Science from the MeV Gamma Ray Sky

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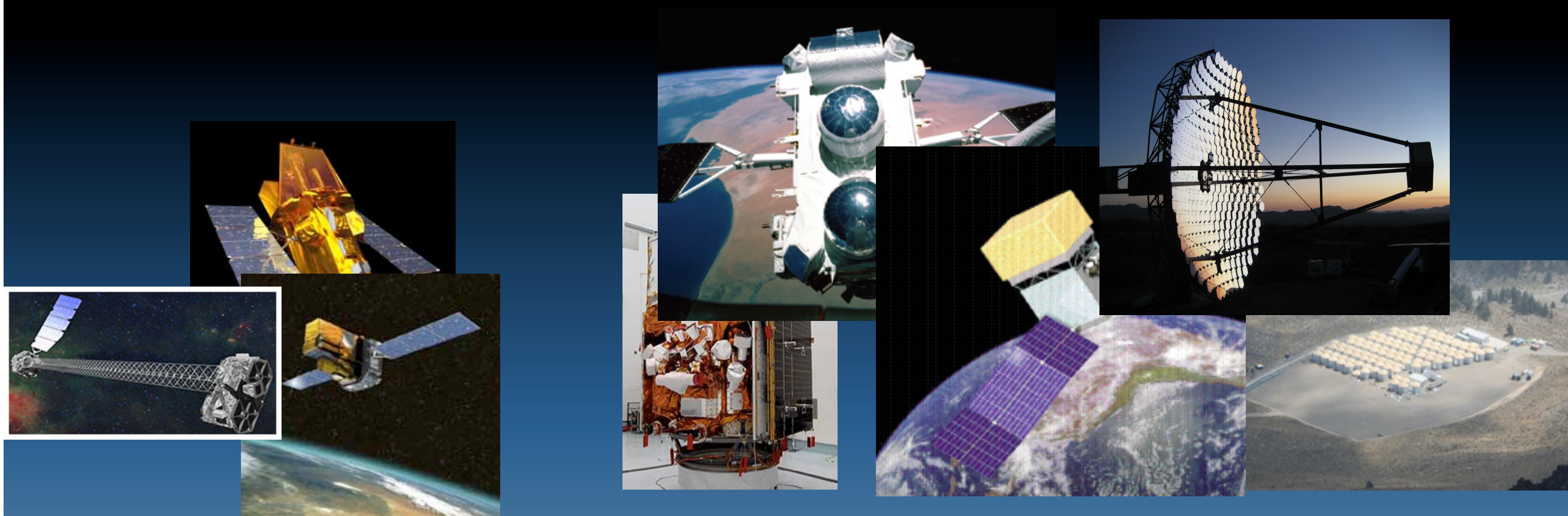
The need ....

- A sensitive survey of the γ-ray sky between 100 keV and 100 MeV

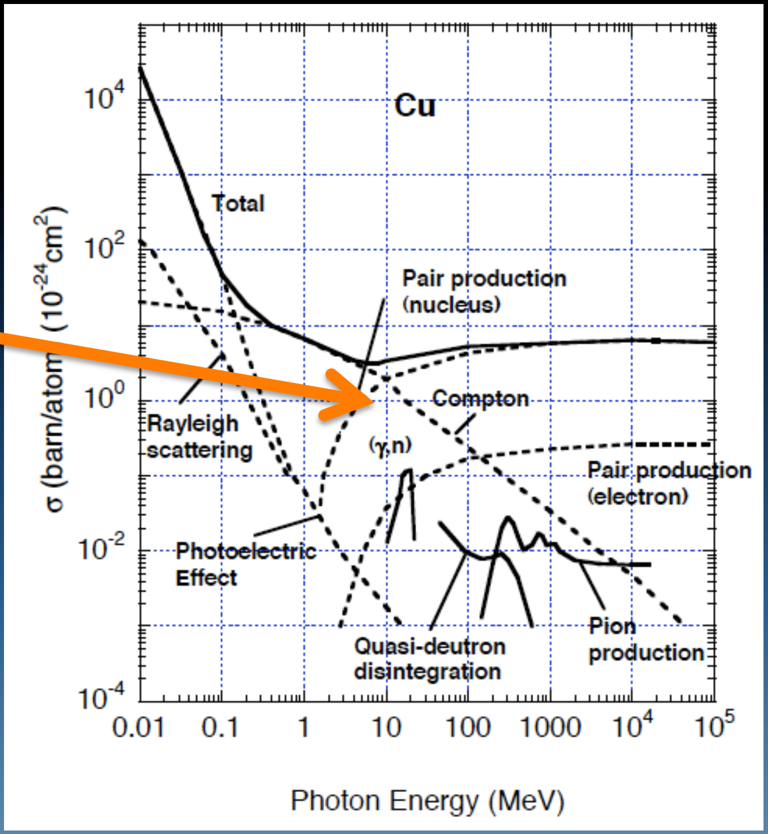


10^{-9} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18} 10^{-20} m

100 keV 0.5 MeV 100 TeV

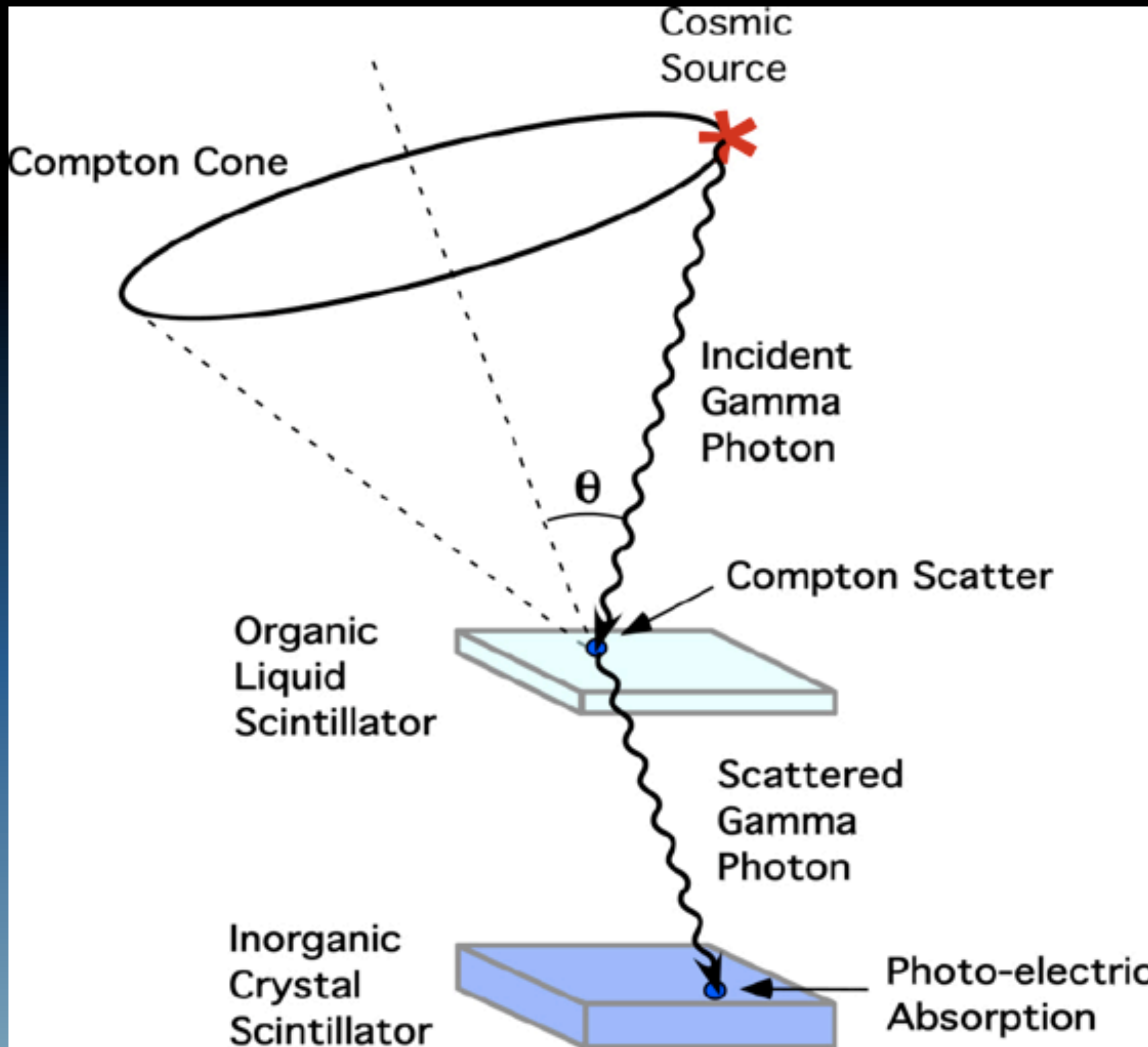
Energy range & challenges

- Energy range 300 keV to ~100 MeV
- "Compton regime" -- notoriously difficult & challenging
- Requires an efficient instrument with an excellent background subtraction
- Last instrument to operate in this range: COMPTEL
- Neither Fermi-LAT nor AGILE are optimized for observations below ~200 MeV or for polarization sensitivity.



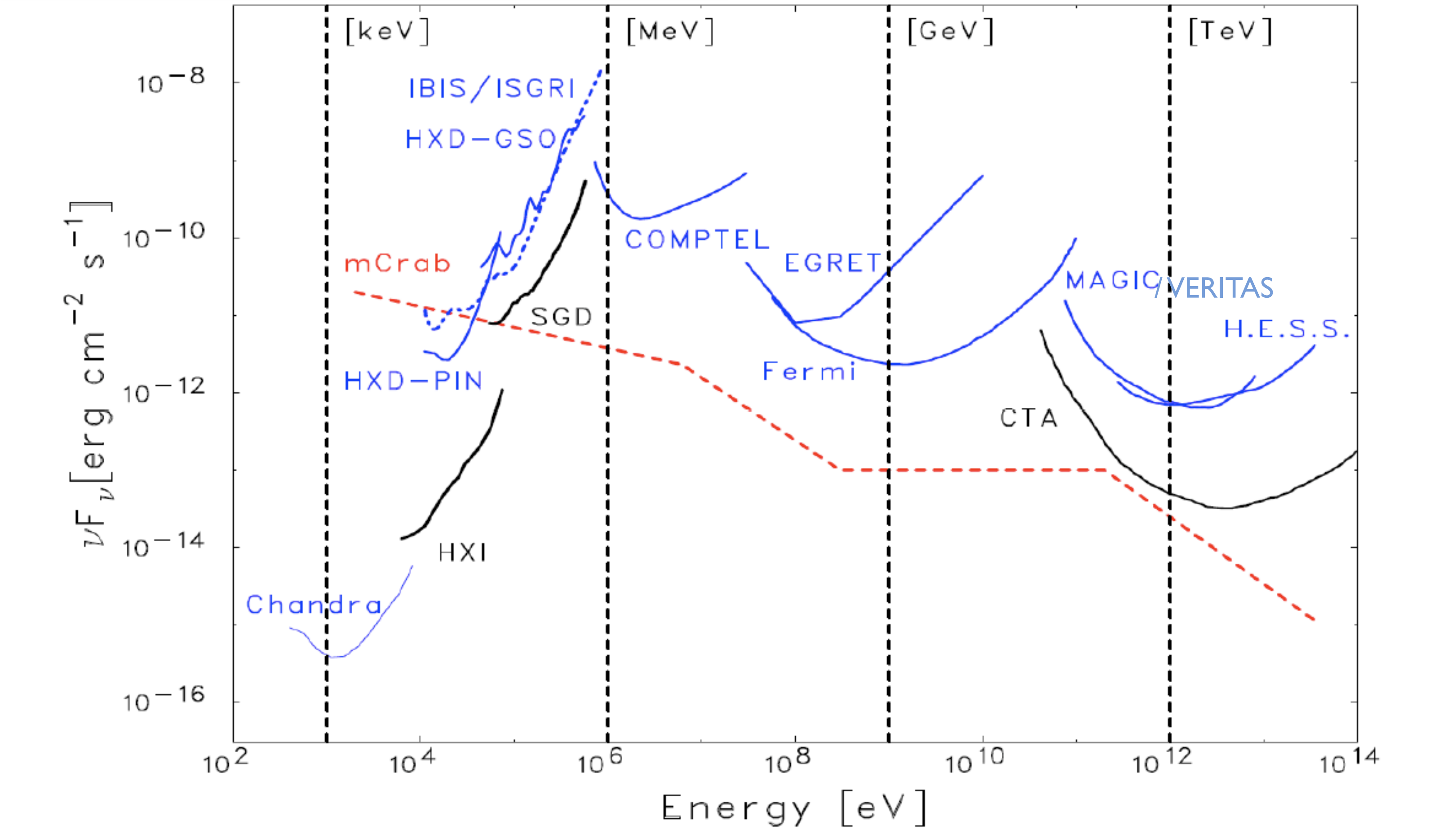
Freytag, Handbook of Accel. Phys. & Eng. (1971)

Compton Imaging



McConnell, AAS 225th

Sensitivities - The MeV "Gap"



From Takahashi 2012

Talk Outline

- *Science motivation*
- Review highlights from “MeV” missions
- Synergy with VHE and keV regime
- Wish list for a future medium-energy instrument

Science goals for the "medium energy"

- Explosive nucleosynthesis : a close look at core-collapse and thermonuclear supernovae

- γ-ray lines (e.g. 511 keV, 70 MeV, + + +)

- Large number of soft γ-ray sources in the Galactic plane, yet to be discovered

- Contribution of soft γ-ray sources to the medium-energy Galactic diffuse emission

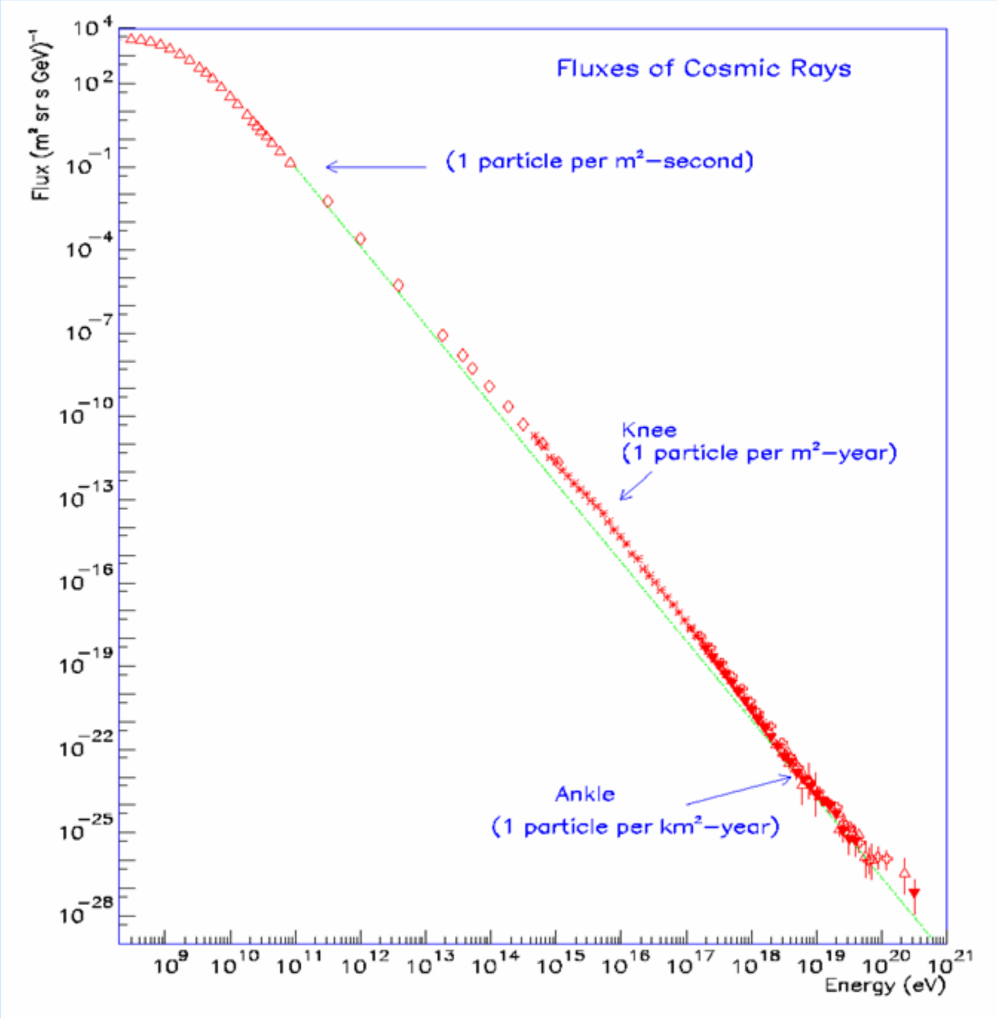
- The laws of physics around neutron stars and black holes

- Measurements of transient phenomena

- Spatially resolve variation between electron dominated and hadron dominated processes in the 70-200 MeV range.. Origin of cosmic rays?

from AstroMeV

Origin of the highest energy cosmic rays?



What is the origin of the highest energy cosmic rays?

- >100 year old mystery !
- Enormous E range
- Mostly charged particles
- E density ~ 1 eV/cm^3

Highest energy cosmic rays: clear evidence of particles above E > 10^{20} eV.

- ~85% protons, ~12% He nuclei, ~1% heavier nuclei, ~1% e^- and e^+.

Talk Outline

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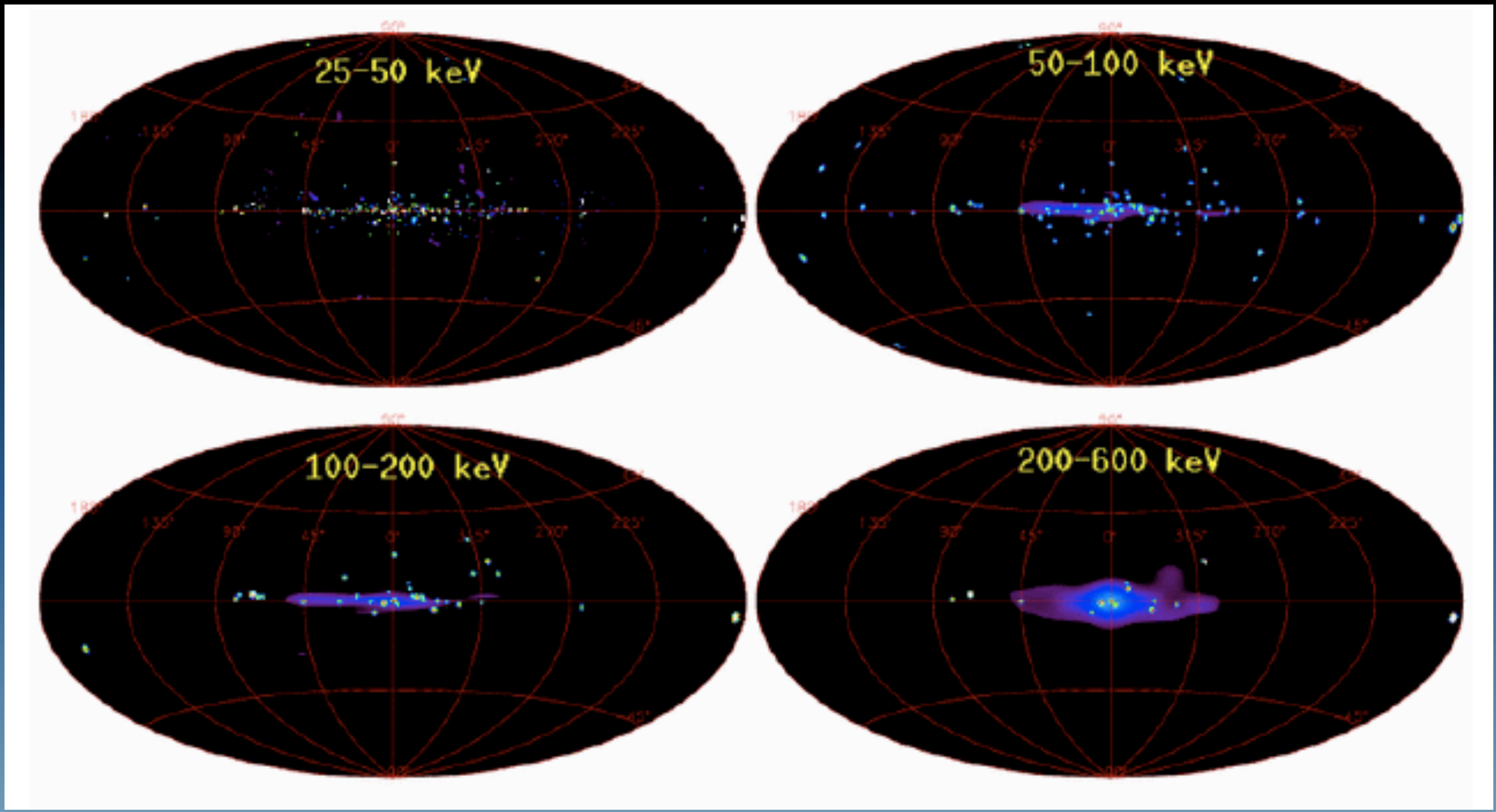
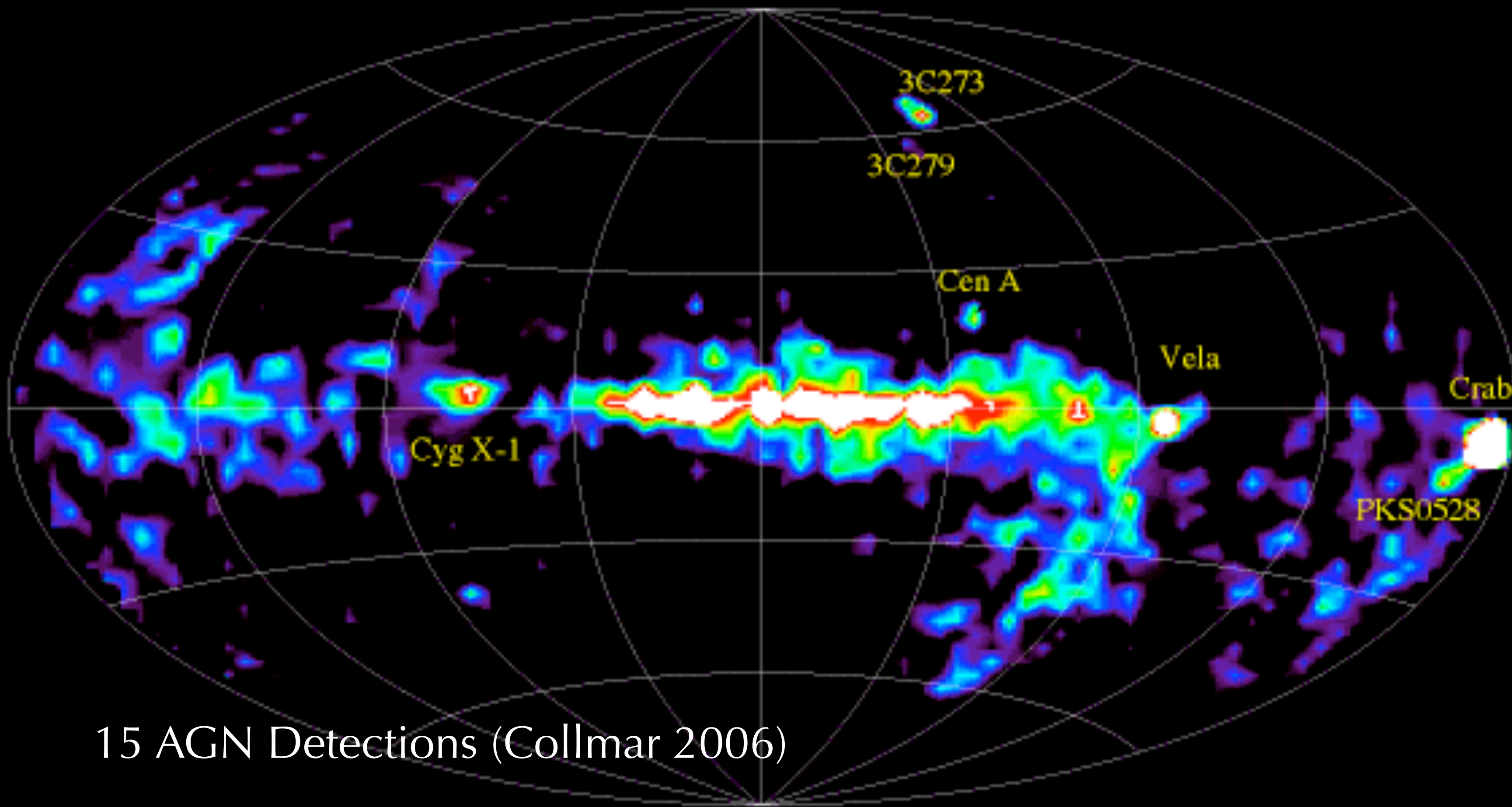
Skymaps: The INTEGRAL Sky



Kn¨odlseder et al. 2007

Skymaps: The COMPTEL Sky

1 – 30 MeV

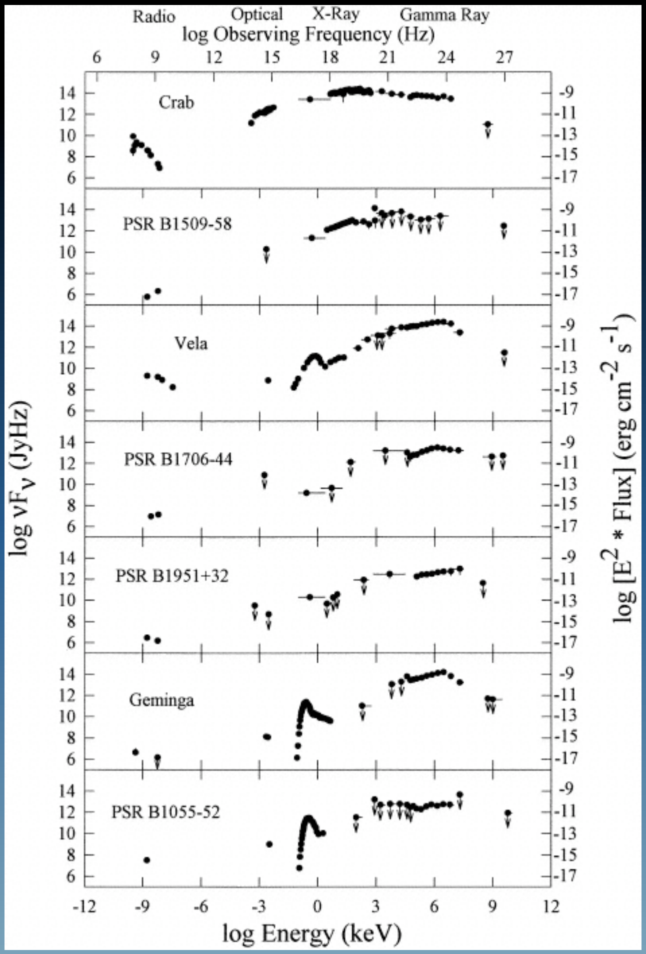


15 AGN Detections (Collmar 2006)

Galactic Sources: COMPTEL

Pulsars: 1 – 30 MeV

Thompson et al. 1999

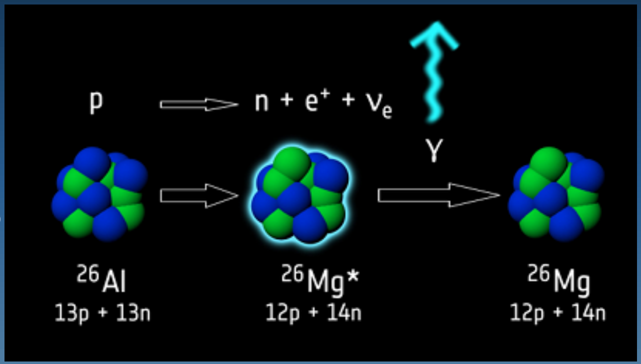


MW spectra of known γ-ray pulsar at the time of CGRO

Nuclear processes: Gamma-ray lines

Some astrophysical objects such as solar flares, stars, novae, supernovae may produce γ-ray lines due to transitions between nuclear energy levels:

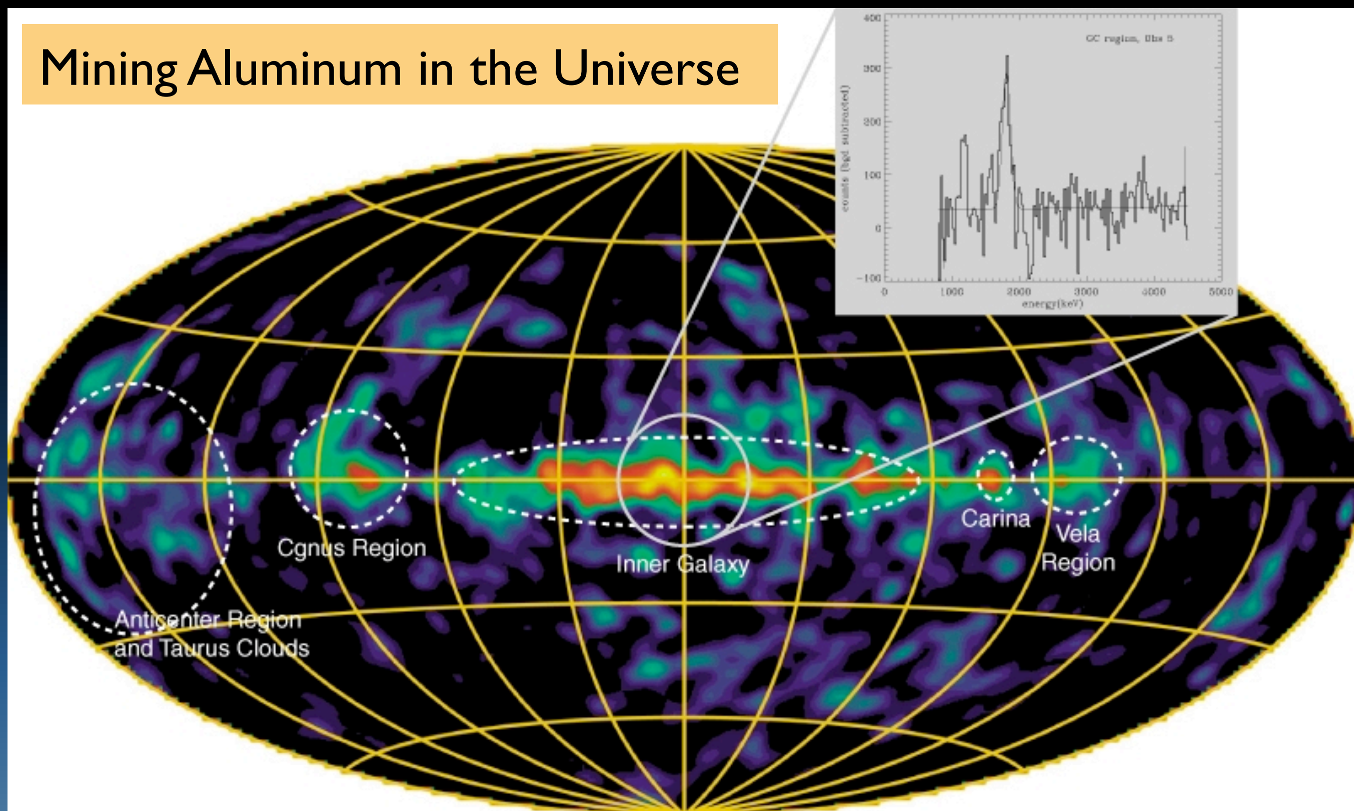
- Deuteron production: E_γ = 2.2 MeV
- Radioactive decay:



ESA

^{44}Ti (1.16 MeV)
^{56,57}Ni, ^{56,57}Co (0.12, 0.85, 1.24 MeV),
^{26}Al (1.81 MeV)
^{60}Fe (0.06, 1.17, 1.33 MeV)
^{7}Be (0.49 MeV), ^{16}O*(6.13MeV)
^{26}Mg* (1.81MeV), ^{12}C* (4.48 MeV)

COMPTEL all-sky image of ^{26}Al γ rays

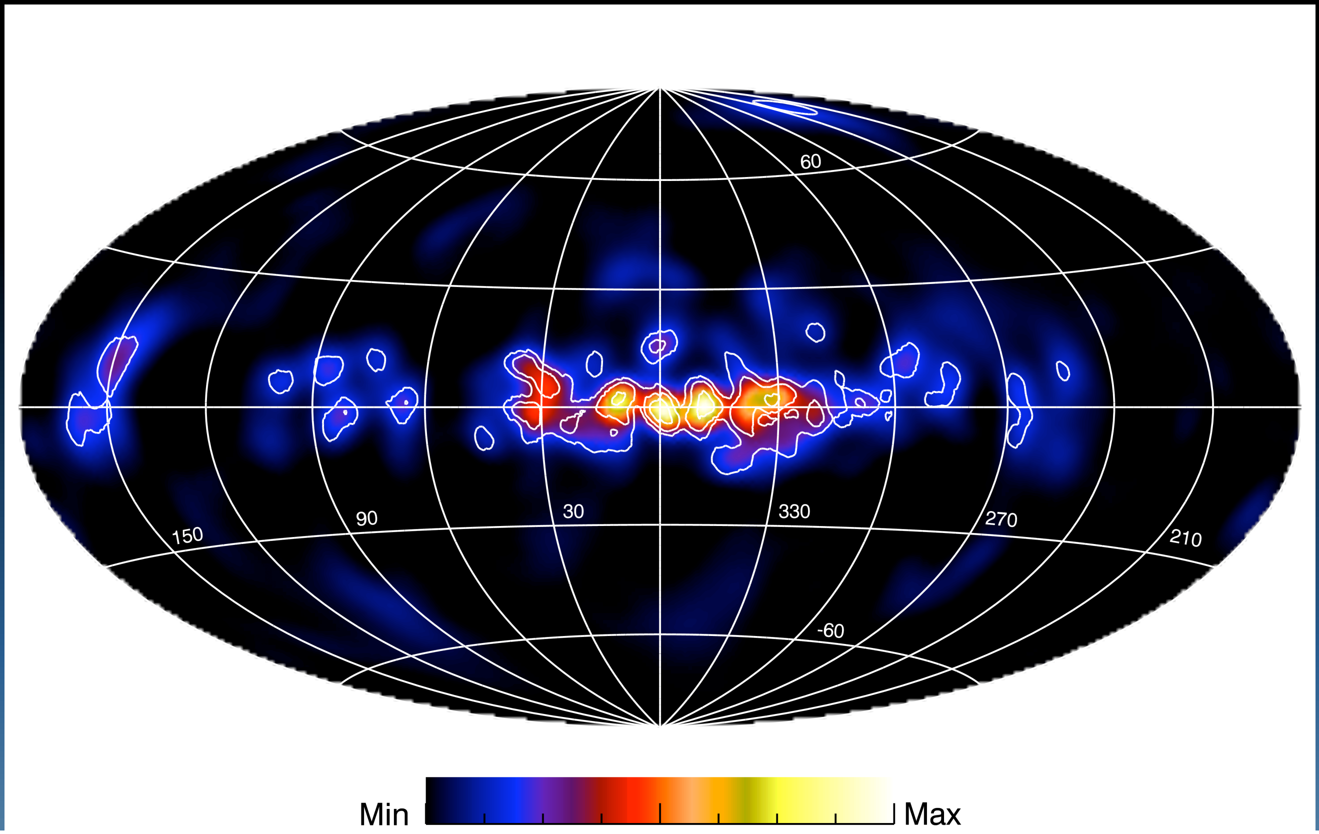


Comptel Collaboration (MPE/SRON/UNH/NASA)

-1.8 MeV γ-ray emission produced by the radioactive decay of ^{26}Al, tracing regions with massive young stars throughout the Milky Way

INTEGRAL all-sky image of ^{26}Al γ rays

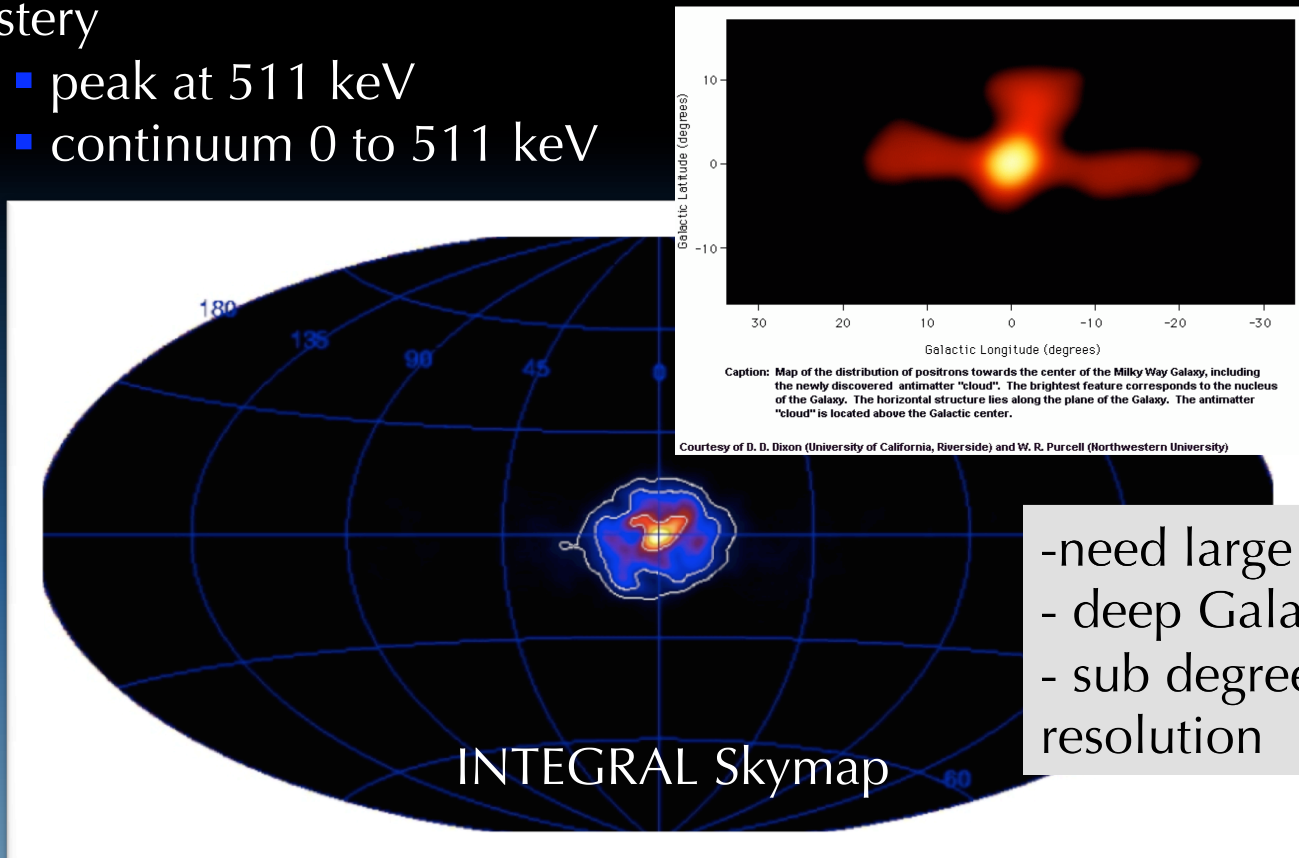
Bouchet, Jourdain & Roques, 2015



- 10 years of INTEGRAL/SPI observations. Spatial resolution of 6°
- Main features previously seen with COMPTEL are confirmed, emission is essentially confined in the inner Galaxy

Particle Physics processes: γ-ray lines

- e^+, e^- annihillation: 511 keV emission from the GC region is still a mystery
    - peak at 511 keV
    - continuum 0 to 511 keV



Caption: Map of the distribution of positrons towards the center of the Milky Way Galaxy, including the newly discovered antimatter "cloud". The brightest feature corresponds to the nucleus of the Galaxy. The horizontal structure lies along the plane of the Galaxy. The antimatter "cloud" is located above the Galactic center.

Courtesy of D. D. Dixon (University of California, Riverside) and W. R. Purcell (Northwestern University)

OSSE, Dixon, Purcell

INTEGRAL Skymap

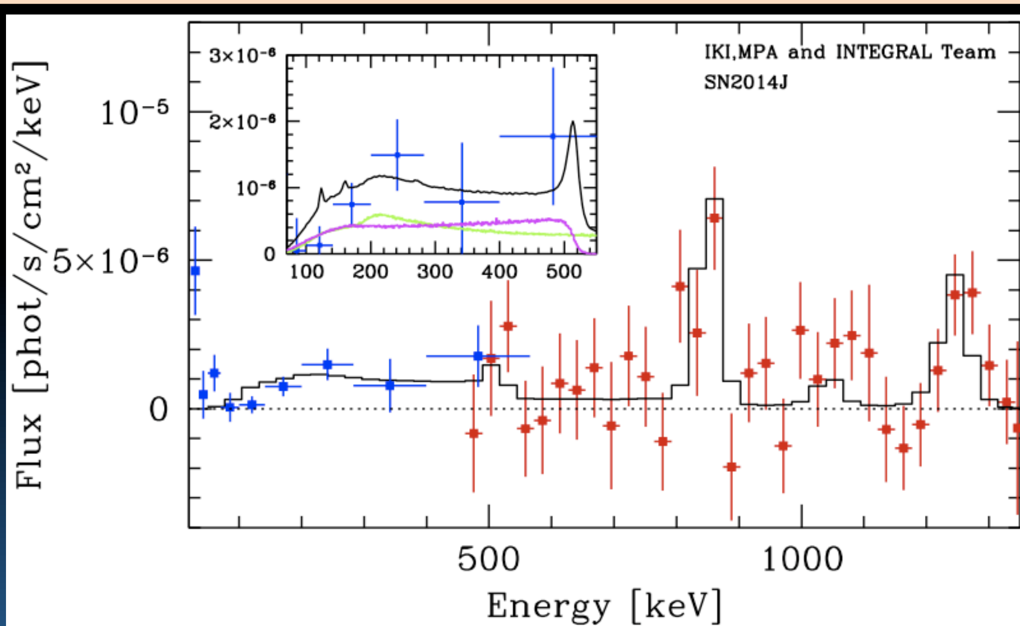
J. Knödlseder - CESR - September 2005

-need large FOV
- deep Galactic survey
- sub degree angular resolution

What are the main sources of positrons?

SN 2014J: Thermonuclear Explosion

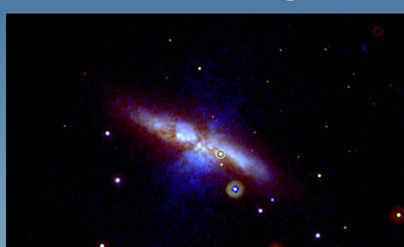
Churazov et al. 2014, Nature

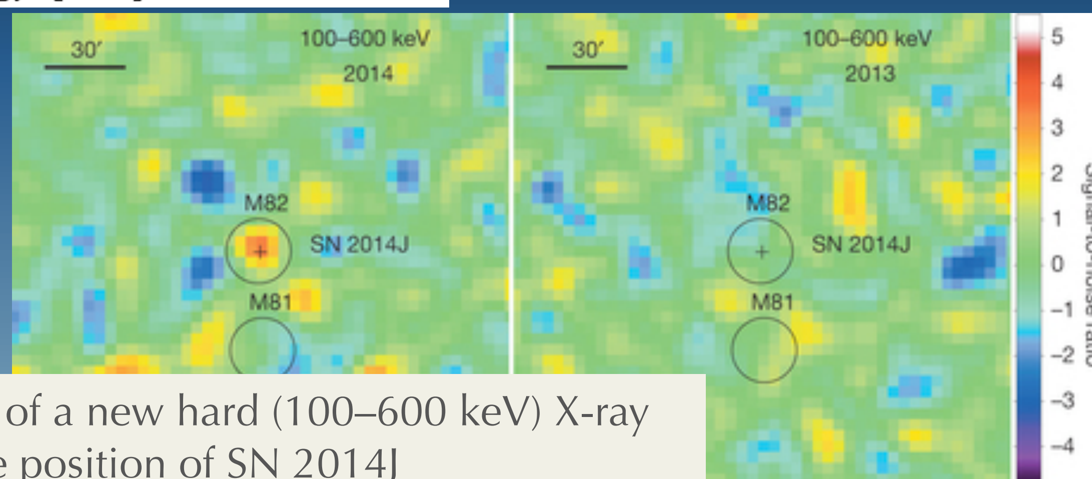


Thermonuclear explosion → fuses a large amount of radioactive ^{56}Ni

Decay chain from ^{56}Ni to ^{56}Co to ^{56}Fe generates γ ray photons

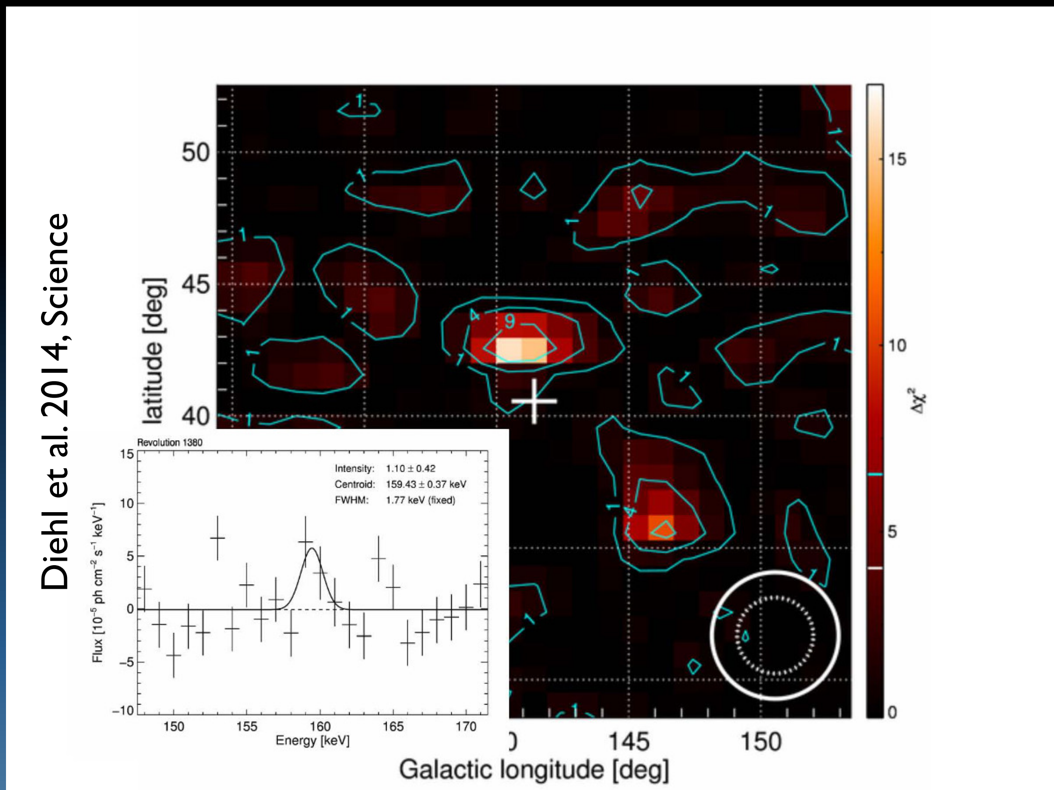
γ-ray lines from ^{56}Co decay ($T_{1/2}$=77 d) and synthesis of ~0.6 M_O of ^{56}Ni





Appearance of a new hard (100–600 keV) X-ray source at the position of SN 2014J

SN 2014J: Surprise Result



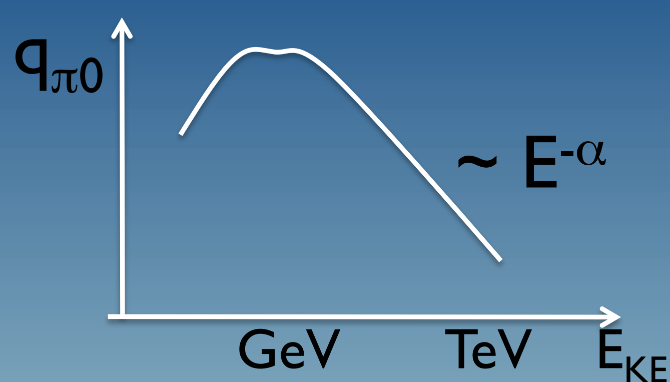
-Physics of bright Type-1a SN not fully understood

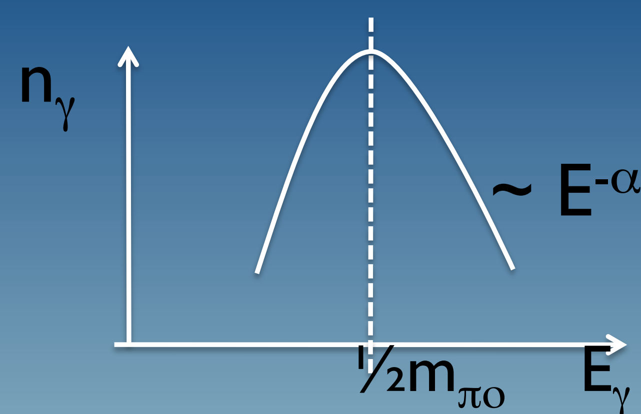
- Results from INTEGRAL and NuSTAR challenge prevailing explosion model for type Ia supernovae

- The ^{56}Ni is commonly believed to be buried deeply in the expanding supernova cloud
- γ-ray lines from ^{56}Ni decay at 158 and 812 keV detected earlier than expected (~20 d after explosion)

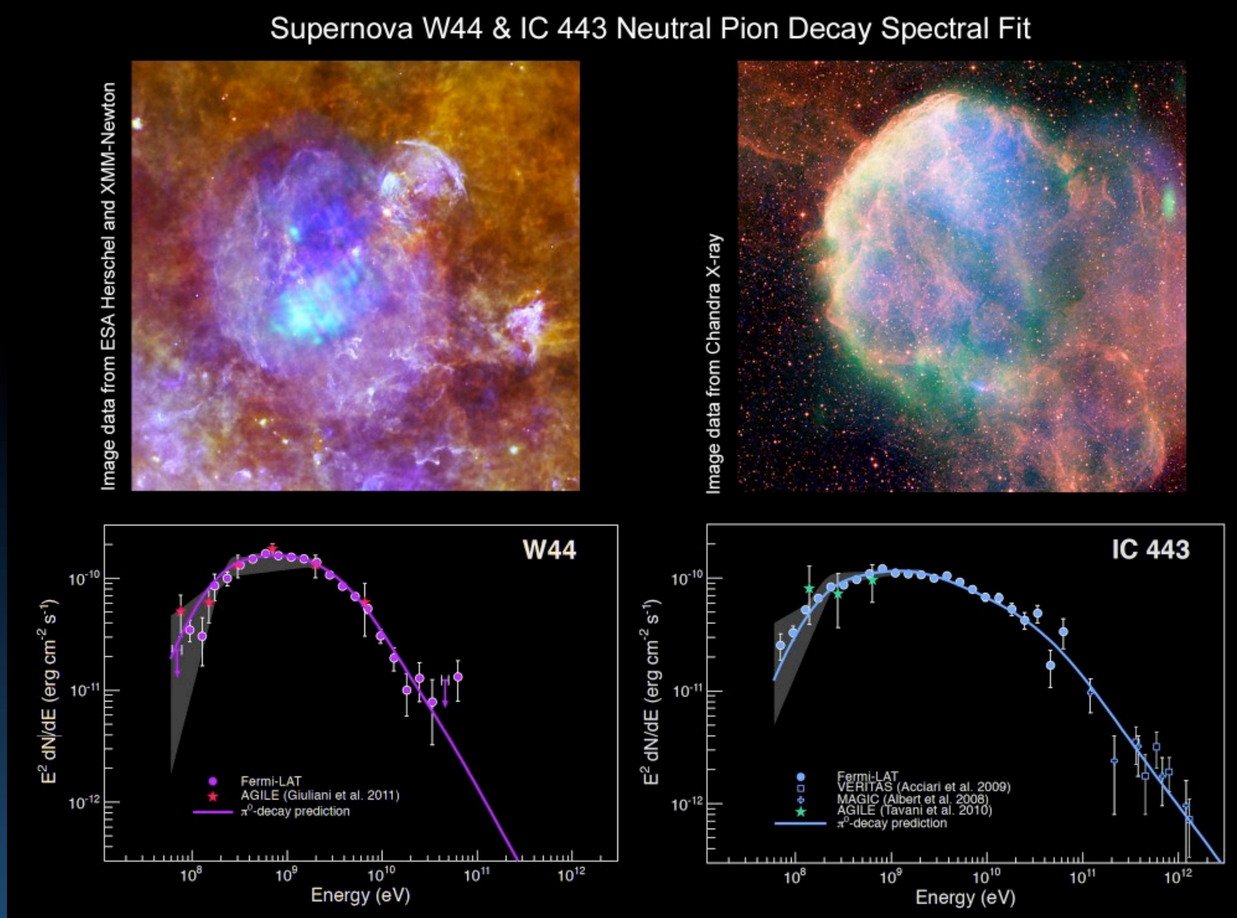
Particle Physics processes: γ-ray lines

- Cosmic Rays undergo hadronic (p – p) interactions in the Interstellar medium (ISM), leading to π^0 production
    - $\pi_0 \rightarrow \gamma + \gamma$
- Measuring γ rays helps trace gas distribution in the galaxy
- Signature spectrum of photons from π_0 decay: pion "bump" at ~70 MeV



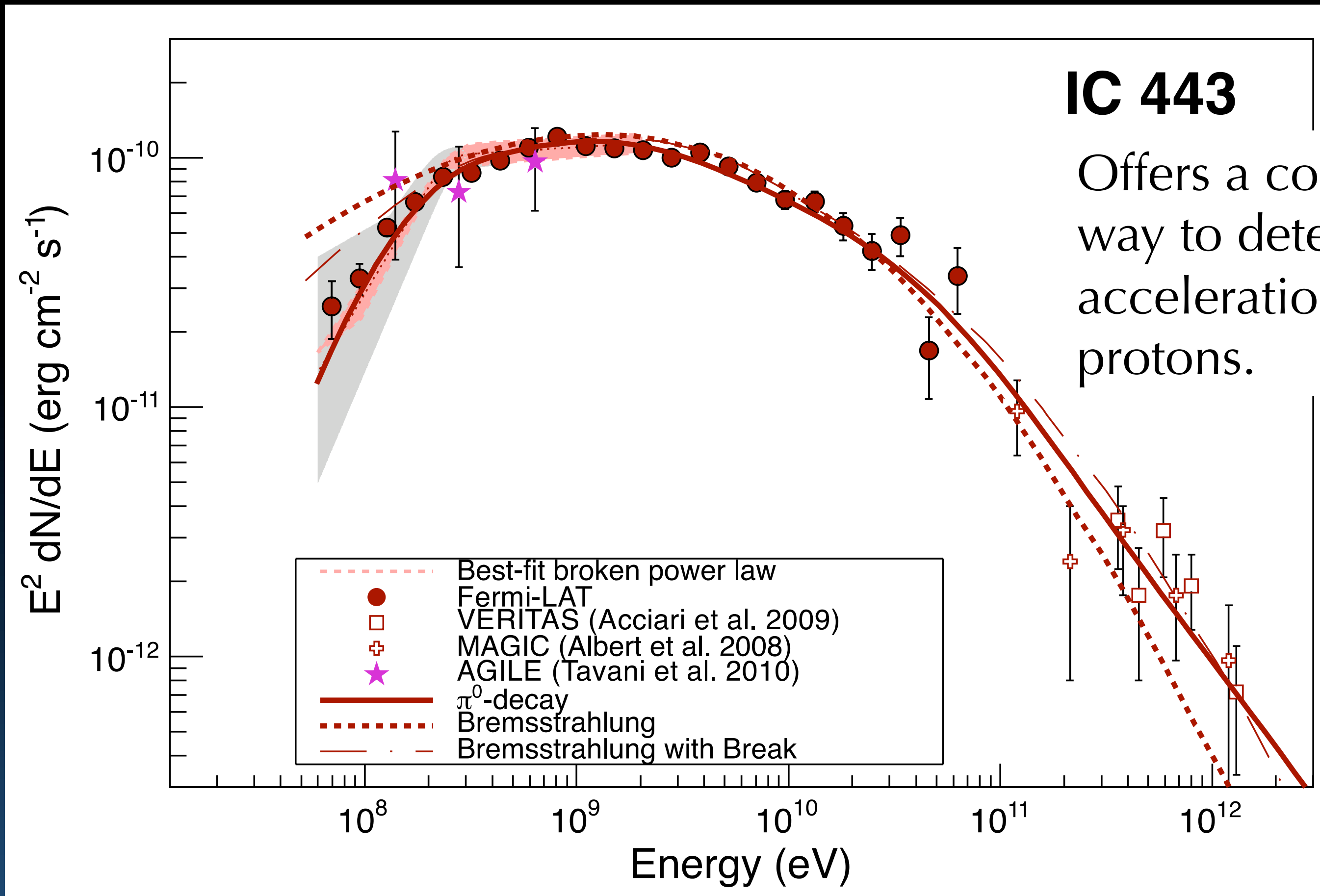


SNRs: Neutral pion decay?



- Low-energy part of the gamma-ray spectrum is critical for interpreting signature of cosmic ray pion decay

Cosmic rays?



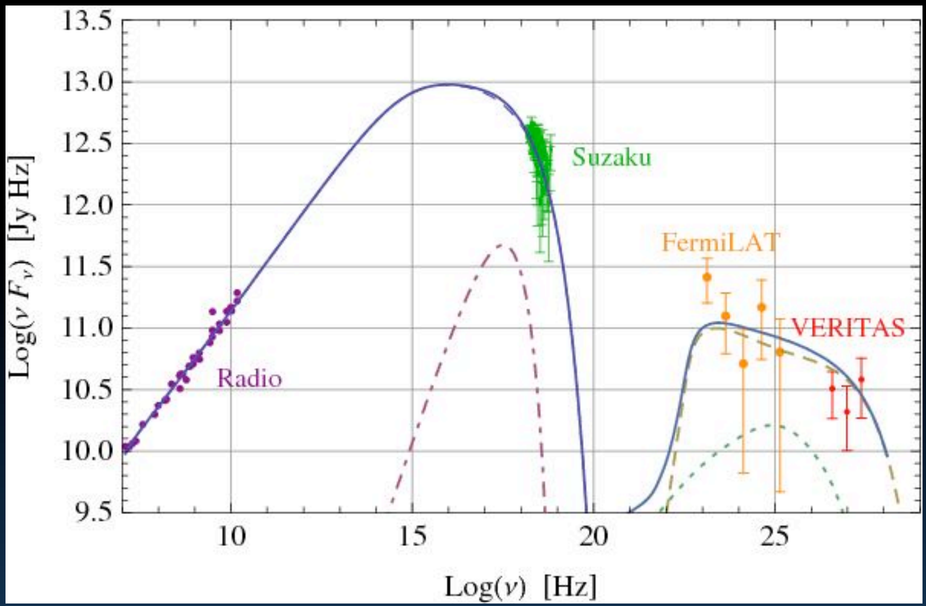
Ackermann et al. 1302.3307

Offers a compelling way to detect the acceleration sites of protons.

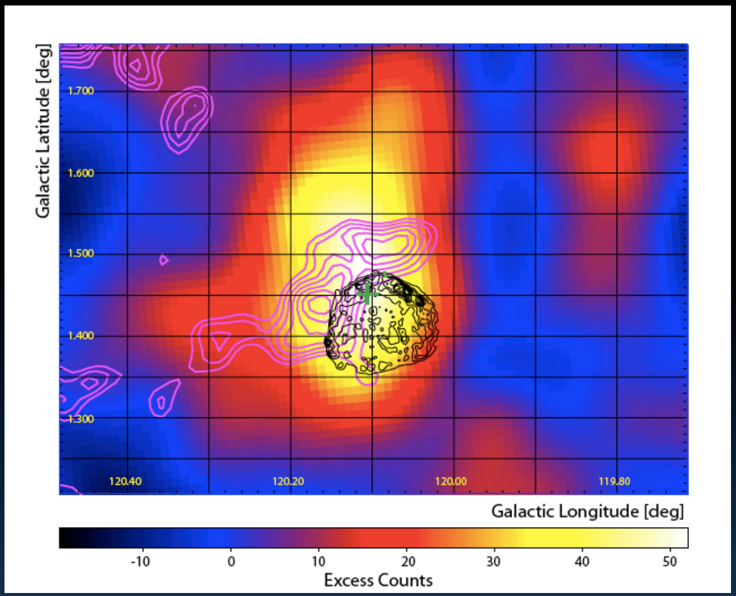
- A good spectral measurement at < 100 MeV will help clinch π^0 spectrum without doubt, and resolve between gamma ray models

Spatial resolution of SNRs

(Morlino and Caprioli, A&A, 2011)



Spatially integrated spectral energy distribution of Tycho

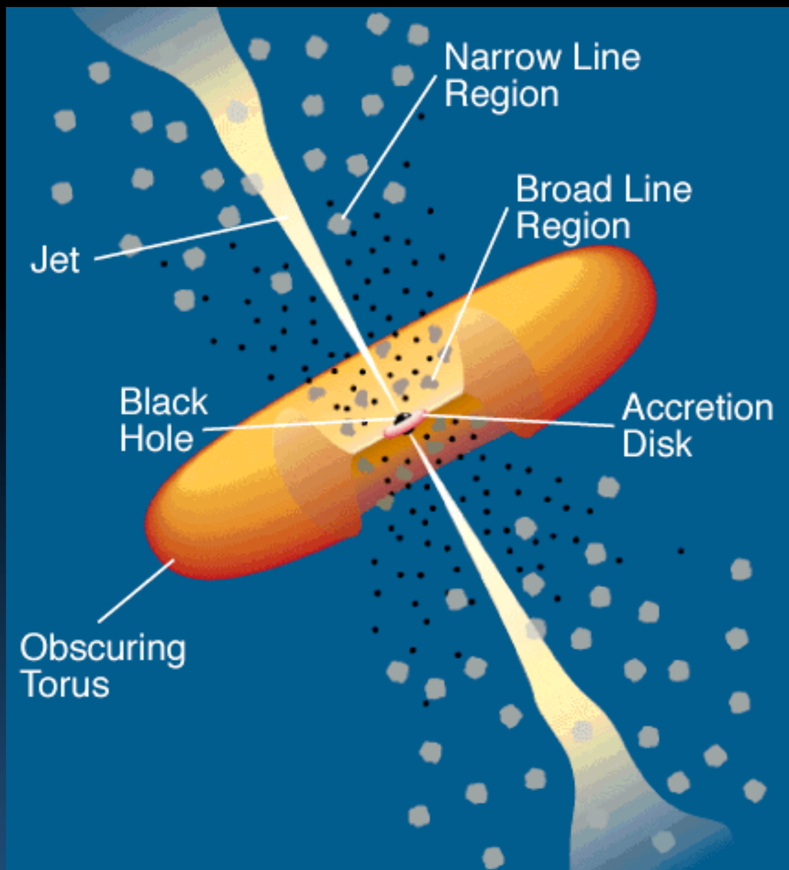


VERITAS image of Tycho SNR, a possible "pevatron"

VERITAS et al. 2011

- Need detailed probe of morphology and coordination with GeV & TeV instruments

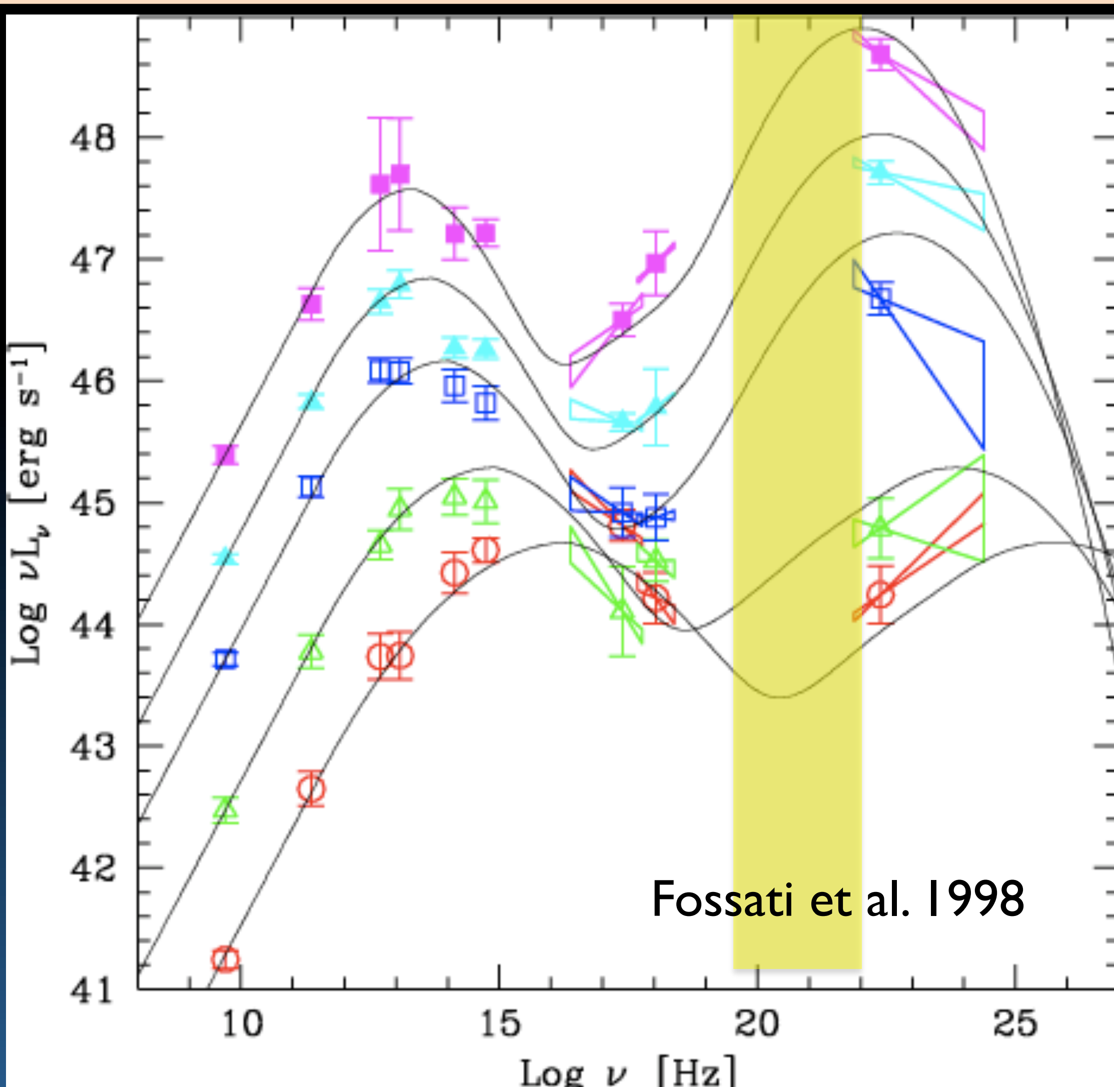
Blazar Physics



Urry & Padovani 1995

- Active galaxies in the MeV domain:
  - Formation and evolution of AGN
  - Origin of the extragalactic MeV γ-ray background
- Blazar spectral energy distributions:
  - leptonic vs hadronic models?
  - origin of UHE cosmic rays & neutrinos?

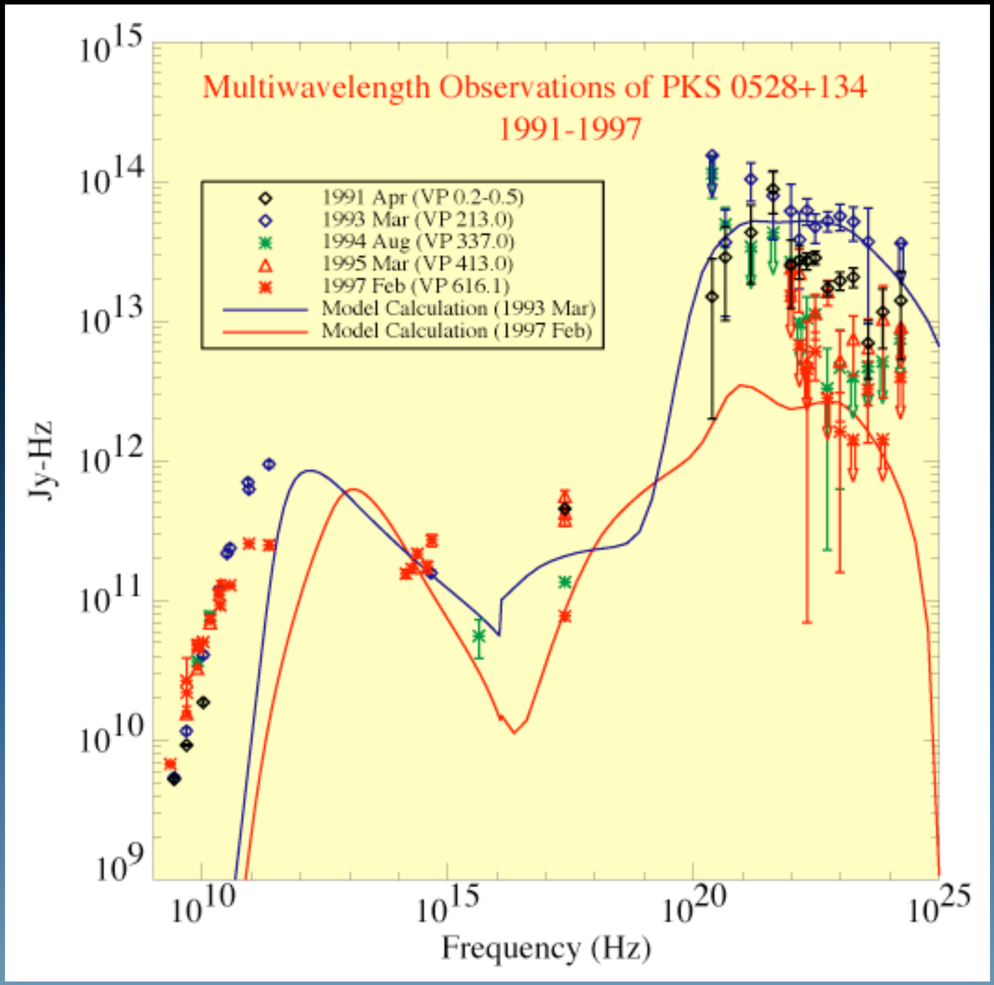
Active Galactic Nuclei



- γ-ray emission for FSRQs and LBLs typically peak in the "MeV" band
- Missing blazar population in the "MeV" band ➔ MeV γ-ray background?
- Where is the Compton peak in the various classes? What is the luminosity?

Blazars detected by EGRET & Fermi-LAT

Mukherjee et al. 1999

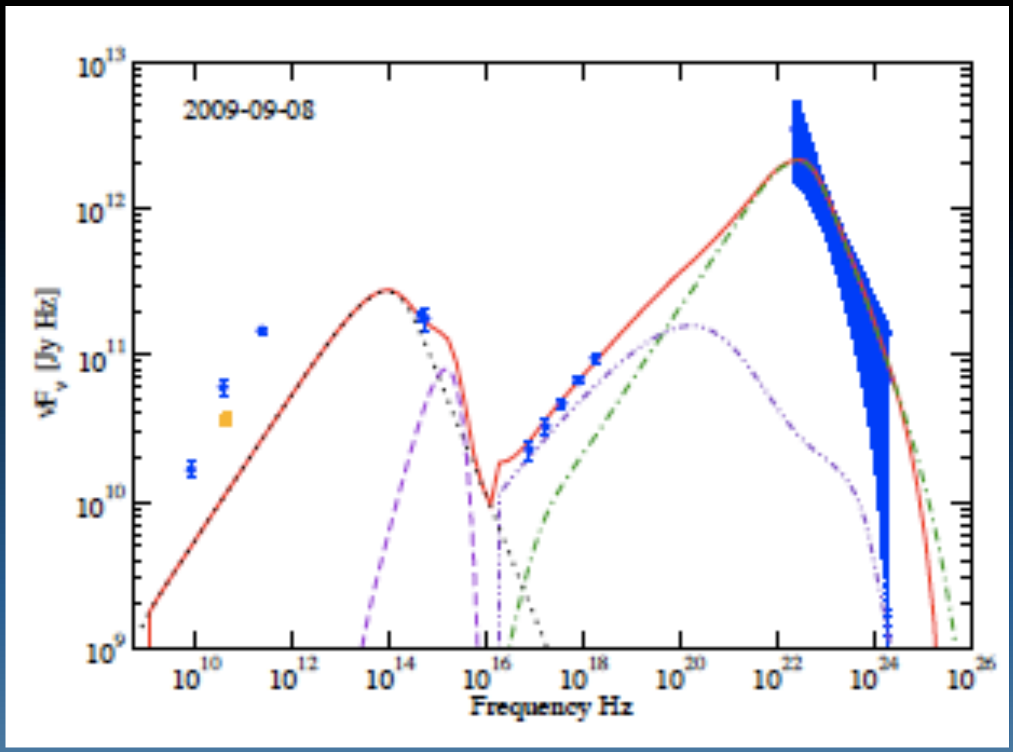


- Bolometric luminosity of blazar dominated by its γ-ray output.
- What is the correlation between γ-ray flux and the bulk Lorentz factor of the emission region along the jet.

γ-ray data from EGRET & COMPTEL

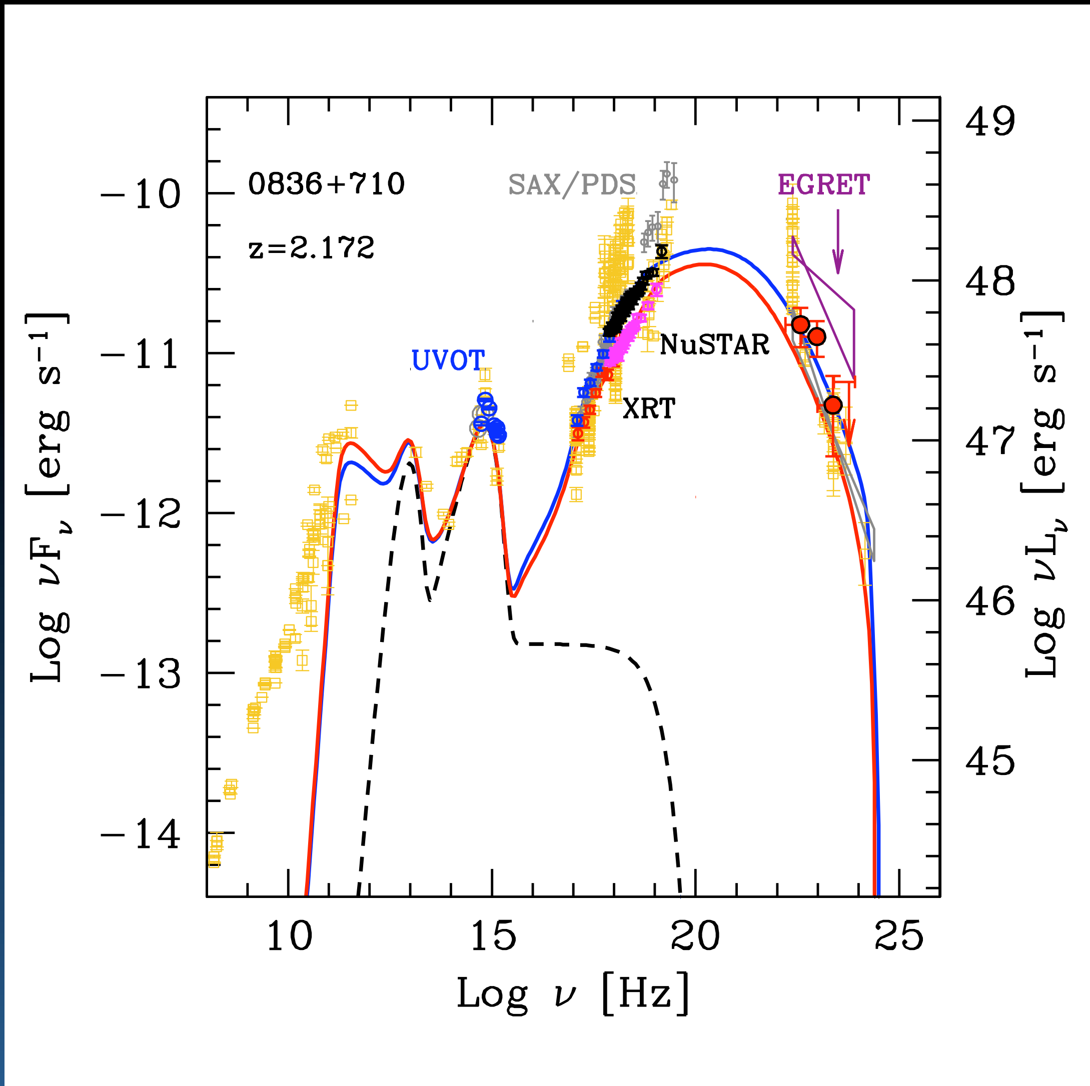
PKS 0528+134 with XMM & Fermi-LAT

Palma et al. 1104.3557



- Lack of observational data in the keV - MeV band makes modeling interpretations challenging.

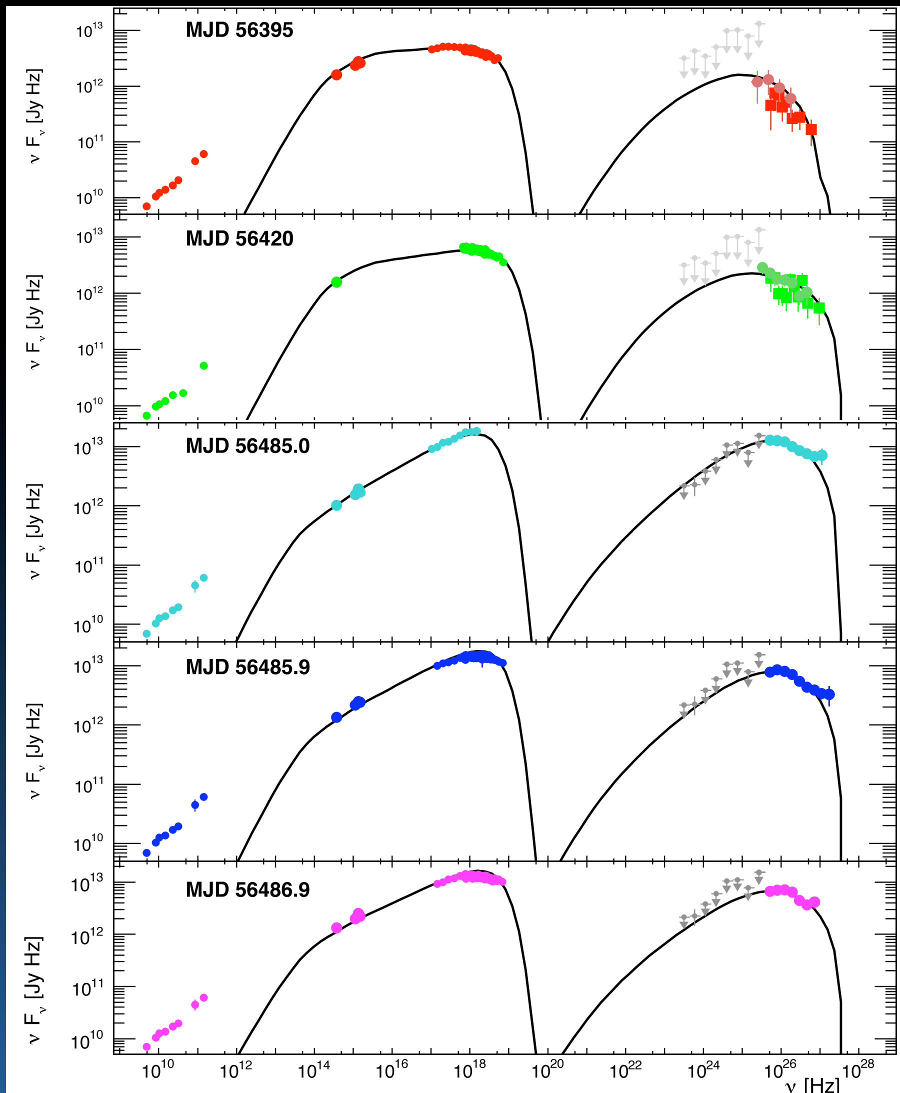
Active Galactic Nuclei



Tagliaferri et al. 1503.04848

- Emission in FSRQs is dominated by a Compton component peaking in the ~100s keV to ~100s MeV
- Where is the peak of the HE bump in the SED?
- Can blazars can contribute to the γ-ray background above 50 keV?

Simultaneous MW Studies of AGN



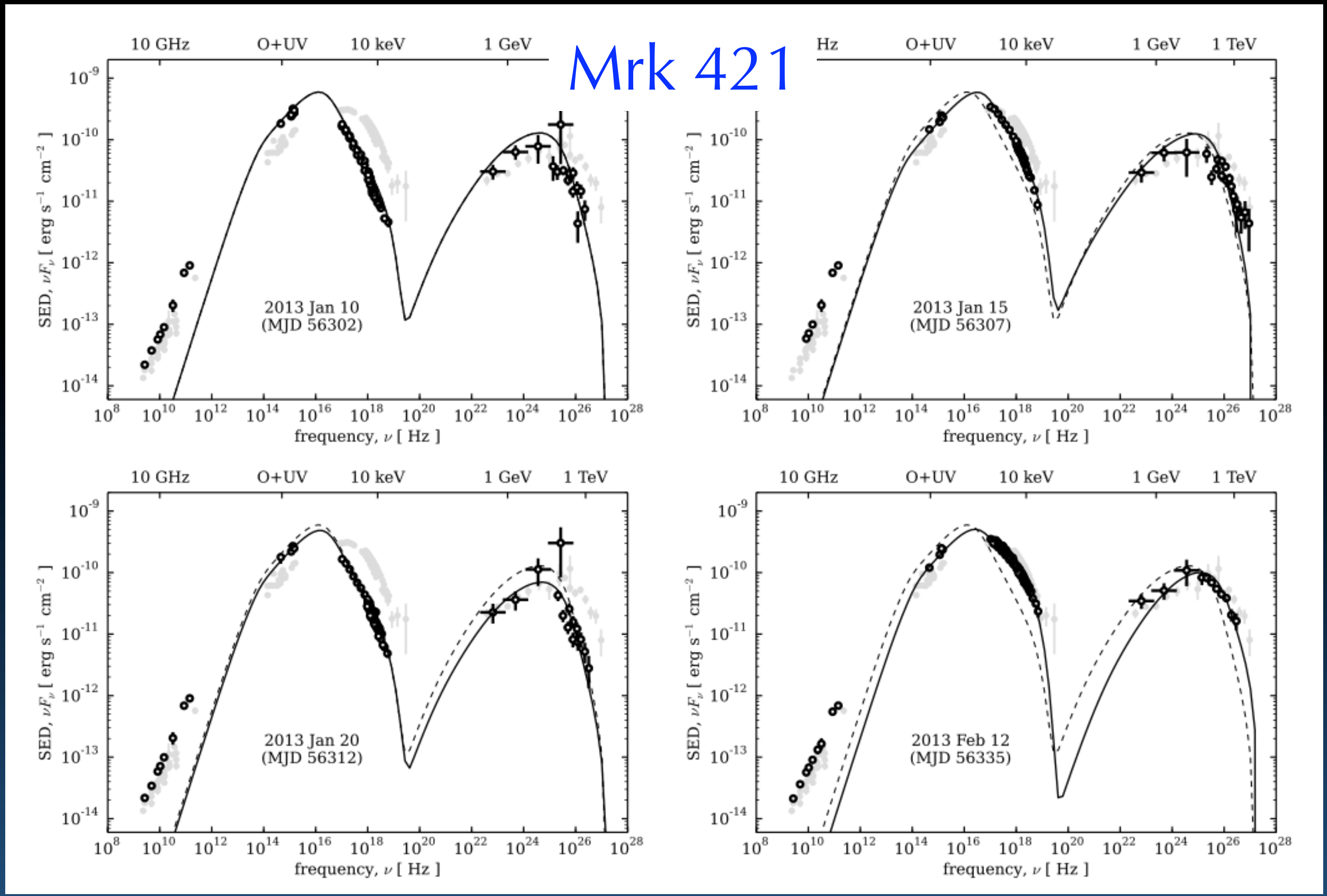
Furniss et al. 2015, in prep

NuStar Monitoring of Mrk 501 with coordinated observations from Radio to TeV energies

- First detailed characterization of the synchrotron peak with Swift and NuSTAR
- Terrific example of truly simultaneous data
- Crucial information missing between the NuSTAR observations and the beginning of Fermi band

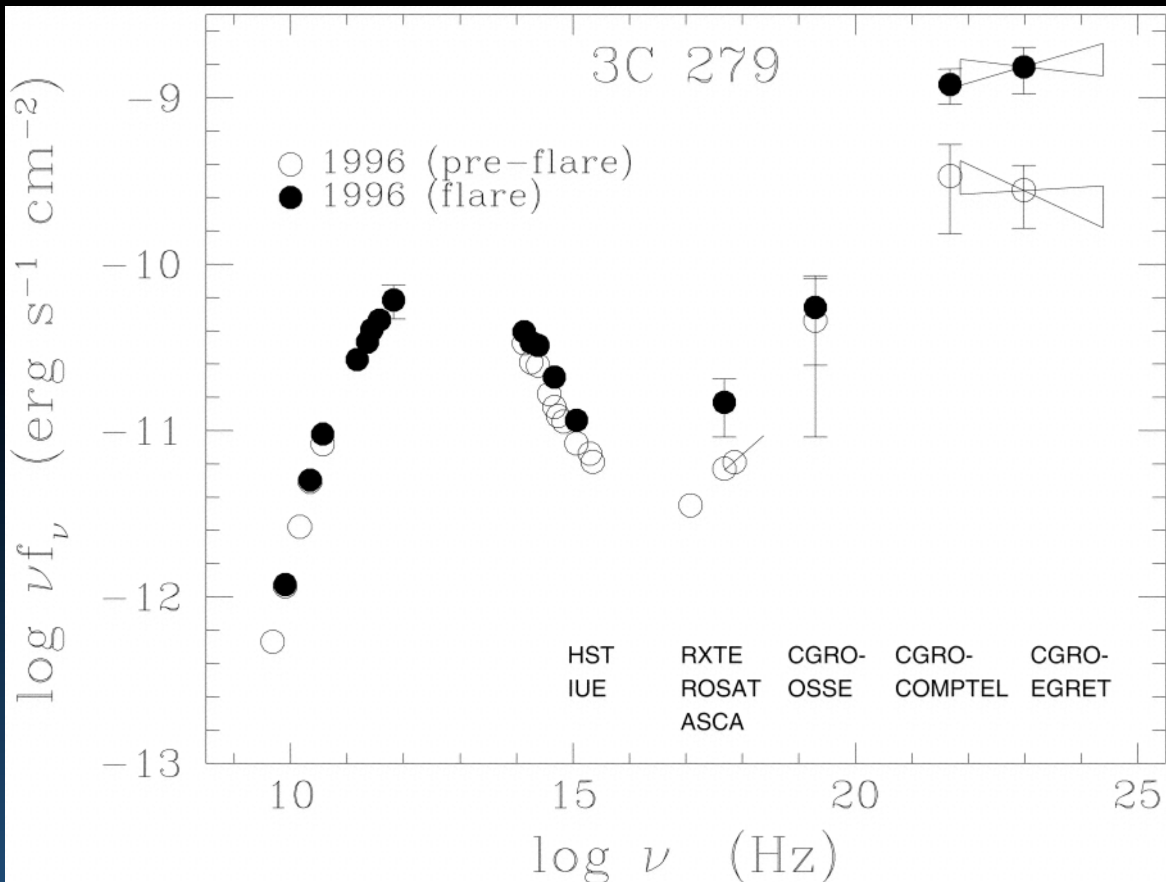
and .....

Furniss et al. 2015, in prep



- Crucial information missing between the NuSTAR observations and the beginning of Fermi band

AGN – Broadband spectra



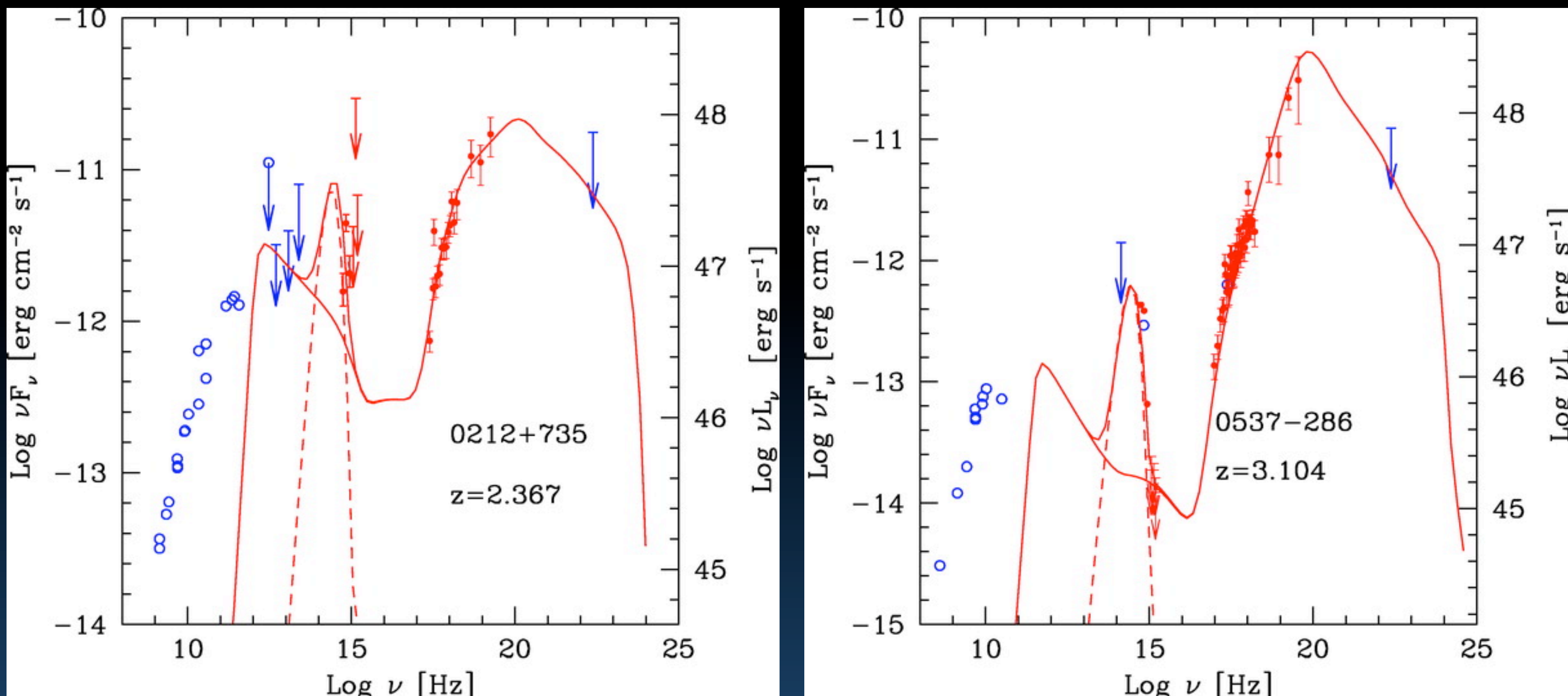
Wehrle et al. 1998

- Not much has changed since CGRO/EGRET days
- Missing "MeV" data

“MeV” Blazars

High-redshift radio loud quasars (z> 2)

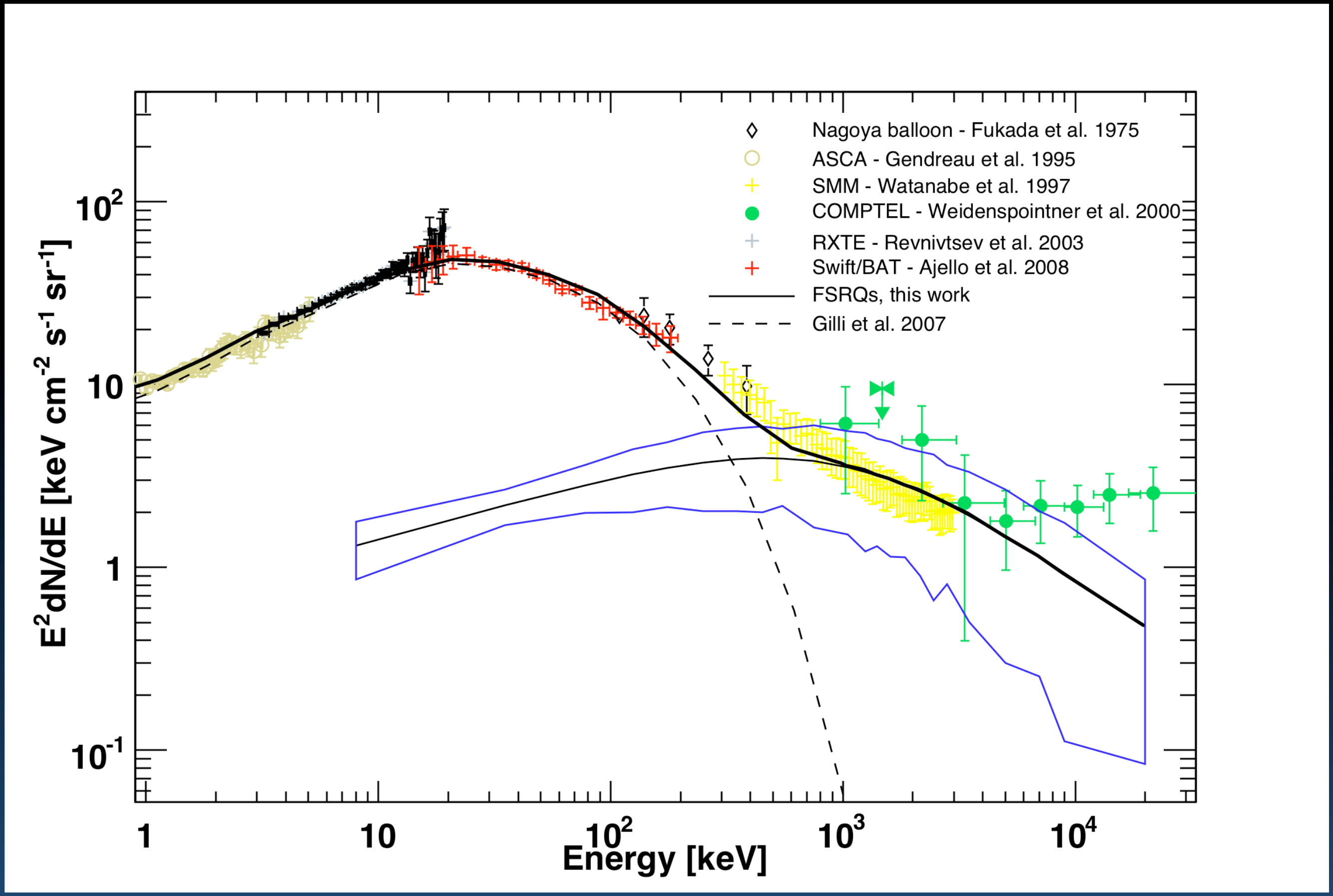
Sambruna et al. 2007



- FSRQs → most powerful blazars, emission dominated by Compton component ~ 100 keV to ~ 100 MeV
- Emission at >10^{16} Hz dominated by the jet, while the steep optical-to-UV continua ~ thermal emission from the accretion disk.

Origin of Cosmic MeV γ-ray Background?

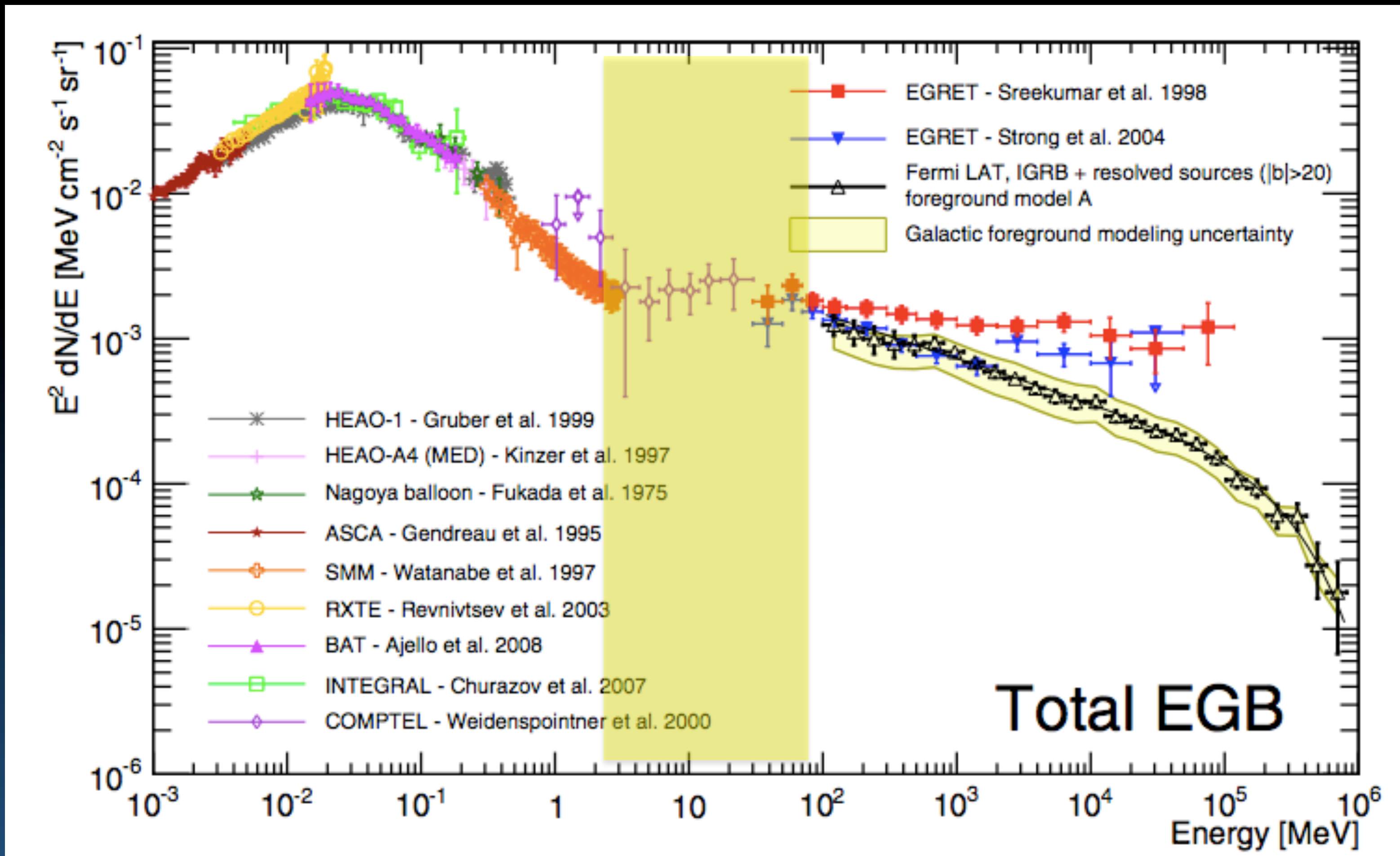
Ajello et al. 0905.0472



- Can FSRQs explain the entire CXB emission for energies above 100 keV?
- IC peak is in the MeV regime
- What is the evolution of luminous FSRQs?

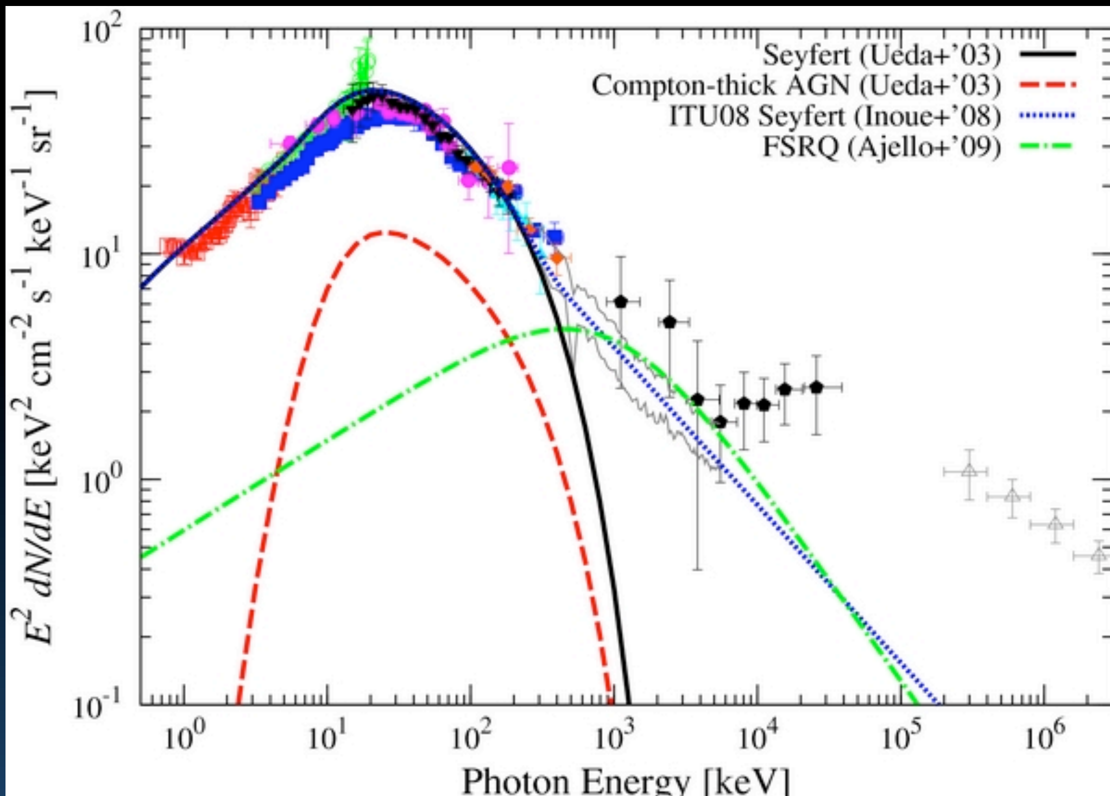
Cosmic MeV γ-ray Background

Ackermann et al. 2014



-MeV background likely due to different source classes: SN Ia, AGN, Star forming galaxies

Cosmic MeV γ-ray Background



Inoue et al. 2013

- MeV γ-ray measurements difficult. MeV sky not fully investigated
- Expected angular power spectra of Seyferts and blazars in the MeV range are different by about an order of magnitude
- Need large numbers of FSRQ detections

- Can future MeV instruments clearly disentangle the origin of the MeV γ-ray background through measurement of the angular power spectrum?

Gamma-ray Polarization

Why are polarization measurements important?

- Polarization measurement in blazar - Gamma-ray polarization can distinguish between emission processes such as synchrotron radiation and other gamma-ray production mechanisms. Are hadrons accelerated in blazar jets?

- Polarized hard X-ray emission detected by space borne instruments, e.g. RHESSI, INTEGRAL, and GAP. Such polarization should extend into the gamma-ray range, given the same basic emission processes

- γ-ray polarimetry remains a frontier in high-energy studies

(see e.g. Hunter 2013)

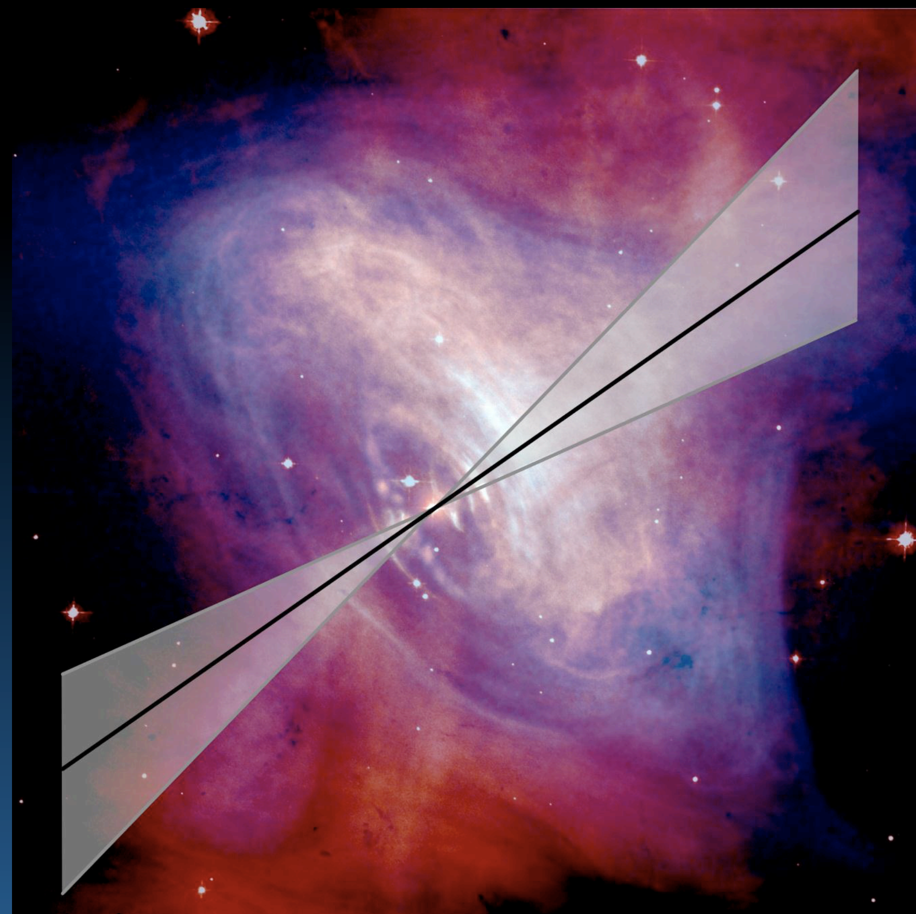
Gamma-ray Polarization

Why are polarization measurements important?

Crab Nebula / Pulsar:
High degree of polarization (46 ± 10 % at 0.1 – 1 MeV; 72 % at 200 – 800 keV); PA consistent with pulsar jet axis (Dean et al. 2008; Forot et al. 2008)

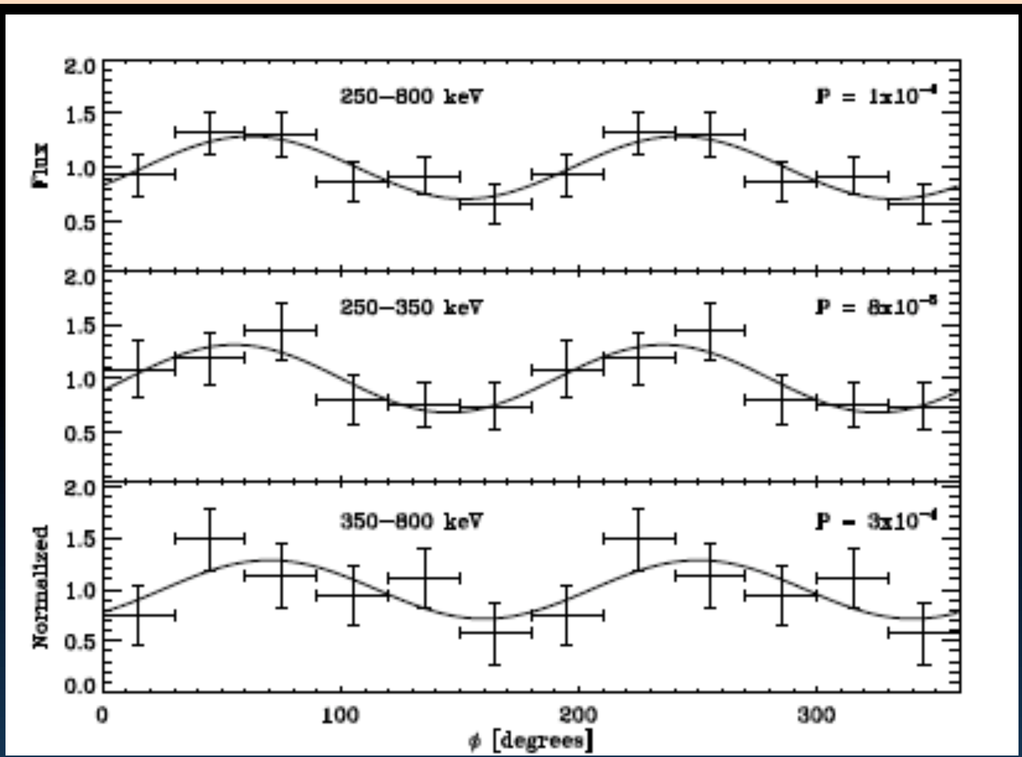
→ Highly ordered B-field structure and particle outflow.

(From Boettcher's talk, GammaSIG2015)



INTEGRAL Picture of the Month September 2008

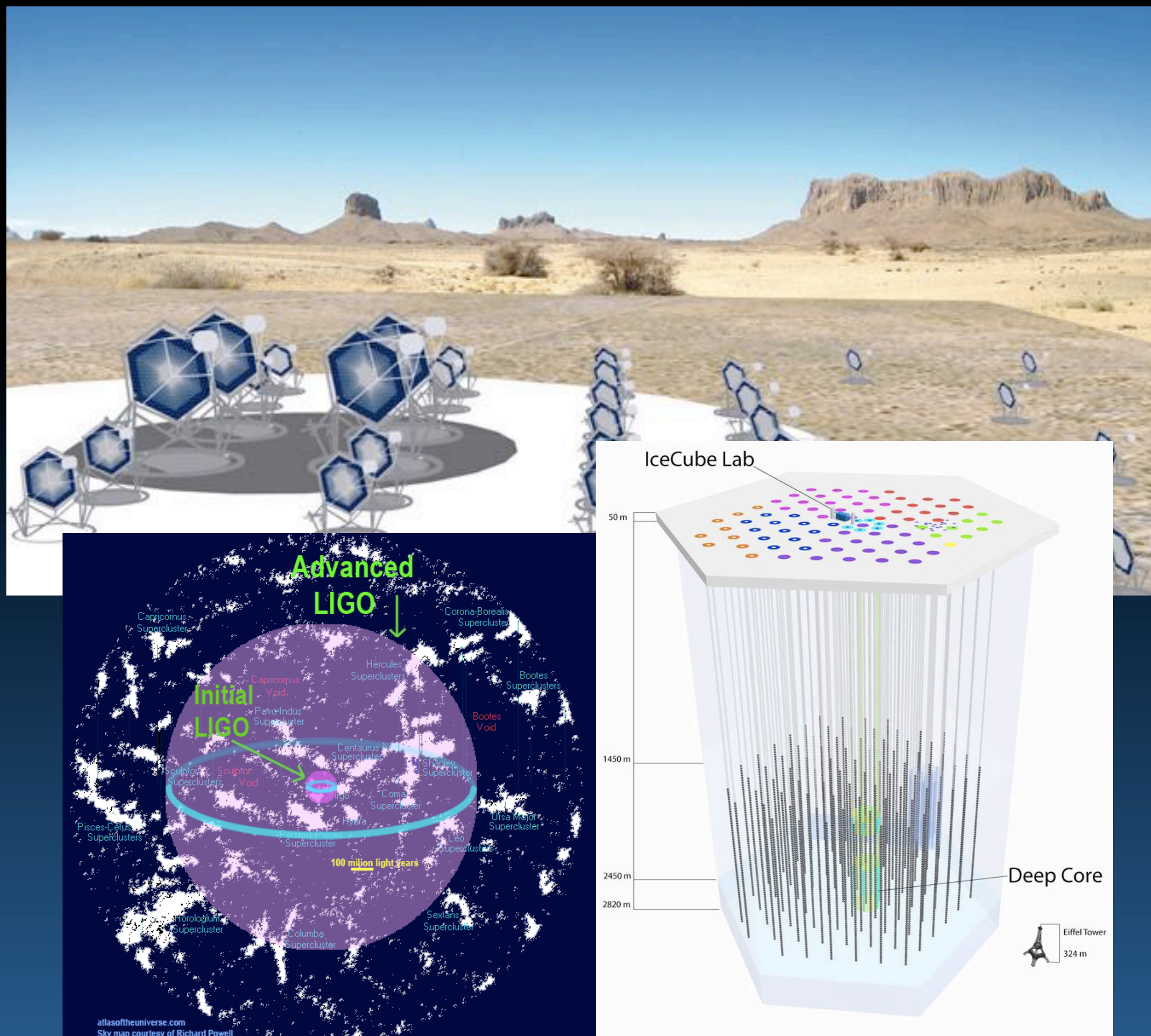
Gamma-ray Polarization - GRBs



Götz et al. 2013

- GRB061122: linear polarization measured in the γ-ray energy band (250–800 keV) during the brightest part of the prompt emission.
- Polarization measurements can shed new light on the strength and scale of magnetic fields, as well as on the radiative mechanisms at work during the GRB prompt emission phase.

Multimessenger Astronomy



- Quick response to transients (ms)
- Wide FOV &
- multi-messenger astronomy (CTA, LIGO & IceCube)

Talk Outline

- Science motivation
- Review highlights from "MeV" missions
- Synergy with VHE and keV regime
- Wish list for a future medium-energy instrument

Unexplored Energy Range: 0.3 MeV - 100 MeV

A science wish list:

- *Science at other wavebands impeded by comparable sensitivity in MeV regime → Need to focus on the MeV band*
- Improvement in gamma-ray sensitivity (order of magnitude)
- Exceptional angular resolution for γ rays in the range (~0.2º or better at 1 GeV)
- Very large field of view (2.5 sr)
- Polarization capability for both steady and transient sources
- Fast trigger & alert capability for transient sources

Scientific topics: medium-energy γ-ray domain

Theme 1: Radioactivity and antimatter

- Radioactive emission from type Ia supernovae
- Core-collapse supernovae and radioactivity
- 44-Ti line emission from young supernova remnants
- Gamma-ray lines from long-lived radioactive isotopes
- Radioactive emission from classical novae
- 511 keV emission from positron annihilation

Theme 2: Cosmic-ray physics

- MeV astronomy of the high-energy interstellar medium
- Nuclear gamma-ray lines from low-energy cosmic rays
- Gamma-ray emission from particle acceleration in supernova remnants and superbubbles
- Continuum emission from particle acceleration in novae
- Cosmic rays in star-forming galaxies
- The Galactic center in the MeV range

Theme 3: Black holes, neutron stars and pulsar wind nebulae

- Active galactic nuclei in the MeV domain
- Gamma-ray binaries
- Gamma-ray line emission from X-ray binaries
- MeV emission of black hole binaries
- Gamma-ray emission from magnetars and rotation-powered pulsars
- Pulsar wind nebulae in the MeV domain
- Gamma-ray bursts

Theme 4: Fundamental physics and cosmology

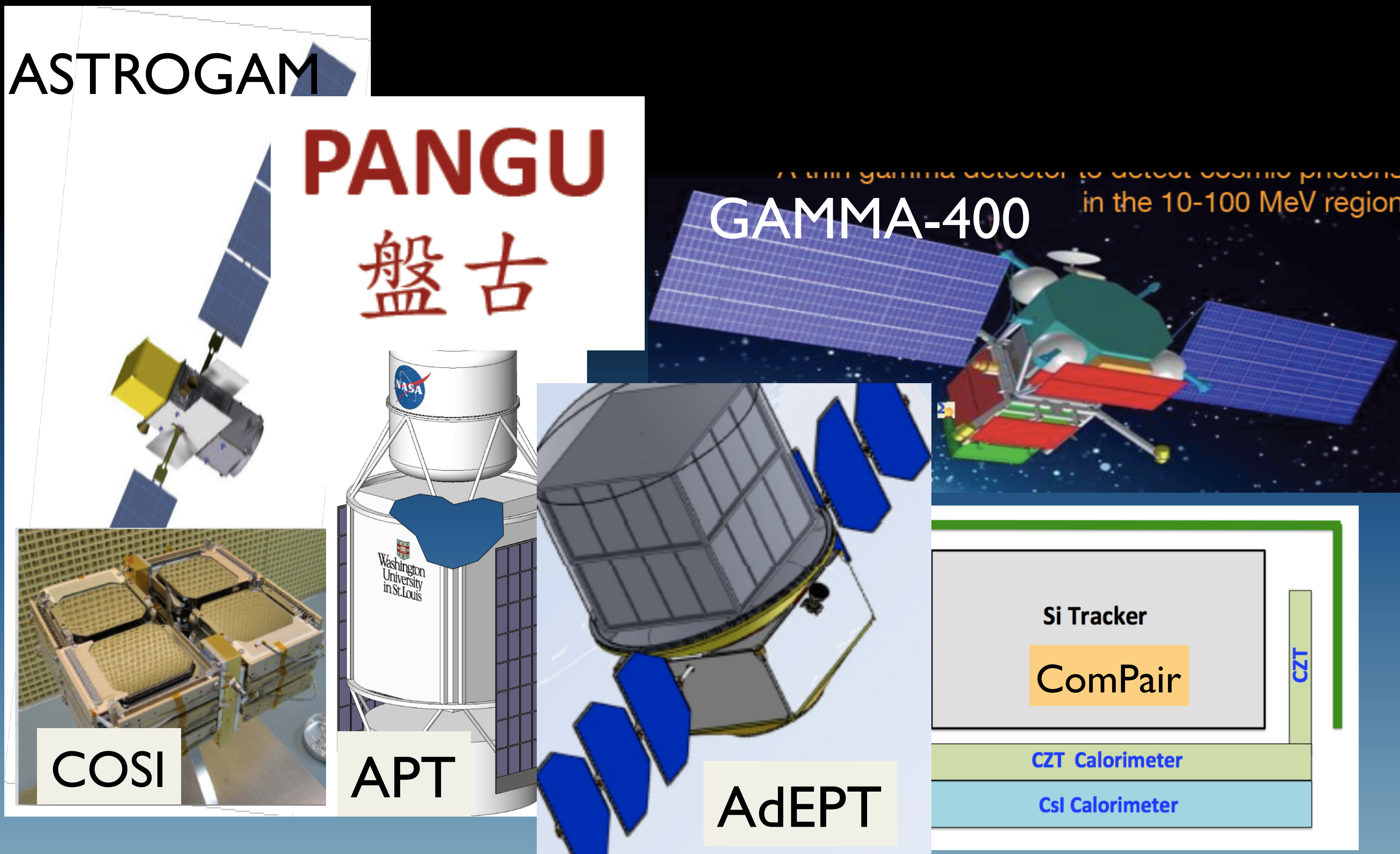
- Dark matter annihilation and decay
- Explore the limits of modern physics

Theme 5: Sun and Earth science

- The sun in the MeV domain
- Terrestrial gamma-ray flashes

AstroMeV: http://astromev.eu/

Future possibilities: MeV γ-ray domain



EXTRAS ....