# *The dawn of low frequency gravitational wave astronomy*

**Alberto Sesana**
**(Universita` di Milano Bicocca)**

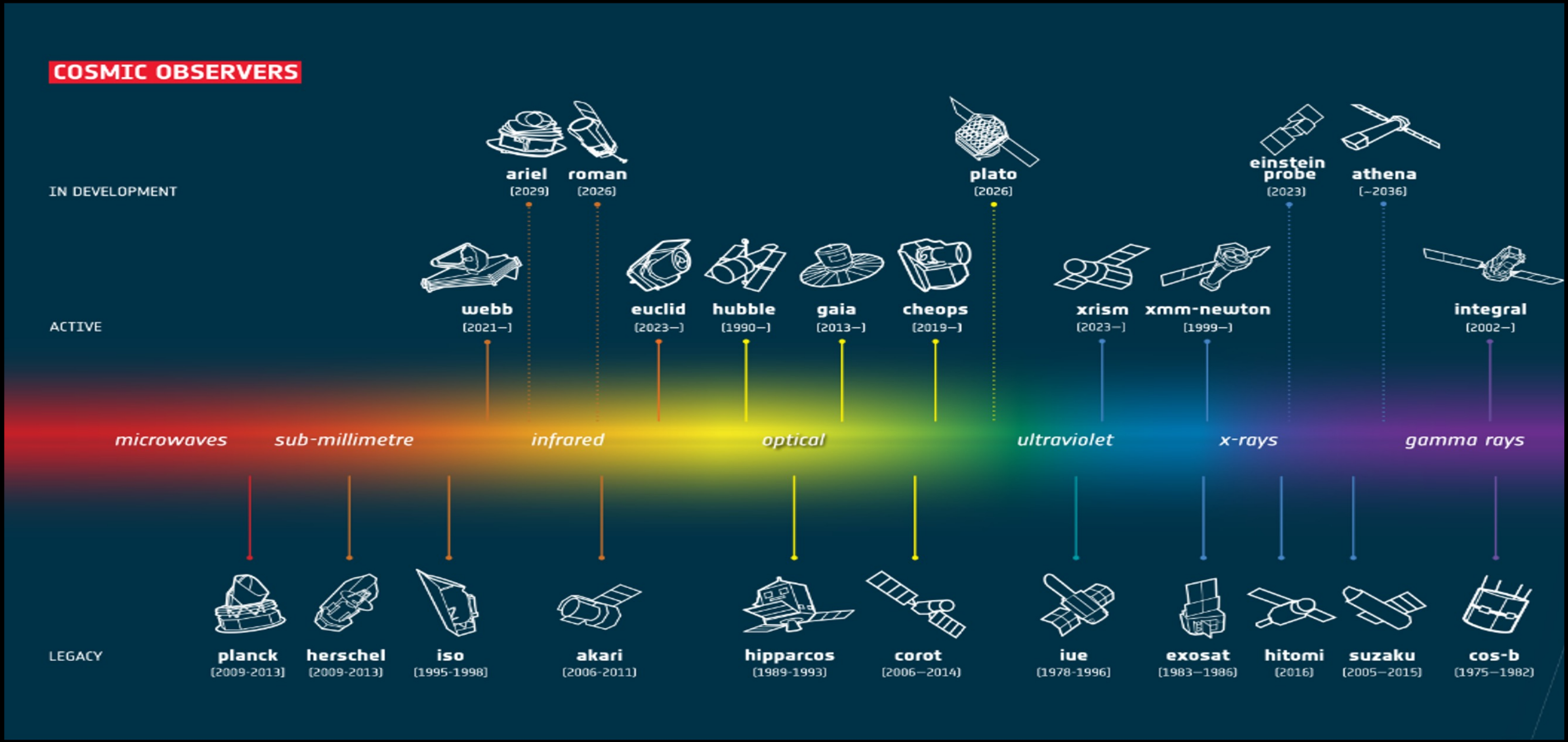
# *OUTLINE*

>Pulsars as ultra-precise clocks for GW detection

> (super)massive black hole binaries (MBHBs)

> Evidence for a GW signal in PTA experiments

> Implications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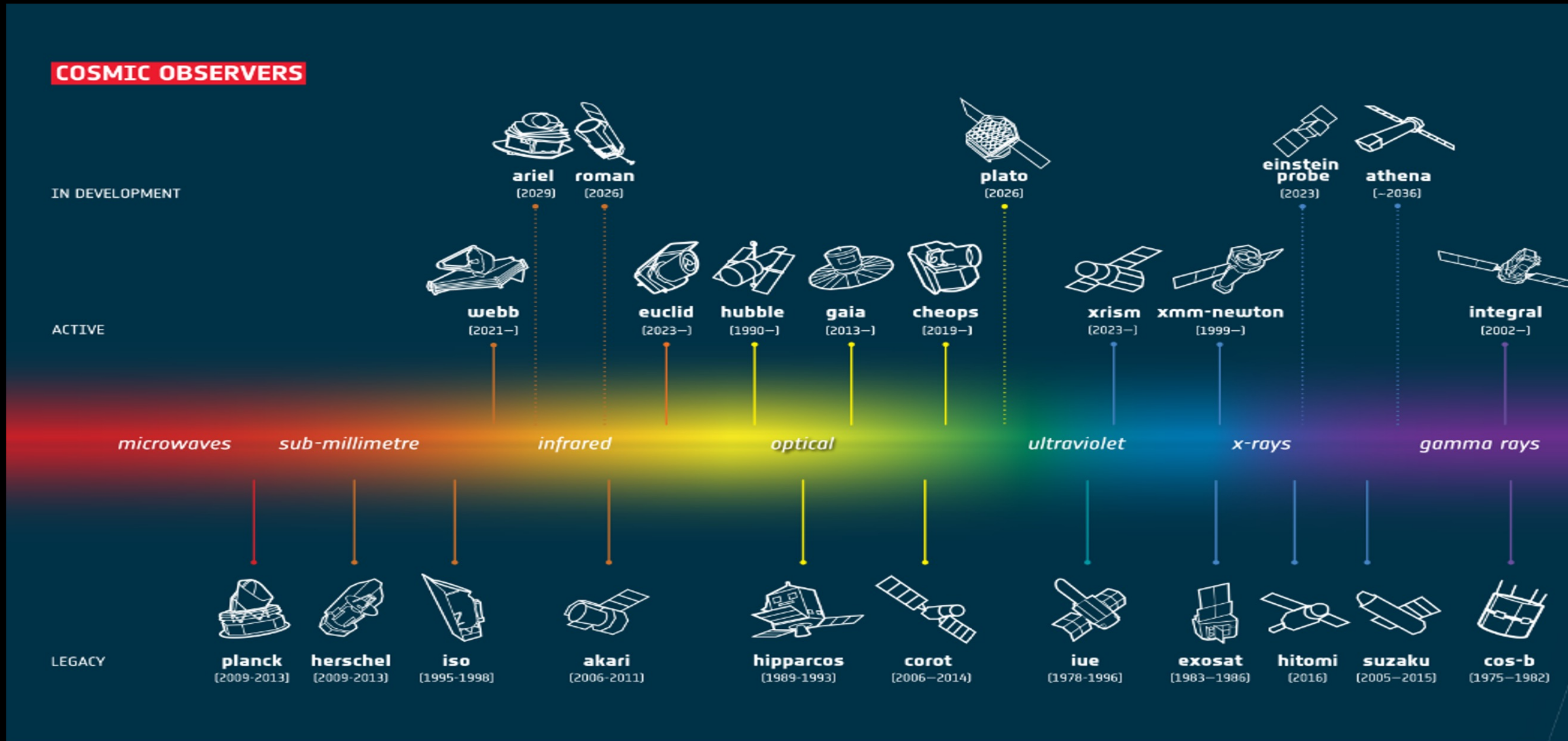
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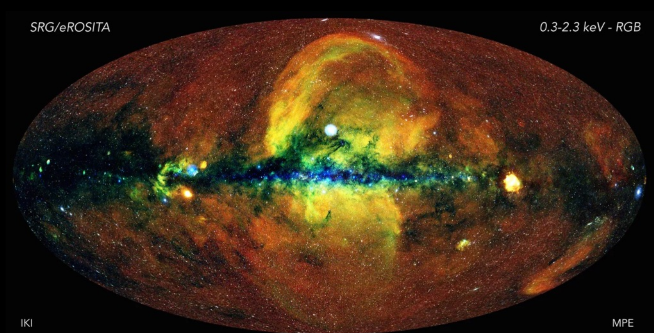
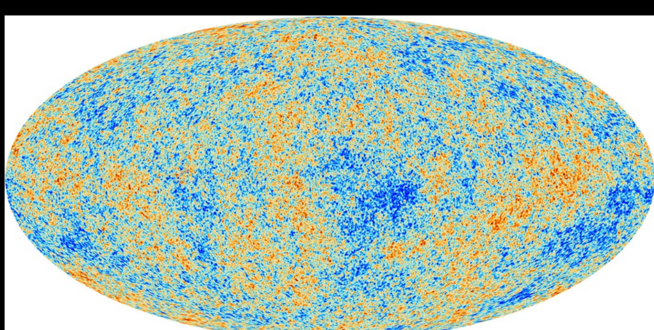
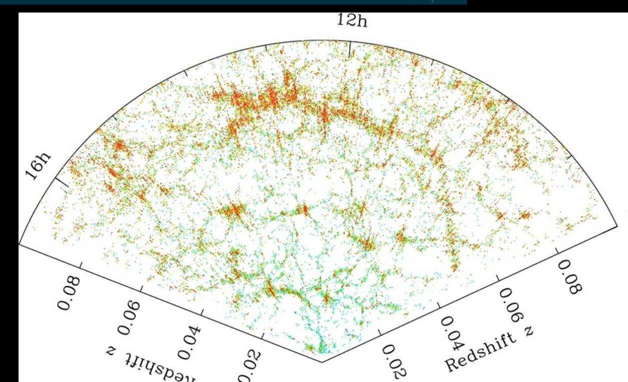
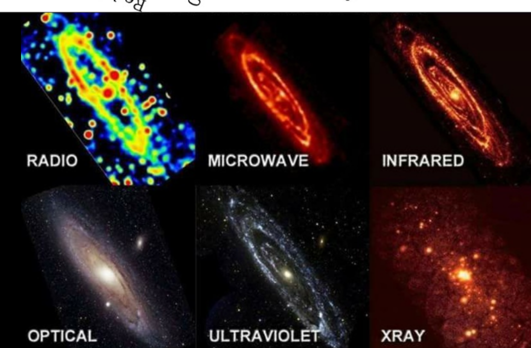
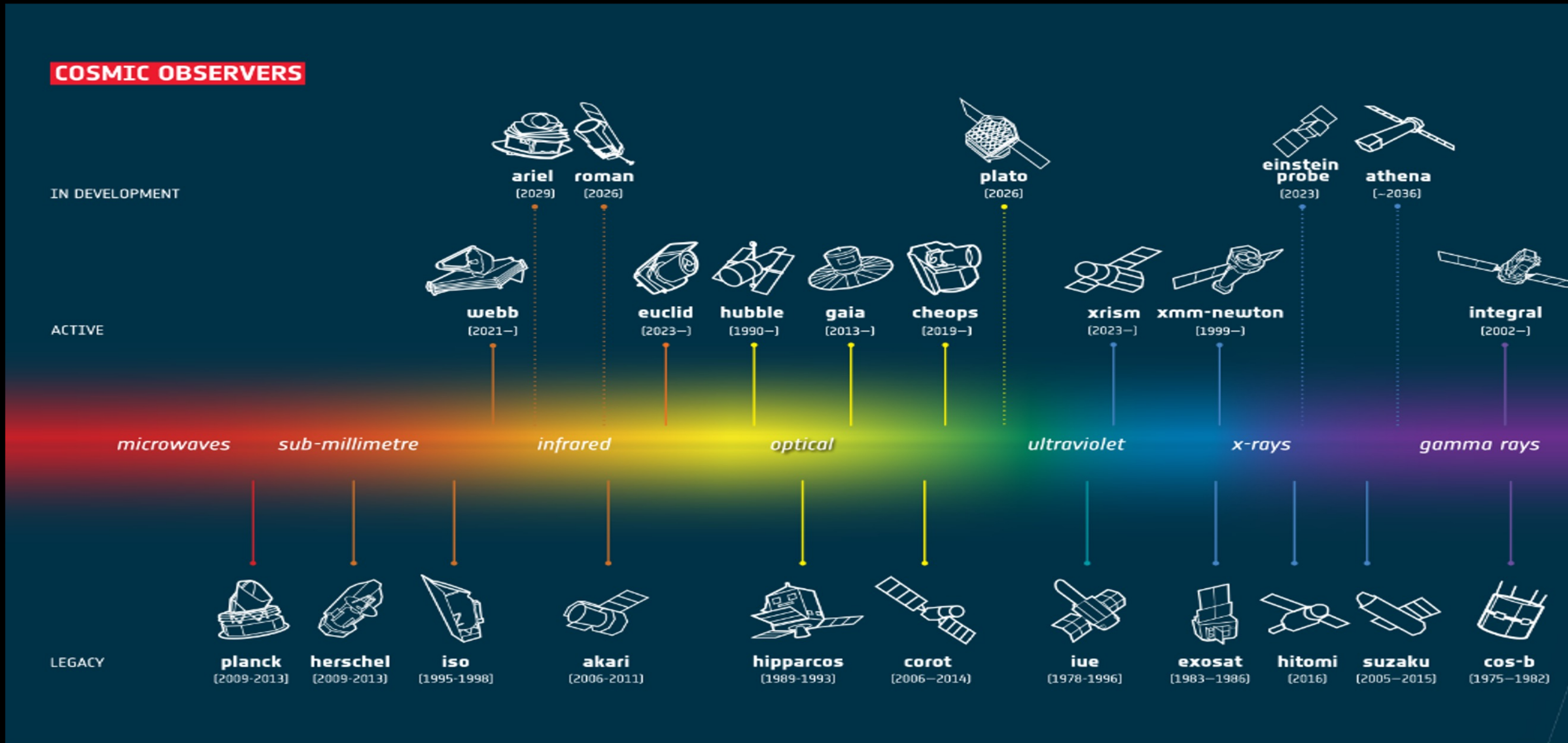

SRG/eROSITA
0.3-2.3 keV - RGB
IKI
MPE




12h
16h
8h
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08
Redshift z


RADIO
MICROWAVE
INFRARED
OPTICAL
ULTRAVIOLET
XRAY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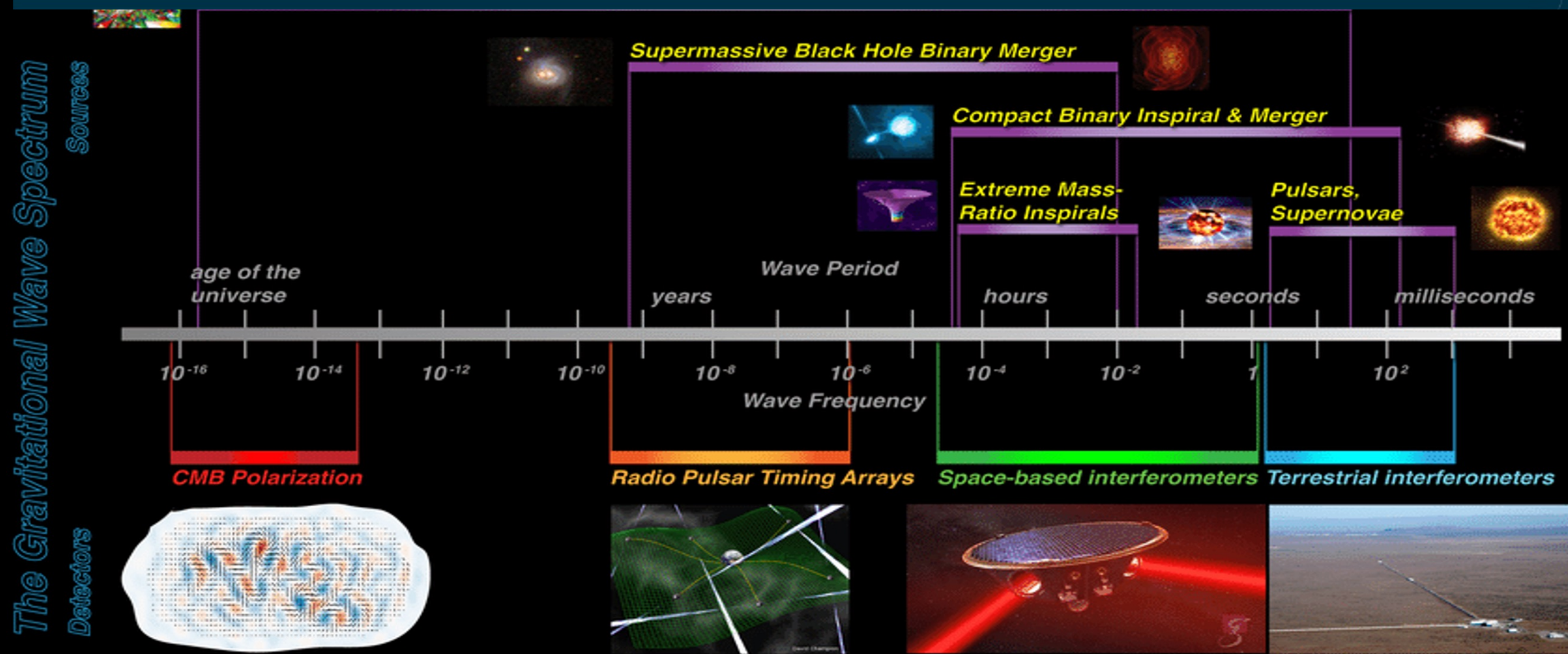
The Gravitational Wave Spectrum
Sources
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Supermassive Black Hole Binary Merger
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Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
Wave Period
age of the universe
years
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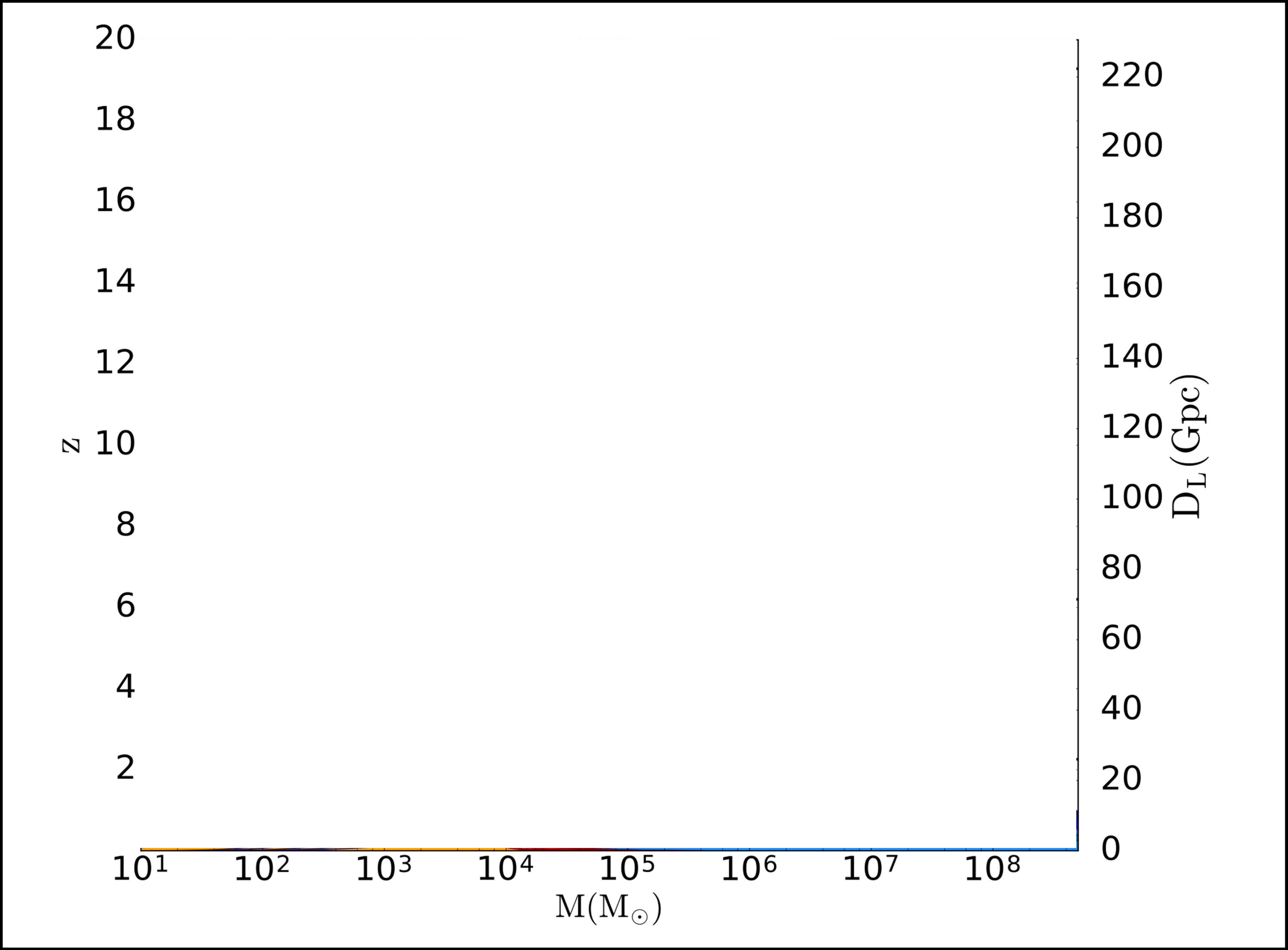
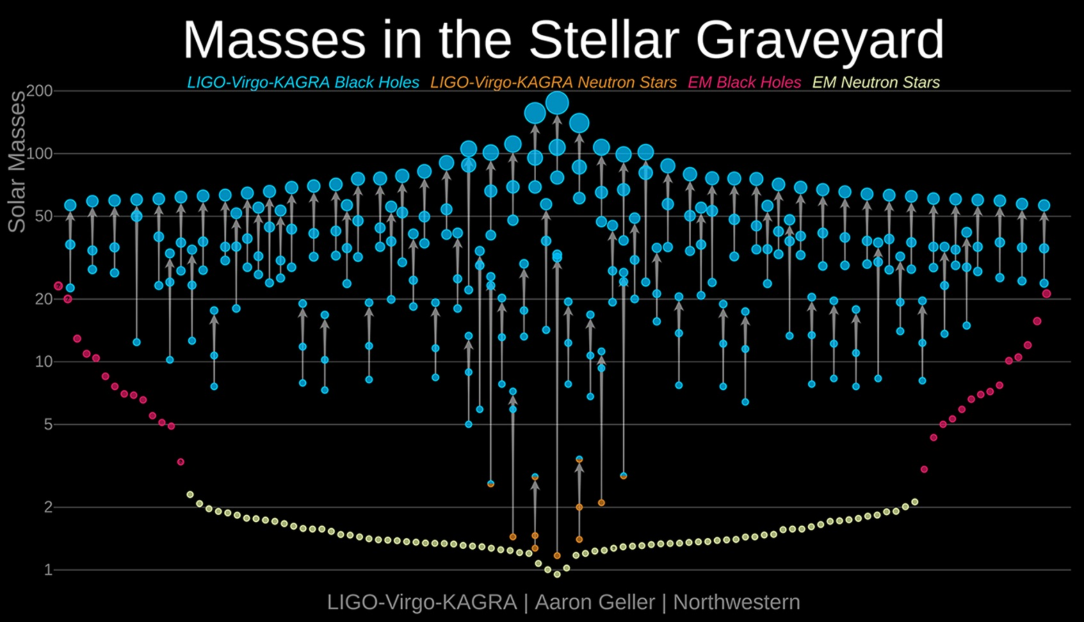
$10^{-16}$
$10^{-14}$
$10^{-12}$
$10^{-10}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers

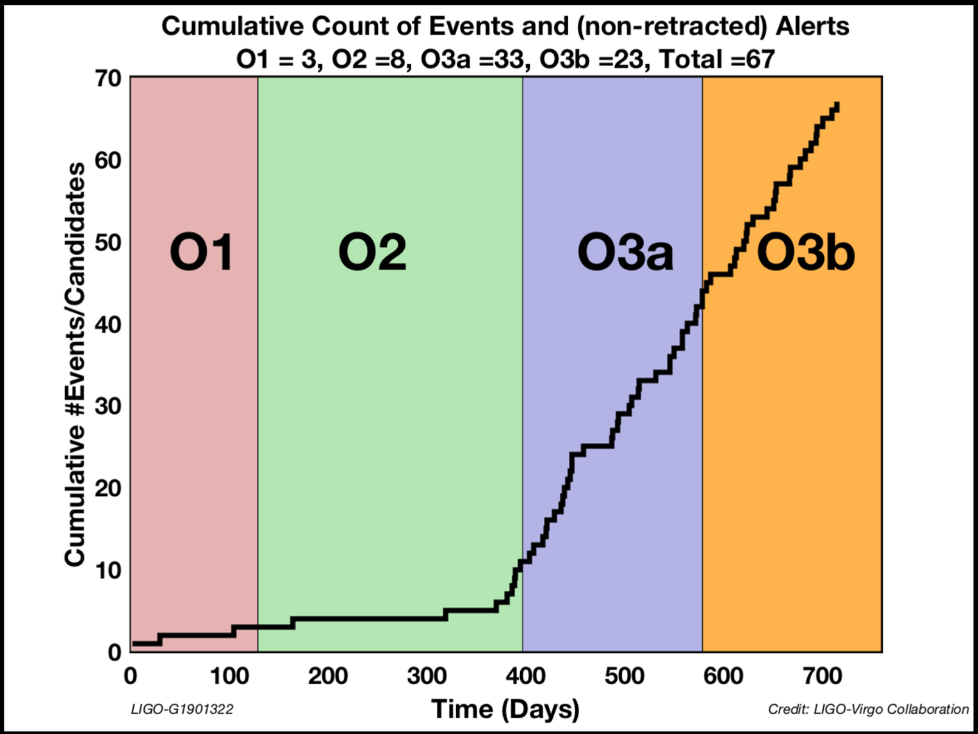
# Before 2015….



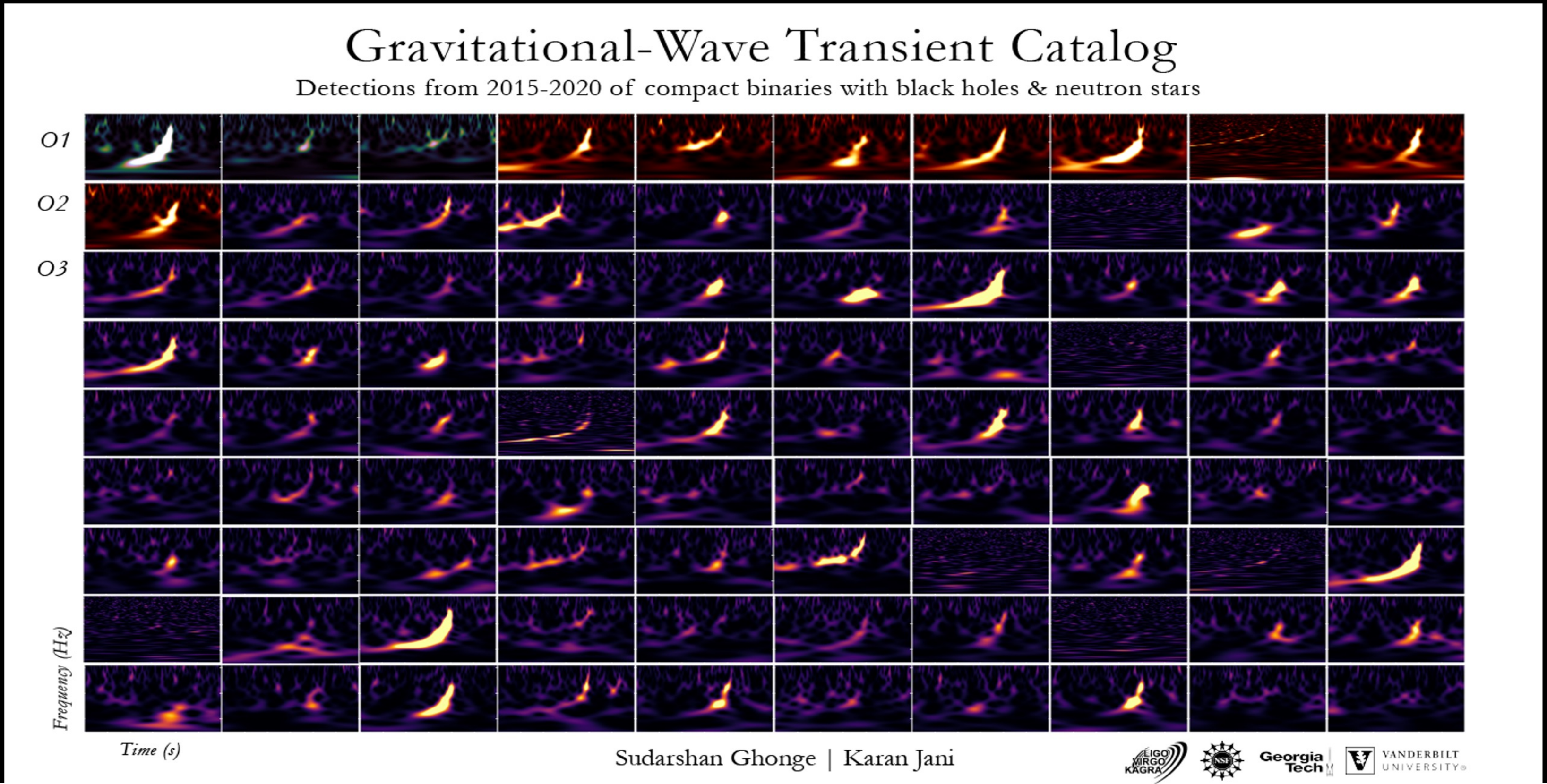
20
18
16
14
12
z
10
8
6
4
2
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$M(M_\odot)$
220
200
180
160
140
120
100
80
60
40
20
0
$D_L(\mathrm{Gpc})$



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

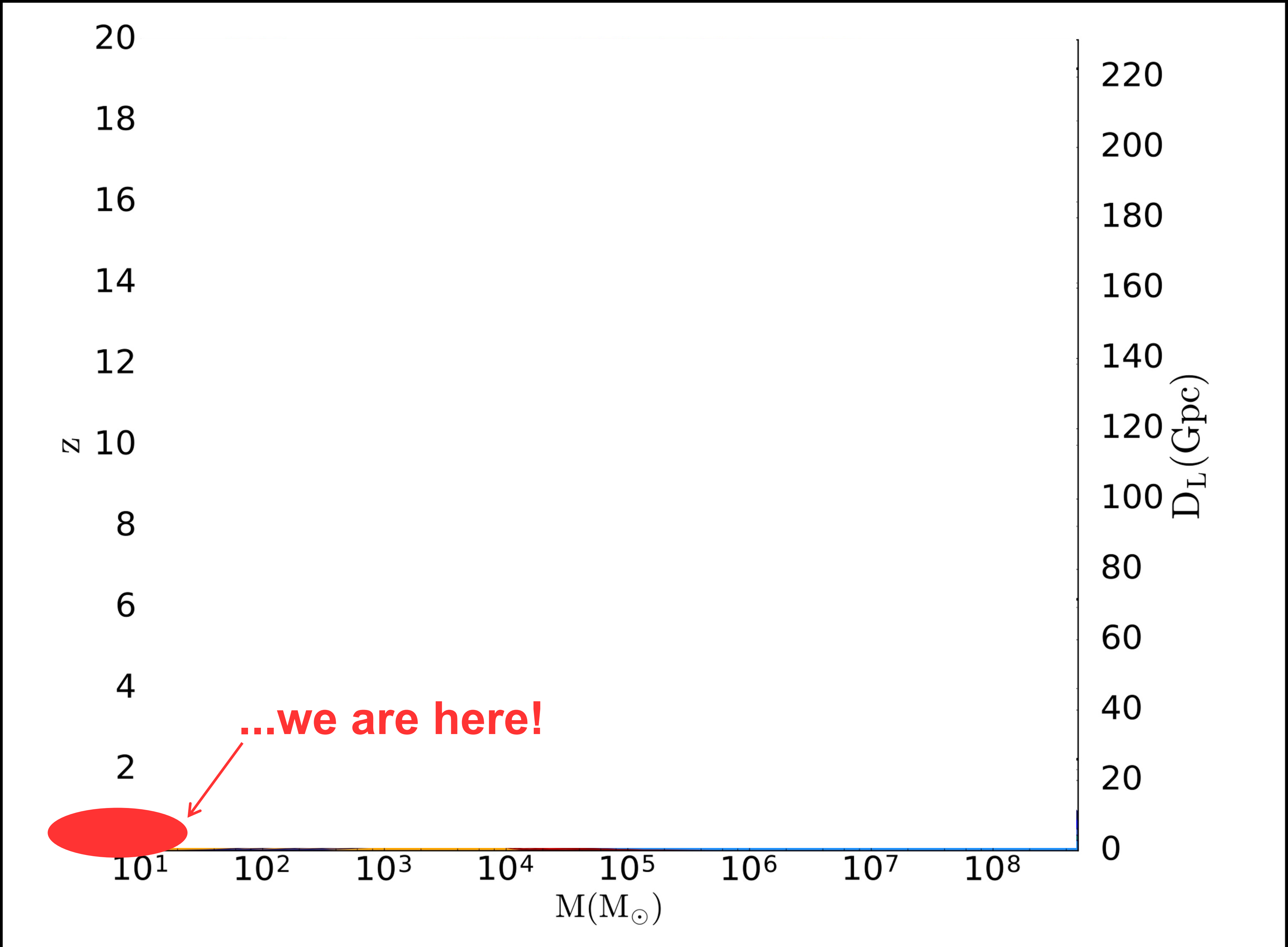



Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67
Cumulative #Events/Candidates
70
60
50
40
30
20
10
0
O1
O2
O3a
O3b
0
100
200
300
400
500
600
700
Time (Days)
LIGO-G1901322
Credit: LIGO-Virgo Collaboration

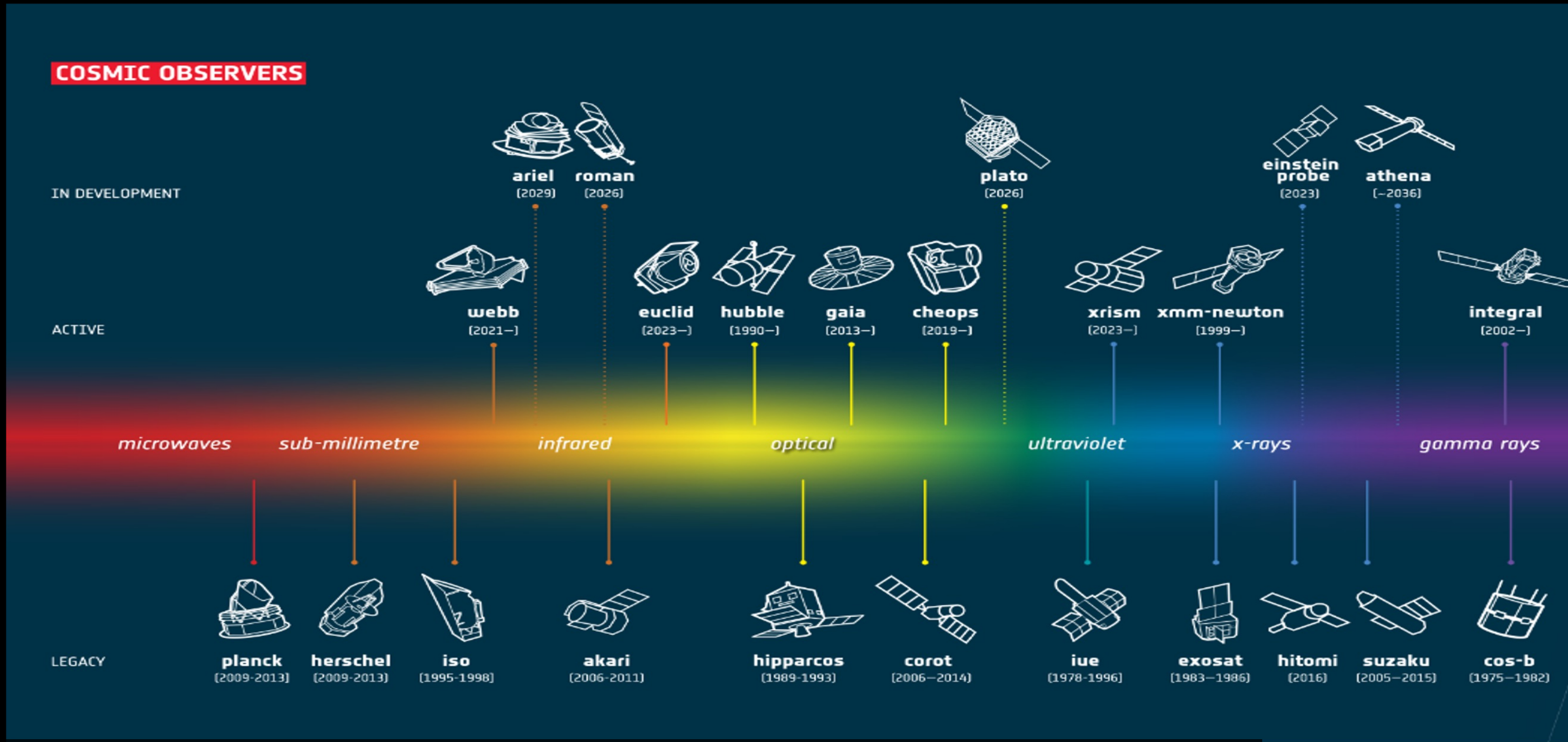



Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
Frequency (Hz)
Time (s)
Sudarshan Ghonge | Karan Jani
Georgia Tech
VANDERBILT UNIVERSITY

# After GWTC-3....



20
18
16
14
12
z
10
8
6
4
2
...we are here!
220
200
180
160
140
120
100
80
60
40
20
0
$D_L(\mathrm{Gpc})$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$M(M_\odot)$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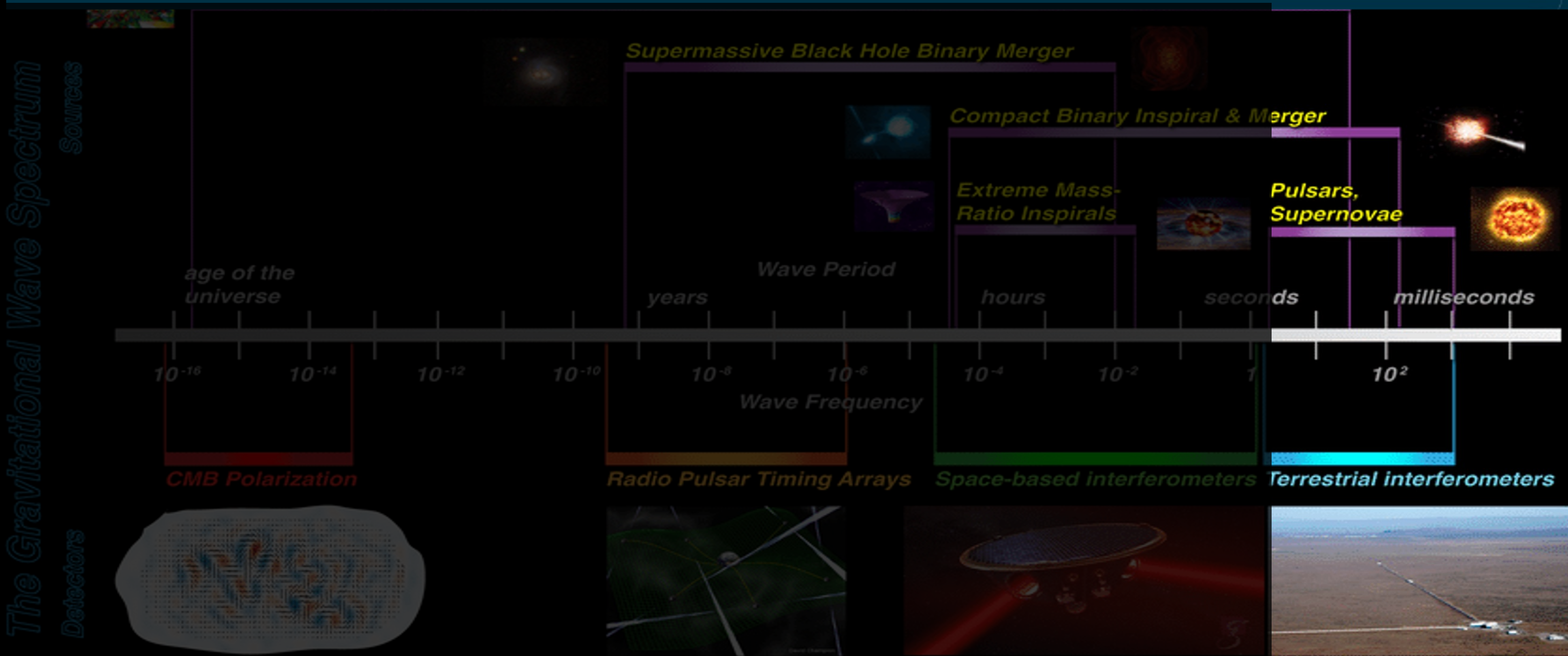
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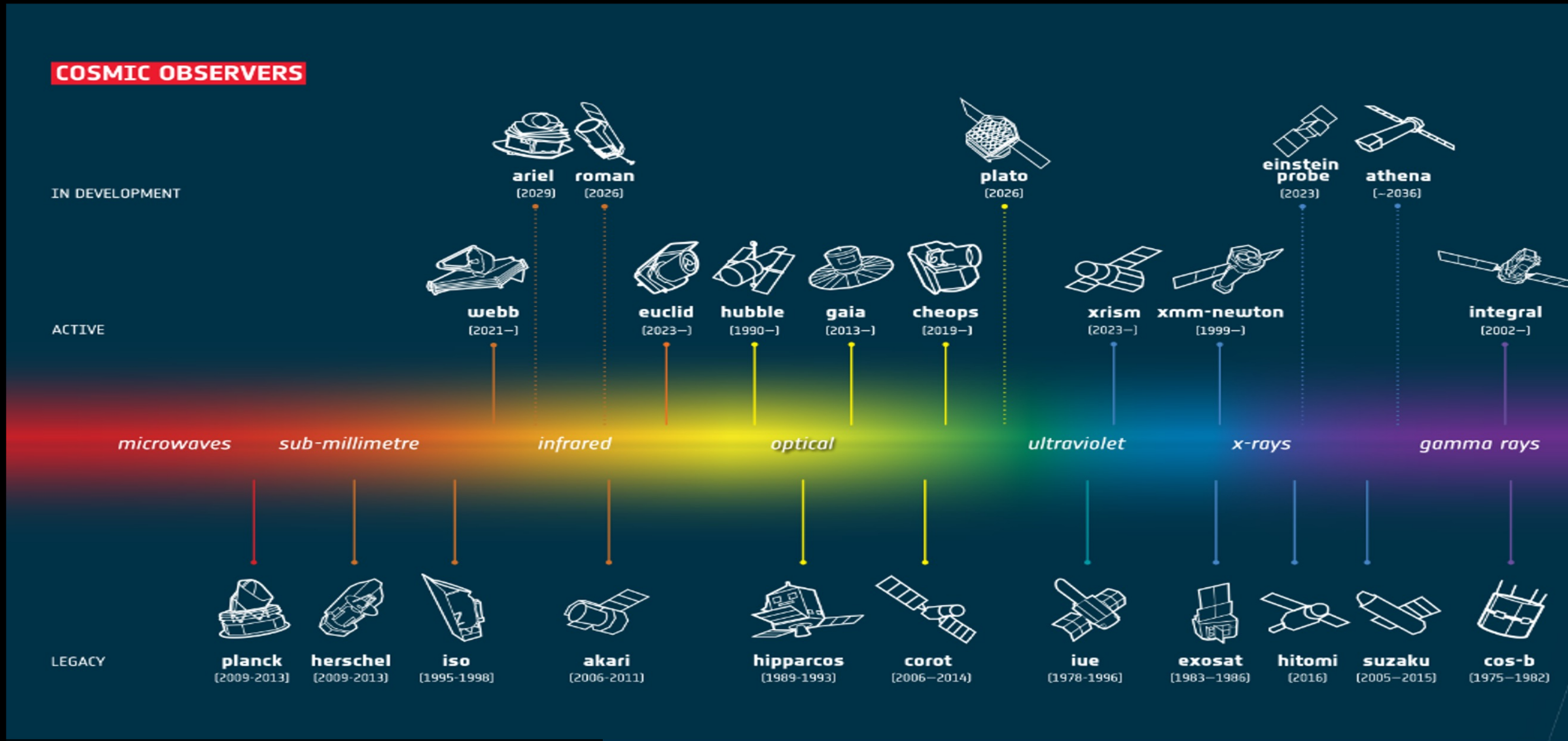

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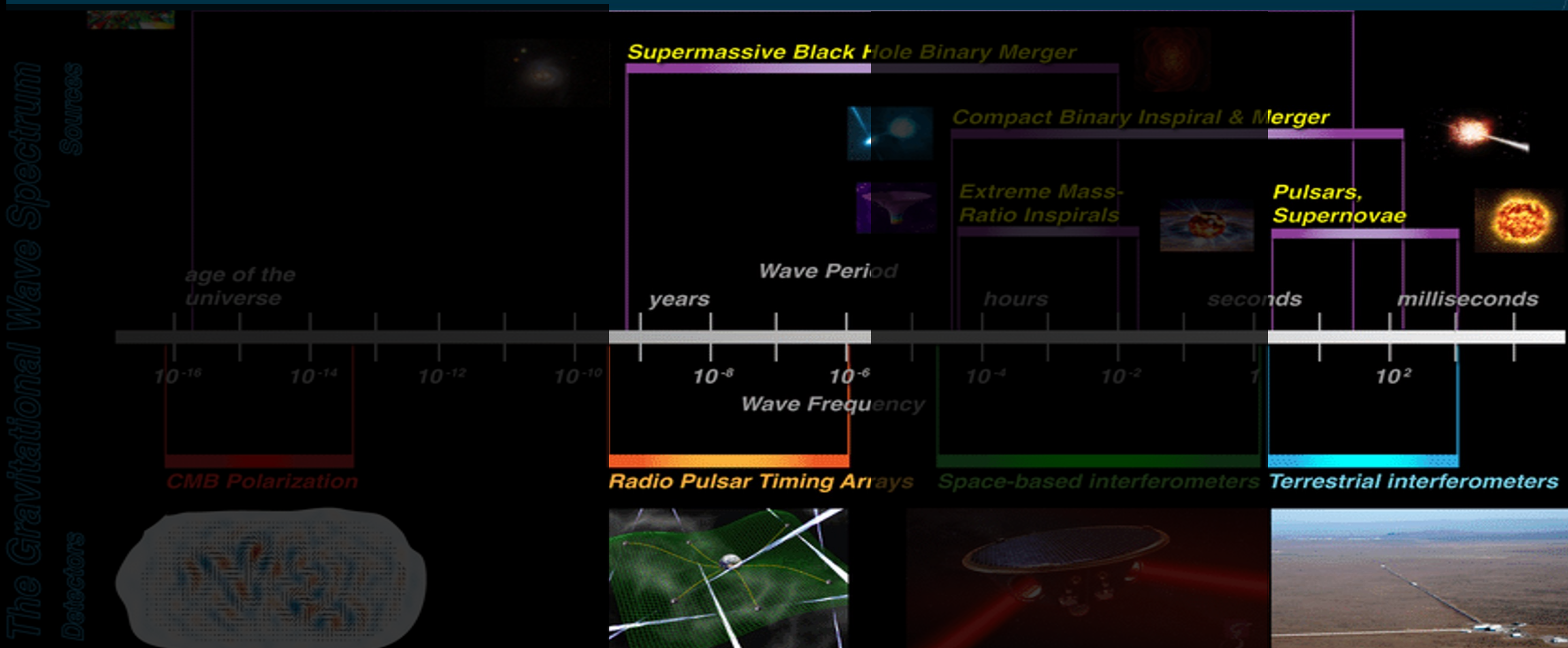

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# *What is pulsar timing*

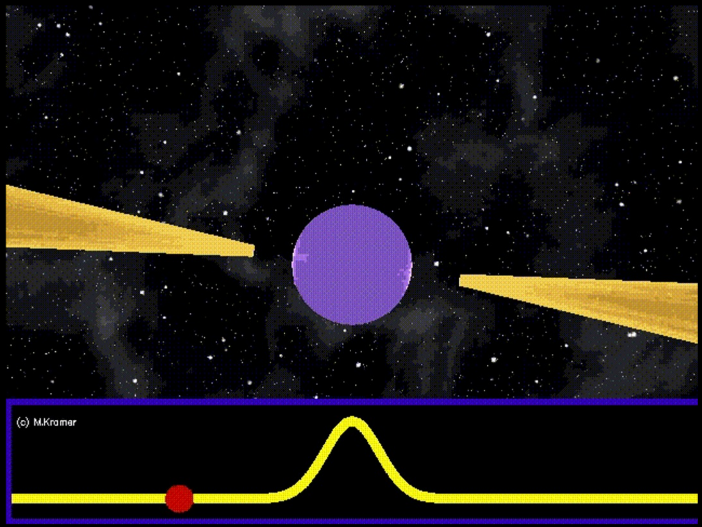
Pulsars are neutron seen through their regular radio pulses

Pulsar timing is the art of measuring the time of arrival (ToA) of each pu

1-Observe a pulsar and measure the ToAs

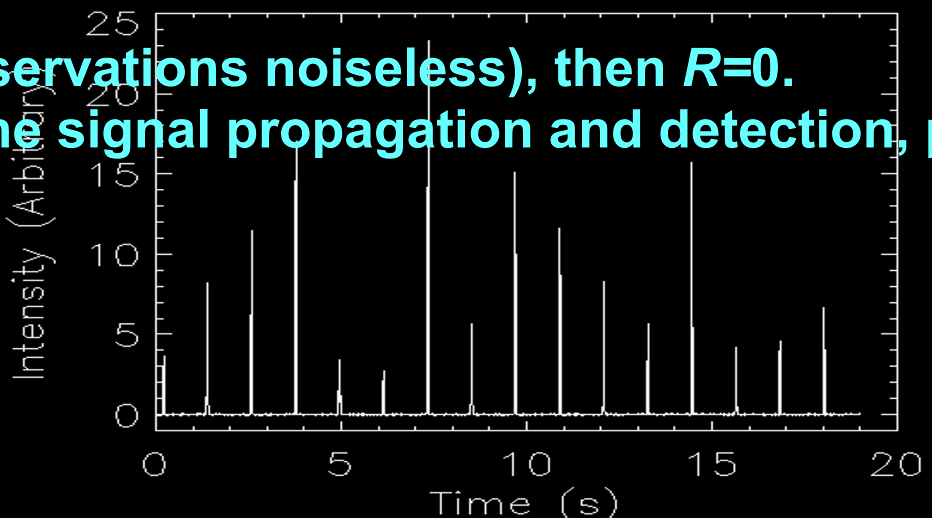
2-Find the model which best fits the ToAs

3-Compute the timing residual R

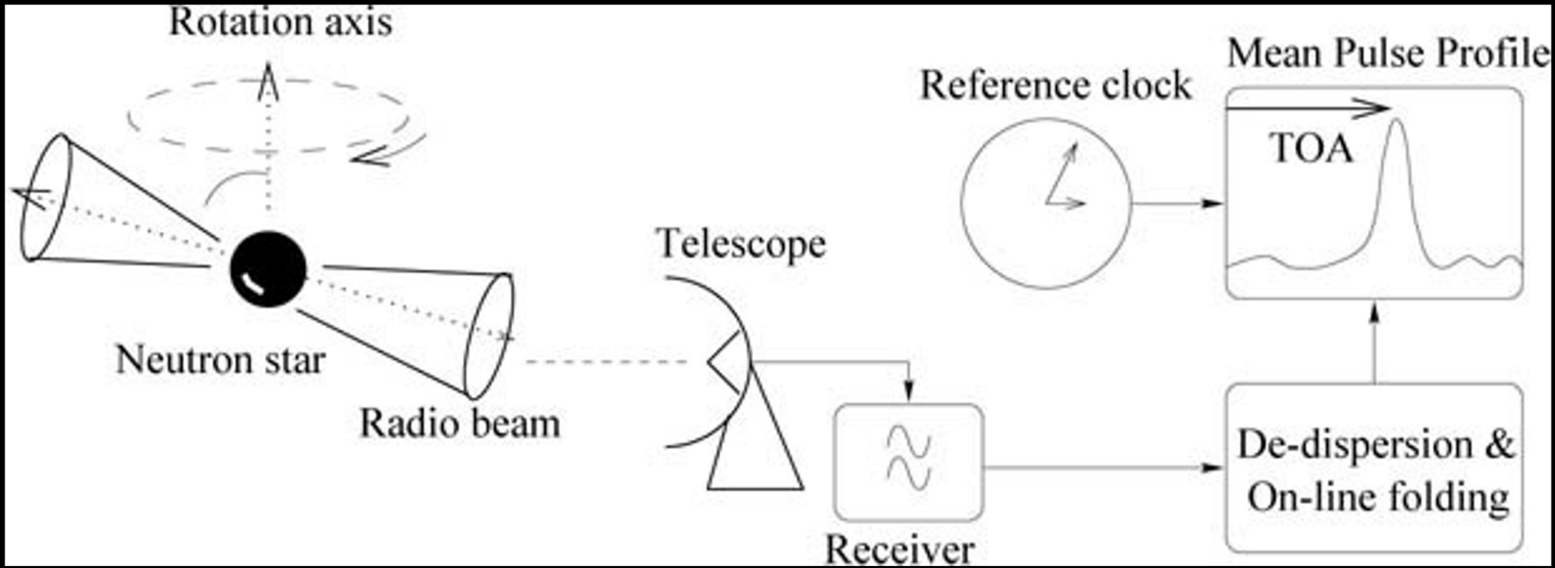


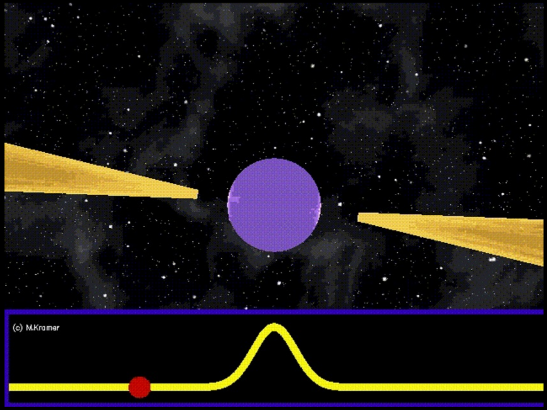

$$R = \mathrm{ToA} - \mathrm{ToA}_m$$

If the timing solution is perfect (and observations noiseless), then $R$=0.
*R* contains all uncertainties related to the signal propagation and detection, plu



# Pulsar timing model



(Kramer & Lorimer 2005)

The N-th rotation of the pulsar is given in terms of the frequency as

$$N = N_0 + \nu\tau + \frac{1}{2}\dot{\nu}\tau^2 + \frac{1}{6}\ddot{\nu}\tau^3 + \ldots$$

Which can be inverted to get the time of arrival of the N-th pulse

$$t_{\rm arr} = \nu^{-1}N - \Delta_{\rm R}(u) - \Delta_{\rm E}(u) + \Delta_{\rm S}(u) - \frac{1}{2}\dot{\nu}\nu^{-3}N^2 - \frac{1}{6}\ddot{\nu}\nu^{-4}N^3 + \ldots$$

(Will 2006)

$tSSB = t_{arr} + t_{clock} + t_{Earth} + DM/f^2$

(Hobbs+ 2006)

The timing model includes:

-Roemer, Einstein and Shapiro delays.

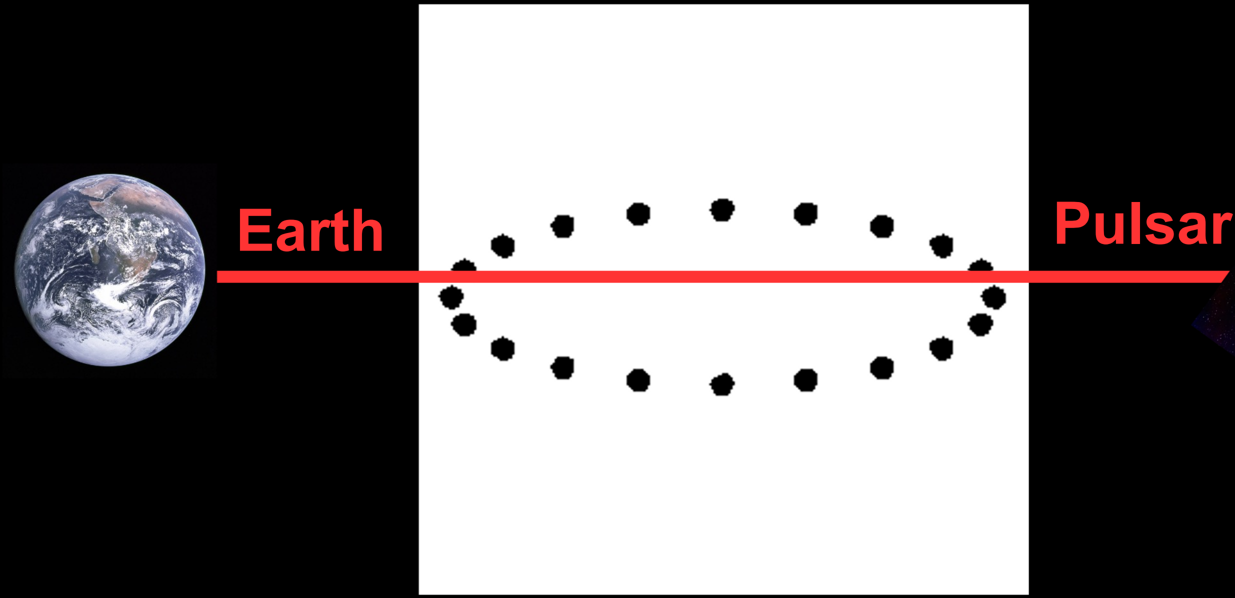
-pulsar frequency and freq derivatives

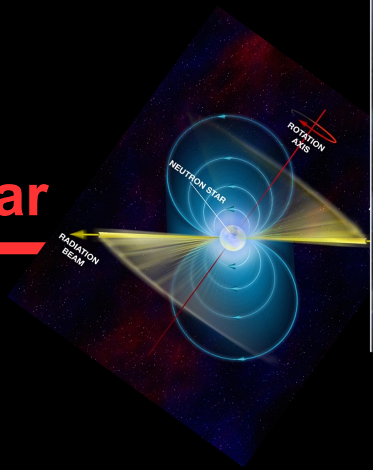
-pulsar position and proper motion

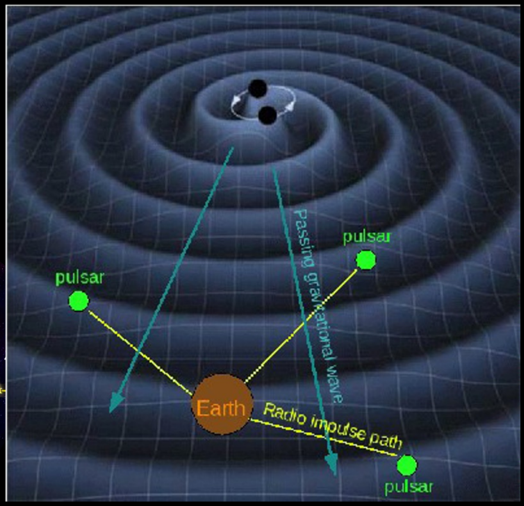
-dispersion measure

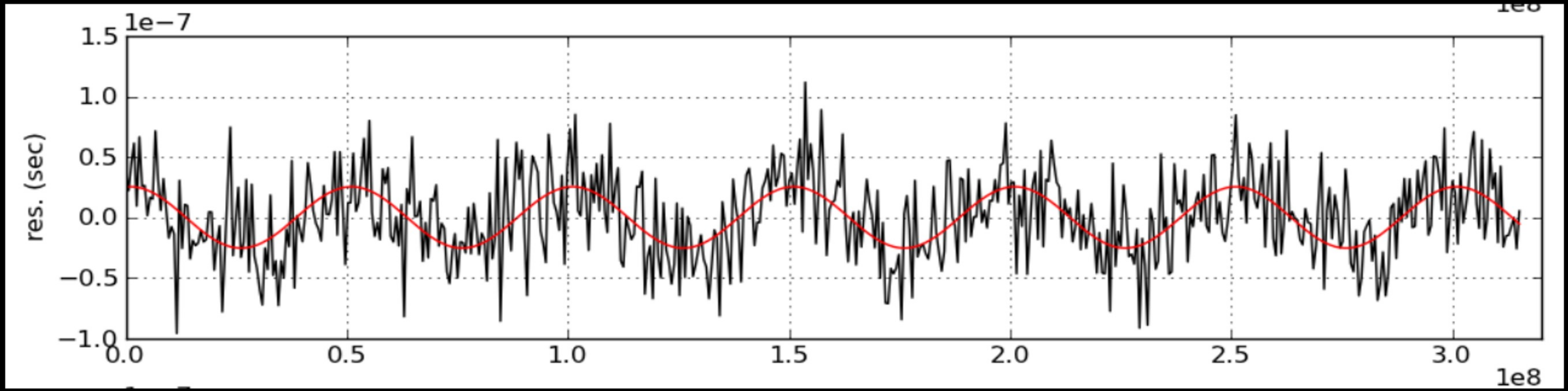
-clock corrections and Earth position wrt SSB

# Effect of gravitational waves



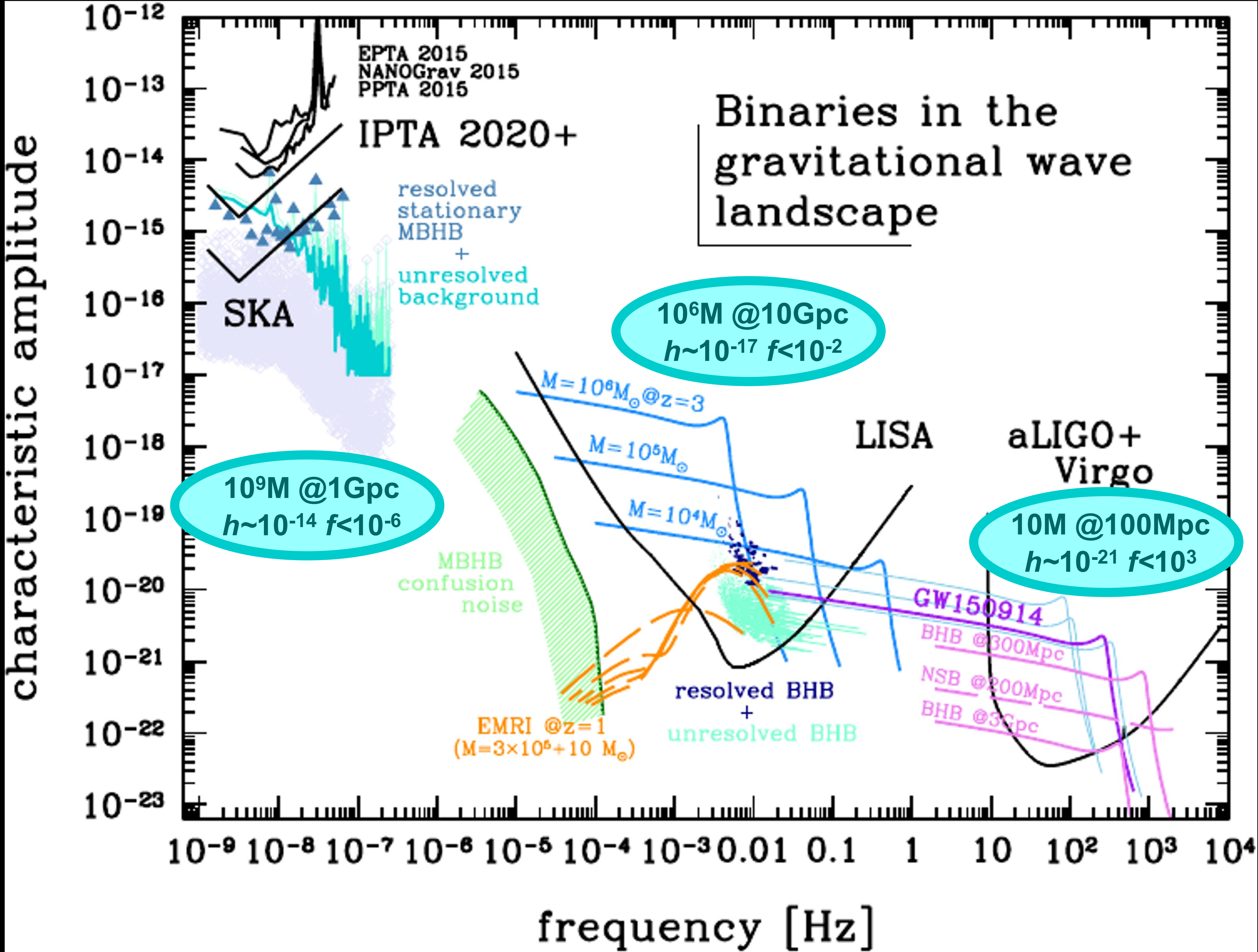






R~h/(2πf)

$$
\begin{aligned}
&= \frac{\mathcal{M}^{5/3}}{D}\,[\pi f(t)]^{-1/3} \\
&\simeq 25.7 \left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3} \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \\
&\quad \times \left(\frac{f}{5\times 10^{-8}\,\mathrm{Hz}}\right)^{-1/3} \mathrm{ns}
\end{aligned}
$$



EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
Binaries in the gravitational wave landscape
resolved stationary MBHB + unresolved background
SKA
10⁶M @10Gpc
h~10⁻¹⁷ f<10⁻²
M=10⁶M⊙@z=3
M=10⁵M⊙
M=10⁴M⊙
LISA
aLIGO+ Virgo
10⁹M @1Gpc
h~10⁻¹⁴ f<10⁻⁶
10M @100Mpc
h~10⁻²¹ f<10³
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB + unresolved BHB
EMRI @z=1 (M=3×10⁵+10 M⊙)
characteristic amplitude
frequency [Hz]

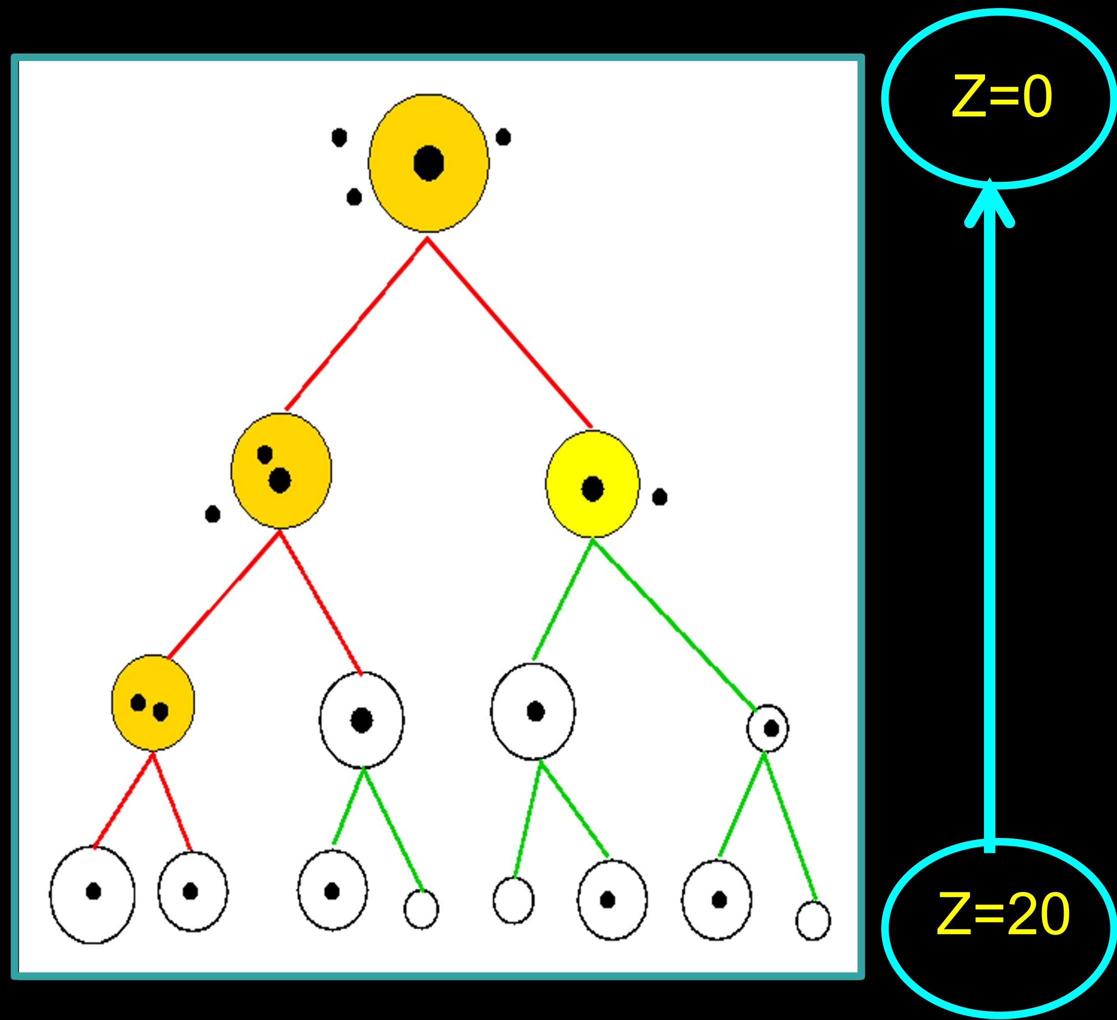
# *HIERARCHICAL GALAXY & MBH EVOLUTION*

**GENERAL FRAMEWORK:**

(Volonteri, Haardt & Madau 2003)

**Galaxies form hierarchically through a series of mergers and accretion events**

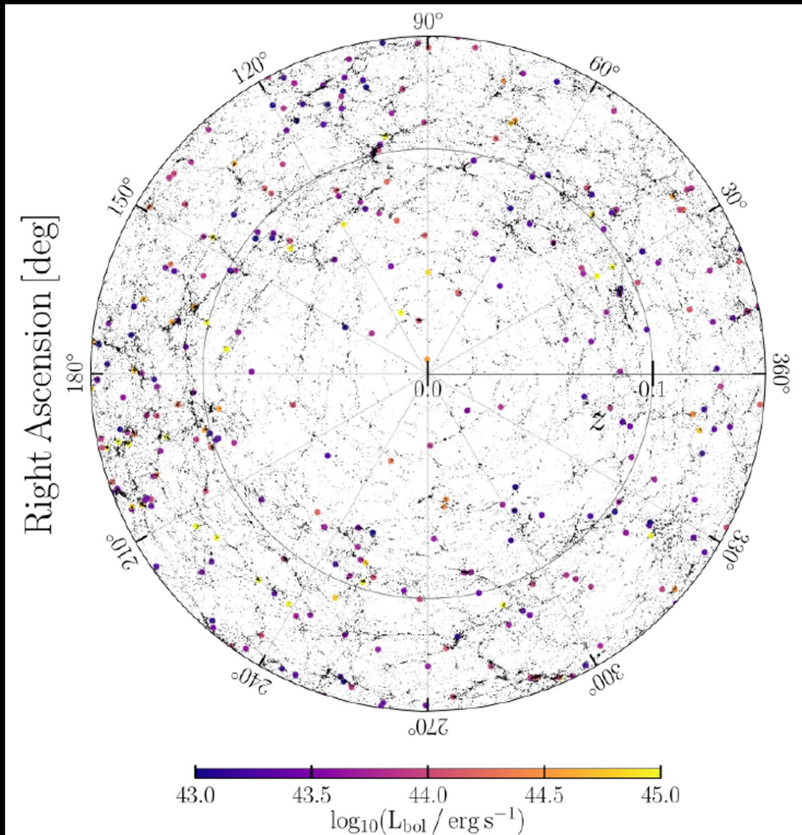
**Protogalaxies can host seed BH that accrete mass and merge with each other following galaxy mergers**




**(Illustris simulation)**

# The expected GW signal in the PTA band

(Izquierdo-Villalba+ 22)



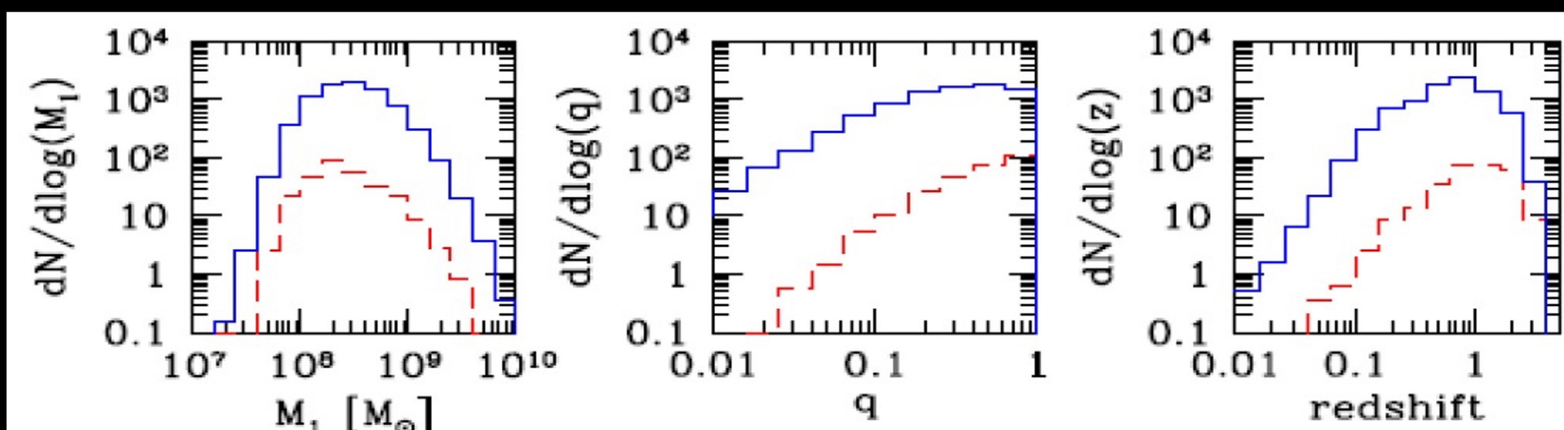

The GW characteristic amplitude coming fr

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r} h^2(f_r)$$

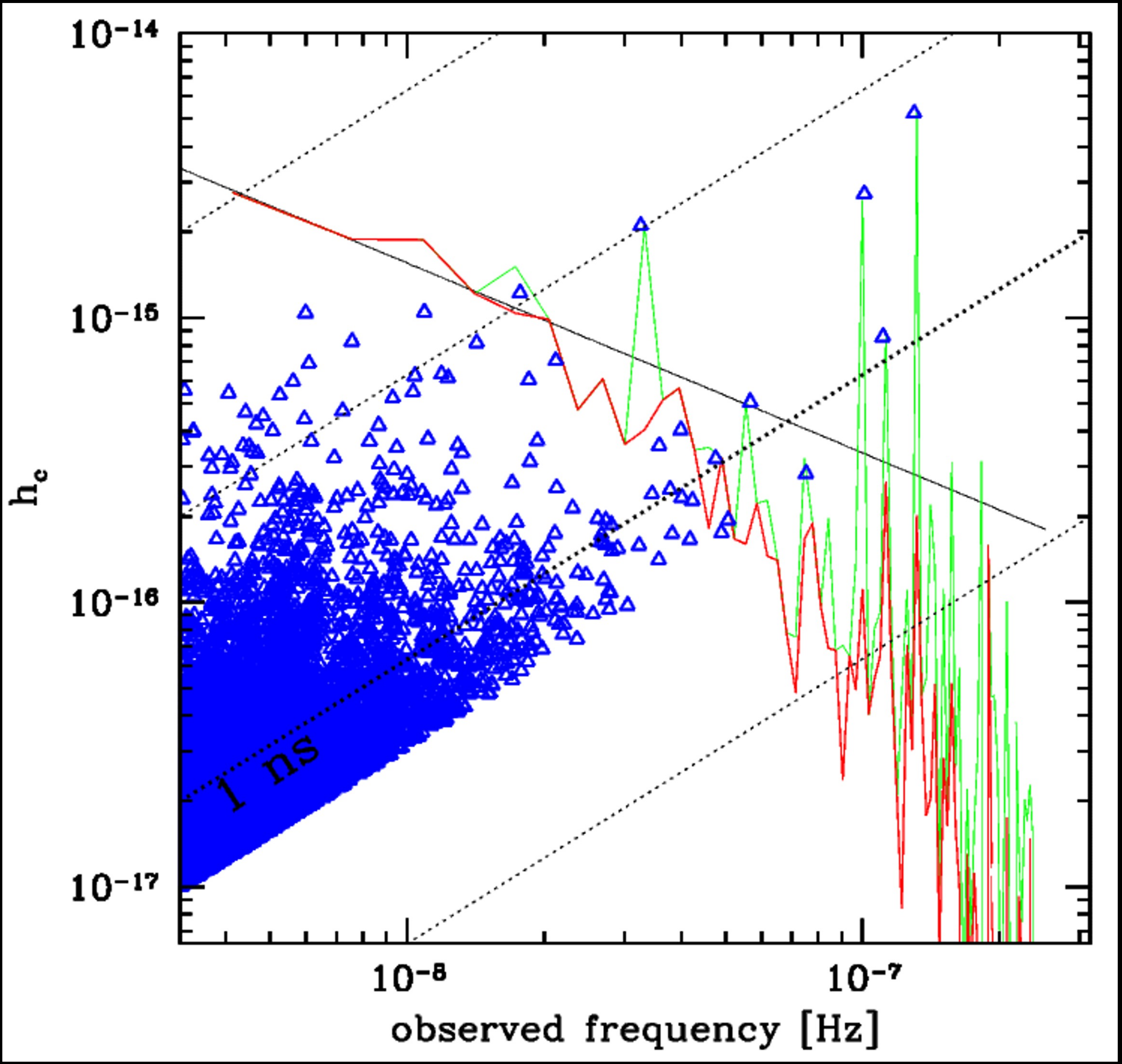
$$\delta t_{\rm bkg}(f) \approx h_c(f)/(2\pi f)$$

Theoretical spectrum: simple power law (

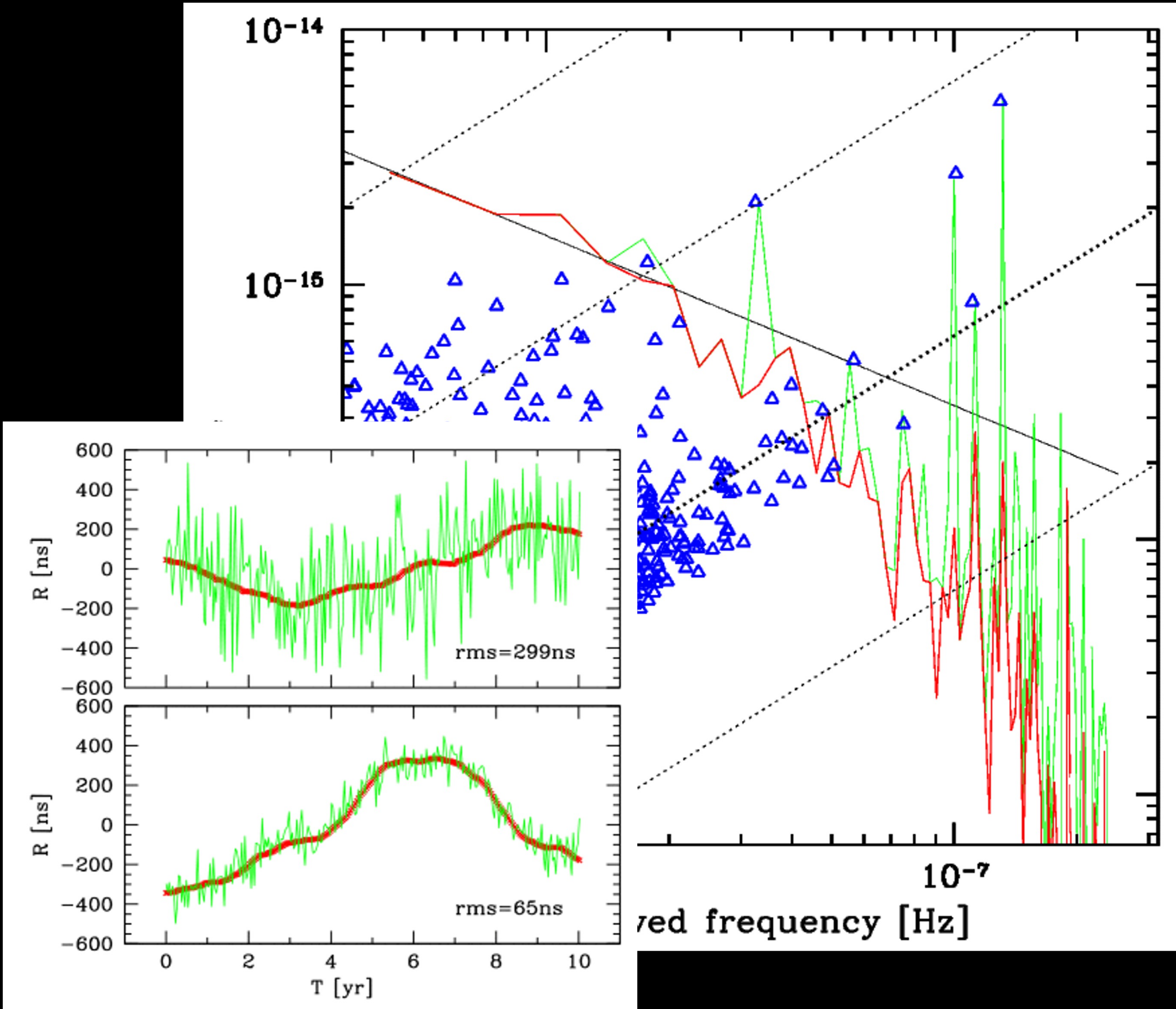
$$h_c(f) = A \left( \frac{f}{\rm yr^{-1}} \right)^{-2/3}$$



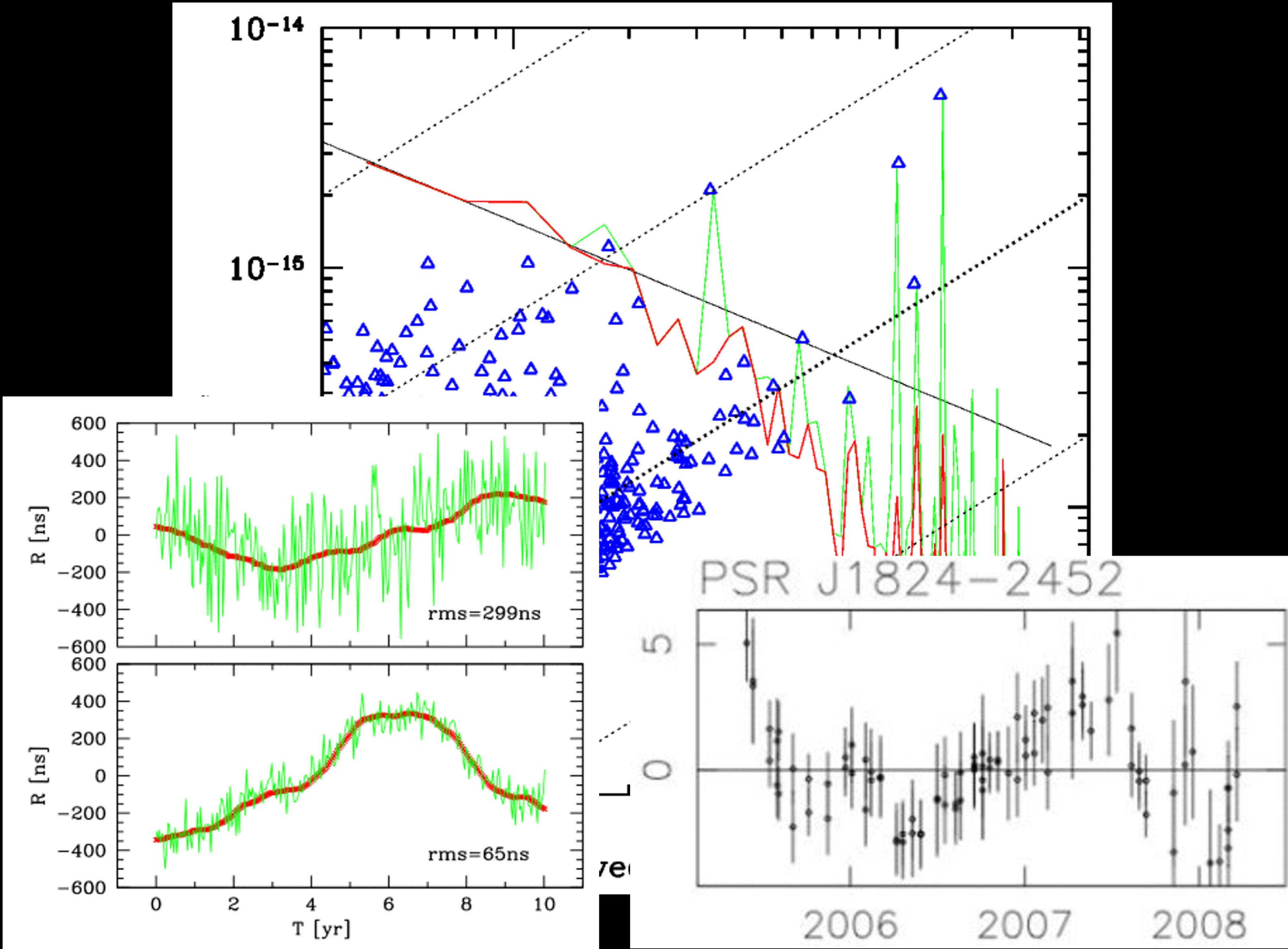

The signal is contributed by extremely massive (>$10^8 M_\odot$) relatively low



$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$h_c$
1 ns
$10^{-8}$
$10^{-7}$
observed frequency [Hz]

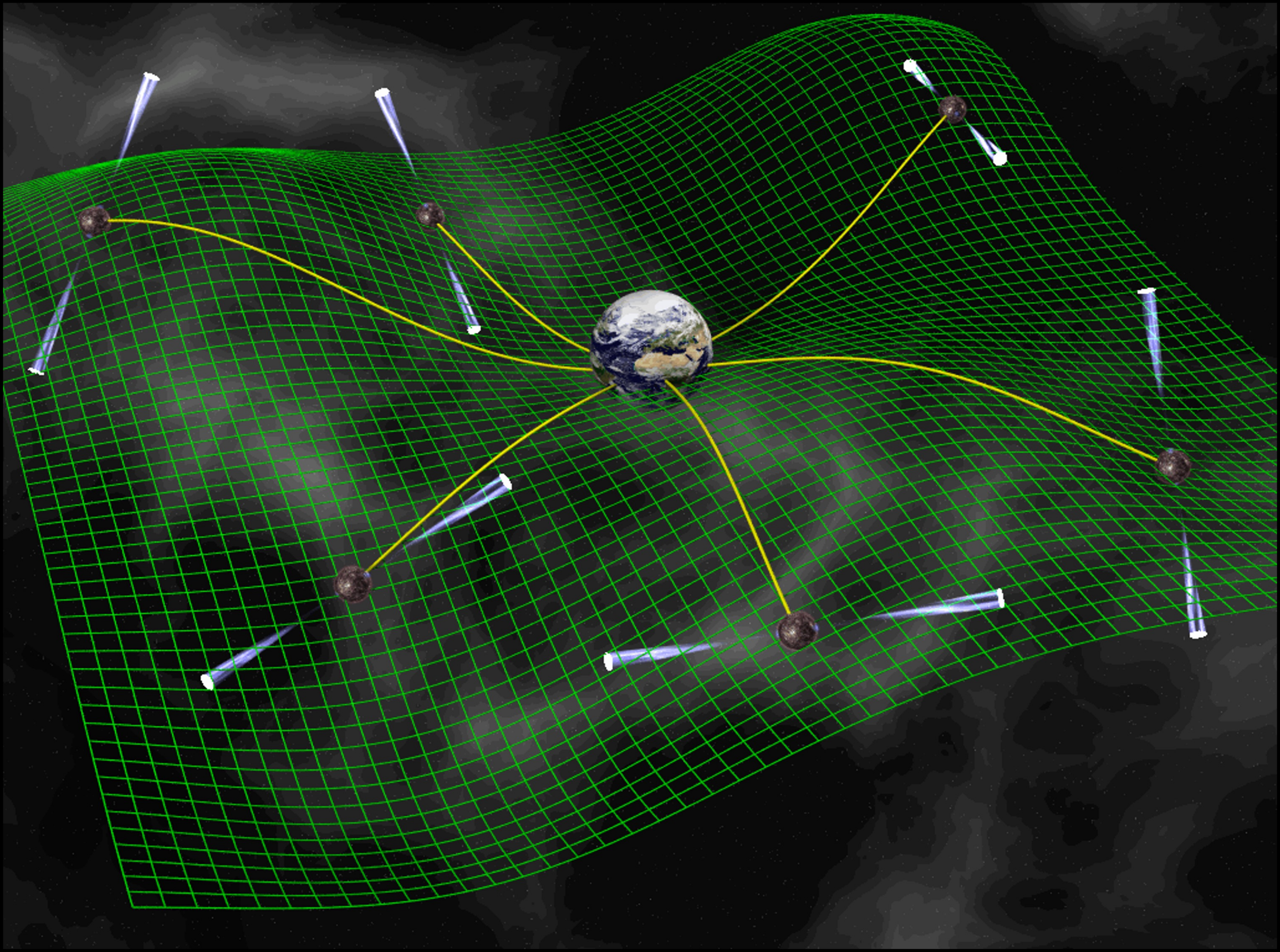


10^−14
10^−15
10^−7
ved frequency [Hz]
600
400
200
0
−200
−400
−600
R [ns]
rms=299ns
rms=65ns
0
2
4
6
8
10
T [yr]



10−14
10−15
R [ns]
rms=299ns
rms=65ns
T [yr]
PSR J1824−2452
2006
2007
2008

# We are looking for a correlated signal



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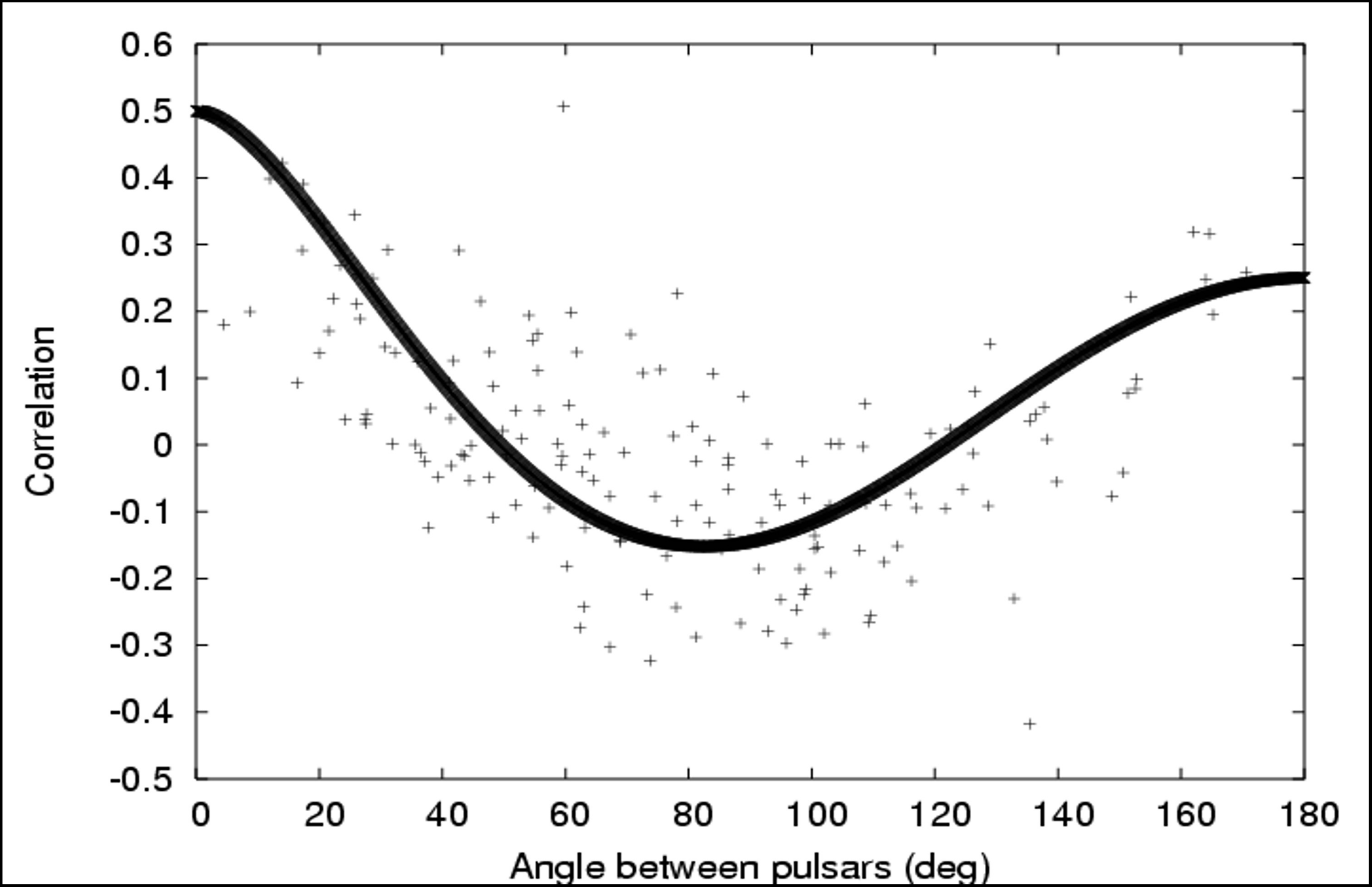
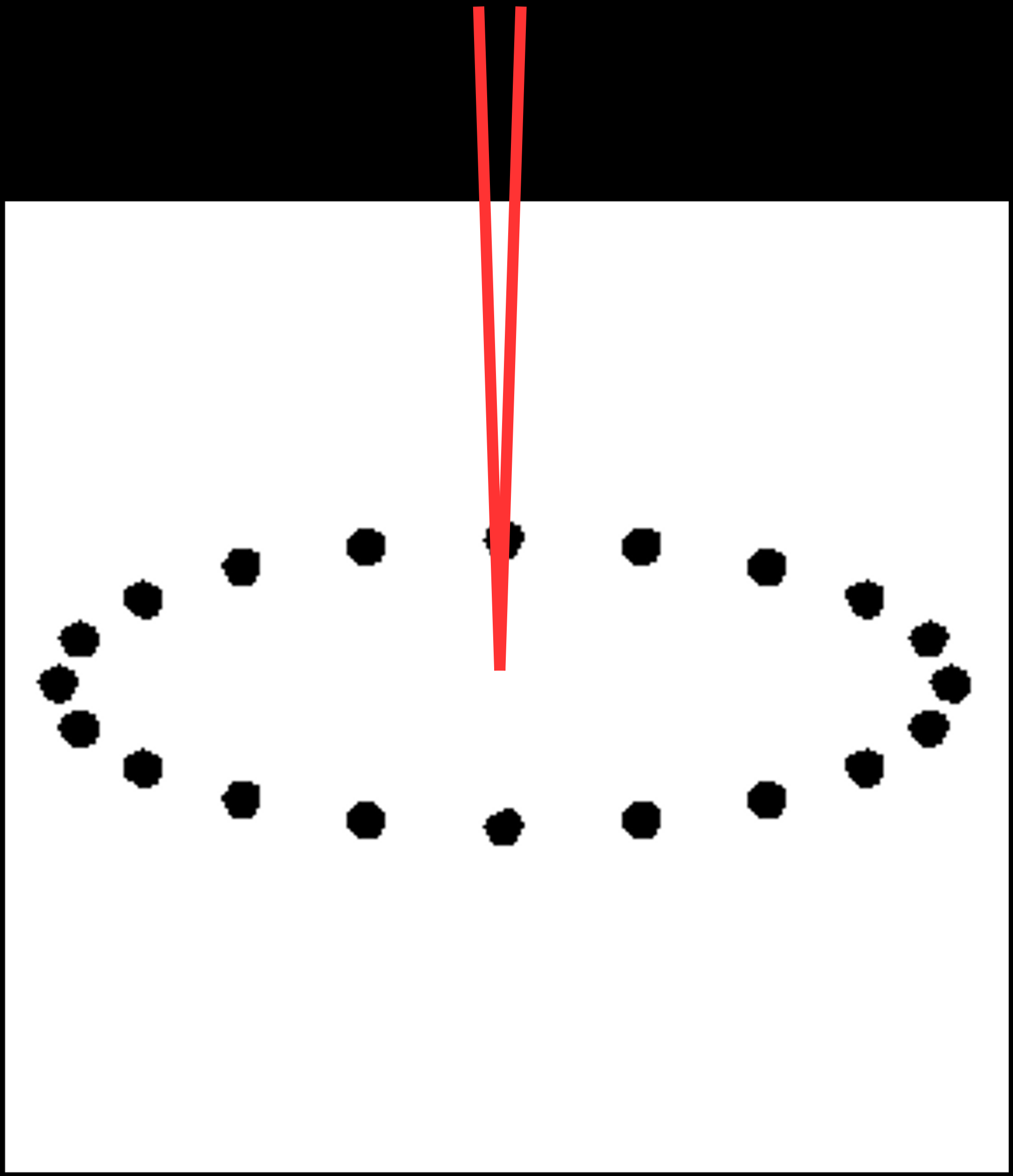
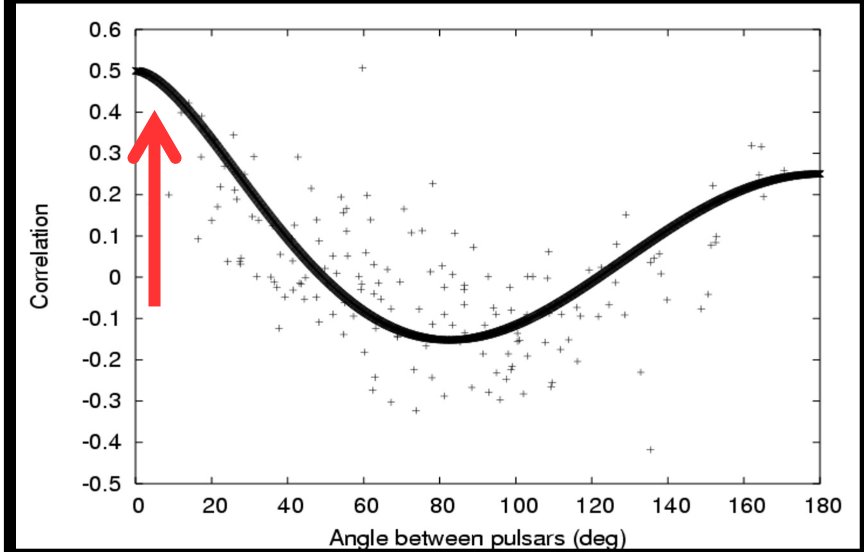
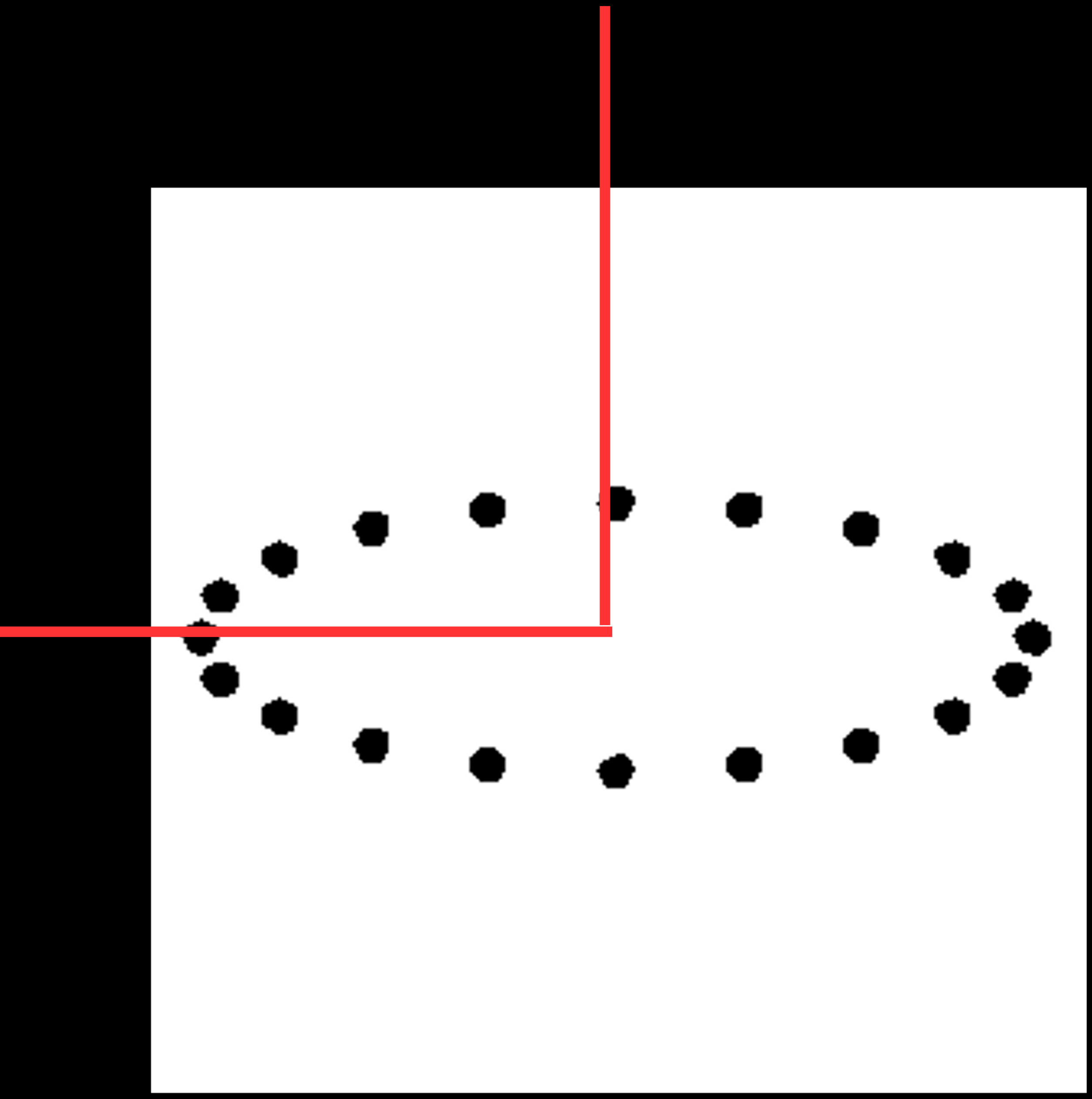


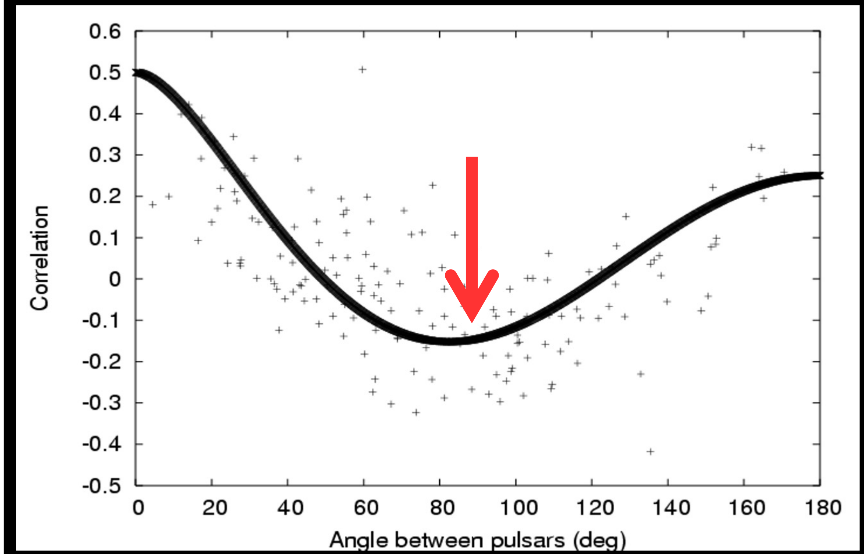

**(Hellings & Downs 1983)**



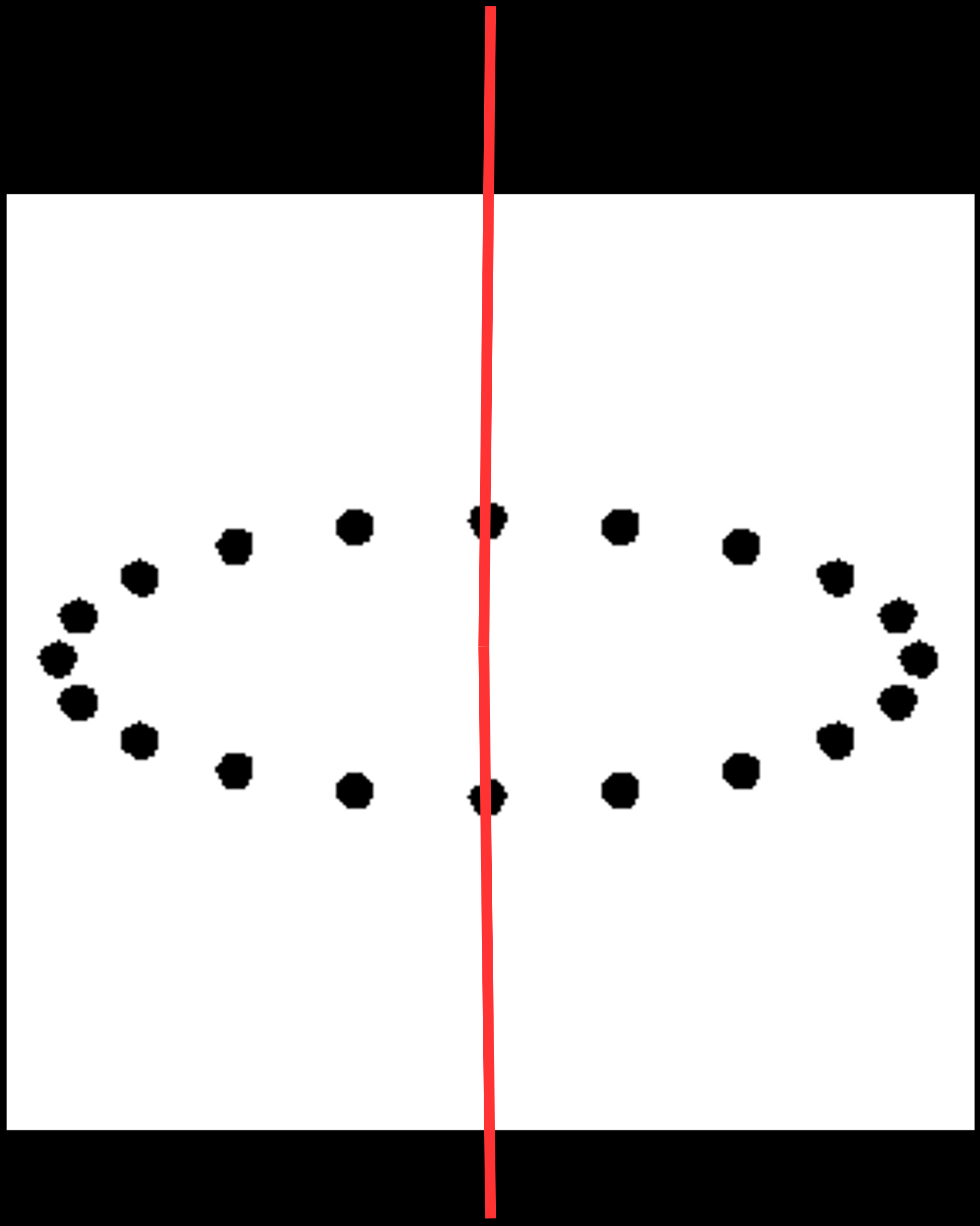


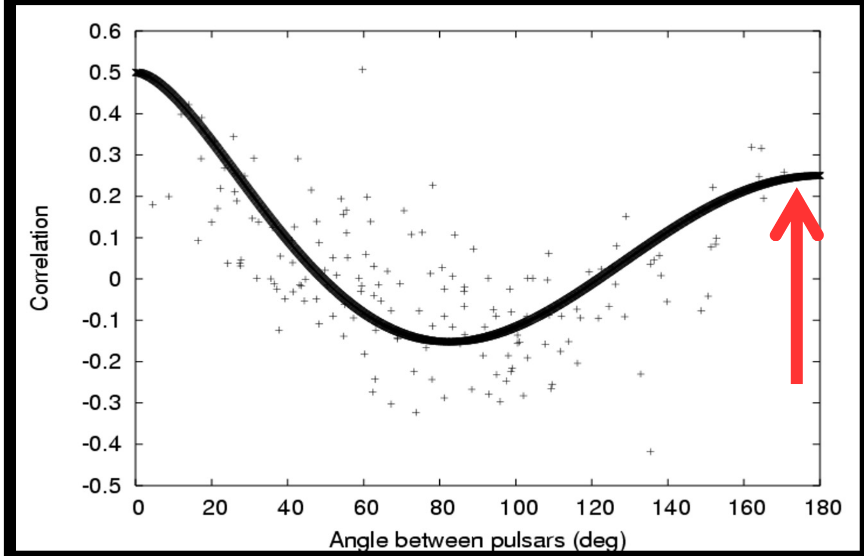
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Correlation
0
20
40
60
80
100
120
140
160
180
Angle between pulsars (deg)





Correlation
Angle between pulsars (deg)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
20
40
60
80
100
120
140
160
180

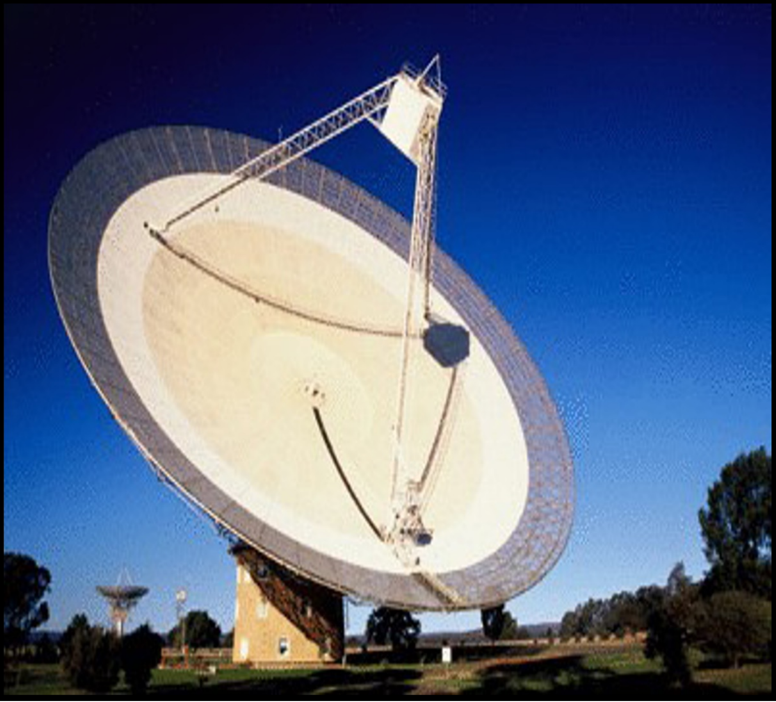



Correlation
Angle between pulsars (deg)

# A worldwide observational effort

**EPTA/LEAP** (Large European Array for Pulsars)

**NANOGrav** (North American nHz Observatory



**PPTA** (Parkes Pulsar Timing Array)

+InPTA (India)
+CPTA (China)
+MeerKAT (South Africa)

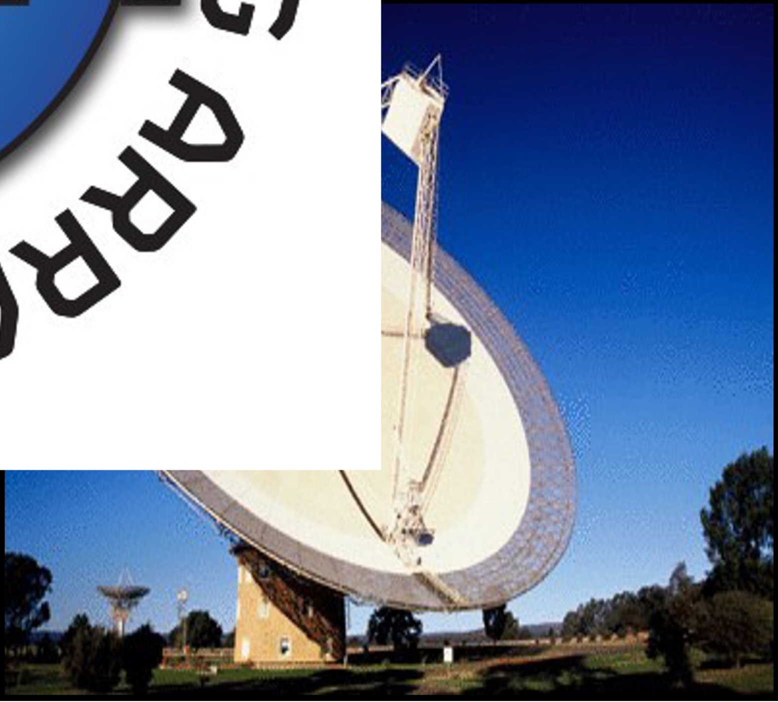
# *A worldwide observational effort*

**EPTA/LEAP** (La

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

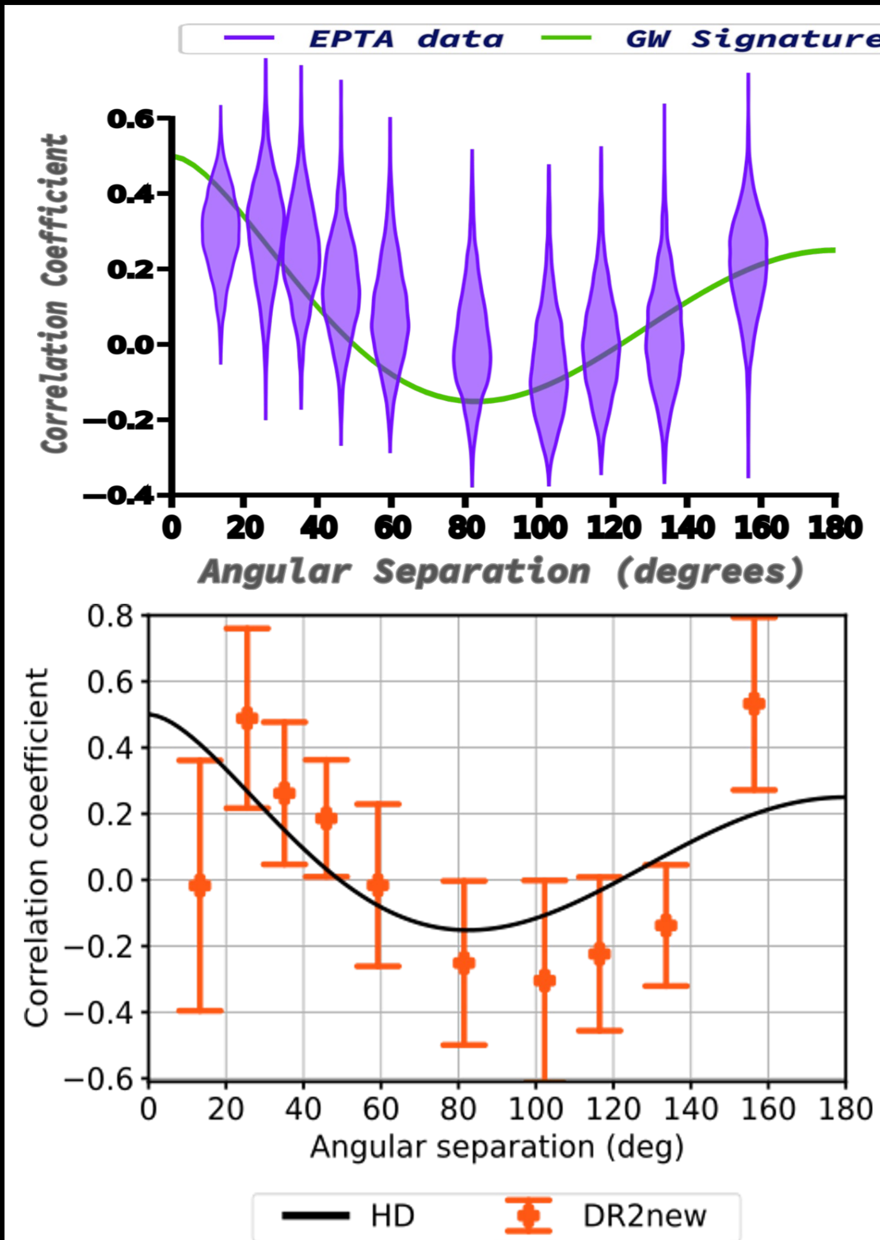
nHz Observatory



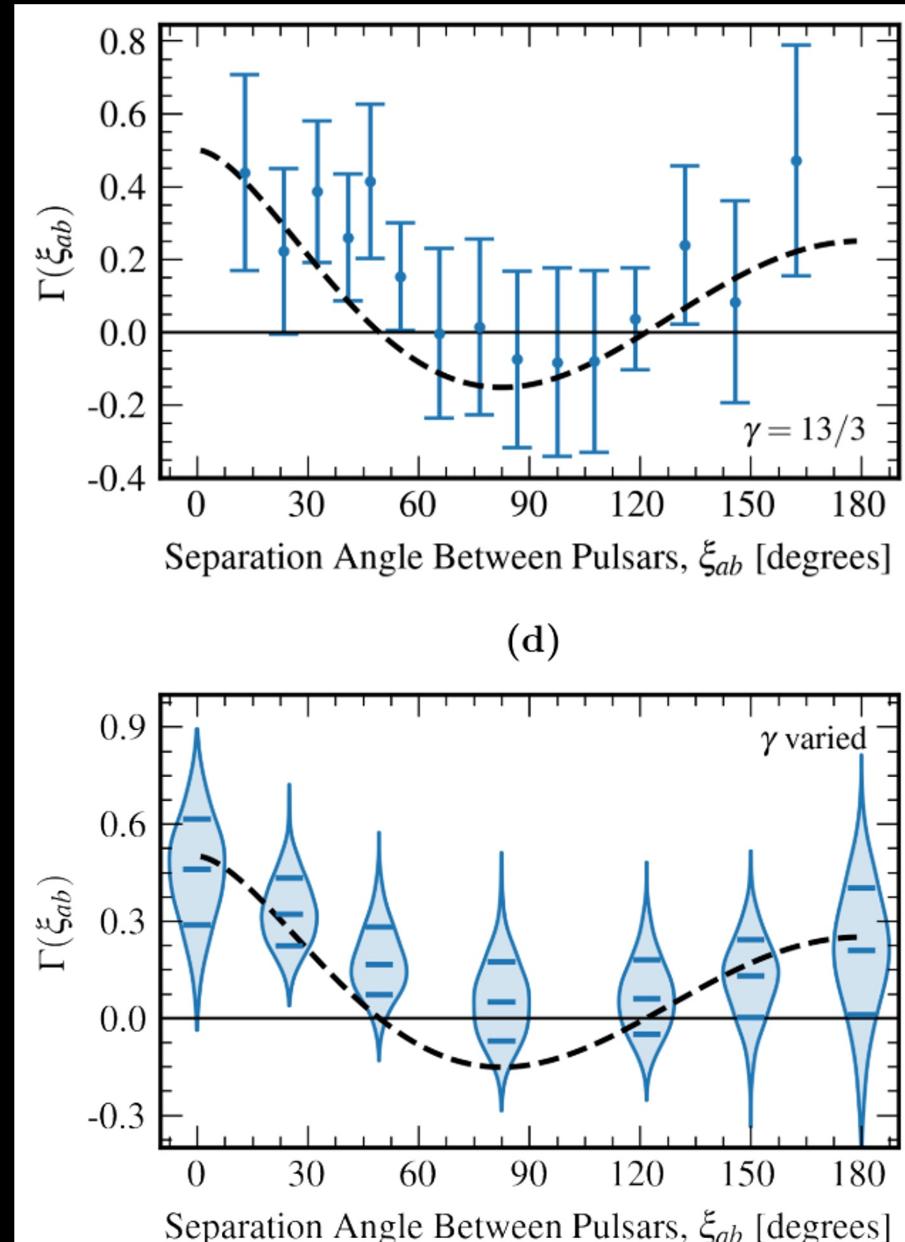
**PPT**

+InPTA (India)
+CPTA (China)
+MeerKAT (South Africa)

# Evidence for GW signal

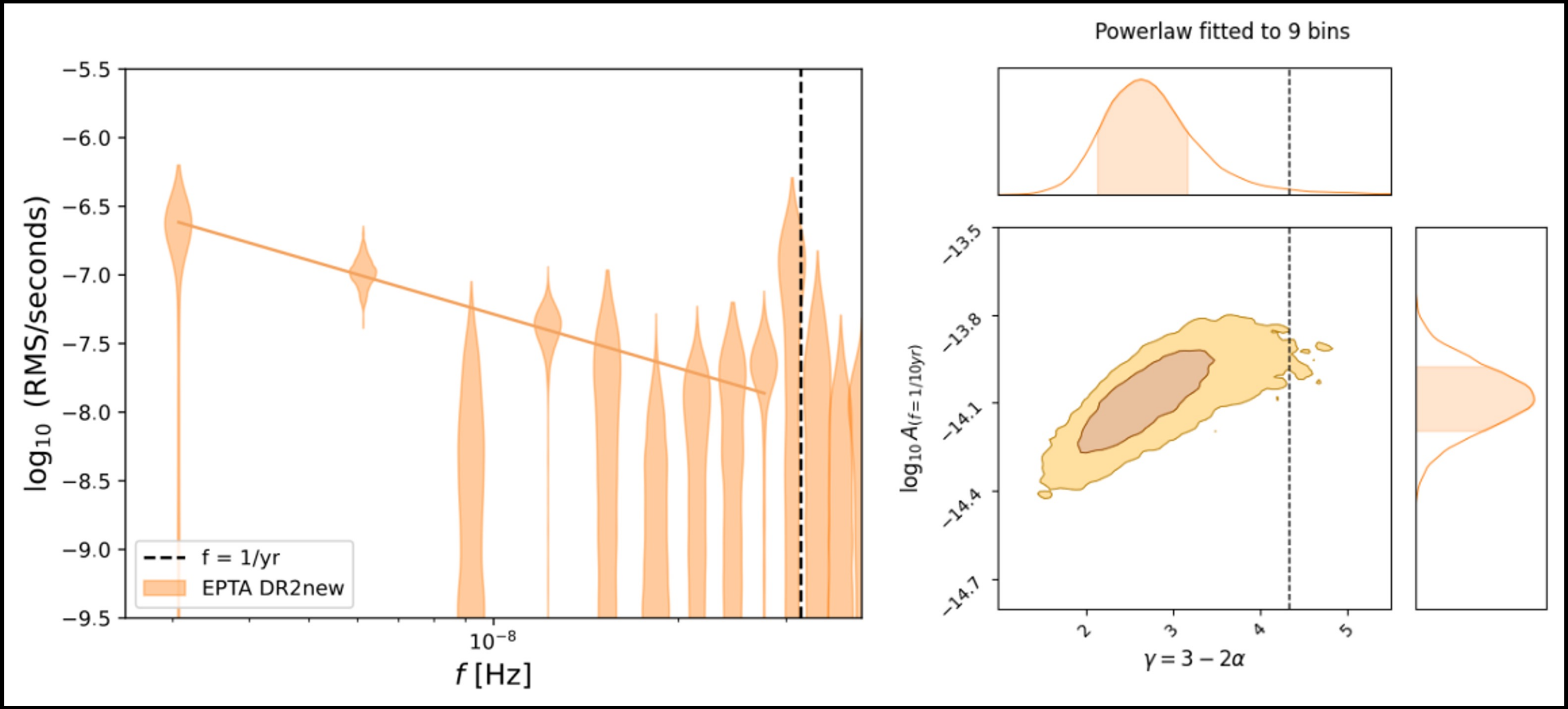



(Antoniadis+23)



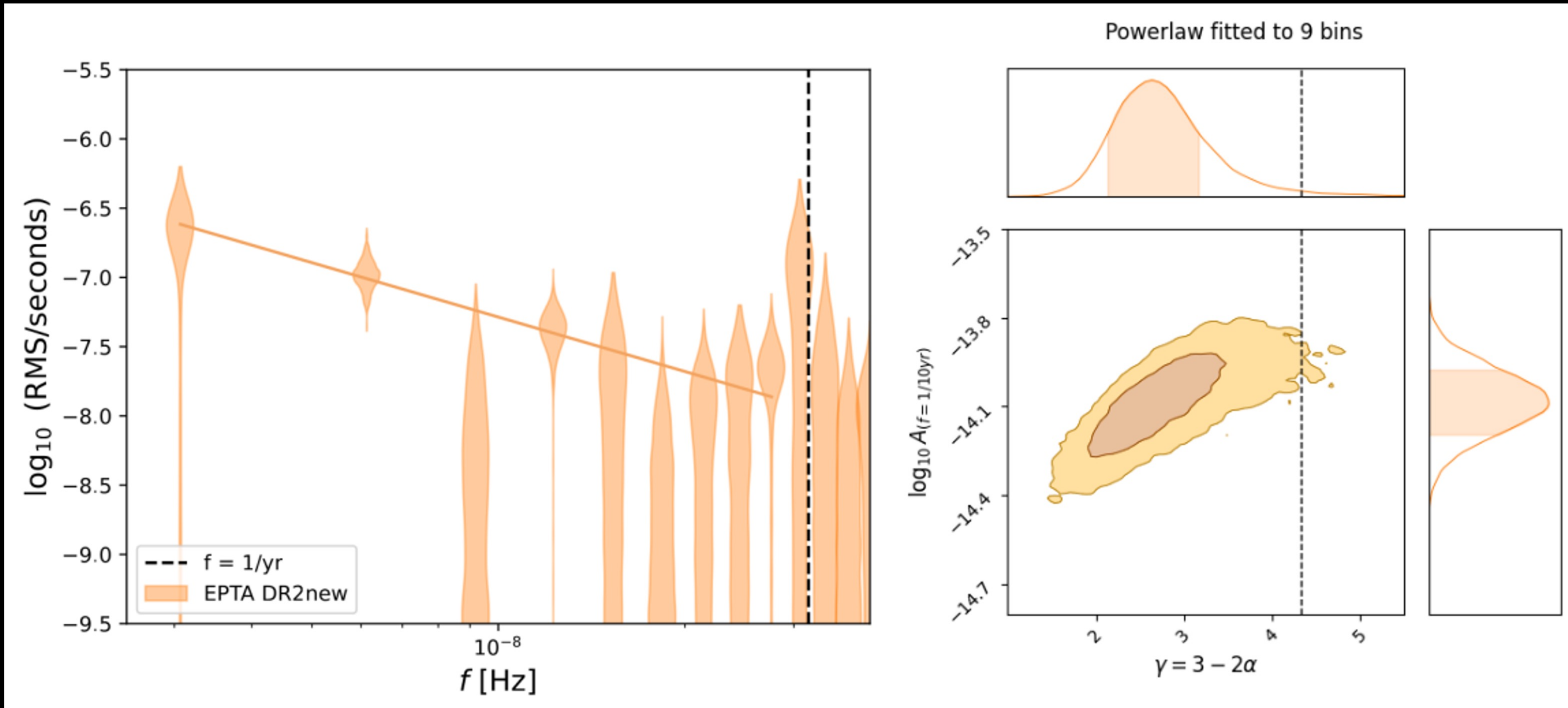

(Agazie+23)

# Results of EPTA DR2




- -4 dataset produced: using DR2new here (only new backend)
- -HD correlated signal favoured with Bayes factor~60
- -power constrained in few bins at low freq
- -powerlaw fit: $\gamma$~2.7 *A*~ -14 [*A*($\gamma$=13/3)~ -14.6]

# Results of EPTA DR2

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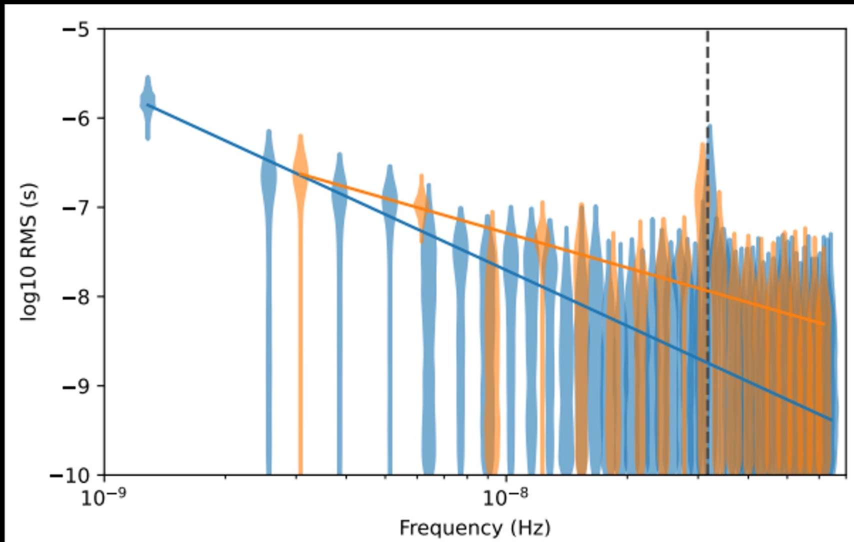
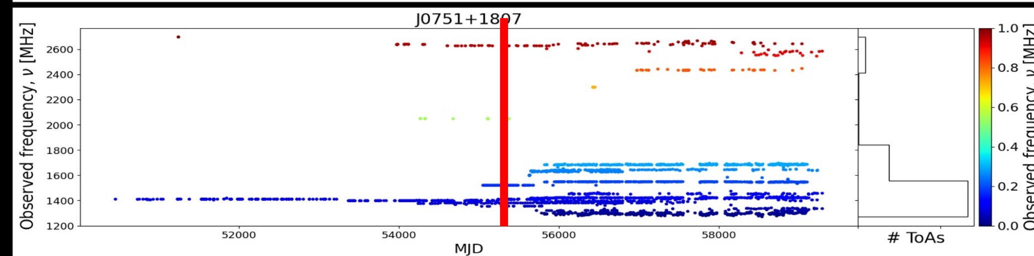
THINGS YOU HEAR: “too flat for SMBHBs [add your favorite early

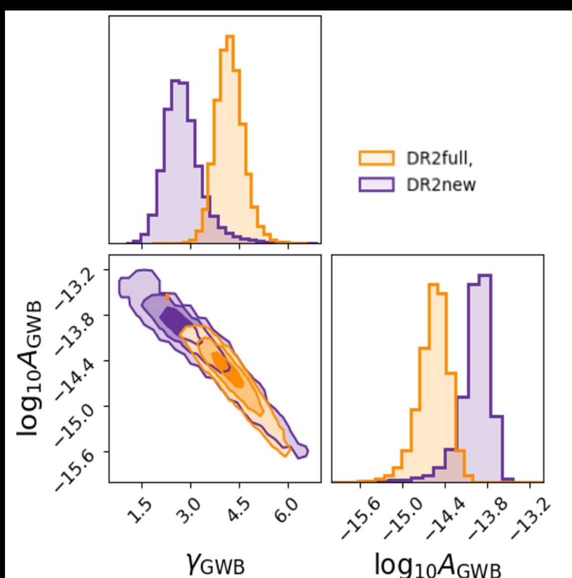
# EPTA DR2full vs DR2new

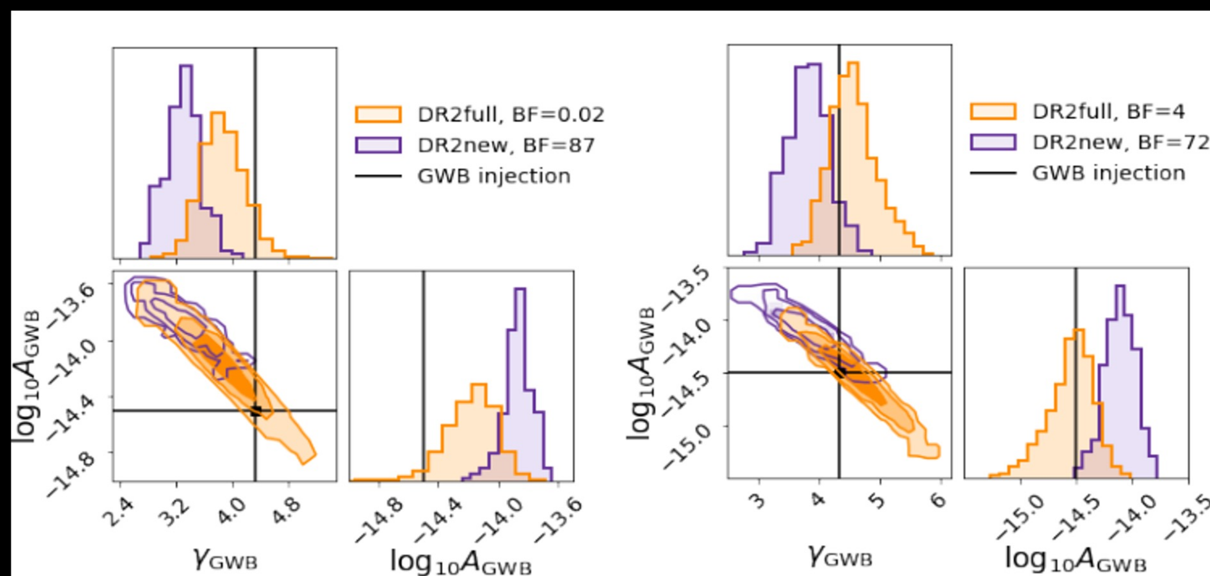



| ID | Model | DR2full ENTERPRISE | DR2full FORTYTWO | DR2full+ ENTERPRISE | DR2new ENTERPRISE | DR2new FORTYTWO | DR2new+ ENTERPRISE |
|---|---|---|---|---|---|---|---|
| 1 | PSRN + CURN | – | – | – | – | – | – |
| 2 | PSRN + GWB | 4 | 5 | 4 | 60 | 62 | 65 |
| 3 | PSRN + CLK | <0.01 | <0.01 | <0.01 | 0.2 | 1.2 | 0.3 |
| 4 | PSRN + EPH | <0.01 | $\sim 10^{-4}$ | <0.01 | 0.2 | 0.2 | 1.3 |
| 5 | PSRN + CURN + CLK | 2 | 1 | 2.7 | 0.8 | 2 | 1.6 |
| 6 | PSRN + CURN + EPH | 1 | 0.1 | 1 | 1 | 1 | 1.6 |
| 7 | PSRN + GWB + CURN | 3 | 3 | 4 | 27 | 13 | 25 |
| 8 | PSRN + GWB + CLK | 5 | 12 | 7 | 28 | 35 | 57 |
| 9 | PSRN + GWB + EPH | 3 | 3 | 3.6 | 33 | 29 | 43 |

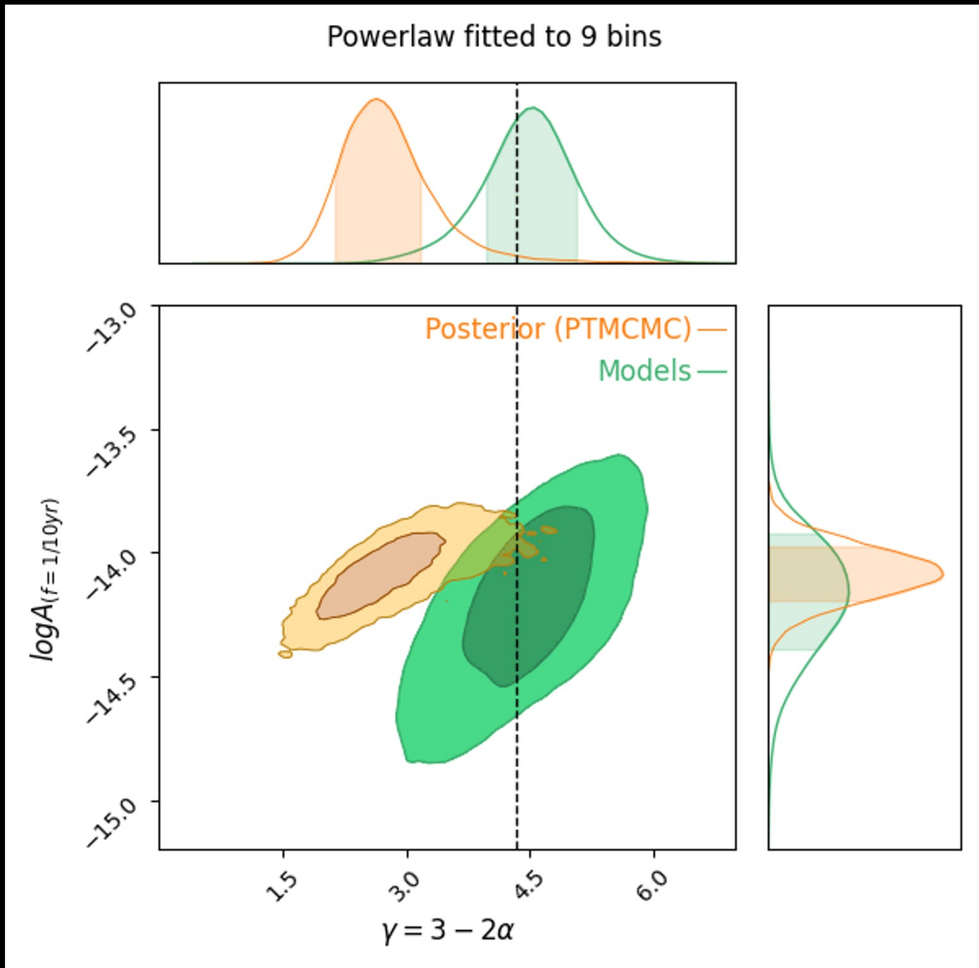



**DR2new yields higher significance despite having shorter baseline!**




**This is possible due to lack of frequency coverage in the old data** (Ferranti et al.




A- gamma plots broadly consistent

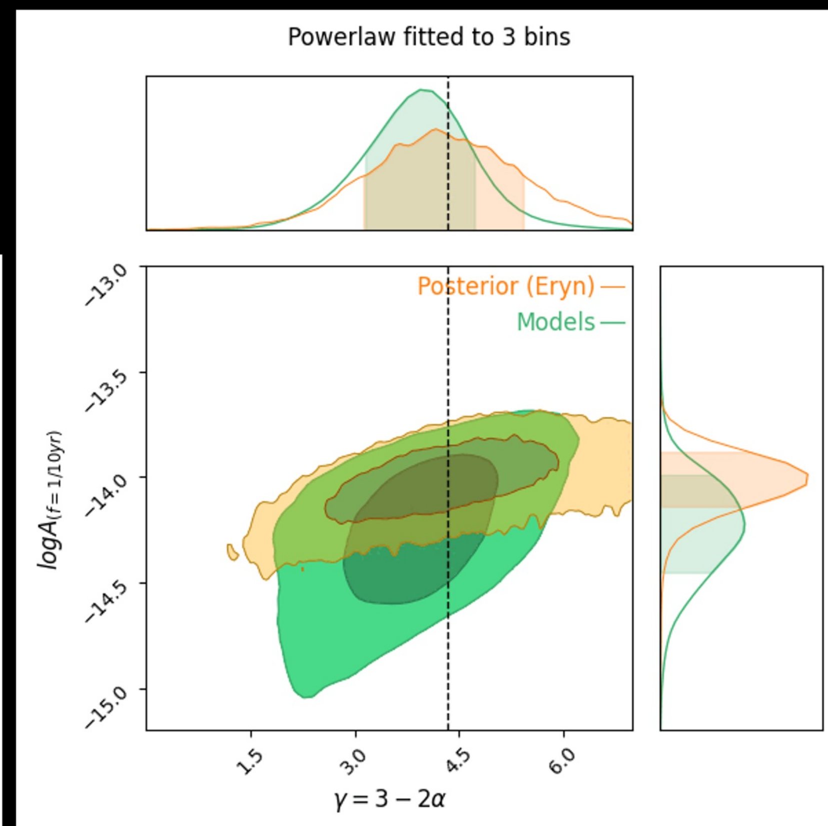
A normalized @1/10yr

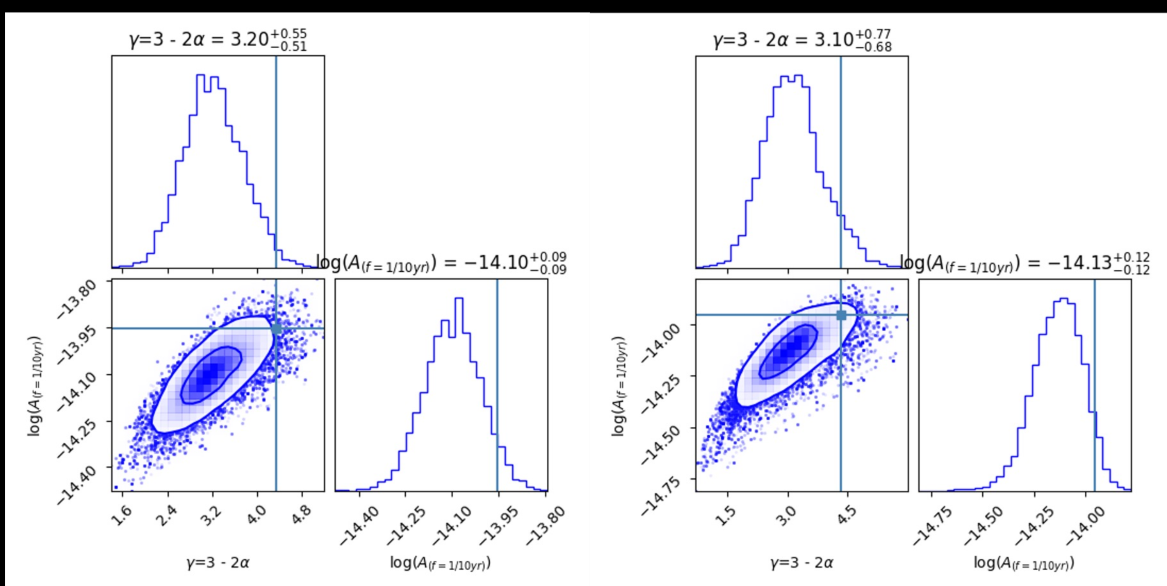
**Warning:**

-fits and mesurements depend on numbers o

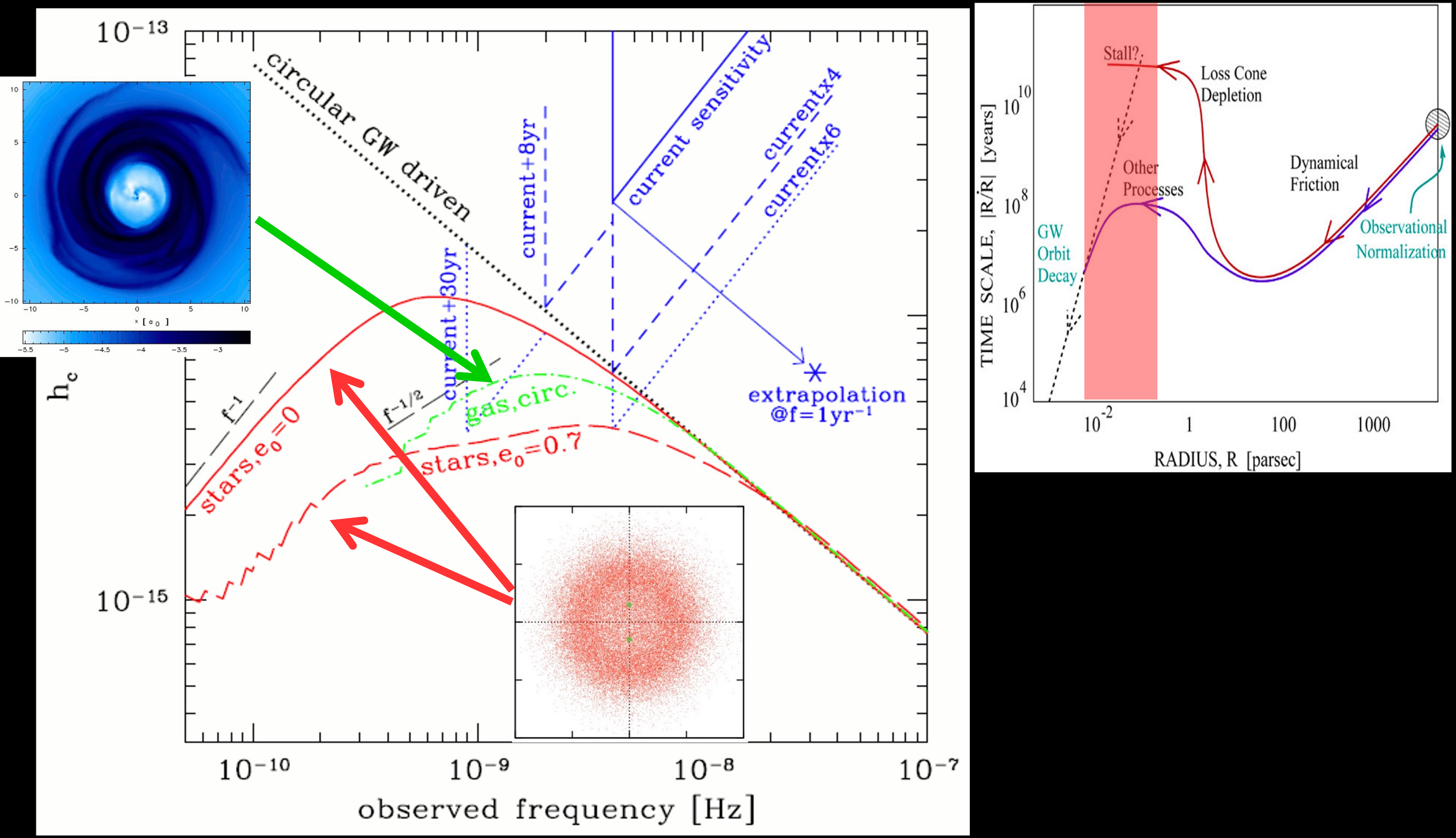
-mesured flat value could be due to low SNR

(Valtolina+24)



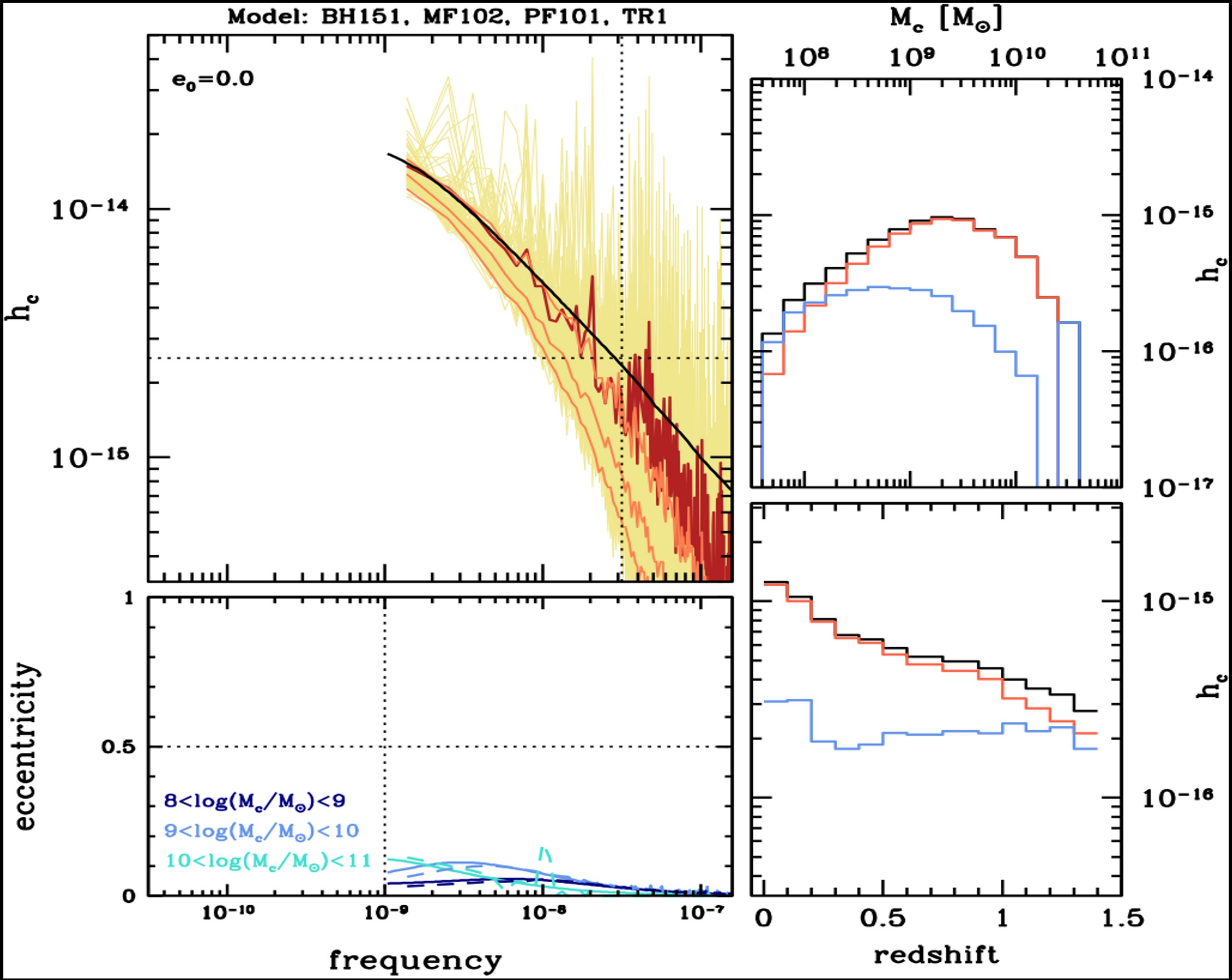



# Uncertainty in the GW background shape



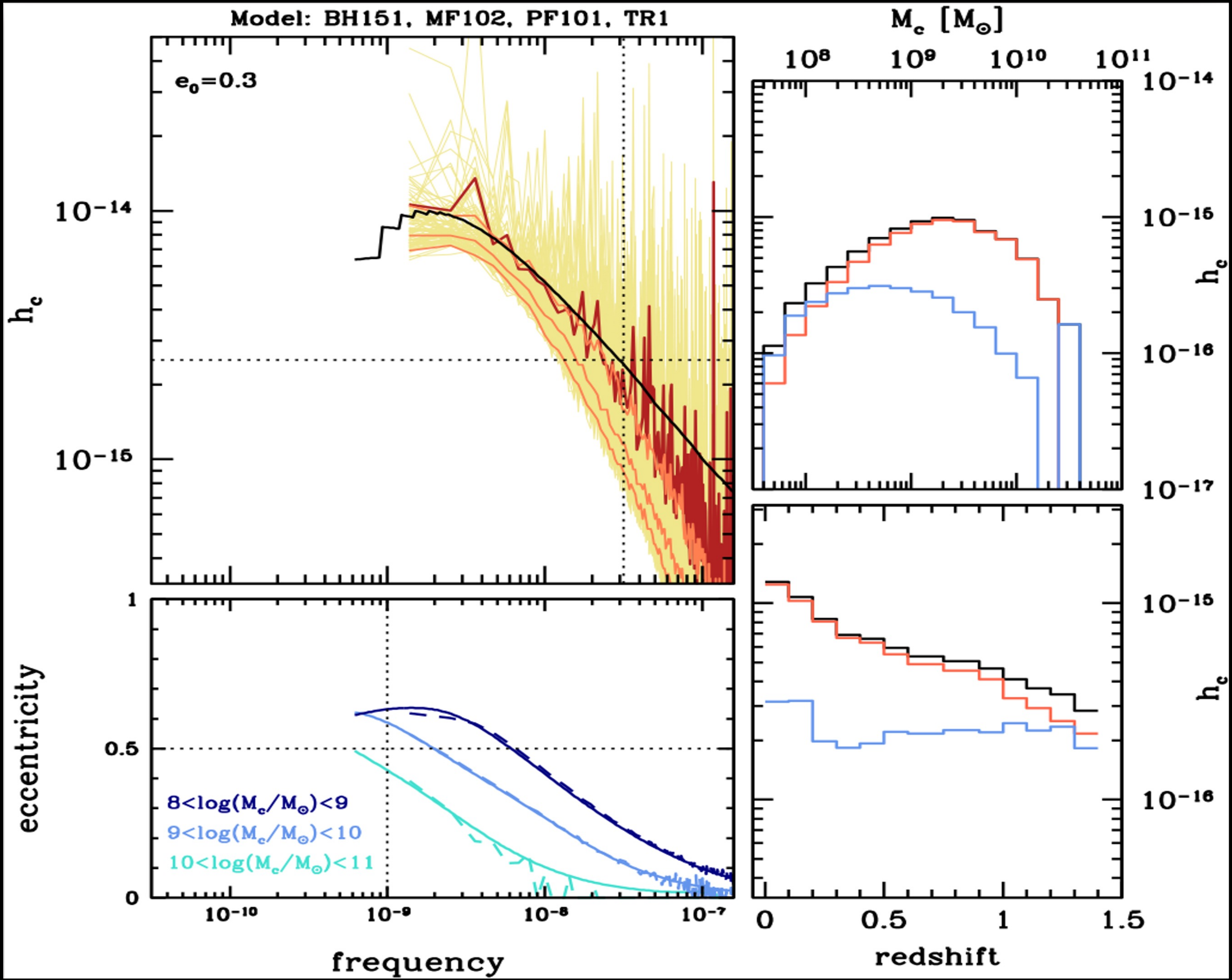

(Kocsis & AS 2011, AS 2013, Ravi et al. 2014, McWilliams et al. 2014)

# Eccentricity




It might even be the dominant effect for flattening.

# Eccentricity

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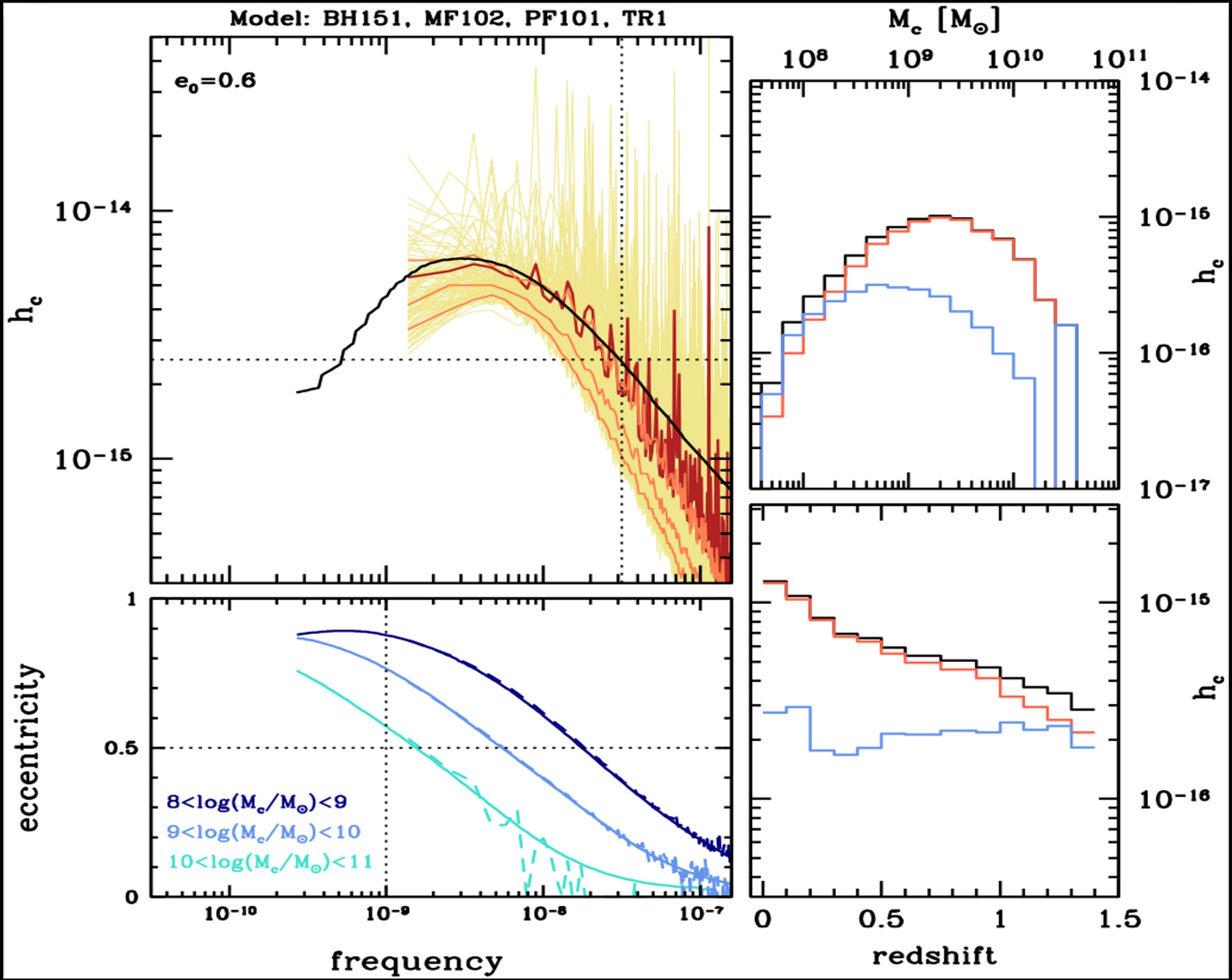


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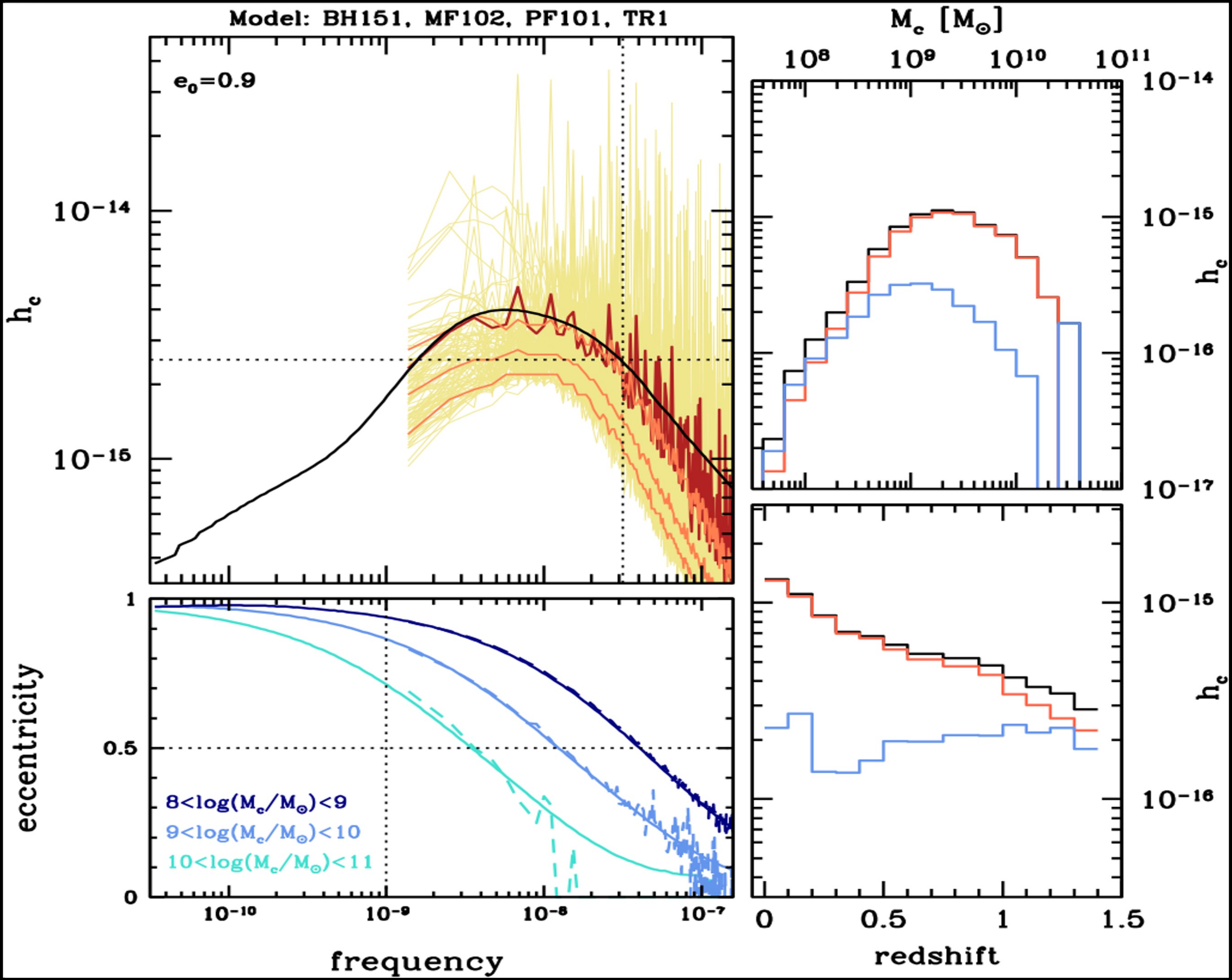
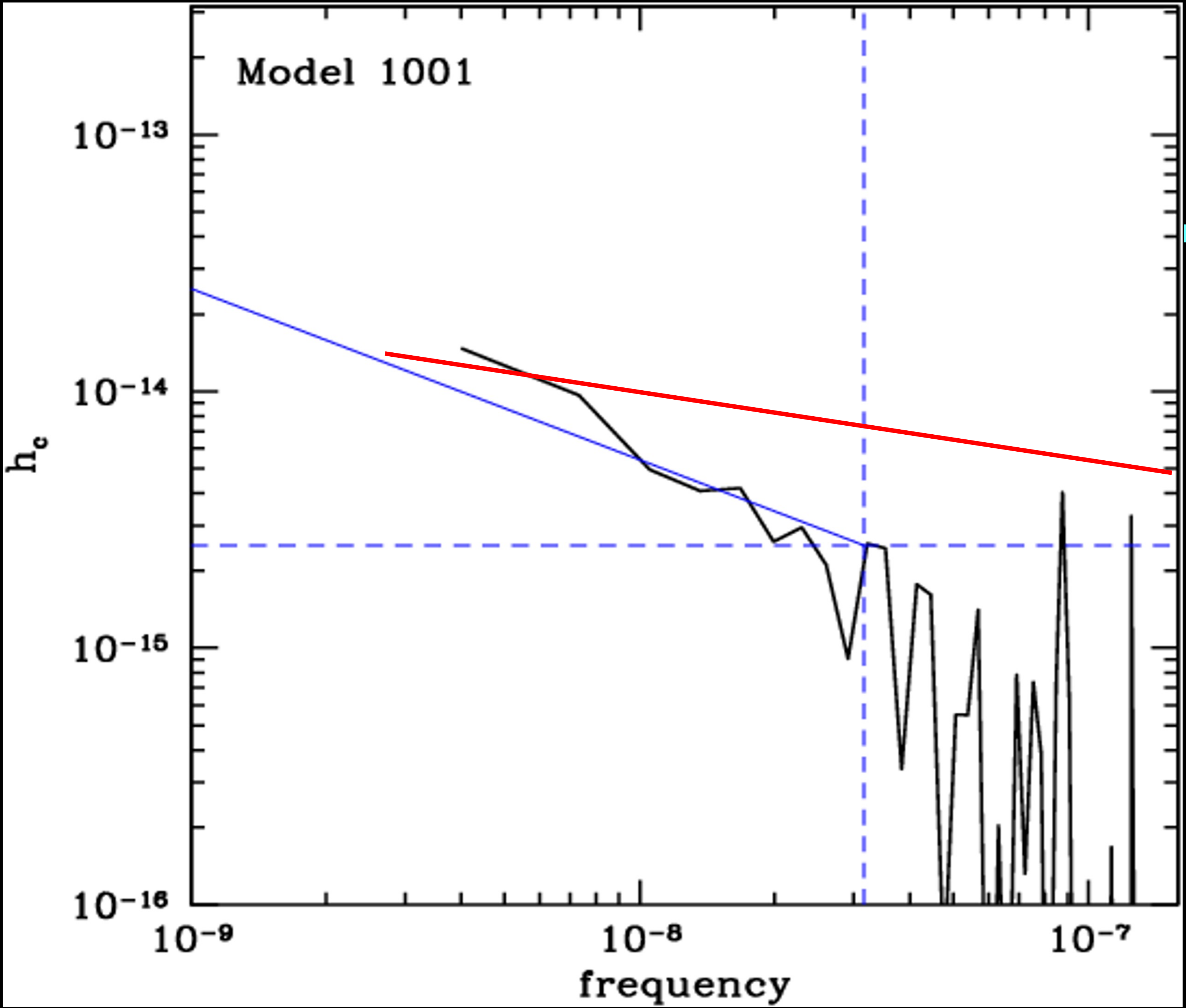


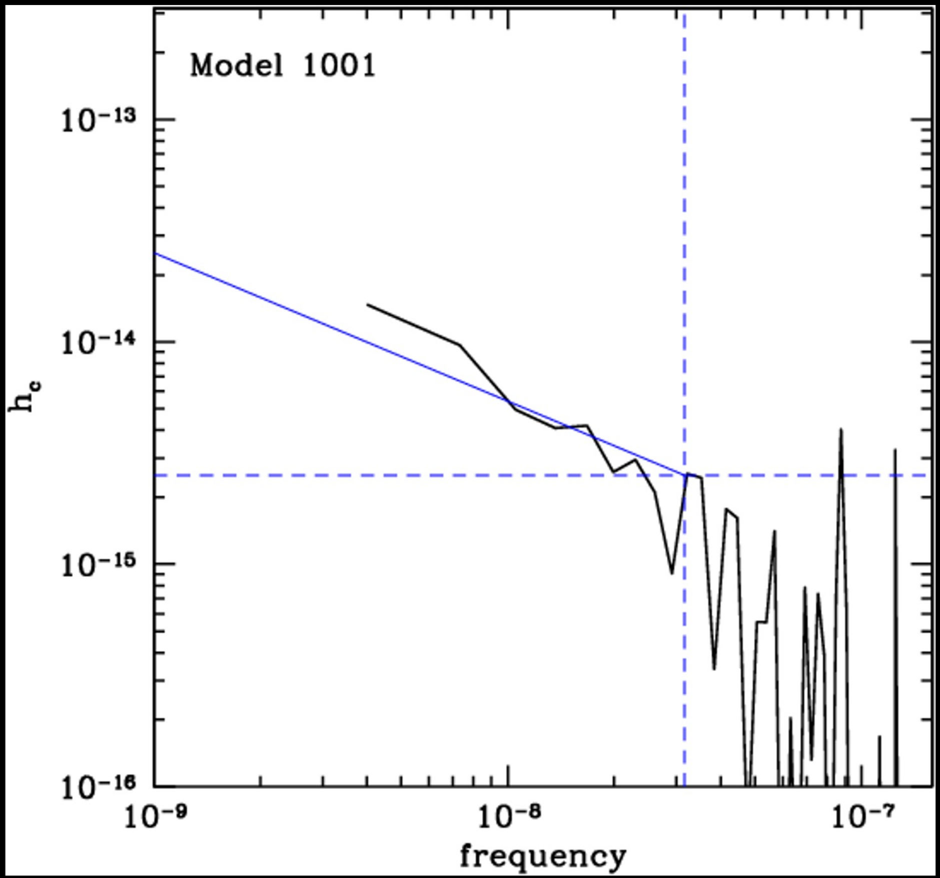

It might even be the dominant effect for flattening.

# Variance of the signal




me etc etc.

# Comparison with empirical models




Qualtitative comparison with Rosado+15 n

-Merger rate determined observationally (S13) via galaxy mass function, pair fractio

-constrained by observations

-adding hardening via stars and eccentrici

324k MC realizations

-captures signal variance

-capture resolvable sources

$$h_c^2(f) = \int dMdqdz \frac{\partial^4 N}{\partial M \, \partial q \, \partial z \, \partial \ln f_p} h_s^2(f_p)$$

$$\frac{\partial^3 \eta_{\text{gal-gal}}}{\partial m_{\star 1} \, \partial q_\star \, \partial z} = \frac{\Psi(m_{\star 1}, z')}{m_{\star 1} \ln(10)} \frac{P(m_{\star 1}, q_\star, z')}{T_{\text{gal-gal}}(m_{\star 1}, q_\star, z')} \frac{\partial t}{\partial z'}$$

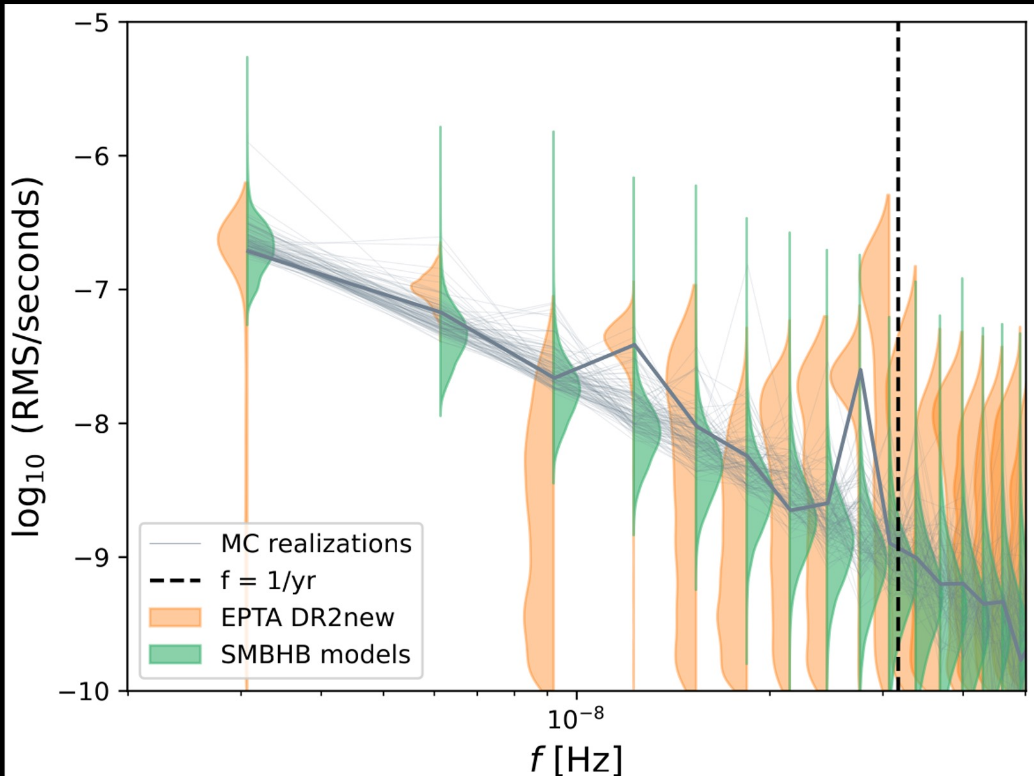
$$\Psi(m_{\star 1}, z) = \ln(10) \, \Psi_0 \cdot \left[\frac{m_{\star 1}}{M_\psi}\right]^{\alpha_\psi} \exp\left(-\frac{m_{\star 1}}{M_\psi}\right)$$

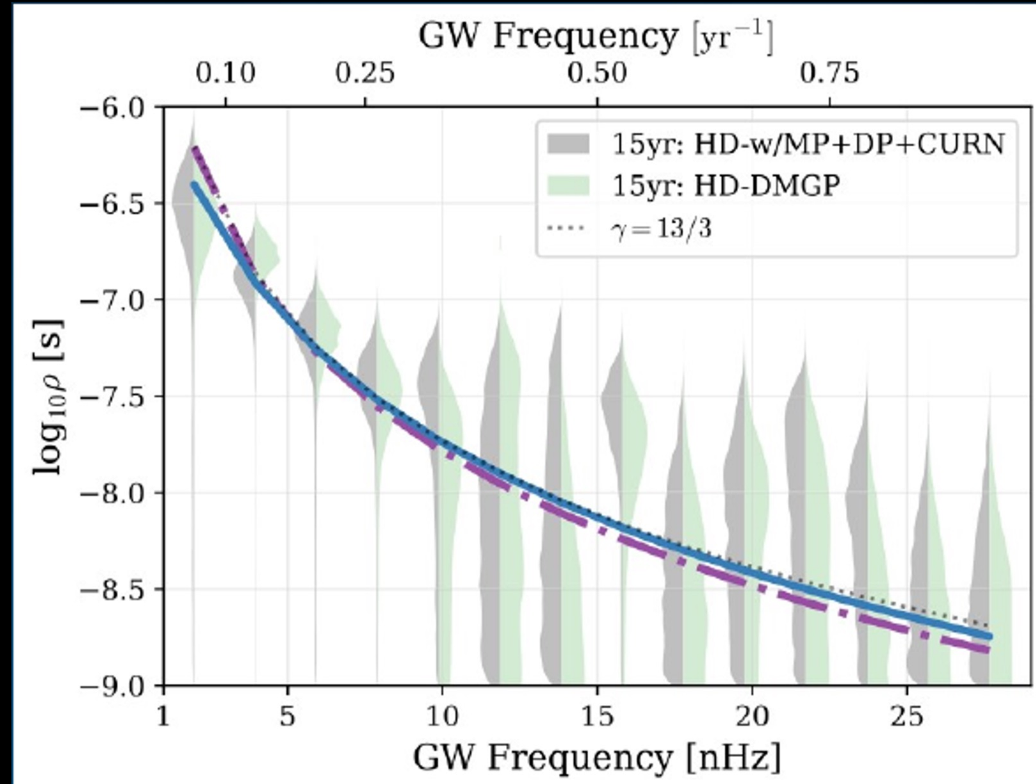
$$P(m_{\star 1}, q_\star, z') = P_0 \left(\frac{m_{\star 1}}{10^{11} \, \mathrm{M}_\odot}\right)^{\alpha_p} (1+z)^{\beta_p} \, q^{\gamma_p}$$

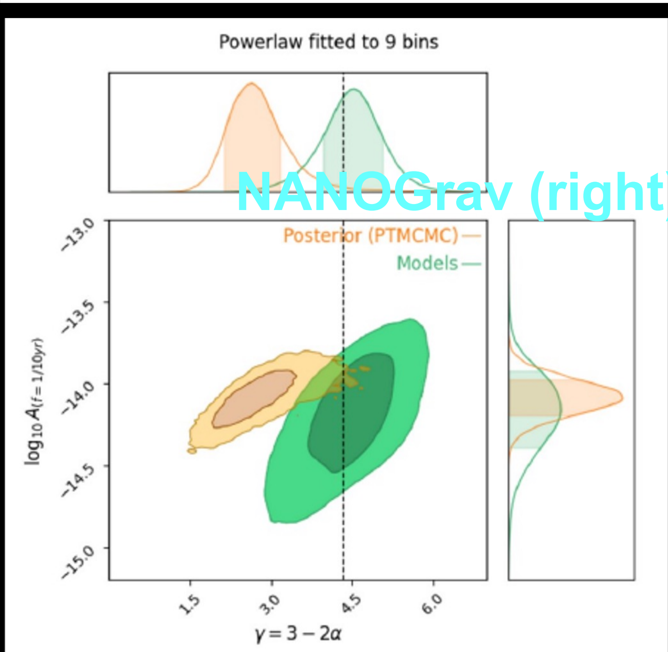
$$T_{\text{gal-gal}}(m_{\star 1}, q_\star, z') = T_0 \left(\frac{m_{\star 1}}{10^{11} \, \mathrm{M}_\odot / h}\right)^{\alpha_t} (1+z)^{\beta_t} \, q^{\gamma_t}$$

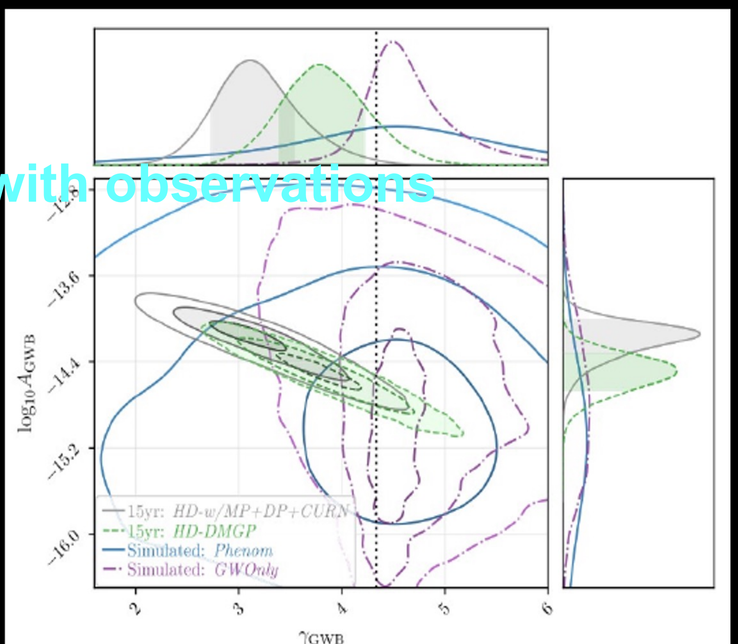
$$\log_{10}(M_{\mathrm{BH}}/\mathrm{M}_\odot) = \mu + \alpha_\mu \log_{10}\left(\frac{M_{\text{bulge}}}{10^{11} \, \mathrm{M}_\odot}\right) + \mathcal{N}(0, \epsilon_\mu)$$

# Spectral comparison



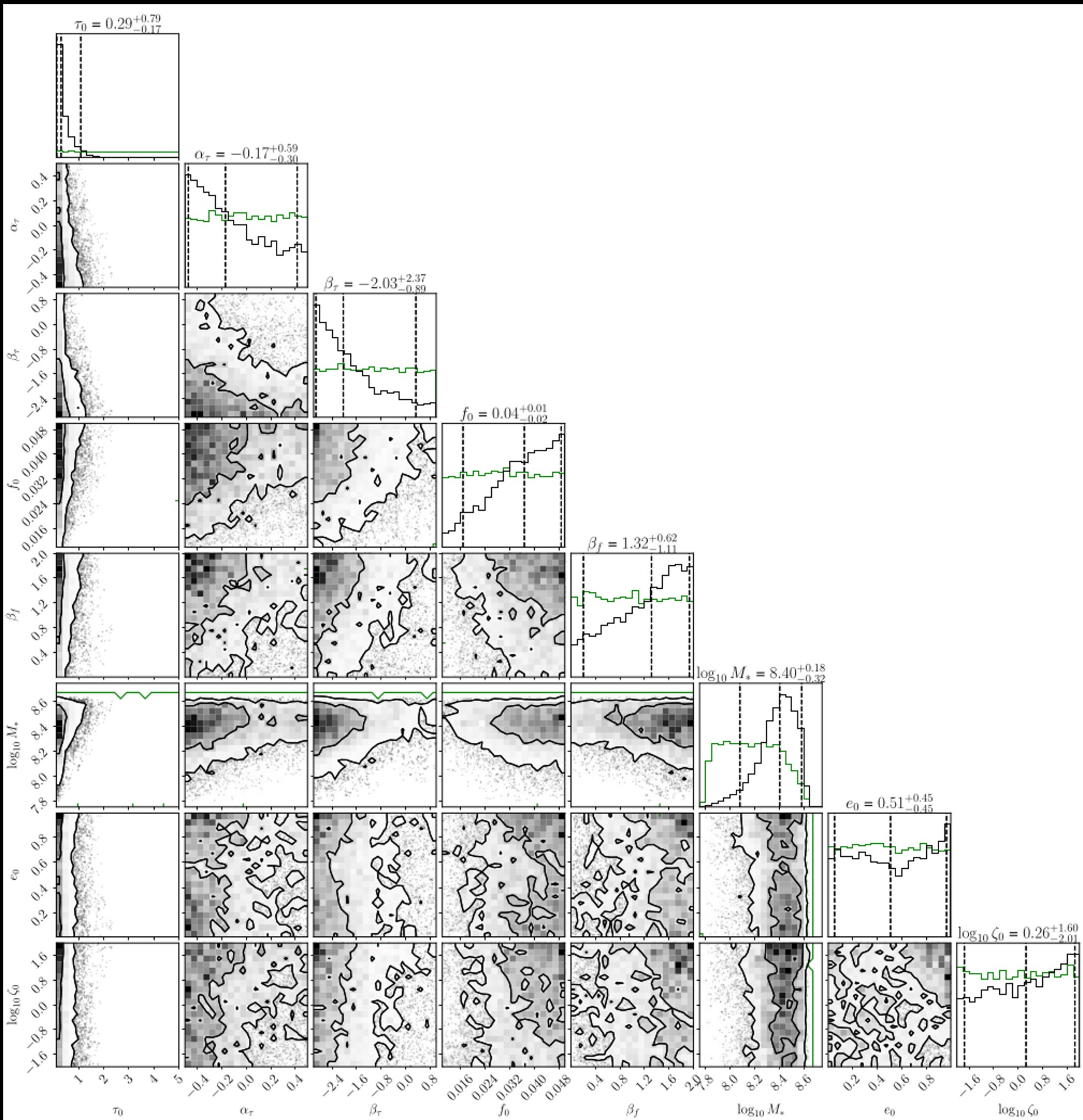




**EPTA (left) and NANOGrav (right) results pretty compatible with observations**

**(Agazie+23, Antoniadis+24)**




**Astro constrained models (Ch**

**-generalization of R**

**-informed by observations:**

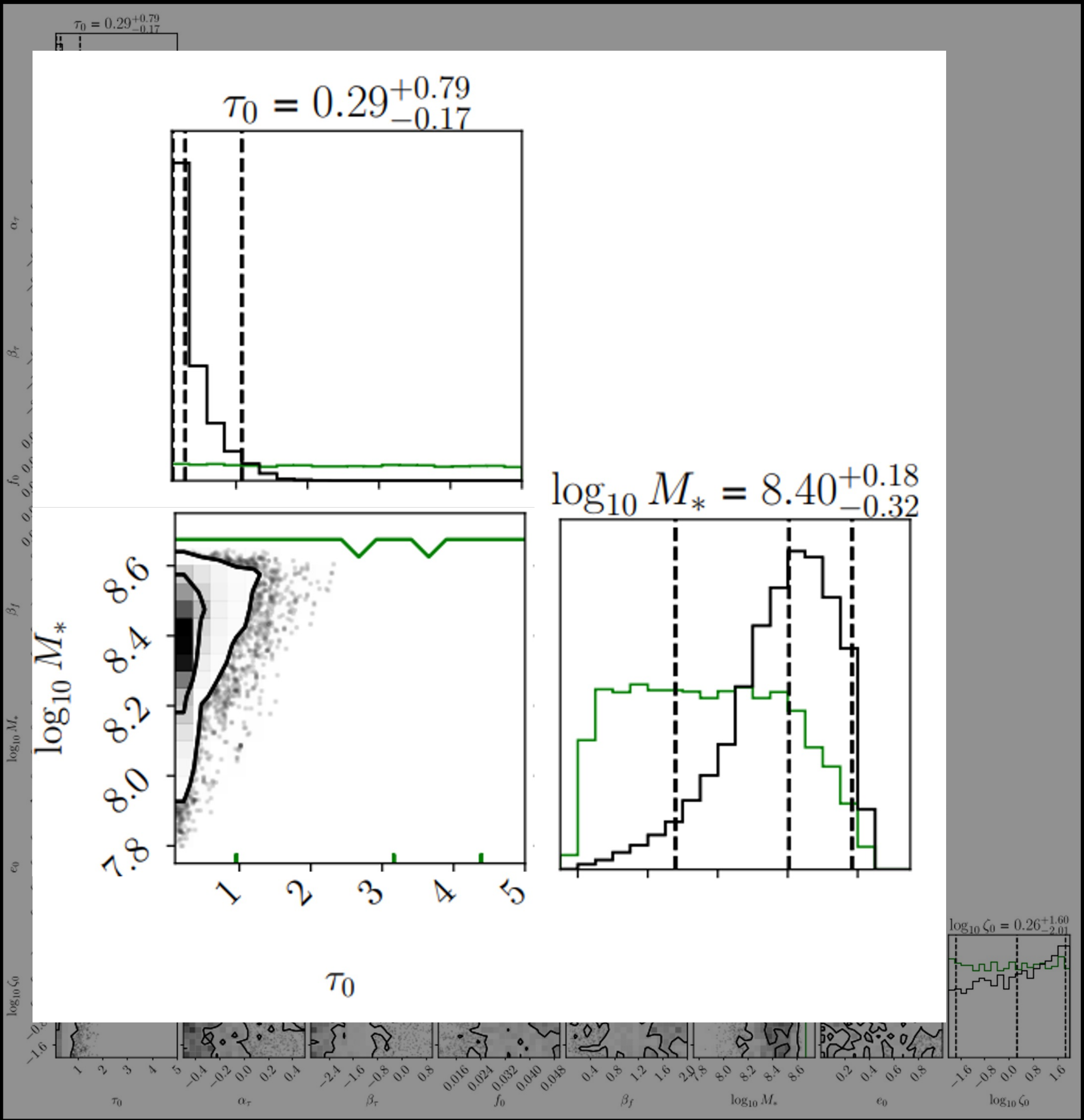
**-Galaxy mass function**

**-Galaxy pair fraction**

**-SMBHB merger timescale**

**-SMBH-galaxy relation**

**-eccentricity and environment**

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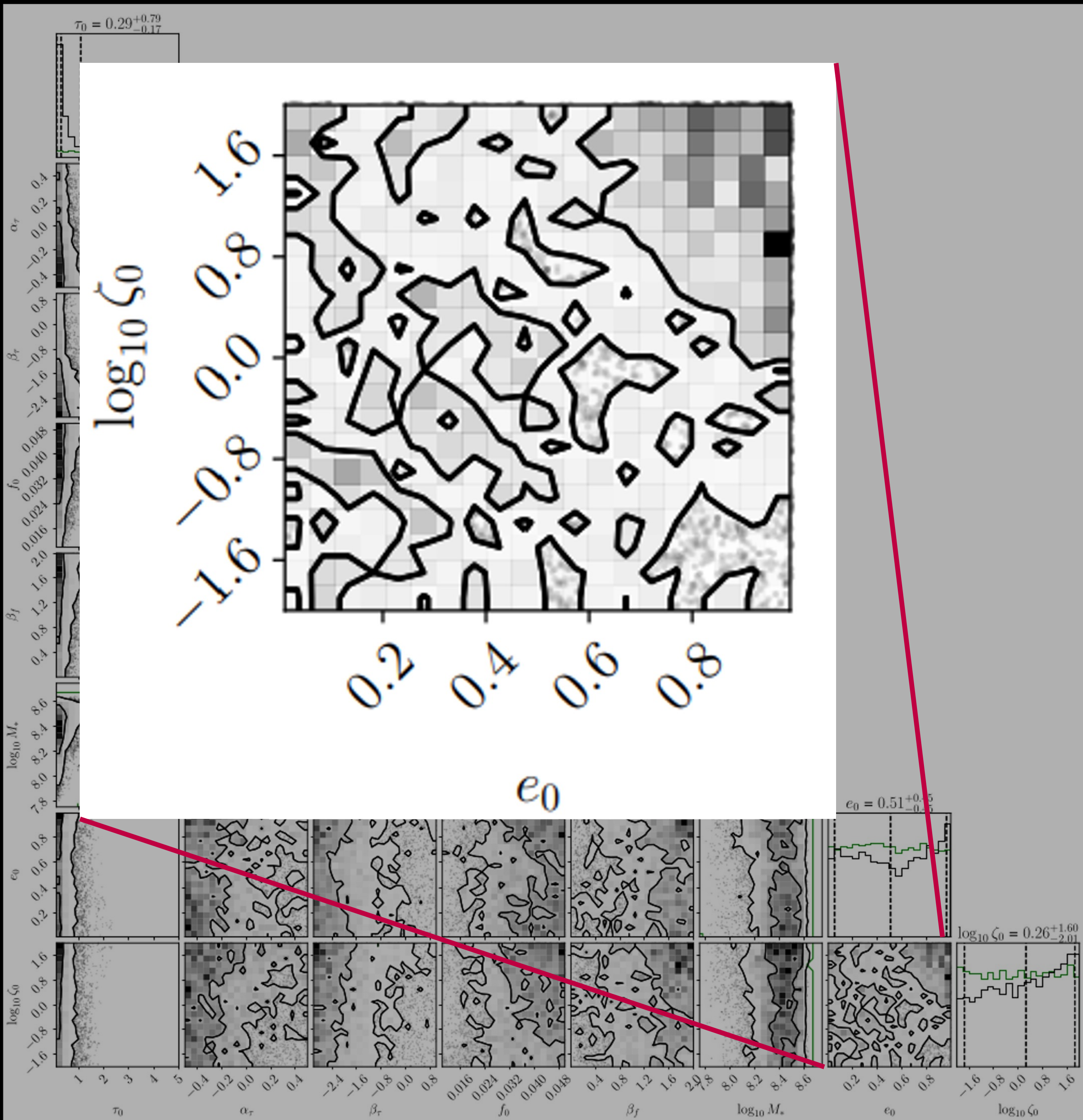
**Best constrains:**
**-SMBHB time to merger**
**-SMBH – $M_*$ relation**

**SMBHB are massive and merge frequently**

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**-SMBH-galaxy relation**

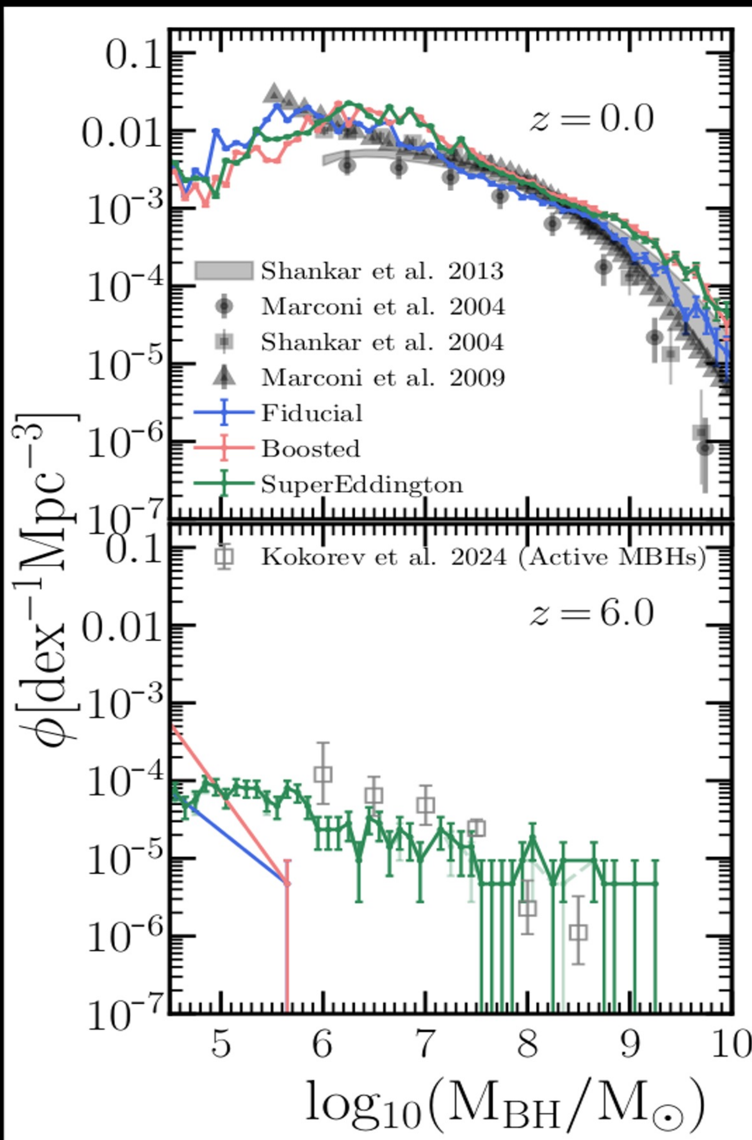
**-eccentricity and environment**

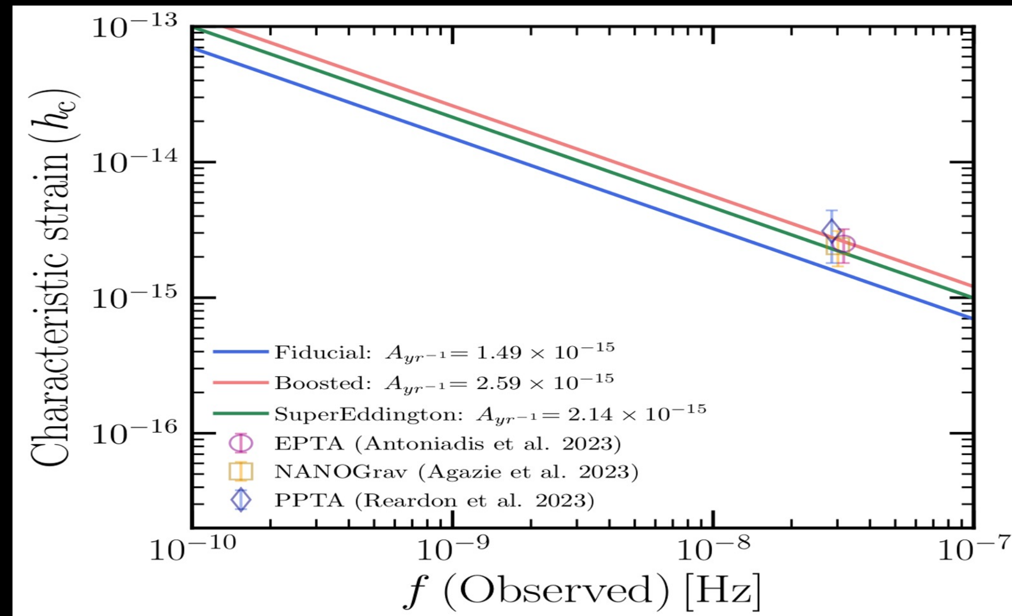
**Best constrains:**
**-SMBHB time to merger**
**-SMBH – $M_*$ relation**

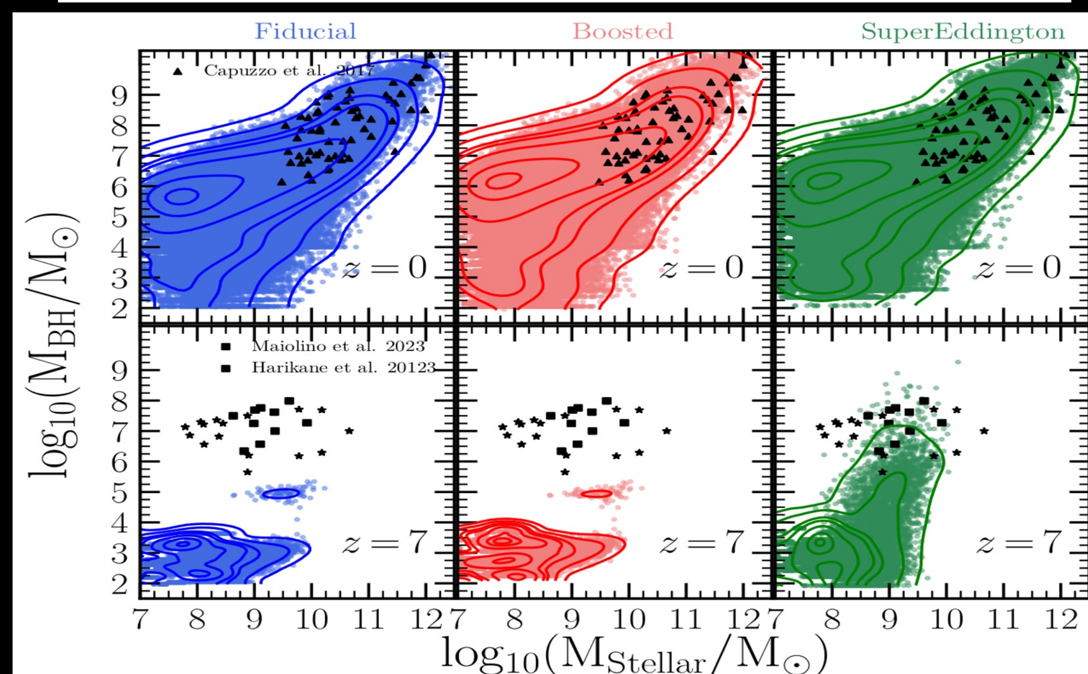
**-Slight preference for eccentri**

# Accomodating low and high z constraints

## Adding a short phase of supereddington accretion in the most

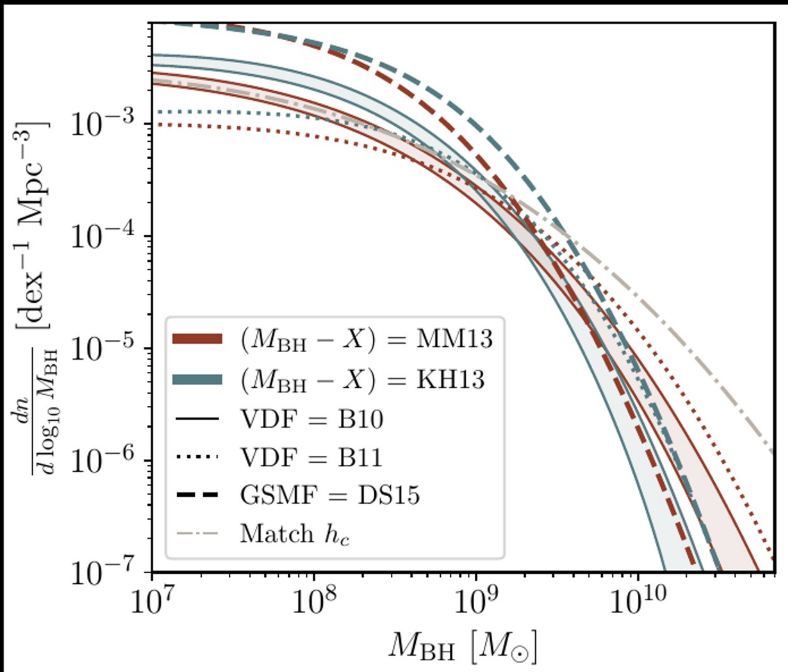


# Constraining the local MBH mass function

(Phinney 2001, Sato Polito+23,24, Liepold & Ma24)




$$h_c^2(f) = \frac{4G}{\pi f^2}\langle(1+z)^{-1/3}\rangle \int dM_{\rm BH}\phi(M_{\rm BH})M_{\rm BH}\langle\epsilon\rangle(M_{\rm BH})$$

-MBH buildup merger driven

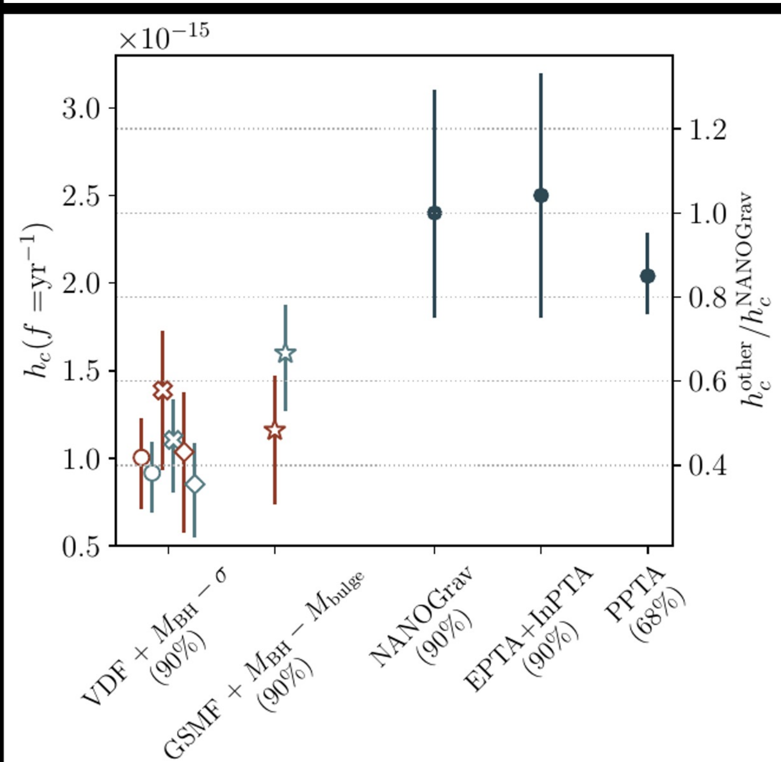
-GWB mostly determined by the local mass function

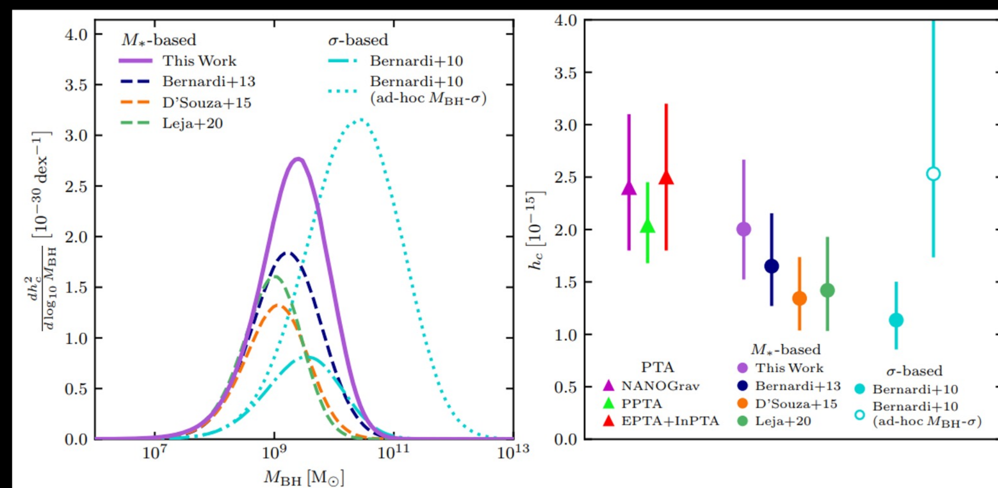
~2 discrepancy (2σ):

-mild dependence on redshift and efficiency

-effect of multiple mergers

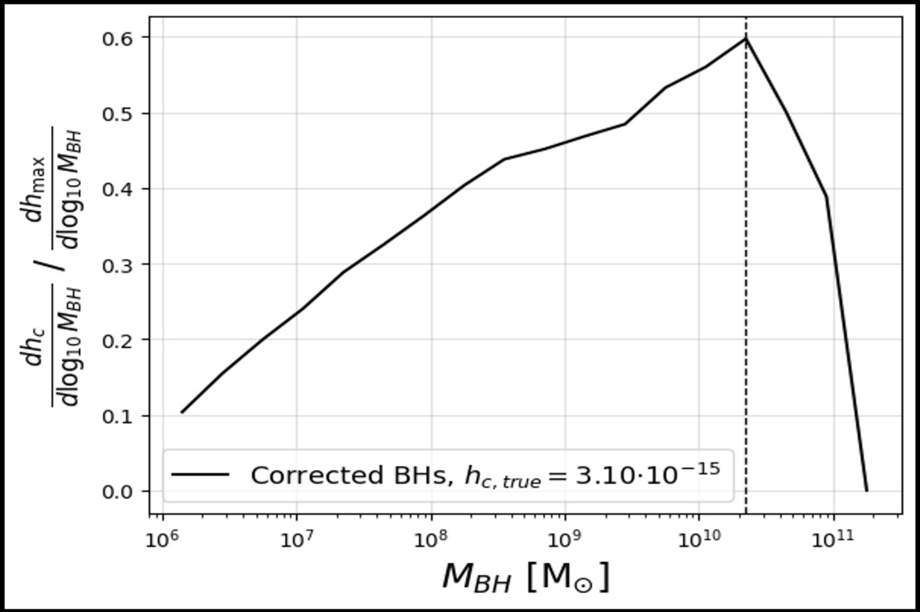
PTA can determine the local mass MBH function?

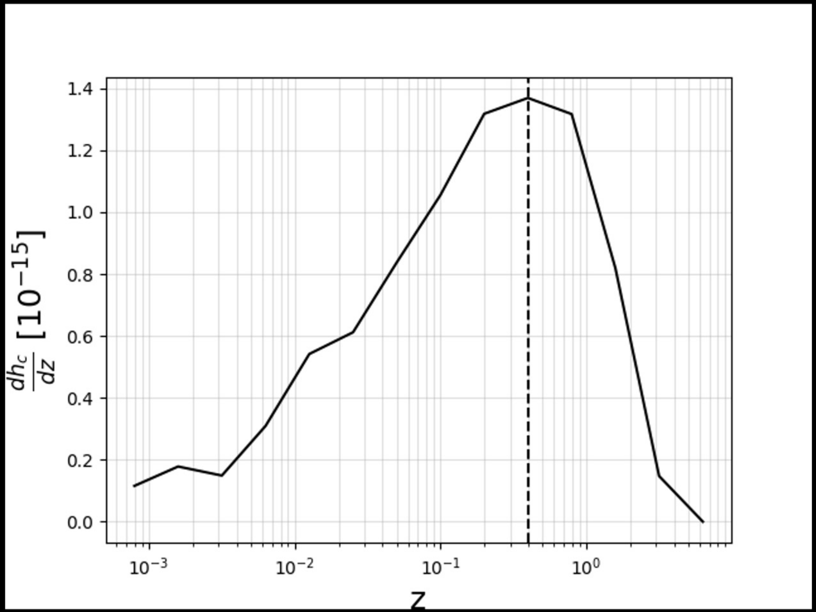


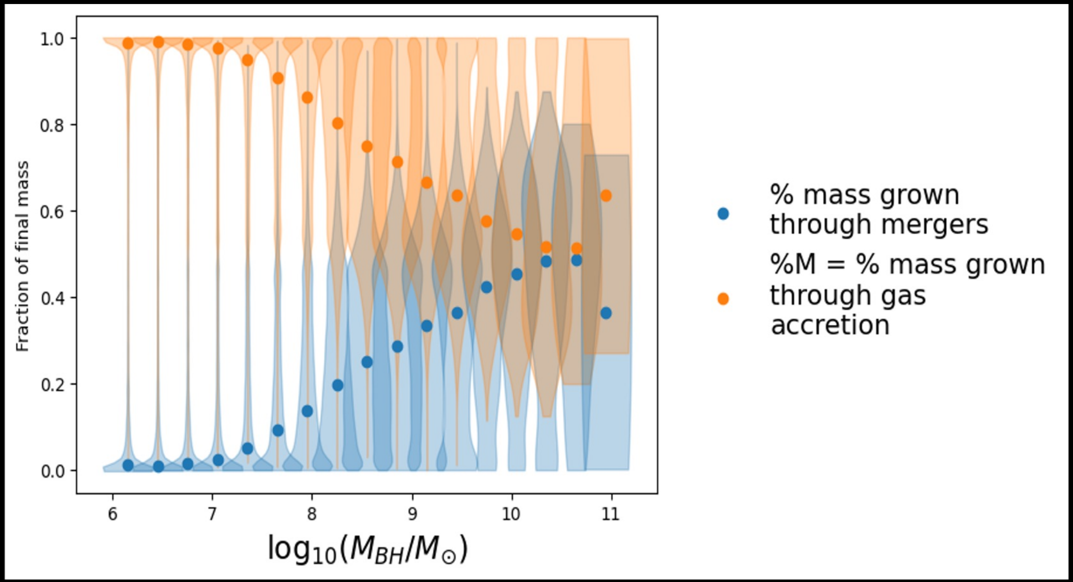




Discrepancy can be accommodated within the uncertain

# The build-up of the GW signal



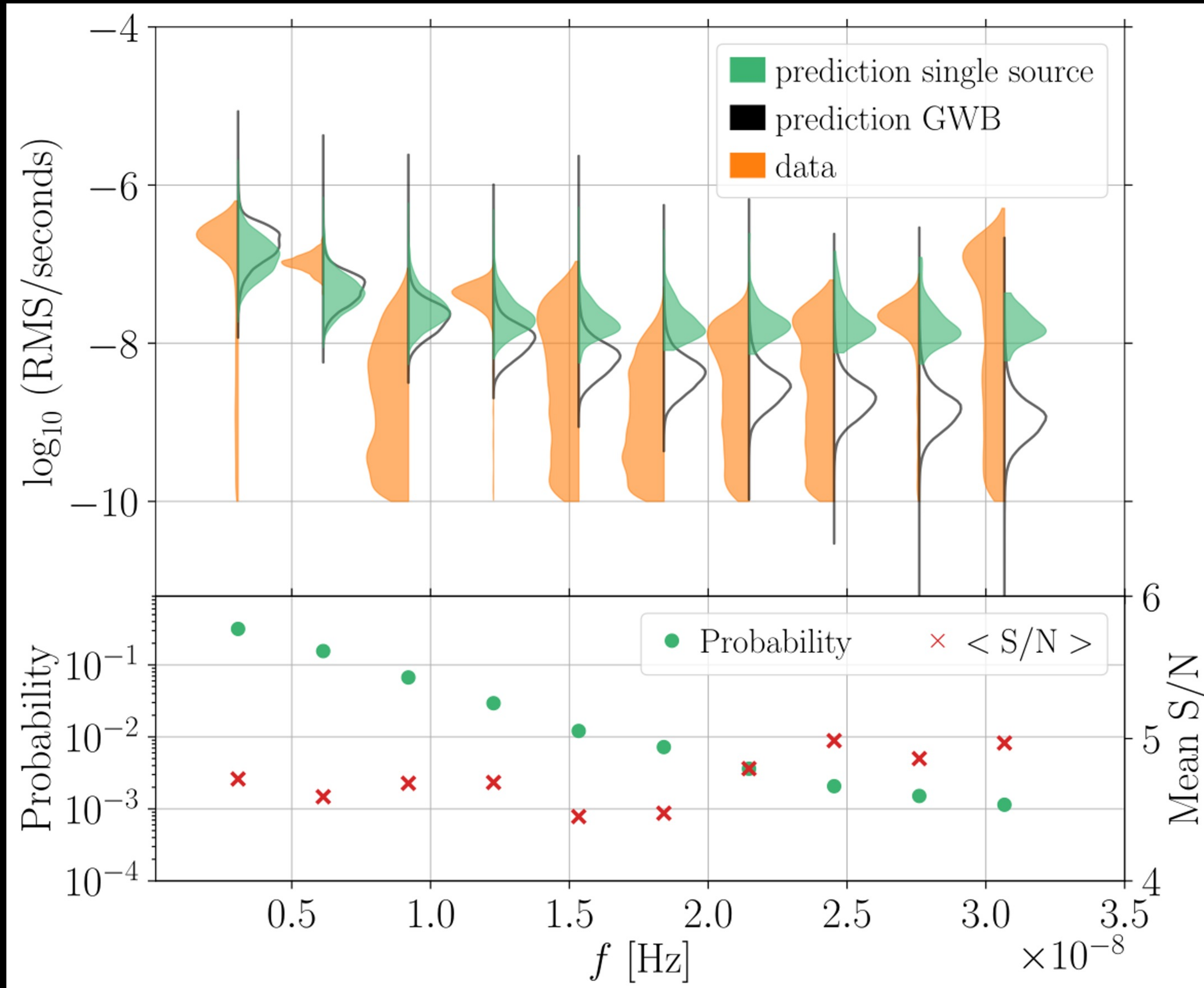




**The GWB from L-Galaxies**
**(Ferranti+ in prep.)**

**-The highest contribution to the GWB co**

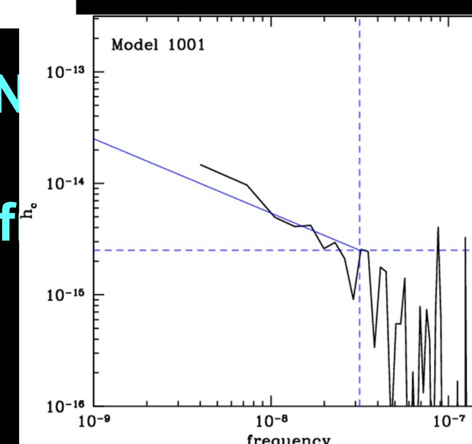
**-MBHs at low z grow mostly by mergers**

**-95% of the GWB comes from z<1**




Models allow to compute CGW detection statistics (circular, SN

~50% probability to have at least a CGW (mostly at the lowest f t



# *The future*

MeerKAT, South Africa

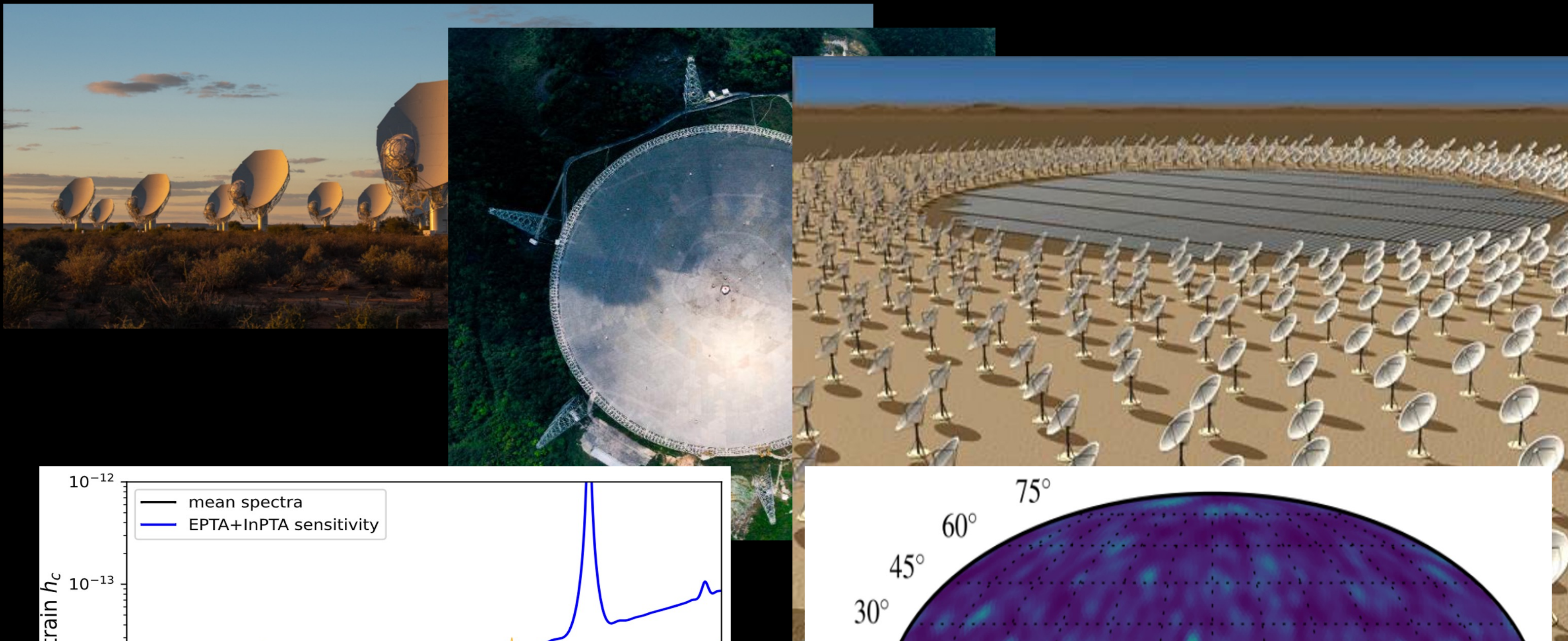
# *The future*

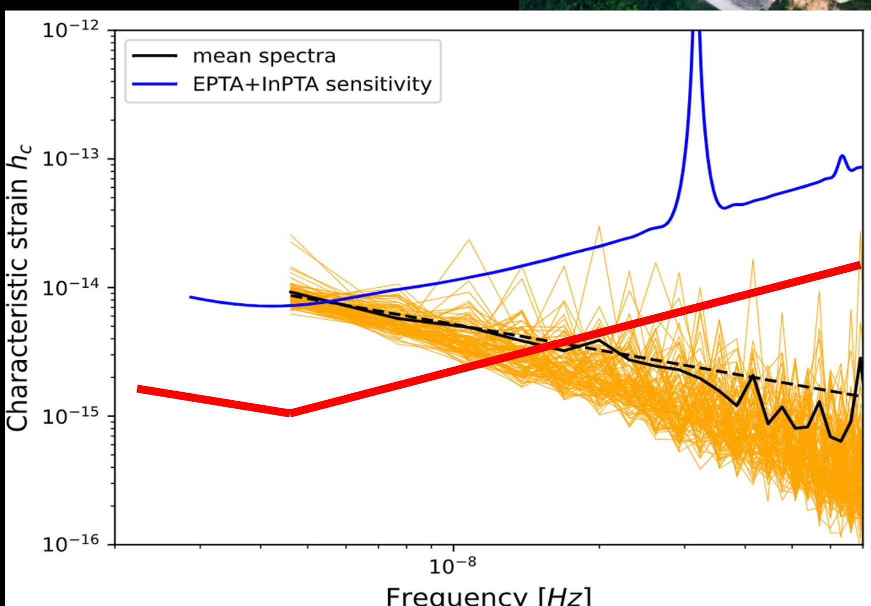
FAST, China

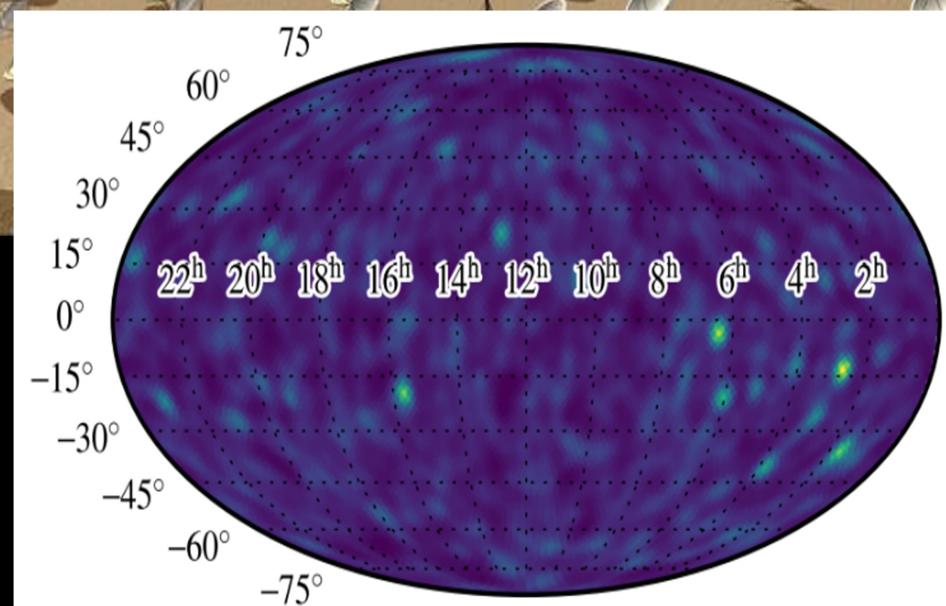
# *The future*

Square Kilometre Array (SKA)

# *The future*






-x10 sensitivity in the next 20 yrs

-sky mapping the nano-Hz GW sky

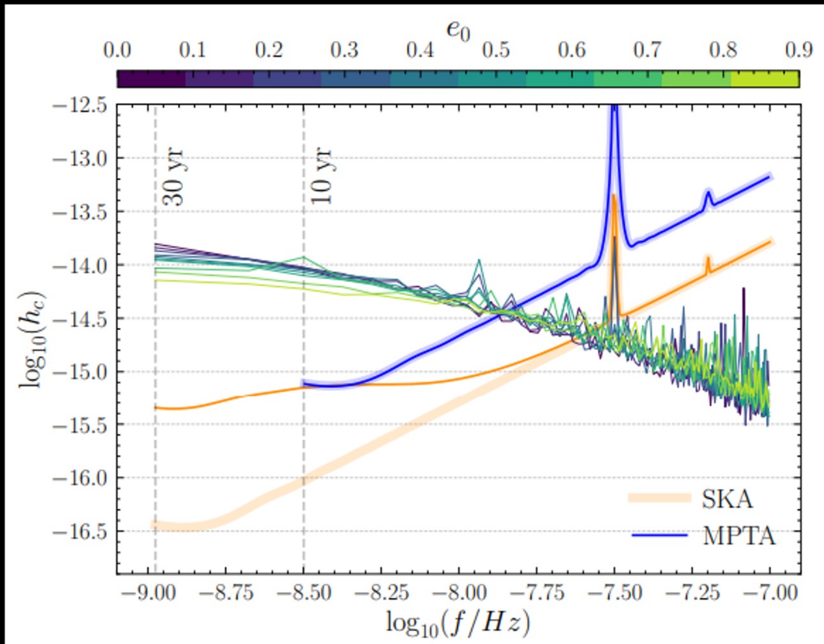
-Constrain SMBHB dynamics

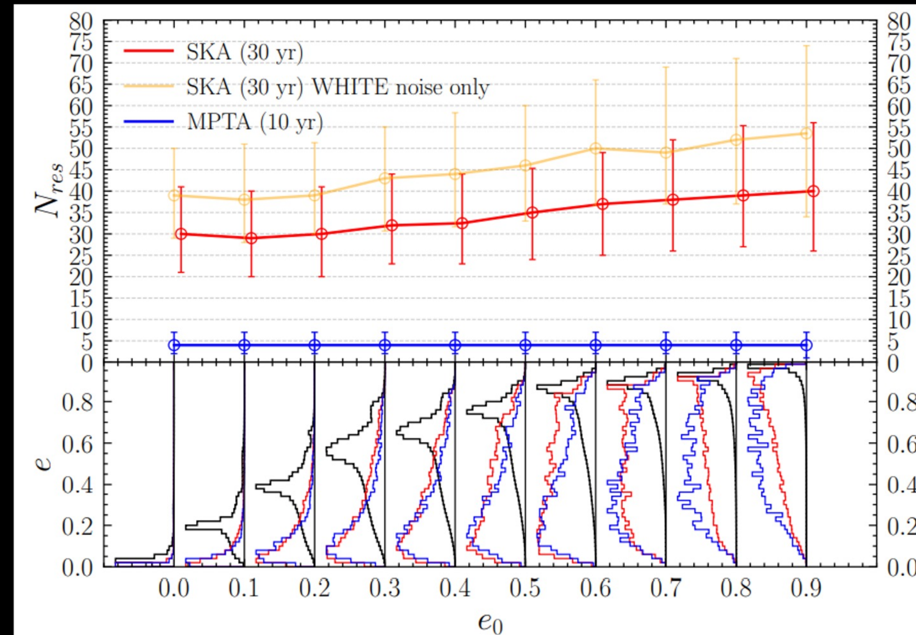
-tens of

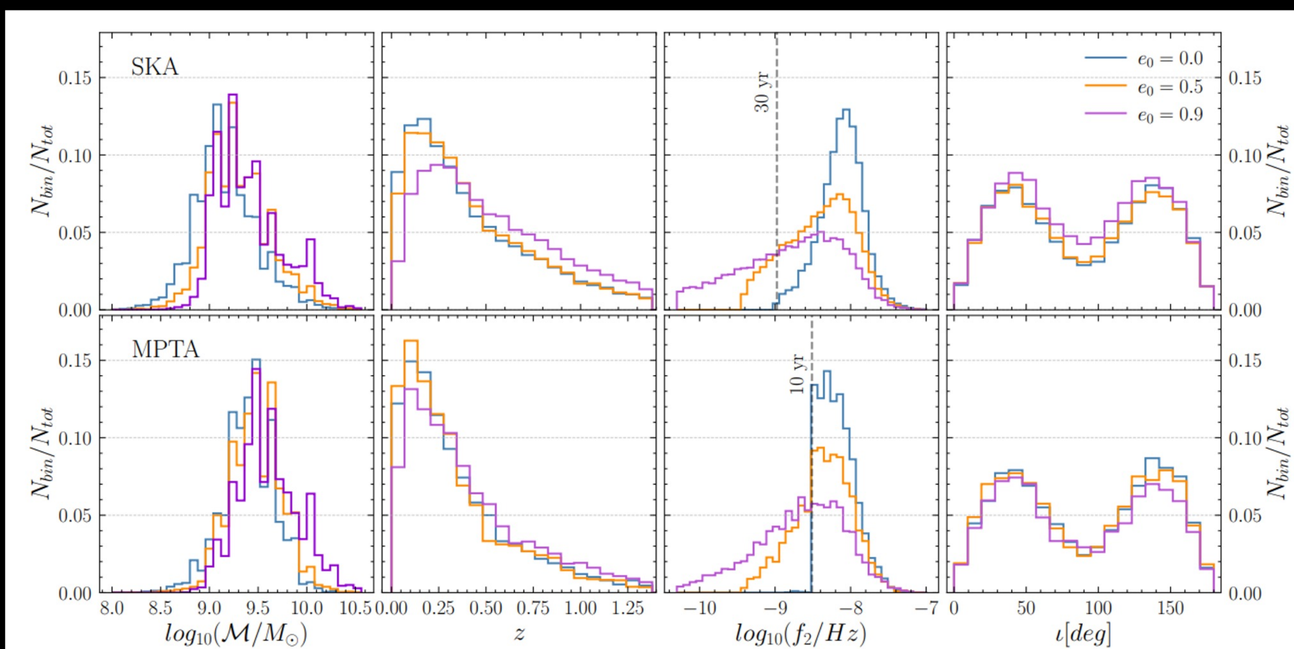
→ -AGN and accretion physics

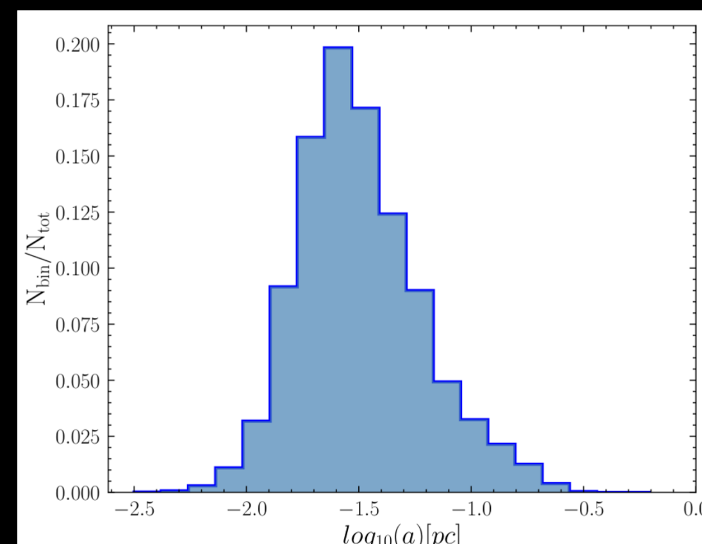
-nHz multimessenger astronomy

# Resolvable sources?



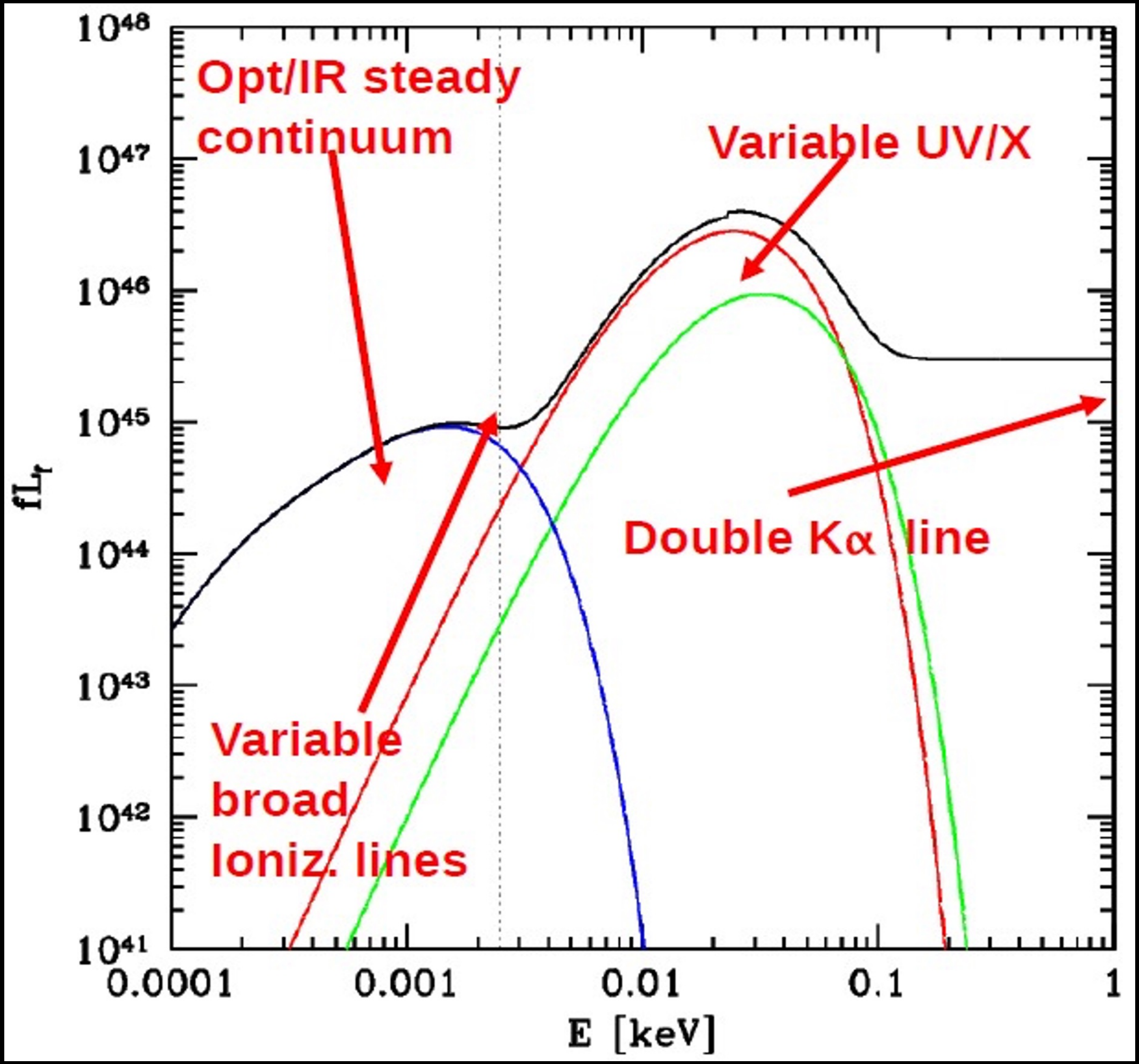




**With 30 years of SKA we might id**

# Associated electromagnetic signatures PTA

**MBH binary + circumbinary disk**




A variety of possibilities:

Optical/IR dominated by the

UV generated by inner strea

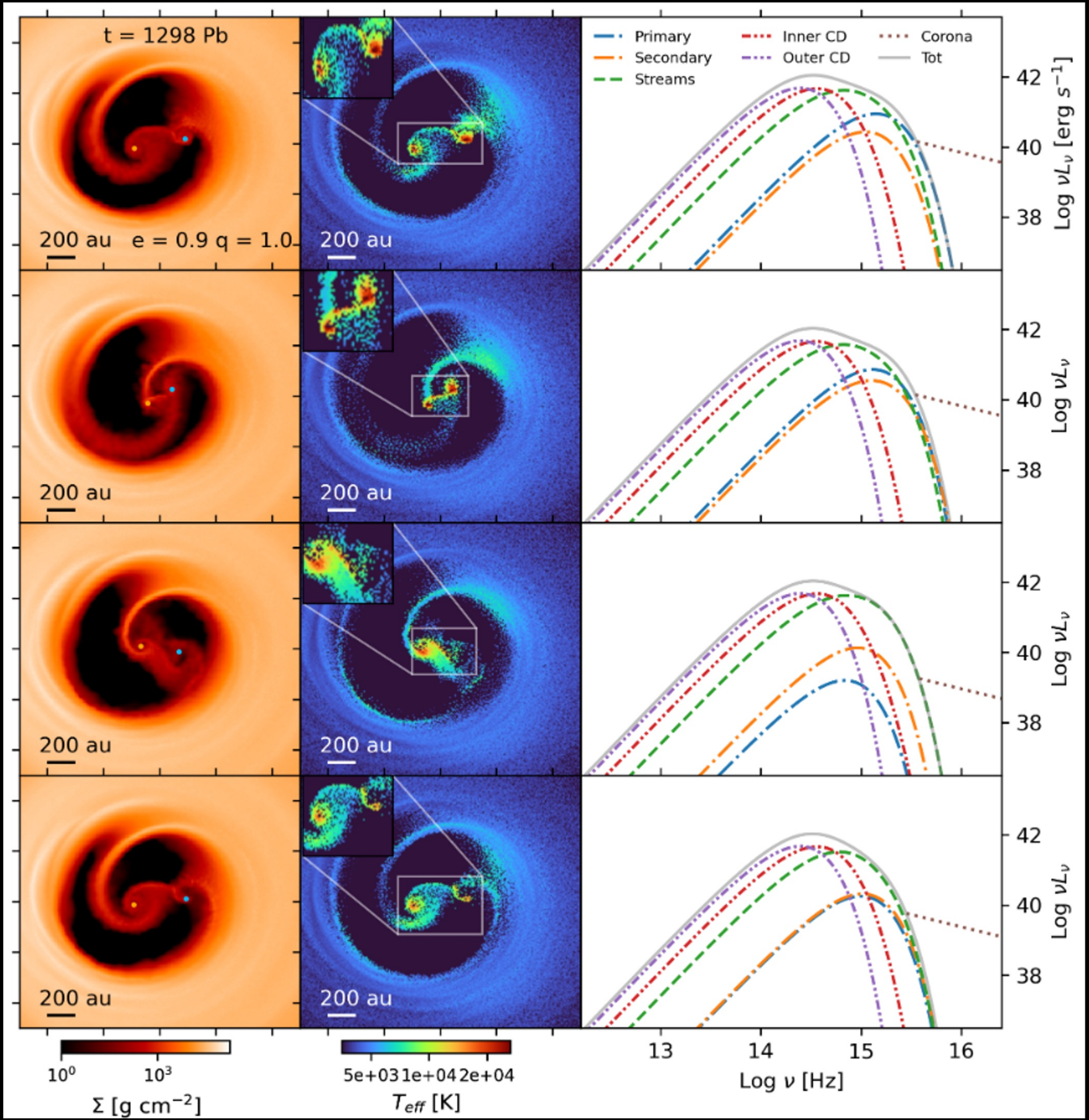
X rays variable from periodic

Variable broad emission line

Double fluorescence lines?

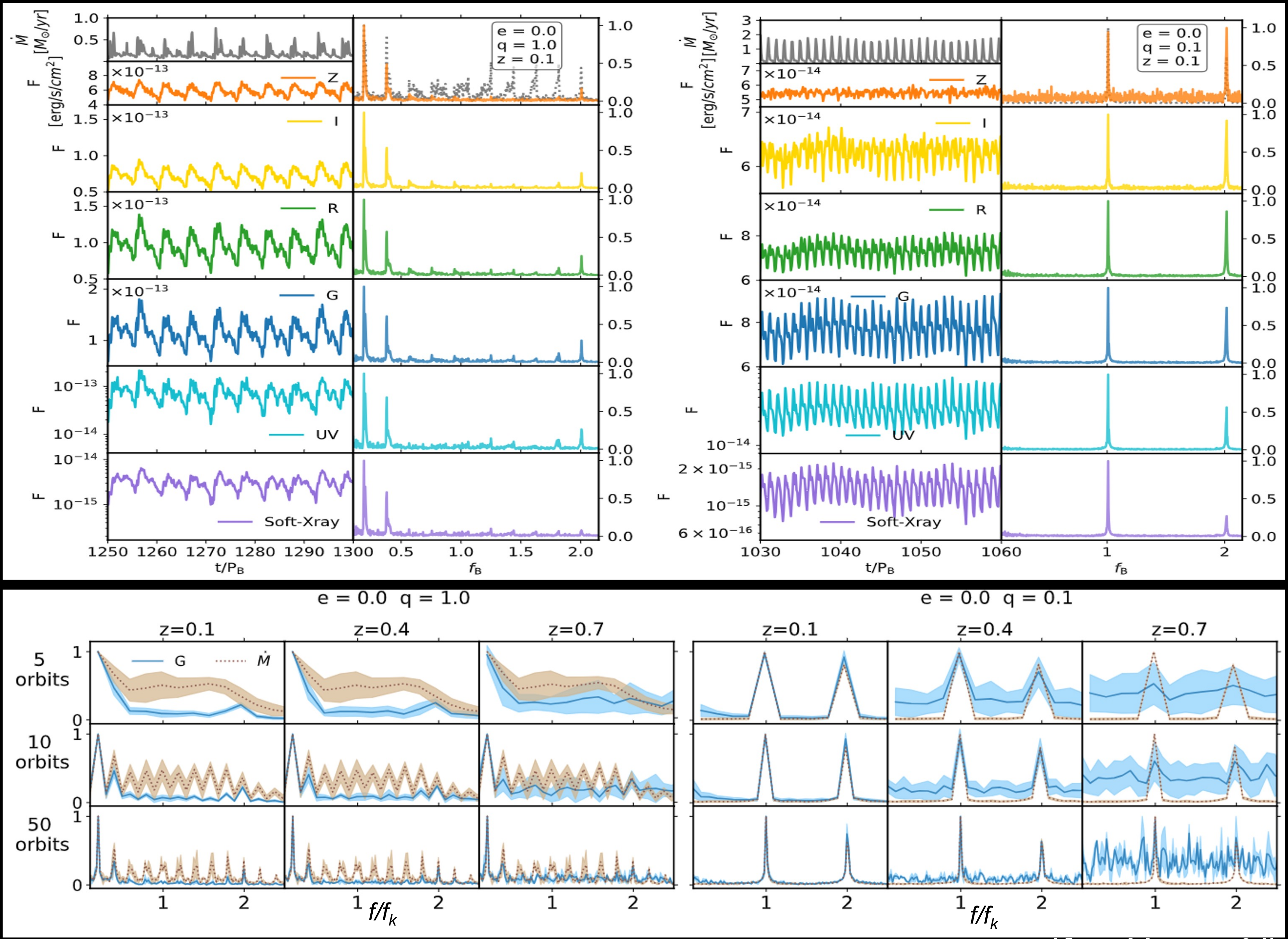
 et al. 2011, AS et al. 2012, Tanaka et al. 2012, Burke-Spolaor 2013, Farris+, D'Orazio+, Haiman+, Tang+,...)

# Associated electromagnetic signatures PTA



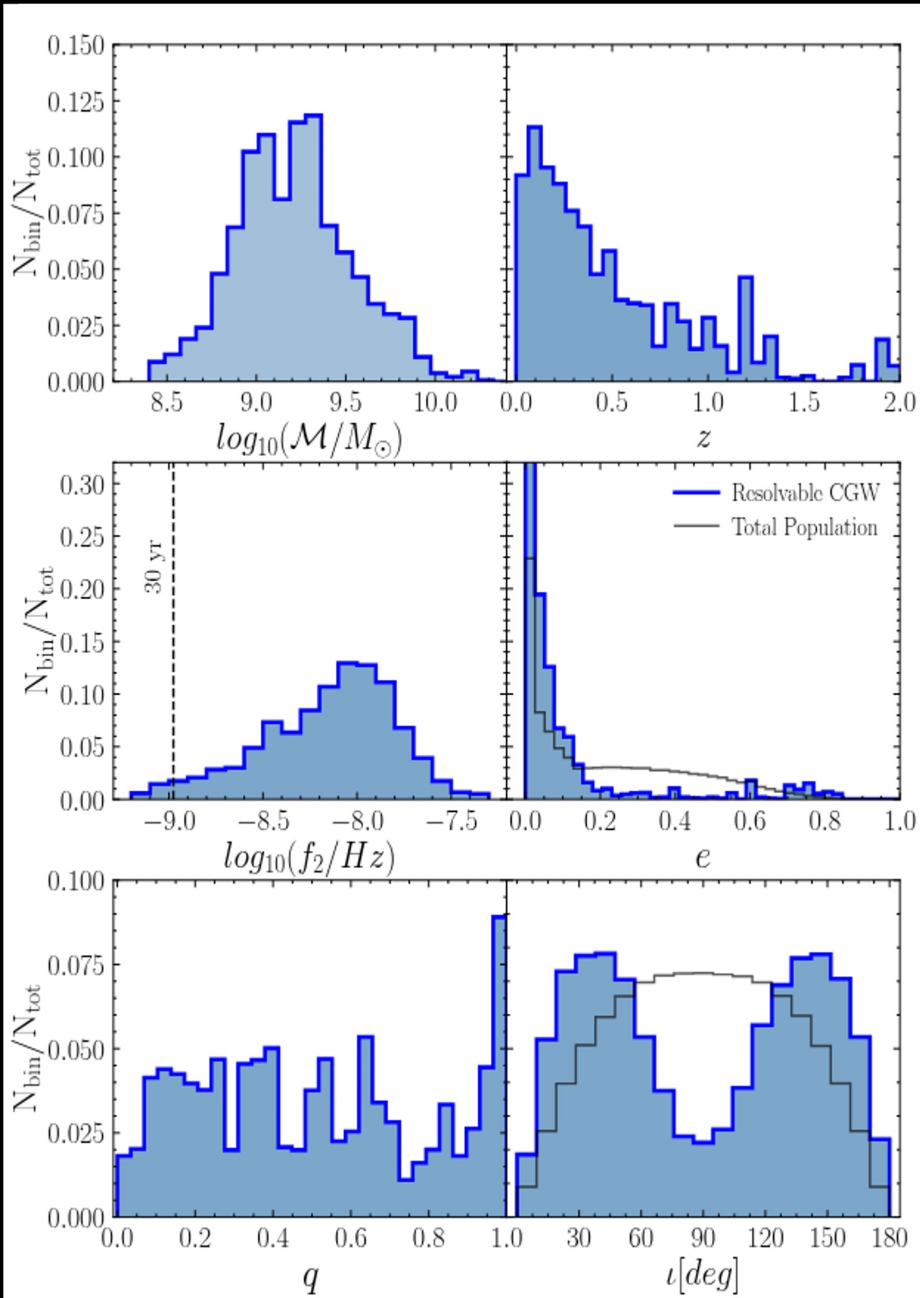

(Cocchiararo+24)

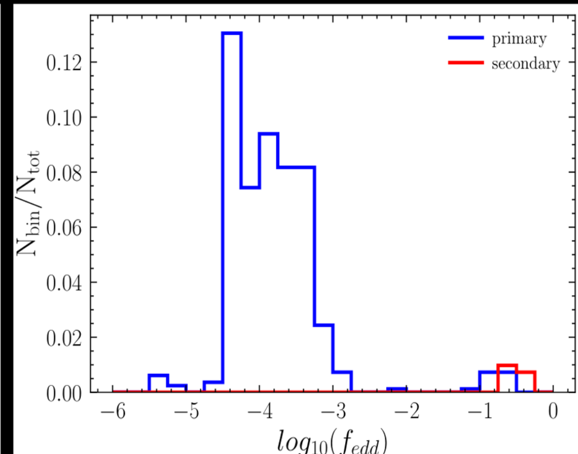
# Associated electromagnetic signatures PTA

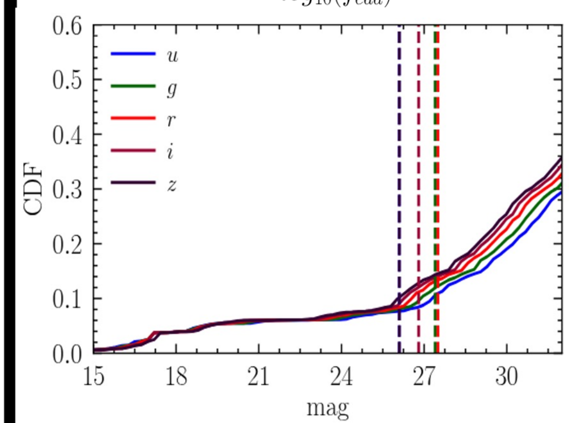


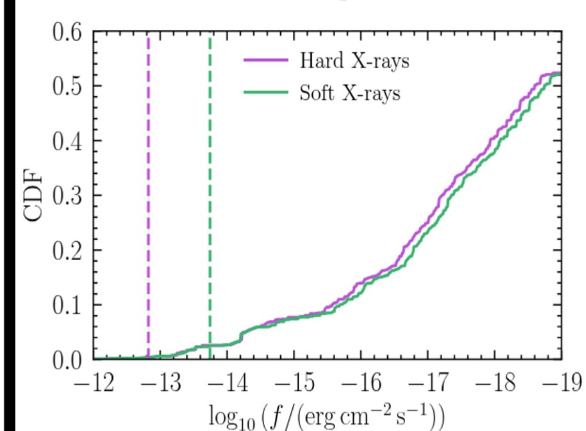

(Cocchiararo+24)

# *Properties of resolvable binaries*




(Truant+25)

Pilot study with 10yr MeerKA

Universes simulated with
*L Galaxies BH* (izquierdo villa

~5 individually resolvable so

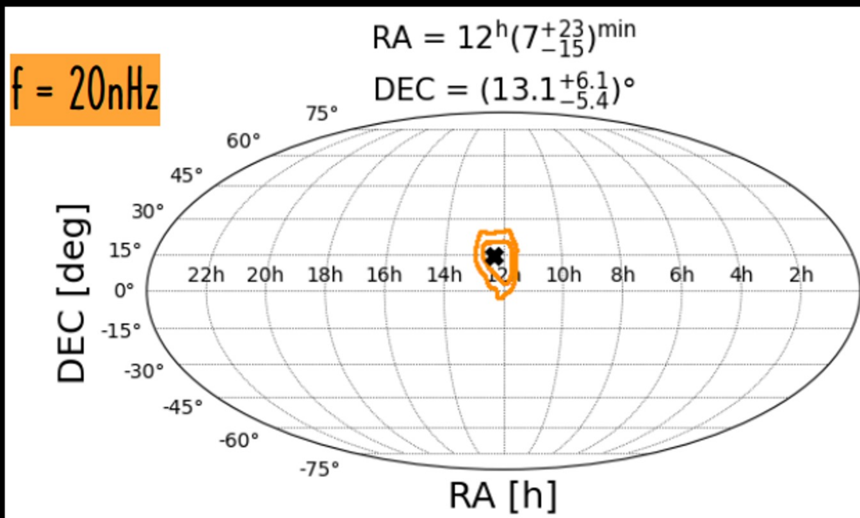
only ~2% of the systems are

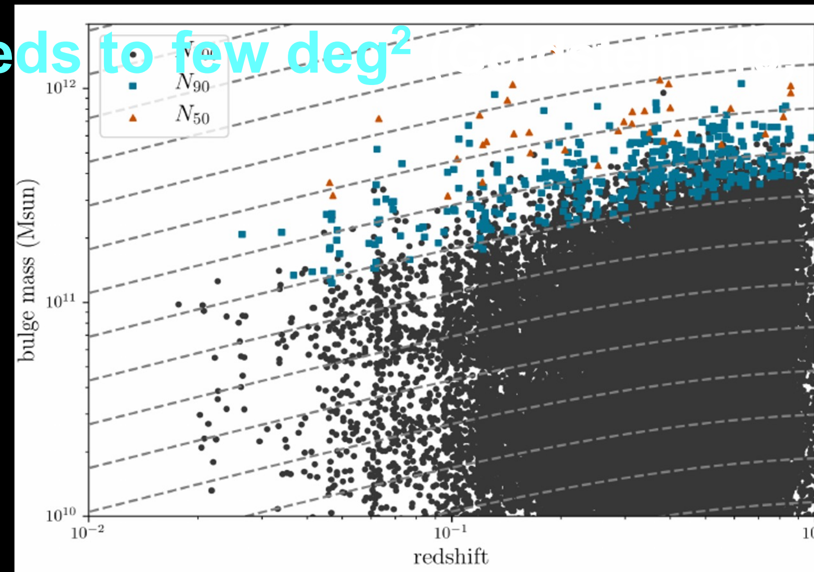
Most of them have low Eddin

only 10% of the systems are

# *MM opportunities: finding the right galaxy*

PTA sky localization is from hundreds to few deg$^2$ Ferranti+2



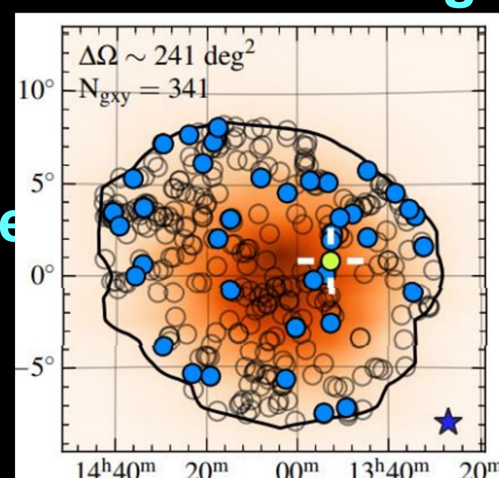

An individual PTA source must be mas

In general, PTA cannot break the distance-mass degeneracy ($A\sim M^{5/3}/D$)

Only a handful of th

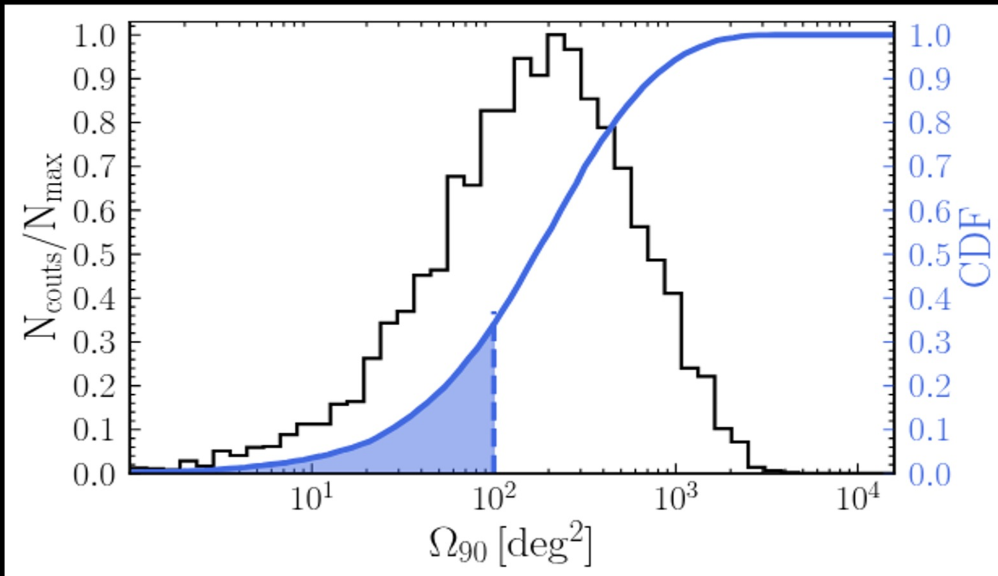
$$A = 4\frac{(G\mathcal{M}_z)^{5/3}(\pi f)^{2/3}}{D_l}$$

ns of deg$^2$ so te

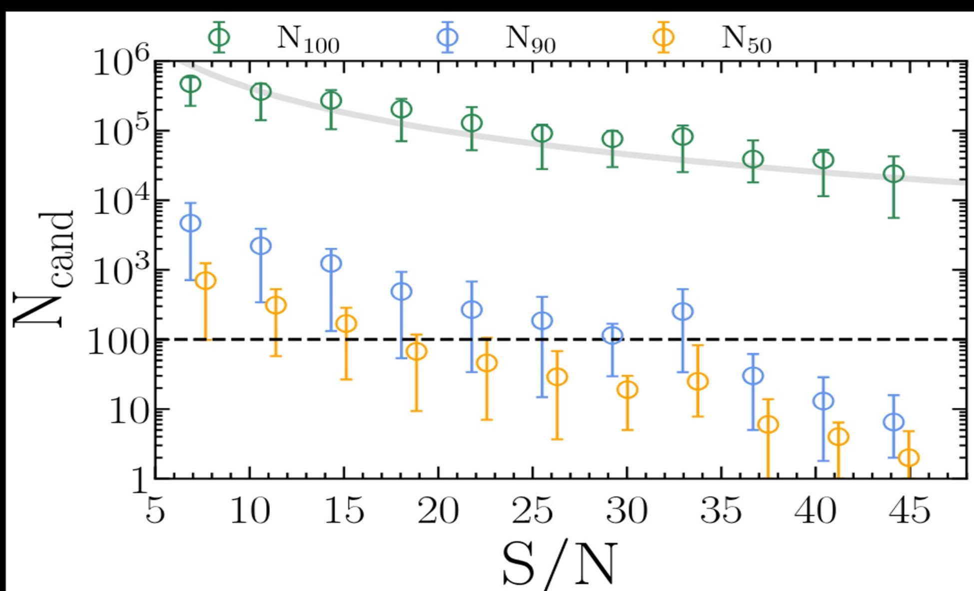


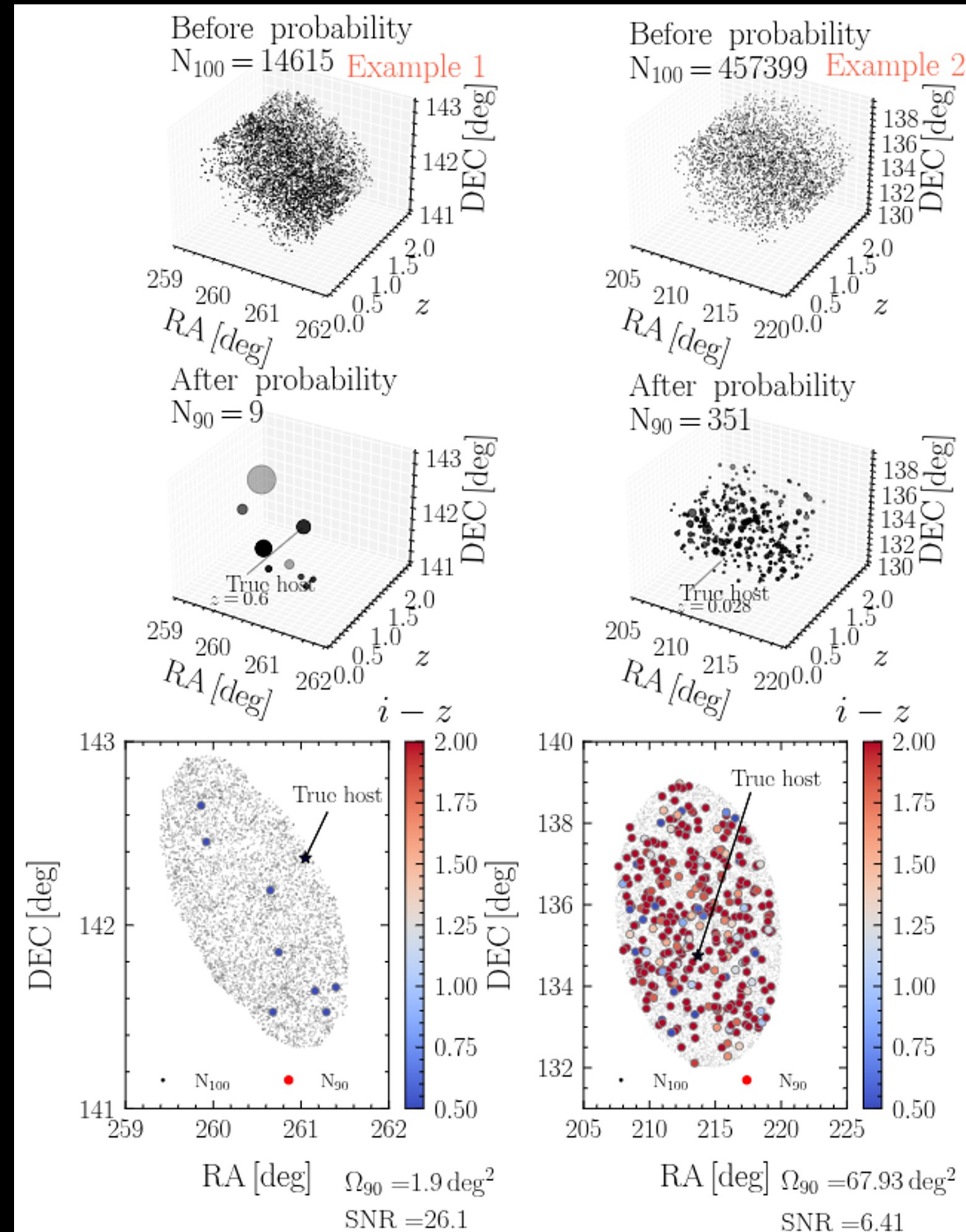

of potential host gala

# MM opportunities: finding the right galaxy




Sky localization sucks

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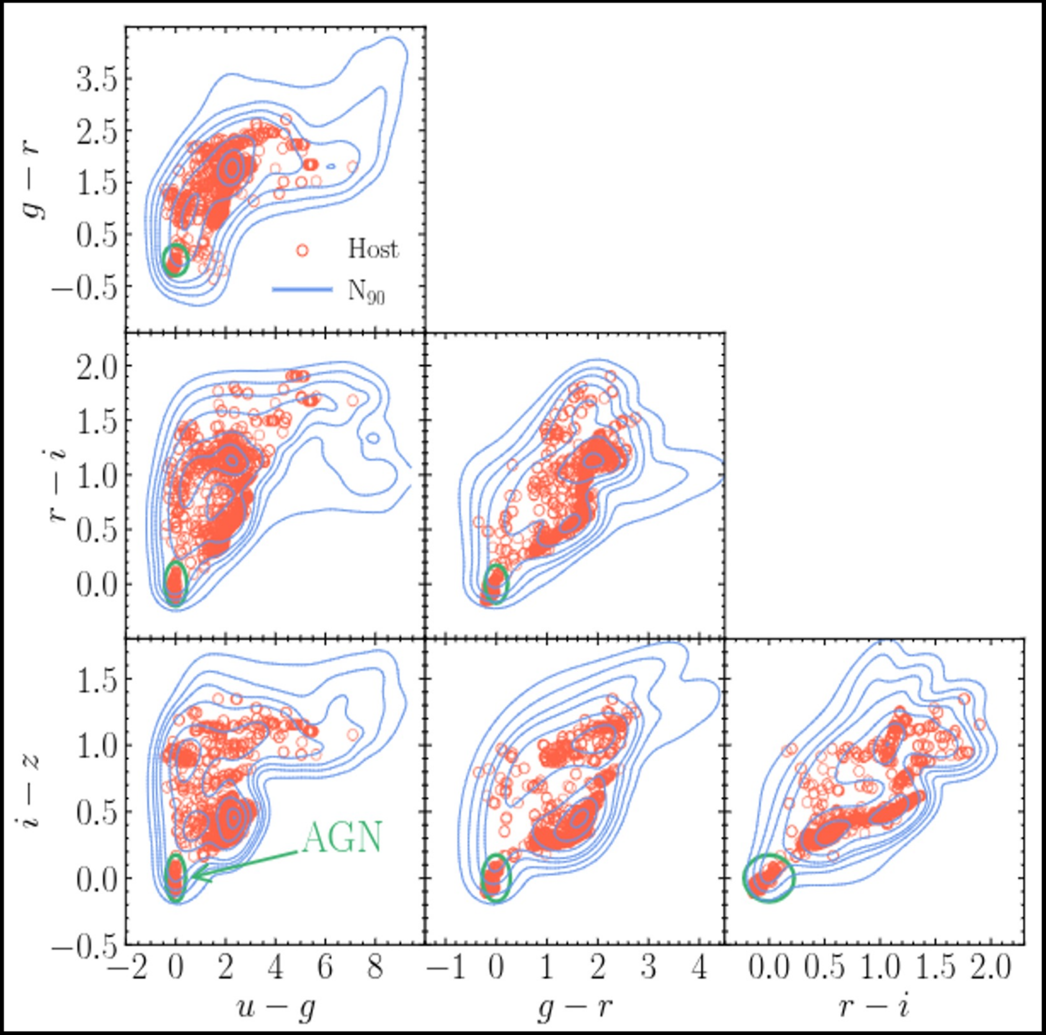
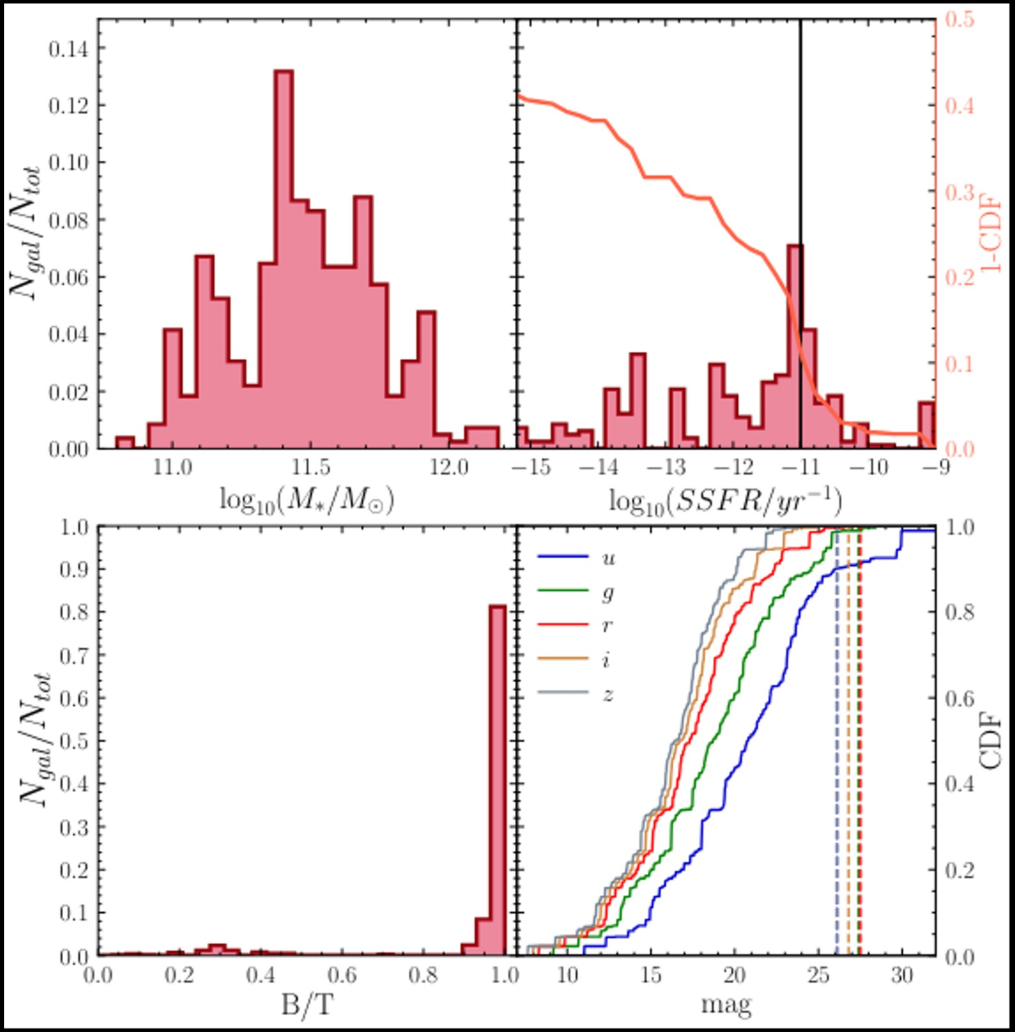
Effective selection of host candidates

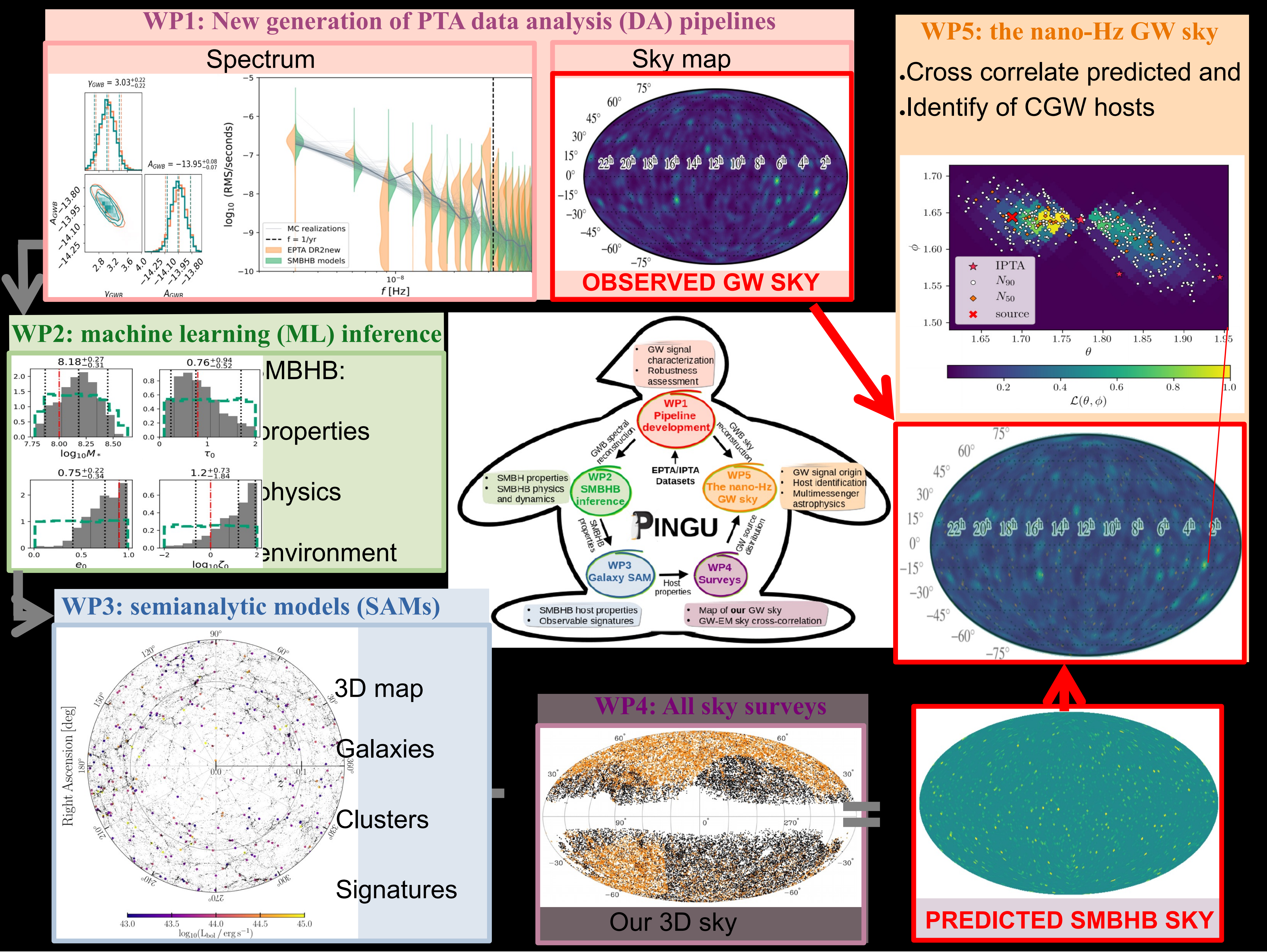
# MM opportunities: finding the right galaxy



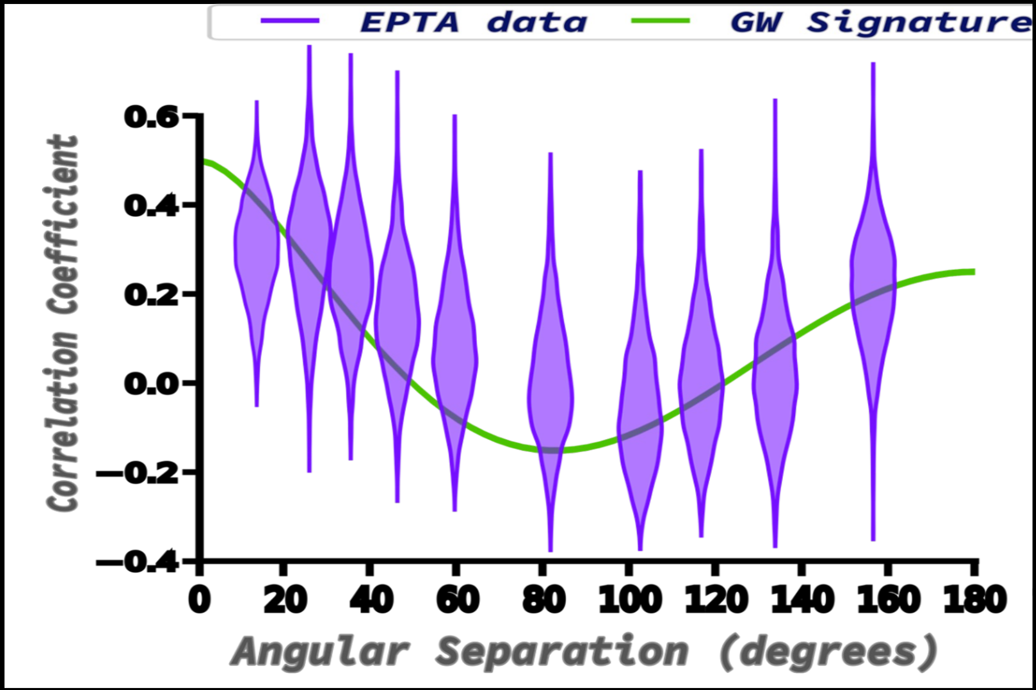

**Host galaxies are regular ellipticals**

**Identifying the host is going to be hard!!**



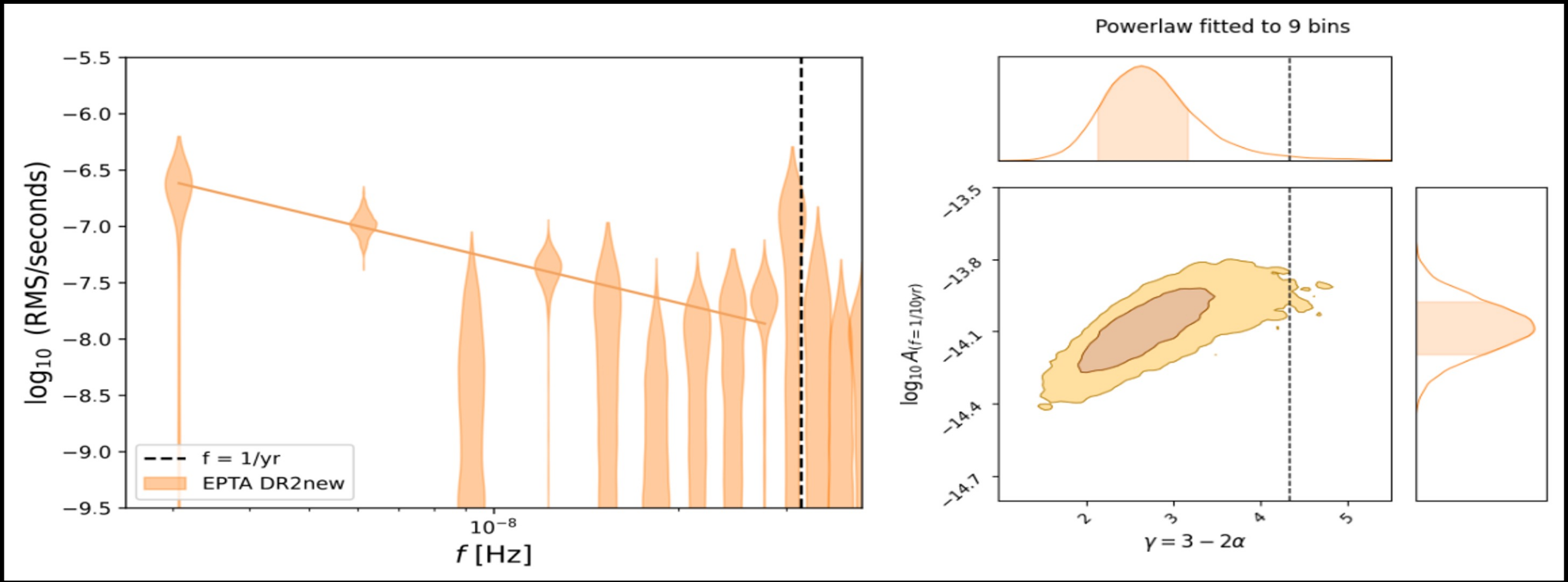
WP1: New generation of PTA data analysis (DA) pipelines
Spectrum
Sky map
OBSERVED GW SKY
MC realizations
f = 1/yr
EPTA DR2new
SMBHB models
log10 (RMS/seconds)
f [Hz]
WP5: the nano-Hz GW sky
.Cross correlate predicted and
.Identify of CGW hosts
IPTA
source
WP2: machine learning (ML) inference
SMBHB:
properties
physics
environment
GW signal characterization
Robustness assessment
WP1 Pipeline development
GWB spectral reconstruction
GWB sky reconstruction
EPTA/IPTA Datasets
SMBH properties
SMBHB physics and dynamics
WP2 SMBHB inference
WP5 The nano-Hz GW sky
GW signal origin
Host identification
Multimessenger astrophysics
PINGU
SMBHB properties
GW source distribution
WP3 Galaxy SAM
Host properties
WP4 Surveys
SMBHB host properties
Observable signatures
Map of our GW sky
GW-EM sky cross-correlation
WP3: semianalytic models (SAMs)
3D map
Galaxies
Clusters
Signatures
Right Ascension [deg]
WP4: All sky surveys
Our 3D sky
PREDICTED SMBHB SKY

# 2023 a new dawn



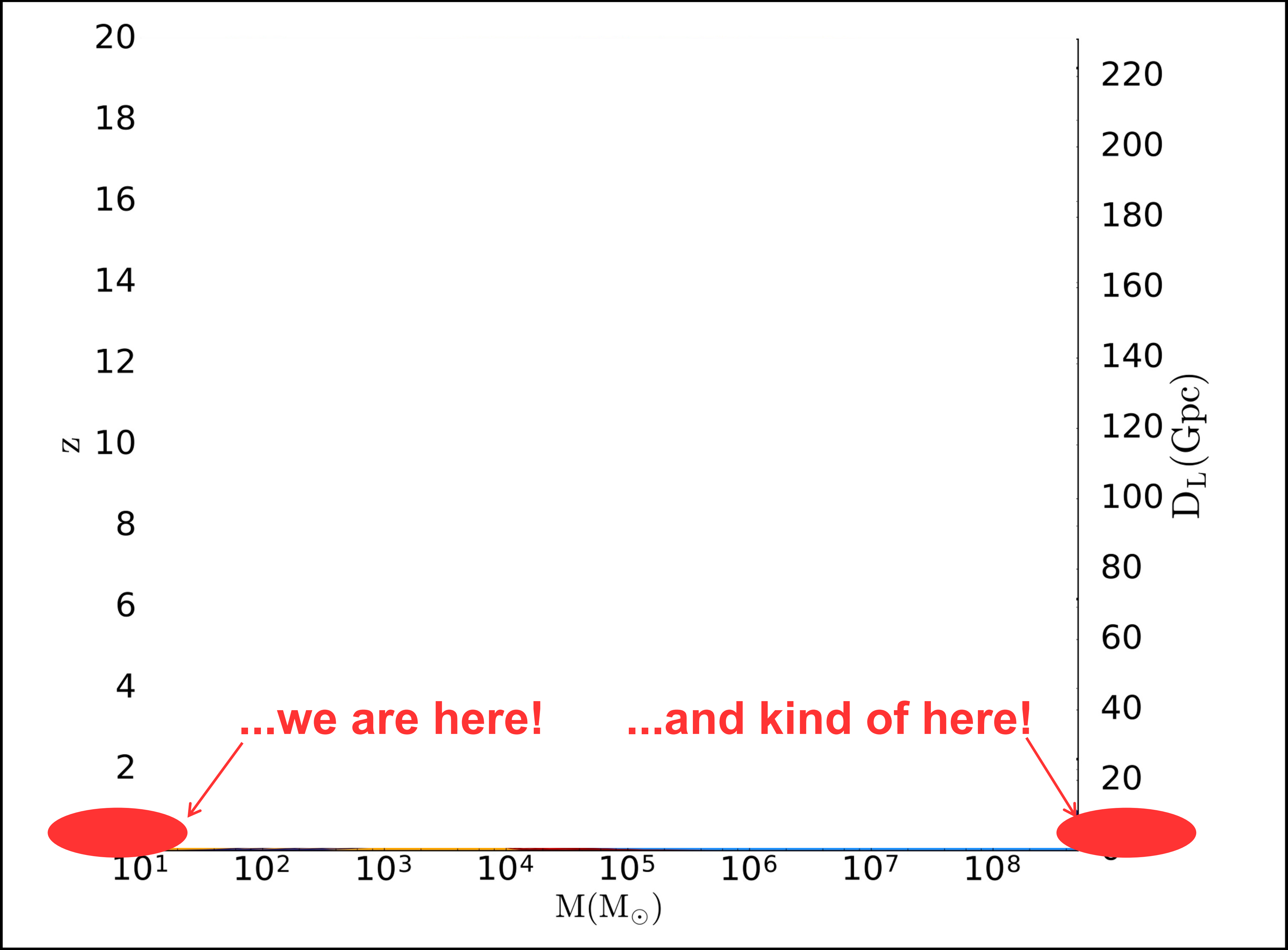

(Antoniadis+23, Agazie+23, Reardon+23, Xu+23)

| ID | Model | DR2full ENTERPRISE | DR2full FORTYTWO | DR2full+ ENTERPRISE | DR2new ENTERPRISE | DR2new FORTYTWO | DR2new+ ENTERPRISE |
|---|---|---|---|---|---|---|---|
| 1 | PSRN + CURN | – | – | – | – | – | – |
| 2 | PSRN + GWB | 4 | 5 | 4 | 60 | 62 | 65 |
| 3 | PSRN + CLK | < 0.01 | < 0.01 | < 0.01 | 0.2 | 1.2 | 0.3 |
| 4 | PSRN + EPH | < 0.01 | $\sim 10^{-4}$ | < 0.01 | 0.2 | 0.2 | 1.3 |
| 5 | PSRN + CURN + CLK | 2 | 1 | 2.7 | 0.8 | 2 | 1.6 |
| 6 | PSRN + CURN + EPH | 1 | 0.1 | 1 | 1 | 1 | 1.6 |
| 7 | PSRN + GWB + CURN | 3 | 3 | 4 | 27 | 13 | 25 |
| 8 | PSRN + GWB + CLK | 5 | 12 | 7 | 28 | 35 | 57 |
| 9 | PSRN + GWB + EPH | 3 | 3 | 3.6 | 33 | 29 | 43 |




Similar results as NANOgrav, PPTA, CPTA

# Today....



20
18
16
14
12
z
10
8
6
4
2
220
200
180
160
140
120
100
80
60
40
20
$D_L(Gpc)$
...we are here!
...and kind of here!
$10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$
$M(M_\odot)$

## *DOGGYBAG*

- -EPTA DR2  show a signal consistent with a GW origin (HD correlation)
- -signal broadly consistent with SMBHB origin
- -SMBHB are massive and merge quickly
- -Signal informative for galaxy formation models
- -Future PTAs will identify tens of SMBHBs
- -Counterpart identification is going to be challenging