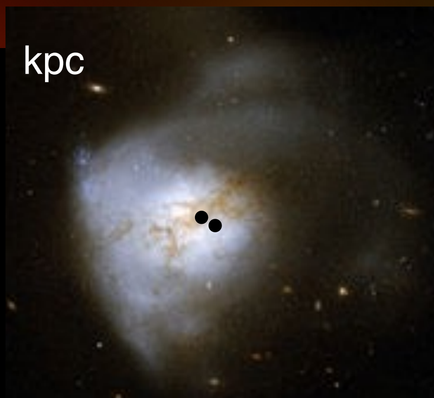
Binary separation



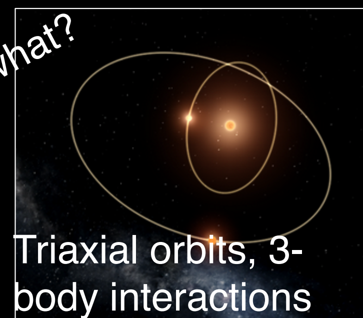
"Hard binary" when binding energy >> kinetic energy of ambient material!

Begelman et al. (1980)

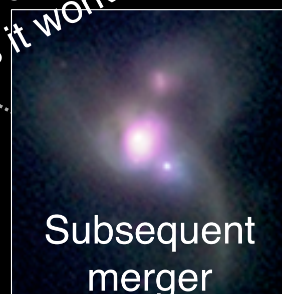
Interactions in the "Final Parsec"



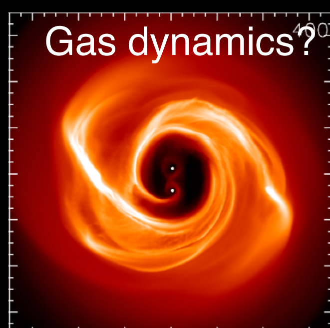
Something drives the binary's evolution here, but what?
How does it work?



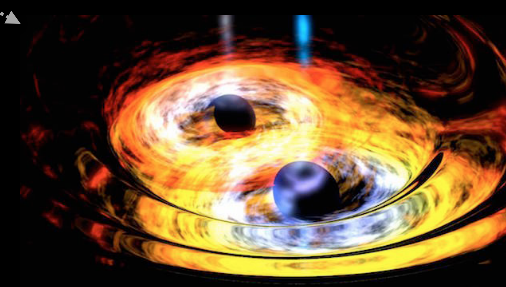
e.g. , Khan et al, 2011; Holley-Bockelmann & Khan, 2015; Vasiliev et al, 2015; Pfister et al, 2017



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



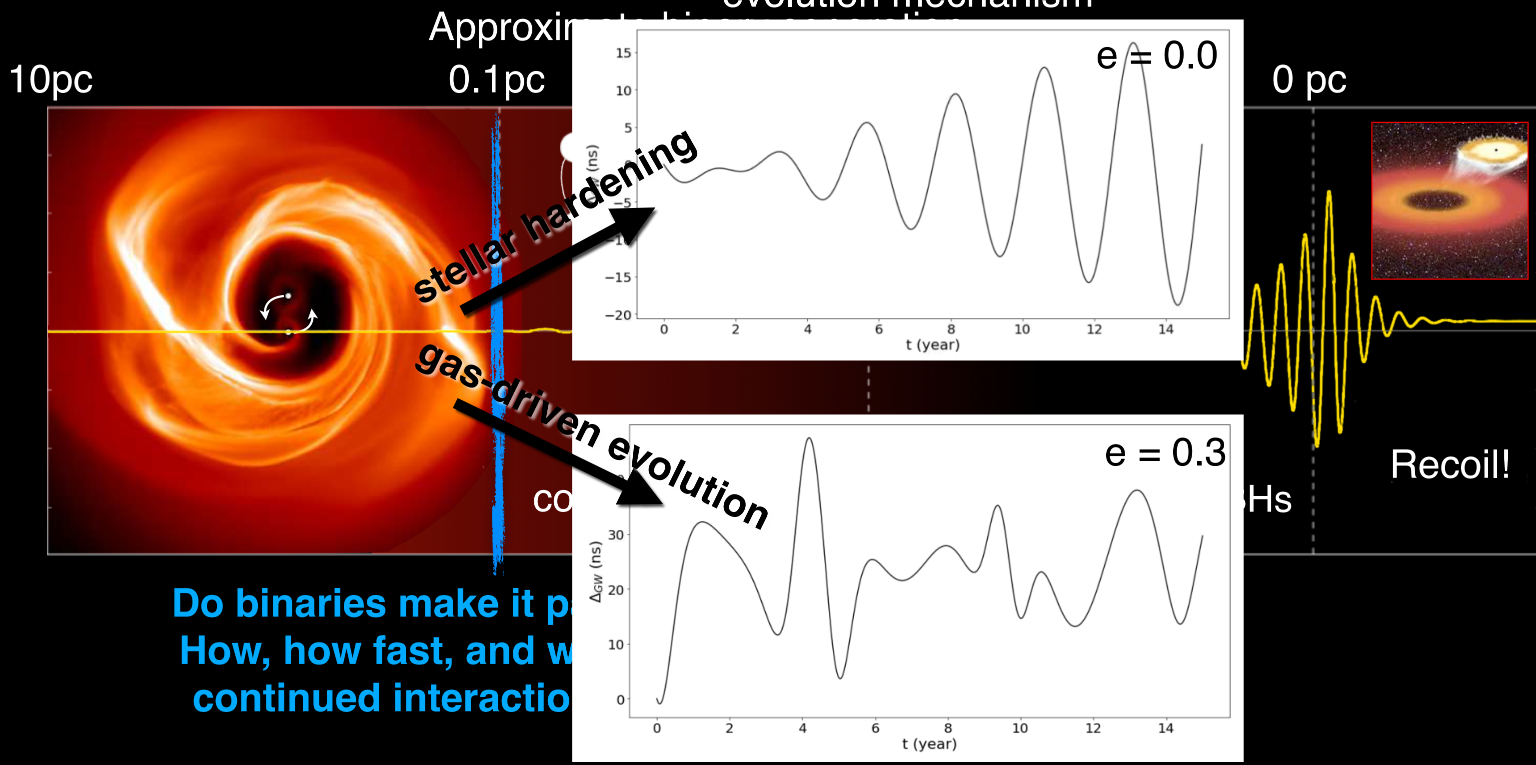
e.g. Cuadra et al. (2009), Chapon et al. (2013), Franchini et al (2021)



<< 0.1 pc

Inspiral of Binary SMBHs

PTA waveforms depend on evolution mechanism



e.g. Burke-Spolaor et al. (2019). B. Cheeseboro thesis (2022)

Interactions in the "Final Parsec"

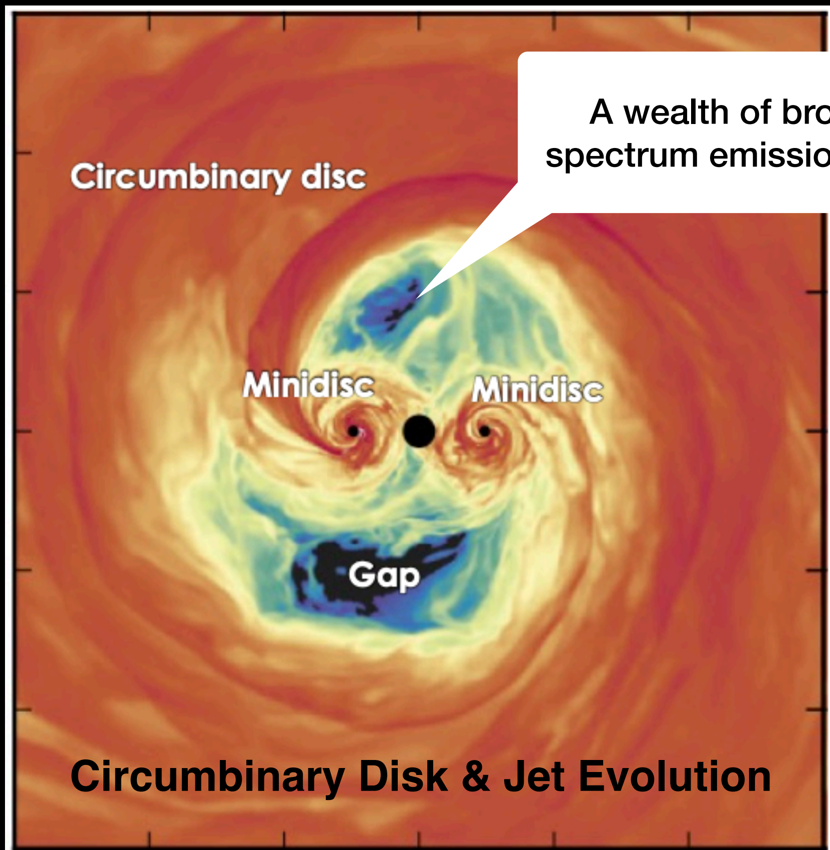
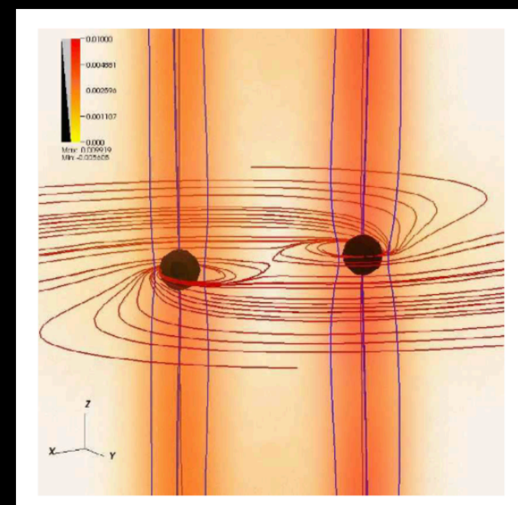


Image Credit: J. Krolik, M Volonteri

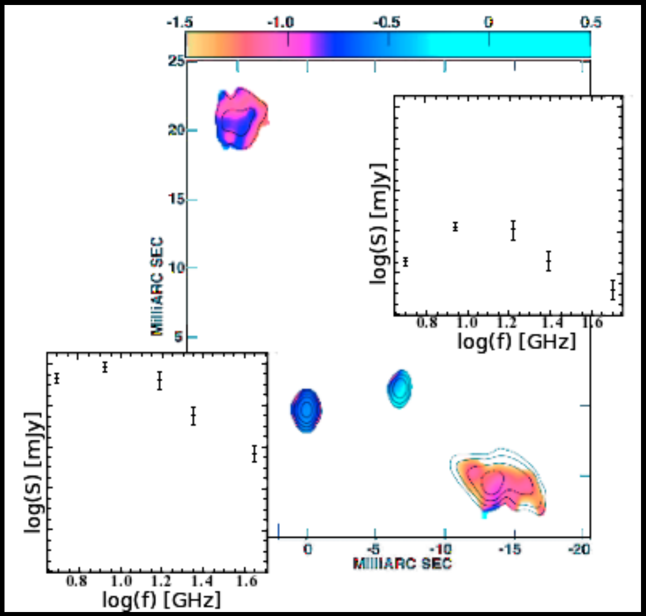
Testing Black hole / plasma / jet interactions



Palenzuela et al. (2010)

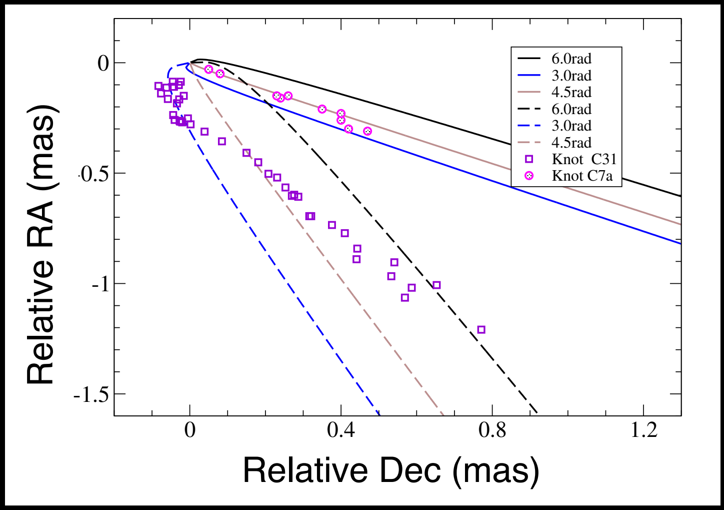
Radio VLBI for Multi-messenger AGN

Resolving/Tracking Dual Cores



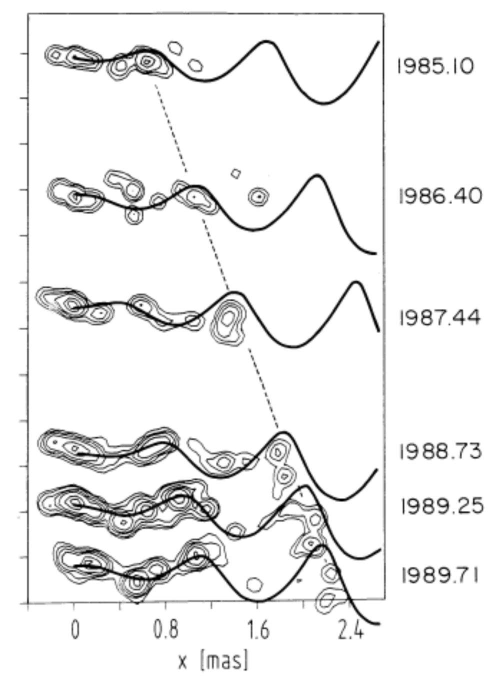
e.g. Rodriguez et al. (2007)
also Wrobel & Lazio (2023 —
tracking sub-pc binaries with ngVLA)

Multiple jets/outflows



e.g. Qian et al. (2019)

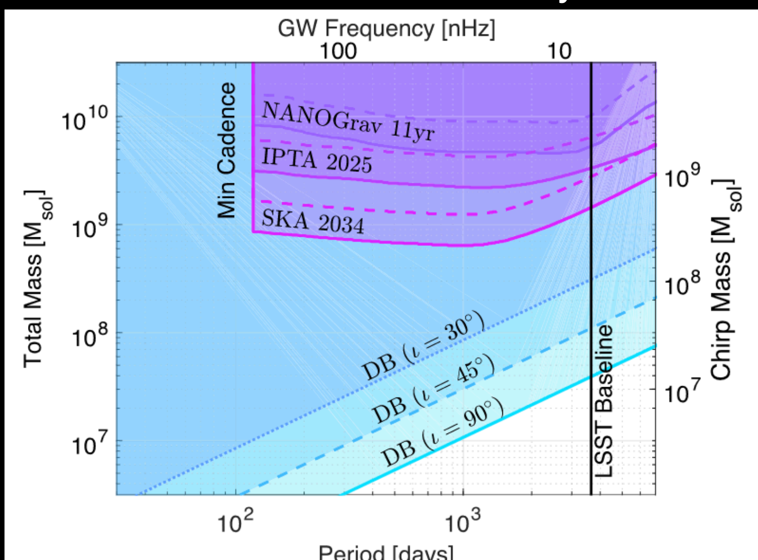
Helical, periodic, or precessing jets



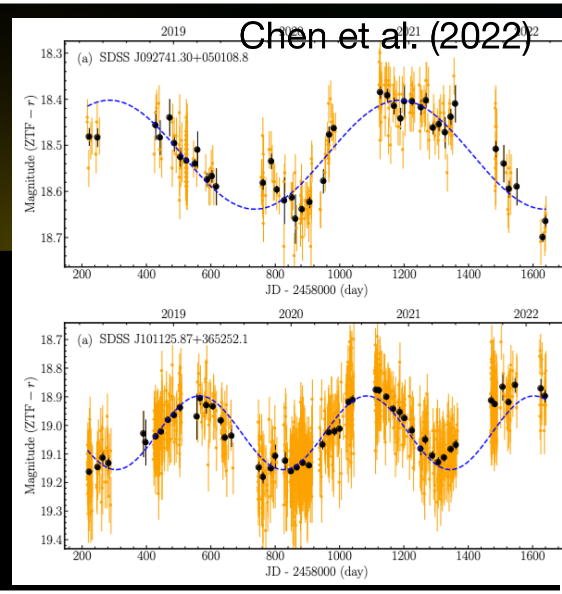
e.g. Kun et al. (2013)

Quasar Periodic Variability

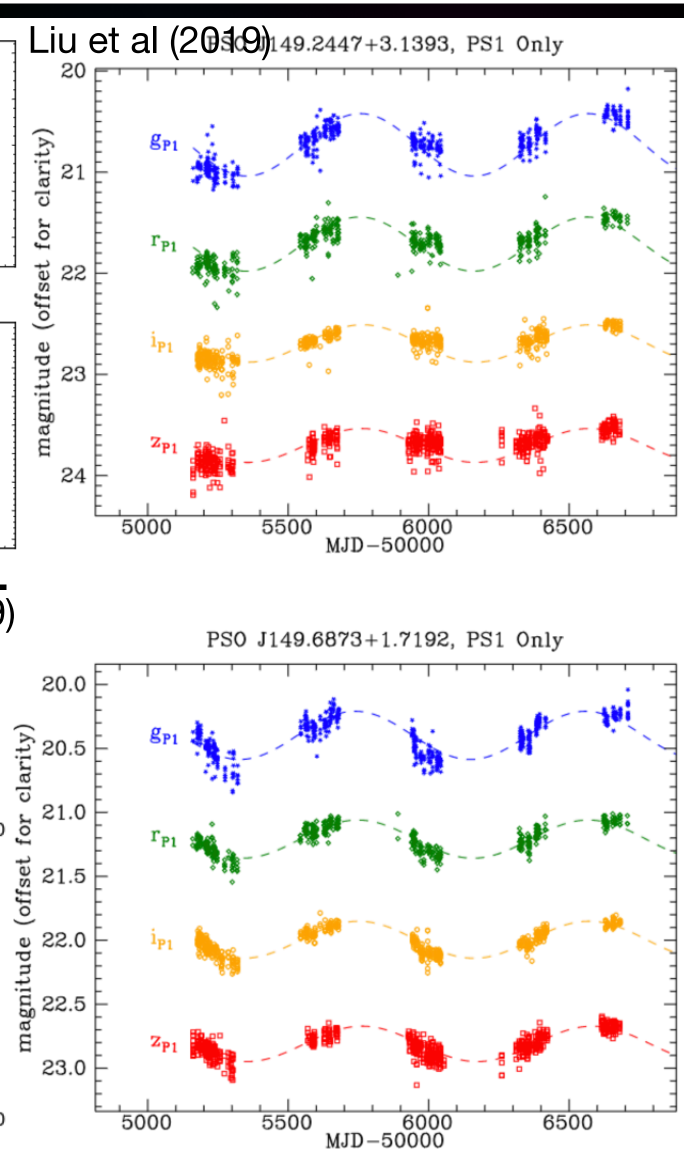
Charisi et al. (2022):
Doppler boosting of material
around cloase binary



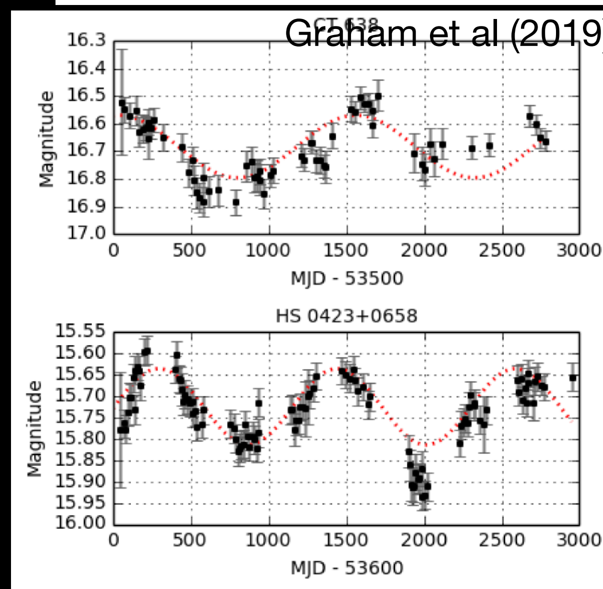
Chen et al. (2022)



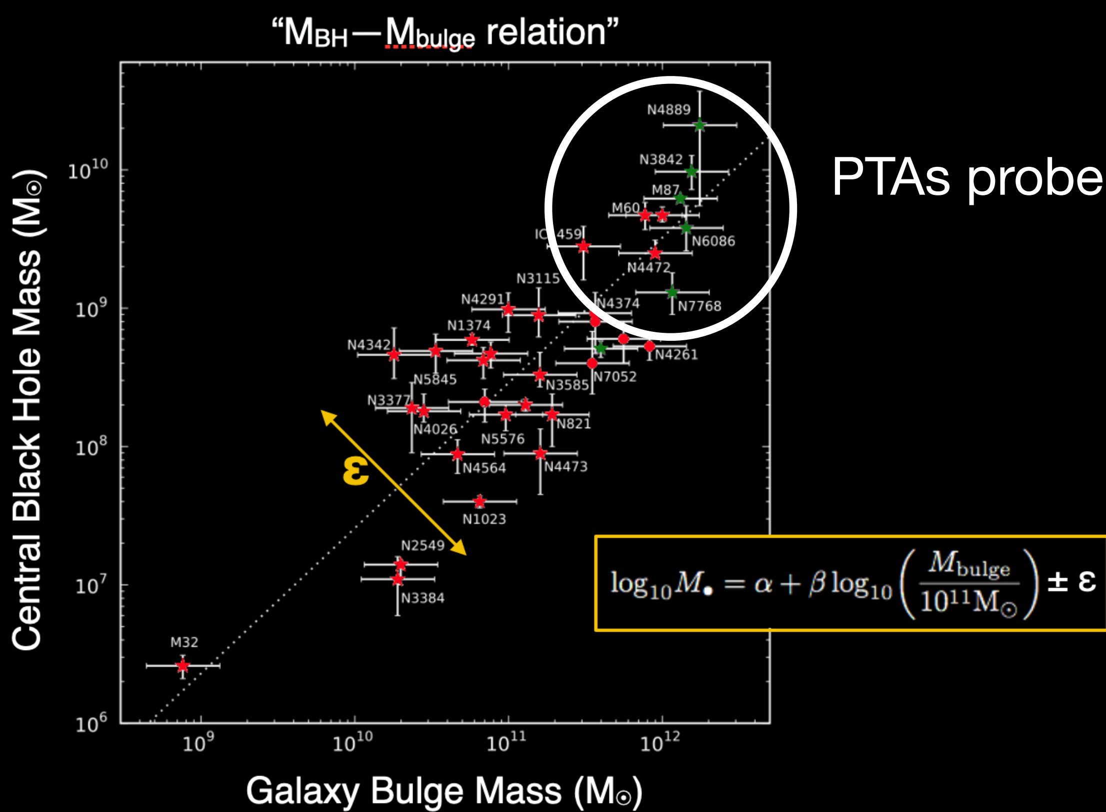
Liu et al (2019)



Graham et al (2019)

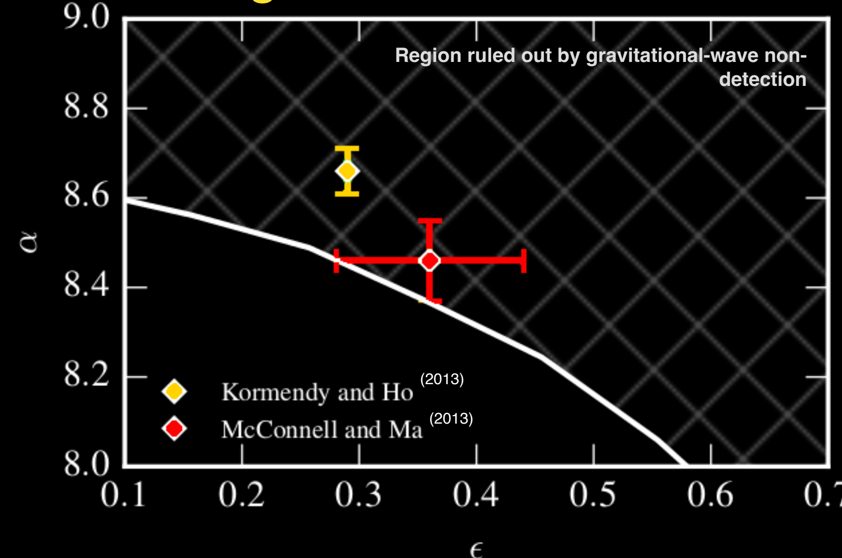


Testing SMBH Binary Influence on Galaxy Growth



PTAs probe here

PTAs probe the background of gravitational waves!



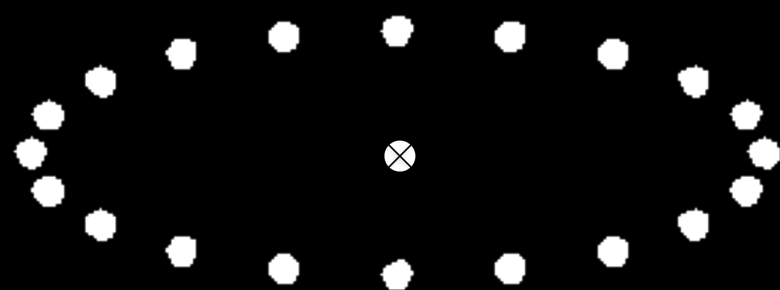
McConnell & Ma (2013), Simon & Burke-Spolaor (2016), Shankar et al. (2016)

Pulsar Timing Arrays…

PTAs will make the first clear identifications of SMBHB sources.

They will also probe the bulk properties of nearby binary SMBHs.

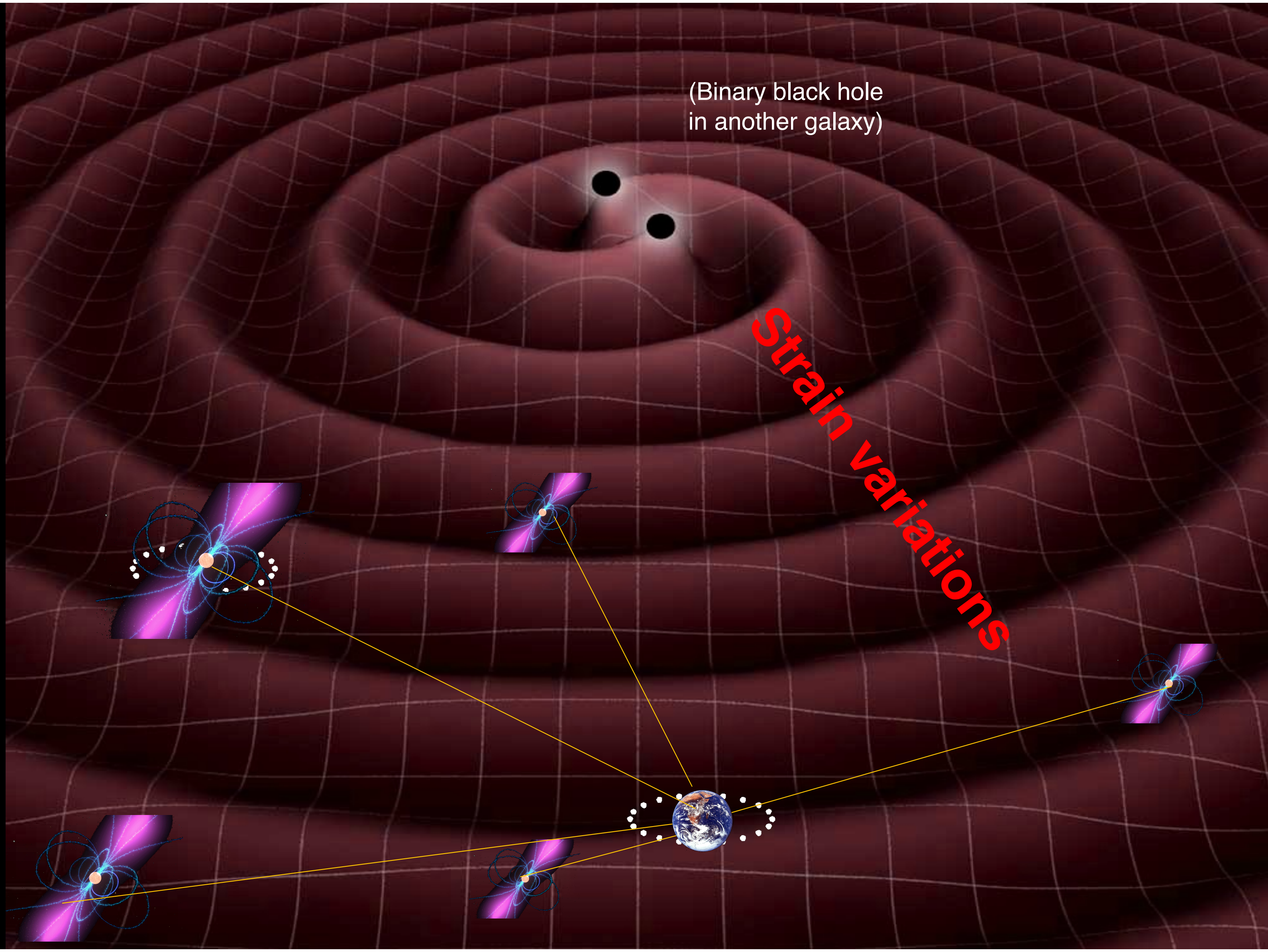
A Really Big Gravitational Wave

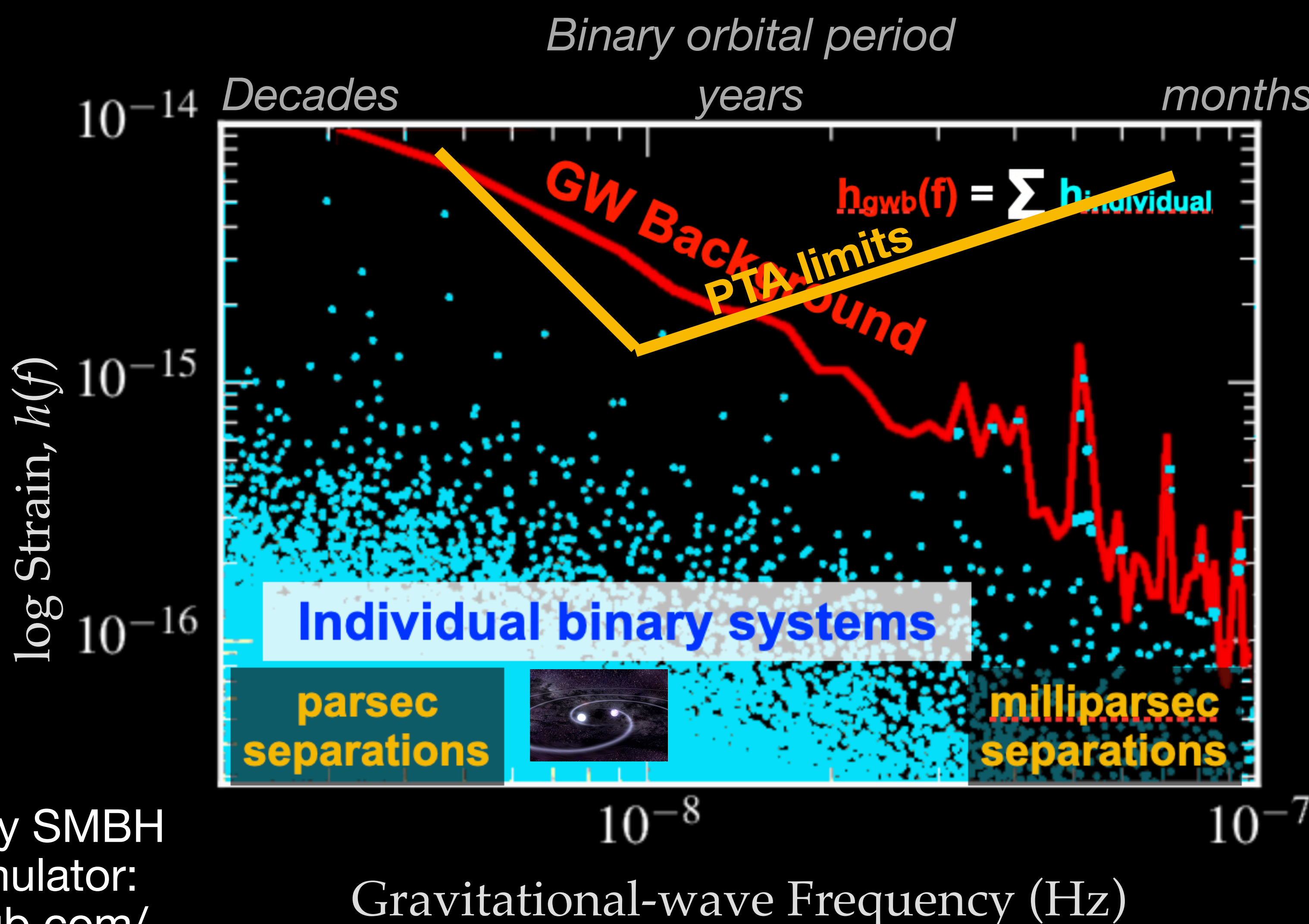


h ~ 0.5

(equivalent to a
$10^9\,M_\odot$ **black hole binary at 2 AU)**

Pulsar Timing Arrays



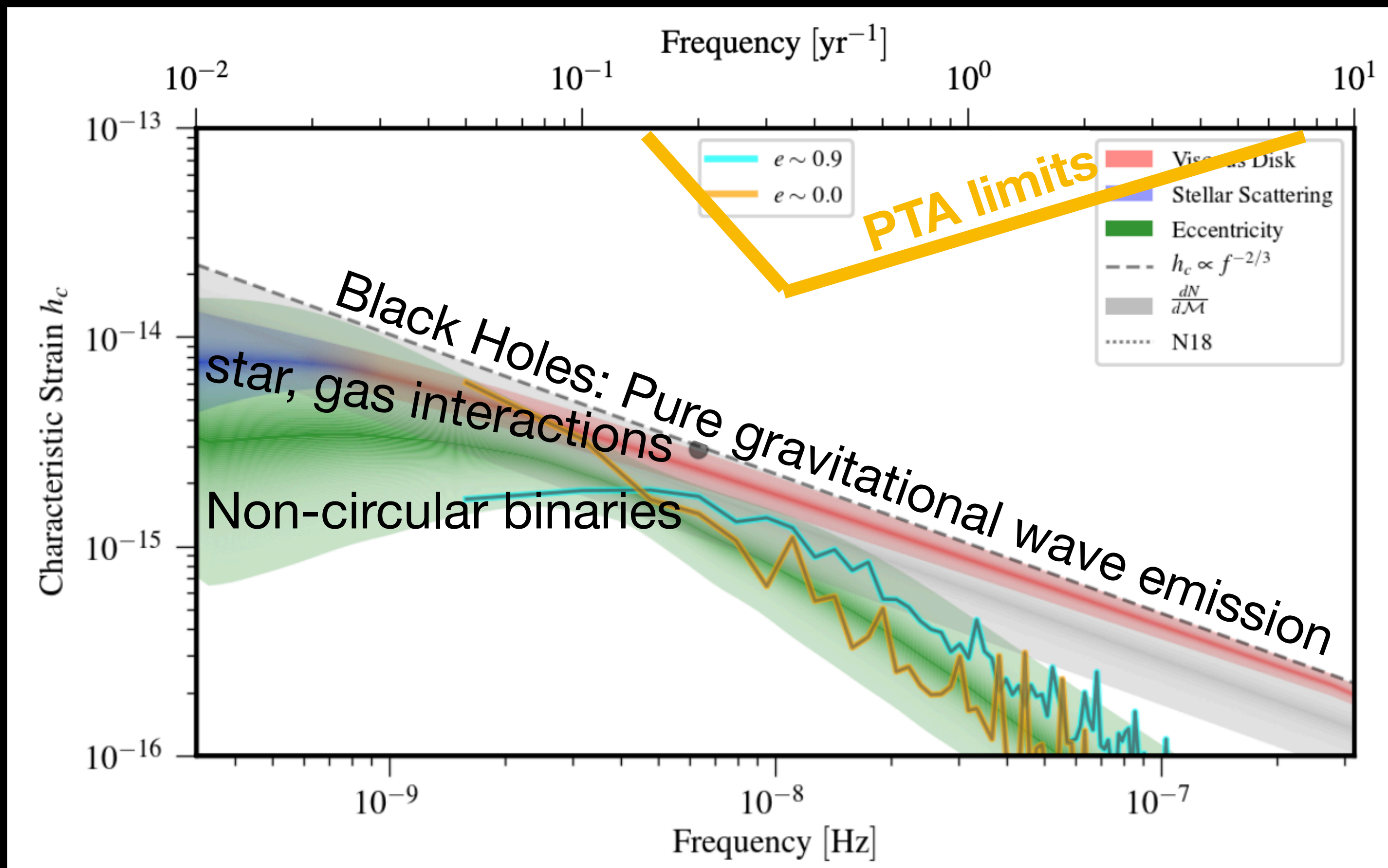


Public binary SMBH universe simulator: https://github.com/nanograv/holodeck

Simulation from Simon & Burke-Spolaor (2016)

“RED”: More noise at low frequency

overall amplitude scale defined by SMBH mass and merger rate



Burke-Spolaor (2019); plot by Luke Kelley

PTA Limits vs. Predictions

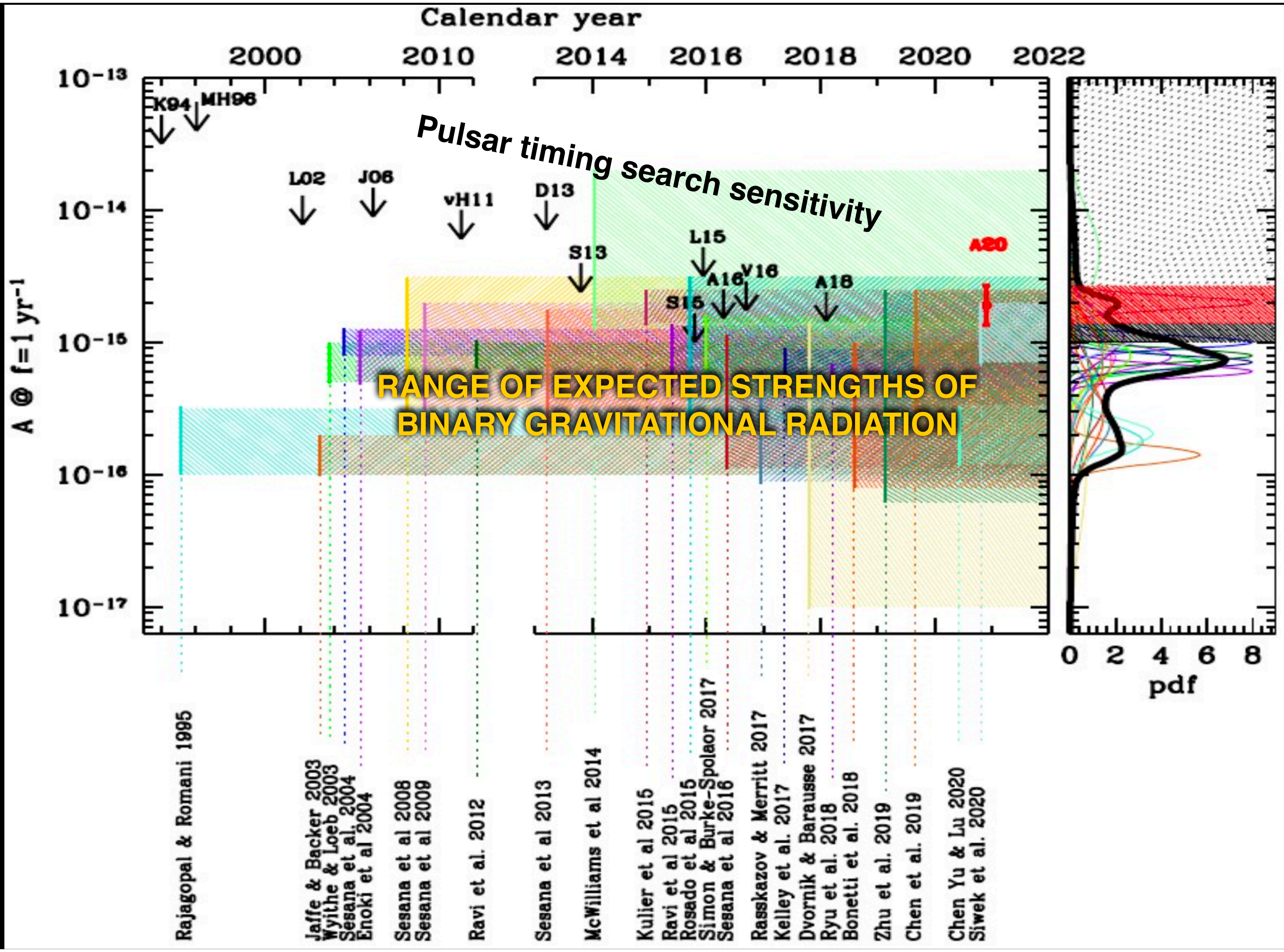
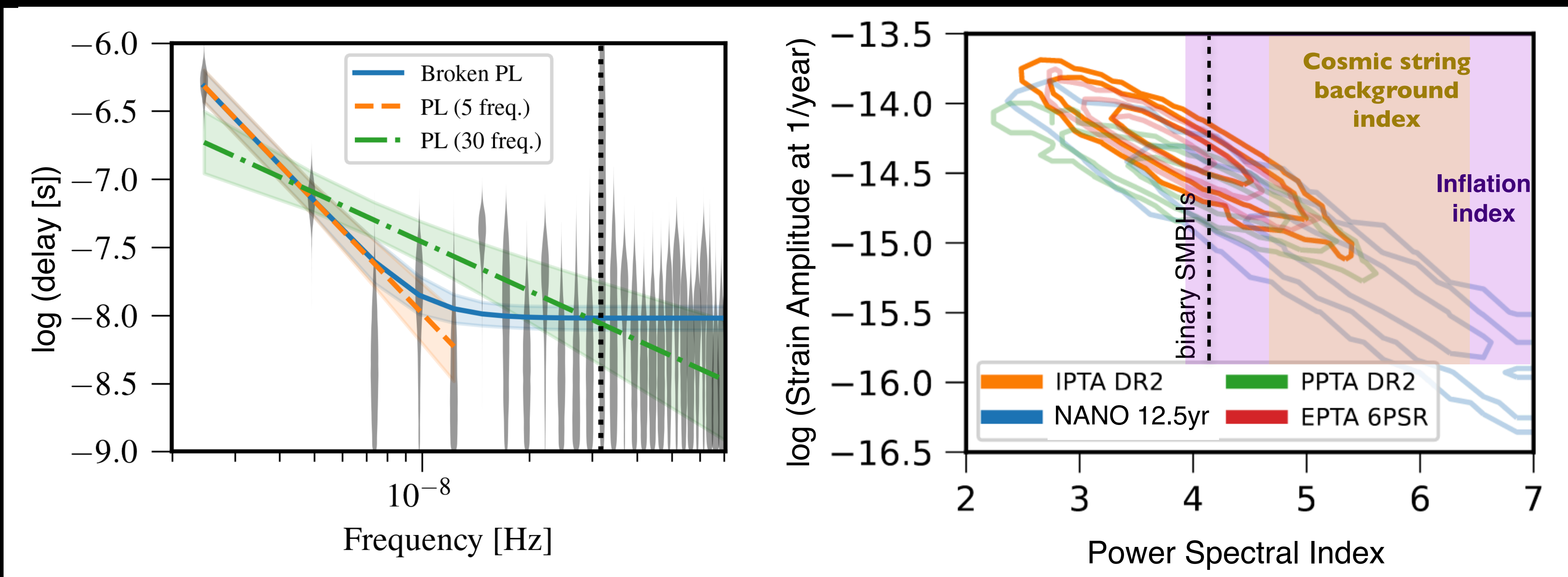


Image Credit:
A. Sesana

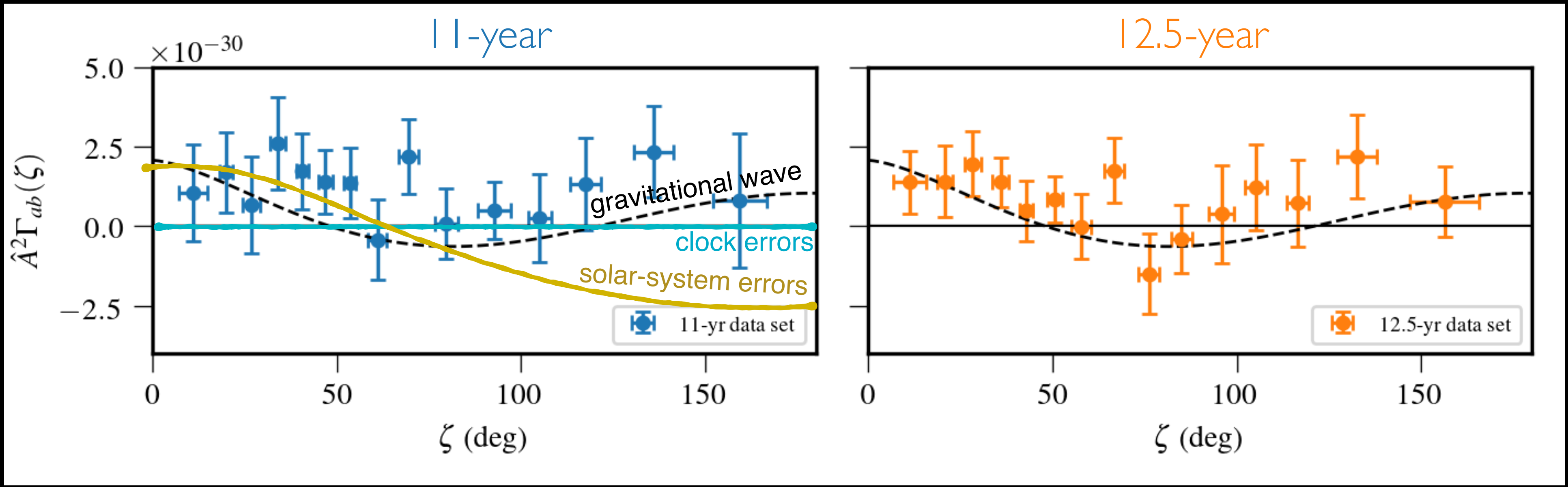
“Common red noise process” (NANOGrav 12.5year data, 2020)



Arzoumanian et al. (2020) [NANOGrav], Antoniadis et al. (2022) [IPTA data release 2]

How much does it look like a quadrupolar gravitational wave?

Quadrupole favored slightly over other correlations but not yet strong (2.5σ level).

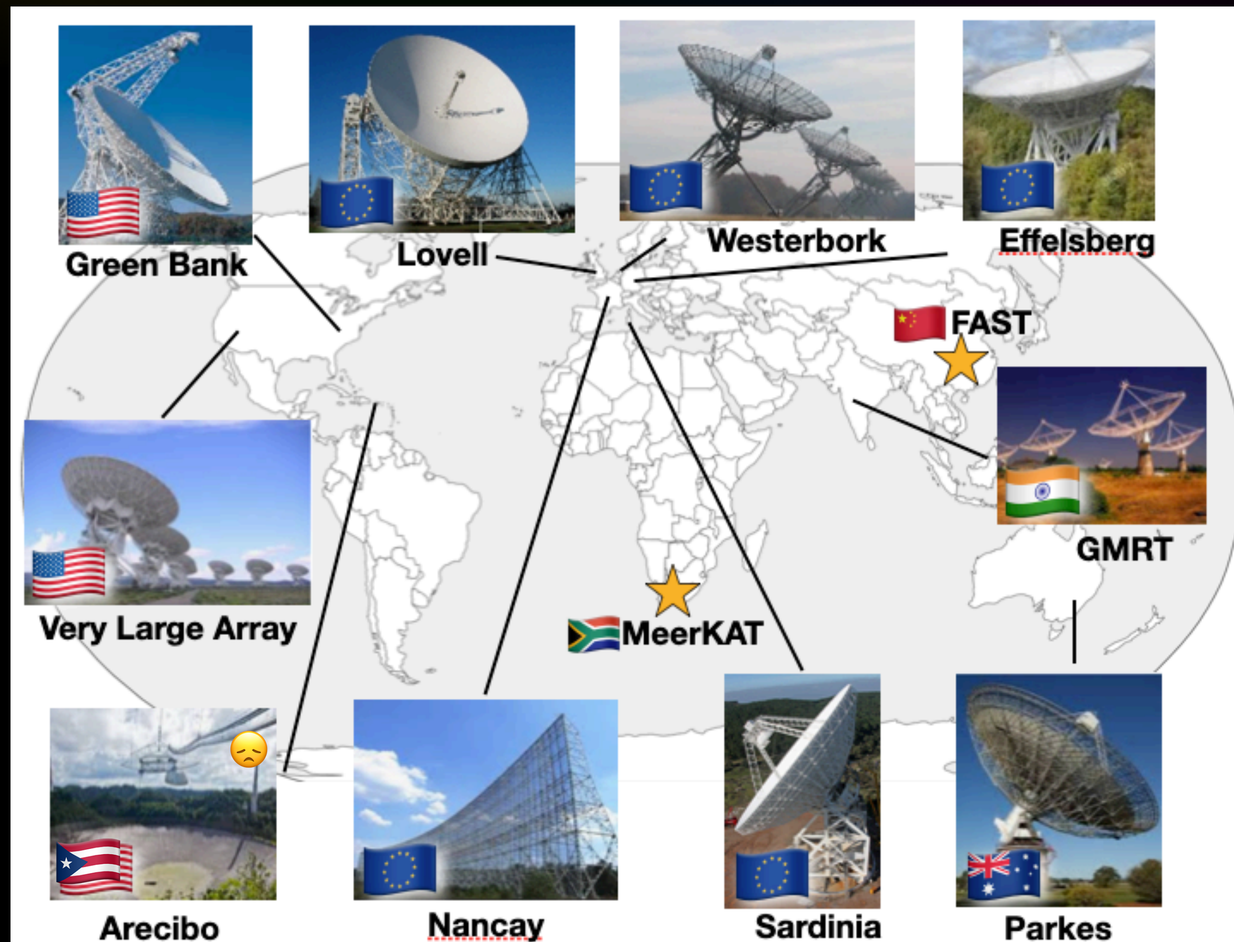


Arzoumanian et al (2020)

Watch for New IPTA-Wide Results: June 29th in ApJL!

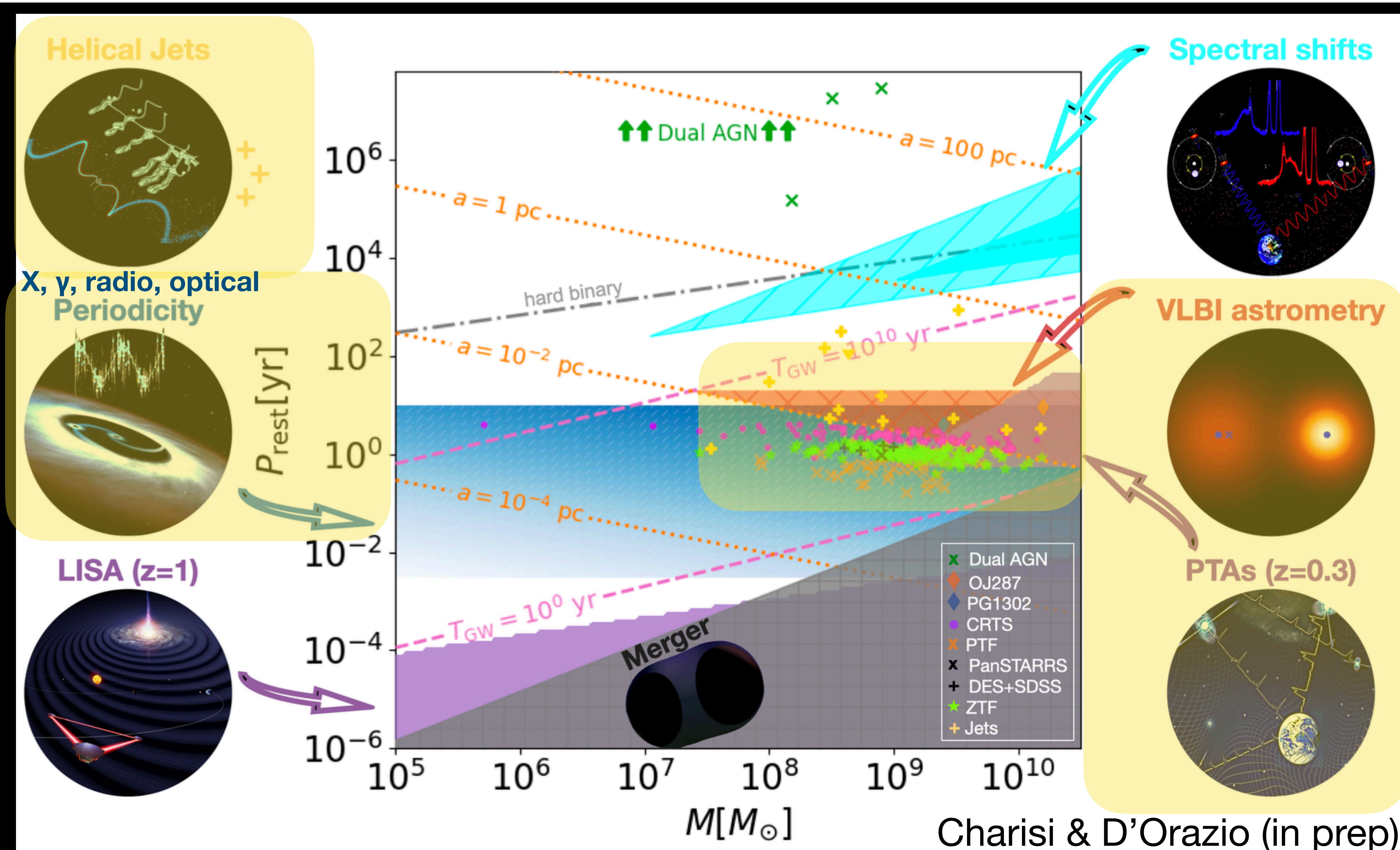
Allen et al. (arXiv 2304.04767)

- Recently:
  Detection protocols document
- Late 2023(?):
  Super-sensitive IPTA "Data Release 3"
  (NANOGrav, EPTA, PPTA, InPTA, CHIME, MeerKAT data)
  (lead: Deborah Good)



If this is a background of binary SMBHs, we are already constraining the demographics of binary SMBHs.

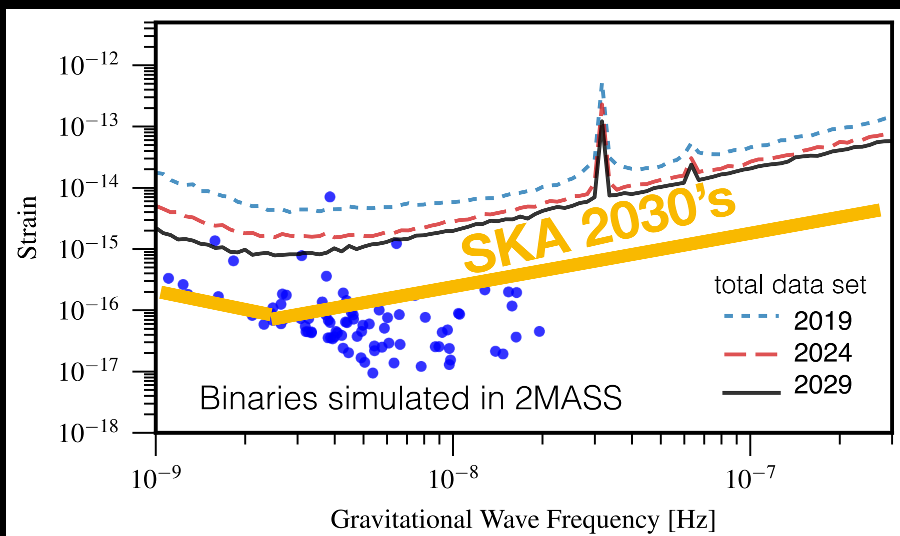
We anticipate in the next 5-10 years, we will be in the “resolved binary” era.



Helical Jets
X, γ, radio, optical
Periodicity
LISA (z=1)
Spectral shifts
VLBI astrometry
PTAs (z=0.3)
Dual AGN
a = 100 pc
a = 1 pc
a = 10^-2 pc
a = 10^-4 pc
hard binary
T_GW = 10^10 yr
T_GW = 10^0 yr
Merger
P_rest [yr]
M[M_⊙]
Dual AGN
OJ287
PG1302
CRTS
PTF
PanSTARRS
DES+SDSS
ZTF
Jets
Charisi & D'Orazio (in prep)

Binary Black Holes Timeline

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



Modelled from local galaxy mergers, merger rates:

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

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

Pulsar timing arrays

Background detection | First individual binary detection | Multiple binaries

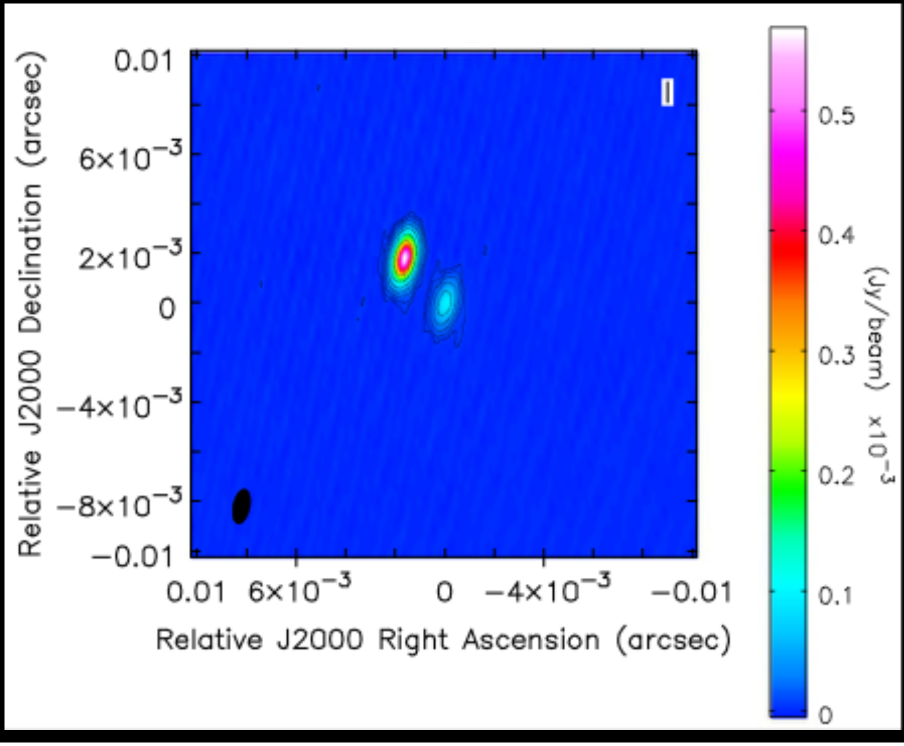
2023 2025 2027 2029 2031 2033

The Roles of SKAO and ngVLA

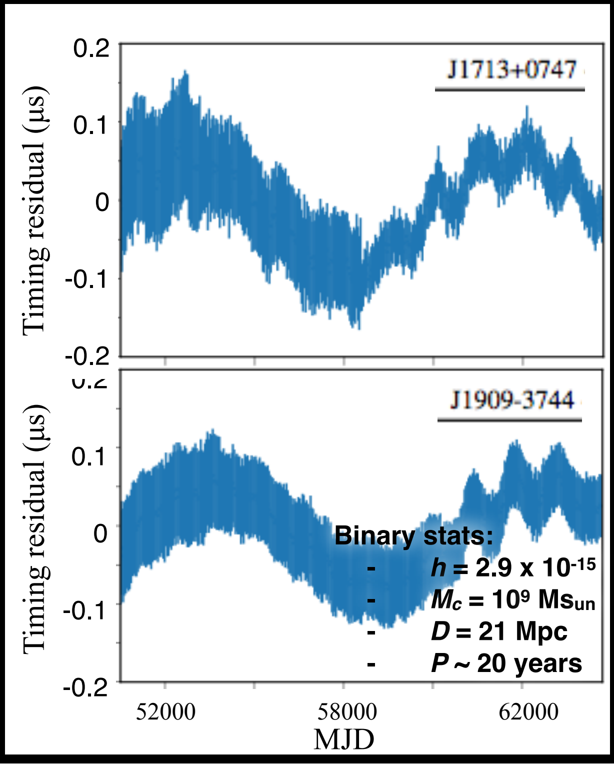
A snapshot of mid-2030's, in just the right universe.

Simulated Binary SMBH ngVLA Observation: 30GHz

214x18m Main Array plus
11 Continental-scale antennae (VLBA + 5x18m at GBO)

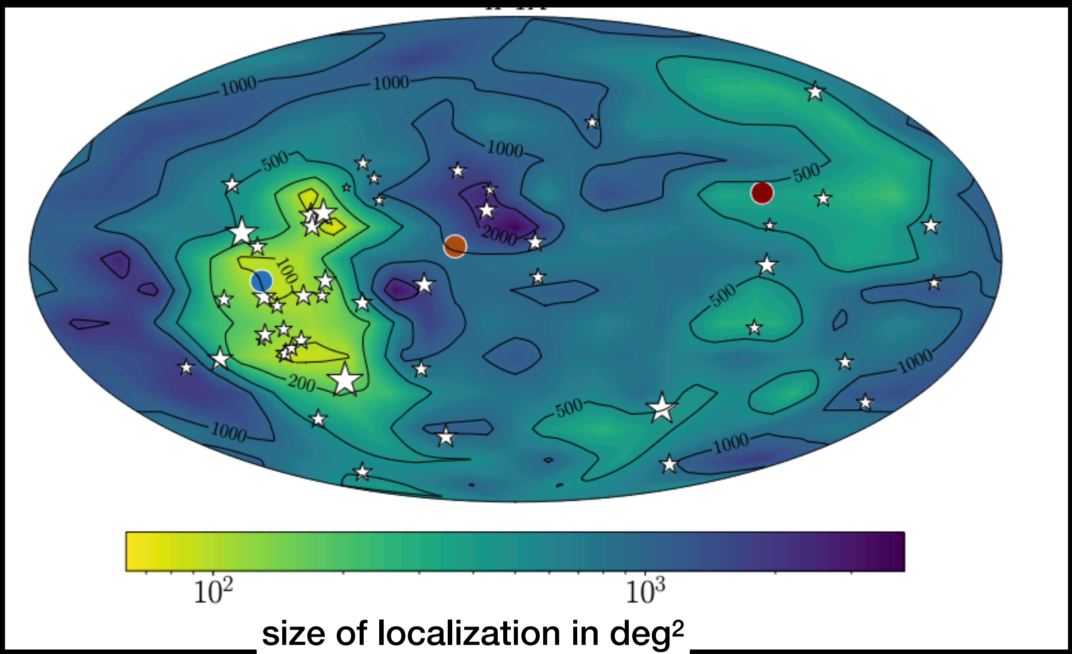


PTA Observation: SKA+IPTA

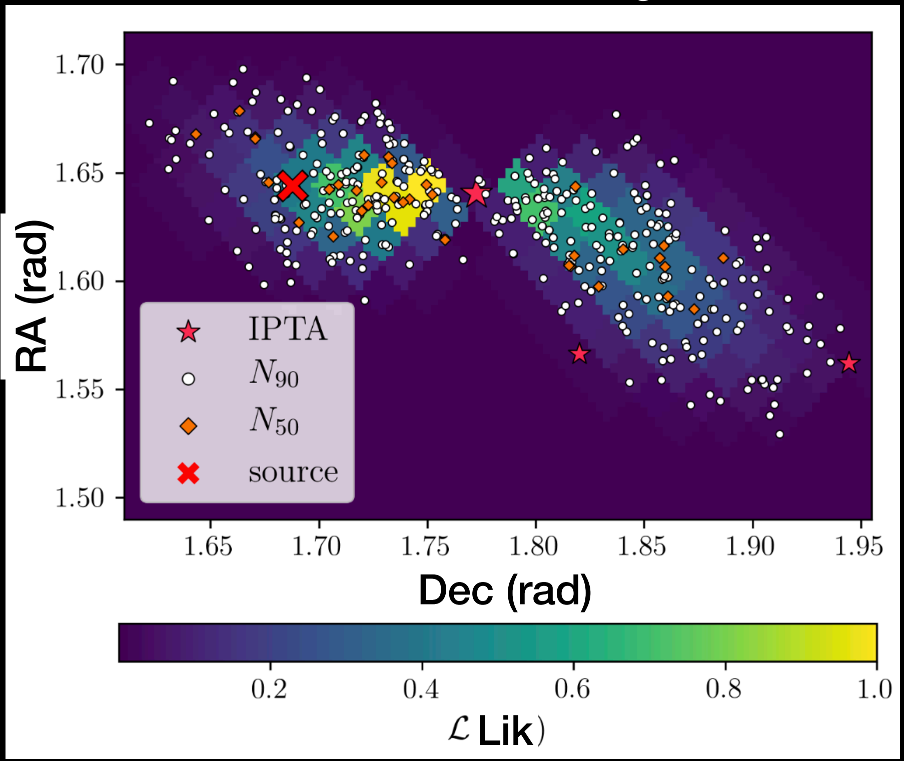


How well can we localize binaries?

Localization capabilities of (simulated) IPTA

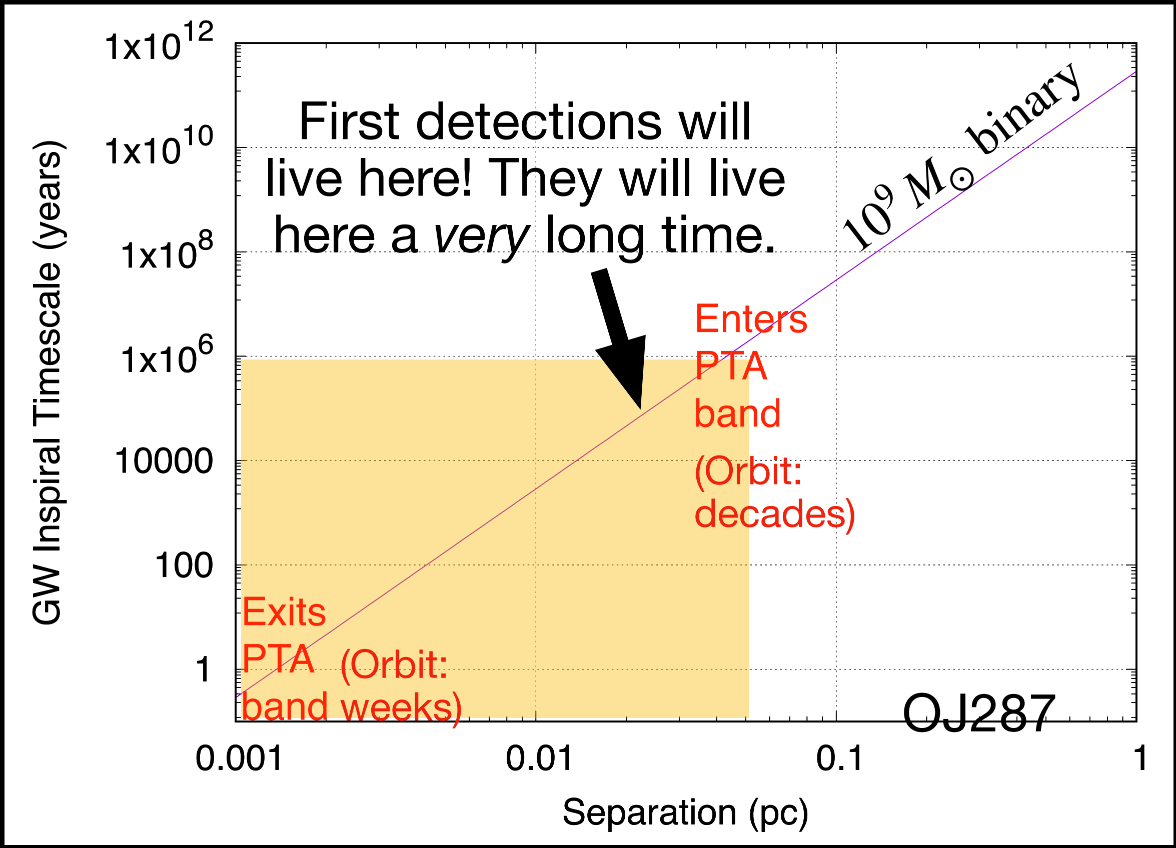


Likely hosts up to $z \lesssim 1.2$, $M_{\mathrm{bulge}} \gtrsim 10^{11}\,\mathrm{M}_{\odot}$



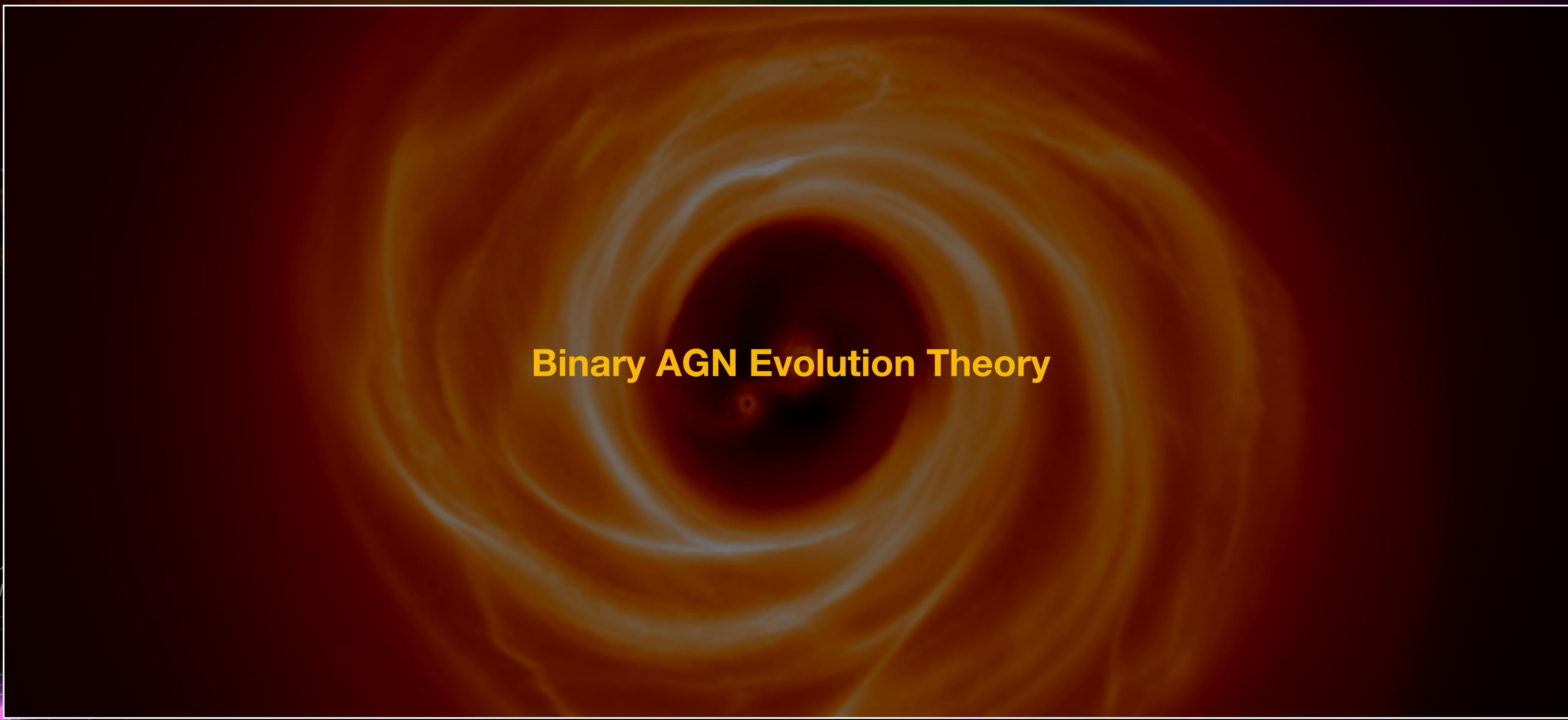
Goldstein et al. (2019)

Long-term monitoring (not urgent response) requred.



Binary Black Holes Dreamline

The next 5-10 years contain many unknowns about what universe we live in!

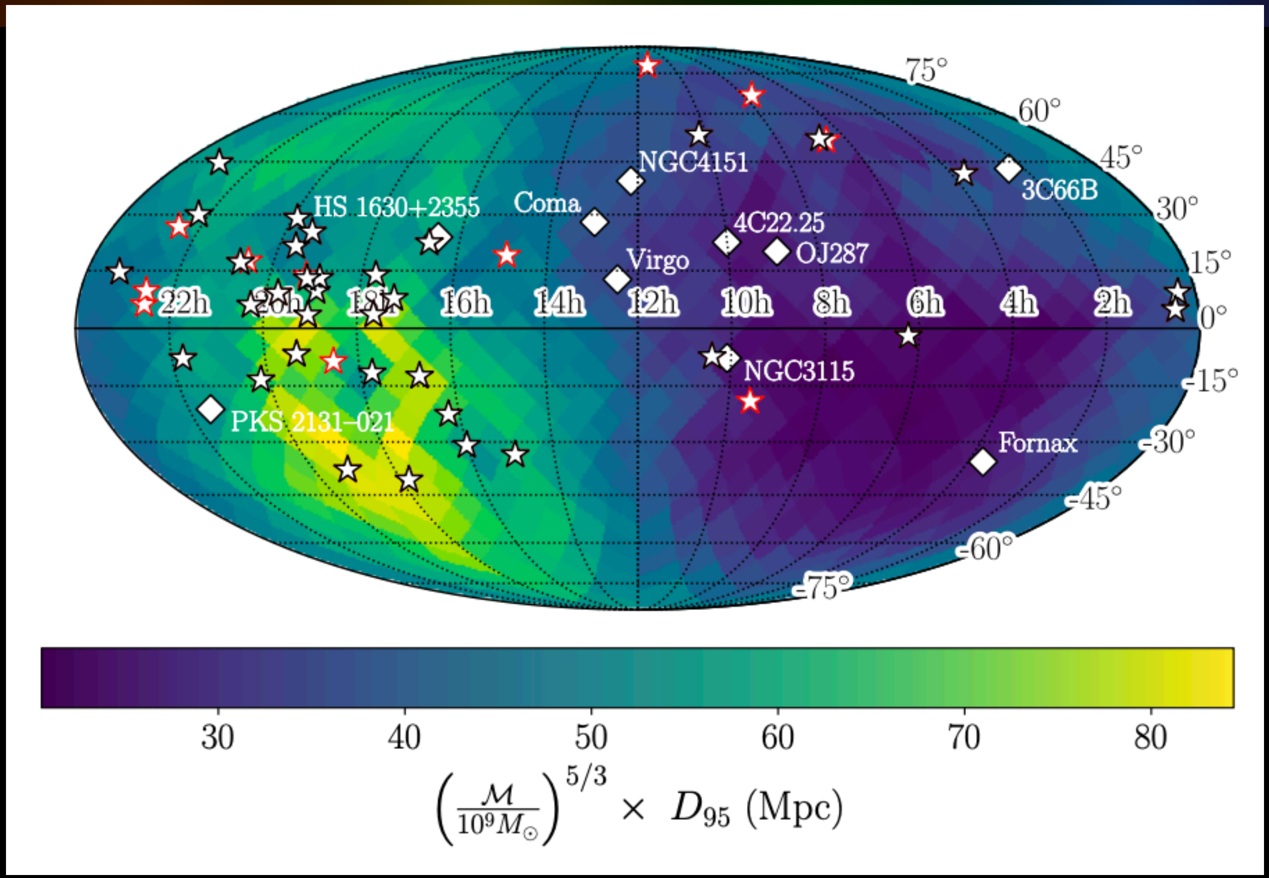


2023 2025 2027 2029 2031 2033

Next 5-10 years with continuous binaries…

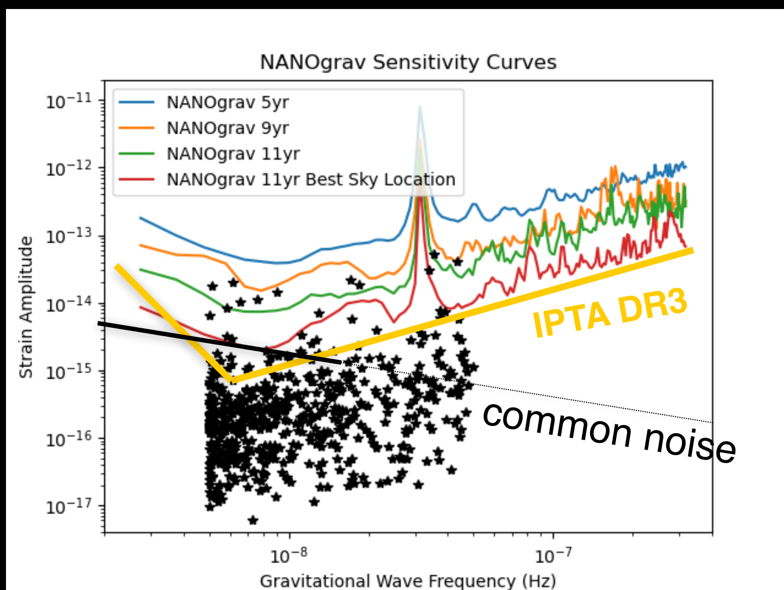
- Detecting SMBH Binaries with PTAs:
  - GW background appears close/imminent.
  - Individual systems are on the horizon.
- Search for the first PTA-detected hosts:
  - Large, archival galaxy surveys.
  - New and archival shallow, wide-field time-domain surveys.
  - New, deep signature searches and deep, large-N monitoring.
- Check out talks by P. Penil, C. Chan!

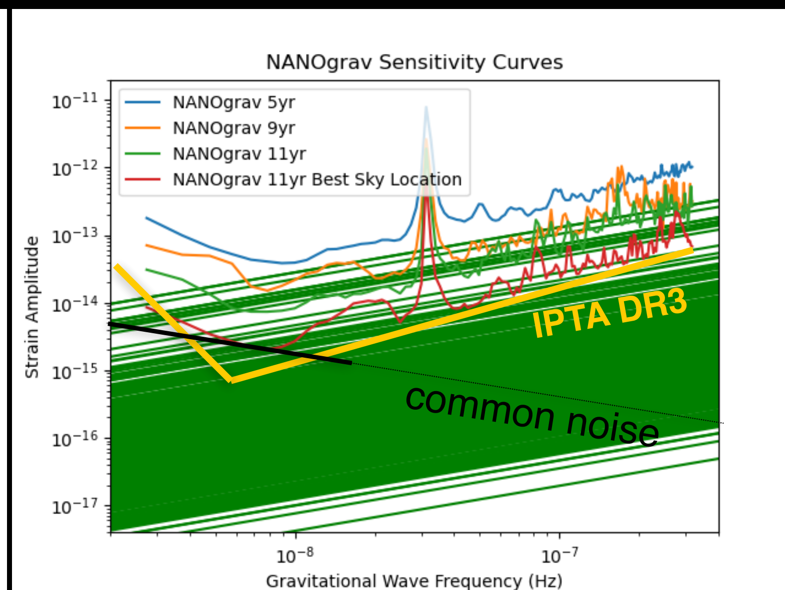
NANOGrav 12.5yr Horizon Map



Arzoumanian et al. (accepted) [led by C. Witt]

Currently ~800 papers / 500 sources in BOBcat list.



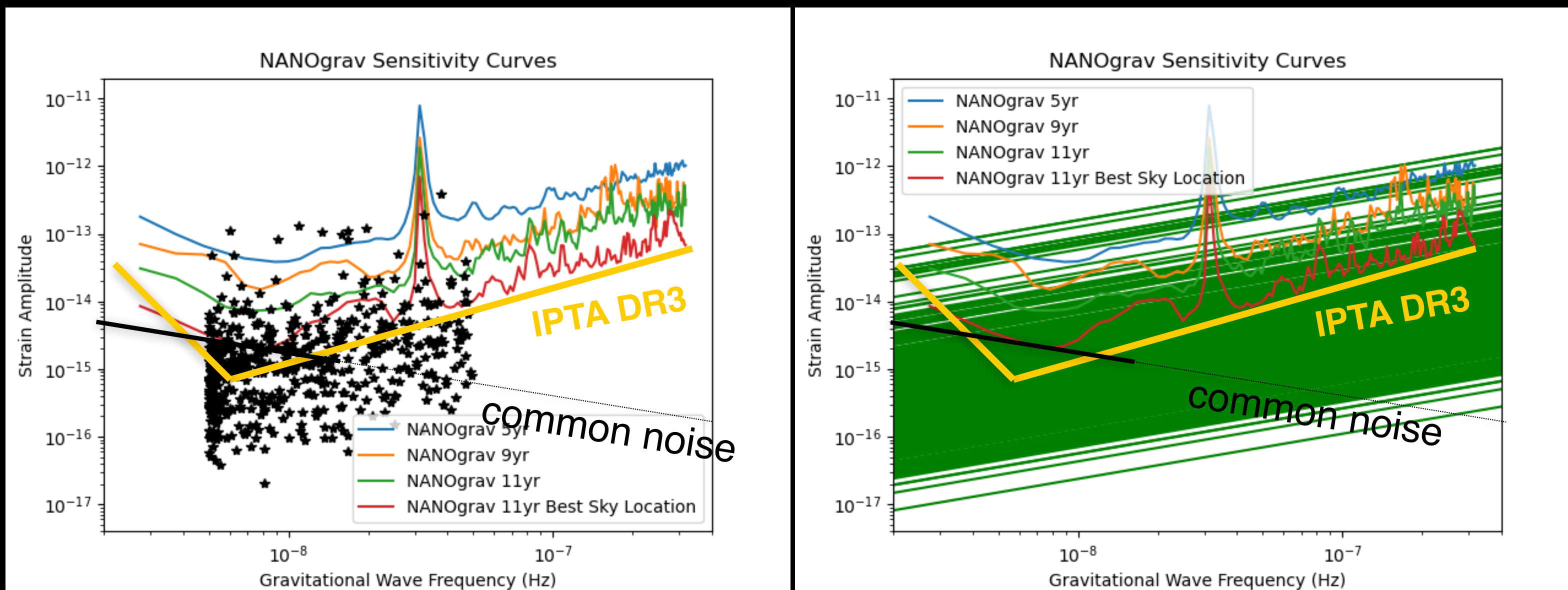


Estimated for two $10^9 M_\odot$ binaries.

Recall $$h_s \propto \frac{M_c^{5/3} f^{2/3}}{D}$$

Sydnor & Burke-Spolaor (in prep)

Currently ~800 papers / 500 sources in BOBcat list.



Estimated for one $10^9 M_\odot$ binary and one $10^{10} M_\odot$ binary.

Recall $h_s \propto \dfrac{M_c^{5/3} f^{2/3}}{D}$

Sydnor & Burke-Spolaor (in prep)

This is a rapidly growing field, lots of unknowns!

We know what to do next,
but the scope may evolve.

Building a Binary Population

The background strain is a literal sum of the discrete binary signals…

$$h_c^2(f) = \int\int\int \frac{d^4N}{dz\ dM\ dq\ d(\ln f)} h_s^2\ dz\ dM\ dq,$$

The SMBH binary distribution directly relates to the host galaxy distribution…

$$\frac{d^4N}{d(\ldots)} \propto \frac{d^3n_G}{dz\ dM\ dq} = \Phi(z, M)\mathscr{R}(z, M, q)$$

Number of galaxy mergers

Galaxy mass function

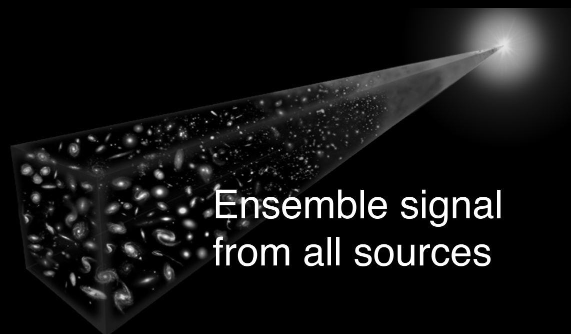
Galaxy merger rate

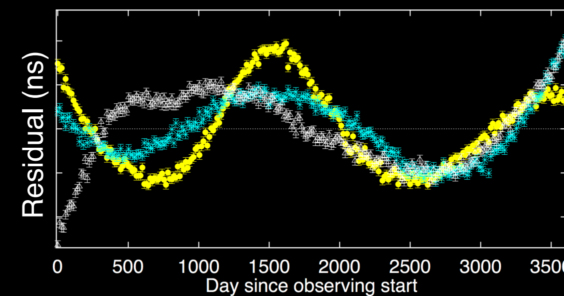
BH masses relate to progenitor properties by M-Mbulge or M-sigma relations.

e.g. Simon & Burke-Spolaor (2016), Kelley et al. (2017), Simon (2023), much work by V. Ravi, A. Sesana

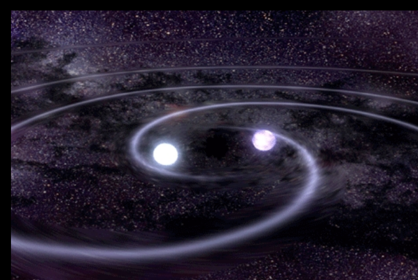
Black holes make several signal types…

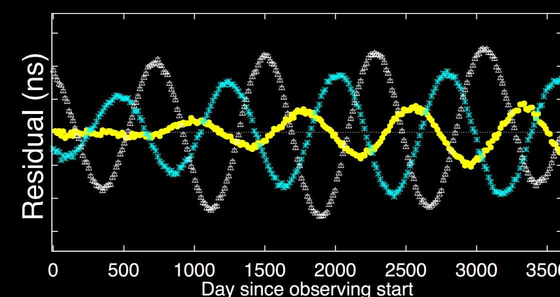
Stochastic Background



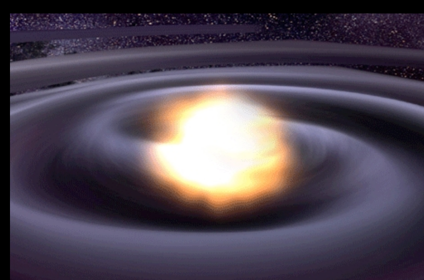


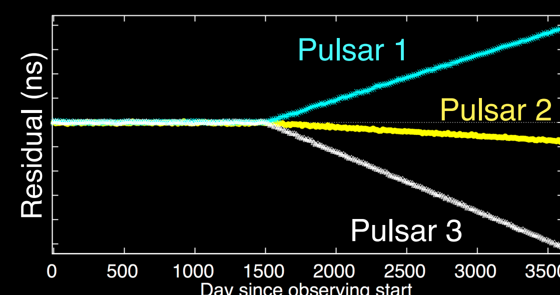
Continuous Wave





Coalescence "memory"

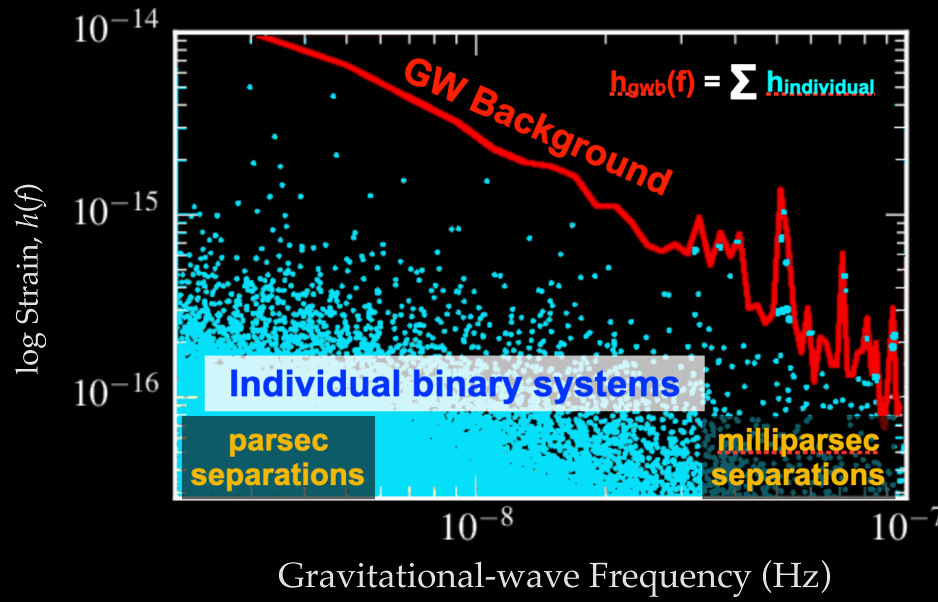




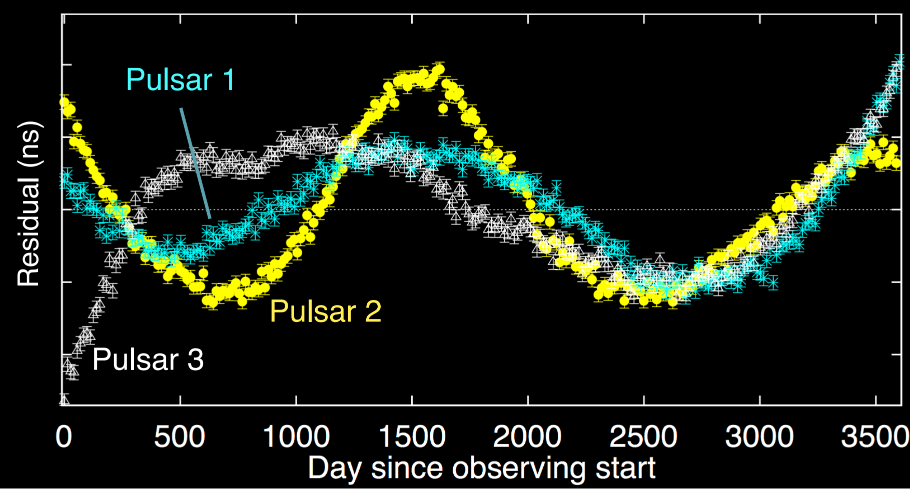
Images: NASA; Plots: Burke-Spolaor (2019)

Showing simulated binary background in Universe…

Strain spectrum:



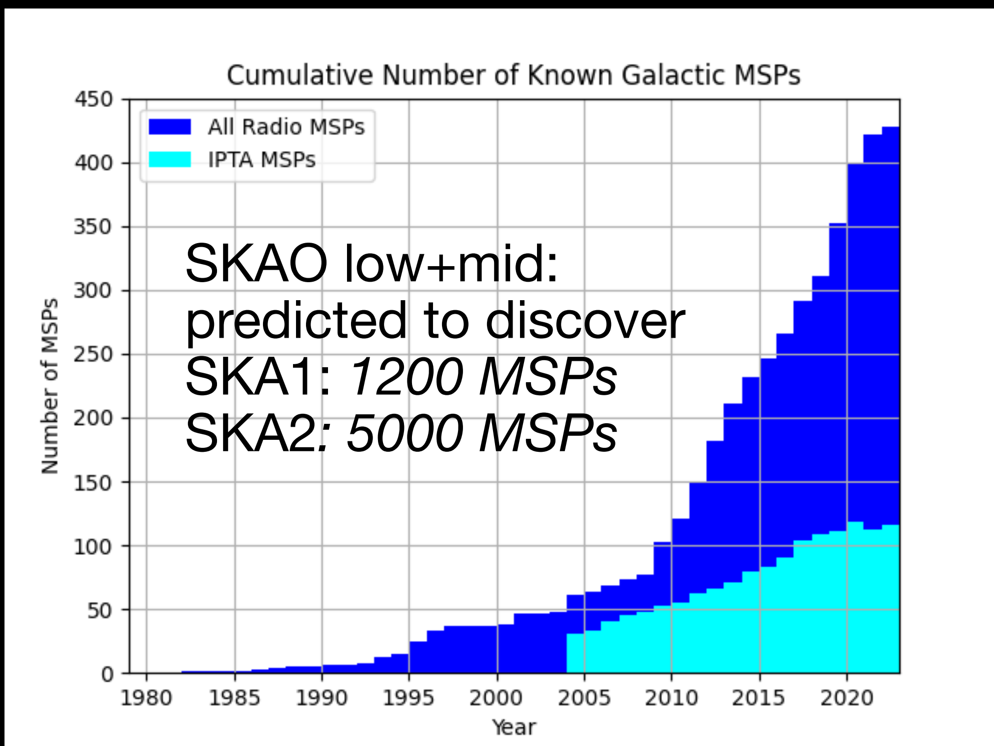
Pulsar residuals:



ngVLA and SKAO Contributions

Building and Characterizing our Pulsar Timing Instruments

The most revealing pulsars are the rarest ones!



1. Understanding our "pulsar antennae" (Find, study rare systems)
2. Efficient all-sky and high-DM searches [see poster P75 - Levin]
3. High-precision timing [Recall Ryan Shannon's MeerKAT talk]

$$\text{GW background S/N} \propto N_{\text{pulsars}} \sqrt{T_{\text{baseline}}} \left(N_{\text{obs}}/\sigma_{\text{pulsar noise}}\right)^{3/2}$$

ngVLA/SKAO…

- **Fast transients are *instruments* that ngVLA, SKAO will calibrate, grow, and enable.**
  - Through FRB localization (~10000/year).
  - Through Pulsar detection and studies (detect, time GC pulsars and hundreds more MSPs).
- **ngVLA, SKAO VLBI can contribute multi-messenger SMBH binary studies.**

If it’s a GWB, what is it?

- Supermassive binary black holes e.g. Arzoumanian et al. (2018)
- Strings e.g. Blanco-Pillado, Olum, & Wachter (2021)
  - Cosmic string loops, Superstrings
- Inflationary and phase-transition GWs
  e.g. Arzoumanian et al. (2021), Xue et al. (2021), Lasky et al. (2016)
  - First-order phase transitions
  - Sensitive at ~1 MeV - 10 GeV scales (e.g. QCD)

EXPECT

THE

UNEXPECTED!

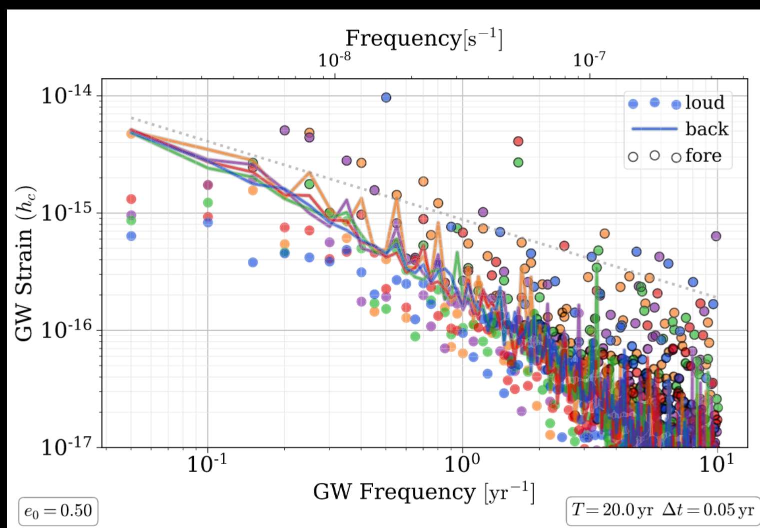
(Cutler et al. 2014)

How can we decide?

- Supermassive binary black holes e.g. Arzoumanian et al. (2018)
  - Detect a "resolved" system.
  - Track spectral turnover.
  - Consistency with galaxy merger models.
- Strings e.g. Blanco-Pillado, Olum, & Wachter (2021)
  - Measure spectrum
  - Support from LISA/LIGO
- Inflationary and phase-transition GWs e.g. Arzoumanian et al. (2021), Xue et al. (2021), Lasky et al. (2016)
  - Constrain spectrum
  - Support from LISA/LIGO

Constraining the spectrum and resolved-system detection need more pulsars, lower receiver noise, longer time baselines.

The horizon may grow…

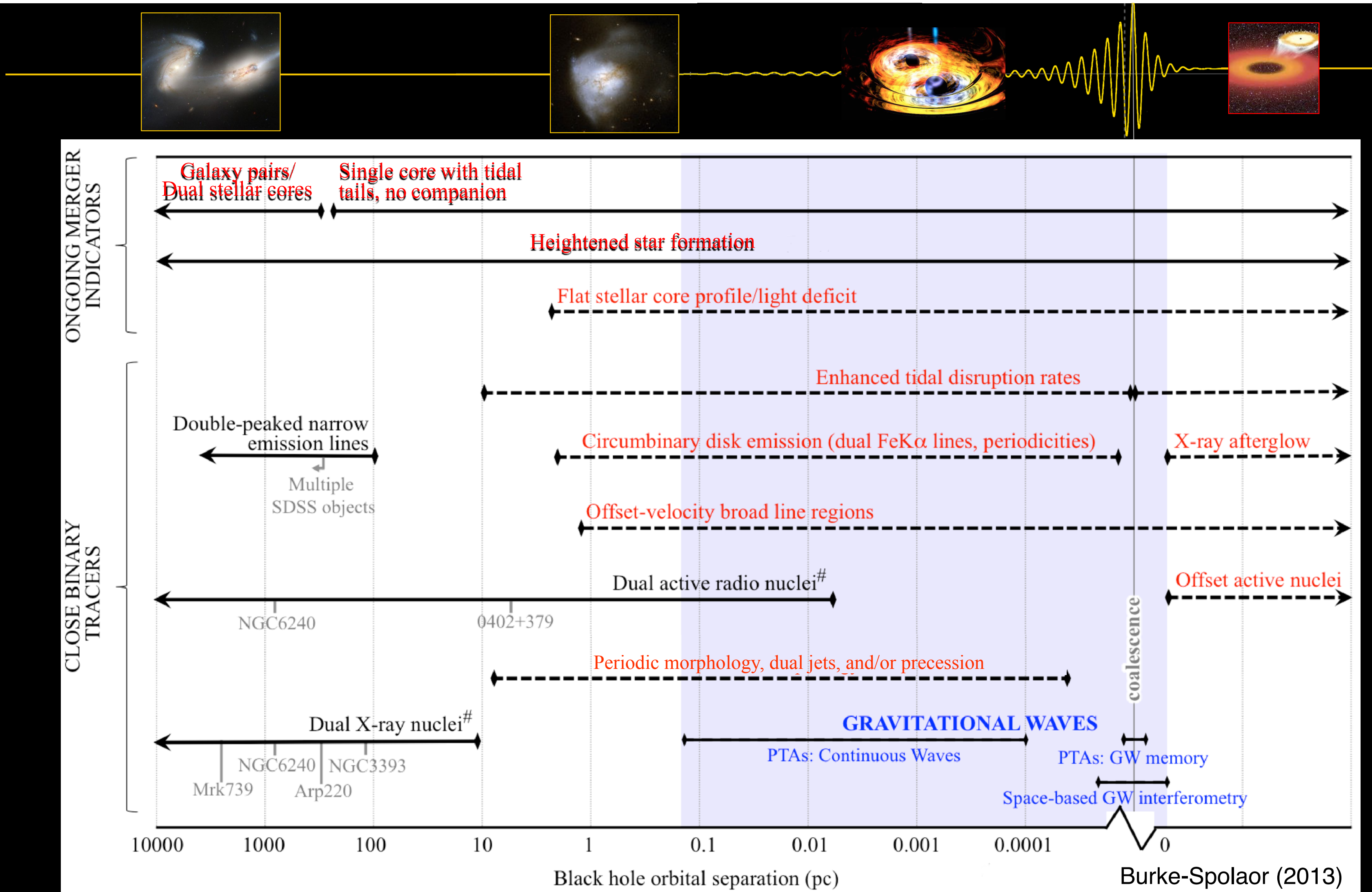


Kelley et al. (2018)

Each color is one realization of a Universe

Black-circled sources contribute $\geq 50\,\%$ of power to the total signal.

See also Boyle & Pen (2012), Ravi (2013), Babak & Sesana (2013),…



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