The (nanohertz) gravity side of the conversation…

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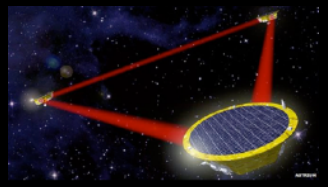
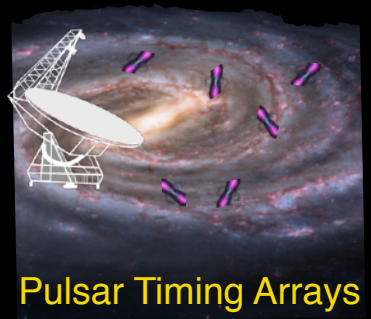
With: NANOGrav collaboration
and WVU team: Peter Breiding, Rodney Elliott, Greg Walsh, Caitlin Witt

LIGO/Virgo
[2015]

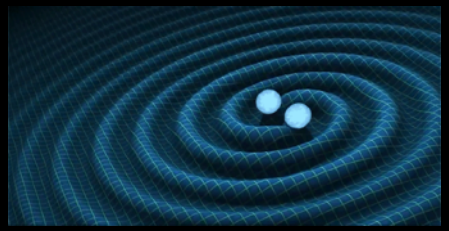


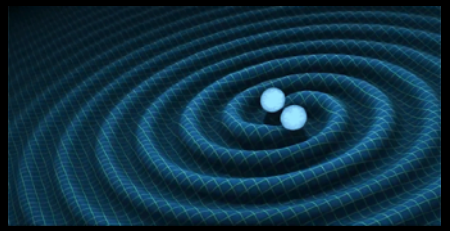
LISA
[launches 2030ish]

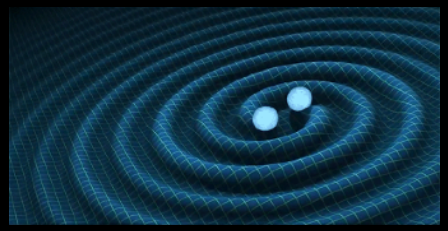


Pulsar Timing Arrays
[first discovery 2020s?]

Mass scale: ~100 M_{sun} 10^4-10^7 M_{sun} 10^8-10^{11} M_{sun}

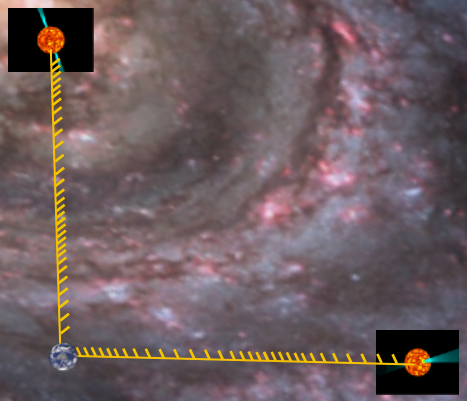






Movements take: seconds hours-days weeks-decades

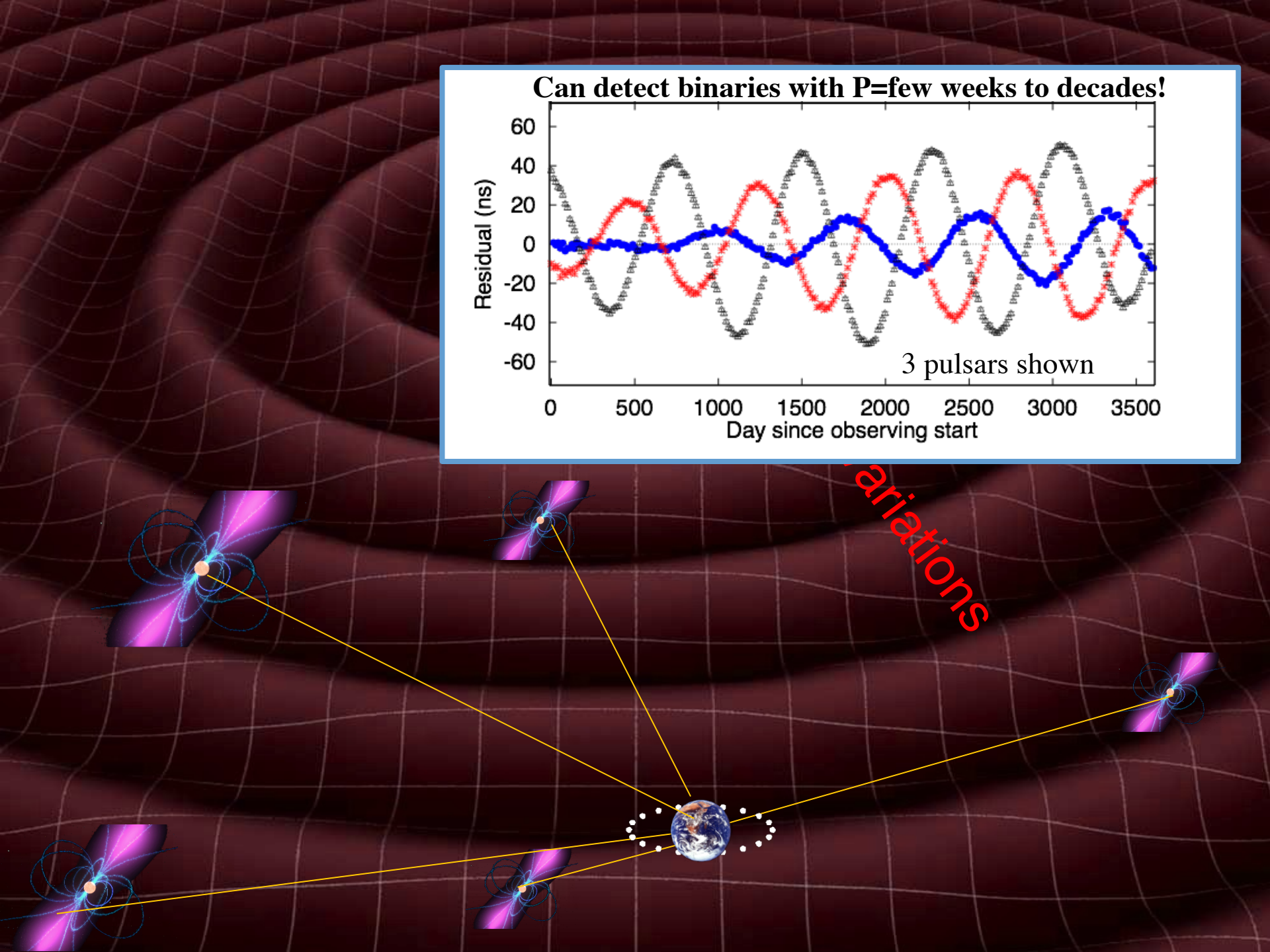
Pulsar Timing Arrays



A Galactic-scale Gravitational Wave Observatory!

PSR B1937+21:

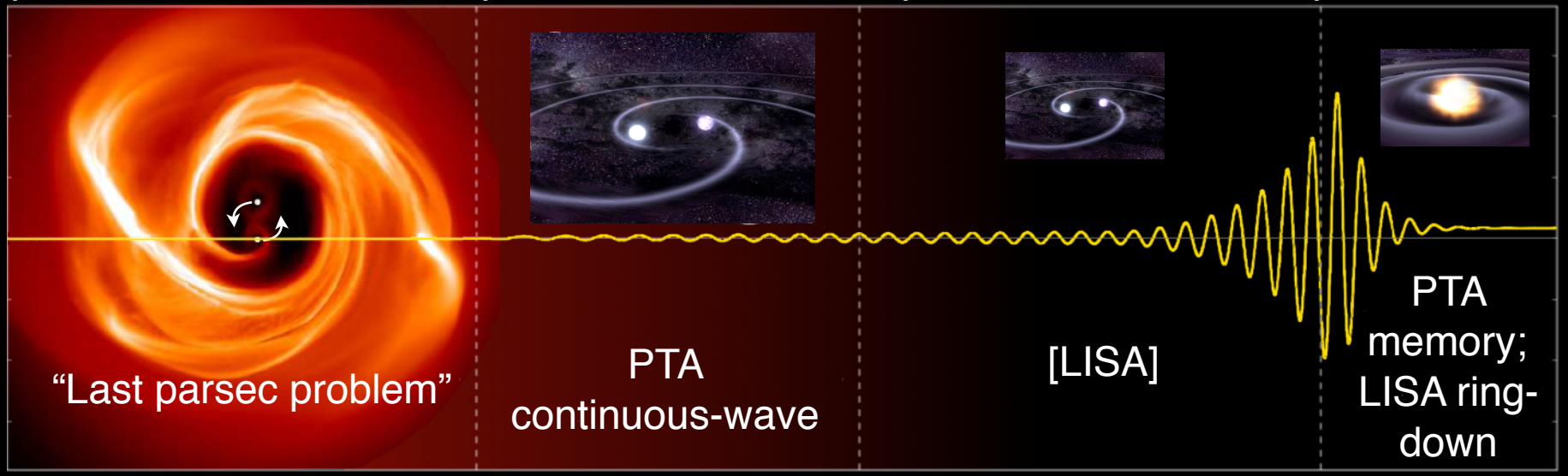
P = 1.5578064688197945 ms
+/- 0.0000000000000004 ms


Can detect binaries with P=few weeks to decades!
Residual (ns)
60
40
20
0
-20
-40
-60
0
500
1000
1500
2000
2500
3000
3500
Day since observing start
3 pulsars shown
ariations

Deep within a merger remnant . . .

Approximate binary separation

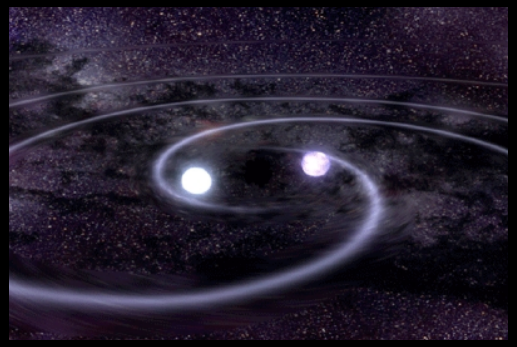
10pc 0.1pc 0.0001pc 0 pc



GW Signals

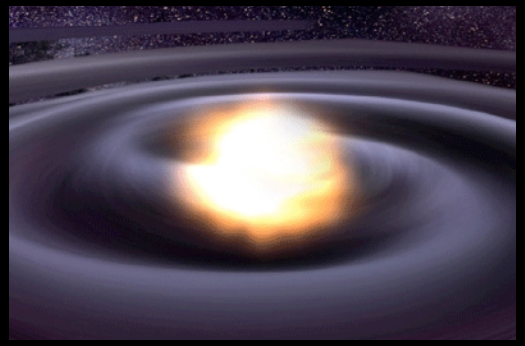
(e.g.)

Continuous Waves



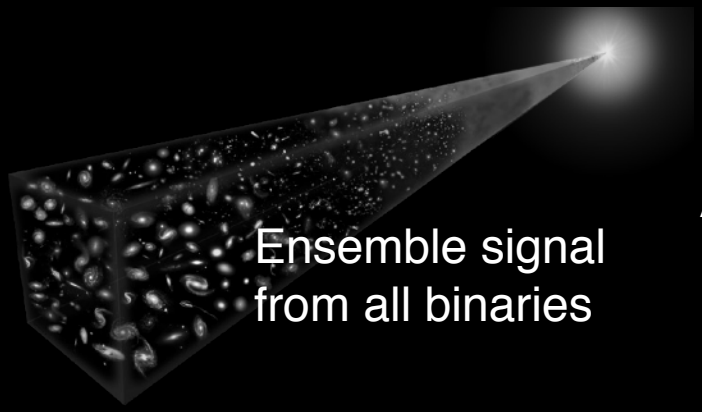
Aggarwal et al. (2019)

BURST ("memory")



Madison et al. (2016)

Stochastic Background



Ensemble signal from all binaries

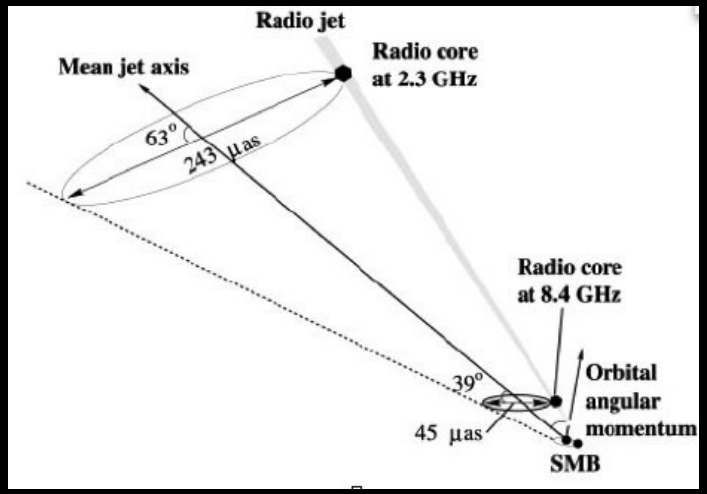
Arzoumanian et al. (2018)

Images: NASA

Current state-of-art: testing “weird AGN”

3C66B: Early Multi-Messenger Astronomy

Sudou et al (2003)



Galaxy

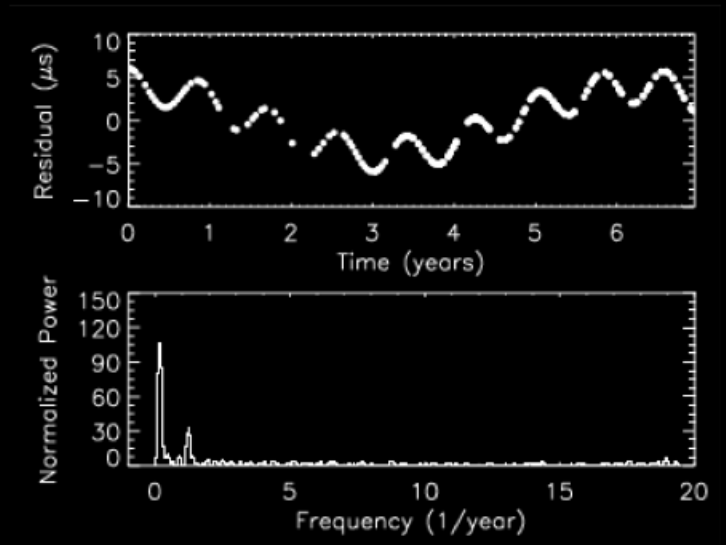
3C66B

Jenet et al (2004)

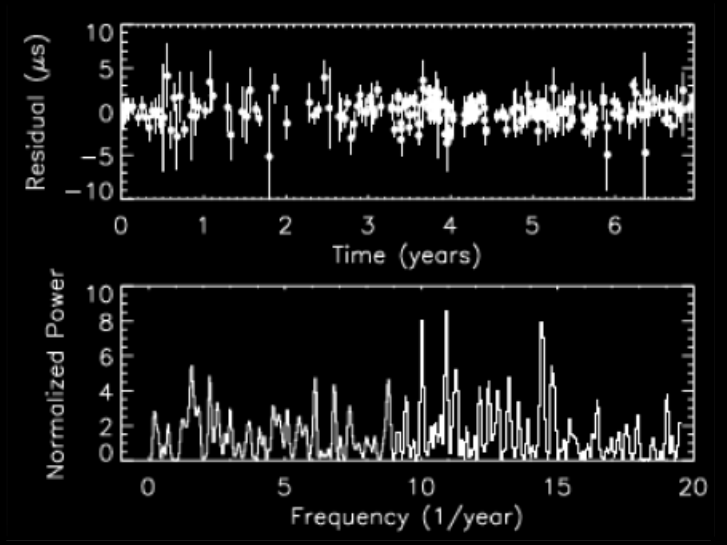
TABLE 1
DETECTION LIMITS

M_c ($10^{10}\ M_\odot$)	MAXIMUM ECCENTRICITY 98%	95%	90%
1.3	0.03	0.49	0.51
1.2	0.02	0.49	0.51
1.1	0.02	0.16	0.23
1.0	...	0.03	0.18
0.9	...	0.02	0.04
0.8	...	0.01	0.03
0.7	...	...	...

Simulated signal…

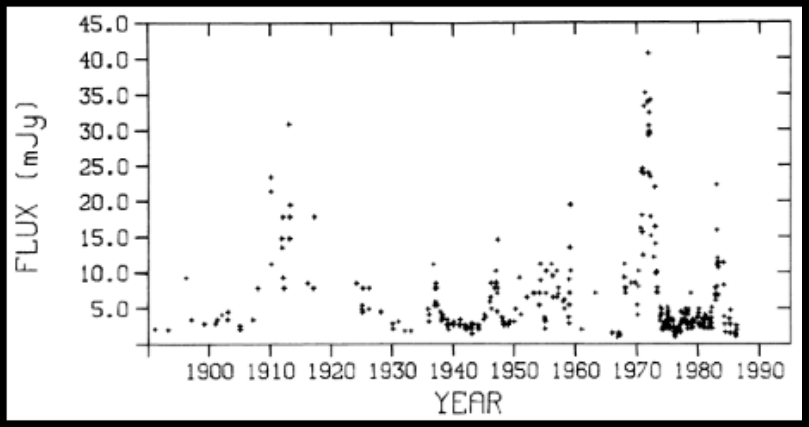


Actually saw…

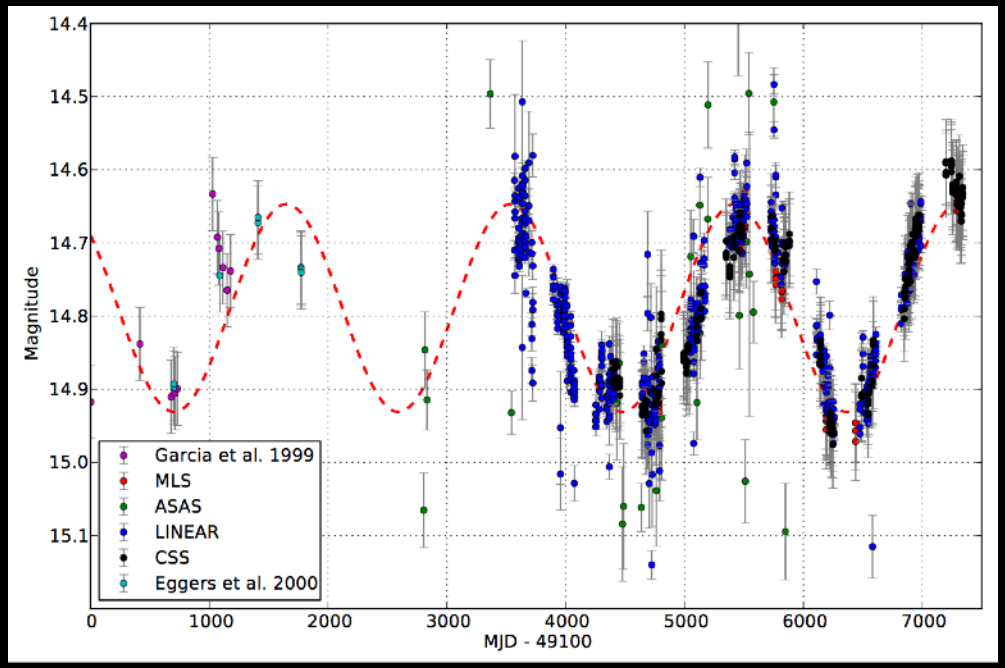


“Weird AGN”

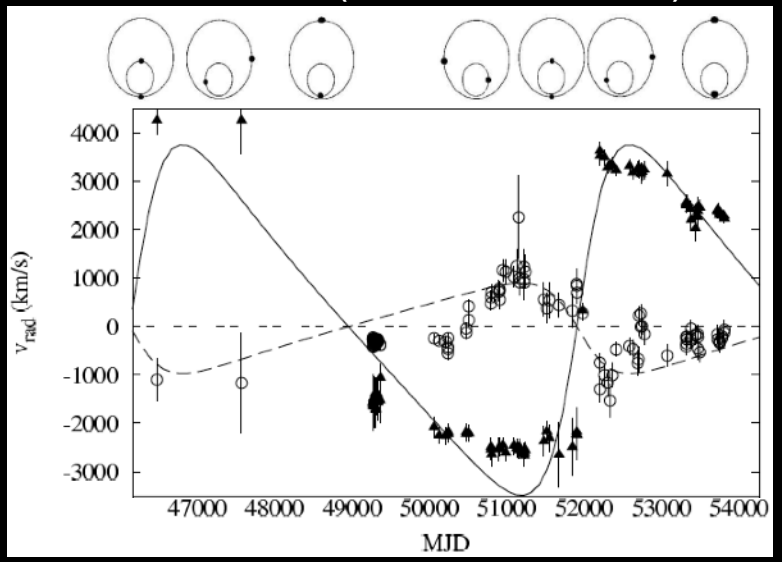
Periodic flares; OJ287 (Valtonen et al. 1988)



Sinusoidal light curves: PG1302-102 (Graham et al. 2015)

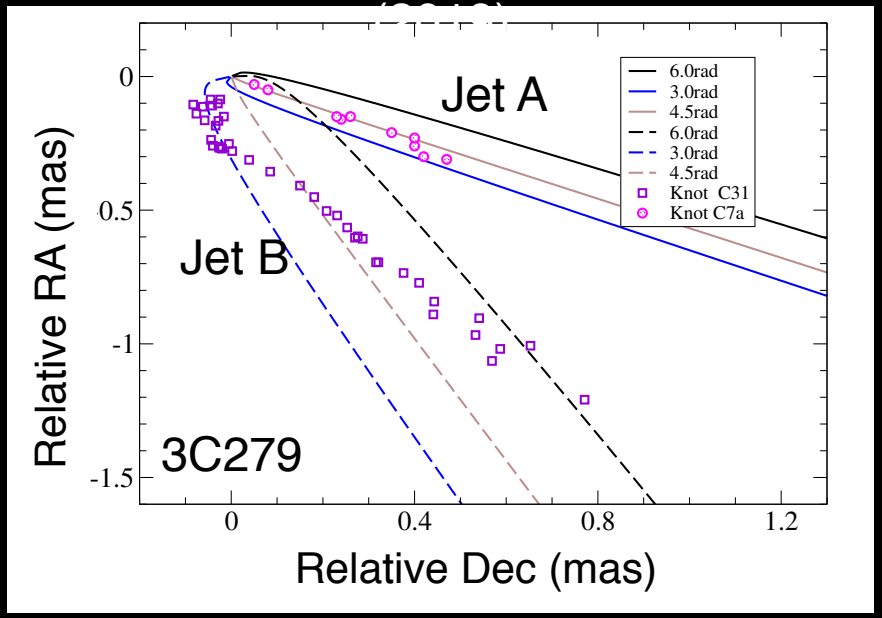


Emission line velocity oscillations; NGC 4151 (Bon et al. 2012)

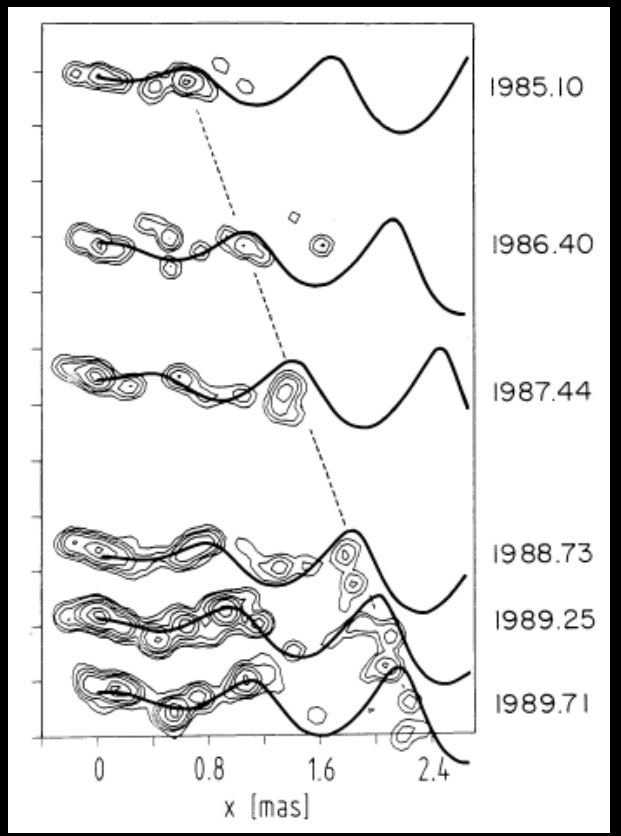


“Weird AGN”

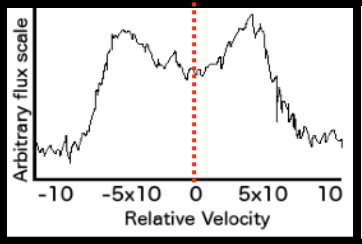
Multiple jets/outflows e.g. Qian et al.

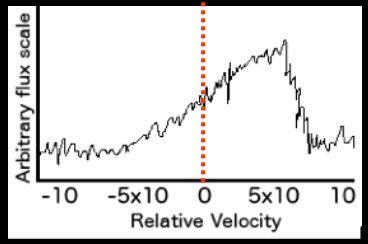


Helical radio jets,
e.g. Kun et al. (2013)



Double-peaked/offset emission lines
(Eracleous, Runnoe, Bogdanovic et al.)

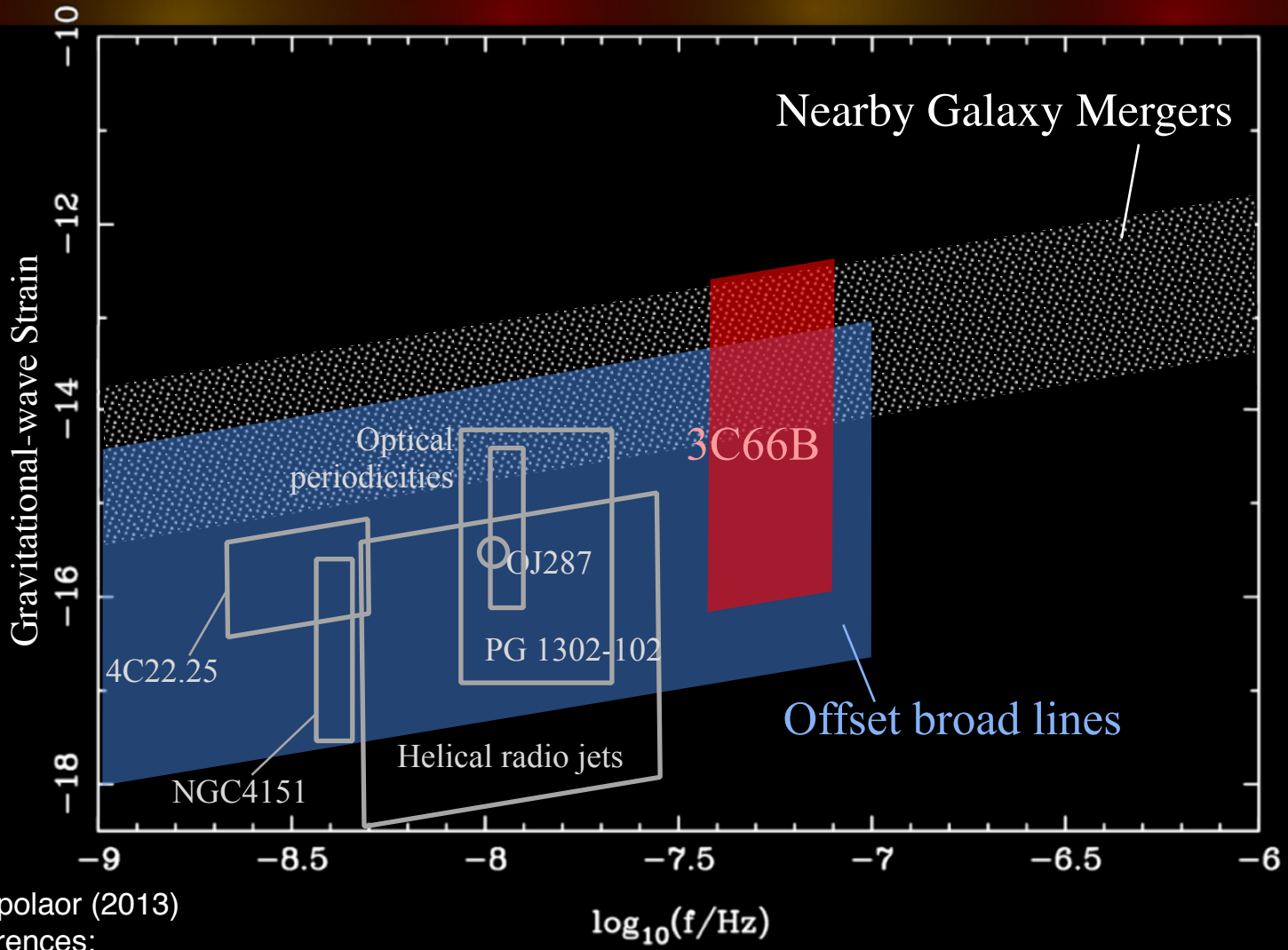




Caveat…

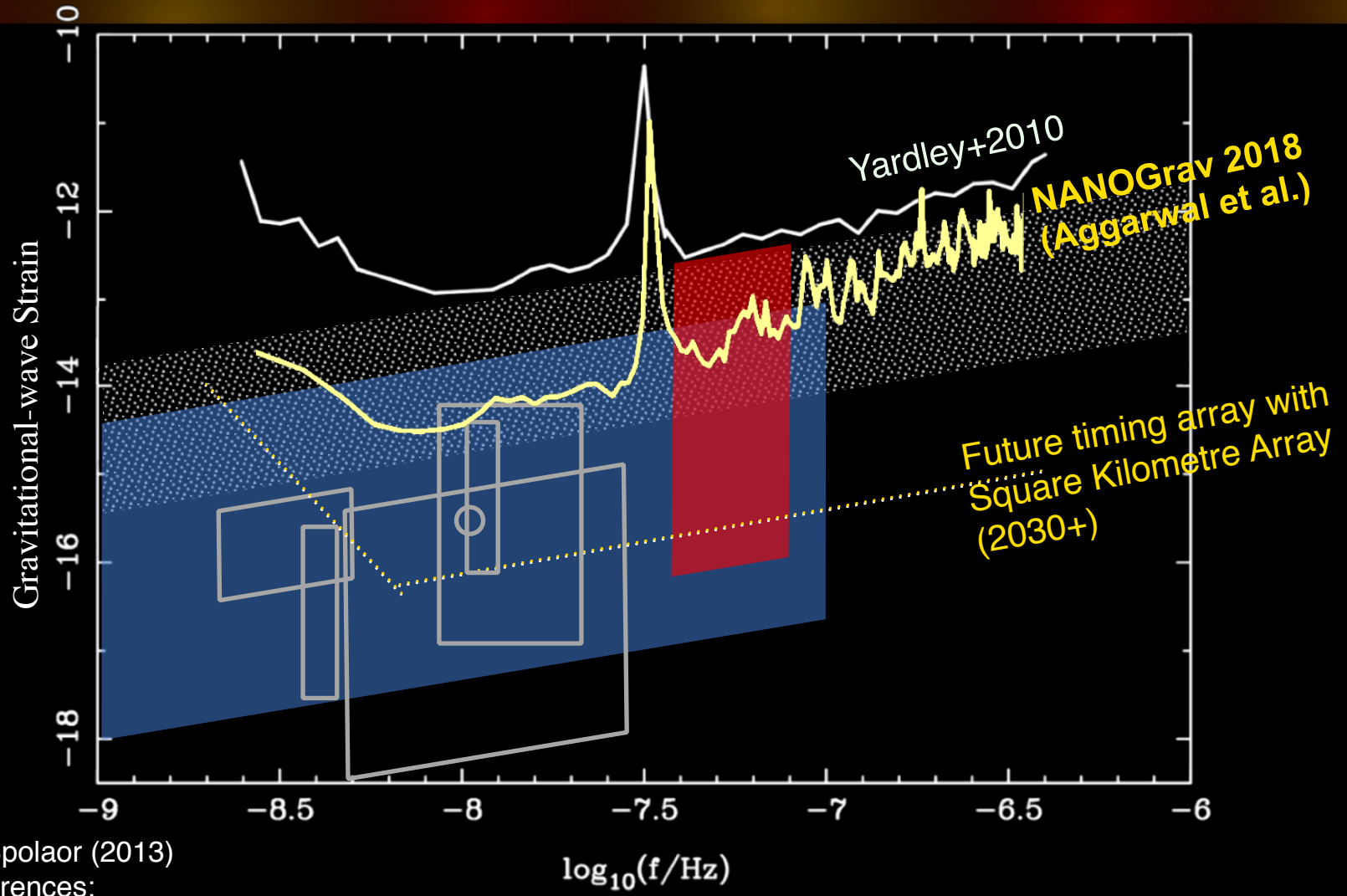
- **Period:**
  - 1 week - 30 years
- **Distance** (Aggarwal et al. 2019):
  - $z <= 2.2$ for 10^{10} $M_\odot$
  - $z <= 0.04$ for 10^{9} $M_\odot$
  - $z <= 0.0005$ for 10^{8} $M_\odot$

Testing abnormal emissions



c.f. Burke-Spolaor (2013)
Source references:
Sundelius+97, Britzen+10, Decarli+10, Kudryavtseva+11, Eracleous+12, Carpineti+12, Bon+12, Ju+13, Sudou+03, Iguchi+10, Graham+15, Liu+15, Graham+15, Runnoe+15/17, d'Ascoli+18, Kelley+18, D'Orazio+18, and more!

Testing abnormal emissions



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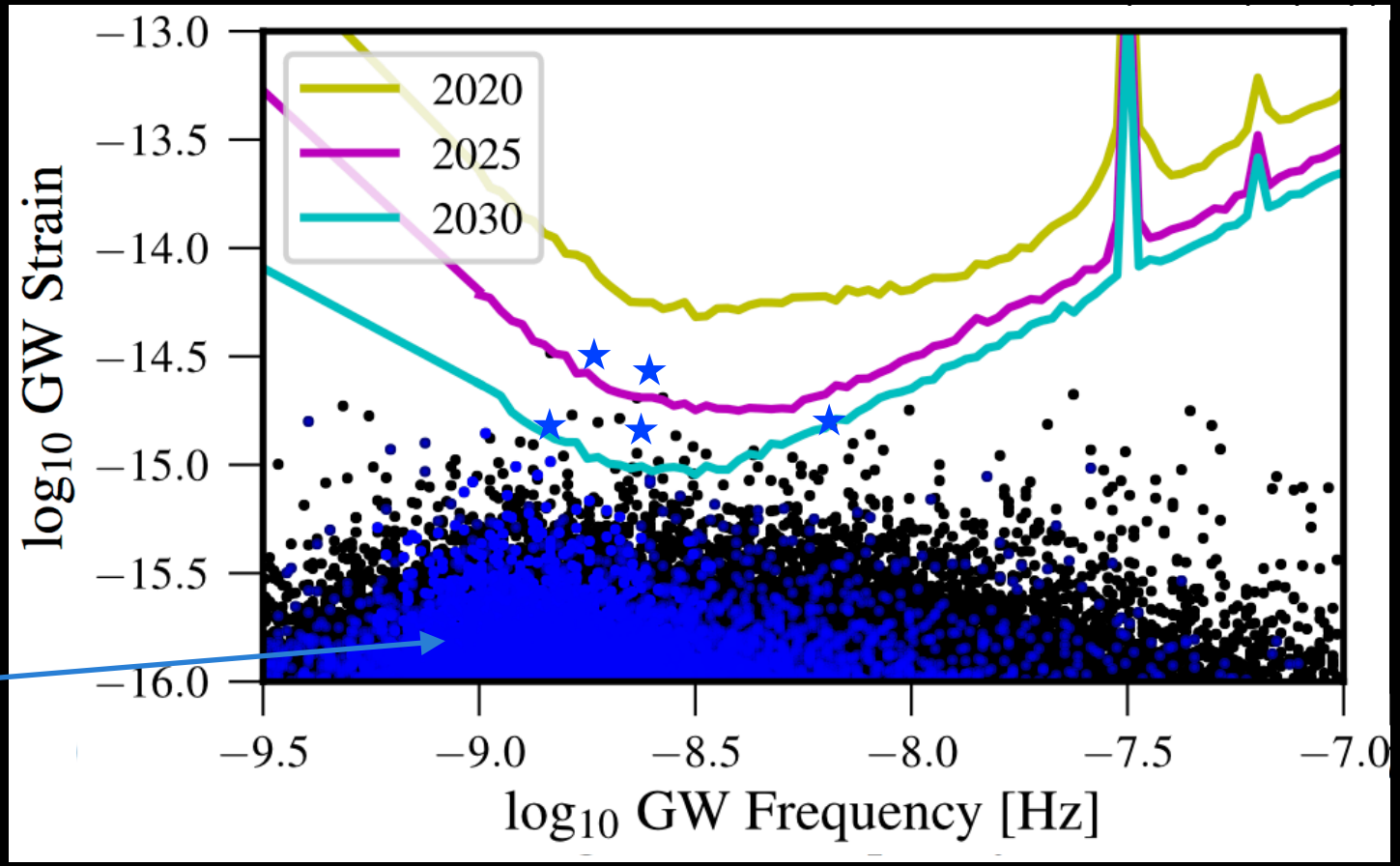
Future state-of-art:
Multi-messenger
AGN/circumbinary disk physics

Future Multi-messenger Targets

“Double-peaked/offset emission line” sources



Simon & Burke-Spolaor (in prep)

PTA Parameter estimation

Orbital Frequency: +/-10%

Inclination, phase: +/- 20 deg

Sky location: 10's of deg^2

Mass/Distance: Degenerate.

Sesana & Vecchio (2010)
CBD image: Cuadra et al. (2009)

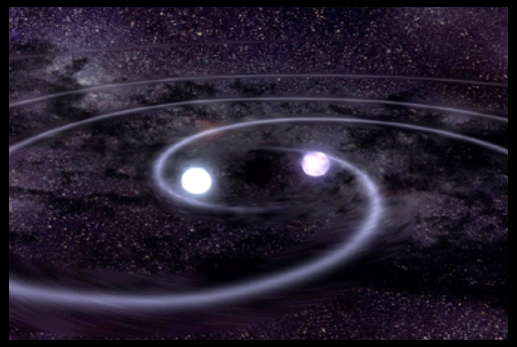
Low-hanging fruit

- Do orbits and jets align?
- Are two jets possible in a binary (geometries, scale sizes)?
- How does light variability compare with orbital period (disk resonances; variable heating; accretion dynamics)?
- Do we see expected BLR flux and velocity variability given measured orbital inclination?
- Is emission correlated between two SMBHs?

GW Signals

(e.g.)

Continuous Waves



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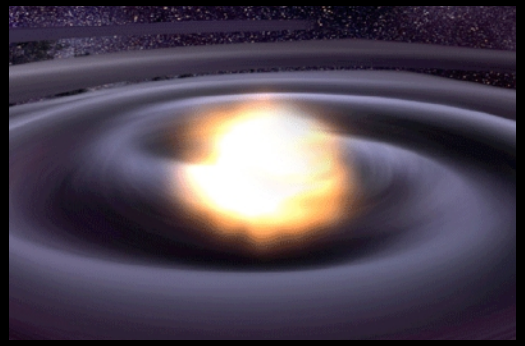

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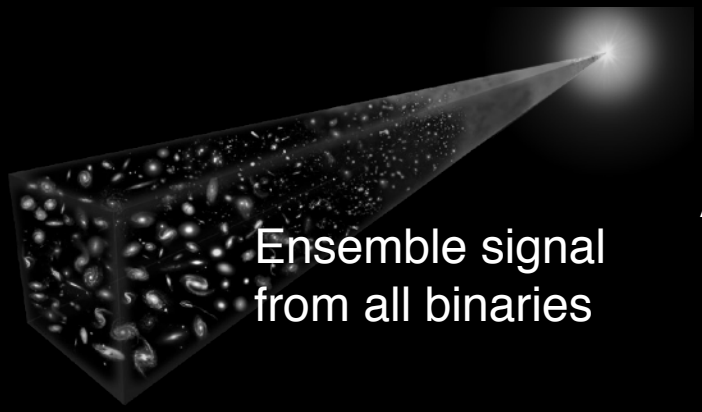
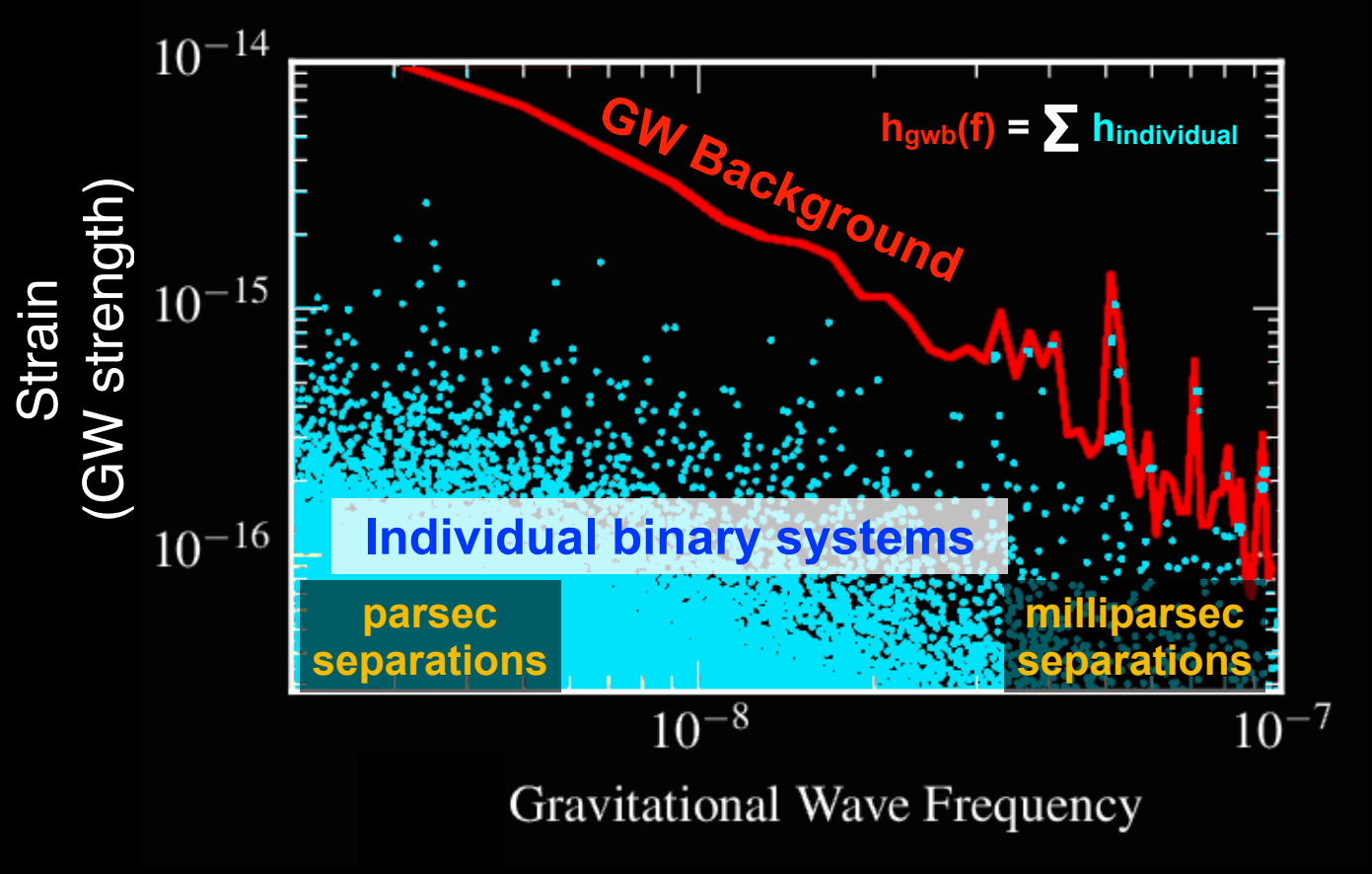


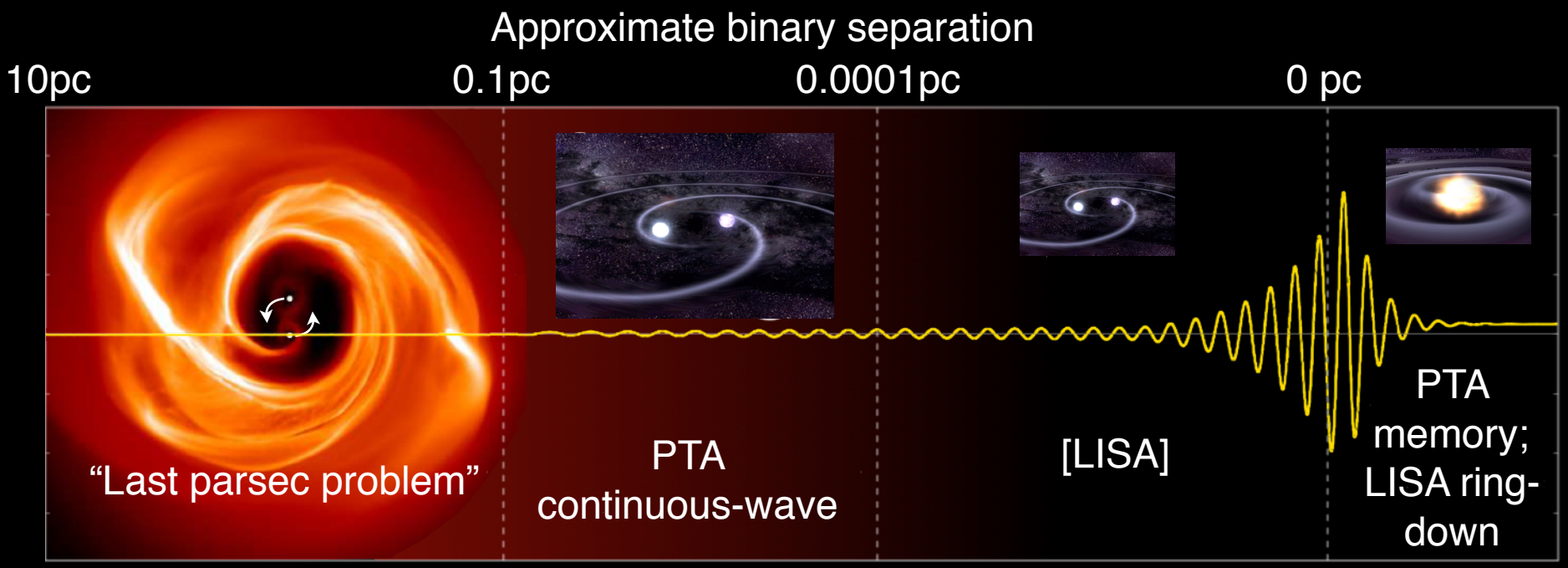
Ensemble signal from all binaries

Arzoumanian et al. (2018)

Images: NASA

The Strain Spectrum

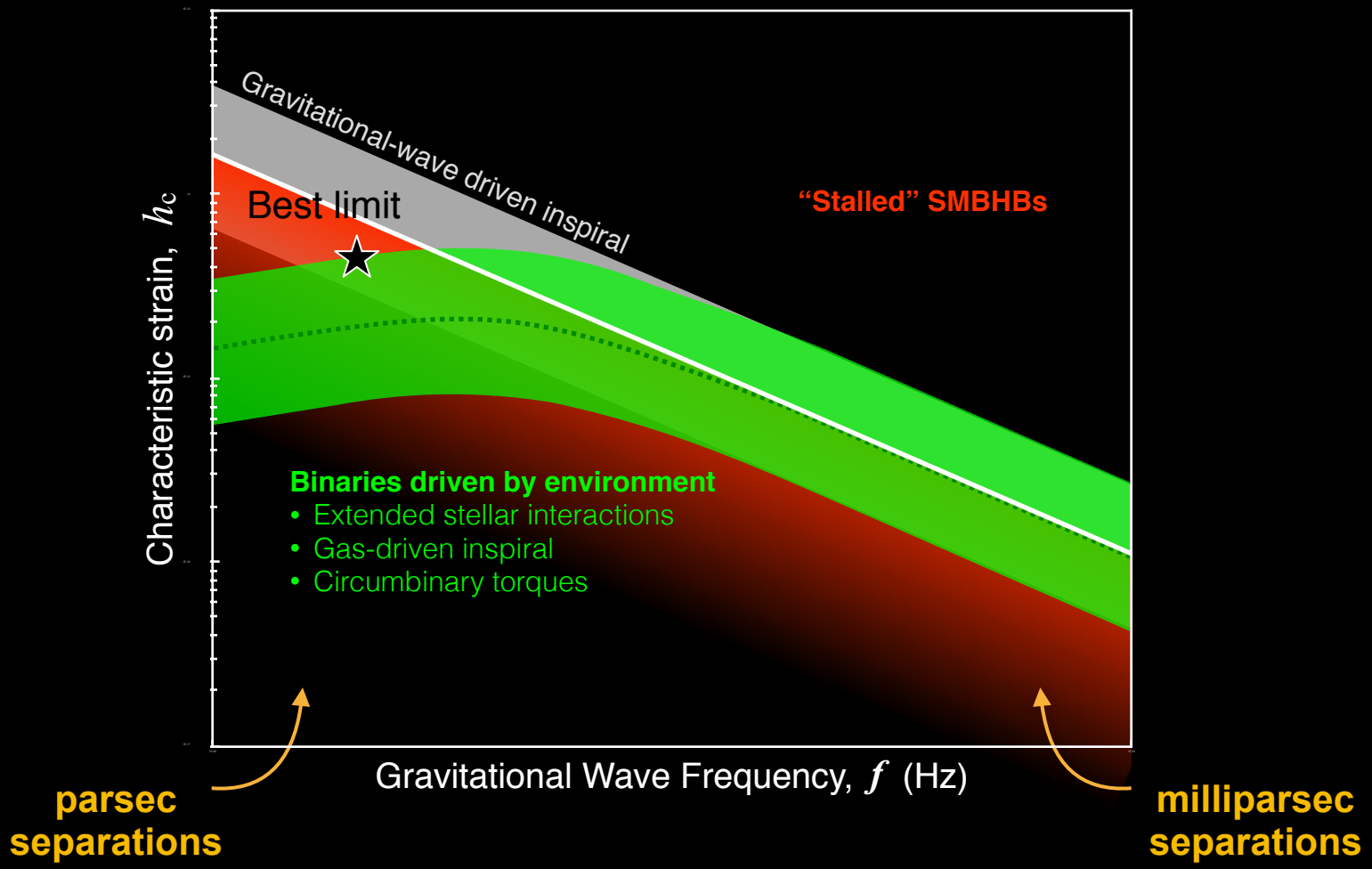




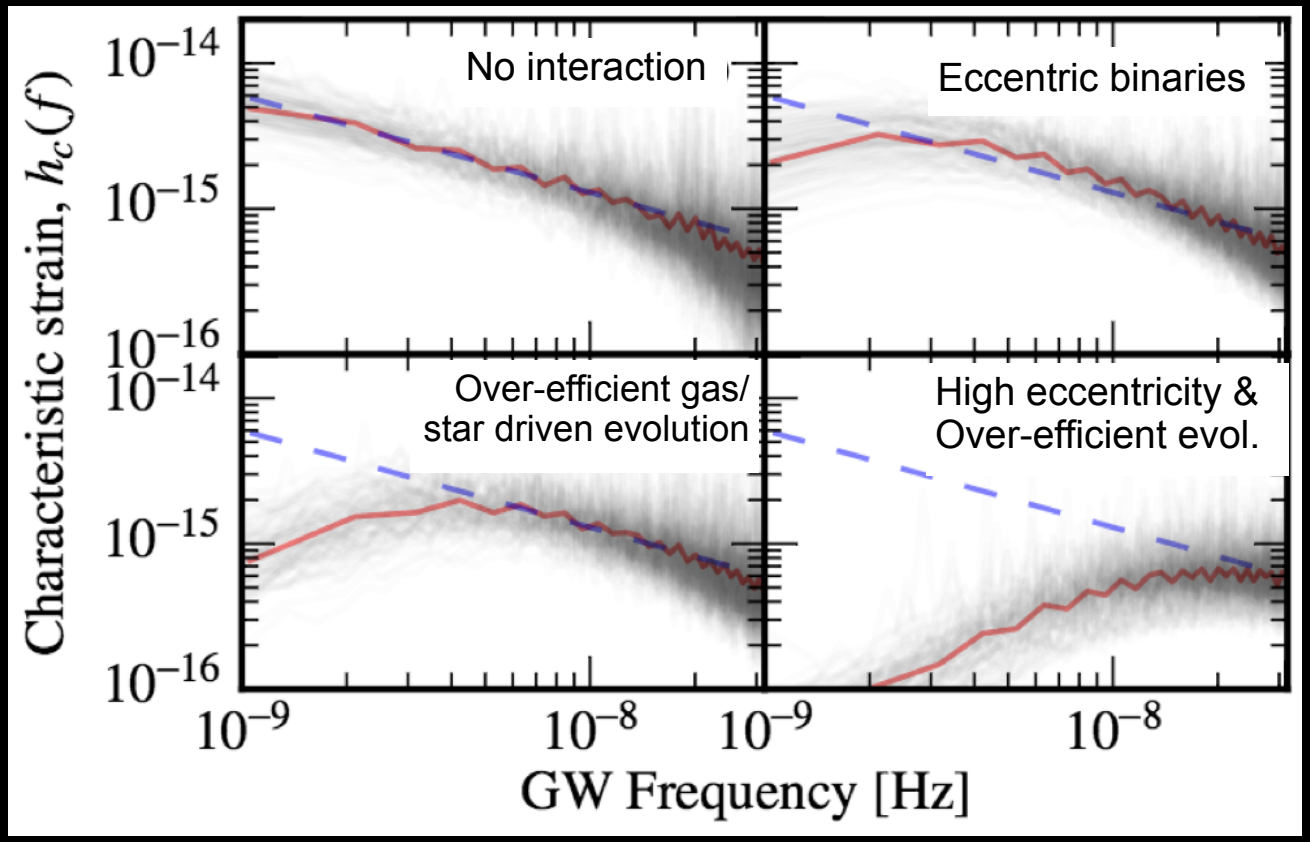
Do binaries stall at >1pc?

Is inspiral “over-efficient” due to disk or stellar interactions?

Understanding the GW Background



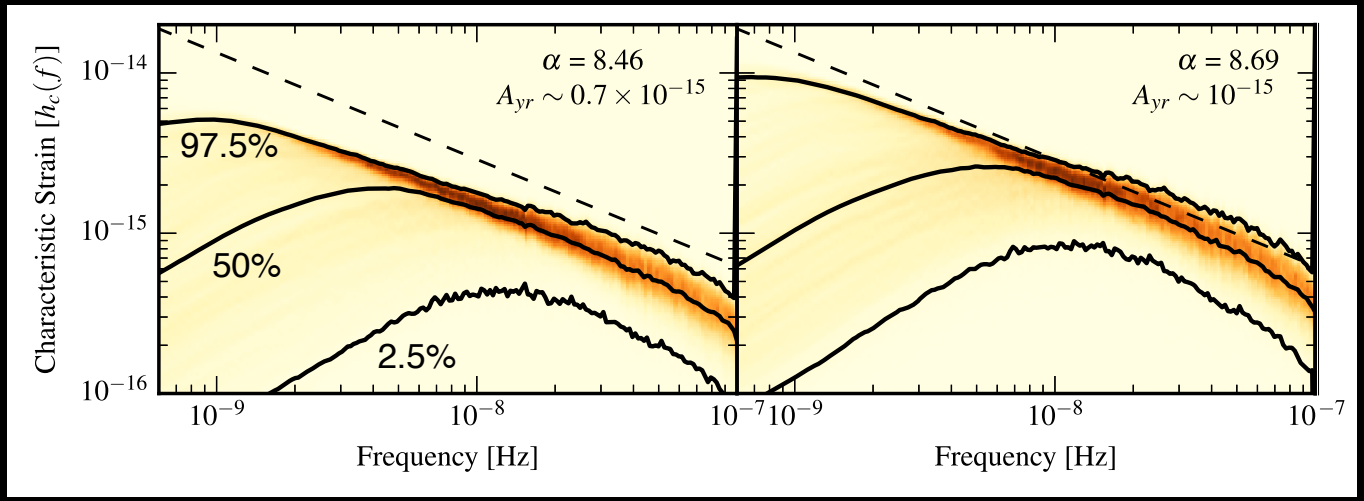
Understanding the GW Background



Taylor, Simon, & Sampson (2017)

Constraining Binary Inspiral!

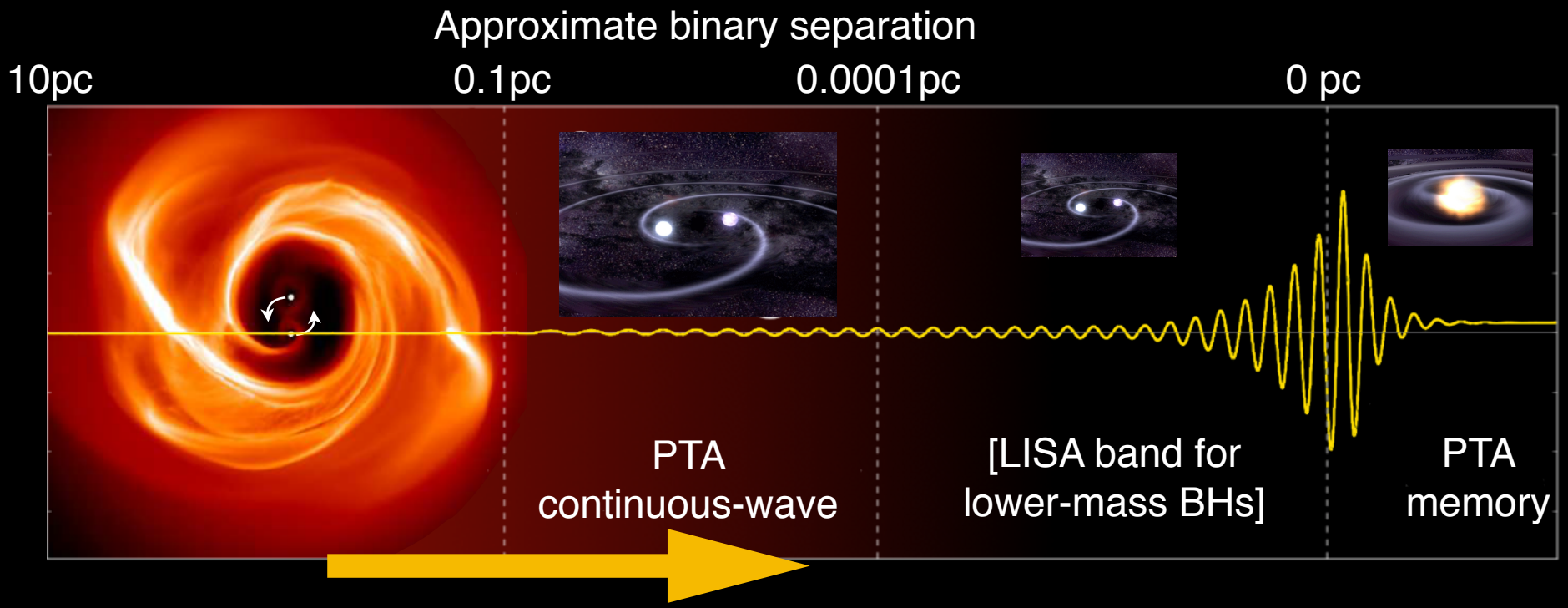
NANOGrav 11-year data set. [Arzoumanian et al. 2018, led by Steve Taylor and others]



McConnell & Ma M_{BH}-M_{bulge}

Kormendy & Ho M_{BH}-M_{bulge}

Pulsar Detection of Binary SMBHs



It appears likely that something drives efficient progression through to PTA band.

Summary

- Pulsar Timing can test AGN binary models!
  - Contact or join NANOGrav if interested.
  - http://nanograv.org
- Few MM sources can assess:
  - AGN geometries.
  - Circumbinary dynamics.
- GW Background AMPLITUDE and SLOPE will measure “last parsec” efficiency!