
WAKE FOREST
UNIVERSITY
NANOGrav
Physics Frontiers Center
ipta
2026
Multimessenger Astrophysics
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“Multi-Messenger”?

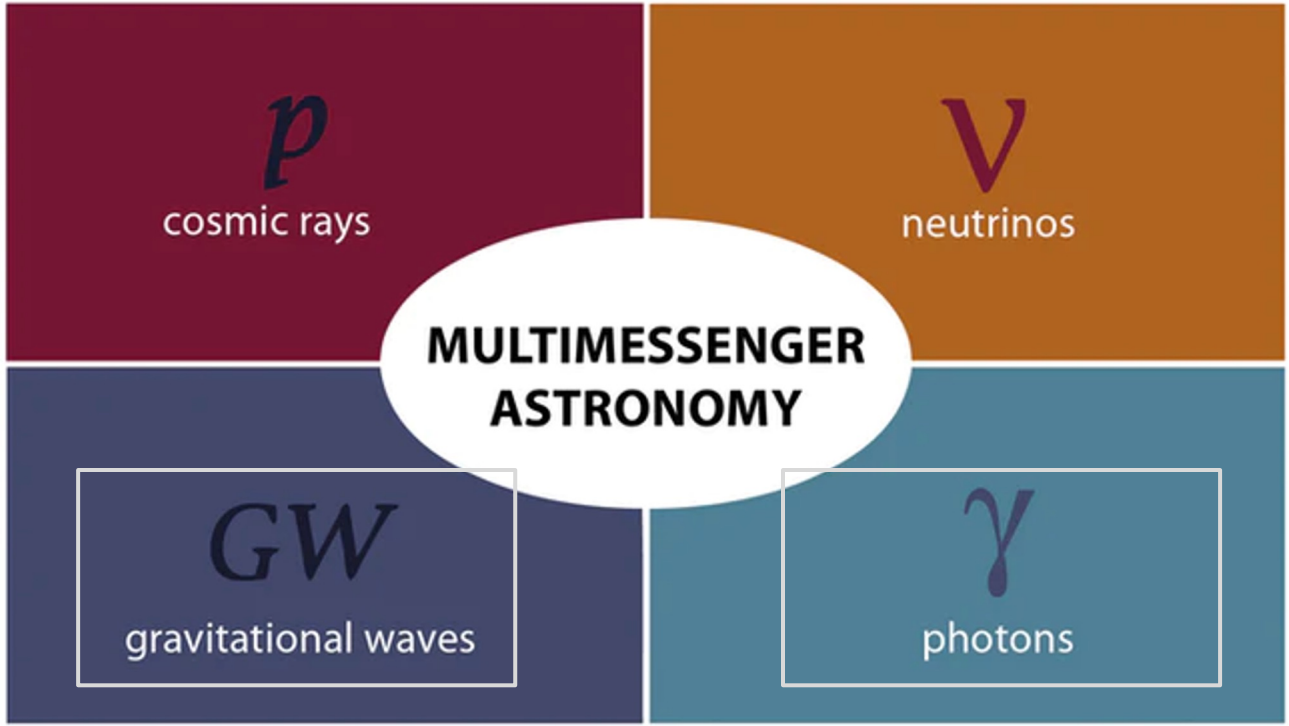
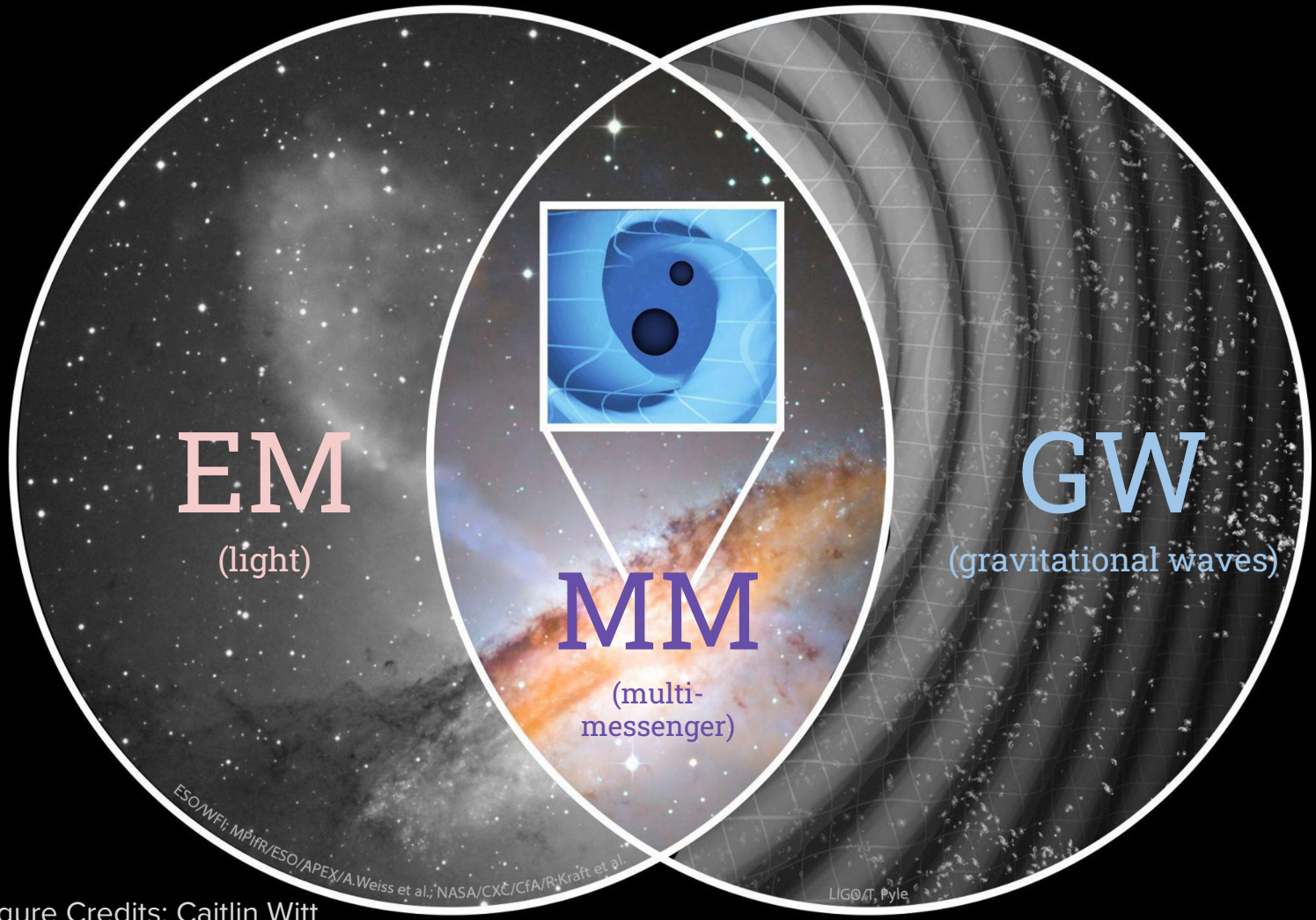
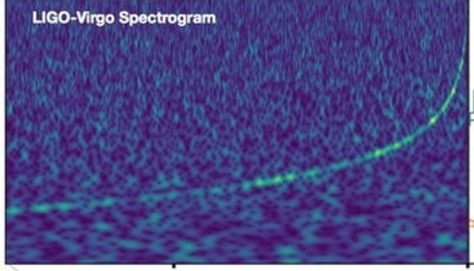
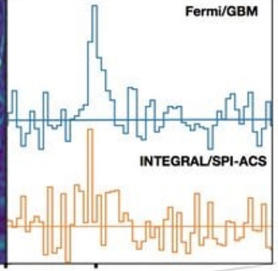


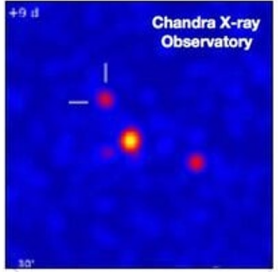
Figure Credit: IceCube Collaboration

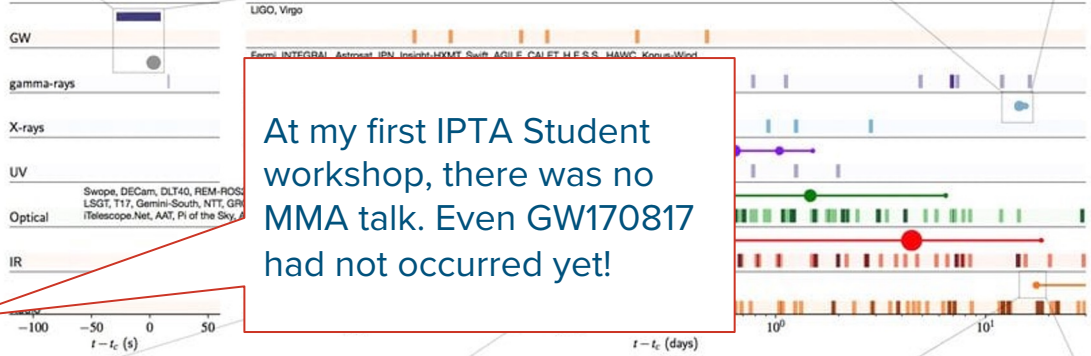


Composite Figure Credits: Caitlin Witt

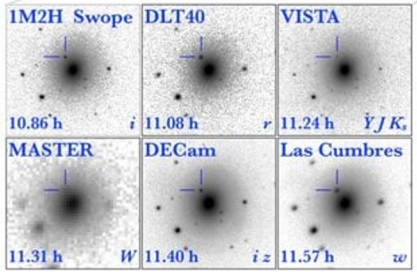


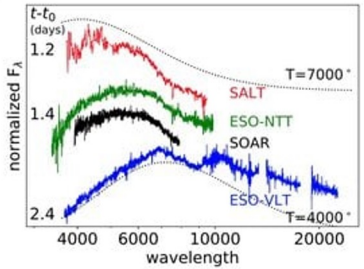


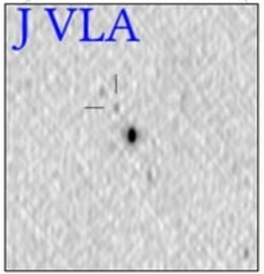


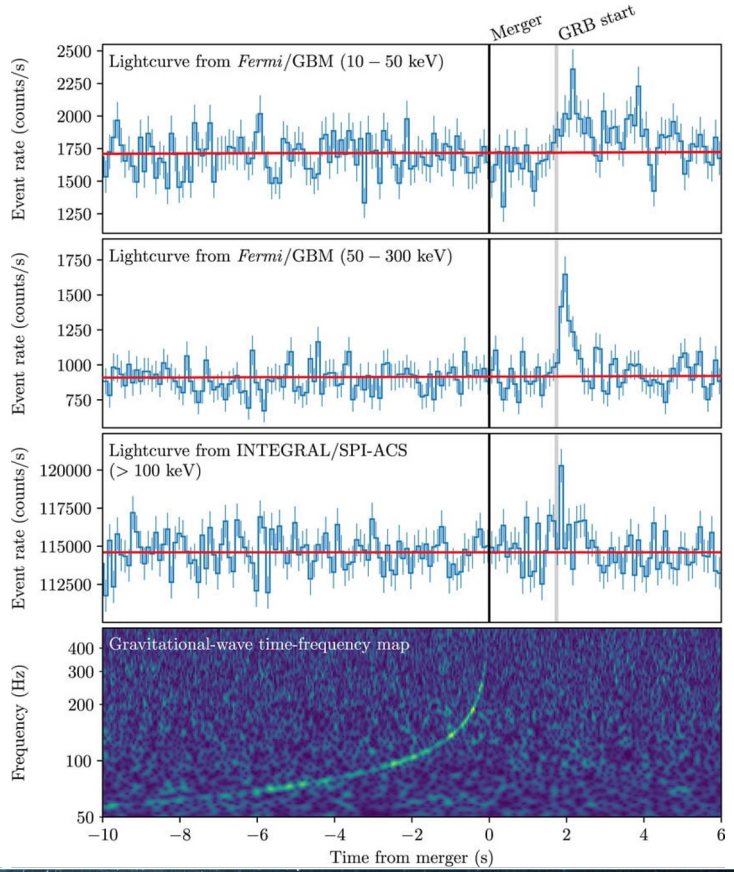


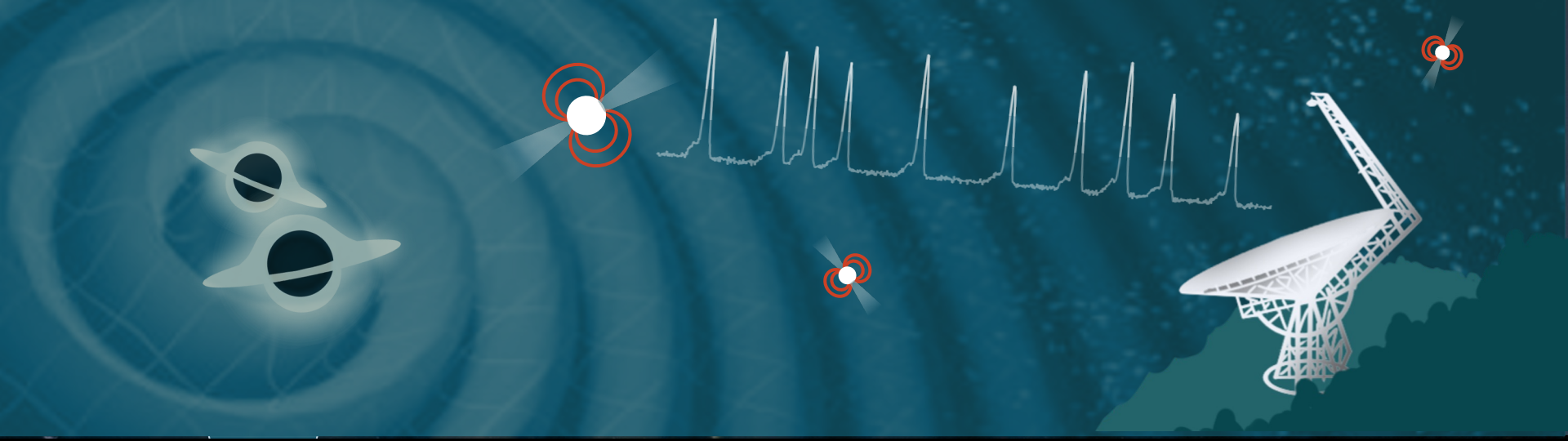
At my first IPTA Student workshop, there was no MMA talk. Even GW170817 had not occurred yet!











PTAs aim to detect GWs and study SMBHBs

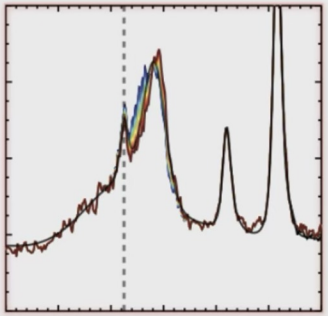
If pulsar science is a safari…

SMBHB observations are landscape photography

And MMA puts the two together to study the whole ecosystem

Multi-Messenger Astrophysics

A1



B1

A2

A3

AXIS/Athena/Lynx

VLBI/EHT

Fermi/AXIS/Athena/Lynx/TAP

JWST/WFIRST

ZTF/SDSS-V/LSST/GMT/TMT

spatial offsets

periodic variability

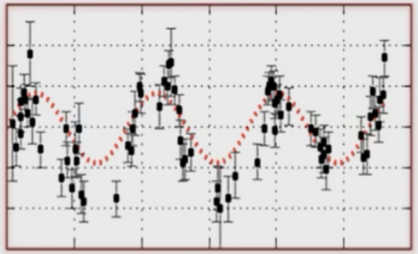
kinematic offsets

coalescence burst

stellar cores / TDE rates & light-curves

spectroscopic disk features

A4

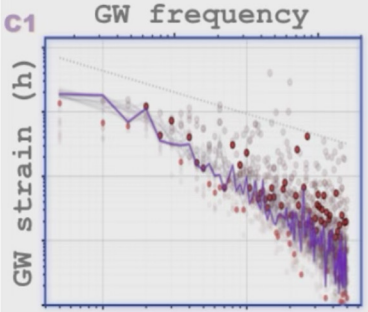


B2

separation (pc)

10^4 10^2 1 10^{-3}

C1



orbital parameters

scattering efficiency

eccentricity distributions

galaxy merger rates

gas coupling

M-sigma

differential growth / merger-triggered accretion

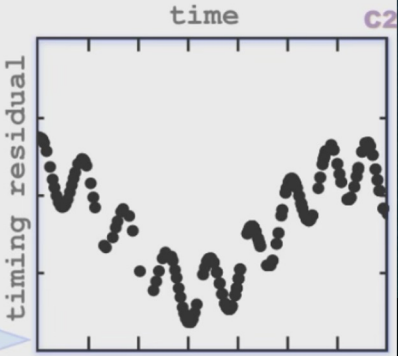
spins

frequency (nHz) 1 10 100

GWB

bursts

CGW



C2

Figure Credit: Kelley+ 2019

There are many ways to observe evidence of SMBHB with EM data

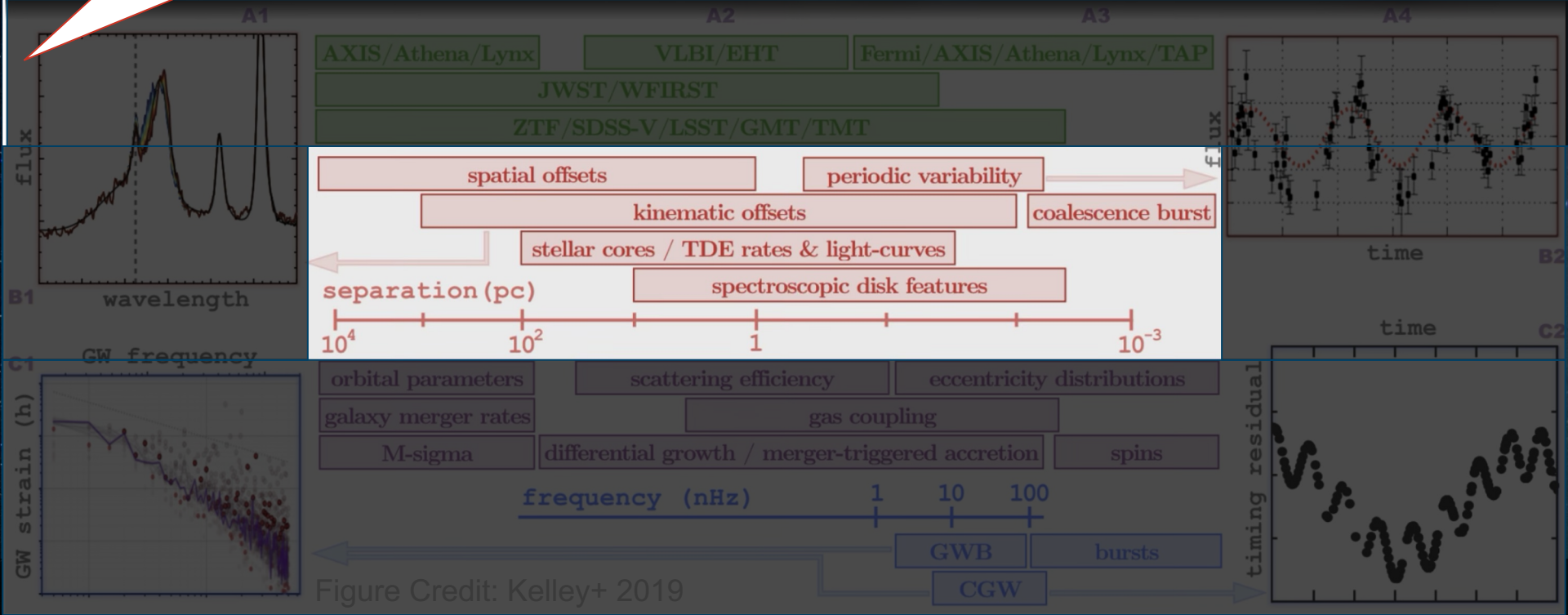


Figure Credit: Kelley+ 2019

A few overlap well with the frequencies we can observe with PTAs

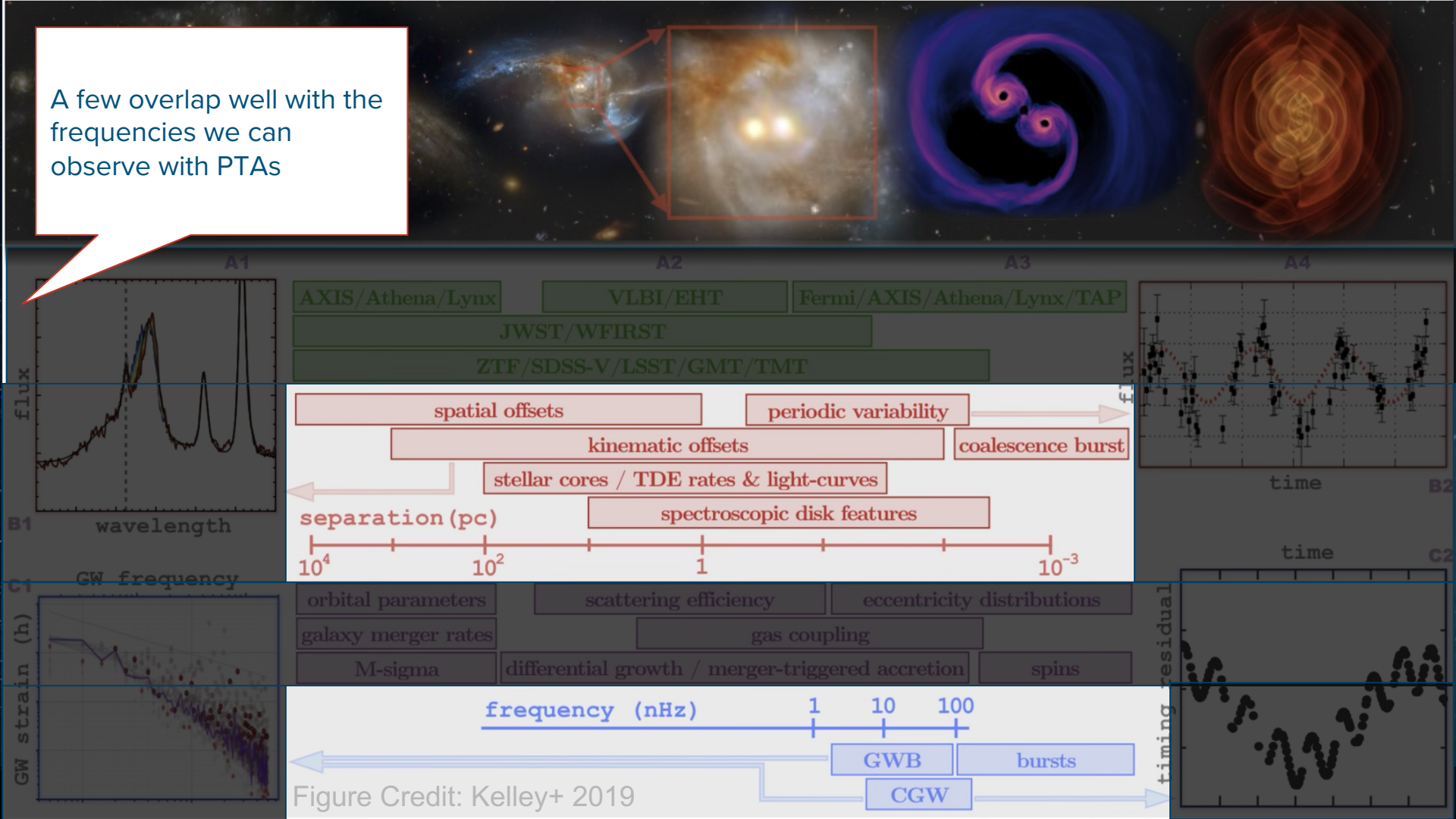
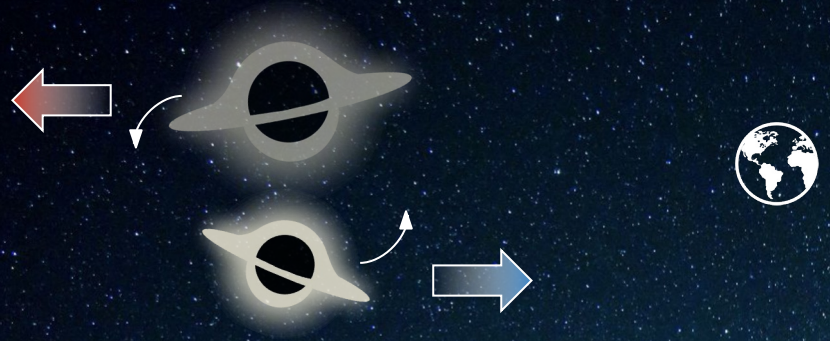


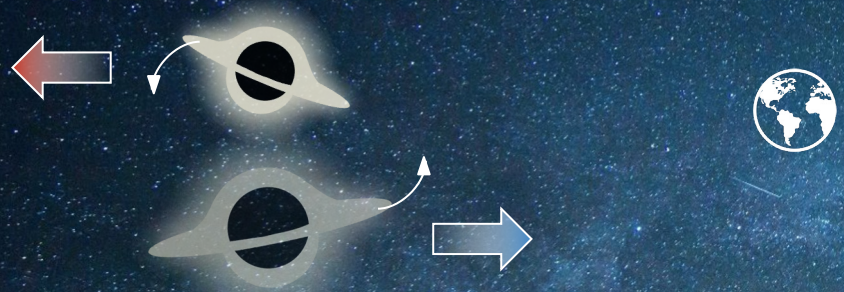
Figure Credit: Kelley+ 2019

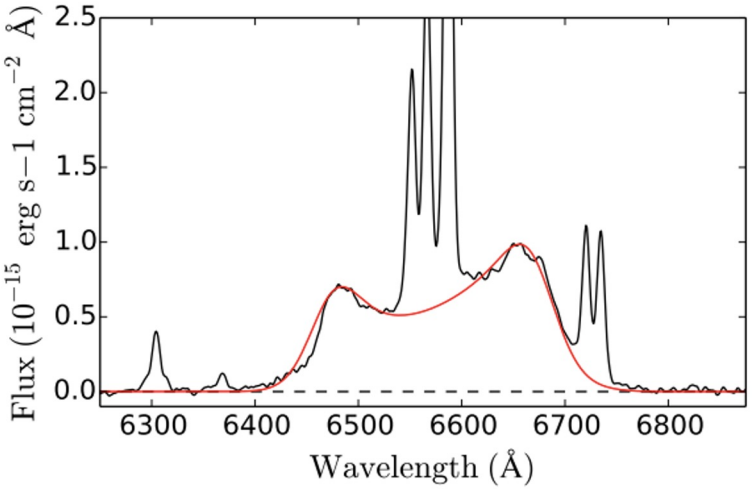
Double Broad Lines

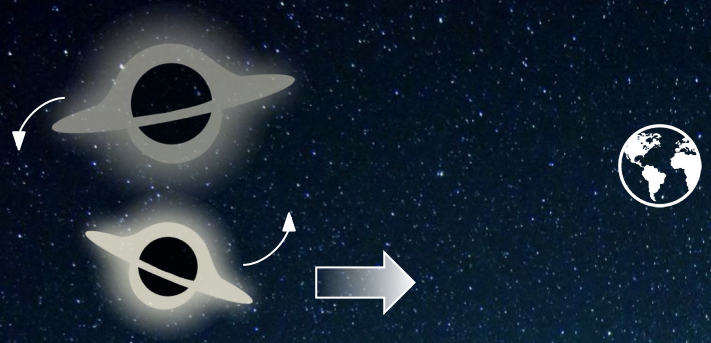
As SMBHs orbit, spectrum evolves over time



Broad line regions red- and blue-shift periodically







Light gets brighter or dimmer from relativistic orbital motion of SMBHs

Periodic Doppler Boost

Over time, this creates a periodic change in the brightness of the quasar

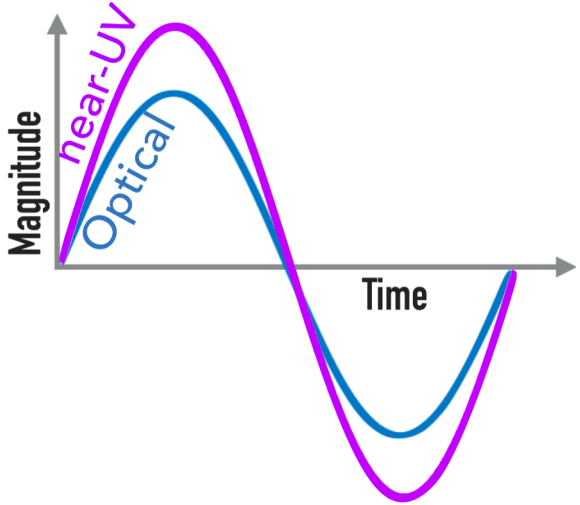
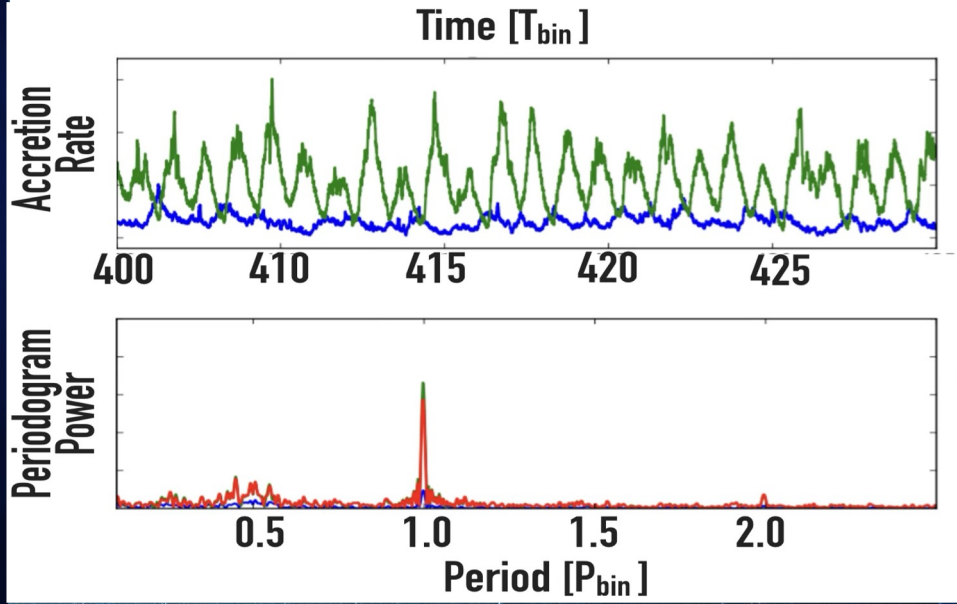


Figure Credit: Maria Charisi

Periodic Accretion



Periodic Self Lensing

As BHs align on line-of-sight, one binary lenses the other and magnifies it's brightness

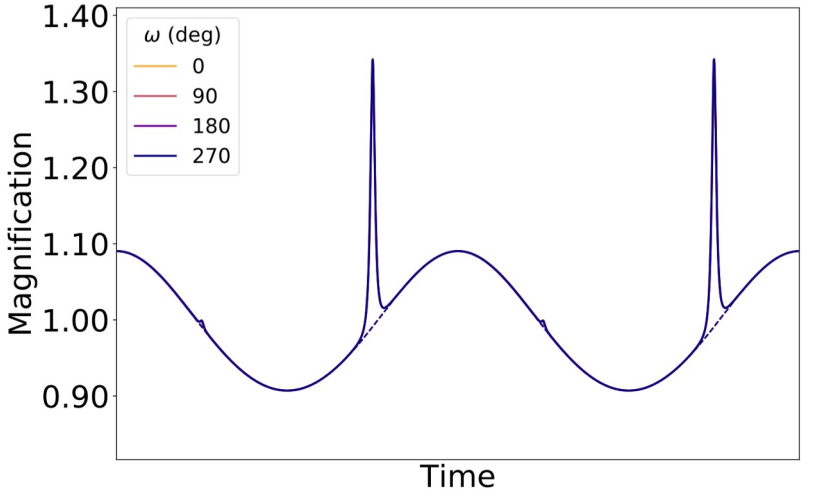
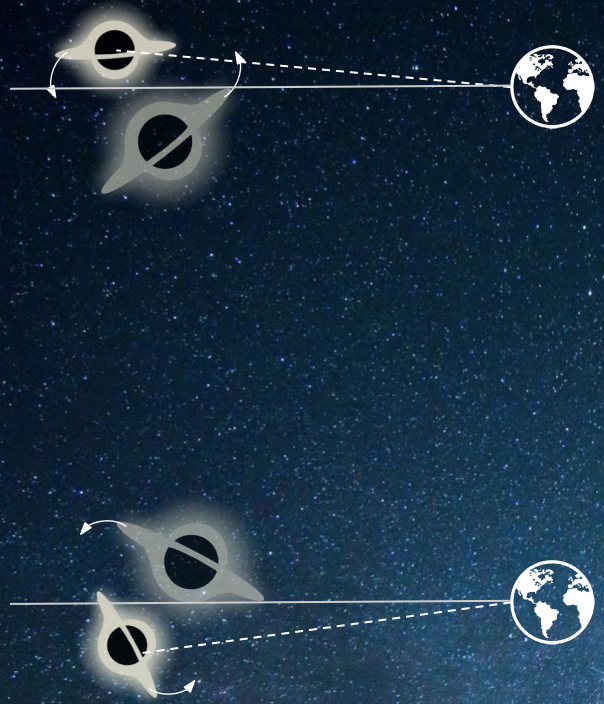
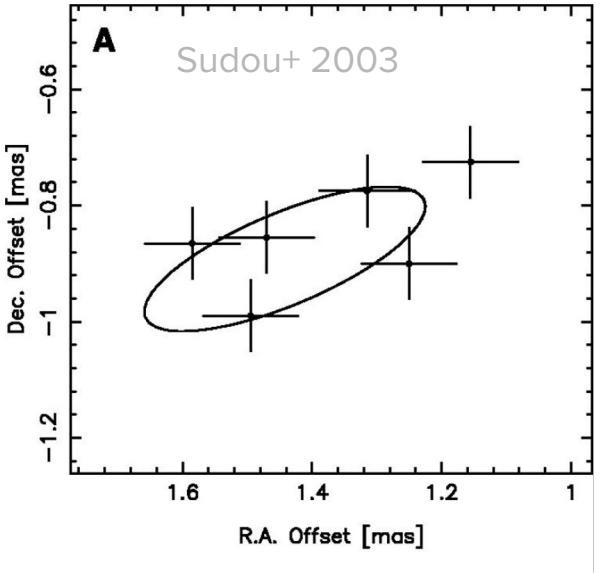
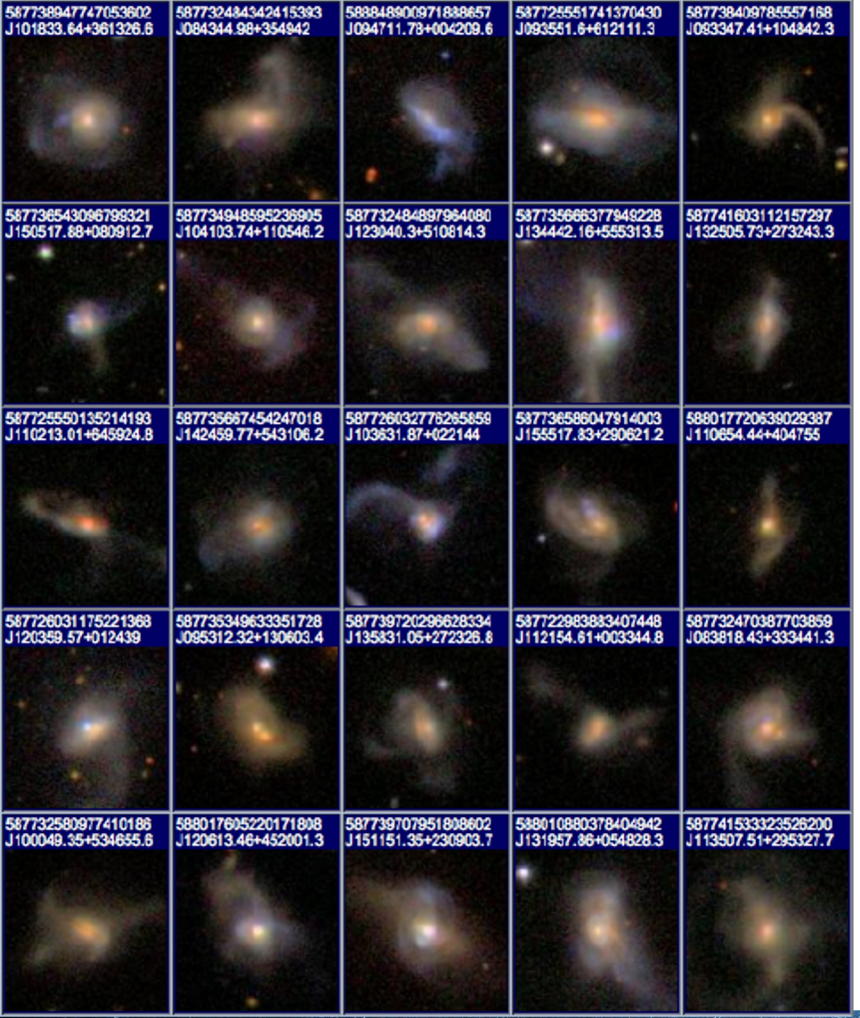


Figure Credit: Hu+ 2020

Variable Position



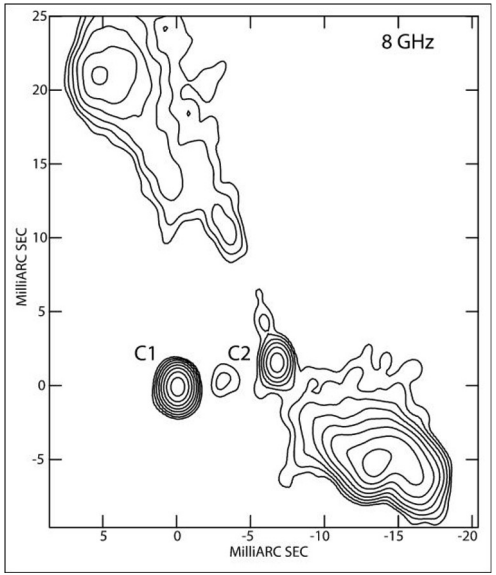




Evidence of past mergers

These methods do NOT indicate orbital frequency

Spatial Offsets



Many signatures can easily be replicated by noise

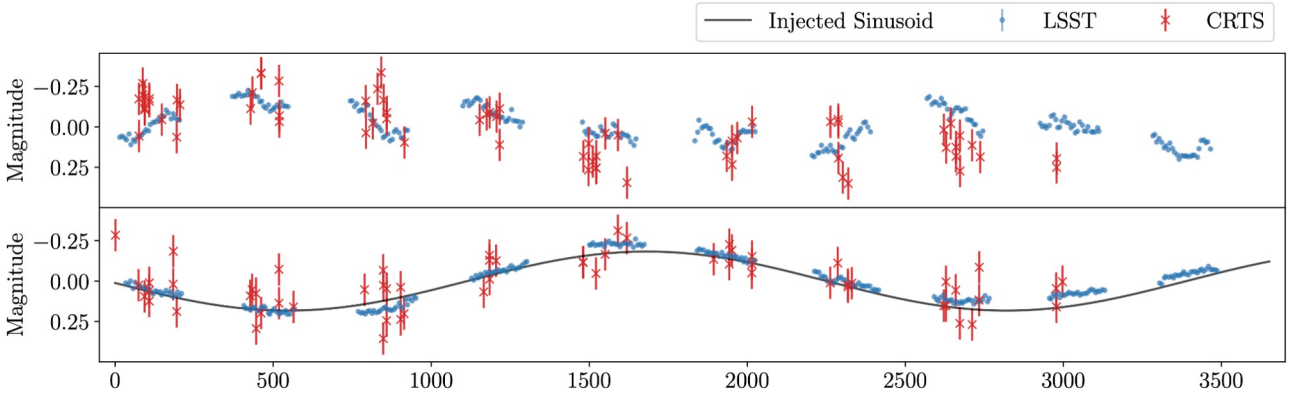
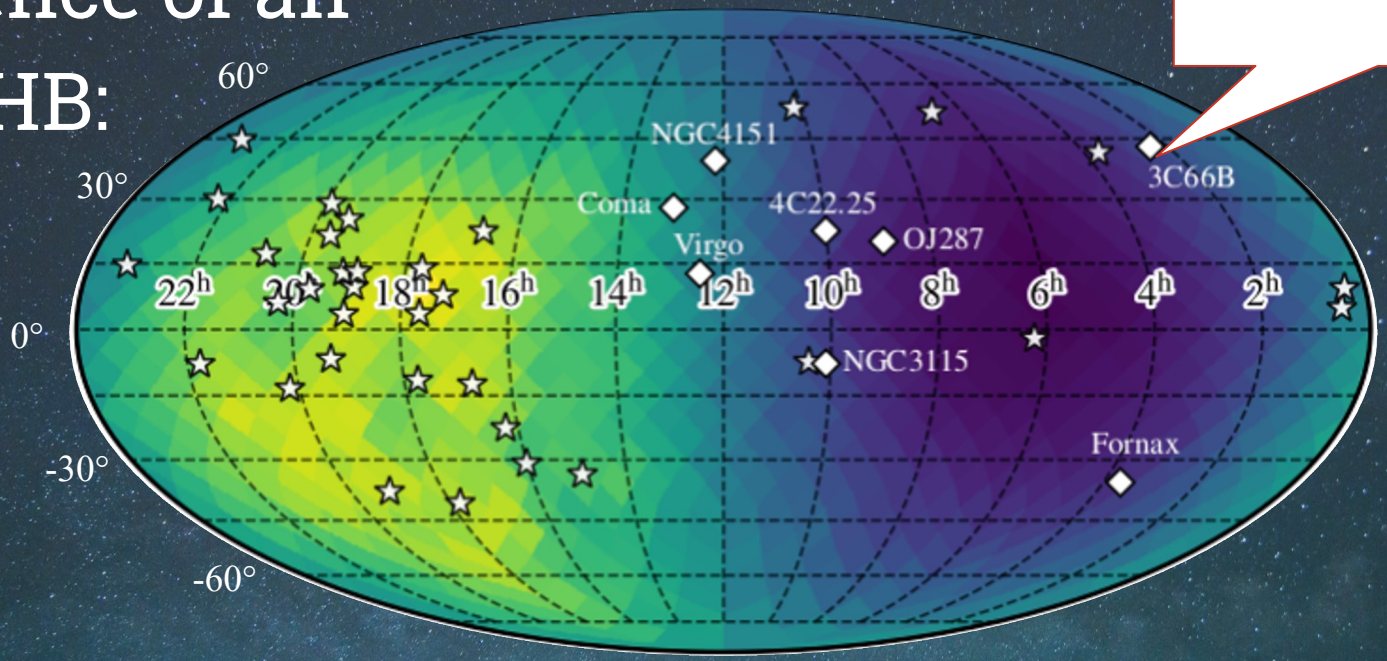


Figure credit: Witt+ 2022

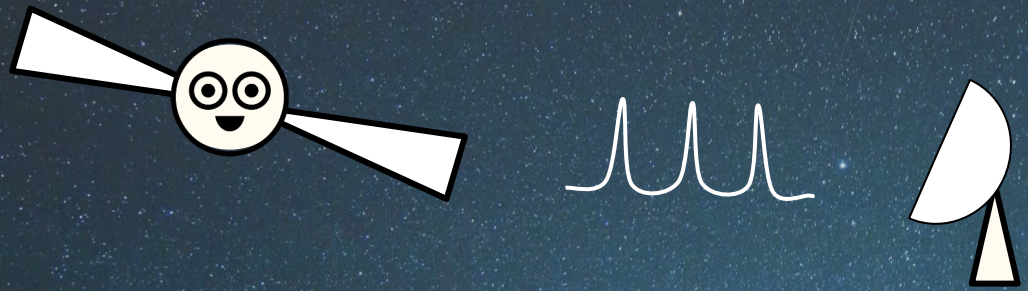
If we see evidence of an SMBHB:



Look at me!

We might want to look for a CW

How PTAs work:



Searching
Search for new pulsars

Timing
Observe and time pulsars, make dataset

Noise budget
Characterize noise, ISM mitigation

Detection
Run and develop new detection analyses

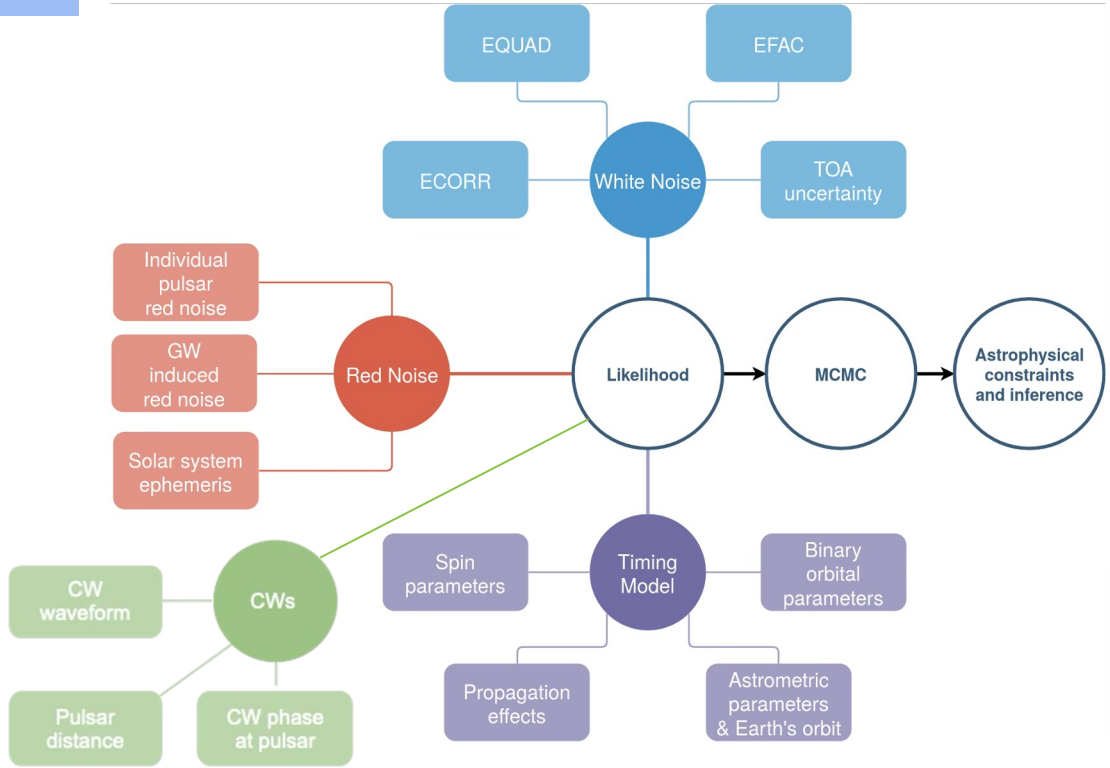
Astrophysics
Interpret GW limits, GW sources

Slide by Megan Jones

Detection

Run and develop new detection analyses

=



In reality, things are more complicated

Can we make anything simpler?

Graphic by Nihan Pol

Multi-messenger astrophysics with PTAs

If some of the GW parameters are constrained, it could be easier to detect the signals

$$\{\theta, \phi, f_{\rm gw}, \Phi_0, \psi, i, \mathcal{M}, d_{\rm L}, h_0\}$$

$$h_0 = \frac{2\mathcal{M}^{5/3}\left(\pi \mathrm{f}_{\rm gw}\right)^{2/3}}{d_L}$$

If we see signatures, we would know:

- Galaxy coordinates
- Distance
- Frequency?
- Size?
- Inclination?

Option #1: Constrain Priors

Constant value prior for:

- Sky location
- Distance
- Frequency?

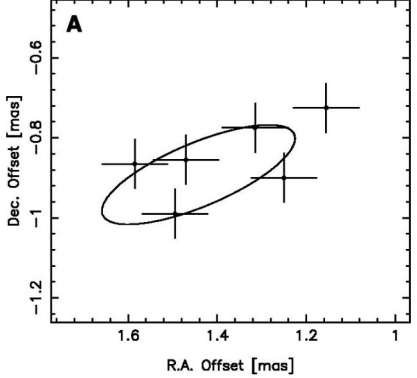
Pros:

- Simpler model → faster analysis, more sensitive
- Make statements about particular systems

Cons:

- Relies on assumptions and other observations
- Complexities with sky localization and repeated searches

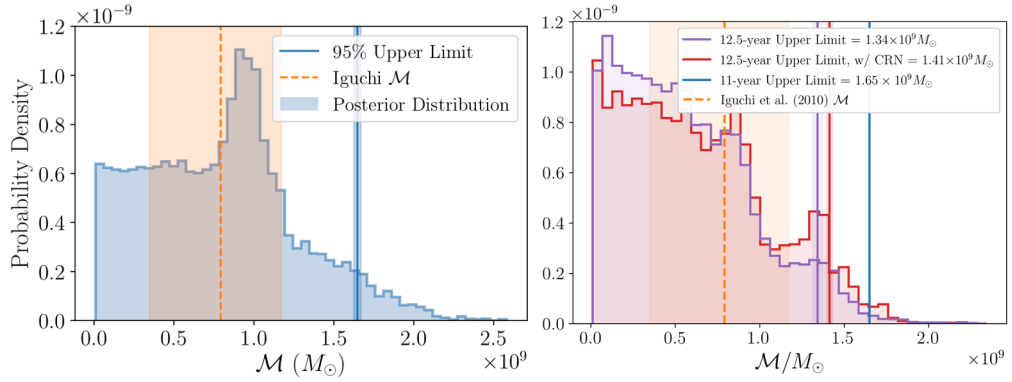
For example: 3C 66B



Classic EM SMBHB candidate with proposed GW frequency of 60.4 nHz

➔ fix sky location, distance, and frequency to constant value

No evidence found in any search



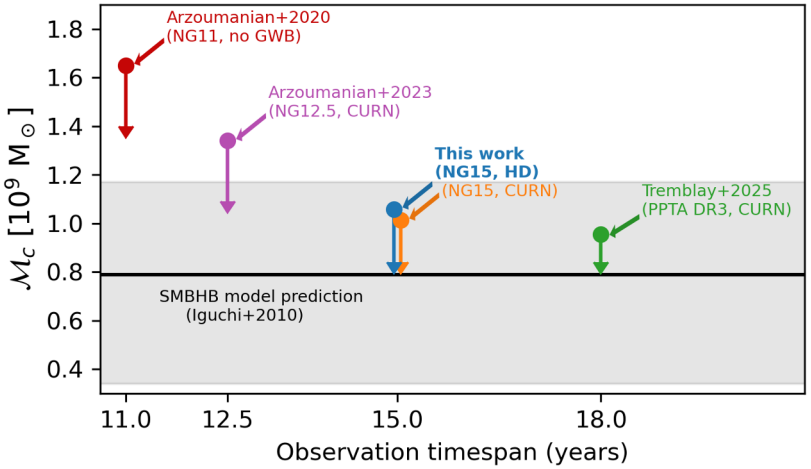


Figure Credit: Arzoumanian+ (2020b, 2023) (lead: Witt)

More sources:

Now extended to a catalog of sources for NG15

Name	RA	Dec	z	Period [days]	Freq [nHz]	$M_{\rm tot}$ [$M_\odot$]	$\mathcal{M}_{\rm c}^{95\%}$ [$M_\odot$]	$h_0^{95\%}$
MCG 5−40−026[a]	17h 01m 07.80s	+29d 24m 24.6s	0.04	1407	16.4	7.24×10^8	1.29×10^9	5.38×10^{-15}
SDSS J072908.71+400836.6	07h 29m 08.60s	+40d 08m 37.0s	0.07	1612	14.4	2.63×10^7	3.38×10^9	1.16×10^{-14}
2MASS J04352649−1643460	04h 35m 26.50s	−16d 43m 45.7s	0.10	1369	16.9	6.03×10^7	3.92×10^9	1.23×10^{-14}
PGC 3096192	12h 50m 29.00s	+06d 36m 11.1s	0.13	1561	14.8	1.15×10^7	3.55×10^9	6.85×10^{-15}
SDSS J110554.78+322953.7	11h 05m 54.80s	+32d 29m 54.1s	0.15	1724	13.4	1.74×10^8	4.52×10^9	8.38×10^{-15}
HS 0423+0658	04h 26m 30.20s	+07d 05m 30.3s	0.17	1123	20.6	–	4.01×10^9	8.00×10^{-15}
HS 2219+1944	22h 22m 21.10s	+19d 59m 48.1s	0.21	1724	13.4	–	3.87×10^9	4.46×10^{-15}
SDSS J121018.34+015405.9	12h 10m 18.30s	+01d 5m 06.2s	0.22	1612	14.4	3.47×10^8	4.12×10^9	5.05×10^{-15}
SNU J13120+0641	13h 12m 04.70s	+06d 41m 07.6s	0.24	1492	15.5	1.38×10^9	6.54×10^9	1.01×10^{-14}
SDSS J161013.67+311756.4	16h 10m 13.70s	+31d 17m 56.s	0.25	1724	13.4	8.23×10^7	1.82×10^9	1.07×10^{-15}
CT 638	03h 18m 06.50s	−34d 26m 37.4s	0.27	1514	15.3	–	9.57×10^9	1.70×10^{-14}
RXS J04117+1324	04h 11m 46.90s	+13d 24m 16.5s	0.28	1850	12.5	1.45×10^8	2.95×10^9	1.99×10^{-15}
BZQJ1305−1033	13h 05m 33.00s	−10d 33m 19.1s	0.29	1693	13.7	3.16×10^8	5.25×10^9	5.30×10^{-15}
SDSS J123821.84+030024.2	12h 38m 21.80s	+03d 00m 24.6s	0.38	1249	18.5	8.32×10^8	6.58×10^9	6.79×10^{-15}
SDSS J153636.22+044127.0	15h 36m 36.20s	+04d 41m 26.9s	0.38	1110	20.8	6.61×10^8	6.33×10^9	6.92×10^{-15}
SDSS J135225.80+132853.2	13h 52m 25.80s	+13d 28m 53.3s	0.40	1754	13.2	5.62×10^8	6.07×10^9	4.44×10^{-15}
KUV 09484+3557	09h 51m 23.90s	+35d 42m 49.2s	0.40	1162	19.9	2.04×10^8	3.83×10^9	2.74×10^{-15}
SDSS J141425.92+171811.2	14h 14m 25.90s	+17d 18m 11.6s	0.41	1785	13.0	3.89×10^8	2.50×10^9	9.77×10^{-16}
SDSS J133631.45+175613.8	13h 36m 31.40s	+17d 56m 14.1s	0.42	1561	14.8	1.07×10^9	8.73×10^9	8.31×10^{-15}
SDSS J224829.47+144418.0	22h 48m 29.40s	+14d 44m 18.4s	0.42	1218	19.0	7.24×10^8	3.52×10^9	2.14×10^{-15}
RXS J10304+5516	10h 30m 25.0s	+55d 16m 23.4s	0.44	1514	15.3	2.69×10^8	1.07×10^{10}	1.14×10^{-14}
SDSS J140600.26+013252.2	14h 06m 00.30s	+01d 32m 52.4s	0.45	1999	11.6	2.57×10^8	8.63×10^9	6.32×10^{-15}
SDSS J094715.56+631716.4	09h 47m 15.60s	+63d 17m 17.3s	0.49	1724	13.4	1.66×10^9	8.46×10^9	6.20×10^{-15}
SDSS J114749.70+163106.7	11h 47m 49.70s	+16d 31m 06.8s	0.55	1449	16.0	1.66×10^8	1.32×10^{10}	1.25×10^{-14}
SDSS J084146.19+503601.1	08h 41m 46.30s	+50d 36m 00.5s	0.56	1693	13.7	2.75×10^7	1.21×10^{10}	9.71×10^{-15}
MS 10548−0335	10h 57m 22.30s	−03d 51m 31.3s	0.56	892	26.0	–	1.02×10^{10}	1.12×10^{-14}
SDSS J161854.64+230859.1	16h 18m 54.60s	+23d 08m 59.3s	0.56	1666	13.9	2.34×10^8	7.33×10^9	4.21×10^{-15}
SDSS J144754.62+132610.0	14h 47m 54.60s	+13d 26m 10.4s	0.57	1960	11.8	3.8×10^8	9.66×10^9	5.85×10^{-15}
6QZ J221925.1−305408	22h 19m 25.20s	−30d 54m 08.1s	0.58	1407	16.4	–	8.42×10^9	5.71×10^{-15}
HS 0946+4845	09h 50m 00.70s	+48d 31m 29.9s	0.59	1586	14.6	3.89×10^8	1.38×10^{10}	1.18×10^{-14}
HS 1715+2131	17h 17m 20.10s	+21d 28m 15.0s	0.59	1249	18.5	–	7.94×10^9	5.48×10^{-15}
SDSS J134820.42+194831.5	13h 48m 20.40s	+19d 48m 31.9s	0.59	1388	16.7	4.27×10^7	8.78×10^9	6.00×10^{-15}
SDSS J143820.60+055447.9	14h 38m 20.60s	+05d 54m 48.1s	0.61	1850	12.5	1.55×10^8	9.39×10^9	5.32×10^{-15}
SDSS J125414.23+131348.1	12h 54m 14.20s	+13d 13m 48.4s	0.66	1754	13.2	8.71×10^8	9.69×10^9	5.36×10^{-15}
SDSS J144755.57+100040.0	14h 47m 55.60s	+10d 00m 40.4s	0.68	861	26.9	8.51×10^8	7.39×10^9	5.26×10^{-15}
RX J024252.3−232633	02h 42m 51.90s	−23d 26m 34.0s	0.68	1817	12.7	–	1.08×10^{10}	6.02×10^{-15}
SDSS J082716.85+490534.0	08h 27m 16.90s	+49d 05m 34.9s	0.68	1612	14.4	9.12×10^8	1.61×10^{10}	1.25×10^{-14}
SDSS J132103.41+123748.2	13h 21m 03.40s	+12d 37m 48.1s	0.69	1538	15.1	8.13×10^8	1.31×10^{10}	9.11×10^{-15}
SBS 0920+590	09h 23m 58.70	+58d 49m 06.3s	0.71	648	35.7	5.75×10^8	1.74×10^{10}	2.50×10^{-14}
SDSS J221016.97+122213.9	22h 10m 17.00s	+12d 22m 14.0s	0.72	1333	17.4	1.00×10^9	7.90×10^9	4.10×10^{-15}
SDSS J124044.49+231045.8	12h 40m 44.50s	+23d 10m 46.1s	0.72	1428	16.2	8.71×10^8	1.41×10^{10}	1.02×10^{-14}
UM 234	00h 23m 03.20s	+01d 15m 33.9s	0.73	1817	12.7	1.55×10^9	1.30×10^{10}	7.47×10^{-15}
SDSS J152157.02+181018.6	15h 21m 57.00s	+18d 10m 19.2s	0.73	1960	11.8	8.91×10^7	1.17×10^{10}	5.94×10^{-15}
163107.34+560905.3	16h 31m 07.40s	+56d 09m 05.1s	0.73	1724	13.4	2.40×10^8	9.08×10^9	4.26×10^{-15}

[a]EM mass from Pal et al. (2024)

Table 6. Electromagnetic and GW-constrained upper limits on chirp mass and strain amplitude for candidate SMBHBs. EM-derived total masses are reported when available in Graham et al. (2015), except when indicated otherwise.

Figure Credit: Agarwal+ 2026 (leads including Bjorn and Forrest)

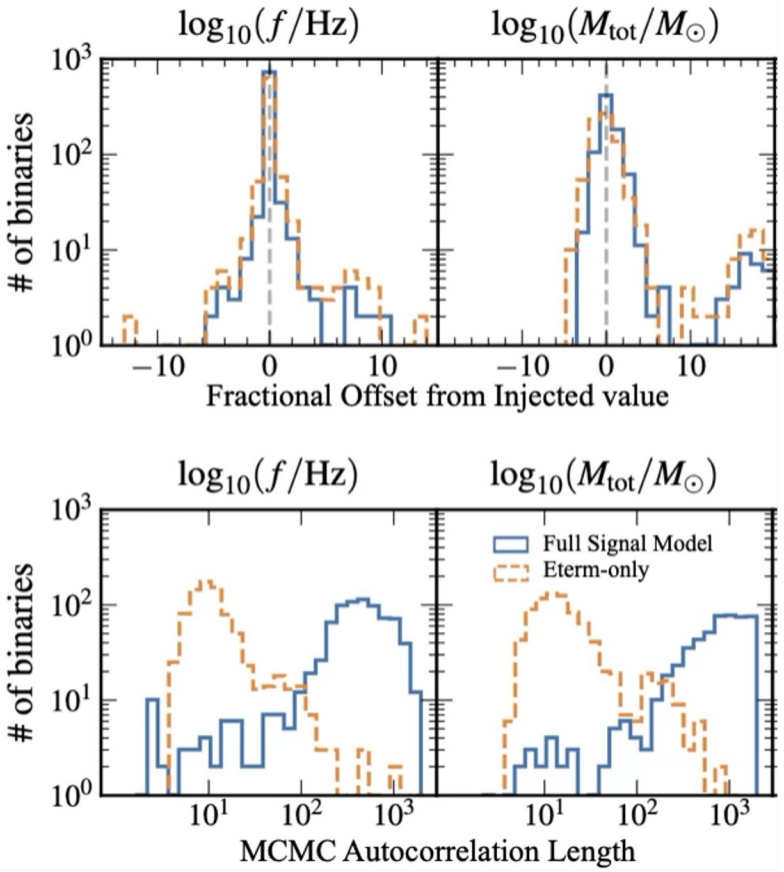
Further Simplifications

Multi-messenger modeling allows simplifications to the GW signal model

$$\Delta s_{+,\times}(t) = s_{+,\times}(t_p) - s_{+,\times}(t)$$

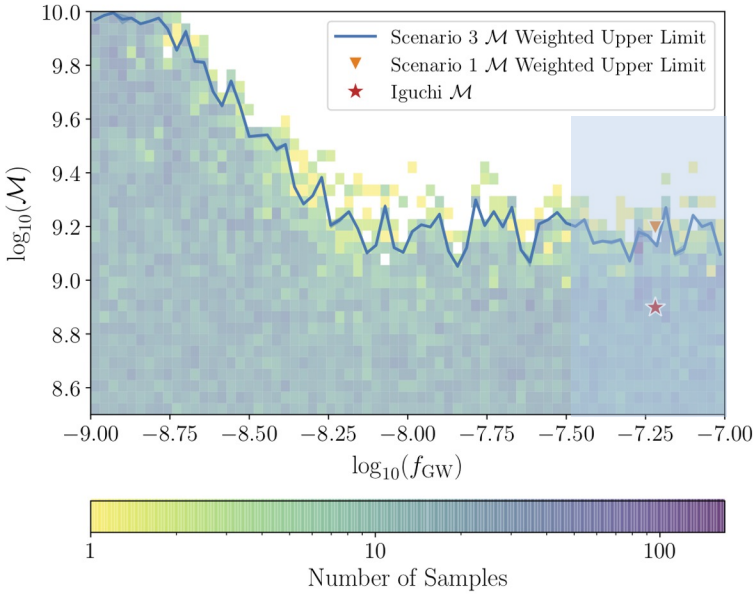
- Allows significantly faster analyses
- Critical expansion in advance of next-generation time-domain surveys

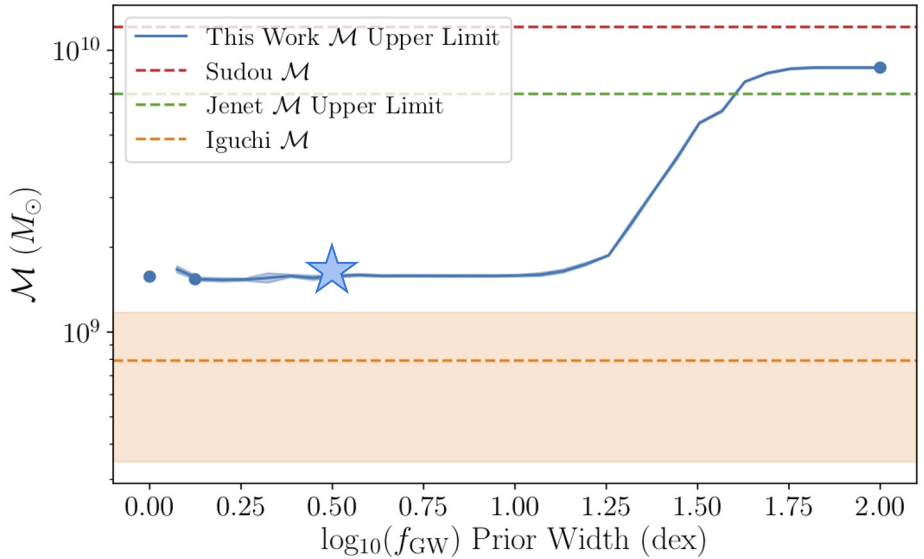
Figure Credit: Charisi+2024, inc CAW



A few variations:

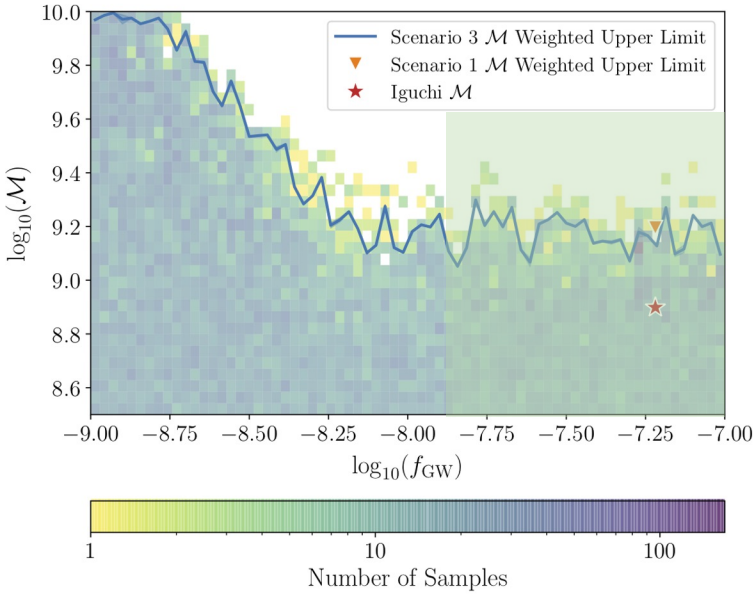
What if we don't know a parameter exactly? We can give it a constrained, but not constant, prior

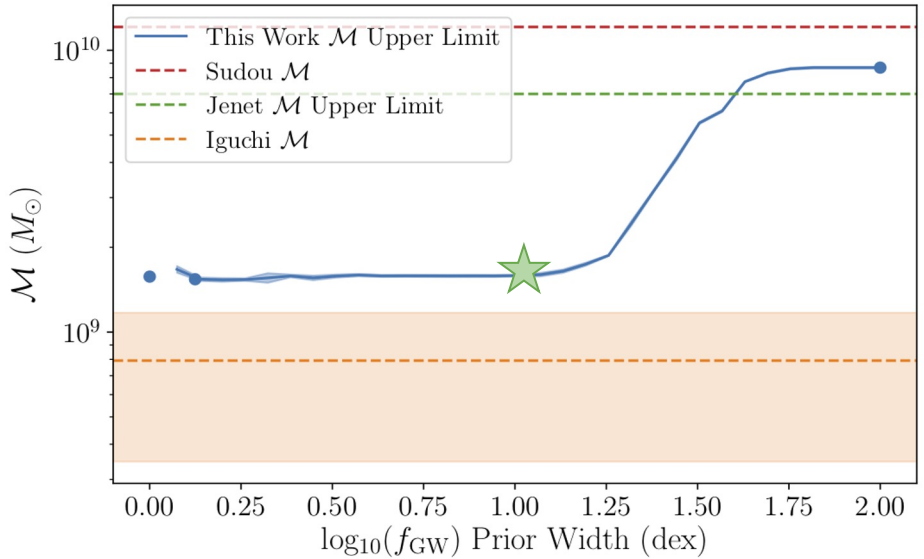




A few variations:

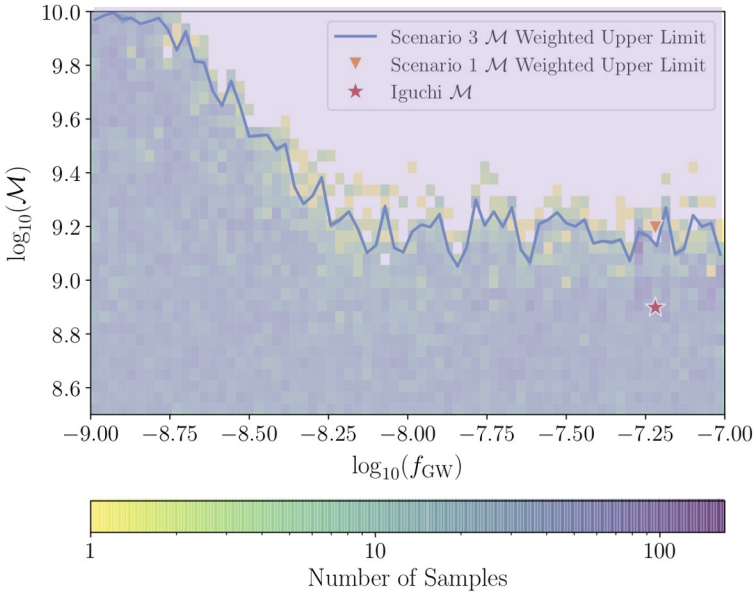
What if we don't know a parameter exactly? We can give it a constrained, but not constant, prior

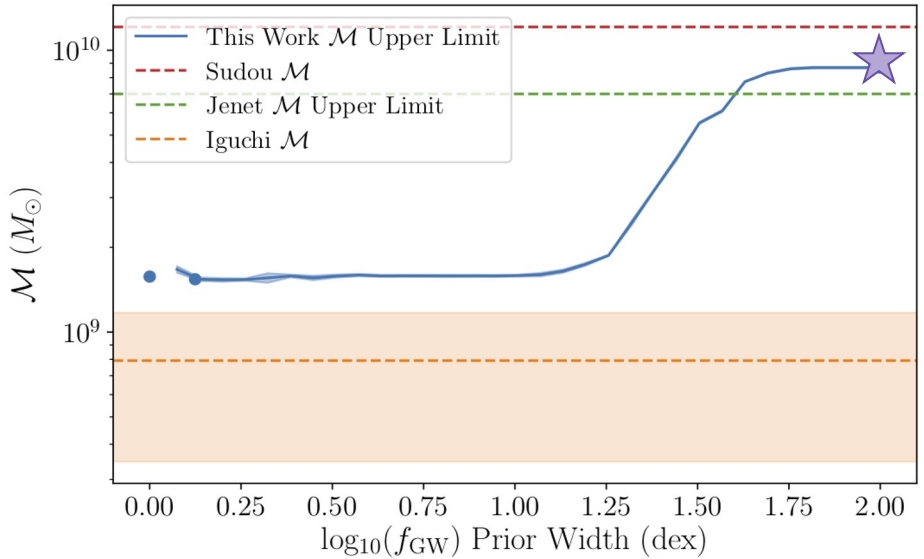




A few variations:

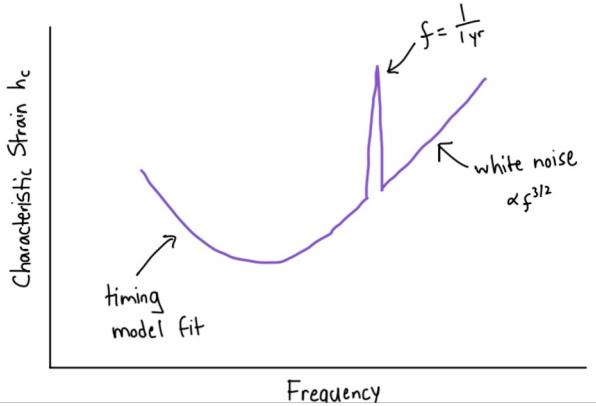
What if we don't know a parameter exactly? We can give it a constrained, but not constant, prior





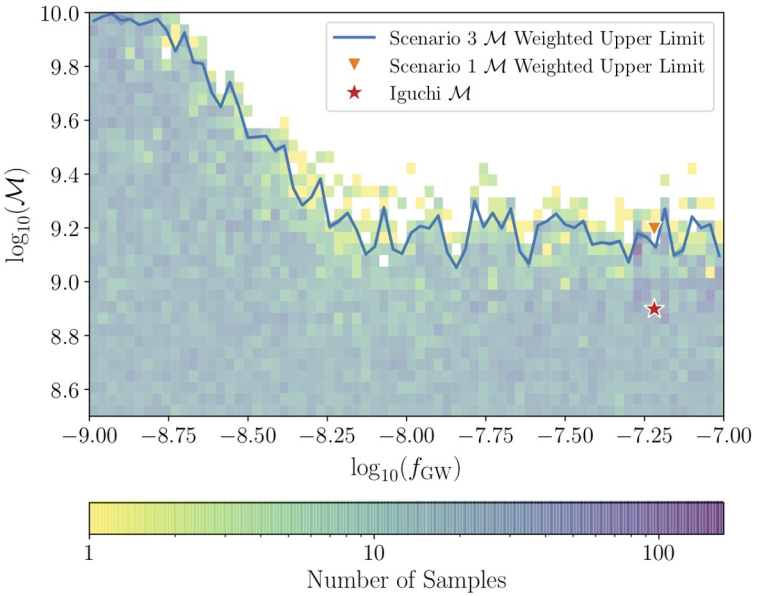
One more bonus

From Sarah's lecture on GWs:

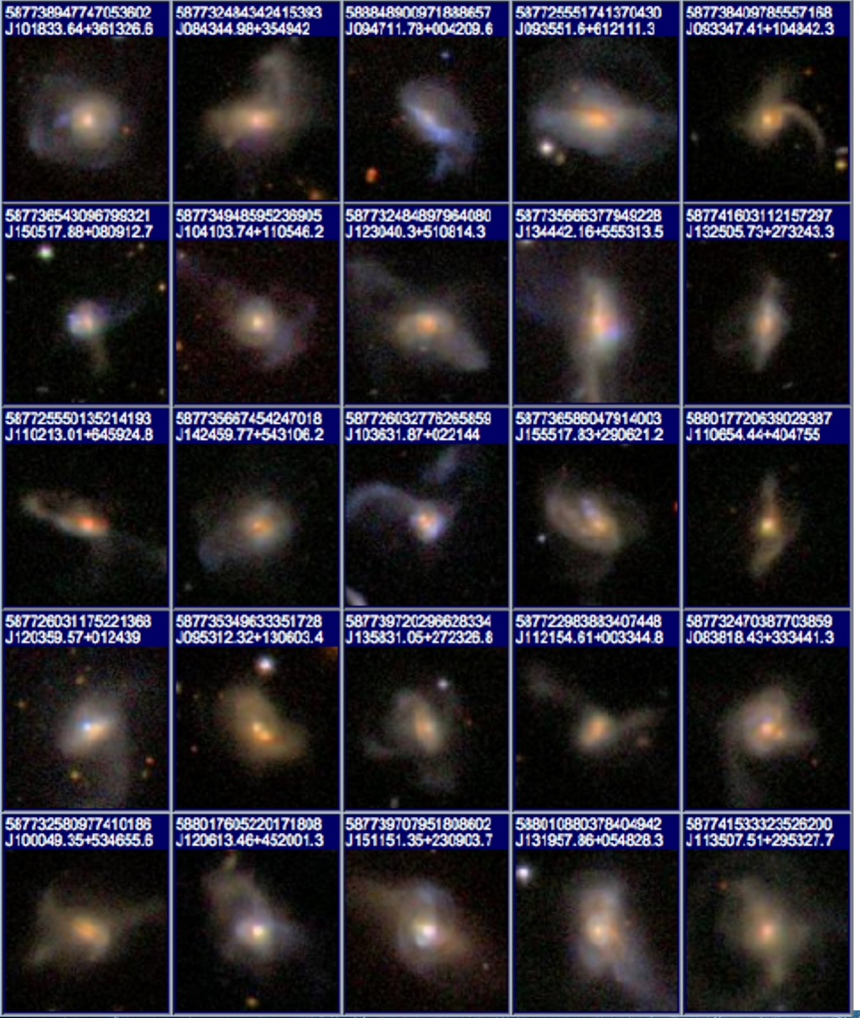


For white noise, $S_r(f) \sim f^0 \Rightarrow h_c(f) \sim f^{3/2}$.

$$h_0 = \frac{2\mathcal{M}^{5/3}\left(\pi f_{\mathrm{gw}}\right)^{2/3}}{d_L}$$



Scalings (and sensitivity) transform when searching directly in chirp mass

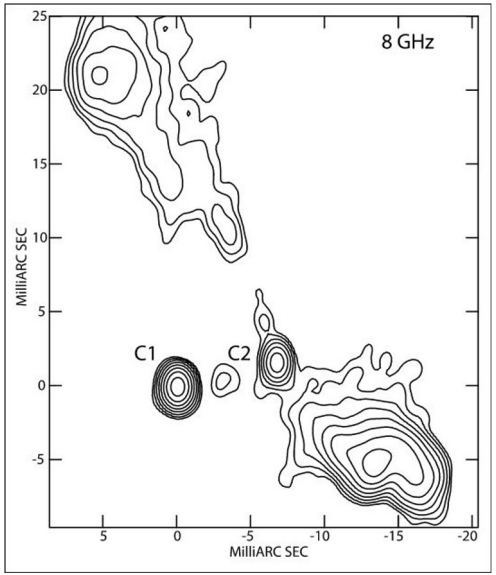


Evidence of past mergers

These methods do NOT indicate orbital frequency

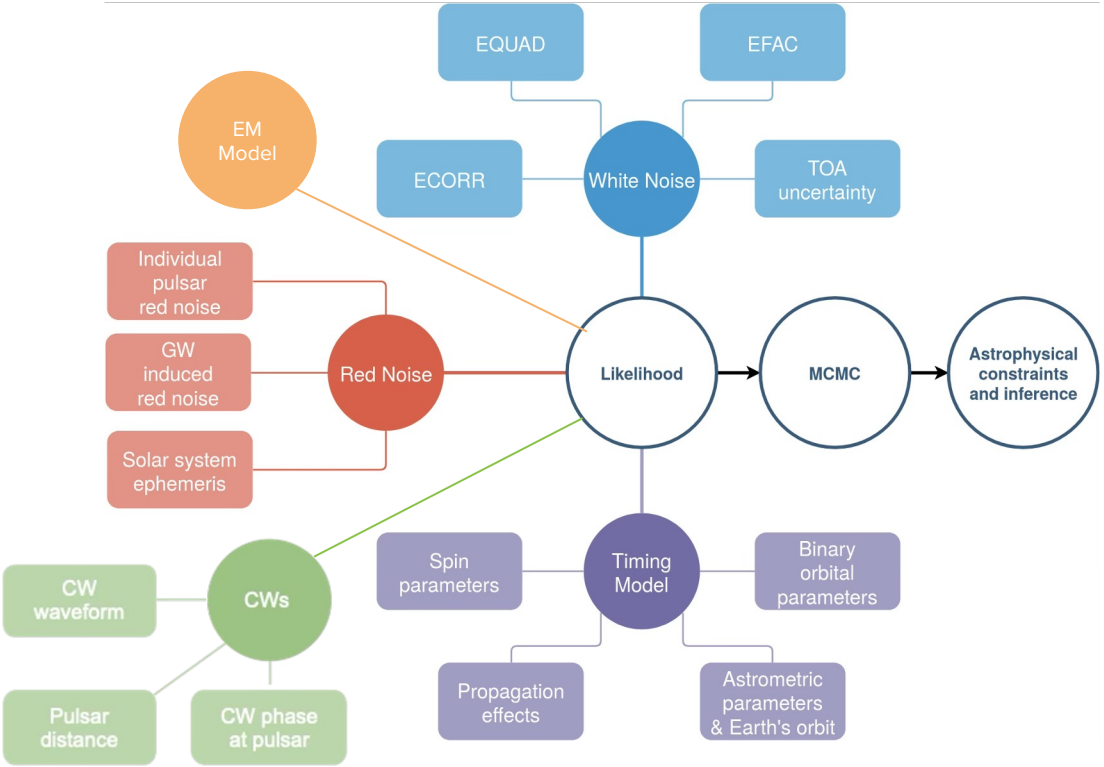
Useful for sources like these!

Spatial Offsets

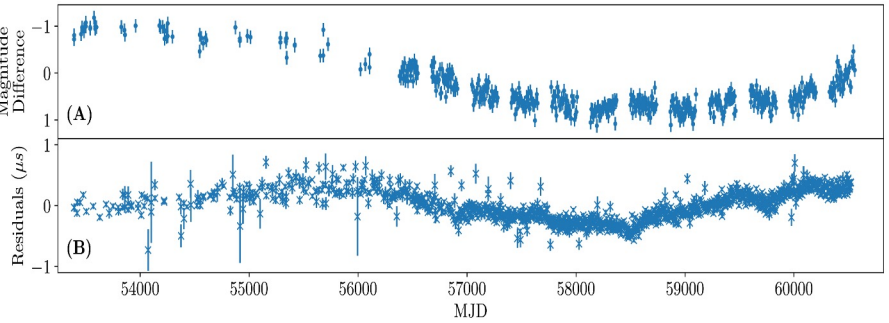


Option #2: Joint Analysis

Adapt your likelihood to accept PTA and EM data at once



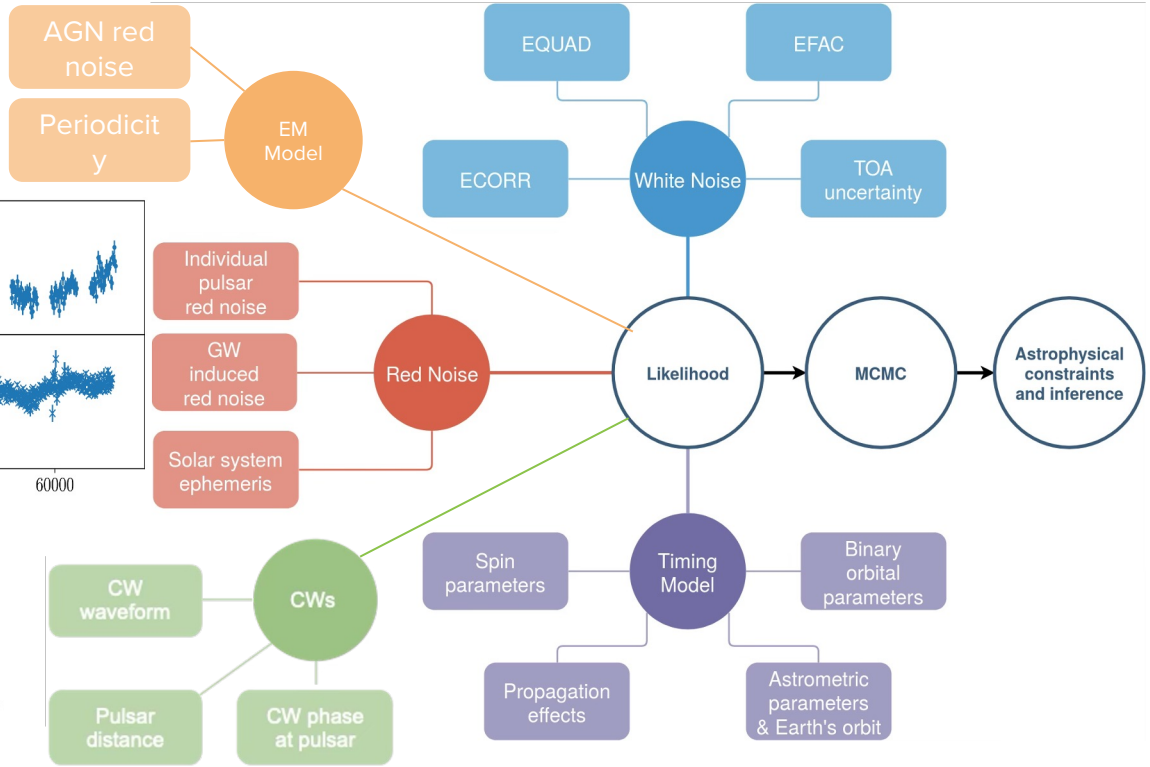
For example: Periodic Quasars



$$\mathcal{L}_{\rm MMA} = \mathcal{L}_{\rm PTA}\mathcal{L}_{\rm EM},$$

or more specifically,

$$\ln p(d_{\rm MMA}|\vec{\theta}_{\rm MMA}) = \ln p(d_{\rm PTA}|\vec{\theta}_{\rm PTA}) + \ln p(d_{\rm EM}|\vec{\theta}_{\rm EM}),$$



For example: Periodic Quasars

Pros:

- Related parameters help constrain each other (ex: period)

Cons:

- More complex model → slower
- Relies on assuming an EM model

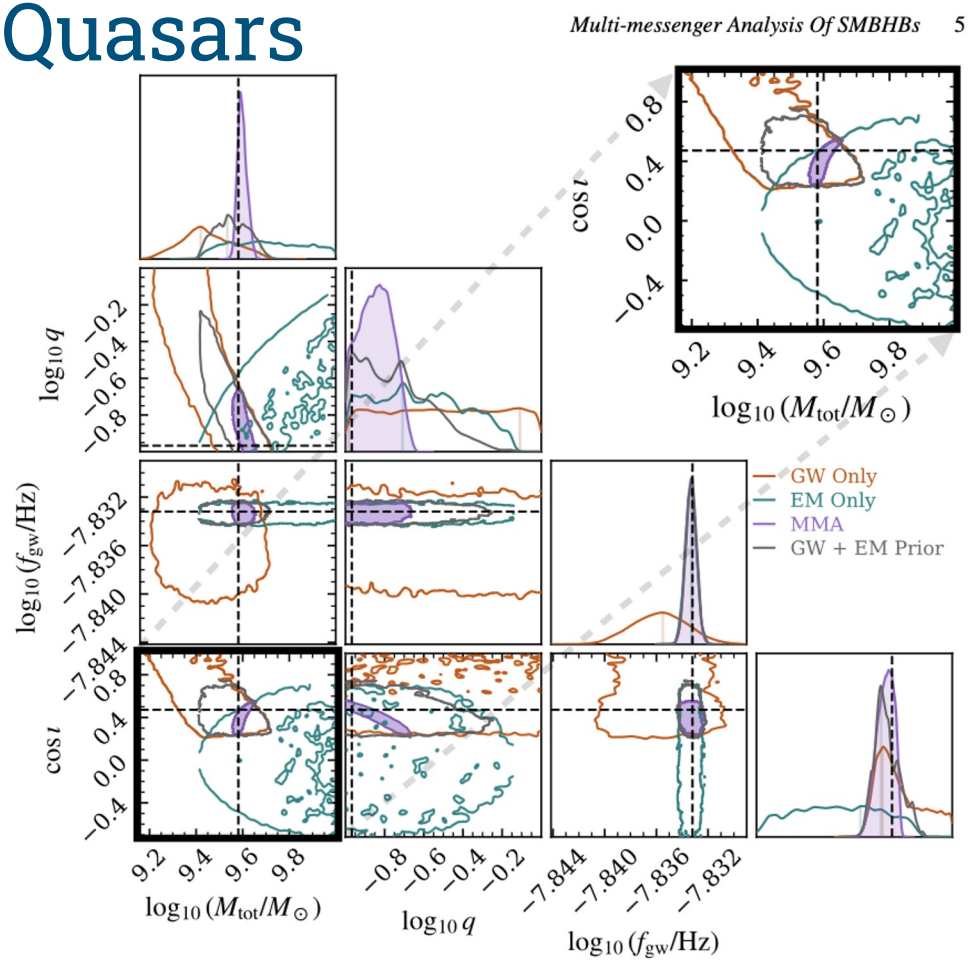


Figure Credit: Charisi+ 2026

MMA for PTAs

We’ve come a very long way!

- We’ve now placed MM limits on dozens of candidates

Lots more to do:

- More robust EM models and analyses
- CW search improvements