Gamma ray Astrophysics from space

an overview and some sparse considerations

by Michela Negro

LSU

Department of
Physics & Astronomy

TeV Particle Astrophysics

TeVPA

Valencia 2025

Build the future

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Know your past

Understand where you stand

Build the future

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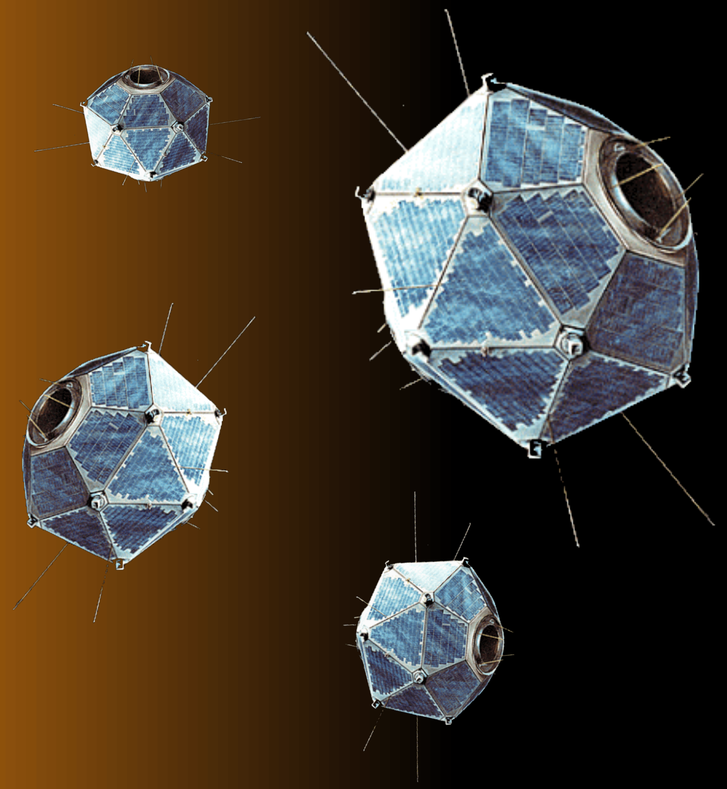
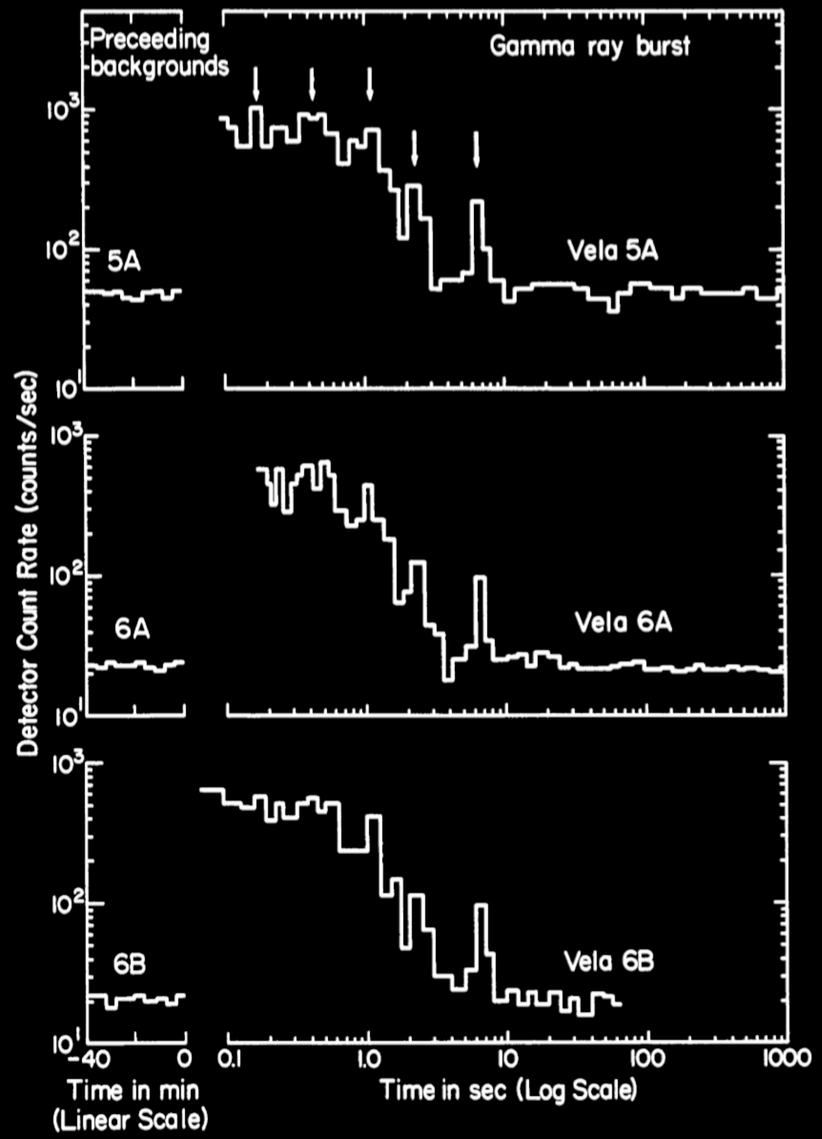
Vela Project





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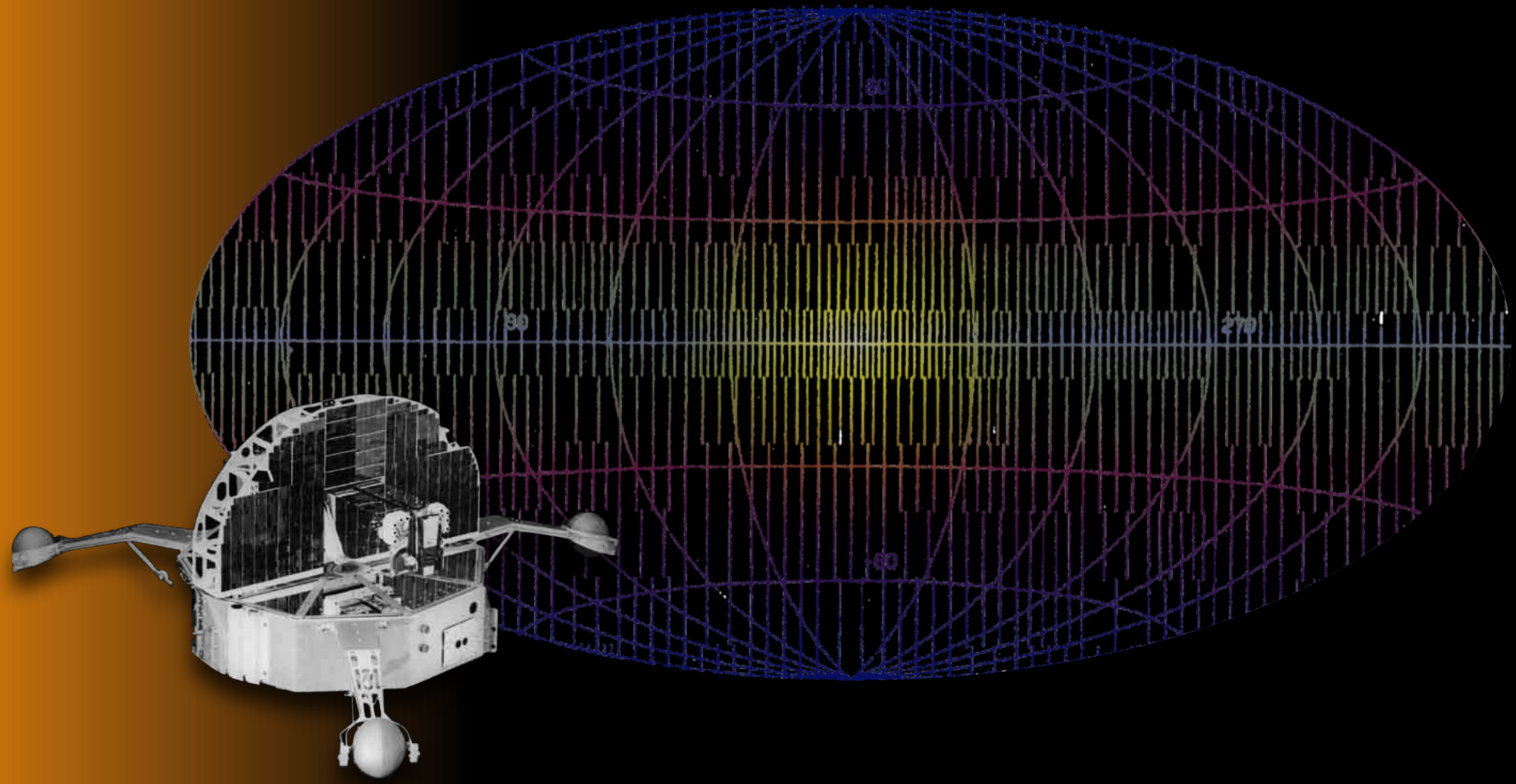
OSO-3

… to confirm that steady cosmic γ-ray background exists beyond solar flares



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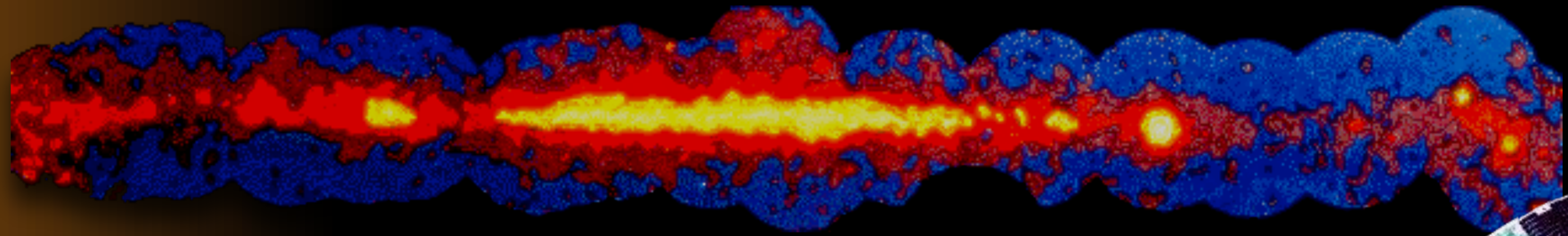
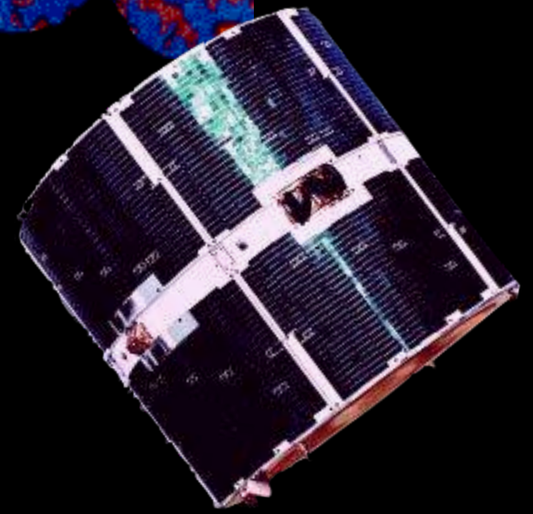
SAS-2 (1972-1973)

COS-B (1975–1982)

… to turn the "detection of γ-rays" into imaging of the high-energy sky





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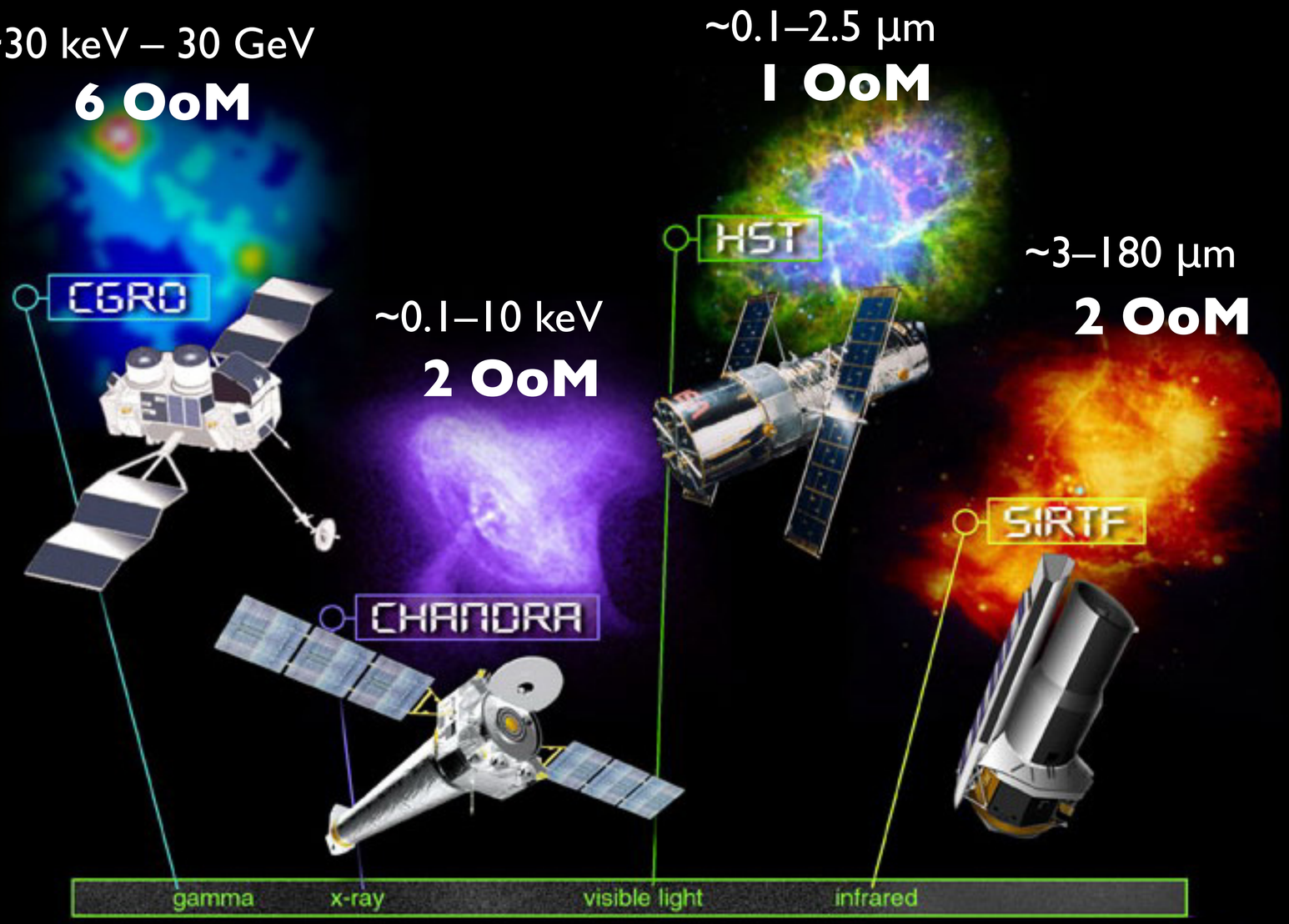
The Great Observatories program – 1990–2003



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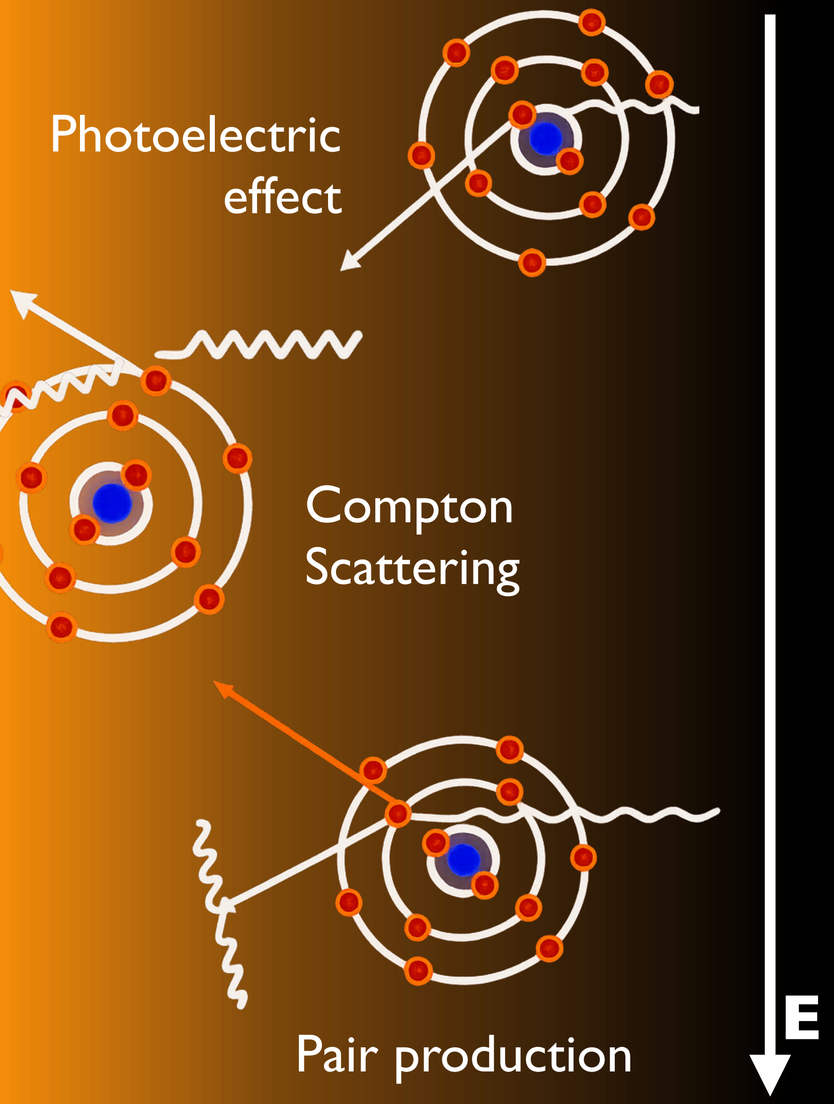
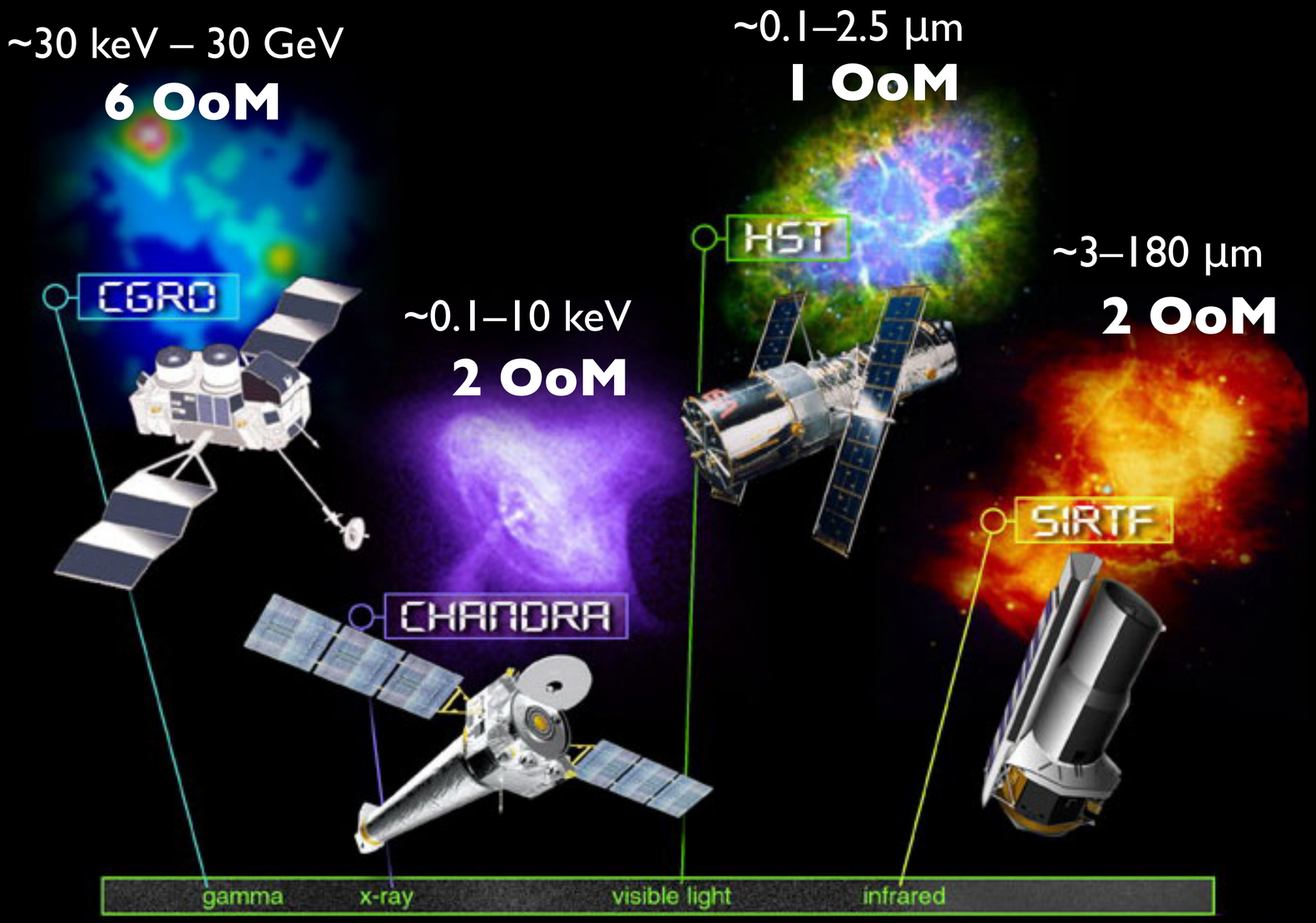
The Great Observatories Program – 1990–2003





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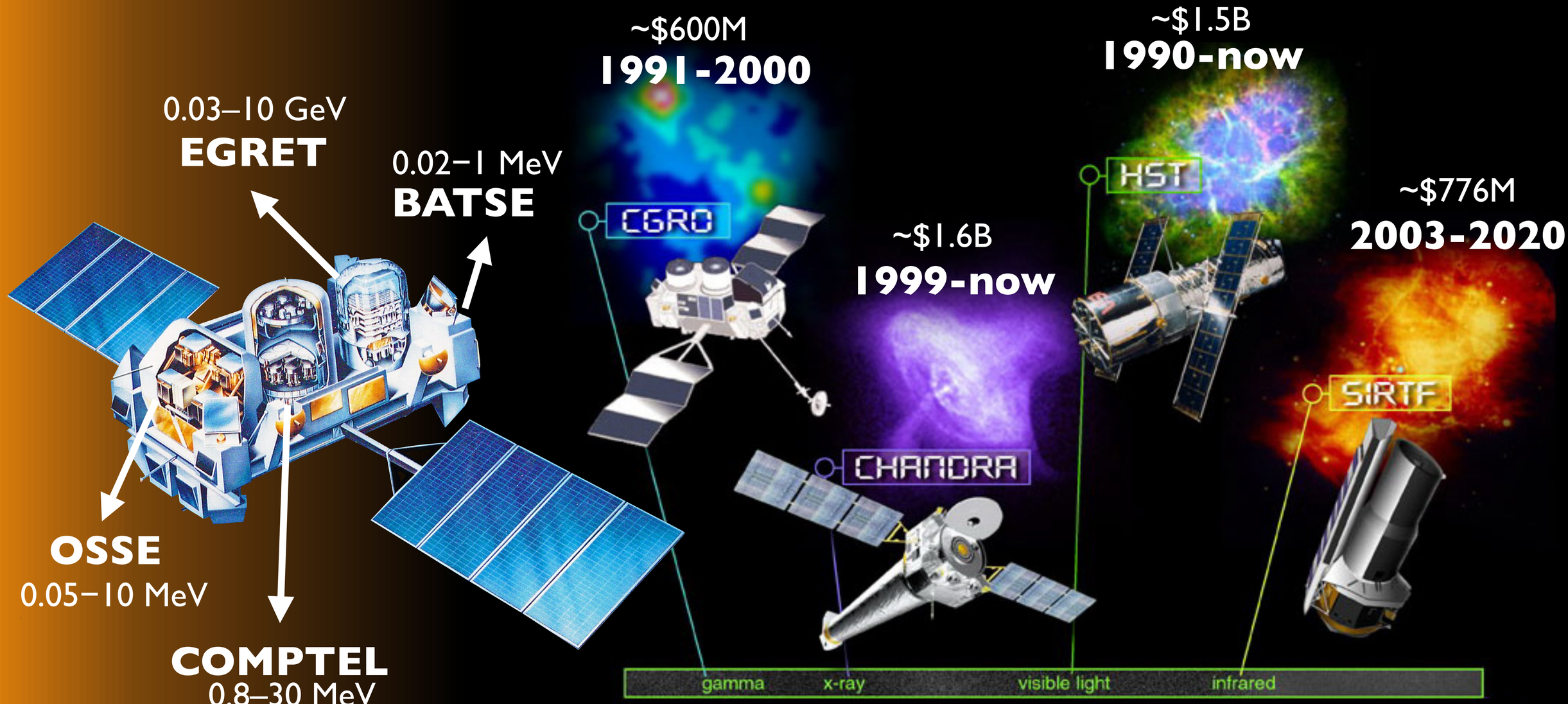

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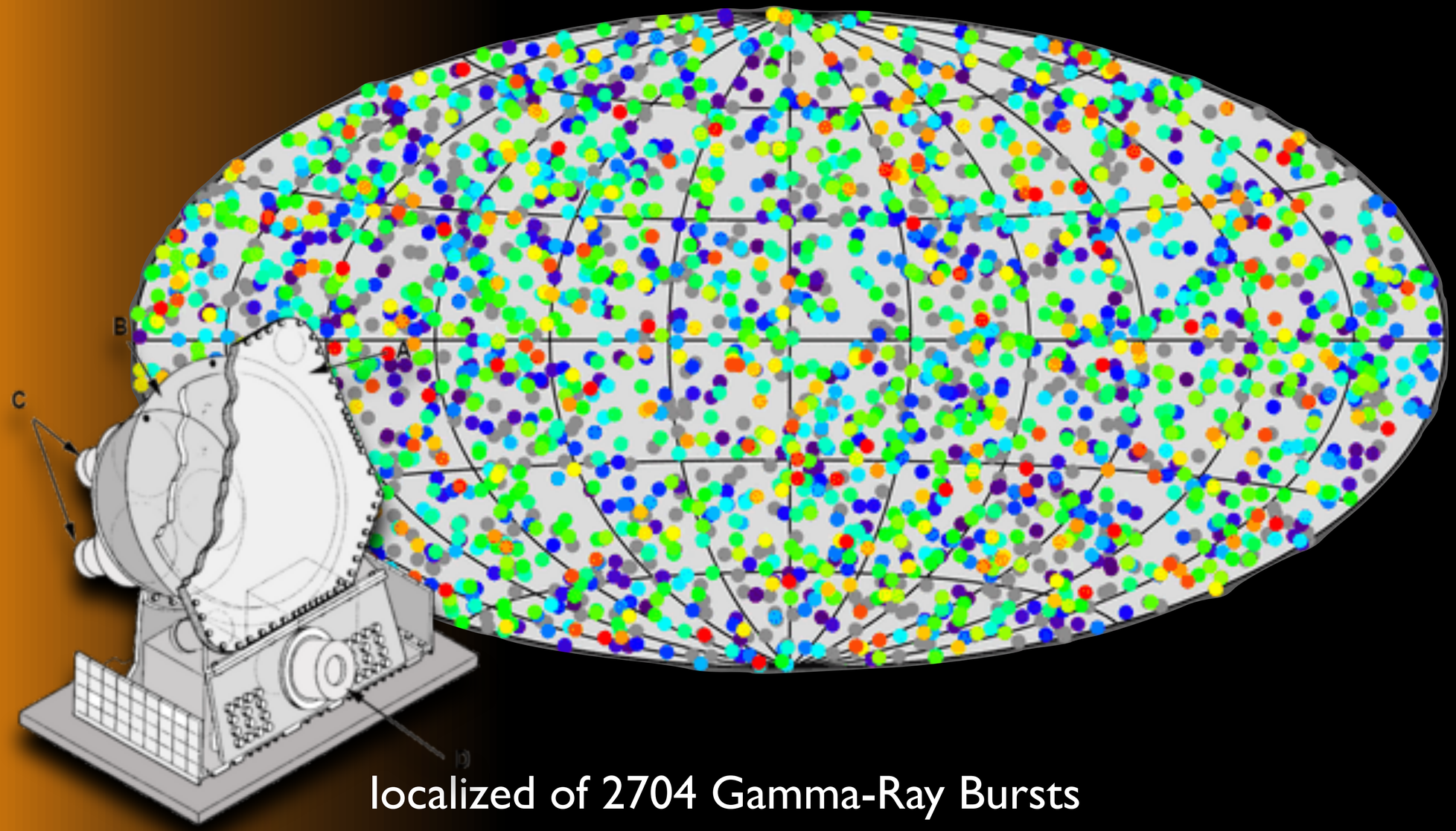
BATSE



localized of 2704 Gamma-Ray Bursts

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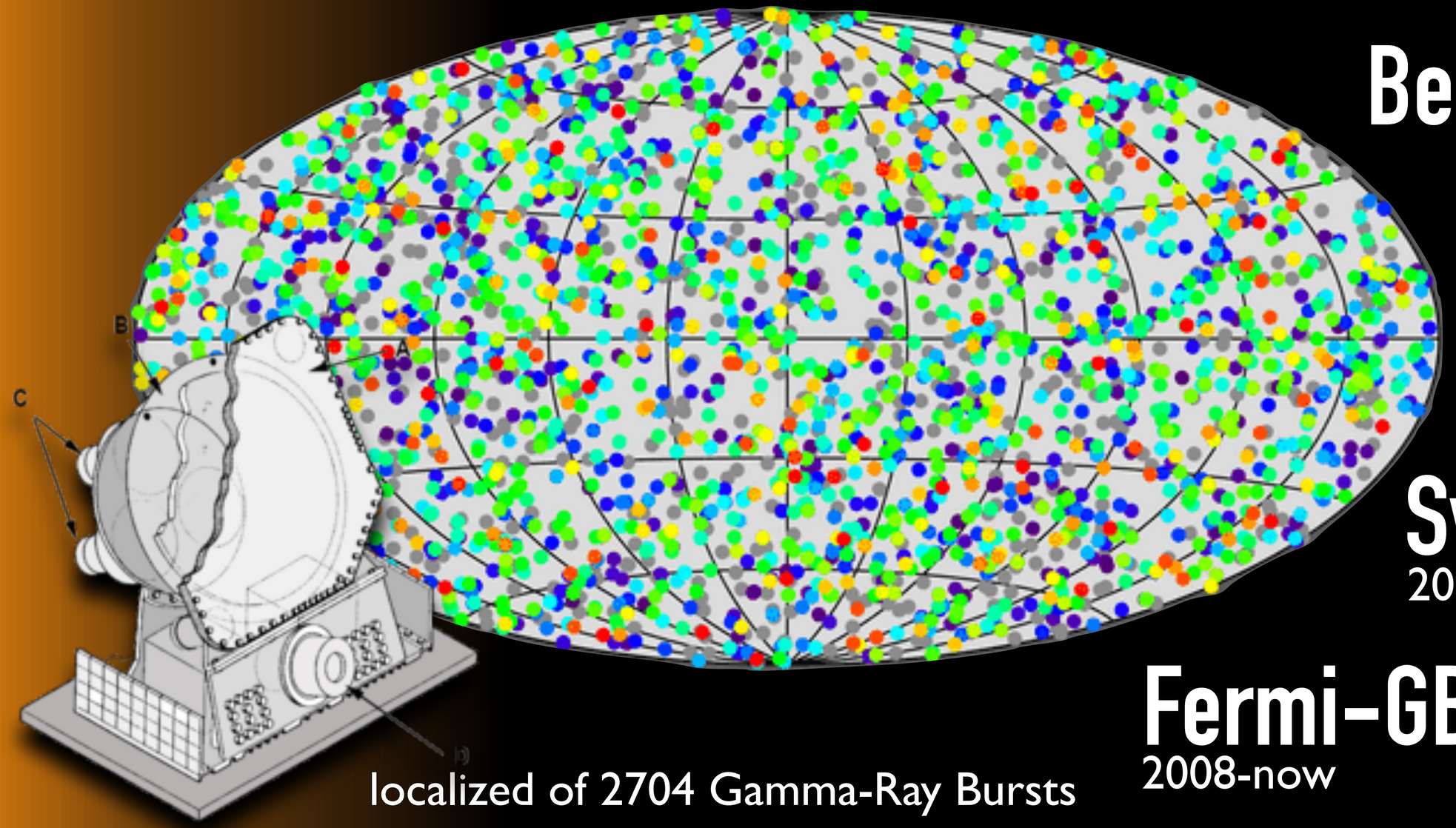
BATSE



localized of 2704 Gamma-Ray Bursts

BeppoSAX
1996-2003

+ OSSE
INTEGRAL
2002-nowish

Swift-BAT
2004-now

Fermi-GBM
2008-now

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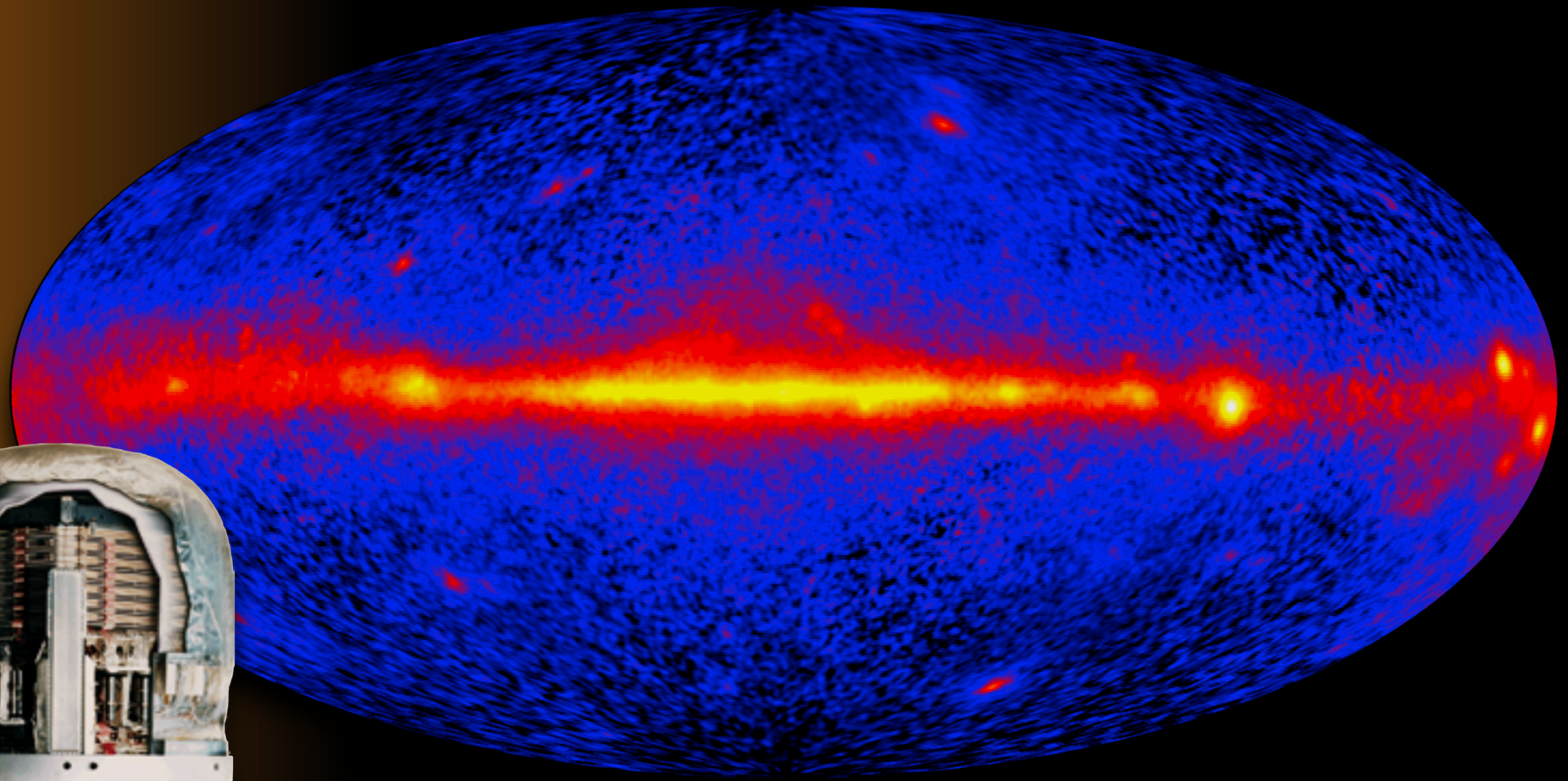
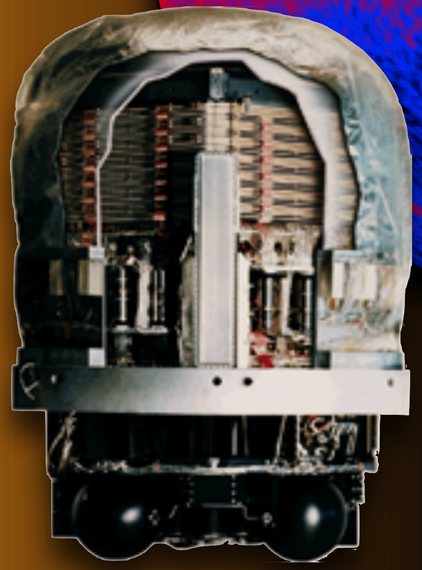
EGRET





discovered 271 sources, 11 ms-pulasrs, 170 of which were unidentified

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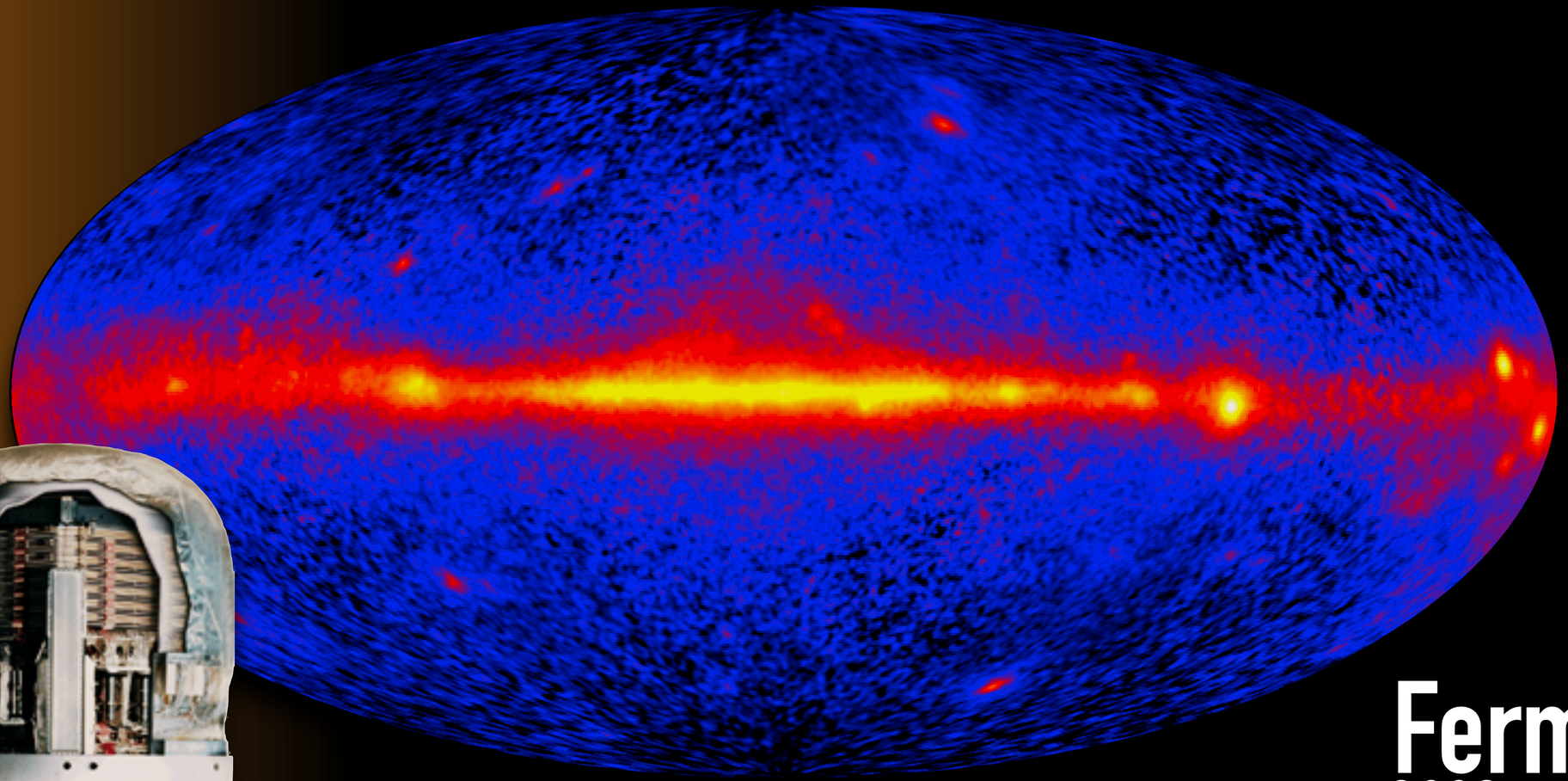
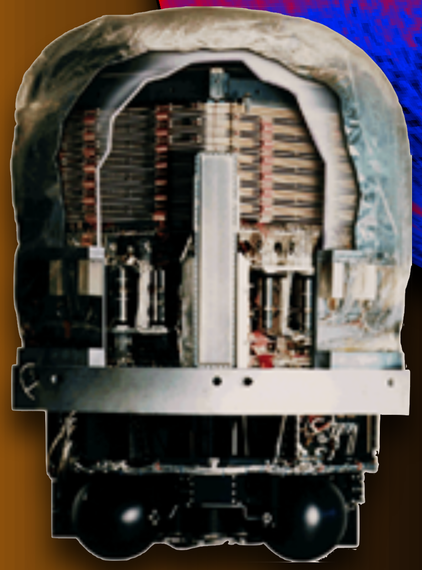
EGRET





AGILE
2007-2024

Fermi–LAT
2008-now

discovered 271 sources, 11 ms-pulasrs, 170 of which were unidentified

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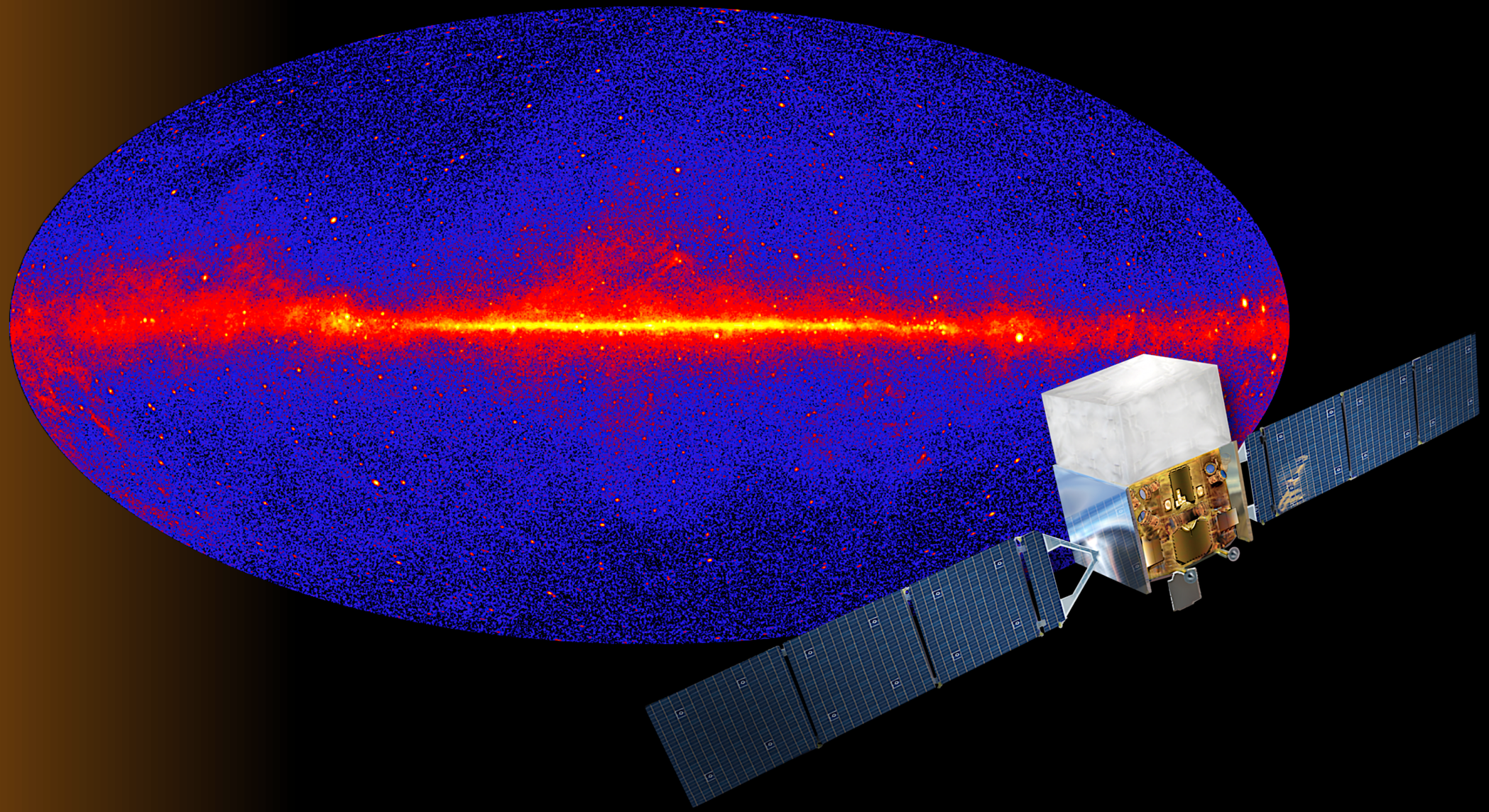
FERMI



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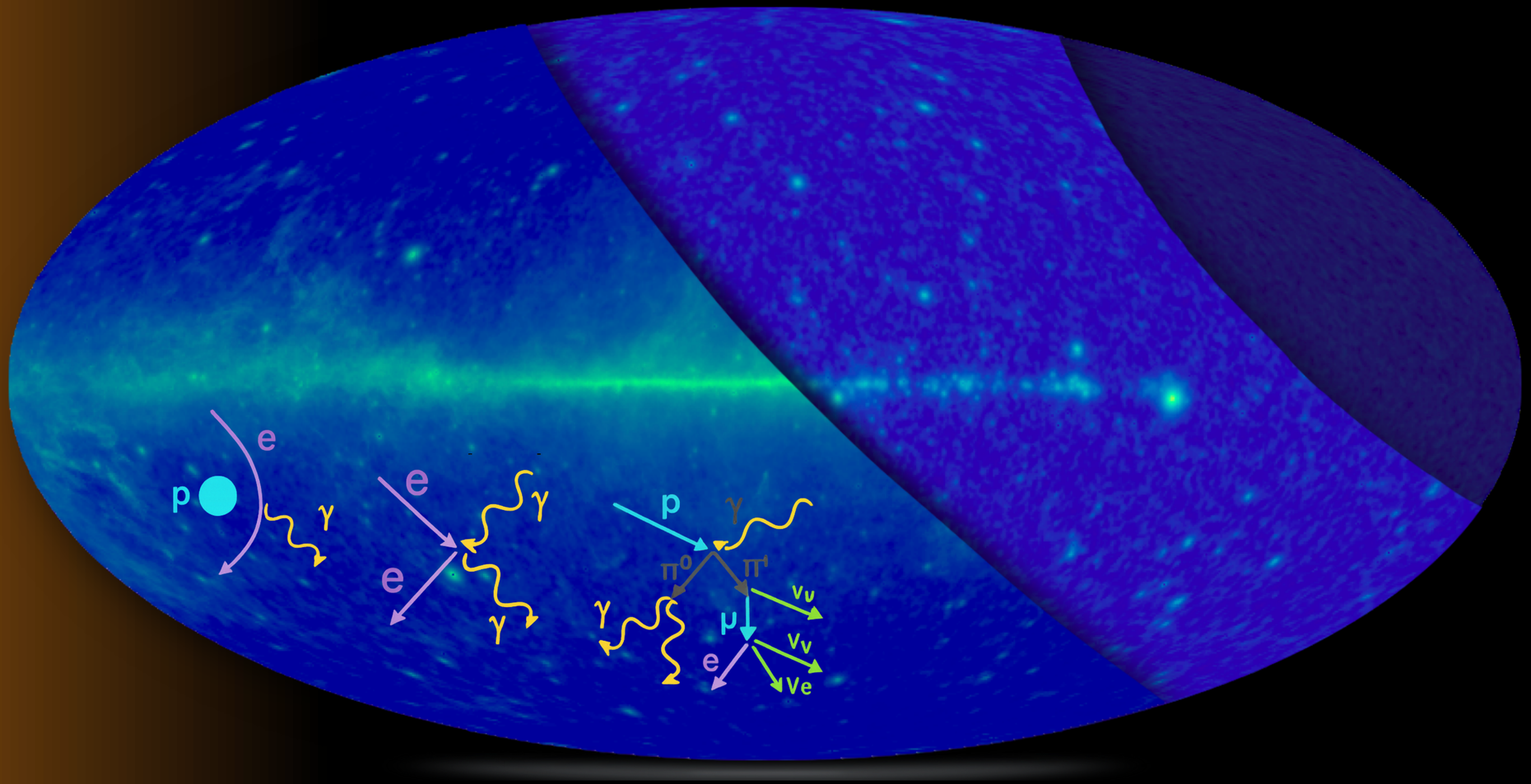

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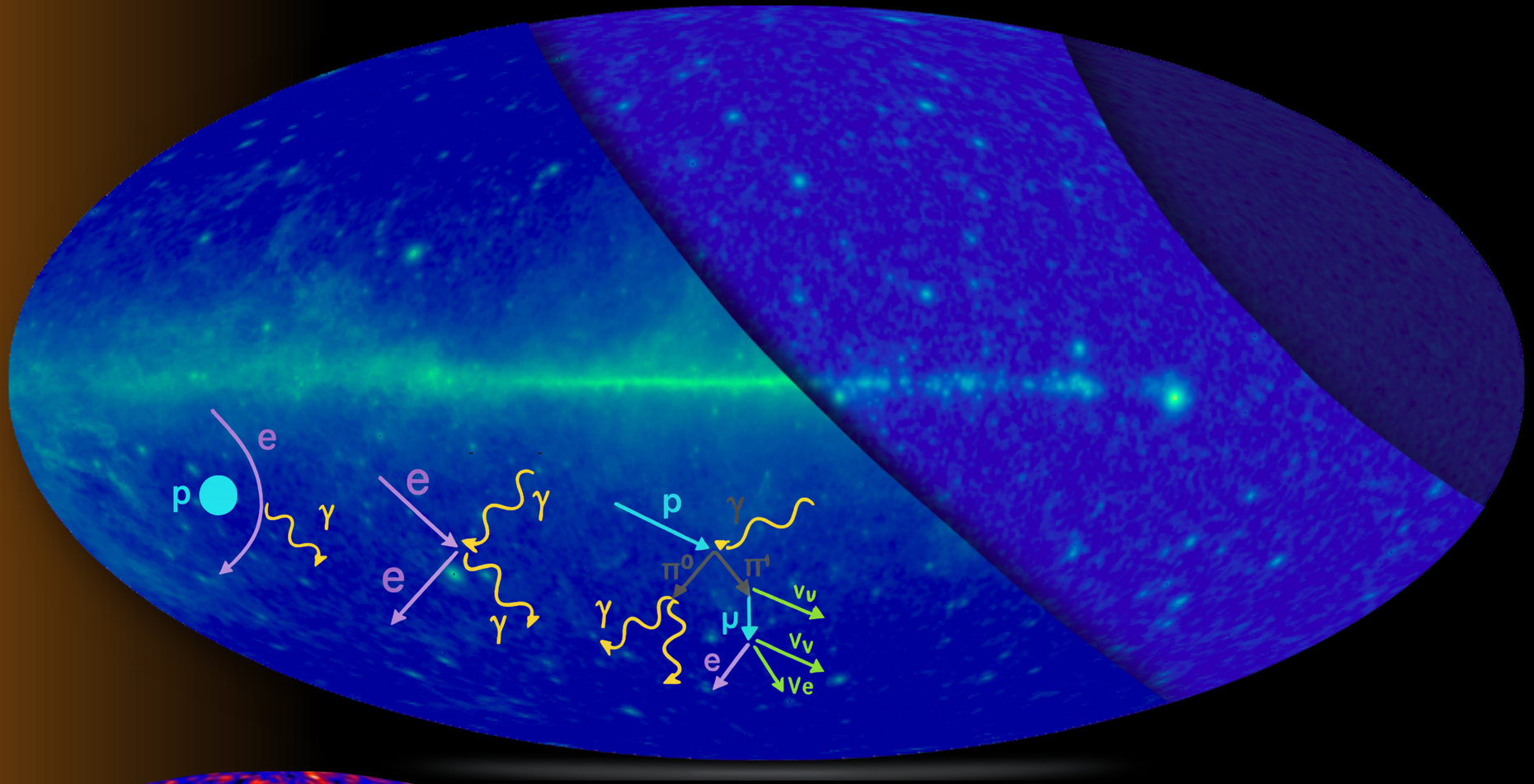

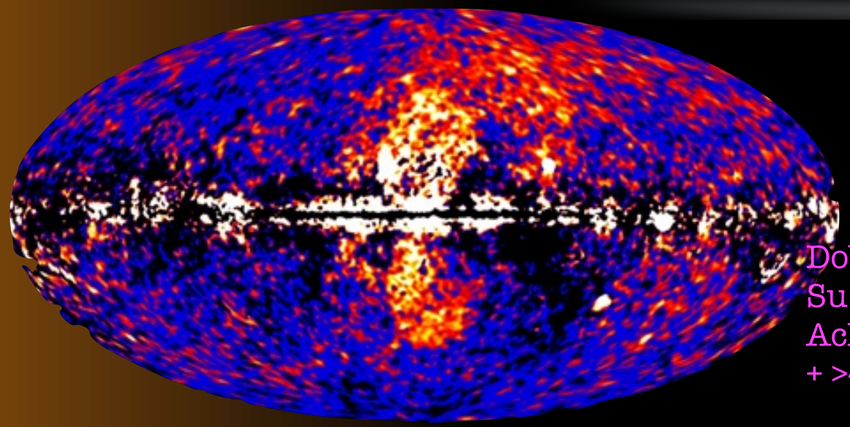

Dobler et al. 2010
Su et al. 2010
Ackermann et al 2015
+ >400

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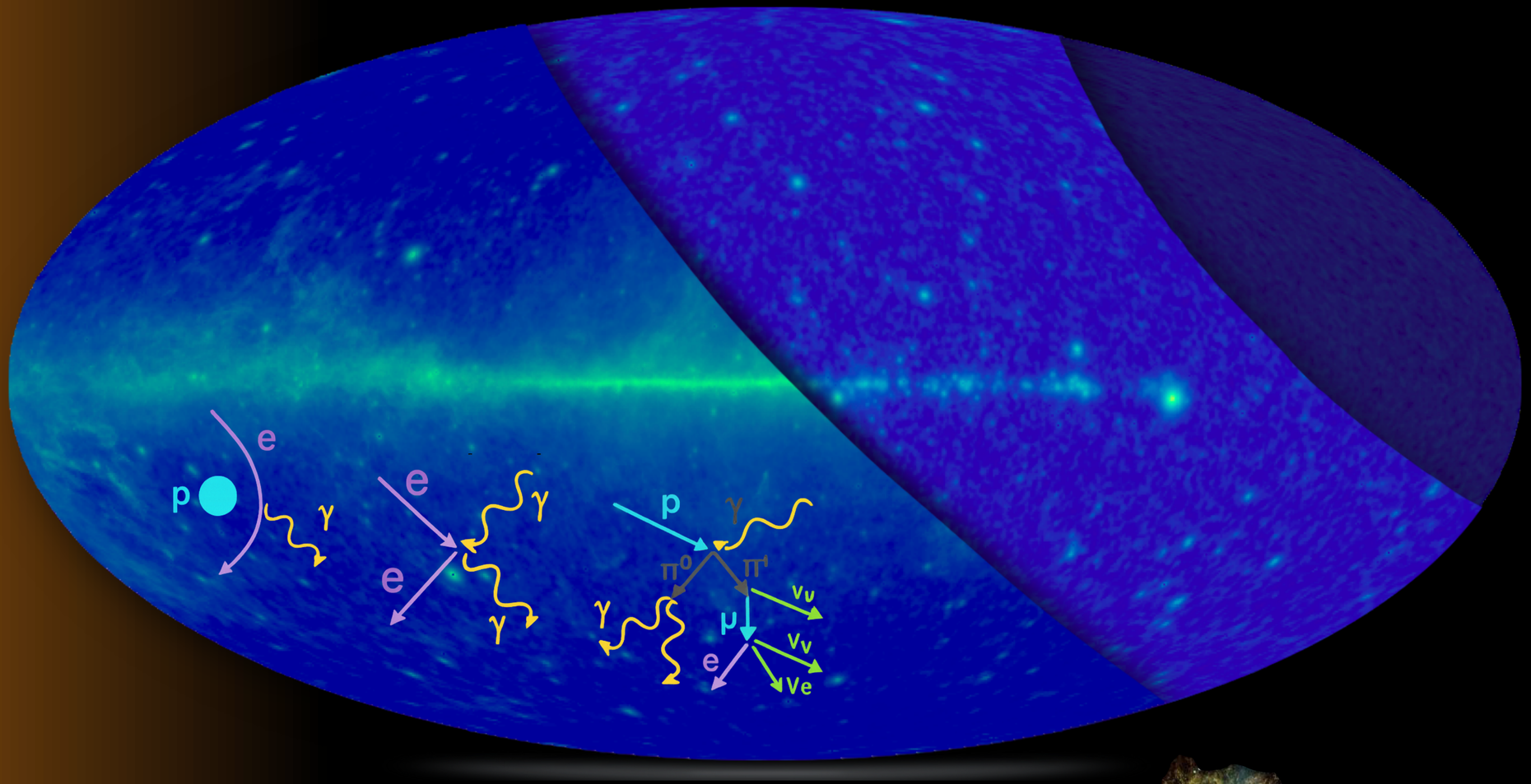

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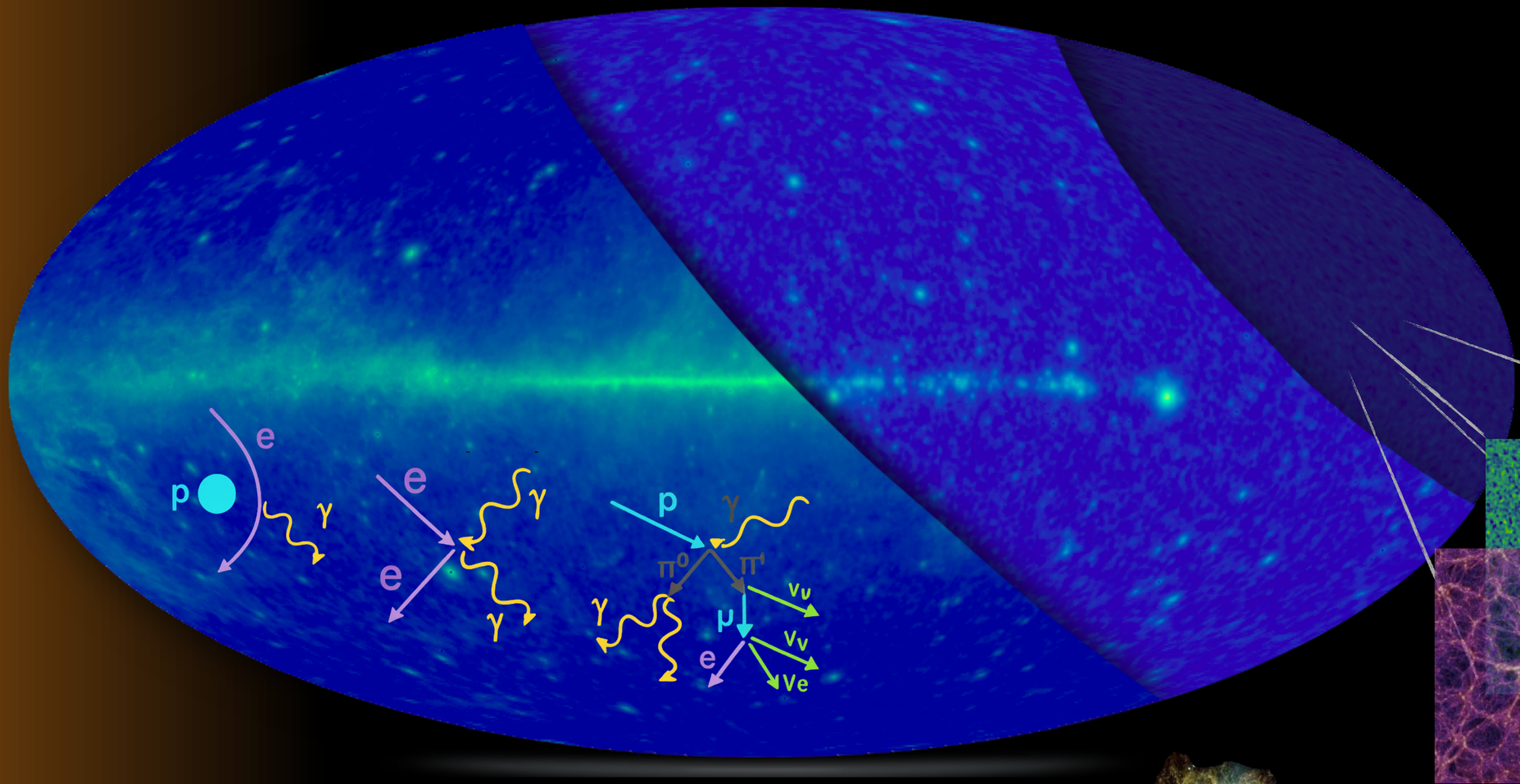
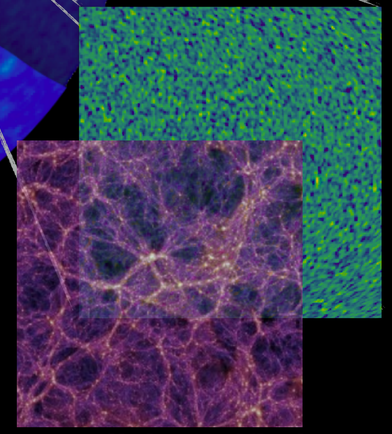
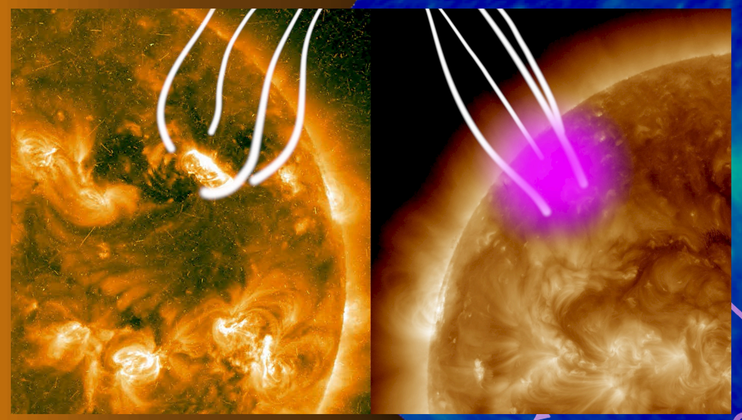


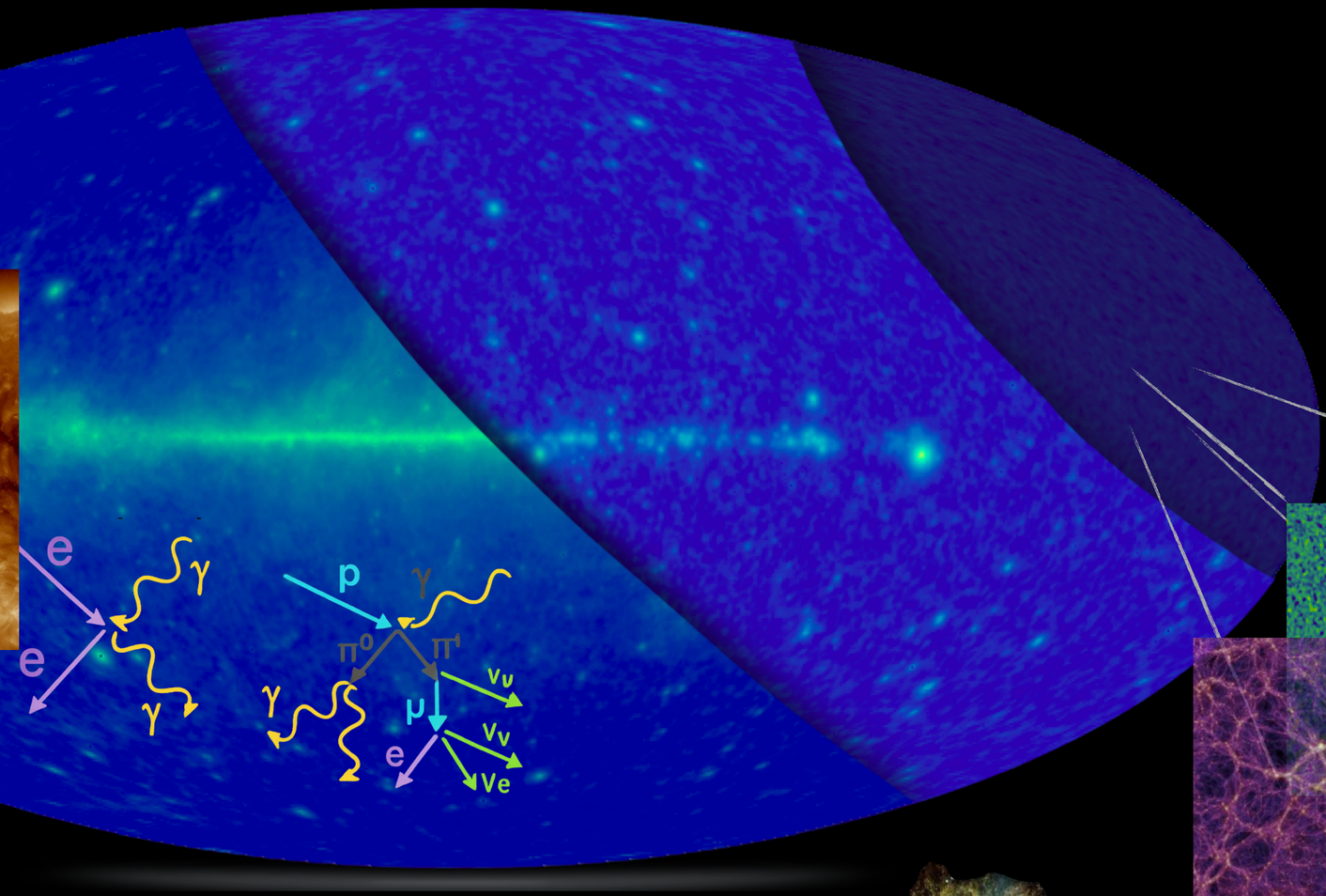


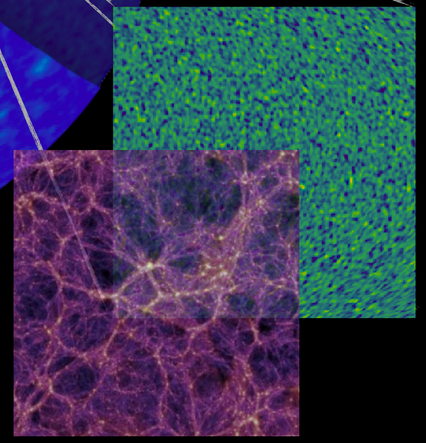
see talk by B. Thakore @18:00 room 3.1+3.2, ADEIT

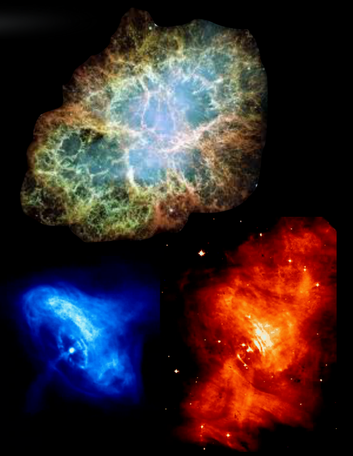
The Sun

Fermi-LAT Observations of High-Energy Behind-the-Limb Solar Flares
Ackermann et al. 2017









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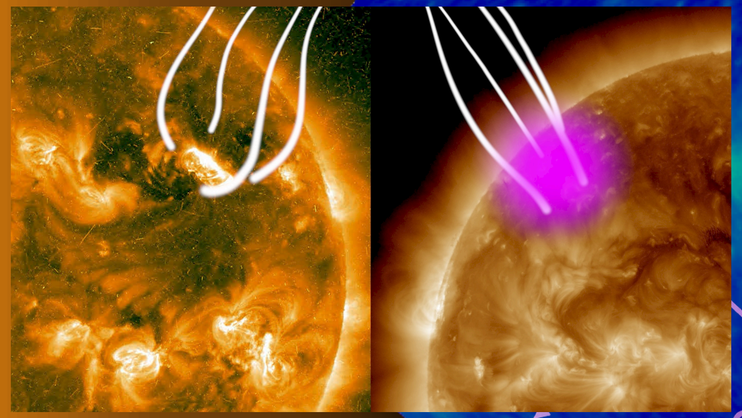
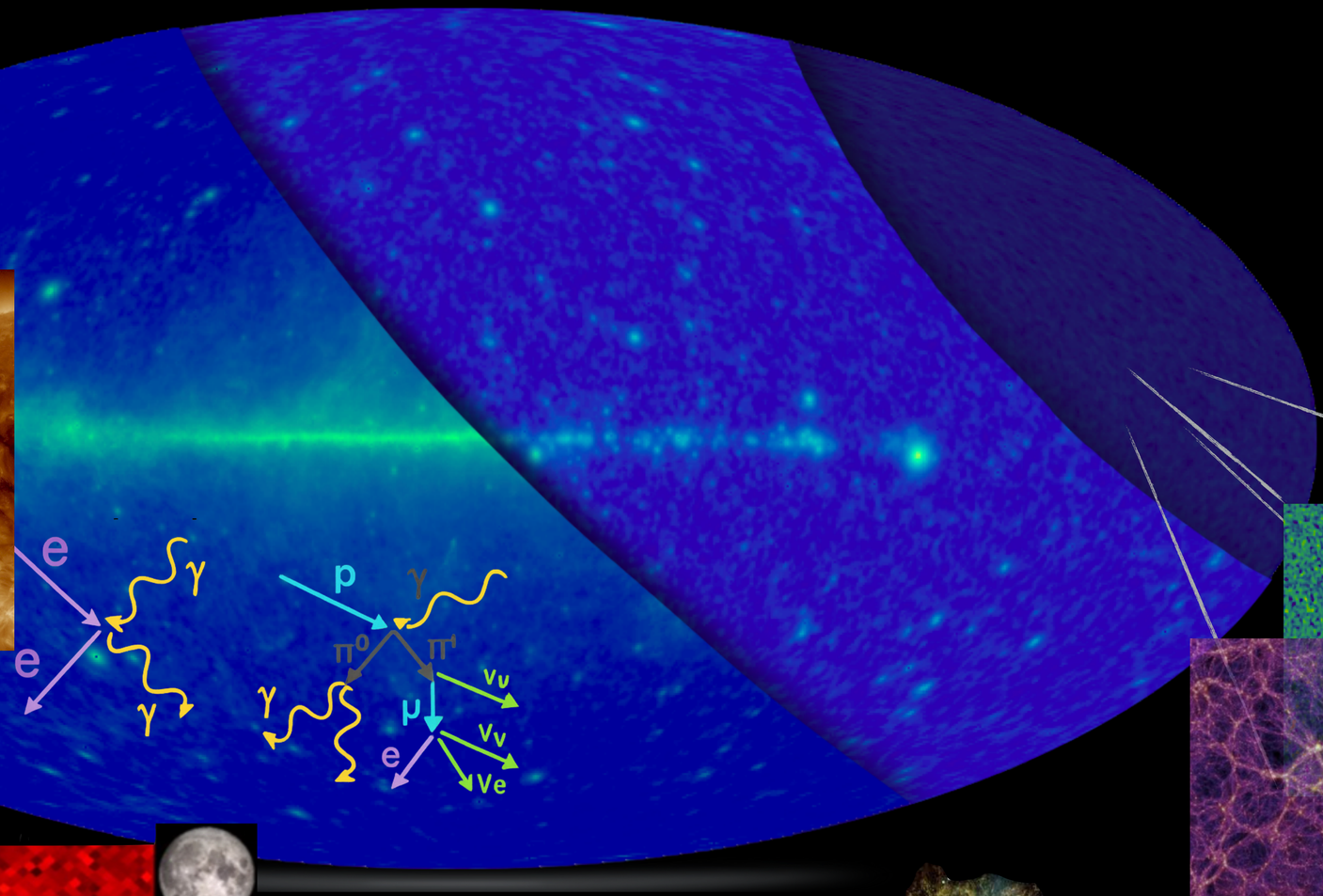
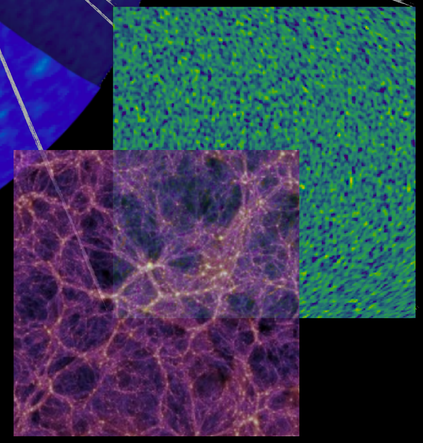
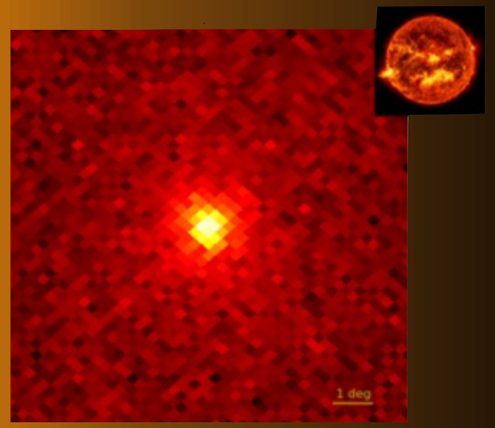
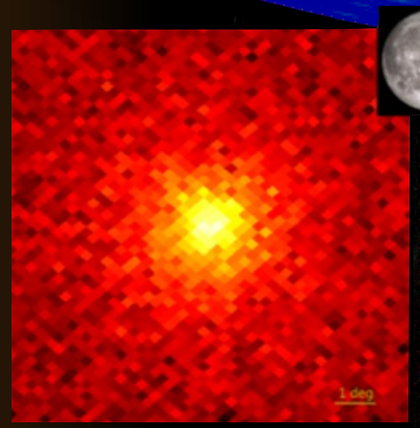






The Moon





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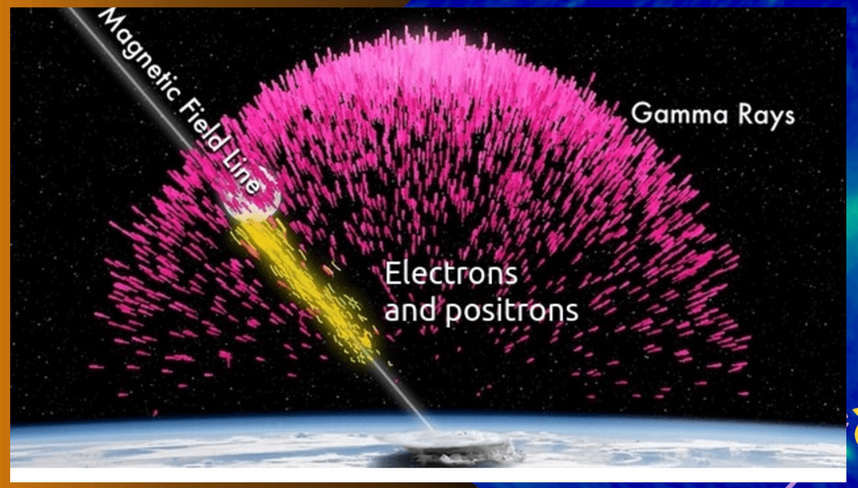
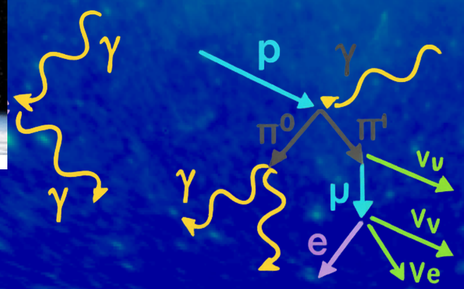
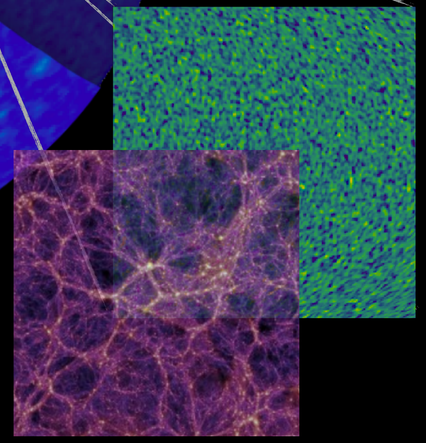
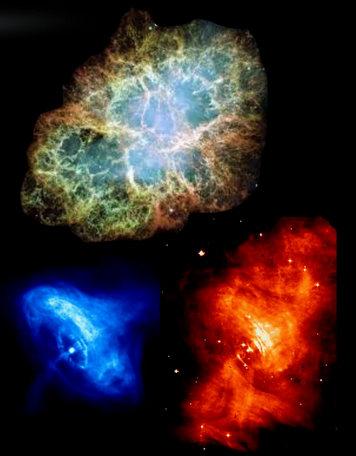
Terrestrial storms









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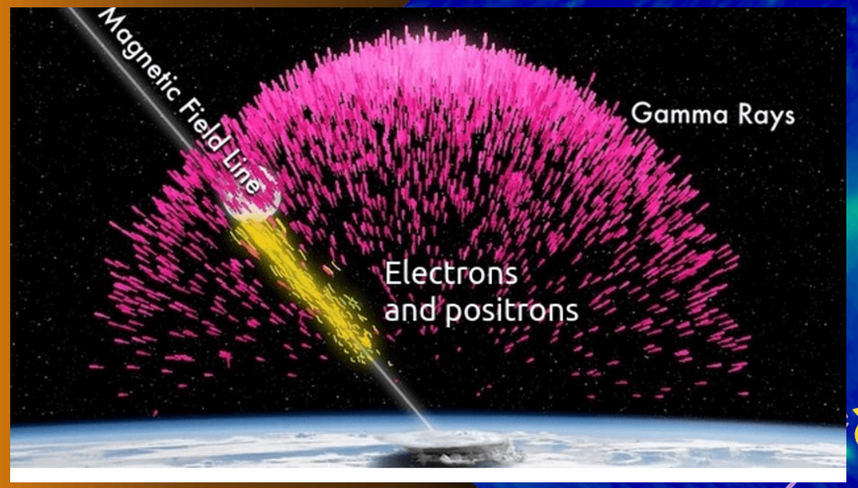
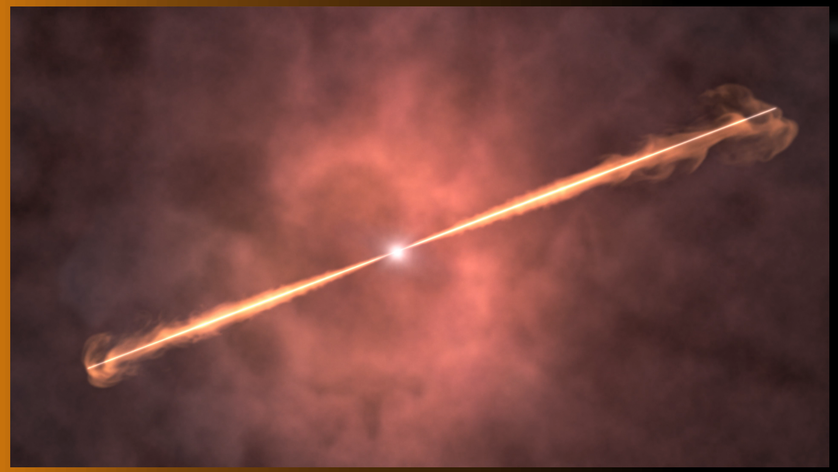
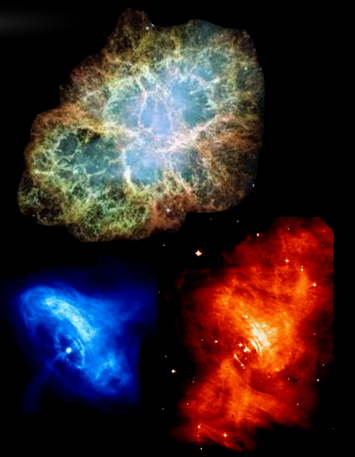


Cosmic transients





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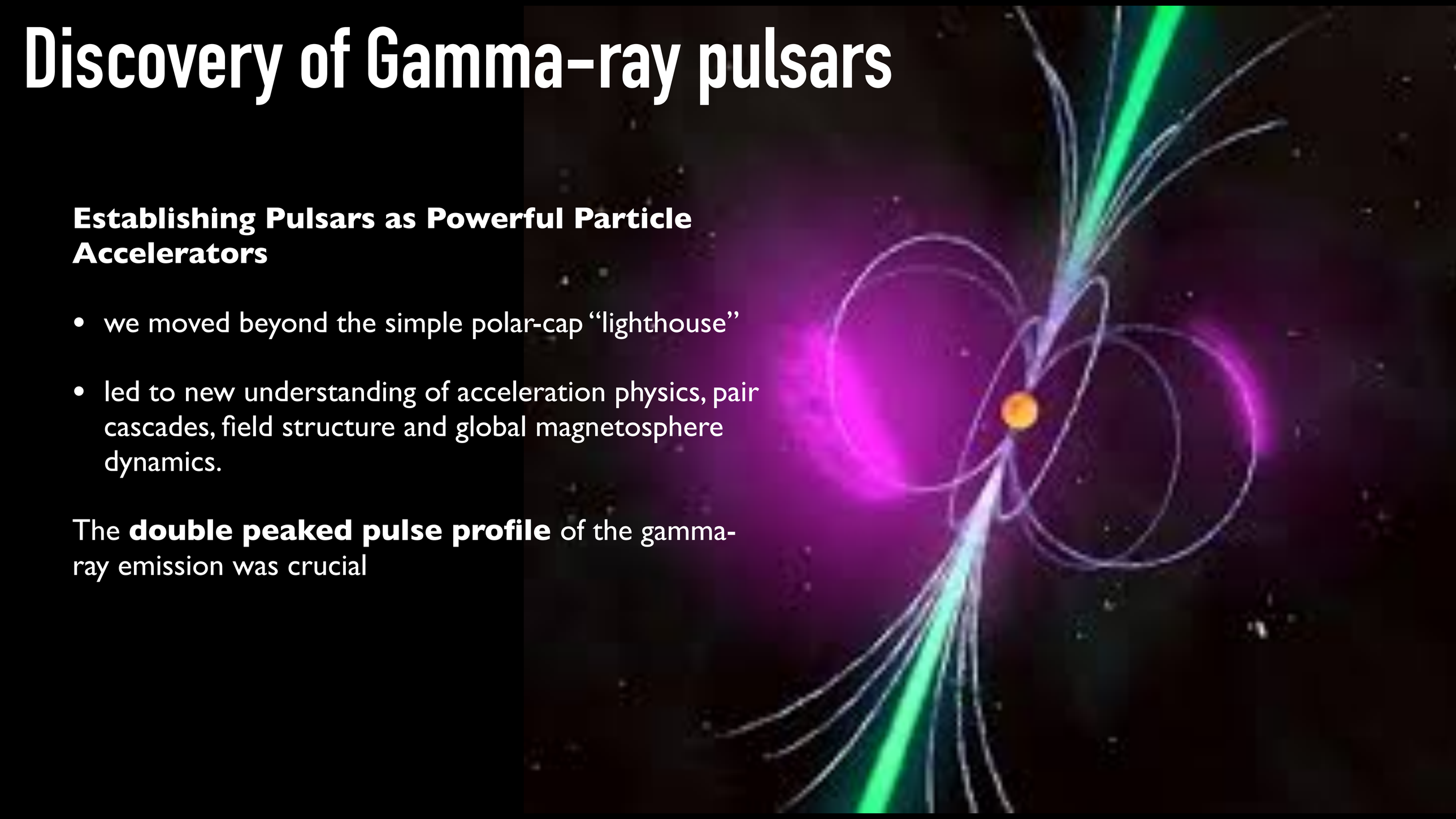
Discovery of Gamma-ray pulsars



Establishing Pulsars as Powerful Particle Accelerators

- we moved beyond the simple polar-cap “lighthouse”
- led to new understanding of acceleration physics, pair cascades, field structure and global magnetosphere dynamics.

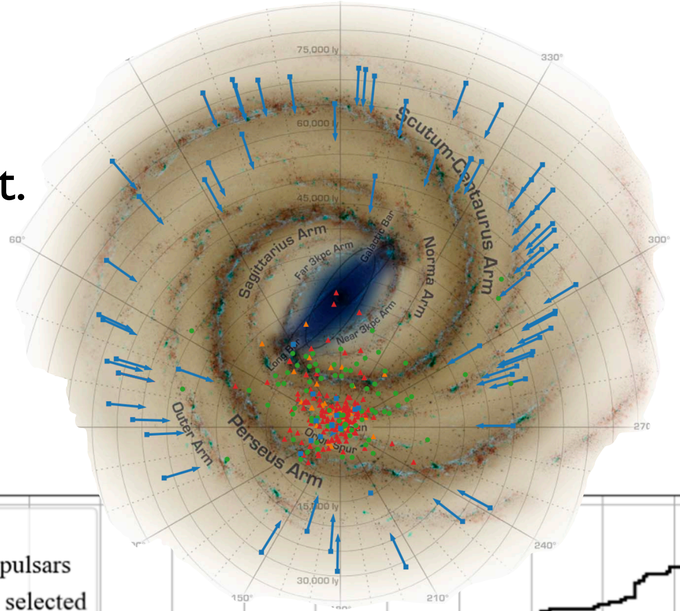
The **double peaked pulse profile** of the gamma-ray emission was crucial

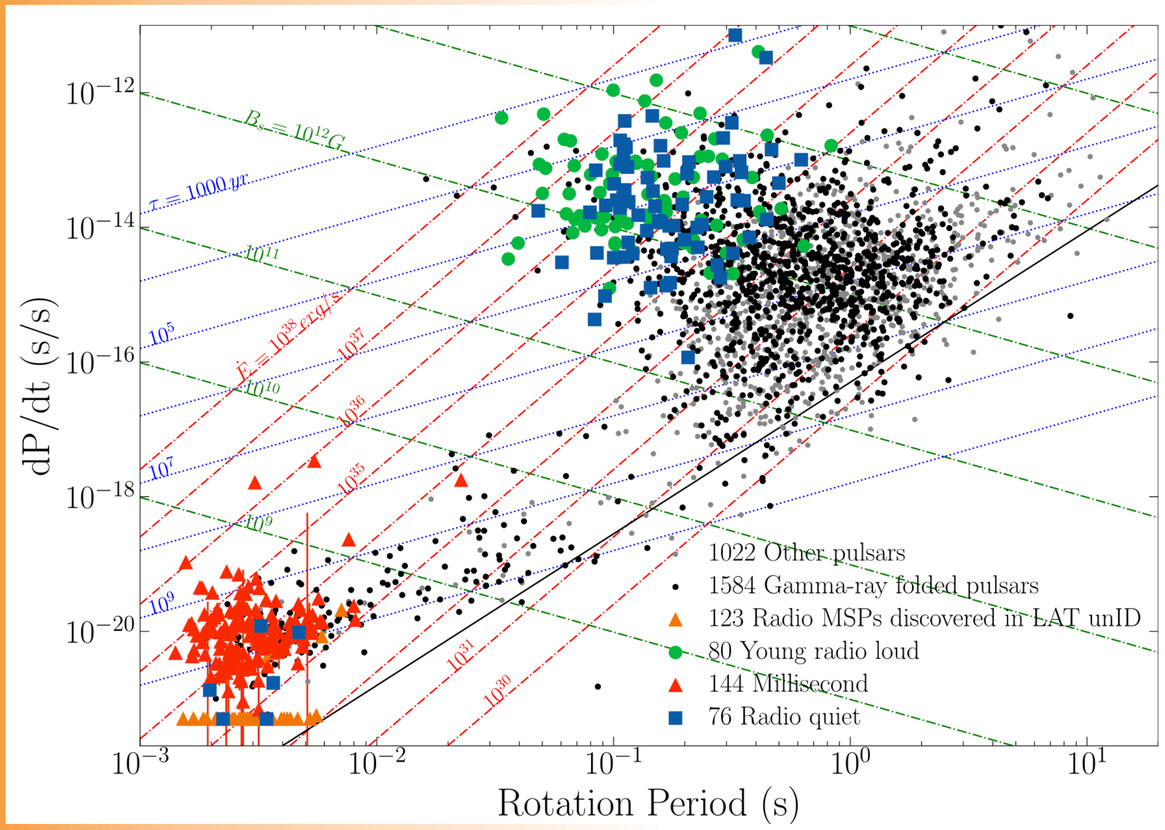
The current pulsar population

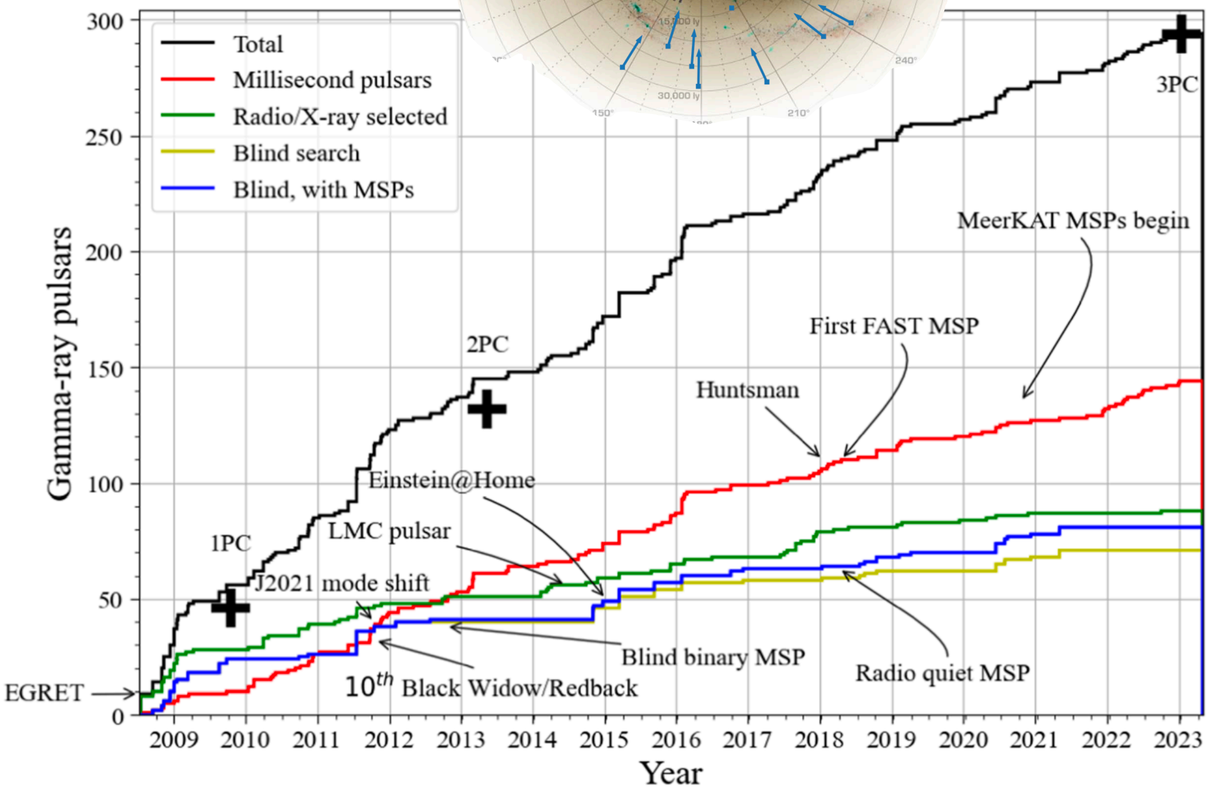
Many ms-pulsars **discovered in gamma rays,** many are radio quiet.

A **numerous** and **varied** population of gamma-ray pulsars

- Young pulsars (both radio loud and radio quiet)
- MSP (many binaries)
- MSP spiders (black widows / redbacks)





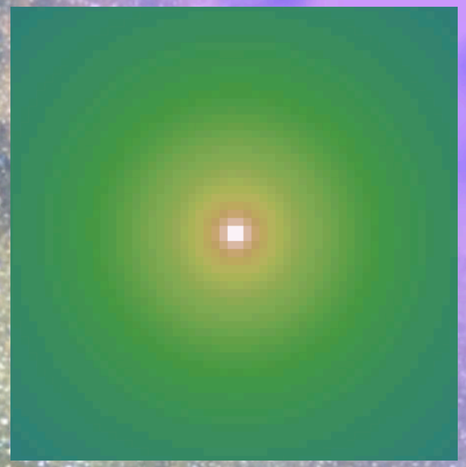


Smith et al (LAT Collaboration) the Third Pulsar Catalog

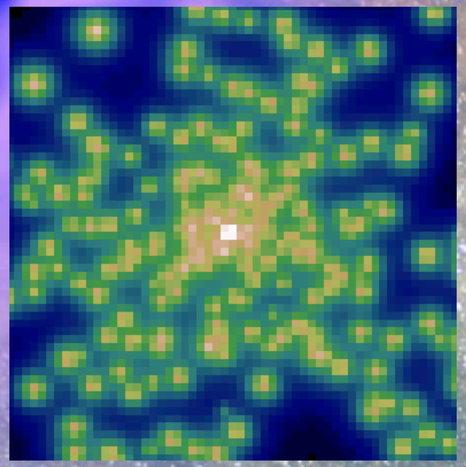
A gamma-ray excess in the center of the Milky Way

~50 publications/yr!

Hooper & Linden 2011
Boyarsky, Malyshev & Ruchayskiy 2011
Abazajian & Kaplinghat 2012
+ > 300



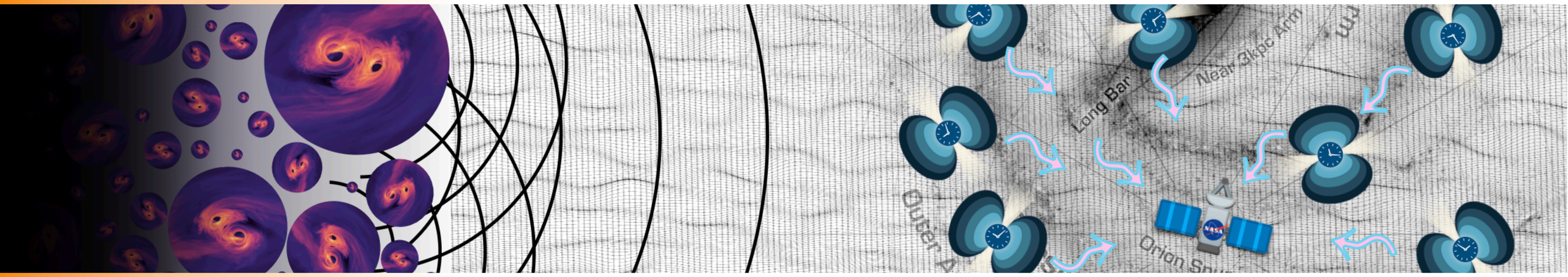
?



Dark matter?

Millisecond pulsars?

Gravitational Wave background through γ-PTA



Using 35 MSP we measured an upper limit on the GWB amplitude and projected that with accumulated data, but GPTA) could detect a GWB at the current NanoGRAV level by ~ **2030**.

Ajello et al. (2022)

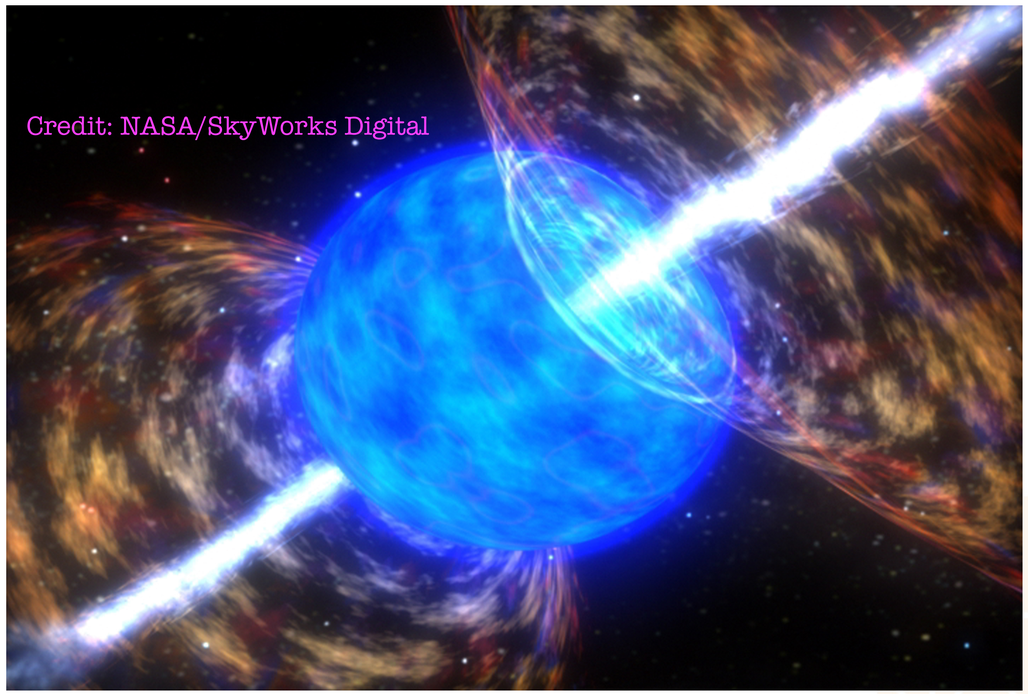
FIGSAG report (in Prep), credits: Z. Wadiasingh

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	👍	👍

Cosmic Transients

Short T90 = 2 s **Long**

2017: Short GRBs come from neutron star mergers, proven by LIGO, Virgo, Fermi-GBM, and INTEGRAL.



1998: Long GRBs come from a rare type of core-collapse supernova (Collapsars), proven by **BeppoSAX** and follow-up observations.

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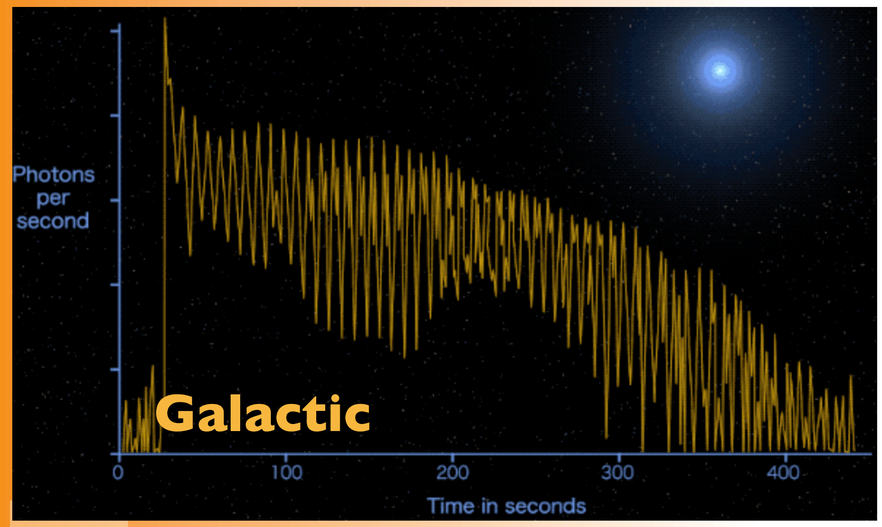
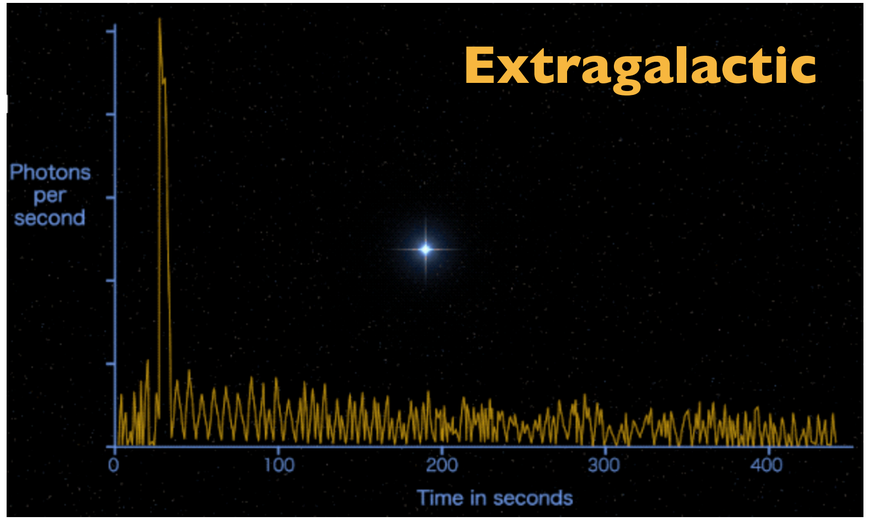
TeVPA

Extragalactic Magnetar Giant Flare population

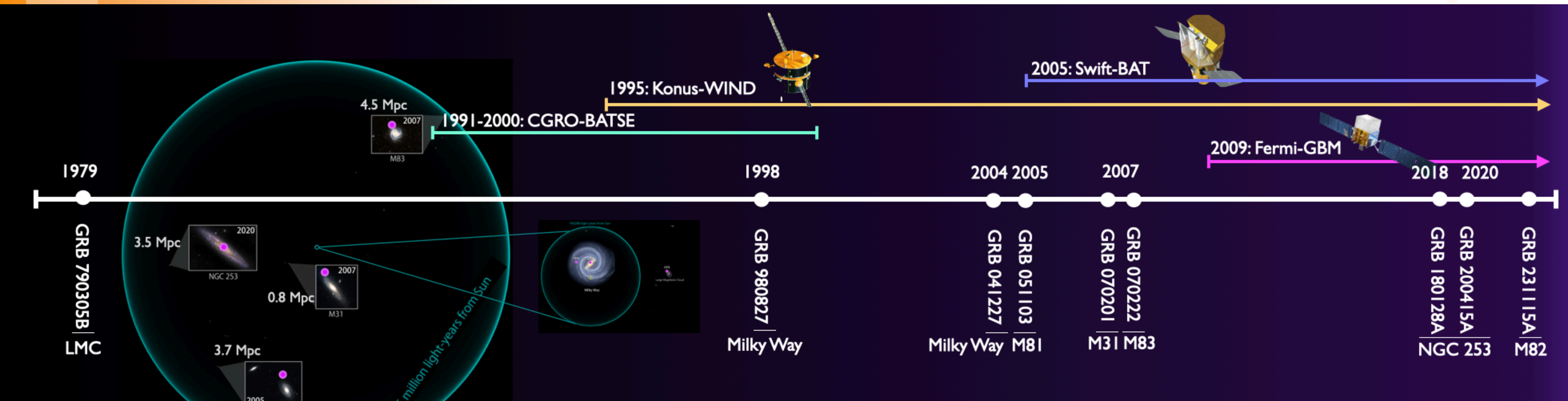




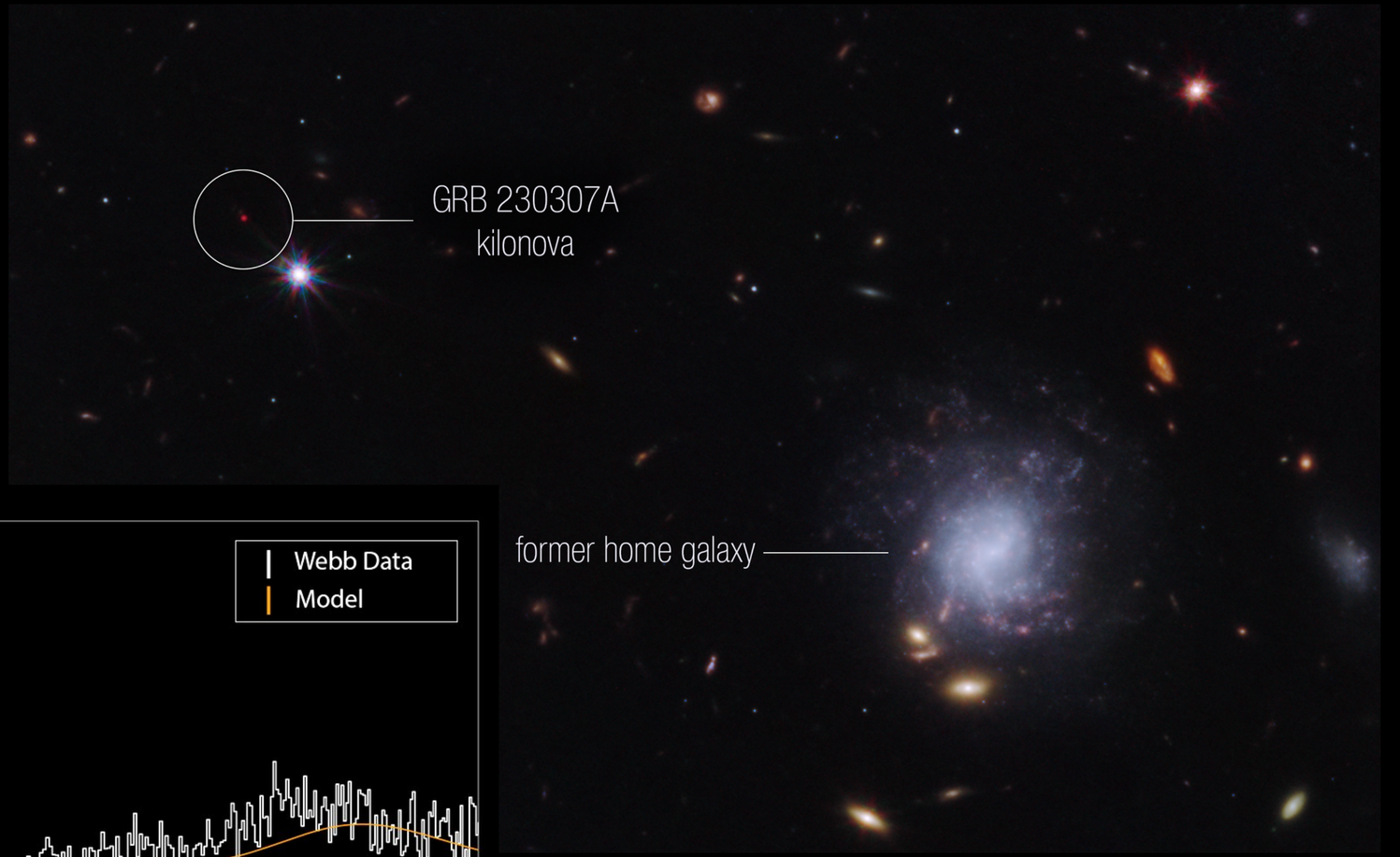
Constraining :

- **MGF rate**
- **Magnetars progenitors** (what can generate the most extreme B in the universe?)
- **rate of MGF/magnetar** (NS EOS)

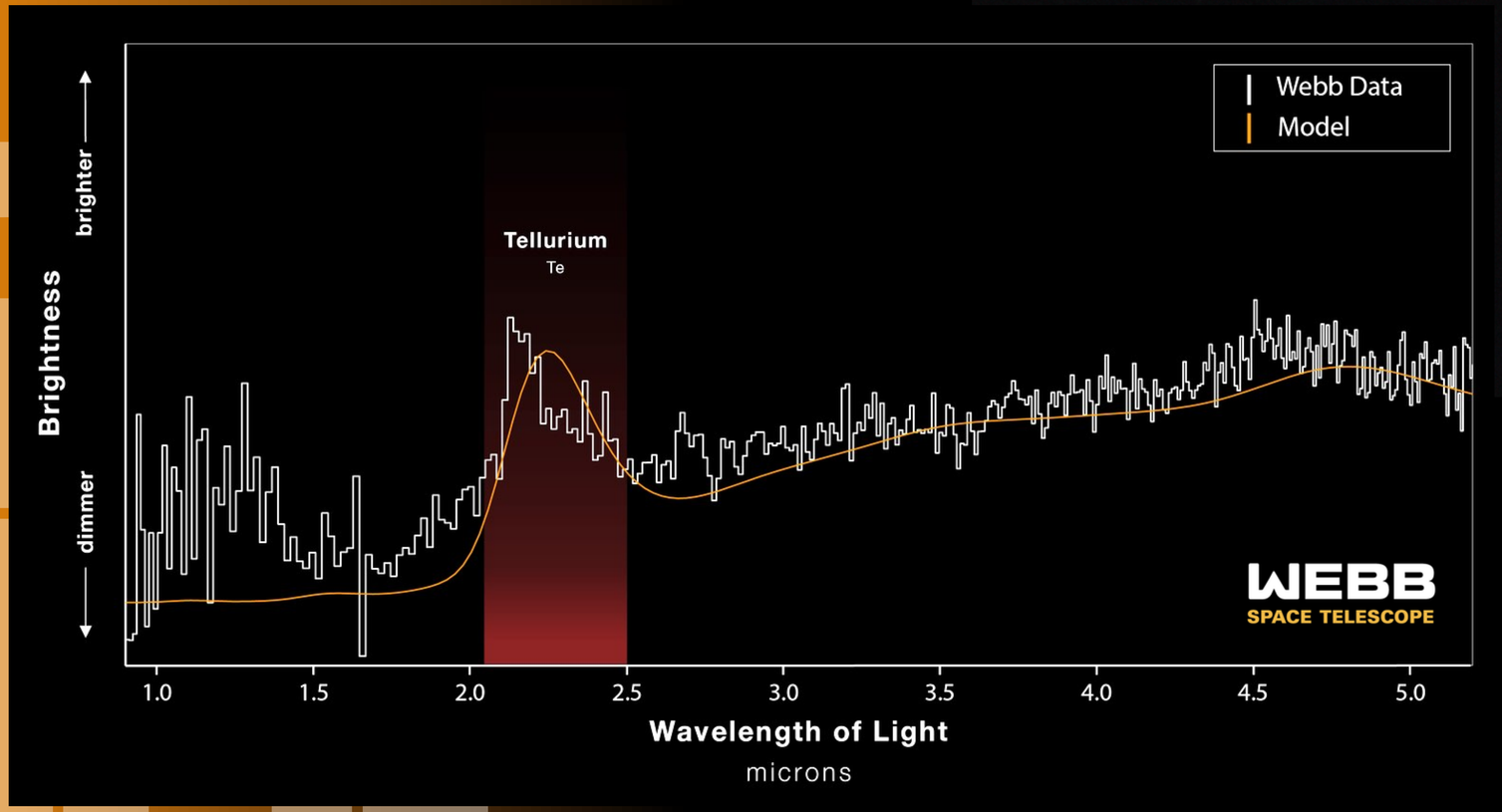
Burns et al 2021
Trigg et al 2025 (submitted)



NS (long) mergers



Evidence of r-process!



Levan et al. 2024 Nature

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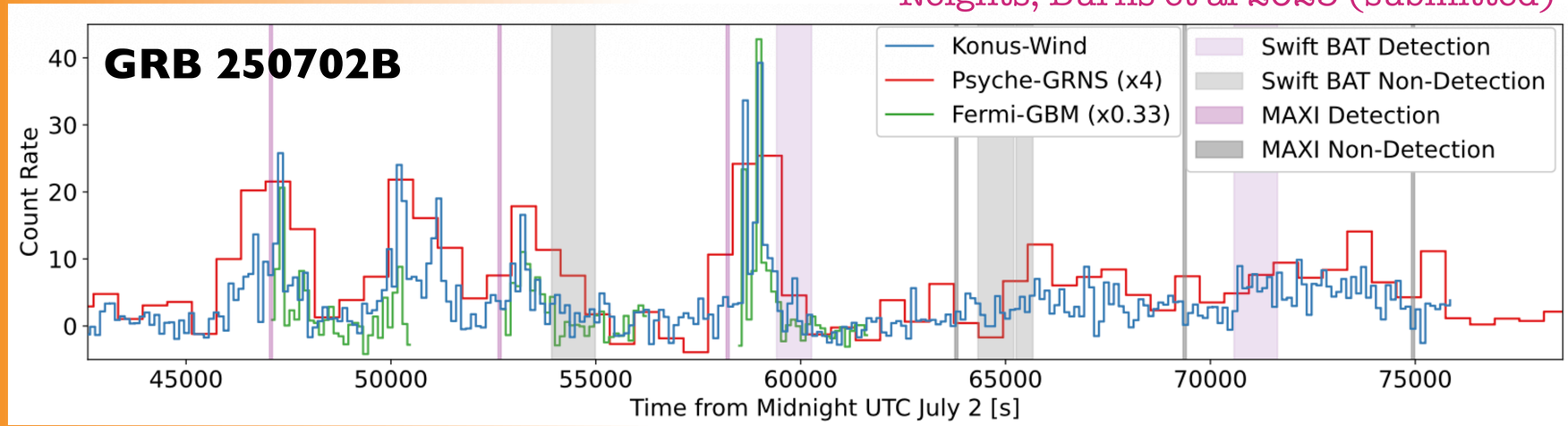
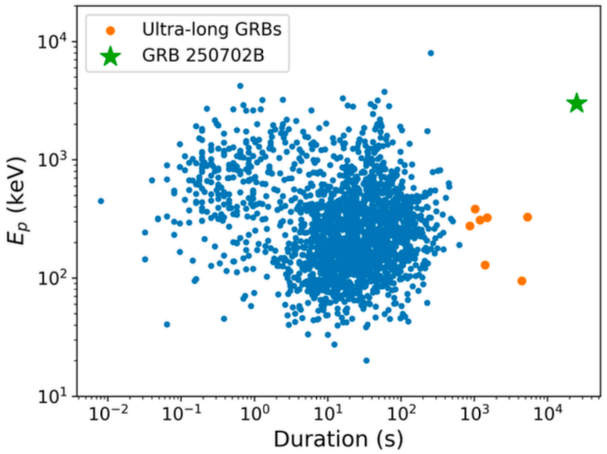
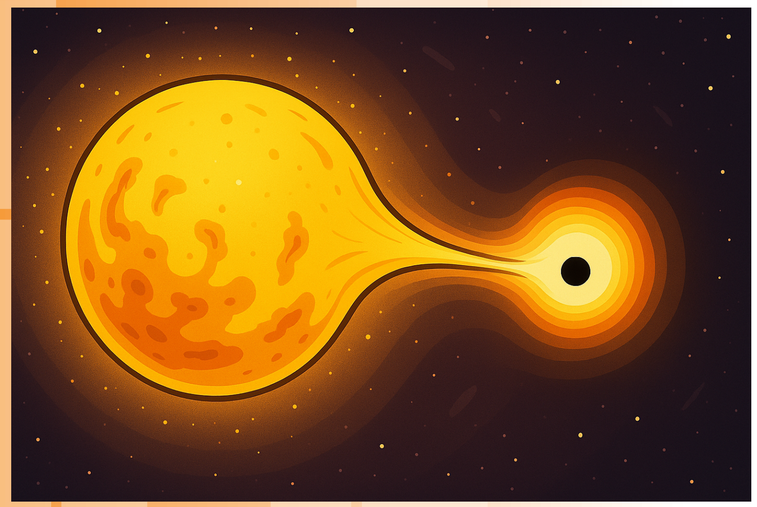
Discovery of a Gamma-Ray Burst from a Black Hole Falling into a Star

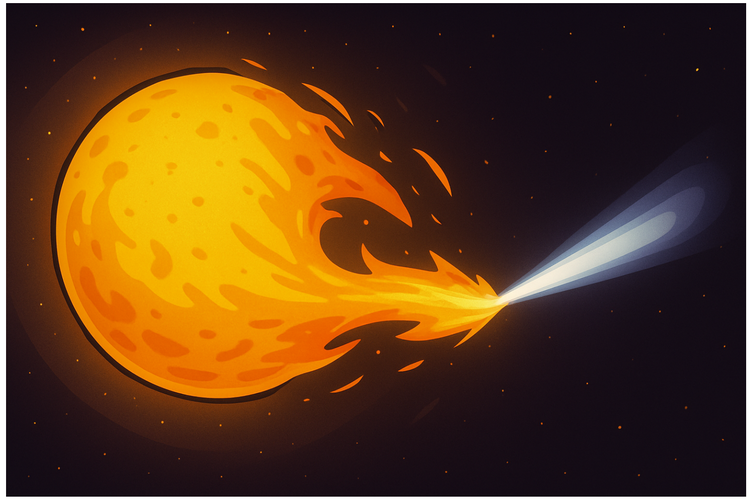
Neights, Burns et al 2025 (submitted)

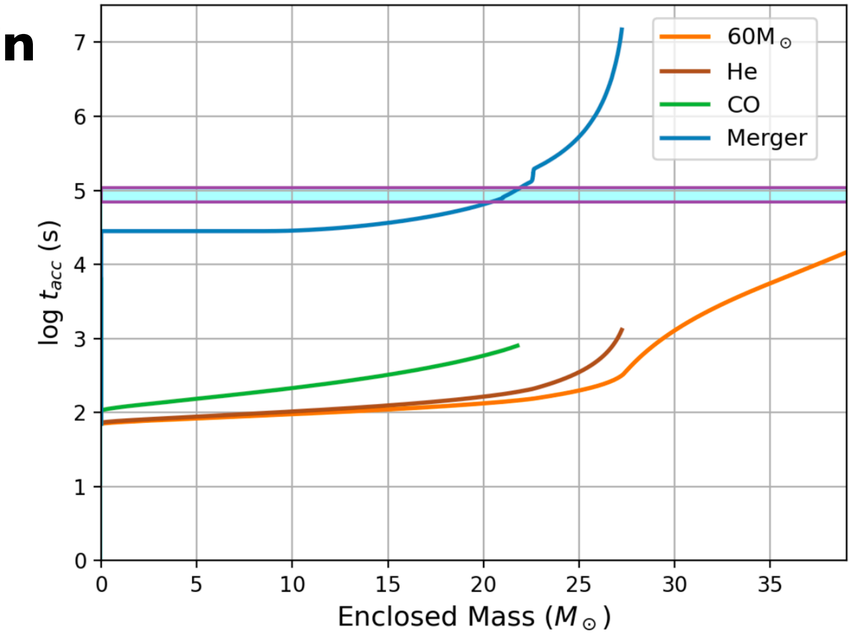




All **gamma-ray** papers are confident about a **stellar mass BH origin**







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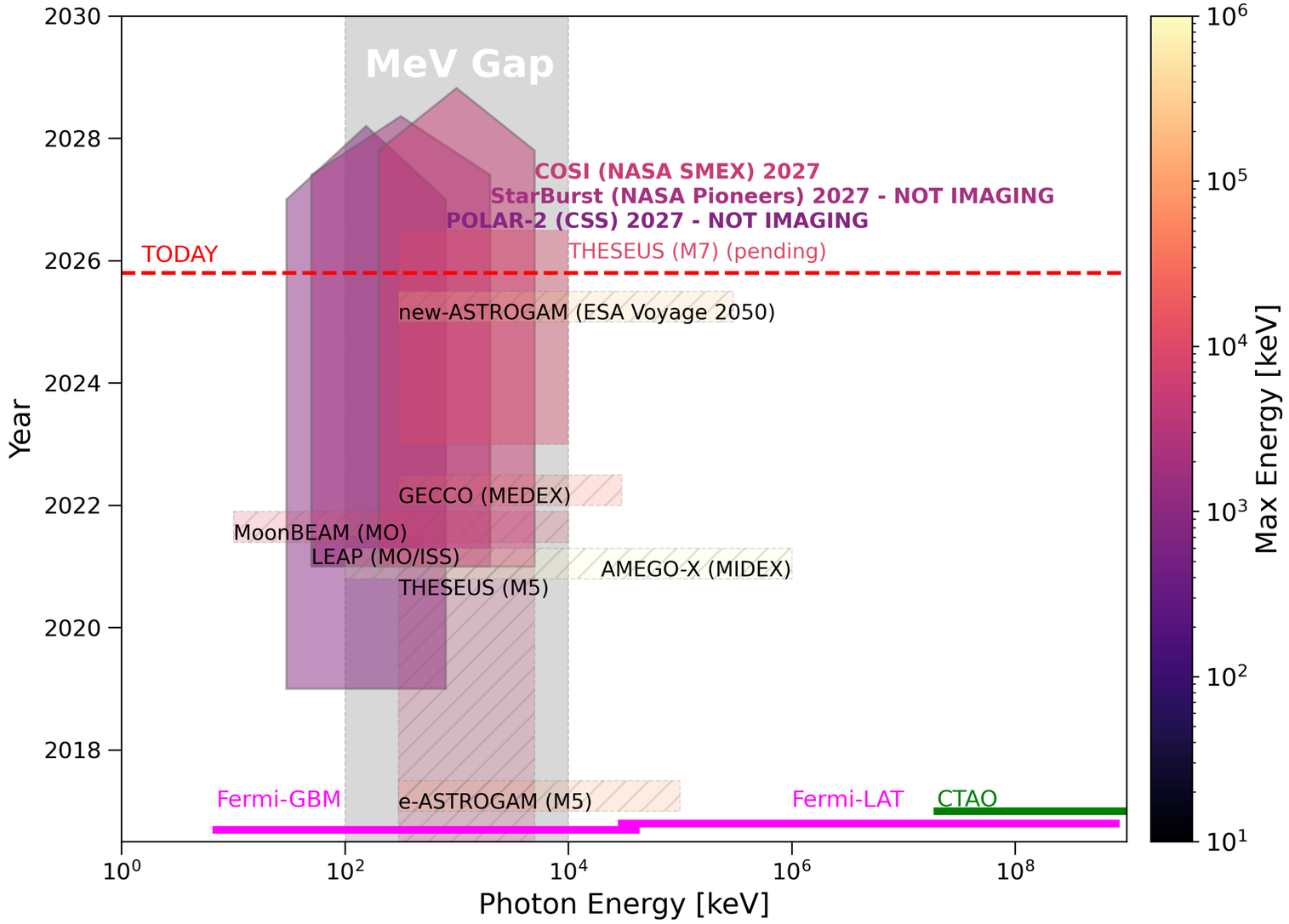
The near future

POLAR-2
GRB polarization, physics of jet launching

Starburst
GRB discovery, joint GW detection

COSI
the biggest gamma-ray mission currently expected to be launched with all-sky monitoring and imaging capabilities



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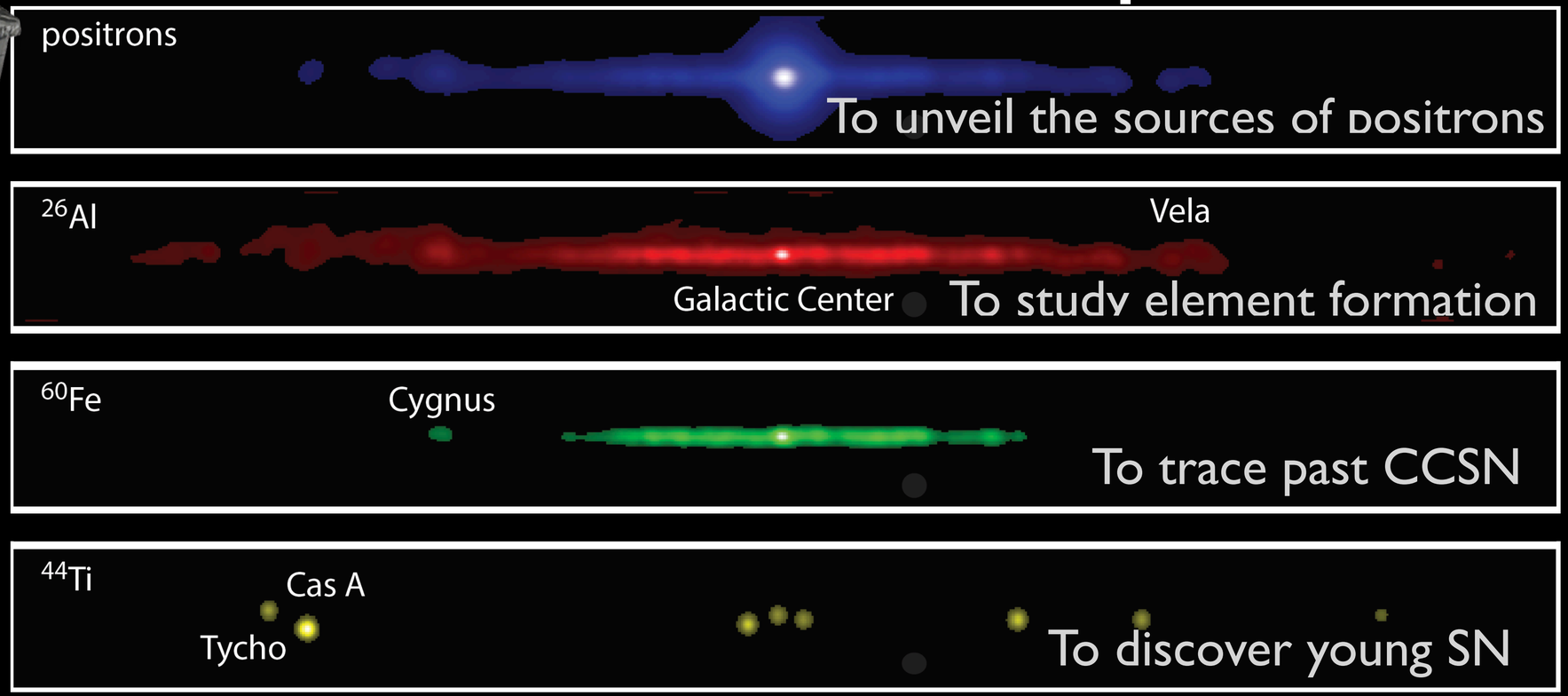
Study the creation and destruction of matter in our Galaxy

… Building on INTEGRAL's Legacy

Parameter	Requirements
Energy range	0.2-5 MeV
Sky coverage	100%-sky each day
Energy resolution	0.2-1% FWHM
Angular resolution	2.1° FWHM @ 1.8 MeV (^{26}Al)
Localizations	<1.0° for GRBs
Polarization sensitivity	For GRBs, AGN, Galactic BHs

Simulated COSI lines maps



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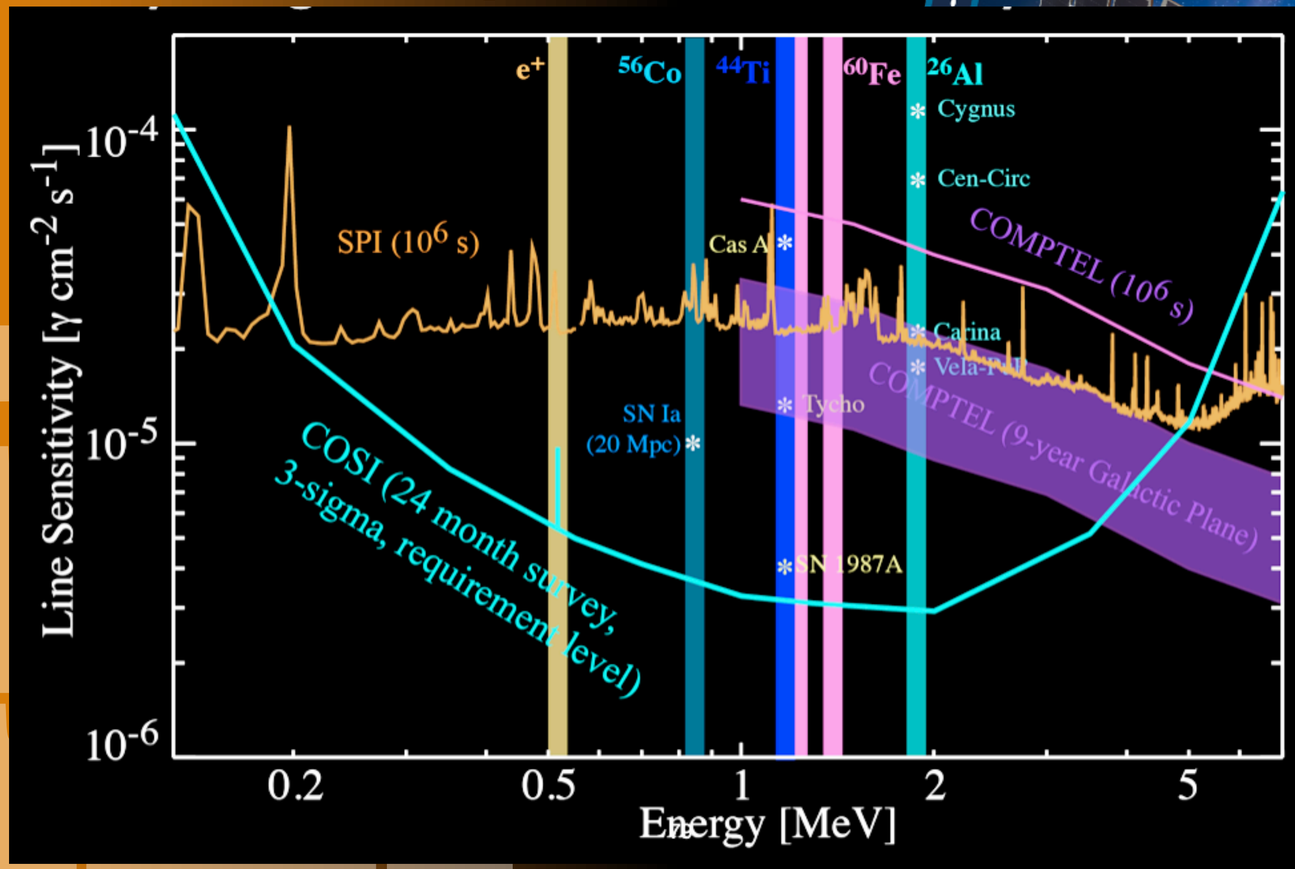
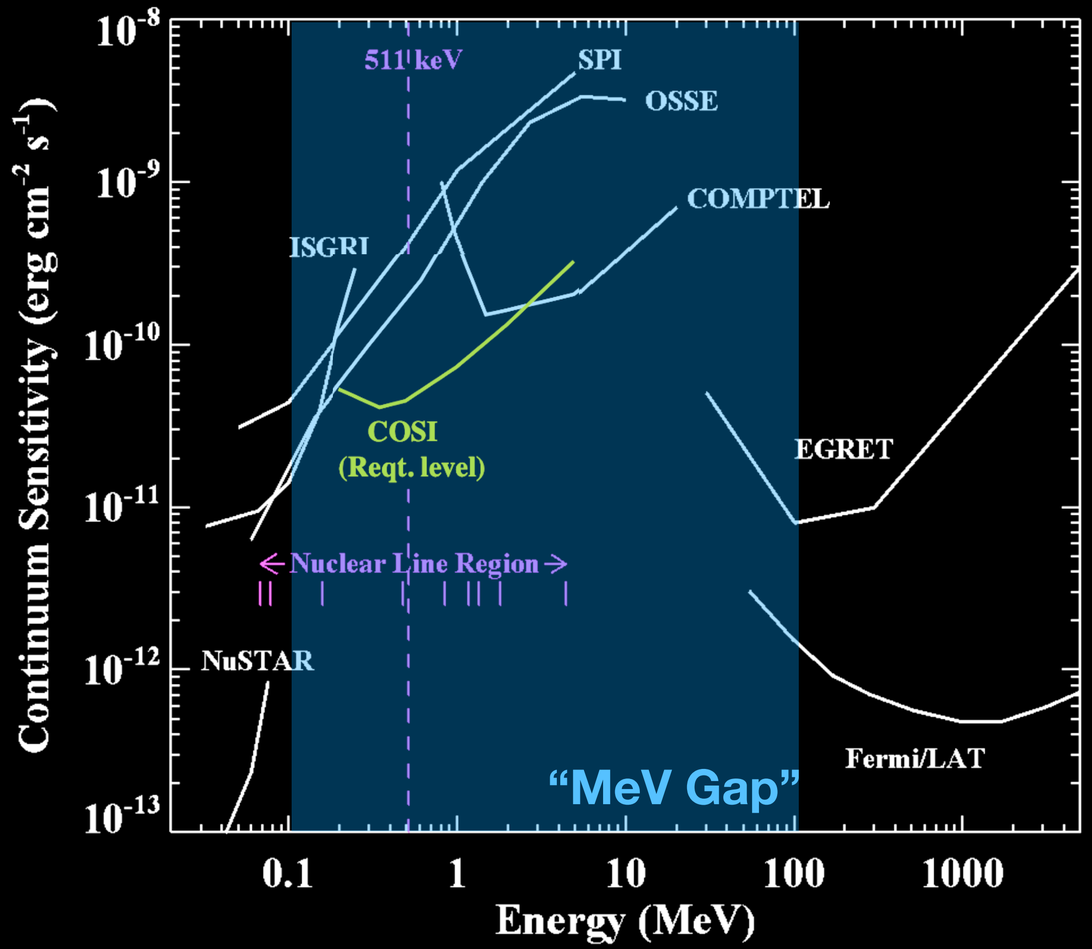
How did we get here?

Line sensitivity



Continuum sensitivity



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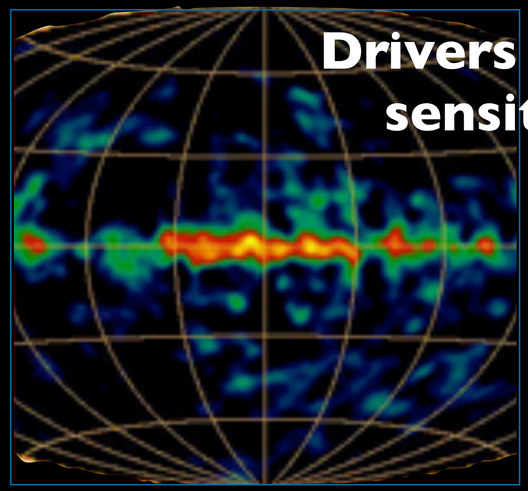
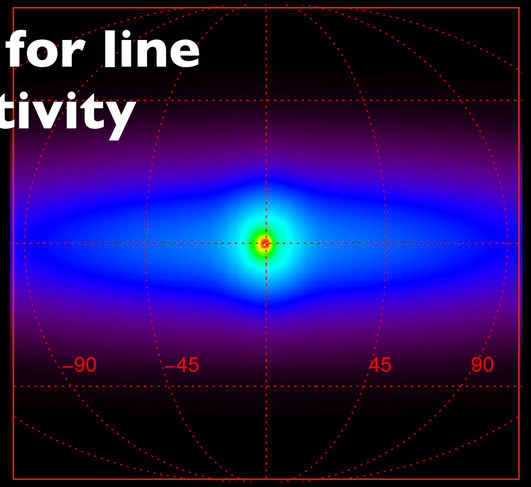
COSI main science objectives

The Science drivers

Reveal Galactic element formation



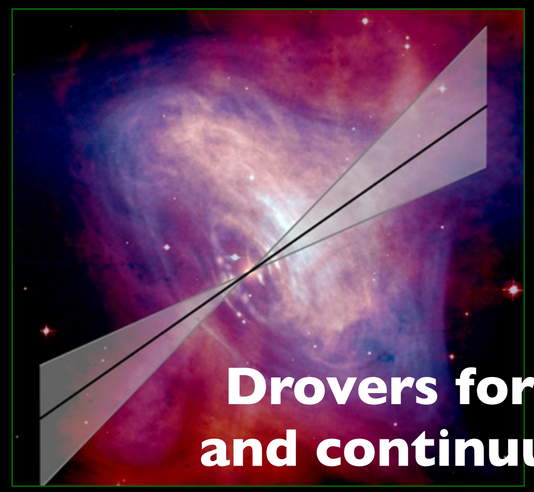
Drivers for line sensitivity

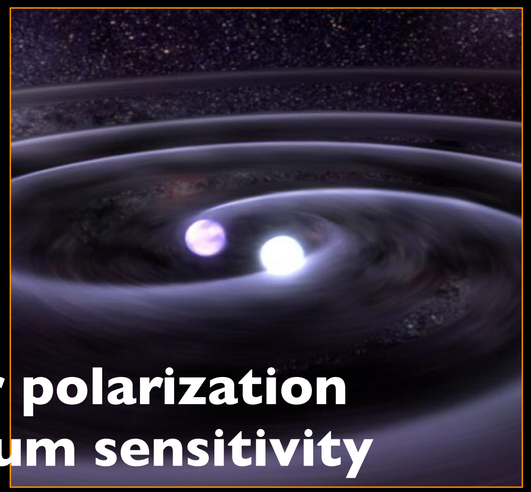


Uncover the origin of Galactic positrons

Gain insight into extreme environments with polarization

GRBs, AGNs





Drovers for polarization and continuum sensitivity

Probe the physics of multimessenger events

short GRBs (GW),
MeV Blazars (HE neutrinos)

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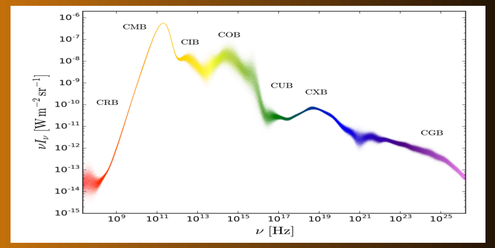
COSI main science objectives

COSI unlocks an observable for many more science!

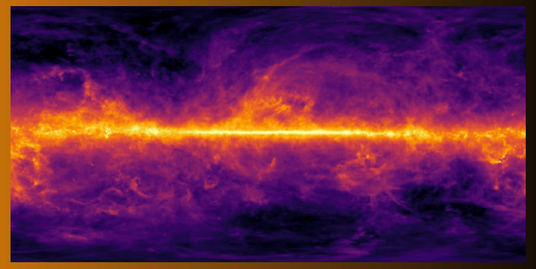
Some of these are natural extension of Fermi science

MeV gamma-ray background



Dark Matter

MeV Diffuse Galactic emission and CR propagation



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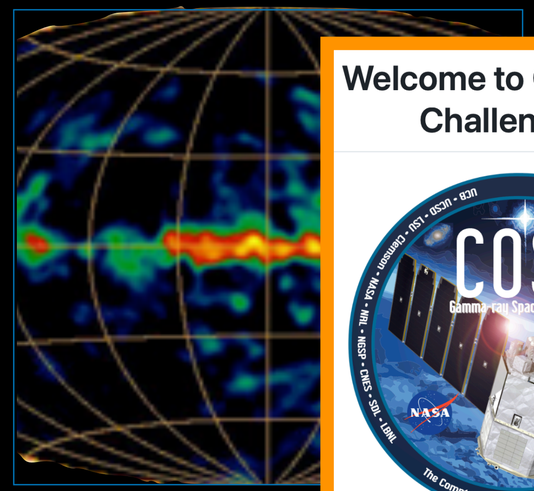

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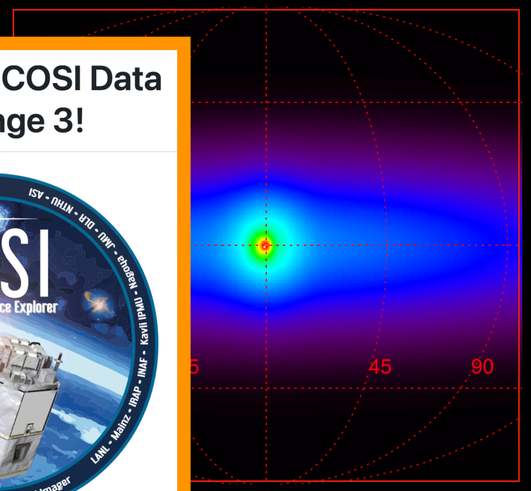

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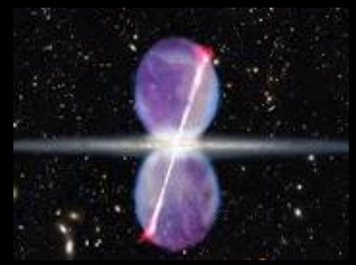
Accreting BH

Magnetars, pulsars

Fermi Bubbles



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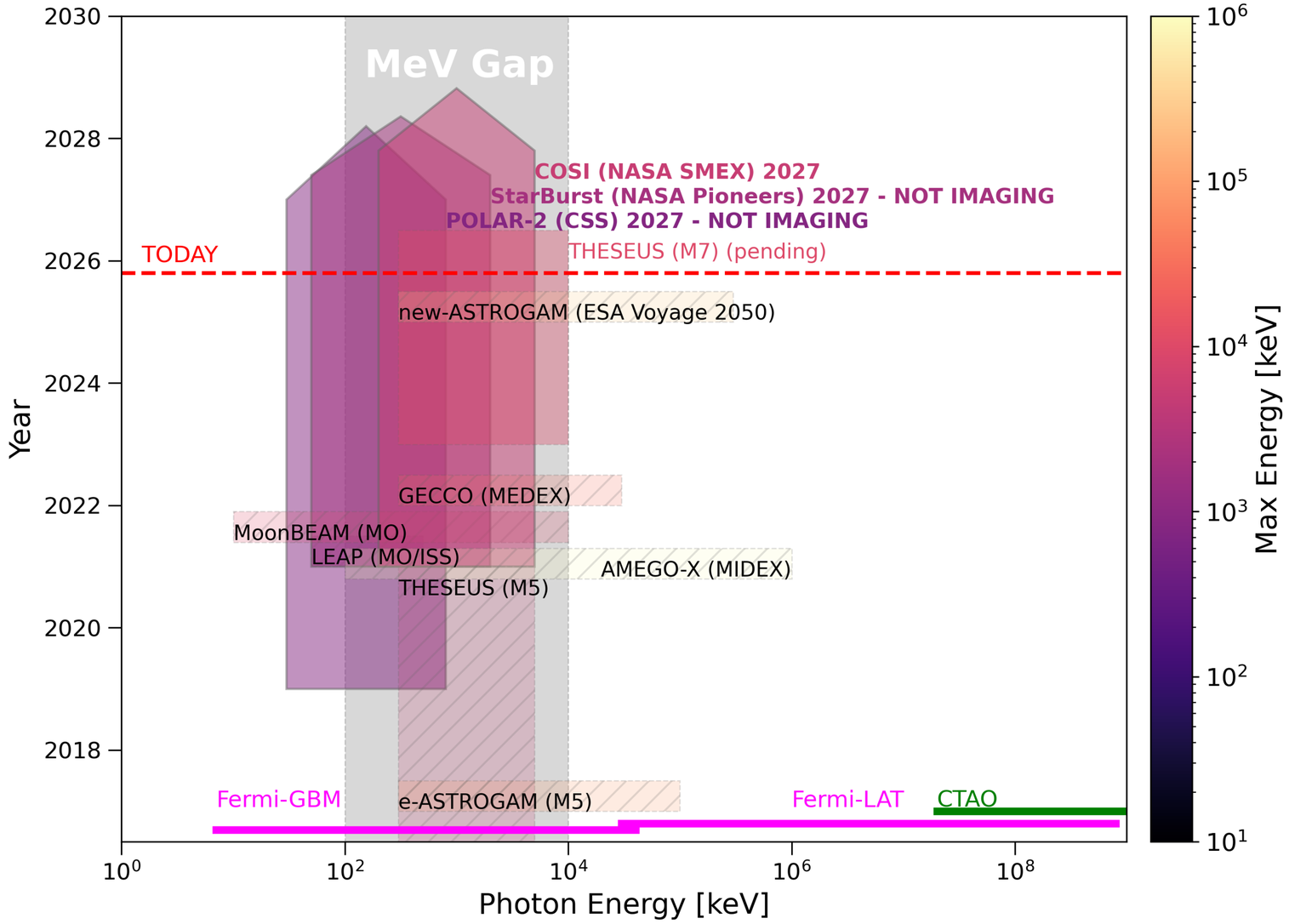
The near future

COSI

is the biggest gamma-ray mission currently expected to be launched with all-sky monitoring and imaging capabilities



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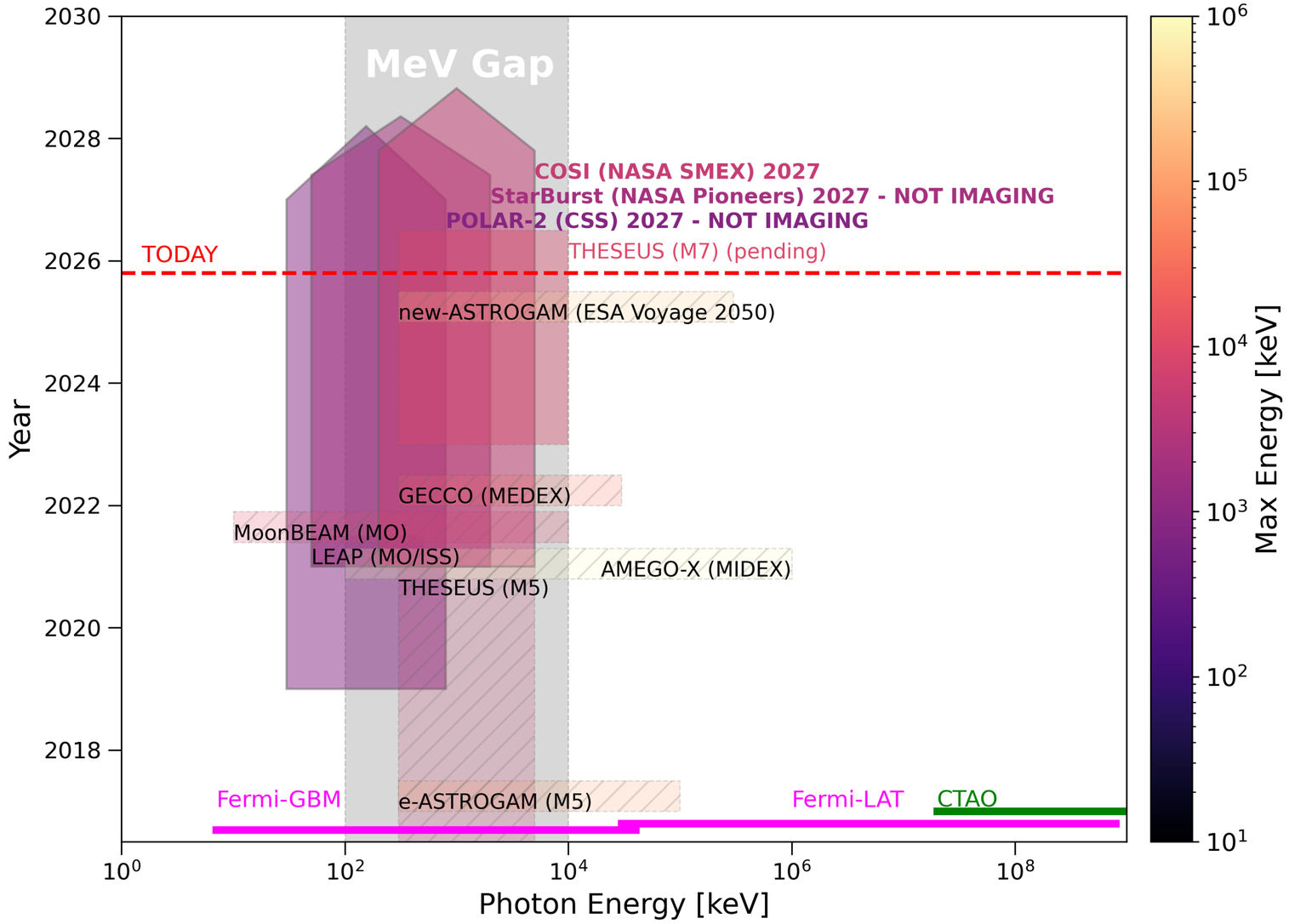
The near future

The **2020 decadal** recommendations don't make gamma-ray astrophysics a priority for **NASA**;

esa shut off INTEGRAL

COSI (1/10 of the cost of Fermi) is the biggest gamma-ray mission currently expected to be launched with all-sky monitoring and imaging capabilities



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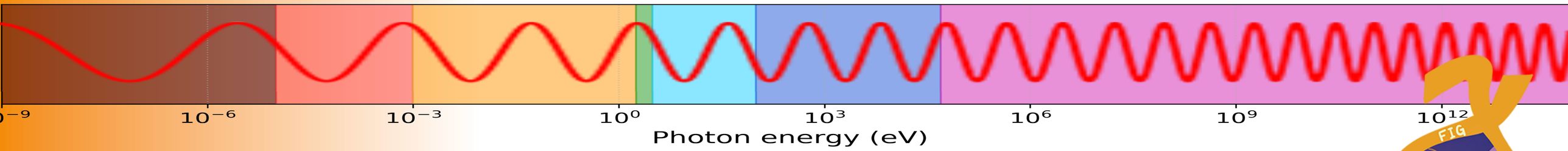
Future Innovations in Gamma Rays (FIG SAG)



STM - identify questions and which tech needs go with each

Rank Priorities within STM according to highest needs

Develop a compelling Science Message around the highest need case

Simplify the question… simplify… simplify… This is the public message

- What is the most exciting and credible science that only gamma-rays from space can do?
- What can you do with a small, medium, or probe scale mission?
- Two tracks identified:
  - high angular + energy resolution
  - wide-field monitor + fast response localization capability

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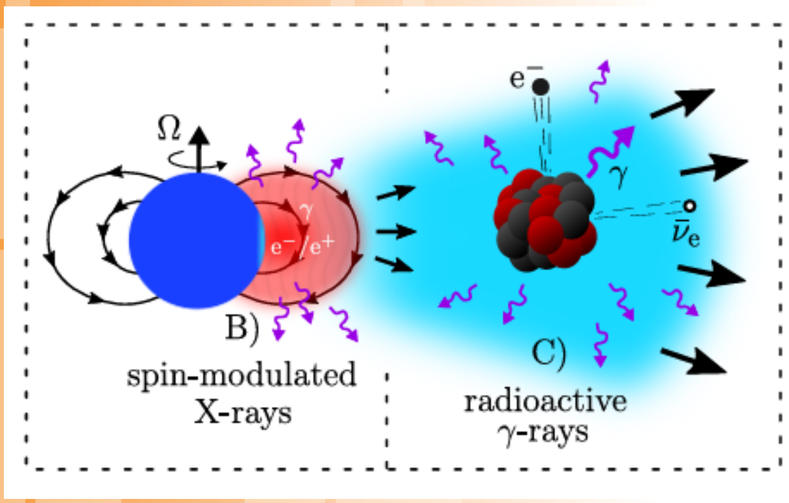
Nucleosynthesis through r-process

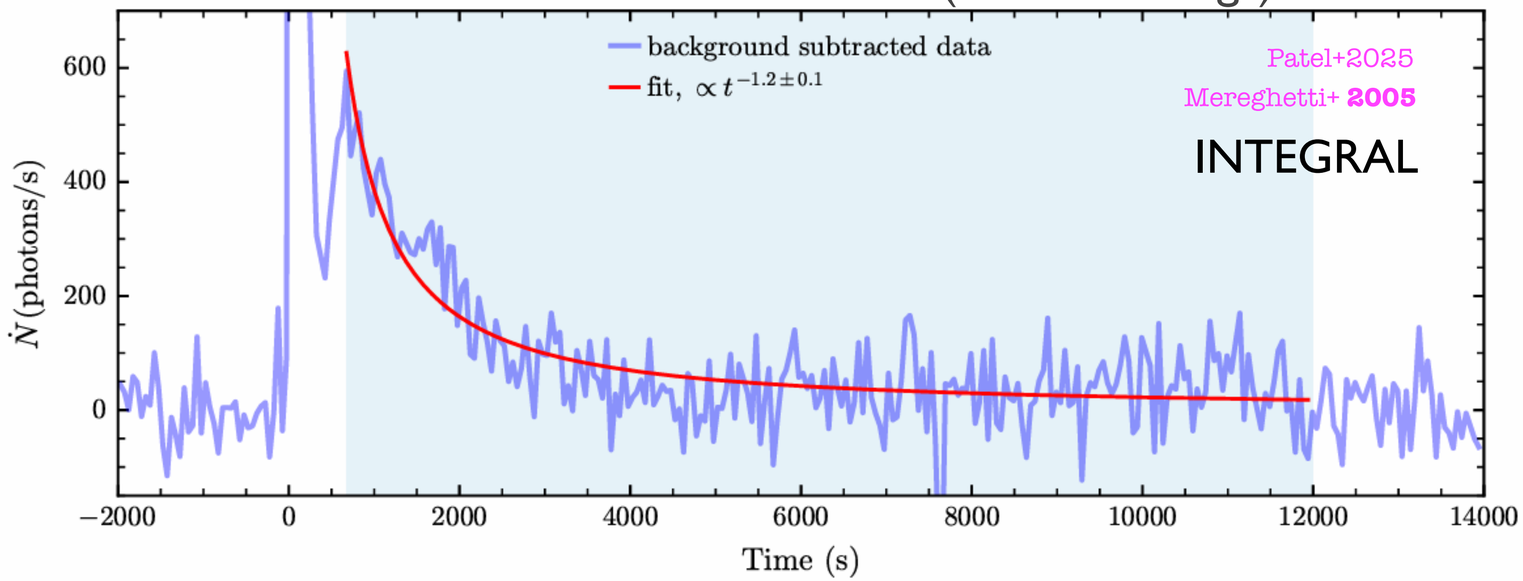
What are the sites of heavy elements nuclei synthesis?

- We did directly observed r-process signatures from **Kilonovae** (GW-GRB 170817, GRB 230307A), but it's not enough to explain the Galactic chemical evolution (Côté+ 2019)
- Based on stellar elemental abundance measurement on the Galaxy we need more heavy elements nucleosynthesis earlier in time

Model from: Patel et al. **2025**



2004 MGF from SGR 1806-21 (Eiso ~ 2^{46} ergs)



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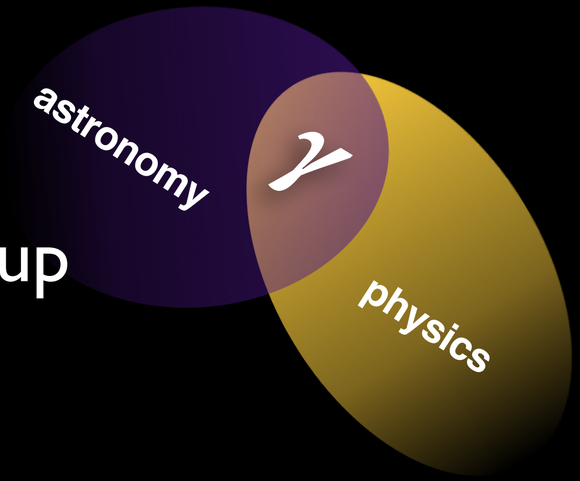
Main take away



- We don't have a secure big gamma-ray observatory lined up

do you have a plan B?

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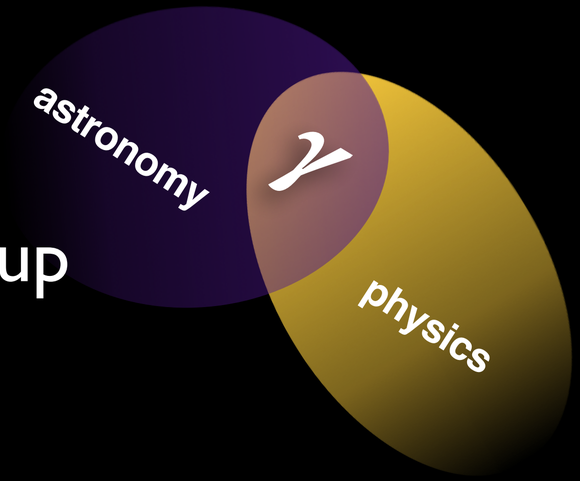
Main take away



- We don't have a secure big gamma-ray observatory lined up

do you have a plan B?

- For Next generation space-based gamma-ray mission: we should focus on science drivers unique to gamma rays from space

Origin of the elements
(through Nuclear lines)

Physics in extreme environments
(photon splitting)

What else?

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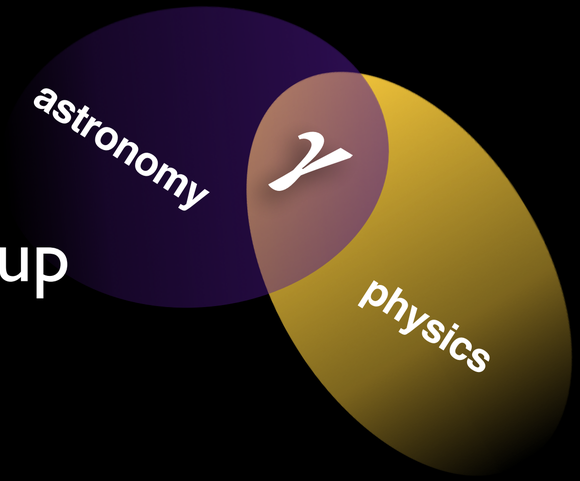
Main take away



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What else?

- We need to reverse the current workflow (ready-to-use technology asking for science cases)

Theorists

Observers

Instrumentalists

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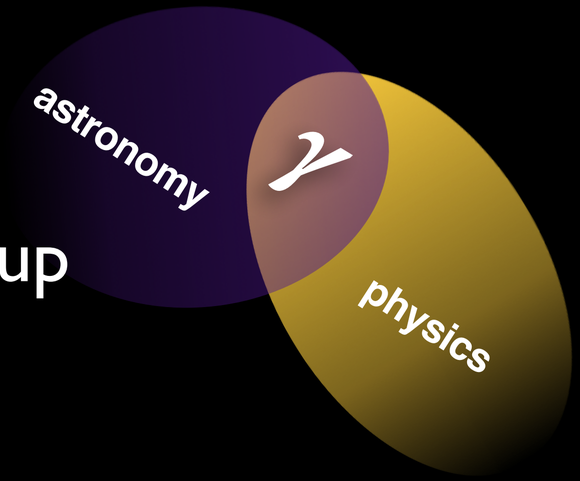
Main take away



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Origin of the elements (through Nuclear lines)

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What else?

- We need to reverse the current workflow (ready-to-use technology asking for science cases)

Theorists

Observers

Instrumentalists

- We need to do this now!

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Community Recognition of greatest achievements in gamma-ray Astrophysics from space

2011 *Rossi Prize*

… for the LAT and insights into **neutron stars, supernova remnants,** cosmic rays, **binary** systems, **active galactic nuclei**, and g**amma-ray bursts.**

2012 *Rossi Prize*

… for gamma-ray **flares** from the **Crab Nebula.**

2013 *Rossi Prize*

… for establishing a theoretical framework for understanding **gamma-ray pulsars**

2014 *Rossi Prize*

… for the discovery of the **Fermi Bubbles**.

2018 *Rossi Prize*

… for the discovery of Gamma-rays coincident with a **neutron-star merger** gravitational wave event GW-GRB 170817

2025 *Cocconi Prize*

… for detection and cataloging of thousands of new gamma-ray **sources**, including pulsars; the first EM counterpart to a **neutrino** IceCube event; the identification of >2000 **GRBs**; and the first detection of EM counterpart to the **gravitational wave** event GW170817

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TeVPA

Thank you!

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LSU

Department of
Physics & Astronomy

TeV Particle Astrophysics

TeVPA

Valencia 2025

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The role to public data to scientific success

- **Transparency • Reproducibility • Reuse** — the foundations of scientific progress

- **Public archives + maintained analysis environments** + **Open tools** (HEASARC, FSSC, MAST,…) enable science far beyond mission teams
    - **Global participation:** hundreds of papers produced by independent researchers using public data Standardized calibration pipelines and response files allow seamless cross-mission analyses

- **Return on investment:** every dollar spent on open data and infrastructure multiplies scientific output and long-term mission legacy

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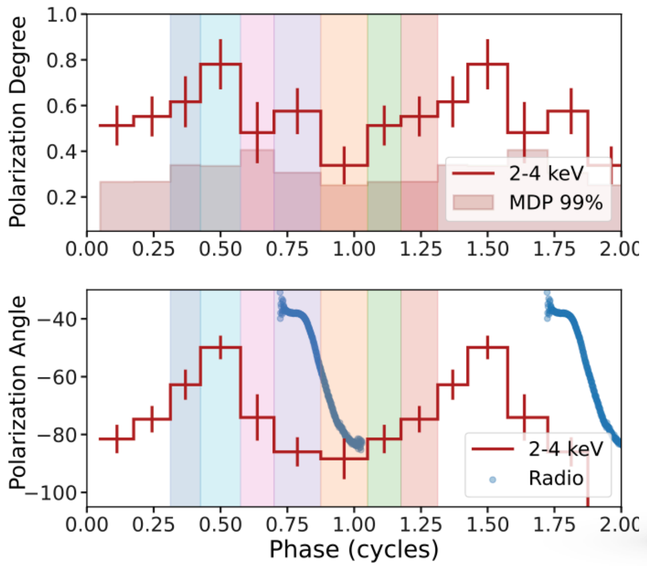
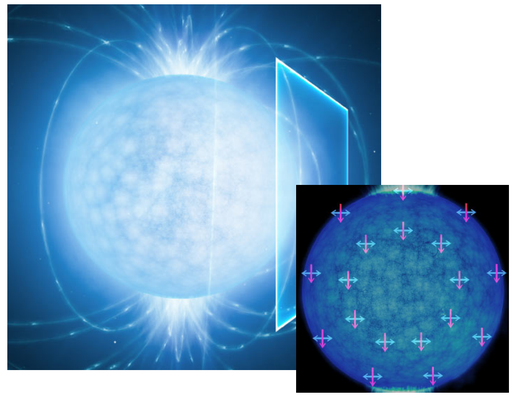
TeVPA

Testing fundamental physics

Is QED in super-critical magnetic field verified?

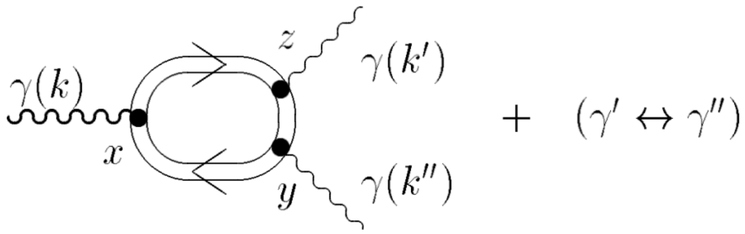
Vacuum birefringence
Radio Magnetar,
soft X-ray polarization



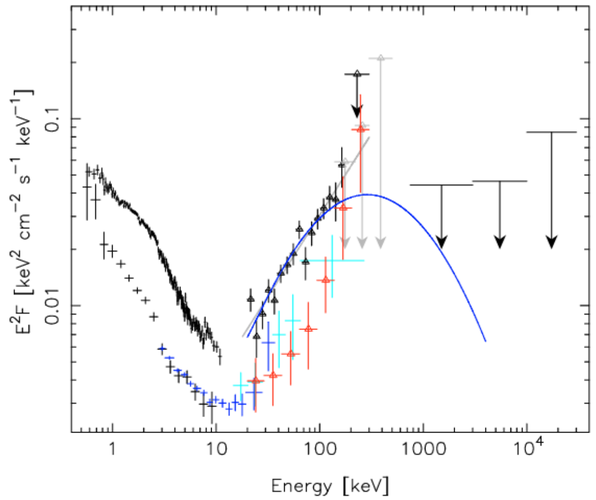


Stewart et al 2025 (arXiv:2509.19446v)
Submitted to Nature

Photon Splitting
Magnetars, high-B pulsars
~ MeV



Zorawar Wadiasingh et al 2019



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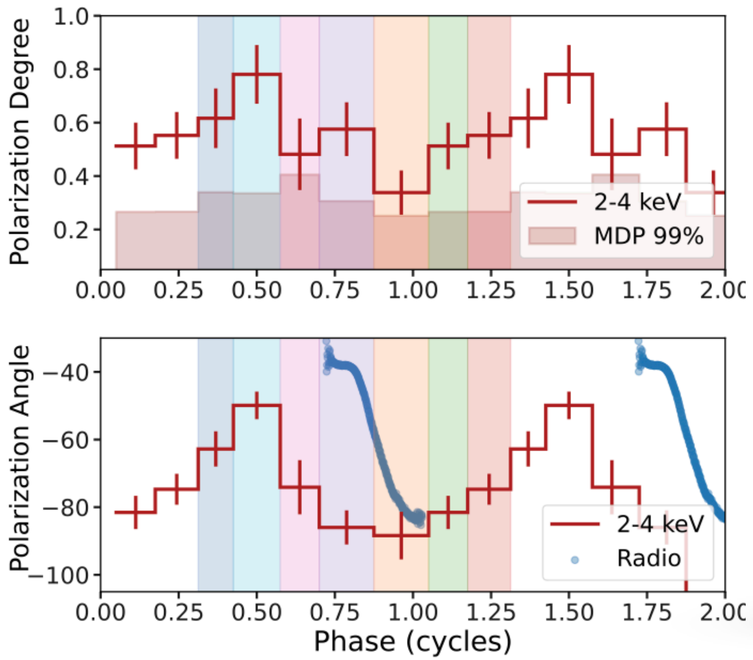
Magnetars as Physics labs

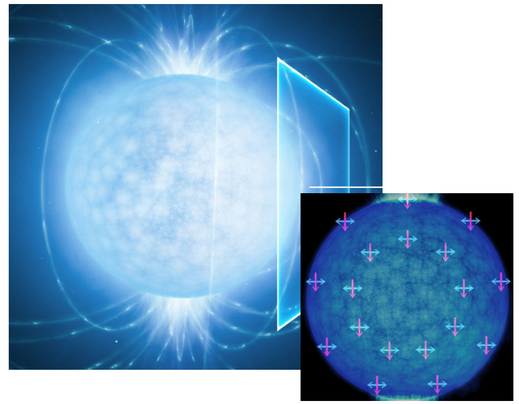
Magnetars host the strongest magnetic fields known in the Universe, up to B~10^{15}G, far above the QED critical field $B_{QED} = 4.4\times10^{13}$ G.

In such environments, light itself becomes nonlinear.

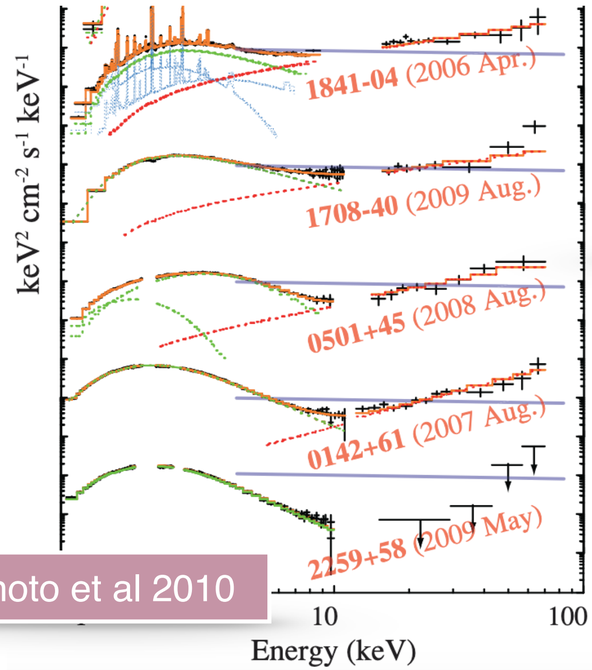
QED predicts higher-order effects such as:

- **Vacuum birefringence (soft X-rays):** polarization-dependent refractive indices in the magnetized vacuum.
- **Photon splitting ($\gamma\rightarrow\gamma\gamma$)**: a higher-order QED process suppressing hard-photon escape above a few MeV in ultra-magnetized regions (also a polarization sensitive phenomenon).





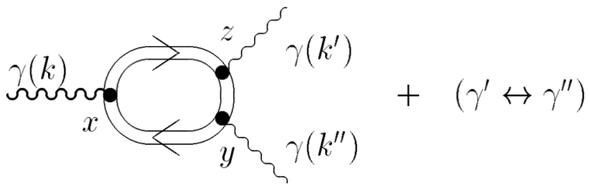
Stewart et al 2025 (arXiv:2509.19446v) Submitted to Nature



Enoto et al 2010

More details for Compton telescopes:

Zorawar Wadiasingh et al 2019



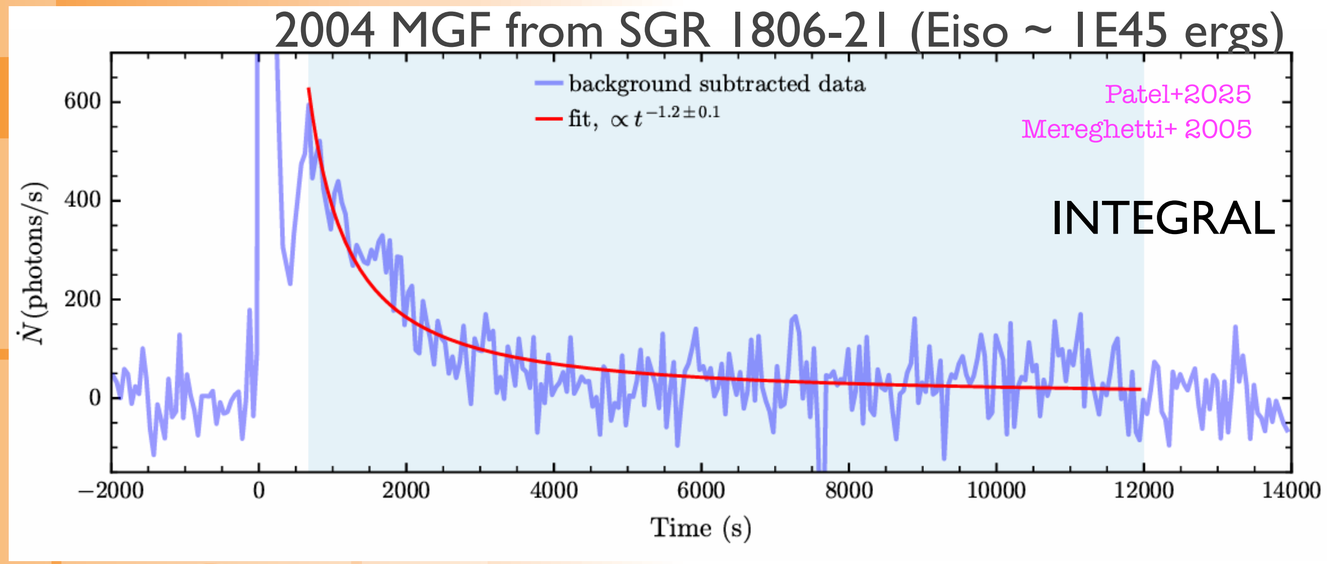
Nucleosynthesis through r-processes

What are the lieux of synthesis of heavy elements?

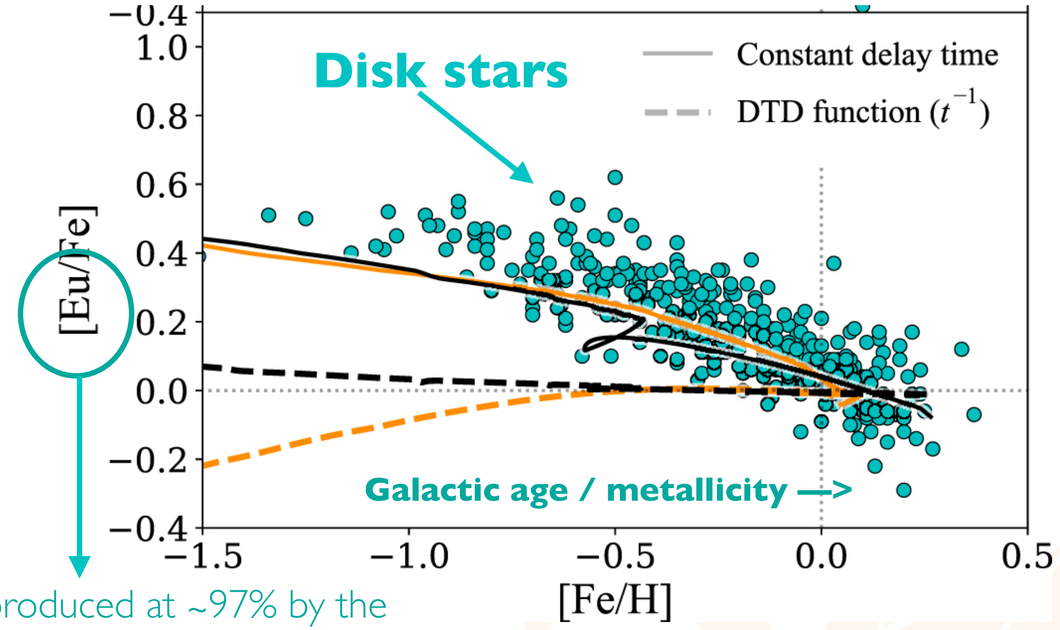
- We did directly observed r-process signatures from **Kilonovae** (GW-GRB 170817, GRB 230307A)
- NSs **take time** to inspire and then merge (coalescence delay-time distribution (DTD)
- Need of an extra Eu produced in the early universe, then less and less with increasing metallicity

Model from: Cehula et al. **2024**

2004 MGF from SGR 1806-21 (Eiso ~ 1E45 ergs)



Côté+ 2019 "Galactic chemical evolution"



Eu was produced at ~97% by the r-process when Solar Syst formed

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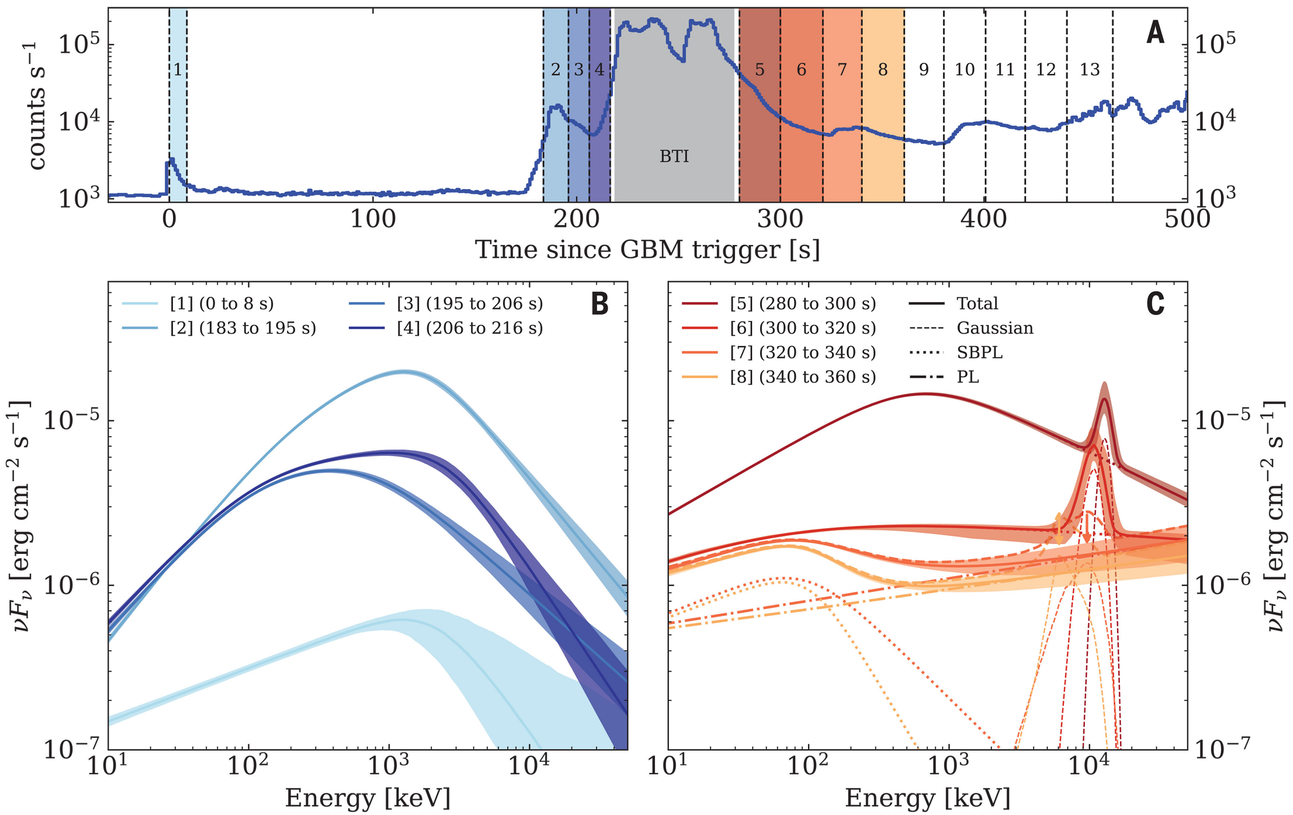
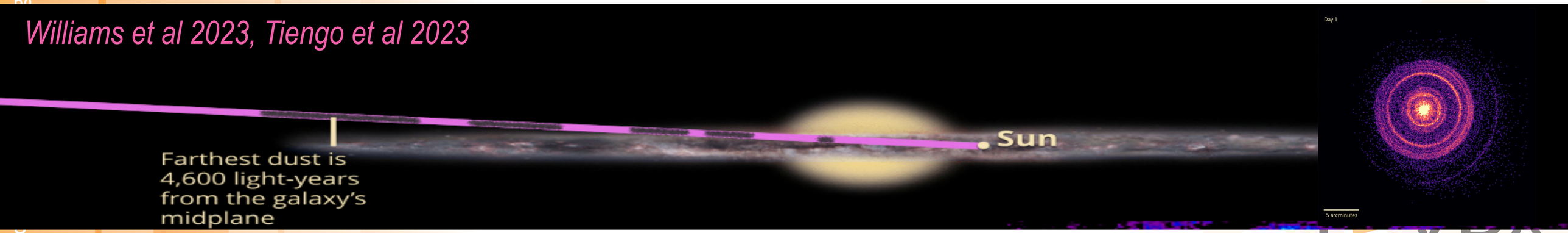
The ‘Ravasio’ line

A mega–electron volt emission line in the spectrum of a gamma-ray burst.

Ravasio et al. 2024



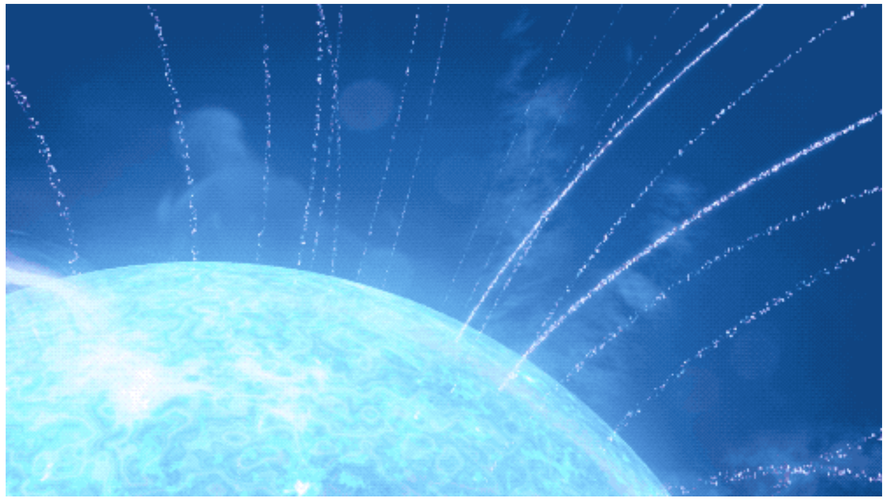
Williams et al 2023, Tiengo et al 2023

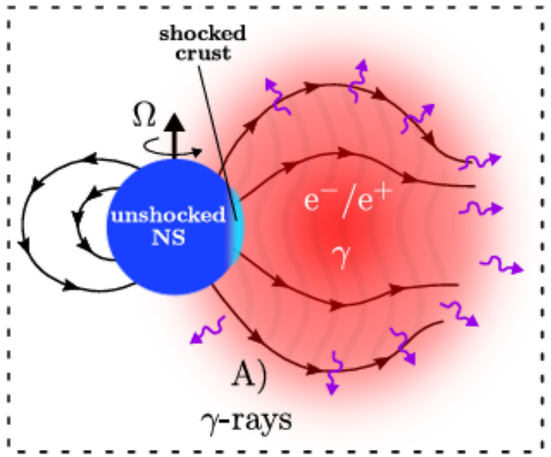


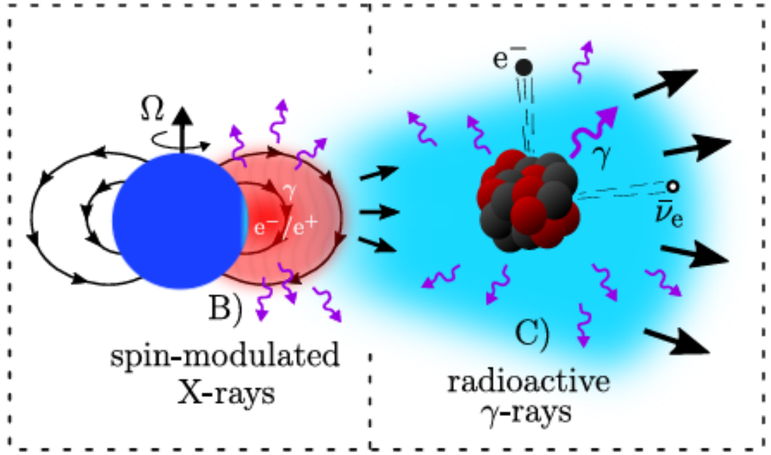
ro@lsu.edu

R-process from MGFs ??

Cehula et al. 2024







1) MGF: NS crust cracks e+e- plasma fireball explosion

2) Shock wave onto the crust heats up baryonic matter

3) baryonic matter has enough energy to escape

4) Expansion and cooling + "α-rich freeze-out"

5) Formation of seed heavy radioactive nuclei

R-process from MGFs !!

Assuming mass ejection occurs during/promptly following the initial flare, the unbound ejecta will approach homologous expansion at t > 100 s.

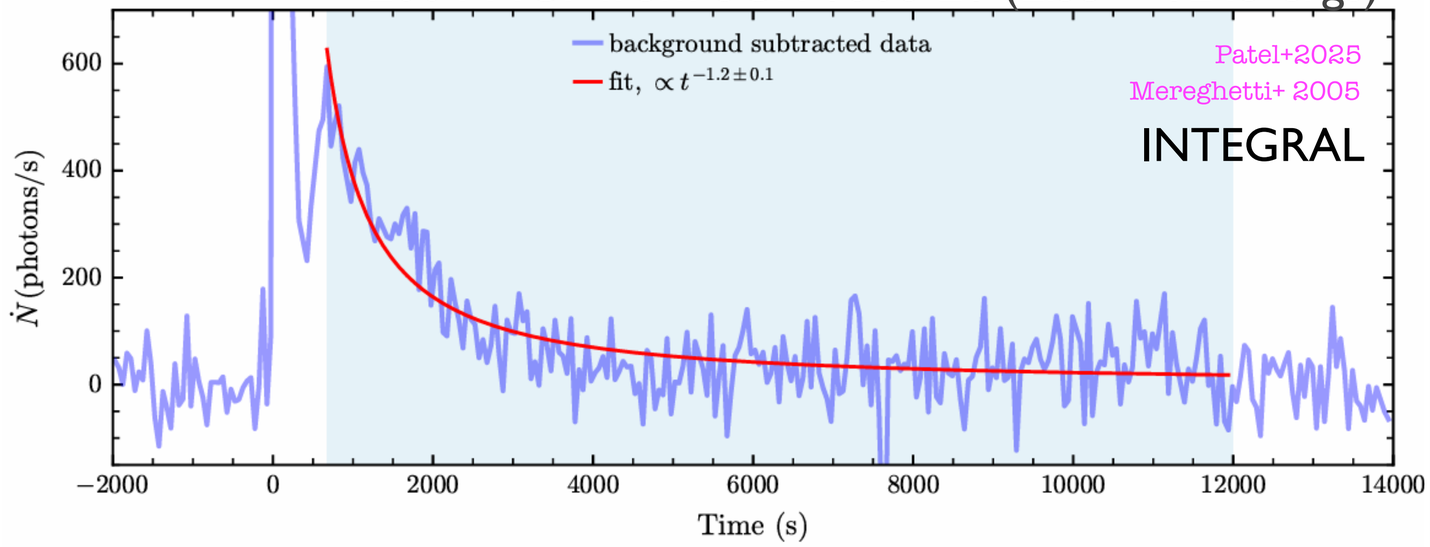
Initially, gamma rays don't escape (photoionization and Compton scattering).

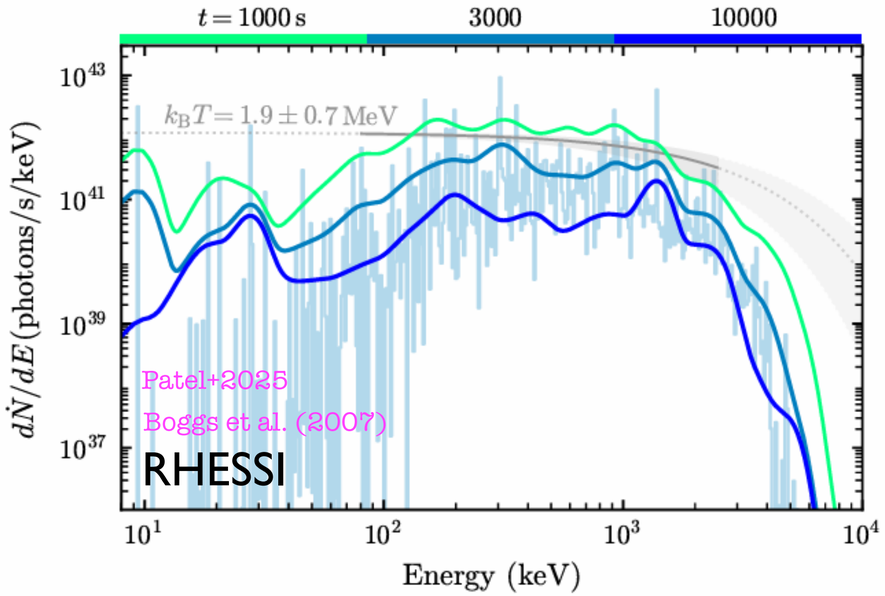
Radioactive energy generation rate of r-process material is:

$$\dot{q}_{\rm r}(t) \approx 5 \times 10^{12} \left(\frac{t}{10^3\ {\rm s}} \right)^{-\alpha} {\rm erg\ s^{-1}\ g^{-1}}$$

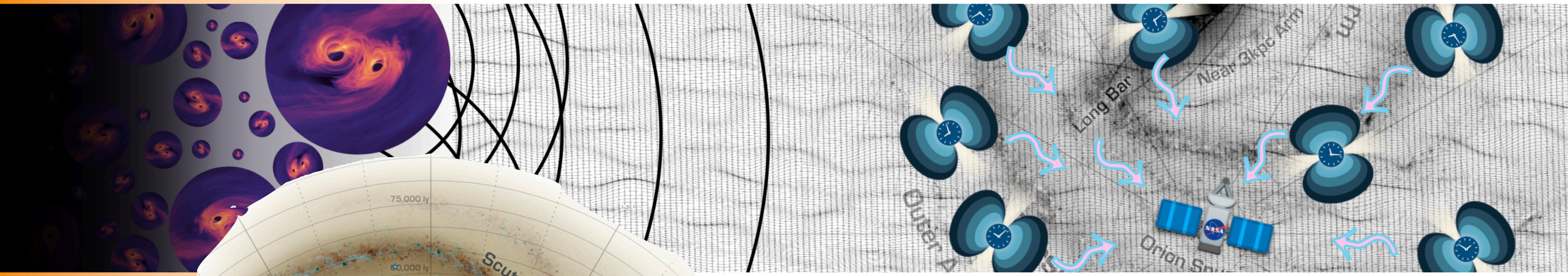
α ≈ 1.1 − 1.4

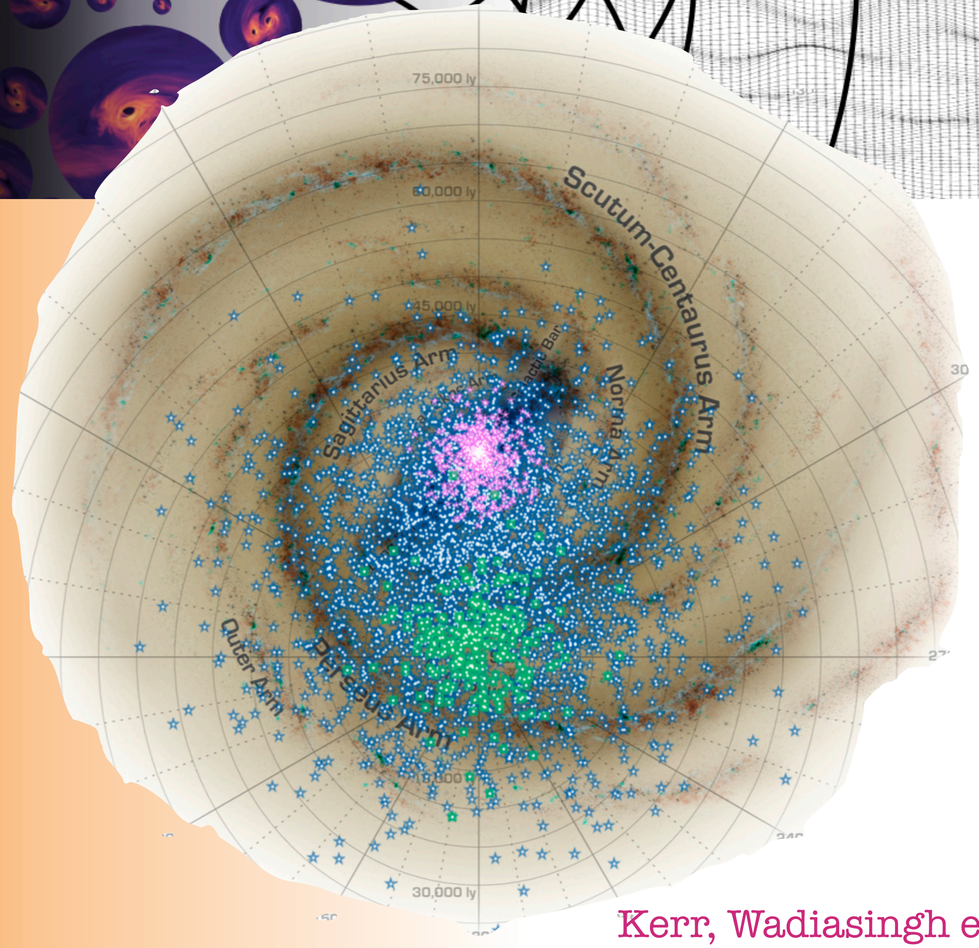
2004 MGF from SGR 1806-21 (Eiso ~ 1E45 ergs)





Future γ-PTA?



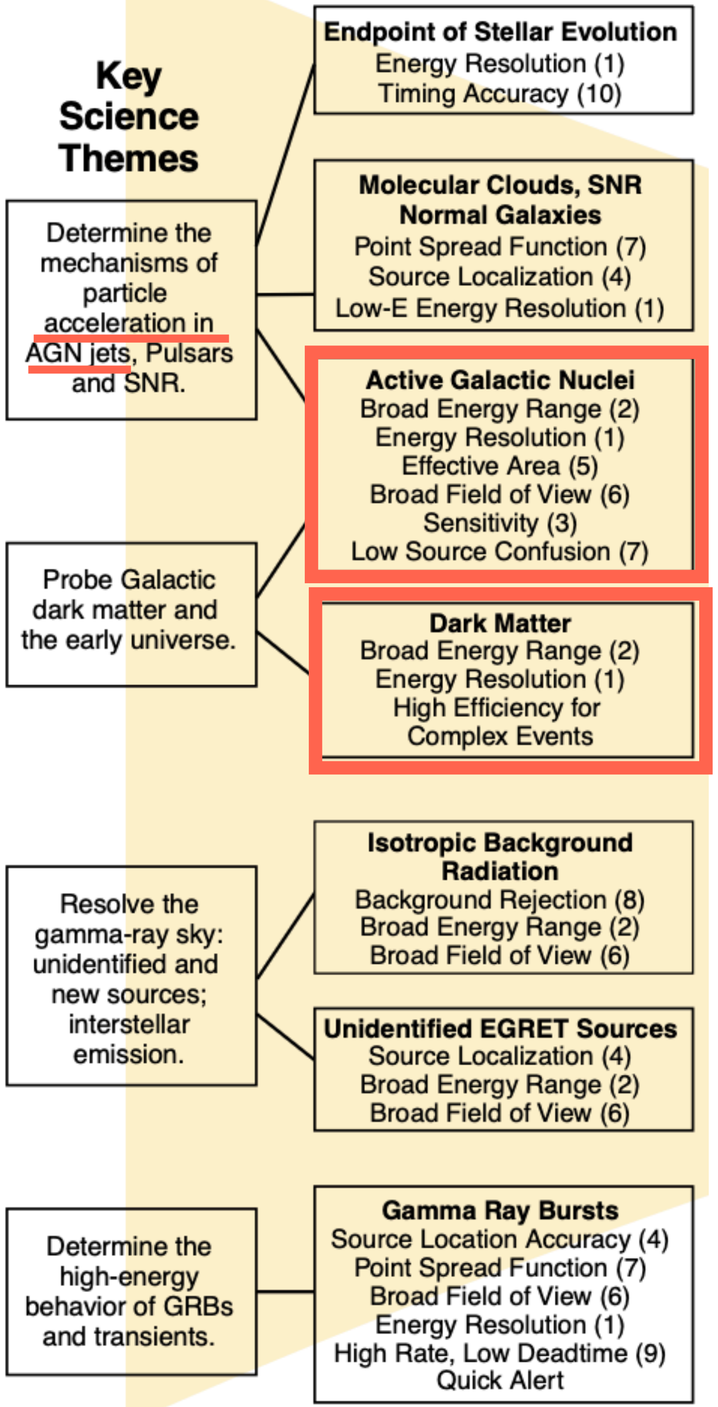


Amplitude of the stochastic GW background $\mathcal{A}_{\rm gwb} \sim 2\times10^{-15}$

Index	Configuration	$N_{\rm disk}$	$N_{\rm bulge}$	$N_{\rm bulge}$	A_{15}
	$A\Omega\times$, PSF$\times$	S1	S2: AIC	S3: Disk	
1	1, 1.00	261	0	1	10.5
2	1, 0.33	577	1	14	7.4
3	1, 0.10	1193	8	86	5.7
4	10, 1.00	863	4	43	3.0
5	10, 0.33	2181	60	285	2.1
6	10, 0.10	5037	456	1035	1.6
7	30, 1.00	1475	23	140	1.6
8	30, 0.33	3707	234	661	1.1
9	30, 0.10	7953	1297	1827	0.9

sensitivity after 12 yr

Kerr, Wadiasingh et al. 2025 (in preparation)



From the original Fermi-LAT proposal

Questions to be answered in 2008:

What powers the relativistic jet? matter-drive, to magnetic-driven?
What is the composition of the jet? Hadronic or Leptonic?
What is the acceleration mechanism? shock acceleration or magnetic reconnection?

What is the nature of dark matter?

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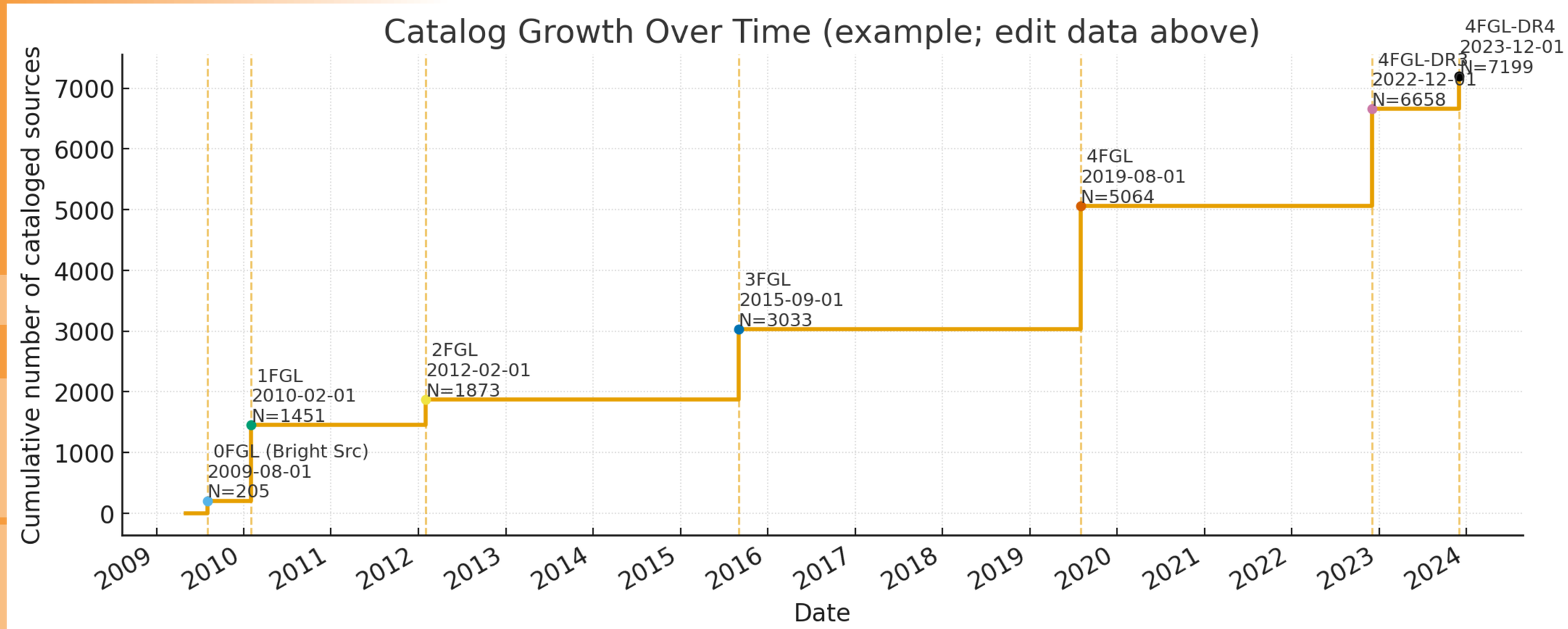
Gamma-ray Sources



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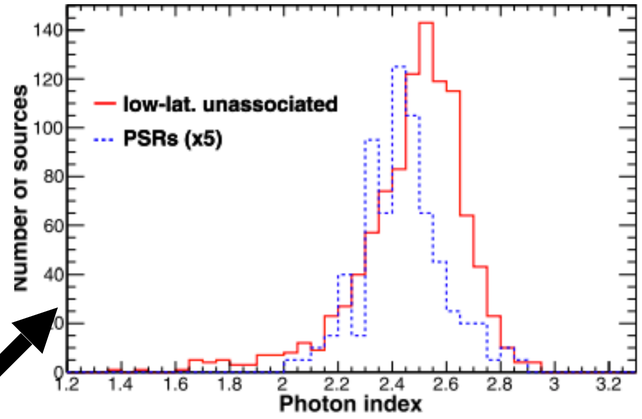
TeVPA

Soft Galactic Unassociated LAT Sources

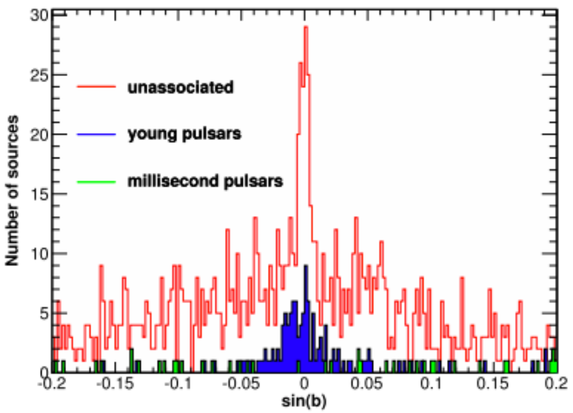
- Many high-energy sources along the Galactic plane remain unidentified, but with features that indicate they may be MeV bright.

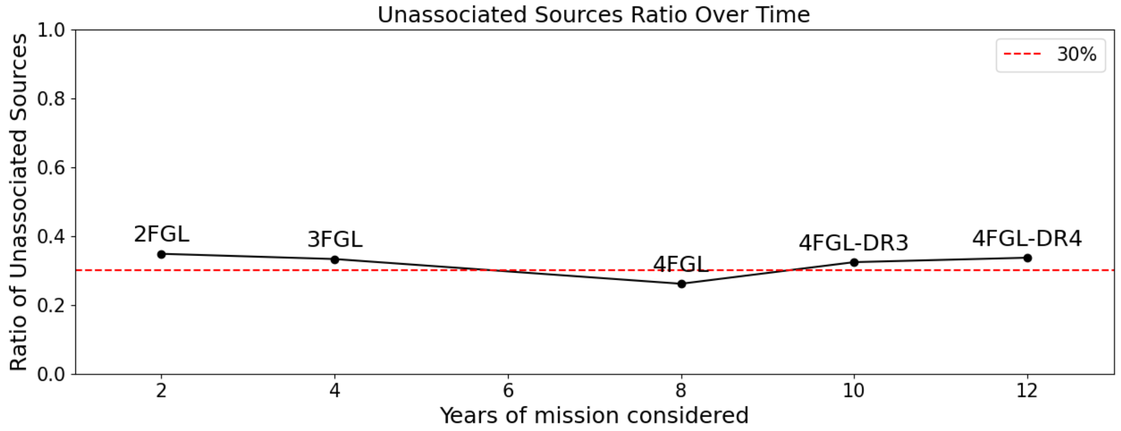
- Exhibit soft ($\Gamma \sim 2.6$) LAT spectra
- Low-latitude ($|b| \sim 1°$)
- Clustered near Galactic Center and other high-density areas
- May be parts of the diffuse Galactic

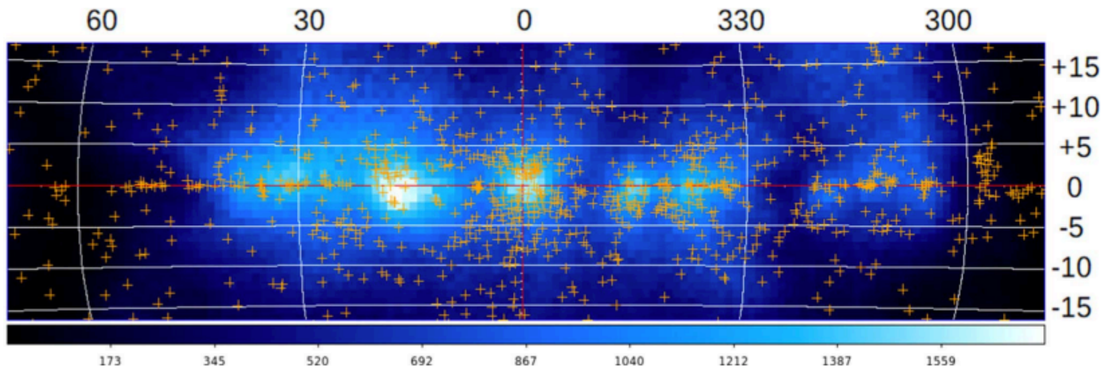
Abdollahi+2022.



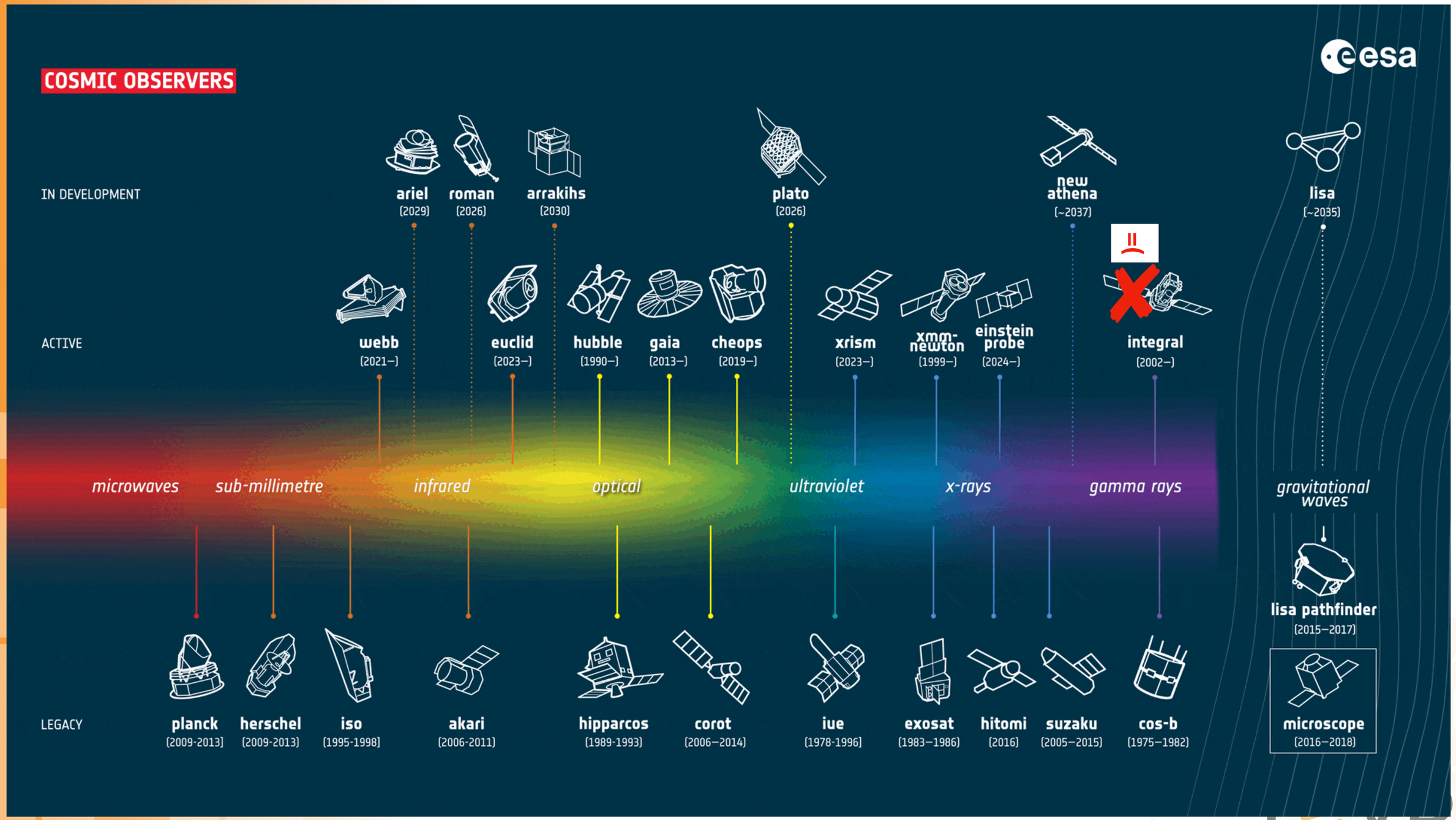
Abdollahi+2022.







Abdollahi+2022.



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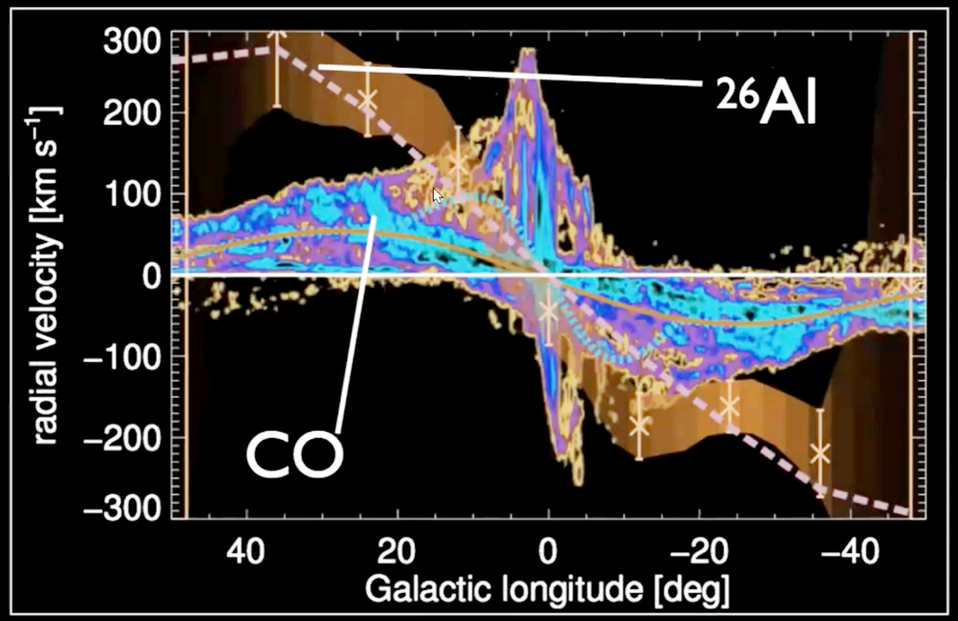
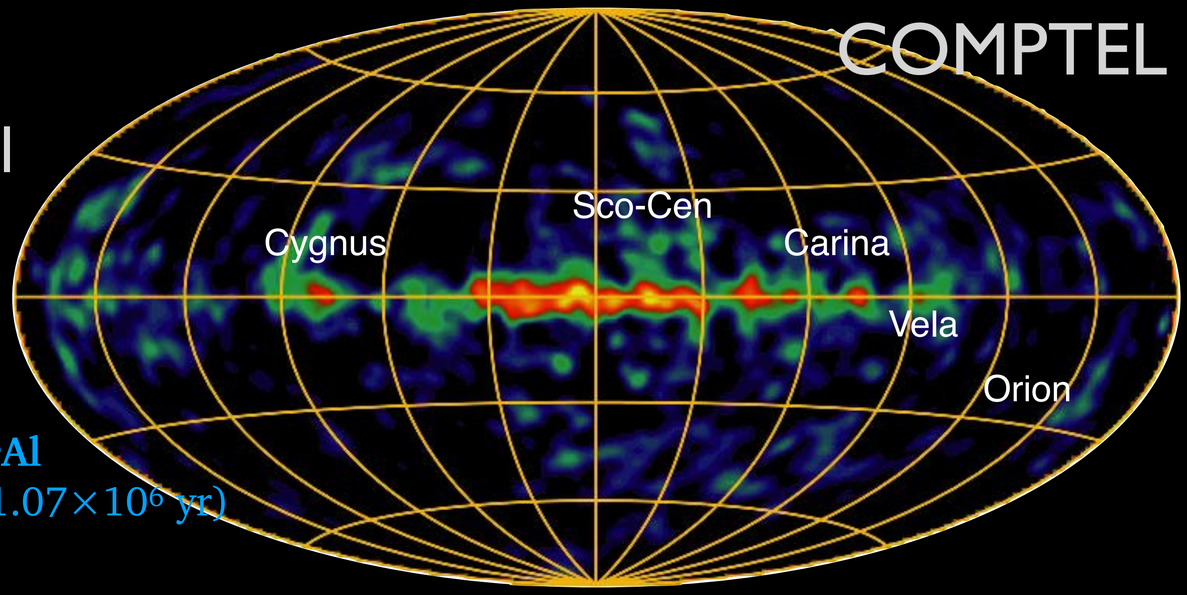
Mapping ^{26}Al in our Galaxy …

^{26}Al is a tracer for SN activity in the Galaxy

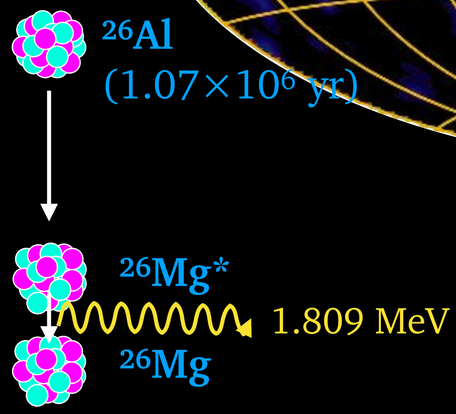
Not smooth: hot spots consistent with spiral arms and active star-forming regions



Kretschmer, Diehl, Krause et al. 2013, A&A 559, A99
Krause, Diehl et al. 2015, A&A 578, A113



Plüschke+ 2001



- How to explain such high velocities?
- What spiral arms geometry can explain this?

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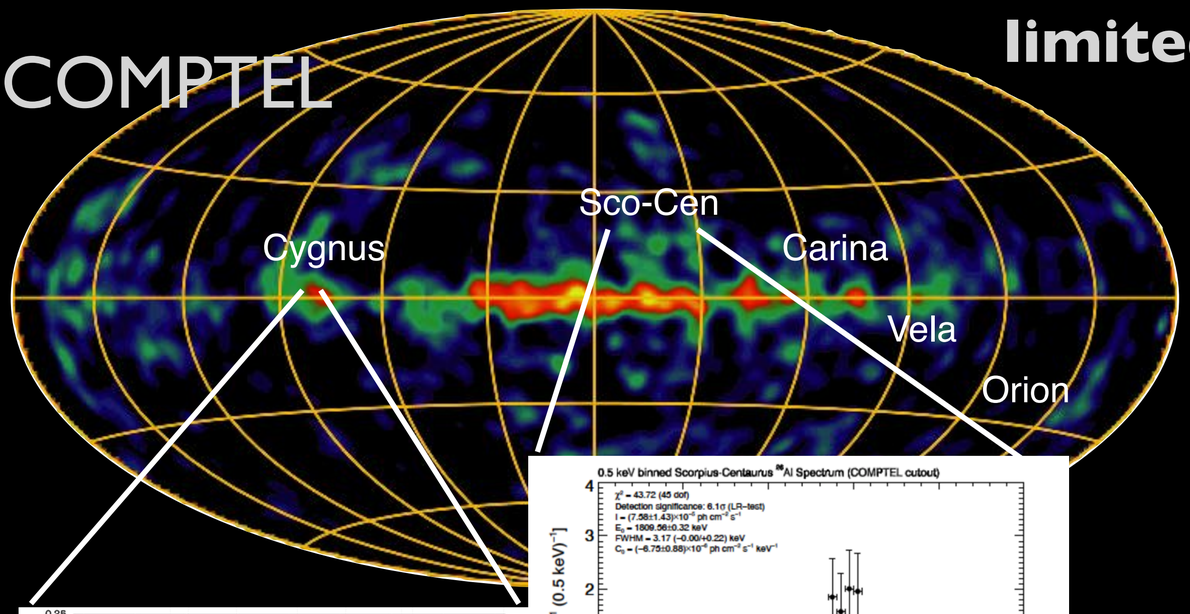
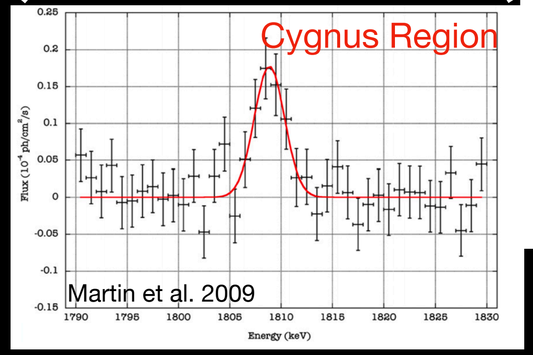
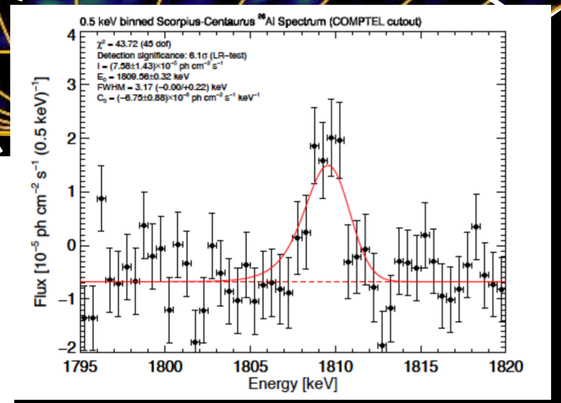
Mapping ^{26}Al in our Galaxy …

INTEGRAL/SPI investigated individual regions, but it has **limited imaging capabilities** for extended sources

COMPTEL

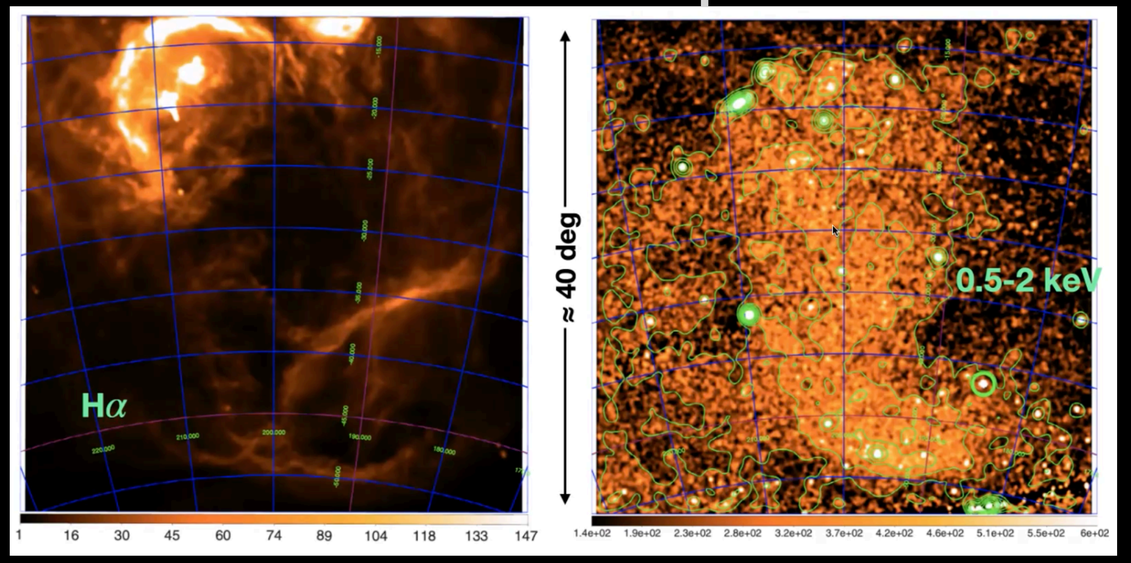






INTEGRAL/SPI

Orion-Eridanus superbubble



Detecting an ^{26}Al shock front could give a better picture of what is going on here and in general in superbubbles from SN feedback

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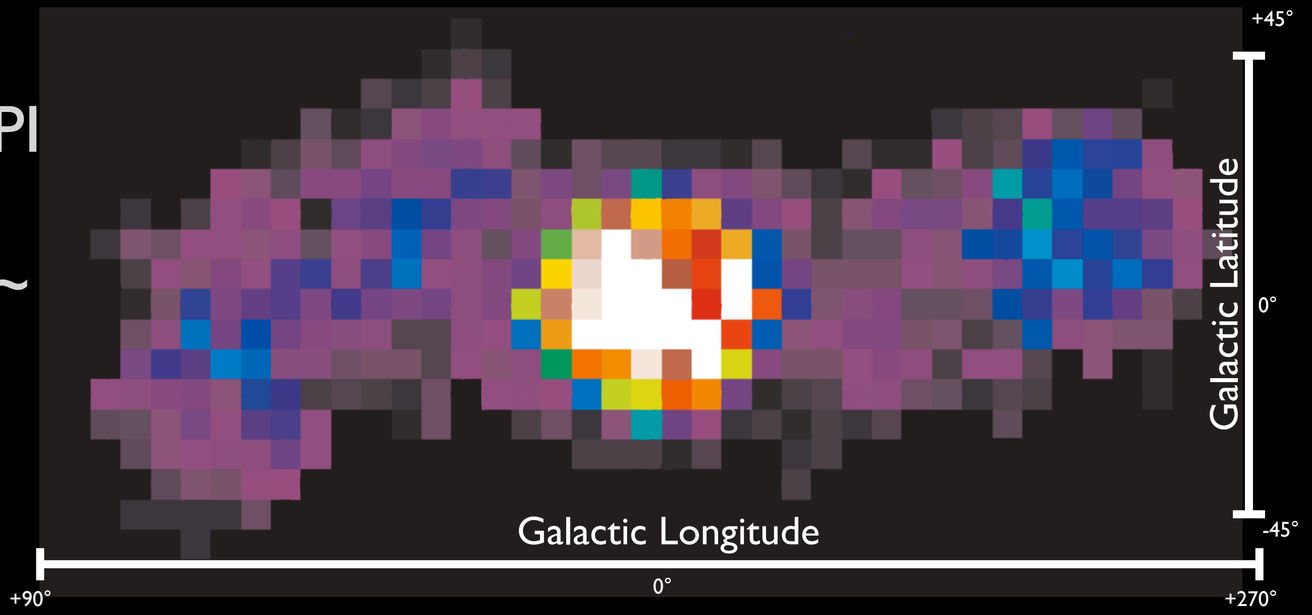
Mapping the 511 keV line

- Discovered in 1969 (Haymes+1969)
- First imaging by OSSE (Purcell+1997)
- Observations improved by INTEGRAL/SPI
  - ❋ postron-electron annihilation
  - ❋ Large scale, smooth emission, peaked ~ GC
  - ❋ Tot production rate of e+ in the MW: $4.3+/-1.7 \times 10^{43}$ e^{+}/s (Siegert+2016)

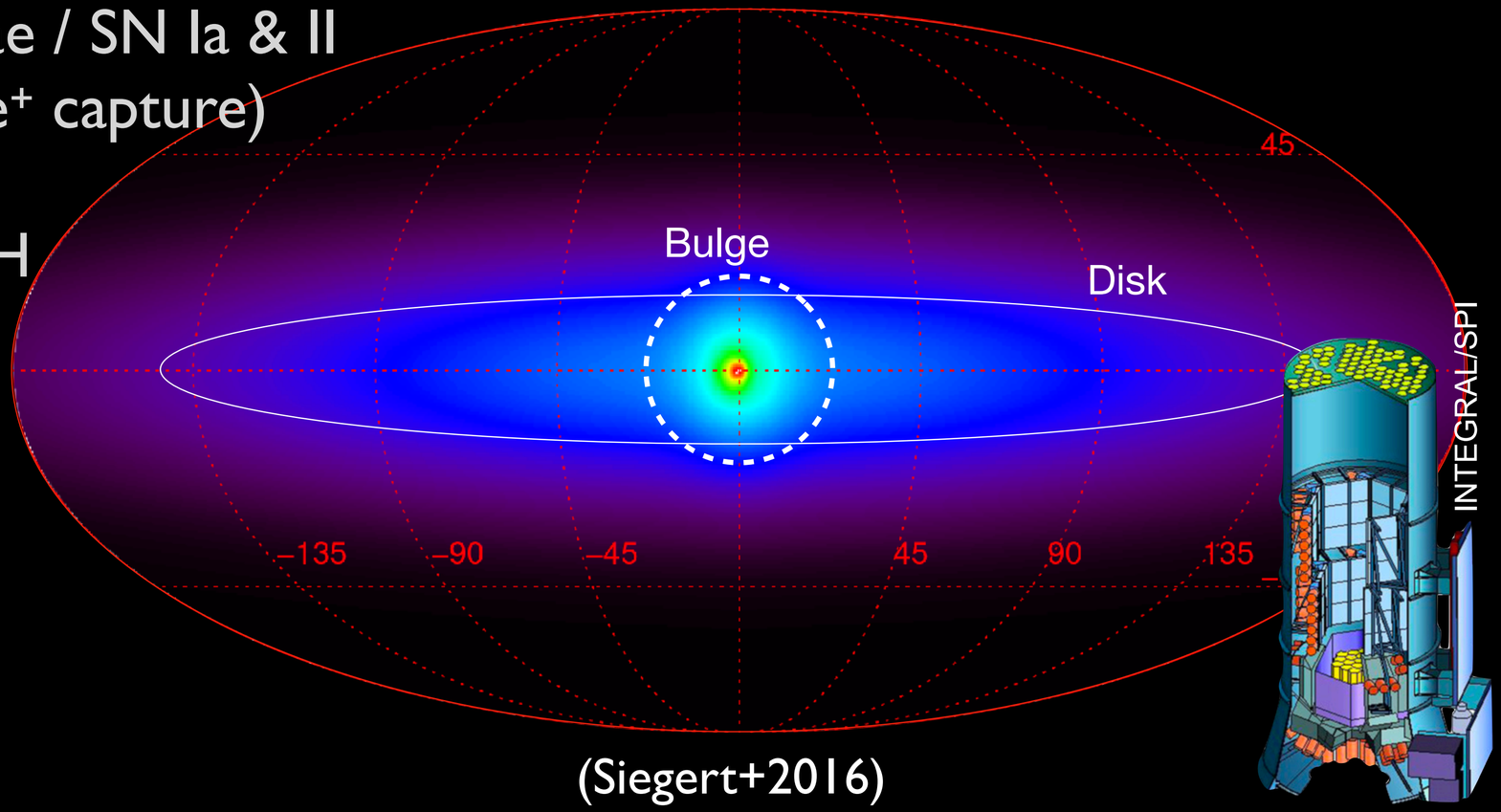
Map: INTEGRAL/SPI (Bouchet+10)



- ❋ What are we seeing?
- ❋ If positron annihilation, what produces those positrons?
- ❋ Why does it look like that? like nothing else!?!

Mapping the 511 keV line - INTEGRAL

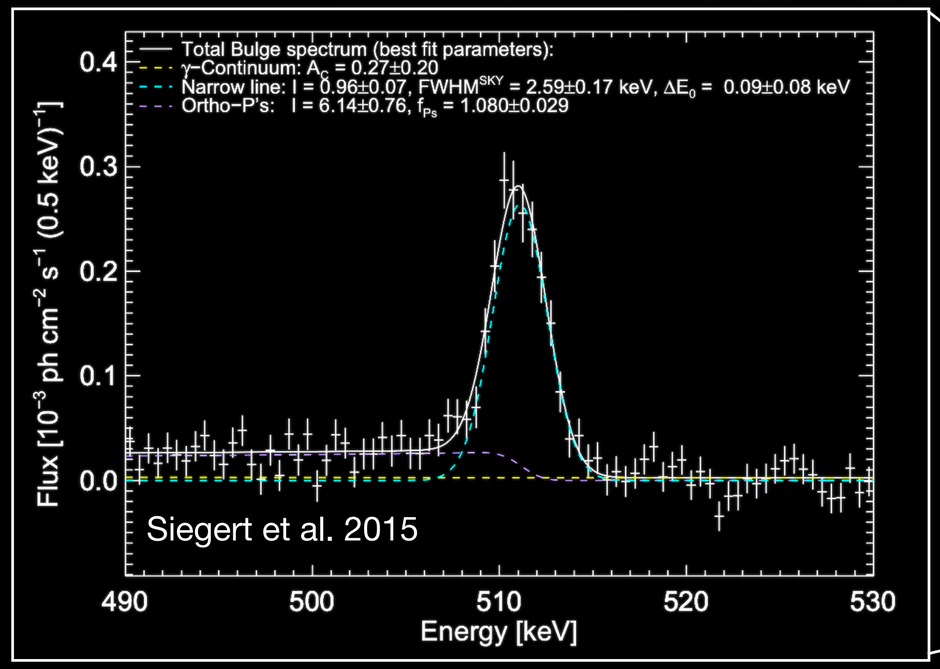
- Should trace nucleosynthesis, but spatial distribution is unlike any other wavelength
- Many expected sources of positrons:
  - massive stars / Novae / SN Ia & II
  - Stars (stellar flares, e^+ capture)
  - XRBs/Microquasars
  - Sgr A* / Accreting BH
  - CR (p-p collisions)
  - Pulsars
  - Dark Matter
  - .... ?

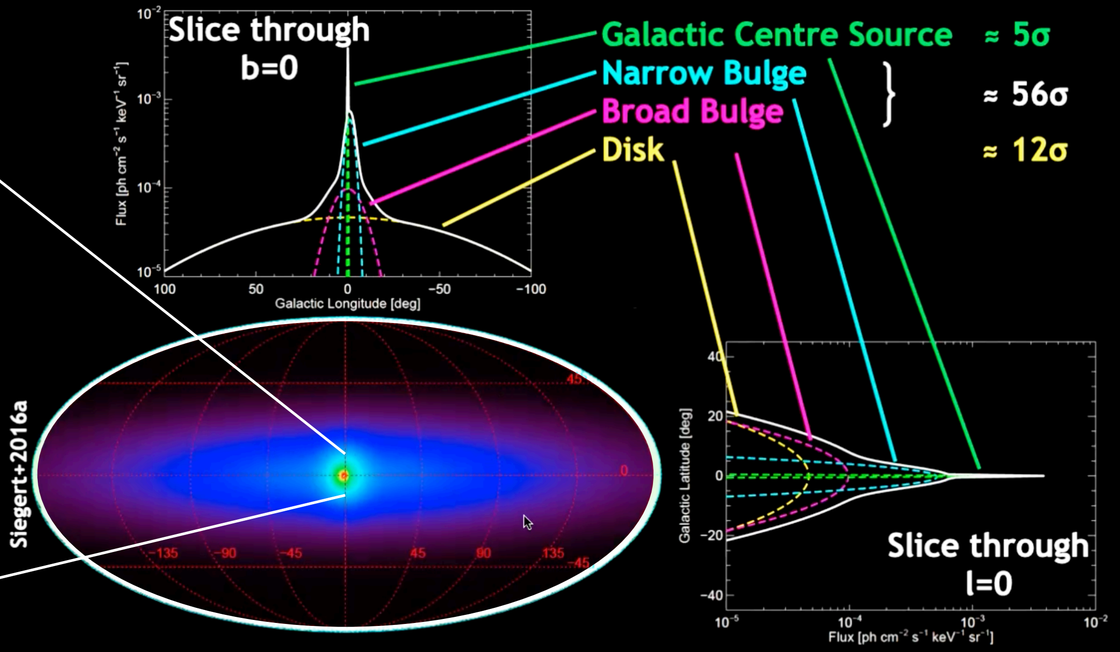


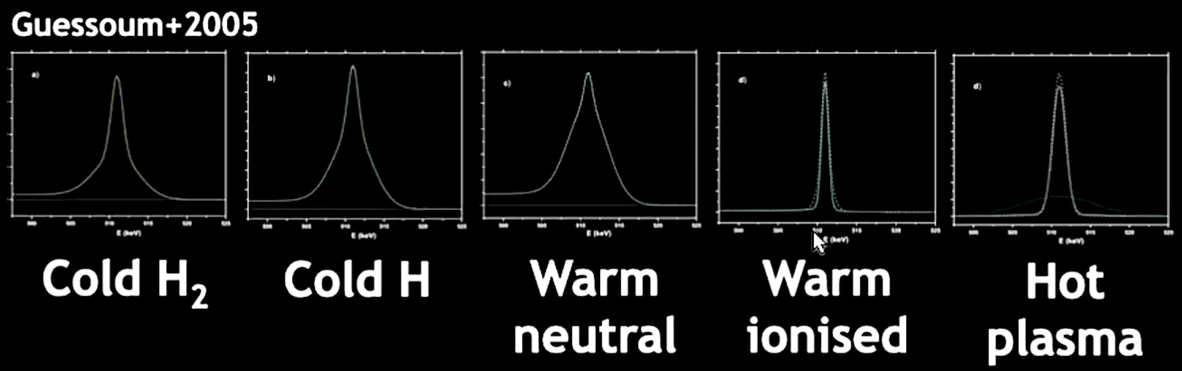
(Siegert+2016)

Mapping the 511 keV line - INTEGRAL

(Skinner+2014, Siegert+2016)





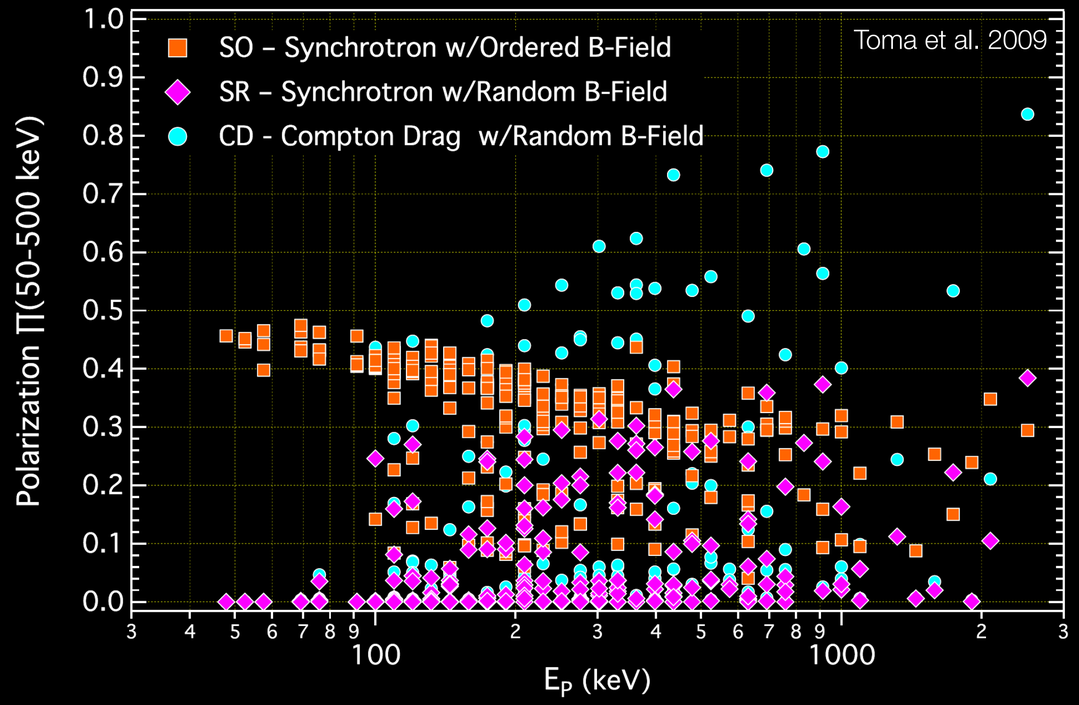


- Line shape is important: it trace warm and partially ionized gas.
- SPI does good at the bulge but better energy resolution and sensitivity is needed for the other components.
- Better imaging for template fitting is needed

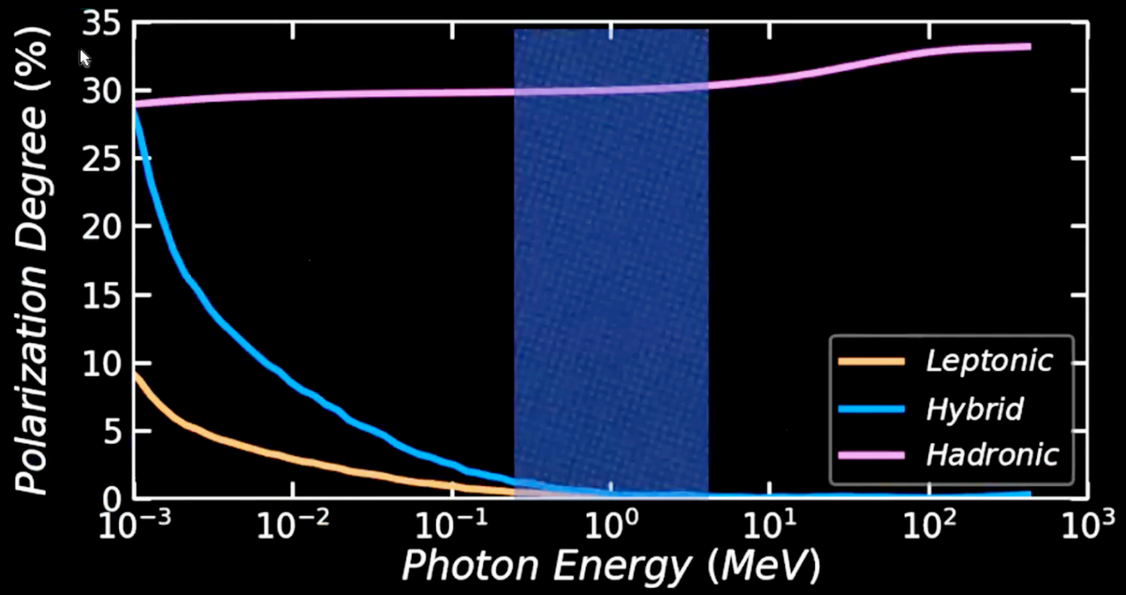
But also... polarization

COSI is also a polarimeter!

GRB Polarization

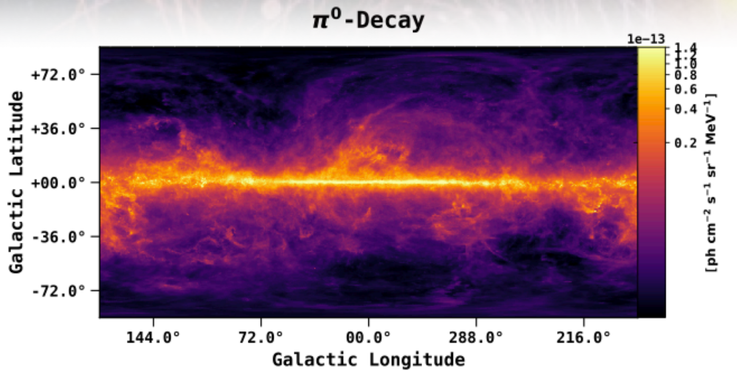


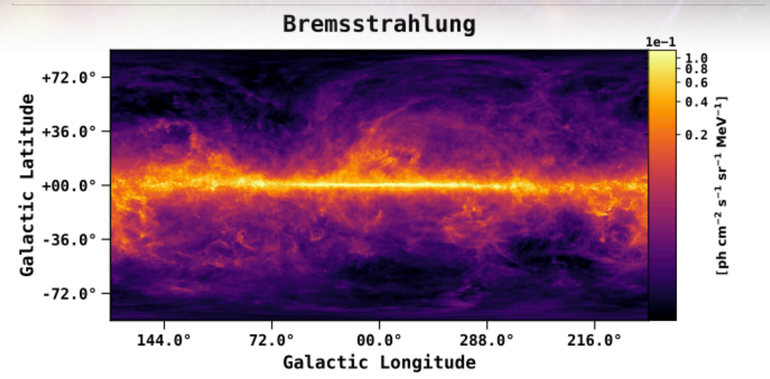
Blazar (LSP, ISP) Polarization

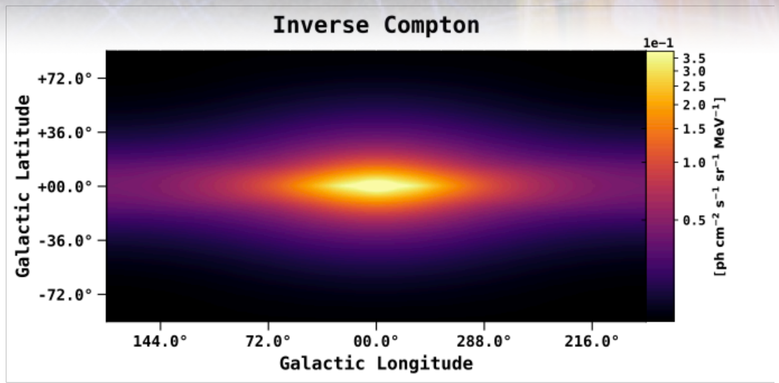


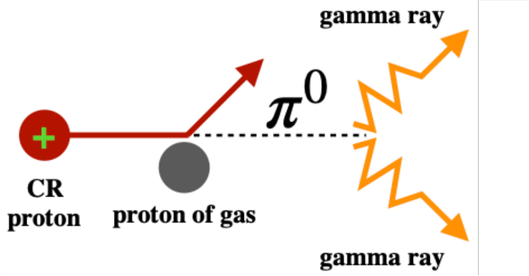
But also MeV polarization from SNR (Crab, Vela), accreting BH (Cyg X-1), magnetars …

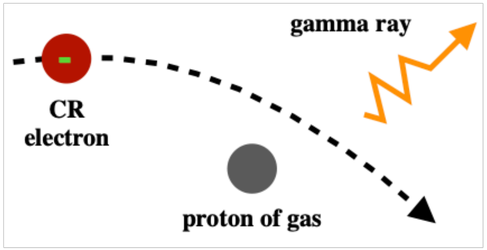
MeV view of the Galactic diffuse emission

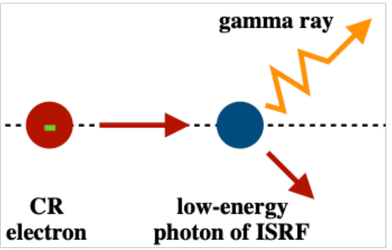


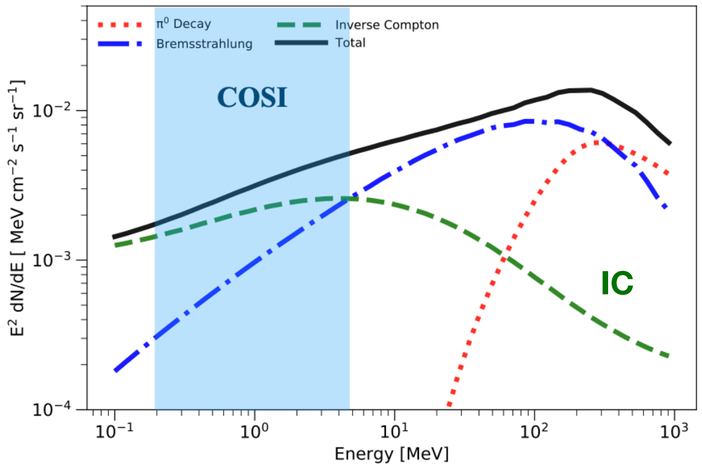


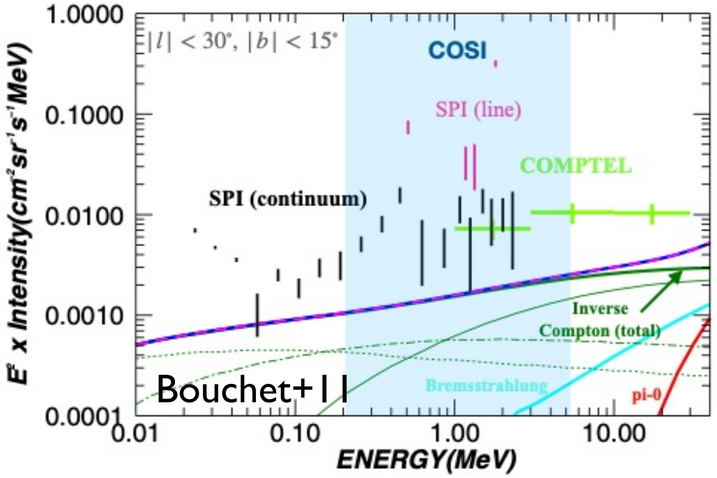










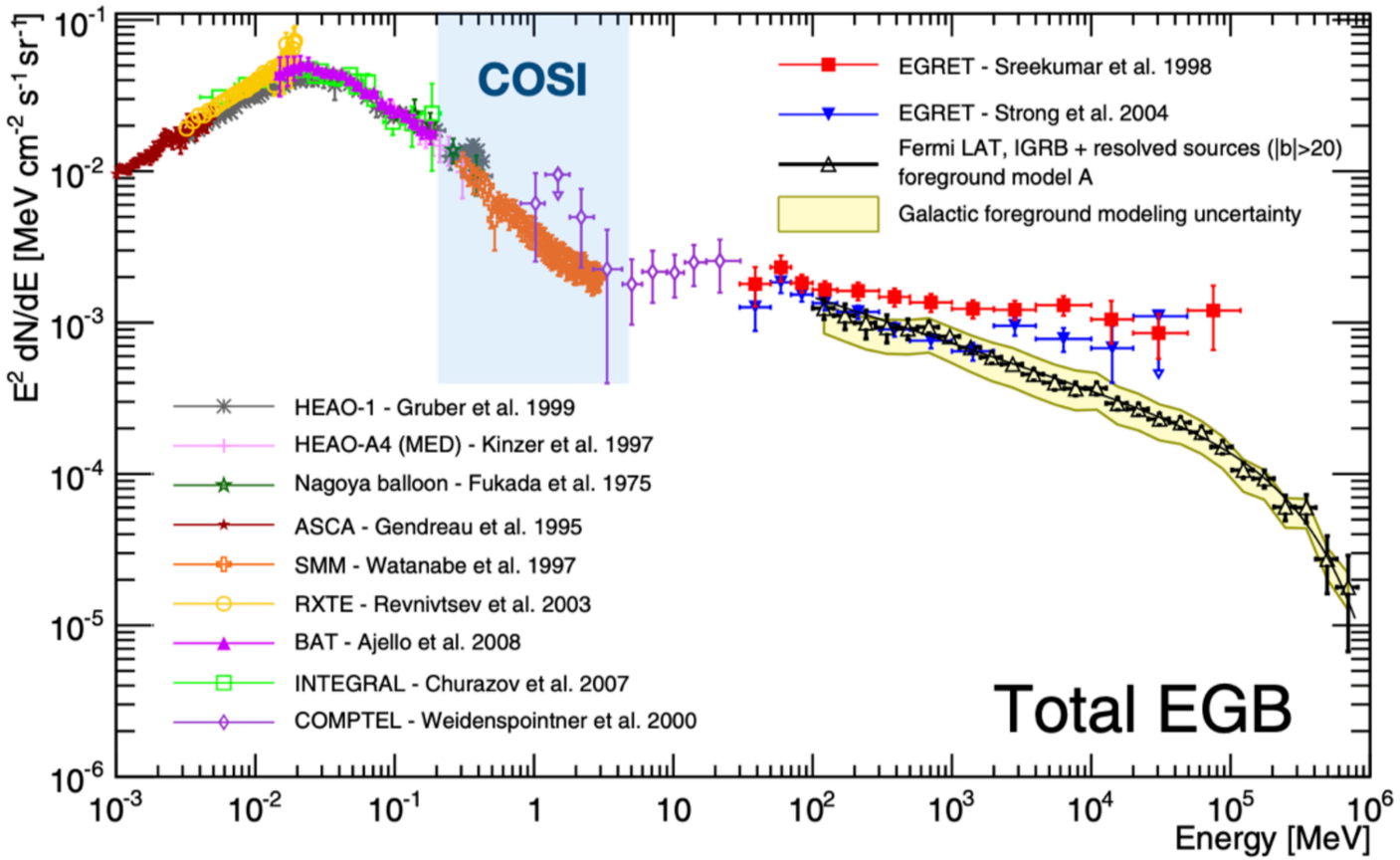


- COSI will give important insights for CRE population that produce MeV gamma-rays though IC
- COSI will access the MeV Galactic diffuse emission with unprecedented sensitivity: enabling better modeling

Slide credit: Chris Karwin

The Unresolved MeV gamma-ray background

The origin of the MeV background remains a longstanding issue in astrophysics [Ajello+8, Ackermann+15]



it could be created by

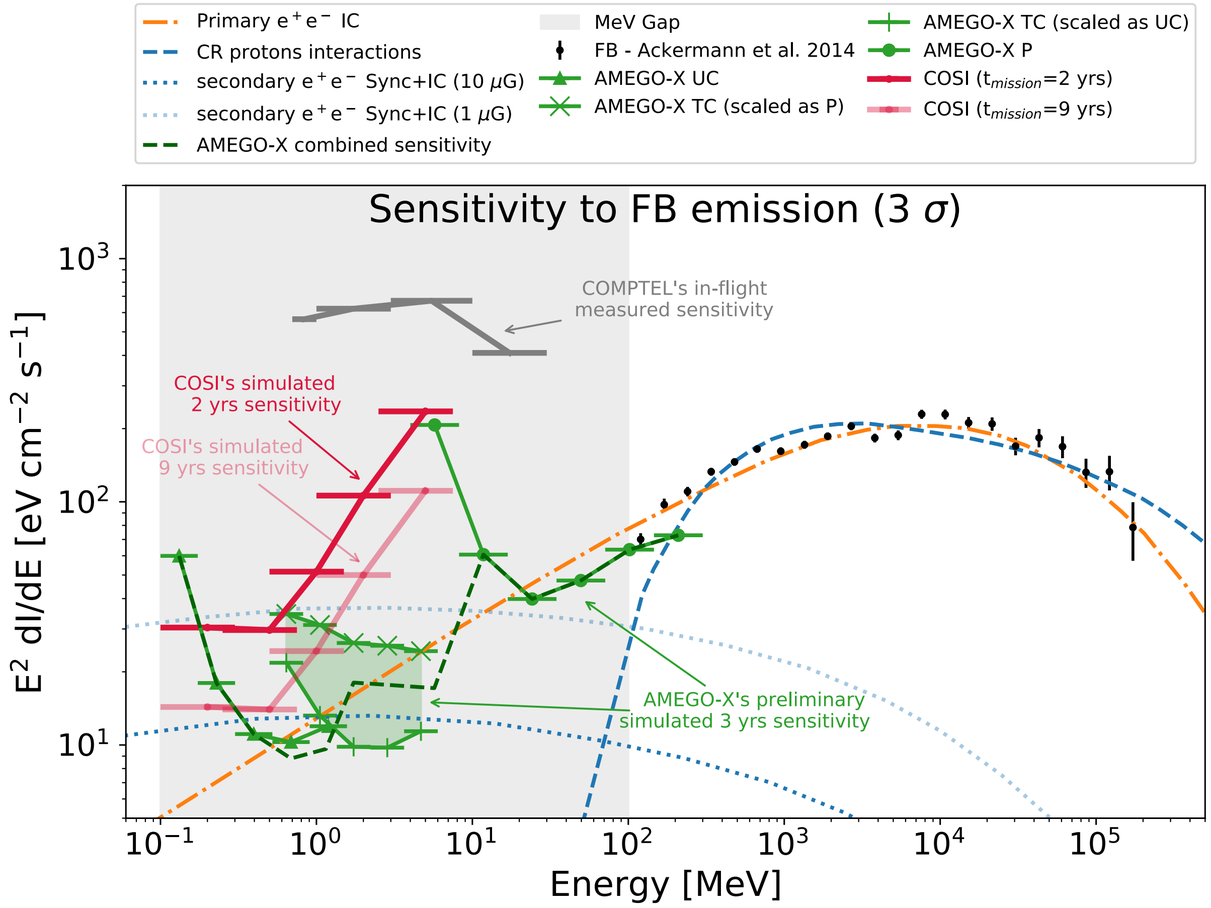
- **MeV blazars**,
- **Type Ia supernovae** [Ruiz-Lapuenta+16], and
- potential **non-thermal electrons in AGN coronae** [e.g. Kimura+21, Murase+20, Inoue+20]

- COSI observation of MeV blazars and AGNs could constrain the origin of the MeV background!

MeV view of the Fermi Bubbles

- Discovered in 2010 (Su+2010)
- Fermi LAT collaboration in depth analysis (Ackermann+2015)
- Both hadronic and leptonic models explain the GeV emission

- COSI could detect a secondary leptons component within the prime mission, constraining the magnetic field inside the FB
- Past AGN jet activity or nuclear star formation? production of positrons or nuclear lines? line observations with COSI will have something to tell



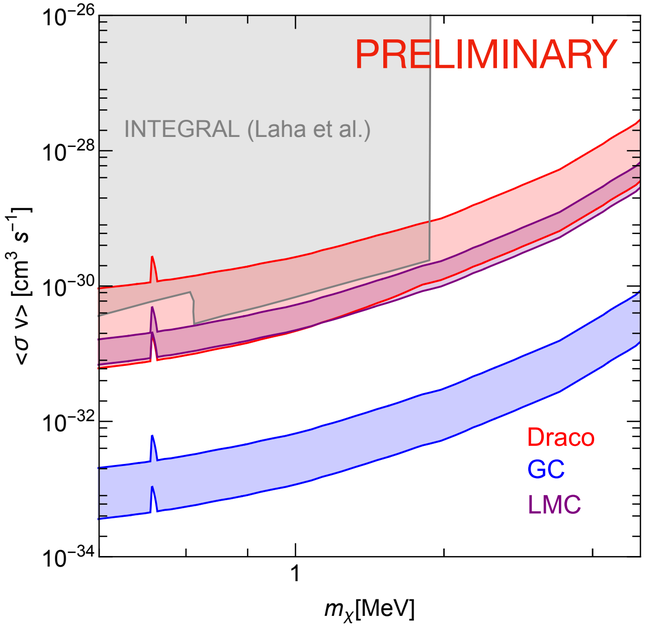
M. Negro+2022

COSI and Dark Matter

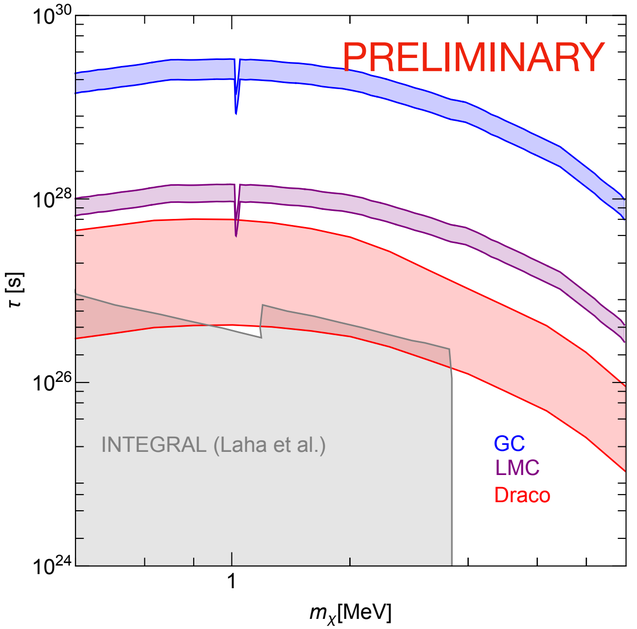
Caputo, Negro, Regis. Taoso in prep.

Observable	DM candidate	γ production mechanism
511 keV line	Axion Like Particles (ALPs) Low mass PBH	Annihilation, decay Evaporation
Other MeV Lines	Axion Like Particles (ALPs)	Annihilation, decay
Continuum	Primordial black holes (PBH) WIMPs	evaporation Ann. into leptons -> $\gamma\gamma$

Ann. DM particle line sensitivity



Decaying DM particle line sensitivity



Low mass PBH -> 511 keV