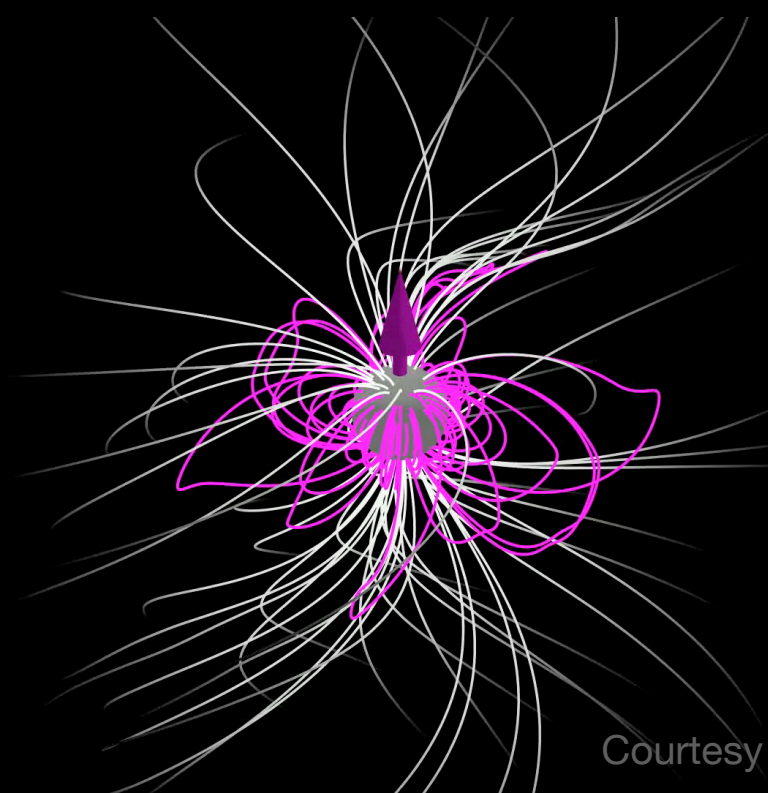


Revolutionary Fundamental Science with Neutron Stars

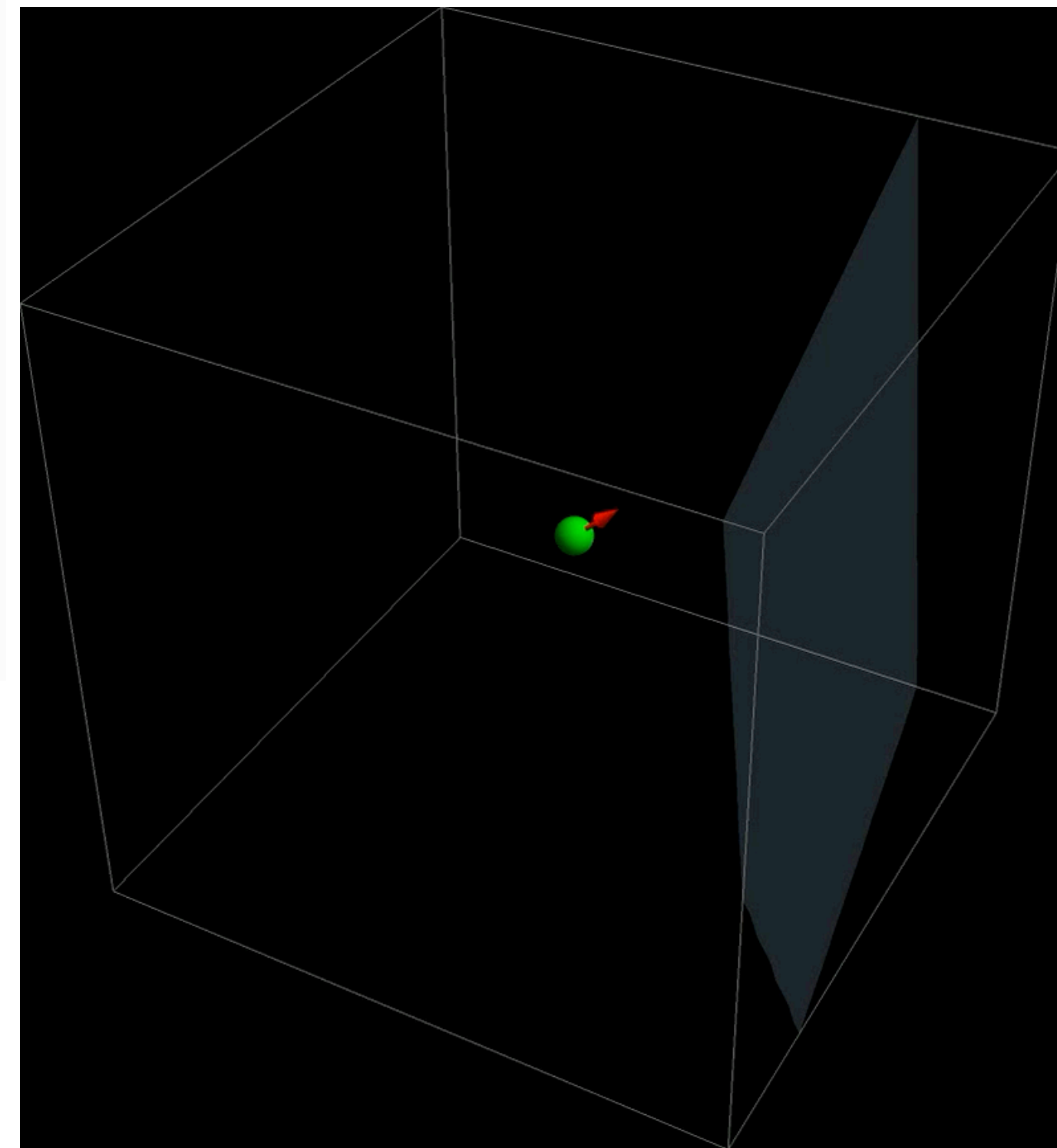
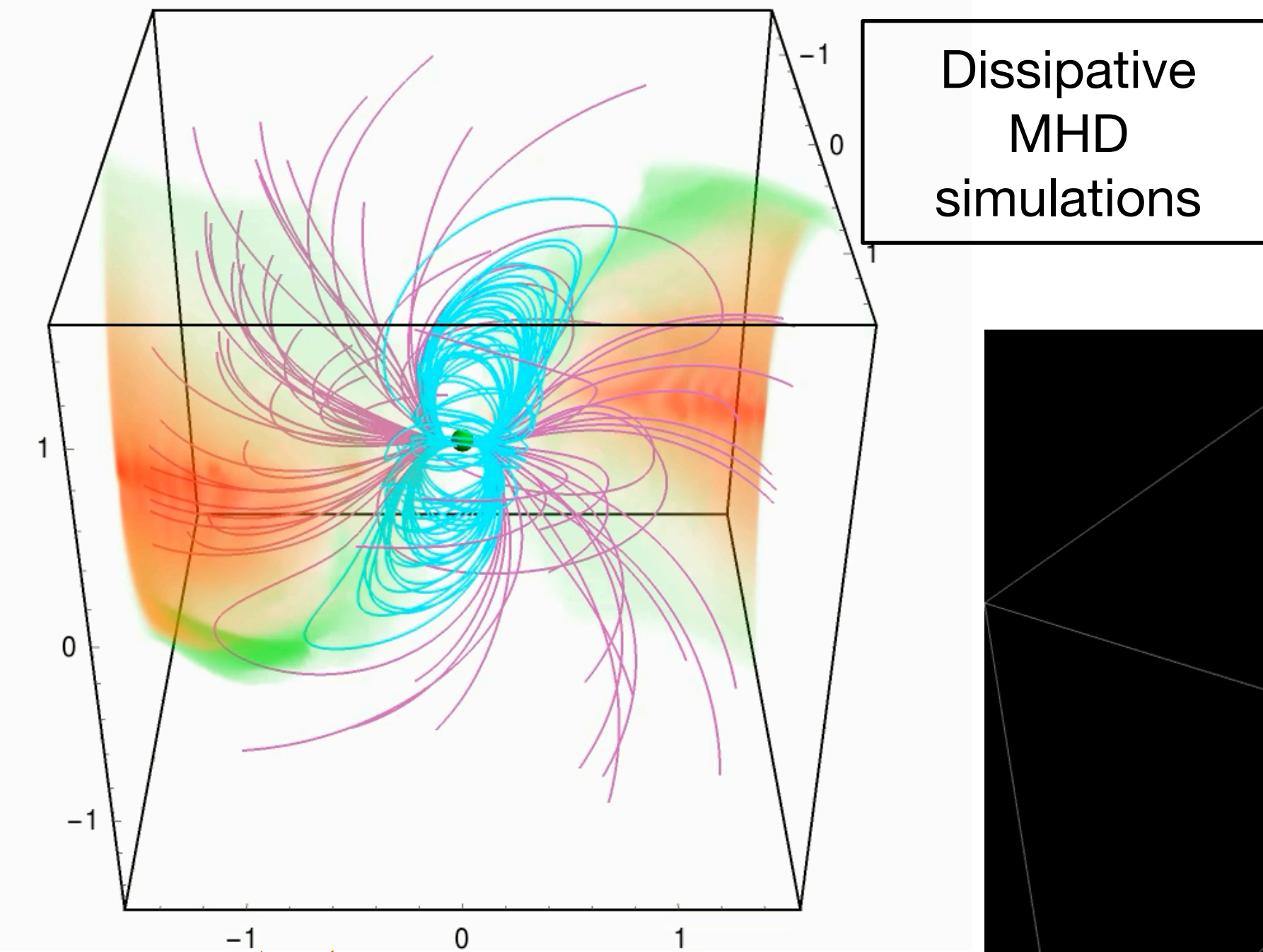
Zorawar Wadiasingh + Matthew Kerr, A. Lavidon,
C. Kalapotharakos, **FIG-SAG** and others

ASTRA Community Workshop

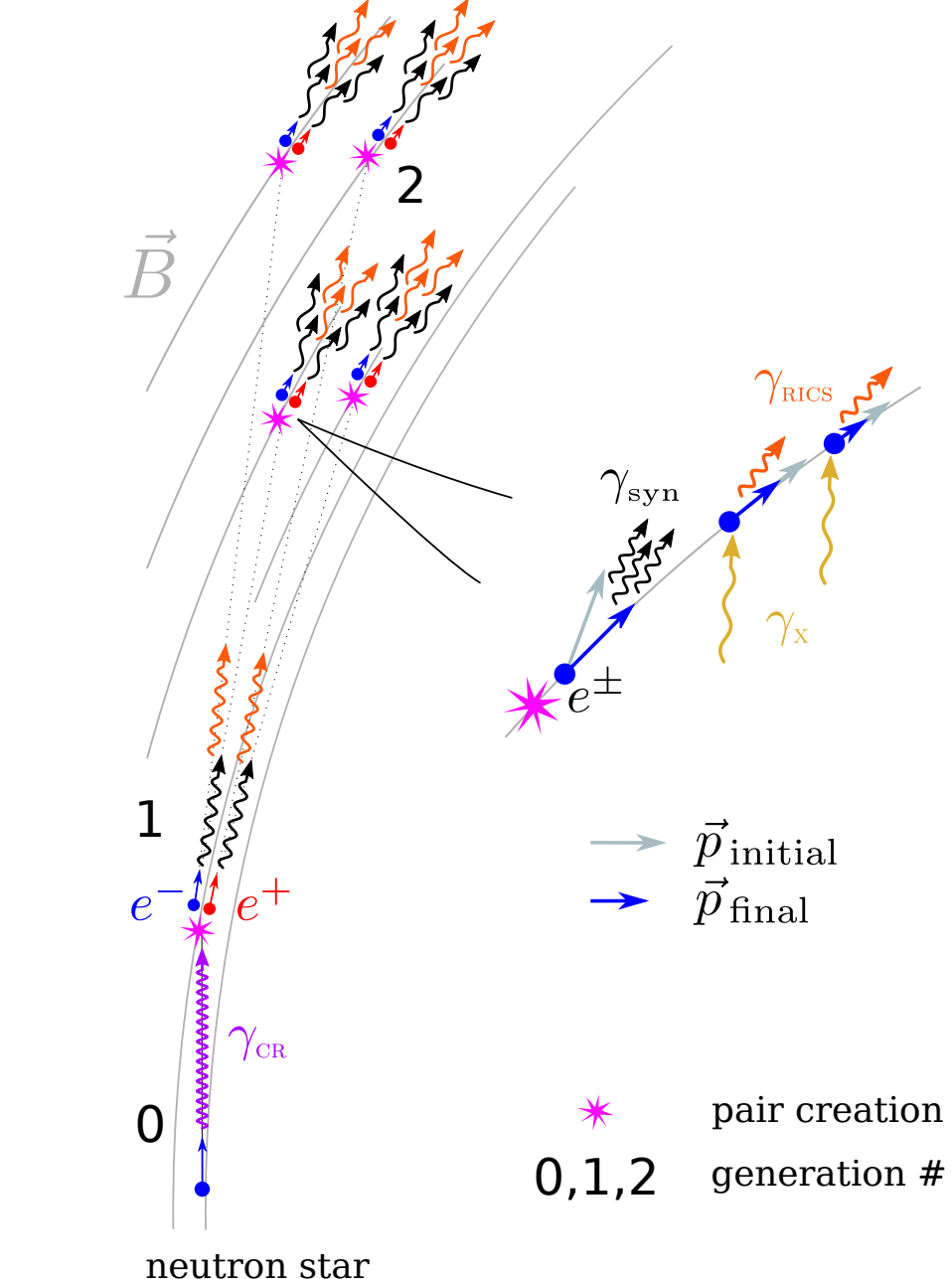


Courtesy D. Skiathas

Pulsars Are Unique Laboratories for Fundamental Physics



- **Precisely measured clocks and energy budgets:** rotation and spin-down provide unusually strong global constraints on the system.
- **Multiple, connected observables:** light curves, spectra, polarization, and multiwavelength emission can simultaneously test magnetospheric models.
- **Cosmic Particle Accelerators:** particle acceleration, radiation reaction, and e^+e^- pair production - antimatter and cosmic rays in the galaxy
- **Physics laboratories:** the same fundamental processes operate, in different environments and geometries, in magnetars/FRBs, black-hole magnetospheres and jets, cosmic-ray accelerators, and merging neutron stars.



* pair creation
0,1,2 generation #

QED Processes
and Cascades

Tracer particles
and photons in
particle-in-cell
kinetic plasma
simulations

Fermi-LAT transformed pulsars from a small gamma-ray source class into a population where detailed magnetospheric physics can be tested. A 30x leap in sensitivity would move this to a qualitatively new regime.

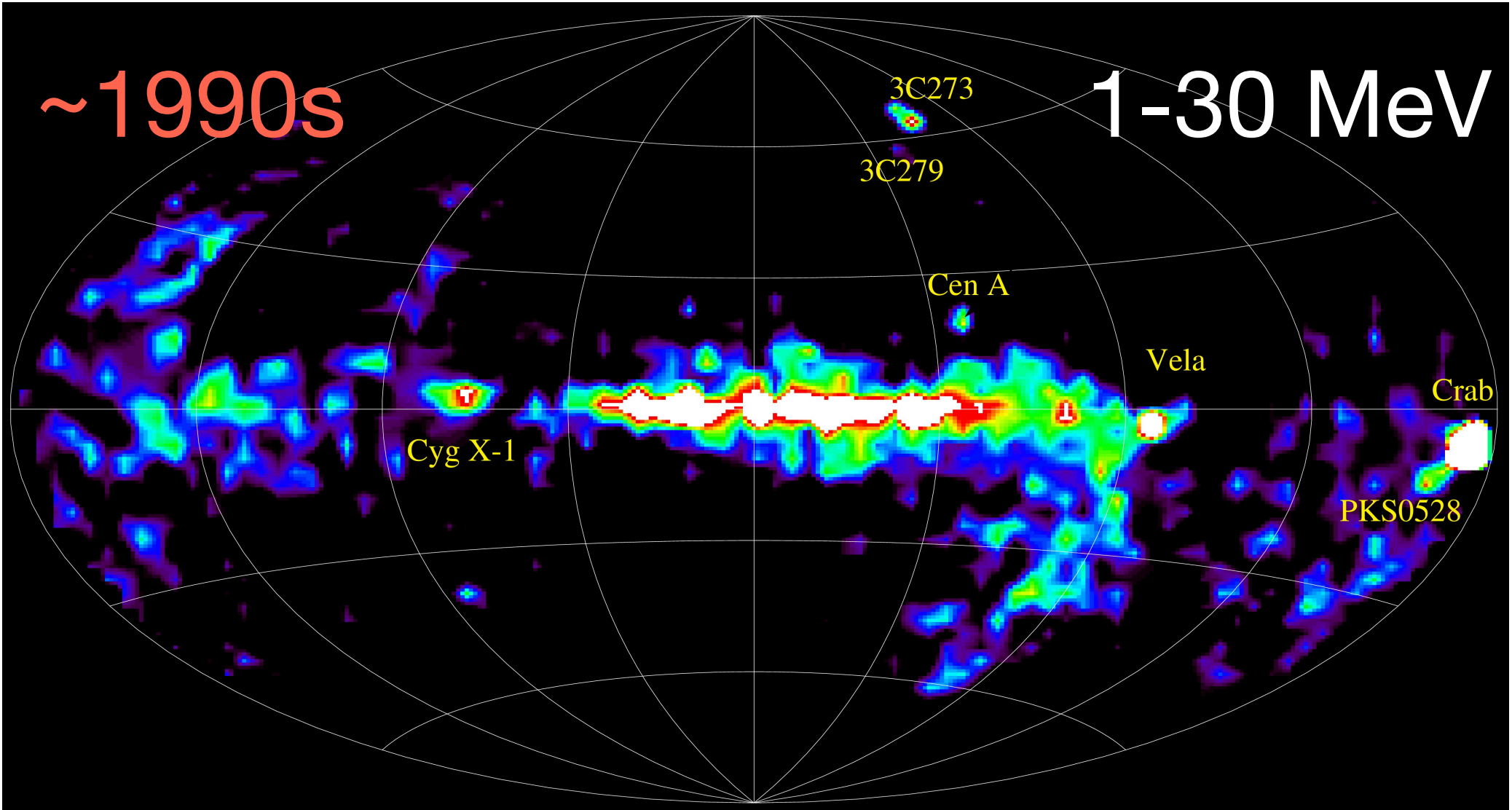
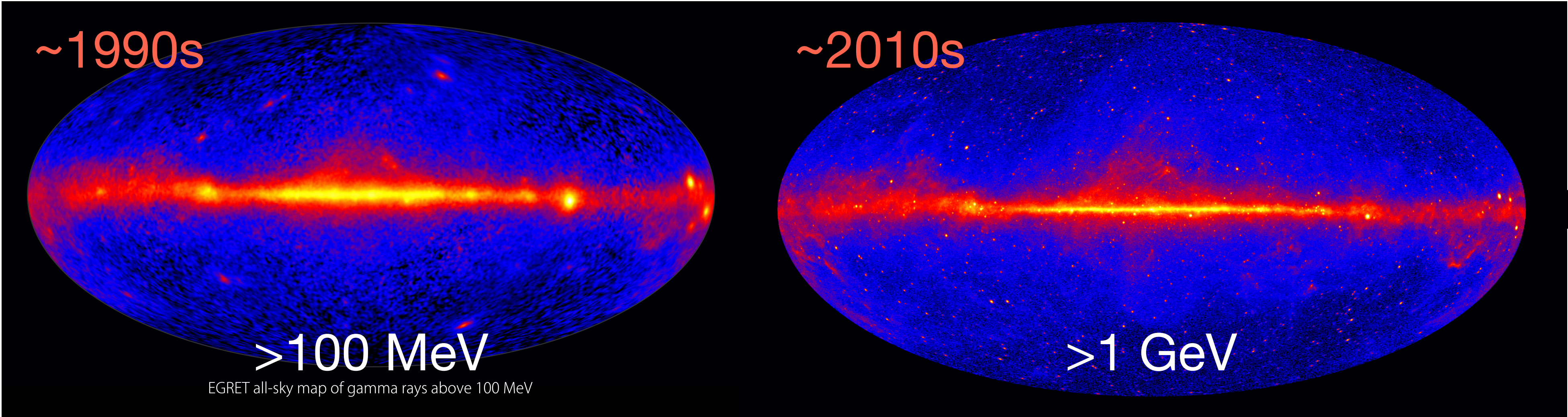
Context

- Gamma-rays relevant for NASA span **>5 decades** in energy, ~100 keV - 10 GeV
- This talk is based on findings in the Future Innovations in Gamma-rays Science Analysis Group report (**FIG-SAG**), mostly comprised of theorists, of which I am a co-chair.
- We sought to answer: what are the **revolutionary science** that can be done with a next-generation leap in capability? What are the **performance requirements**? What energy range?
- Science using neutron stars forms two pillars in the report, motivating future gamma-ray great observatories and detector/instrument R&D

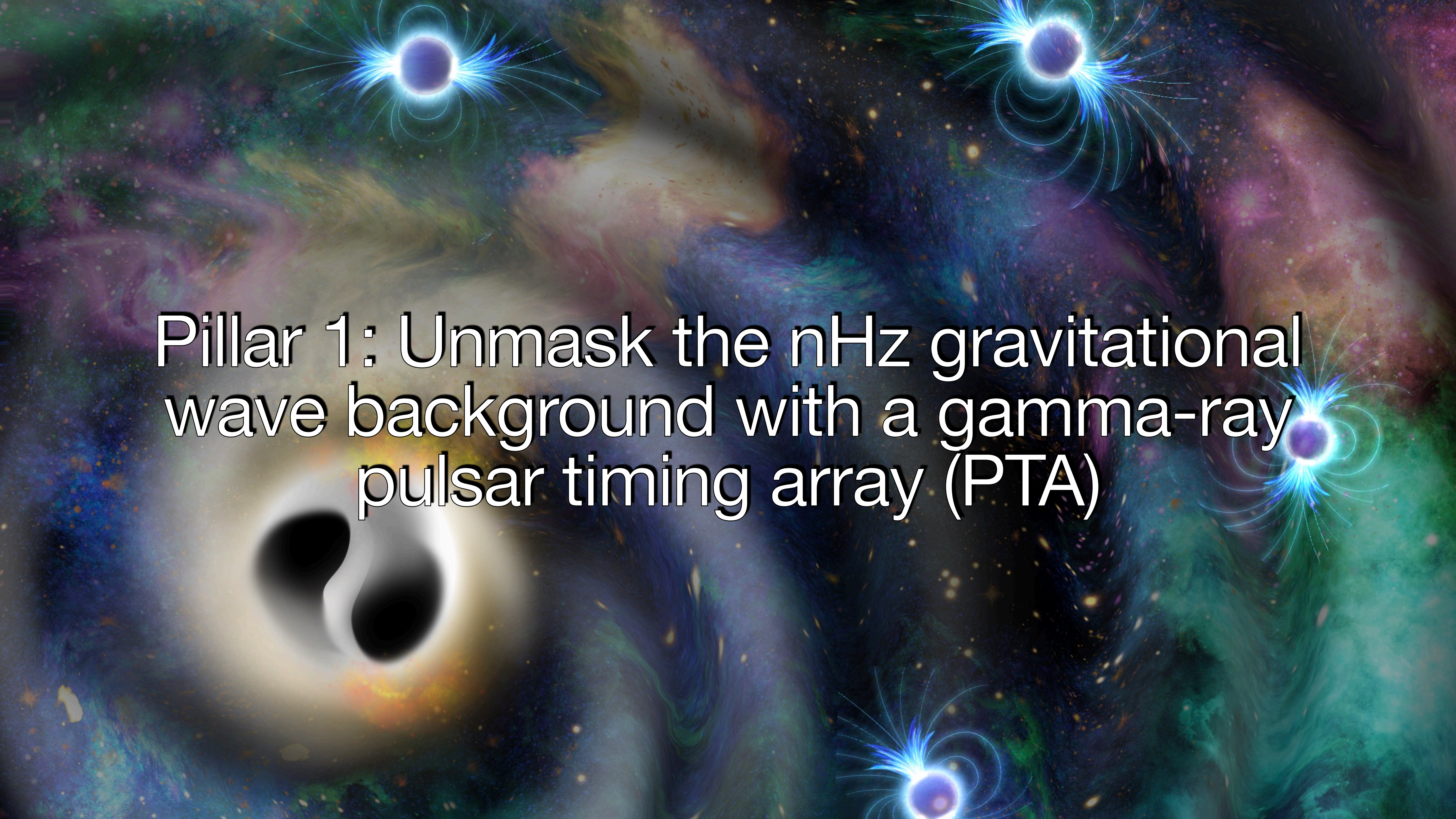
Context - where do we go for gamma-rays?

Compton Gamma-ray Observatory - EGRET

Fermi-LAT

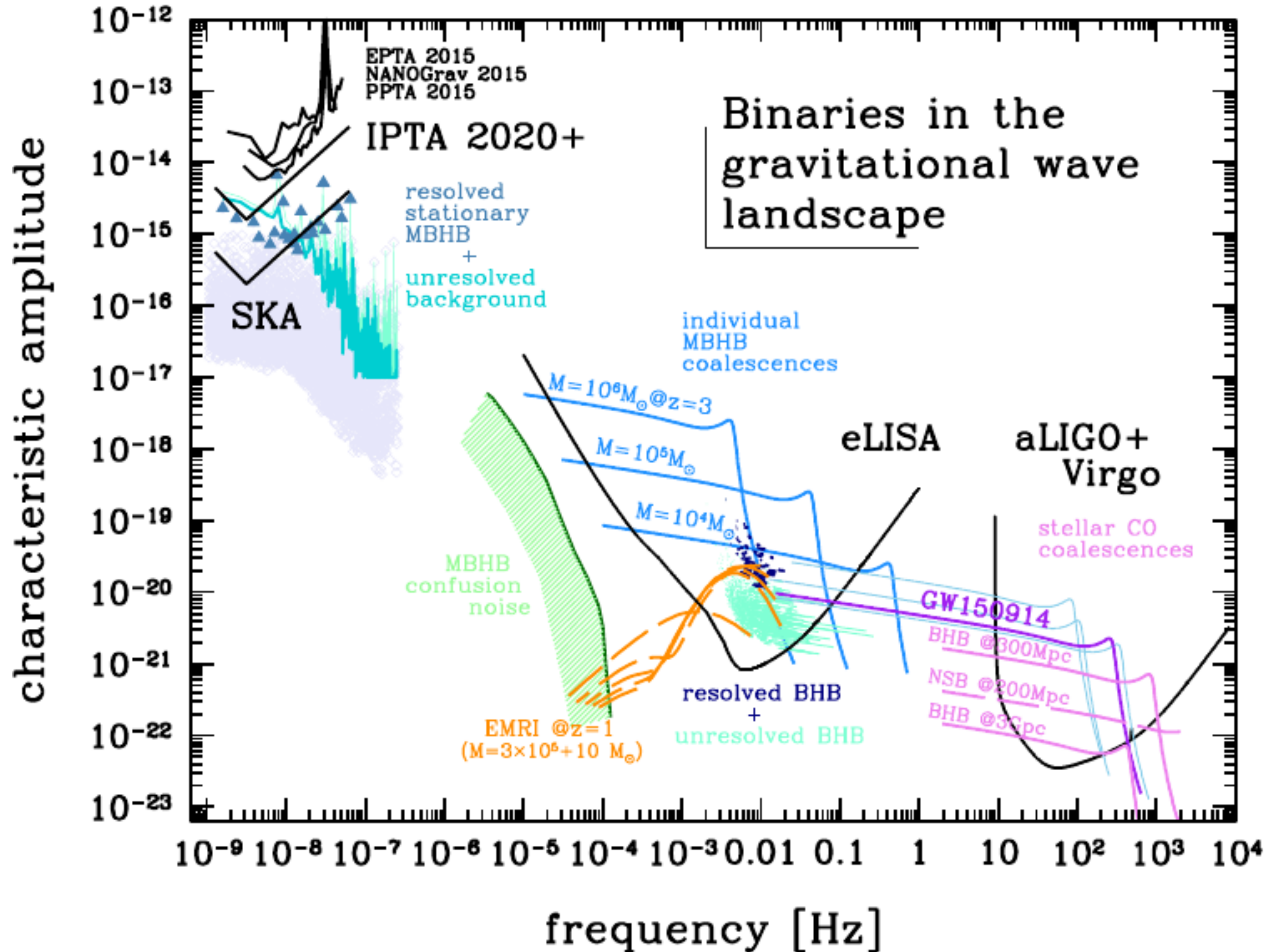


Compton Gamma-ray Observatory - COMPTEL

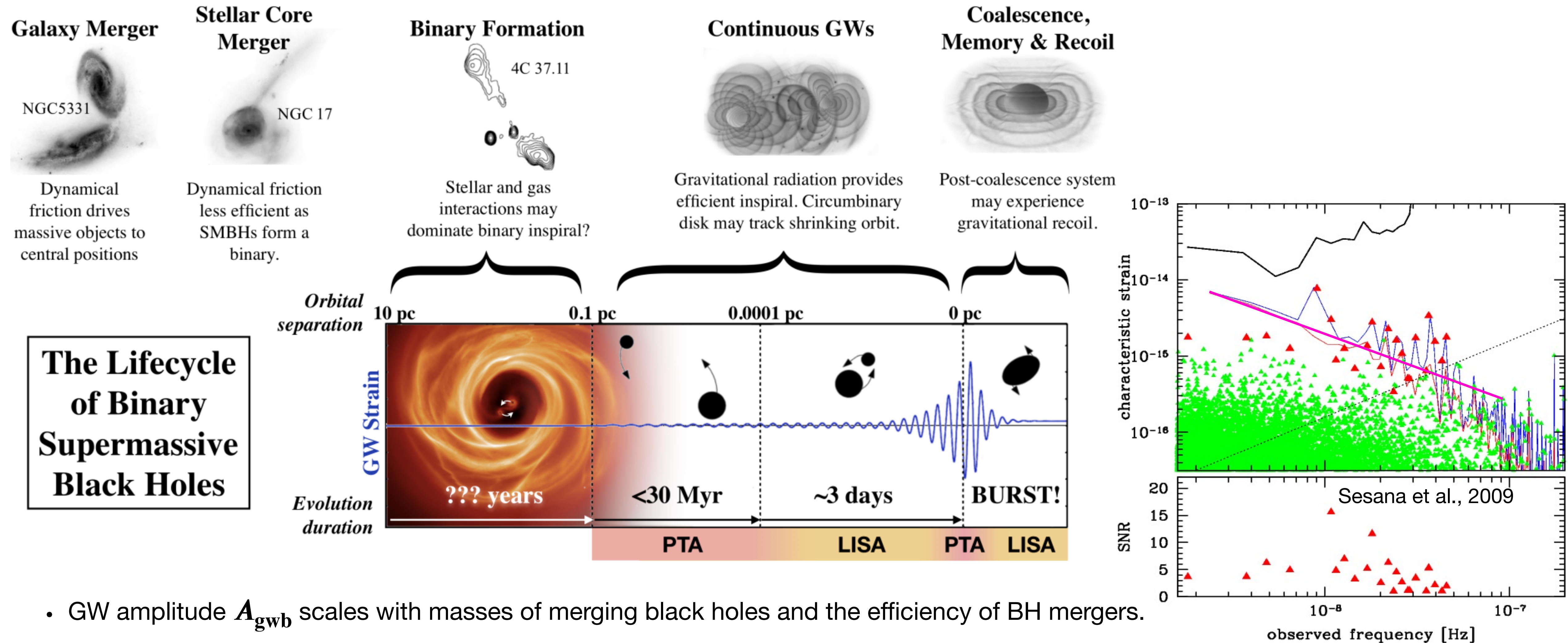
The background of the slide is a vibrant, abstract representation of the universe. It features swirling patterns of purple, blue, and green, suggesting cosmic dust or the propagation of gravitational waves. Four bright, blue, star-like objects with long, thin, radiating lines are positioned at the corners, representing pulsars. In the lower-left quadrant, there is a large, dark, irregular shape that resembles a black hole or a deep gravitational well. The overall effect is one of dynamic, high-energy cosmic phenomena.

Pillar 1: Unmask the nHz gravitational
wave background with a gamma-ray
pulsar timing array (PTA)

The Gravitational Wave Landscape



What are the properties of the gravitational wave background on the sky?



- GW amplitude A_{gwb} scales with masses of merging black holes and the efficiency of BH mergers.
- 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.**

Open Questions

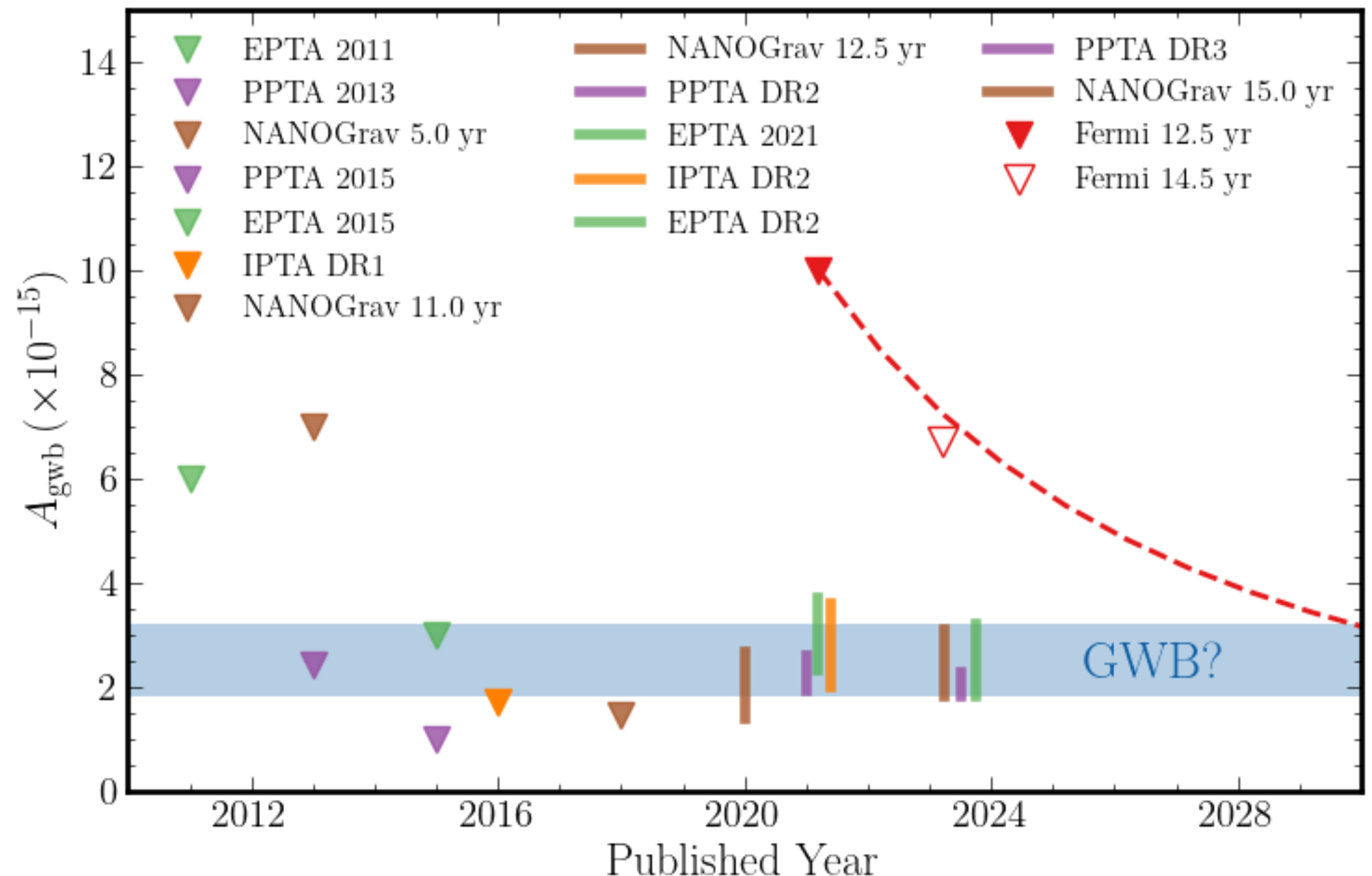
- Can the nHz gravitational wave background be explained fully by supermassive black hole binaries, or are more exotic early-universe sources required?
- What is the background's spectrum?
- What is the eccentricity, mass, and redshift distribution of SMBHB mergers?
- How does the GW amplitude vary across the sky? How big are anisotropies? On what angular scales? How does anisotropy vary with frequency? **[NB. scales strongly with the number of pulsars]**
- Can we find individual binaries? Can we use them for cosmology?

It turns out answering these questions requires a PTA with a large N number of pulsars distributed widely across the sky

Why Gamma-rays for a PTA? Why now?

- Fermi-LAT: ~100 MSPs x 10–20 years
- Fermi-LAT GPTA DR1 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 unique properties:
 - Immunity to IISM effects.
 - Retrospective pulsar timing.
 - (Mostly) unchanged experimental setup.
 - Brightest MSPs are different to radio.
 - Computationally inexpensive.

What could a mission designed from the onset as a gamma-ray PTA could do?
What is needed? 🤔🤔🤔



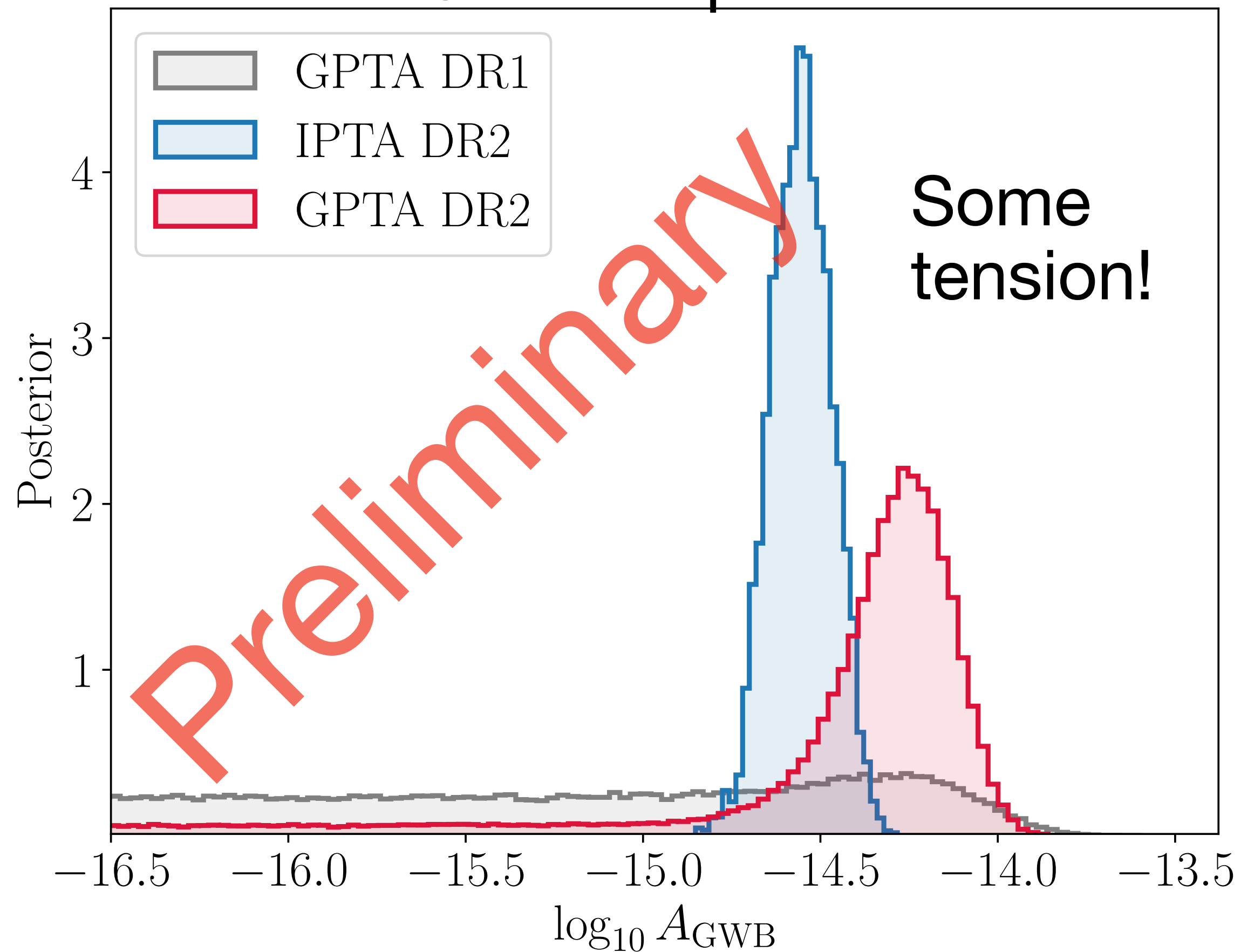
Why Gamma-rays for a PTA?

Property	Space Gamma-ray PTA	Ground Radio PTA
Uniform and unbiased all-sky coverage of pulsars		
Homogeneous single-instrument dataset		
Retroactive additions of pulsars to array		
Contiguous gap-free and long time span datasets		
Potentially thousands of pulsars simultaneously timed		
Systematics: Free of ionized interstellar medium effects		
Systematics: Free of solar wind effects		
Long-term stability of pulsar pulse profiles		
High precision pulsar single TOA measurements		
High signal-to-noise pulsar single TOA measurements		
Dynamic allocation of telescope time/resources		
Mostly disjoint/independent set of pulsars in PTA		

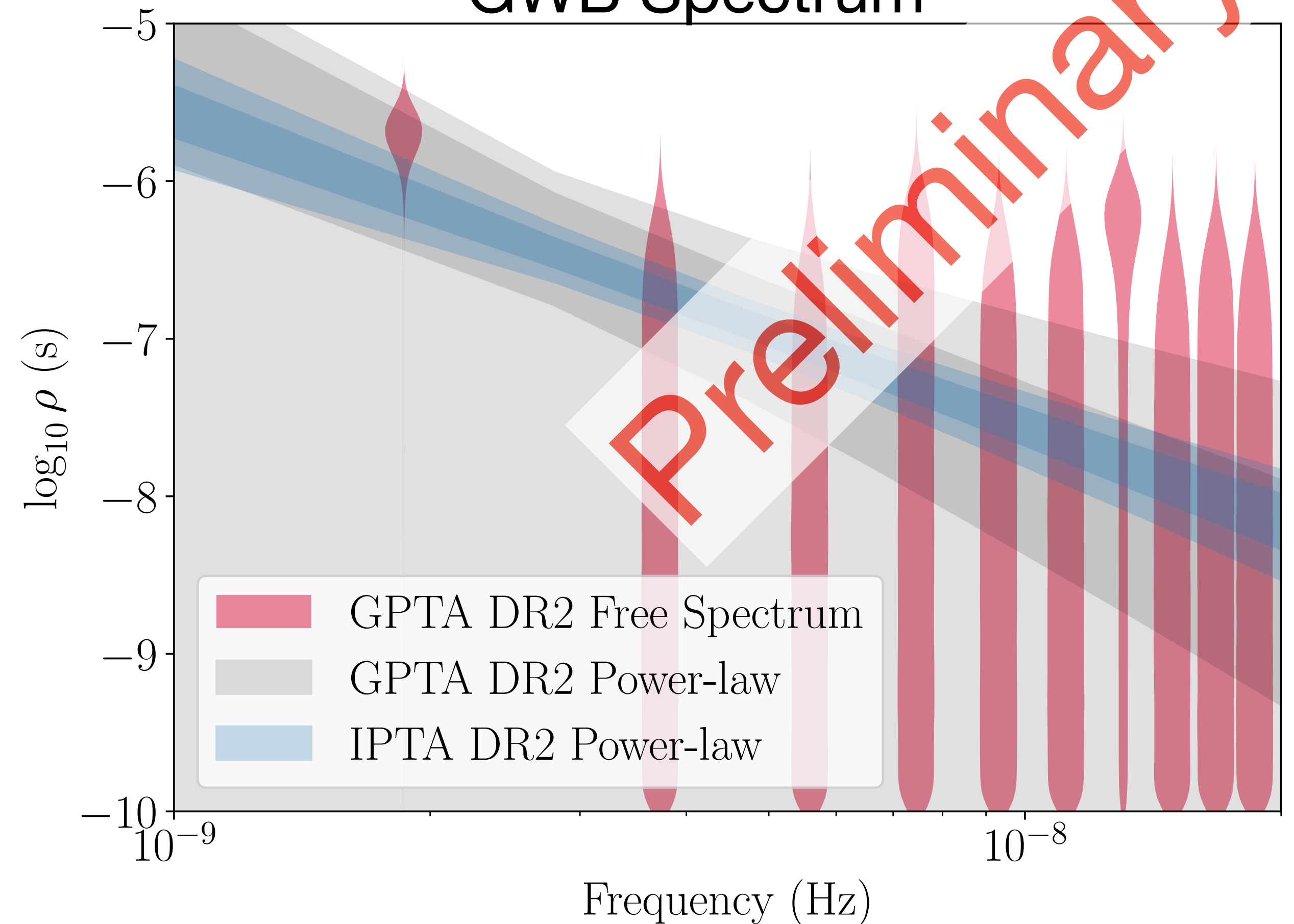
Fermi-LAT has now begun to detect a background!

(which it was never designed to do)

GWB Amplitude



GWB Spectrum



Recipe for Forecasting Capability

build a virtual population and virtual instrument and see how well it does

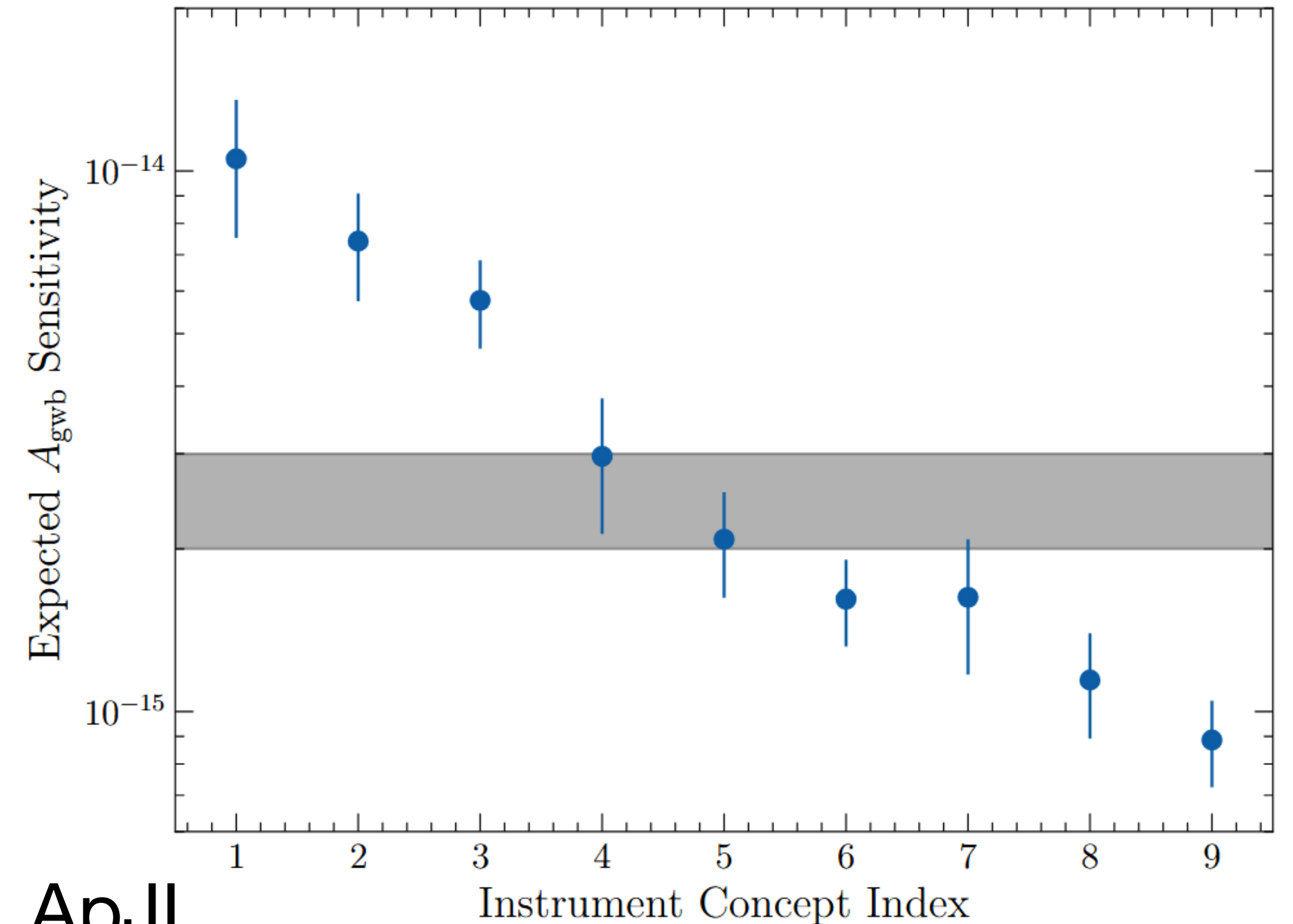
1. Build a realistic population of Galactic millisecond pulsars, motivated by theory and calibrated to observations (radio surveys and Fermi-LAT)
 - A. Assume gamma-ray luminosity functions and spectral cutoff scaling from Kalapotharakos, Wadiasingh+2019,22,23,25
2. Assume standard isotropic and cosmic ray gamma-ray backgrounds in the MeV-GeV
3. For every instrument “concept” scaled from Fermi-LAT acceptance ($A_{\text{eff}} \cdot \text{FoV}$ and PSF):
 - A. Assign an unbiased timing precision to each MSP based on detection significance
 - B. Assess pulsar timing array performance using standard tools (hasasia)

For details, see Kerr, Wadiasingh+2026 ApJL

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!

Index	Configuration	N_{disk}	N_{bulge}	N_{bulge}	A_{15}
	$A\Omega\times, \text{PSF}\times$		(AIC)	(Disk-like)	
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

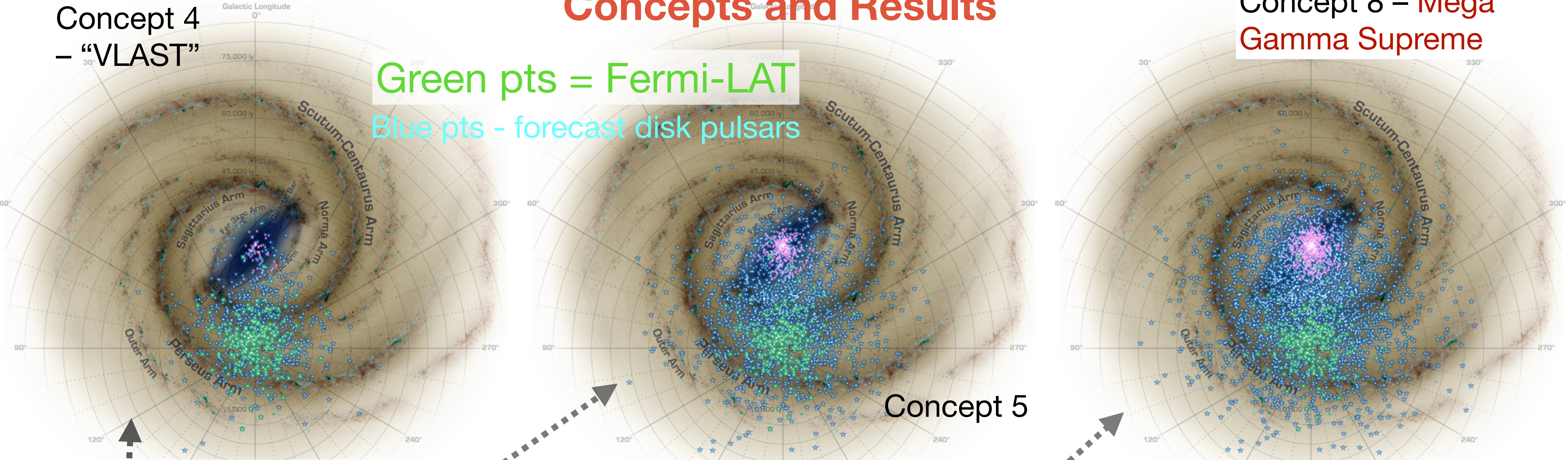


Concept 4
– “VLAST”

Concepts and Results

Concept 8 – Mega
Gamma Supreme

Green pts = Fermi-LAT
Blue pts - forecast disk pulsars



Concept 5

Index	Configuration $A\Omega\times, \text{PSF}\times$	N_{disk}	N_{bulge} (AIC)	N_{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
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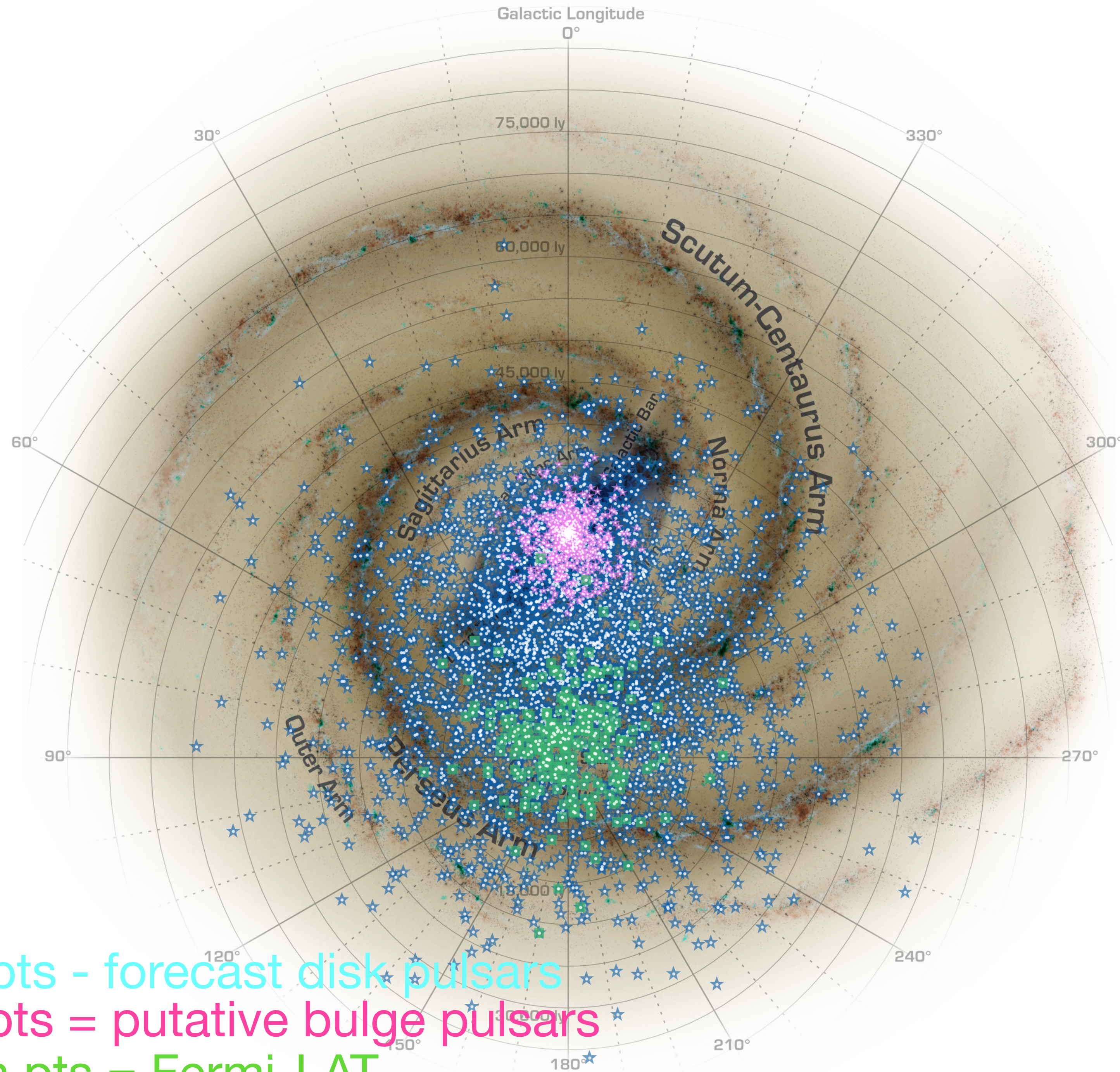
- Most concepts can detect a **bulge population**, potentially resolving the mystery of the Fermi **Galactic Center Excess**
 - **Secondary: understand the origin of the MSP population also possible.**
- The role of the PSF is especially important for sensitivity given the diffuse emission in the galaxy

Concept 8 – Mega Gamma Supreme

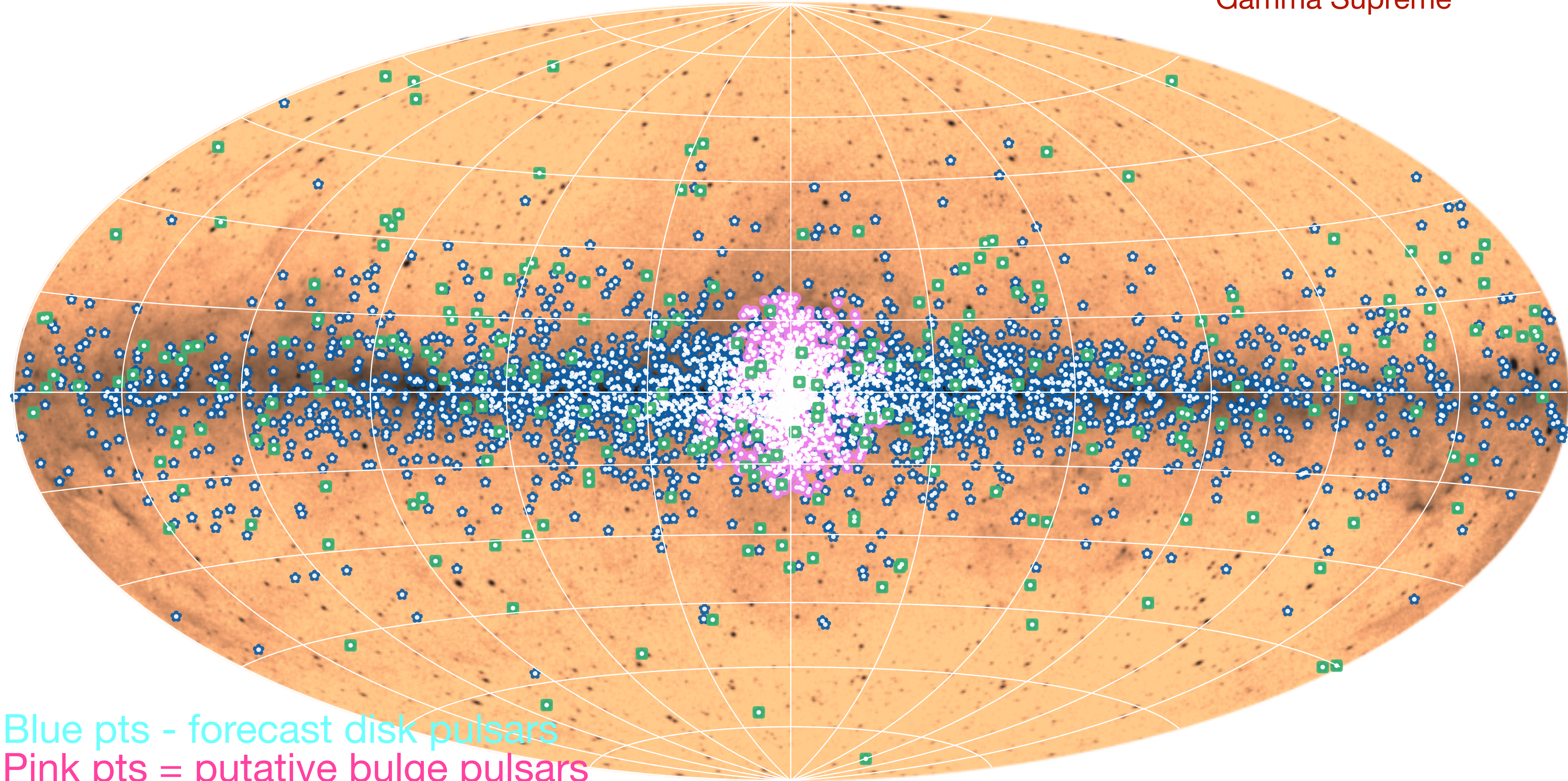
30X LAT Grasp
1/3 PSF

Detect
thousands of
pulsars to the
edge of the
Galaxy

Blue pts - forecast disk pulsars
Pink pts = putative bulge pulsars
Green pts = Fermi-LAT



Kerr, Wadiasingh+2026, ApJL



Pillar 2: Testing untested nonlinear QED
processes with Photon Splitting (in
magnetars)

Magnetars are the most magnetized objects we know of

QED treatment necessary when $\hbar\omega_B \sim m_e c^2$
 $\longrightarrow B_{\text{cr}} \equiv m_e^2 c^3 / (e\hbar) \approx 4.4 \times 10^{13} \text{ G}$

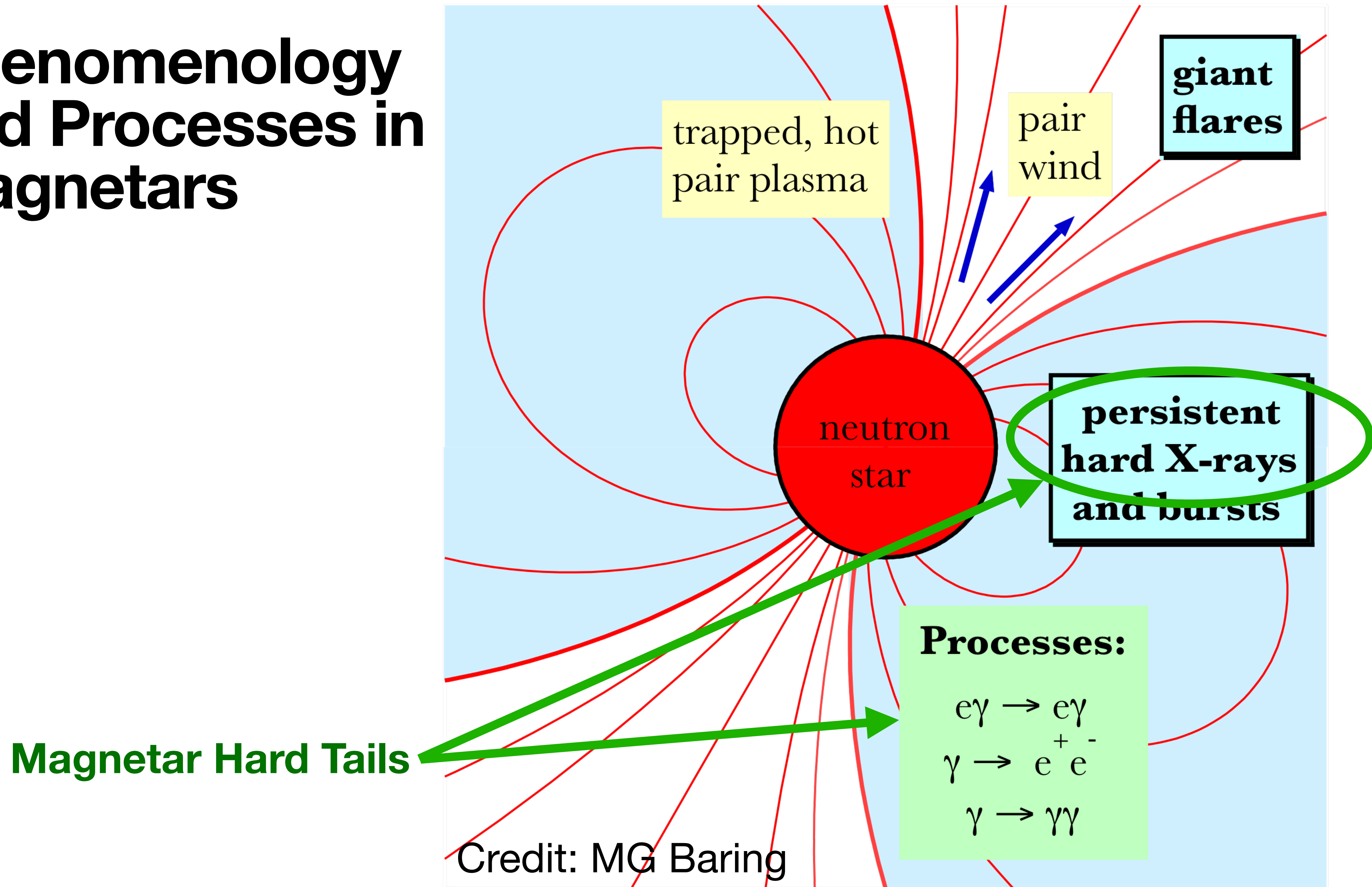
Cyclotron losses inverse timescale (width)

$$\Gamma \sim \alpha_f \left(\frac{B}{B_{\text{cr}}} \right)^2 \frac{c}{\lambda} \sim 10^{18} B_{13}^2 \text{ s}^{-1}$$

Many exotic *untested* QED processes occur in this regime

Electron states are relativistic and quantized

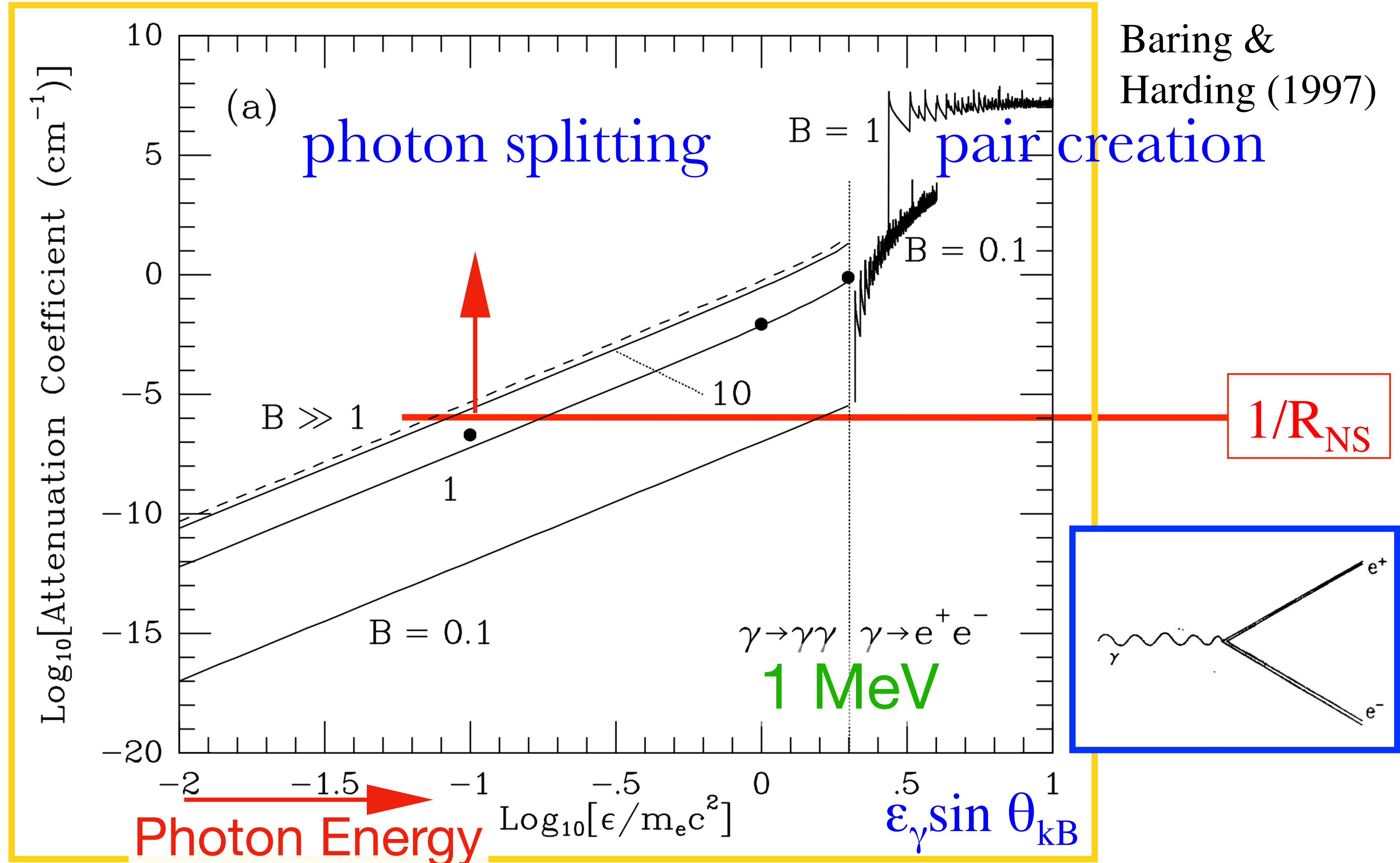
Phenomenology and Processes in Magnetars



Photon Splitting and Pair Creation Rates

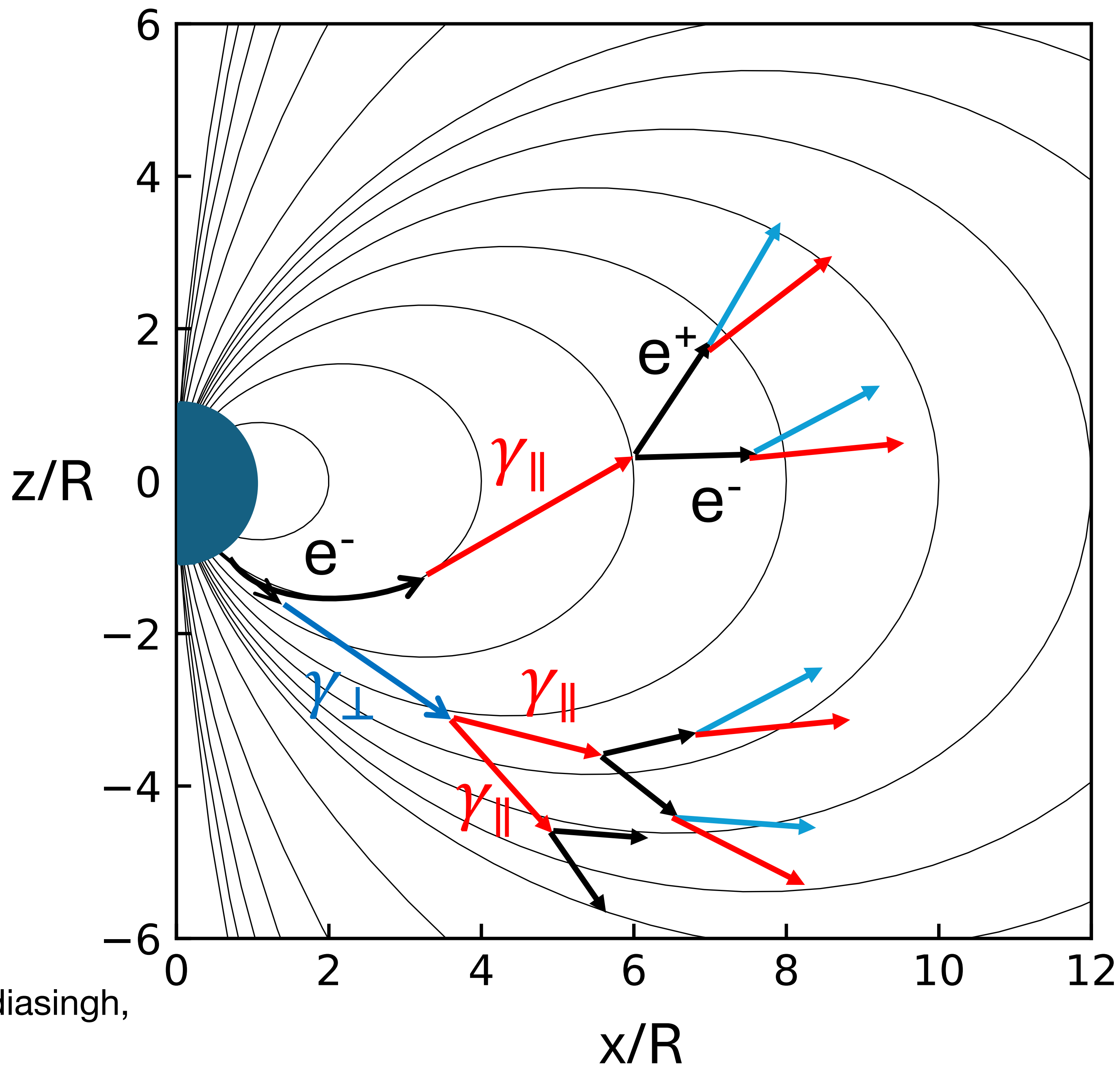
$$B = 1 \\ \rightarrow 4.4 \times 10^{13} \text{ G}$$

Process
efficiency



Baring &
Harding (1997)

- Splitting rate calculated originally by Adler (1971); see also Papanyan & Ritus (1972); Stoneham (1979), Baier et al. (1986); Weise et al. (1998); Baring (2000).



Open questions:

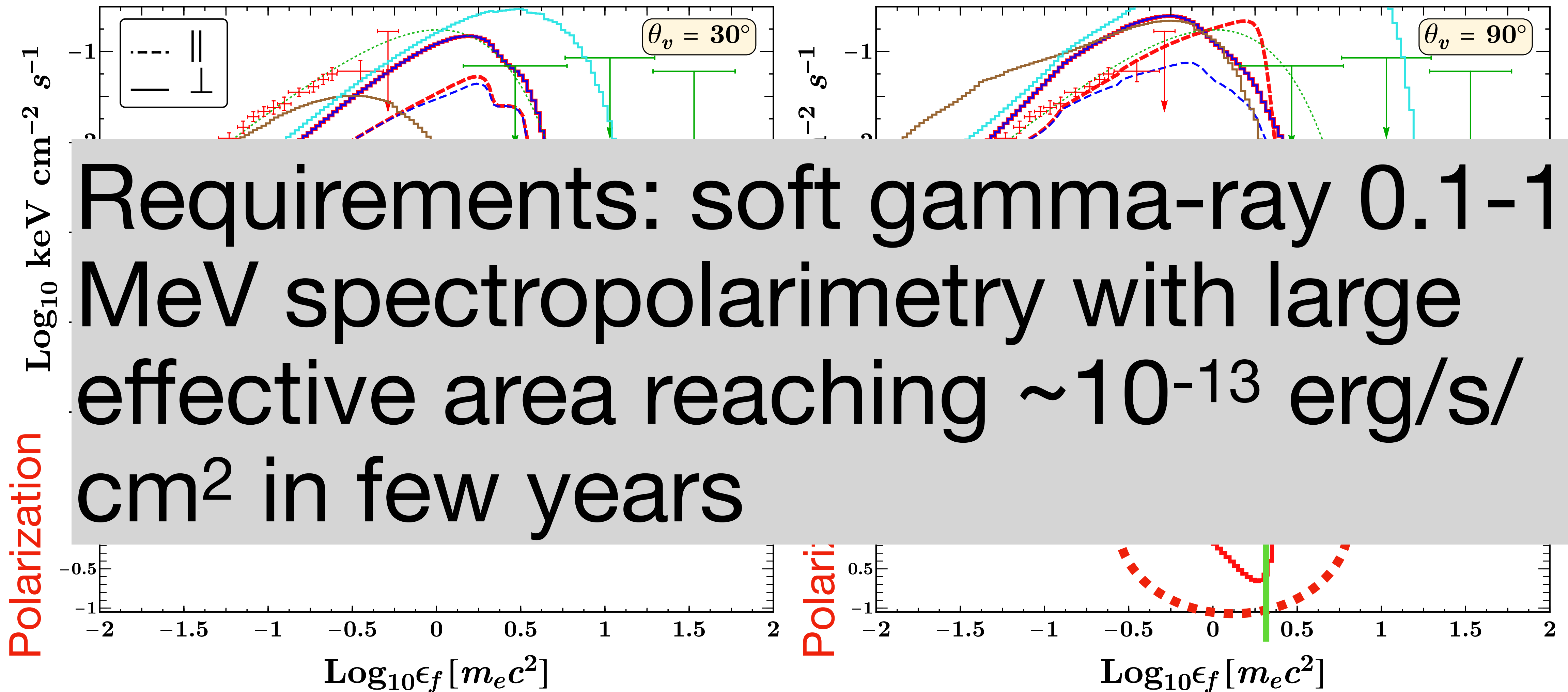
Where and why do magnetars cutoff around 0.1-1 MeV?

What is the strong-field nature of the quantum vacuum?

What photon modes split? Where?

Do the modes follow those allowed in the weakly dispersive limit of QED or that by CP symmetry?

IS PHOTON SPLITTING THERE OR NOT? WHAT MODES OF PHOTON SPLITTING ARE REALIZED?



Requirements: soft gamma-ray 0.1-10 MeV spectropolarimetry with large effective area reaching $\sim 10^{-13}$ erg/s/cm² in few years

Takeaways

- Large 0.1-10 GeV gamma-ray telescopes can be gravitational wave detectors with guaranteed compelling and fundamental science about our universe
 - Fermi-LAT has begun detecting the a GW background. It was never designed as a PTA — much subsequent design mission/optimization possible
- Anisotropy searches/measurements scale strongly with number of pulsars for which a gamma-ray PTA is highly suited for
- Of course, a very capable MeV-GeV gamma-ray telescope will also be extraordinary for all other areas of astrophysics
- Meanwhile the ~ 1 MeV regime can answer fundamental questions about quantum electrodynamics