Lines, Features, Continua, and Polarization in MeV-GeV Science

5 February 2015
Chuck Dermer (NRL)

medium-energy γ rays
0.1 – 100 MeV regime (MeV domain)

Future Space-based Gamma-ray Observatories
NASA Goddard Space Flight Center, 5-6 February 2015
"…Science Drivers for a new space-based gamma-ray experiment..."

Sources; Technology; Mission caps; Timing; Multiwavelength/multi-messenger

Roadmap for the MeV Domain (von Ballmoos et al.; Jan 2013)

- Galactic center
- 511 keV
- ***SN Ia***
- ***Core collapse SN***
- ^{44}Ti
- Classical novae
- Continuum emission from Novae
- High-energy ISM
- Nuclear γ-ray lines from cosmic rays
- ***Gamma-ray binaries***
- Gamma-ray lines from X-ray binaries
- ***Black Holes and accreting objects***
- ***Gamma-Ray Bursts***
- ***Active Galactic Nuclei***
- ***Magnetars and isolated pulsars***
- ***Pulsar wind nebulae***
- ***Supernova remnants/superbubbles***
- ***Starburst galaxies***
- ***Sun at high energy***
- ***Terrestrial γ-ray flashes***
- Long lived radioactive isotopes
- ***Dark matter annihilation or decay***
- ***Limits of modern physics***
- ***MeV background***
- ***MeV polarization***
- ***TDEs***
- ***Crab flares***

Discovery Matrix and Prime Science

- **Early Universe/Cosmology**
- **Black Holes/Neutron Stars**
- **Dark Matter**
- **Exoplanets**

"The formation of stars and planets, and the development of the chemistry of life, can be understood only in the context of the creation and evolution of elements." --Steve Boggs, *The Advanced Compton Telescope Mission* (2006)

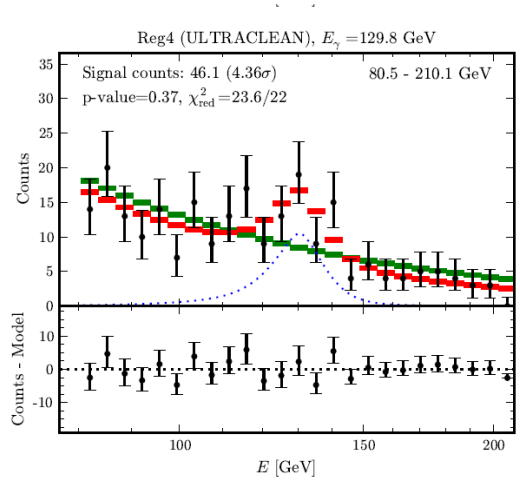
- **Cosmic Rays (particle acceleration)**

Based on past results, where and how to go forward?

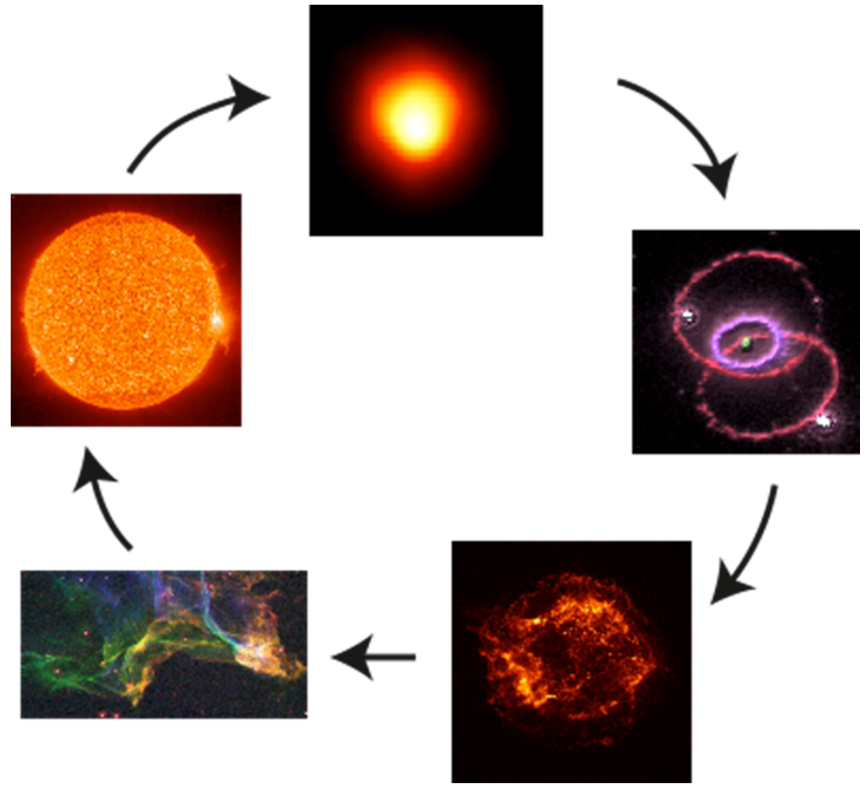
Lines

- **Electron-positron annihilation radiation**
  - **$e^+ - e^- \rightarrow 2\gamma$ (0.511 MeV), 3γ**
- **Nucleosynthesis**
  - **Giants, CCSNe** (^{26}Al)
  - **Supernovae** (^{56}Ni, ^{57}Ni, ^{44}Ti)
  - **ISM** (^{26}Al, ^{60}Fe)
- **Cosmic-ray induced lines**
  - **Sun** (2.2 MeV neutron capture; 0.511 MeV; $^{12}C^{*4.4}$, $^{16}O^{*6.1}$)
  - **ISM** ($^{12}C^{*4.4}$, $^{16}O^{*6.1}$, 0.511 MeV)
  - Broad vs. narrow lines
- **Dark matter lines**
  - **Annihilation**
  - **Decay**

Measurements of composition



Life Cycles of Matter

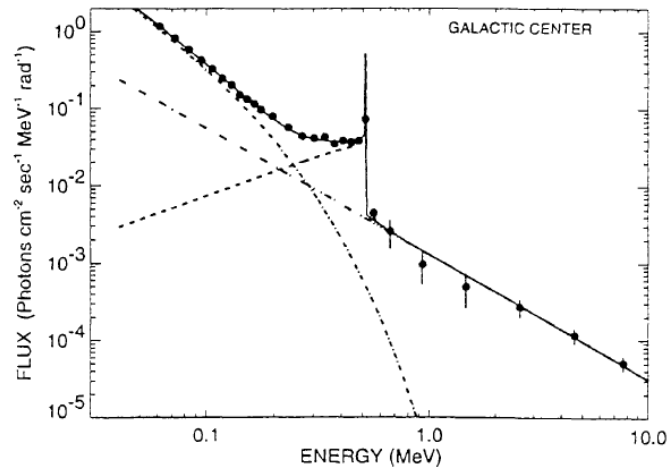


^{56}Ni: 158 keV 812 keV (6 d)
^{56}Co: 847 keV, 1238 keV (77 d)
^{57}Co: 122 keV (270 d)
^{44}Ti: 1.157 MeV (78 yr)
^{26}Al: 1.809 MeV (0.7 Myr)
^{60}Fe: 1.173, 1.332 MeV (2.6 Myr)

Weniger (2012)

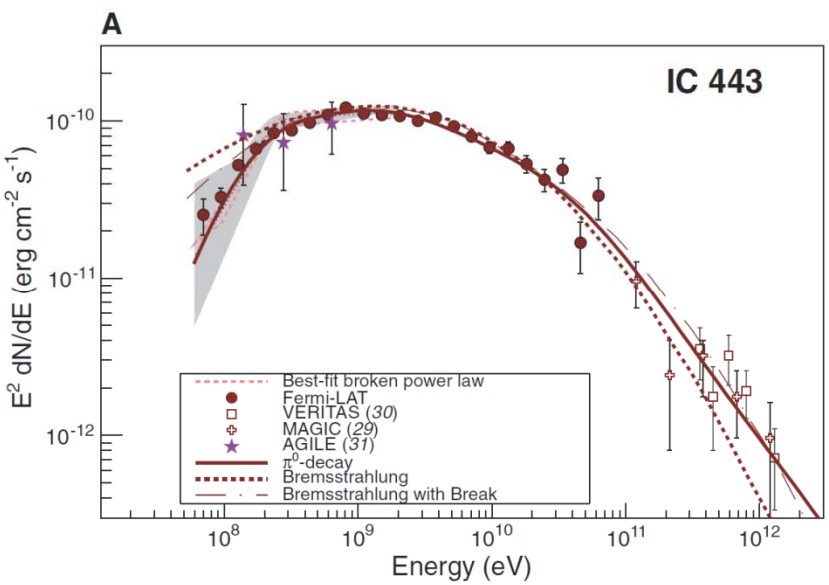
Features

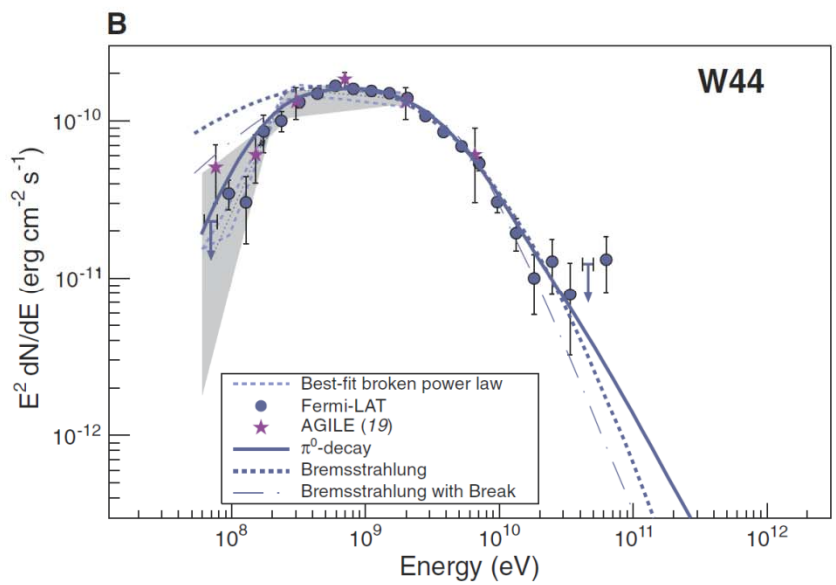
- **Proton-antiproton annihilation radiation**
  - **$p + \bar{p} \rightarrow \pi$**
- **p+A → π^0 decay feature**
  - **Solution to Galactic cosmic-ray origin**
  - **Found in IC 443, W44**, W51C
- **Ps continuum feature**
  - **$3\gamma/2\gamma$ ratio ⇒ annihilation medium**
  - **Galaxy mapping**
- **Dark matter signatures**



OSSE data (Kinzer et al. 1999)

Ackermann et al. (2013) Science

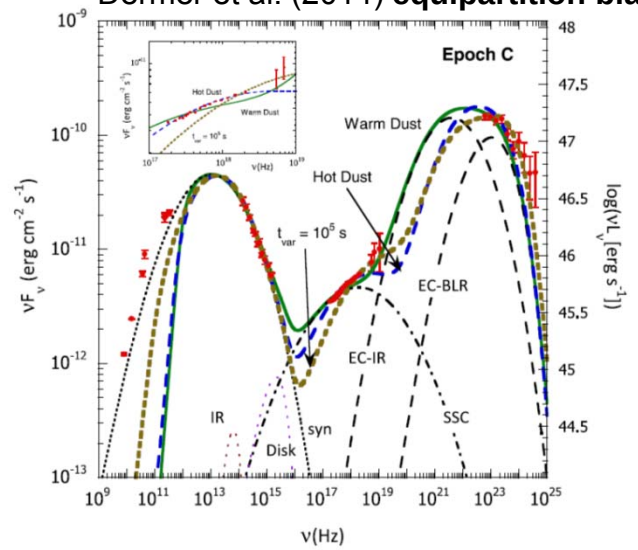


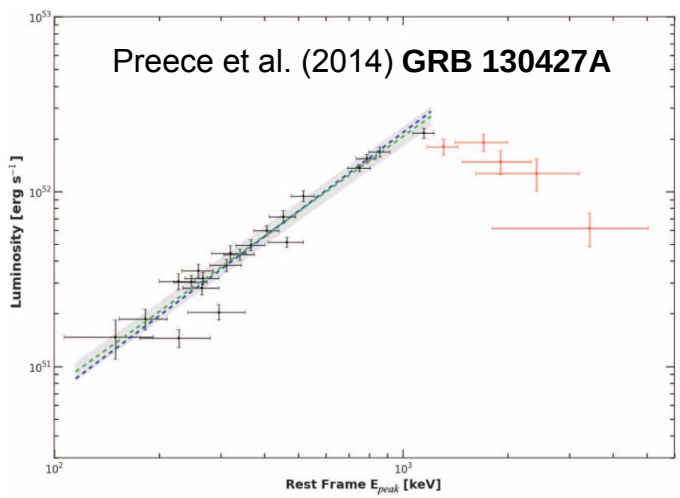


Continua

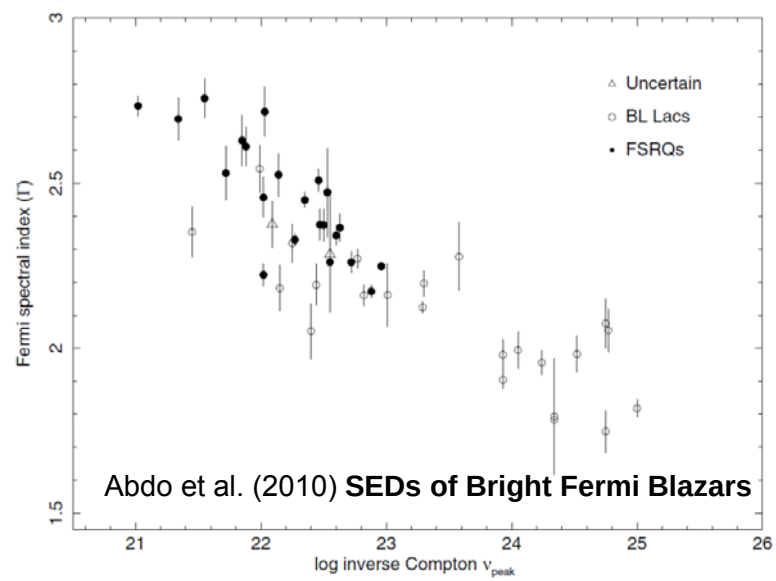
- **Thermal vs. Nonthermal**
  - **~ 20 MeV maximum lepton temperature**
  - **~ few hundred MeV maximum ion temperature**
- **Spectral characterization**
  - **Power law (1st order Fermi acceleration)**
  - **PLEX (outer gap vs. polar cap)**
  - **Log-parabola (2nd order Fermi acceleration)**
  - **Band Function (synchrotron vs. photosphere)**
- **Peak and frequency of νF_ν SED**
  - **Bulk of power output**
  - **Correlation analysis**

Dermer et al. (2014) **equipartition blazars**





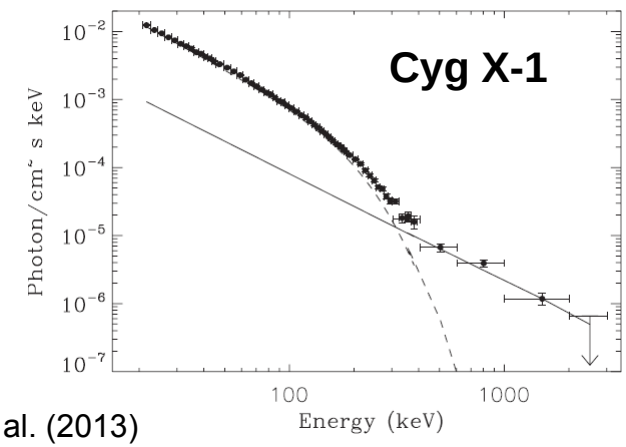
Γ_γ



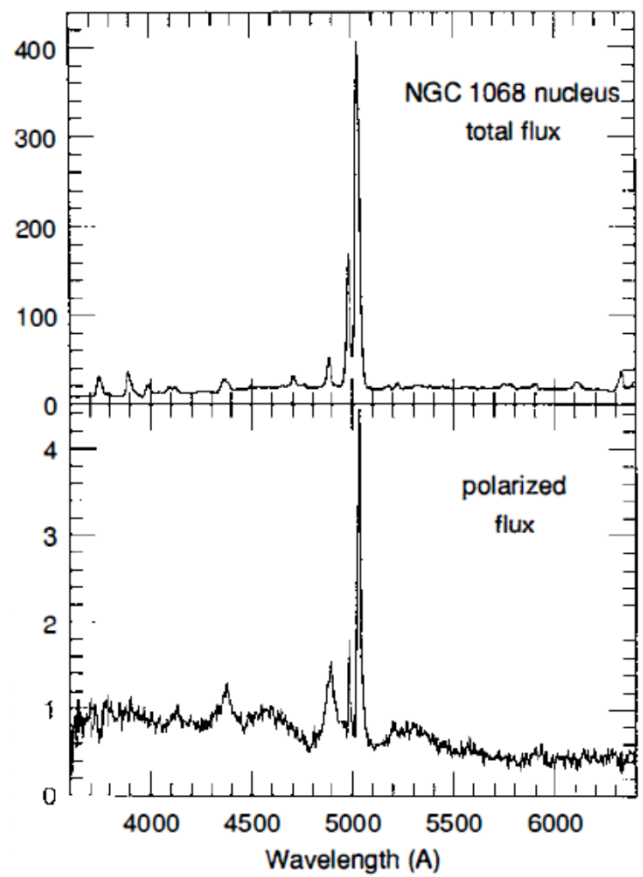
$\nu_{pk,C}$

Polarization

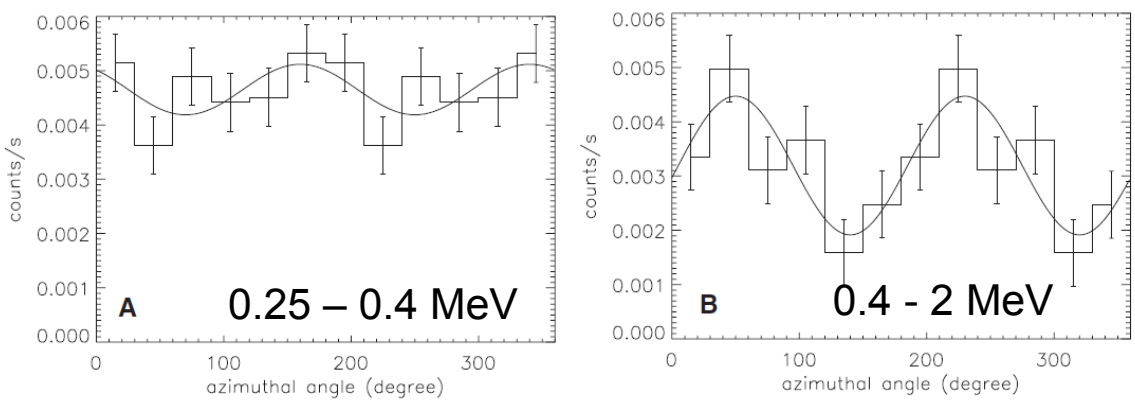
- **Synchrotron emission in an ordered magnetic field**
  - **Detection would undermine simple source models**
  - **Discriminate between synchrotron and photospheric emission**
- **Compton scattering**
- **New Physics**



Antonucci (1993)

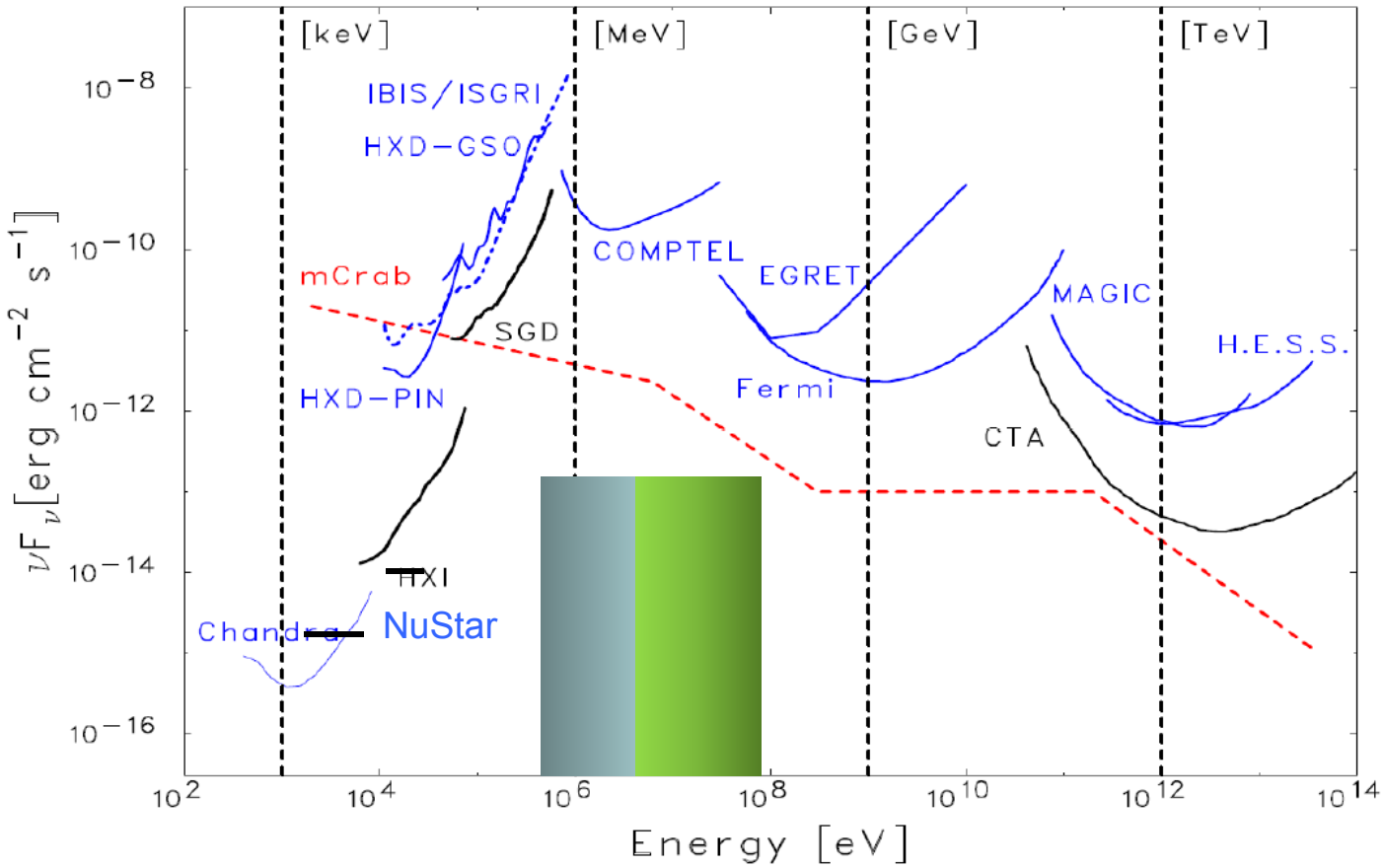


Laurent et al. (2013)



Point-source sensitivity of X-ray and γ-ray observatories

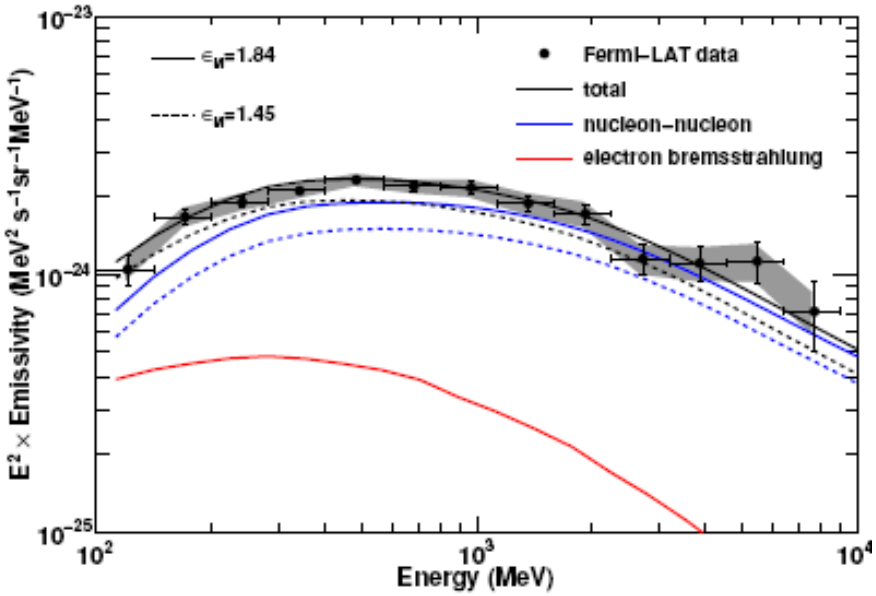
Takahashi et al. (2012)



- **Lack of sensitivity due to 1) non-focusing; 2) transition from Compton scattering (low-energy) to pair production (high-energy); 3) minimum interaction cross section of photons at ~ 1MeV; 4) strong instrumental and particle background**
- **MeV-regime science = Fermi science + MeV-line science**

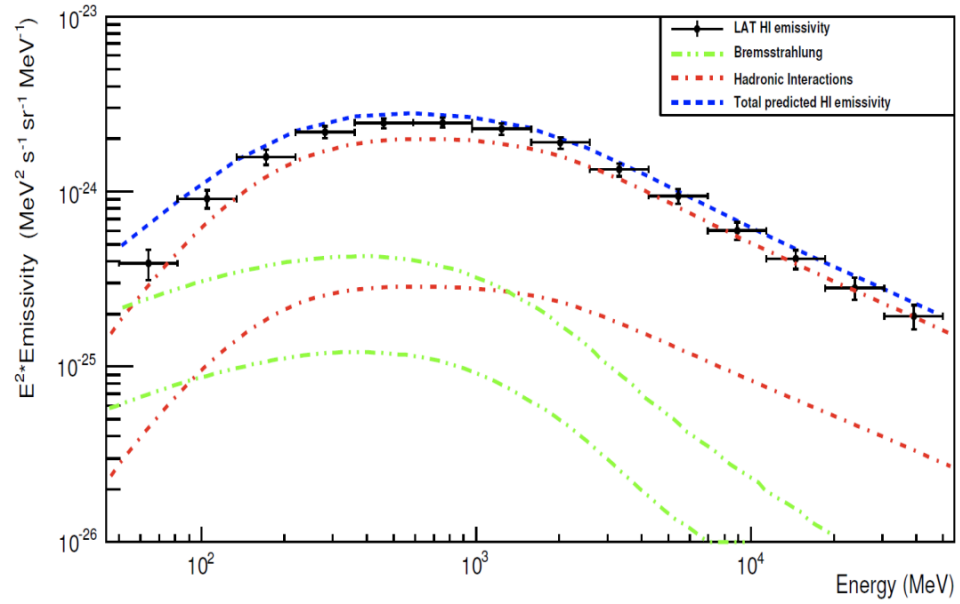
Fermi LAT Emissivity Measurements: A Cautionary Tale

Abdo et al., Ap J, 703, 1249, 2009



- 4 Aug 2008 – 31 Jan 2009 (6 mos)
- LAT observations in third quadrant ($200^o < \ell < 260^o$, $22^o < |b| < 60^o$)
- No known molecular clouds, point sources subtracted; low ionized H column density N(HII)~1-2×10^{20}cm^{-2}

J.-M. Casandjian, AIP Conf Proc. 1505, 2012



- 4 Aug 2008 – 1 Aug 2011 (3 years)
- $0^o < \ell < 360^o$, $10^o < |b| < 70^o$)
- Template mapping, after subtracting point and extended sources and isotropic emission; low-energy dispersion correction
- J.-M. Casandjian (4 yr data sets), to be submitted

Invert γ-ray spectrum to get cosmic-ray spectrum

Is there a break (hardening) in the spectrum of cosmic rays at <~ few GeV?

Measured vs. ISM Cosmic-Ray Spectrum

Naïve Theoretical Expectations:

1st order Fermi shock spectrum

- Test particle limit
- Strong shock

$$\frac{d\dot{N}}{dp} \propto p^{-s_{inj}}, s_{inj} = 2.1 - 2.2$$

Steepening due to escape

$$t_{esc} \propto p^{\delta}, \ \delta \approx 0.6$$

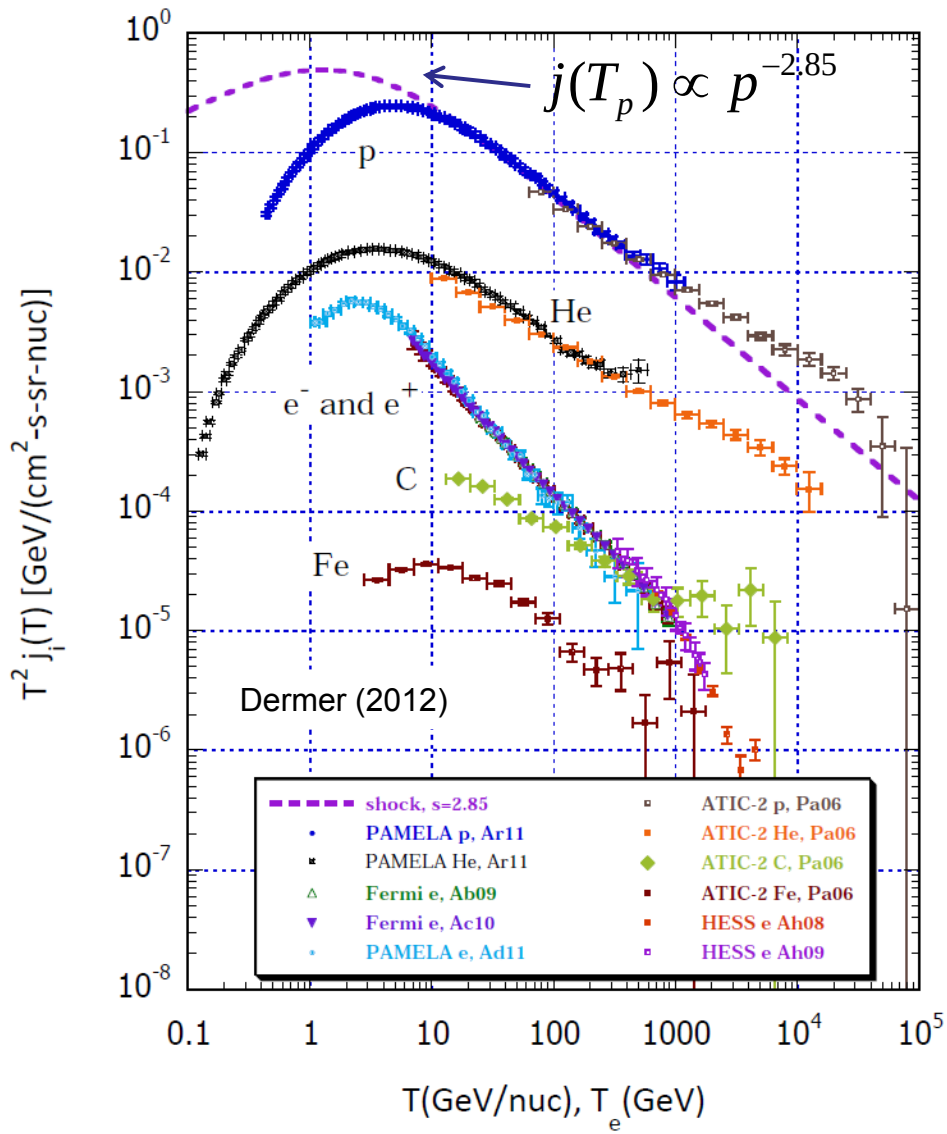
$$\frac{dN}{dp} \propto \frac{d\dot{N}}{dp} t_{esc} \propto p^{-s}, \ s = s_{inj} + \delta$$

$$\therefore j(T_p) \propto \beta \frac{dN}{dT_p} \propto \frac{dN}{dp} \propto p(T_p)^{-s}$$

Power-law momentum spectrum makes break in kinetic energy representation (index $\propto -s/2$ at $T_p << m_pc^2$, index $\propto -s$ at $T_p << m_pc^2$)

Search for deviations from cosmic ray flux from power-law in momentum

Break in CR Spectrum
Neronov, Semikoz, & Taylor (2012)



Definite conclusions require better knowledge of nuclear production cross sections (Dermer 2012)

Power-law injection for protons and electrons

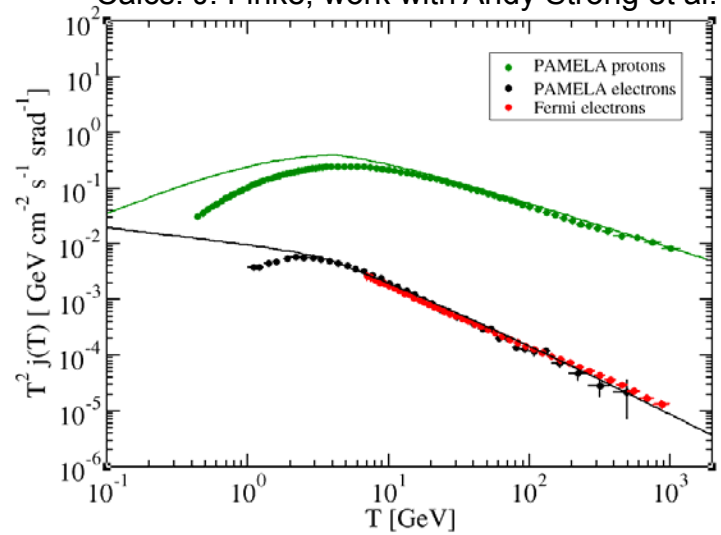
Power in ions: 3.0×10^{40} erg/s
power law index: 2.3 (in momentum)
minimum injection momentum; $\beta\gamma = 10^{-4}$

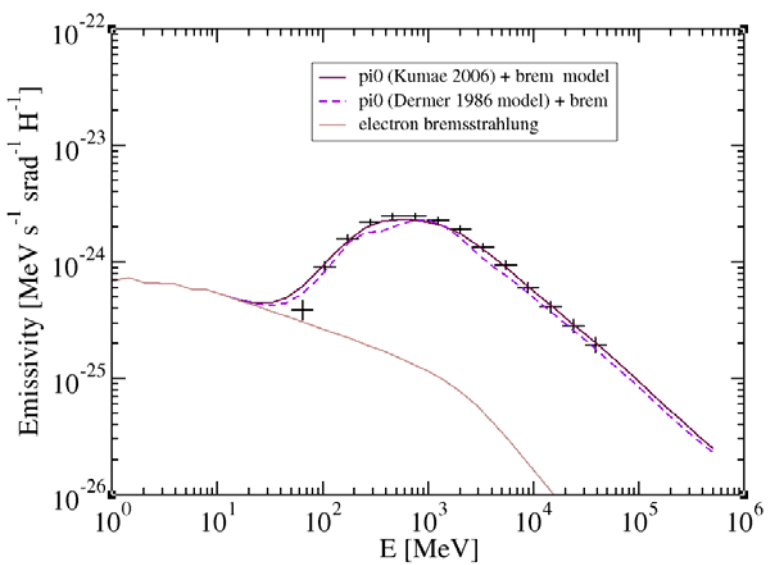
Power in electrons: 2.0×10^{38} erg/s
power law index: 1.6 below the break; 2.5 above the break
(same as Strong, Orlando, & Jaffe 2011)
break at 4 GeV (momentum $\beta\gamma$ = 7840)
minimum injection momentum (electrons) $\beta\gamma$ = 0.05

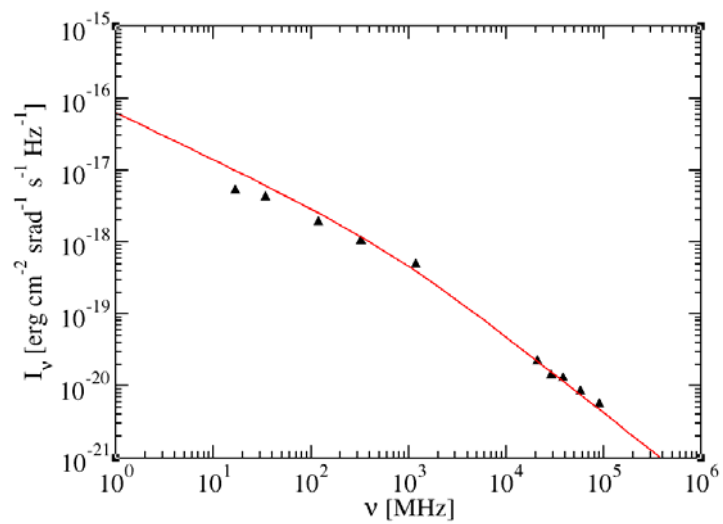
Nuclear enhancement factors = 2 for both π^0 production and bremsstrahlung

$$t_{esc}(p) = 20\,Myr[p/p(T_p = 1GeV)]^{-0.5}$$

Calcs: J. Finke; work with Andy Strong et al.

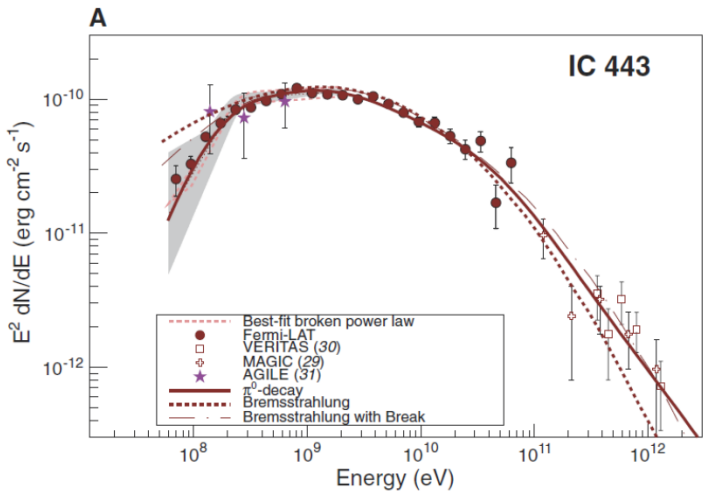


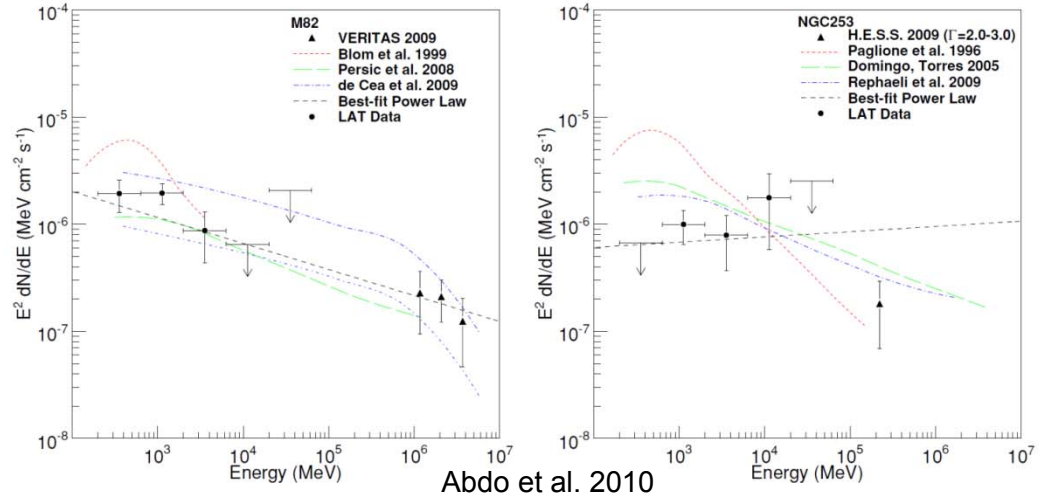




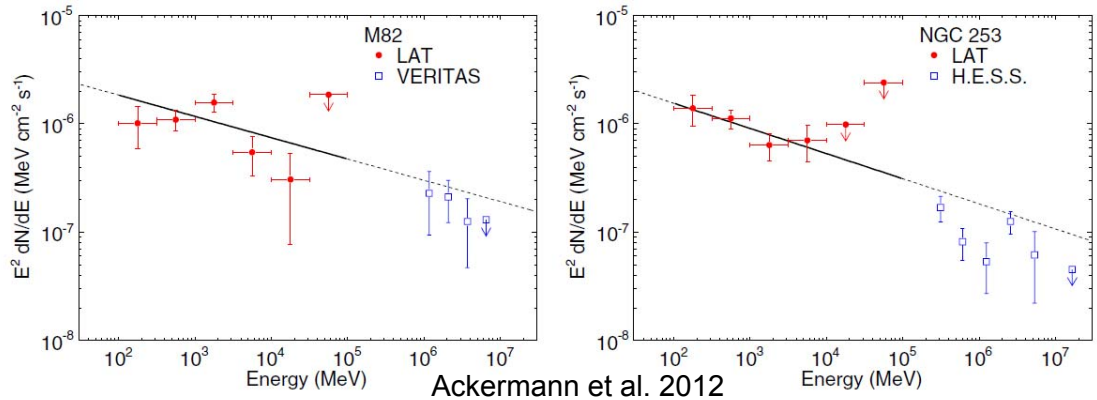
Quality of data exceeds quality of cross sections used to interpret data
Need new laboratory astrophysics measurements of p+p, p+A, A+A' → π

Low-energy γ-ray spectra of SNRs and Cosmic-Ray Galaxies





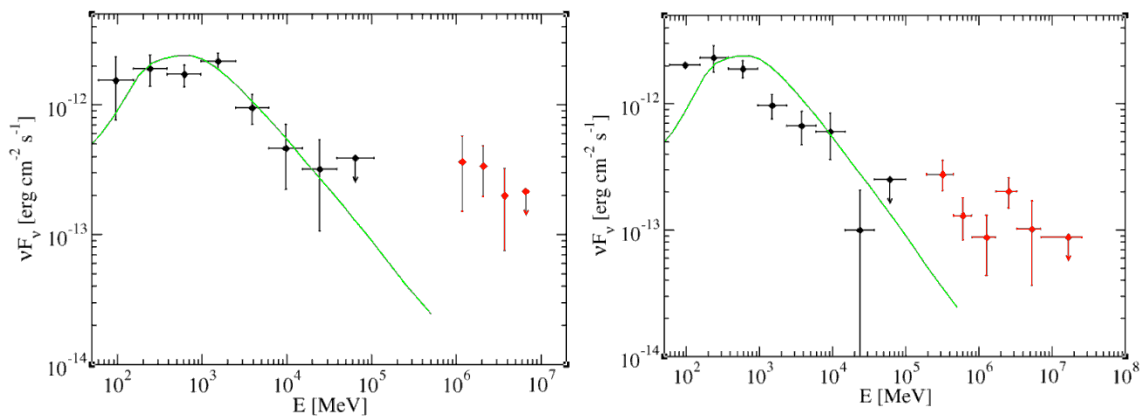
Abdo et al. 2010



Ackermann et al. 2012

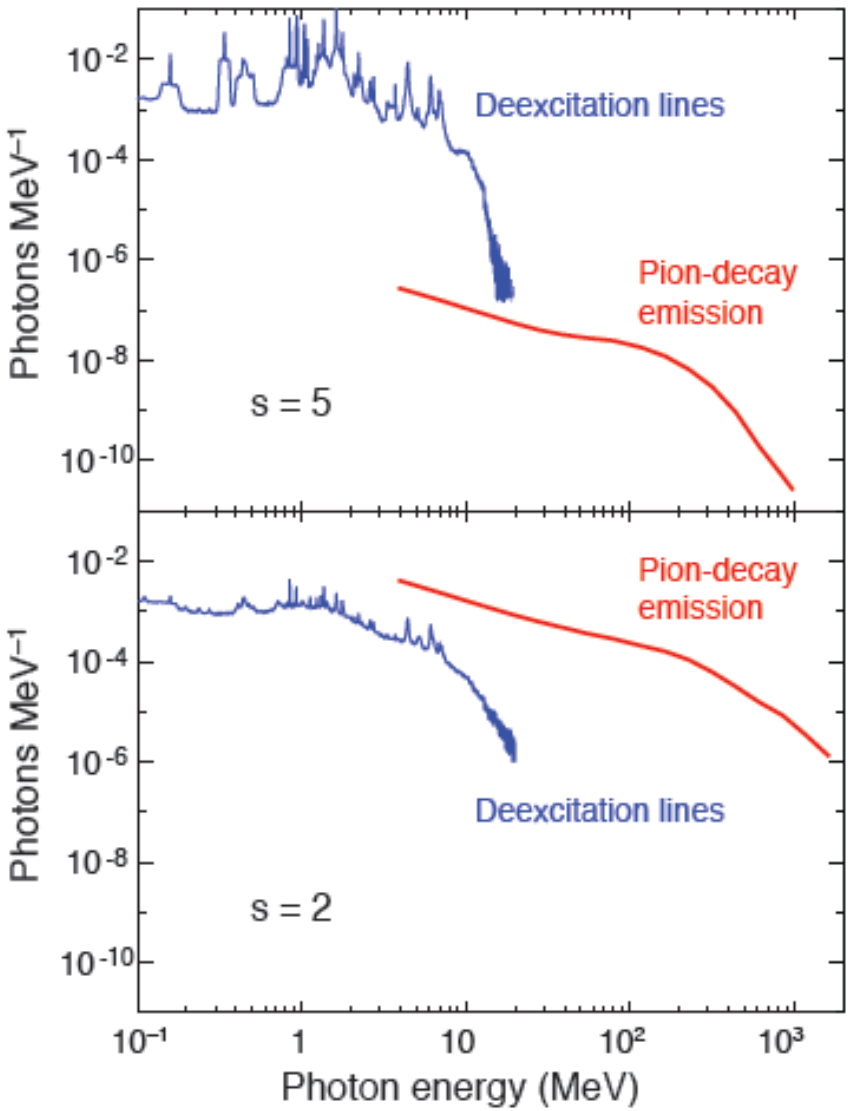
Interpretation
of low-energy spectra of SNRs sensitive to primary electrons, magnetic field, secondaries, and metallicity,

(work with J. Becerra and J. Finke)

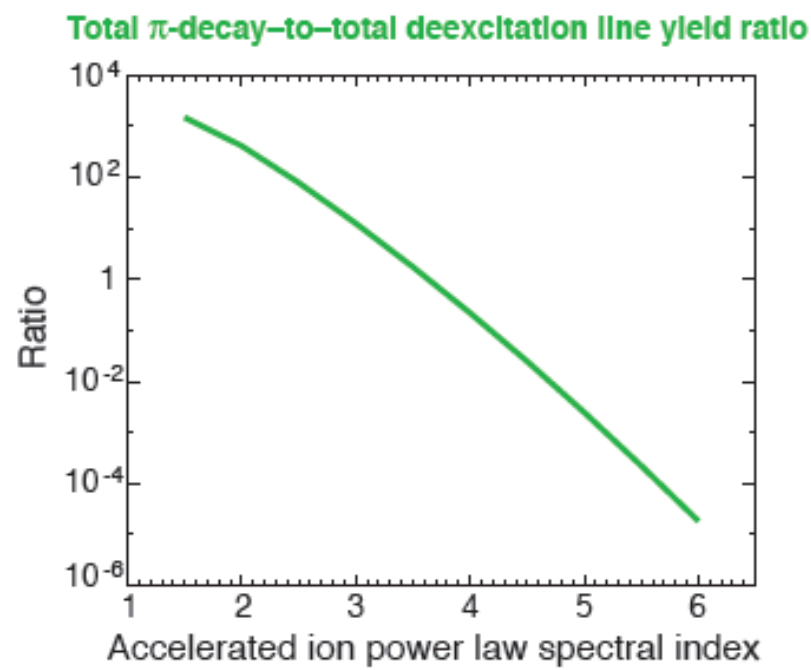


MeV Regime Connections

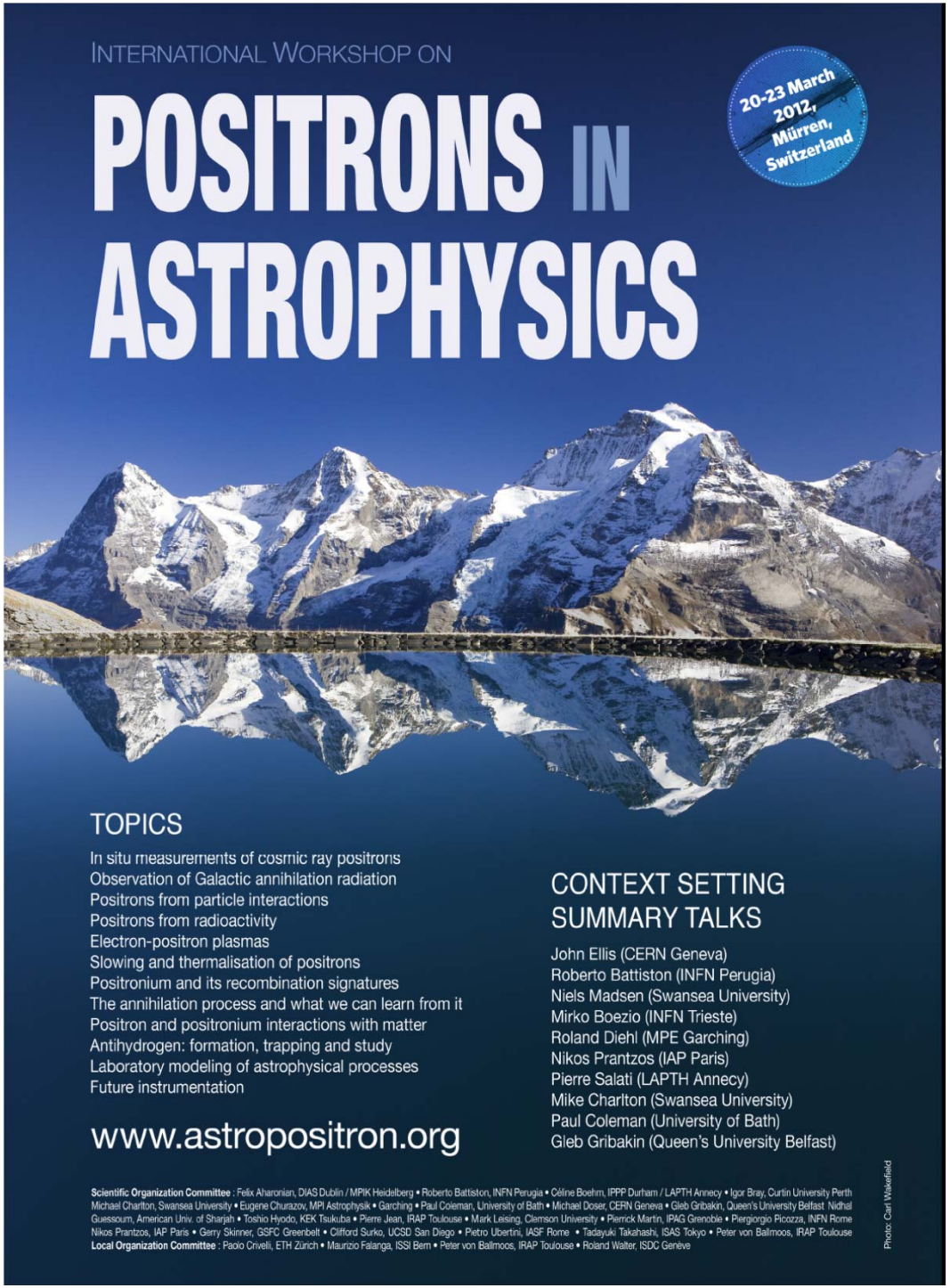
(calculations: R. Murphy)



The ratio of pion-decay emission to nuclear deexcitation-line emission depends very strongly on the steepness of the accelerated-ion kinetic-energy spectrum



This ratio can be used to determine the accelerated-ion spectral index



"Positrons in Astrophysics"

Mürren, Switzerland

20-23 March 2012

Session 1 - Direct Detection of Cosmic-Ray Positrons
Session 2 - Positron and Positronium Scattering
Session 3 - Astrophysical Sources of Galactic Positrons
Session 4 - Other Aspects of Positron-matter Interactions
Session 5 - Low-Energy Positron-Matter Interactions
Session 6 - Antimatter in Cosmic Rays
Session 7 - Antihydrogen
Session 8 - Annihilation Detection
Session 9 - Galactic e-e+ Annihilation
Session 10 - Antimatter from Dark or Domestic Matter
Session 11 - Positron and Positronium Interactions with Solids
Session 12 - Terrestrial and Extraterrestrial Positrons
Session 13 - Baryon Asymmetry
Session 14 - Future instruments for Observing e-e+ Radiation

Positron annihilation radiation from the Galactic center region

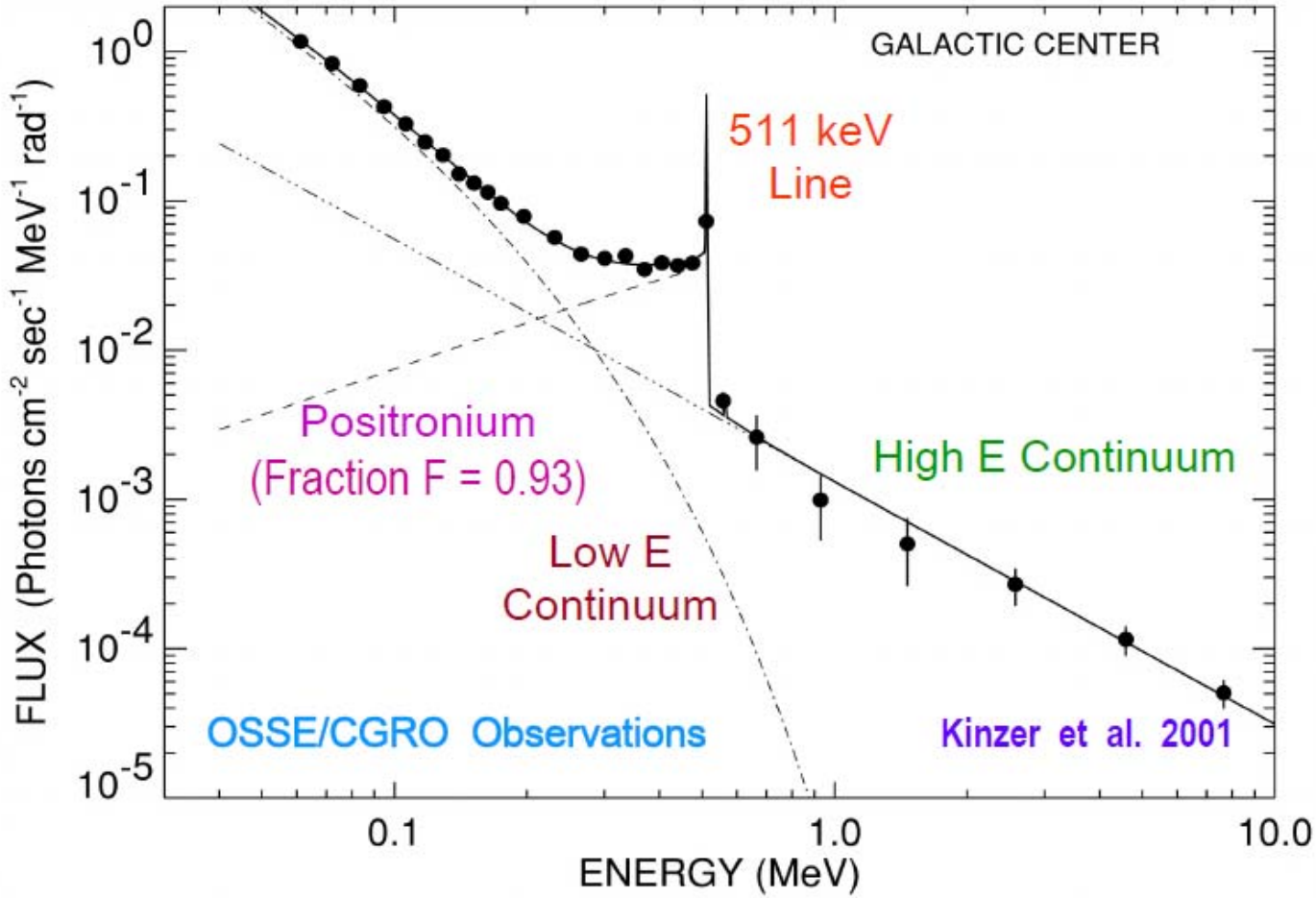
First (and brightest) γ-ray line detected from outside the solar system

(Johnson et al. 1972, *Rice U*. Na detector : **Leventhal et al. 1978** *Bell-Sandia* Ge detector)

Flux (~10^{-3} cm^{-2} s^{-1}) + Distance (8 kpc~27000 l.y.)⟹ Luminosity ~10^{37} erg/s (a few 10^3 $L_\odot$)

Positron annihilation rate : ~2 10^{43} s^{-1}

If activity maintained for 10^{10} years : 3 $M_\odot$ of positrons annihilated



Prantzos

Laboratory Positron Physics

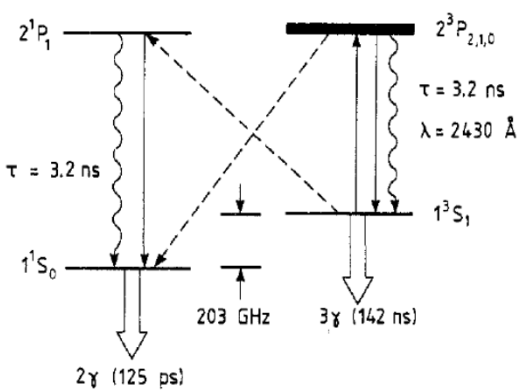
Michael Charlton, Swansea University

1949:- Discovery of Ps
1949-50:- Discovery of "ACAR"
1955:- Discovery of antiproton
1950's:- First attempts to make positron beams
1963:- Anomalous annihilation rates on some molecules
1968:- Ps formation in powders
1971-2:- First lab-based beam
1978-88:- Understanding of beam production
1981:- Discovery of Ps^-
1986:- Solid neon moderator
1988:- First positron plasma in lab. (accumulation device)
1995-6:- Discovery of ant
2000's:- Development of r
2002:- First cold antihydr
2007:- Discovery of Ps_2
2010:- Trapped antihydrog
2011-12: First measureme

RL 108, 043401 (2012) PHYSICAL REVIEW LETTERS

Efficient Production of Rydberg Positronium

D. B. Cassidy, T. H. Hisakado, H. W. K. Tom, and A. P. Mills, Jr.
Department of Physics and Astronomy, University of California, Riverside, California 92521-0413, USA
(Received 14 October 2011; published 26 January 2012)



Direct Annihilation:

$$e^+ + A \longrightarrow 2\gamma + A^+$$

Cross section at low energies = $\pi r_0^2 c Z_{eff}/v$

Positronium Formation:

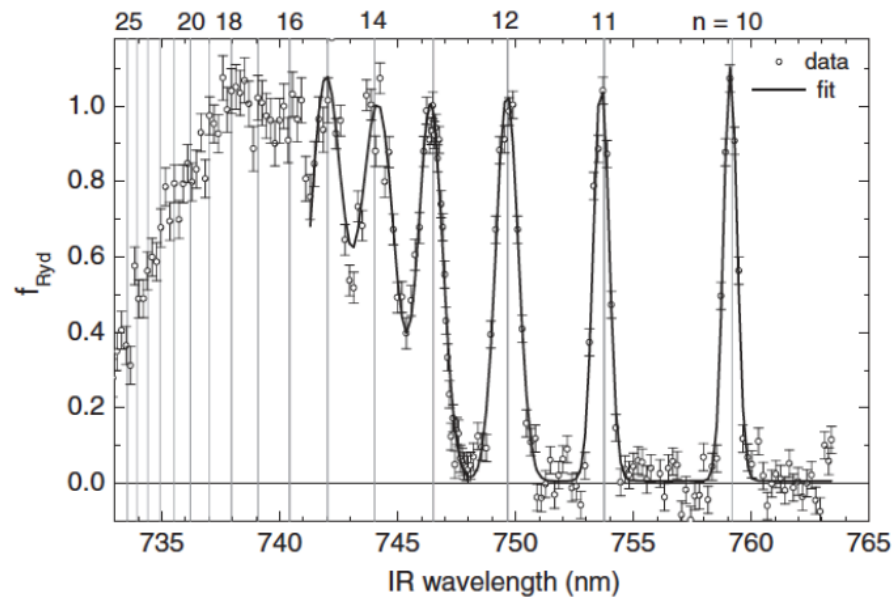
$$e^+ + A \longrightarrow Ps + A^+$$

Excitation:

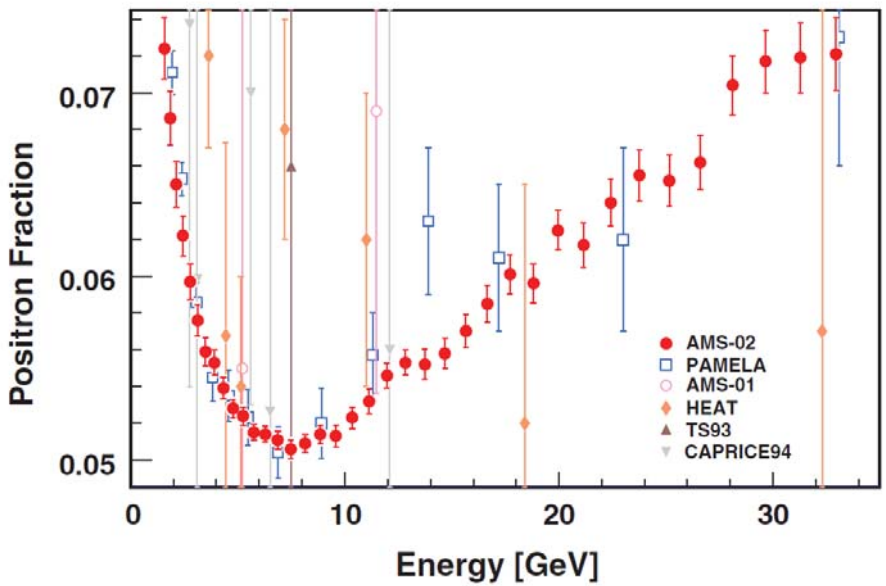
$$e^+(E) + A \longrightarrow e^+(E - E_{ex}) + A^*$$

Ionization:

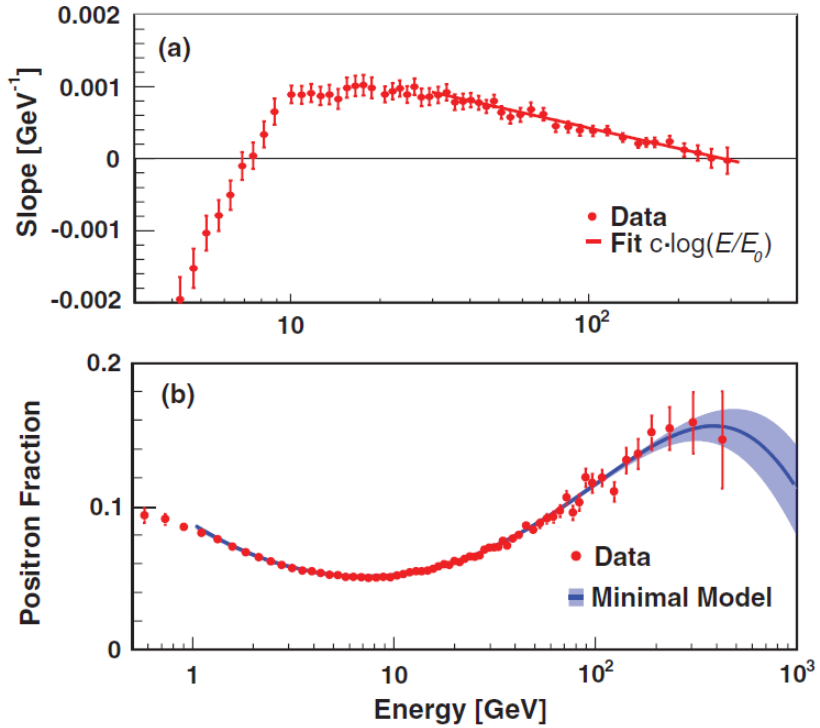
$$e^+(E) + A \longrightarrow e^+(E - \Delta E) + A^+$$

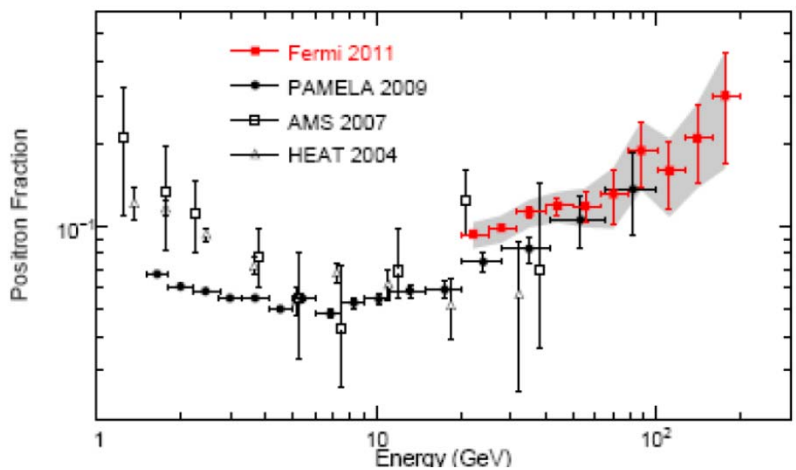


Direct Detection of Cosmic-Ray Positrons



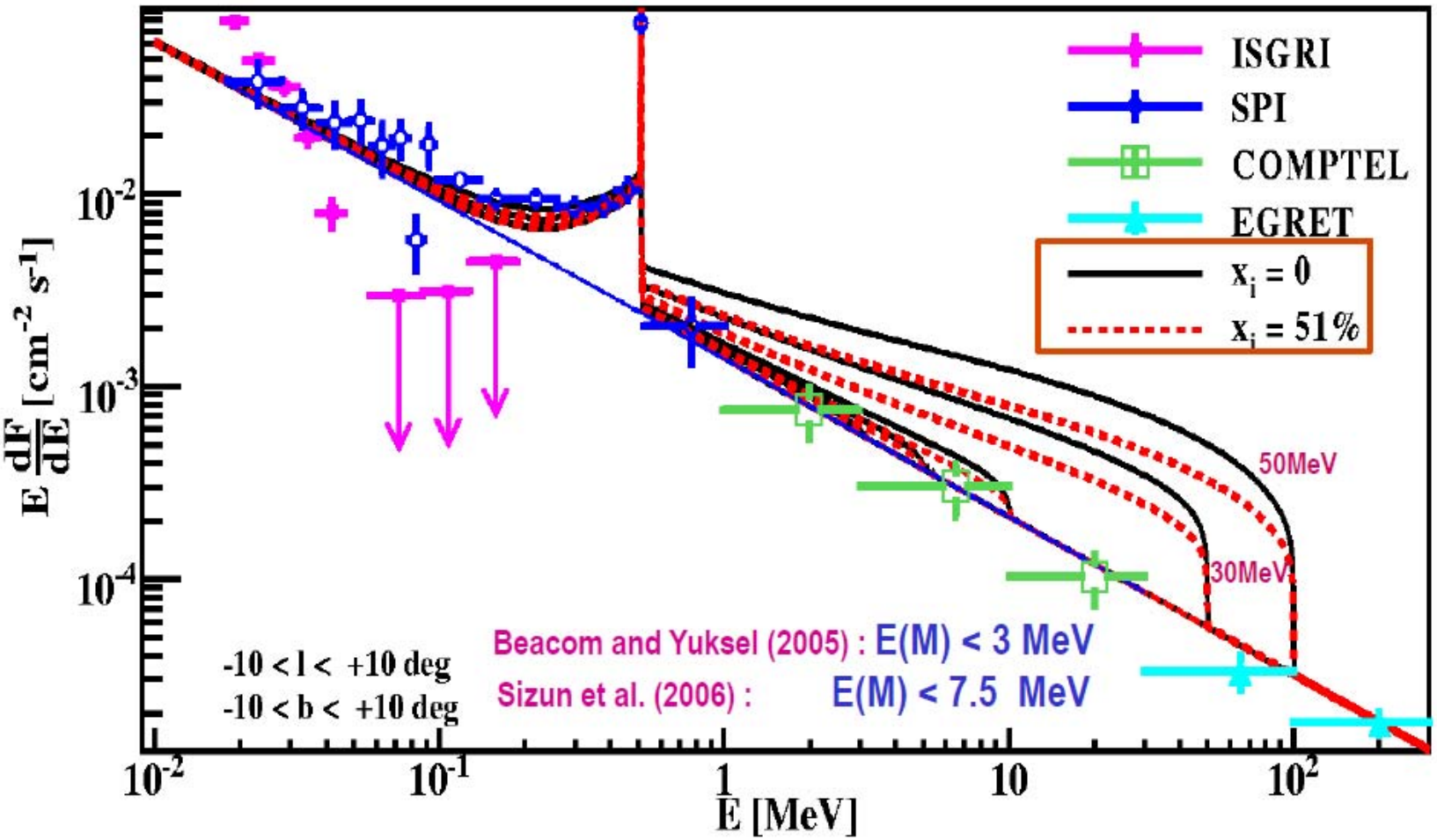
Accardo et al. 2014: AMS-02 e+ fraction





"A Challenging Puzzle for Cosmic Ray Physics"

Spectrum in the > MeV region: constrains the energy of *released* e+
(or the mass of their parent dark matter particles)
because they may annihilate in-flight

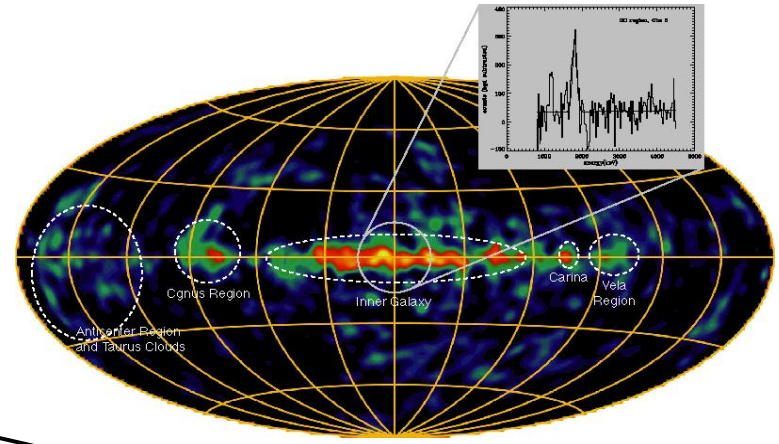


IF Dark Matter : particle mass much smaller than "canonical" (GeV) values

Positron sources

Supernova radioactivity

- ^{26}Al
- ^{44}Ti
- ^{56}Co (Type Ia)



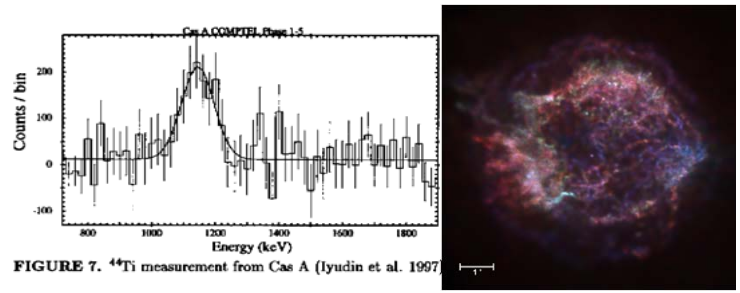
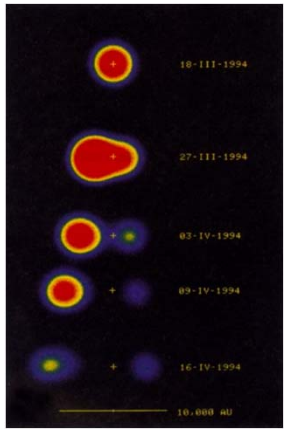


FIGURE 7. ^{44}Ti measurement from Cas A (Iyudin et al. 1997)

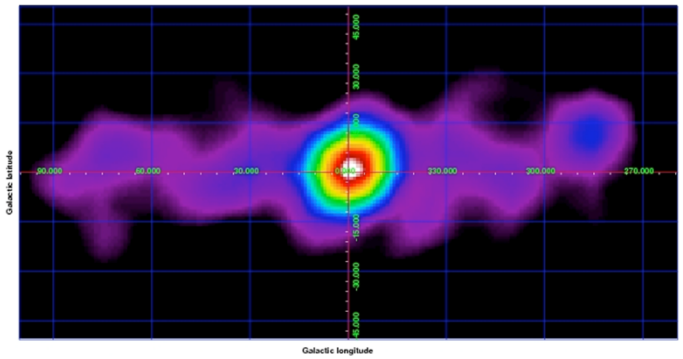
Pulsars

Black Holes (accreting)

- Pair plasmas
- Microquasars



Dark matter production



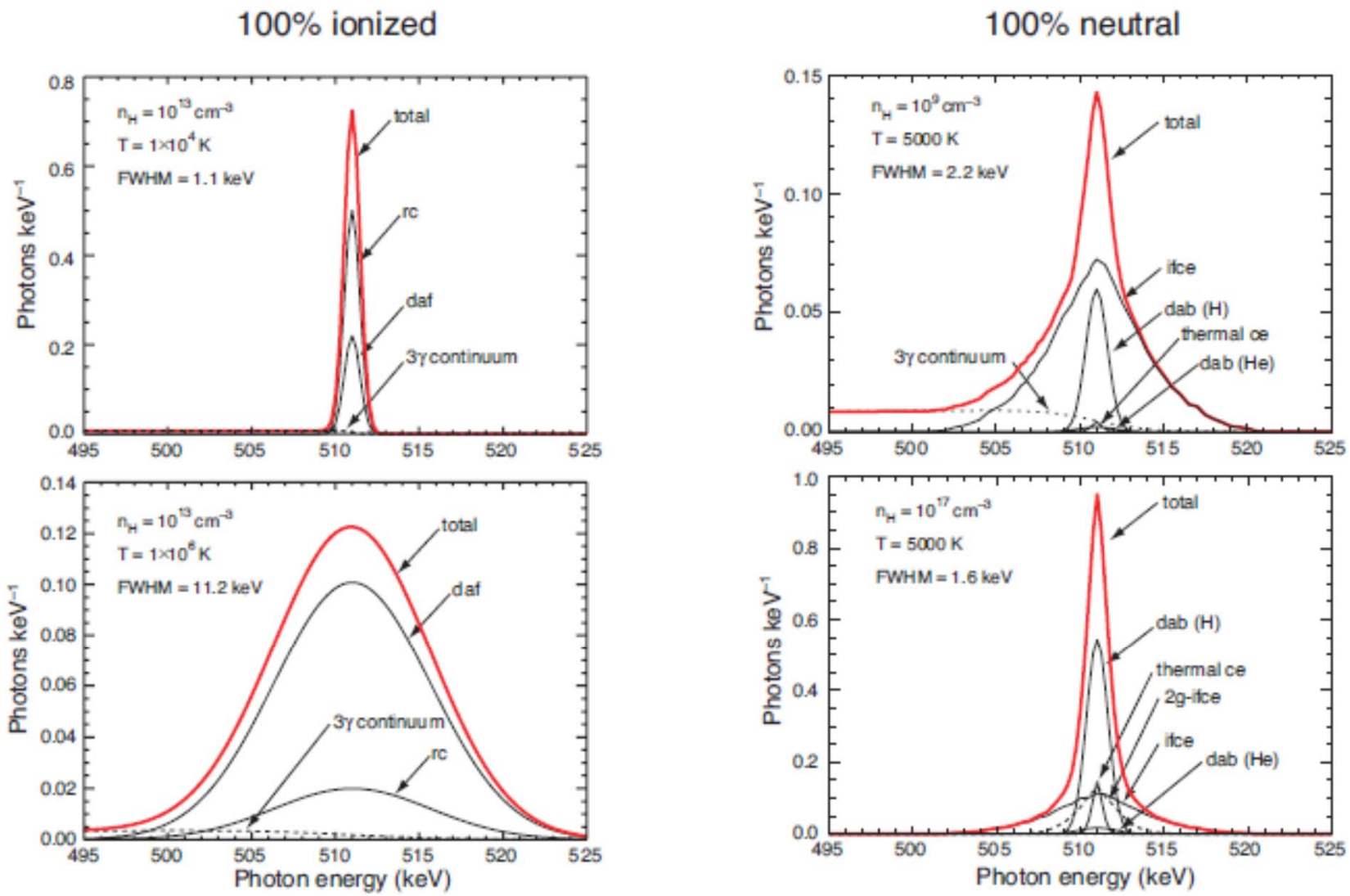
The origin of the brightest, longest known, celestial gamma-ray line is unknown.

Models for Galactic Annihilation Radiation

Source	Process	Comments
Massive stars: ^{26}Al	β^+-decay	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{24}Ti	β^+-decay	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	Assuming $f_{e^+,esc}$=0.04
Novae	β^+-decay	Insufficent e^+ production
Hypernovae/GRB: ^{56}Ni	β^+-decay	Improbable in inner MW
Cosmic rays	p-p	Too high e^+ energy
LMXRBs	$\gamma-\gamma$	Assuming L_{e+} ~0.01 $L_{obs,X}$
Microquasars (μQs)	$\gamma-\gamma$	e^+ load of jets uncertain
Pulsars	$\gamma-\gamma$ / $\gamma-\gamma_B$	Too high e^+ energy
ms pulsars	$\gamma-\gamma$ / $\gamma-\gamma_B$	Too high e^+ energy
Magnetars	$\gamma-\gamma$ / $\gamma-\gamma_B$	Too high e^+ energy
Central black hole	p-p	Too high e^+ energy, unless B >0.4 mG
	$\gamma-\gamma$	Requires e^+ diffusion to ~1 kpc
Dark matter	Annihilation	Requires light scalar particle, cuspy DM profile
	Deexcitation	Only cuspy DM profiles allowed
	Decay	Ruled out for all DM profiles
Observational constraints		

Prantzos et al. (2011)

Annihilation Line Shapes



Summary

- **Need better near-threshold cross section measurements**
  - **Strong interaction; metallicity effects**
  - **Absence of accurate cross section information makes interpretation difficult**
- **Need to grow the community**
  - **Lab astro; cosmic rays; dark matter; black holes**
  - **γ-ray observations demonstrate level of absolute Solar modulation on interstellar cosmic-ray spectrum**
- **Lack of comparable sensitivity in MeV regime hinders progress in other wavebands**