Surveying the MeV gamma-ray sky with AMEGO-X

CANCELLED?

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THE CATHOLIC UNIVERSITY OF AMERICA

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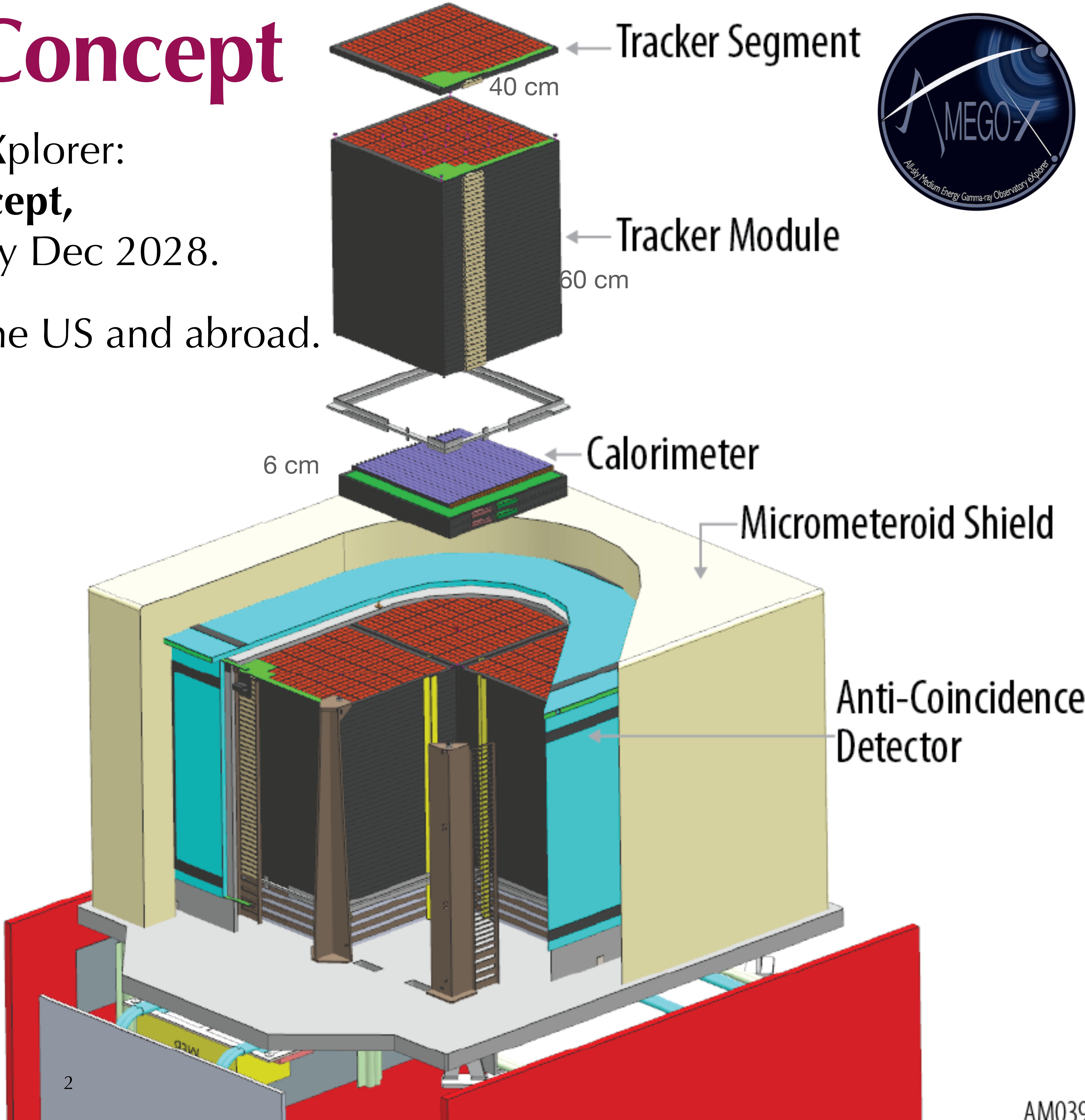
The AMEGO-X Mission Concept

All-sky **M**edium **E**nergy **G**amma-ray **O**bservatory e**X**plorer:
MIDEX-sized (medium-class explorer) **mission concept,**
submitted to Dec 2021 MIDEX call, launch ready by Dec 2028.

PI: Regina Caputo (NASA GSFC), collaborators in the US and abroad.

https://asd.gsfc.nasa.gov/amego-x/
https://pos.sissa.it/395/649/pdf
https://arxiv.org/abs/2208.04990



- Energy range: 100 keV - 1 GeV (survey); 25 keV - 1 GeV (transients).
- Wide field of view: 2 sr - 6 sr.
- Detects gamma-ray photons via photo-electric effect, Compton scattering, and pair production.
- Low-earth orbit.

The Team

With collaborators at INFN, U. Hiroshima, U. Johannesburg, KIT,
U. Western Australia, Georgia Tech, Drexel, UNH and members of LIGO, IceCube, CTA

Science Drivers: Multi-Messenger Astronomy

How do binary neutron star mergers produce relativistic jets and what is the structure of those jets?

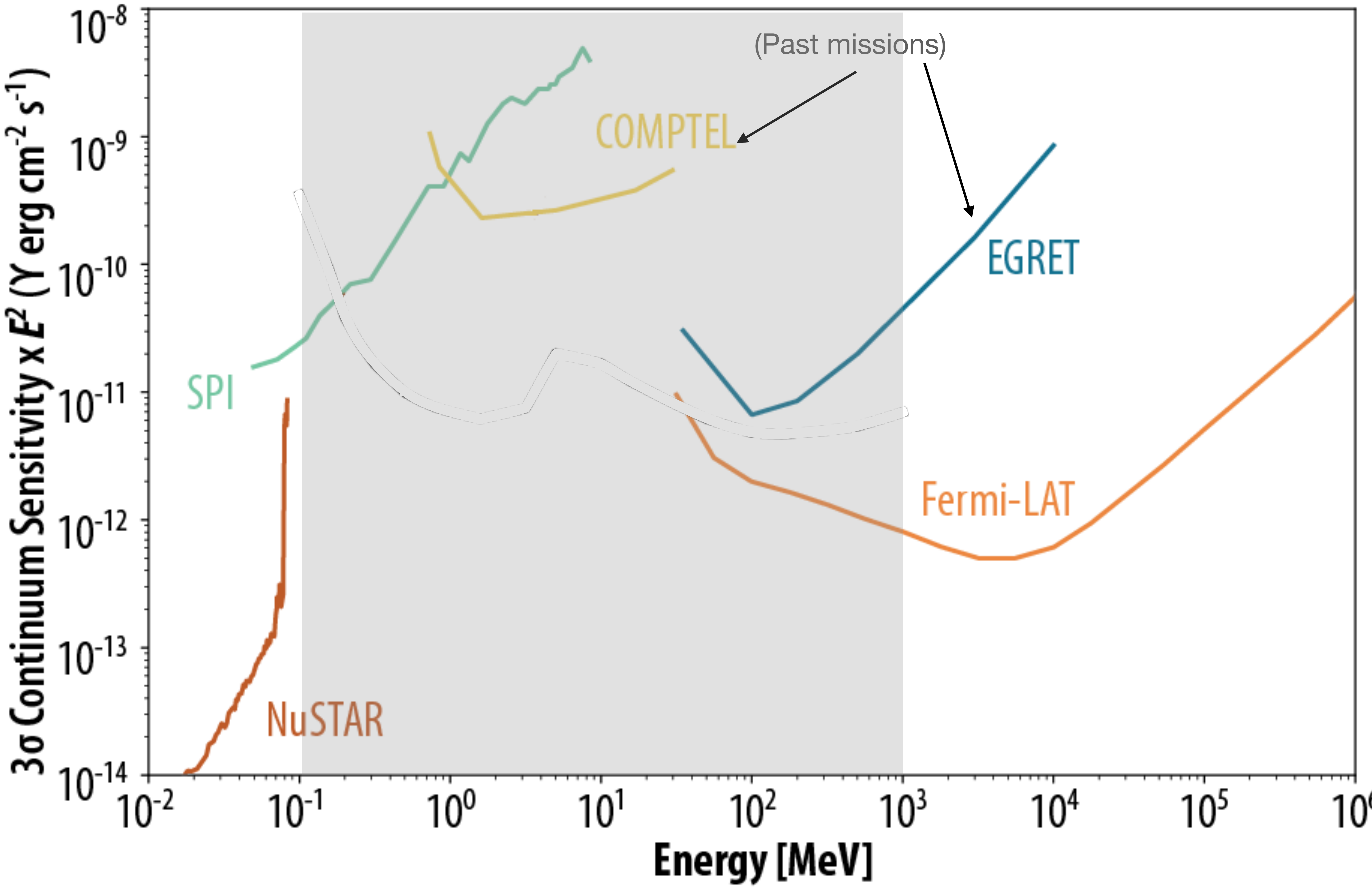
Where are cosmic rays accelerated in the Galaxy?

Do supermassive black holes accelerate cosmic rays and produce neutrinos?

Multi-Messenger Astronomy and MeV Gamma Rays

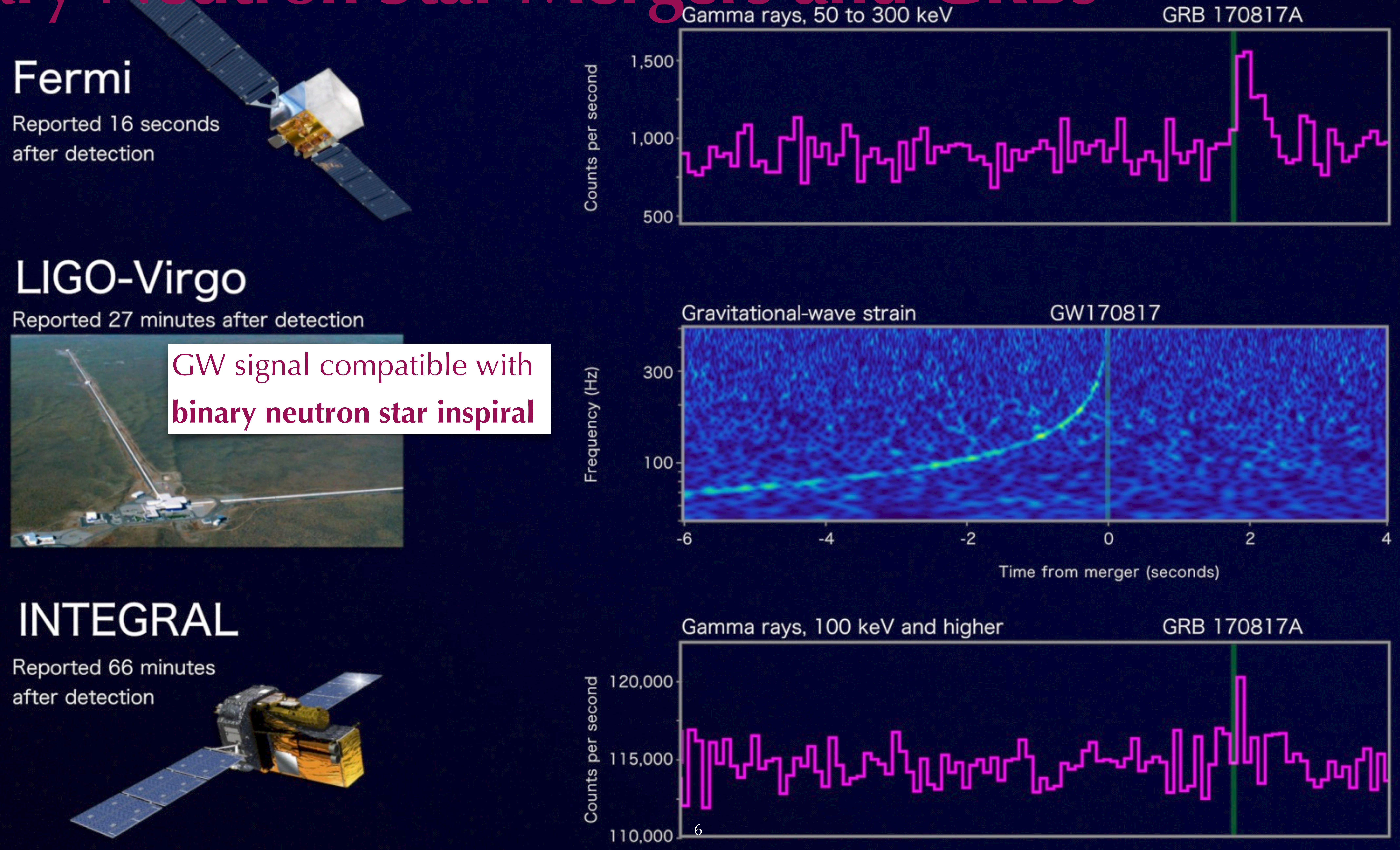
- **Multi-messenger sources are ɣ-ray sources!**
- Recent and near-future MW/MM advances:
  - **GW**: Upgrades to LIGO and VIRGO, new detector KAGRA
  - **Neutrinos**: IceCube Gen2, KM3net
  - **Optical** transient surveys: Zwicky Transient Facility, Vera C. Rubin Observatory (LSST), ...
- **MeV ɣ-ray band is under-explored!**
- Advances in silicon detector technology (e.g., AstroPix).

survey sensitivity (lower = more faint sources)



https://heasarc.gsfc.nasa.gov/docs/objects/heapow/archive/transients/gw170817.html

Binary Neutron Star Mergers and GRBs



GW signal compatible with **binary neutron star inspiral**

https://heasarc.gsfc.nasa.gov/docs/objects/heapow/archive/transients/gw170817.html

Binary Neutron Star Mergers and GRBs

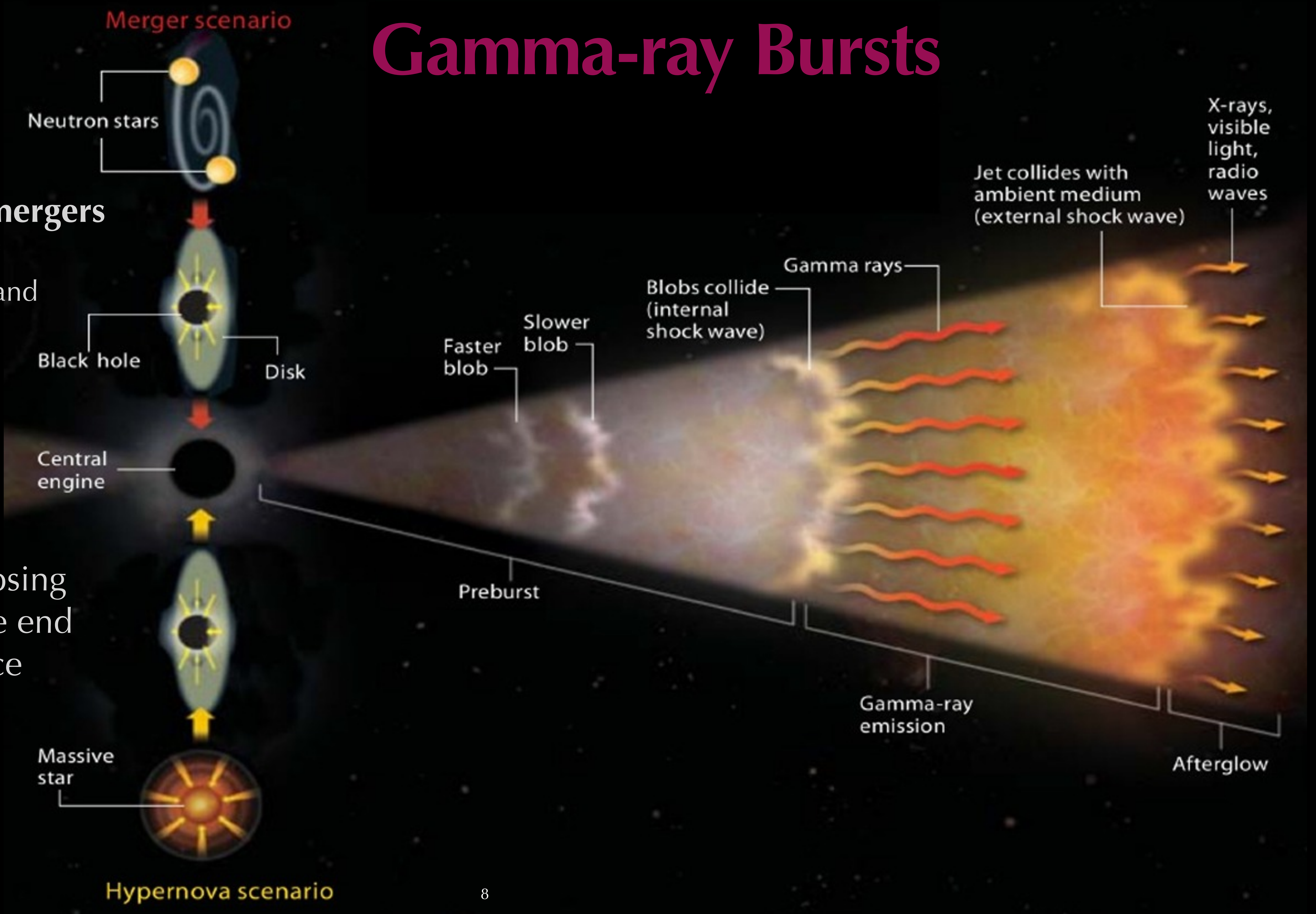
Spatial and temporal coincidence!

Time-domain multi-messenger astronomy!

Gamma-ray Bursts

Binary **neutron star mergers** produce **short GRBs***
*also: "Failed" collapsars and magnetar giant flares

Massive stars collapsing to black holes at the end of their lives produce **long GRBs***

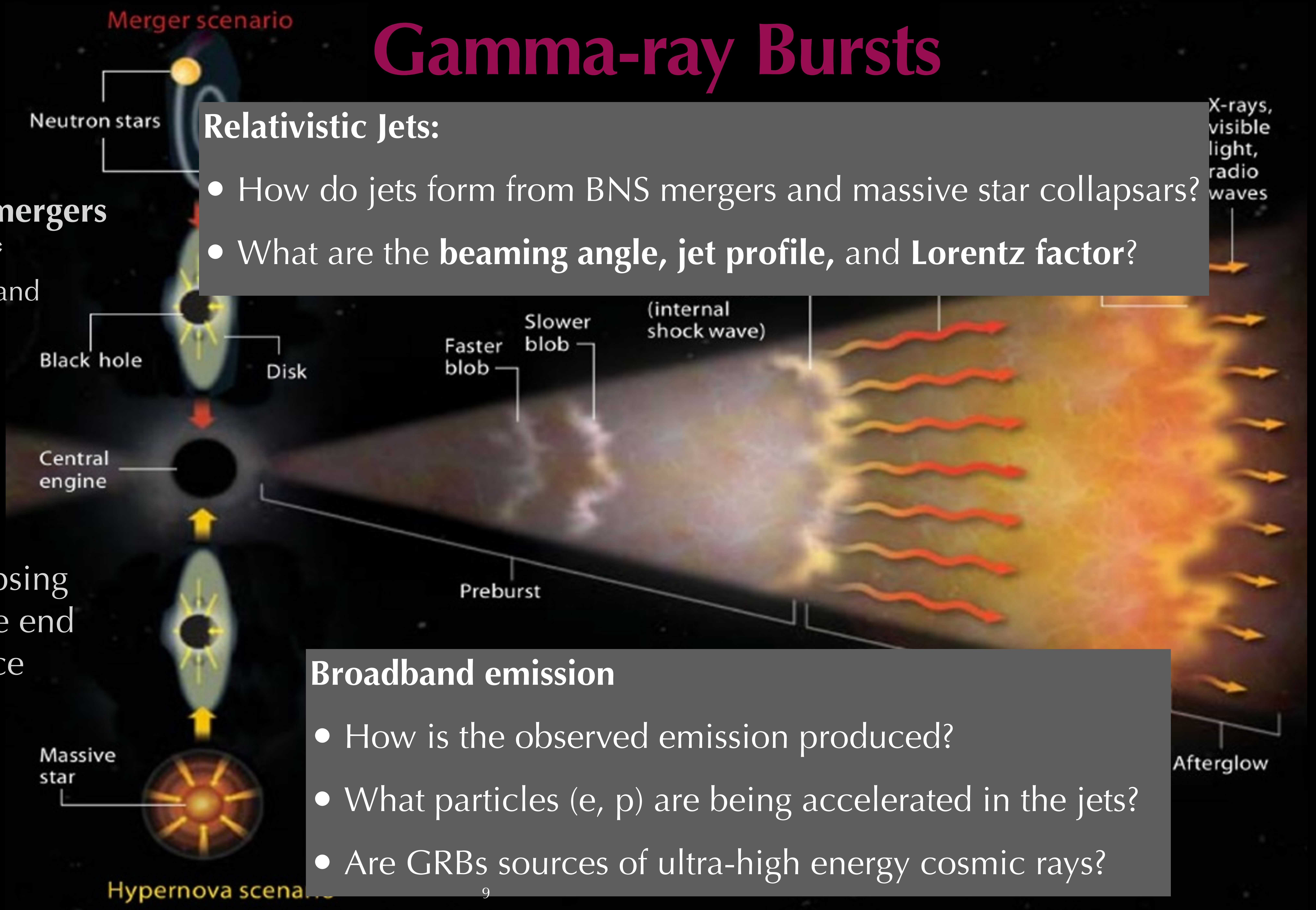


Gamma-ray Bursts

Binary **neutron star mergers** produce **short GRBs***
*also: "Failed" collapsars and magnetar giant flares

Relativistic Jets:

- How do jets form from BNS mergers and massive star collapsars?
- What are the **beaming angle, jet profile,** and **Lorentz factor**?

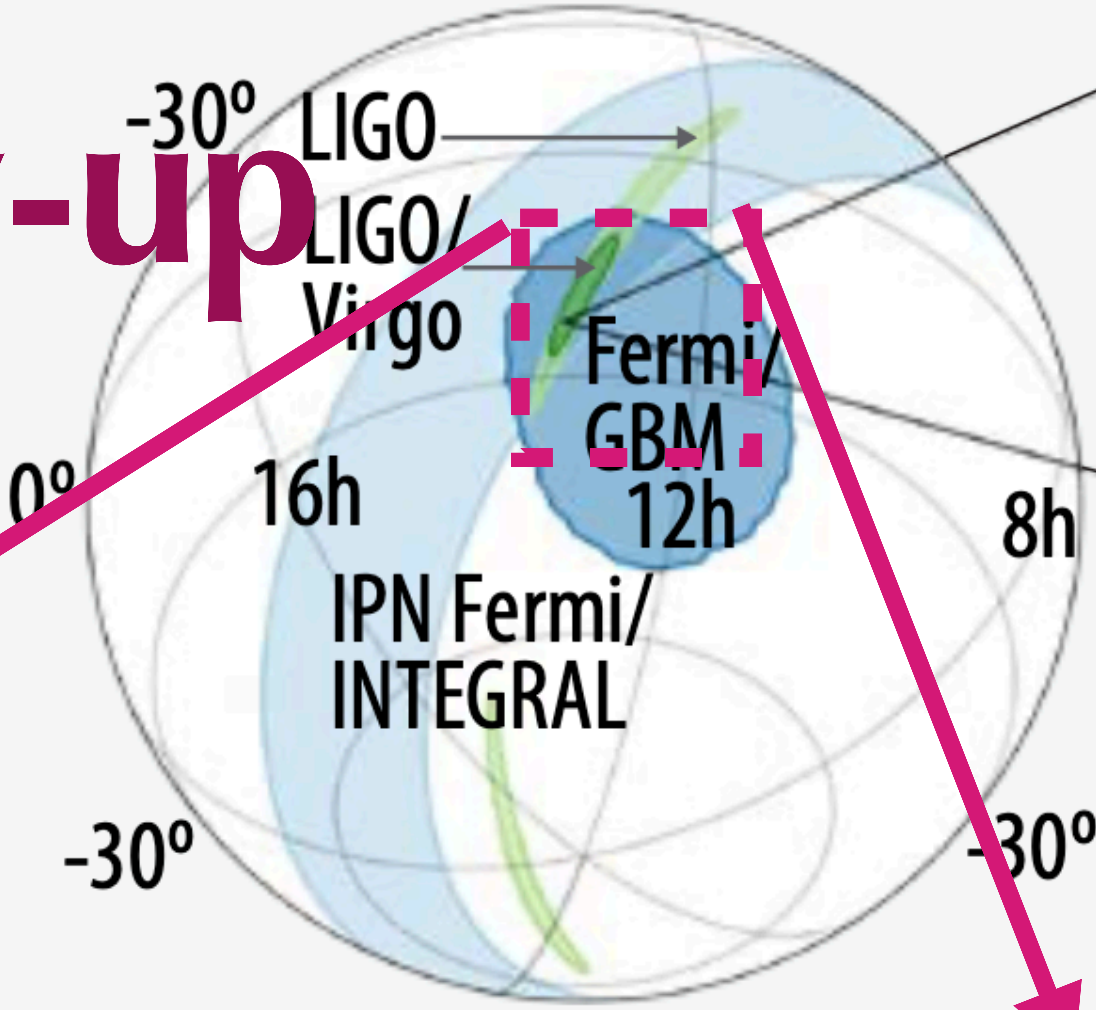


Massive stars collapsing to black holes at the end of their lives produce **long GRBs***

Broadband emission

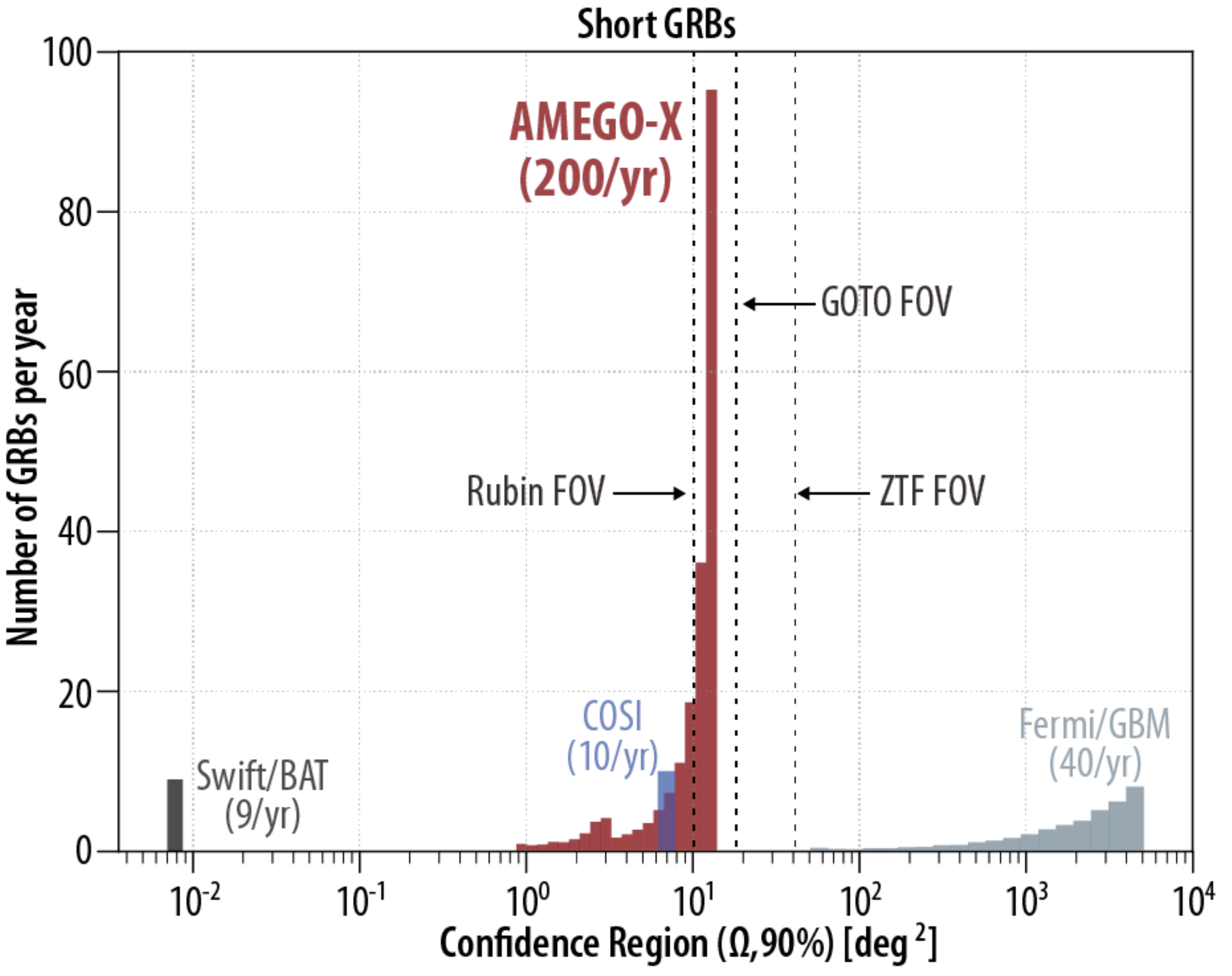
- How is the observed emission produced?
- What particles (e, p) are being accelerated in the jets?
- Are GRBs sources of ultra-high energy cosmic rays?

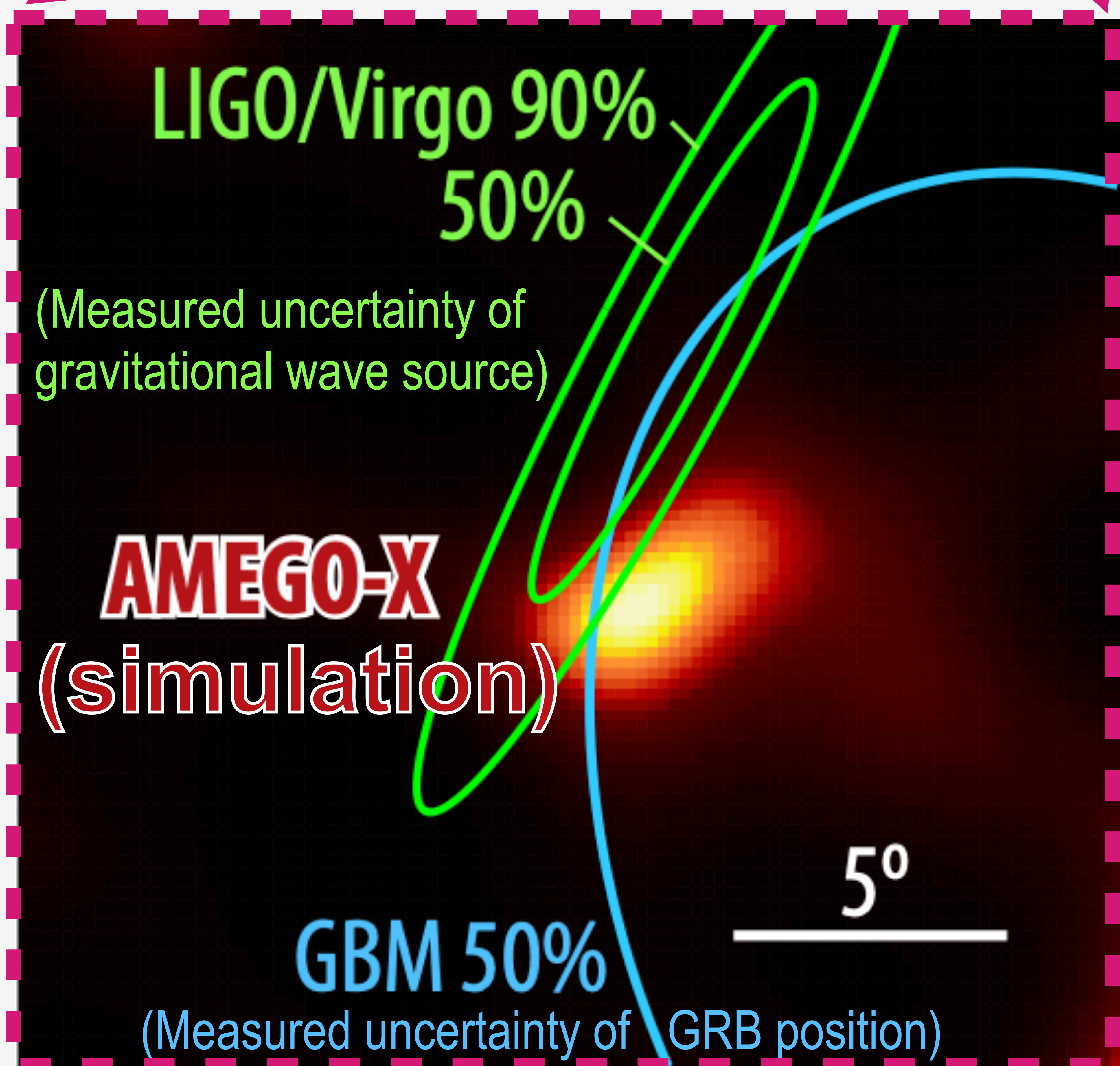
Precise localization to enable rapid follow-up



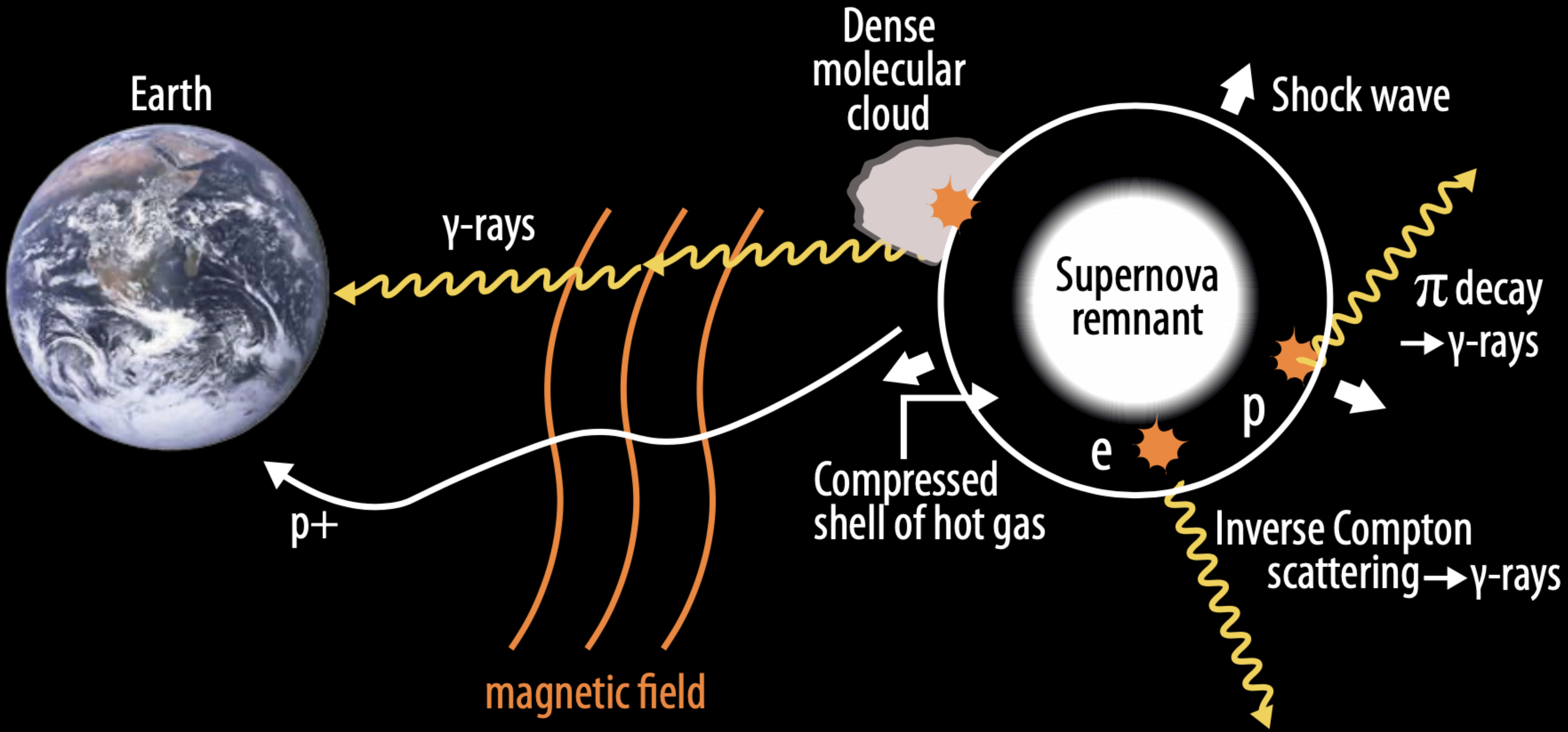
AMEGO-X will be able to:

- Detect hundreds of short and ~thousand long GRBs every year.
- Provide ≤ 2° localizations within 30 s to enable **follow-up observations**.
- Detect GRBs coincident with GW signals (or provide limits).





What are the sources of Galactic Cosmic Rays?



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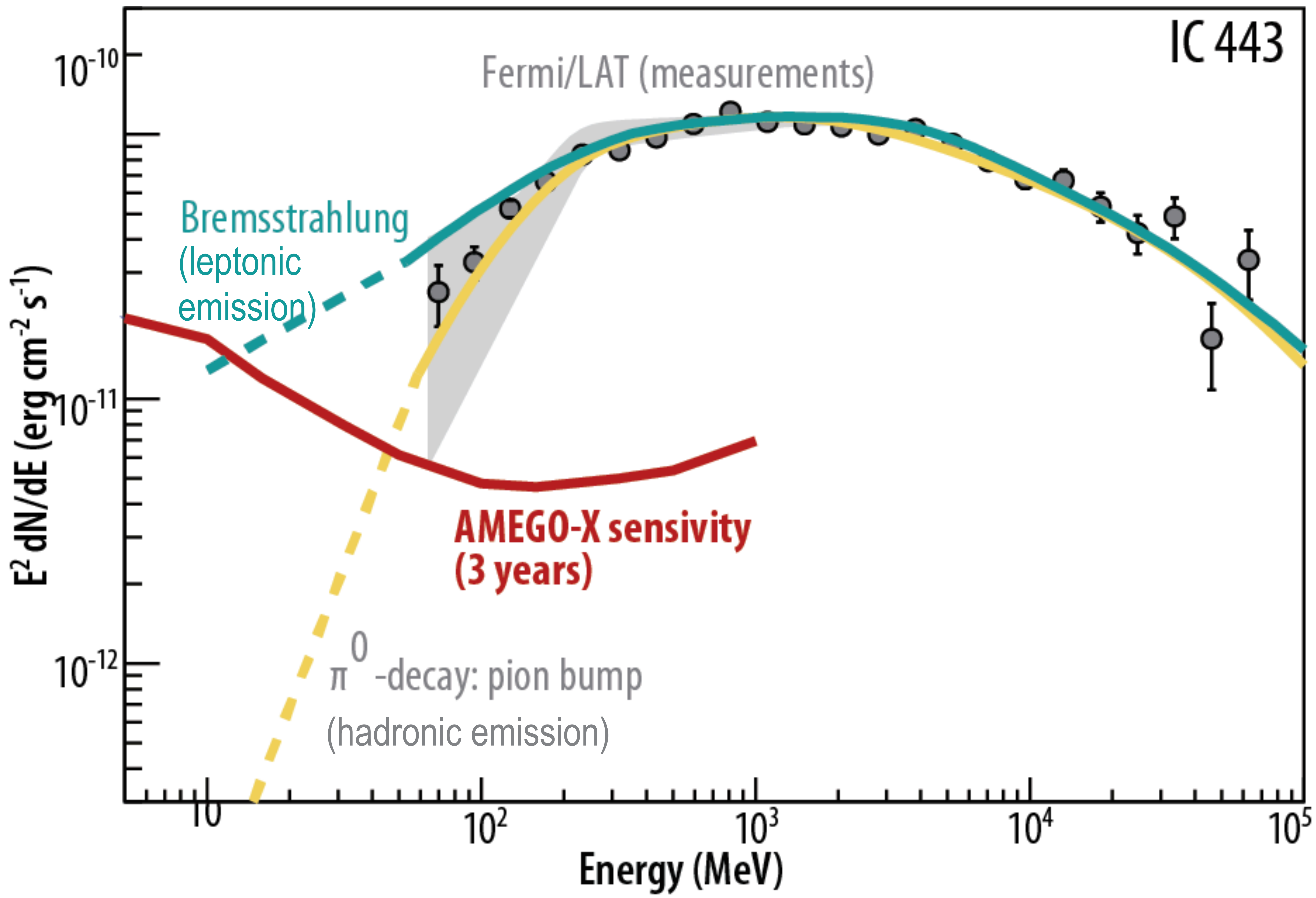

AMEGO-X will:

- detect **pion decay signatures** in supernova remnants, star forming regions, and novae,
- divide known and suspected CR accelerators into sources of **hadronic CR (protons, ions) vs CR electrons,**
- Study how and where CR electrons and positrons are accelerated in **pulsars** and their surroundings, and
- Determine the source(s) of the observed **excess in local energetic positrons**.

How and where do AGN accelerate CR protons?

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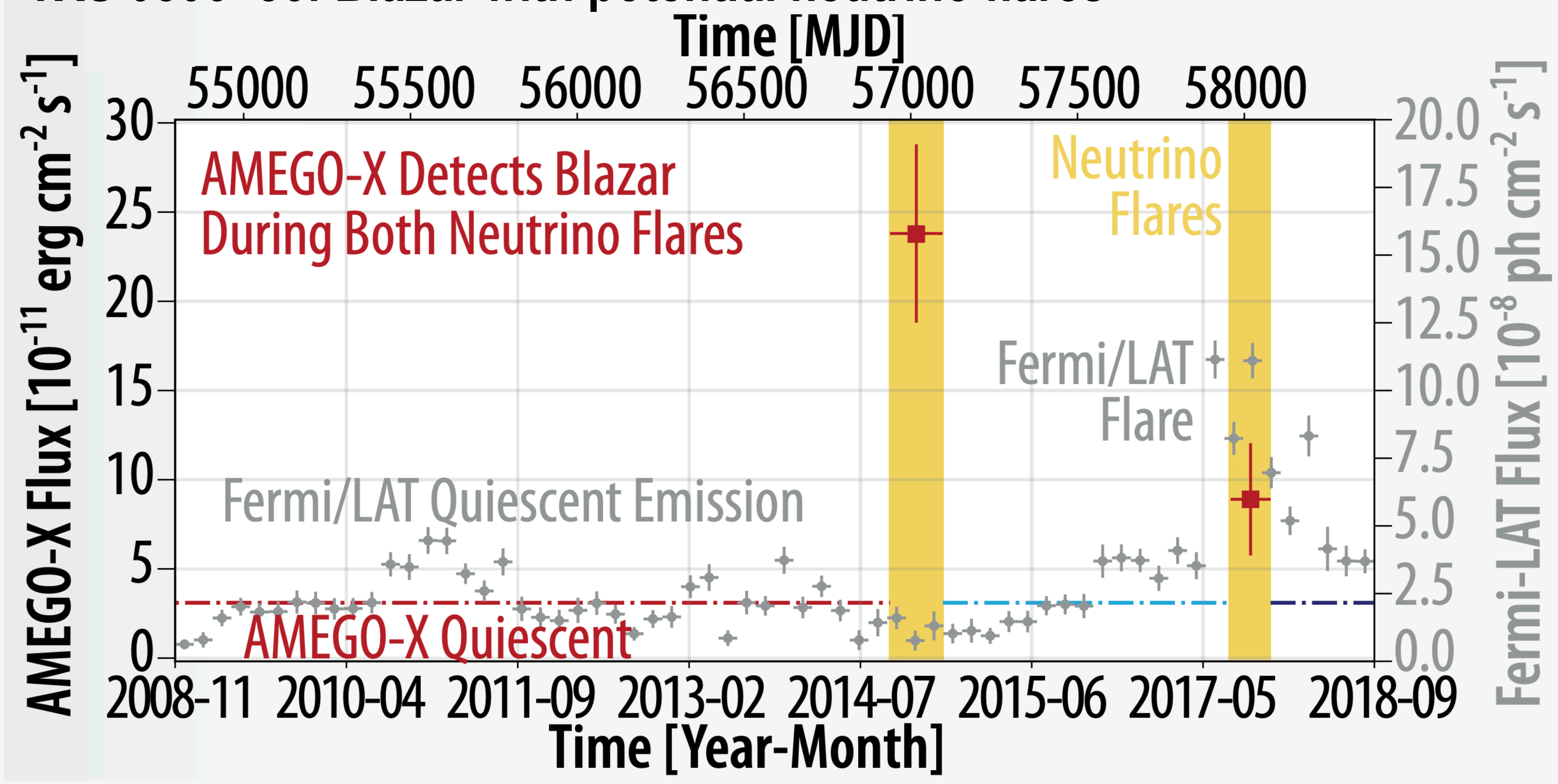
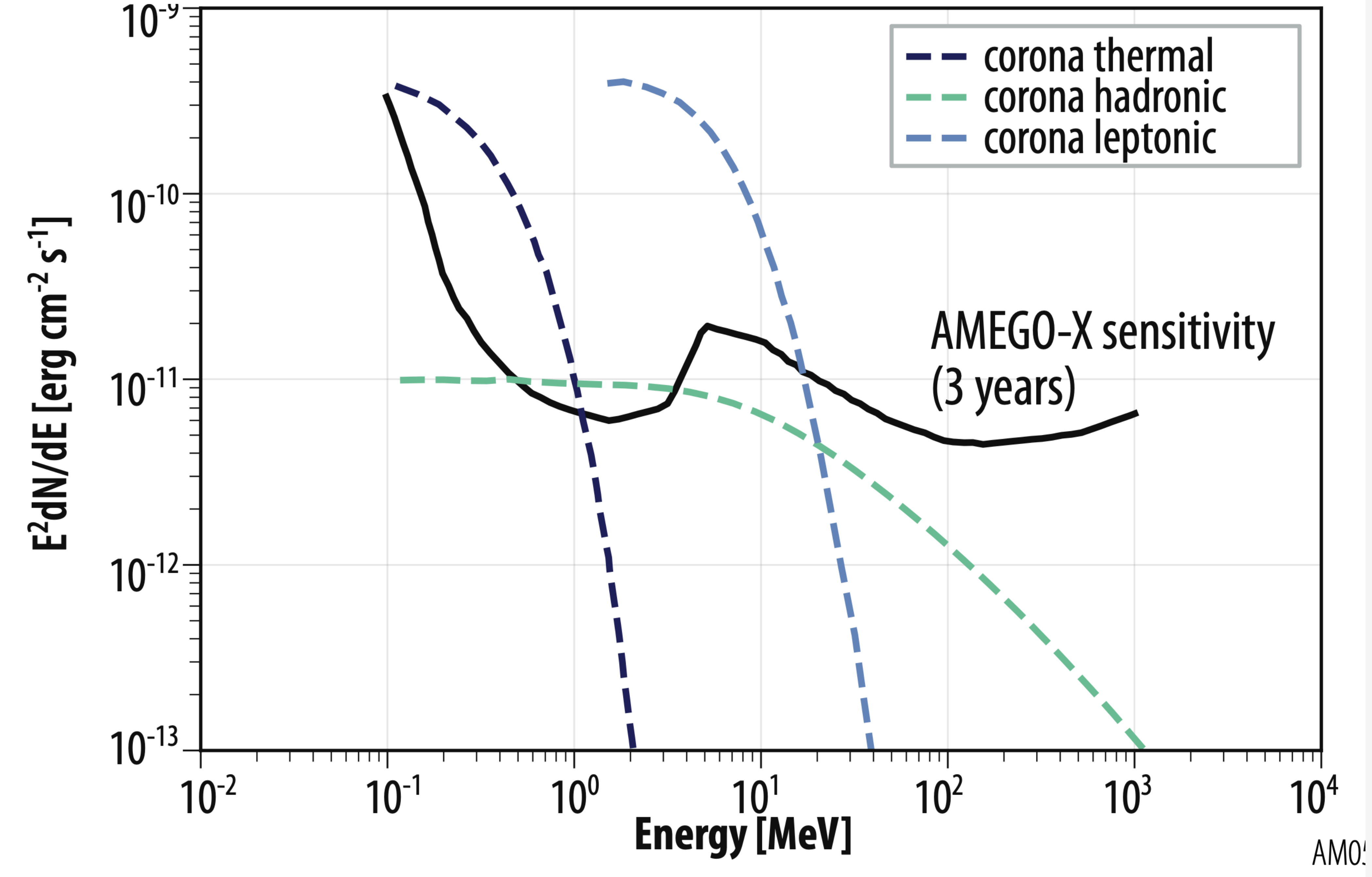
TXS 0506+56: Blazar with potential neutrino flares

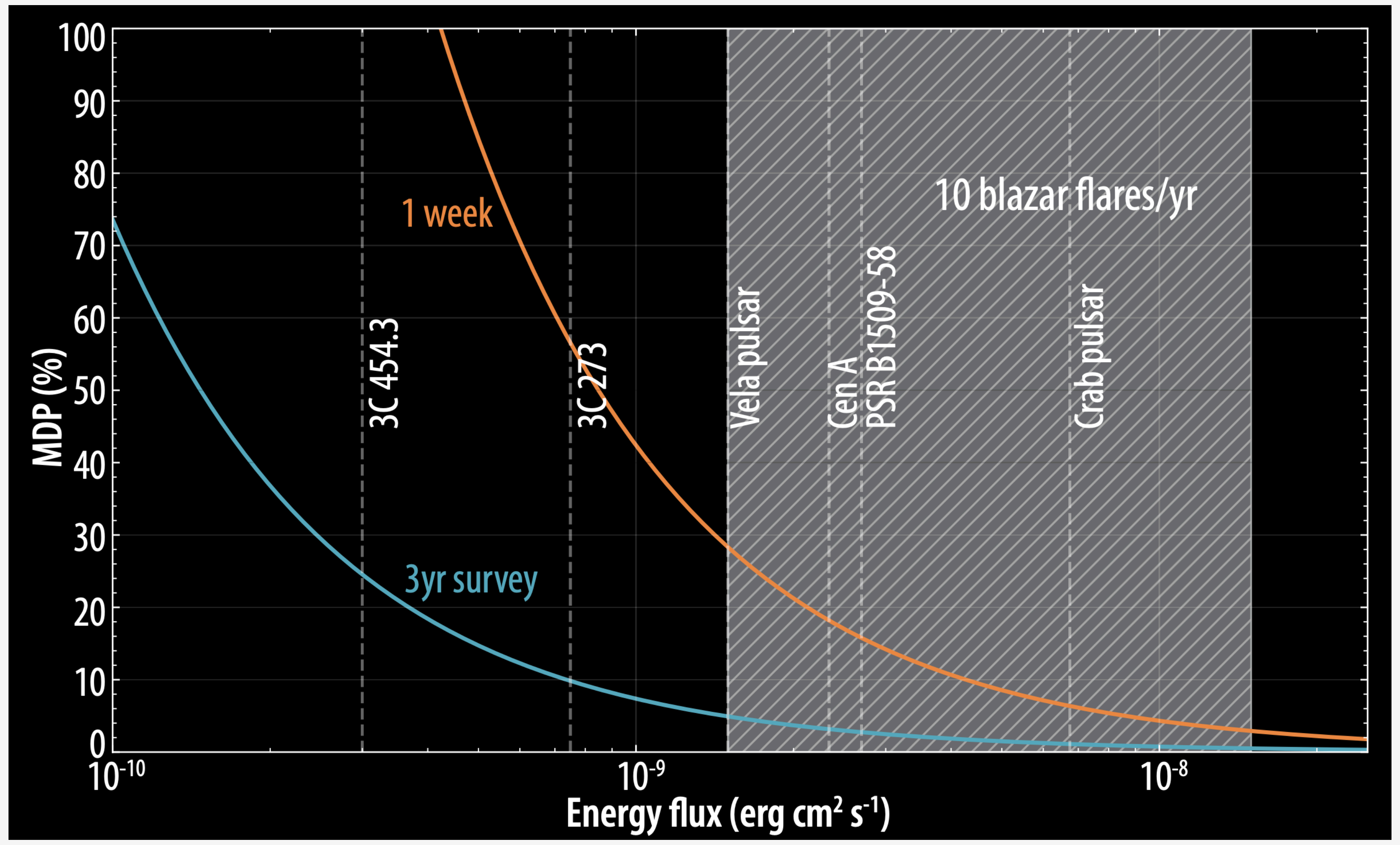


NGC 1068: Seyfert Galaxy with potential neutrino cluster



AMEGO-X could:

- Have detected an MeV gamma-ray flare from TXS 0506+56 in coincidence with its first neutrino flare
- Distinguish leptonic and hadronic emission models from NGC 1068 via its MeV energy spectrum.
- Measure polarization signals from ~10 blazar flares/year.



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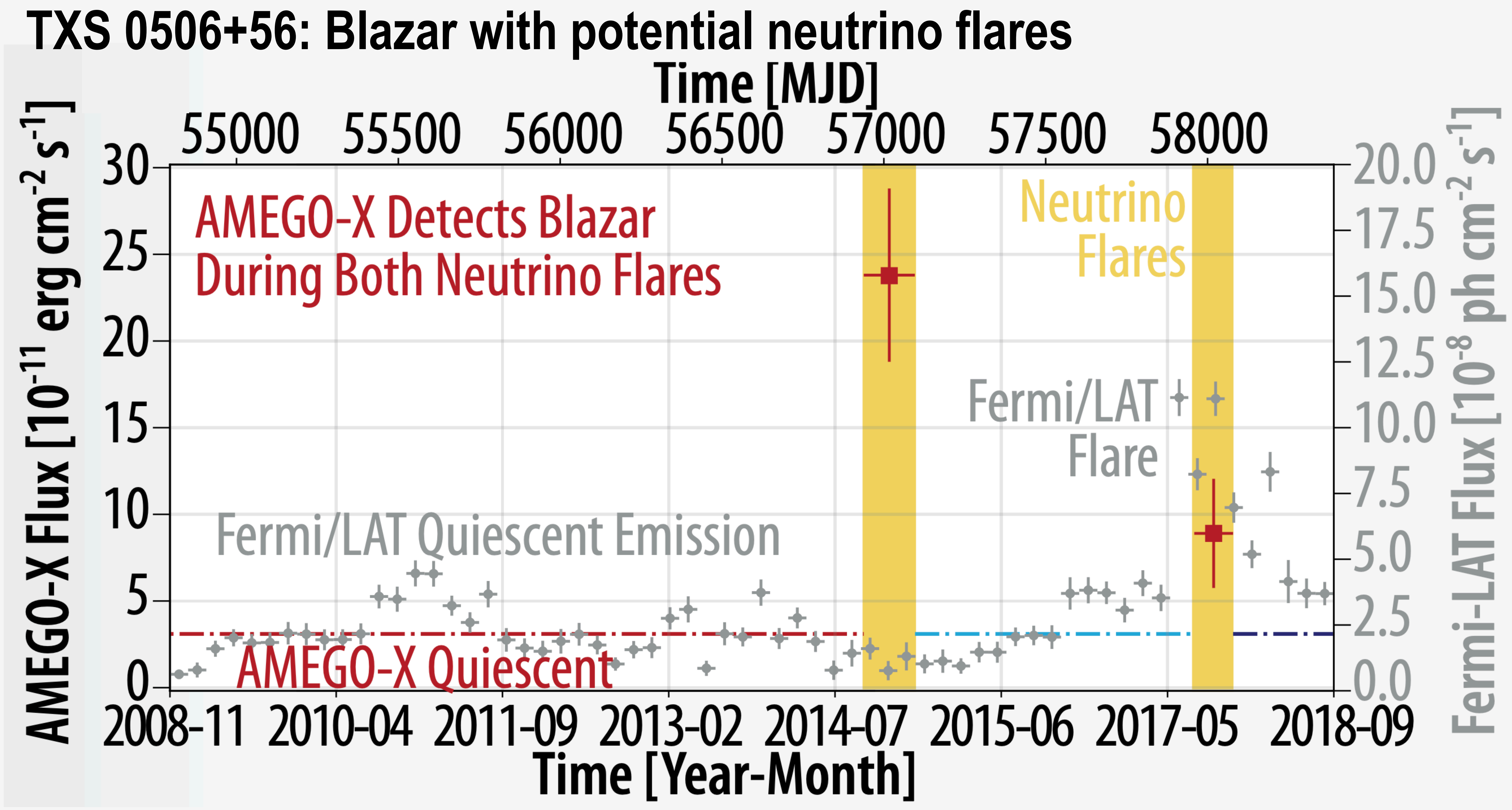

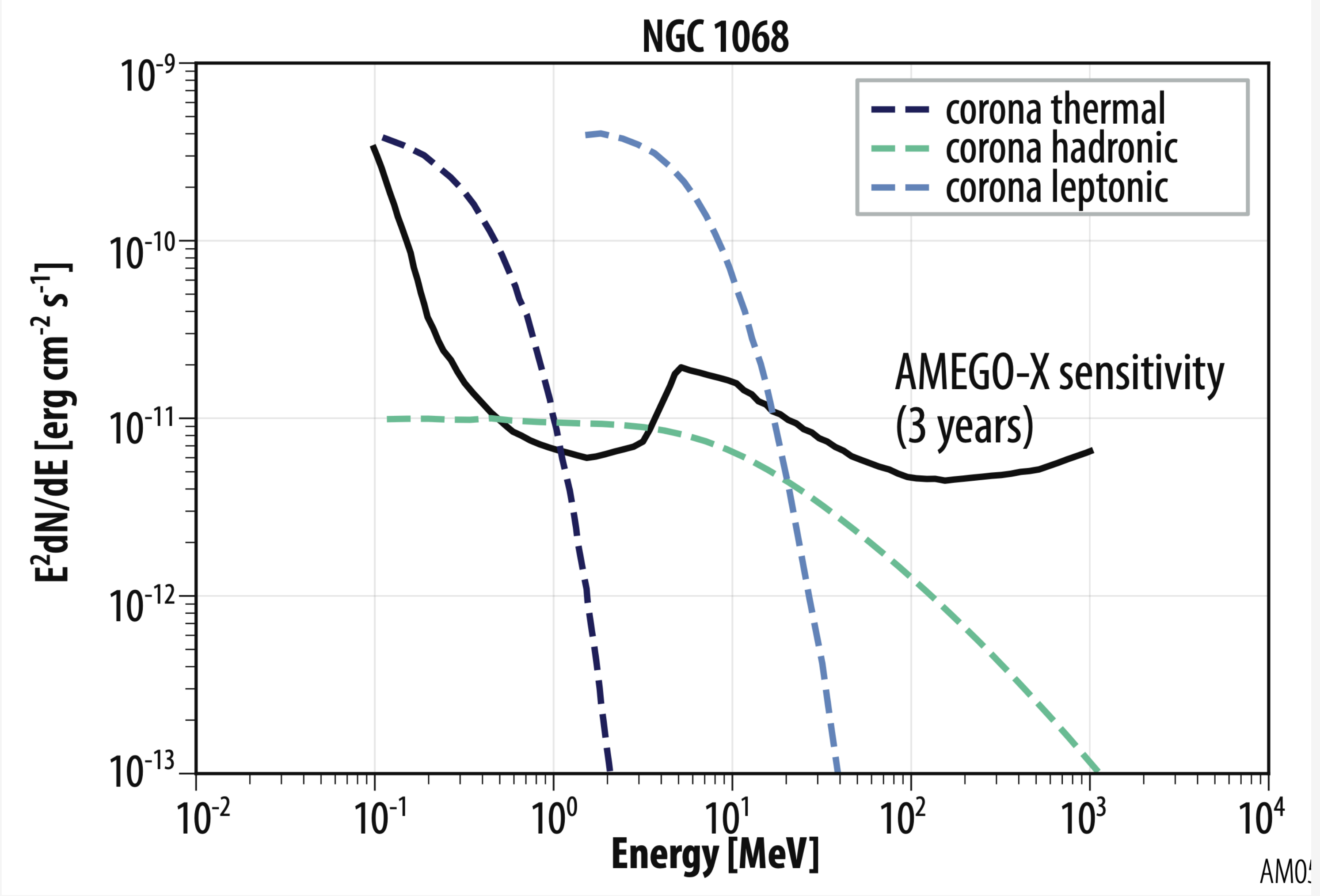

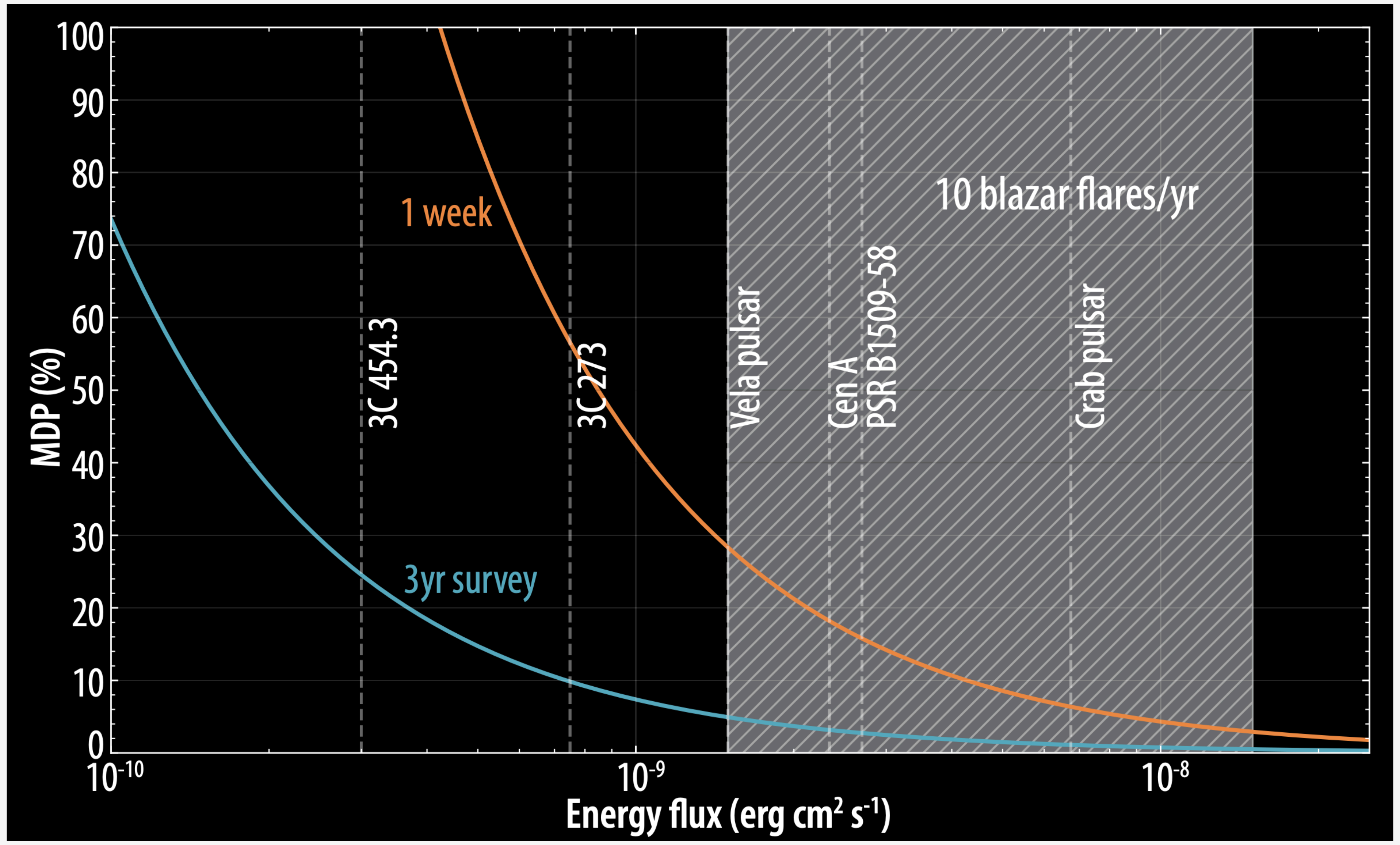

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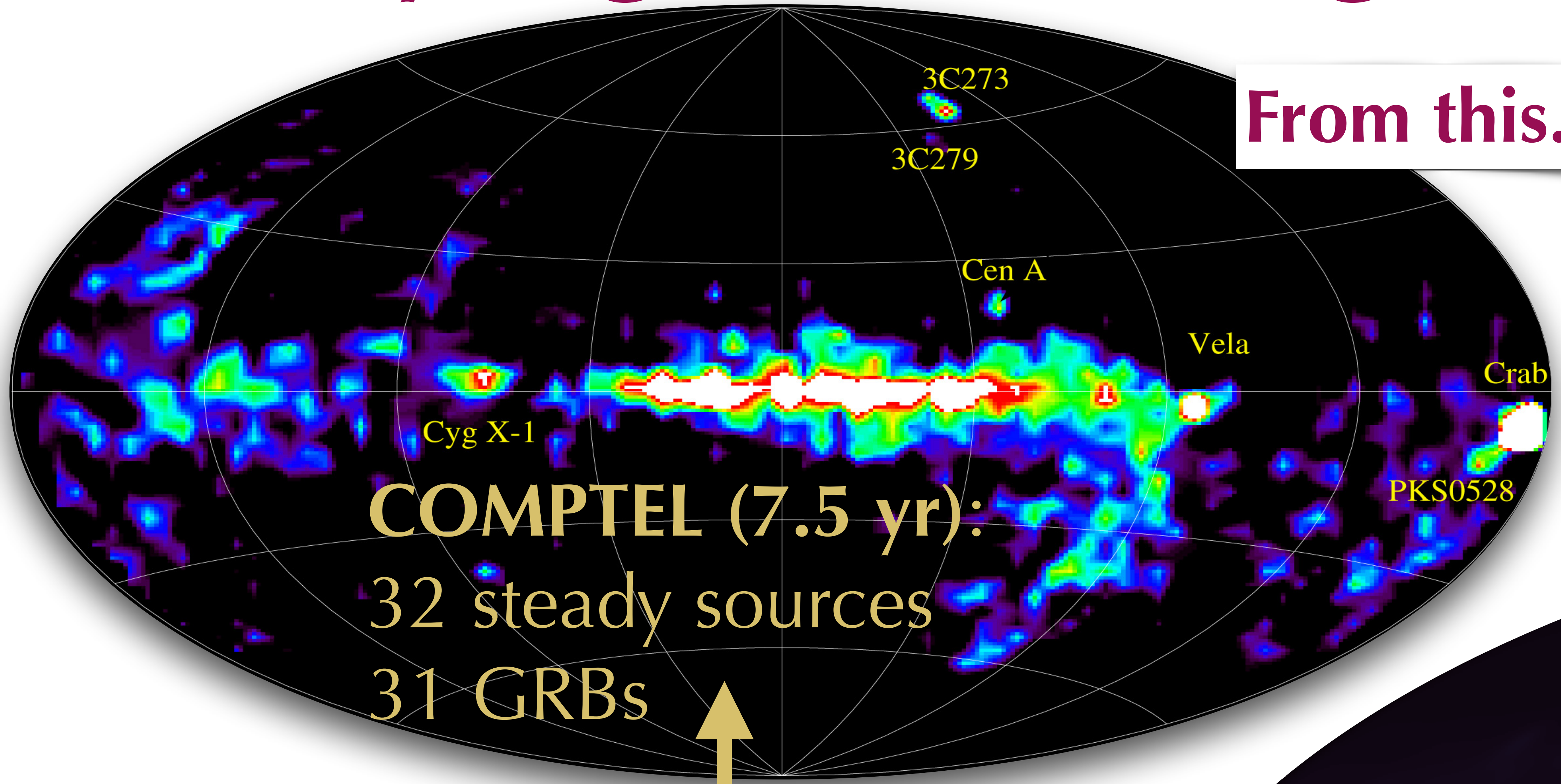
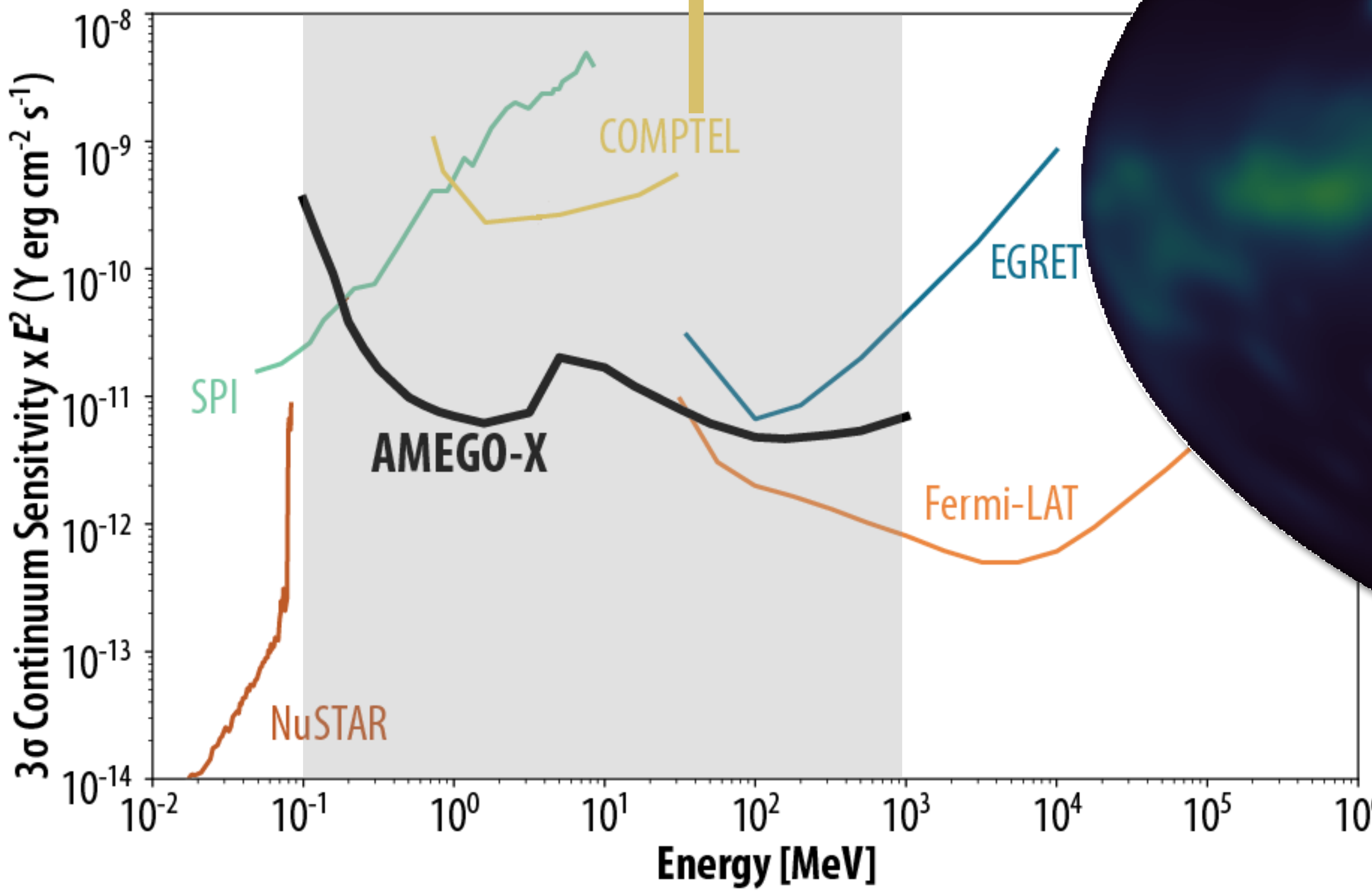
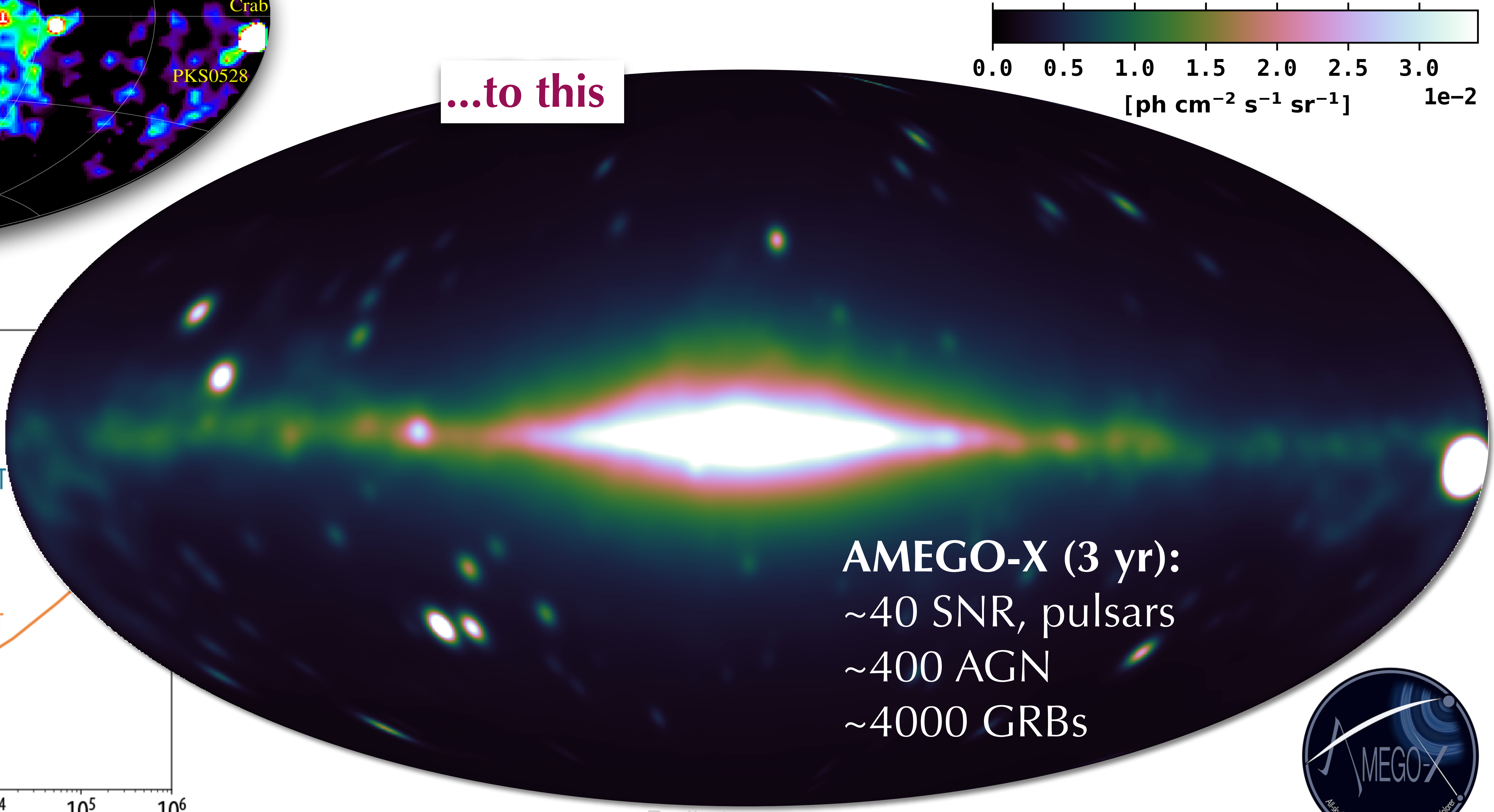
From this...





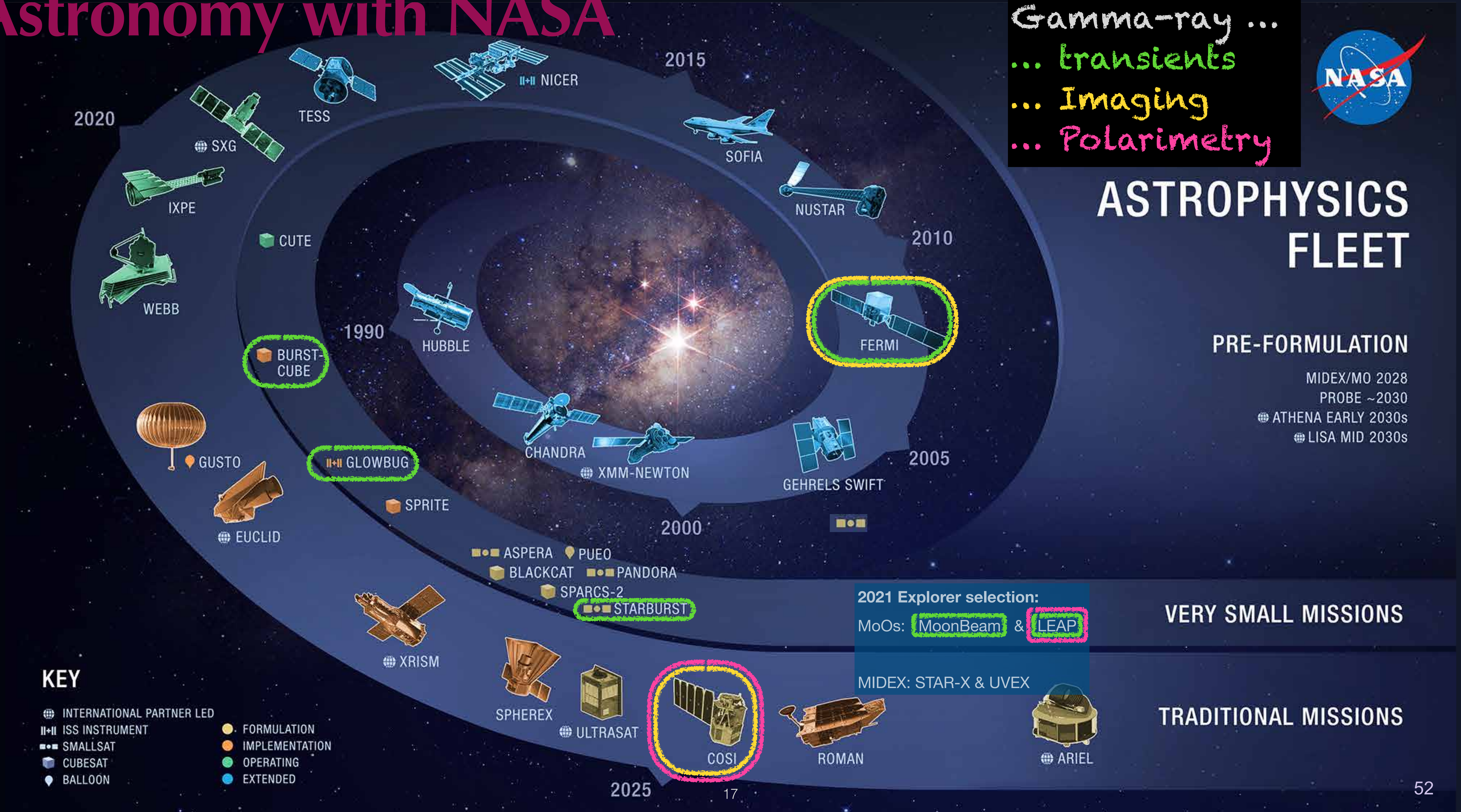
Curious? Check out
https://asd.gsfc.nasa.gov/amego-x/

...to this



Astronomy with NASA

Gamma-ray ...
... transients
... Imaging
... Polarimetry

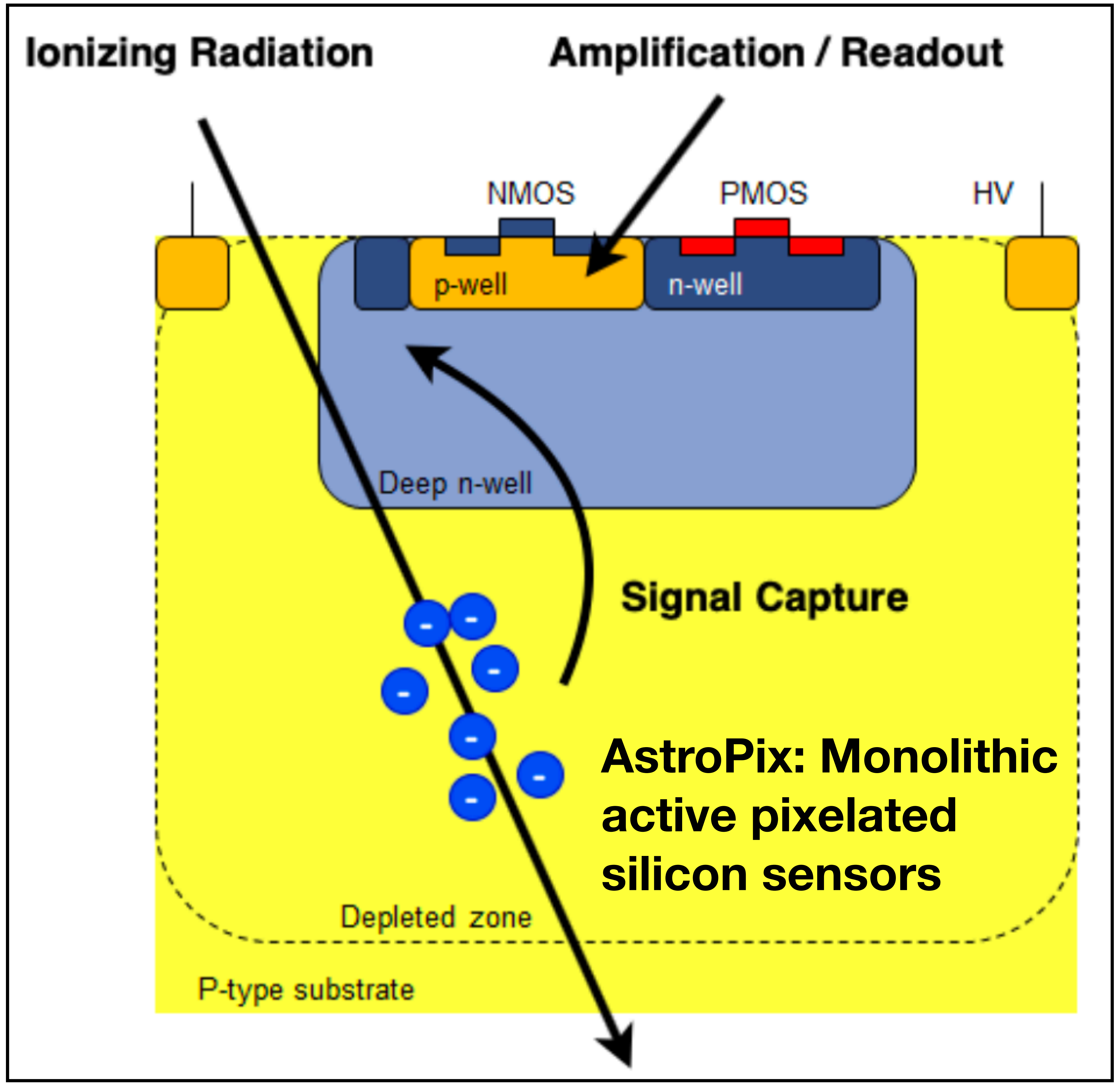


Summary and Conclusions

- AMEGO-X is an MeV gamma-ray observatory designed for Multi-Messenger astronomy.
- Demand for sensitive all-sky survey and monitoring in keV-GeV unmet by existing and future missions.
- Plan to re-propose AMEGO-X′ to upcoming calls.

Ongoing technology development:

- ComPair (balloon payload):
    - CsI (and CZT) calorimeter
    - DSSD tracker
    - plastic scintillator ACD
- AstroPix (Monolithic active pixelated silicon sensors):
    - Converging on final design
    - Characterization in lab & test beams
    - Suborbital rocket flight in 2024.
- First plans for a larger balloon with AstroPix tracker.



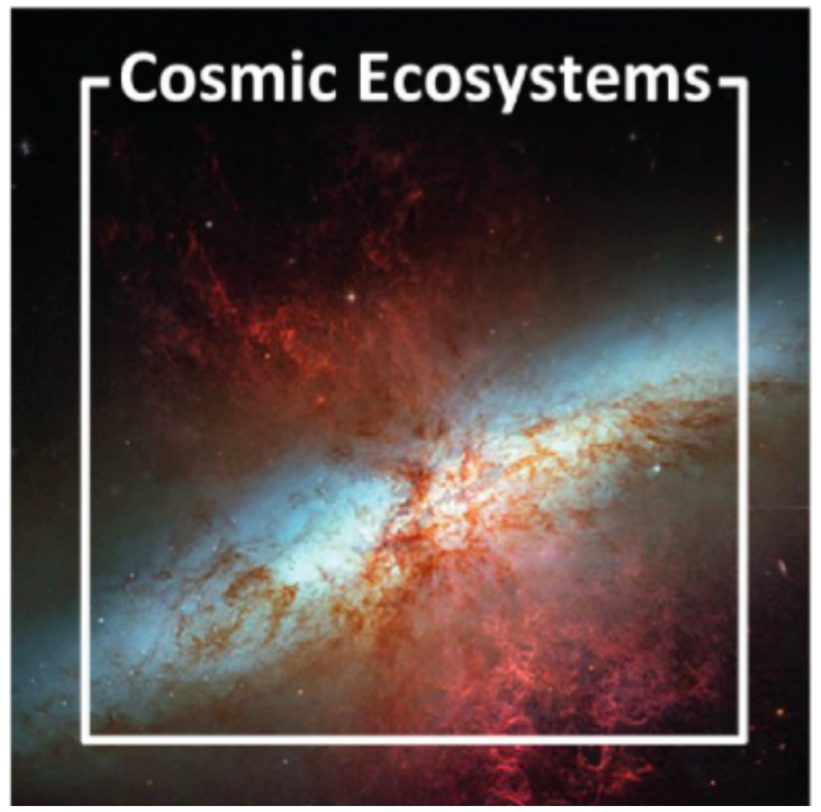
https://arxiv.org/abs/2209.02631 & https://doi.org/10.1016/j.nima.2021.165795

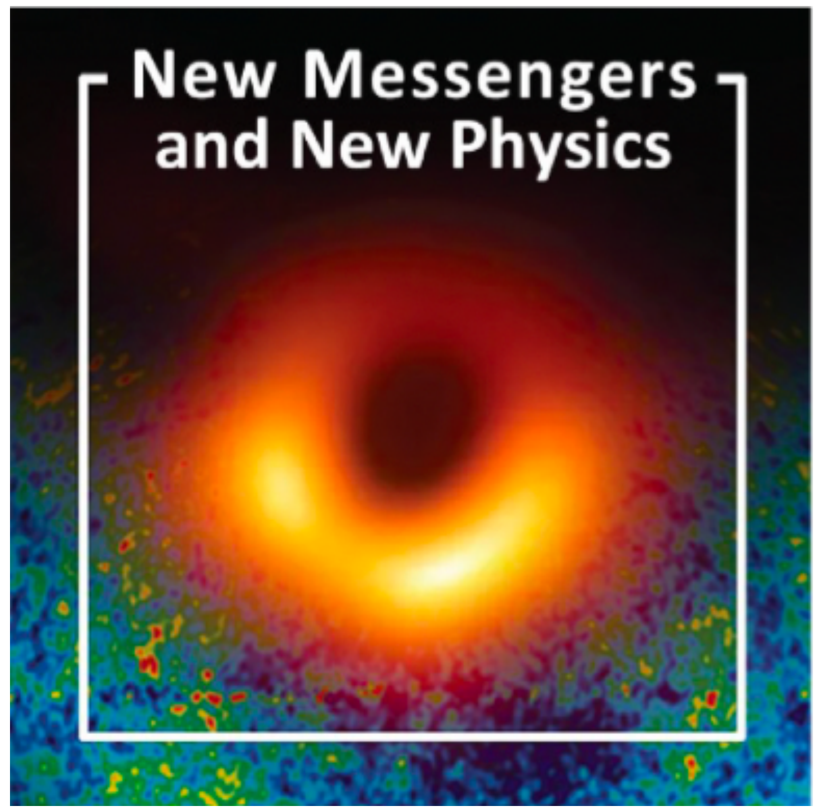
Backup

Results from the 2020 Decadal Survey

Worlds and Suns in Context: formation, evolution, and interconnected nature of exoplanets, stars and solar systems.
Priority Area: "**Pathways to Habitable Worlds**"

Cosmic Ecosystems: formation and evolution of stars, galaxies, and intergalactic gas.
Priority Area: "**Unveiling the Drivers of Galaxy Growth**".



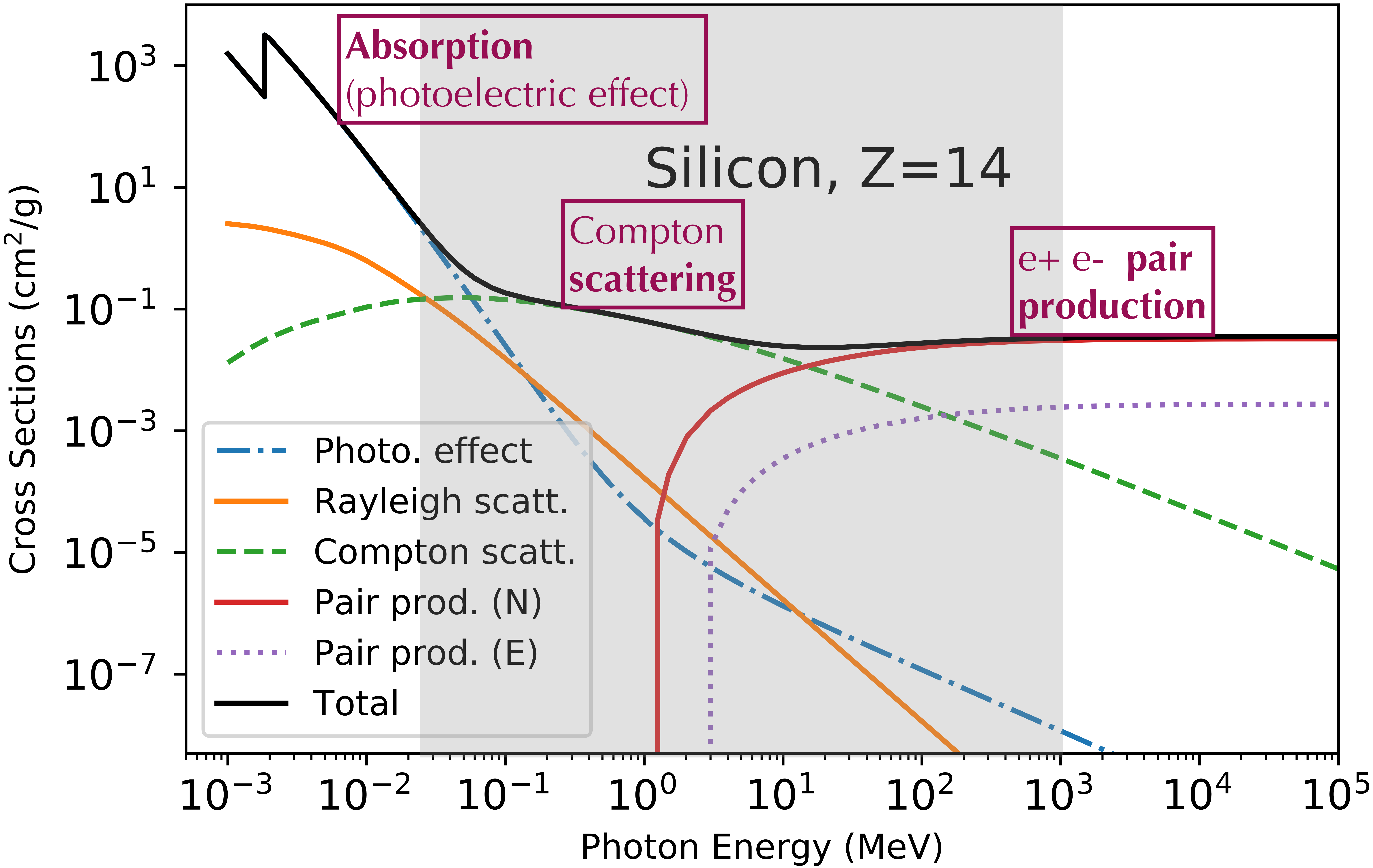


New Messengers and New Physics: gravitational waves, particles, time-domain astronomy, dark matter, dark energy.
Priority Area: "**New Windows on the Dynamic Universe**" (time-domain MW and MM astronomy)

See https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020
Thanks to Carolyn Kierans for summarizing!

Detecting MeV gamma rays

Plot: R. Caputo, Data: M. Berger, J. Hubbell, S. Seltzer, J. Chang, J. Coursey, R. Sukumar et al., "XCOM: Photon Cross Section Database (version 1.5), National Institute of Standards and Technology." http://physics.nist.gov/xcom , accessed: 2022/01/02



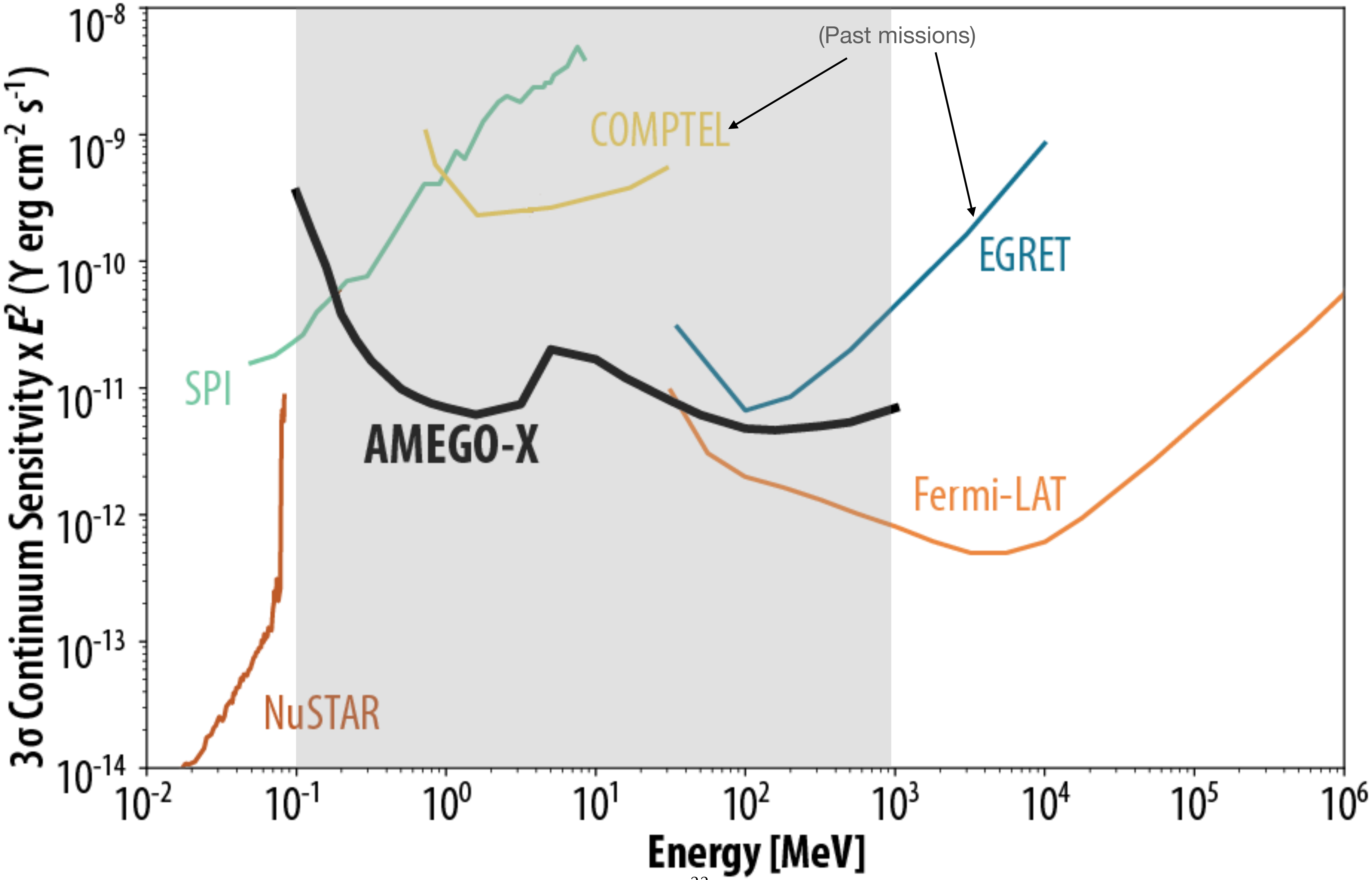
Secondary particles travel macroscopic distances (several cm).

Detection:

- Silicon detectors (trackers): electrical signal
- Scintillator crystals: scintillation light (-> PMTs or SiPMs: electrical signal)

A. Steinhebel (**S13.7**, this session)

AMEGO-X 3-year survey sensitivity



Haven't we seen enough?

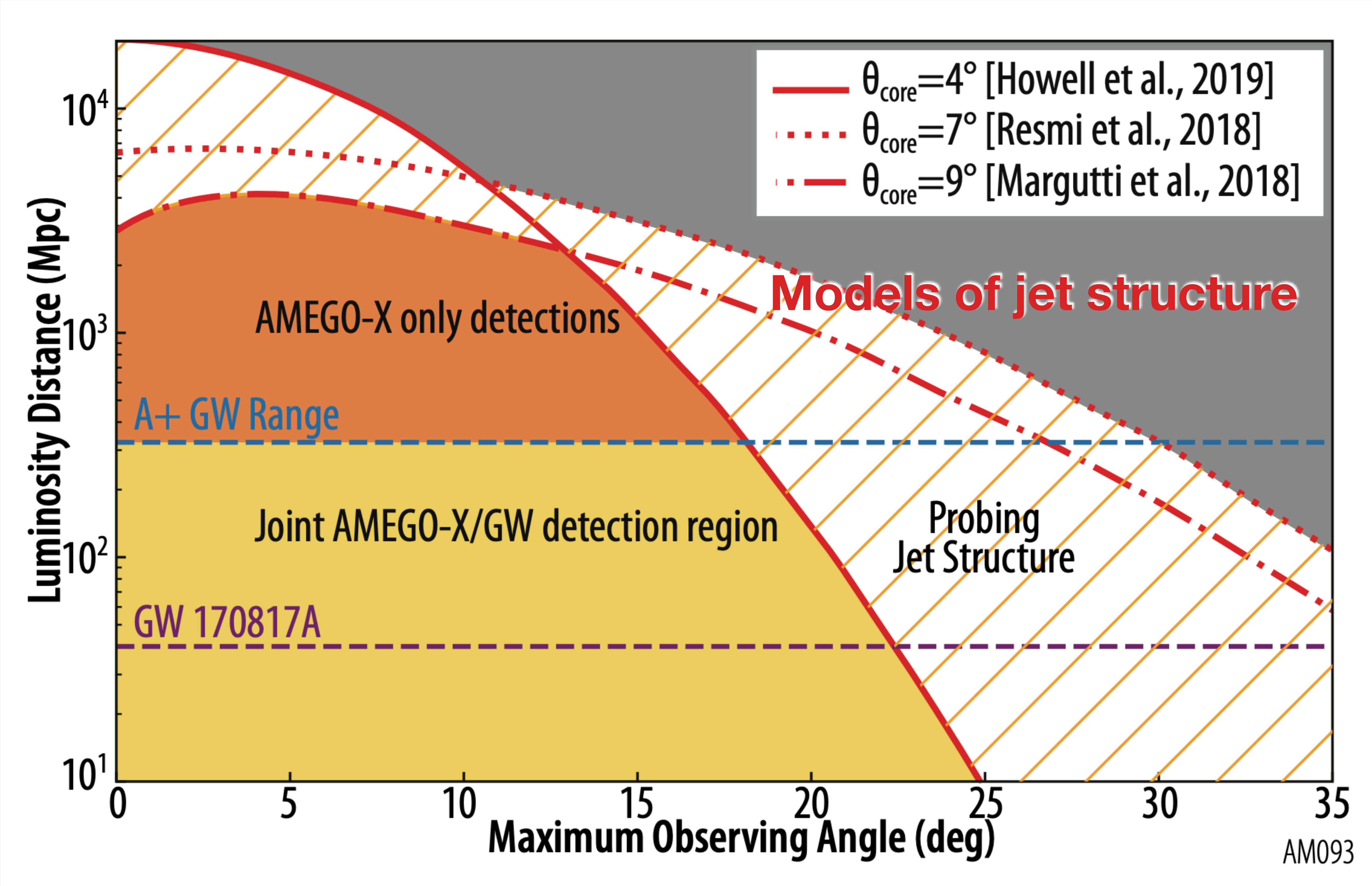
All GRBs are different.

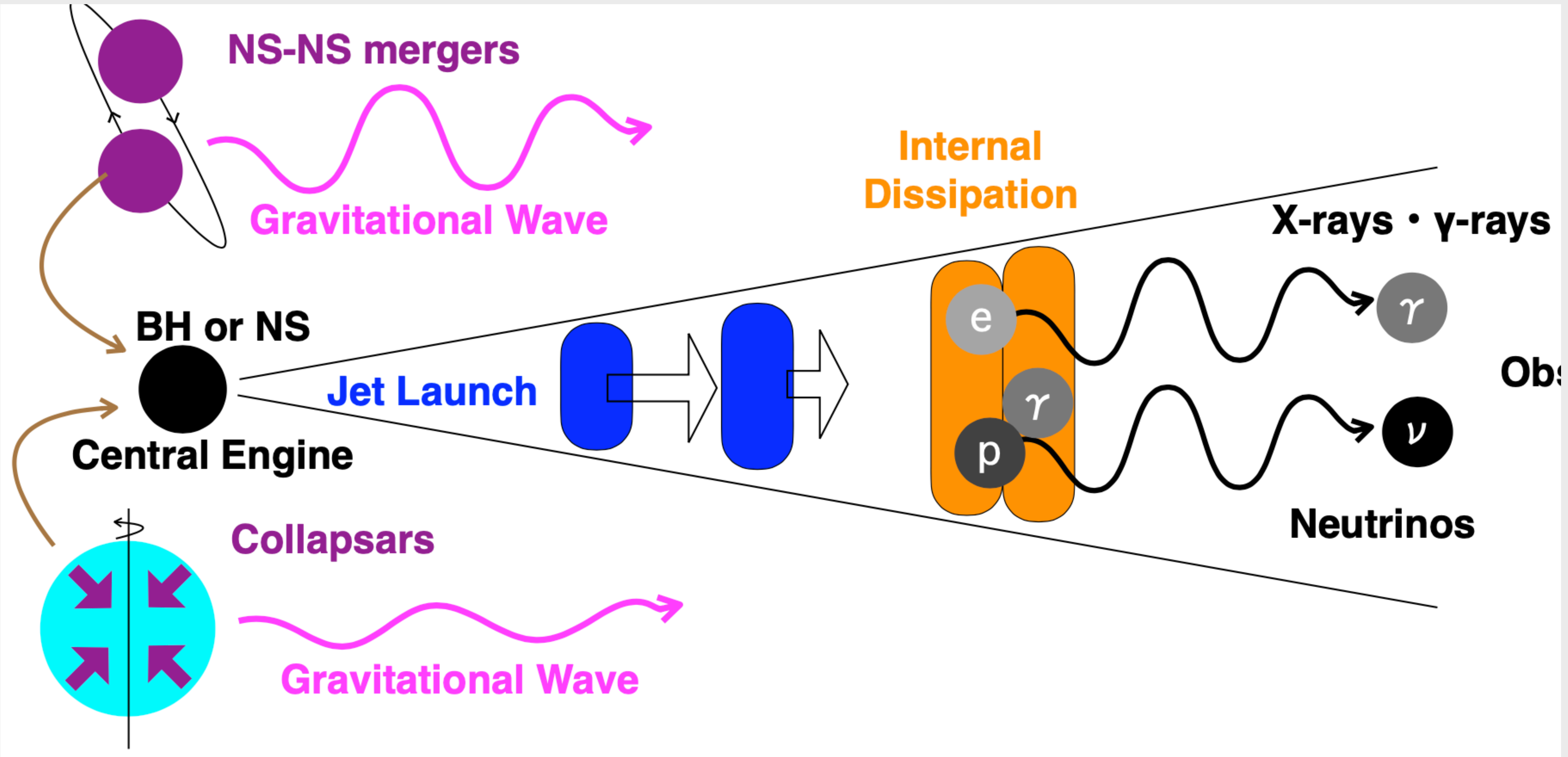
More statistics are needed for population studies.

Need more GRBs with counterparts in

- **Gravitational waves:**
    - Time delay → jet formation, LIV
    - Ratio of photon fluence vs GW intensity
      → jet structure, opening angle
    - (Non-detections can be constraining!)
- **Optical** (afterglow):
    - Distance → total energy release
- **VHE** (>100 GeV) gamma rays:
    - Onset/peak time → emission sites.
    - Photon energy → emission mechanism.

Time-resolved broad-band coverage is needed to resolve gamma-ray emission sites and mechanisms.



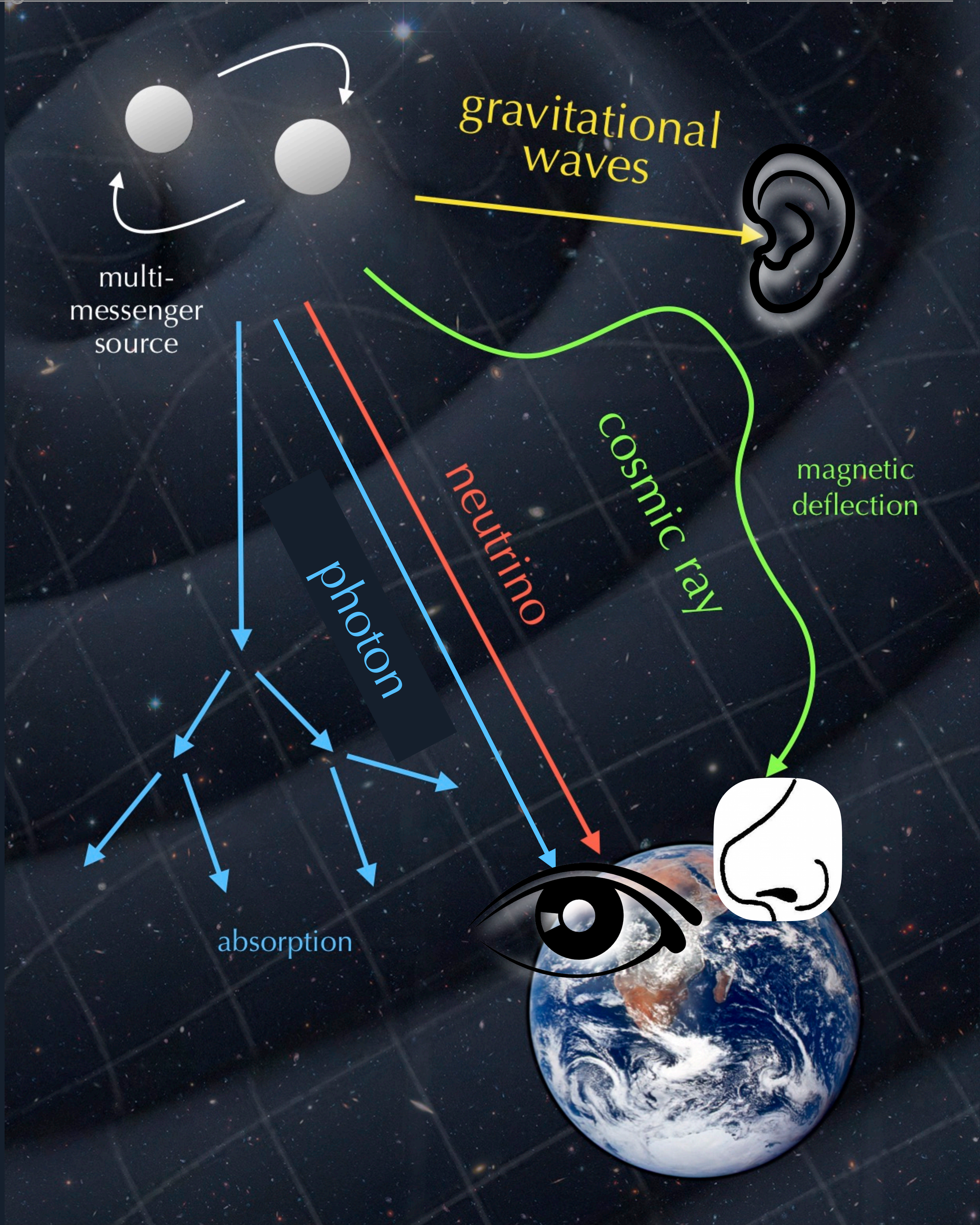


https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

Multi-Messenger Astronomy: Using all cosmic "senses"

Messenger	**Imaging?**	**First detection**	**Universe transparent?**
Photon	Yes 👍	Pre-history	Yes 👍/No 👎 *
Cosmic ray	No 👎	1917	(Yes 👍)
Neutrino	Yes 👍	1967 (solar) 1987 (SN) 2013 (HE)	Yes 👍
Gravitational wave	Yes-ish	2015	Yes 👍

* depending on photon energy



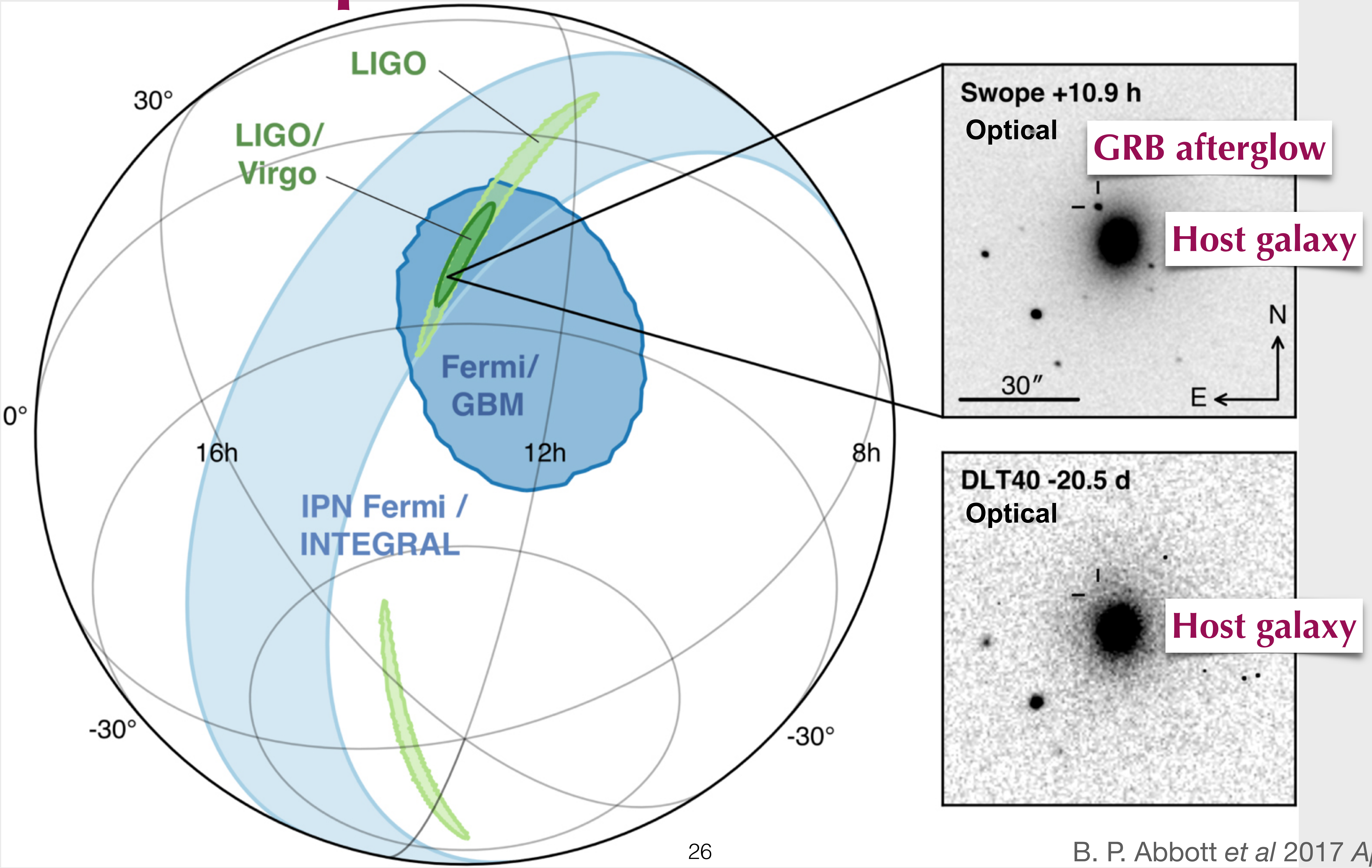
The Fireball model (still)

Relativistic jet explains the (apparently) large energy release

Shocks at c**olliding shells** accelerate **electrons** which emit **gamma-rays** via synchrotron emission

Progenitors = Supernovae?

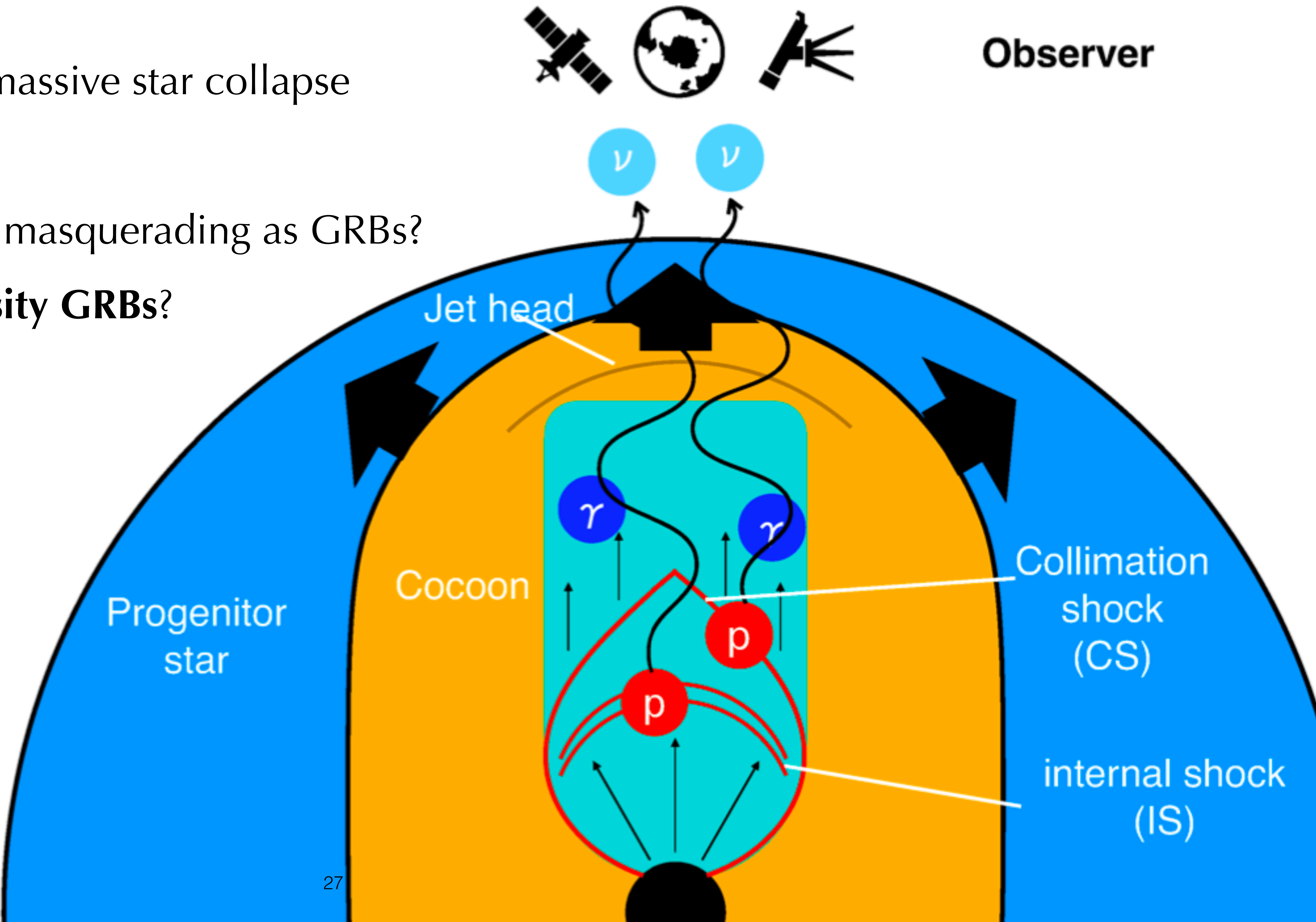
Temporal and spatial coincidence



B. P. Abbott *et al* 2017 *ApJL* **848** L12

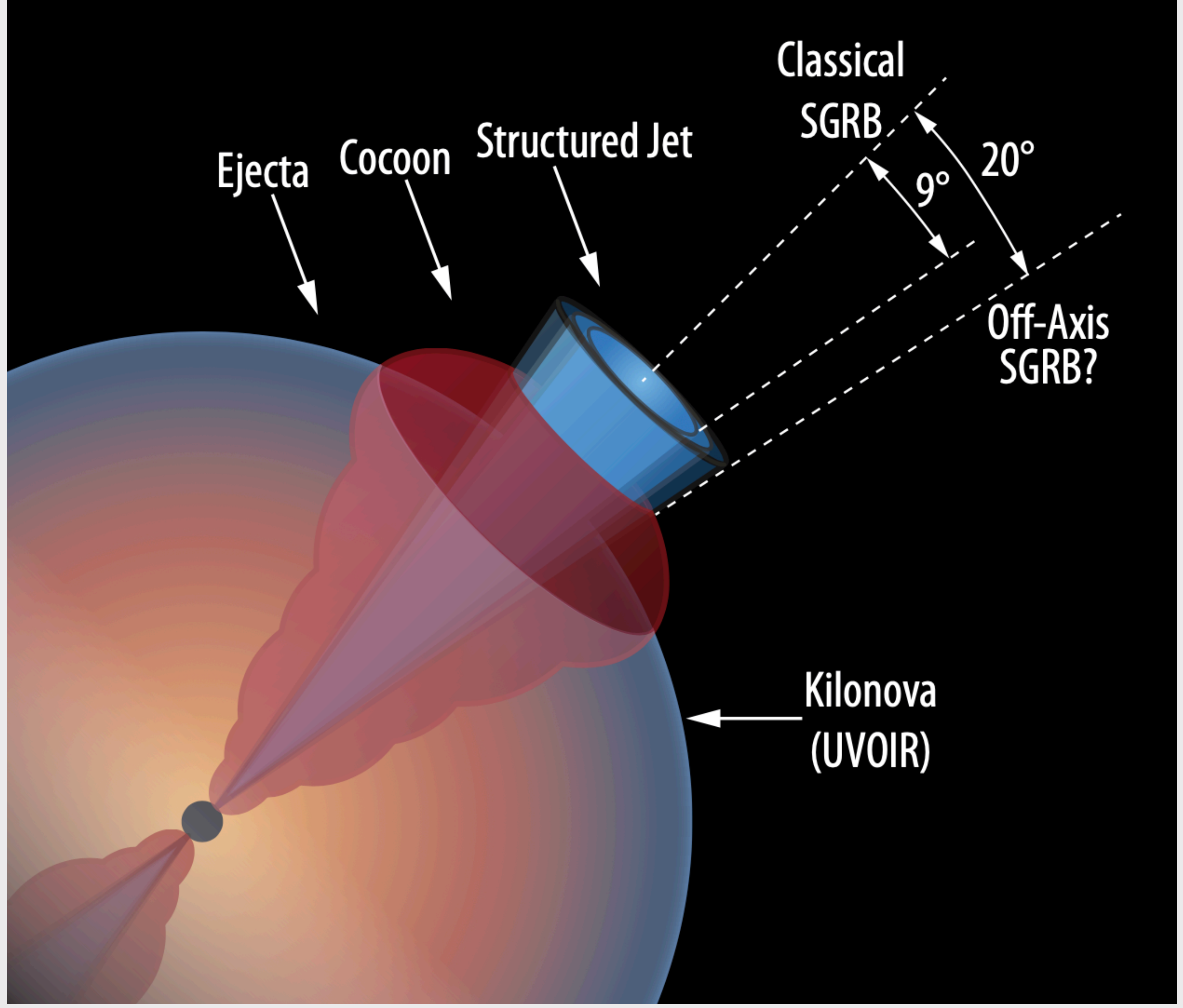
GRB progenitors

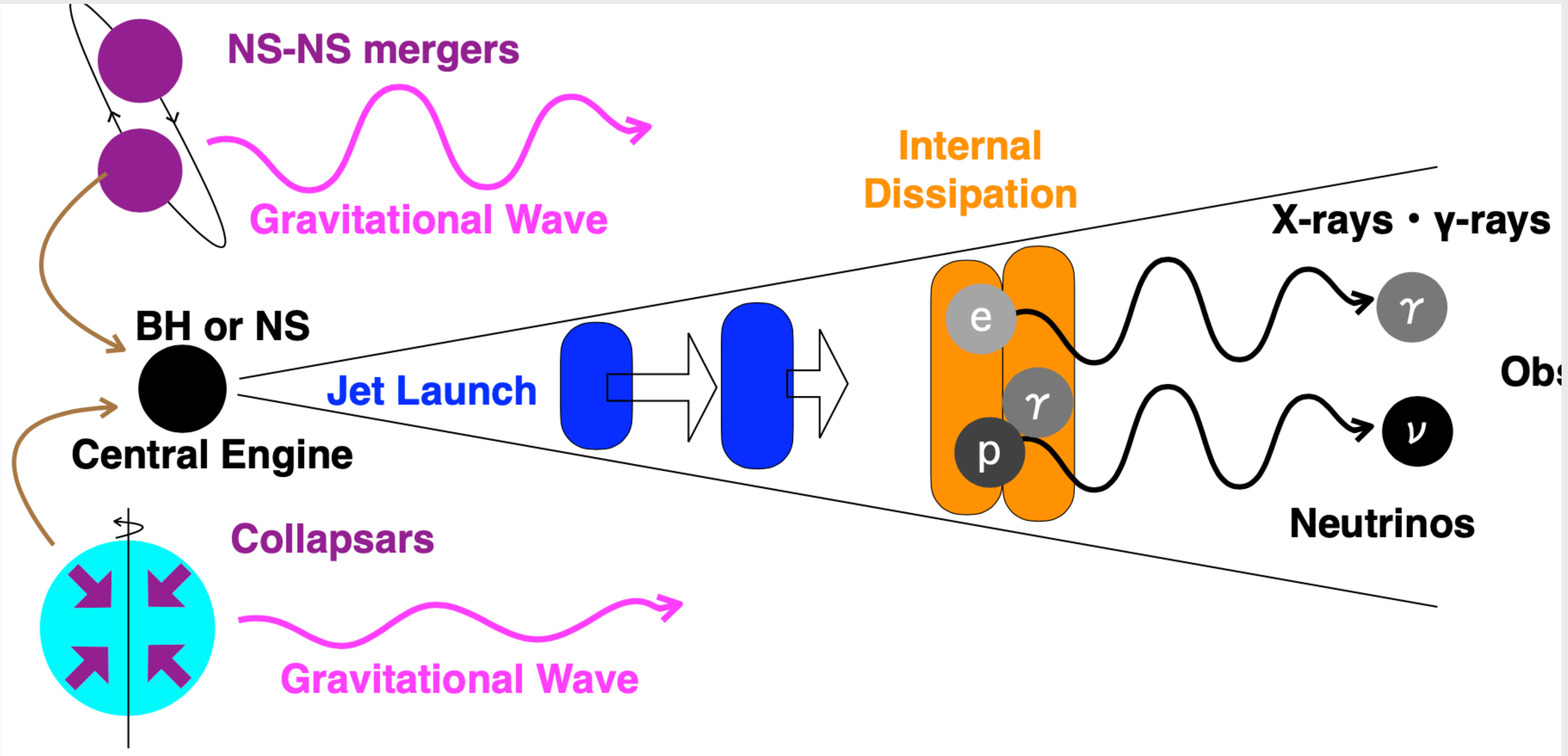
- How common are GRBs?
- Do all neutron star mergers and massive star collapse events produce relativistic jets?
- Are distant **magnetar giant flares** masquerading as GRBs?
- What is the cause of **low-luminosity GRBs**?

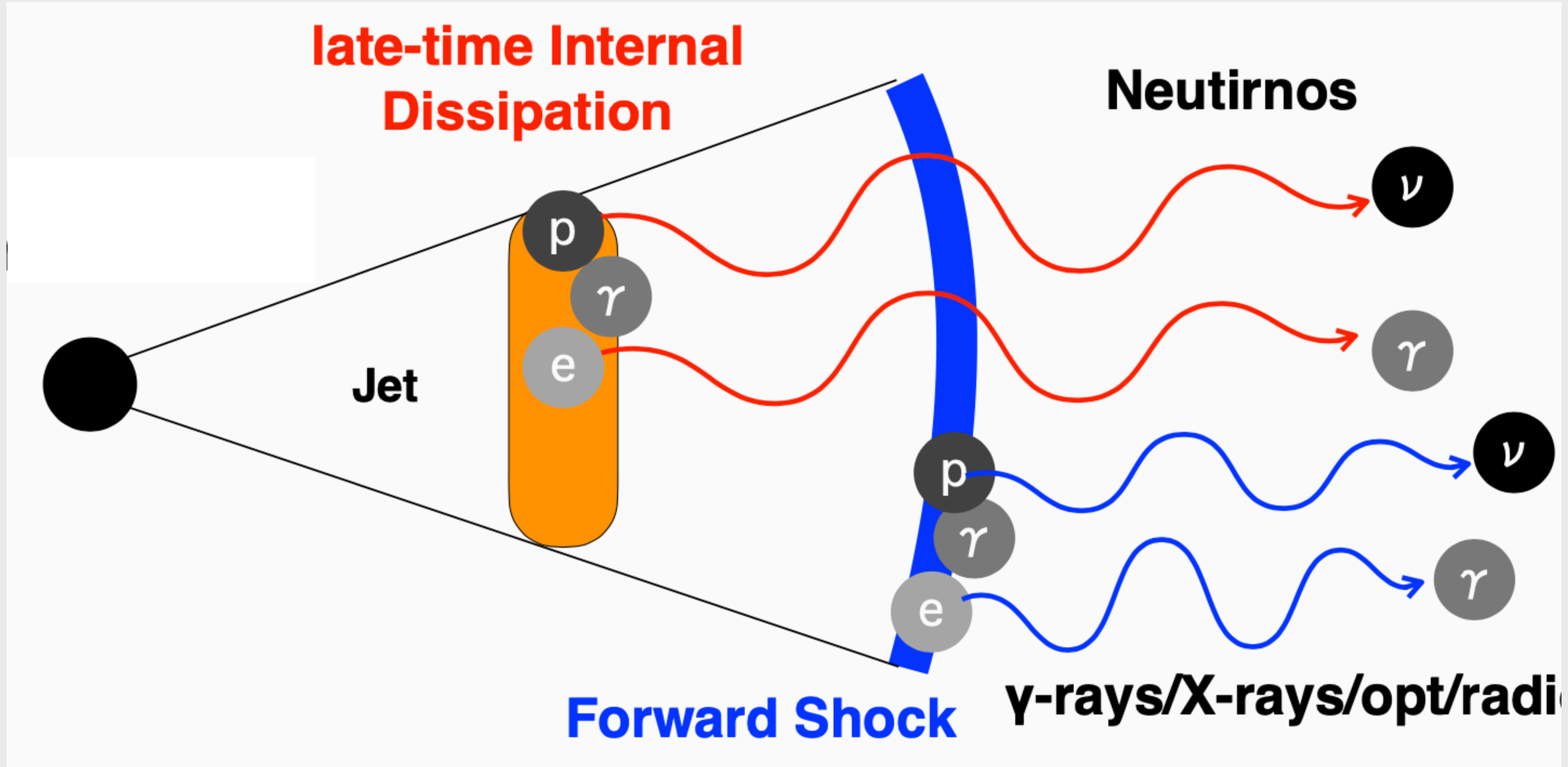


Jet physics

- **How do relativistic jets form** from BNS mergers and collapsars?
- What particles (e, p) are being accelerated in the jets?
- Are GRBs sources of Ultra-High energy Cosmic Rays (**UHECRs**)?
- How is the observed broadband emission produced?
- What is the **beaming angle/jet profile** and **Lorentz factor**?
- What is driving **late-time emission?**







https://arxiv.org/pdf/2202.06480.pdf

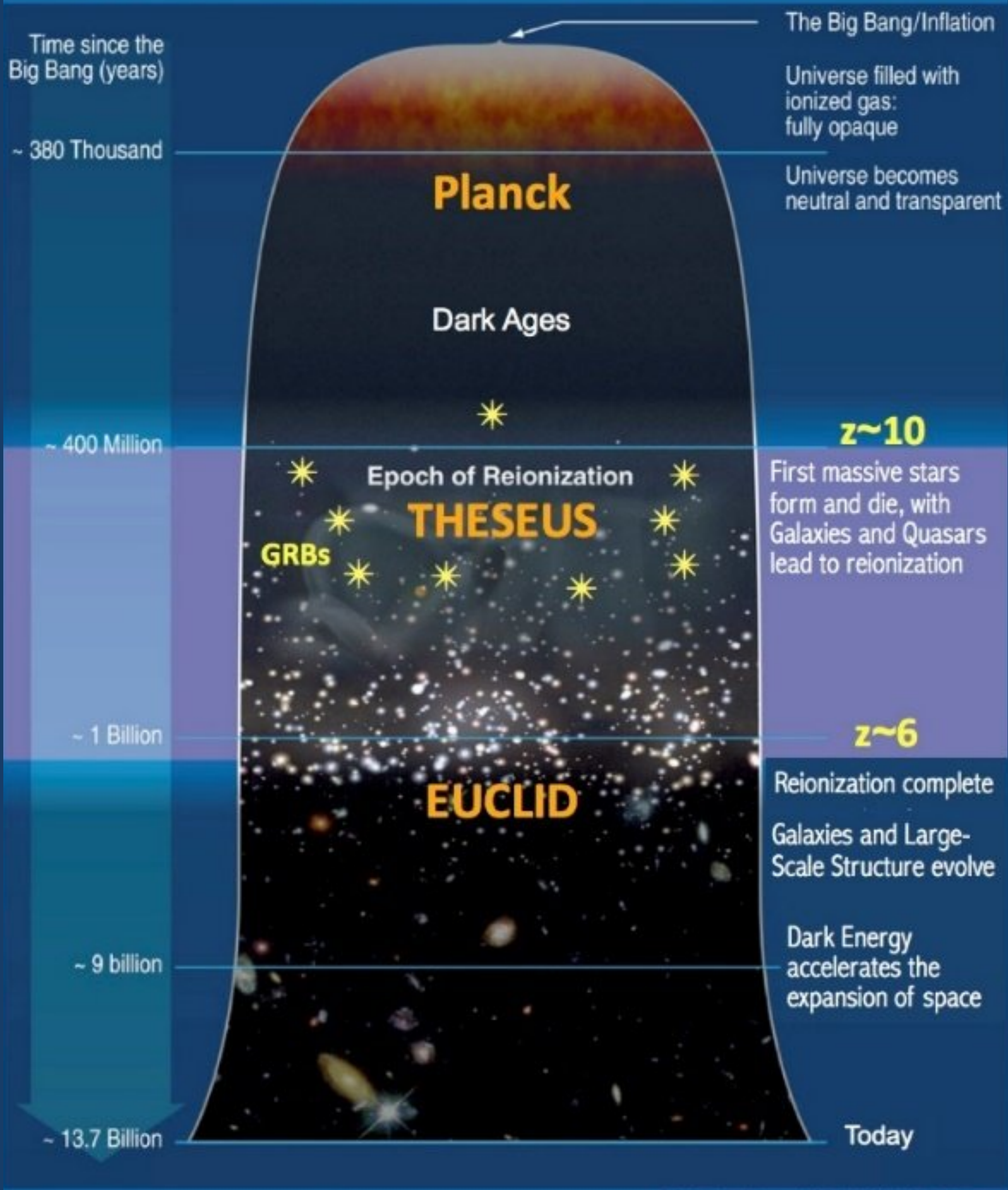
Physics and Cosmology

Fundamental physics/Lorentz invariance:

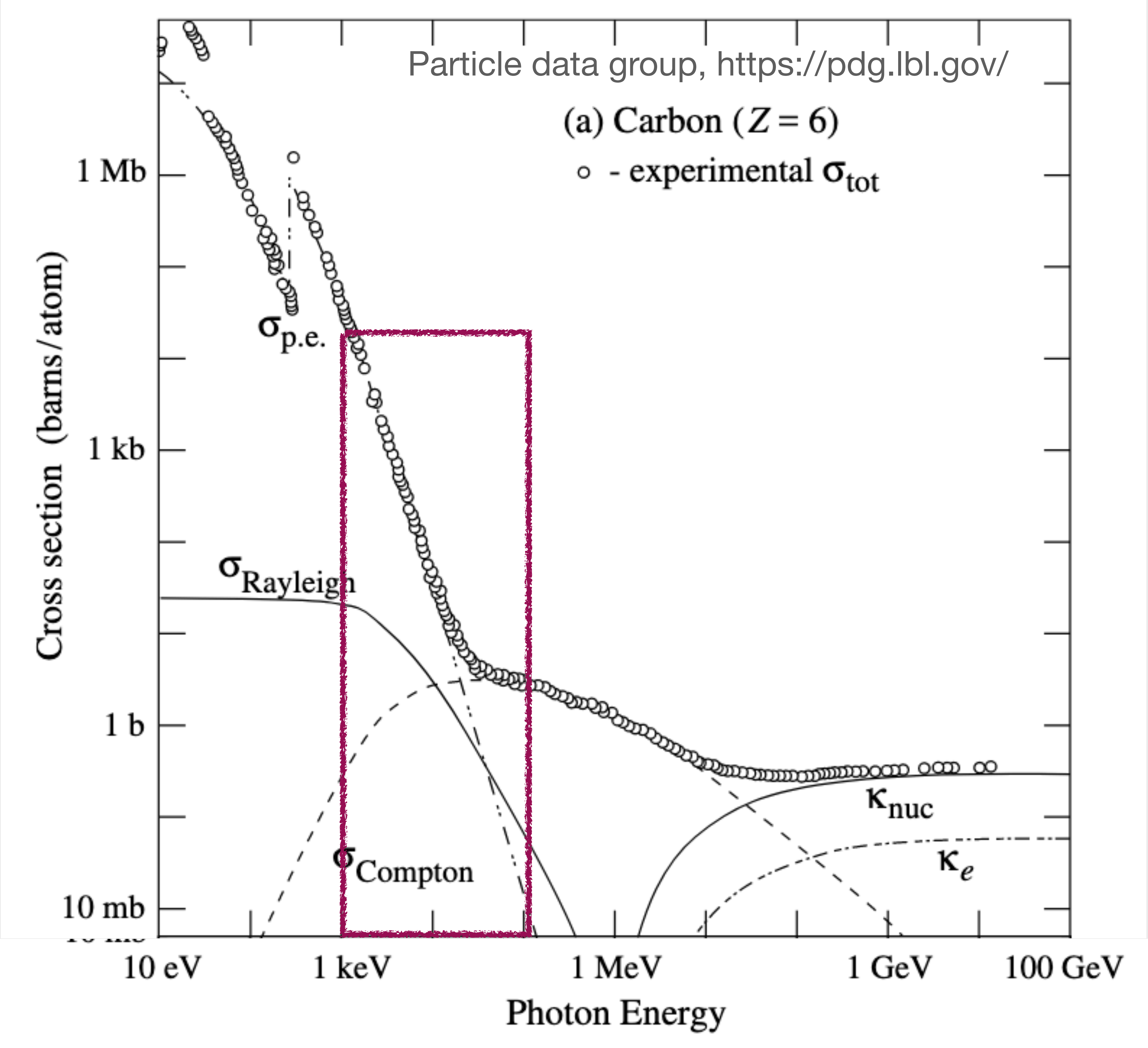
- Does **gravity** move at the speed of light?
- Does the **speed of light** depend on the photon energy?

Cosmology:

- How did the earliest stars form?
- How did early galaxies form and evolve?



X-ray/ɣ-ray Detection: Photo-electric effect



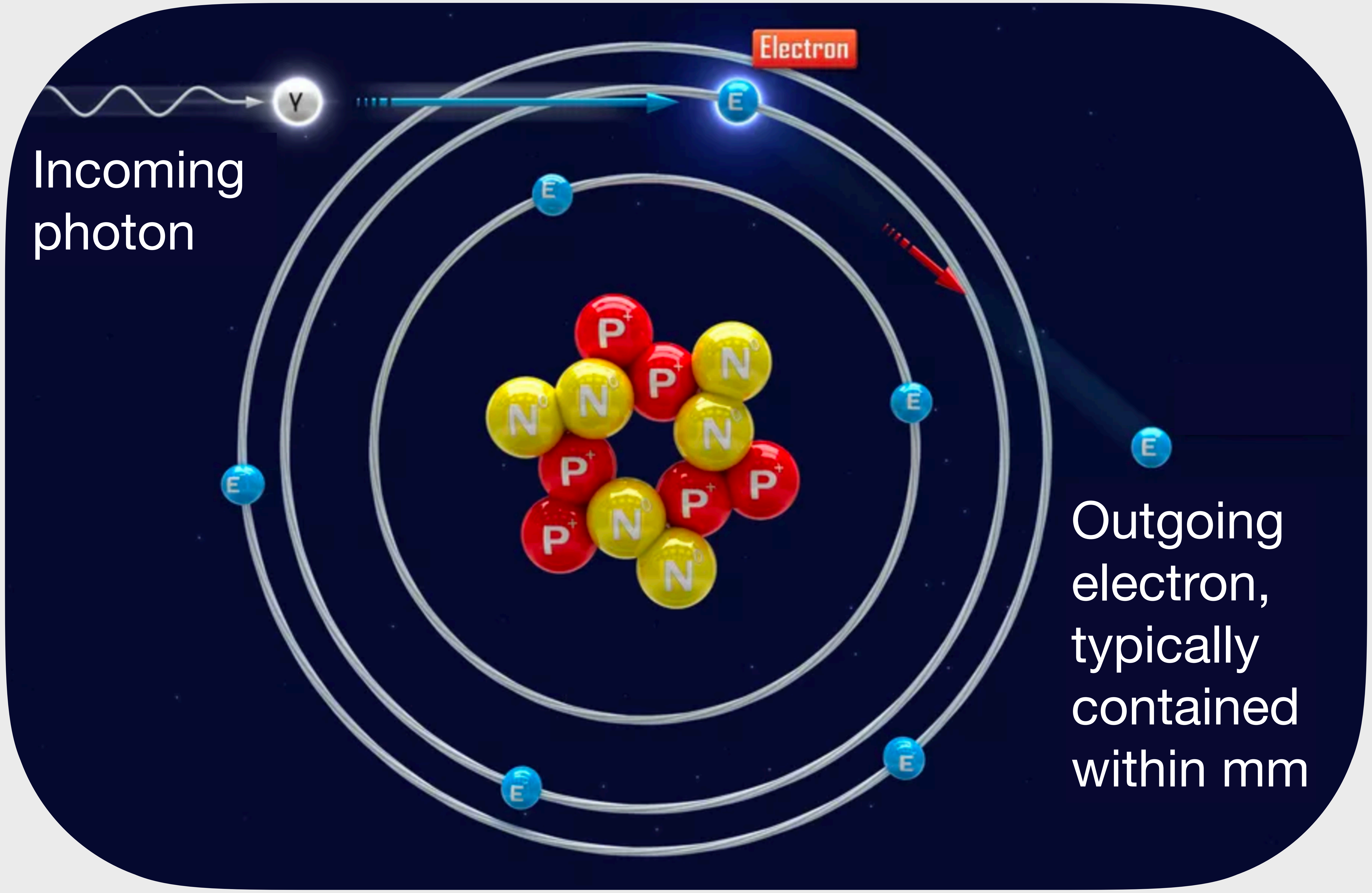
$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)

σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited

σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

κ_{nuc} = Pair production, nuclear field

κ_e = Pair production, electron field



https://www.livescience.com/58816-photoelectric-effect.html

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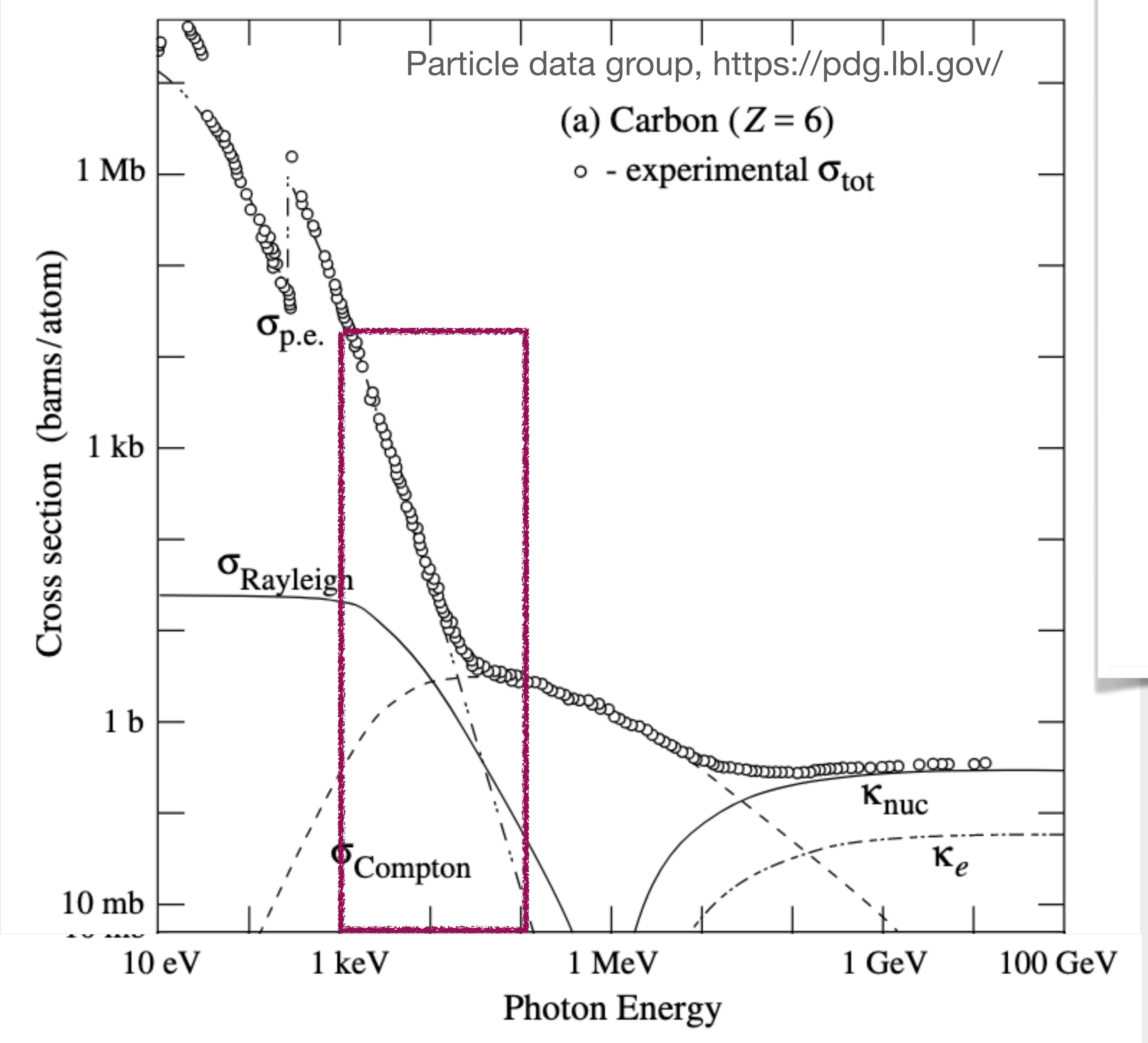

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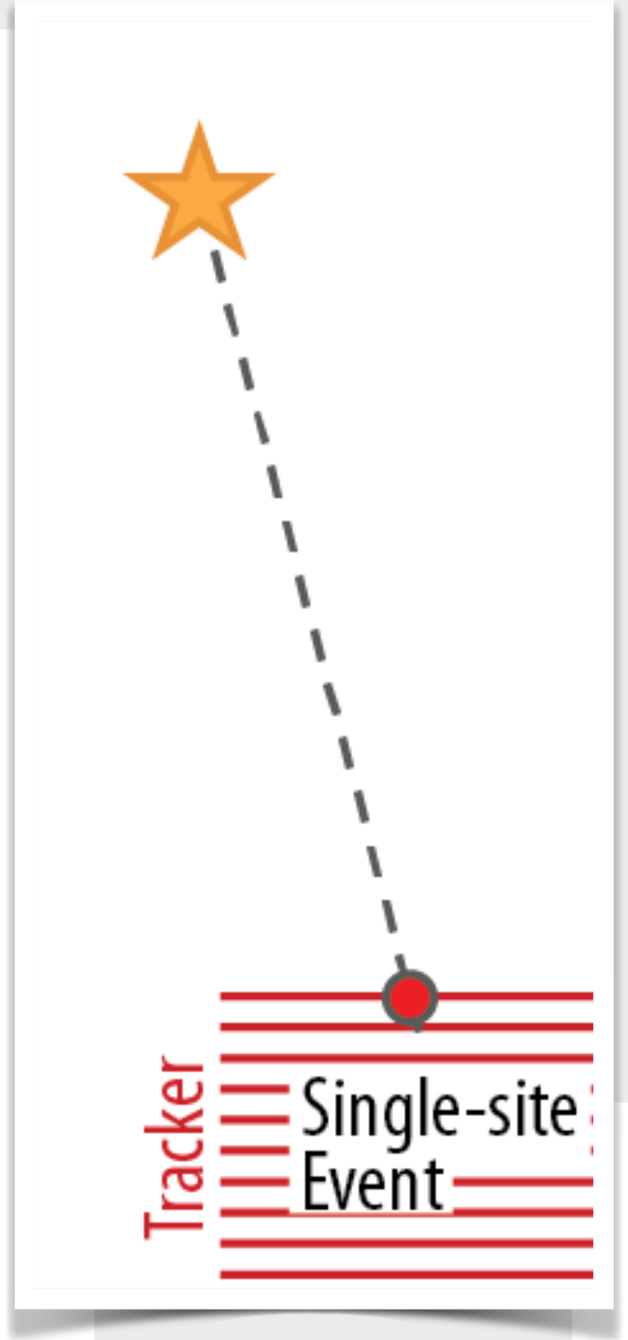
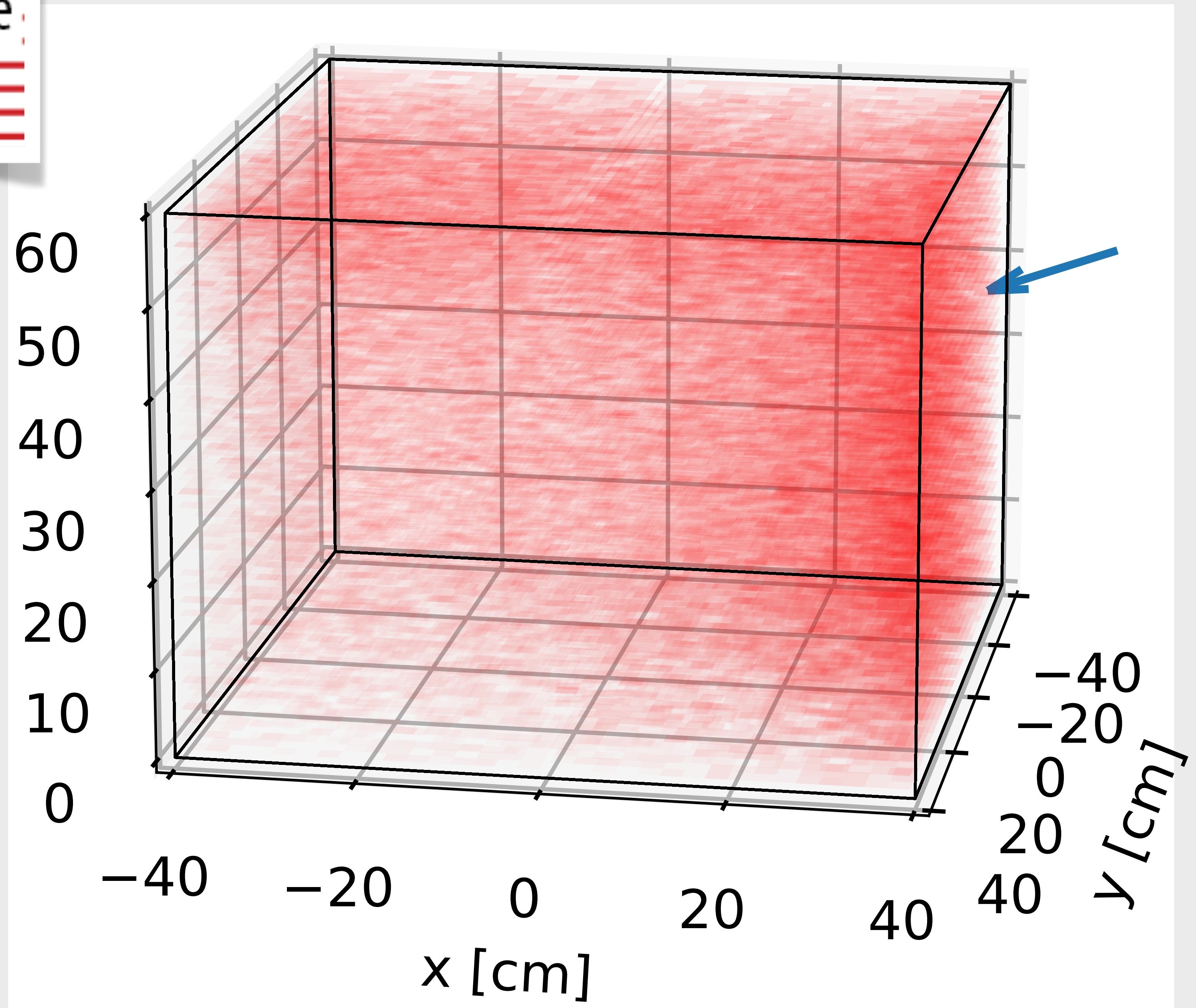
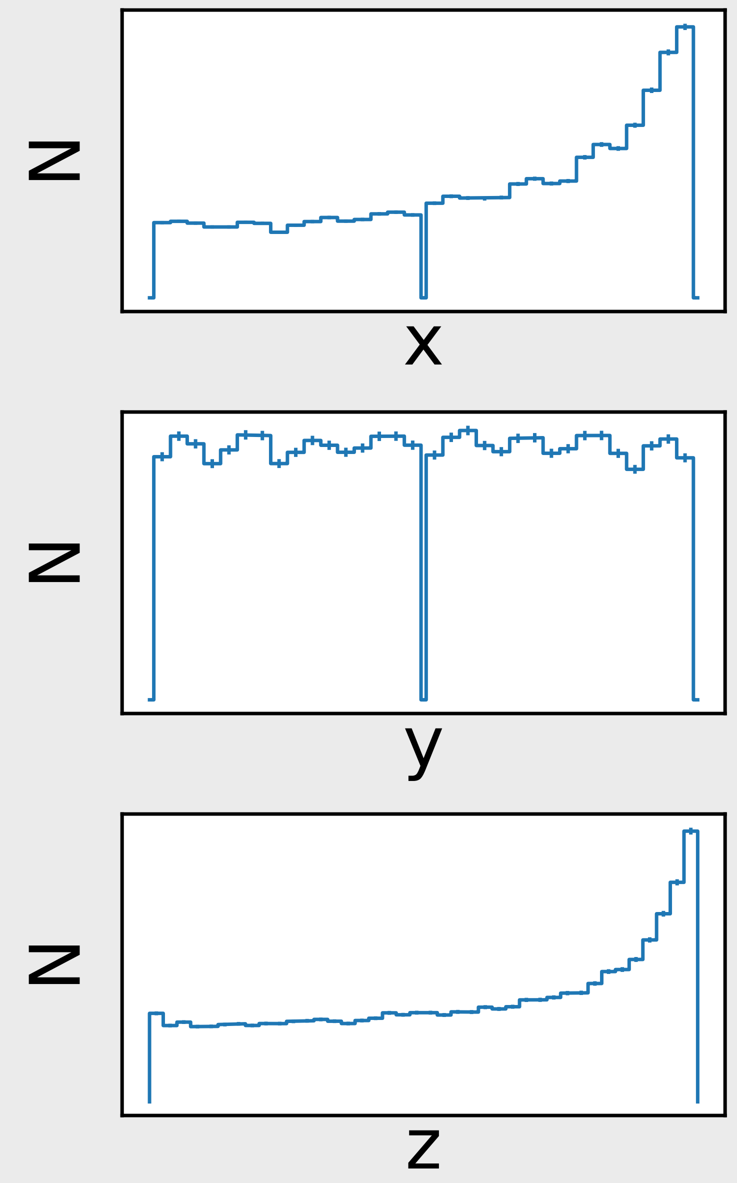
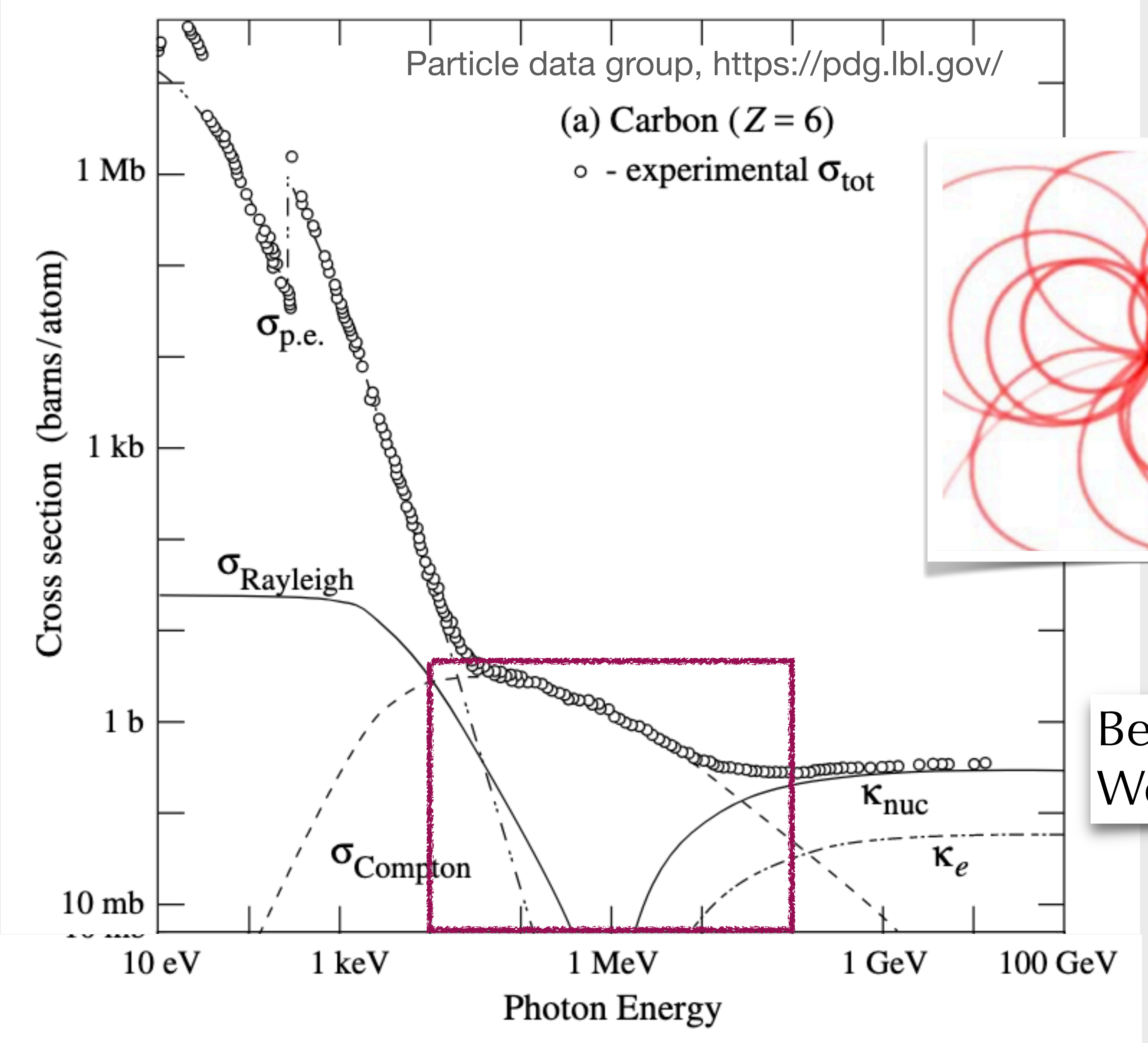


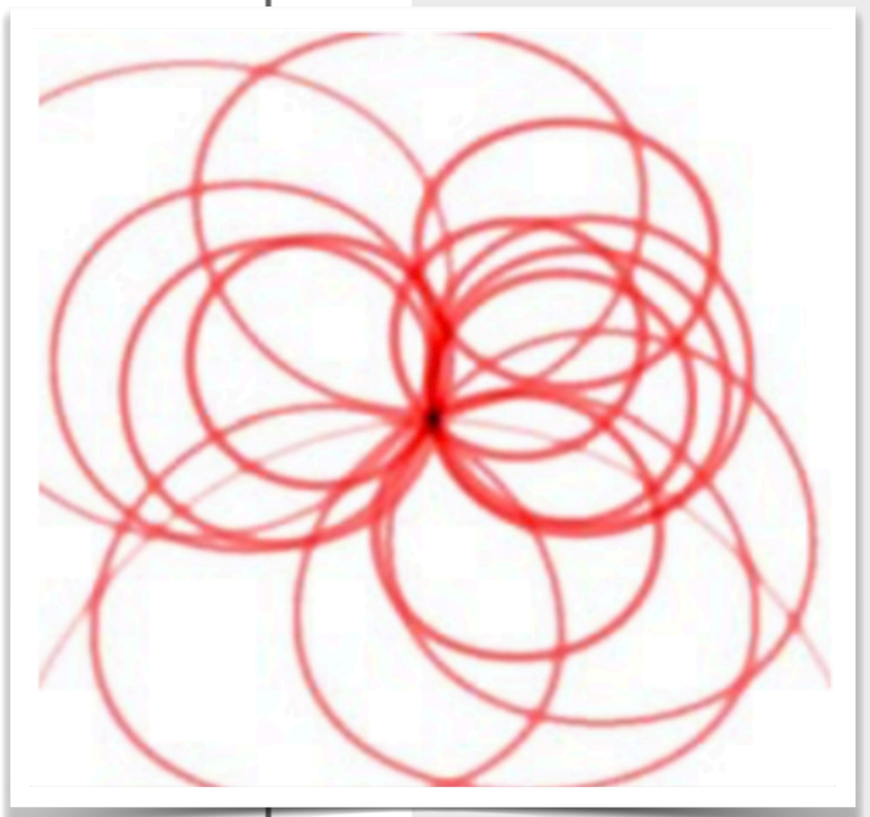
- No direction reconstruction for a single photon.
- Hit distribution in detector correlated with source position.
- Can localize transient events!





ɣ-ray Detection: Compton scattering





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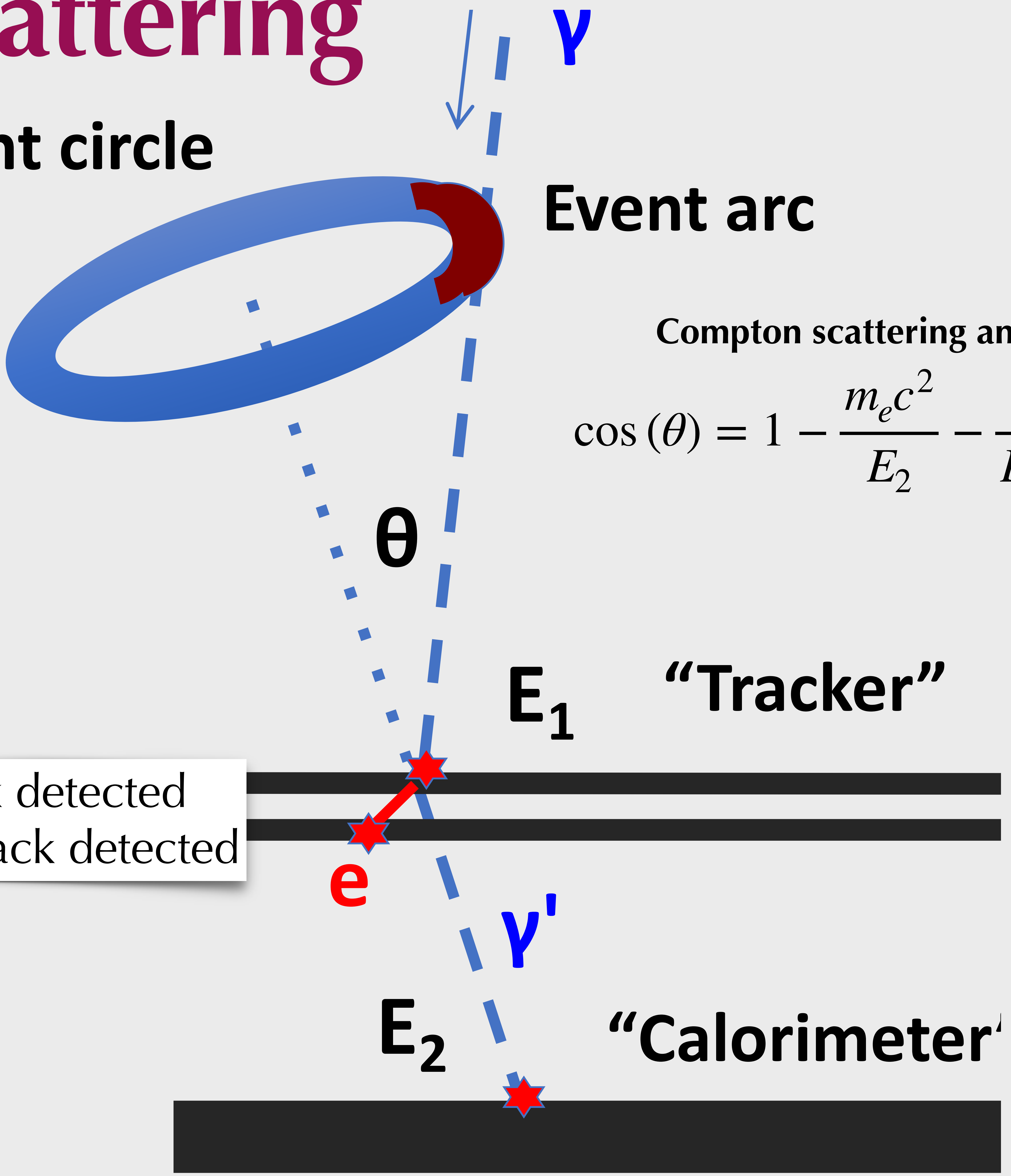


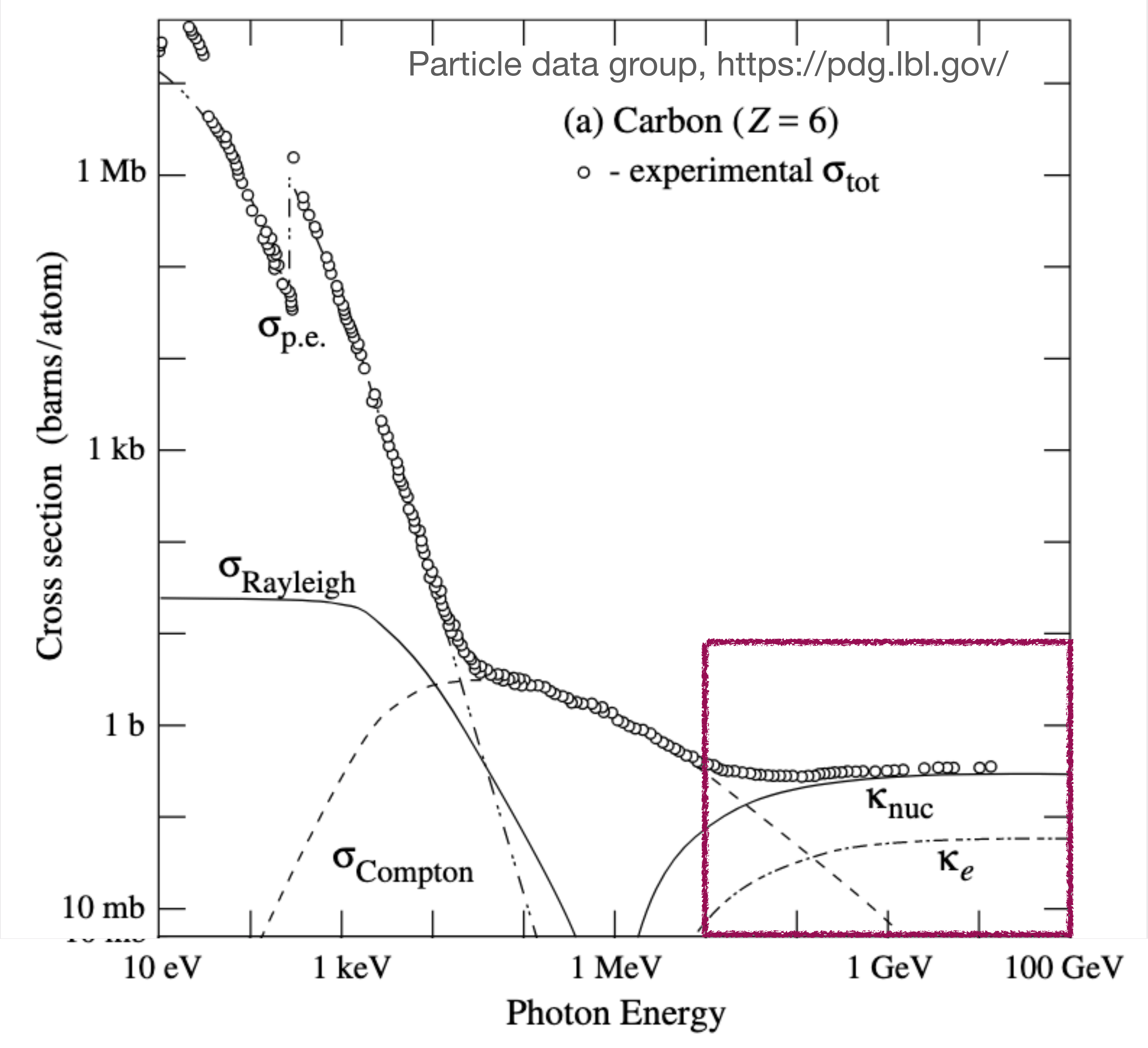
Compton scattering angle:

$$\cos(\theta) = 1 - \frac{m_e c^2}{E_2} - \frac{m_e c^2}{E_1 + E_2}$$

Best case: e- track detected
Worst case: no track detected

Best case: 2nd interaction via photoelectric effect
Worst case: sequence of Compton scatter interactions

MeV ɣ-ray Detection: Pair events



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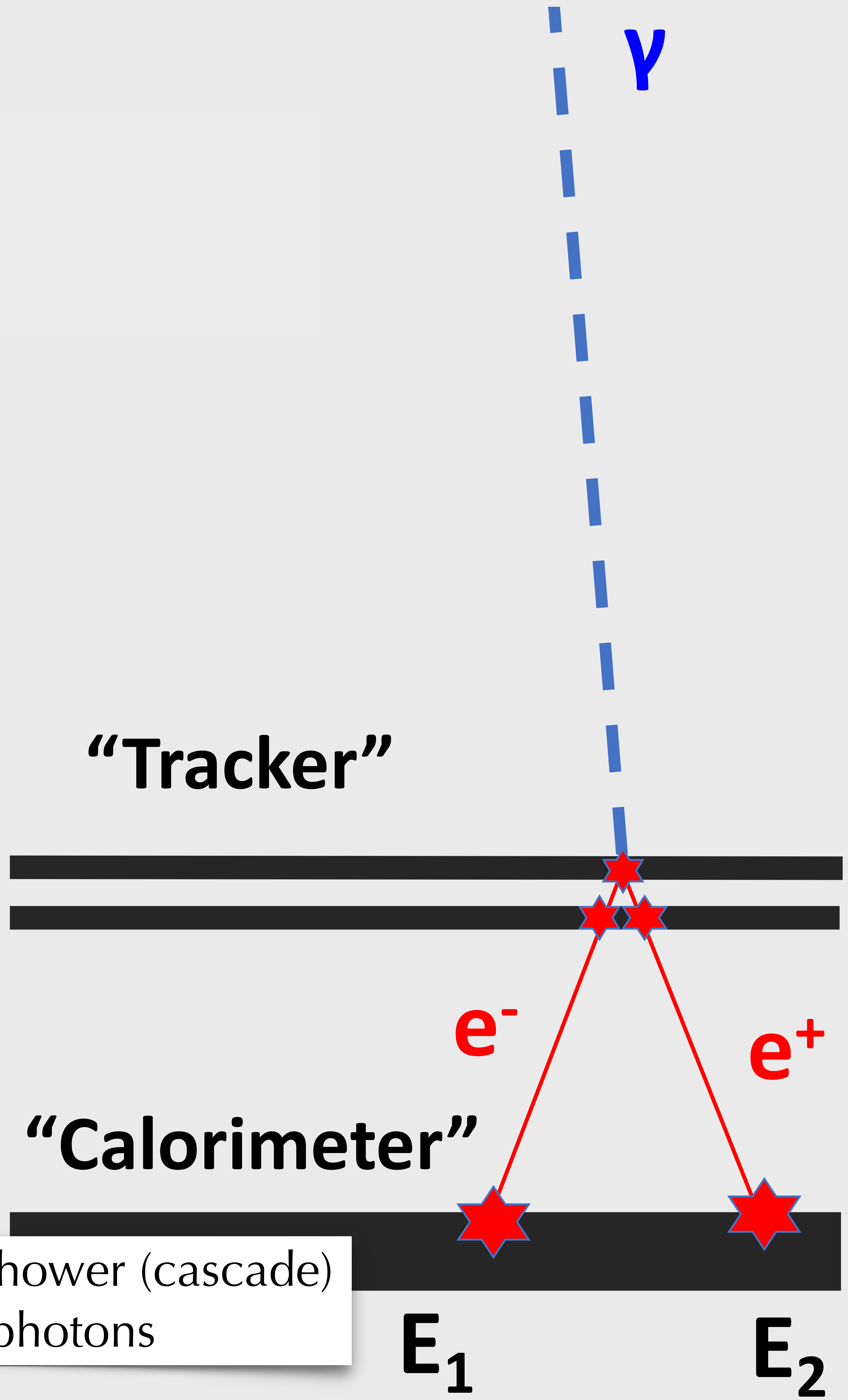
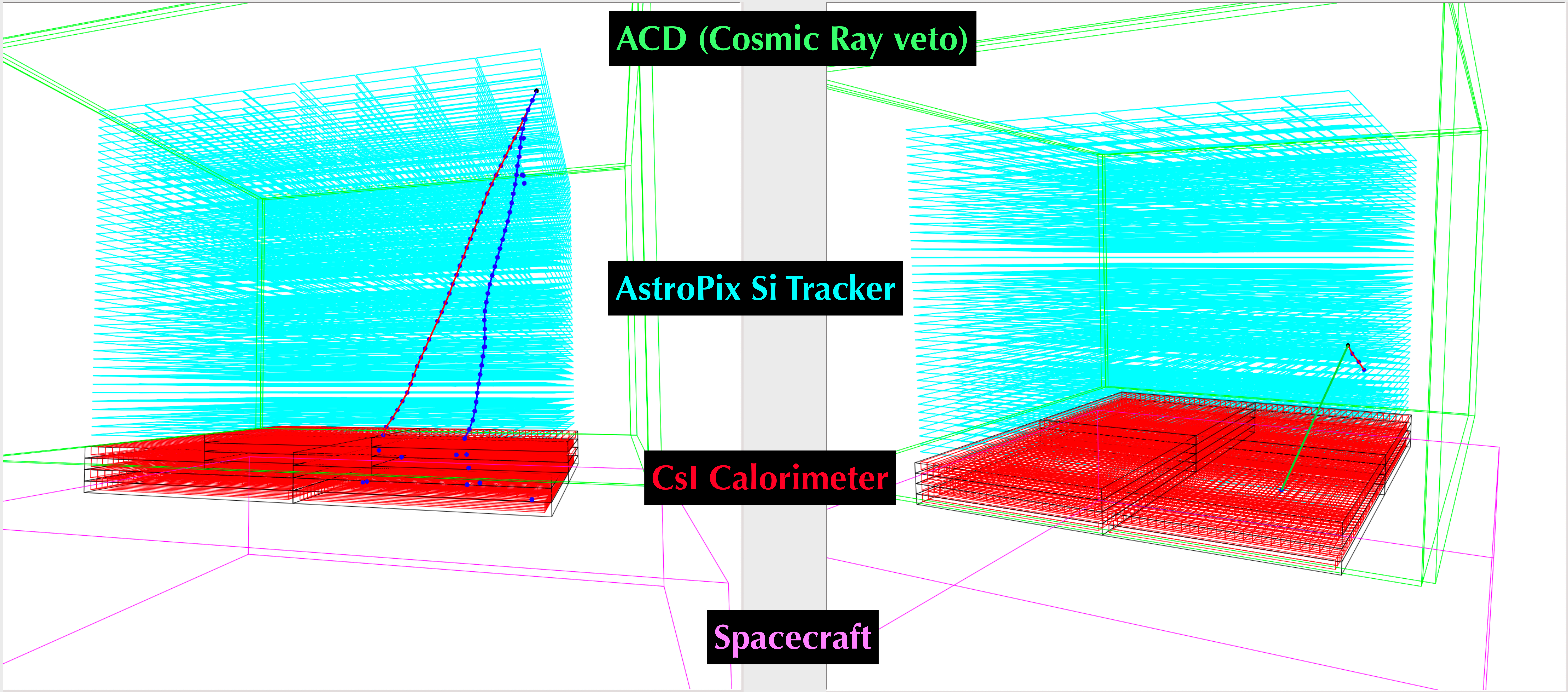


e^+ and e^- produce shower (cascade) of e^+, e^-, and ɣ-ray photons

Interactions in AMEGO-X

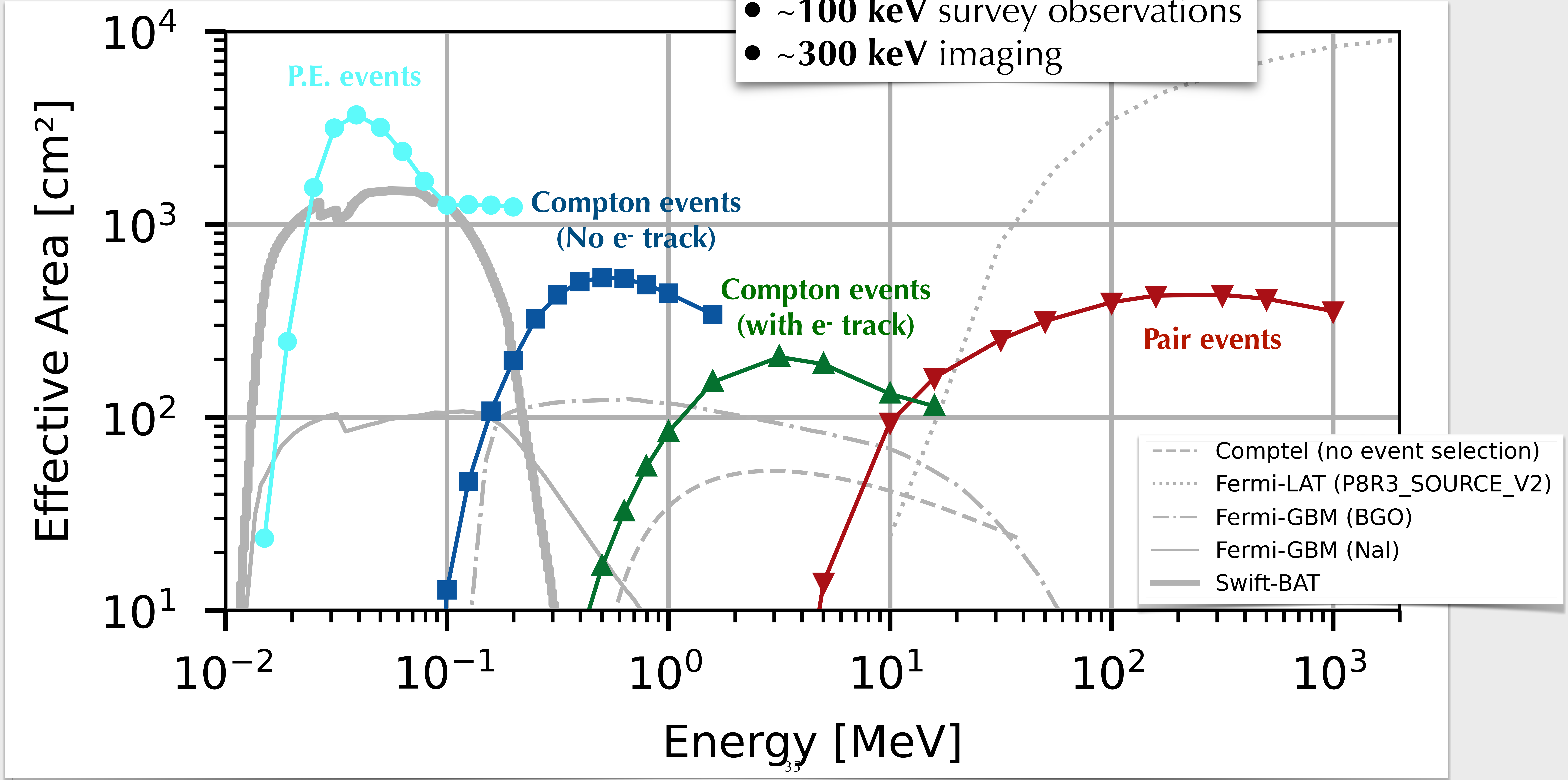


Pair interaction

Compton interaction

Predicted Performance

Energy threshold:
- ~**25 keV** bursts (< 2 minutes)
- ~**100 keV** survey observations
- ~**300 keV** imaging



Predicted Performance