Towards Revolutionary Observations of The MeV Sky

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On behalf of the

COSI Team

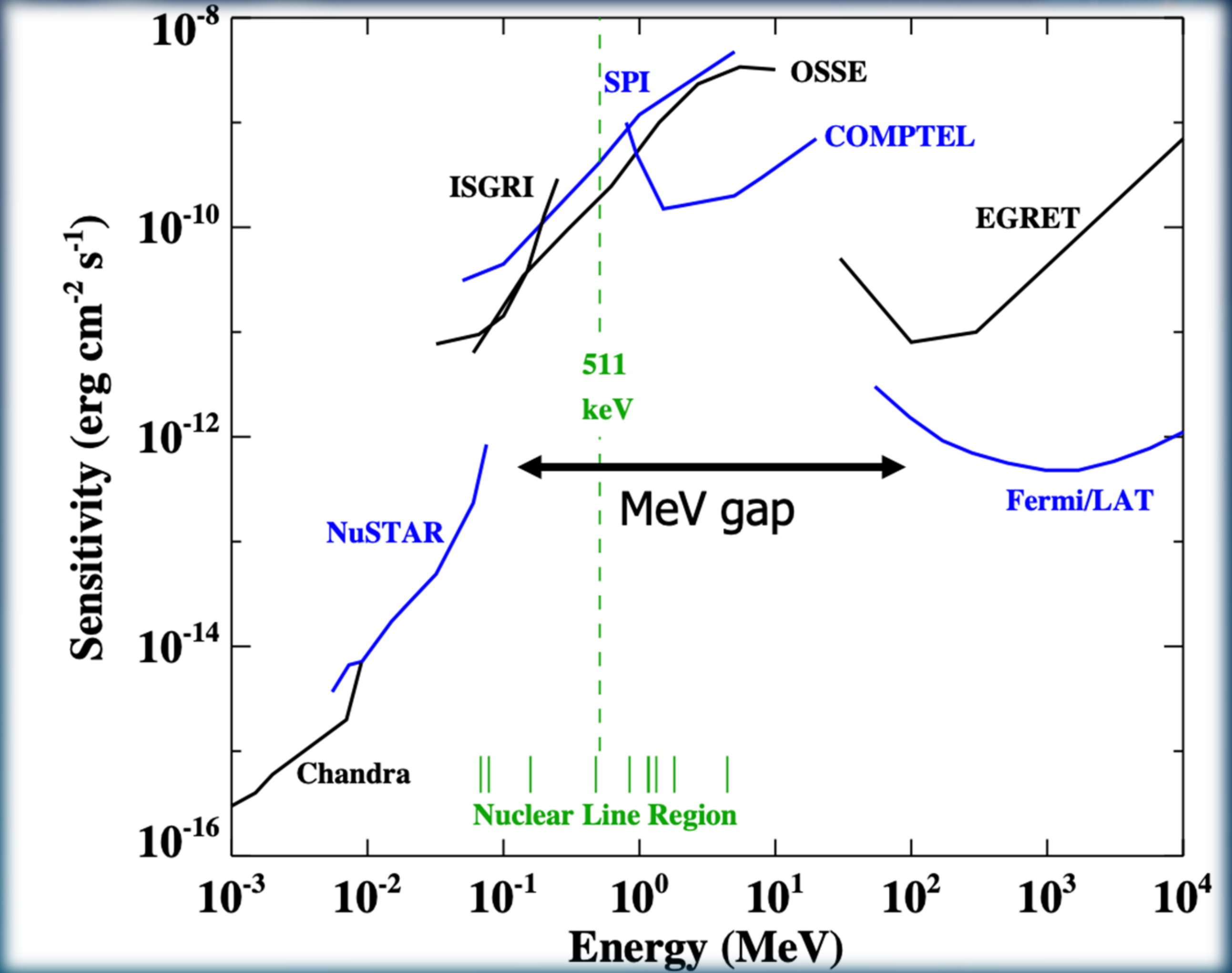
AMEGO-X Team

Fermi-LAT Collaboration

XVIII TAUP Conference, Vienna 2023

The MeV Band

- Previous and current missions have had relatively poor sensitivity in the MeV range



Missions/instruments with COSI connections:
CGRO/COMPTEL (1991-2000): Compton telescope
INTEGRAL/SPI (2002-now): germanium detectors
Fermi/LAT (2008-now): all-sky coverage every day
NuSTAR (2012-now): nuclear line spectroscopy

Why do we care ?

Huge Discovery Space

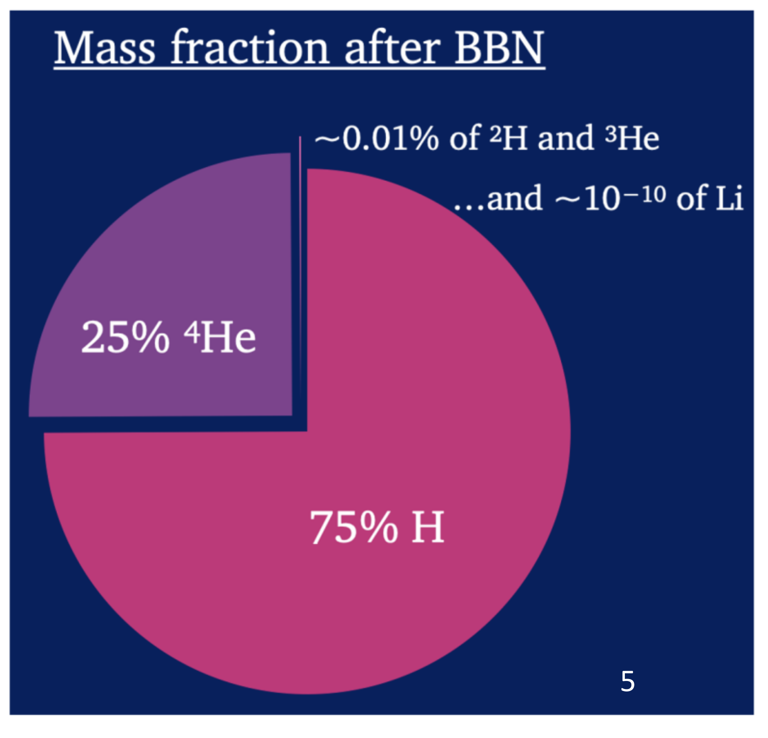
- 511 keV e^-e^+ annihilation line
- Nuclear lines for studies of nucleosynthesis
- High levels of polarization
- Time-domain and Multi-messenger astrophysics

Origin of the Elements

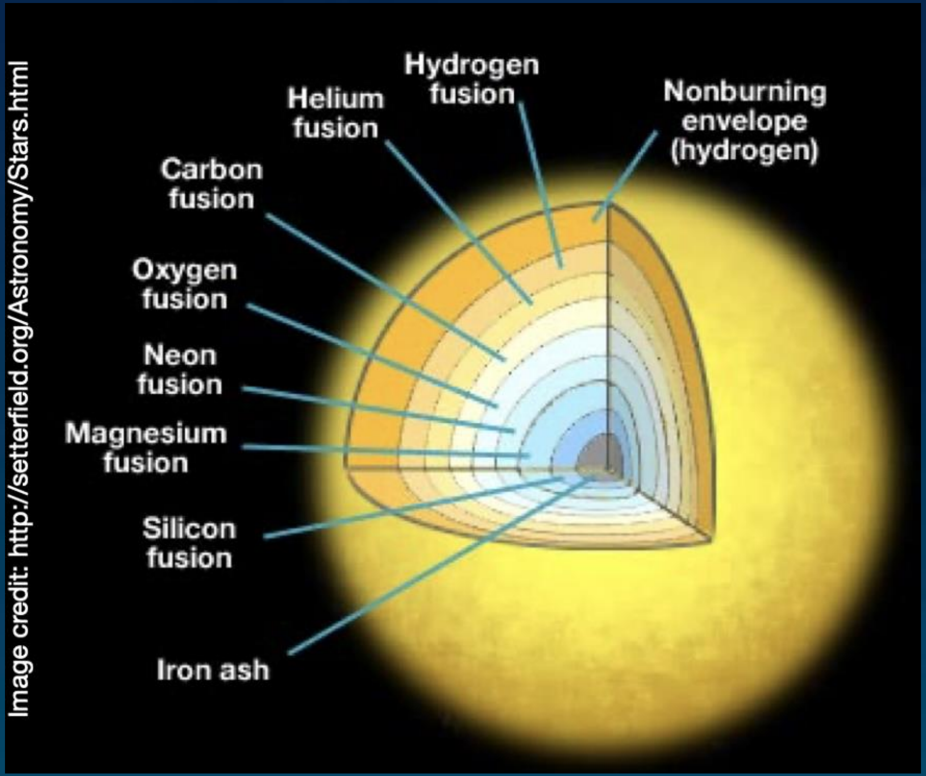
- H and He were able to form in the 10 sec to 20 min after the Big Bang.
- BBN stopped at Li due to the absence of stable nuclei with mass numbers of 5 and 8.

$$
\begin{aligned}
p + n &\longrightarrow {}^{2}\mathrm{H} + \gamma \\
p + {}^{2}\mathrm{H} &\longrightarrow {}^{3}\mathrm{He} + \gamma \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\longrightarrow {}^{3}\mathrm{He} + n \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\longrightarrow {}^{3}\mathrm{H} + p \\
{}^{3}\mathrm{He} + {}^{2}\mathrm{H} &\longrightarrow {}^{4}\mathrm{He} + p \\
{}^{3}\mathrm{H} + {}^{2}\mathrm{H} &\longrightarrow {}^{4}\mathrm{He} + n
\end{aligned}
$$

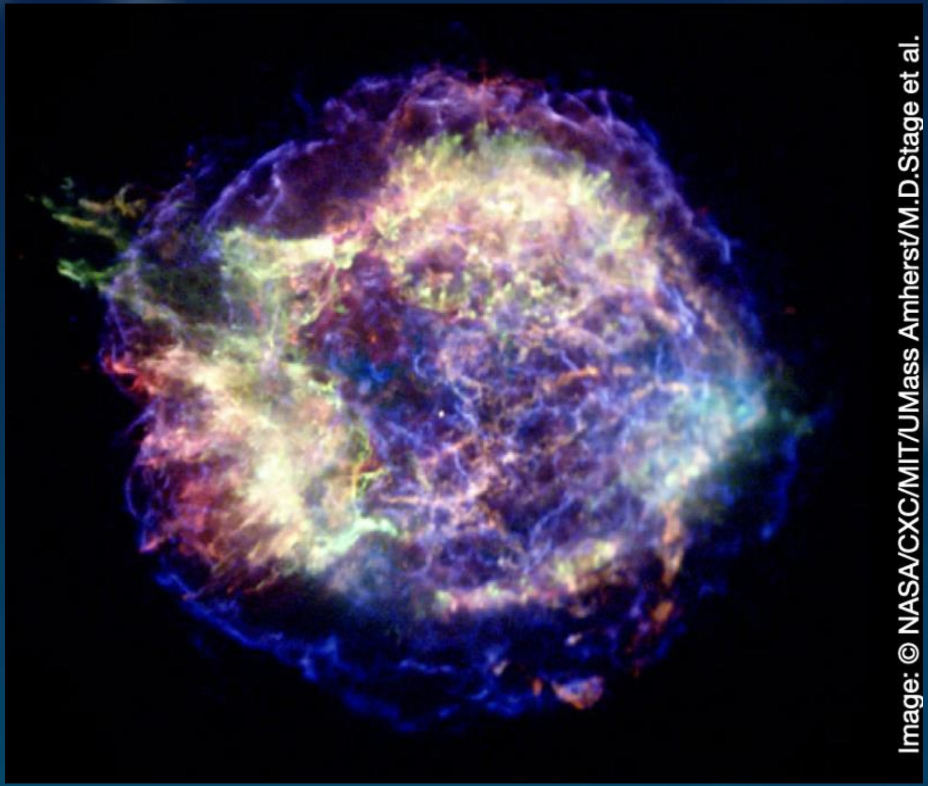
Alpher, Bethe, & Gamow (1948)



Creation of the elements beyond H and He



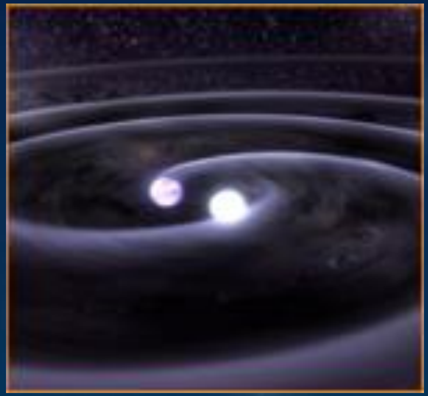
Stellar Nucleosynthesis

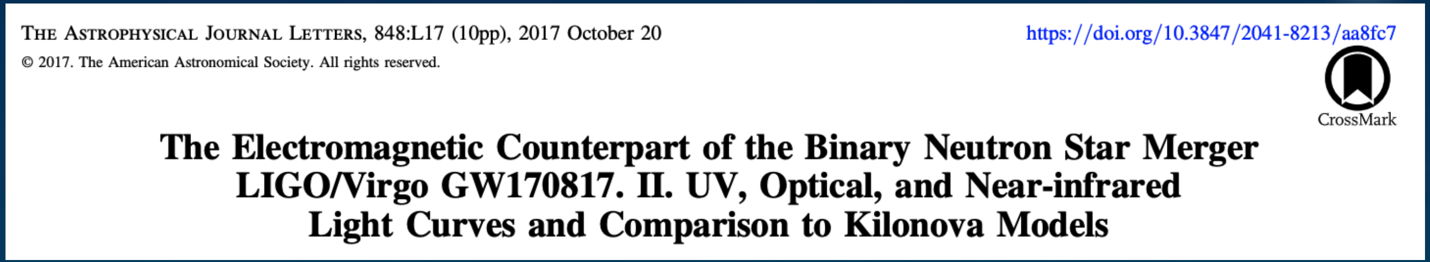


Explosive Nucleosynthesis

Merging neutron stars and element creation

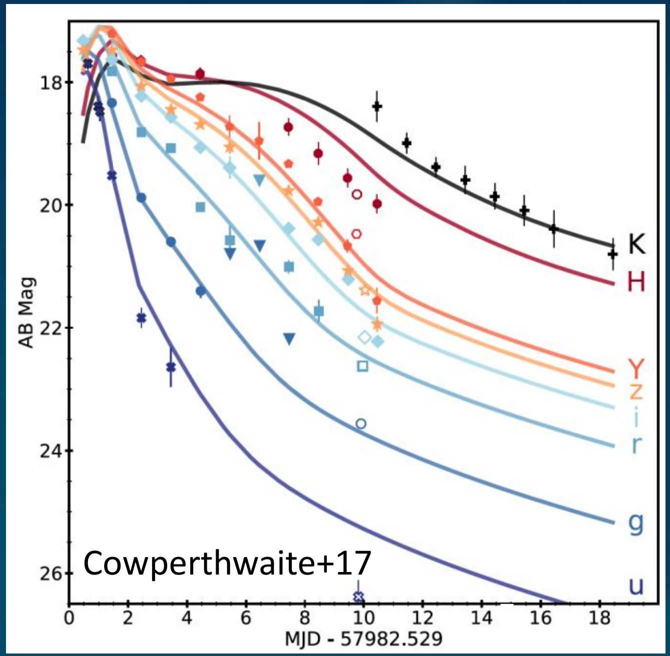
- The event GW 170817 and subsequent kilonova showed that merging NSs play a major role in the formation of heavy elements.




THE ASTROPHYSICAL JOURNAL LETTERS, 848:L17 (10pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa8fc7

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models

- ❑ Kilonova model (Barnes & Kasen 2013)
  - ▪ based on heating of material by heavy radioactive isotopes.



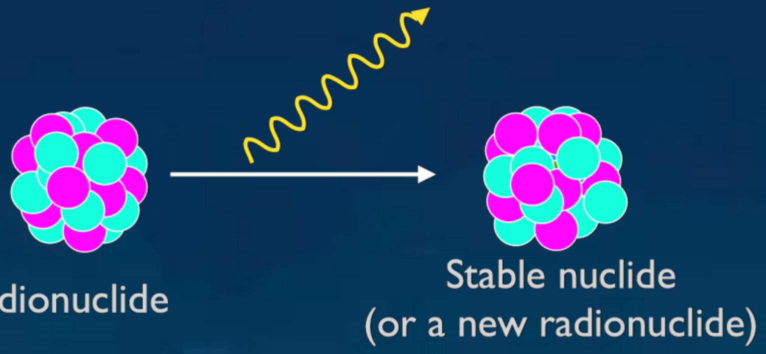
Element Creation

Image Credit: Jennifer Johnson (SDSS)

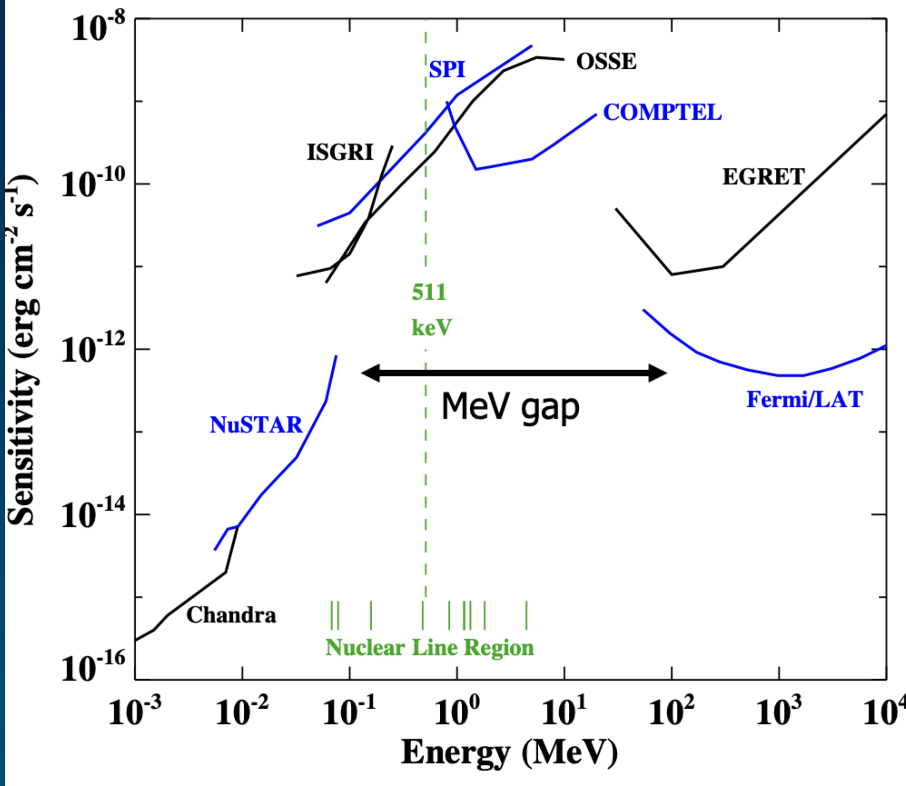
Big Bang
Cosmic Ray Fission
Exploding Massive Stars
Exploding White Dwarfs
Merging Neutron Stars
Dying Low Mass Stars

Nuclear Lines

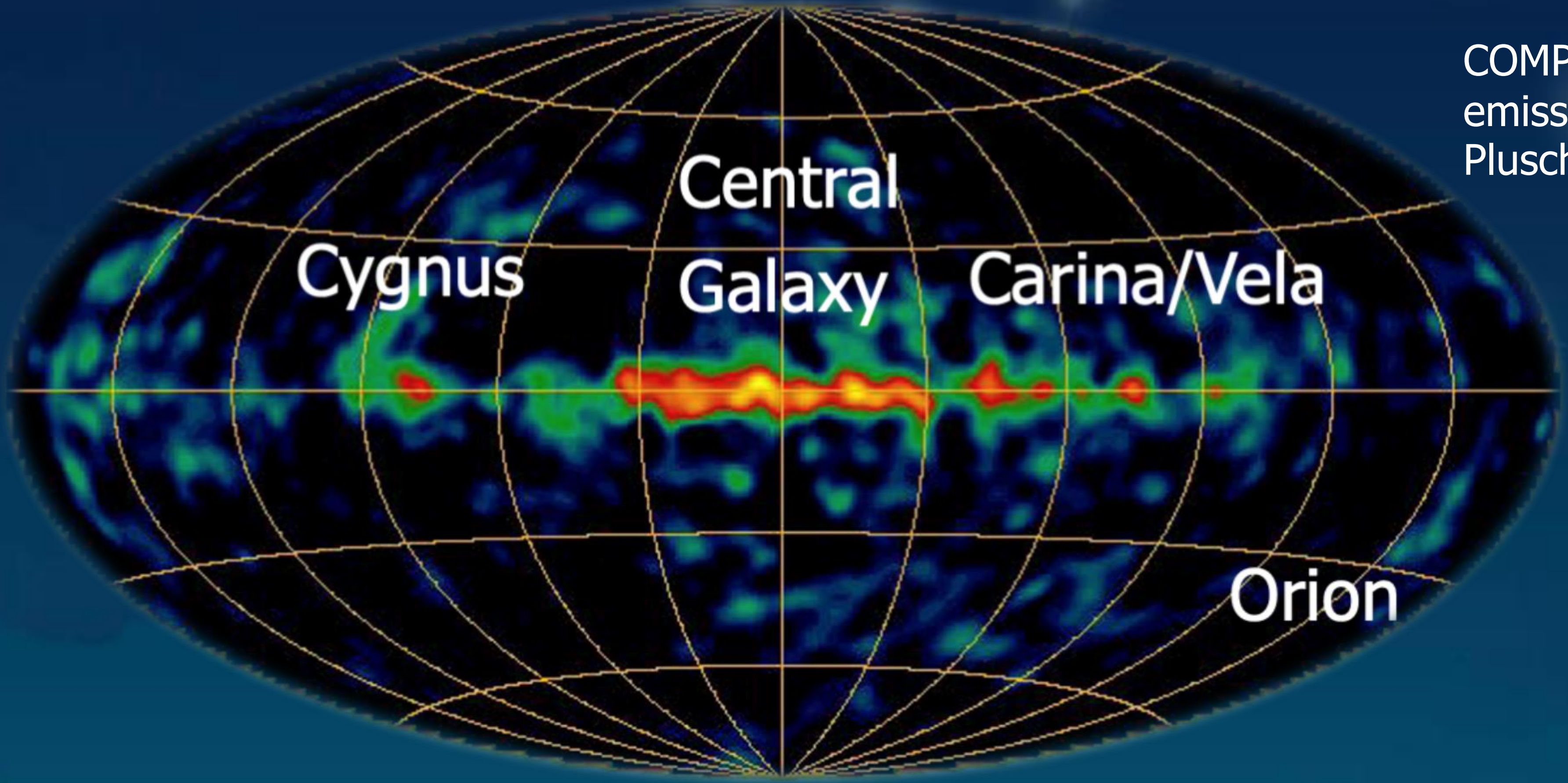
- Stellar processes and SNe lead to radioactive isotopes which produce nuclear emission lines



Isotope	Lifetime	Decay Chain	Line Energy [keV]
^{56}Ni	111 d	^{56}Ni -> ^{56}Co -> ^{56}Fe* + e^{+}	158, **812, 847, 1238**
^{44}Ti	89 yr	^{44}Ti -> ^{44}Sc* -> ^{44}Ca* + e^{+}	78, 68, **1157**
^{26}Al	1.04 x 10^{6} yr	^{26}Al -> ^{26}Mg* + e^{+}	**1809**
^{60}Fe	3.8 x 10^{6} yr	^{60}Fe -> ^{60}Co* -> ^{60}Ni	59, **1173, 1332**



^{26}Aluminum



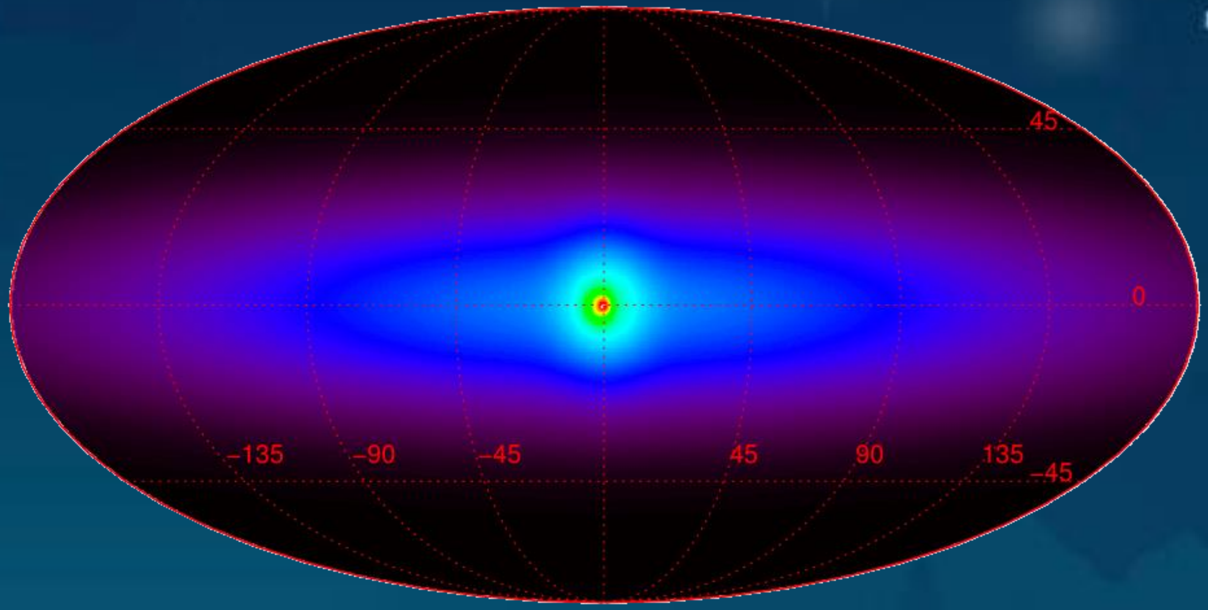
COMPTEL map of ^{26}Al emission (Oberlack+97, Pluschke+01)

^{26}Al (1.809 MeV) traces massive stars throughout their evolution: pre-supernova (SN) and post-SN

511 keV annihilation line

- Discovered in 1969 (Haymes+1969)
- Imaged by OSSE (Purcell+1997)
- Lately observed by INTEGRAL/SPI
  - Large scale emission from the disk
  - Pronounced emission from the bulge
- Sources of positrons:
  - Massive stars/SN Ia
  - X-ray binaries
  - Sgr A* / accreting BH
  - CRs
  - Pulsars
  - Dark Matter

It should trace nucleosynthesis, but spatial distribution is unlike any other wavelength



Siegert et al. 2016

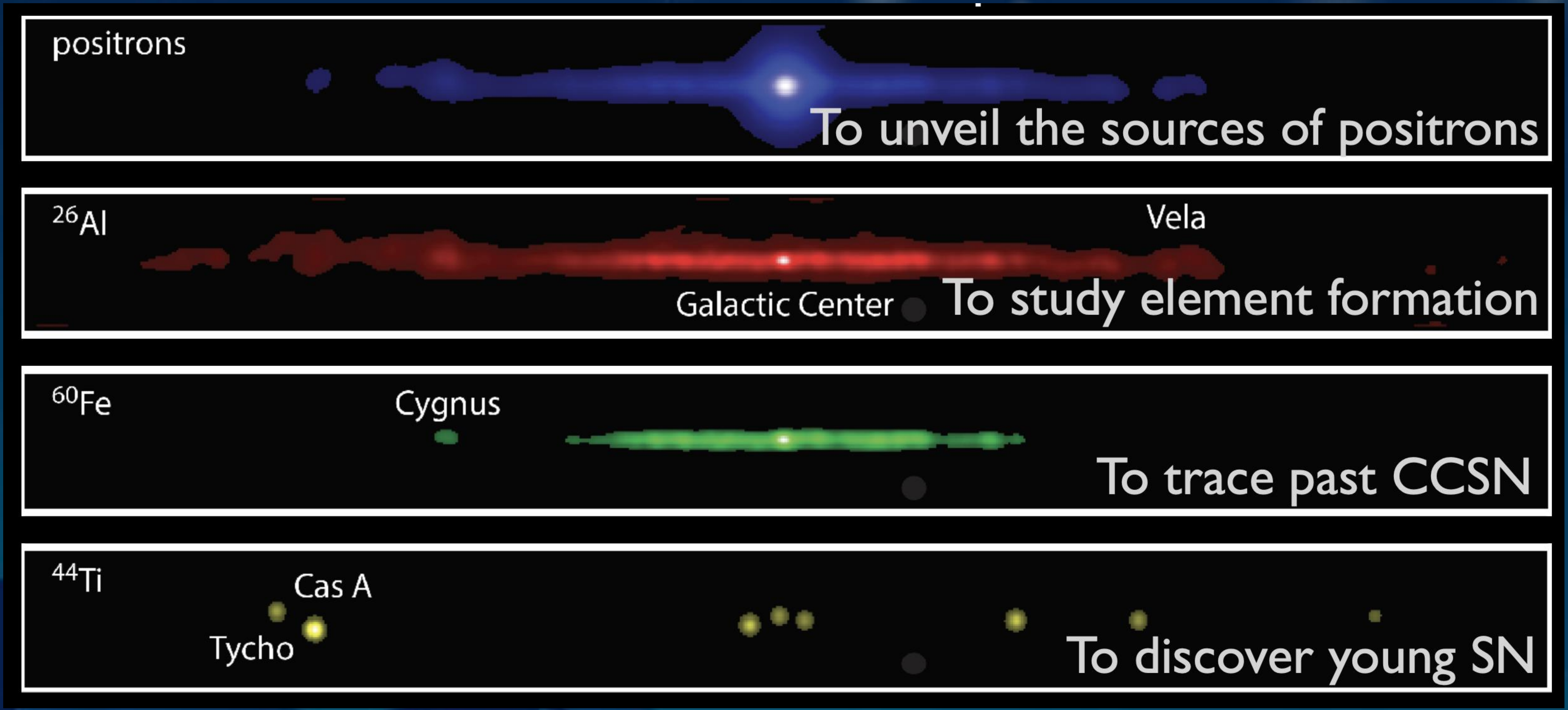
An MeV View of our Galaxy

Simulated for COSI

τ~1 million yr

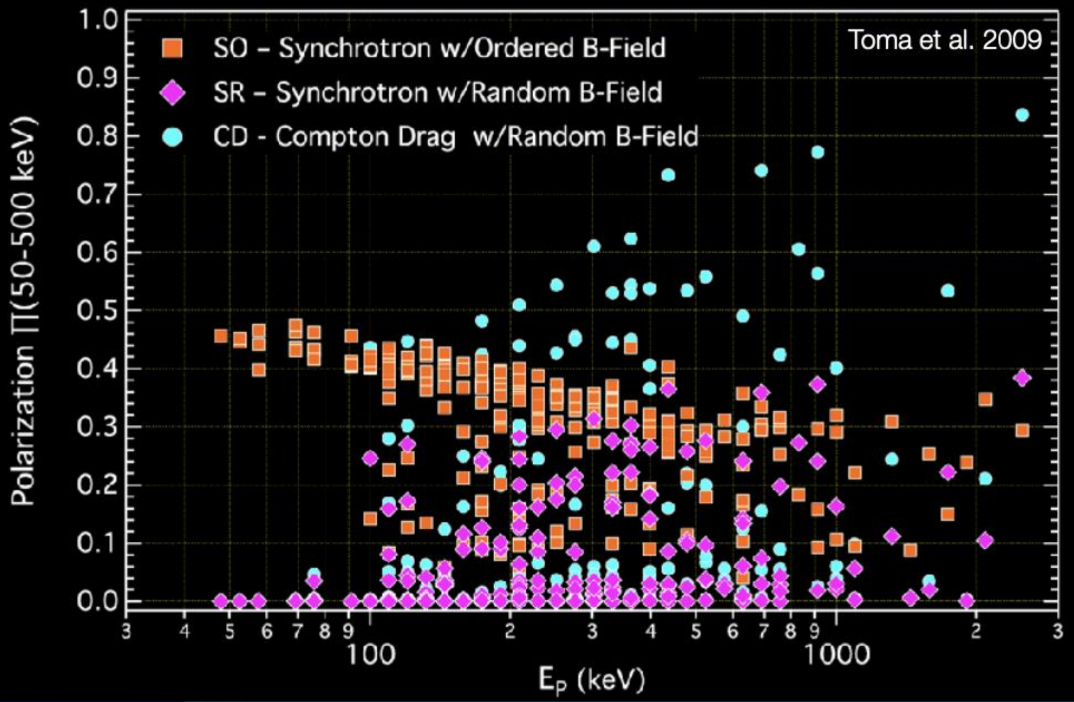
τ~3.8 million yr

τ~89 yr

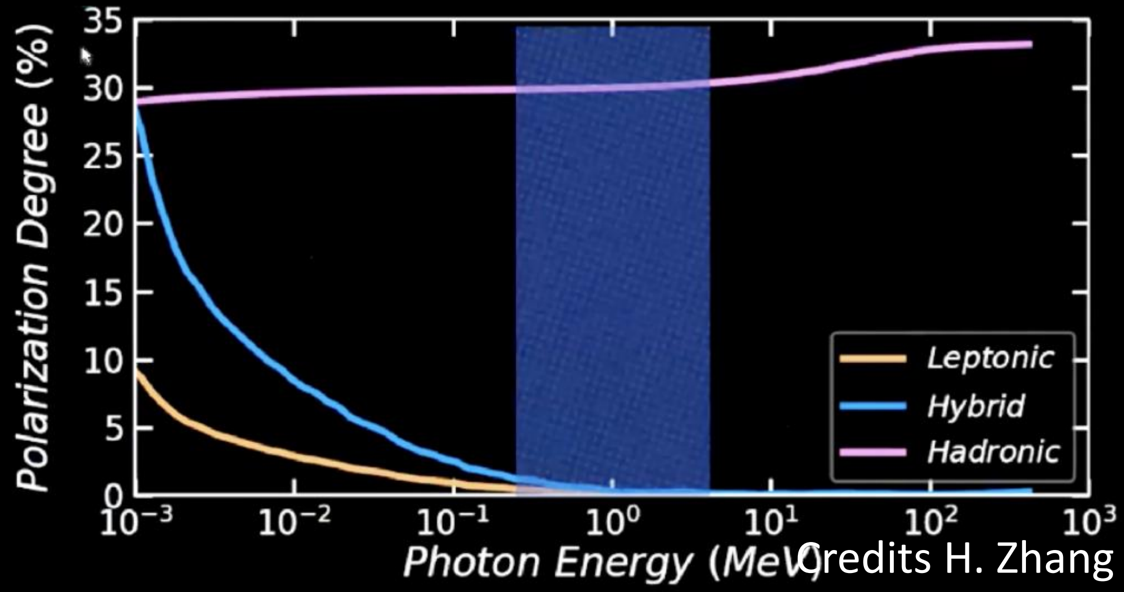


Polarization

GRB Polarization



Blazar Polarization

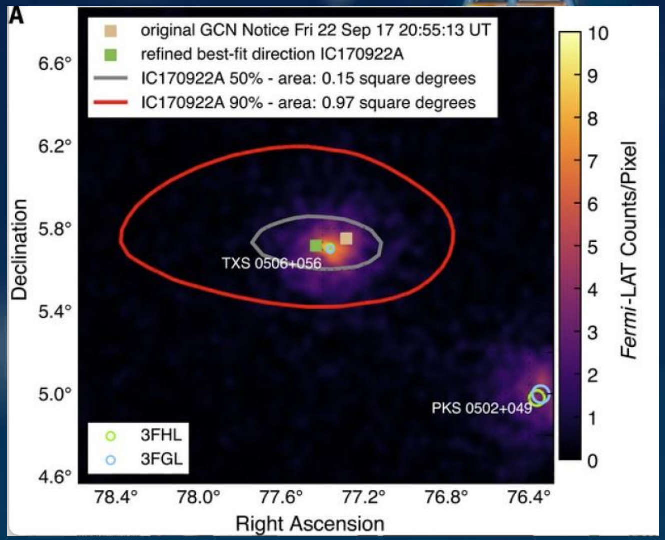


Credits H. Zhang

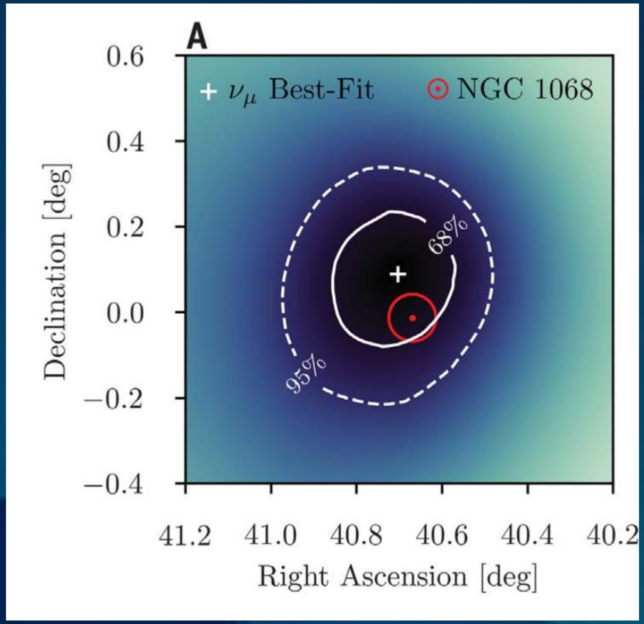
- But also polarization from SNR (Crab, Vela), accreting BH (Cyg X-1), magnetars…

Multi-messenger Science - Neutrinos

IceCube collab. 2018



- High-energy neutrinos observed in the direction of TXS 0506+056 establish some blazars are hadronic accelerators (IceCube collab. 2018)

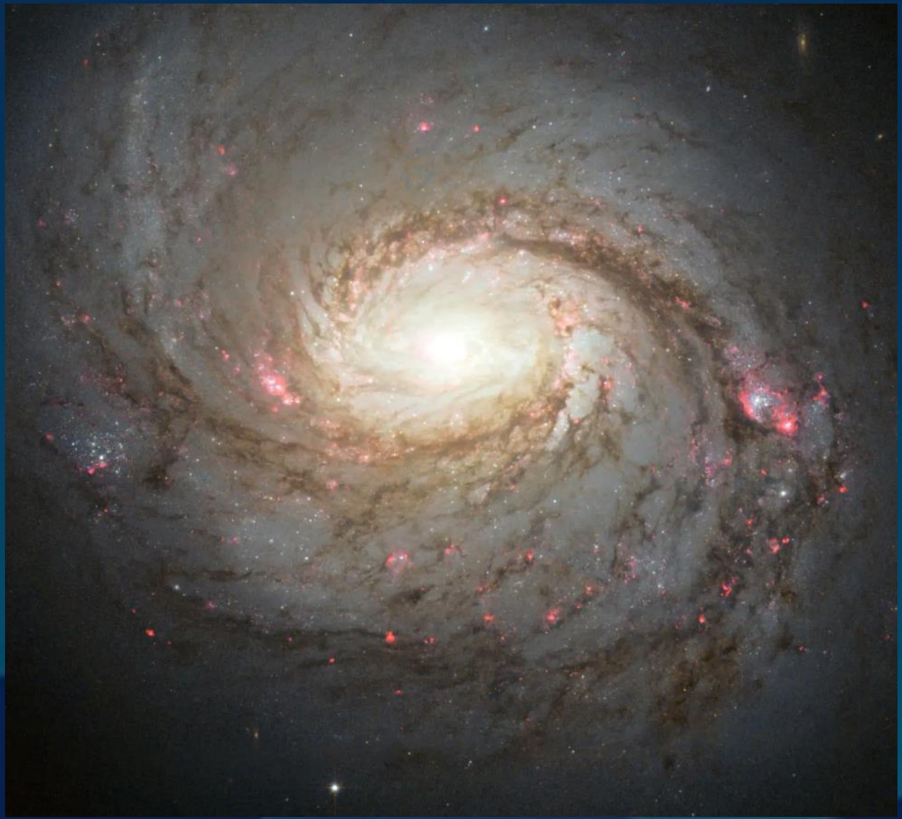


- High-energy neutrinos observed in the direction of NGC 1068 establish some cores of AGN are hadronic accelerators (IceCube collab., 2022)

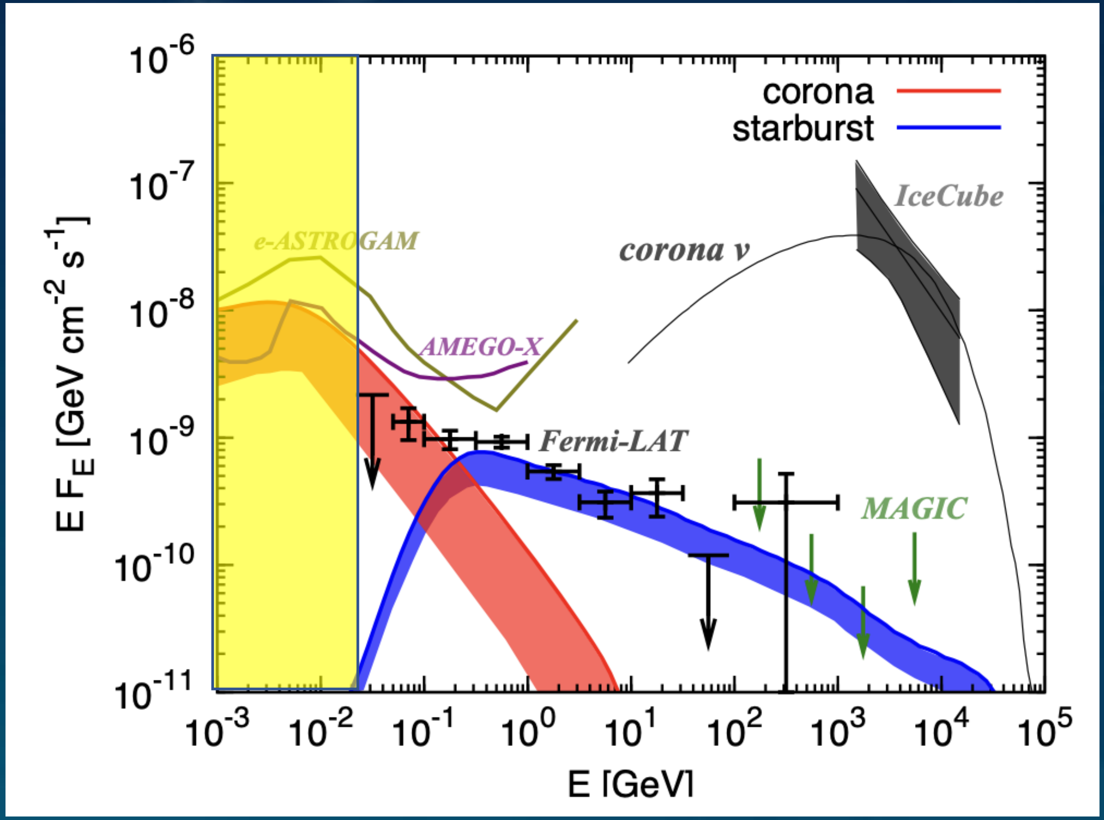
IceCube Collaboration 2022

Multi-Messenger Science - Neutrinos

- Counterparts to hidden neutrino sources (like NGC 1068) are brightest in the MeV band (Murase+20,22)

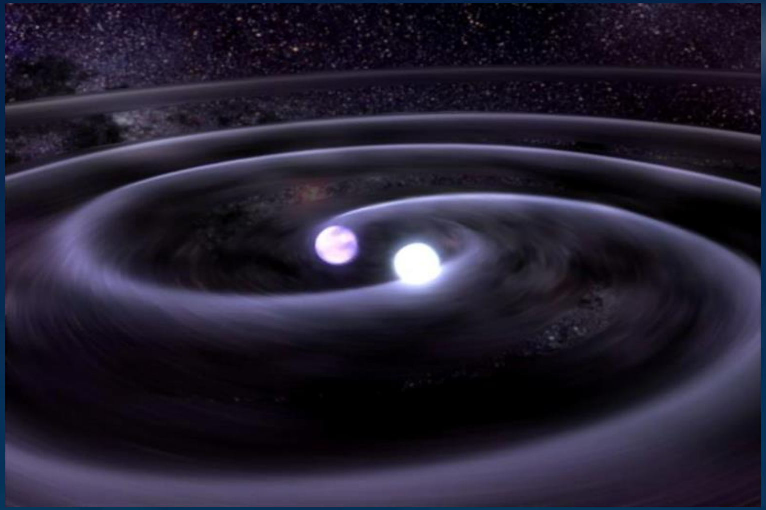


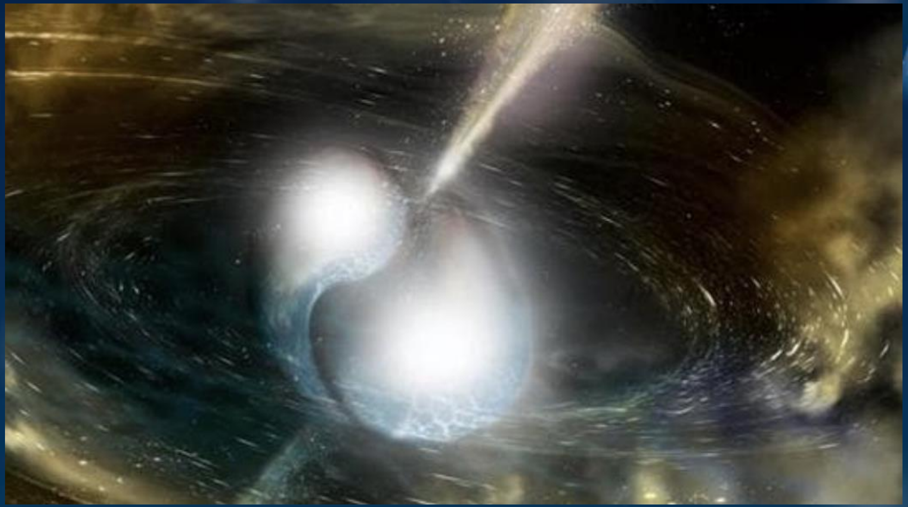
IceCube Collaboration 2022



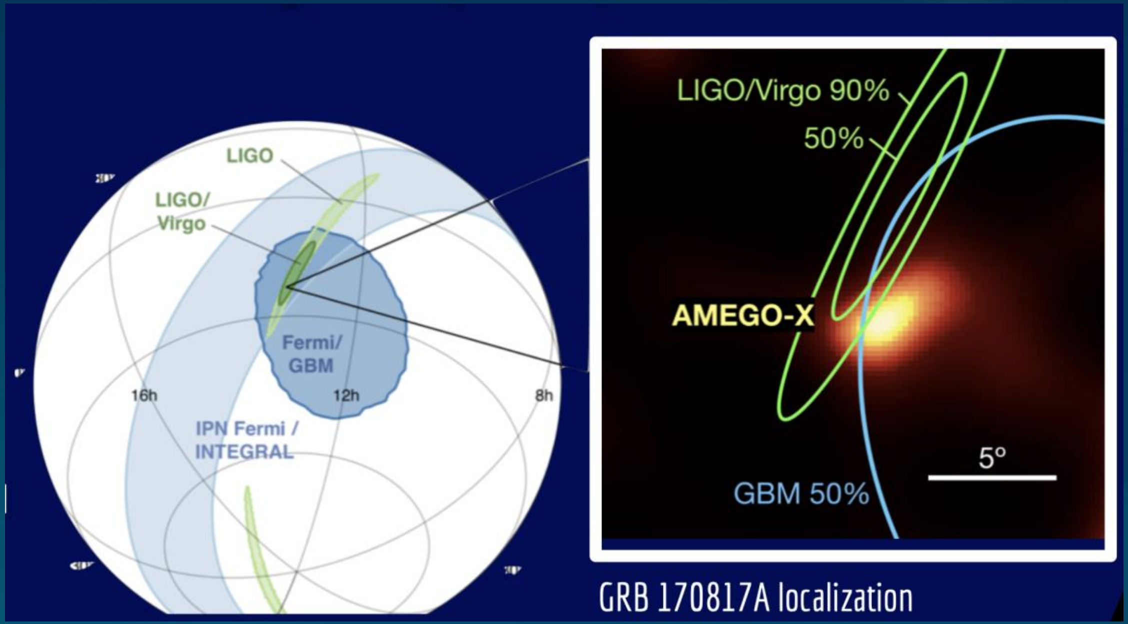
Ajello, Murase, McDaniel 2023

Multi-Messenger Science - GWs



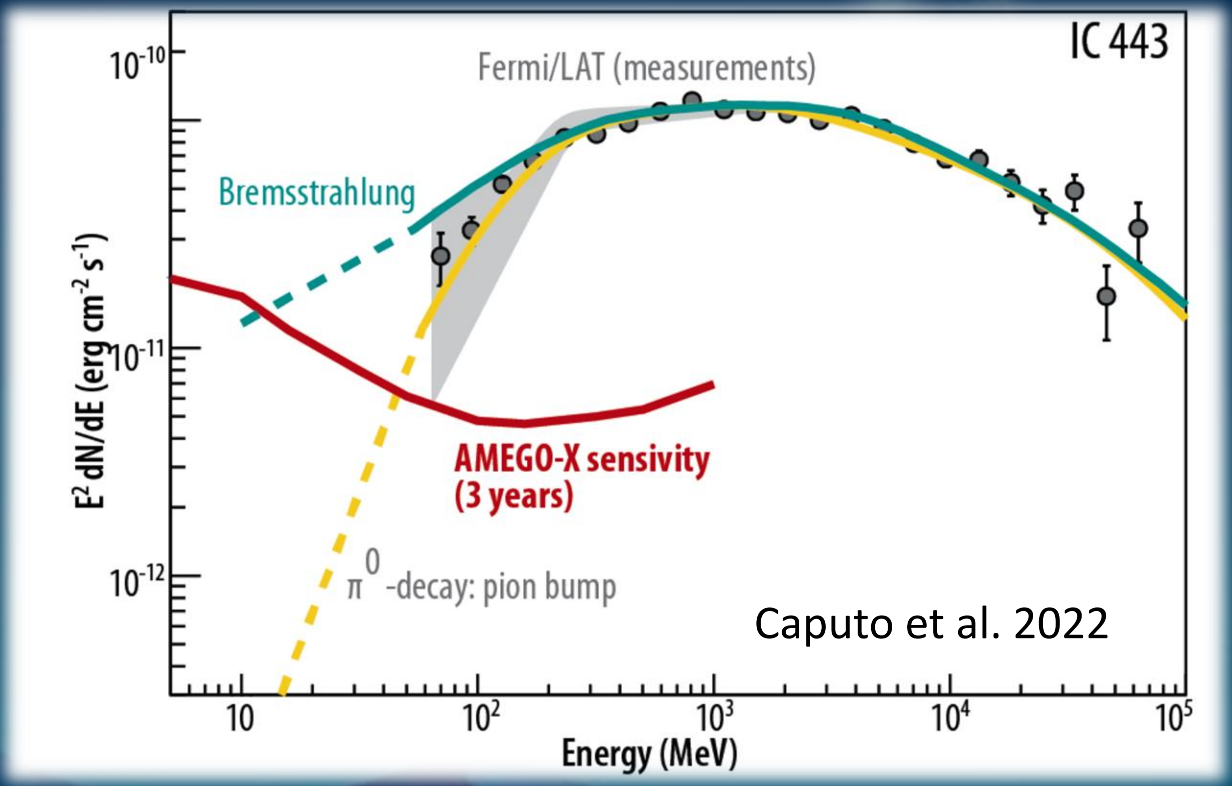


- Short gamma-ray burst, e-m counterparts of NS-NS mergers like GW170817 (Abbot et al. 2017), can be localized to a few degrees



Multi-Messenger Science: Cosmic Rays

- Sensitivity in the MeV is needed to differentiate leptonic vs hadronic emission in supernova remnants

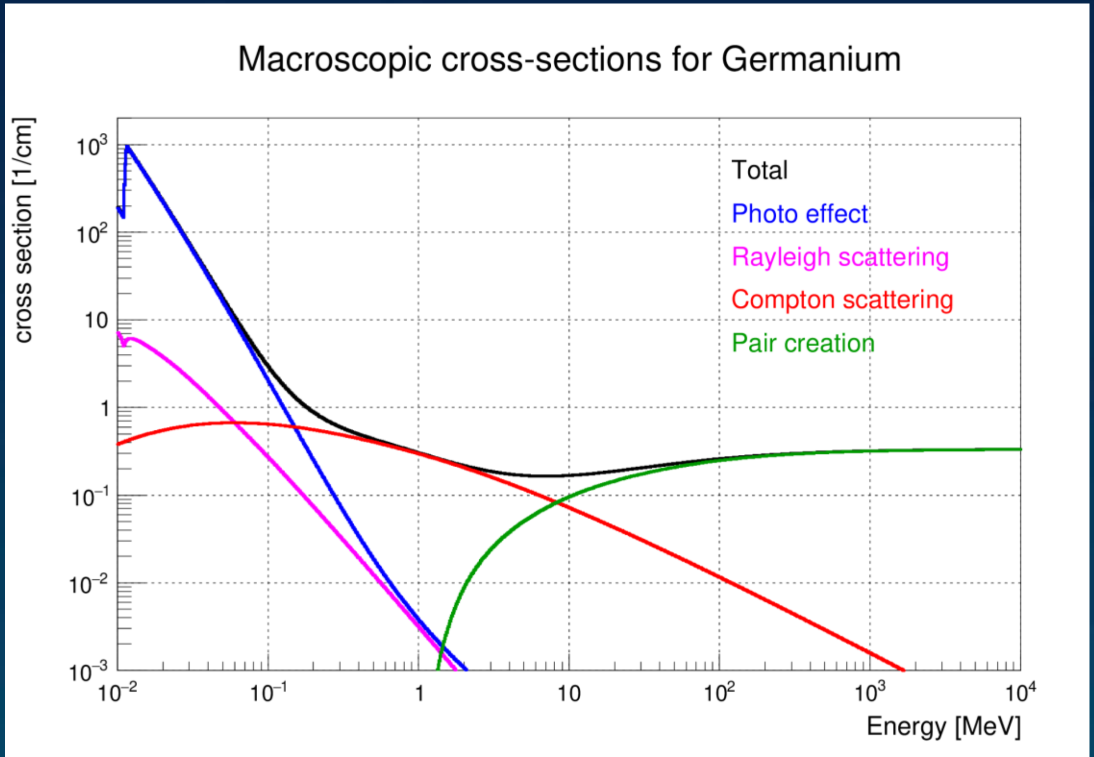


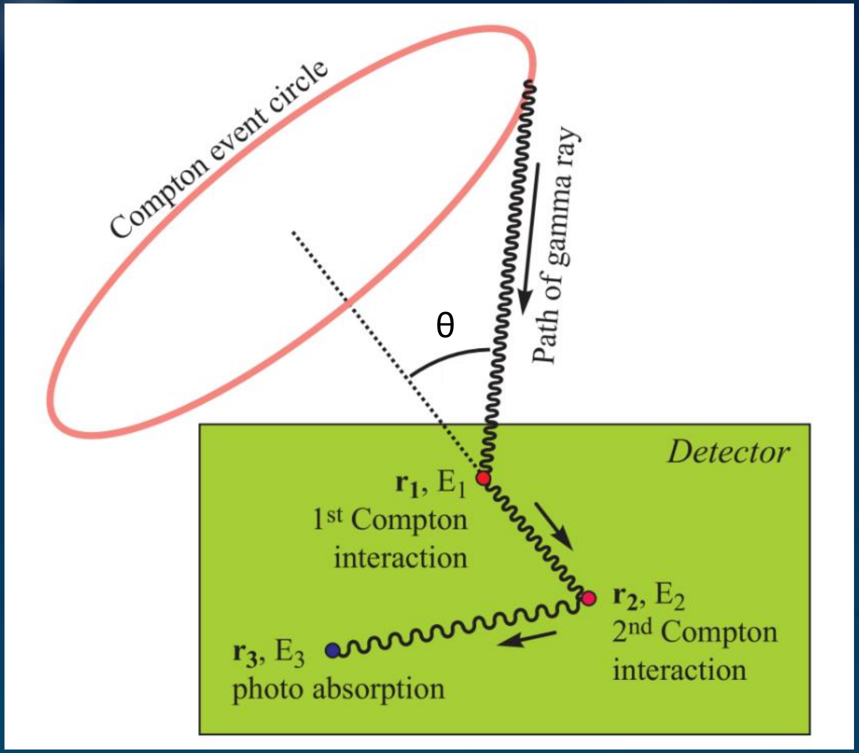
Caputo et al. 2022

We need a new mission in the MeV band

- Key capabilities:
  - Good spectral resolution
  - Good polarization capabilities
  - Good imaging performances
  - All-sky coverage

Why Wasn't it Done Before ?





- We need a position sensitive detector that can reconstruct Compton scattering in 3D
- Low cross sections imply heavy detectors (more expensive in space)

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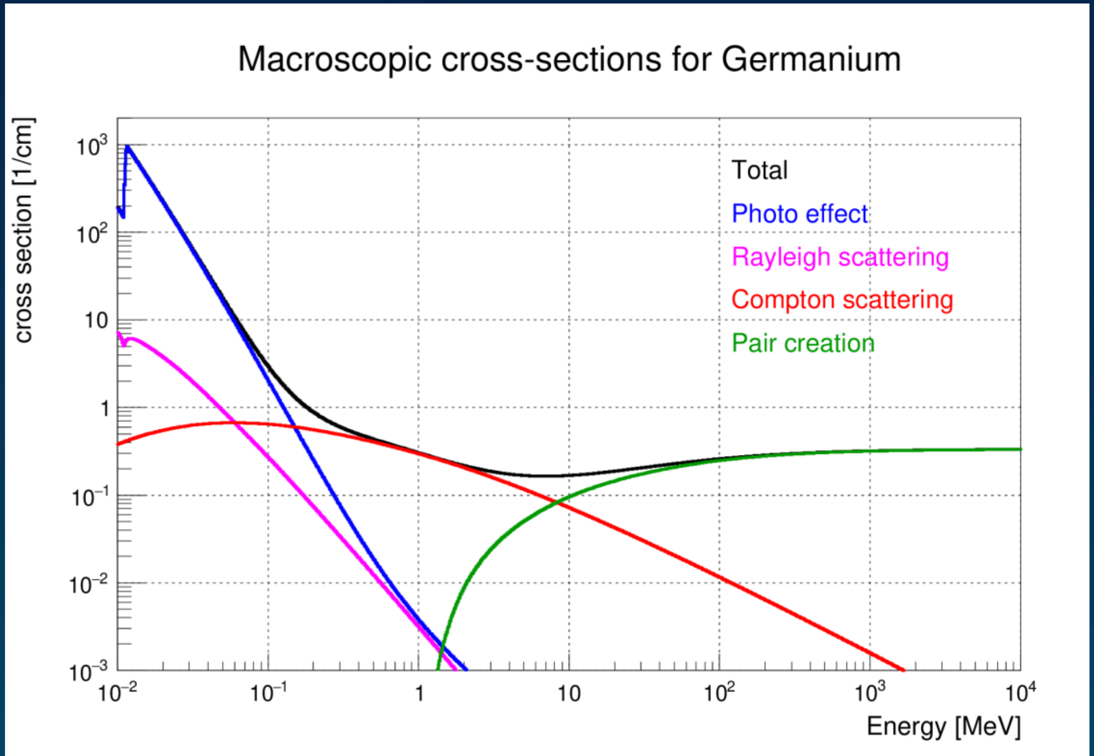
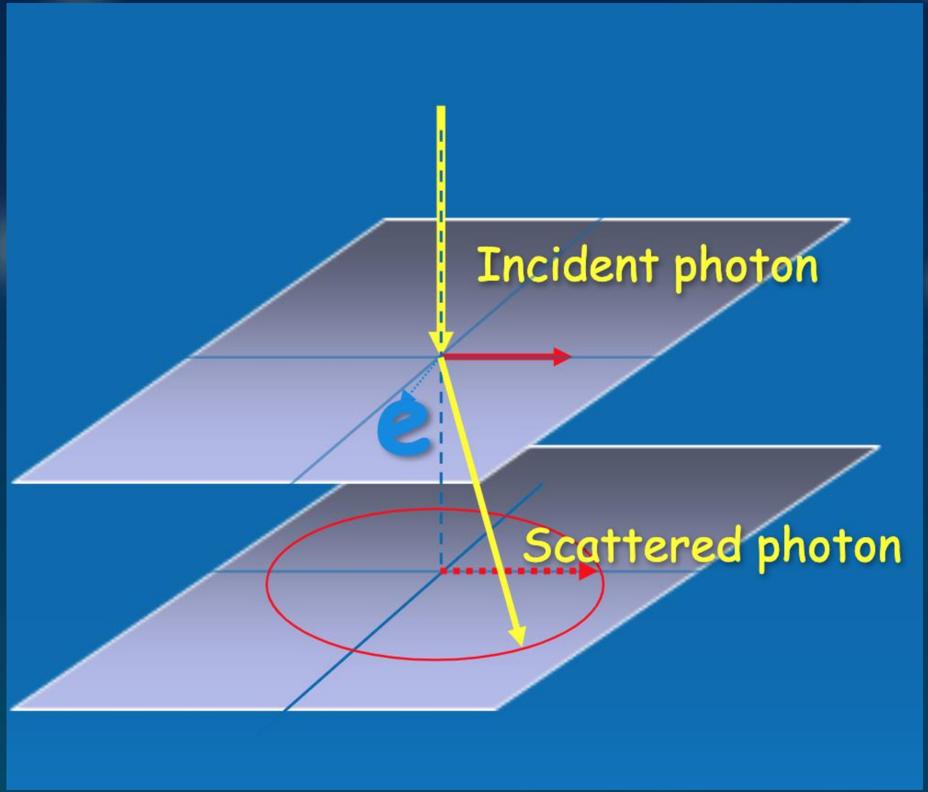




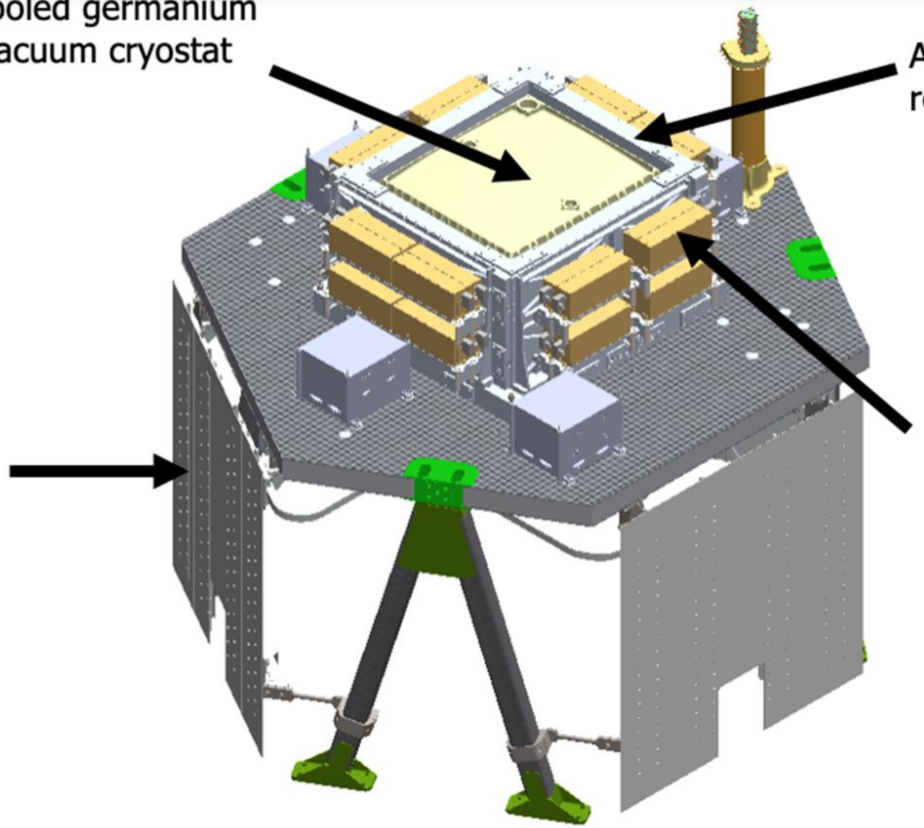
- We need a position sensitive detector that can reconstruct Compton scattering in 3D
- Low cross sections imply heavy detectors (more expensive in space)
- Compton detectors are good polarimeters

The Compton Spectrometer and Imager

- COSI (PI J. Tomsick) has been selected by NASA as a SMEX to launch in 2027
  - 0.2-5 MeV
  - Cryogenically-cooled germanium detectors to provide excellent energy resolution (0.2-1%)
  - Instantaneous field of view >25%-sky and covers the whole sky every day

COSI: Mission Concept and Design

- Excellent energy resolution and unprecedented sensitivity at 0.2-5 MeV



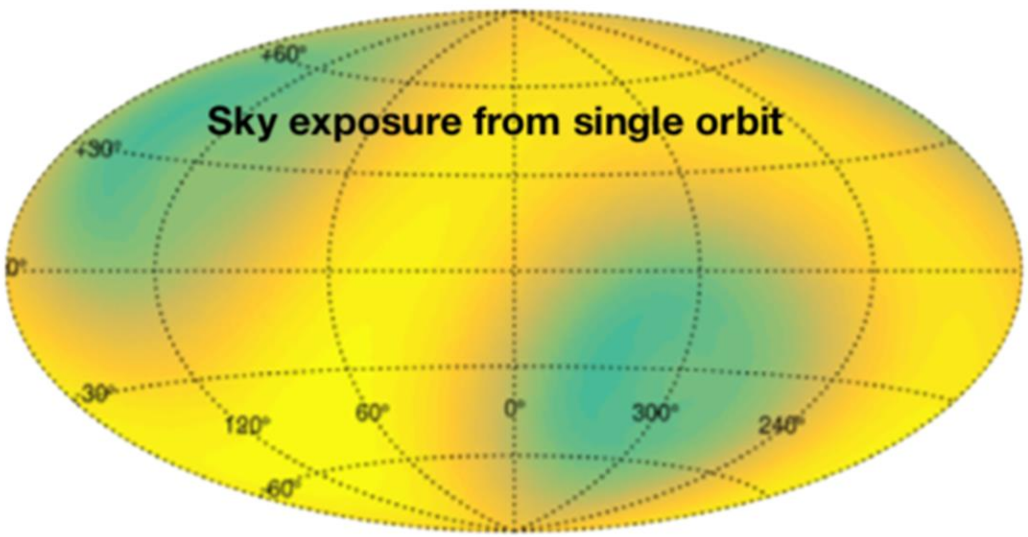
COSI instrument/payload
Scale: payload interface plate is ~1 meter flat-to-flat

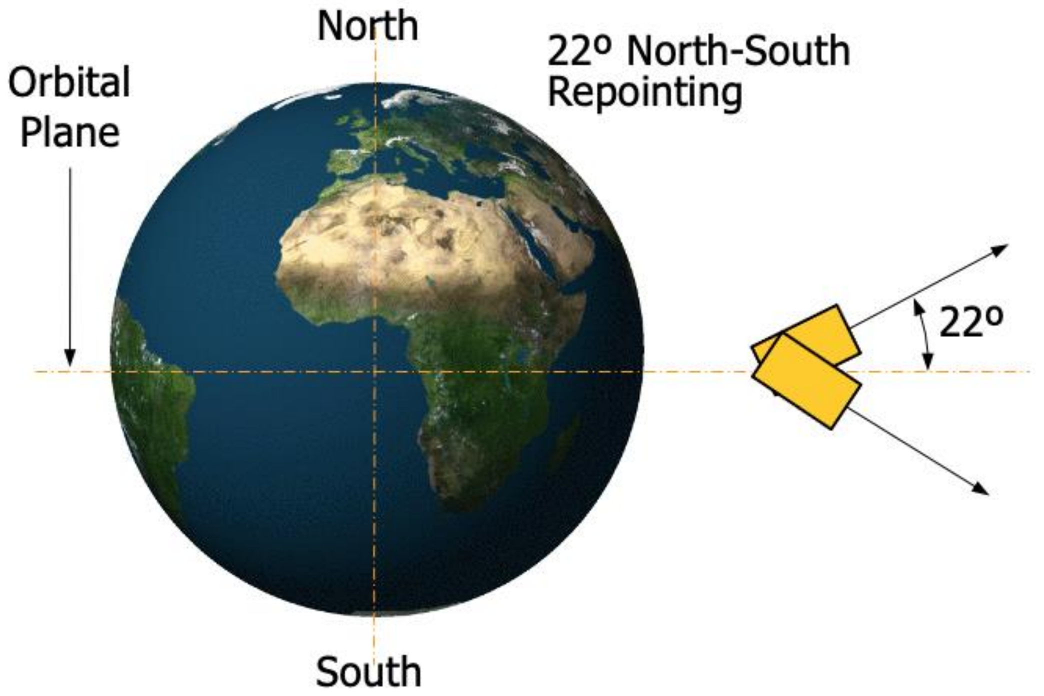
Germanium detectors from COSI-balloon: 8x8x1.5 cm^3 each

The Mission

Daily full-sky uniform coverage

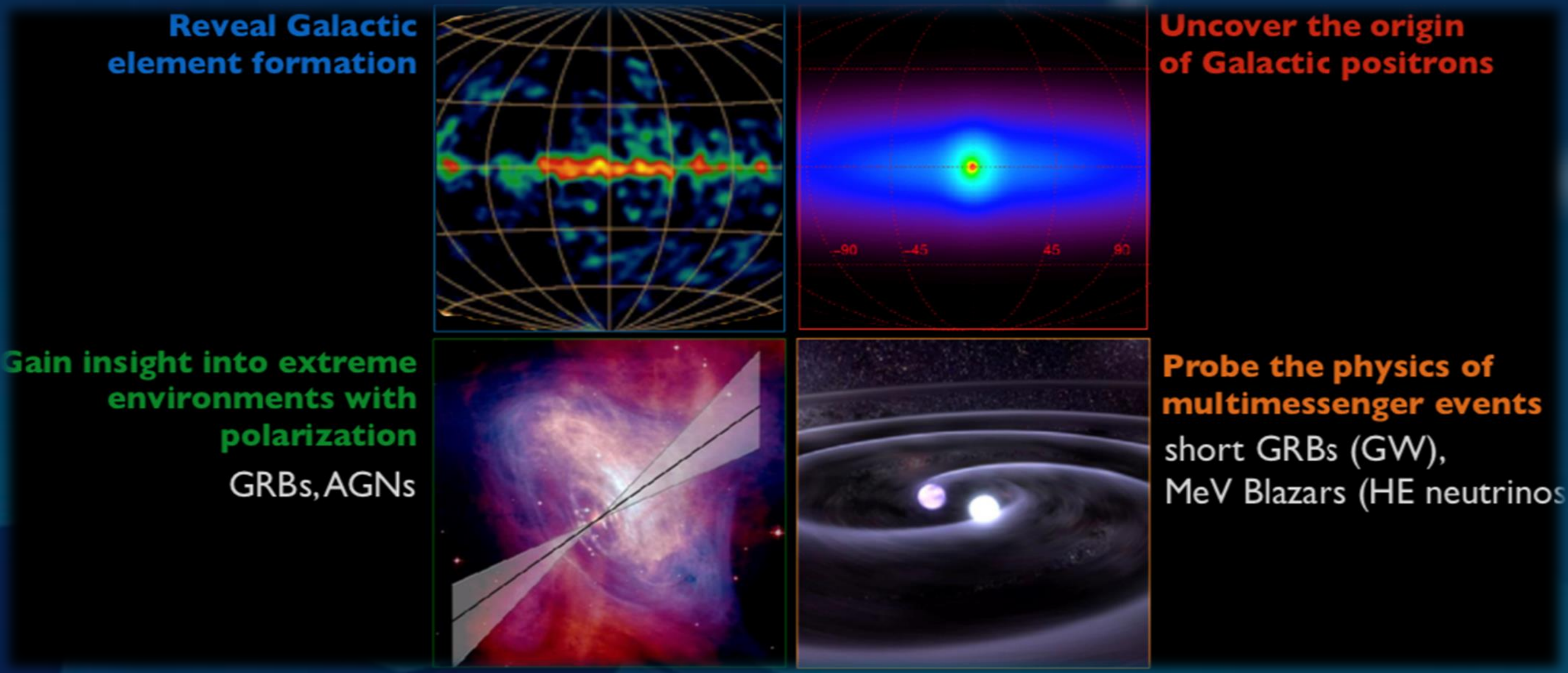
- Near-equatorial orbit to avoid South Atlantic Anomaly to minimize background
- North-South repointing every 12 hours





COSI Main Science Objectives

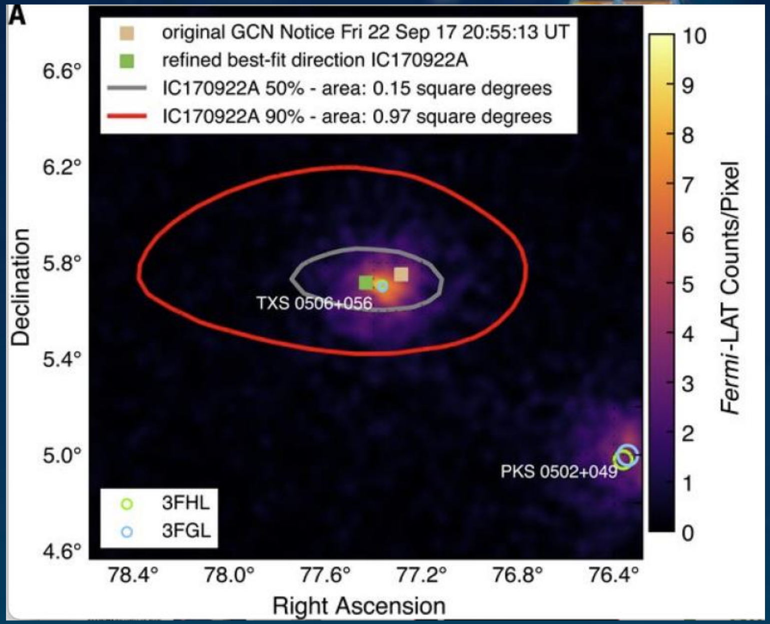
- COSI will revolutionize our understanding of creation and destruction of matter in our Galaxy

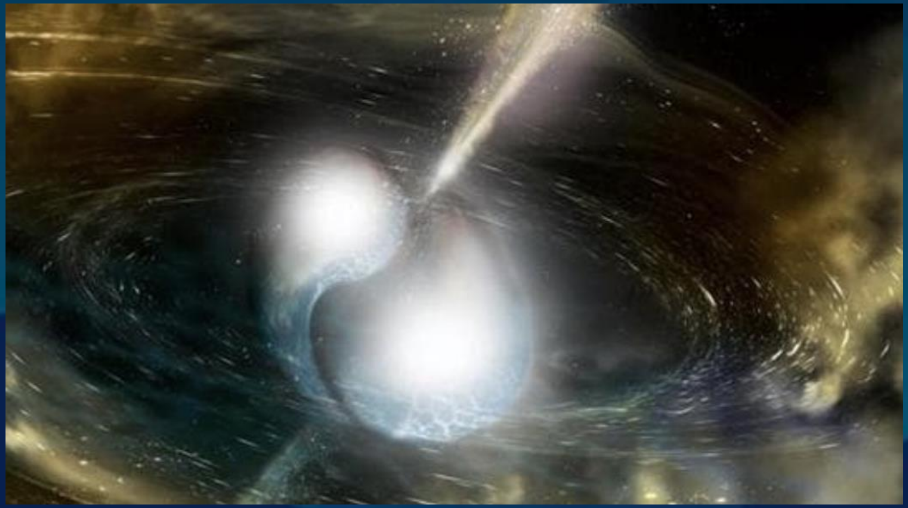


Multi-messenger Science

- COSI will provide coverage of all high-energy neutrino events (~60/year)
- COSI may perform TOOs to improve the sensitivity at specific locations

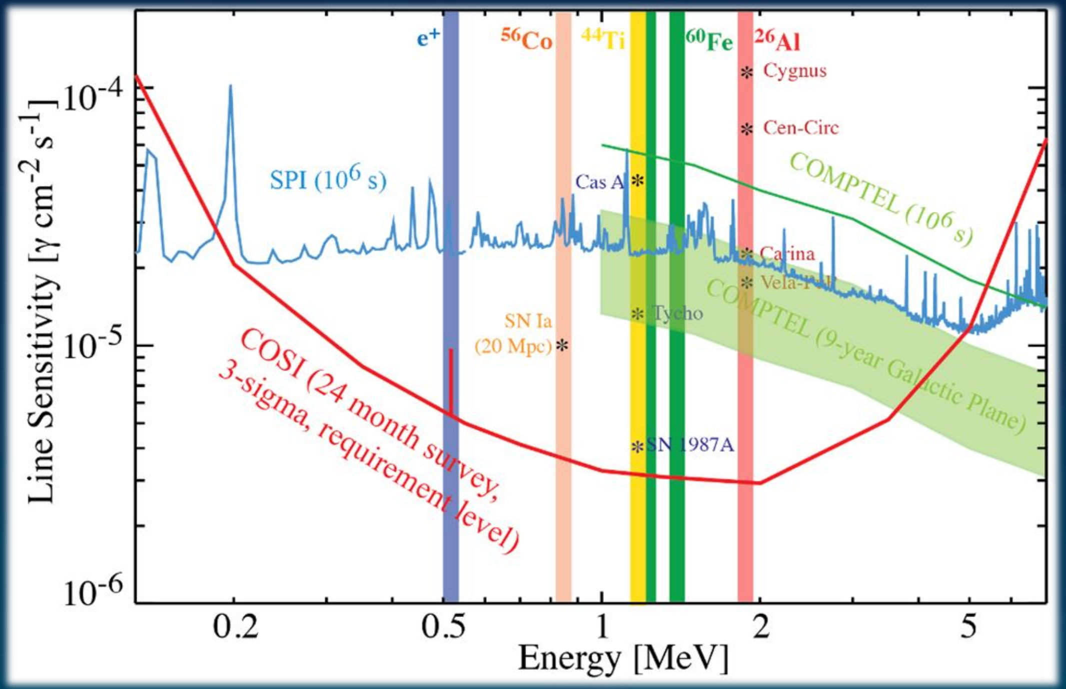
IceCube collab. 2018





- COSI will detect *O*(10) short gamma-ray burst/year
- Those will be localized to ~1deg accuracy

Supernovae

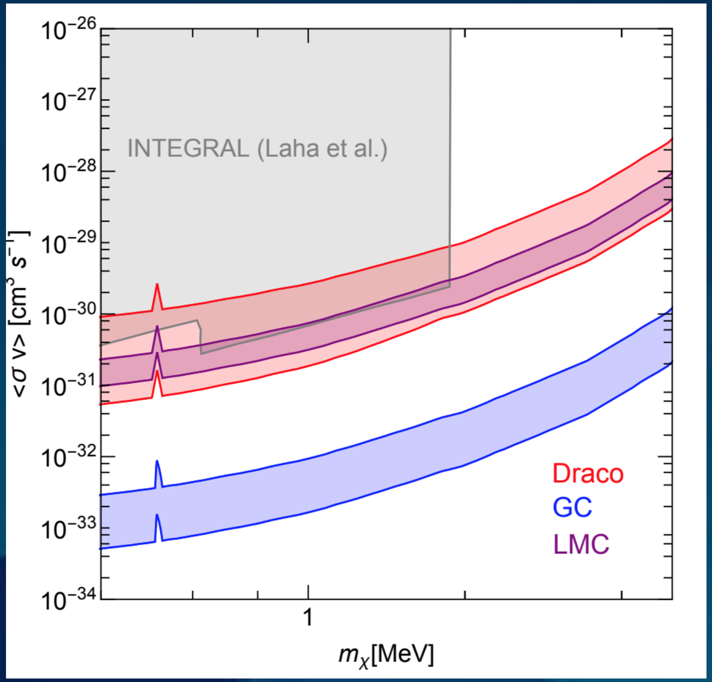


- COSI will detect SN Ia up to 20 Mpc and SN II up to the LMC
- For the brightest cases, COSI will resolve the line velocity profiles, yielding independent determinations of the synthesized 56Ni mass, its distribution within the ejecta, and total ejecta mass and kinetic energy

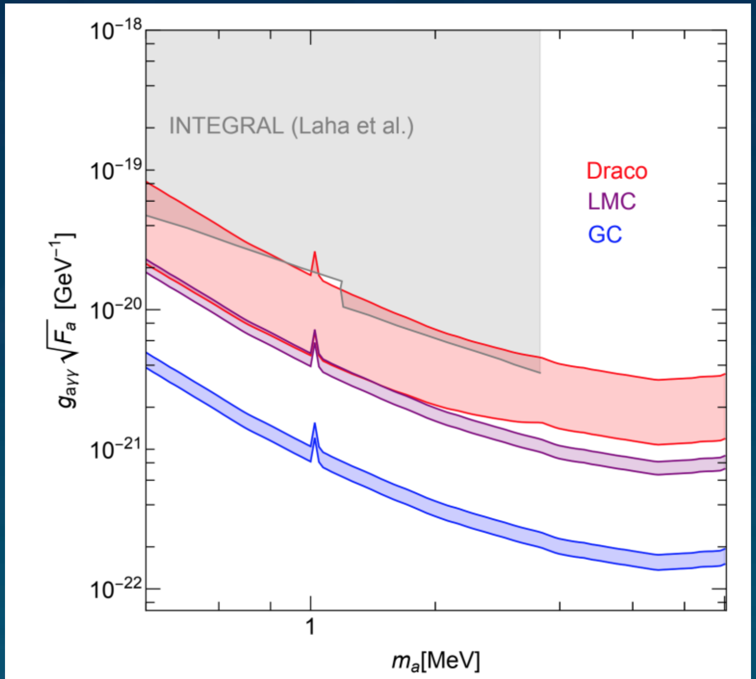
Dark Matter Studies with COSI

- COSI will provide stringent limits on annihilating/decaying DM, Axion like particles and primordial black holes

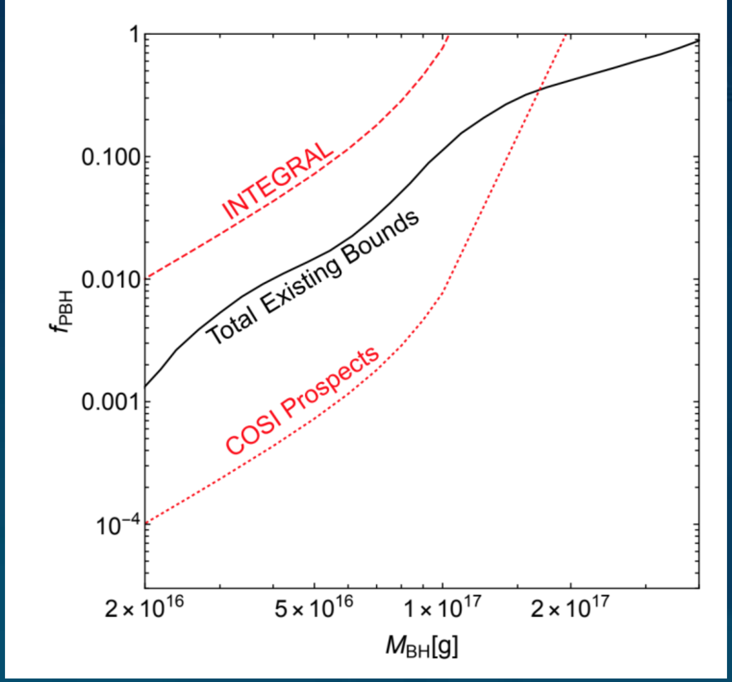
Annihilating Dark Matter



ALPs

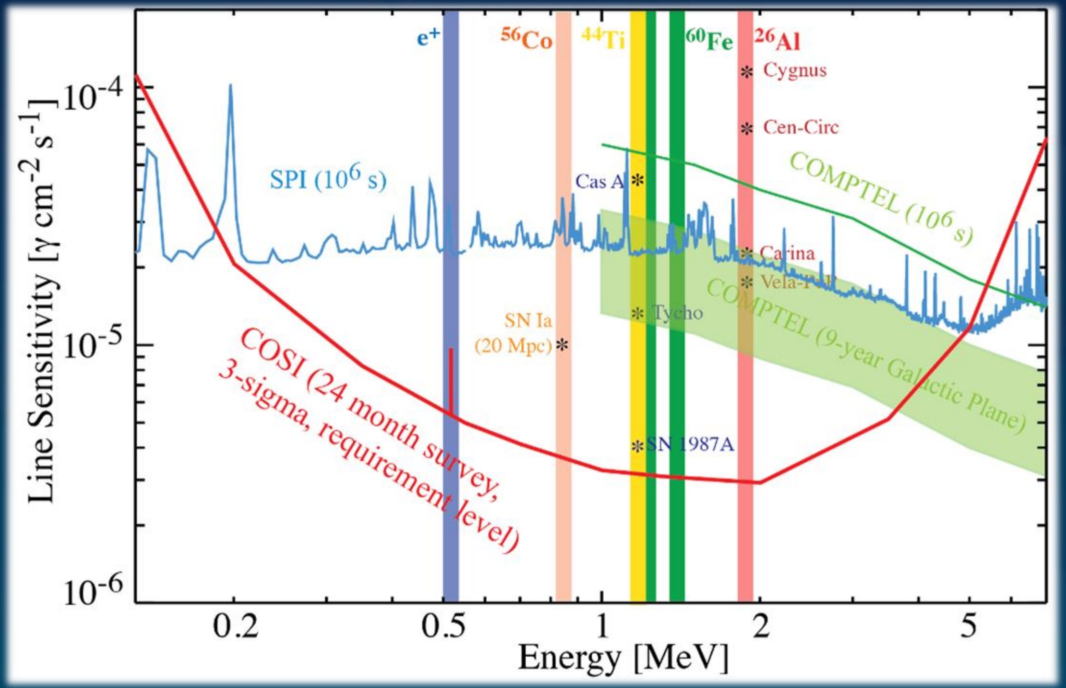


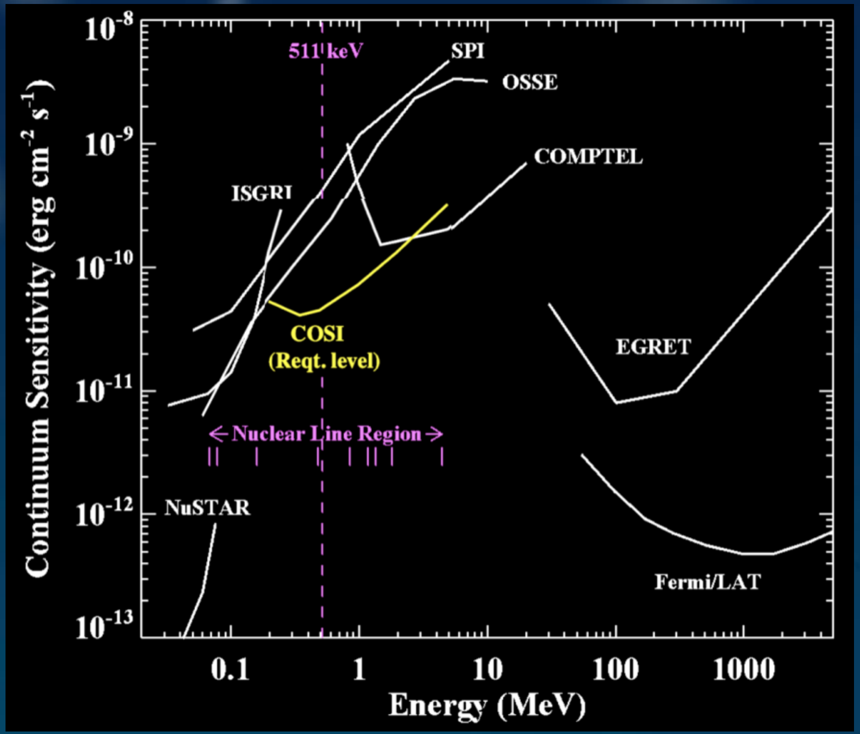
Primordial Black Holes



Caputo et al. 2023

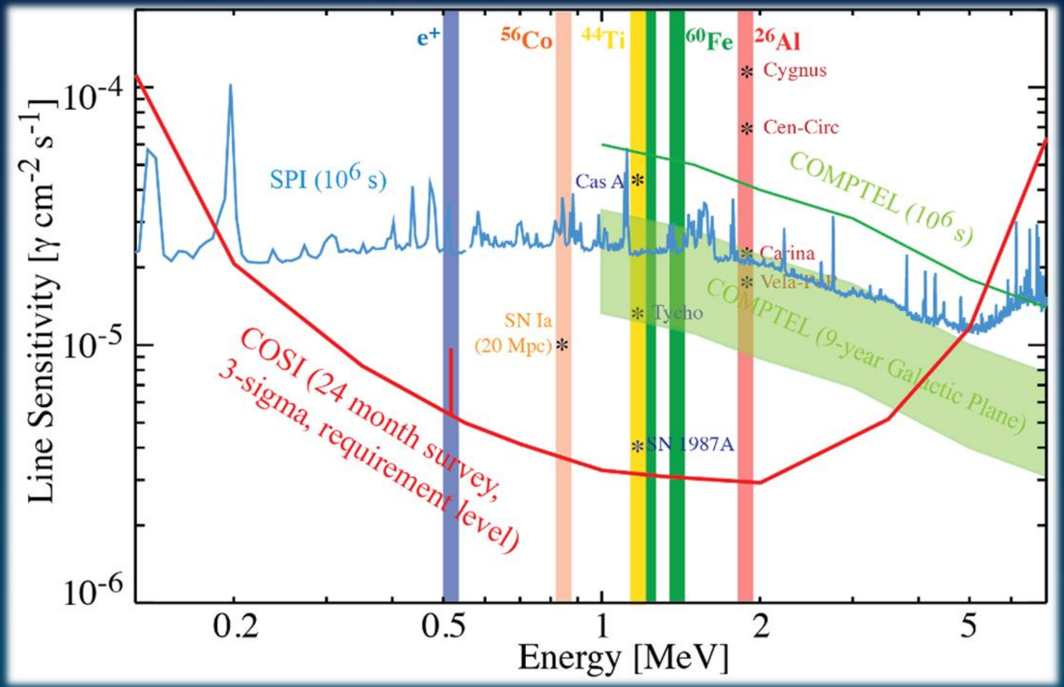
COSI's Sensitivity

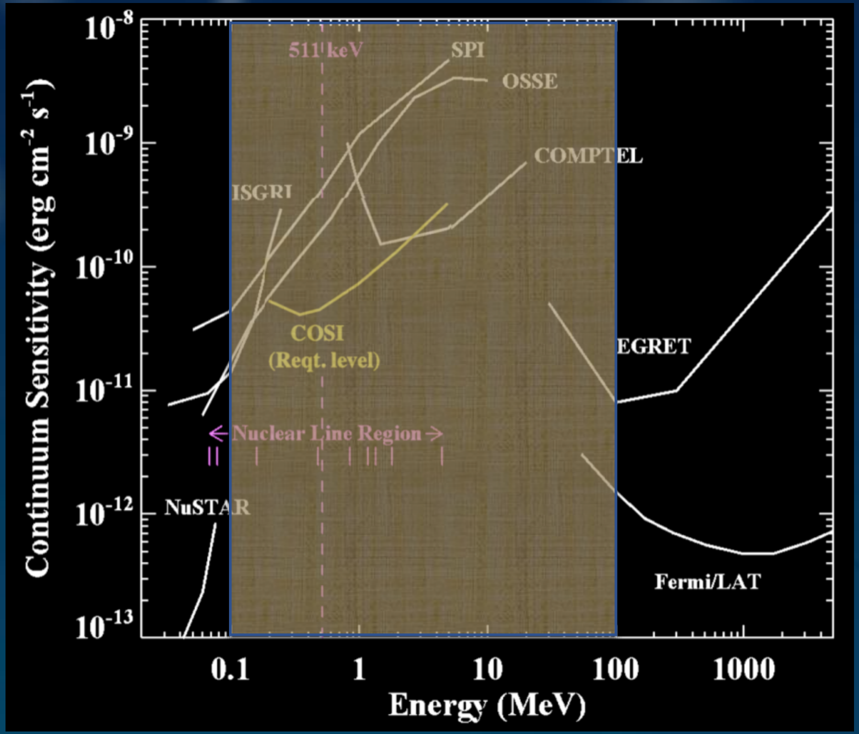




- Optimized for emission lines but still provides a significant improvement for continuum emission

COSI’s Sensitivity





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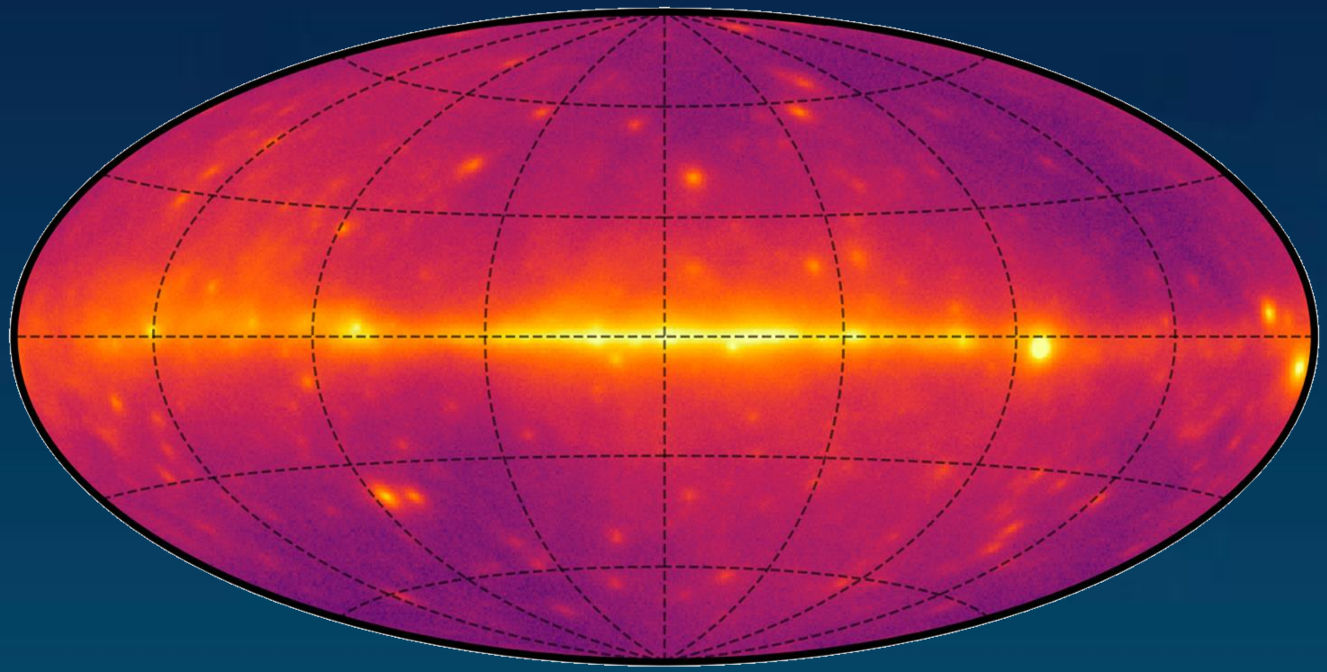
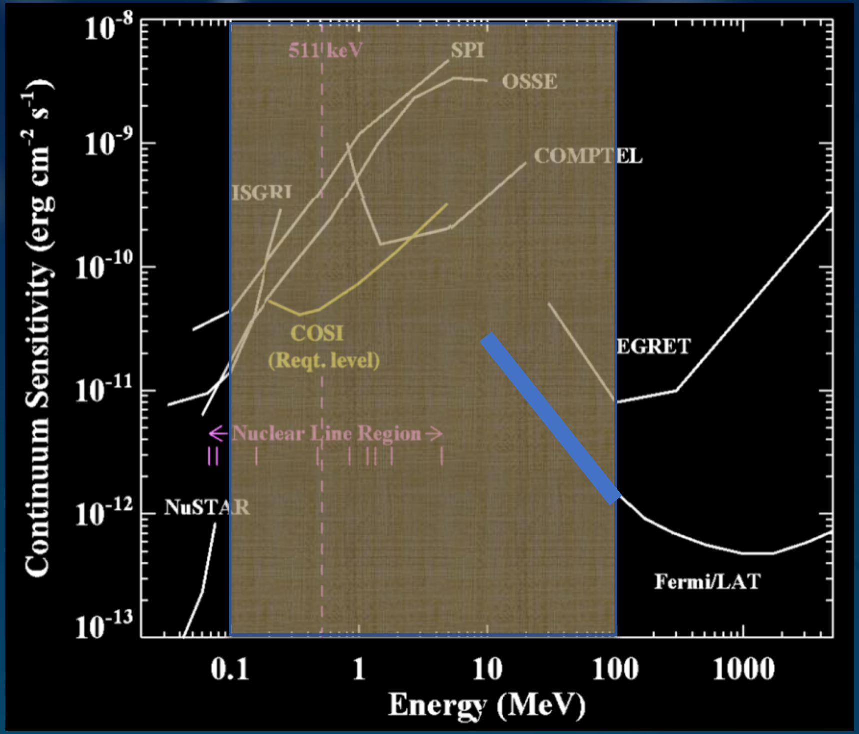
Fermi-LAT's Sensitivity

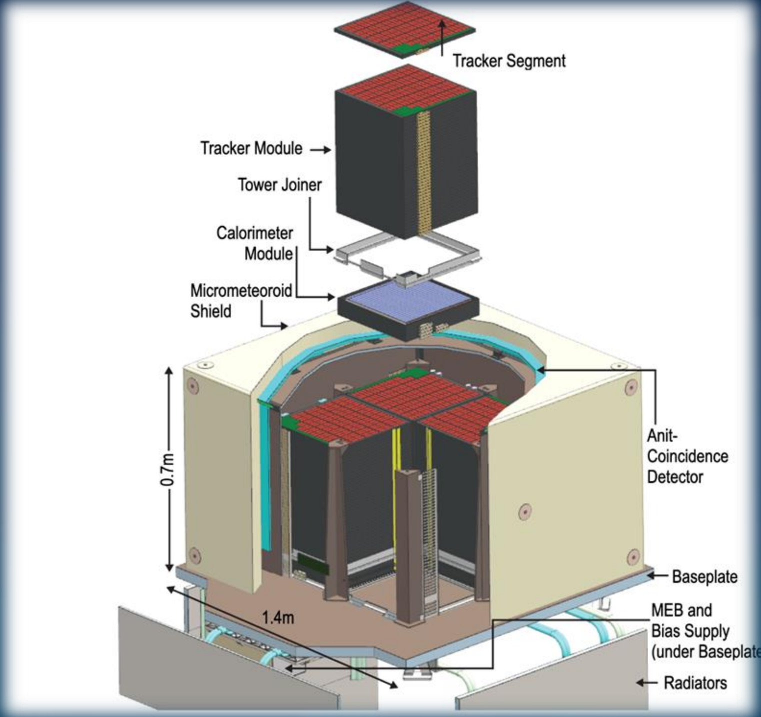
20 MeV – 200 MeV – 14 years

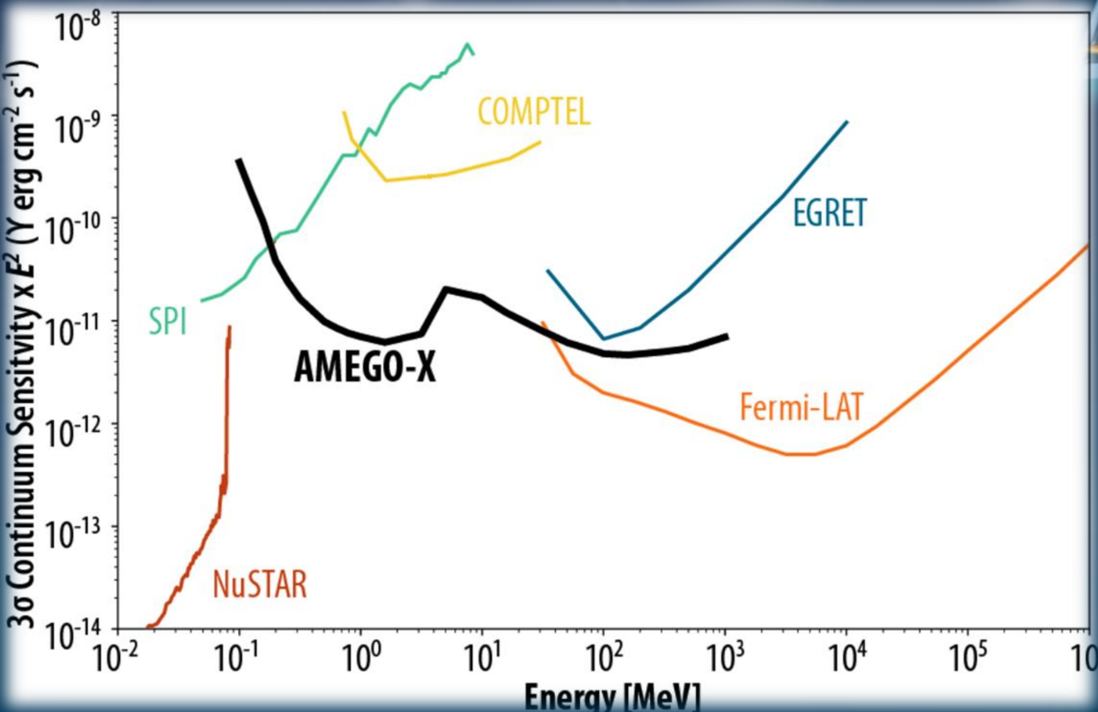




- Fermi-LAT is sensitive to photons with E>20 MeV
- A catalog of low-energy (20-200 MeV) sources is in preparation (Marcotulli, Joffre, Karwin, Ajello)

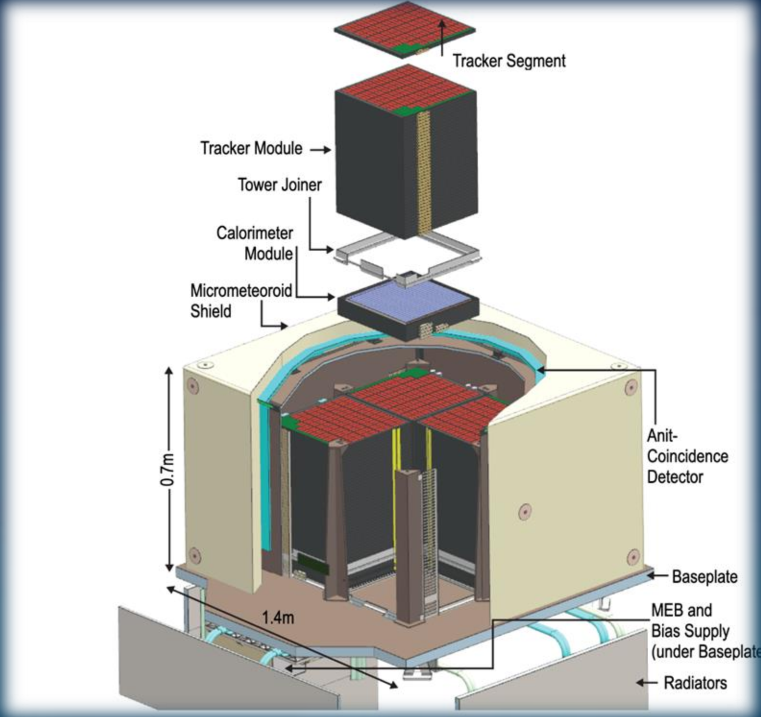
AMEGO-X (see also e-ASTROGAM)

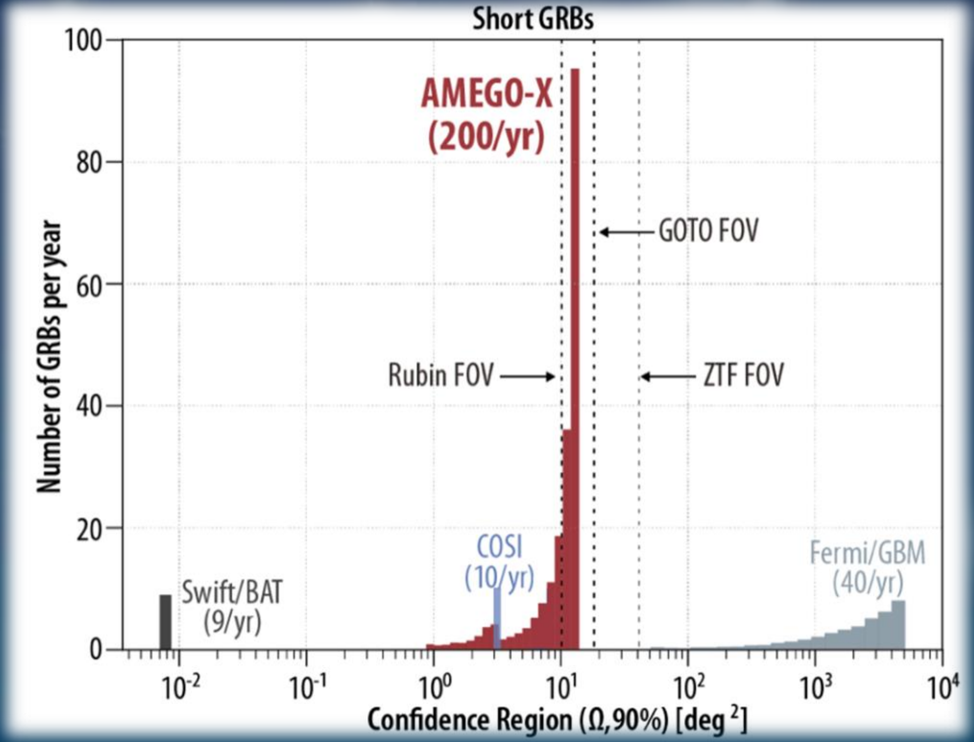




- AMEGO-X is a mission concept for the NASA MIDEX call (Caputo et al. 2022)
- It is a Compton-Pair telescope sensitive from 100 keV to 1 GeV

AMEGO-X





- AMEGO-X is a mission concept for the NASA MIDEX call (Caputo et al. 2022)
- It is a Compton-Pair telescope sensitive from 100 keV to 1 GeV
- It would detect hundreds of SGRBs/year and localize some to within 1-2 deg

AMEGO-X/CompPair balloon flight – 8/27/2023

AMEGO-X/CompPair balloon flight – 8/27/2023

Thank you!