The Gamma Pulsar Timing Array: Data Release 2 and the Future

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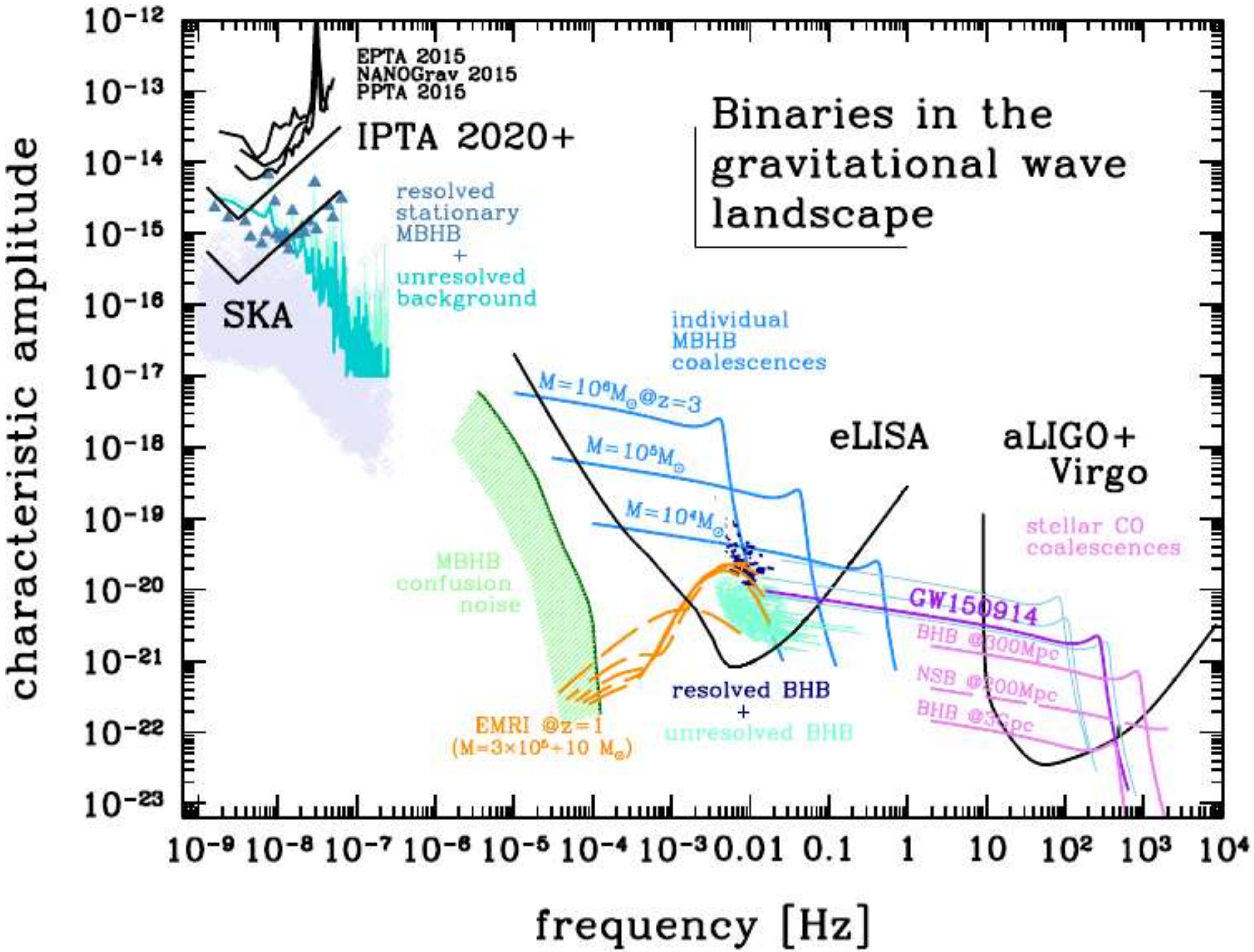
on behalf of the Fermi-LAT Collaboration

GRSIG, 17th November, 2023

Image credit: Danielle Futselaar / MPIfR

The Gravitational Wave Landscape for Binaries



Supermassive Black Hole Binaries Emit nHz Gravitational Waves

- Basic physics: GR (Einstein, 1918) $\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} = \frac{c^3}{16\pi G} \iint |\dot{h}|^2 \mathrm{d}S = \frac{1}{5}\frac{G}{c^5} \sum_{i,j=1}^{3} \frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3} \frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3}$

  \+ Mechanics ($Q \propto r^2$) + Kepler's Laws ($r^3 = \frac{GM}{(2\pi f)^2}$) lead to a simple relation:

  A circular binary with frequency $\frac{f}{2}$ emits GW with frequency f and amplitude $h \propto f^{\frac{2}{3}}$.

- For typical SMBH masses, GW emission dominates at binary separations of <0.01—0.1pc, i.e. orbital periods $\gg$ 10 years.

- Binaries spend more time at wide separations. Adding them up over the cosmological population and adding in the $\frac{1}{d}$ amplitude scaling (Phinney (2003), Sesana et al. (2004)) leads to the prediction of a "stochastic", nHz **gravitational wave background (GWB)** with a power-law spectrum ($\alpha = -\frac{2}{3}$):

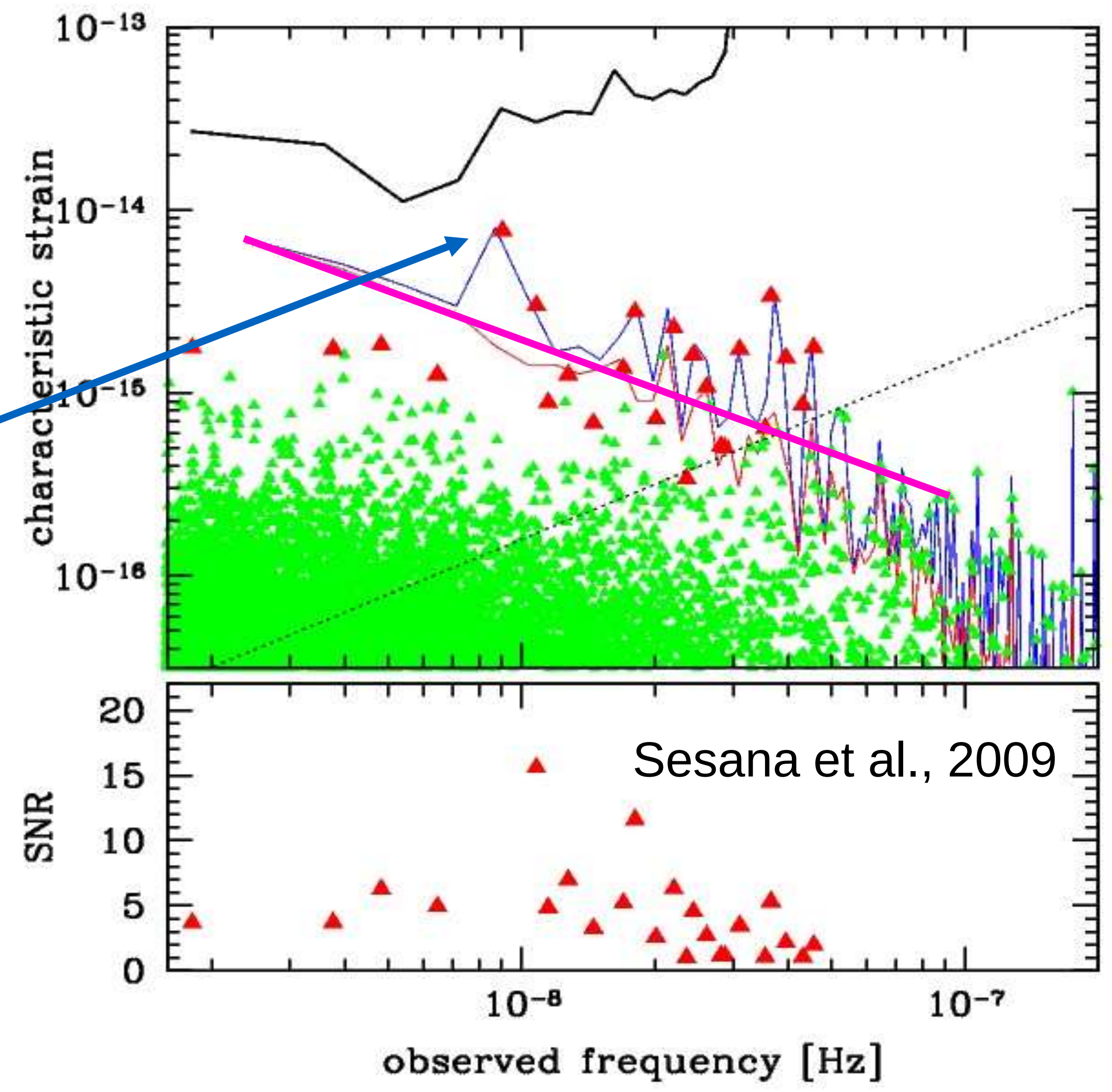
$$h_c(f) = A_{\mathrm{gwb}} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{\alpha}$$

Probing the SMBHBs Population with the GWB

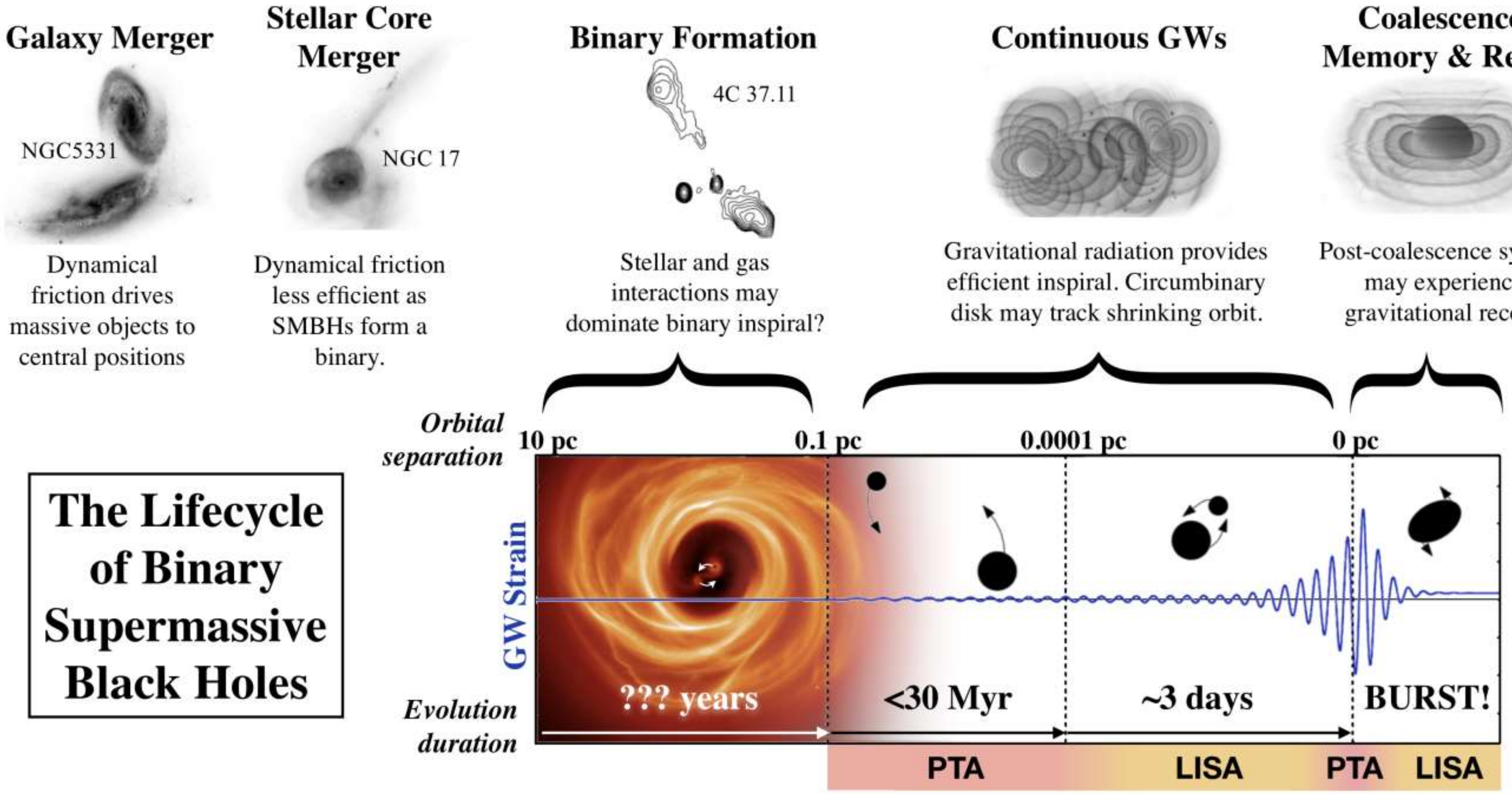
(see Burke-Spolaor et al. 2019 for a review)

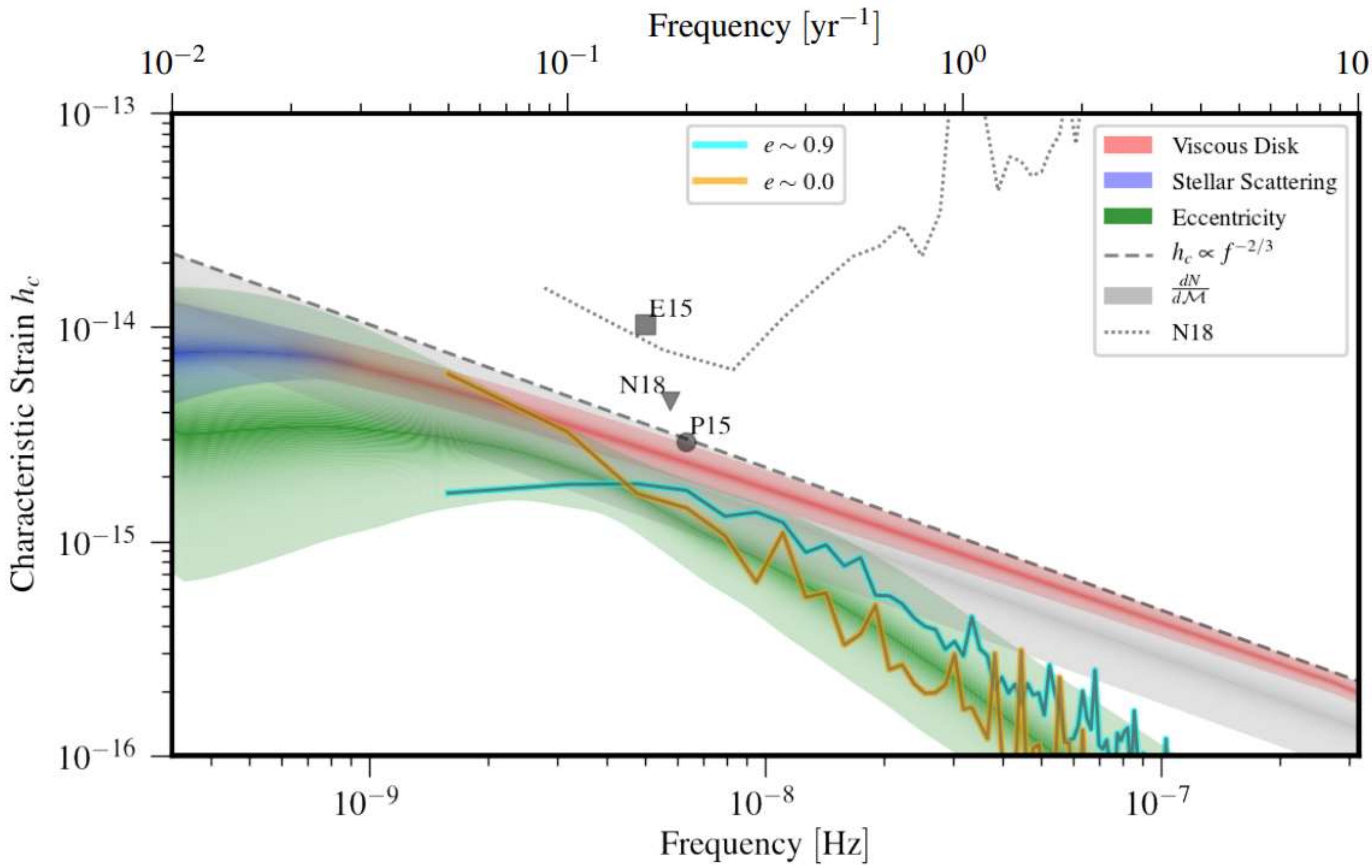
- GW amplitude A_{gwb} scales with masses of merging black holes and the efficiency of BH mergers.
- BHs must reach center of merged galaxy and must shed angular momentum to close from 1pc to <0.1pc, the “**Final Parsec Problem**”. Stalled mergers will produce different spectral shapes and amplitudes, as does eccentricity.
- The background is not necessarily a power law! Brightest (mass/distance) mergers can dominate.

- **Detecting the amplitude A_{gwb} and ultimately, the shape of the GWB spectrum provides a direct constraint on a process whose large dynamic range makes it difficult to observe/simulate, and complements other probes of BH masses.**



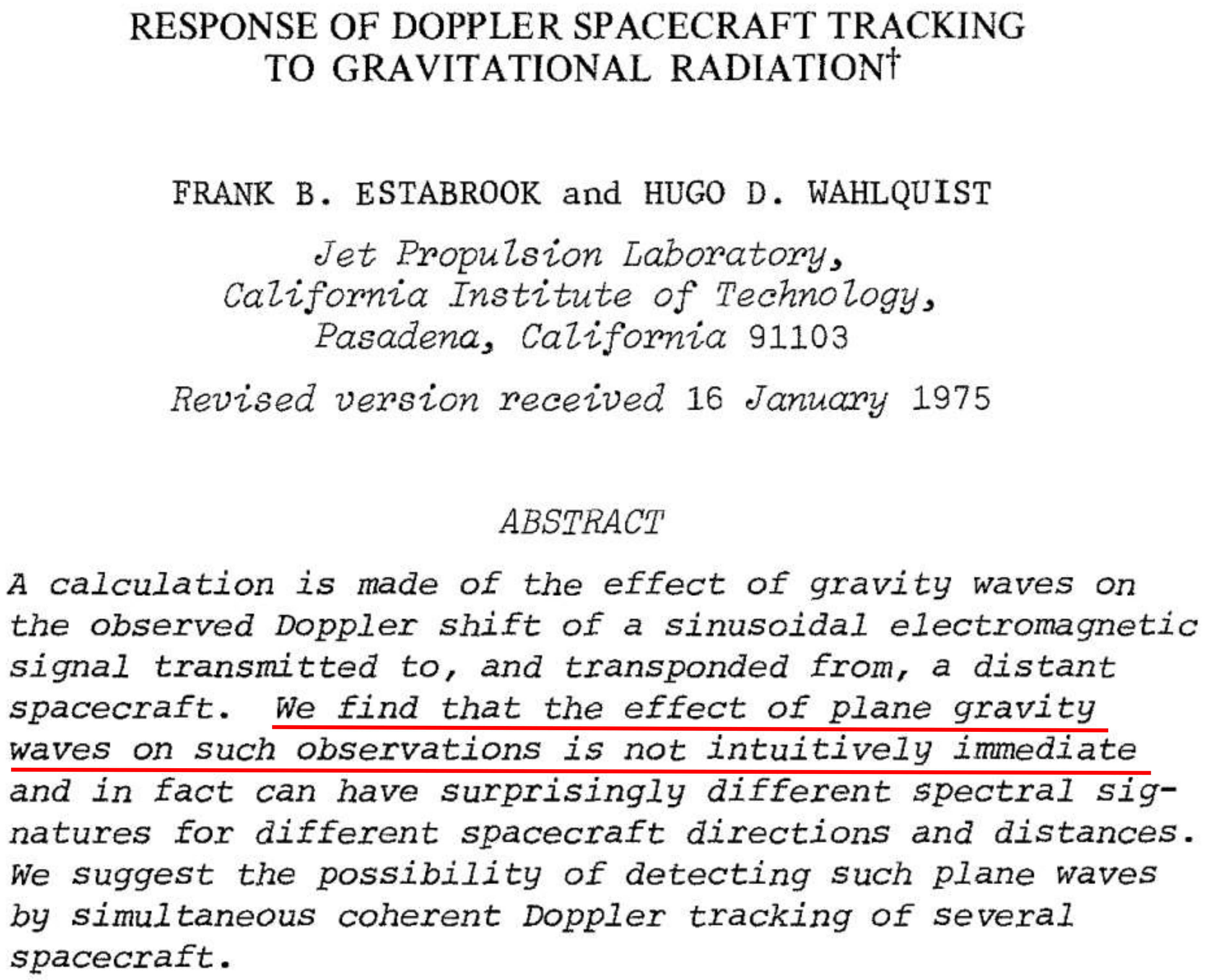
Sesana et al., 2009





How to detect nHz GWs?

- Lightyear-wavelengths too long for LISA.
- **Pulsars** can be celestial clocks (next slide).
  - At ~kpc distances, many wavelengths of nHz GWs fit along one “detector arm”. But NOT an interferometer.
  - The longer one monitors a pulsar, the lower GW frequencies one can access. 1yr = 32 nHz.
- How do GWs affect pulsar timing signals?
  - Intuitively, the bulk effect washes out, so the result depends only on the GW strain at the “detector endpoints”.



RESPONSE OF DOPPLER SPACECRAFT TRACKING
TO GRAVITATIONAL RADIATION†

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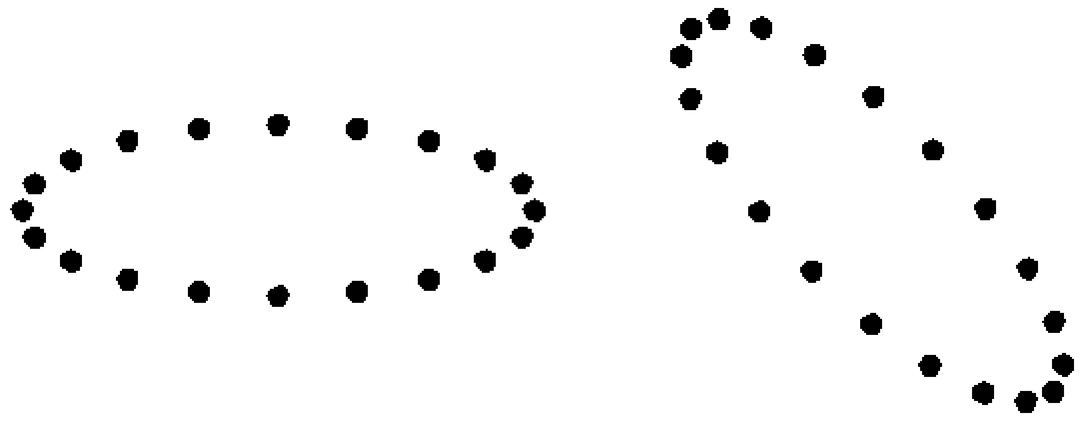
Revised version received 16 *January* 1975

ABSTRACT

A calculation is made of the effect of gravity waves on the observed Doppler shift of a sinusoidal electromagnetic signal transmitted to, and transponded from, a distant spacecraft. We find that the effect of plane gravity waves on such observations is not intuitively immediate and in fact can have surprisingly different spectral signatures for different spacecraft directions and distances. We suggest the possibility of detecting such plane waves by simultaneous coherent Doppler tracking of several spacecraft.

Wave polarization averages out for stochastic background.



$$\frac{\Delta\nu}{\nu} = \tfrac{1}{2}\cos 2\phi[1-\cos\theta]$$

$$\times[h(t) - h(t - l - l\cos\theta)],$$

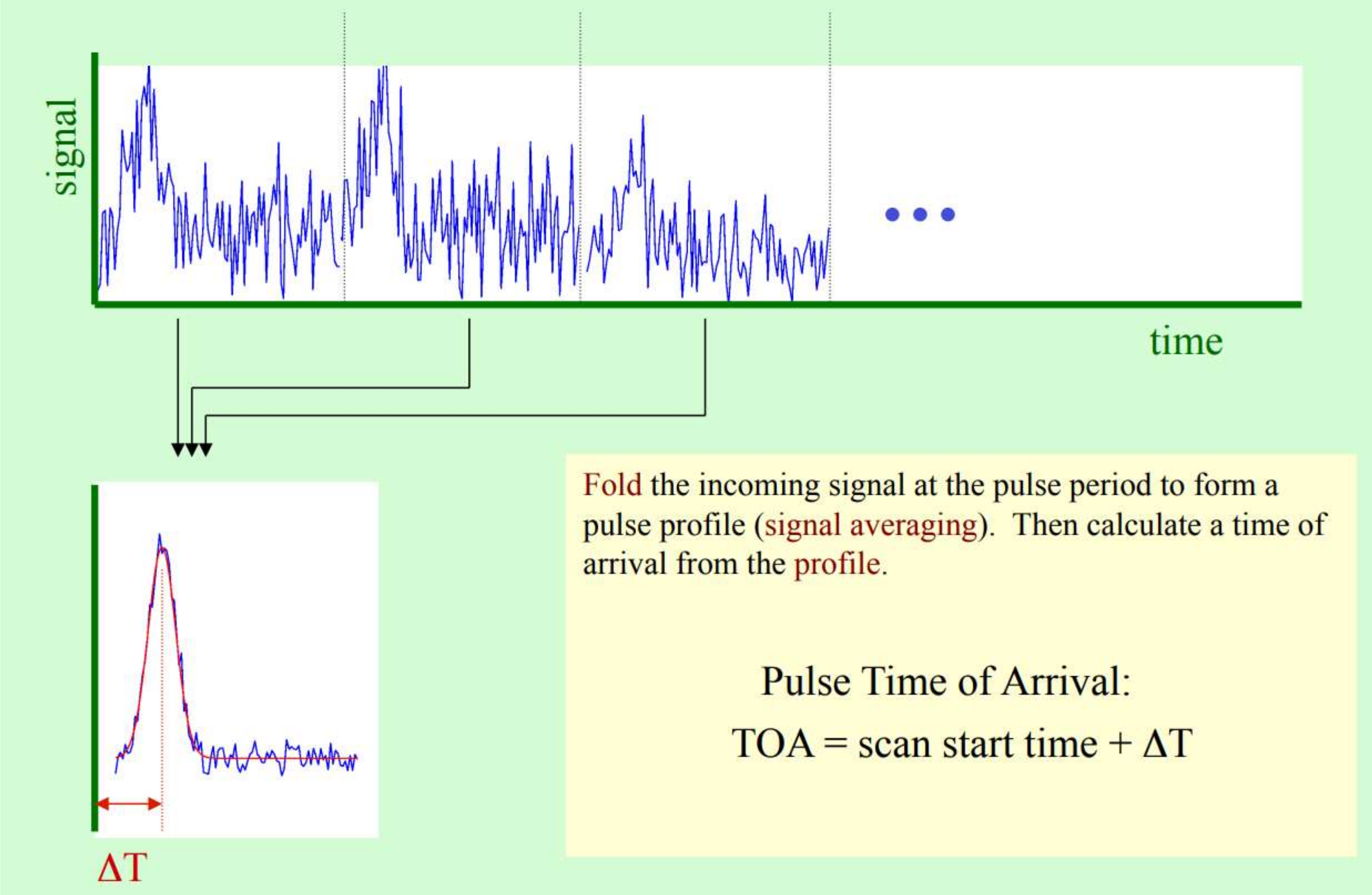
Angle between line-of-sight and GW propagation vector also averages, but leaves hallmark correlations (next slide).

The “earth” term: The GW amplitude at Earth.

The “pulsar” term: The GW amplitude at the pulsar with distance l. Unknown. (But could, with great luck, be measured if the pulsar distance is known to <1ly precision.)

Pulsar Timing with Radio Telescopes

- Point a big dish at a pulsar and **“fold”** the signal to stack pulses.
- Cross-correlate pulse profile with “standard template” to estimate offset relative to observatory clock (typically referenced to GPS).
- This is a “pulse time of arrival” or **TOA**.
- **Pulsar timing** is the science and art of comparing the observed TOAs with a prediction for when they should have arrived (next slide).



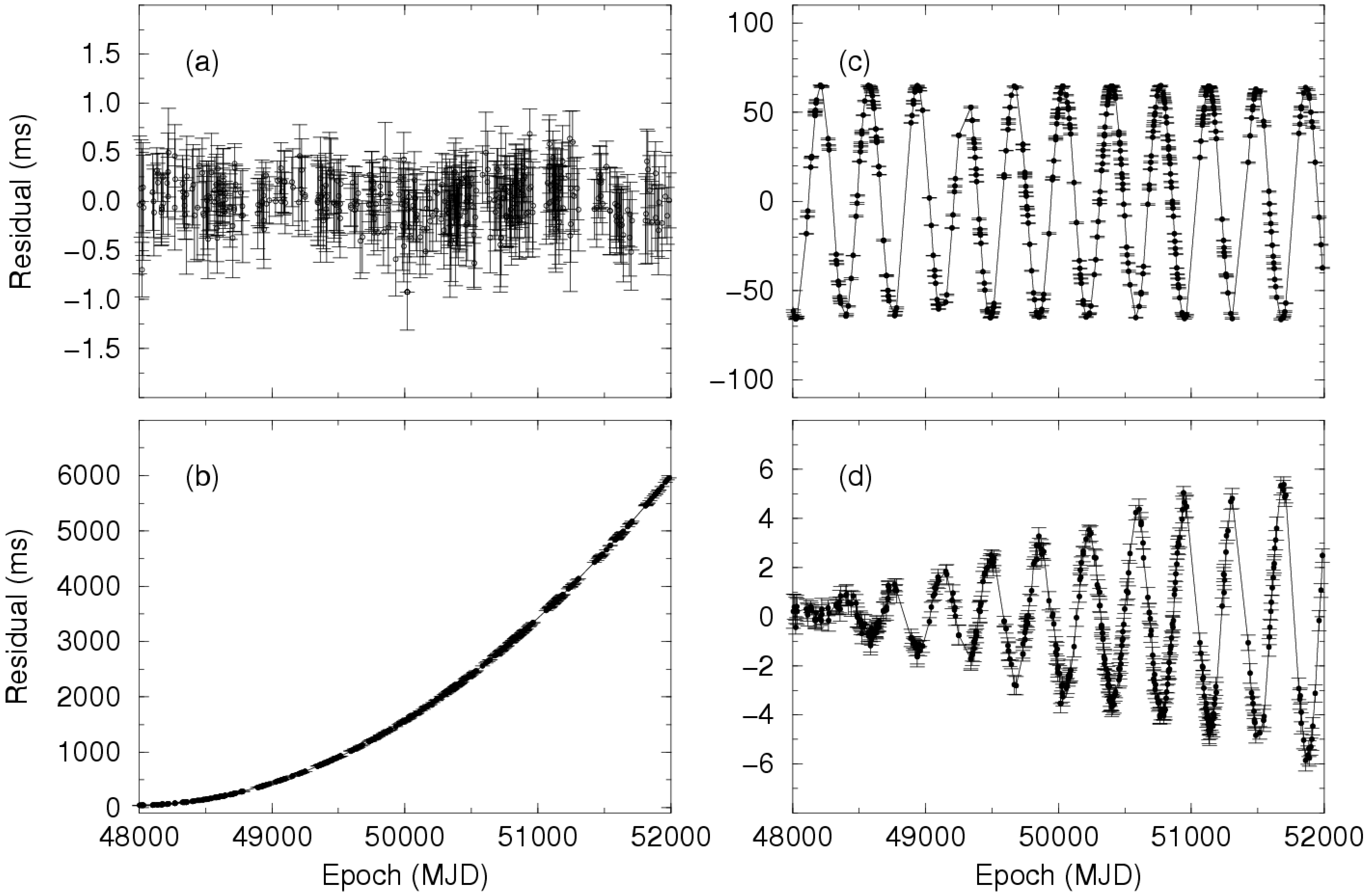
Fold the incoming signal at the pulse period to form a pulse profile (signal averaging). Then calculate a time of arrival from the profile.

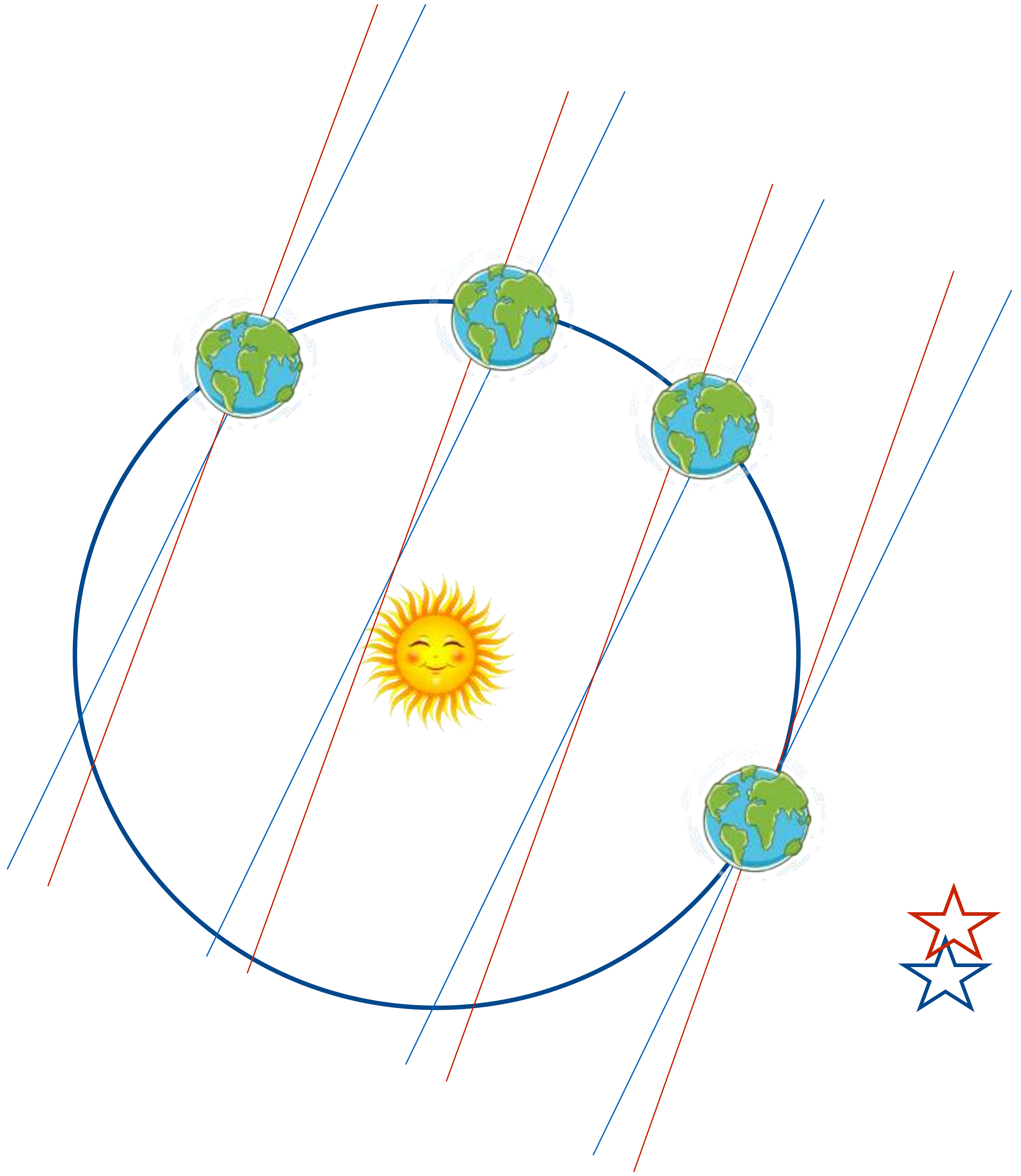
Pulse Time of Arrival:

TOA = scan start time + ΔT

Pulsar Timing: Basic Models

Every pulsar will need a model for position, proper motion, spindown-rate, parallax. Some need binary properties, including post-Newtonian effects. And eventually, we need to model GWs!





Positions measured using a 1AU baseline! Pulse times shifted by up to 480s. Parallax measured through relative delay between plane wavefronts.

Pulsar Timing Arrays

(PTAs are arrays of *pulsars* not of telescopes!)

- PTAs are monitored collections of high-precision millisecond pulsars (MSPs).
- The GWB induces time-dependent residuals in pulse arrival times with a power spectral density (with $\Gamma = {}^{13}/_{3}$) which is **common to every pulsar**:

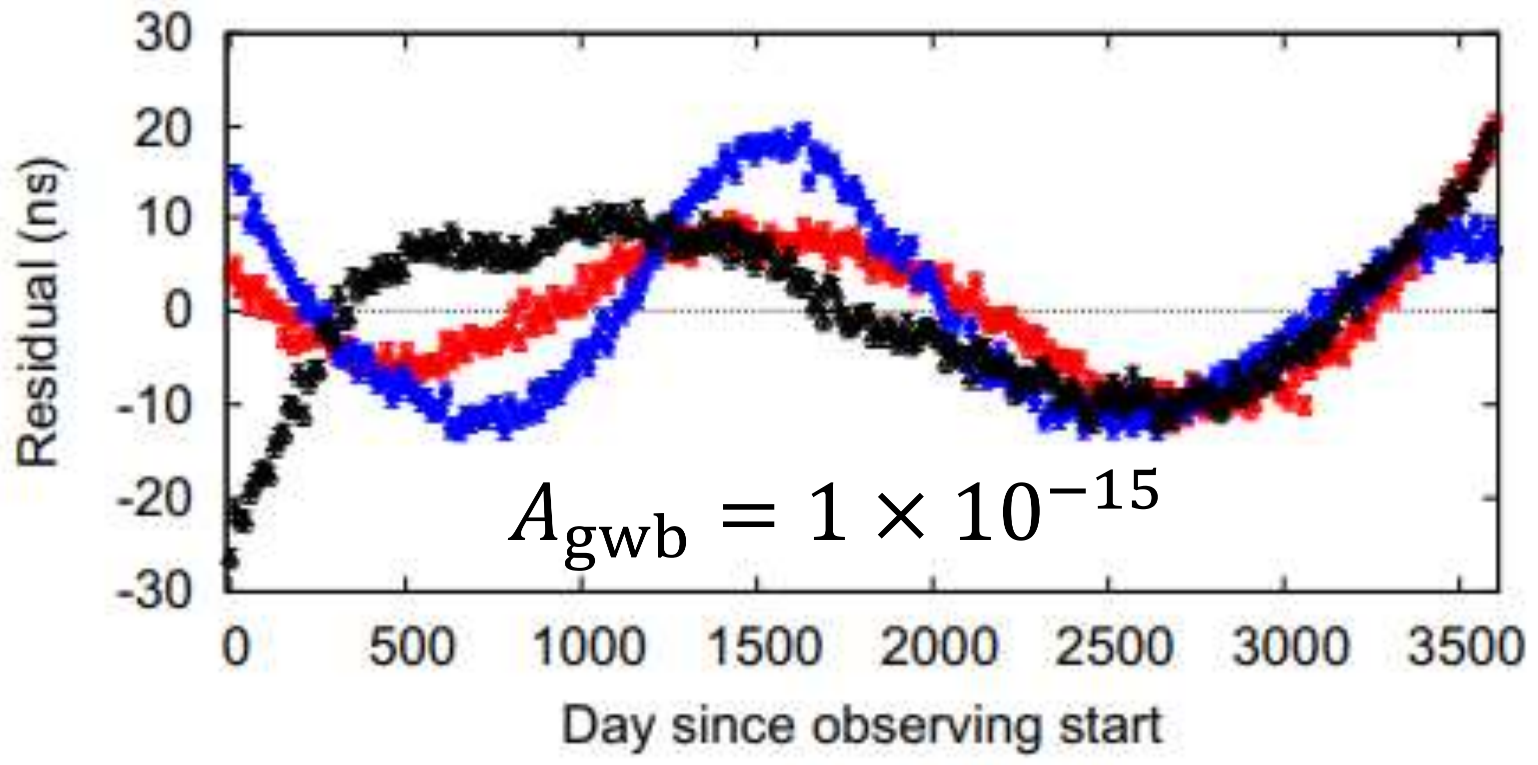
$$h_c(f) = A_{\rm gwb}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}$$

$$+$$

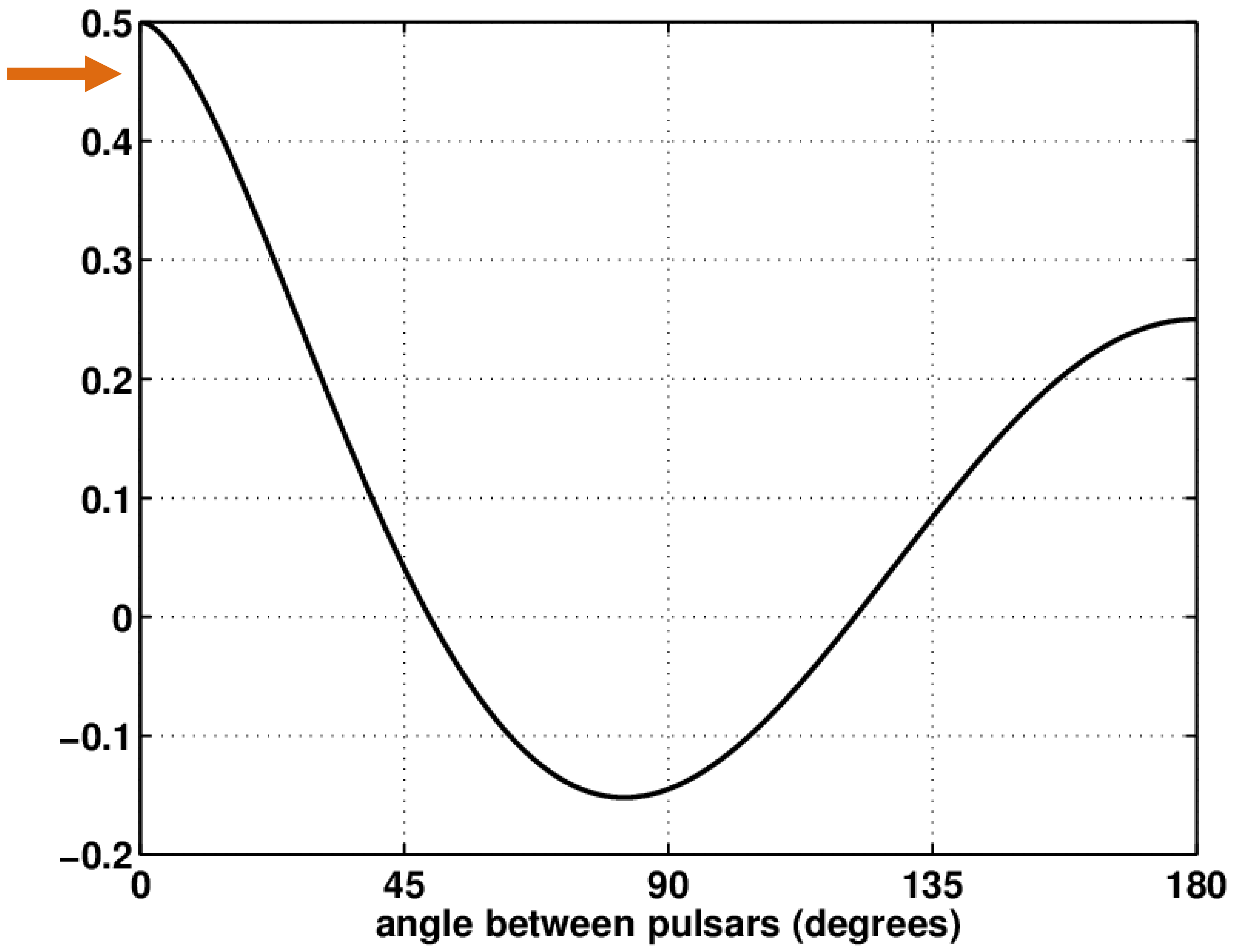
$$\frac{\Delta\nu}{\nu} = \tfrac{1}{2}\cos 2\phi\,[1-\cos\theta] \times [h(t) - h(t-l-l\cos\theta)],$$

$$=$$

$$\boxed{P(f)\,[\mathrm{yr}^{-3}] = \frac{A_{\rm gwb}^{2}}{12\pi^{2}}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-\Gamma}}$$



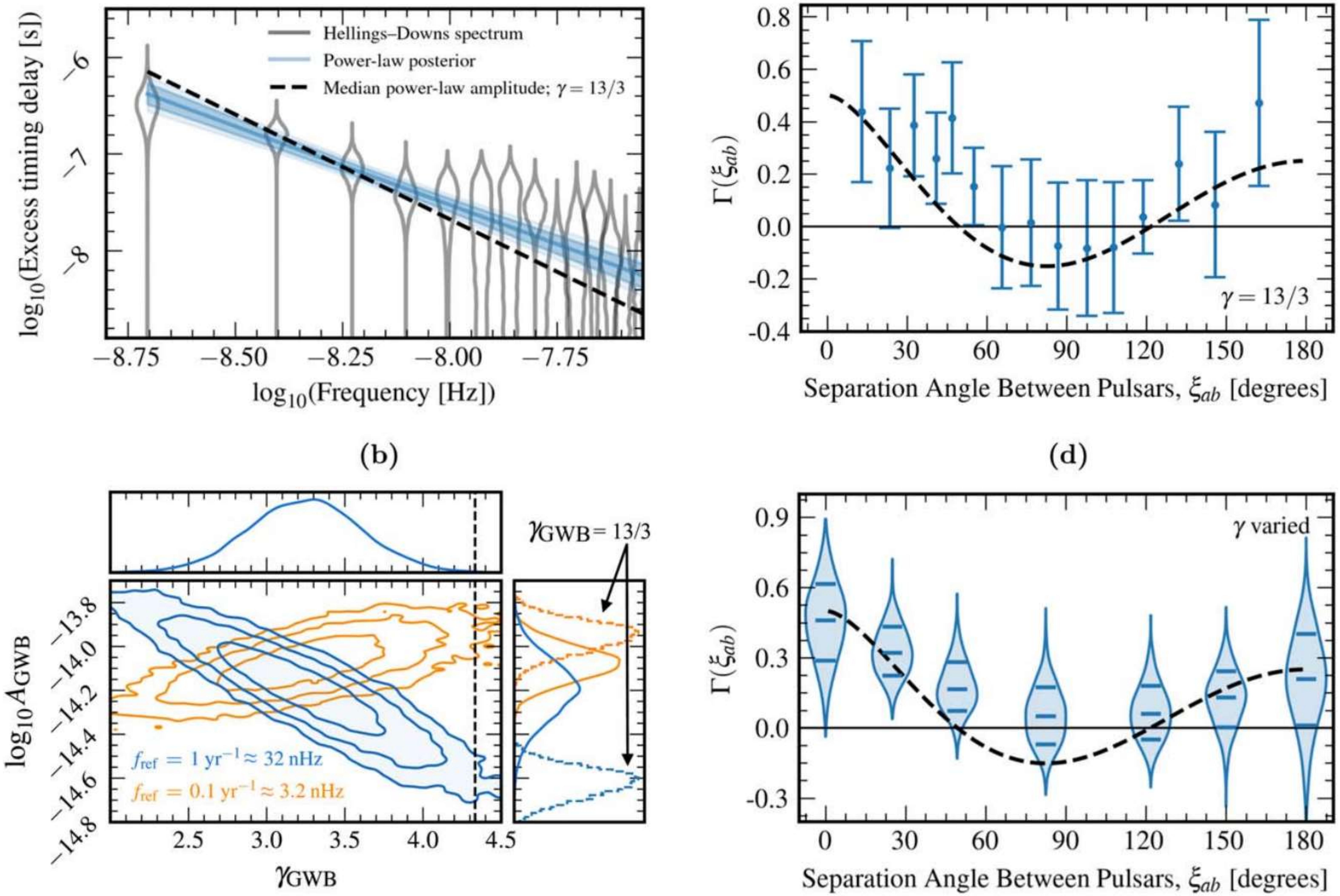
- Because pulsars share the "**earth**" term, the noise is correlated between pulsars depending on their angular separation. This is the famous "**Hellings-Downs**" curve.
- So searching for the GWB has two prongs:
  1. Identification of noise processes with the right spectral shape, present at the same amplitude in *every* pulsar..
  2. Detection of the HD curve. However, because the typical correlation coefficient is small (absolute value < 0.2), it is likely that the first method will yield the first detection.



- Ancillary: **the expected power spectrum is very steep (-13/3)**, so the first detection will also come from the lowest frequencies. Long data sets are good!

Radio PTA Results

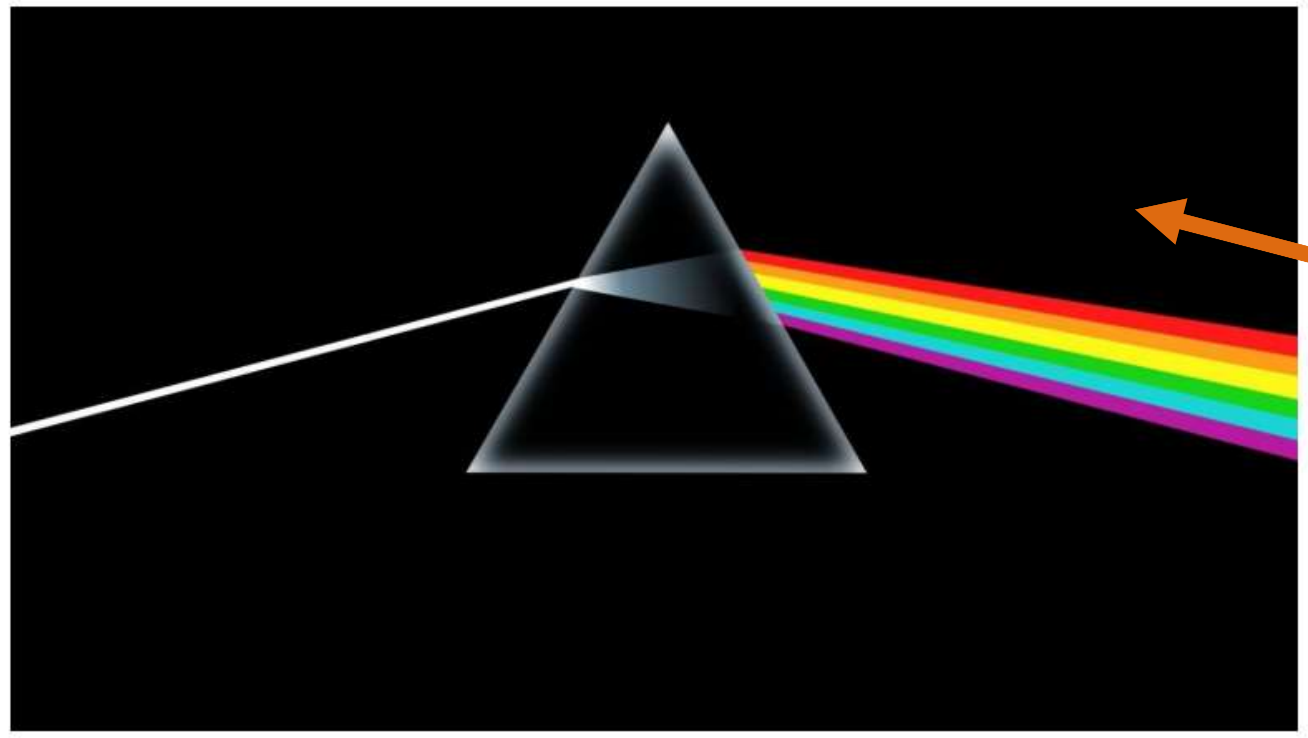
- **Recently, PTAs published "evidence for" Hellings-Downs spatial correlations.**
  - **See papers from NANOGrav, EPTA/InPTA, PPTA, CPTA**
- **This follows detections in 2021 of "common noise processes".**
- **Thus, potential evidence (both prongs) for a GWB!**
- **Spectrum largely agrees with expectations from SMBH binary mergers.**
  - **(Or your favorite new physics source…)**

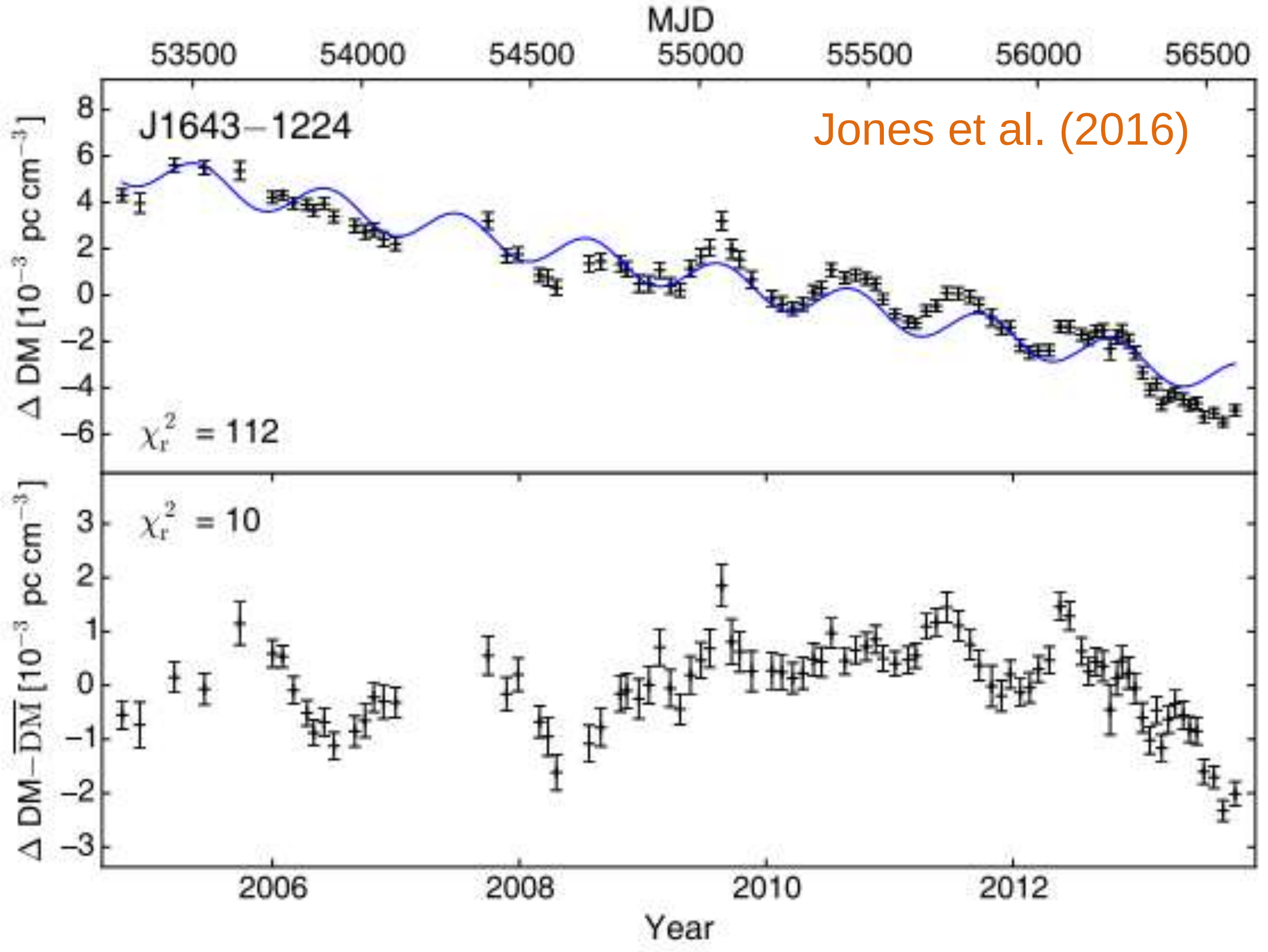


Agazie et al., 2023 (NANOGrav 15 year results)

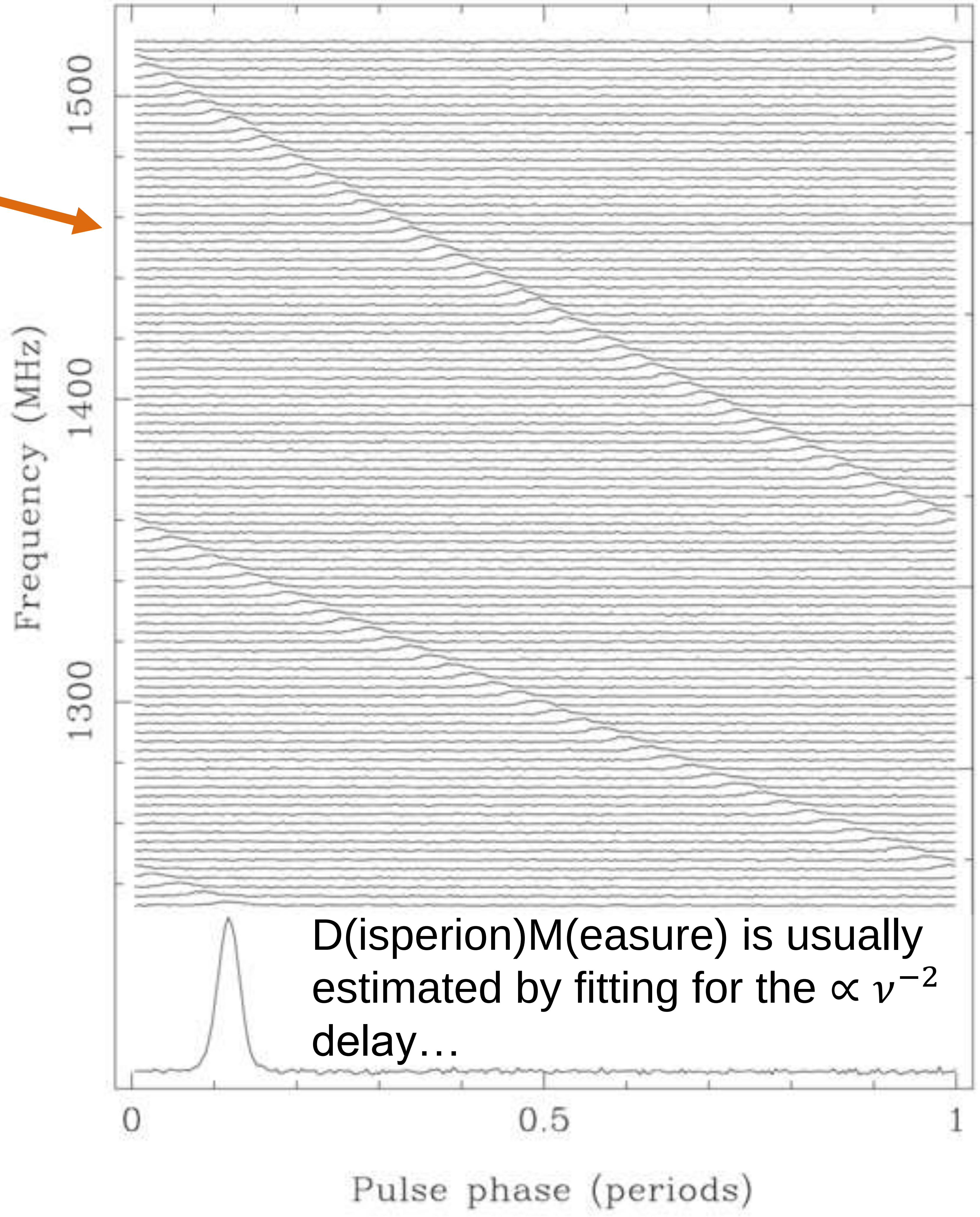
Confounding Effects from the ISM

The (ionized) interstellar medium (IISM) disperses, diffracts, and refracts radio waves. Main effect is dispersion, which introduces a frequency-dependent delay (relative, and absolute.)



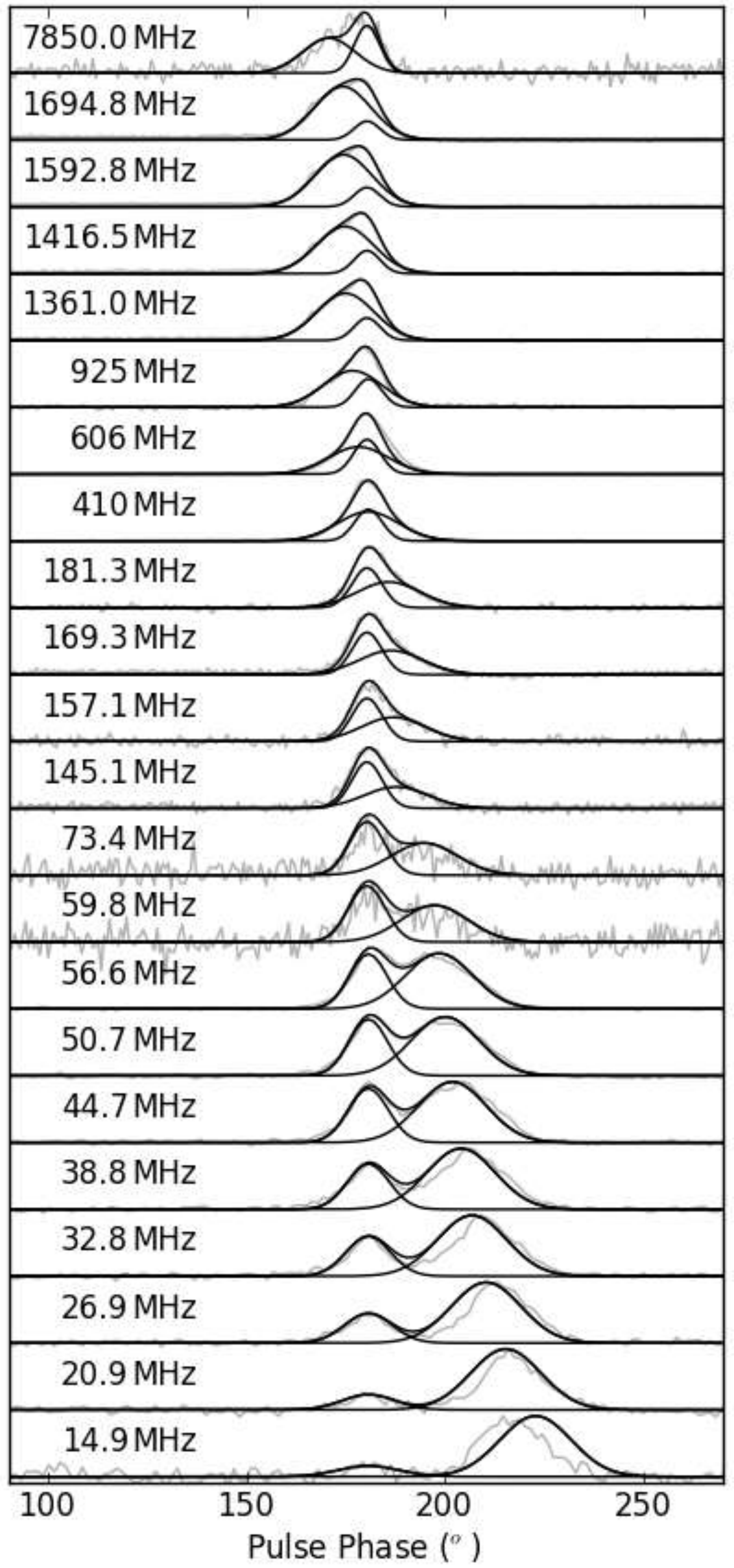


DM varies with time because of relative motion. Here, note parallactic terms and a gradient from proper motion.



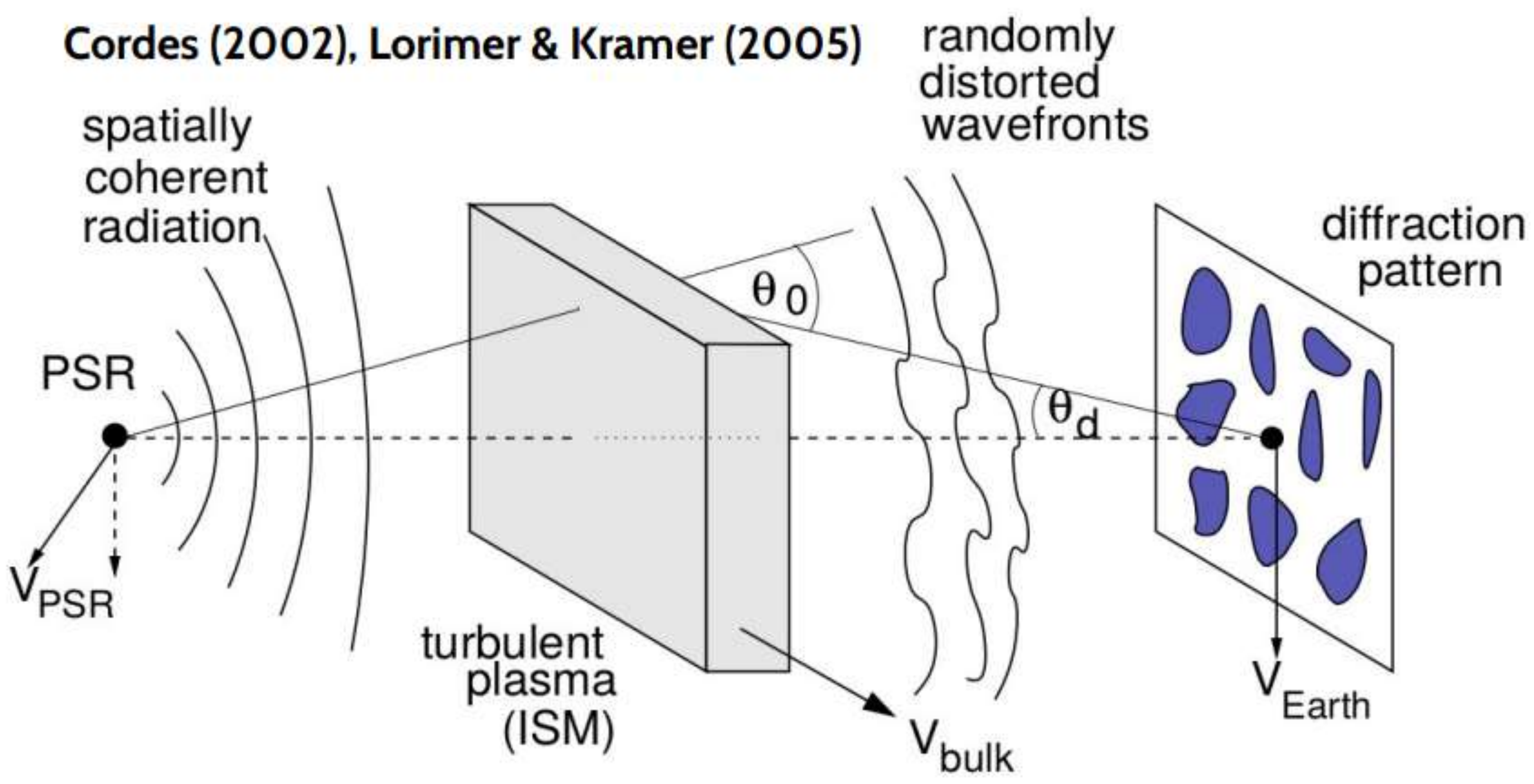
D(isperion)M(easure) is usually estimated by fitting for the $\propto \nu^{-2}$ delay…

Hassall et al. (2012)

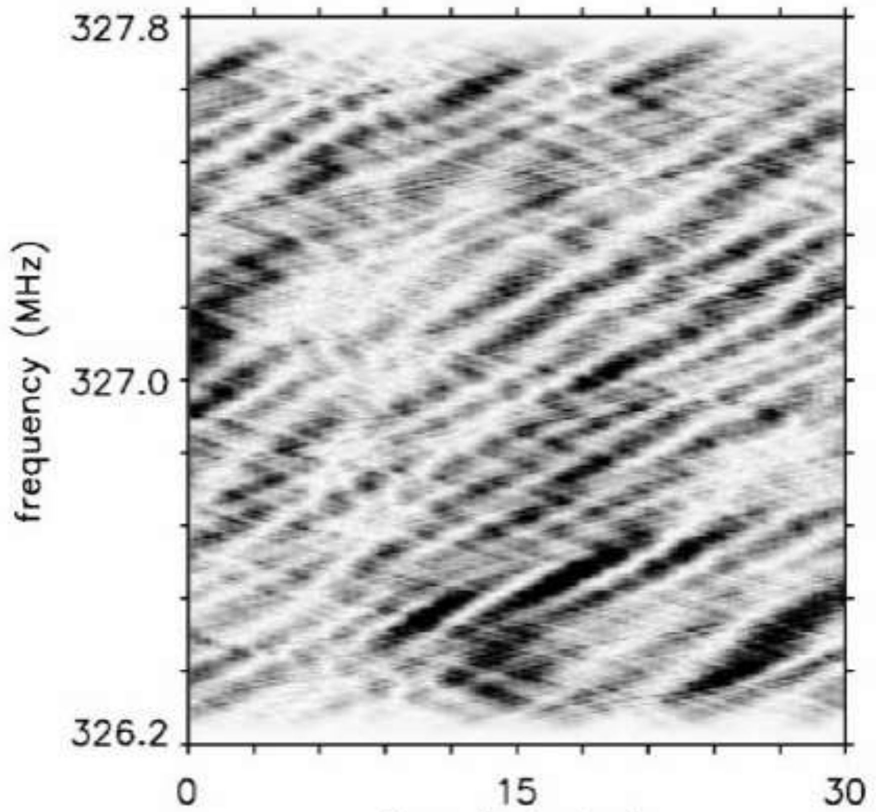


…but the pulse profile itself varies as a function of frequency!

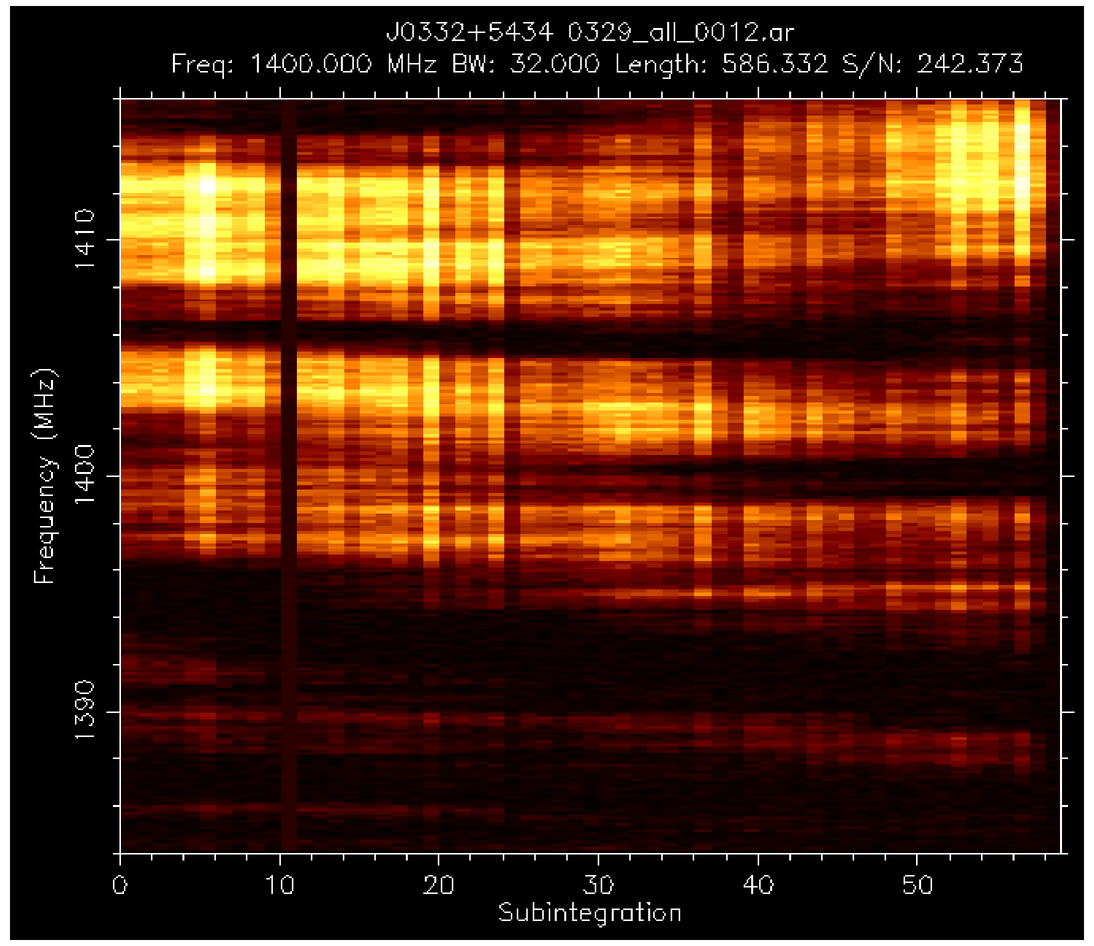
Confounding Effects from the IISM



Cordes (2002), Lorimer & Kramer (2005)

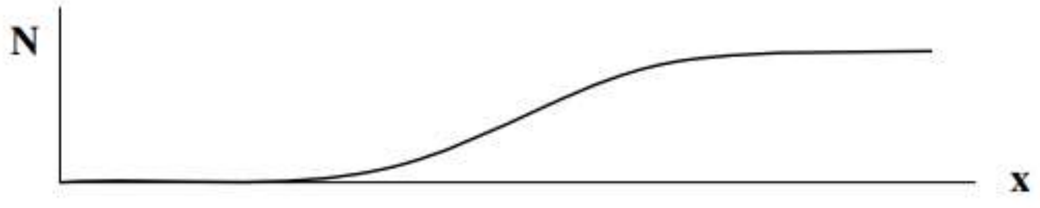


Hill et al. (2005)

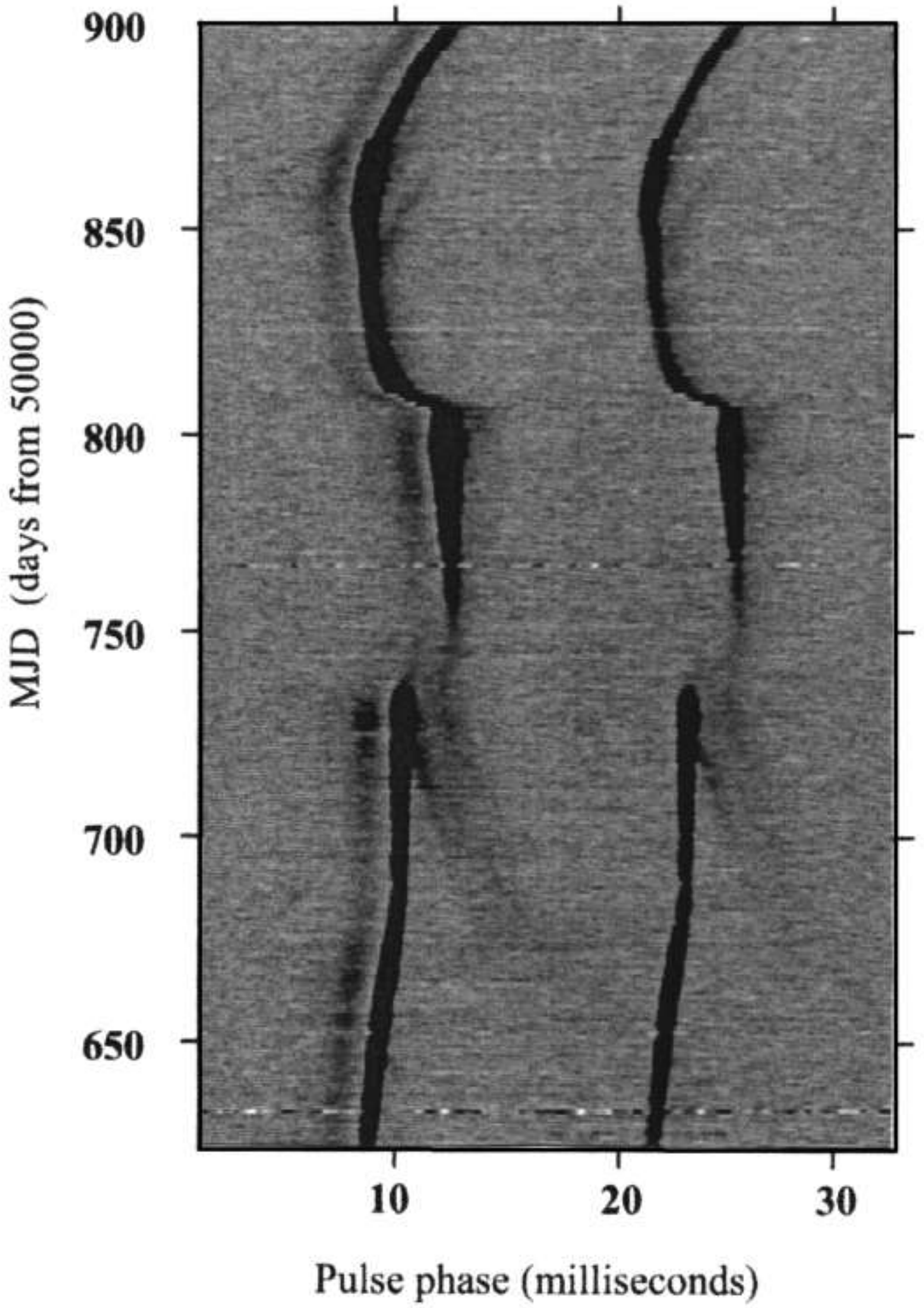


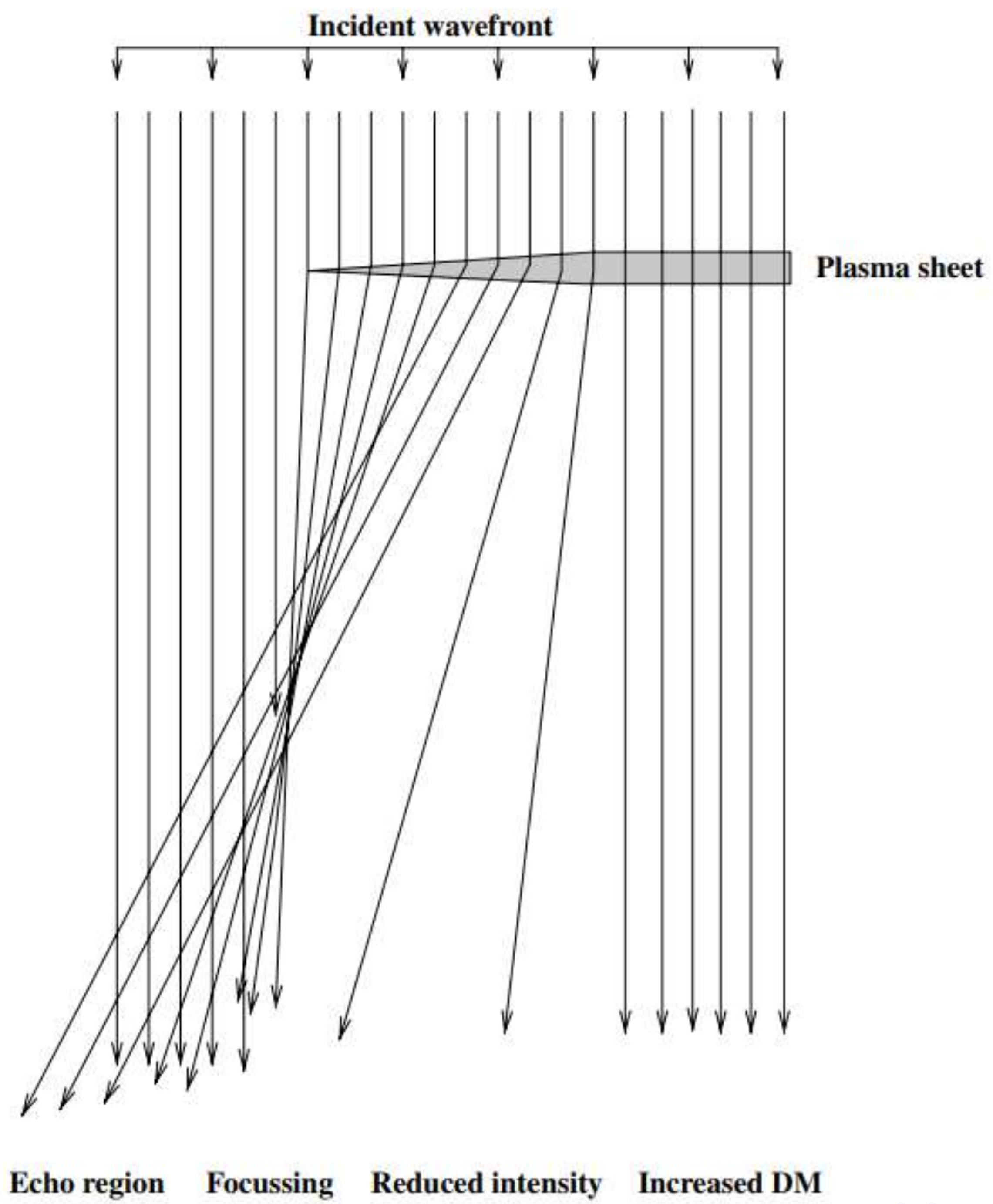
Further effects:

- Radio frequency interference (RFI)
- Instrumental “jumps”
- Jitter and other “white noise”
- Pulsar red/timing/spin noise

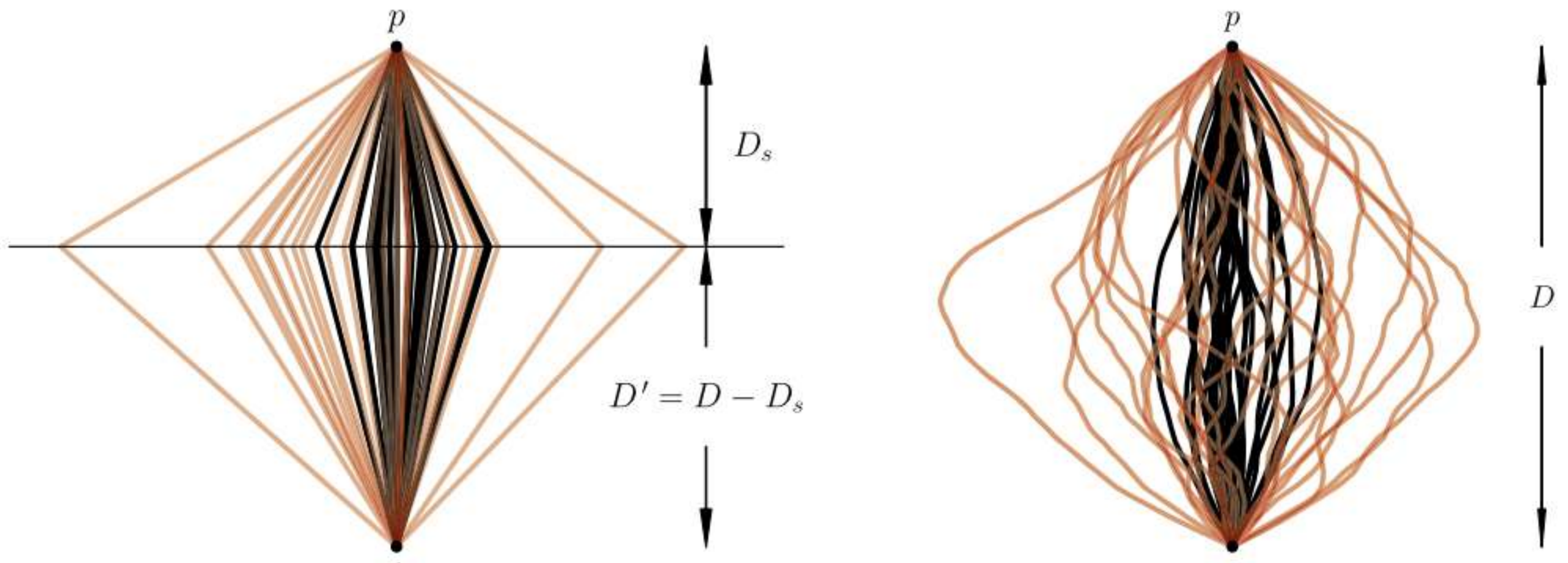


- Because low-frequency light is bent more, **DM can be measured very precisely at low frequencies**.
- But, the electron column isn’t the same! So you **can’t correct high-frequency dispersion with low-frequency data**.
- Refraction and diffraction complicate observability and couple in higher-order time-delays that can **neither be modeled nor measured**.

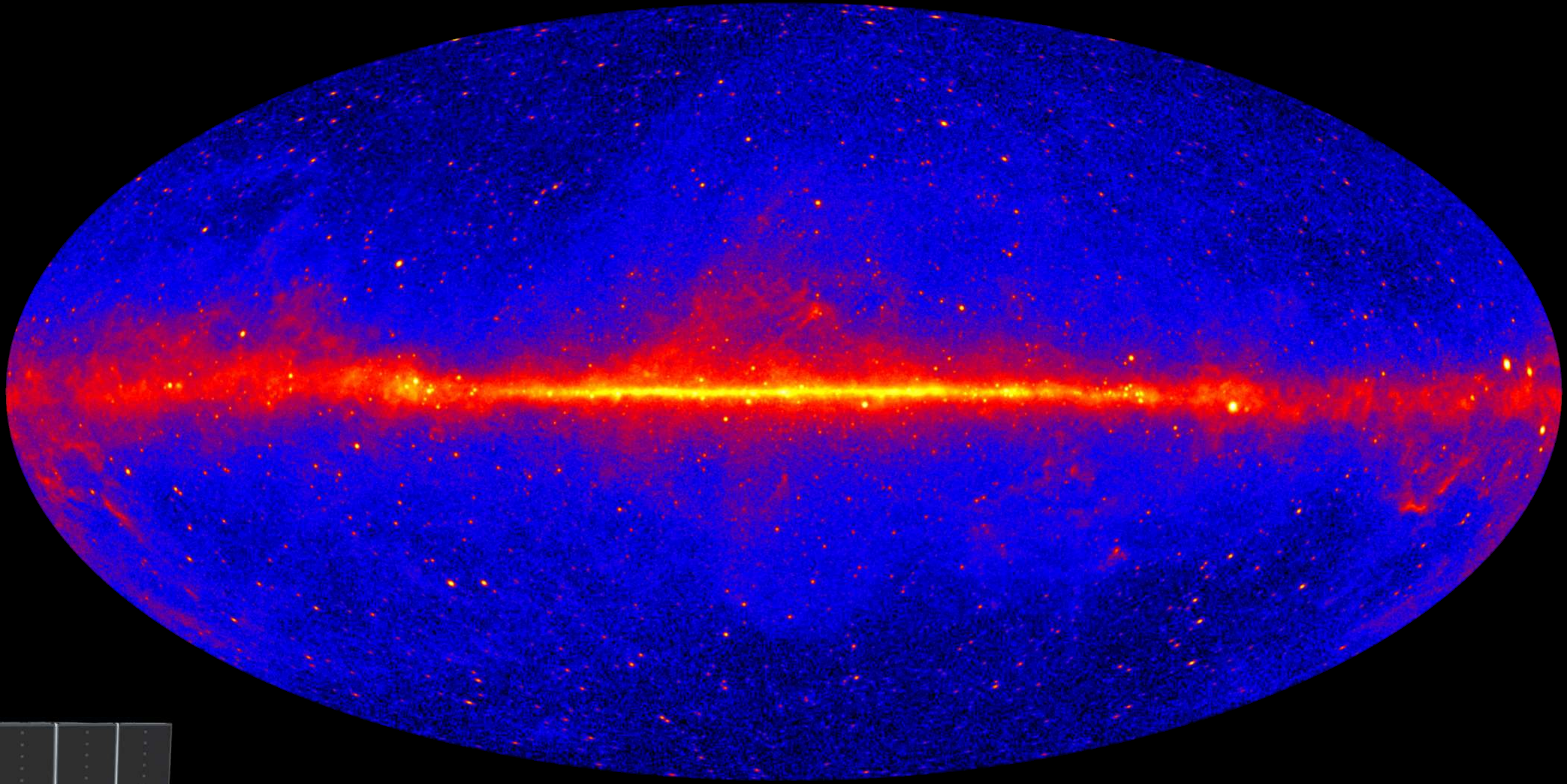


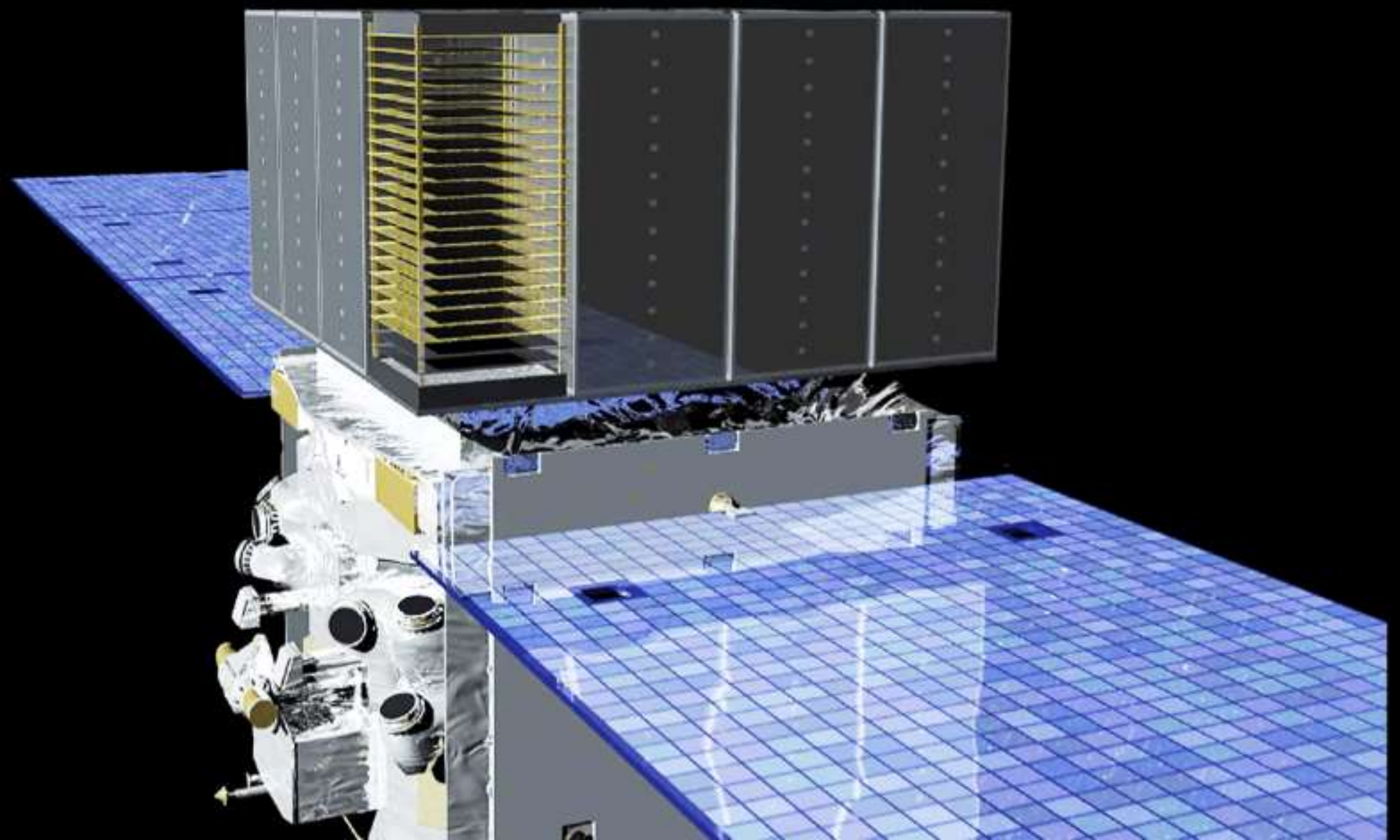


Graham-Smith, Lyne, & Jordan (2011)



Cordes, Shannon, & Stinebring (2016)





Fermi-LAT is a widefield pair-conversion telescope operating between ~50 MeV and ~1 TeV, most sensitive at ~1 GeV.

Major sub-subsystems: anticoincidence detector, silicon strip tracker, and CsI hodoscopic calorimeter.

Good energy resolution, good (for gamma rays) PSF that varies strongly with energy. Source confusion is a way of life.

Operating since 2008: long uninterrupted dataset.

Timestamping accurate to <300 ns and onboard GPS provides accurate absolute time reference.

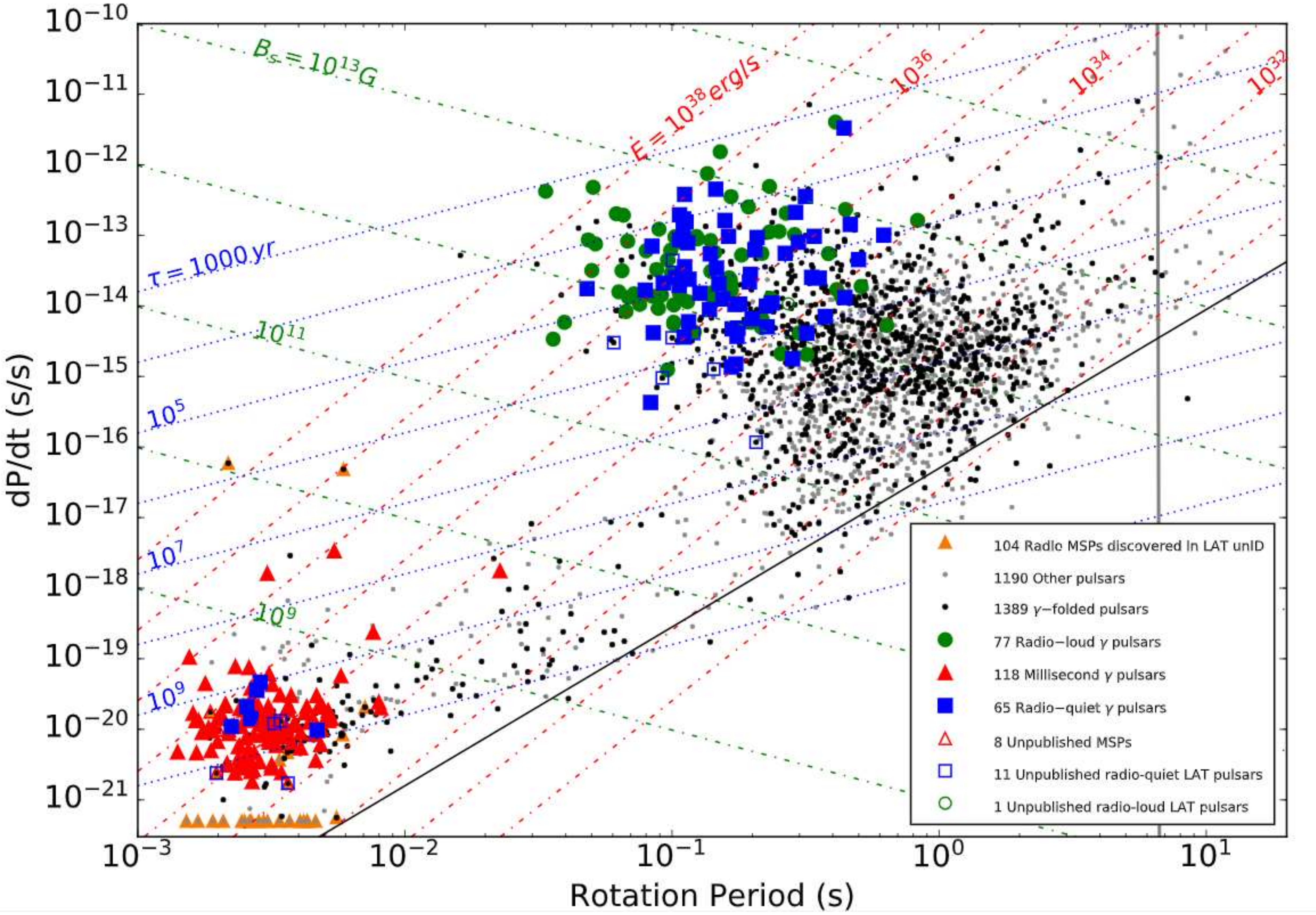
Image credit: Danielle Futselaar (artsource.nl)

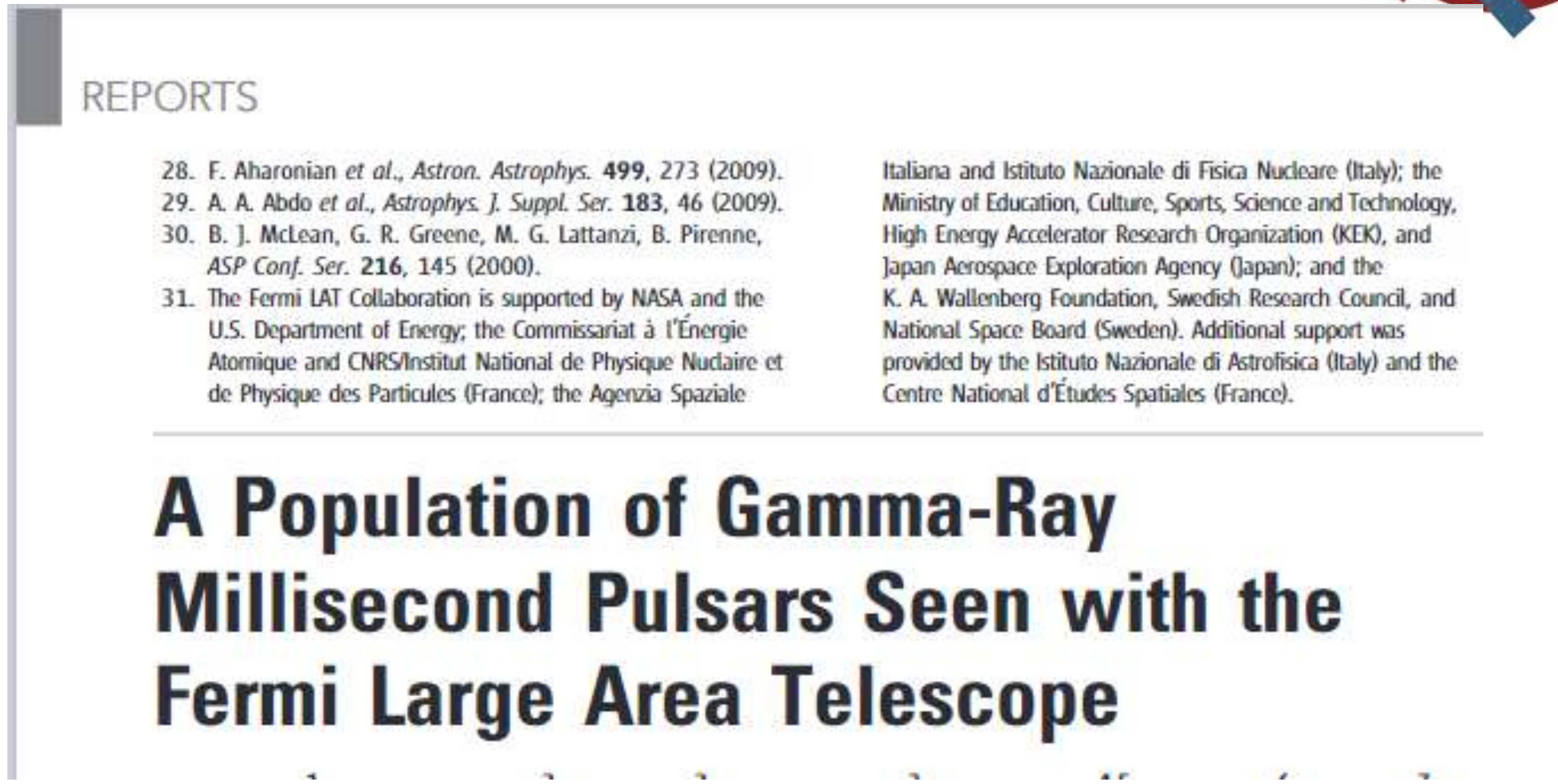
Pulsars with the LAT

Fermi has detected nearly 300 GeV pulsars!

- Three main groups: (1) young radio pulsars, (2) “unguided search” pulsars (mostly young, radio quiet), and (3) millisecond pulsars (MSPs)

- We now know pulsars are VERY efficient gamma-ray emitters; MSPs reach 10s of percent!





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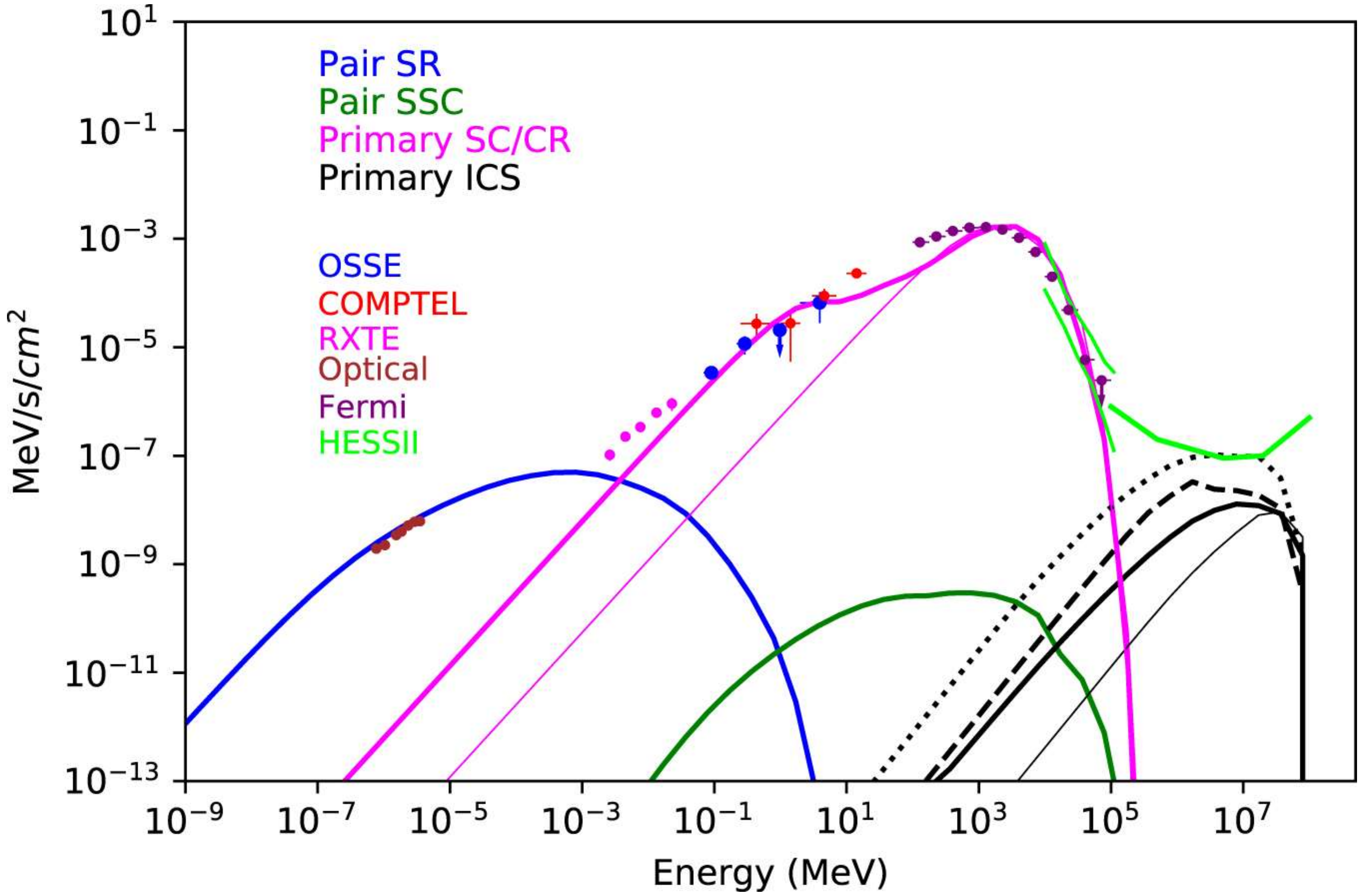
28. F. Aharonian *et al.*, *Astron. Astrophys.* **499**, 273 (2009).
29. A. A. Abdo *et al.*, *Astrophys. J. Suppl. Ser.* **183**, 46 (2009).
30. B. J. McLean, G. R. Greene, M. G. Lattanzi, B. Pirenne, *ASP Conf. Ser.* **216**, 145 (2000).
31. The Fermi LAT Collaboration is supported by NASA and the U.S. Department of Energy; the Commissariat à l'Énergie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France); the Agenzia Spaziale Italiana and Istituto Nazionale di Fisica Nucleare (Italy); the Ministry of Education, Culture, Sports, Science and Technology, High Energy Accelerator Research Organization (KEK), and Japan Aerospace Exploration Agency (Japan); and the K. A. Wallenberg Foundation, Swedish Research Council, and National Space Board (Sweden). Additional support was provided by the Istituto Nazionale di Astrofisica (Italy) and the Centre National d'Études Spatiales (France).

A Population of Gamma-Ray Millisecond Pulsars Seen with the Fermi Large Area Telescope



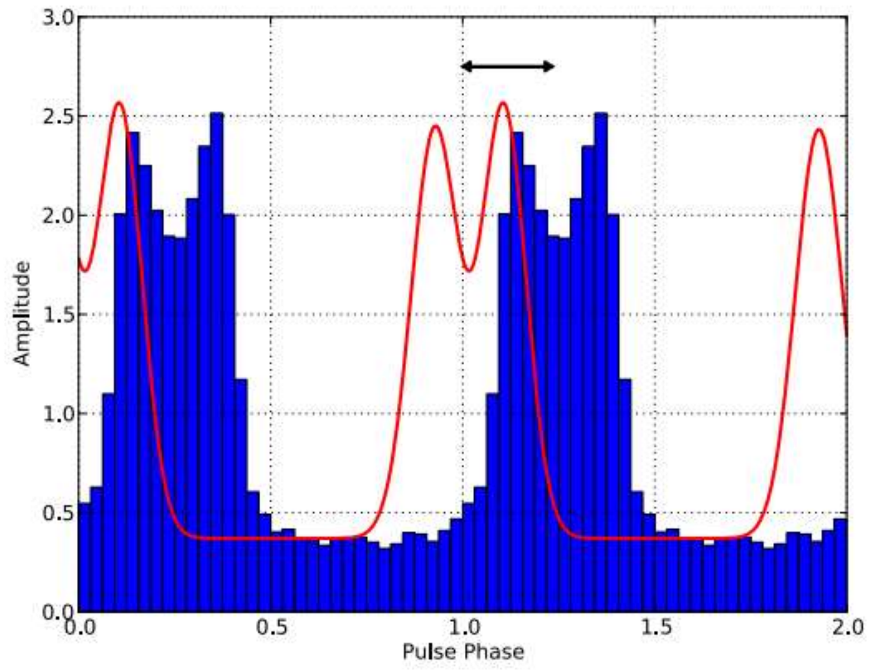
The Fermi Treasure Map

Of the nearly 300 detected gamma-ray pulsars, about 130 are MSPs.
Many were detected by the PSC and related efforts.

Pulsar Search Consortium
(Ray et al., 2012)

LAT Data vs. Radio Data

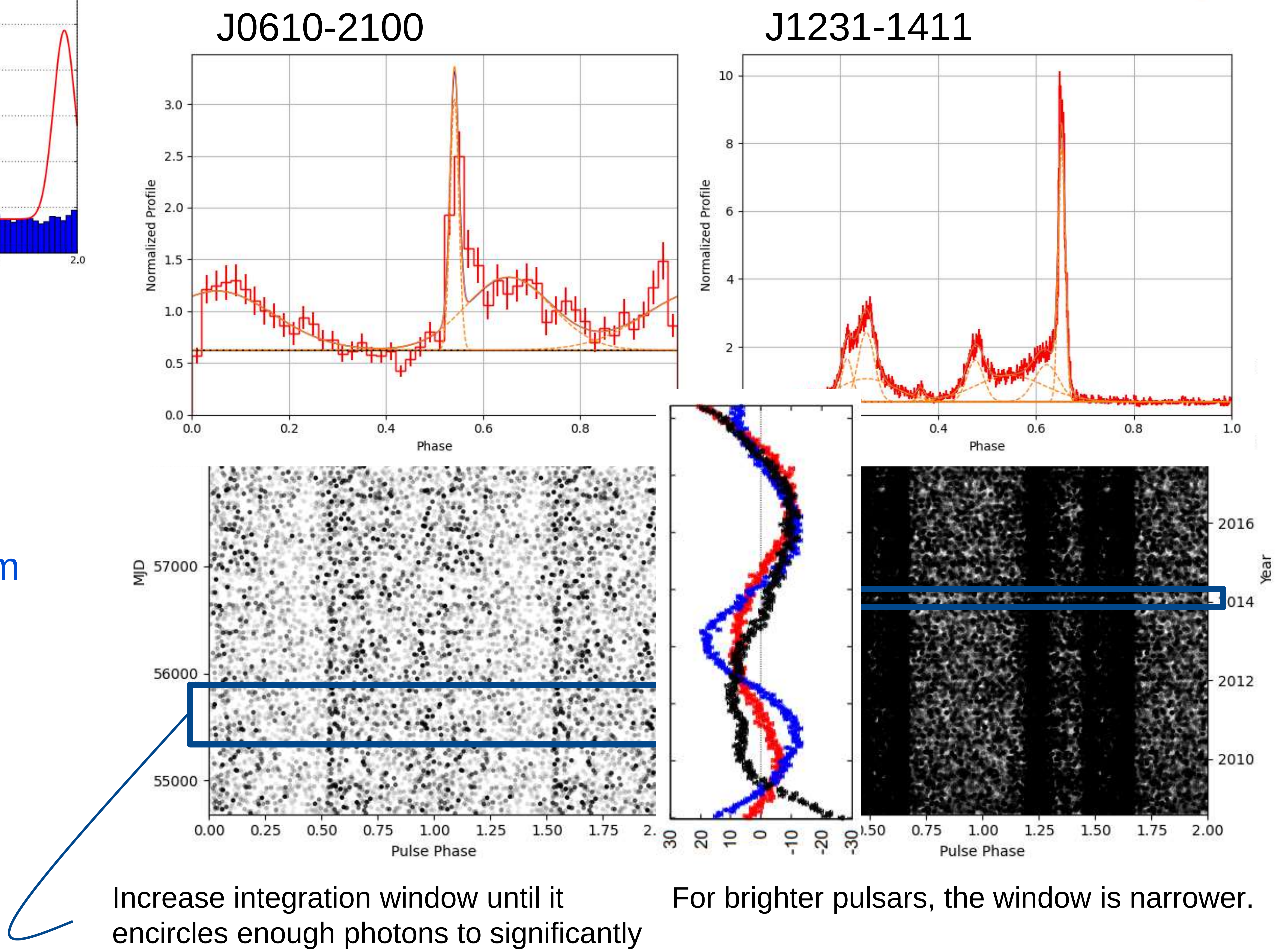
- In some cases pulsar timing is similar to radio:
  - Observe a pulsar “long enough” to detect its pulse profile and reference it to the GPS clock.
  - Use Poisson likelihood instead of gaussian for LAT.



- Integration times vary <u>wildly</u>: ~10 minutes for Vela, up to 1 year for faintest pulsars.
  - Averaging so much data together smears out signals, e.g. from the 1-year annual sinusoid from position fitting.

- Best to use an “unbinned” approach – compute the spin phase of each photon and maximize the likelihood.

- We have developed pipelines for both TOA-based and unbinned gamma-ray pulsar timing.



Increase integration window until it encircles enough photons to significantly see the pulse profile.

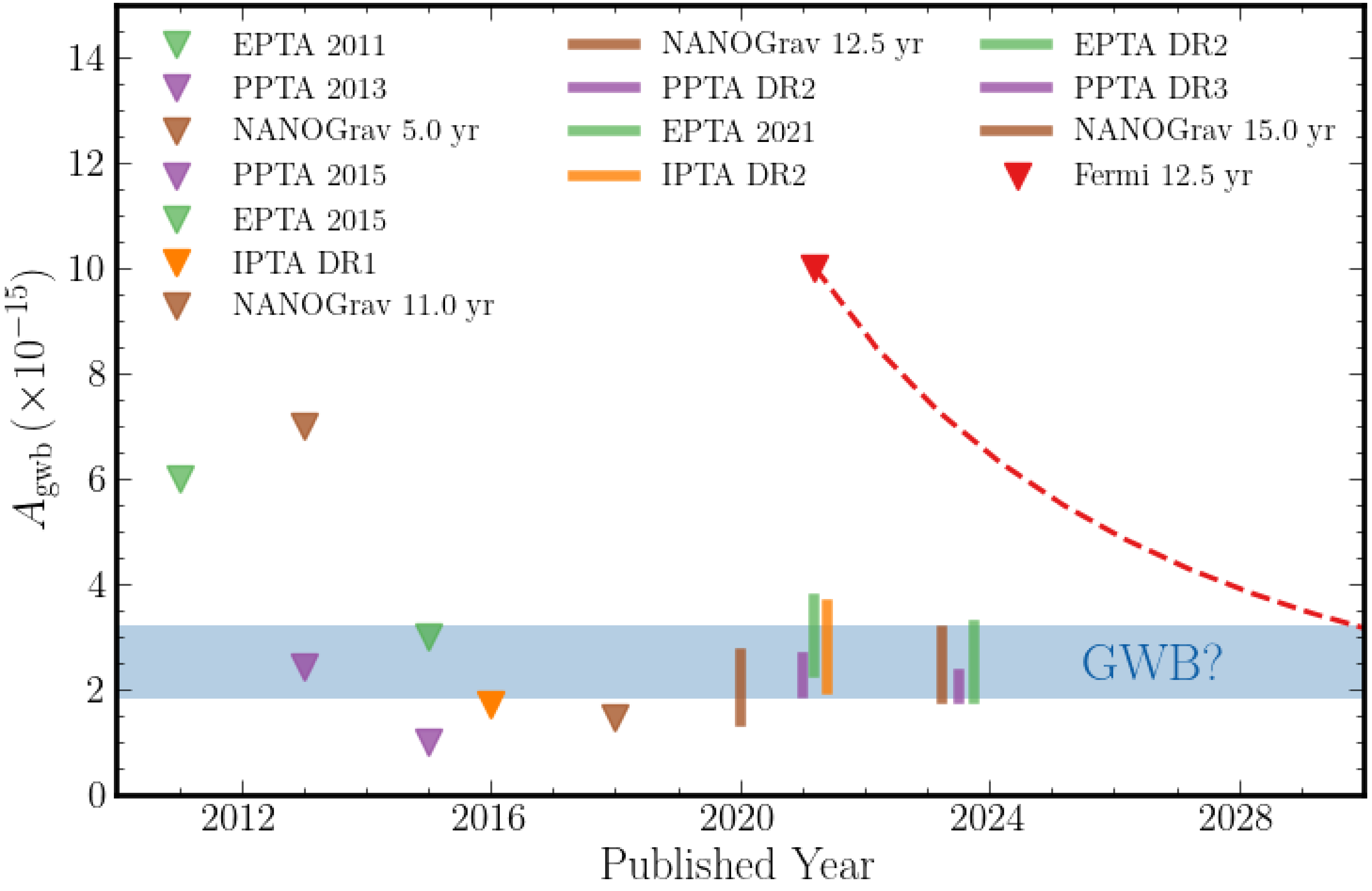
For brighter pulsars, the window is narrower.

Thus, for some applications, e.g. determining a position, only bright pulsars (many windows per year) are suitable.

Gamma Pulsar Timing Array (DR1)

- Fermi-LAT team developed high-precision pulsar timing tools to analyze 35 gamma-bright MSPs
- With 12.5 years of data (now called DR1), set an upper limit on the canonical GWB: $A_{\mathrm{gwb}} < 10 \times 10^{-15}$.
- Time scaling ("weak signal regime") shown in red:
  - With continued data collection, the gamma-ray PTA will detect and characterize the GWB!
-

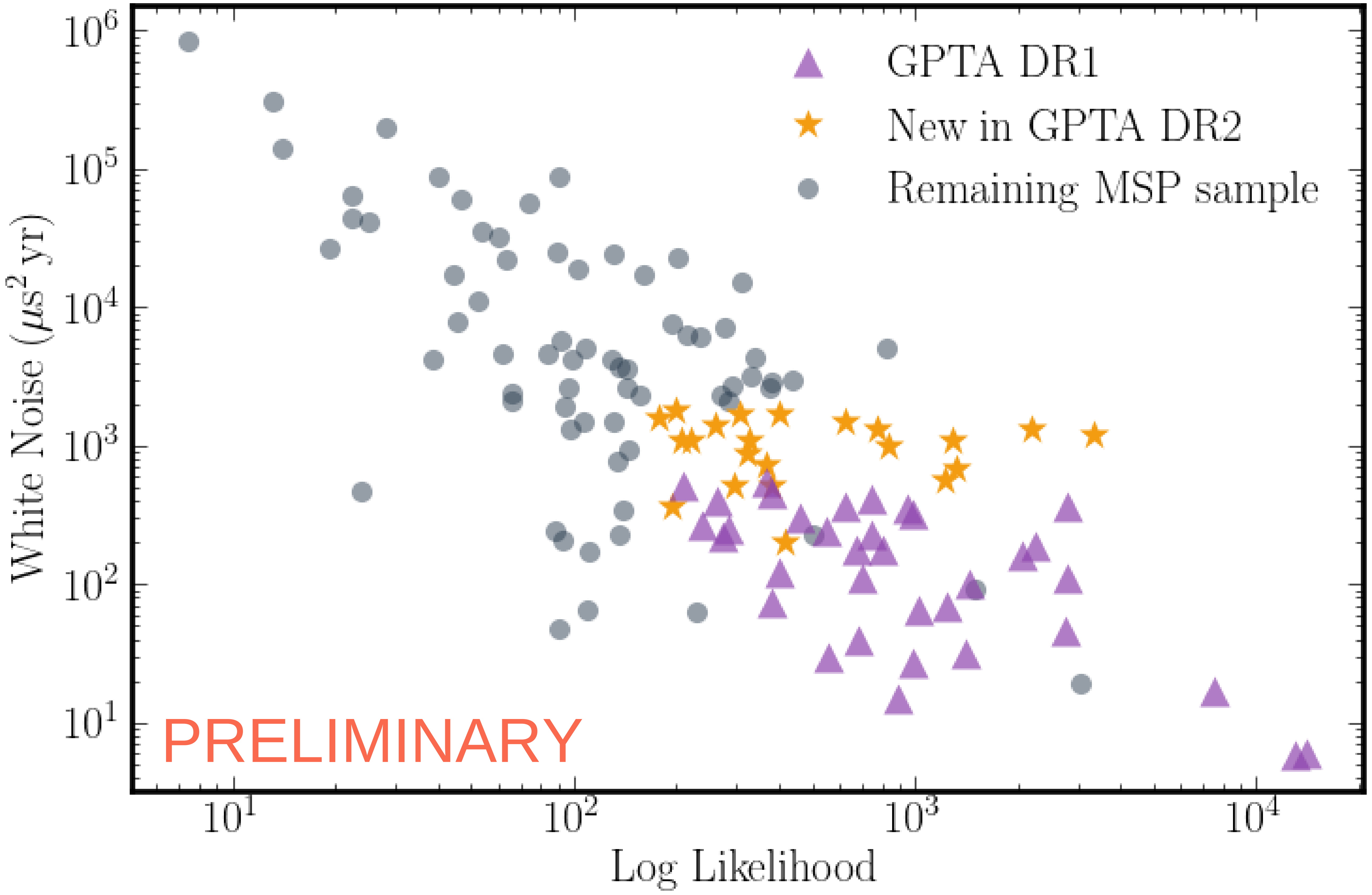
VERY MINIMAL SYSTEMATIC UNCERTAINTY.



Adapted and updated from Ajello et al., 2022 (Fermi-LAT Collaboration)

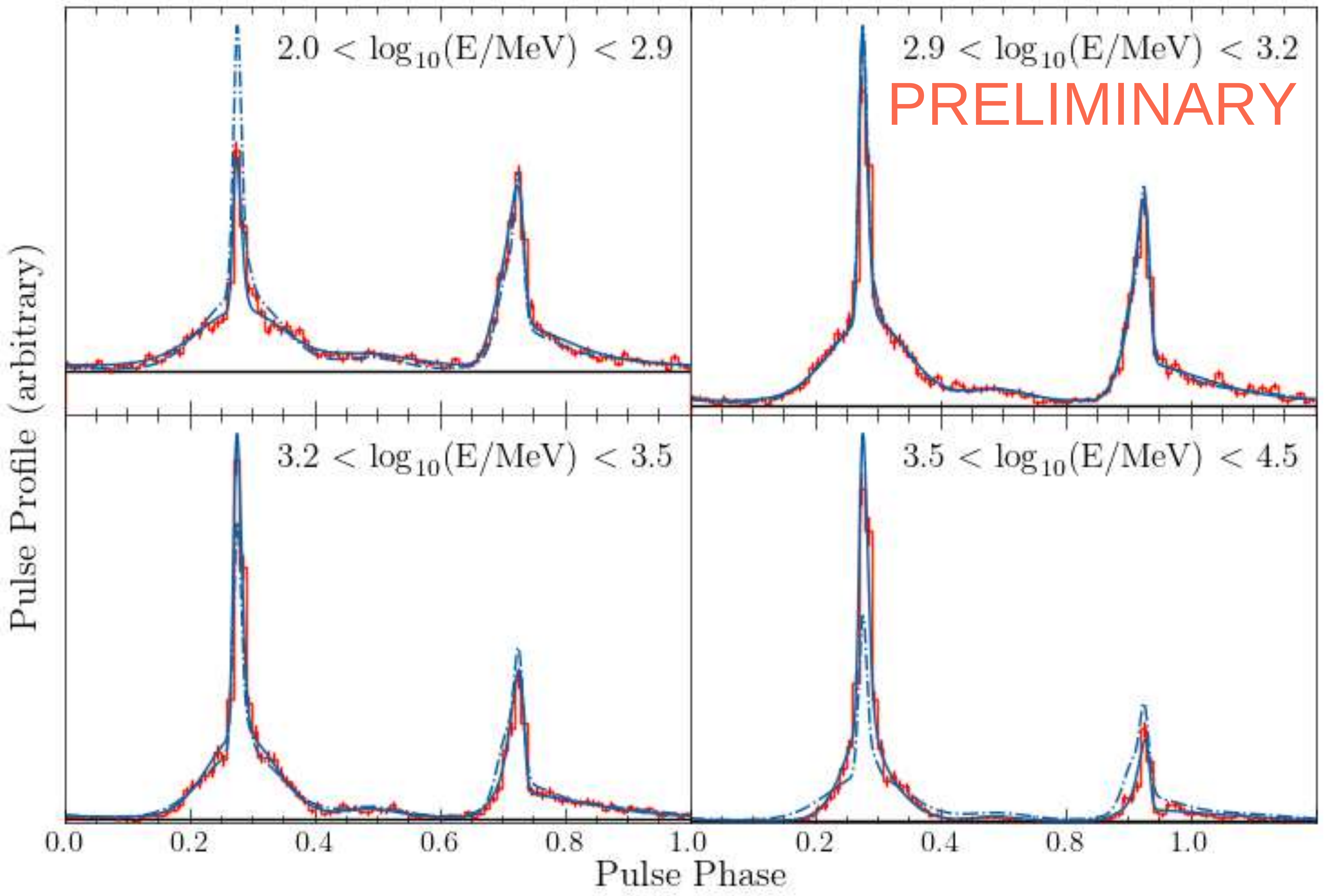
Upgrades: More Data, More Pulsars

- We are expanding the data set to 15 years (~14.5 reported here).
- In the weak signal regime, more data wins: S/N ~ $N_p^{0.5}T^{2.17}$.
- In the strong signal regime, S/N ~ $N_p^{0.5}T^{0.25}$.
- DR1 used the best pulsars, in terms of both sheer number of photons received and good “clock” properties (high spin rate, sharp pulse).
- But as we near detection, more pulsars might be helpful.



Upgrades: Better Pulse Models

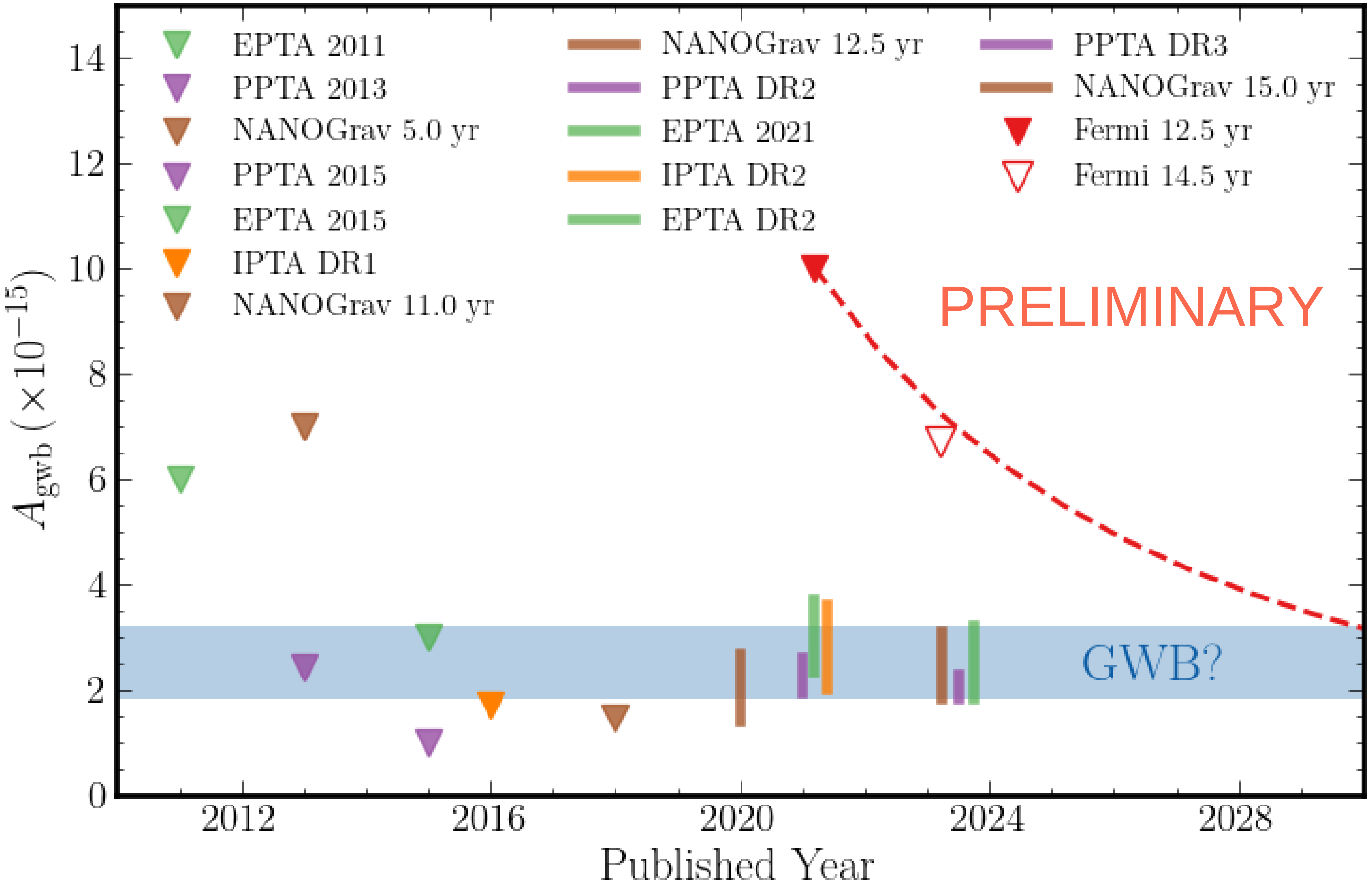
- We have also upgraded the software to more accurately model the change in pulse profile shape over the LAT energy range.
  - Previous, energy-averaged model loses information, e.g. by blurring a feature as i evolves with energy, so new models offer more sensitivity.
  - Energy-resolved models also guard against possible systematic errors from changes in exposure.
    - (The LAT exposure is generally stable but has some episodic changes, e.g. in rocking profile, Galactic center stare, modified survey.)



The pulse profile of J0614-3329 (red histogram), one of the best-timed gamma-ray pulsars, evolves strongly with energy. The new model (solid) captures this evolution effectively, unlike the previous model (dashed).

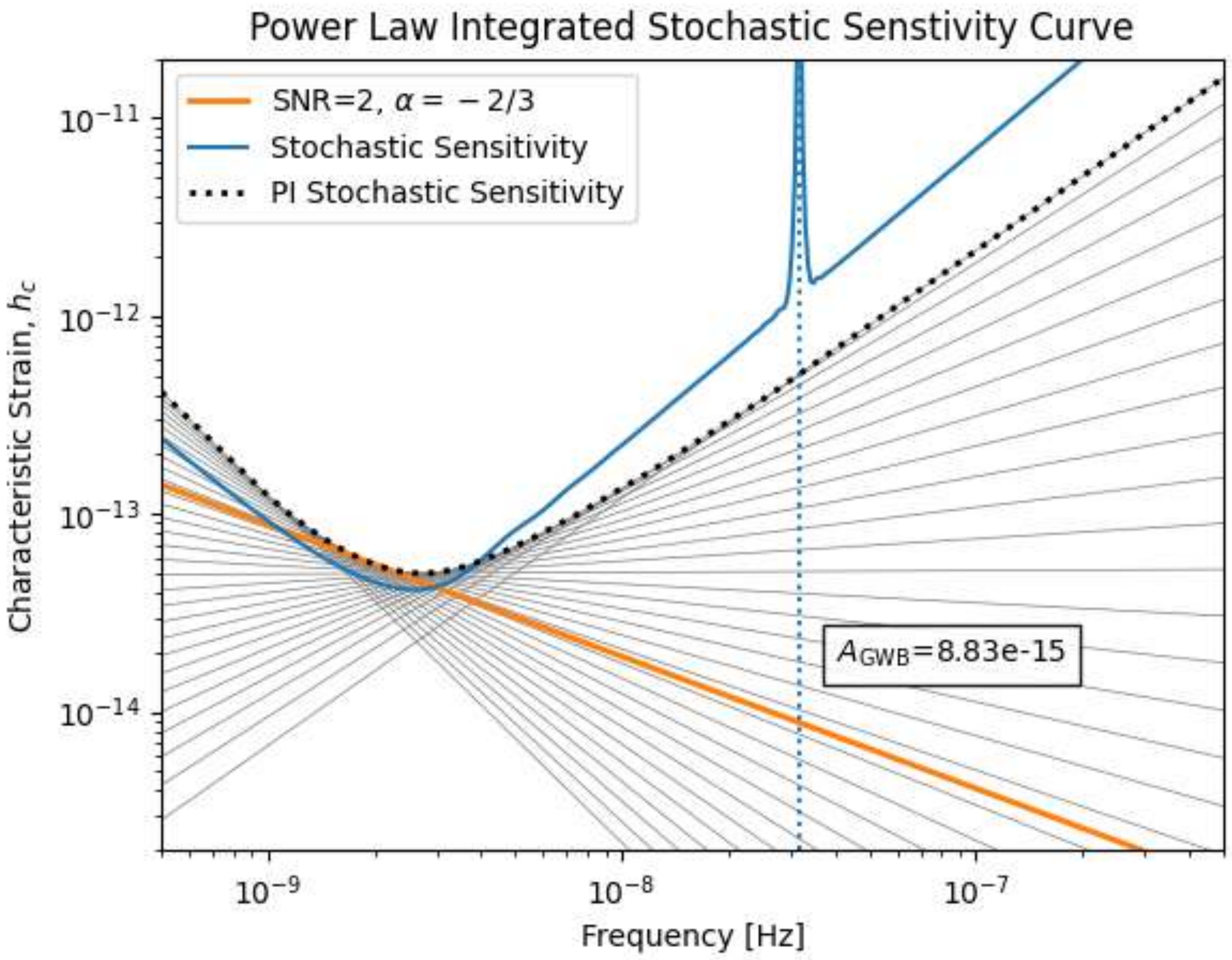
Preliminary Results and Conclusions

- With the additional pulsars and energy-dependent profiles, we performed a new search for the GWB, obtaining $A_{gwb} < 6.7 \times 10^{-15}$.
  - This is about 10% better than the time scaling alone, indicating upgrades are effective.
- With continued time scaling and improvements, on target to detect GWB within 5 years.
- Other applications: check radio PTA results with many fewer systematic uncertainties.



Assessing Current and Future Capabilities

Developing a metric of timing quality for each pulsar which allows the construction of an equivalent set of “TOAs”, thus use of existing PTA software like hasasia.



The differential sensitivity curve for 15 years of “DR1” equivalent data, for a S/N of 2, along with limits for various power-law GW spectra.

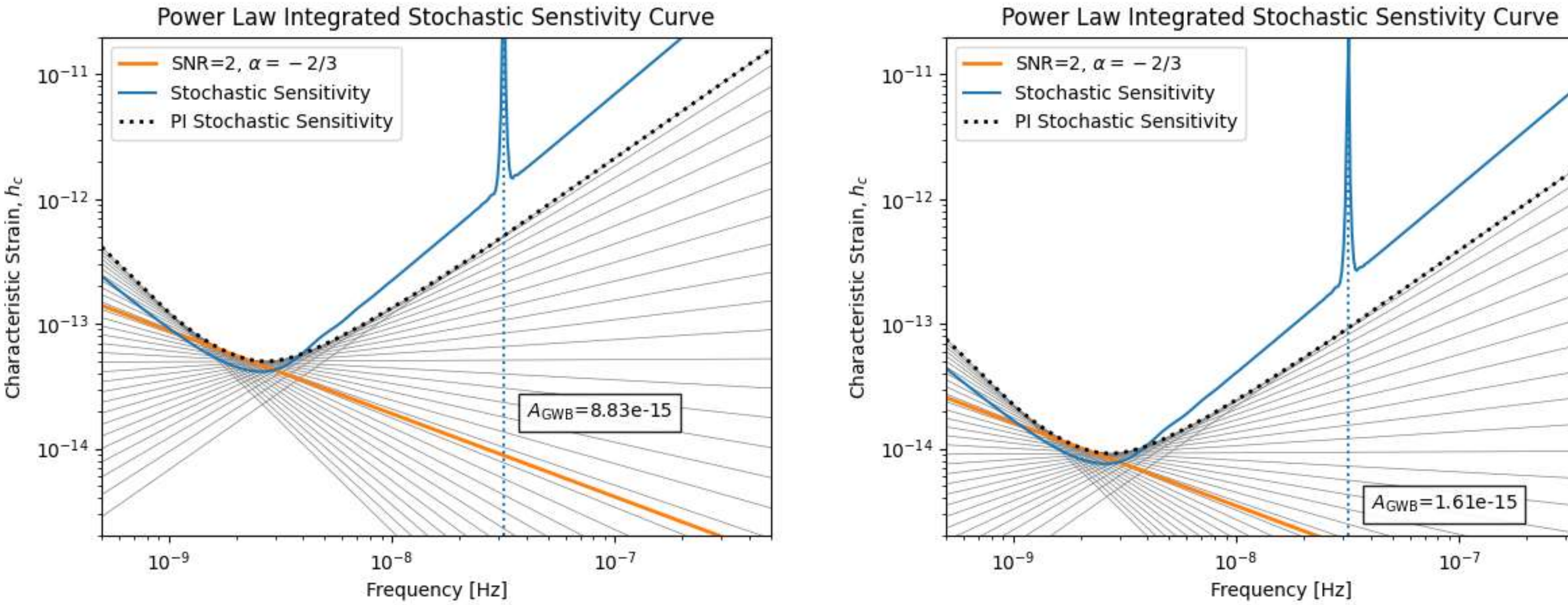
Agrees with the upper limits obtained reasonably well.

Allows rapid exploration of changing parameters: which pulsars contribute, sky maps for continuous wave searches, longer/shorter data sets, more sensitive instruments…

Assessing Current and Future Capabilities

Suppose Fermi had 30x the sensitivity: easily detect GWB via spatial correlations!

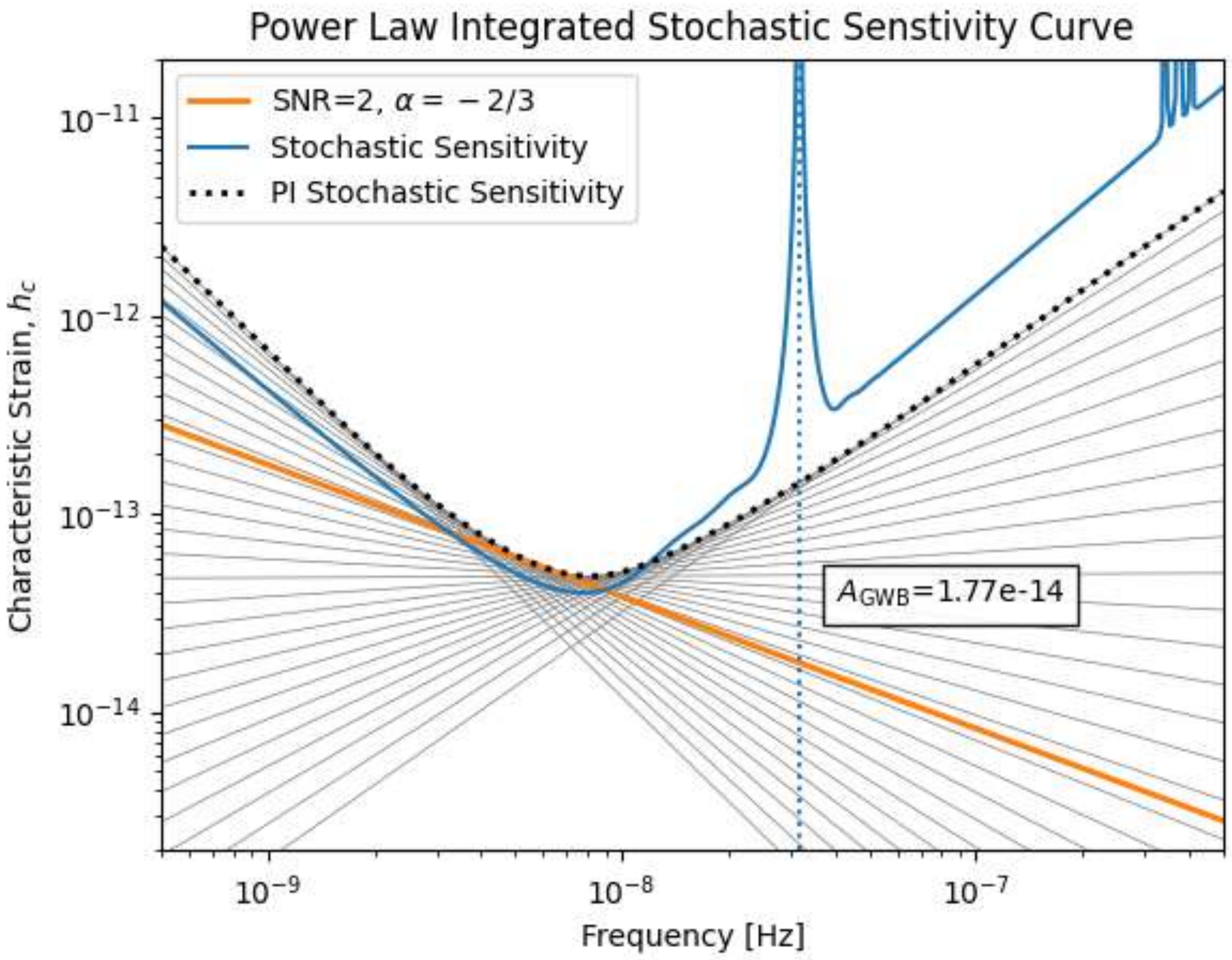
GWB sensitivity improves by $\sqrt{30}$. Less favorable scaling than radio dishes…



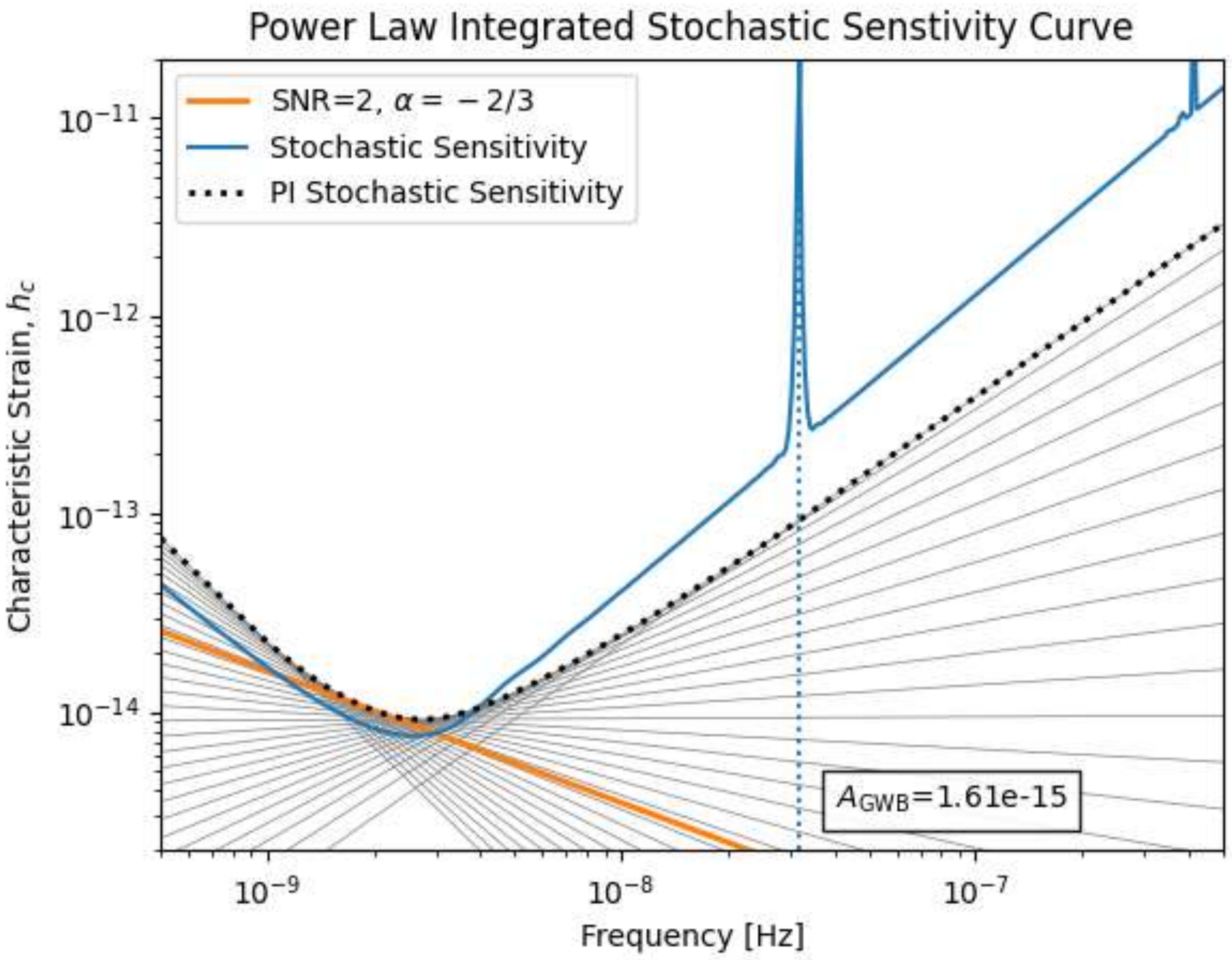
Assessing Current and Future Capabilities

Within a prime mission?

Five Years



Fifteen Years



Key Takeaways

- The **length and stability** of the Fermi-LAT data set are the main drivers of its sensitivity to low-frequency gravitational waves.
  - Goal: **achieve independent measurement of GWB within 5 years**.

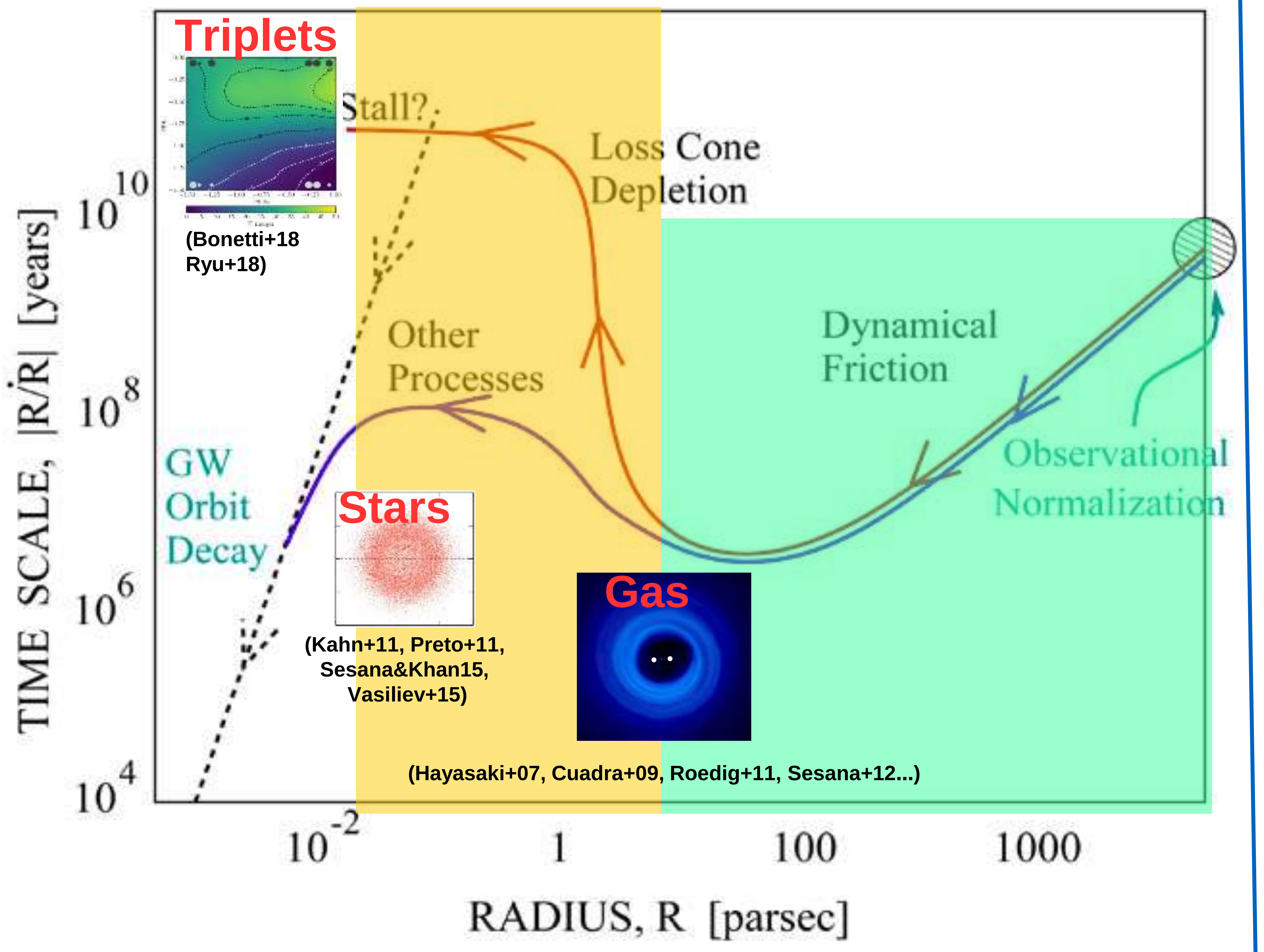
- Many new personnel and capabilities beginning to work on full utilization of data set and incorporation with IPTA data and tools.

- The **Gamma-ray Pulsar Timing Array (γPTA) DR2** will be available soon with 15 years of data.

- A substantially more sensitive GeV (MeV) capability could much more accurately measure GWB, but (probably) only with >10 years of integration.
  - However, shorter data spans could enable much more effective studies of radio/gamma timing consistency.

What Happens to the Supermassive Black Holes?

Begelman, Blandford, & Rees (1980)



Triplets

(Bonetti+18
Ryu+18)

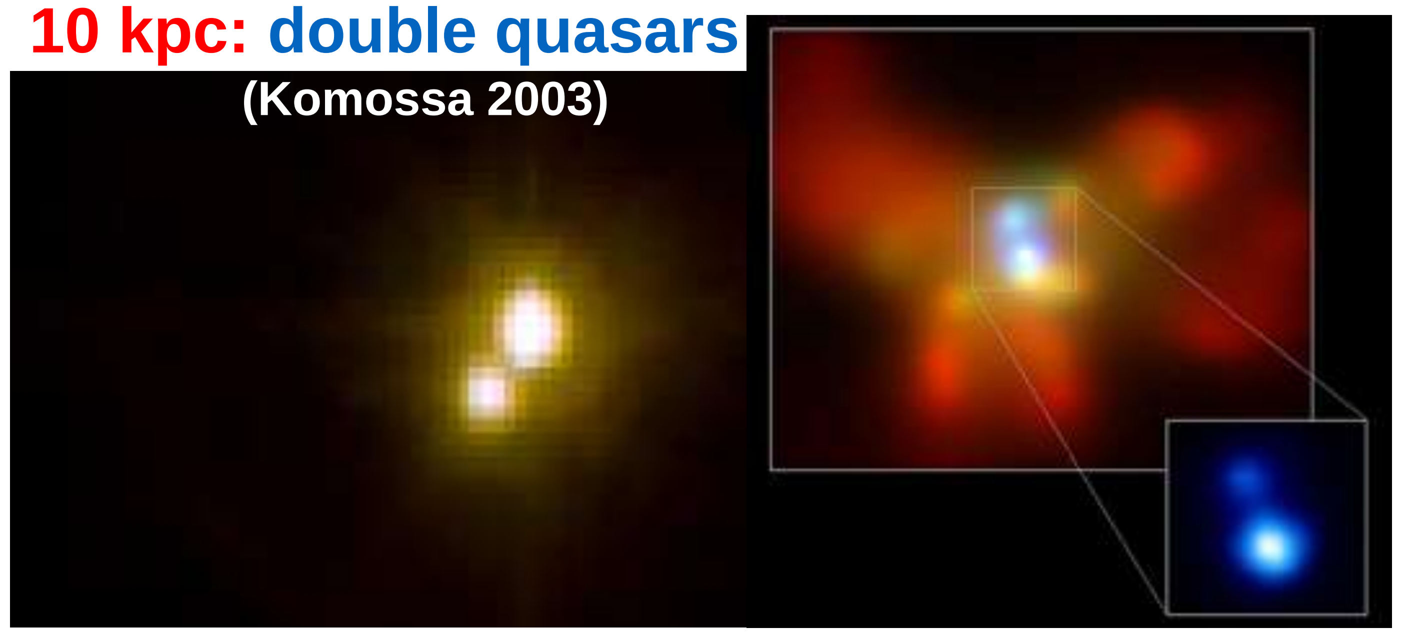
Stars

(Kahn+11, Preto+11,
Sesana&Khan15,
Vasiliev+15)

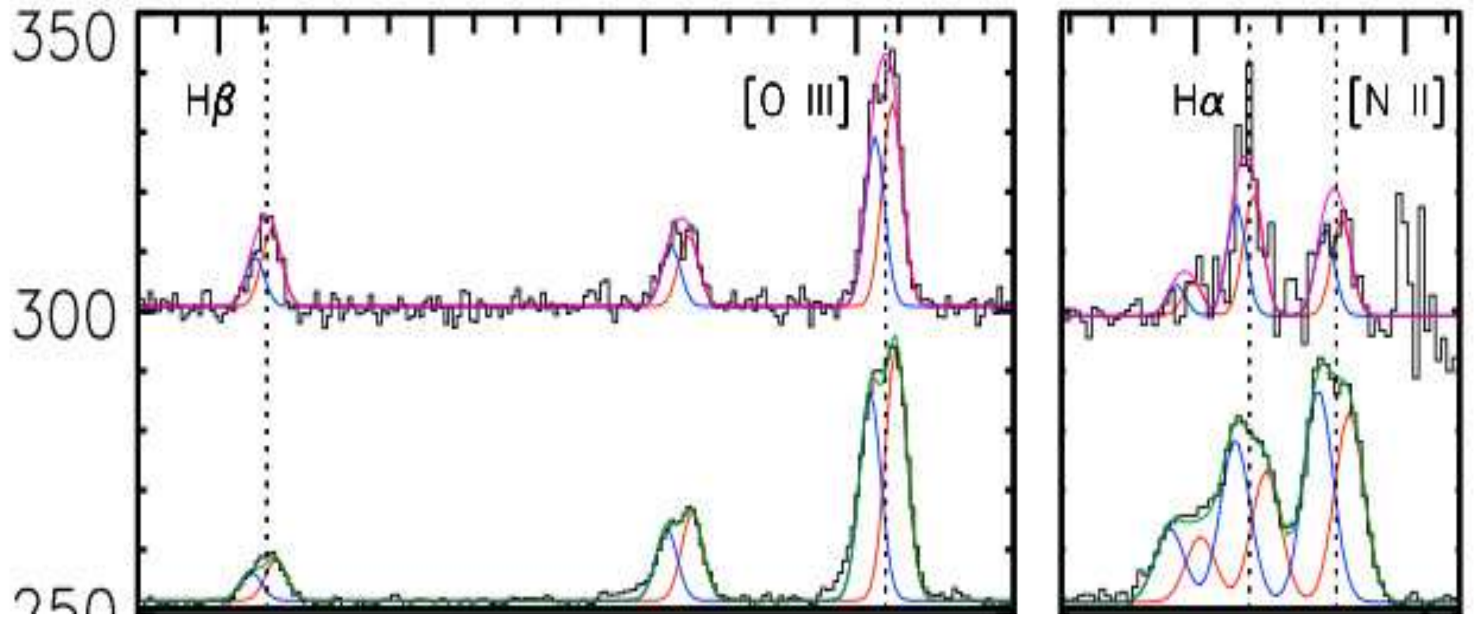
Gas

(Hayasaki+07, Cuadra+09, Roedig+11, Sesana+12...)

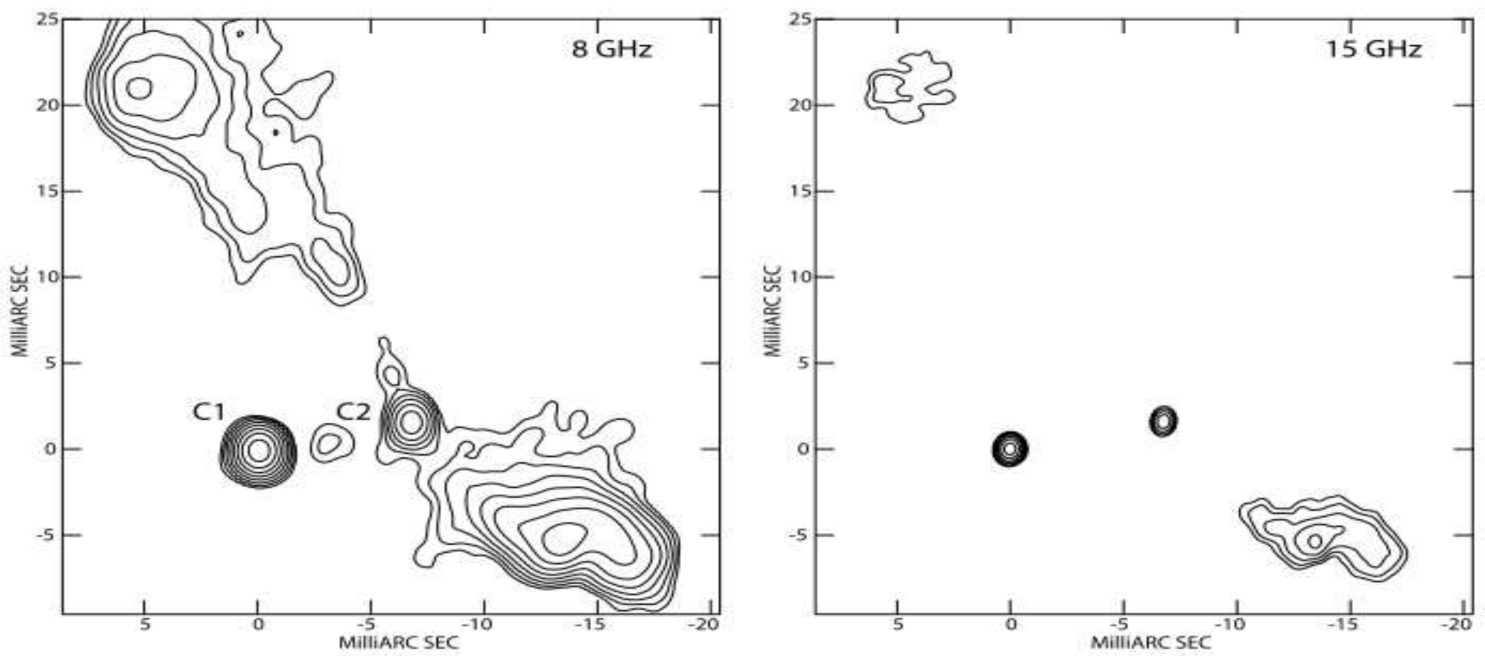
10 kpc: double quasars (Komossa 2003)



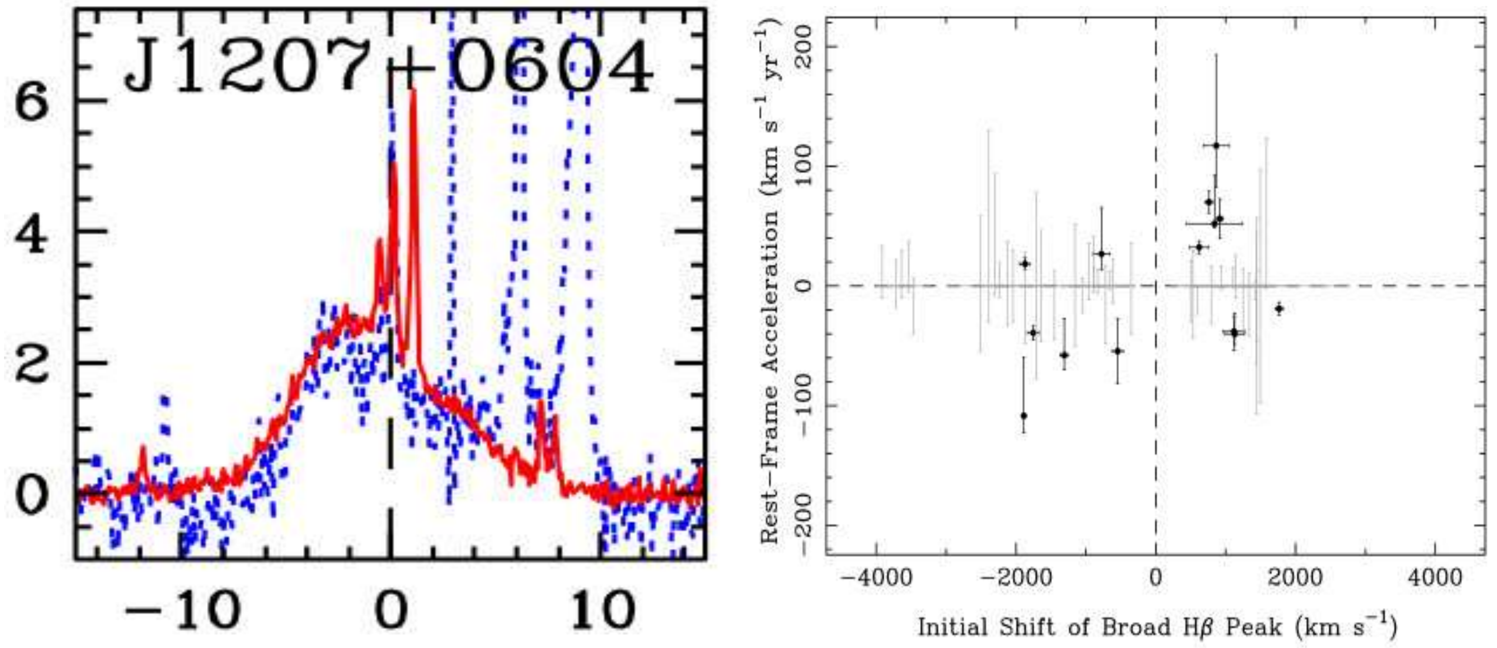
1 kpc: double peaked NL (Comerford 2013)



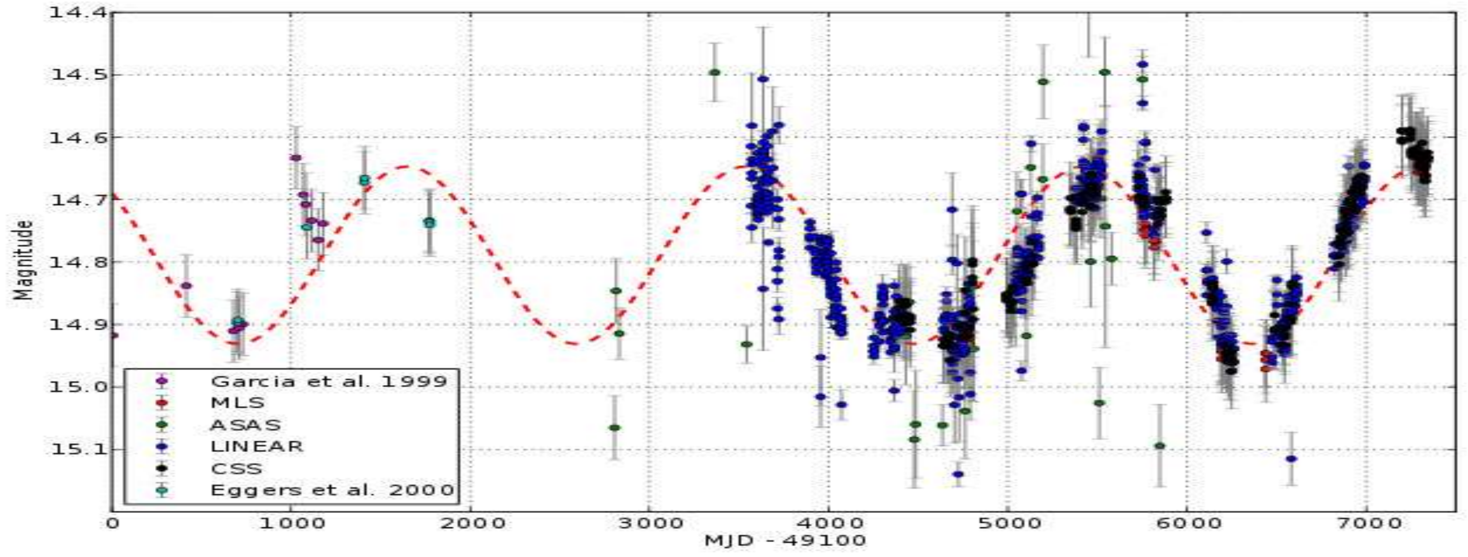
10 pc: double radio cores (Rodriguez 2006)



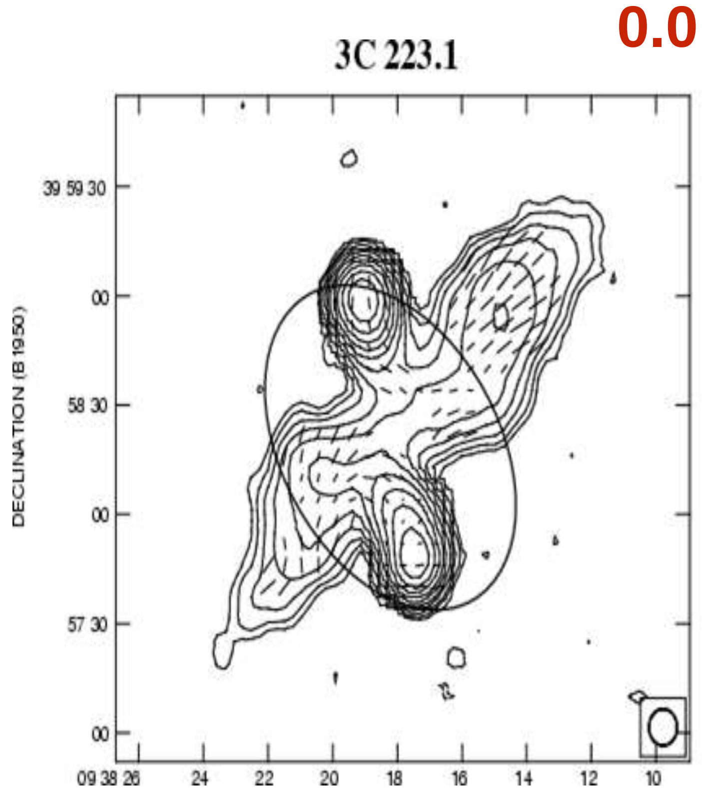
1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)



0.01 pc: periodicity (Graham 2015)



0.0pc:-X-shaped sources (Capetti 2001)
-displaced AGNs (Civano 2009)



Thanks to Alberto Sesana, from whom I shamelessly stole this slide material!