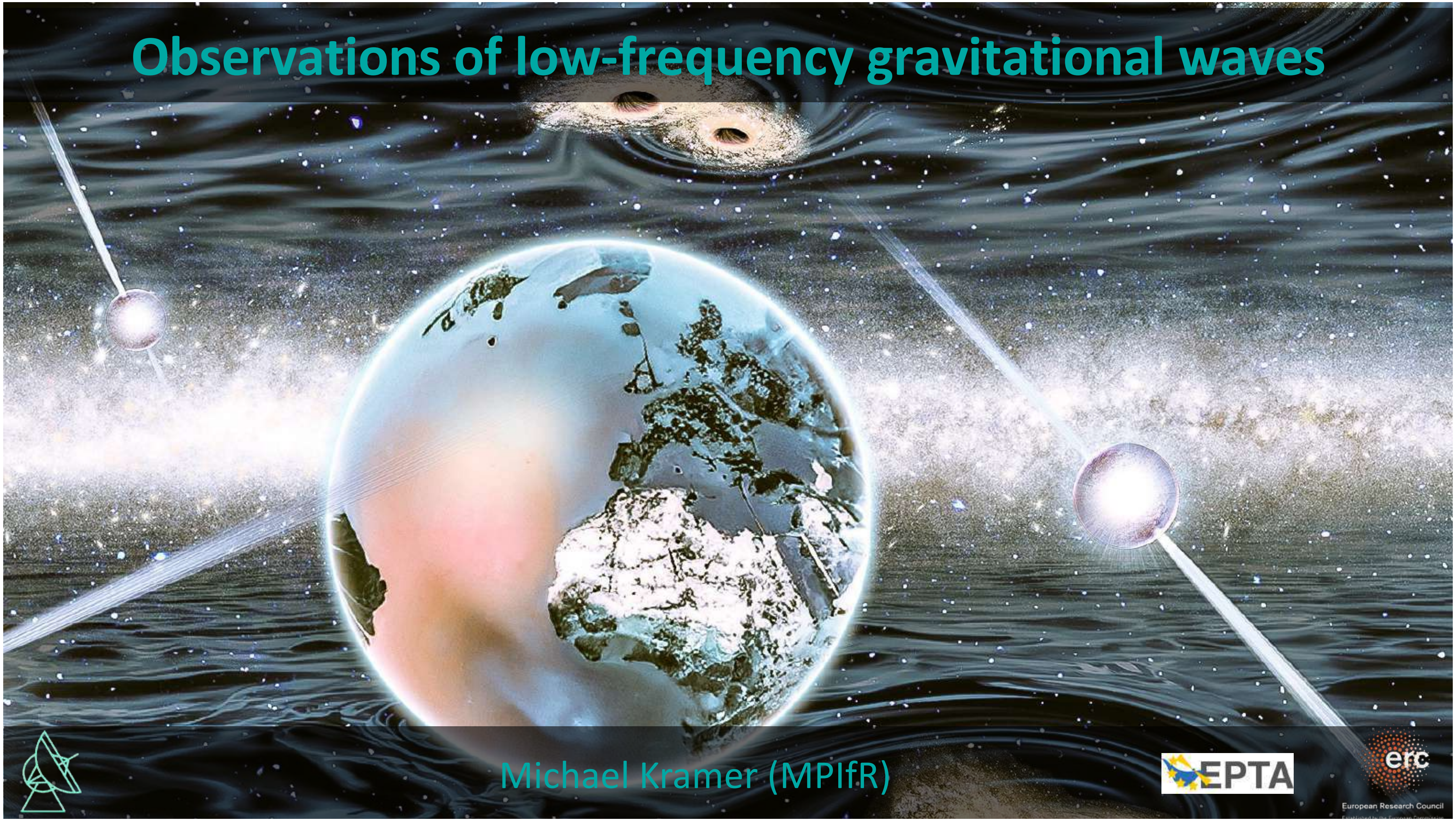
Observations of low-frequency gravitational waves



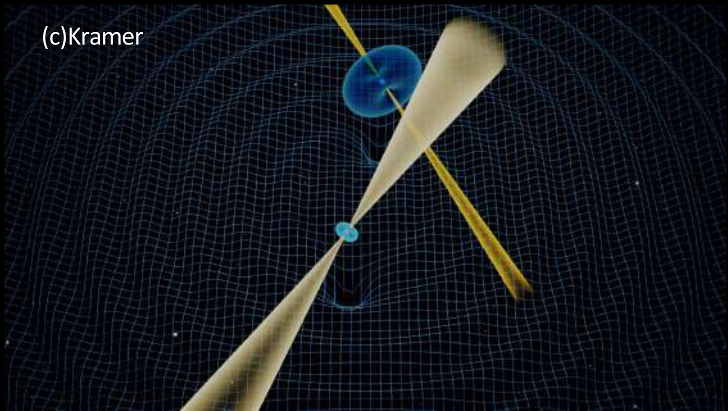
Michael Kramer (MPIfR)

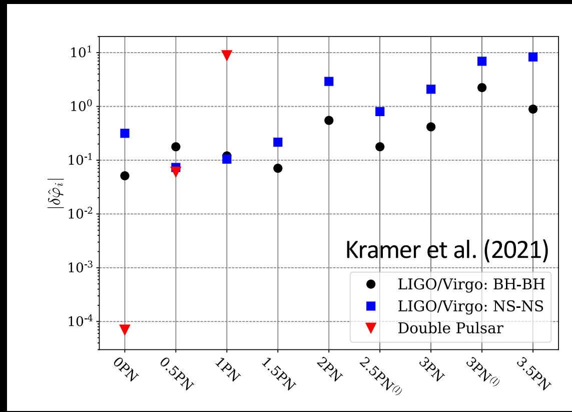
EPTA

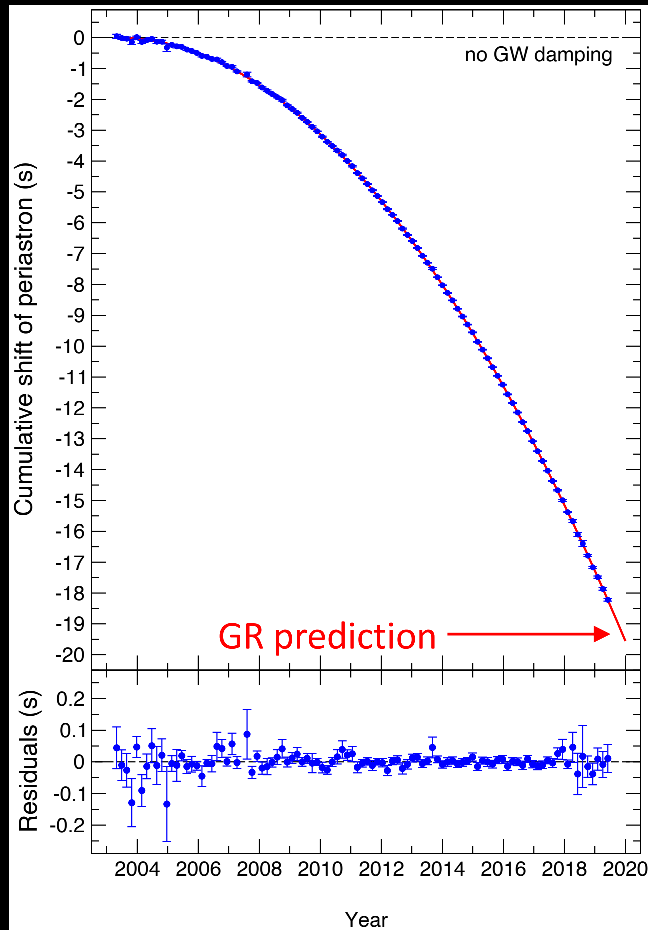
European Research Council

Most precise evidence for gravitational waves today: Double Pulsar

Kramer et al. (2021)





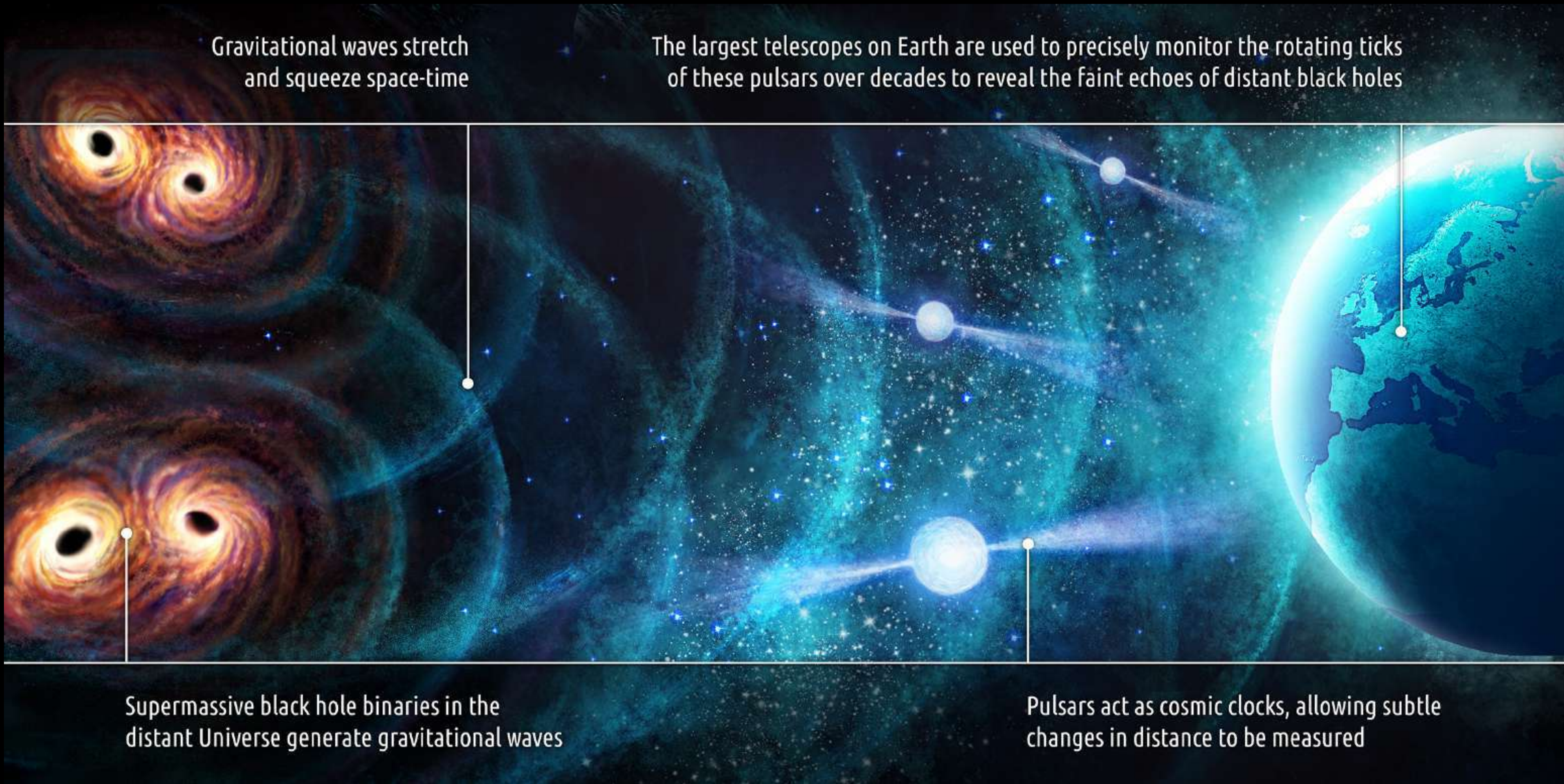


- Pulsars approach each other by 7.1490 ±0.0008 mm
- Most precise test of GR's quadrupole formula:

  Observed/Expected = 0.99996 ±0.00006 (95% c.l.)
- Precision is so high that we need to take mass loss due to rotational spin-down into account, i.e.

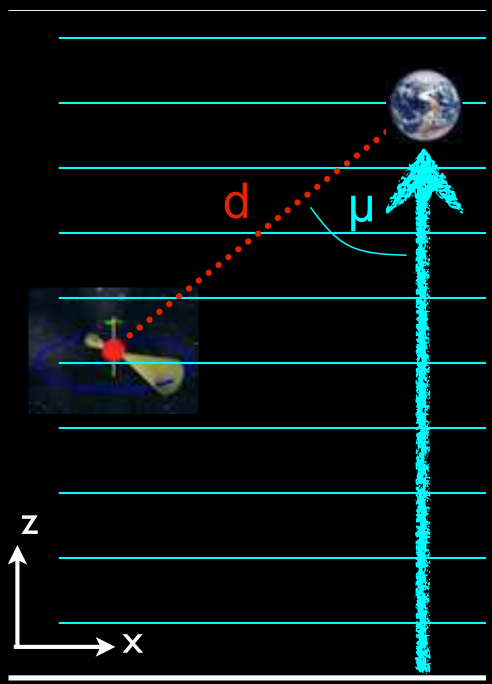
  8.4 Million tons/second = 3.2 x 10^{-21} M_A per second
- But, pulsars not only as sources of GW – also as detectors

Building a galaxy-sized gravitational wave detector: an array of pulsars



Pulsar-Earth arm of a GW detector

The timing residual is the integral over TOA variation over the duration of the timing experiment:



Wex

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$

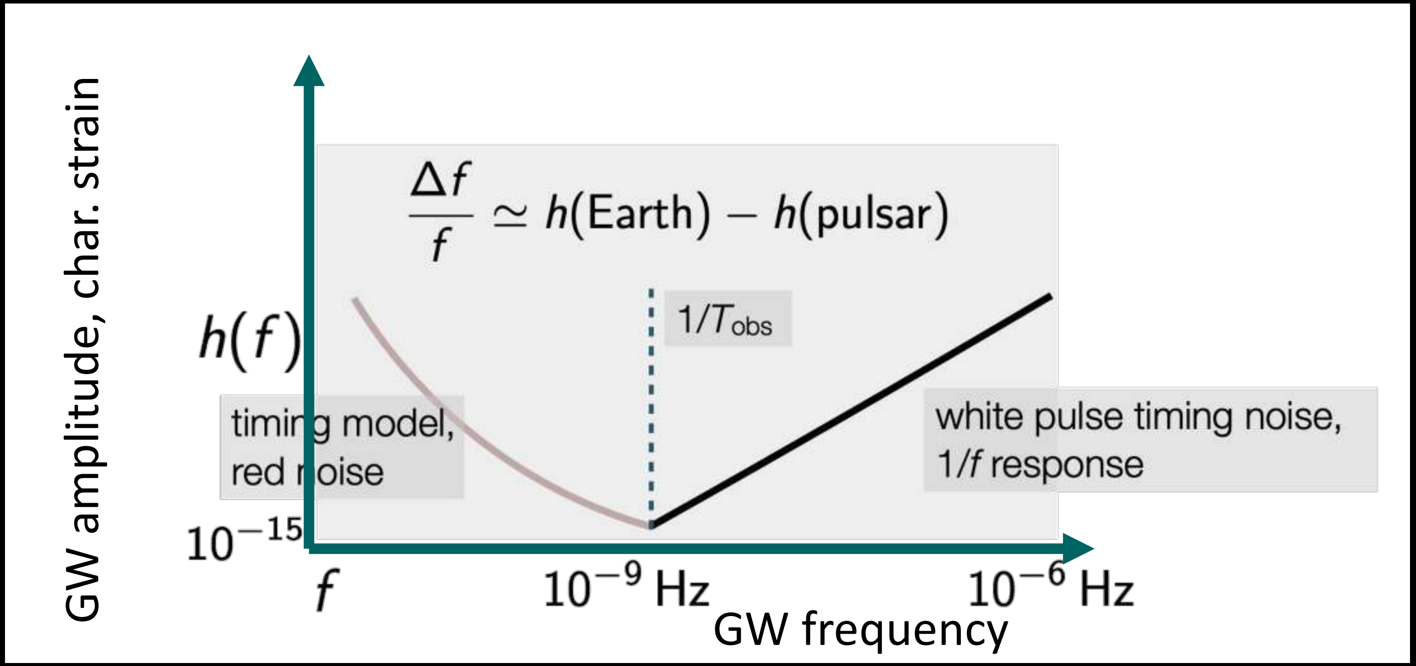
With Doppler shift due to GW given by:

$$\frac{\delta\nu}{\nu} = H^{ij}(h^e_{ij} - h^p_{ij})$$

Note: geometry Earth pulsar

- We can assume distant sources: planar waves
- We will see: wavelengths = tens of parsecs
- While pulsars further away: long-arm detector, L >> λ (unlike LIGO, where arms are shorter than wavelengths)
- Two terms: Earth and pulsar term

Frequency range of a Pulsar Timing Array (PTA)

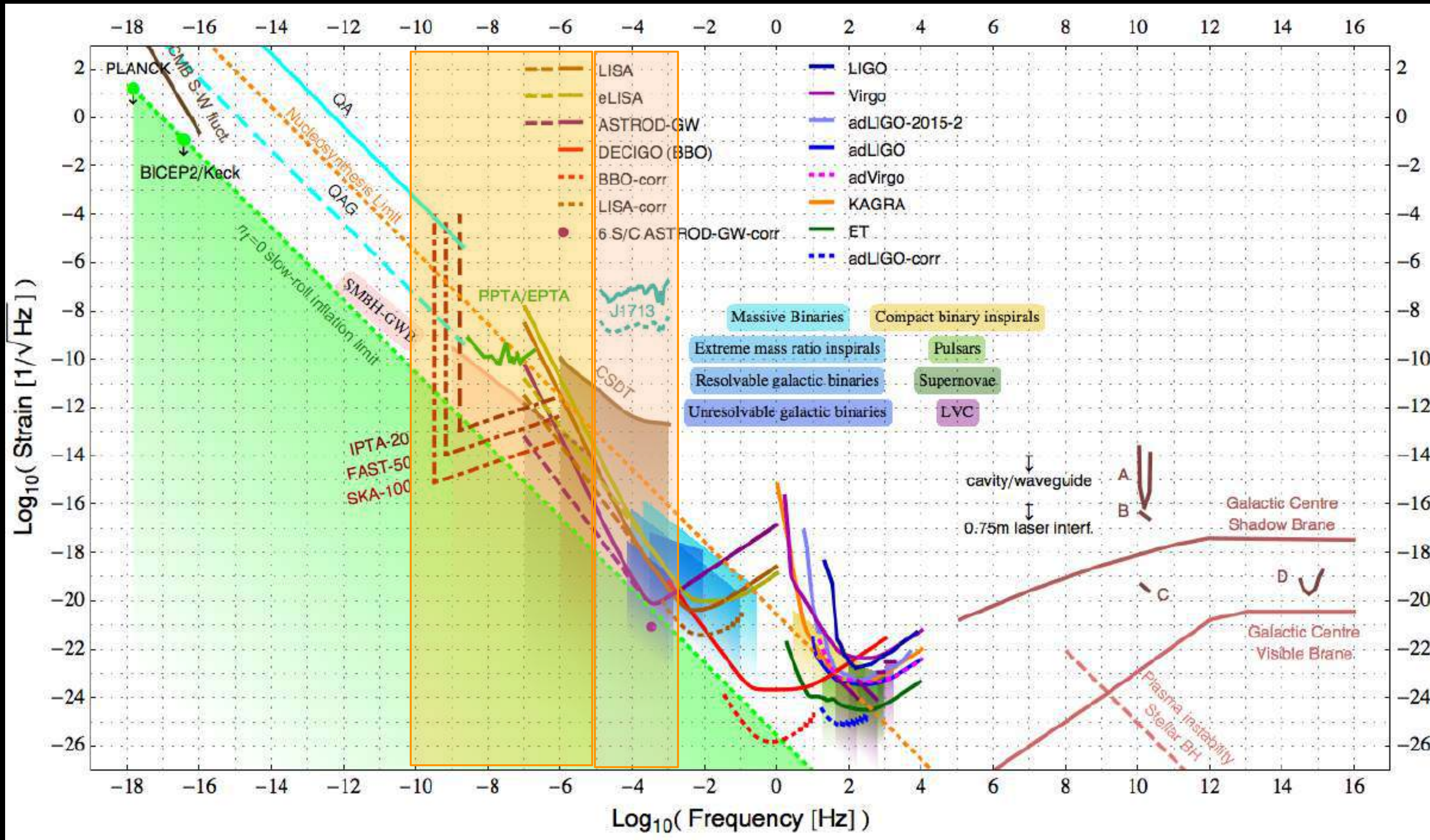


Highest frequency is given by cadence: ~1 per month => ~400 nHz

Lowest frequency is given by observing length: ~10 years => ~3 nHz

We are sensitive to gravitational waves with nHz frequencies - wavelengths of 10-100 pc

Frequency range of a Pulsar Timing Array (PTA)



Chen et al. 16

Expected amplitudes & sources

Highest frequency is given by cadence: ~1 per month => ~400 nHz

Lowest frequency is given by observing length: ~10 years => ~3 nHz

Timing residuals for a monochromatic GW (i.e. $h = h_0 \cos(2\pi ft)$), assuming it to be 100ns:

$$r(t) = \int_0^t h(\tau)\, d\tau = \frac{h_0}{2\pi f} \sin(2\pi f t)$$

In order to get residuals of 100 ns, one needs:

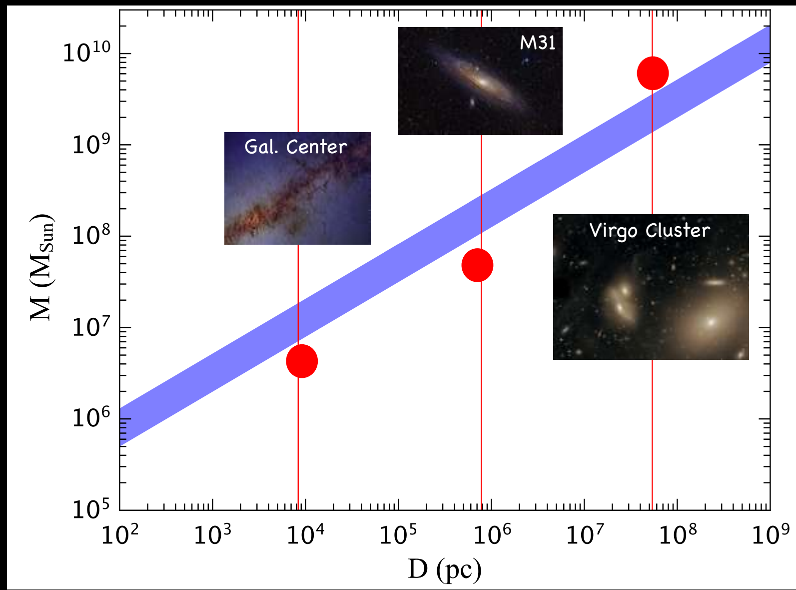
$h_0 = 1.9 \times 10^{-15}$ at 3 nHz

$h_0 = 2.5 \times 10^{-13}$ at 400 nHz

What sources can produce those?

Binary system ($m_1=m_2$):

$$h_0 = \frac{c}{D} \left(\frac{GM}{c^3} \right)^{5/3} (\pi f)^{2/3}$$

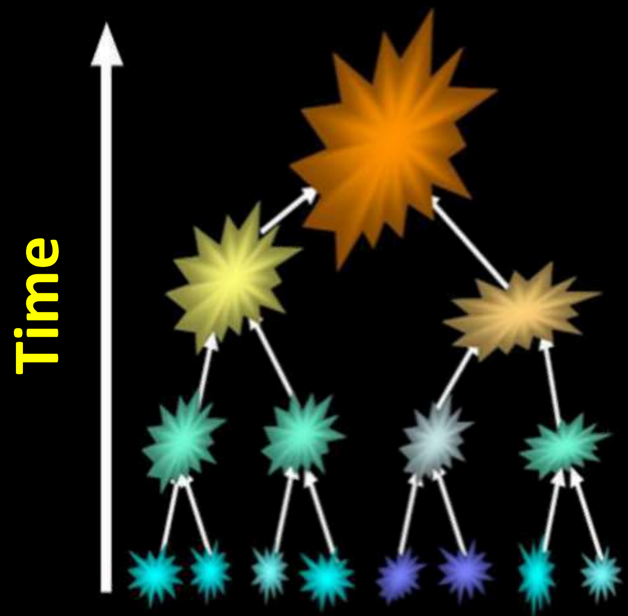


We could expect to see binary supermassive BH at distances of >50 Mpc

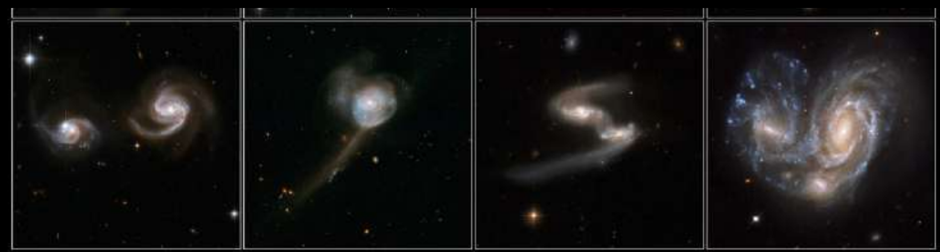
Slide courtesy N. Wex

A stochastic background : merging galaxies

Galaxy evolution models predict a hierarchical formation of galaxies



HST/STScI



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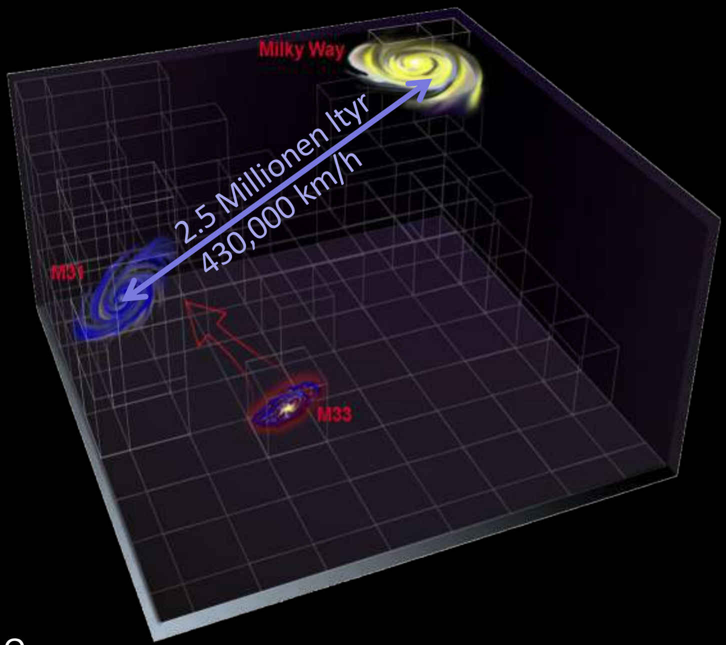
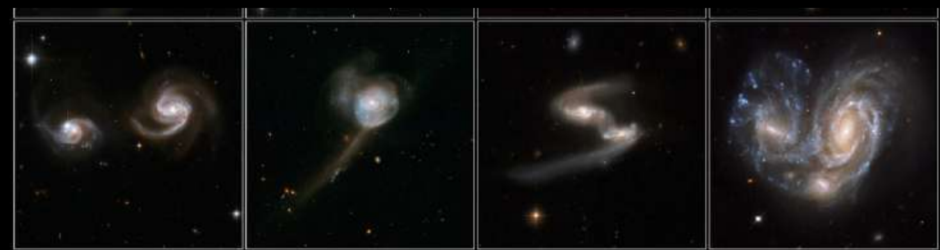


NRAO



NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a

We expect a background of SMBH!

A stochastic background : merging galaxies

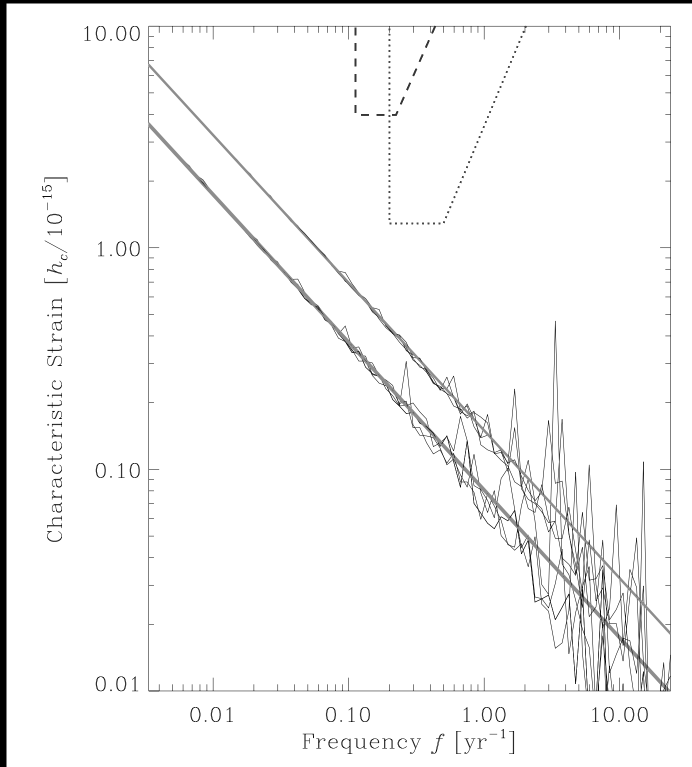
- Isotropic, stochastic GW background (GWB) signal should essentially have power law (with index $\boldsymbol{\alpha}$ = -2/3)

$$h_c(f) = A\left(\frac{f}{f_0}\right)^{\alpha}$$

- Creating a spectrum with amplitude A and index, $\boldsymbol{\gamma}$, expected to be 13/3 in simplest case

$$S(f) = \frac{h_c^2(f)}{12\pi^2 f^3} = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma},$$

Jaffee & Backer (2003)



See also Rajagopal & Romani (1995)

A stochastic background : merging galaxies

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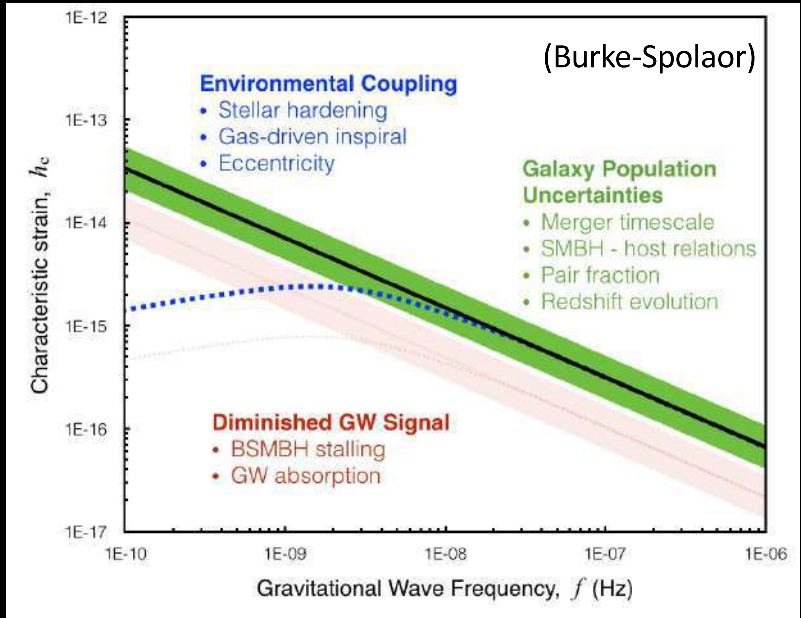

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- But, astrophysics can modify this

Spectrum may be significantly flatter than γ = 13/3 due to different reasons: e.g. strong coupling with the environment, predominance of highly eccentric SMBHBs (see e.g., Sesana 2013), or by presence of extra power at high frequencies due to sparse and loud marginally resolvable individual binaries (Middleton et al. 2021).

A stochastic background : merging galaxies

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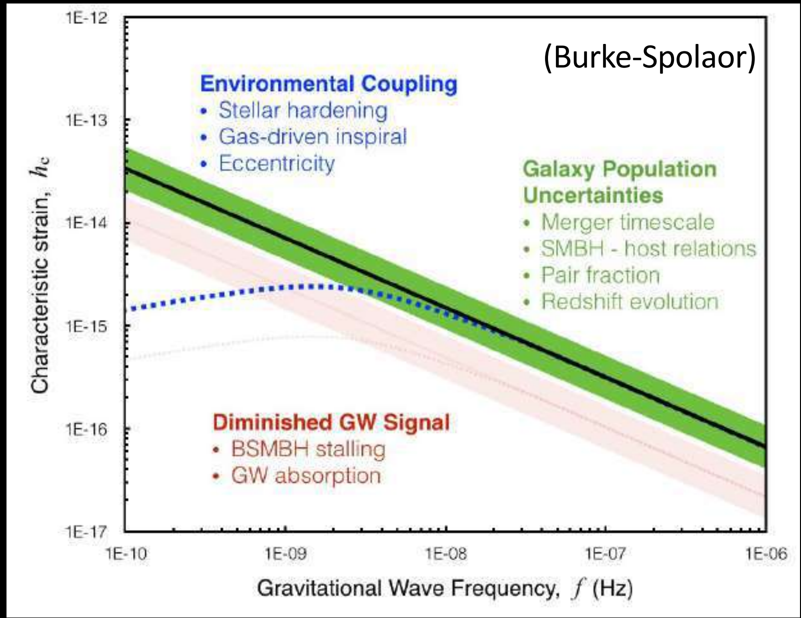

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- But, astrophysics can modify this

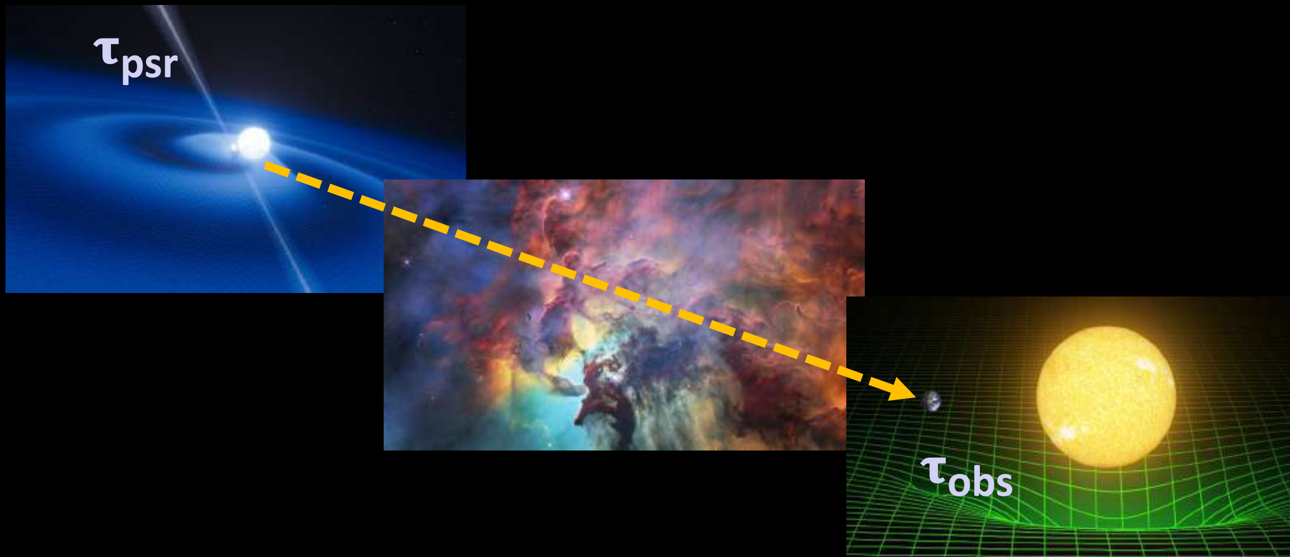
In other words: Measuring amplitude and spectrum can give access to astrophysics of SMBHBs!

What are the challenges?

Timing precision of 100 ns is non-trivial.

We have to detect relative frequency change of the order of 10^{-15} over many years.

There are other sources of noise with similar or larger amplitudes:



Pulsar (jitter, spin)

ISM (dispersion, scattering)

Solar system (ephemerides)

Incl. asteroids!

Red noise vs white noise, chromatic vs achromatic noise, correlated vs. uncorrelated noise

What are the challenges?

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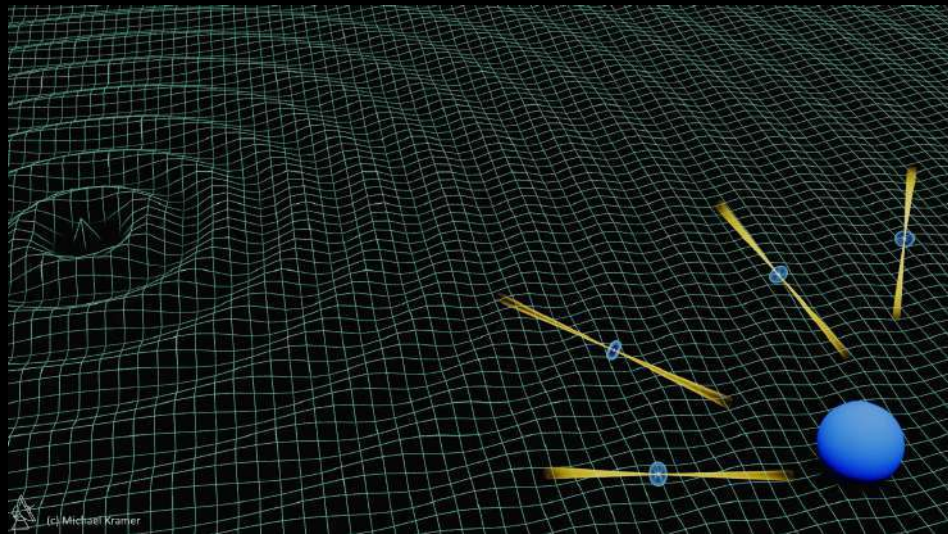
The signal of interest:



Systematic for single source but red noise for stochastic background

Correlated for Earth term, but uncorrelated for pulsar term

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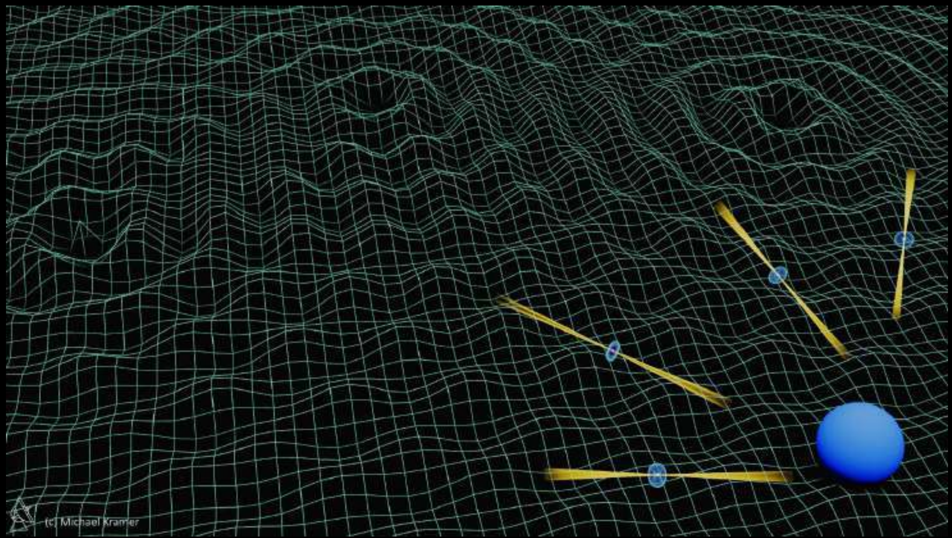

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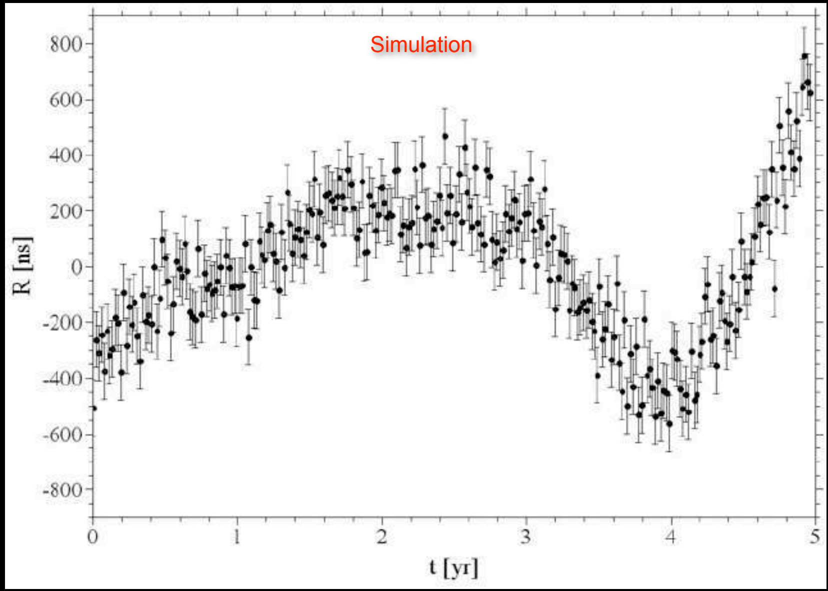
Note: nanosecond time scale



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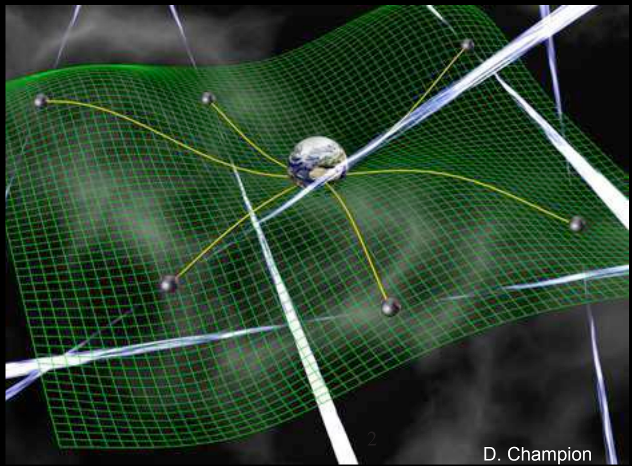
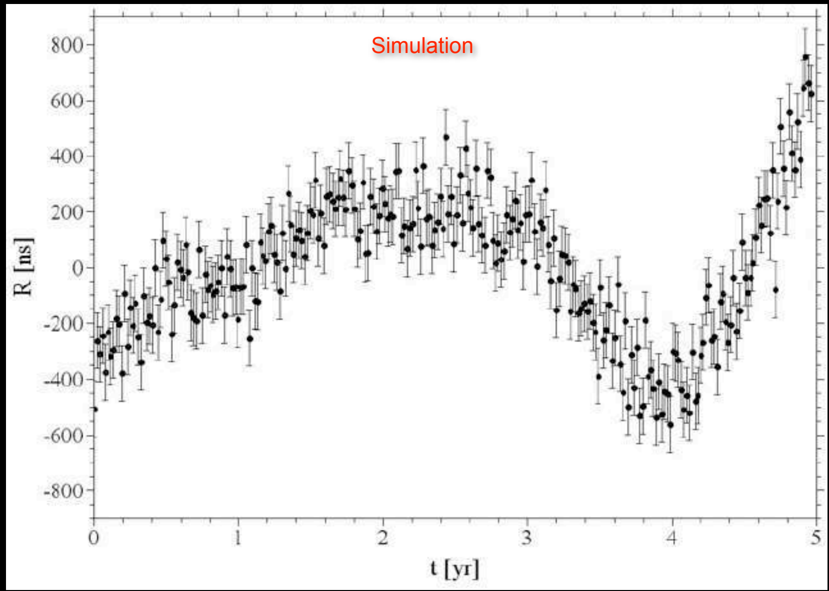
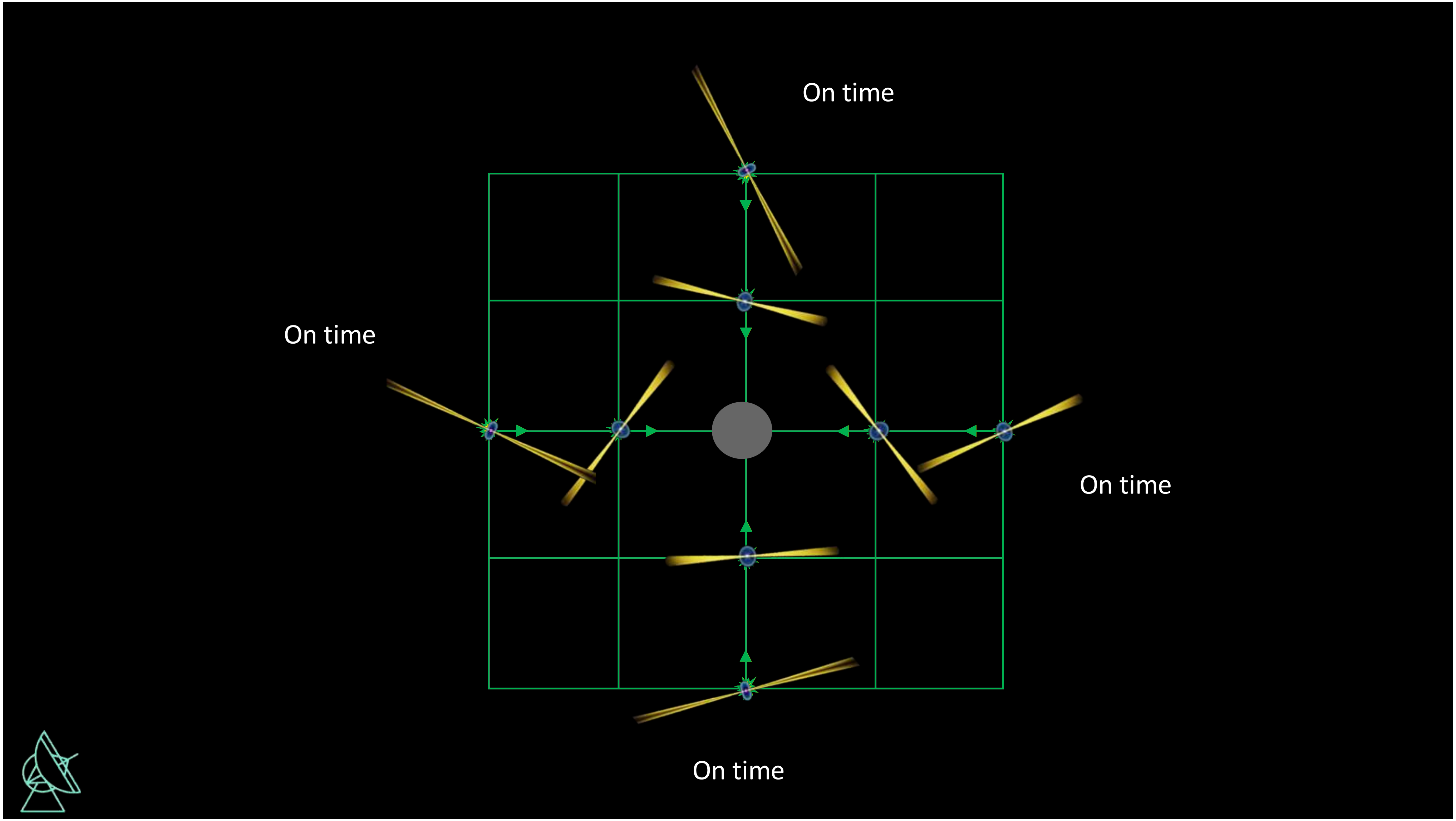
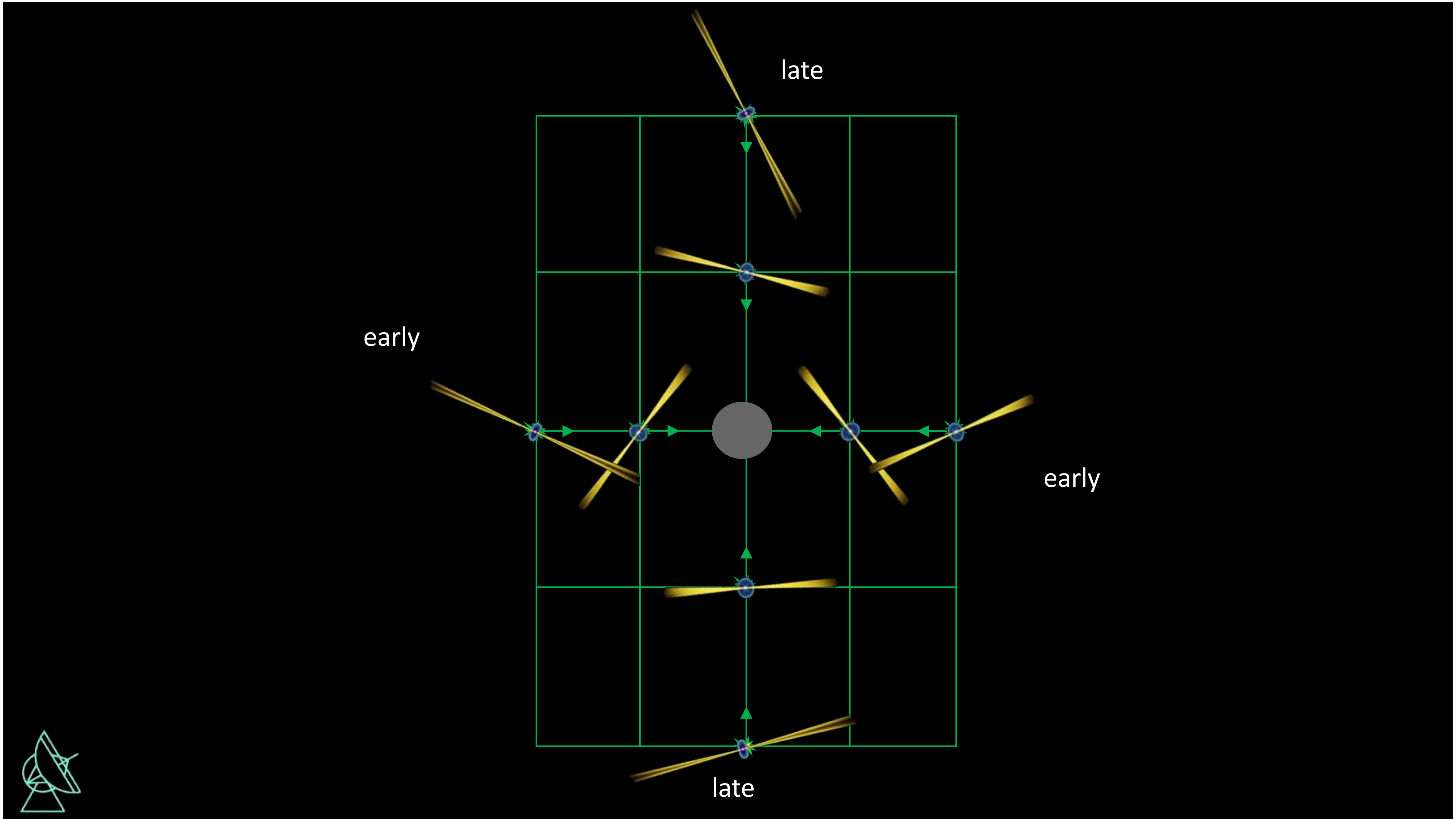
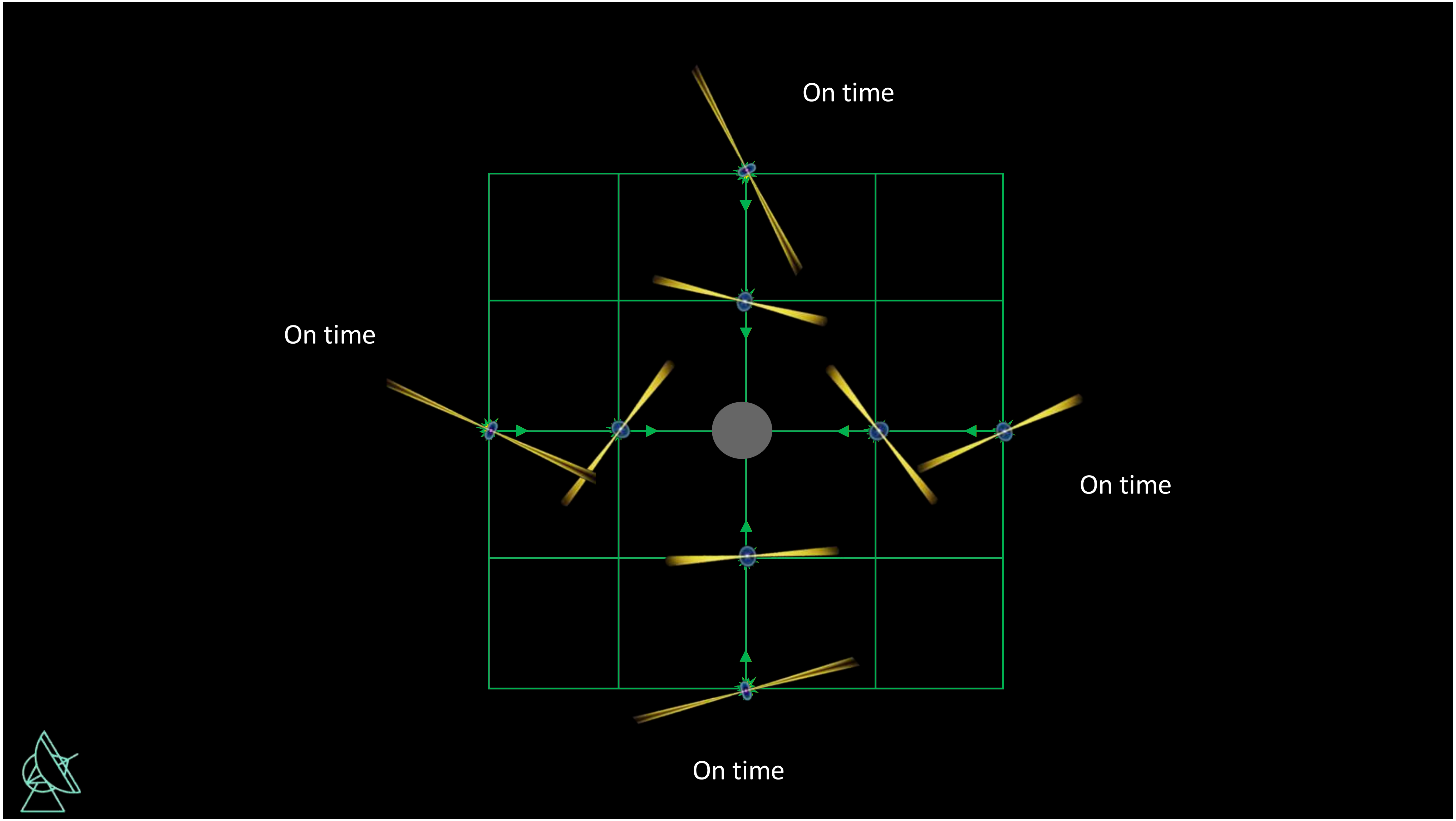


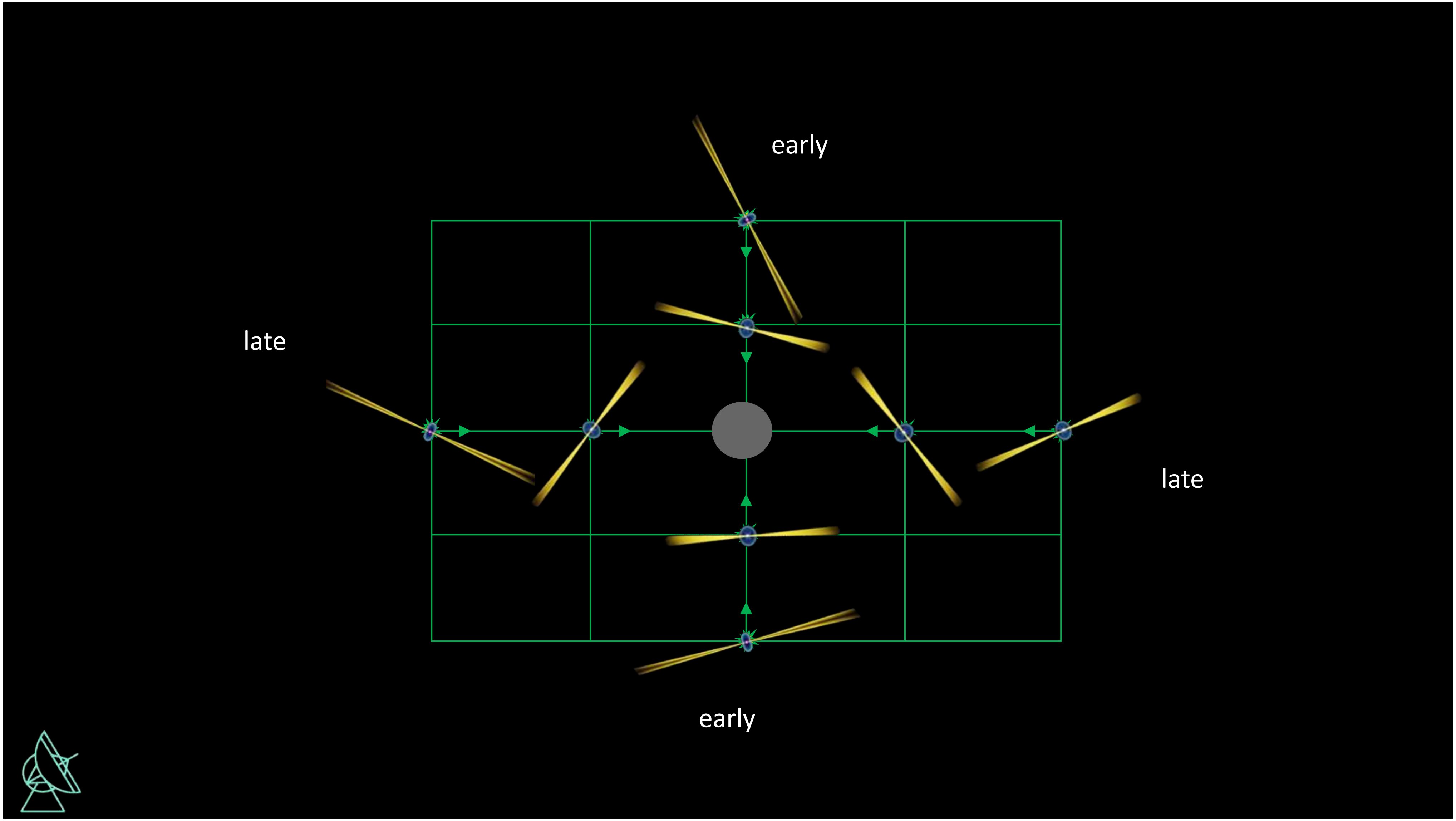


Solution: compare variations in timing residuals between pulsars! – A pulsar timing array (PTA)

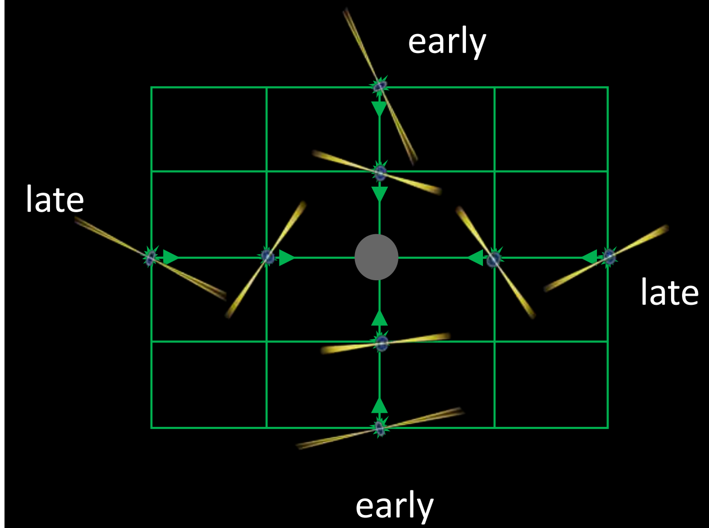

On time
On time
On time
On time

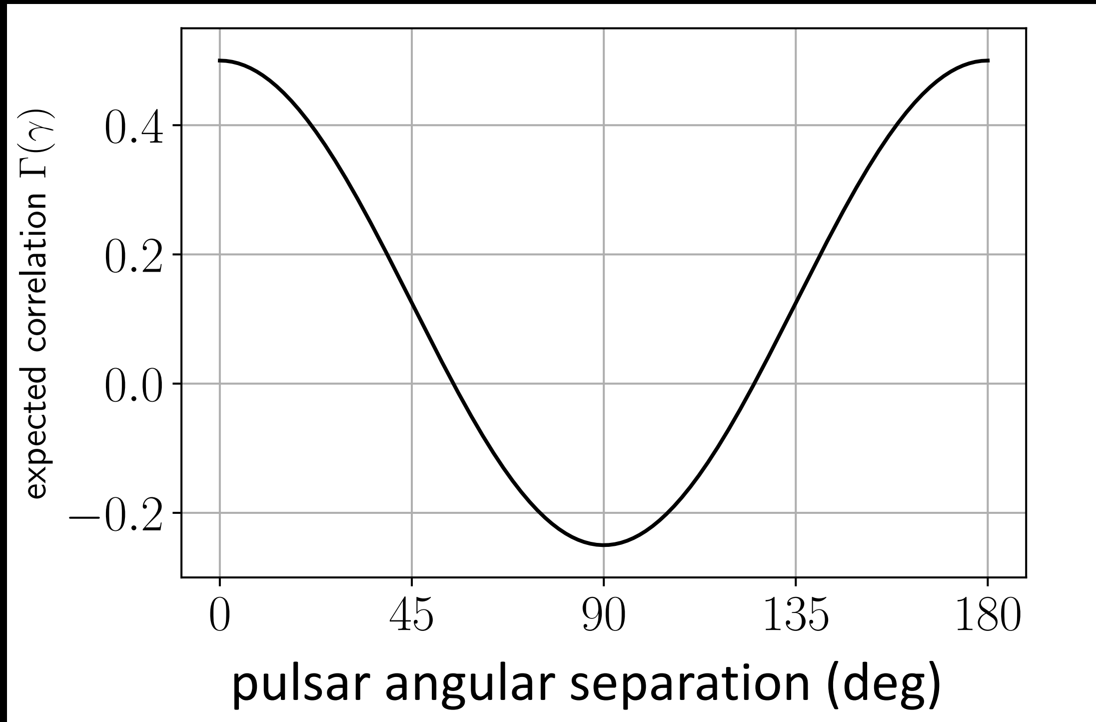

late
early
early
late


On time
On time
On time
On time


early
late
late
early

Correlation between arrival times of pairs of pulsars:





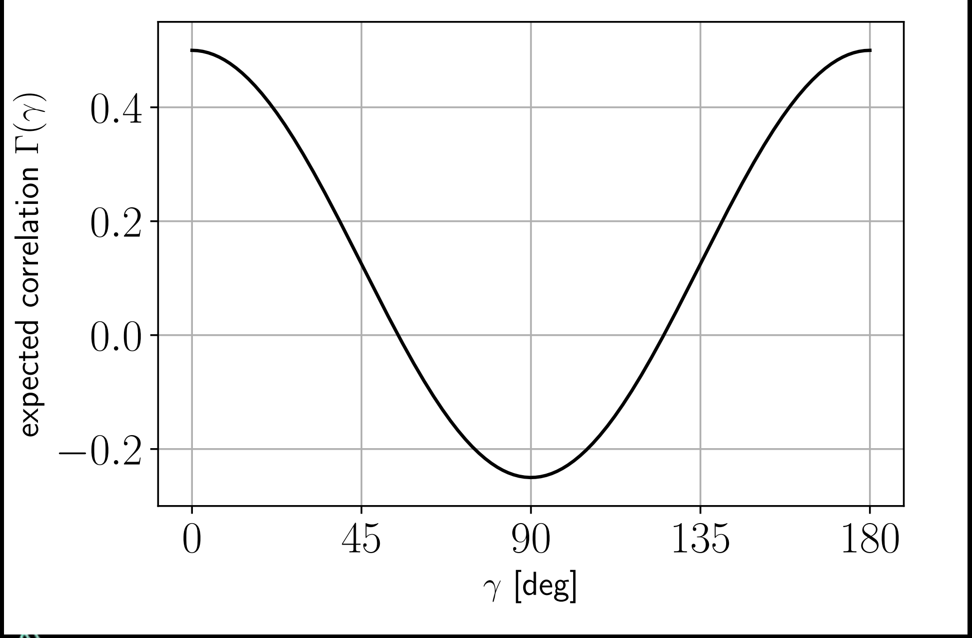
But, actual shape depends on relative size of GW wavelength and detector

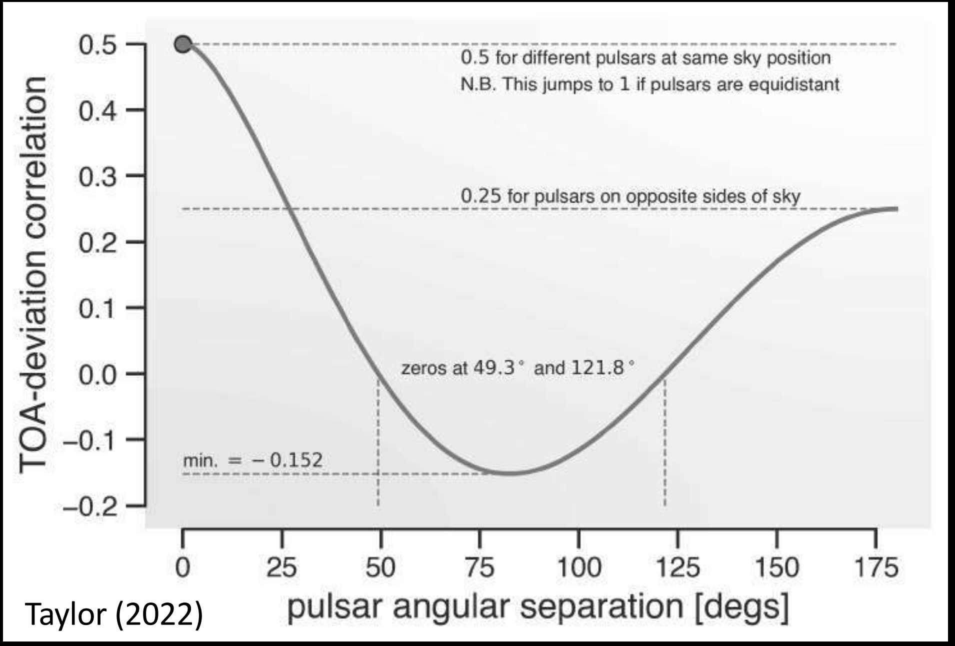
The Hellings & Downs Curve

At nHz frequencies, wavelengths are 10 – 100 pc – smaller than the distances to the pulsars

This changes the expected correlation curve.

The curve was first calculated by Hellings & Downs (1983) – it also applies to background





Short-arm detector (as LIGO)

Long-arm detector (as PTA)

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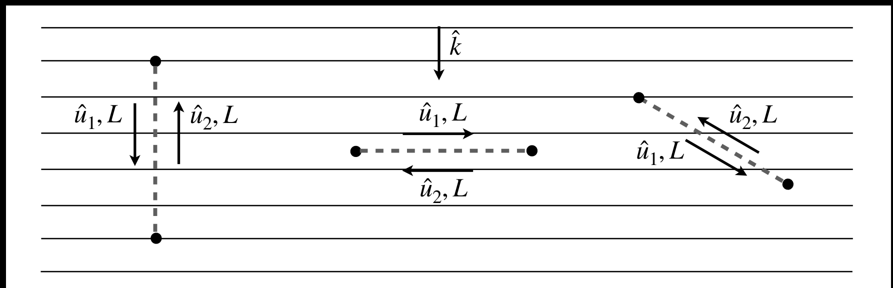
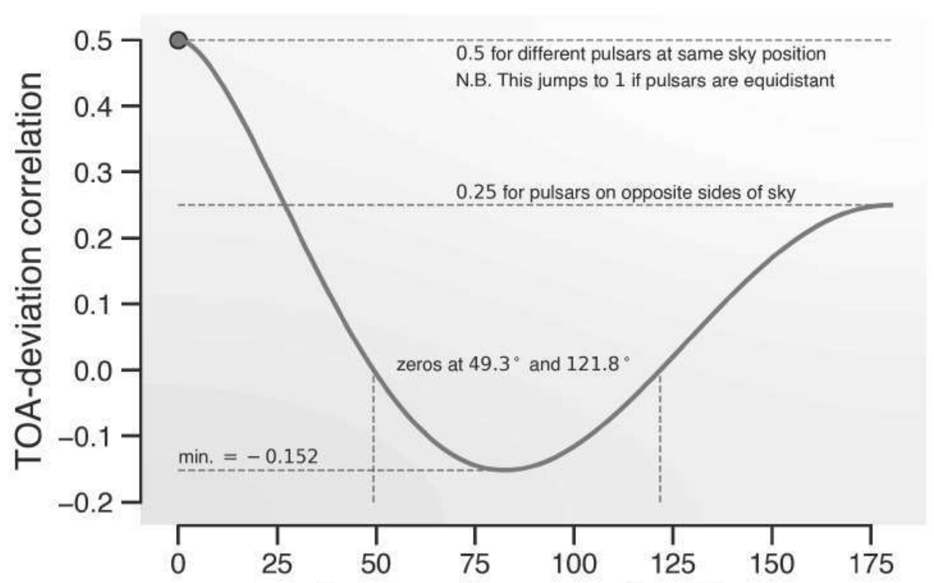


The HD curve is a signature of a GW signal in PTA data (equivalent to chirp in LIGO)

Idea: Measure the curve with as many pulsar pairs as possible over different angles

For n pulsars, we have n(n-1)/2 pairs.

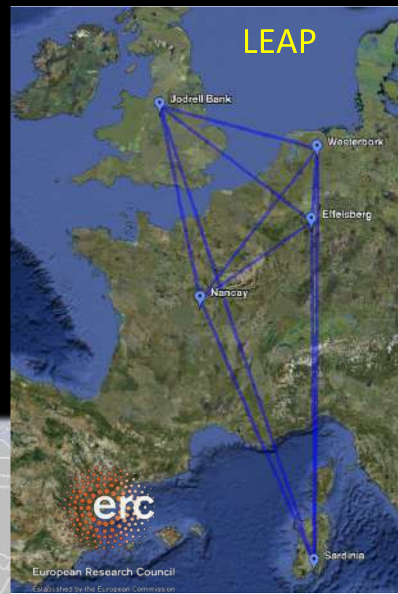


Taylor (2022)

Long-arm detector (as PTA)

The European Pulsar Timing Array (EPTA)

An array of 100-m class telescopes to form a pulsar timing array

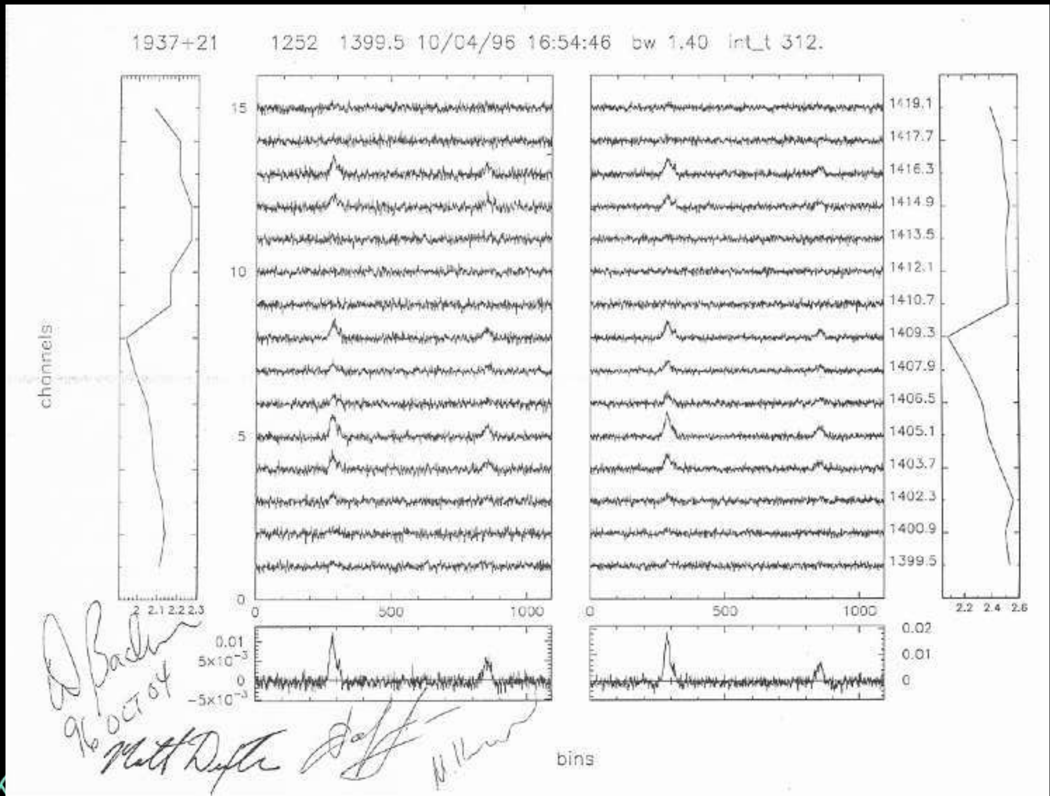


EPTA

and together forming the Large European Array for Pulsars (LEAP) monthly

PTA observations in Effelsberg since 1996

First light of the Effelsberg Berkeley Pulsar Processor (EBPP) – longest existing data set



Collaboration with Don Backer (UC Berkeley)

RESEARCH AGREEMENT NO. M2393

between

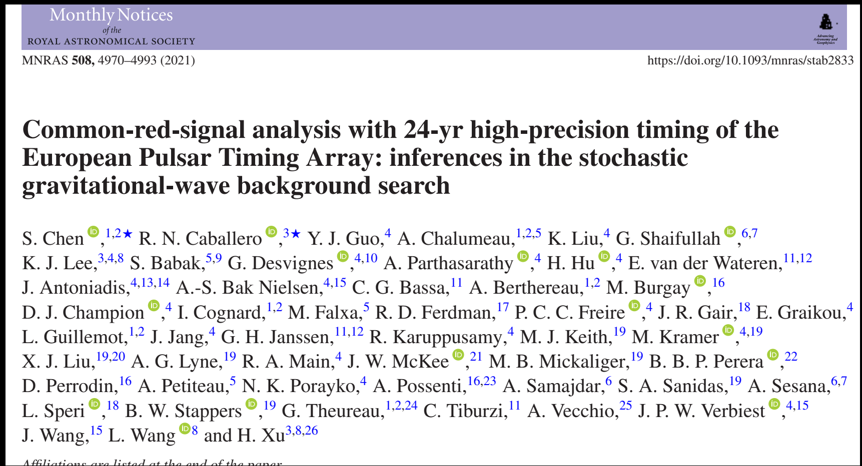
THE REGENTS OF THE UNIVERSITY OF CALIFORNIA, BERKELEY

and

MAX PLANCK INSTITUT FUR RADIOASTRONOMIE, GERMANY

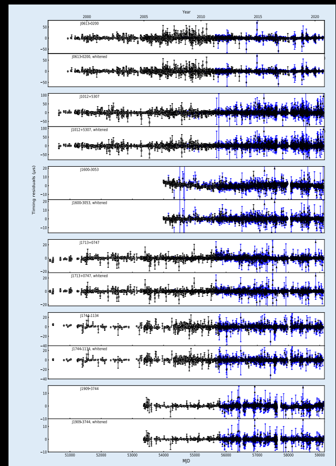
with emphasis on the precision timing of millisecond pulsars and related astrophysical investigations. These studies include detection of gravitational-wave background radiation through its subtle effects on pulsar pulse arrival times, the nature and origin of interstellar plasma

A couple of years ago: A smoking gun ?

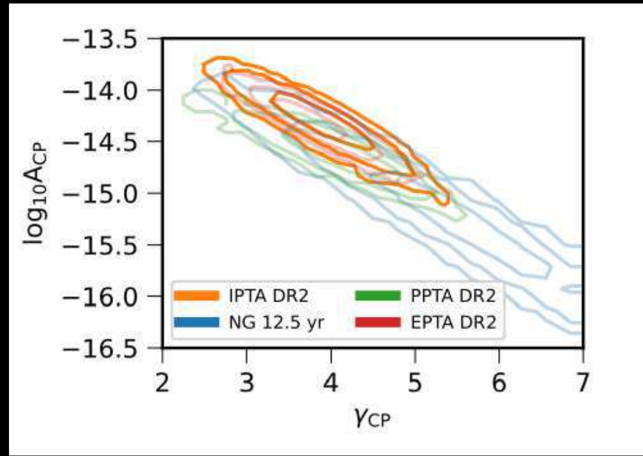

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **508**, 4970–4993 (2021) https://doi.org/10.1093/mnras/stab2833

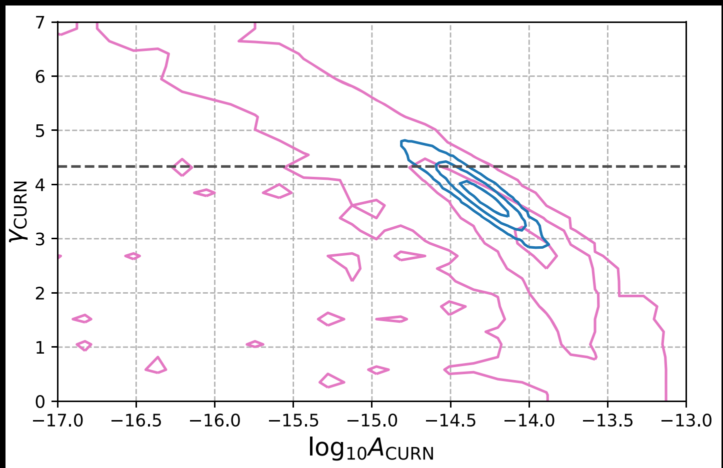
Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: inferences in the stochastic gravitational-wave background search

S. Chen,[1,2★] R. N. Caballero,[3★] Y. J. Guo,[4] A. Chalumeau,[1,2,5] K. Liu,[4] G. Shaifullah,[6,7] K. J. Lee,[3,4,8] S. Babak,[5,9] G. Desvignes,[4,10] A. Parthasarathy,[4] H. Hu,[4] E. van der Wateren,[11,12] J. Antoniadis,[4,13,14] A.-S. Bak Nielsen,[4,15] C. G. Bassa,[11] A. Berthereau,[1,2] M. Burgay,[16] D. J. Champion,[4] I. Cognard,[1,2] M. Falxa,[5] R. D. Ferdman,[17] P. C. C. Freire,[4] J. R. Gair,[18] E. Graikou,[4] L. Guillemot,[1,2] J. Jang,[4] G. H. Janssen,[11,12] R. Karuppusamy,[4] M. J. Keith,[19] M. Kramer,[4,19] X. J. Liu,[19,20] A. G. Lyne,[19] R. A. Main,[4] J. W. McKee,[21] M. B. Mickaliger,[19] B. B. P. Perera,[22] D. Perrodin,[16] A. Petiteau,[5] N. K. Porayko,[4] A. Possenti,[16,23] A. Samajdar,[6] S. A. Sanidas,[19] A. Sesana,[6,7] L. Speri,[18] B. W. Stappers,[19] G. Theureau,[1,2,24] C. Tiburzi,[11] A. Vecchio,[25] J. P. W. Verbiest,[4,15] J. Wang,[15] L. Wang[8] and H. Xu[3,8,26]



See also IPTA result (Antoniadis et al.)





- Data suggest a "common red noise process" seen by EPTA, Nanograv and PPTA – and IPTA
- EPTA signal has been increasing since 2015
- But, this was not a detection of a GWB yet – no HD curve

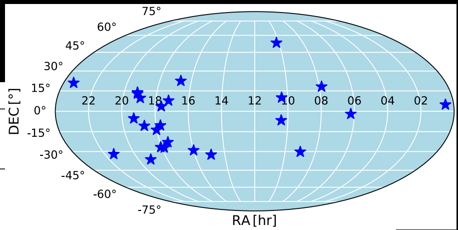
But what was it? A hint of GWs?

Not consistent with previous Nanograv & PPTA upper limits!

- It could be similar intrinsic noise in (some) pulsars
- It could be extrinsic (non-GW) sources

EPTA Data Release 2 (DR2)

Astronomy & Astrophysics manuscript no. output
May 8, 2023



The second data release from the European Pulsar Timing Array

III. Search for gravitational wave signals

J. Antoniadis[1,2], S. Babak[3], A.-S. Bak Nielsen[24], E. Barausse[5], C. G. Bassa[6], A. Berthereau[7,8], M. Bonetti[9,10,11], E. Bortolas[9,10,11], P. R. Brook[12], M. Burgay[13], R. N. Caballero[14], A. Chalumeau[9], D. J. Champion[2], S. Chanlaridis[1], S. Chen[15⋆], I. Cognard[7,8], G. Desvignes[2], M. Falxa[3,7] R. D. Ferdman[16], A. Franchini[9,10], J. R. Gair[17], B. Goncharov[18,19] E. Graikou[2], J.-M. Grießmeier[7,8], L. Guillemot[7,8], Y. J. Guo[2⋆⋆], H. Hu[2], F. Iraci[2013], D. Izquierdo-Villalba[9,10], J. Jang[2], J. Jawor[2], G. H. Janssen[6,21], A. Jessner[2], R. Karuppusamy[2], E. F. Keane[22], M. J. Keith[23], M. Kramer[2,23], M. A. Krishnakumar[2,4], K. Lackeos[2], K. J. Lee[3,8,2], K. Liu[2], Y. Liu[24,4], A. G. Lyne[23], J. W. McKee[25,26], R. A. Main[2], M. B. Mickaliger[23], I. C. Niţu[23], A. Parthasarathy[2], B. B. P. Perera[27], D. Perrodin[13], A. Petiteau[28,3], N. K. Porayko[9,2], A. Possenti[13], H. Quelquejay Leclere[3] A. Samajdar[29], S. A. Sanidas[23], A. Sesana[9,10,11], G. Shaifullah[9,10,13], C. Smarra[5], L. Speri[17], R. Spiewak[23], B. W. Stappers[23], S. C. Susarla[30], G. Theureau[7,8,32], C. Tiburzi[13], E. van der Wateren[6,21], A. Vecchio[12], V. Venkatraman Krishnan[2], J. P. W. Verbiest[31,4,2], J. Wang[4,33,34], L. Wang[23], Z. Wu[24,4] , P. Arumugam[35], S. Arumugam[36], M. Bagchi[37,37], A. Bathula[38], S. Dandapat[39], D. Deb[37], S. Desai[40], N. Dhanda-Batra[41], C. Dwivedi[42], A. Gopakumar[39], Y. Gupta[43], S. Hisano[44], B. C. Joshi[43,35], F. Kareem[45,46], D. Kharbanda[40], T. Kikunaga[44], N. Kolhe[47], Y. Maan[43], K. Nobleson[48], A. K. Paladi[49], T. Prabu[50], P. Rana[39], J. Singha[35], A. Srivastava[40], M. Surnis[51], A. Susobhanan[52], K. Takahashi[53,54] and P. Tarafdar[37]

(Affiliations can be found after the references)

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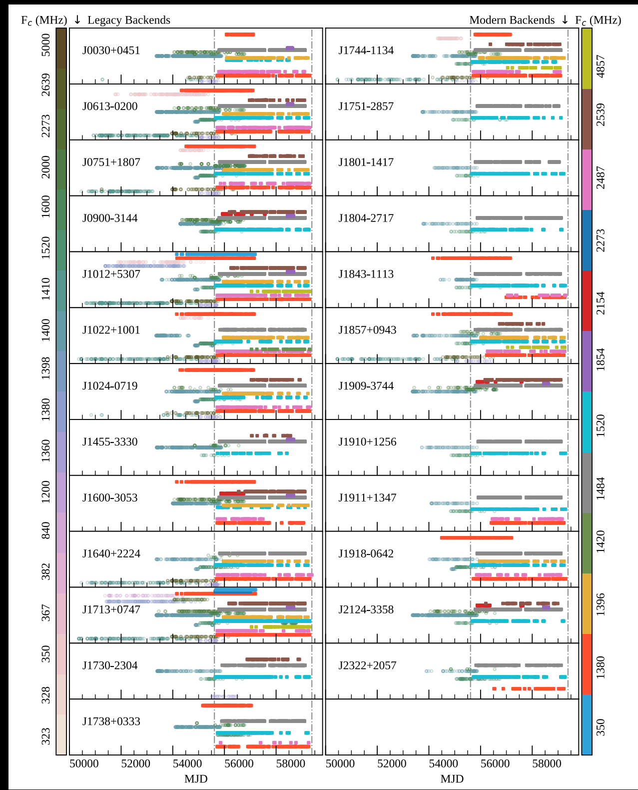
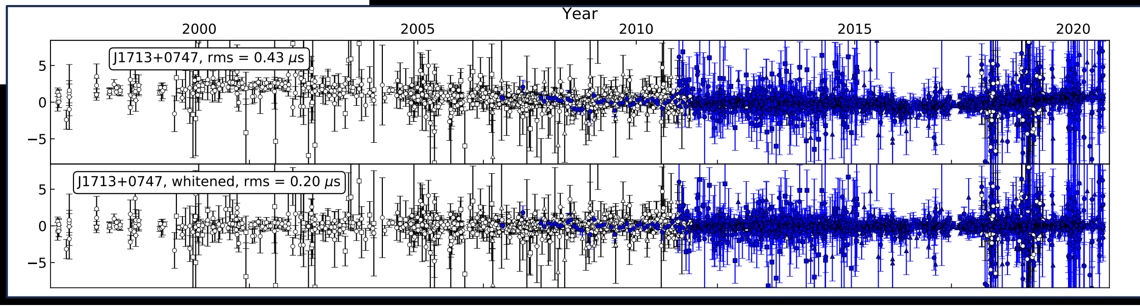
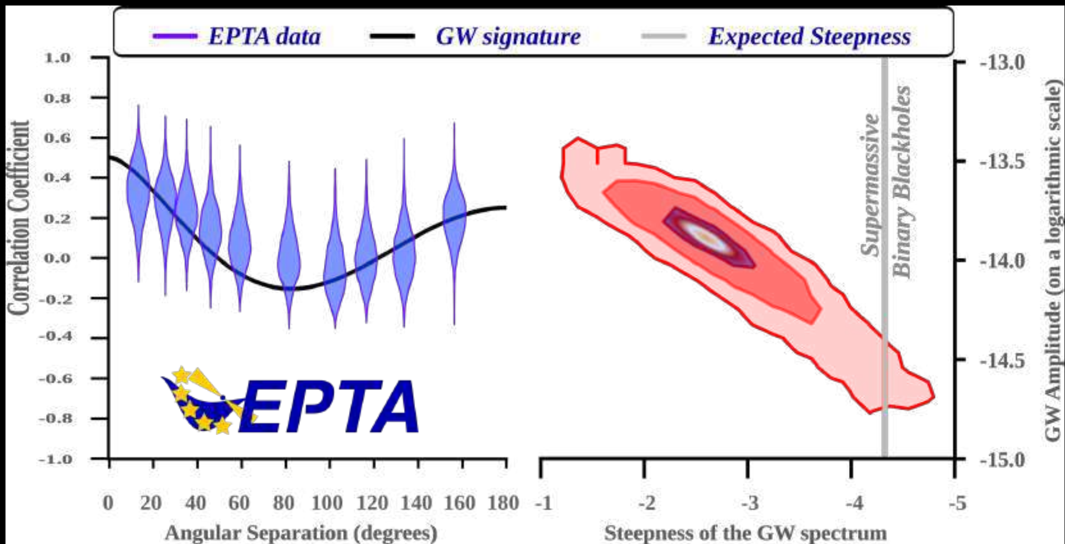


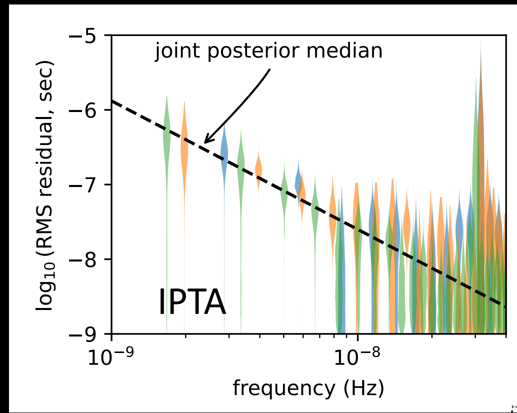


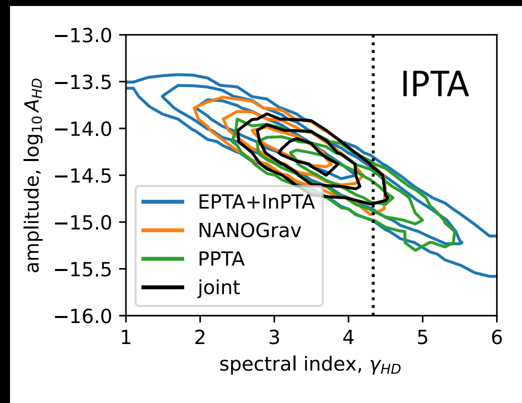
- More than 50 pulsars are being timed
- 25 pulsars included in the analysis
- Up to 25 years of data
- Supplemented by InPTA data (11 pulsars, 10 yrs)

On June 29th, 2023: Consistent results between all PTAs: > 20 papers

- No PTA has a detection but consistent compelling evidence: coordinated publications
- In Europe, observations for PTA purposes ongoing since 1996
- With 6 telescopes + LEAP EPTA/InPTA is longest and densest data set
- Four EPTA subsets studied







Achieved precision: $$\frac{\Delta L}{L} = \frac{30\ \mathrm{m}}{1\ \mathrm{lt\text{-}yr}}$$

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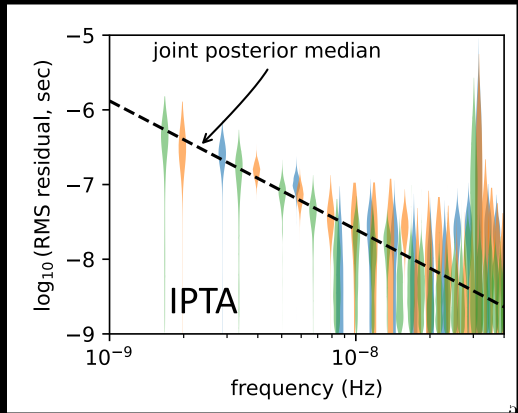
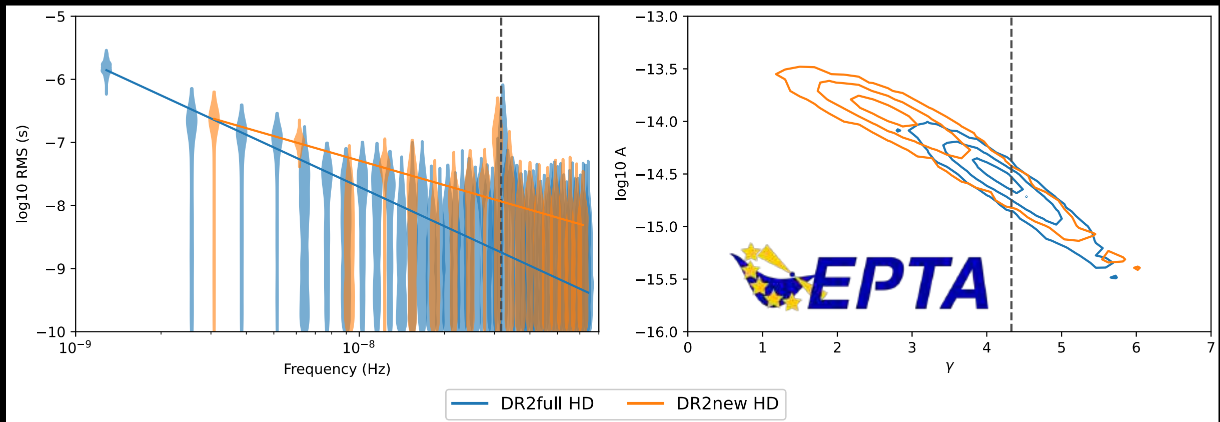
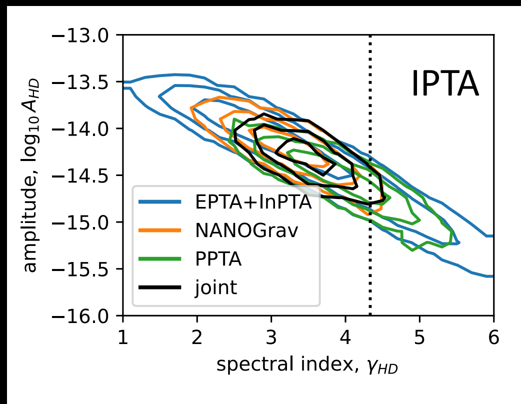
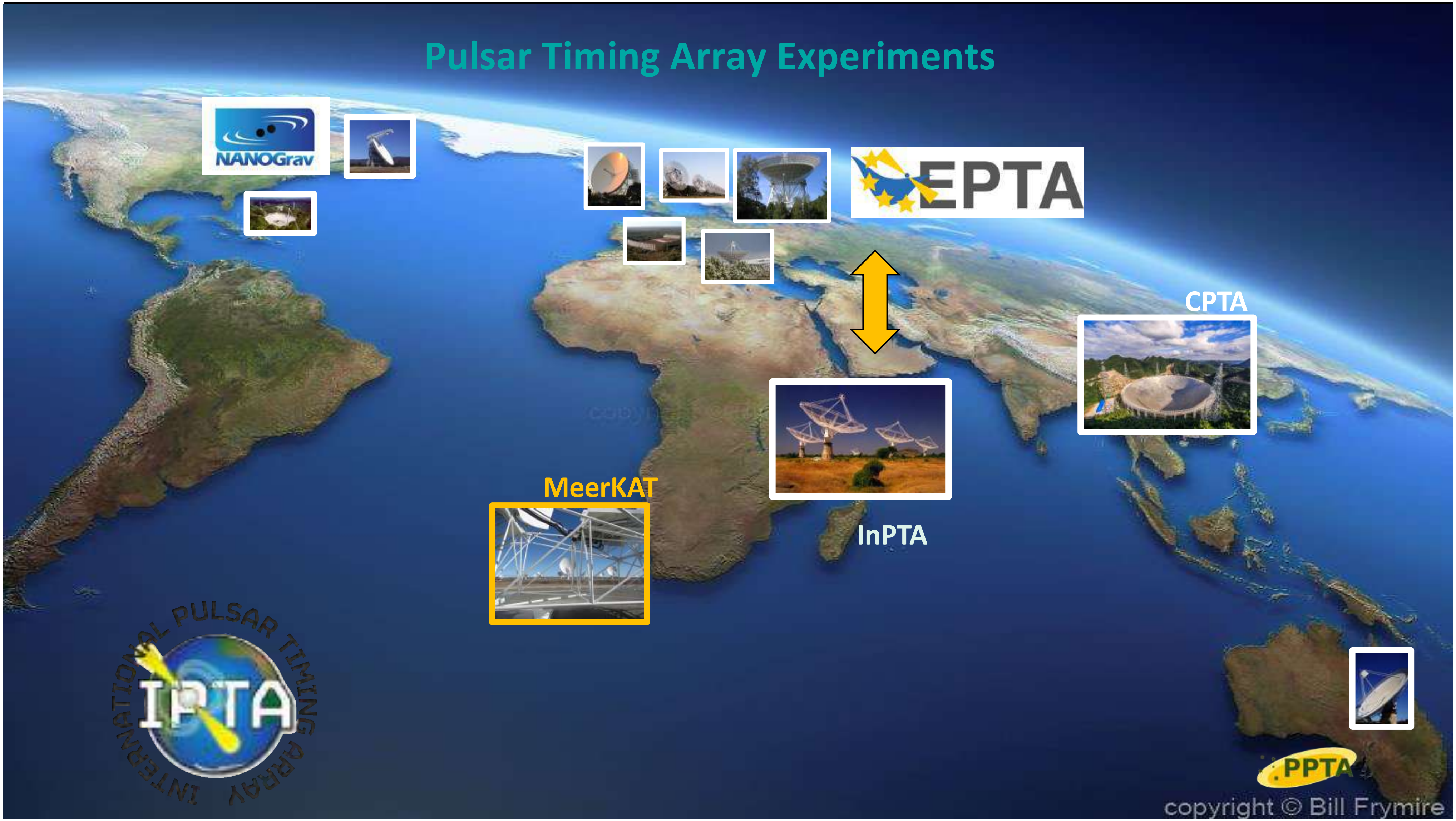


Comparison of DR2 and DR2 new:





- A small amount of eccentricity in the SMBHB population would account for a flatter spectrum as suggested by DR2new
- It this is true, gives example of kind of astrophysics possible with PTAs



Pulsar Timing Array Experiments
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EPTA
CPTA
MeerKAT
InPTA
INTERNATIONAL PULSAR TIMING ARRAY
IPTA
PPTA
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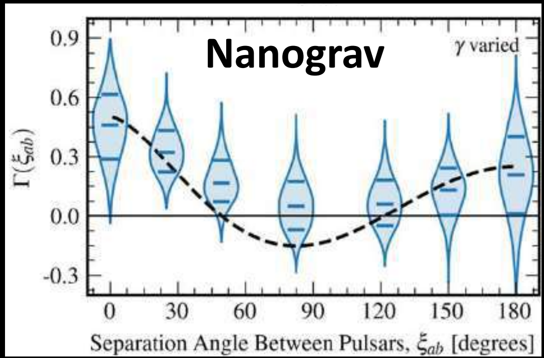
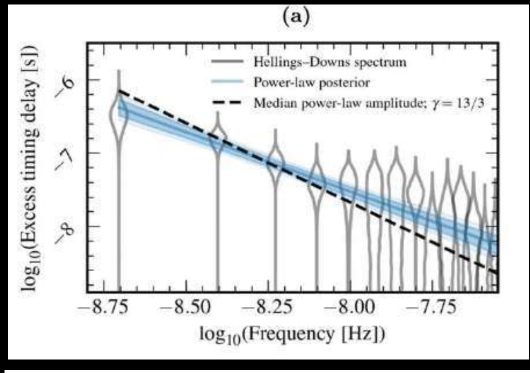
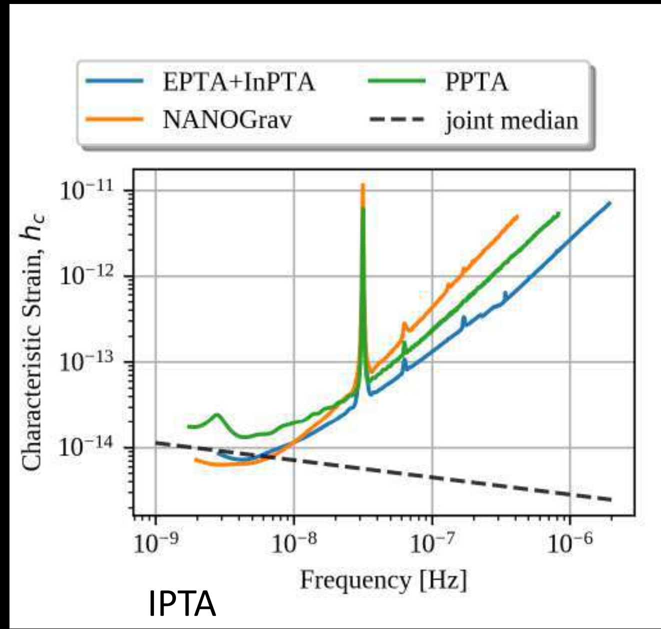
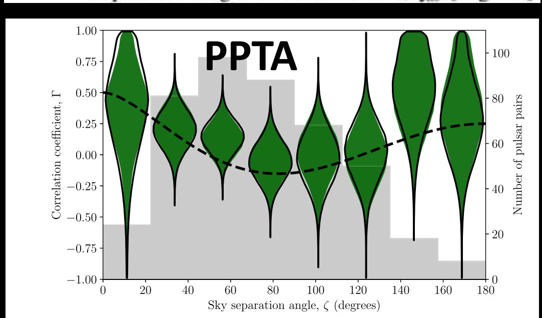
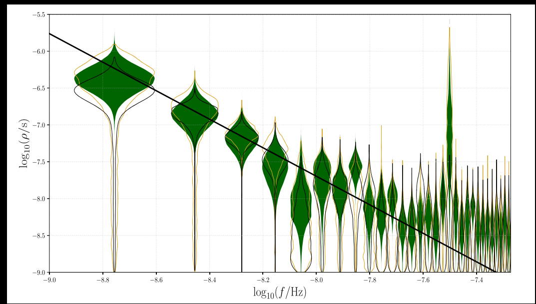
On June 29th, 2023: Consistent results between all PTAs: > 20 papers

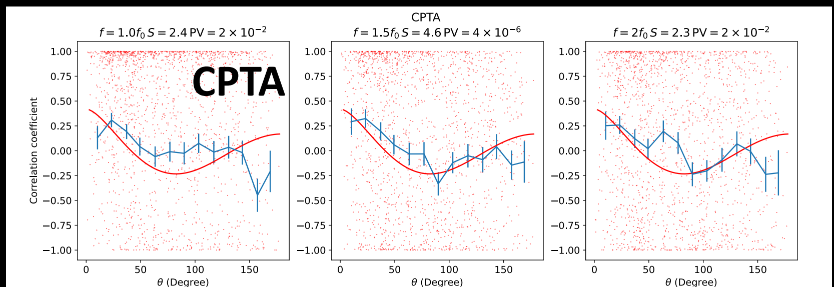


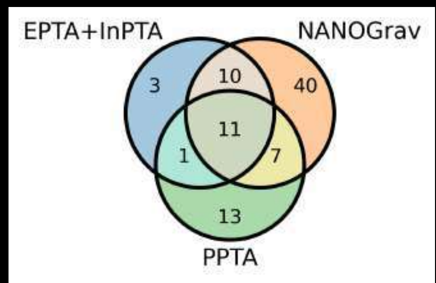








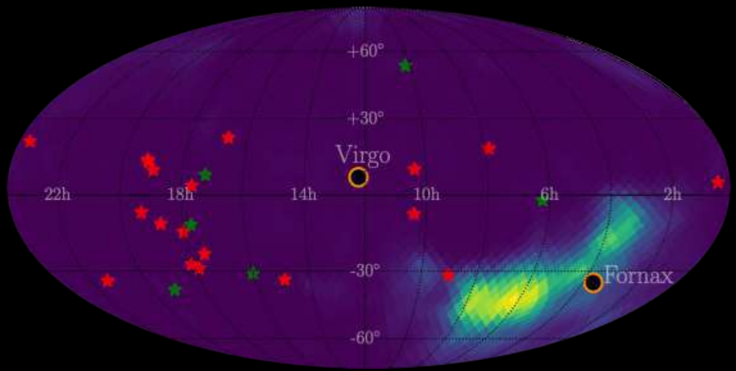




Next: combine to IPTA data set – also, use MeerKAT
But, still some important questions need to be answered: anisotropic, single-source, time-variable?

Opportunities for/via multi-messenger science

- Individual source(s) – EM follow-up, transition into LISA band, galaxy surveys, simulations
- Relic (primordial) gravitational waves – seeing through the CMB – to detect signal from inflation
- Cosmological phase transition
- Cosmic strings
- Dark matter, axions etc.



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June 29, 2023

The second data release from the European Pulsar Timing Array

IV. Search for continuous gravitational wave signals

Astronomy & Astrophysics manuscript no. eptaDR2_interpretation ©ESO 2023
June 29, 2023

The second data release from the European Pulsar Timing Array

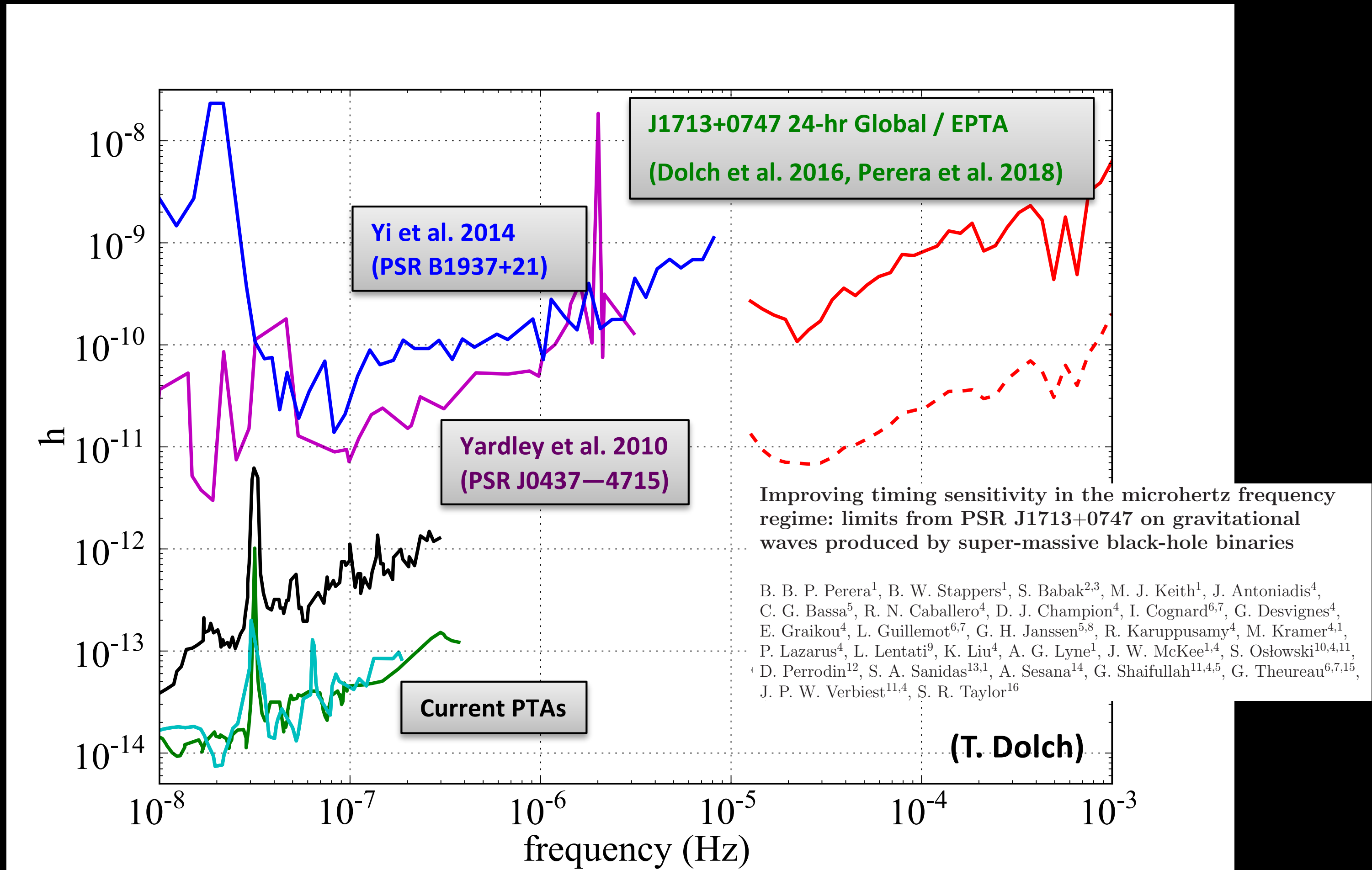
V. Implications for massive black holes, dark matter and the early Universe

The second data release from the European Pulsar Timing Array:
VI. Challenging the ultralight dark matter paradigm

The Astrophysical Journal Letters, 951:L11 (56pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdc91

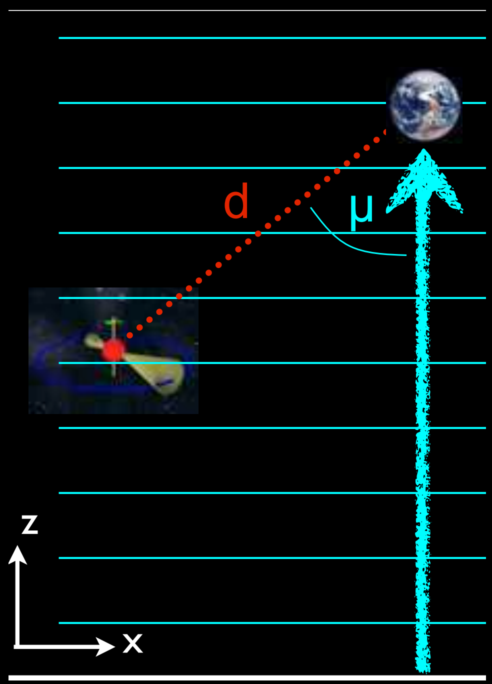
The NANOGrav 15 yr Data Set: Search for Signals from New Physics

”High-Frequency Observations” via high cadence



What would be the effect of a single source on a the pulsar-Earth arm?

The timing residual is the integral over TOA variation over the duration of the timing experiment:



$$R(t) = \frac{1}{2}(1 + \cos\mu)[r_+(t)\cos(2\psi) + r_\times(t)\sin(2\psi)],$$

$$r_{+,\times}(t) = r^e_{+,\times}(t) - r^p_{+,\times}(t),$$

$$r^e_{+,\times}(t) = \int_0^t h^e_{+,\times}(\tau)\,d\tau, \qquad \text{"Earth term"}$$

$$r^p_{+,\times}(t) = \int_0^t h^p_{+,\times}\left[\tau - \frac{d}{c}(1 - \cos\mu)\right]d\tau, \qquad \text{"pulsar term"}$$

Retardation

Retardation & Source evolution

Like in binary pulsars, GW damping will cause the BH binary to shrink, leading to increase in GW frequency. For a circular orbit one has:

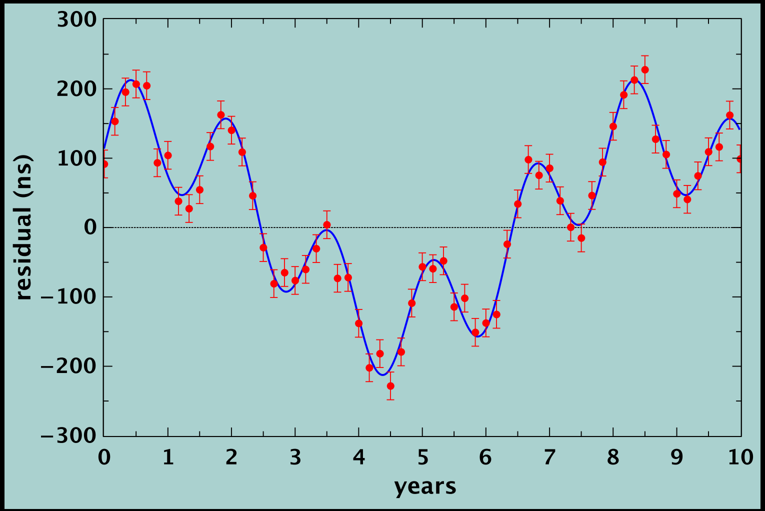
$$\frac{\dot{f}}{f} = \frac{96}{5}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3}(\pi f)^{8/3}$$

with "chirp mass"

$$\mathcal{M}_c \equiv \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$

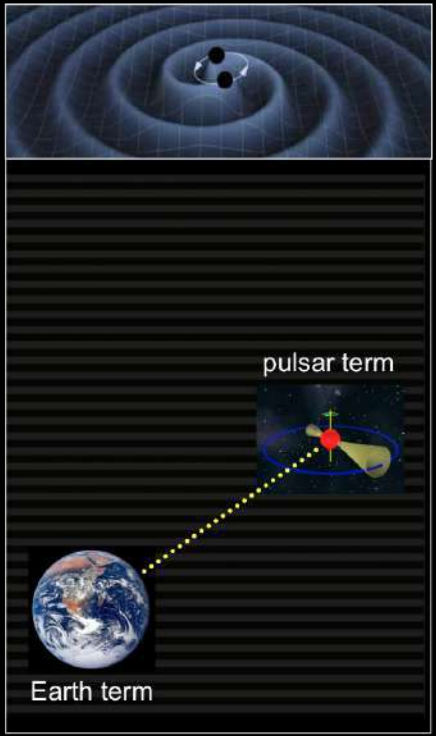
Single source affects both pulsar & Earth at different times (retardation)

Frequency evolution during Tobs generally negligible, but some sources could have significant frequency evolution between pulsar term and Earth term.



N. Wex

- Signal is superposition of two parts:
  - GW impacting on pulsar
  - GW impacting on Earth
- Different frequencies due to retardation
- Access to source evolution with more pulsars



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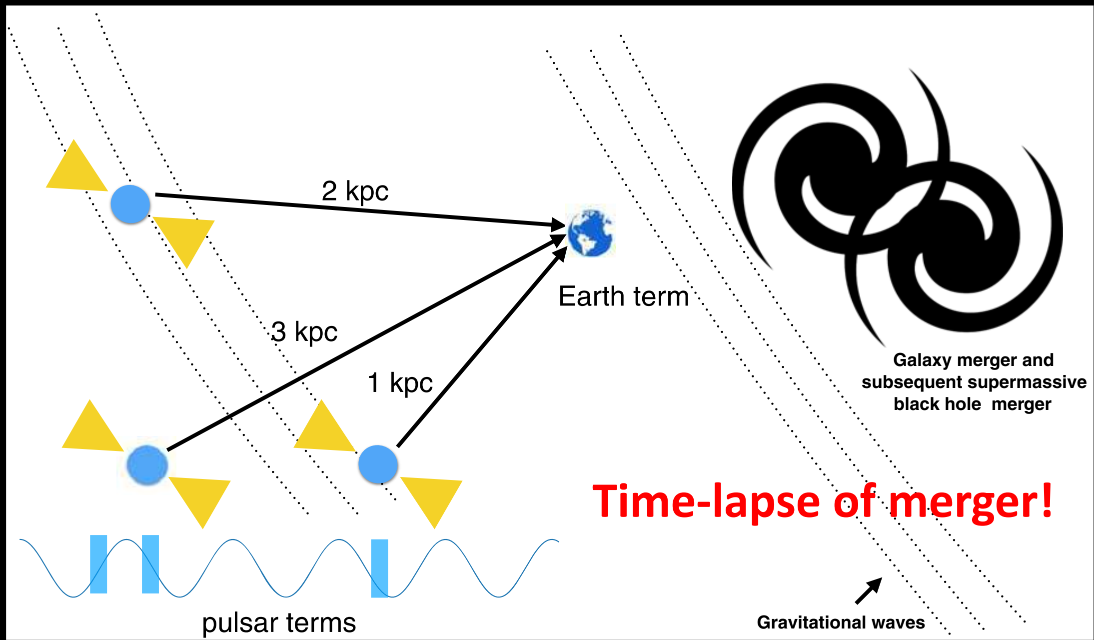
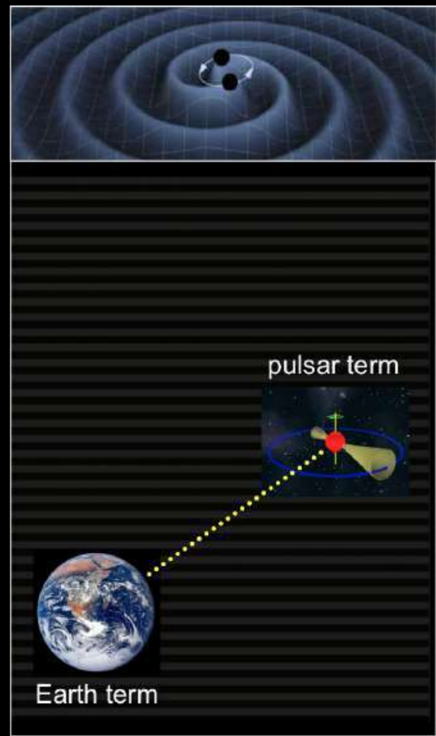
Mingarelli (2012)

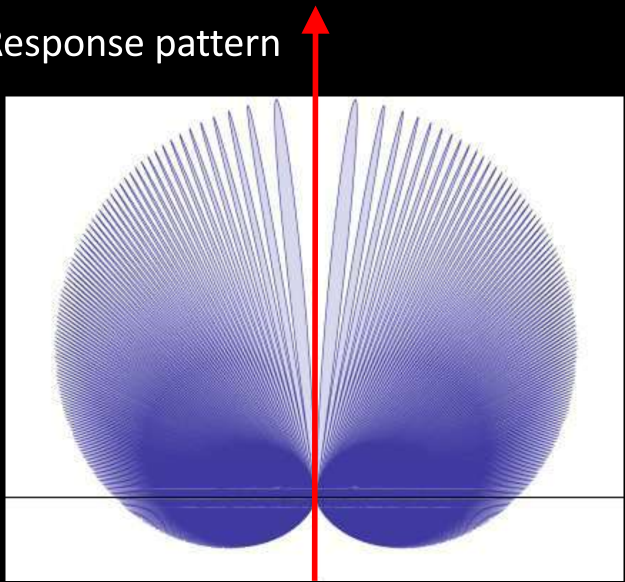




Precise localisation of single GW sources

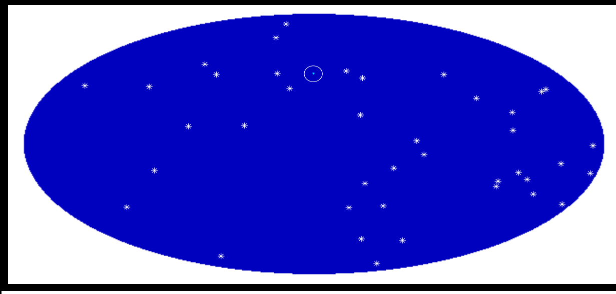
With future ISKA-IPTA we can locate the binary SMBH in the sky:

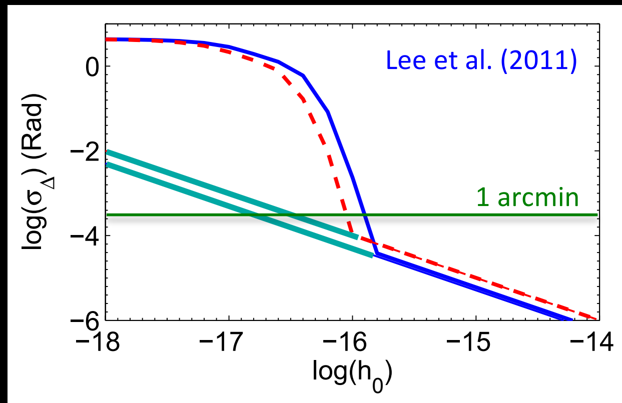
Response pattern



40 millisecond pulsars at ~2 kpc distance

One 15 ns TOA every two weeks for 5 years





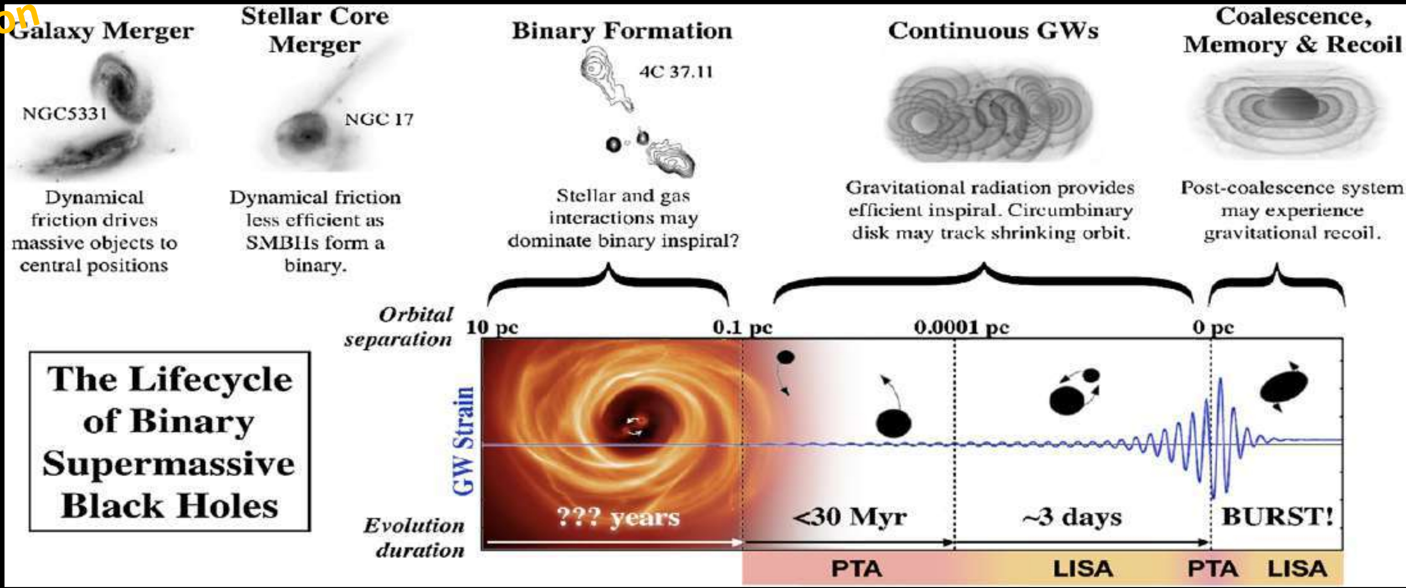
Enabled by precise distance measurements:

$$\sigma_{D_{\rm psr}} = \frac{4\sqrt{2}\,\sigma_{\rm n} D_{\rm psr}^2}{\sqrt{N_{\rm obs}}\, r_\oplus^2 \cos^2\beta_{\rm psr}} \simeq \frac{2.34}{\cos^2\beta_{\rm psr}} \left(\frac{N_{\rm obs}}{100}\right)^{-\frac{1}{2}} \left(\frac{D_{\rm psr}}{1\,{\rm kpc}}\right)^2 \left(\frac{\sigma_{\rm n}}{10\,{\rm ns}}\right)\ {\rm pc}$$

Allowing EM follow-up of GW sources!

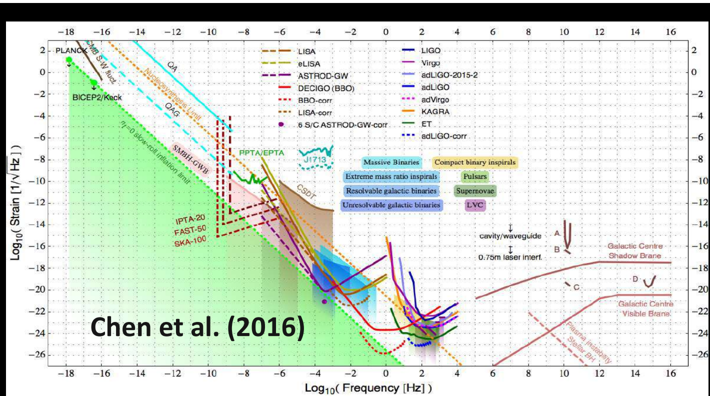
True complementarity & synergies with EM & GW

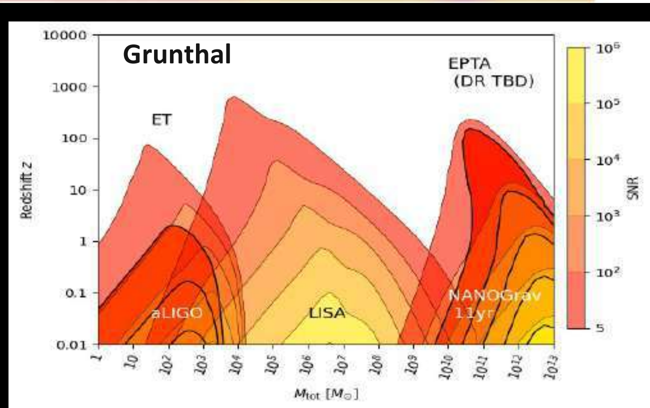
Source evolution



(Burke-Spolaor et al. 2019)

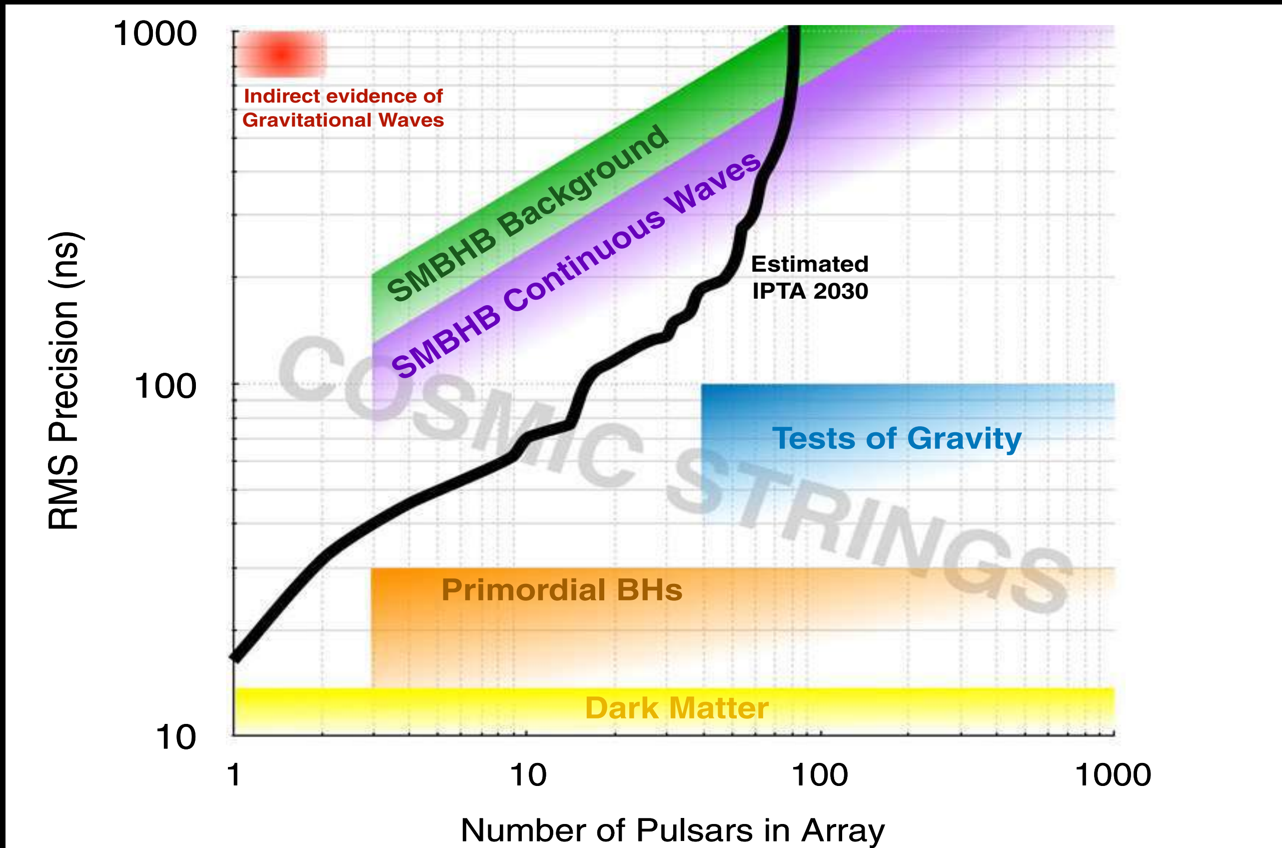
Frequency range





Source reach

Prospects

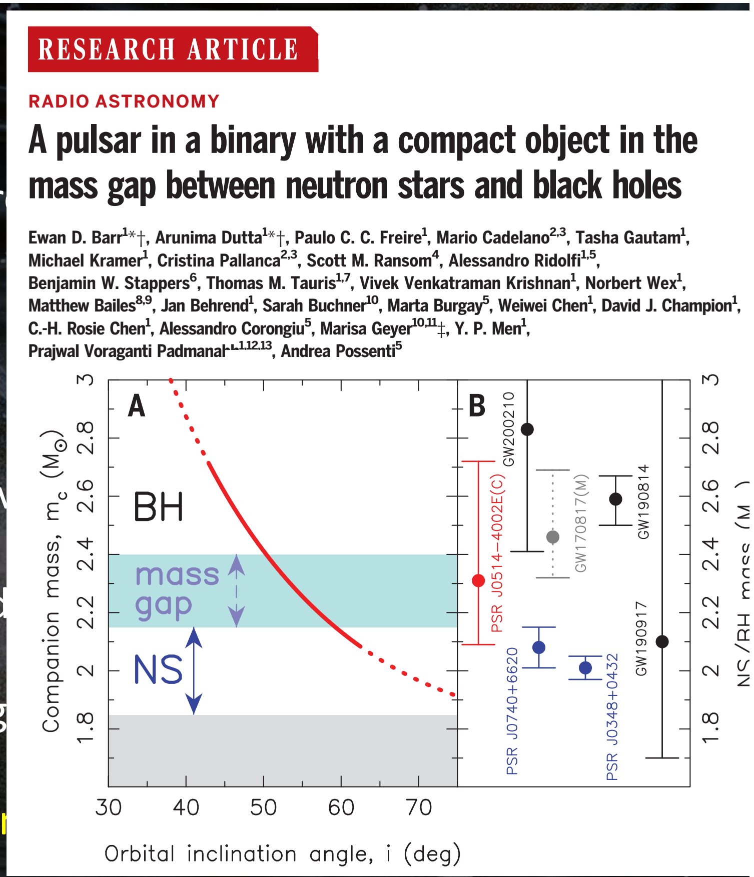


(Burke-Spolaor et al. 2019)

Update needed...!

Summary and Conclusions

- PTAs have found compelling evidence for a HD curve, with measur
  consistent with GW background of SMBHBs
- EPTA has the longest, densest and best chromatic data set
- Not a formal 5-sigma detection yet, but IPTA combination will deliv
- Other sources (e.g. CW sources) cannot be excluded (or confirmed
- Limits on exotic sources (e.g. ultra-light dark matter) – which will g
- Exciting synergies for multi-messenger science: EM follow, GW cor
  evolution with surveys and simulation – See also FERMI – PTA!
- 40 years after the first evidence of GWs with pulsars, pulsars open up a new window to GW astronomy
  providing further links to ground- and space-based GW detectors


RESEARCH ARTICLE

RADIO ASTRONOMY

A pulsar in a binary with a compact object in the mass gap between neutron stars and black holes

Ewan D. Barr[1*†], Arunima Dutta[1*†], Paulo C. C. Freire[1], Mario Cadelano[2,3], Tasha Gautam[1], Michael Kramer[1], Cristina Pallanca[2,3], Scott M. Ransom[4], Alessandro Ridolfi[1,5], Benjamin W. Stappers[6], Thomas M. Tauris[1,7], Vivek Venkatraman Krishnan[1], Norbert Wex[1], Matthew Bailes[8,9], Jan Behrend[1], Sarah Buchner[10], Marta Burgay[5], Weiwei Chen[1], David J. Champion[1], C.-H. Rosie Chen[1], Alessandro Corongiu[5], Marisa Geyer[10,11‡], Y. P. Men[1], Prajwal Voraganti Padmanal[1,12,13], Andrea Possenti[5]

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J. Jawor, A. Jessner, R. Karuppusamy, E. F. Keane, M. A. Krishnakumar, K. Lackeos,

K. Lazaridis, P. Lazarus, K. J. Lee, K. Liu, O. Löhmer, J. W. McKee , R. A. Main,

A. Parthasarathy, N. K. Porayko, C. Tiburzi, V. Venkatraman Krishnan, J. P. W. Verbiest

N. Wex

Thanks also to Effelsberg Operators

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