Predictions for Future Gamma-ray Pulsar Timing Arrays and Prospects for Millisecond Pulsar Discovery

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Sep 25, 2025 / FIG-SAG meeting

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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 $h \propto f^{\frac{2}{3}}$.

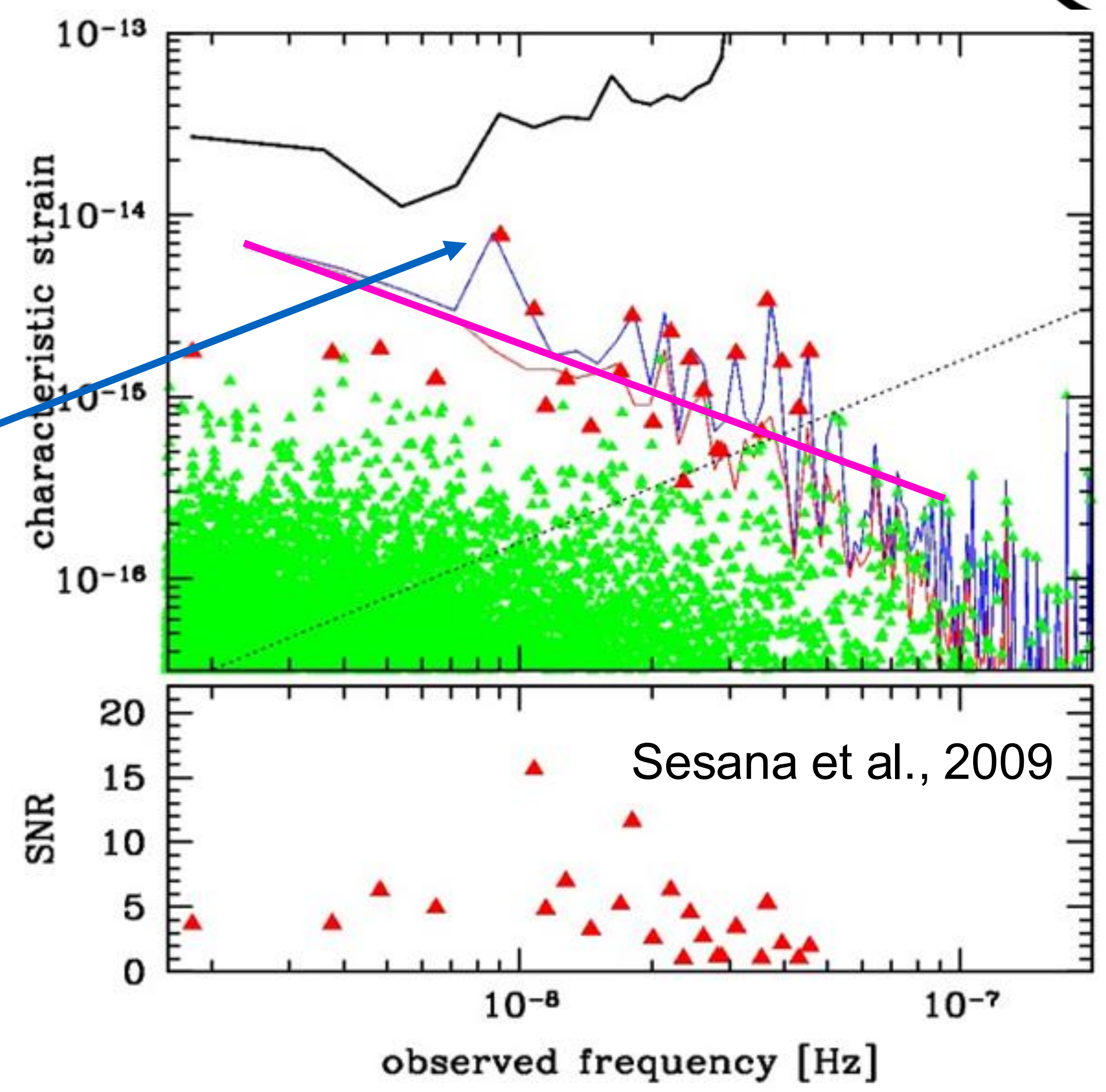
- For typical SMBH masses, GW emission dominates at binary separations of <0.01—0.1pc, i.e. orbital periods ≫ 10 years.

- 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 ($\alpha = -\frac{2}{3}$):

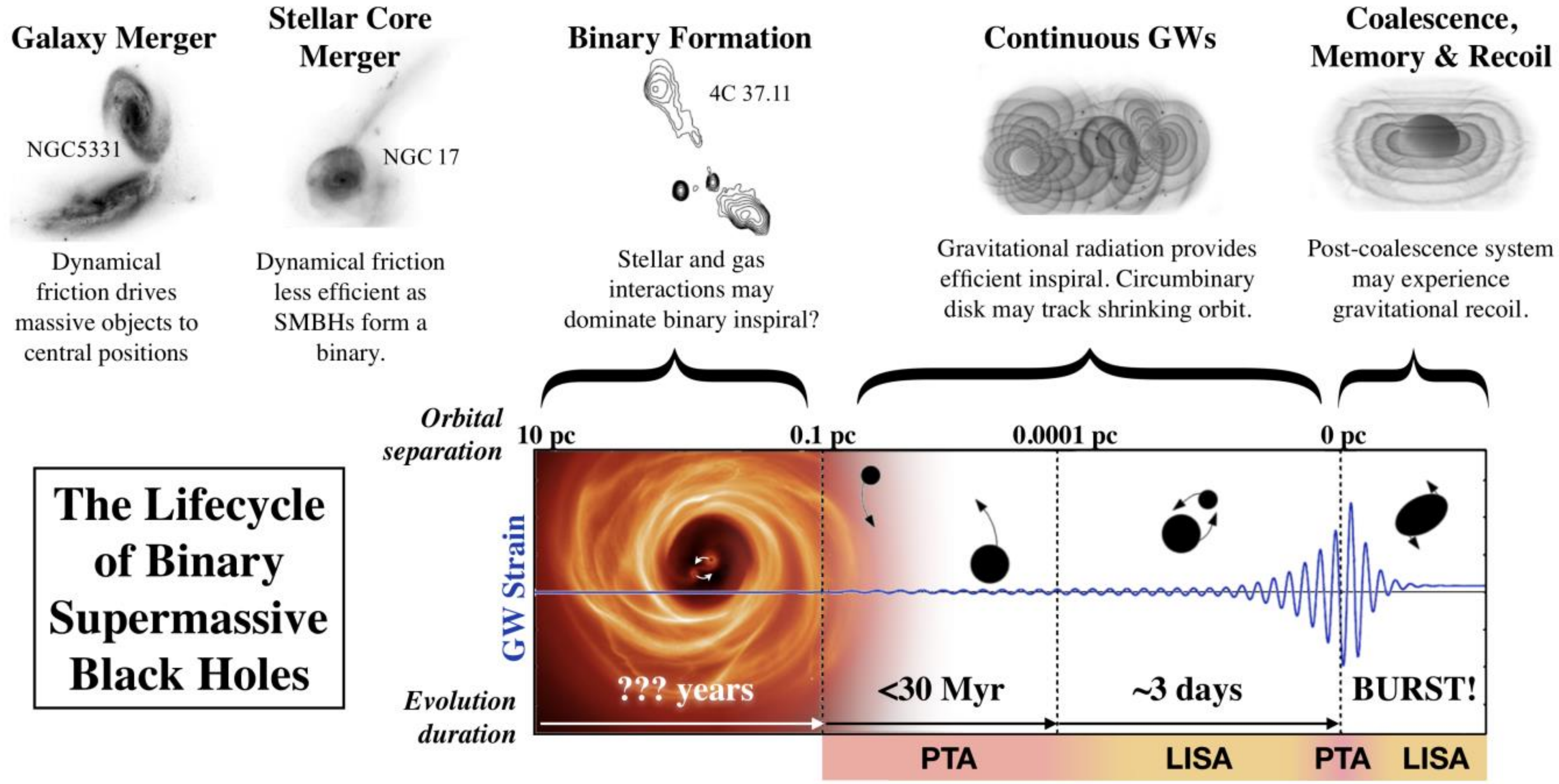
$$h_c(f) = A_{\mathrm{gwb}}\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{\alpha}$$

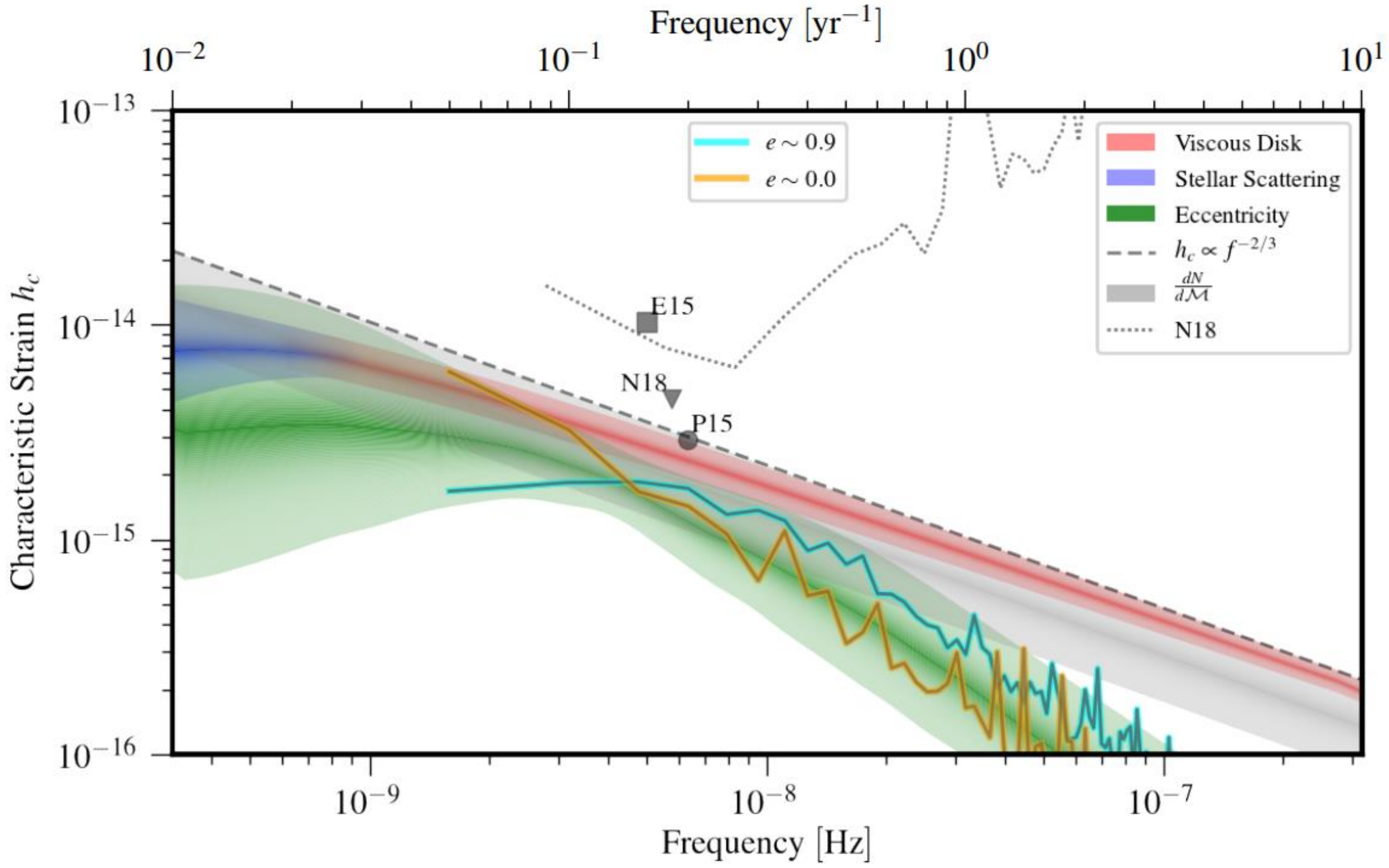
Probing the SMBHBs Population with the GWB
(see Burke-Spolaor et al. 2019 for a review)

- 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.

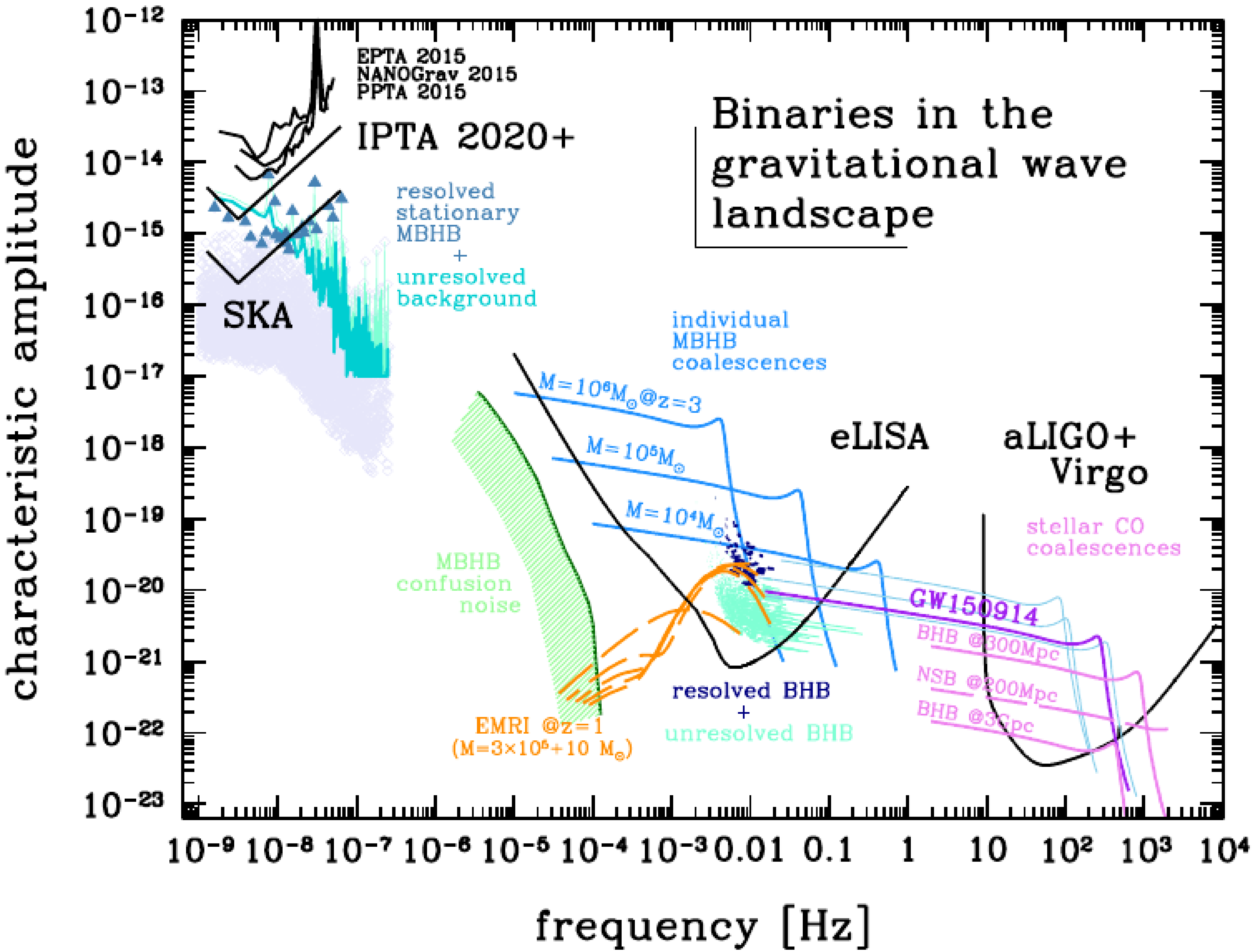


- **Detecting the amplitude A_{gwb} and ultimately, the shape of the GWB spectrum provides a direct constraint on a process whose large dynamic range makes it difficult to observe/simulate, and complements other probes of BH masses.**

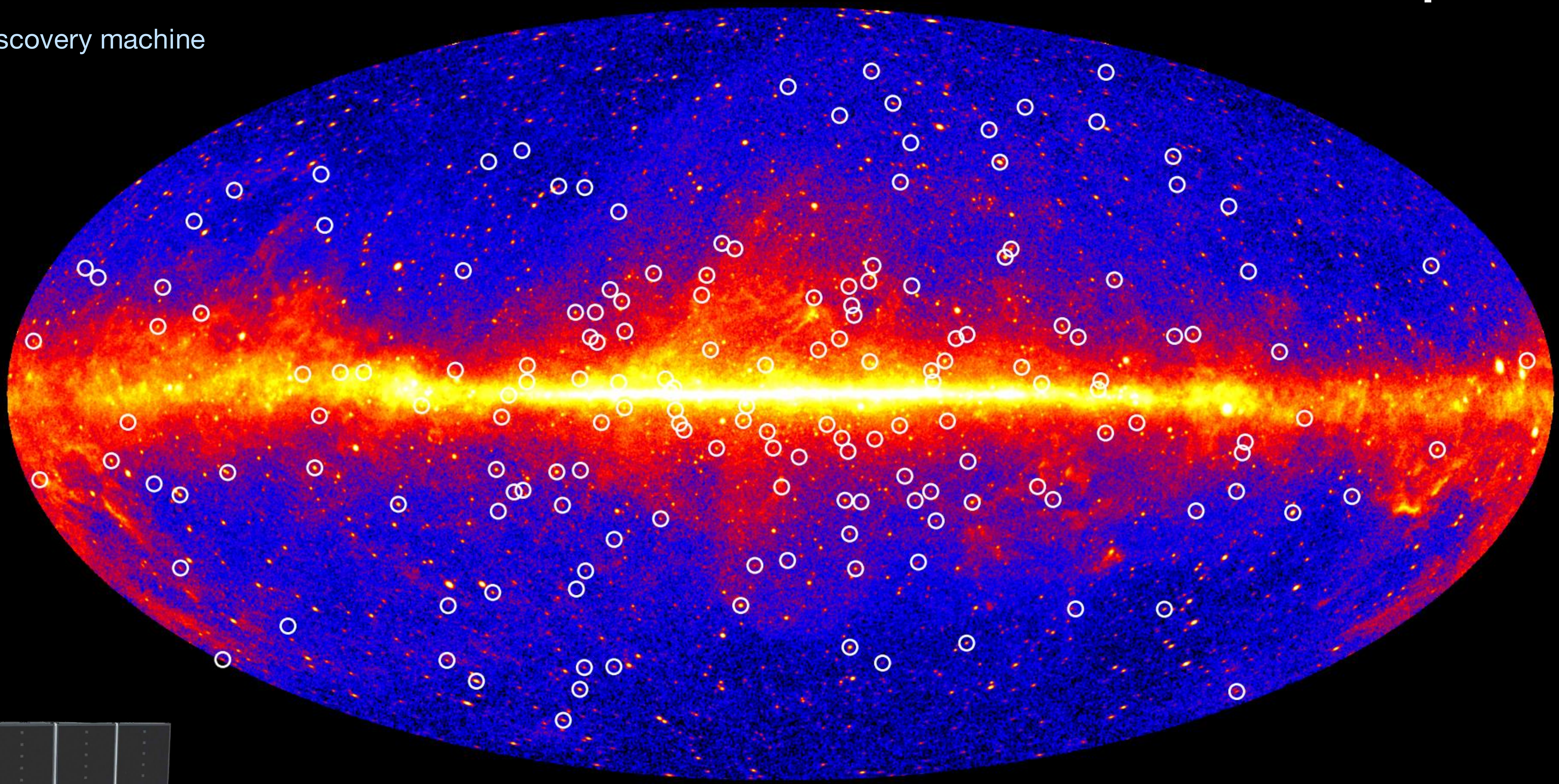


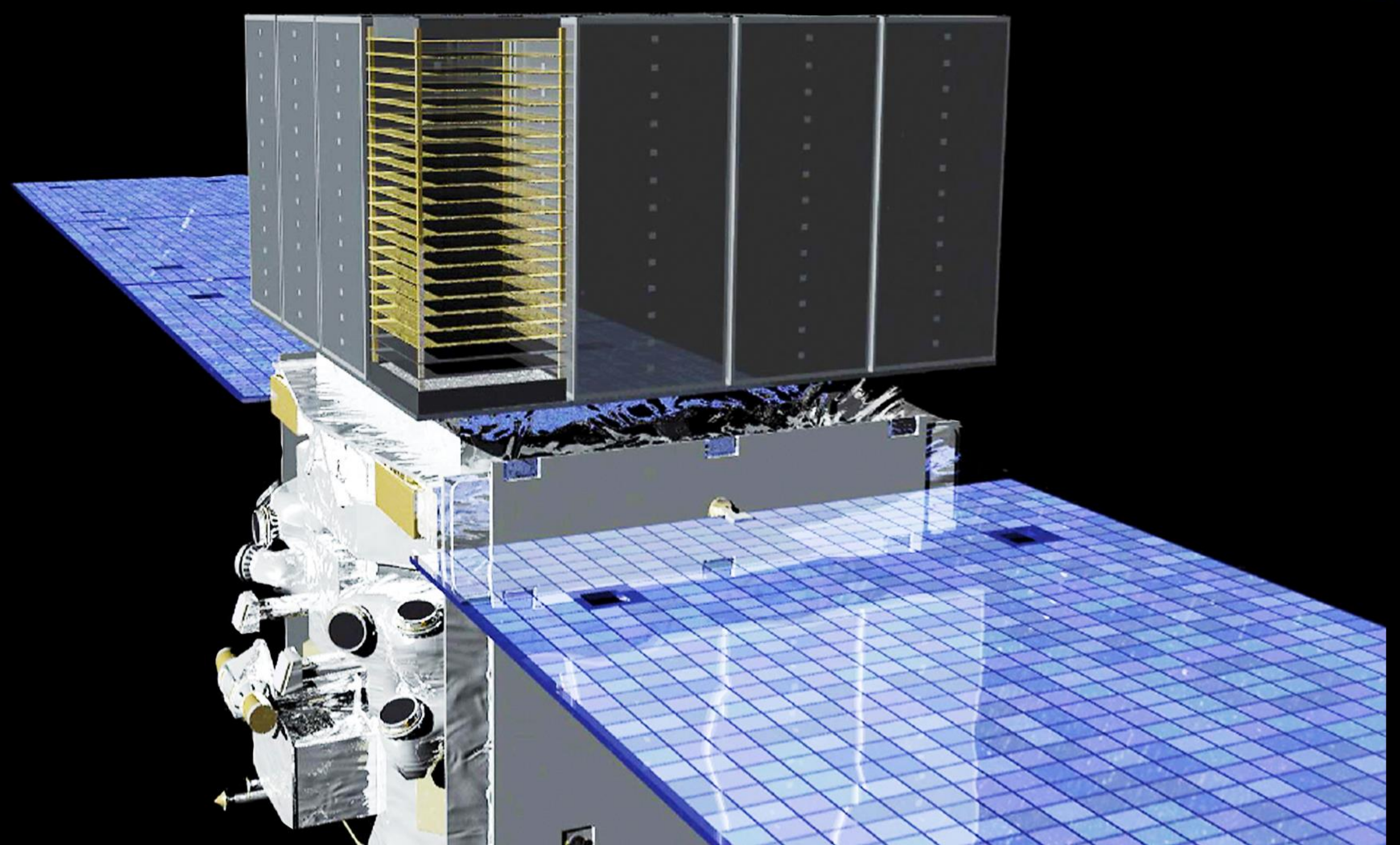


The Gravitational Wave Landscape for Binaries



Fermi the MSP discovery machine





Fermi is an exceptional pulsar machine: over 300 gamma-ray pulsars detected, including well over 100 MSPs.

A particular success is the “Pulsar Search Consortium” (Ray+, 2012), which targets pulsar-like LAT sources for radio observations. This approach has discovered about 100 MSPs, <u>of which 25 are now used in radio PTAs</u>.

This is a substantial fraction of all IPTA pulsars!

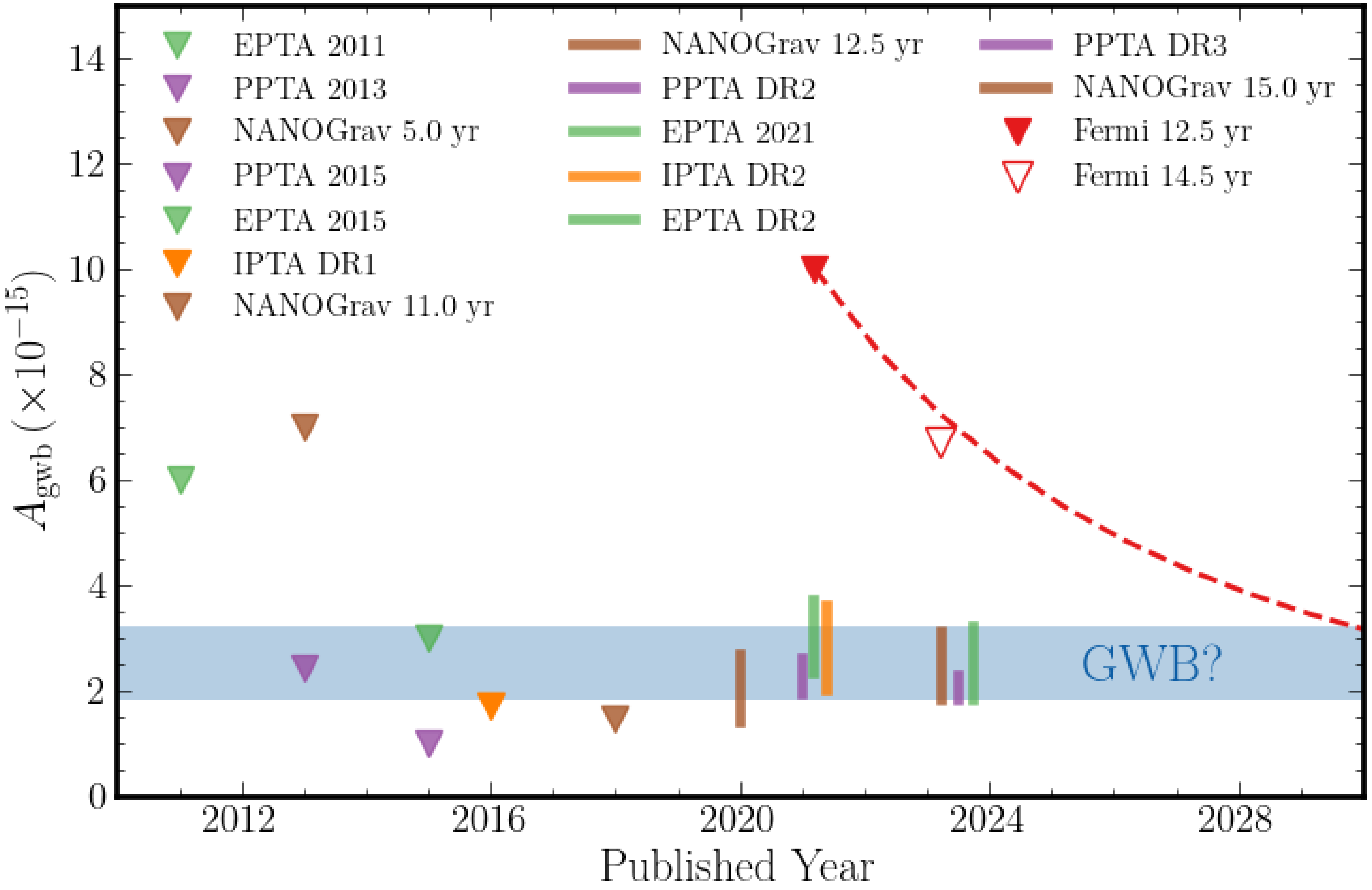
Fermi as a PTA

- ~100 MSPs x 10—20 years sounds like a Gamma-ray Pulsar Timing Array! (GPTA)

- The retconned GPTA DR-1 was released in 2022 (Ajello et al.) along with a search for a stochastic GWB, and predictions for reaching the $\sim 2 \times 10^{-15}$ level by the late 2020s with continuing data accumulation.

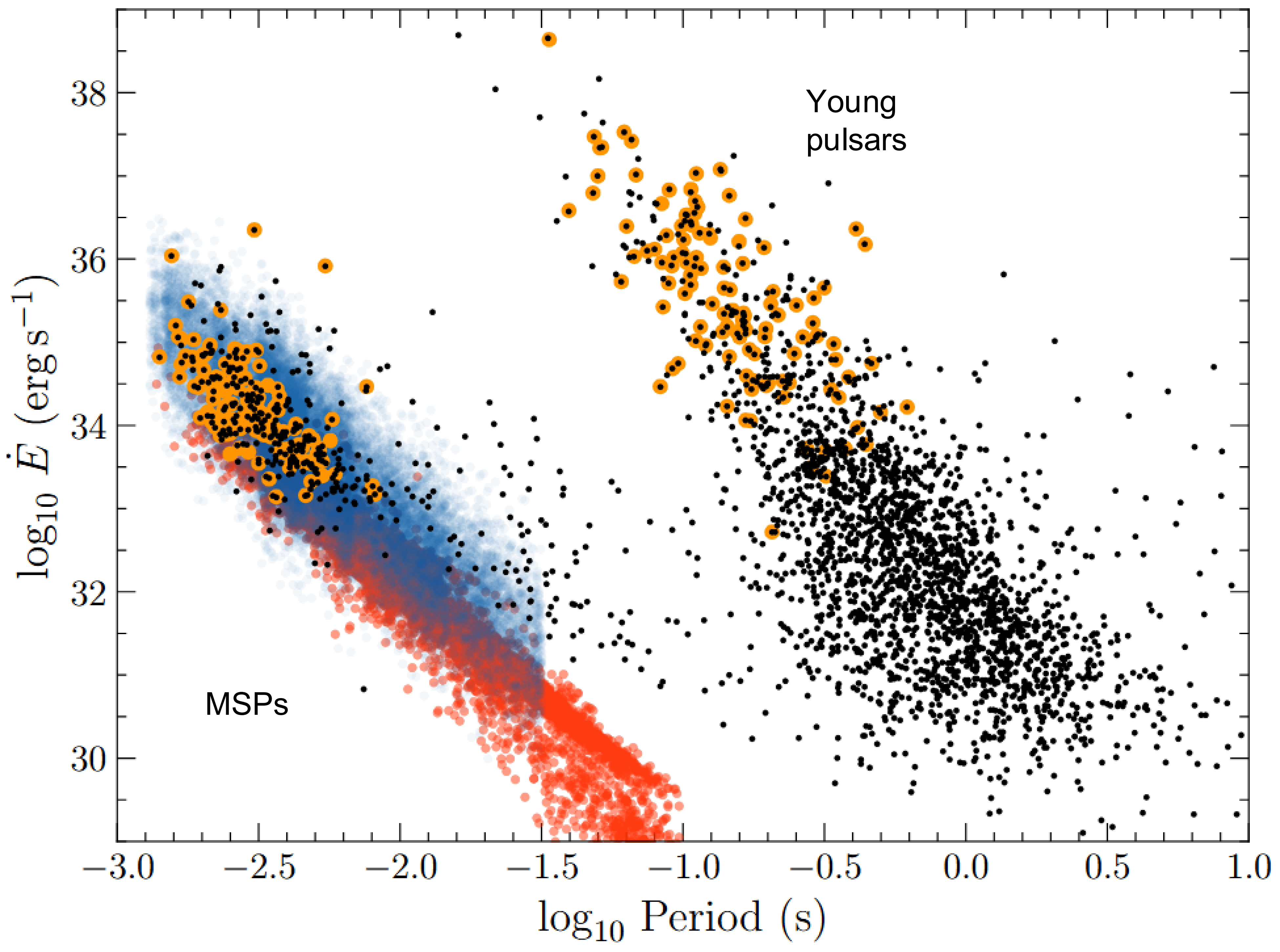
- The GPTA has some nice properties:
  - Immunity to IISM effects.
  - Retrospective pulsar timing.
  - (Mostly) unchanged experimental setup.
  - Brightest MSPs are different to radio.
  - Computationally inexpensive.

- So it would be nice to consider expanding the GPTA to include other instruments…



Predicting Gamma-ray MSP Populations (1)

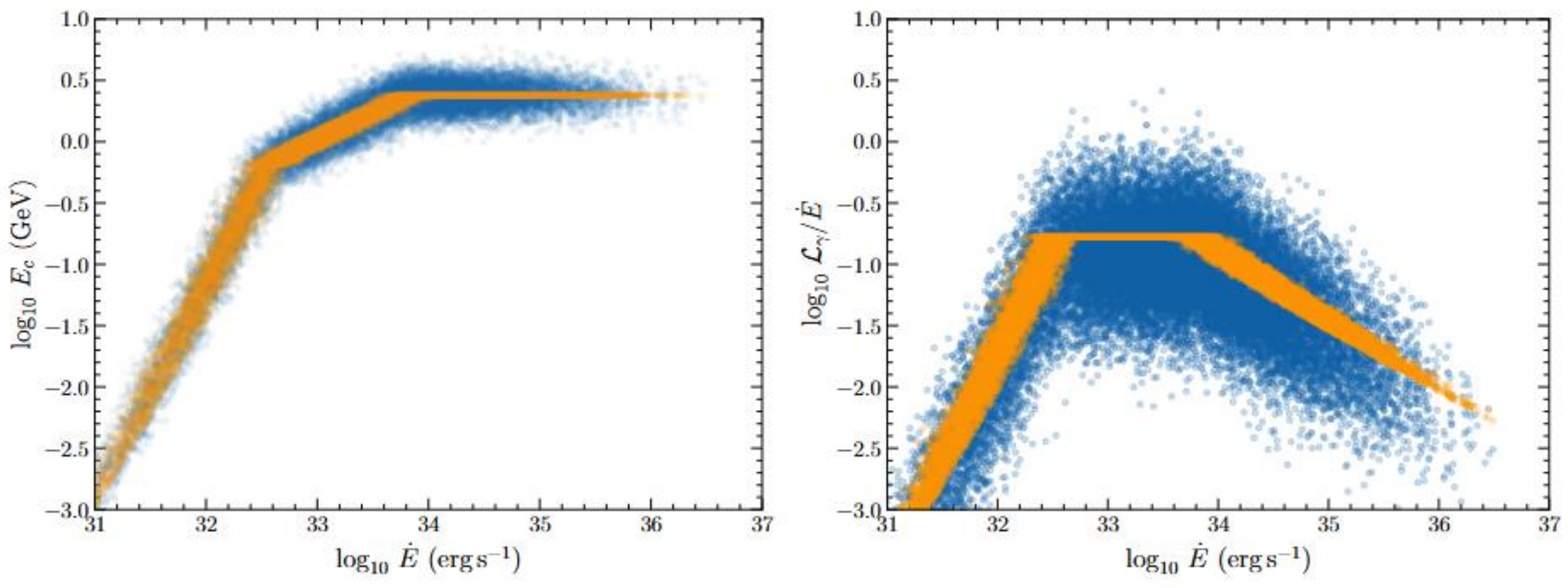
- MSP population: used PSRPOPPy to simulate the MSP population in the Galactic disk following T. Liu+, 2023. (Thanks to Tyler Cohen).
  - S1: disk model distributed like a gaussian in r, with a scale height, numbers constrained by radio survey data.
  - Additionally considered two possible bulge populations. Both are set to trace the "Fermi Galactic center excess" spatially and spectrally.
    - S2: S1 + 120k older MSPs from accretion-induced collapse
    - S3: S1 + 7k disk-like MSPs

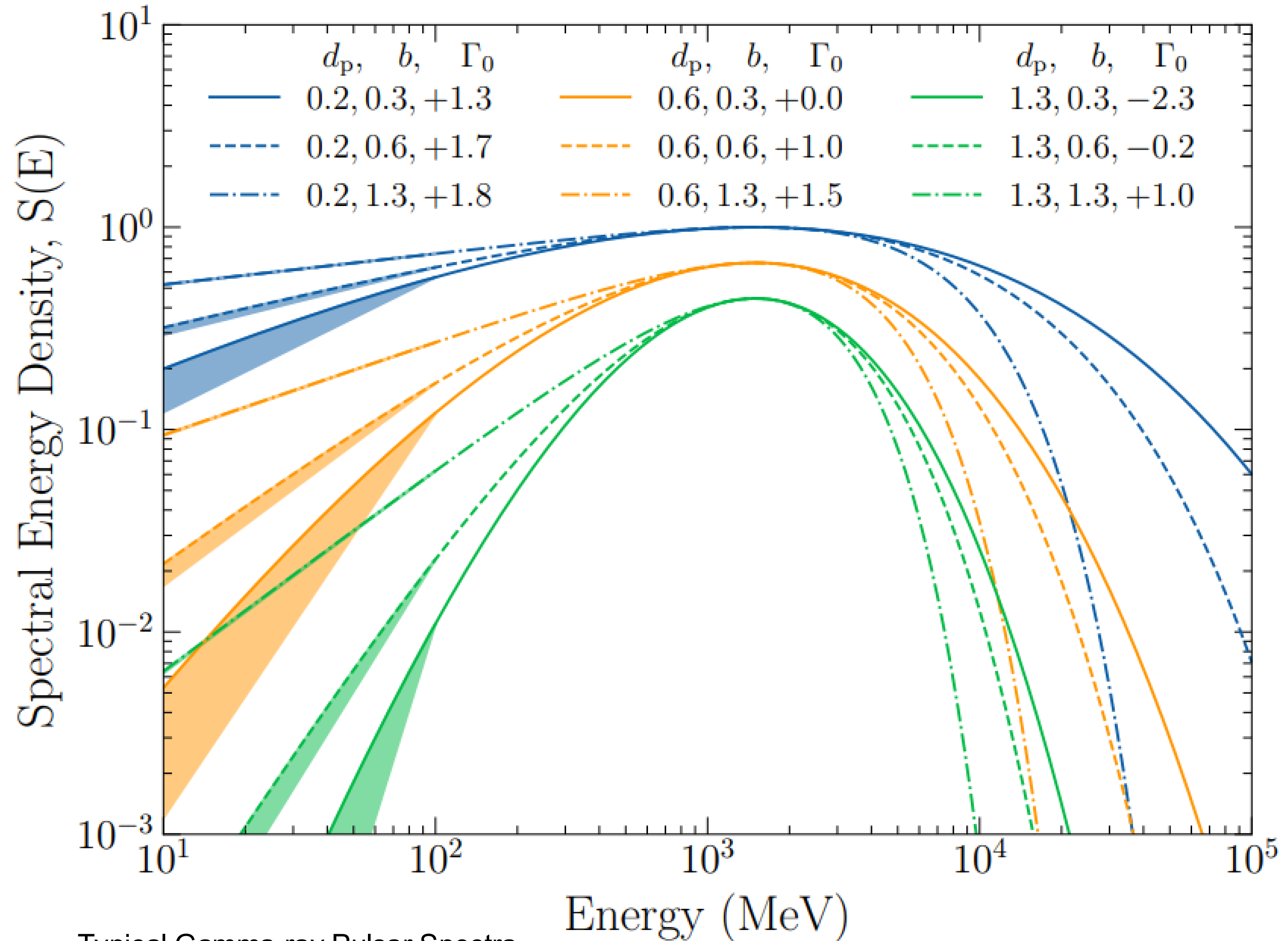


Black dots are ATNF psrcat entries.
Orange points indicate LAT-detected pulsars.
Blue points are one realization of the disk population.
Red points indicate one realization of the S1 (AIC) bulge population.
(The disk population has the same distribution as the blue points.)

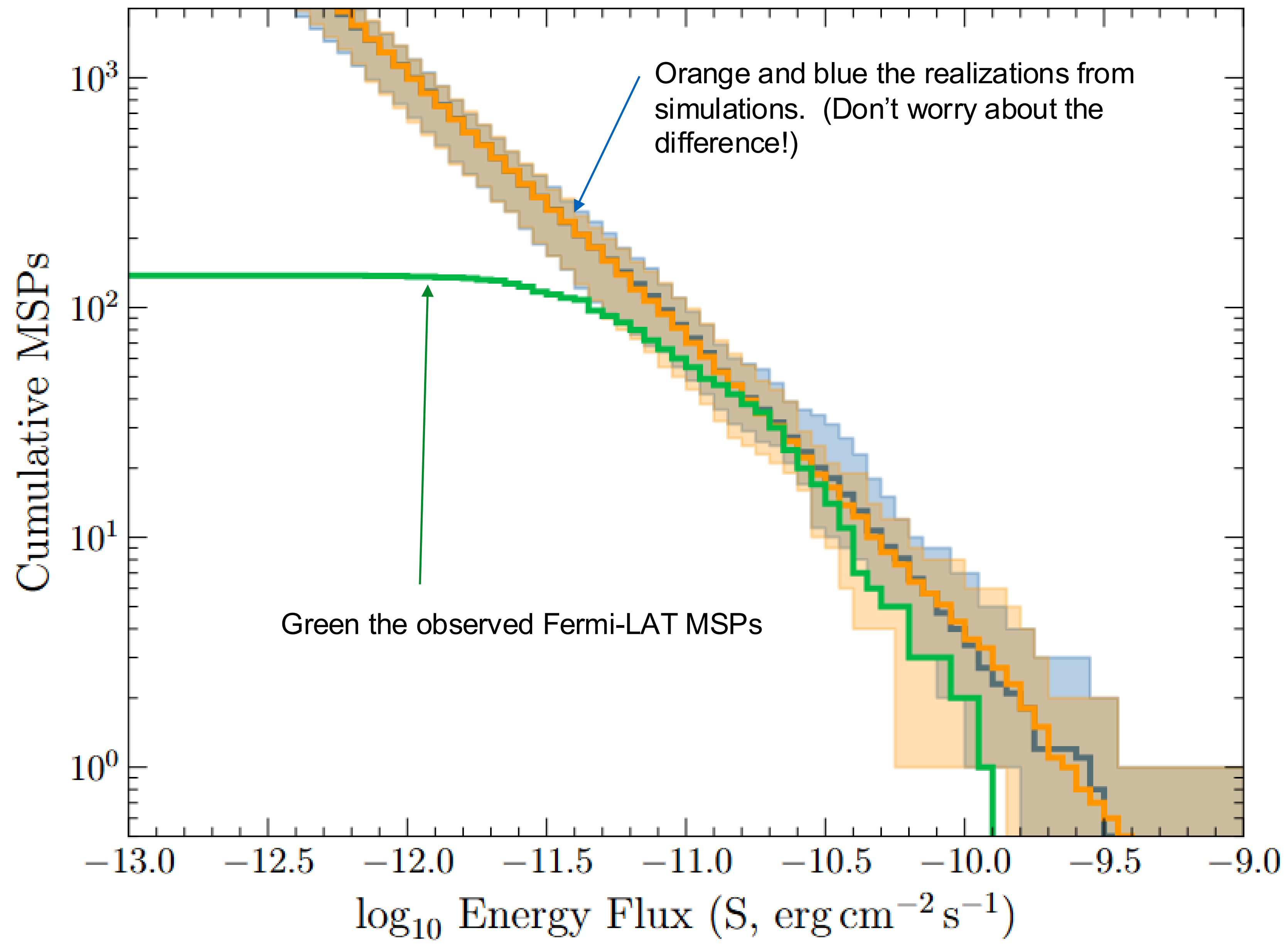
Predicting Gamma-ray MSP Populations (2)

- **Gamma-ray mechanism:**
  - Need both a luminosity AND a spectrum because we care about the full MeV to GeV range!
  - Use the “Fundamental Plane” relation of Kalapotharakos+, 2022, along with a prescription for determining the pulsar cutoff energy, spectral curvature, and breadth from empirical relations obtained in the Fermi Third Pulsar Catalog (3PC).
  - Compare to the observed Fermi MSP logN-logS: pretty dang good agreement!



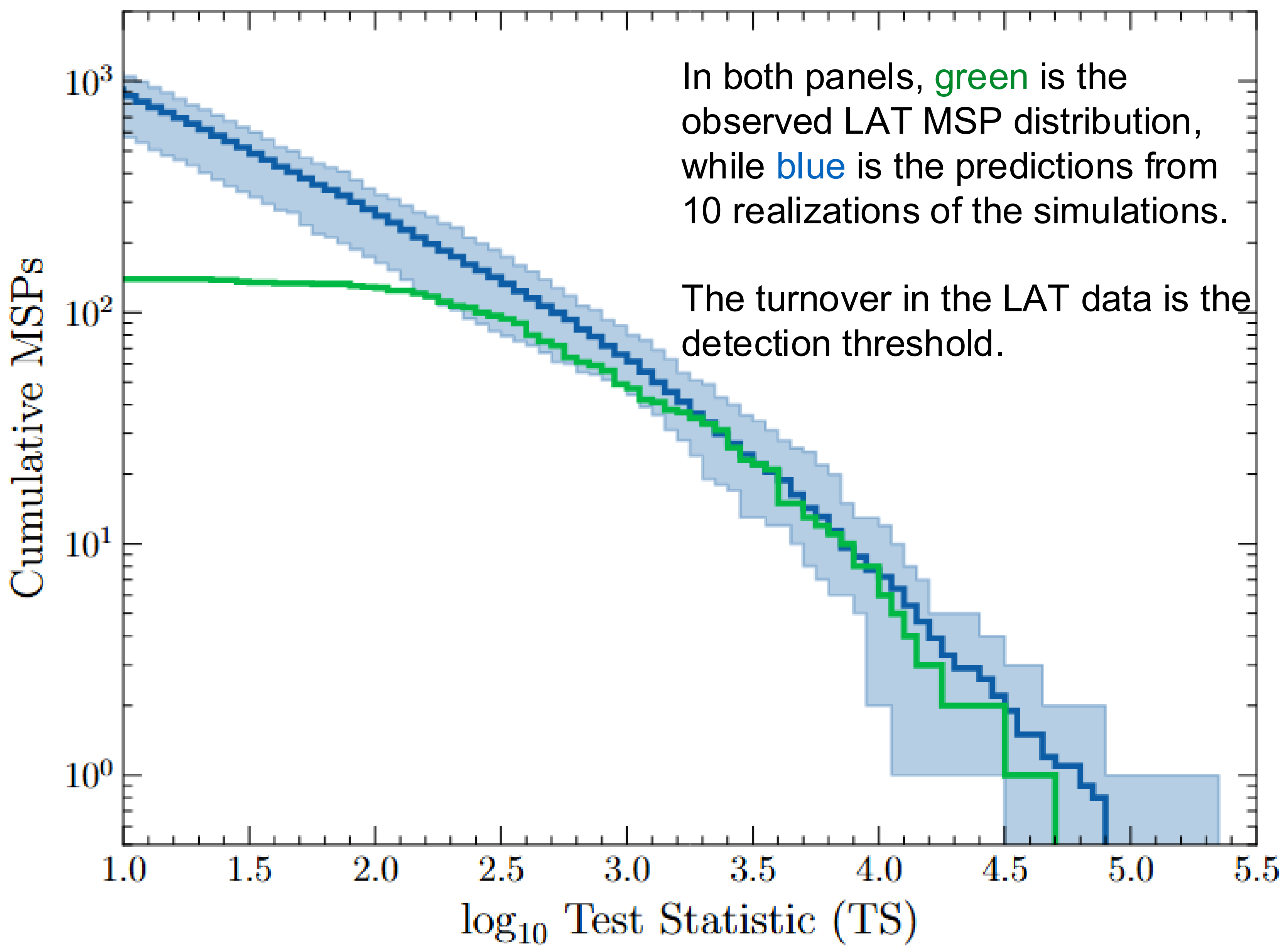


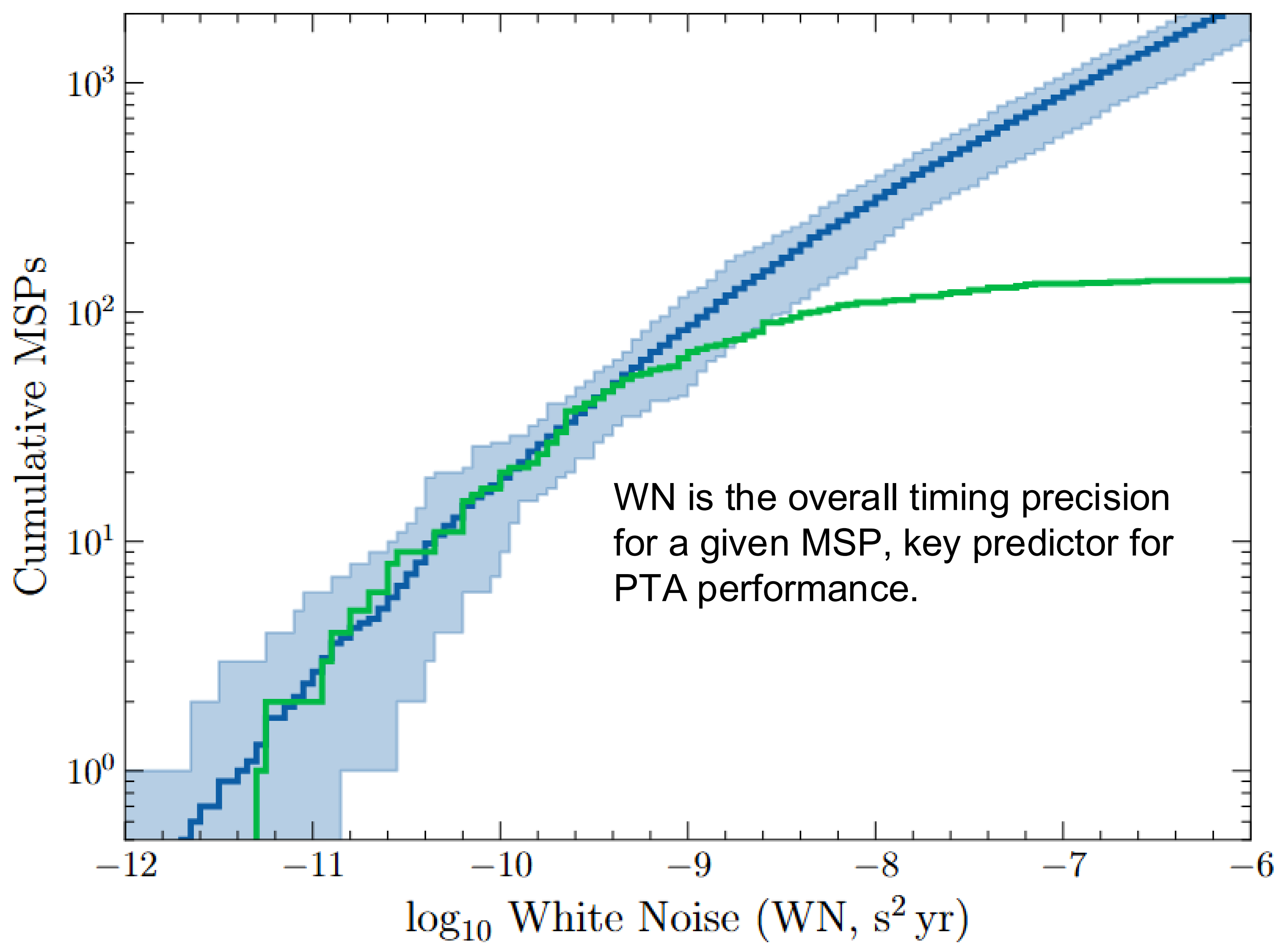
Typical Gamma-ray Pulsar Spectra



Predicting Gamma-ray MSP Populations (3)

- Gamma-ray instrumentation:
  - Build a "virtual LAT" where we can adjust the effective area, PSF, and energy range to coarsely simulate future instrument concepts.
  - This allows prediction of the point source sensitivity at a given position on the sky, so with the MSP spectrum, we can predict the counts/log likelihood/test statistic our virtual instruments receive.
  - Calibrate the virtual LAT to the real data and scale everything from it!
  - Once we know the point source sensitivities and the MSP spin frequency, can estimate TOA precision based on the observed relation for LAT (essentially, the range in pulse profile shapes).





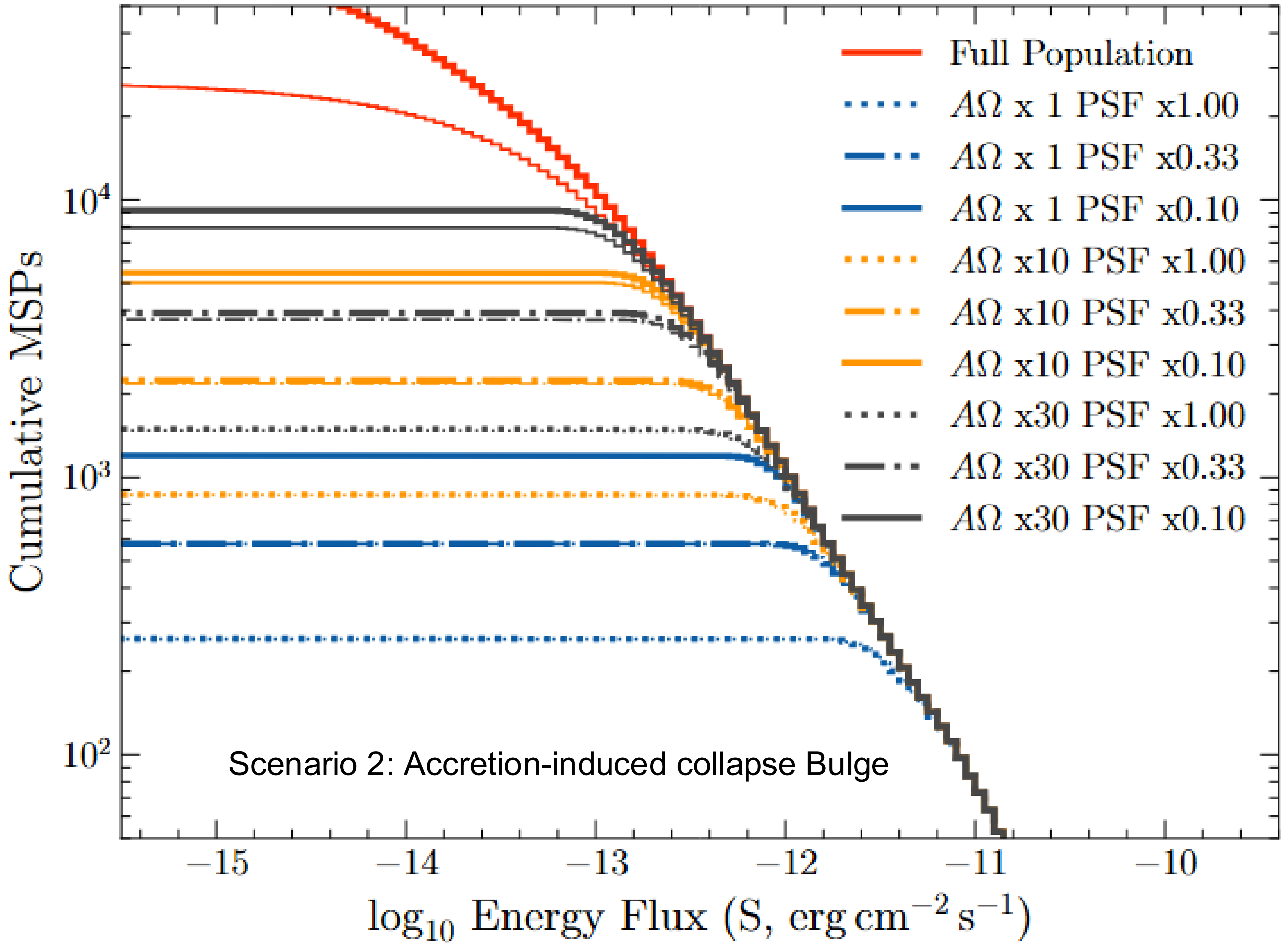
Concepts

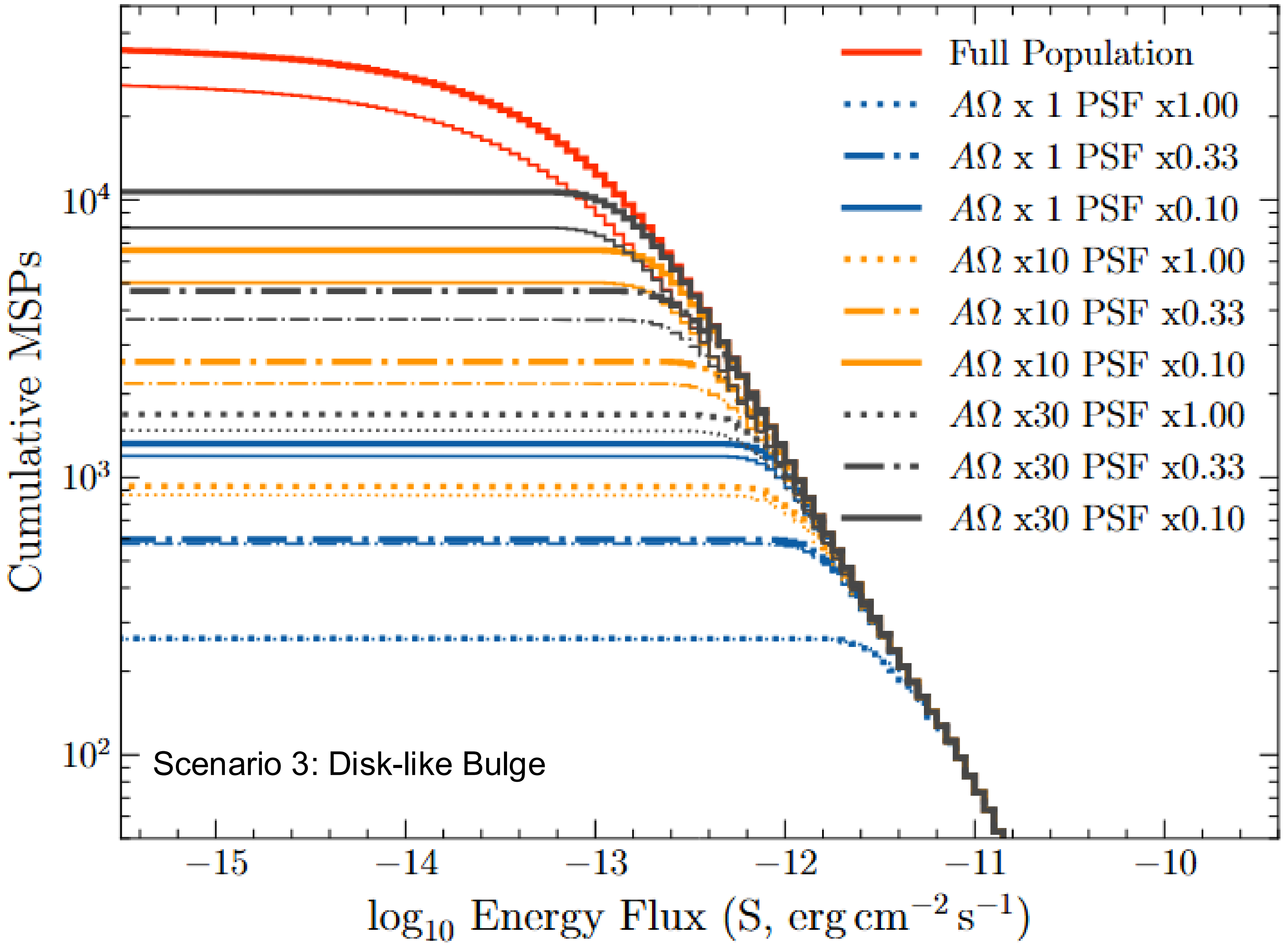
- So, have a general mechanism for predicting gamma-ray emission from MSP populations and for predicting performance given effective area + PSF.
  - What to assume about future instruments? Don't want to get in the weeds, explore what one could do and also study tradeoff between area and angular resolution.
- Natural separation of pair production regime & Compton regime
- In pair regime, LAT is pretty close to optimal; only room for improvement is ~20-100 MeV. PSF will generally have similar energy dependence for tracking e+/-.
  - Thus, can encapsulate most concepts by scaling LAT effective area and PSF.
- Moreover, for a PTA, acceptance is essentially the main criterion because MSPs are widely distributed over the sky.
  - Thus, can also encapsulate concepts that tradeoff effective area for FOV.
    - E.g., an instrument at L2 with 4pi FoV but the same (FoV-averaged) effective area as LAT would have roughly 6x the acceptance.
- Thus, primary concept is an "acceptance and PSF" scaled LAT.
  - Can then relatively easily calculate TS etc. from simulated spectra.
  - Also allows us to calibrate all of the simulations to the LAT pulsar population properties.
- Compton / other low energy deferred until later slide.

Pair-regime Concepts and Results

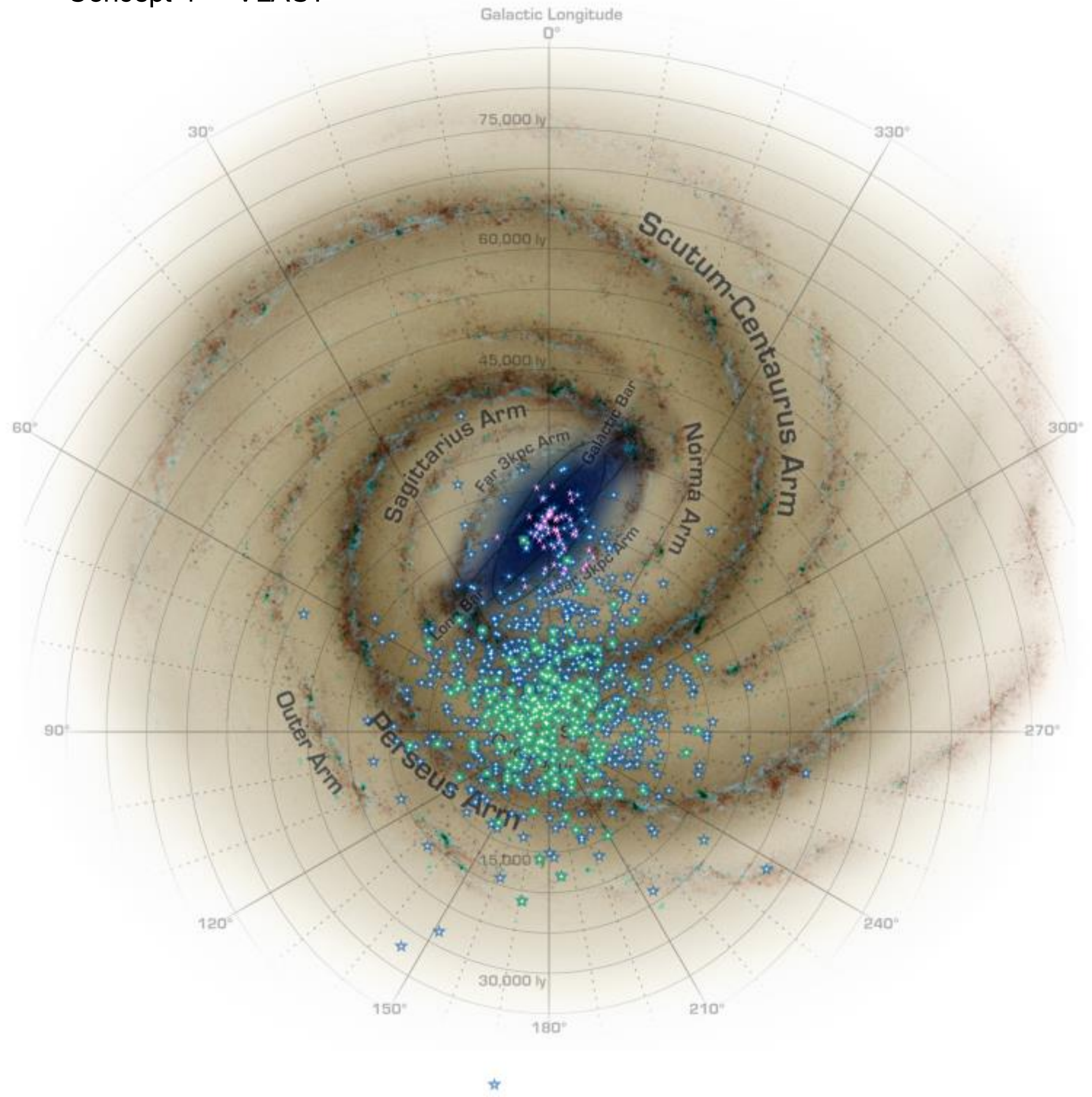
- 9 concepts, with range of acceptance/etendue (1x, 10x, and 30x LAT acceptance) and PSF angular resolution (1x, 0.33x, and 0.10x LAT PSF)
- Recall there are disk MSPs ("S1") and two bulge MSP scenarios ("S2" from AIC and "S3" with MSPs similar to the disk).
- Calculated detected number of MSPs (TS > 100) for each of the concepts, from each of the populations.
  - S2 and S3 identically include all of the MSPs in S1.

- Here: SOLID lines indicate disk + bulge detections, while THIN lines are disk-only.
- GENERALLY, all concepts are volume limited (logN/logS has similar slope), but the most powerful concepts begin to observe a turnover as the remaining MSPs are on the other side of the Galaxy.

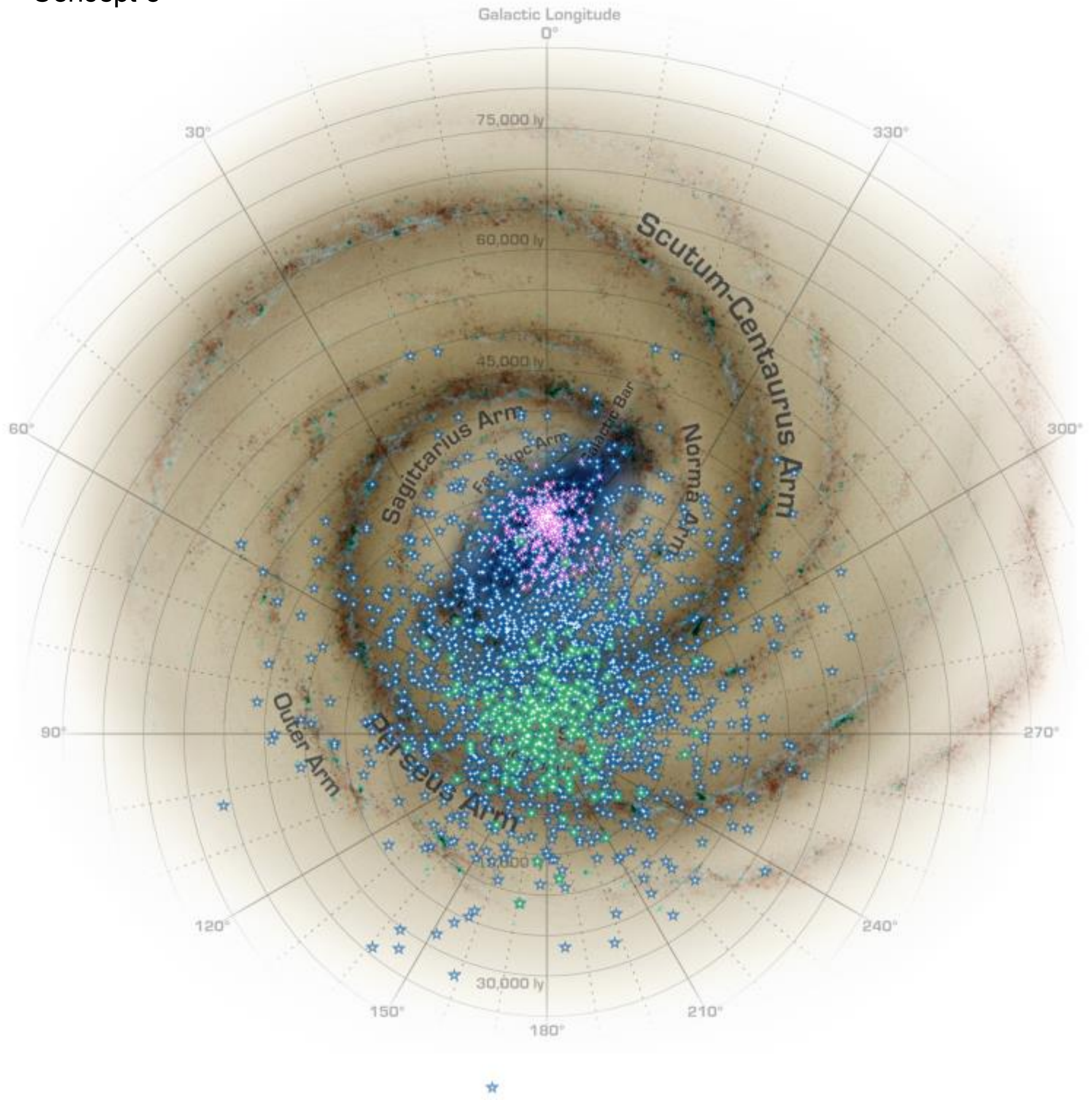




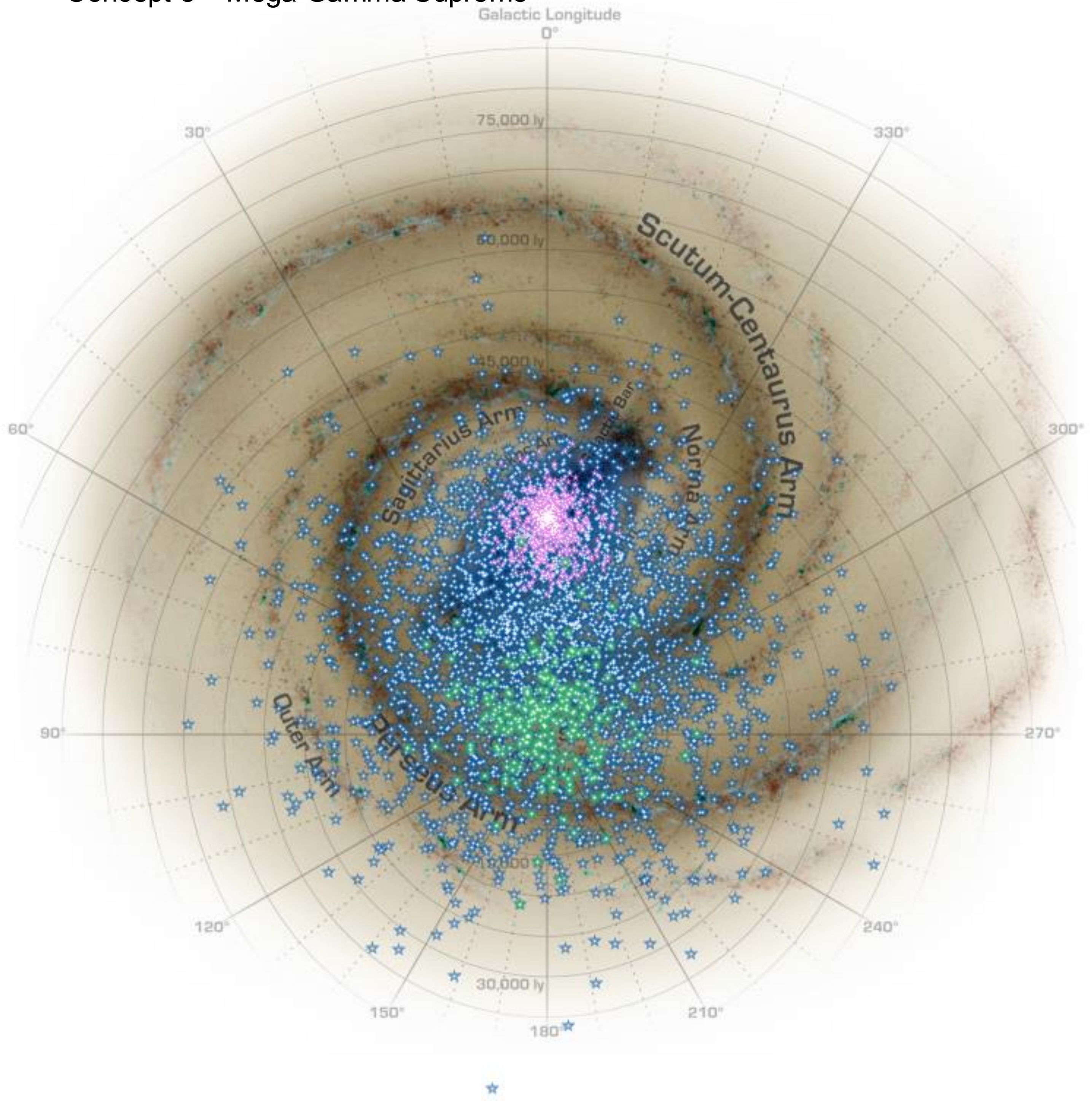
Concept 4 – "VLAST"



Concept 5



Concept 8 – Mega Gamma Supreme



Index	Configuration $A\Omega\times$, PSF$\times$	$N_{\rm disk}$	$N_{\rm bulge}$ (AIC)	$N_{\rm bulge}$ (Disk-like)	A_{15}
1	1, 1.00	261	0	1	10.5
2	1, 0.33	577	1	21	7.4
3	1, 0.10	1193	7	131	5.7
4	10, 1.00	863	3	65	3.0
5	10, 0.33	2181	57	433	2.1
6	10, 0.10	5037	422	1555	1.6
7	30, 1.00	1475	20	213	1.6
8	30, 0.33	3707	214	995	1.1
9	30, 0.10	7953	1227	2741	0.9

- By the numbers.
- Most concepts can detect the bulge population, potentially resolving the mystery of the Fermi GCE!
  - Secondary: understand the origin of the MSP population also possible.
- The role of the PSF is especially important for reducing the dominant diffuse emission.

Pair-regime Concepts and Results

- For gravitational waves:
  - 1x LAT right on target with our actual estimate.
  - Acceptance/effective area generally most important here compared to PSF.
  - The most sensitive concepts easily reach and surpass the implied GWB level.
    - This means the GPTA can potentially perform as well as radio PTAs in many scenarios, because the GWB itself limits sensitivity!

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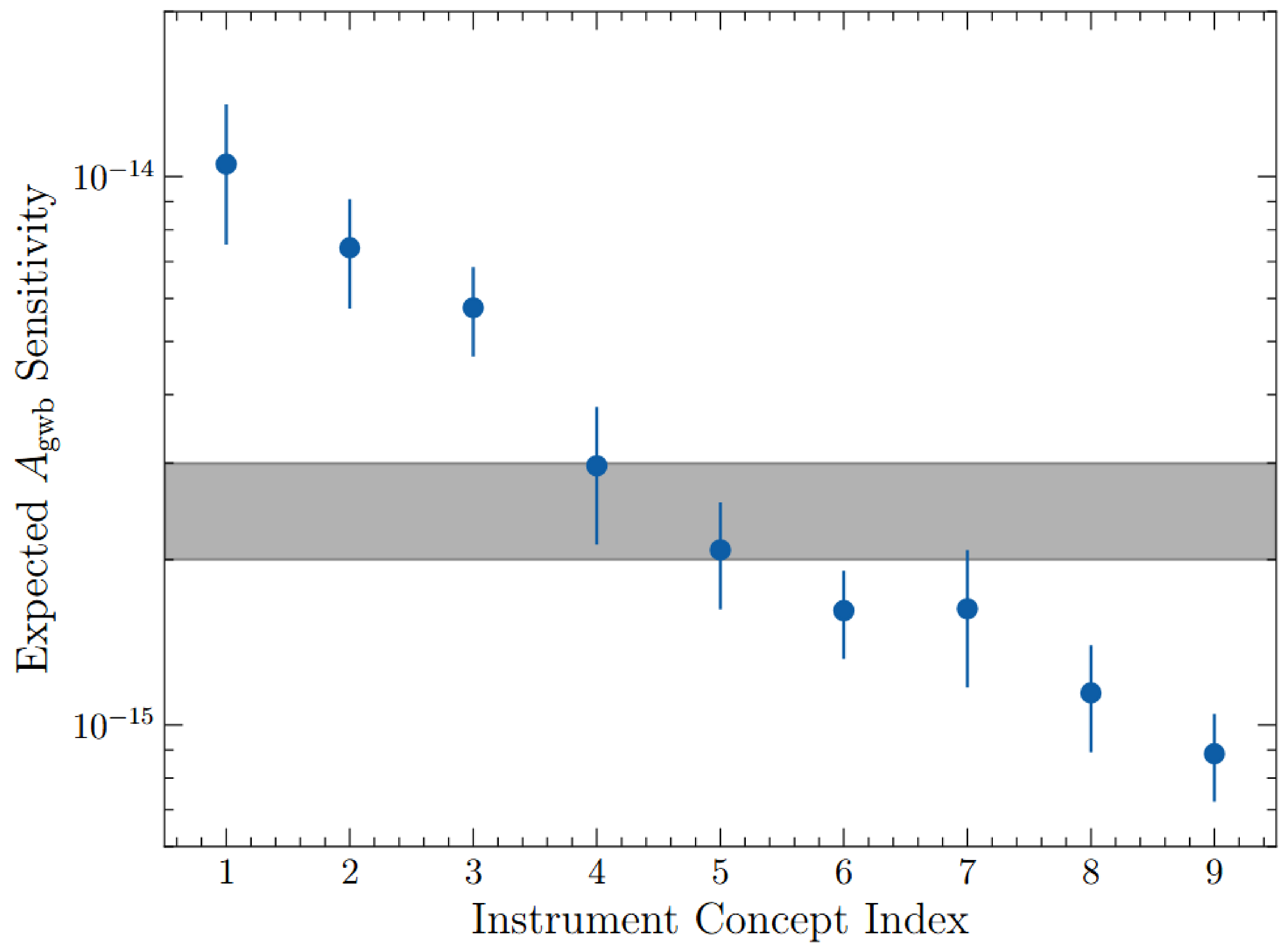
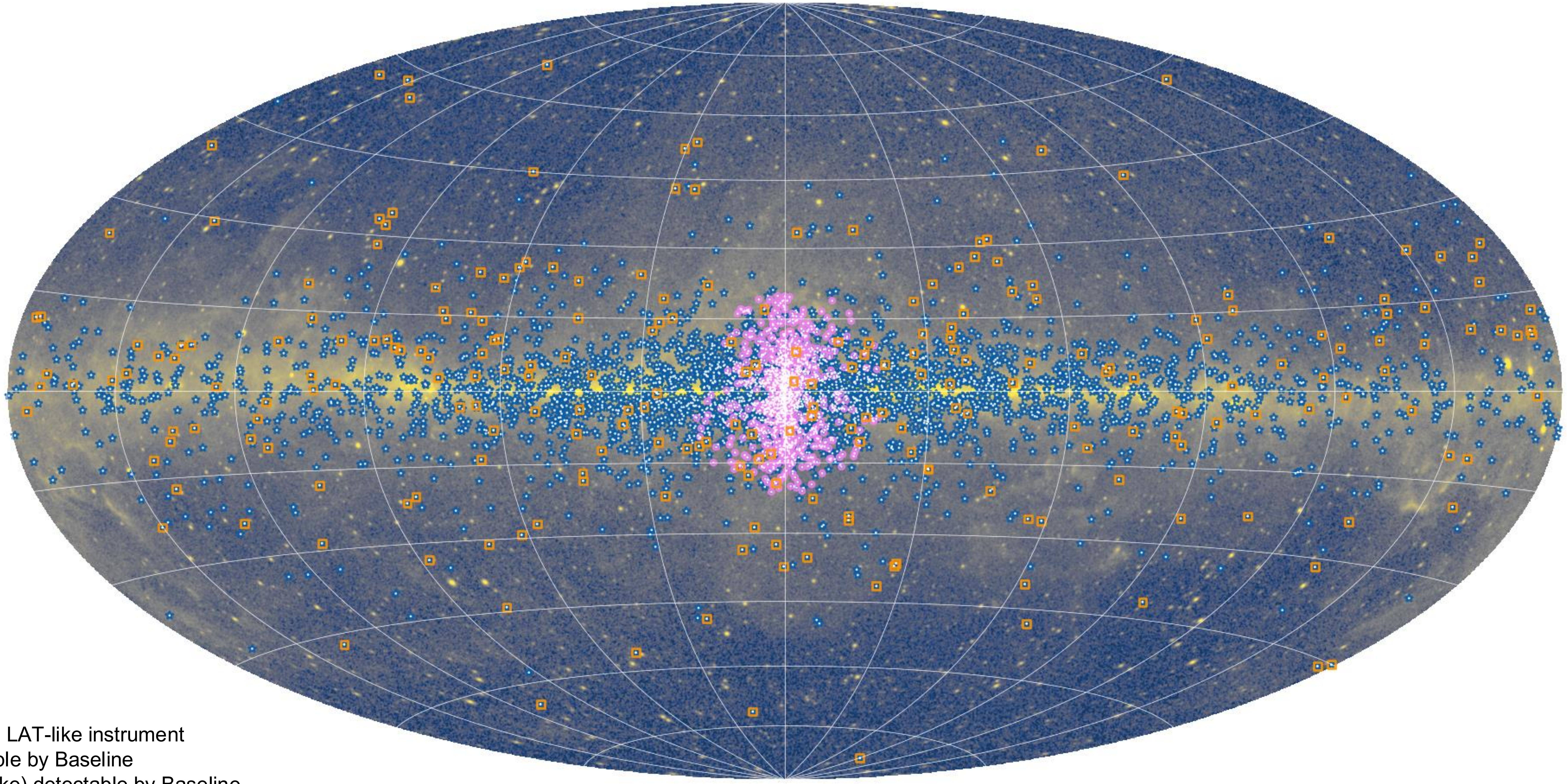


Contribution to the Report

- Pick one of the GeV concepts as the “baseline” and compare it to the LAT:
  - Concept 8: 30x acceptance, 3x better PSF



Orange = detectable by a LAT-like instrument
Blue = disk MSP detectable by Baseline
Pink = bulge MSP (disk-like) detectable by Baseline

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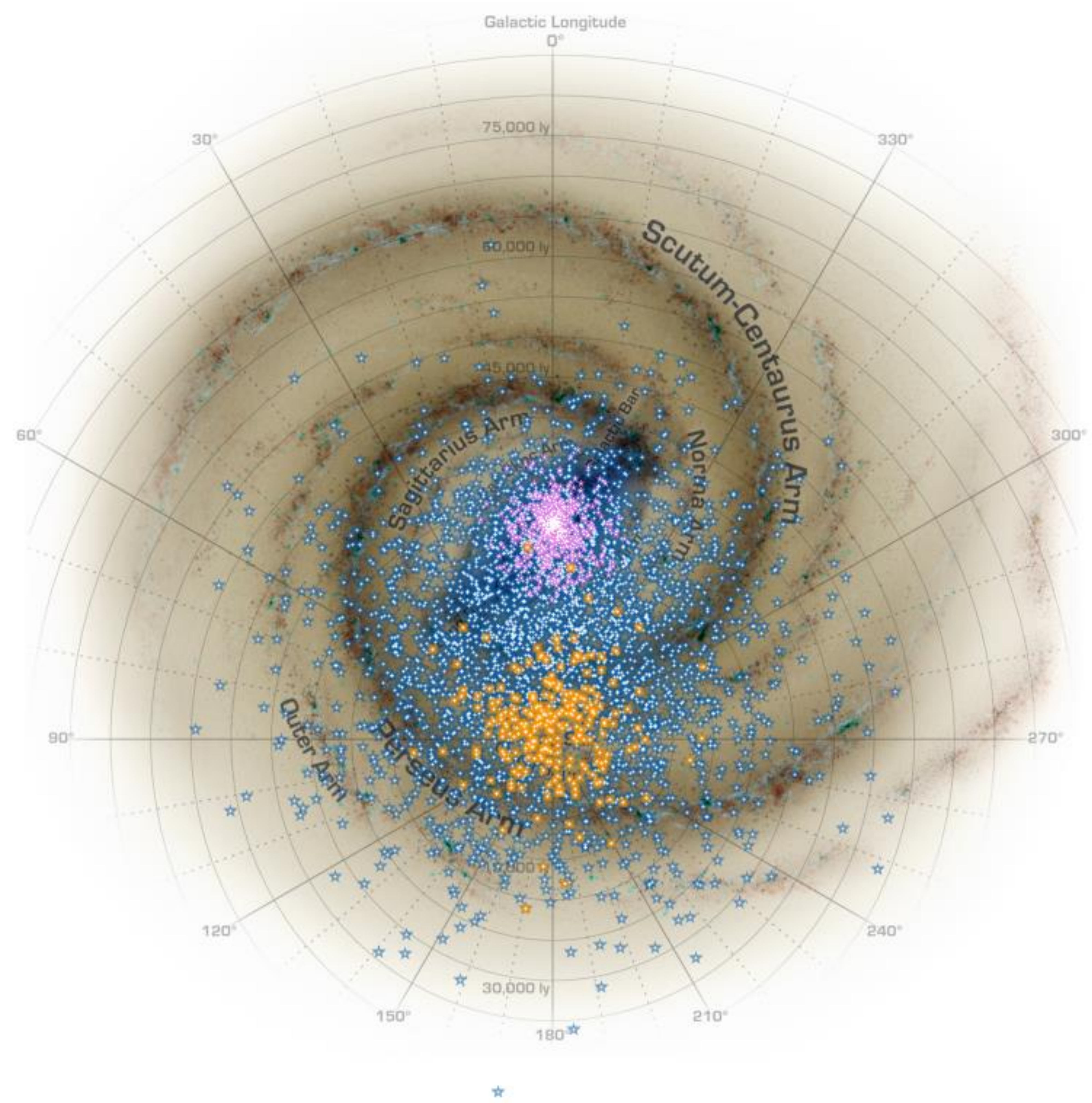

Low(er) Energy Results

- Aside from “LAT scalers”, we looked at less trivial modifications, including a version of the LAT with better electronics efficiency < 100 MeV.
  - Specifically, something that turns on quickly at ~25 MeV and saturates at 100 MeV.
  - PSF scaling same as LAT.
  - With the effective area expanded in this way, do the same 9 concepts as before.

- Extending the energy range this way---effectively, going as far as you can in the pair regime:
  - Results in essentially no change in MSP discovery rate. The photons are in the GeV range.
  - Does enhance pulsar timing precision, by 5—10%.

- Take home message: going lower in the pair regime would be great for pulsar physics but not for pulsar timing.

Low Energy Results

- We also considered a fairly powerful Compton telescope:
  - 15,000 cm^2, 2-deg flat PSF, 0.3-3 MeV
  - Background similar to LAT, but dominated by isotropic, not Galactic.
- With the assumed MSP spectra, you just don't win:
  - MSP spectra are very hard, whereas the background is steeper than -2. So the ratio of source/background per logE is better in the GeV band.
  - The baseline concept detects essentially no MSPs.
- For fun, also consider a coded mask that, somehow, achieves 0.1-deg angular resolution without substantially degrading the FoV.
  - In this case, you can detect the brightest 10s of MSPs.
- Of course, the HUGE CAVEAT is that we don't know anything about MSPs in the MeV band. If there is a soft, bright component…

- Take home message: with the caveat, the MeV band isn't useful for PTA science.

Thoughts

- The MSP discovery bonanza, particularly in the Galactic mucky-muck, represents a real potential boon to radio PTAs, not to mention gamma-ray astrophysics.
  - The sooner MSPs can be discovered, the sooner they can be timed.
  - Gamma ray particularly good for detecting “spider” pulsars, which MAY be good timers.
  - And the direct measurements of GWs through the upgraded GPTA is also appealing!

- Are there feasible ways to achieve these concepts?
  - GammaTPC is a liquid-Ar time projection chamber that could function as a pair telescope with ~10x LAT grasp and ~3-5x better angular resolution.
  - A solid-state, scaled up AMEGO-X could achieve substantially better angular resolution and modestly increased grasp.
  - VLAST (in progress?) represents a 4x increase in grasp with similar angular resolution.
  - With handwavium electronics, a gas TPC could achieve 30x increase in grasp and 10x increase in angular resolution.
  - One can always build more than one… hey, it works for PTAs!