Title: Recent Results from the ATIC Experiment

Date: Jun 11, 2009 09:40 AM

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Abstract: The balloon-borne Advanced Thin Ionization Calorimeter (ATIC) experiment has measured the cosmic-ray electron spectrum over the energy range from 20 GeV to 3 TeV. The totally active Bismuth Germanate (BGO) calorimeter provides energy measurements with resolution of ~2%. The finely segmented Silicon matrix provides charge measurements with an excellent resolution of ~0.2 e. Below 100 GeV, the ATIC spectrum agrees with previous data and with a calculated spectrum based on a conventional galactic propagation model. Above ~100 GeV the results depart from the calculated spectrum and show an excess electron flux up to about 650 GeV, above which the spectrum drops rapidly. The source of this electron surplus would need to be a previously unidentified and relatively nearby cosmic object within ~1 kilo parsec of the Sun. It could be an astrophysical source, but it might also result from annihilation of dark matter particles. The measurement technique, and the implication of the results will be discussed.

Recent Results from the ATIC Experiment

New Lights on Dark Matter, Perimeter Institute, Waterloo, June 11-13, 2009

Eun-Suk Seo for the ATIC Collaboration

nature Vol 456|20 November 2008|doi:10.1038/nature07477

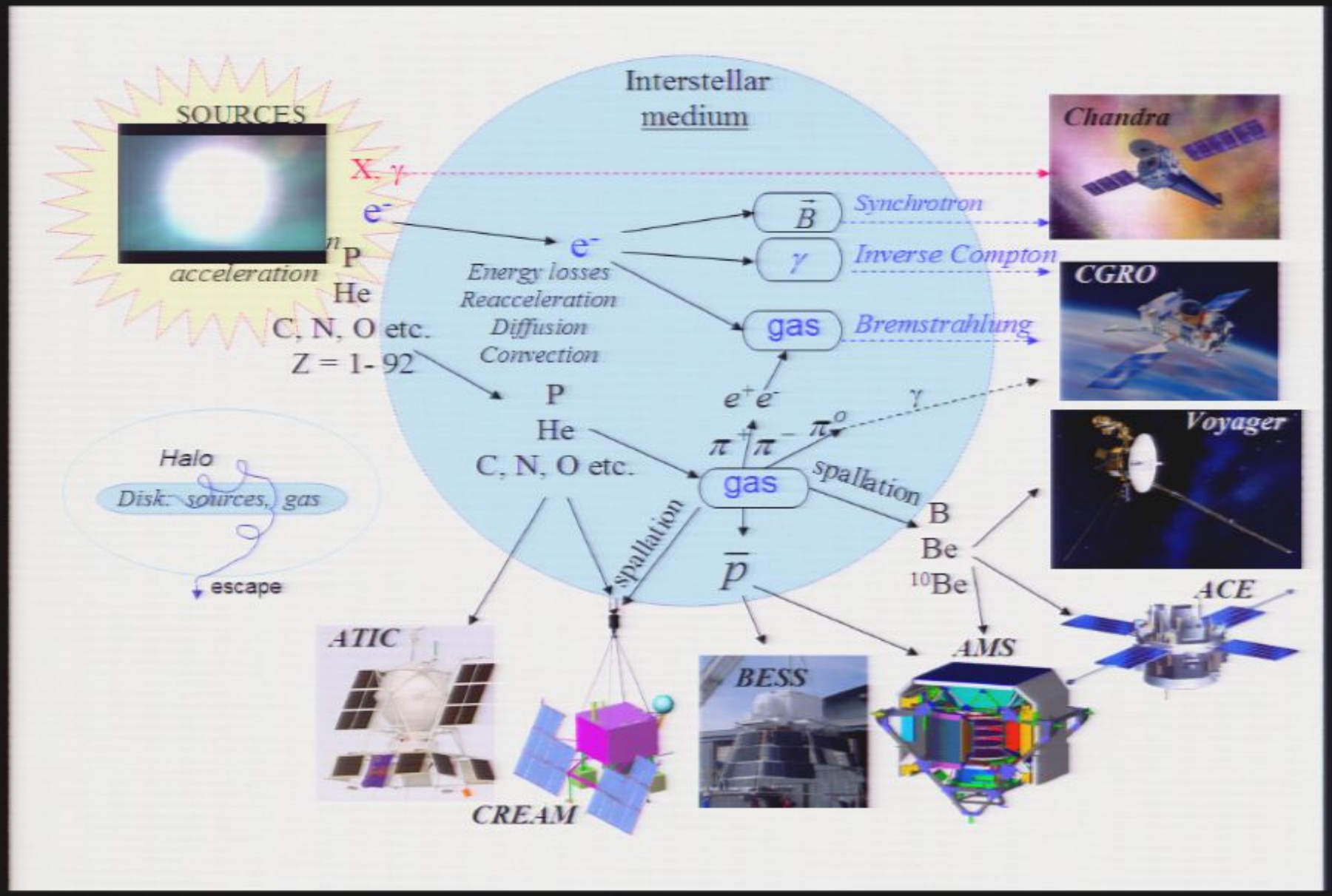
LETTERS

An excess of cosmic ray electrons at energies of 300–800 GeV

J. Chang[1,2], J. H. Adams Jr[3], H. S. Ahn[4], G. L. Bashindzhagyan[5], M. Christl[3], O. Ganel[4], T. G. Guzik[6], J. Isbert[6], K. C. Kim[4], E. N. Kuznetsov[5], M. I. Panasyuk[5], A. D. Panov[5], W. K. H. Schmidt[2], E. S. Seo[4], N. V. Sokolskaya[5], J. W. Watts[3], J. P. Wefel[6], J. Wu[4] & V. I. Zatsepin[5]

Galactic cosmic rays consist of protons, electrons and ions, most of which are believed to be accelerated to relativistic speeds in supernova remnants[1–3]. All components of the cosmic rays show an

reviewed briefly here and in the Supplementary Information (section 1). The basic ATIC energy calibration is provided by cosmic-ray muons recorded just before each flight, as well as by the shower data itself.


SOURCES
acceleration
X, γ
e⁻
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Z = 1- 92
Interstellar medium
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Energy losses
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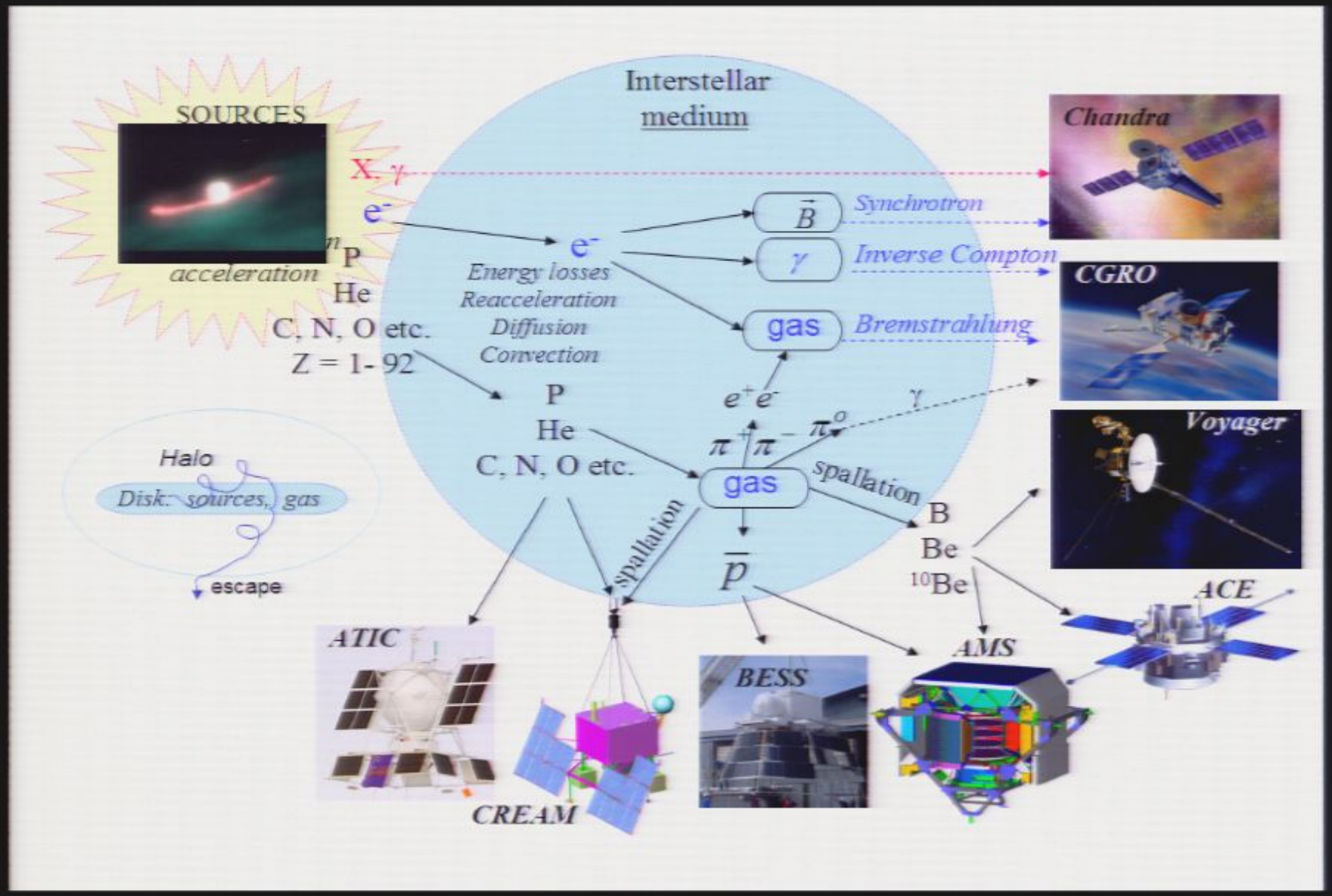
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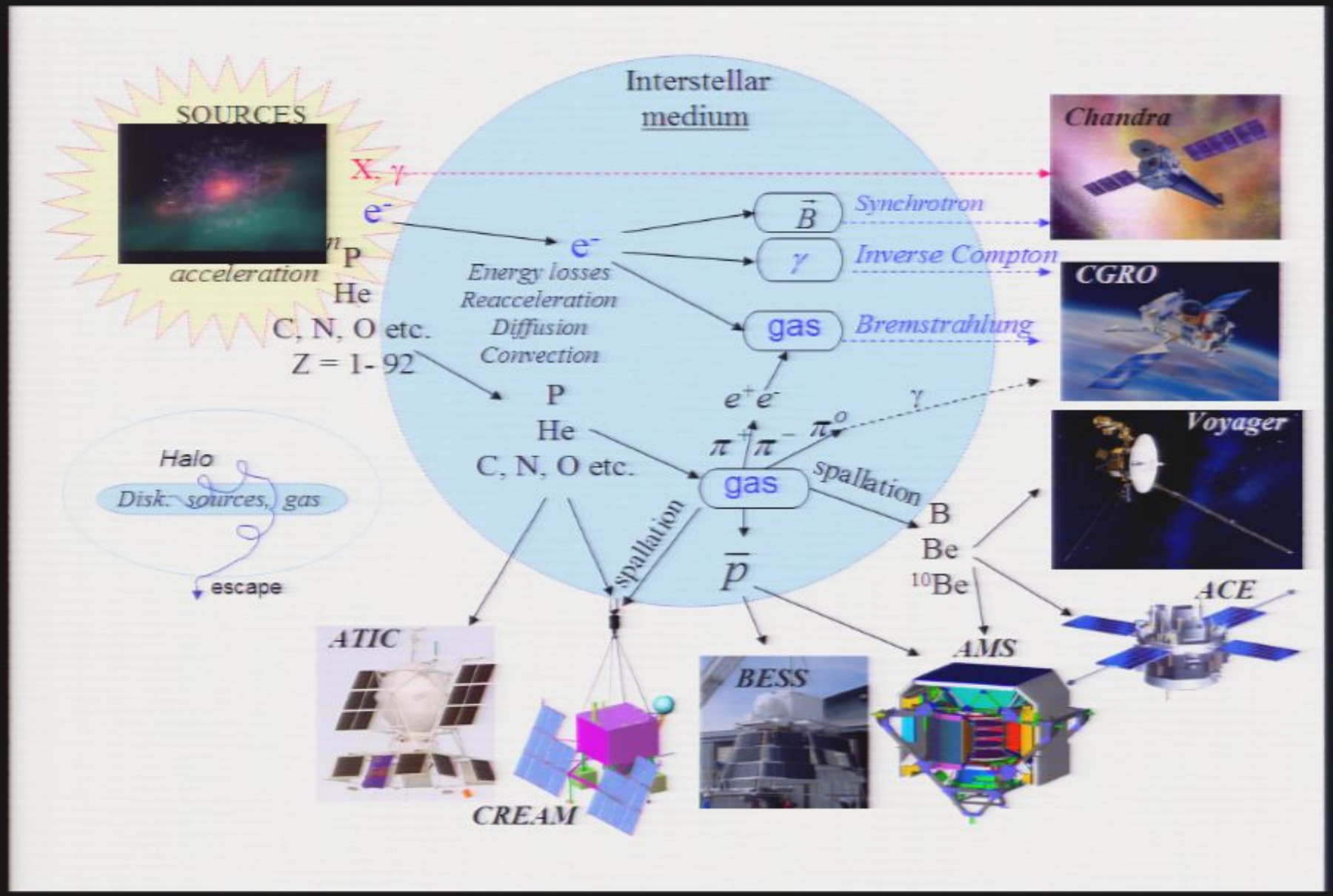
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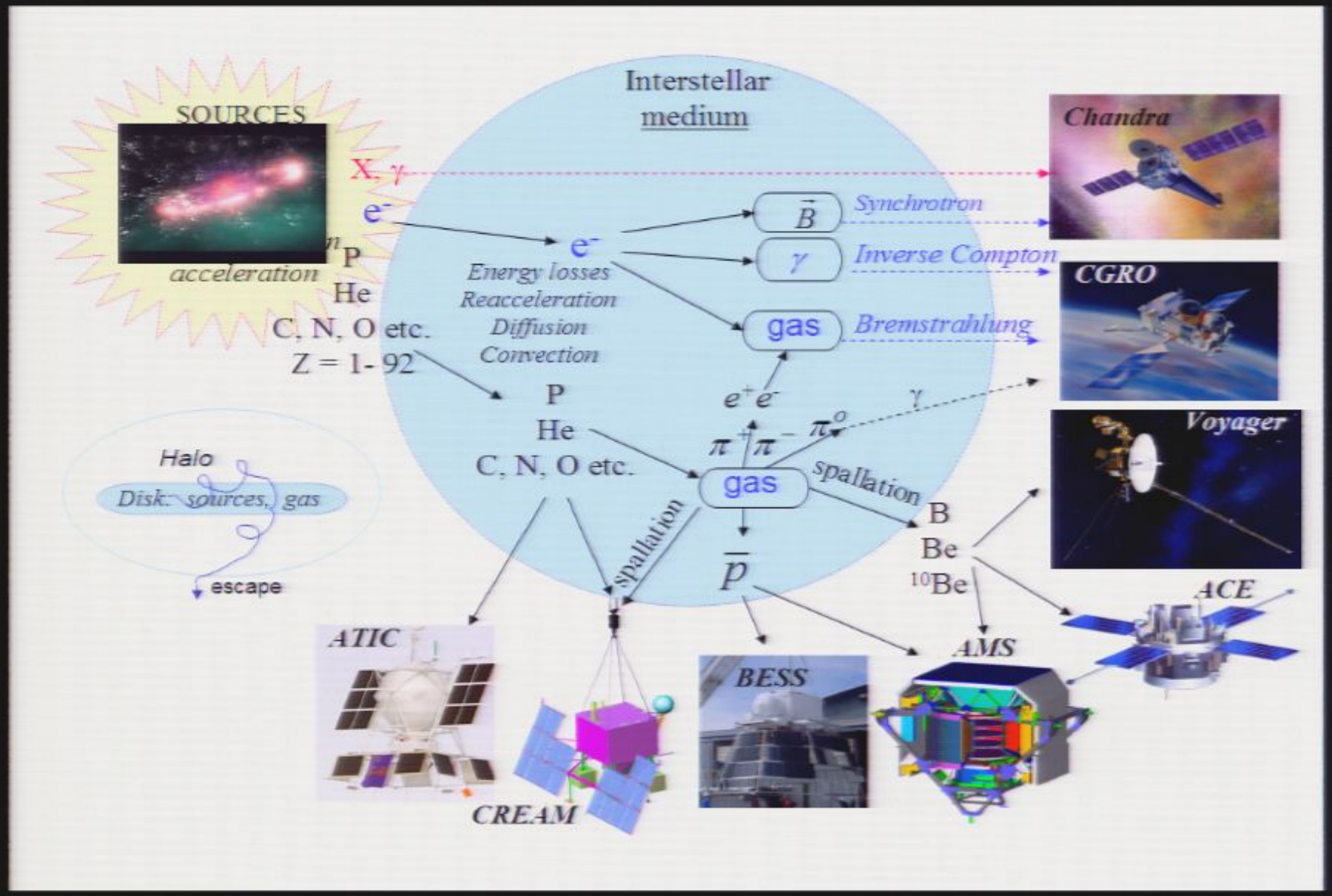
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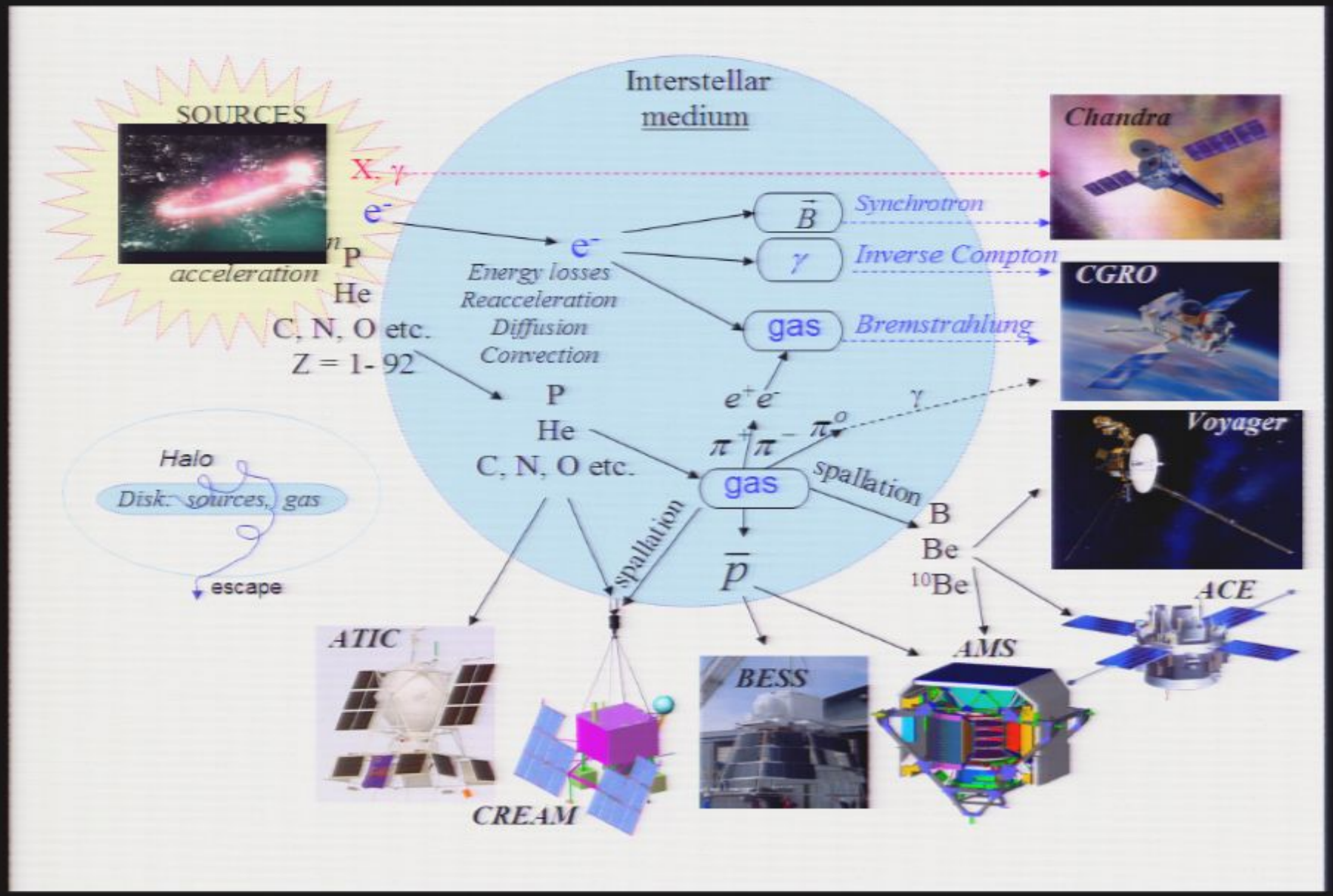
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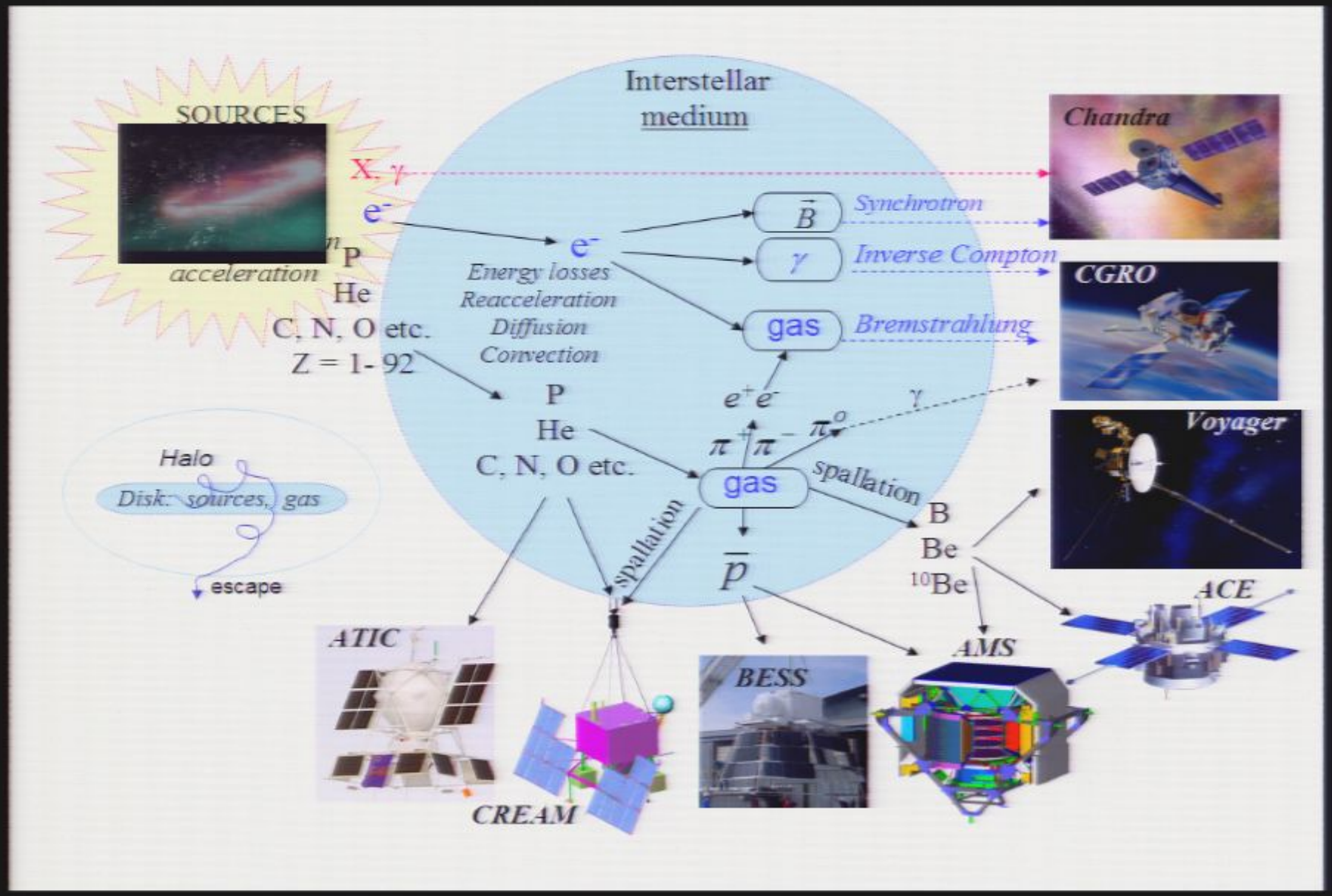
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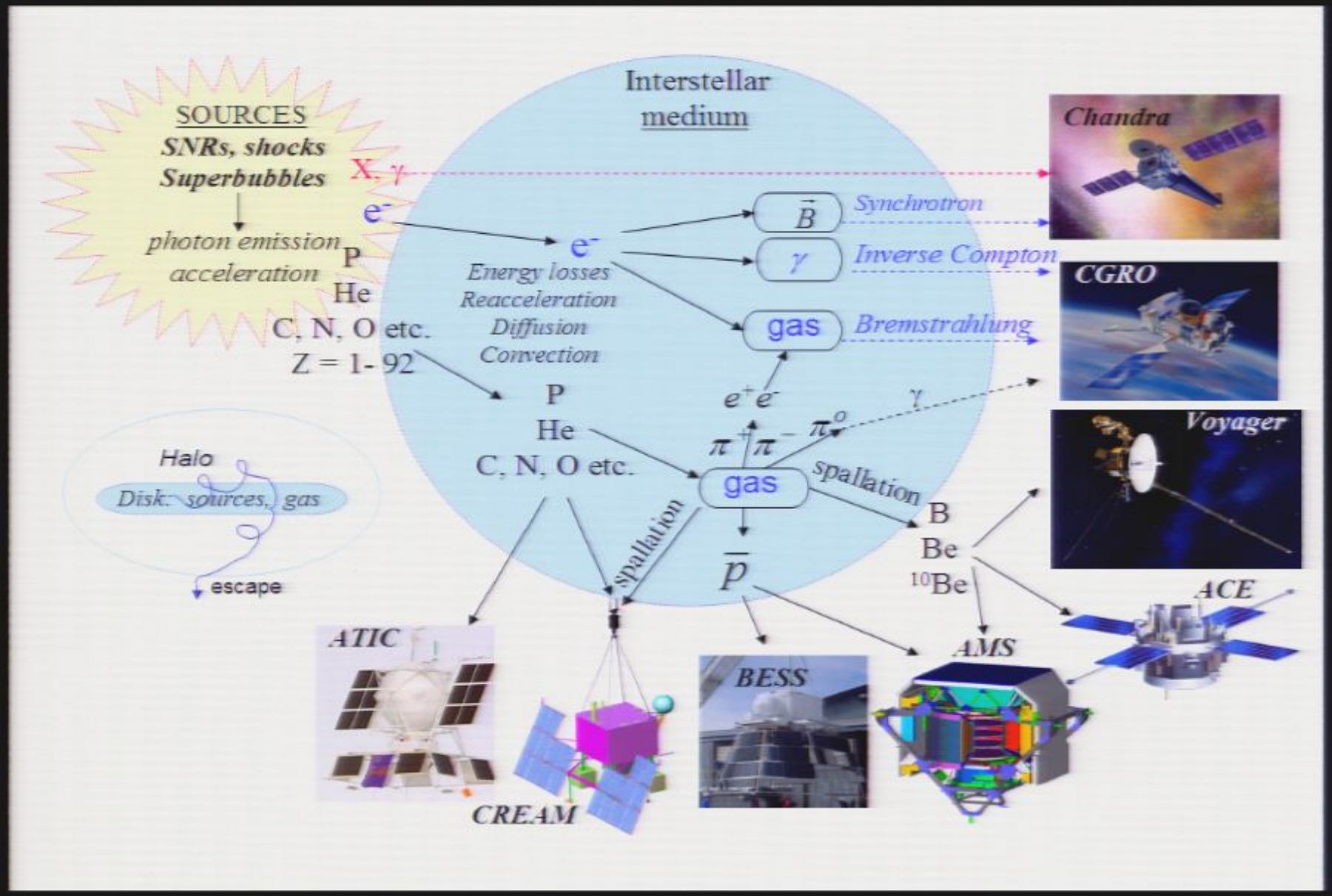
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Superbubbles
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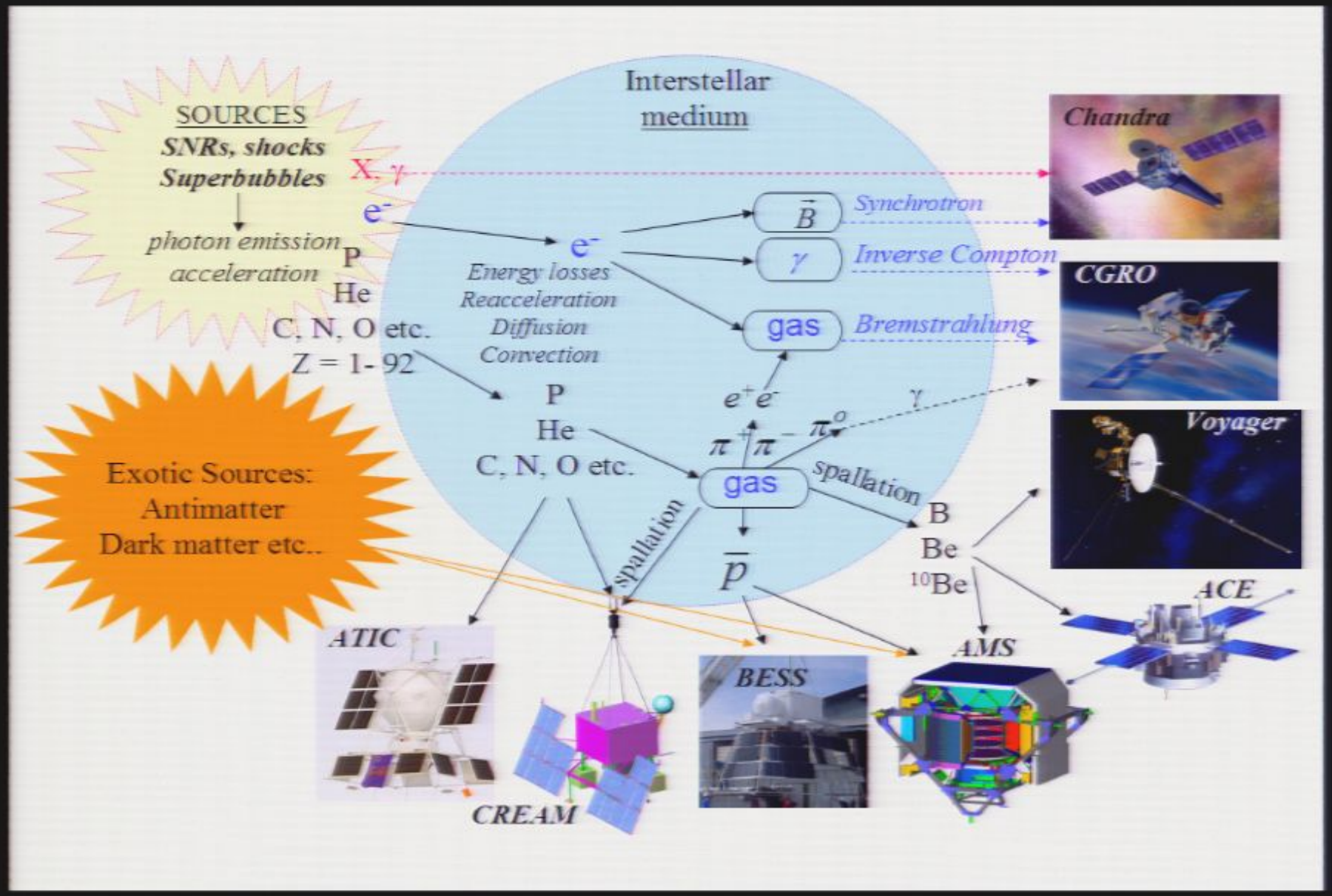
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Exotic Sources:
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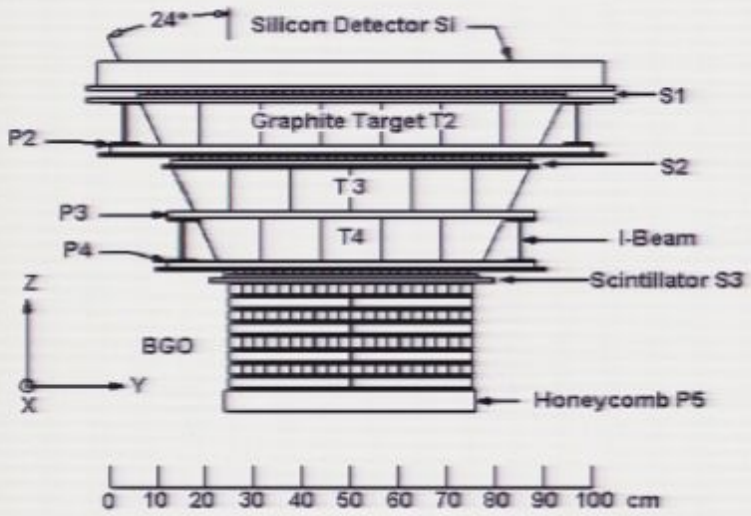
Advanced Thin Ionization Calorimeter (ATIC)



- Uses the ionization calorimetry technique
  - Measure incident particle energy
  - EM shower details discriminate between electrons and protons

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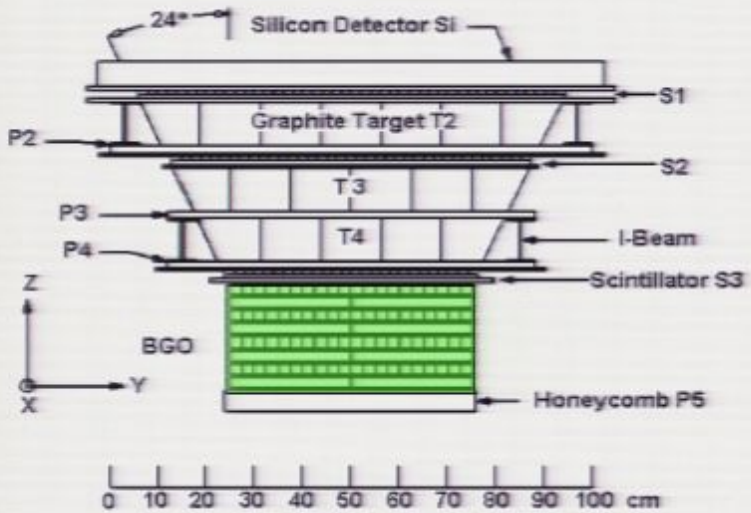

- Uses the ionization calorimetry technique
  - Measure incident particle energy
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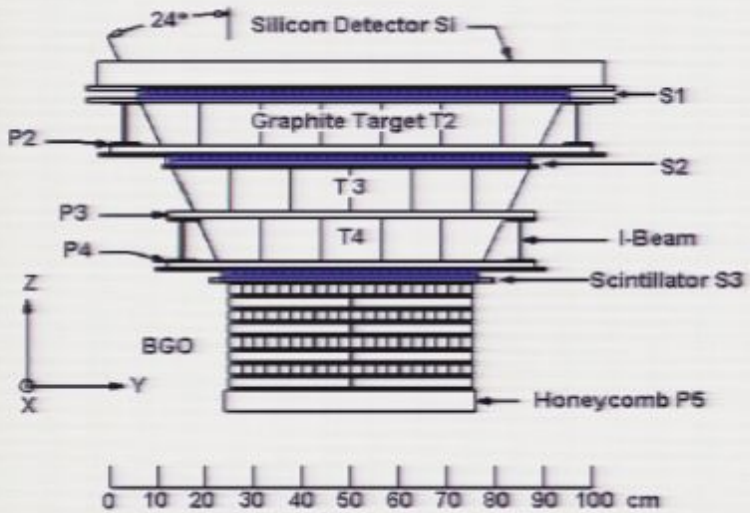
- The Bismuth Germanate (BGO) calorimeter fosters development of the shower
  - ATIC-4 had ten layers of 40 BGO crystals dimensioned 2.5 cm x 2.5 cm x 25 cm each
  - Calorimeter has ~1.14 λ and ~22.4 X_0 for vertical incident particles

Advanced Thin Ionization Calorimeter (ATIC)



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- Target section includes scintillator hodoscopes and graphite material
  - S1, S2, S3 provide initial trigger, auxiliary charge & trajectory information
  - 30 cm of graphite (~1.72 g/cm^3) provides ~0.7 λ to foster hadron interactions, ~1.4 X_0 to start EM showers and a distance to allow lateral shower development

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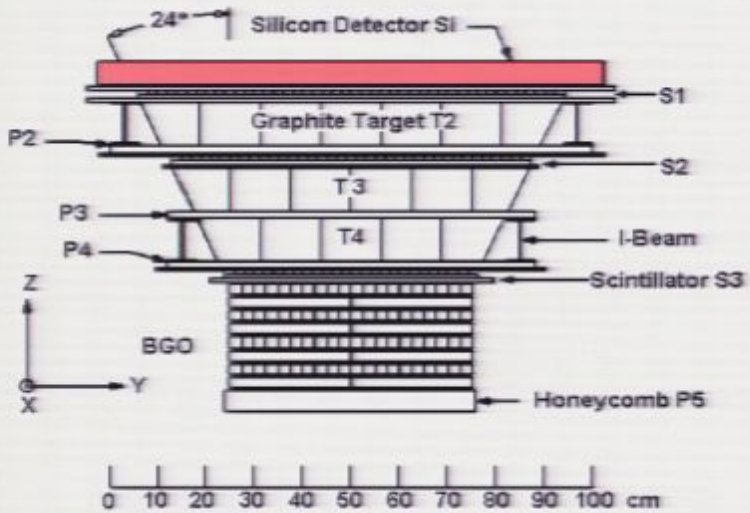

- Uses the ionization calorimetry technique
  - Measure incident particle energy
  - EM shower details discriminate between electrons and protons
- Silicon Matrix detector provides measure of incident particle charge $1 \leq Z \leq 28$
  - 4,480 pixels of dimensions 2 cm x 1.5 cm each
  - Active area is 0.95 m x 1.05 m
- Target section includes scintillator hodoscopes and graphite material
  - S1, S2, S3 provide initial trigger, auxiliary charge & trajectory information
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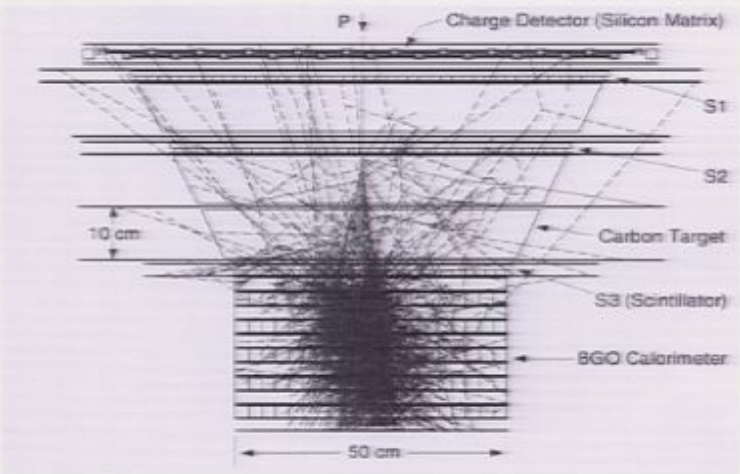
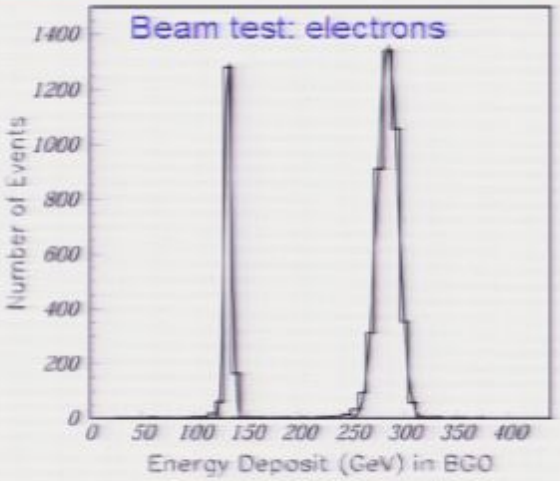
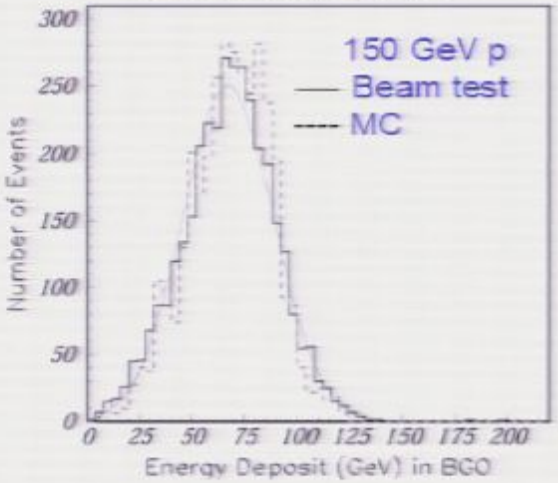
Monte Carlo Simulations and Beam Tests



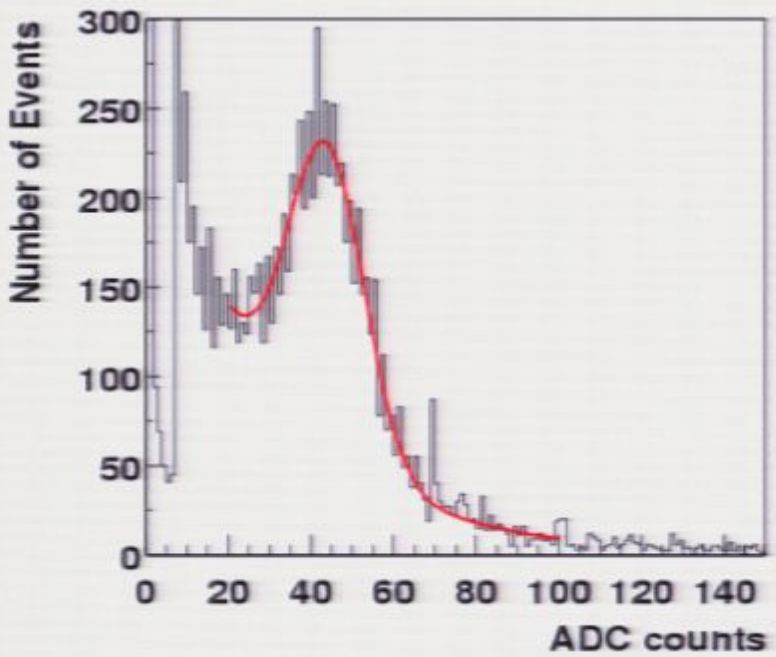




- Beam measurements for 150 GeV electrons show 91% containment of incident energy, with a resolution of 2% at 150 GeV
- Proton containment ~38%

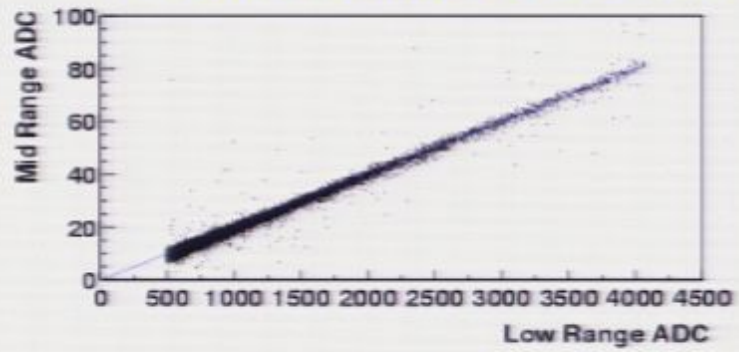
BGO Calorimeter Calibration

- **Inter-Crystal:**
  pre-flight cosmic ray muons

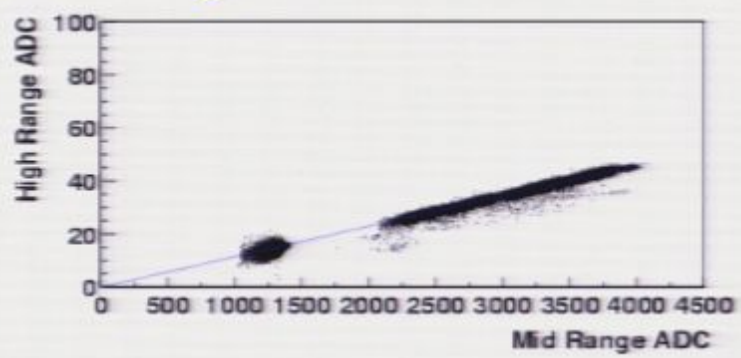


Slide courtesy of H. S. Ahn

- **Inter-Range:**
  in-flight cosmic ray showers

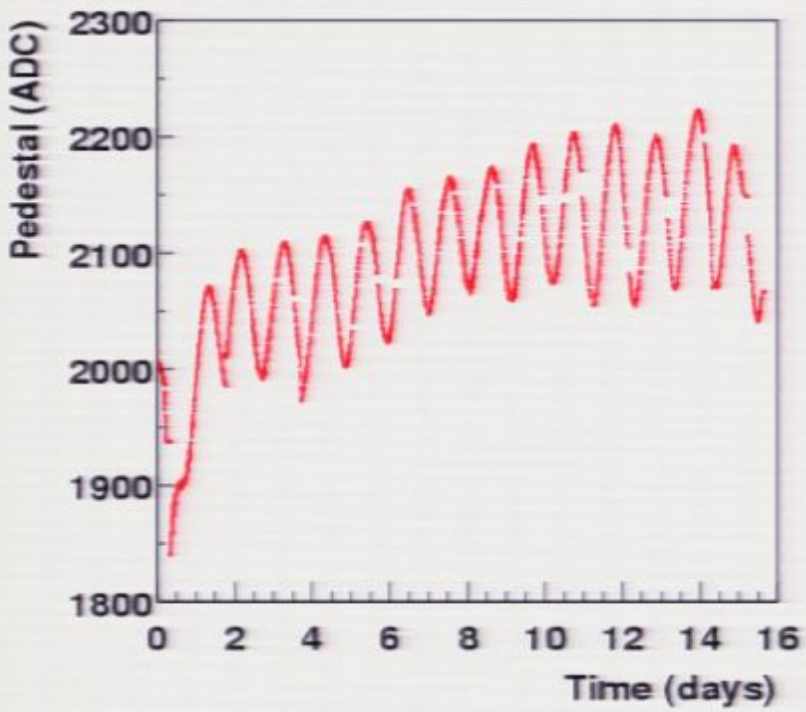


in-flight LED flasher

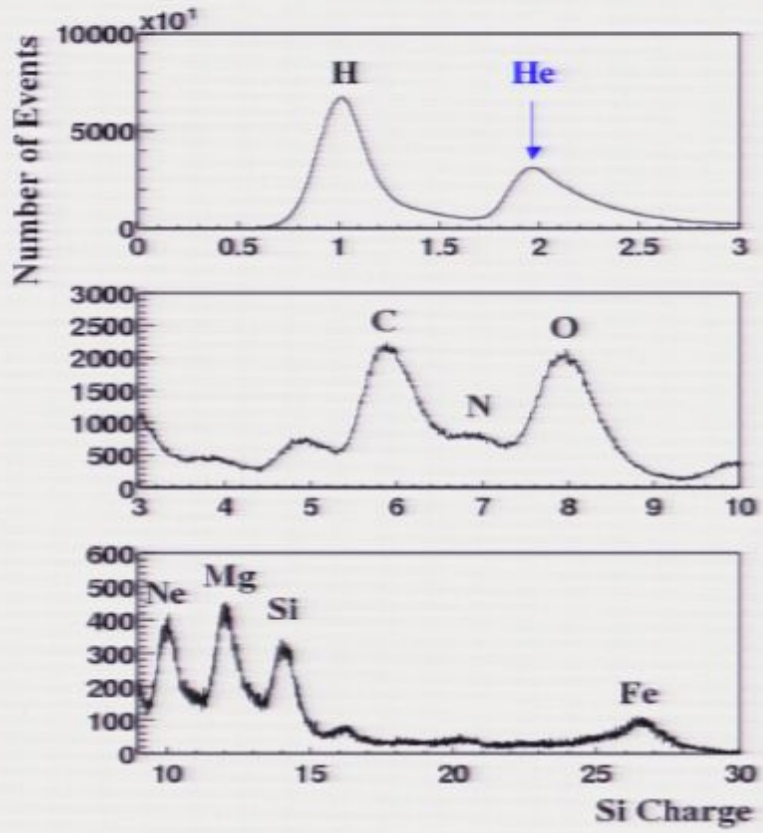


Si Matrix Calibration

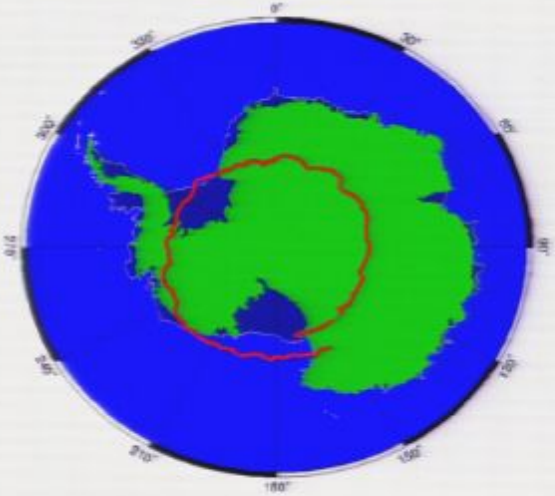
- **Pedestal Subtraction:**
  pedestal run every 6 minutes,
  ~ 20 ADC / °C



- **In-flight cosmic ray He**



Long Duration Balloon Flights in Antarctica



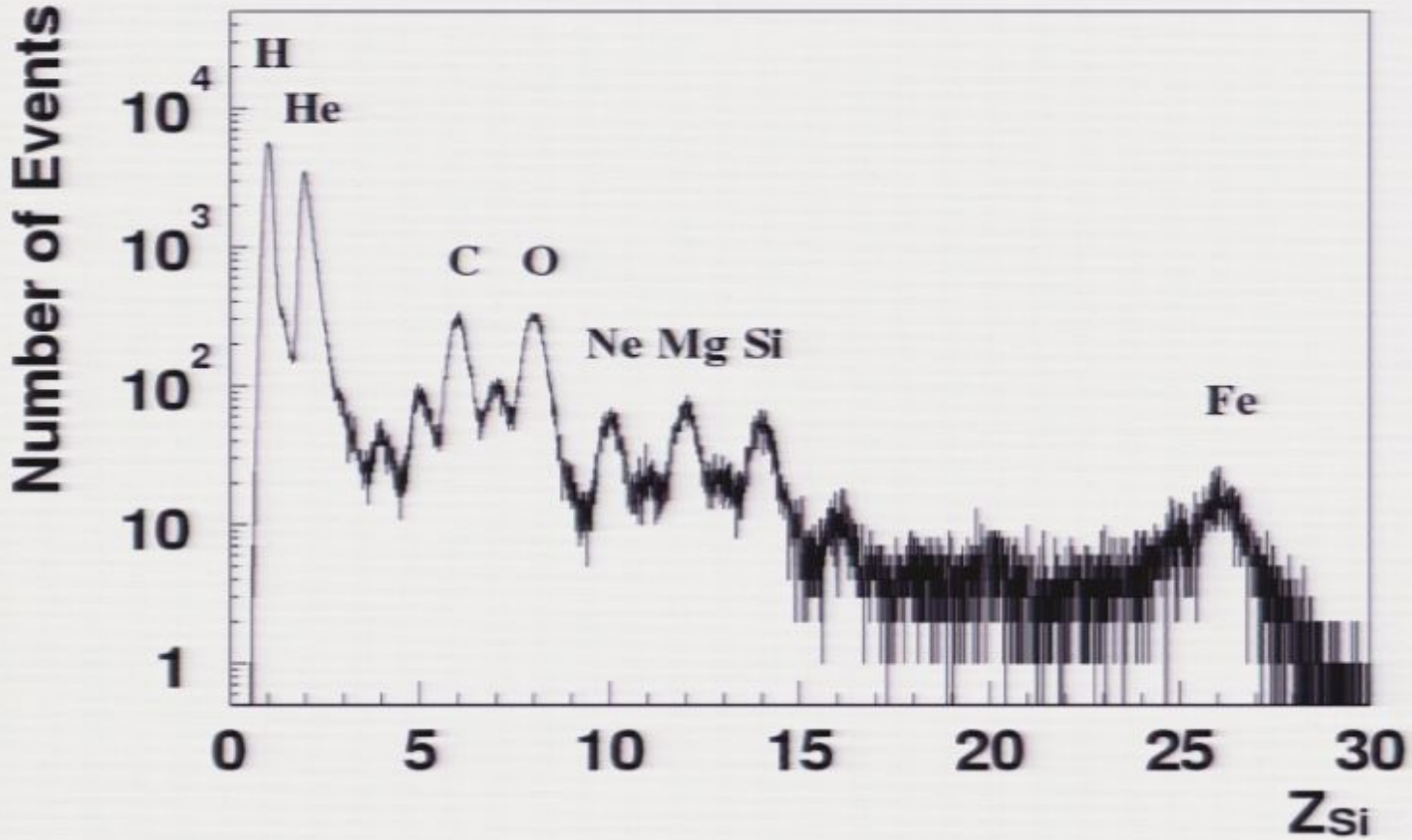
ATIC-1: ~16 days
12/28/00 - 1/13/01

ATIC-2: ~20 days
12/29/02 - 1/18/03

ATIC-3: fail to reach float
12/19/05

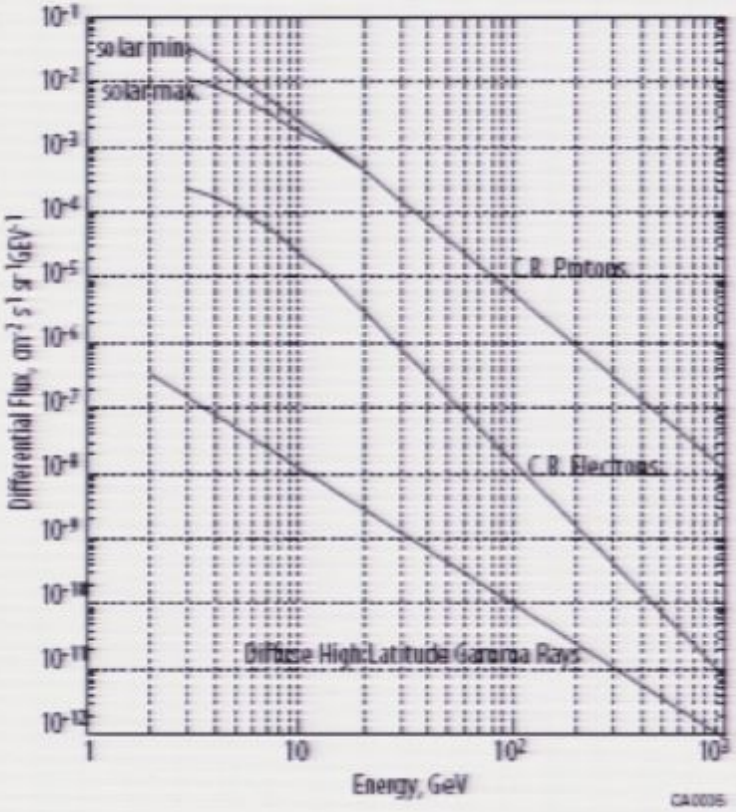
ATIC-4: ~20 days
12/26/07 - 1/15/08

Particle Charge Histogram



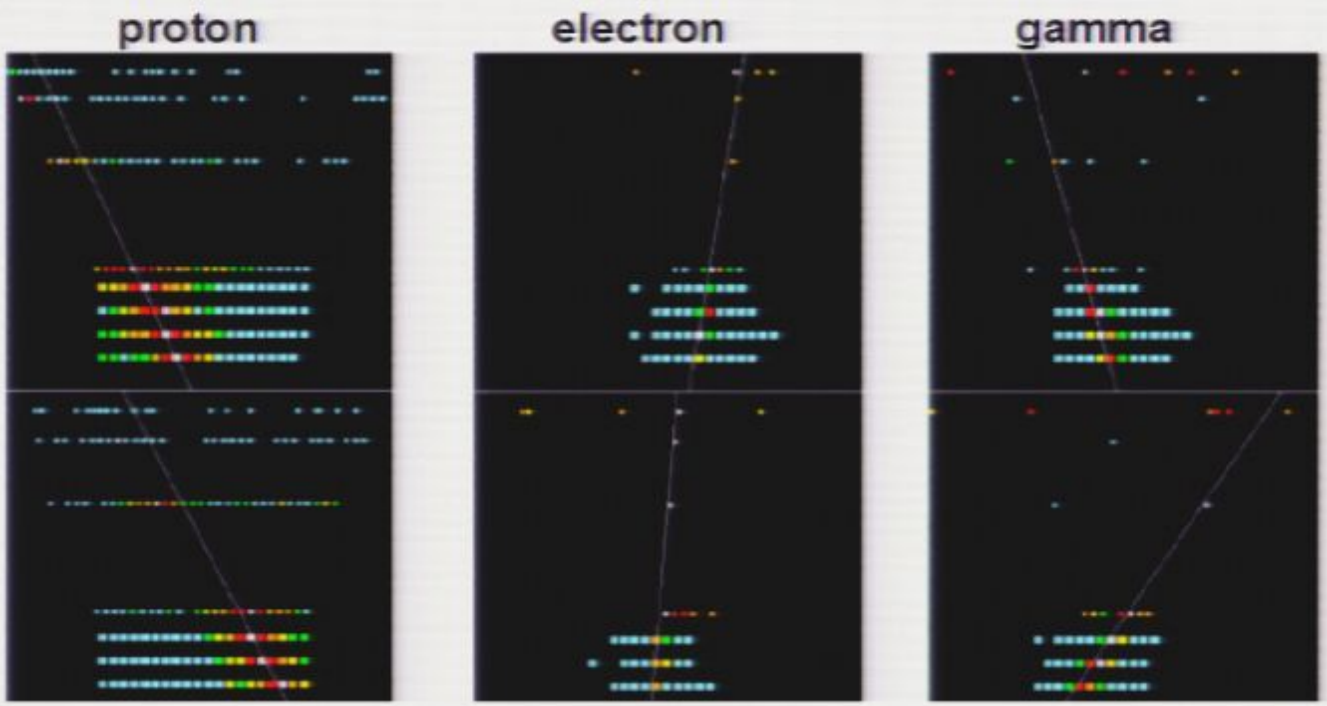
How are electrons measured?

- Silicon matrix identifies charge
  - Good tracking resolution is required
- Calorimeter measures energy to ±2%
- Key issue: Separating protons and electrons
  - Require interactions in the target
    - 78% of electrons and 53% of protons interact
  - Energy deposited in the calorimeter helps:
    - Electrons 85%; Protons 35% $\Rightarrow E_p = 2.4 X E_e$
    - Reduces proton flux by X0.23
  - Combined reduction is X0.15, then
  - Examine shower longitudinal profile
  - Examine shower lateral profile



Electron Selection

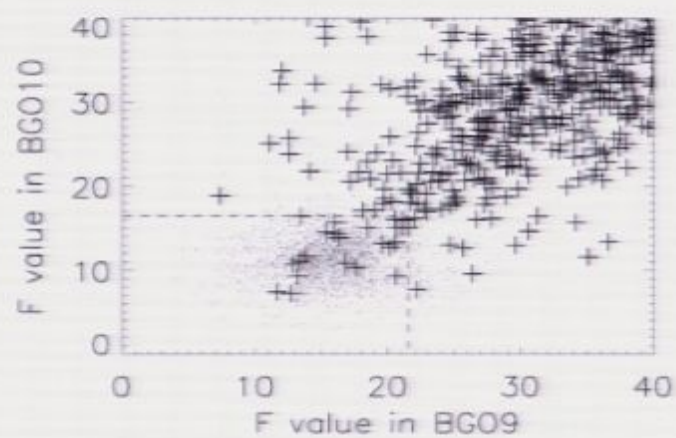
- Remove heavy ions with $Z_{Si} \geq 2$ and γ-ray with $Z_{Si} = 0$
- Separate e from p using shower profile in the calorimeter
  - Electron and gamma-ray showers are narrower than the proton showers



$E_d \sim 250$ GeV

Combine shower characteristics into a single parameter

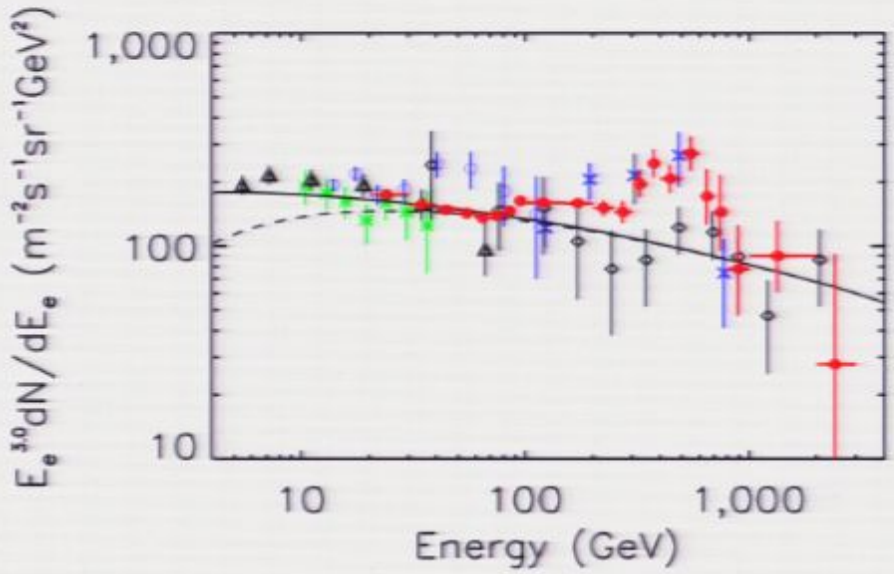
- Shower lateral spread is calculated as $(r.m.s.)^2 = \sum_{i=1}^{n} E_i (x_i - x_c)^2 / \sum_{i=1}^{n} E_i$
  - X_c is coordinate of energy center; X_i is coordinate of crystal "i" center; E_i is energy deposit in crystal "i"
- Energy fraction, *Ef(k)*, is calculated as $Ef(k) = Ed_k / \sum_{j=1}^{m} Ed_j$
  - Ed_k is total energy deposit in the kth layer of the calorimeter and there are a total of m layers.
- The F-value for calorimeter layer k is then $F(k) = Ef(k) * (r.m.s.)^2$
- Plotting the F-value for two BGO layers allows protons & electrons to be well separated.
- Reject all but 1 in 5000 protons while keeping 84% of the electrons



The ATIC electron results exhibits a "feature"

Chang et al., Nature, **456**, 362-365 (2008), doi: 10.1038, 20 November 2008

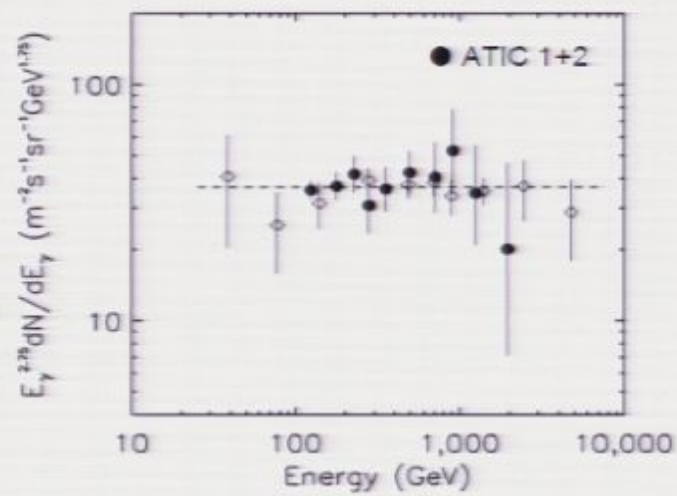
- Sum of data from both ATIC 1 and ATIC 2 flights
- Curves are from GALPROP diffusion propagation
  - Solid curve is local interstellar space
  - Dashed curve is with solar modulation
- Spectral index is -3.23 below ~ 100 GeV
- "Feature" at about 300 - 800 GeV
- Significance is about 3.8 sigma
- Also seen by recent PPB-BETS
- Emulsion chamber data is currently being re-analyzed



● ATIC 1+2, ✱ Alpha Magnetic Spectrometer, △ HEAT magnetic spectrometer, ○ BETS, × PPB-BETS, ◇ Emulsion chambers

Electron Measurement Background

- The effective proton rejection factor is close to 1 in 5,000
  - Protons & electrons deposit energy in the calorimeter differently
  - A proton that deposits the same energy as an electron has a higher incident energy
  - Consequently there is a lower flux of protons mixed with the electrons
- The background of secondary electrons is a function of the balloon altitude
  - For an average altitude of 122,000 ft the electron background is about2.7% at 100 GeV rising to about 12% at 1 TeV
- Secondary gamma rays are also a function of the balloon altitude
  - Identified by requiring no "signal" in the silicon matrix
  - Misidentified gammas provide a background of only ~1% at 1 TeV
- Identified gammas provide a method for checking the electron data analysis
  - Flat spectrum agrees with calculations
- No bumps or breaks in the background or measured secondary gamma rays



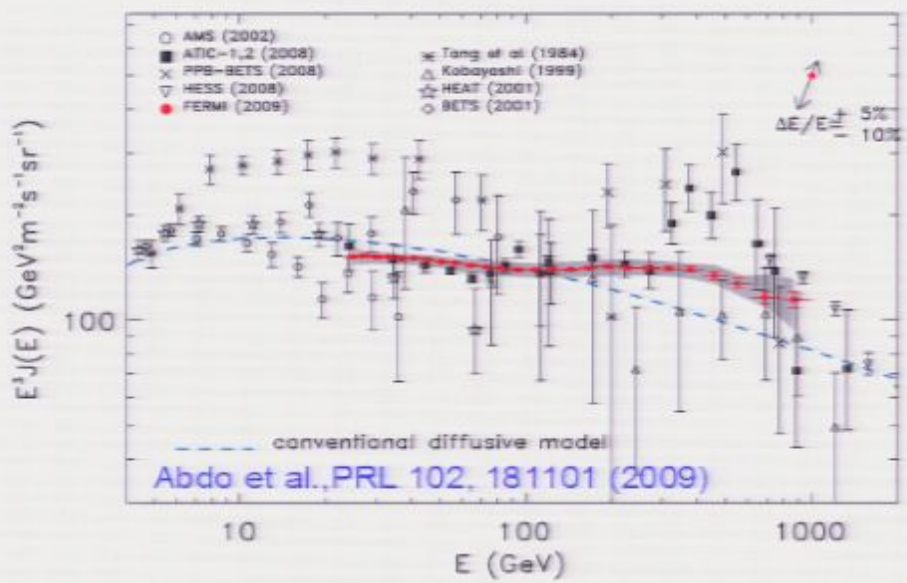
ATIC vs. Fermi

- ATIC BGO calorimeter
  - 18 - 22 Xo
  - fully contains the electron shower
  - energy resolution of ~2 %

- Fermi CsI calorimeter
  - **Thinner**, 8.6 Xo
  - showers are not fully contained
  - distribution of the reconstructed energy is asymmetric with a longer tail toward lower energies
  - **Poorer energy resolution** ~20%

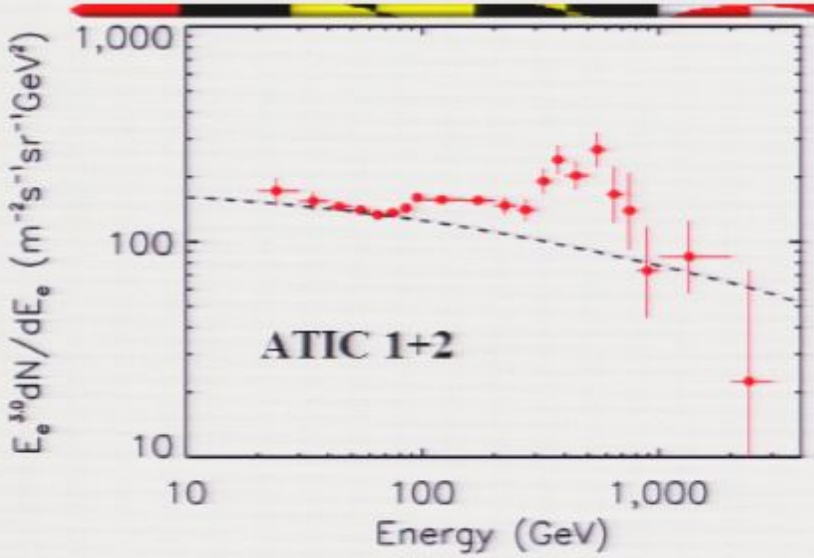
Analysis method comparison

- ATIC analysis uses quantities measured during flight (e.g. atmospheric secondary gammas) to set selection cuts and determine background rates.
- In Fermi much of the electron identification and background rejection is based on simulations only.



Abdo et al.,PRL 102, 181101 (2009)

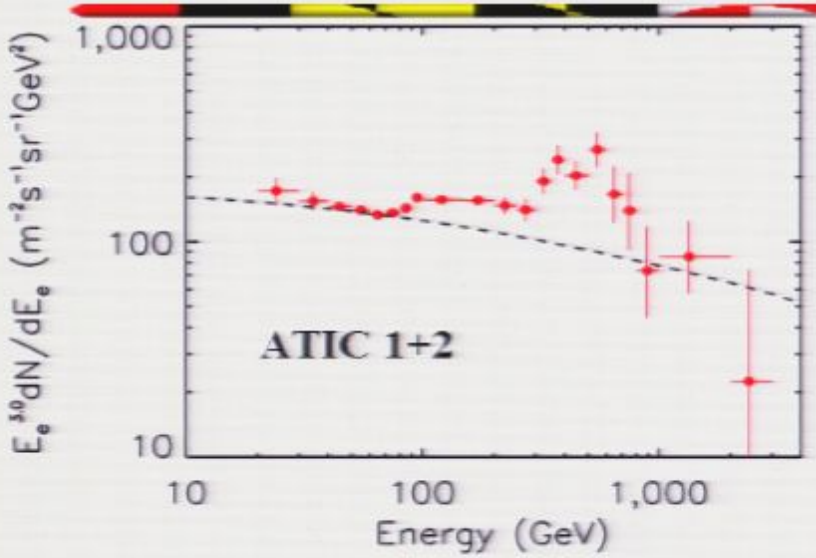
All three ATIC flights are consistent

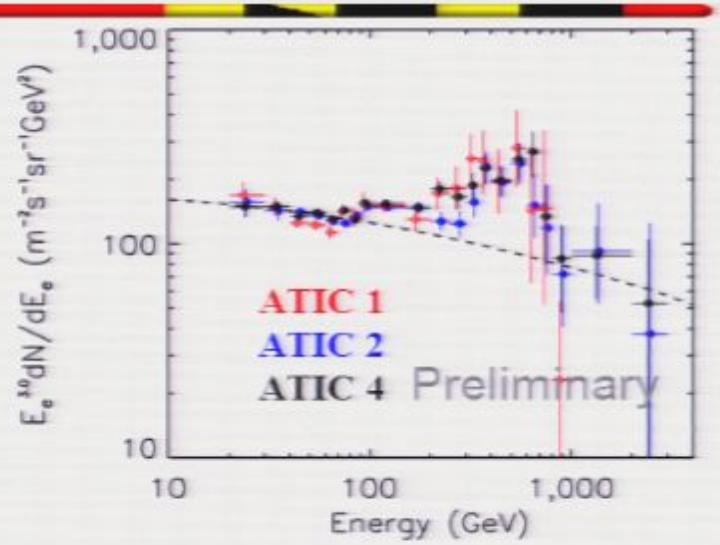


"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

Slide courtesy of J. P. Wefel

All three ATIC flights are consistent





"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

Slide courtesy of J. P. Wefel

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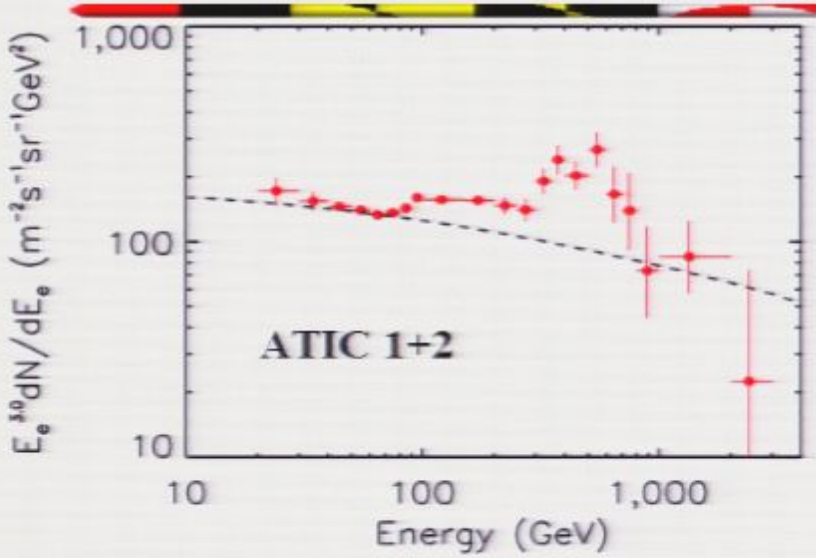

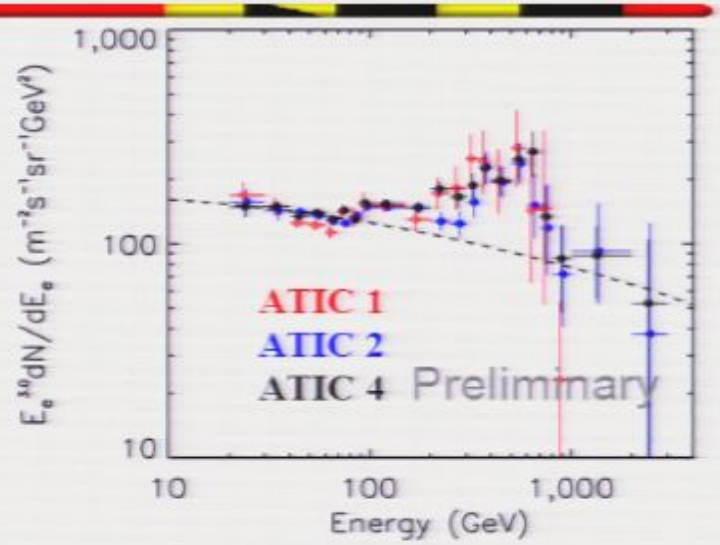

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ATIC-4 with 10 BGO layers has improved e/p separation. **(~4x lower background)**

"Bump" is seen in all three flights.

Slide courtesy of J. P. Wefel

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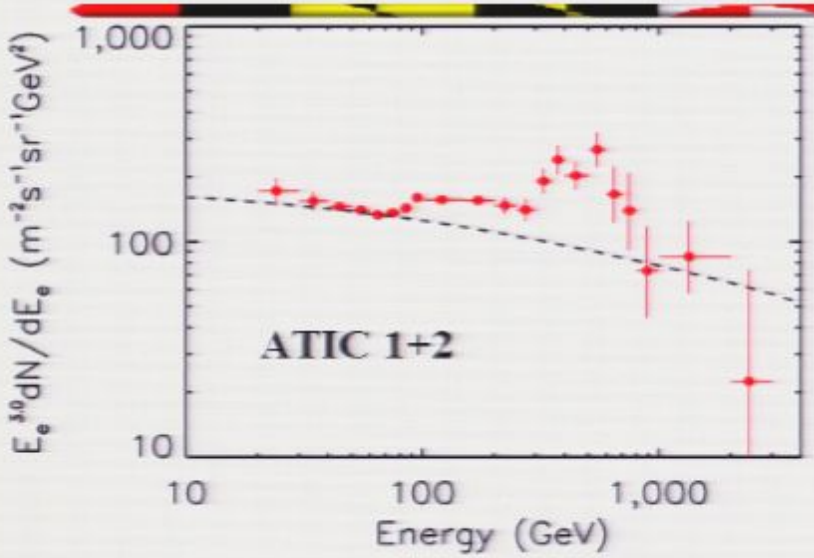

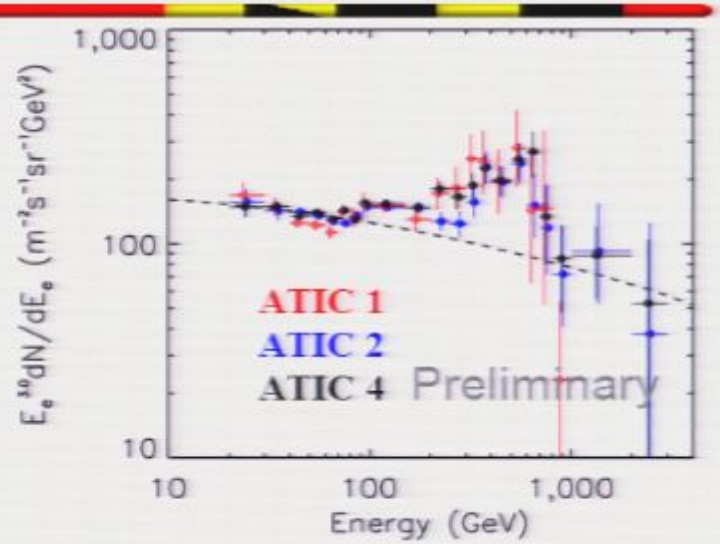

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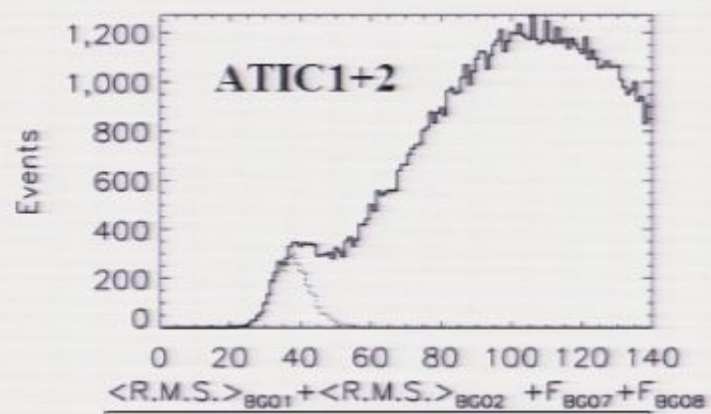

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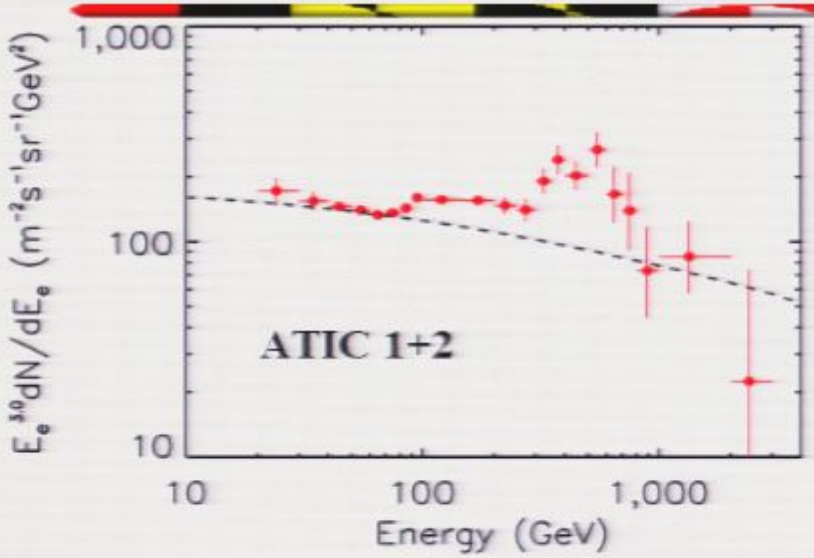

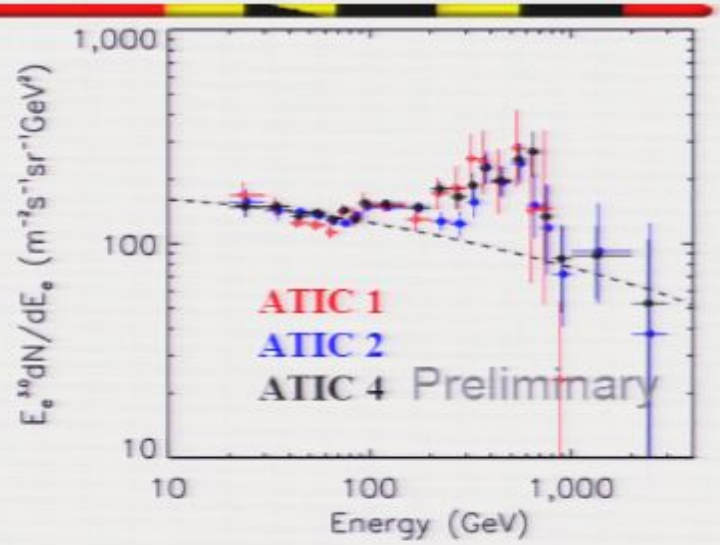

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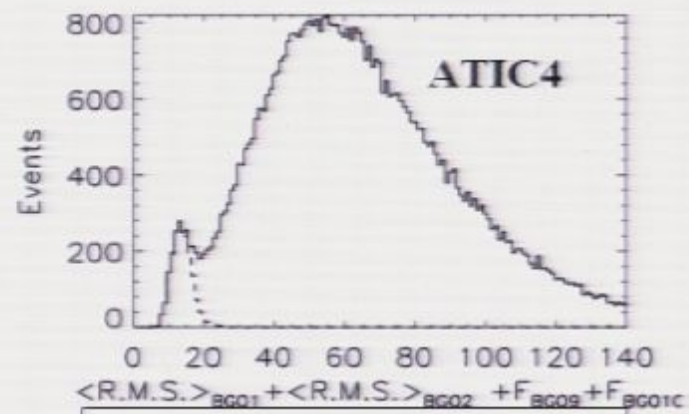

Slide courtesy of J. P. Wefel

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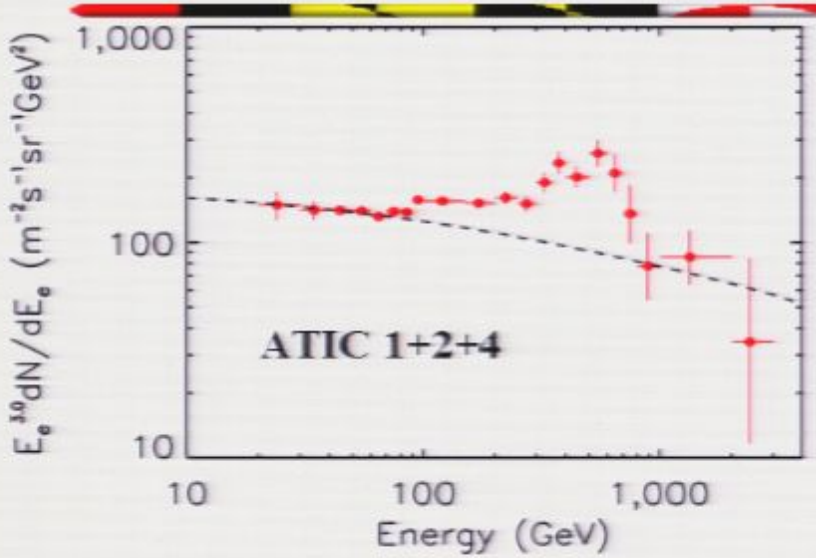

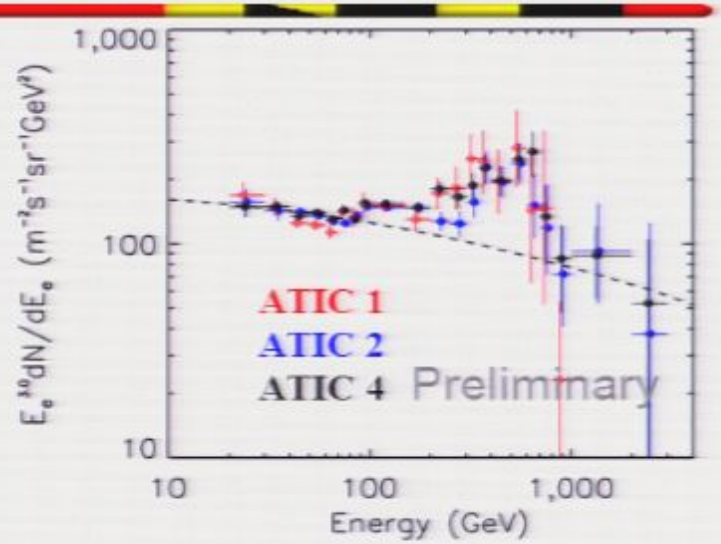

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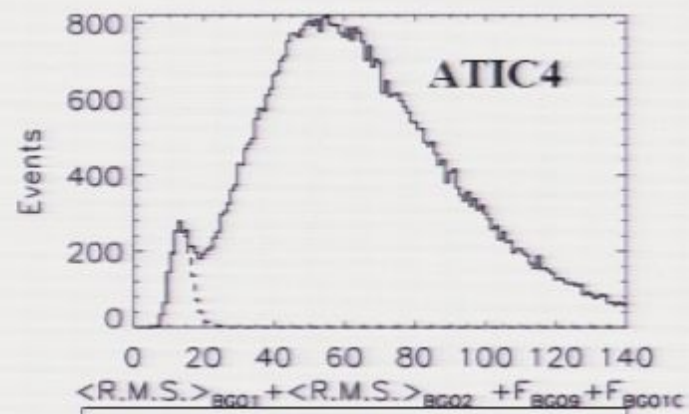
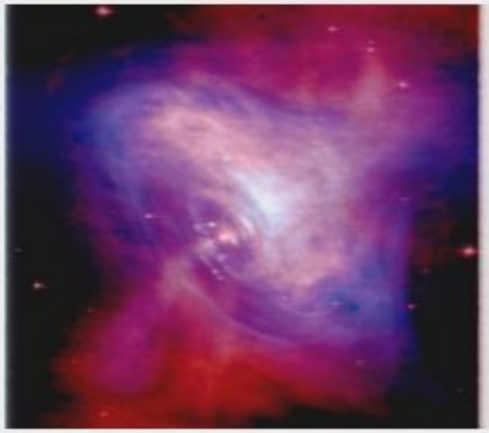


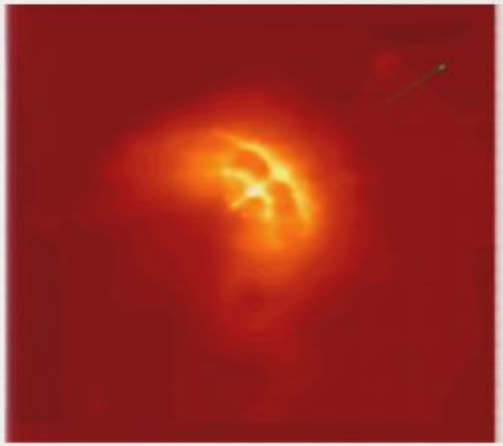
Slide courtesy of J. P. Wefel

Could this be a sign of a local source?

- High energy electrons are known to be produced at many astrophysical sites
- Possible candidate sources include supernova remnants (SNR), pulsar wind nebulae (PWN) and micro-quasars
- SNR and PWN are thought to produce high energy particles via shock acceleration
  - Results in an injection energy spectrum $\propto E^{-2} \exp(E/E_c)$ where E_c is ~ 10 TeV
- Kobayashi et al. predicts that signatures of the most obvious SNRs (e.g. Vela, Cygnus Loop) would appear at energies > 1 TeV
- To fit the ATIC feature would require a very hard spectrum (index ~1.4) with a cut-off at about 600-700 GeV

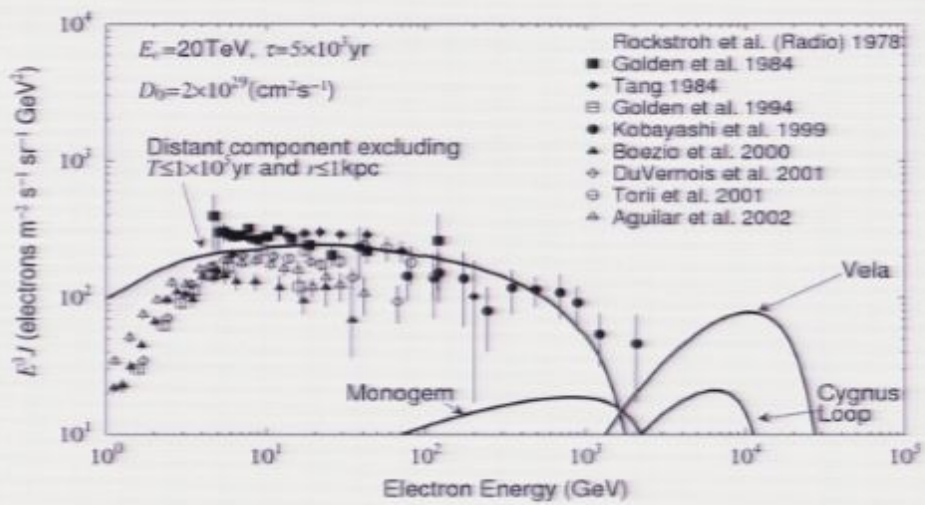


Crab Pulsar shown in X-ray plus optical from Chandra and Hubble (left) and the Vela Pulsar X-ray emission (right). High Energy Particles are accelerated in Pulsar magnetospheres near the neutron star, interact with the nebulae and give rise to X-ray and gamma ray radiation.



Electrons from SNR

- High energy electrons have a high energy loss rate $\propto E^2$
  - Lifetime of ~10^5 years for >1 TeV electrons $(T \approx 2.5 \times 10^5 \times E[TeV]^{-1}\ years)$
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of electrons is < 1 kpc away $(R \approx 600/\sqrt{E[TeV]}\ pc)$
- Electrons <u>are</u> accelerated in SNR
- Only a handful of potential sources meet the lifetime & distance criteria
- Kobayashi et al (2004) calculations show structure in electron spectrum at high energy



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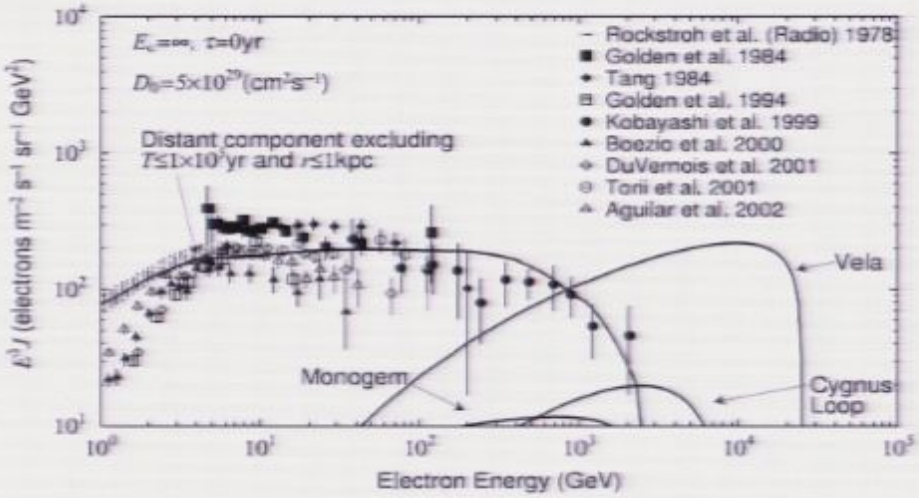

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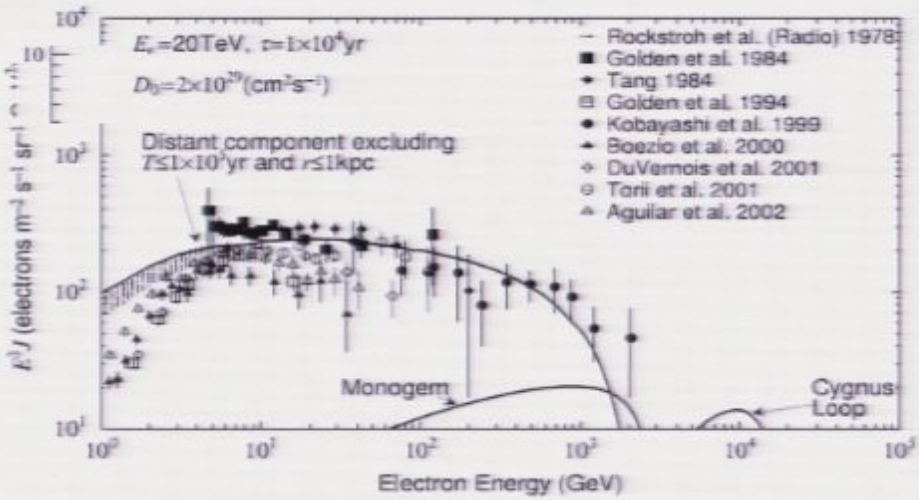
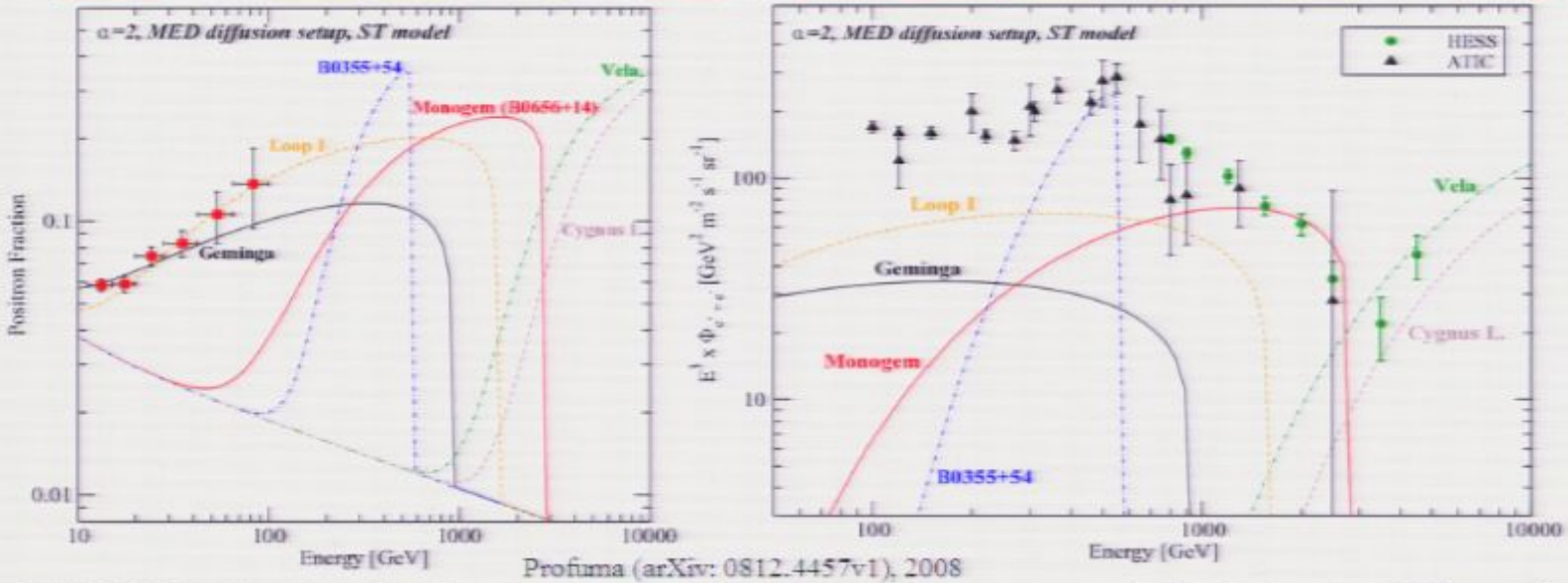


Can e^+e^- accelerated by pulsars explain the data?



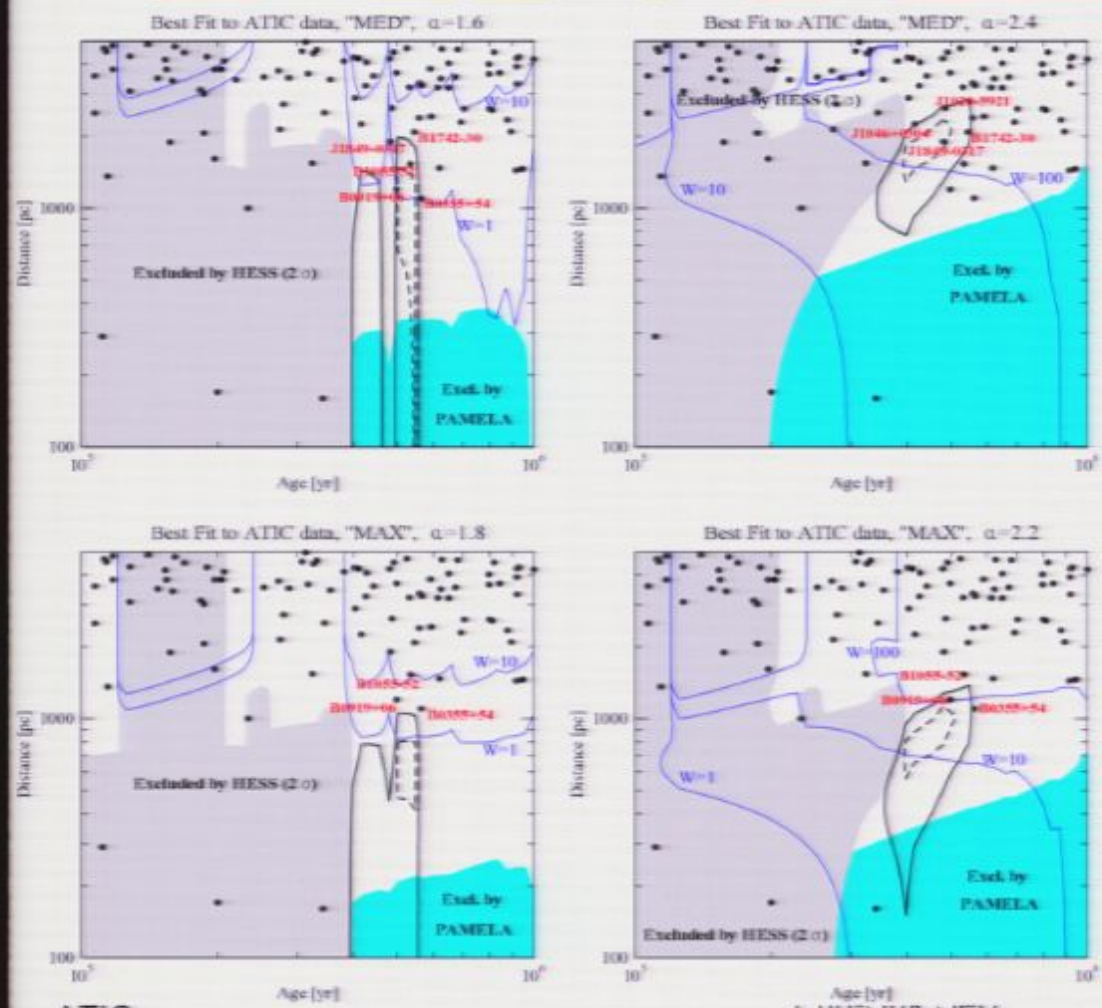
Profumo (arXiv: 0812.4457v1), 2008

TABLE II: Data for a few selected nearby pulsars and SNR's. E_{out} is the energy output in $e^{\pm}$ pairs in units of 10^{48} erg. The energy output for the SNR Loop I and Cygnus Loop are not estimated within the ST model, but via estimates of the total SNR output. The $f_{e\pm}$ column indicates the $e^{\pm}$ output fraction used to compute the fluxes shown in fig. 3 and 4 within the ST model.

Name	Distance [kpc]	Age [yr]	$\dot{E}$ [ergs/s]	E_{out} [ST]	E_{out} [CCY]	E_{out} [HR]	E_{out} [ZC]	$f_{e\pm}$	g
Geminga [J0633+1746]	0.16	3.42×10^5	3.2×10^{34}	0.360	0.344	0.013	0.053	0.005	0.70
Monogem [B0656+14]	0.29	1.11×10^5	3.8×10^{34}	0.084	0.456	0.004	0.372	0.015	0.14
Vela [B0833-45]	0.29	1.13×10^4	6.9×10^{36}	0.044	0.133	0.133	0.005	0.020	0.70
B0355+54	1.10	5.64×10^5	4.5×10^{34}	1.366	0.677	0.022	0.121	0.2	0.61
Loop I [SNR]	0.17	2×10^5		*0.3*				0.006	
Cygnus Loop [SNR]	0.44	2×10^4		*0.03*				0.01	

Pulsar "best fit" to ATIC data

Profuma (arXiv: 0812.4457v1), 2008



Use ATNF catalog of known pulsars

Assume injection spectrum index and diffusion coefficient, then adjust the output energy to produce best fit.

PAMELA and HESS "exclusion zones" over predict data by 2 σ

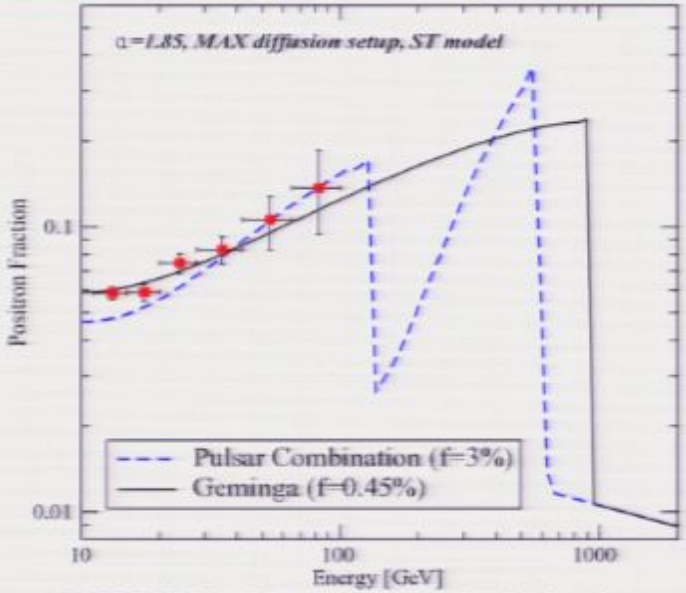
Unless the injection spectrum is very hard (α ~ 1.6), existing pulsars must be extremely powerful (w~100, i.e., E_{out} ~10^{50} ergs) to account for the ATIC data.

Possible in principle, but unlikely for the standard energy budget of supernova explosions

"The pulsar scenario is compatible, but does not favor, for natural values of the parameters, a peaked spectrum such as what [is] reported by ATIC."

Possibly a combination of pulsars?

Profuma (arXiv: 0812.4457v1), 2008



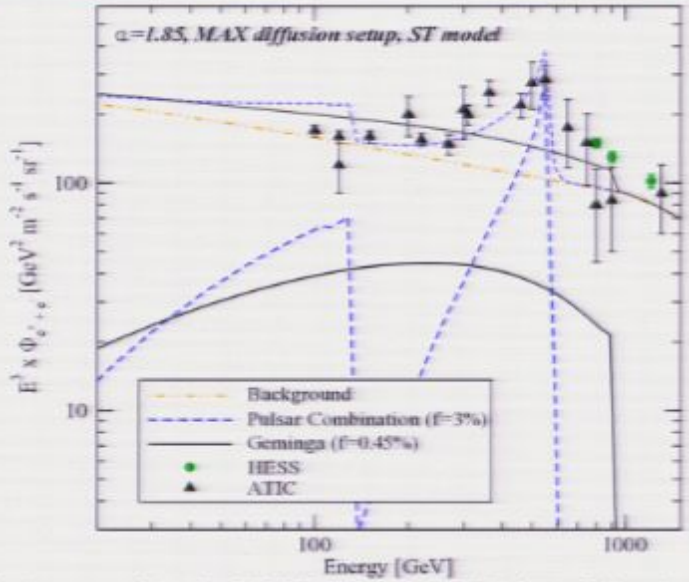
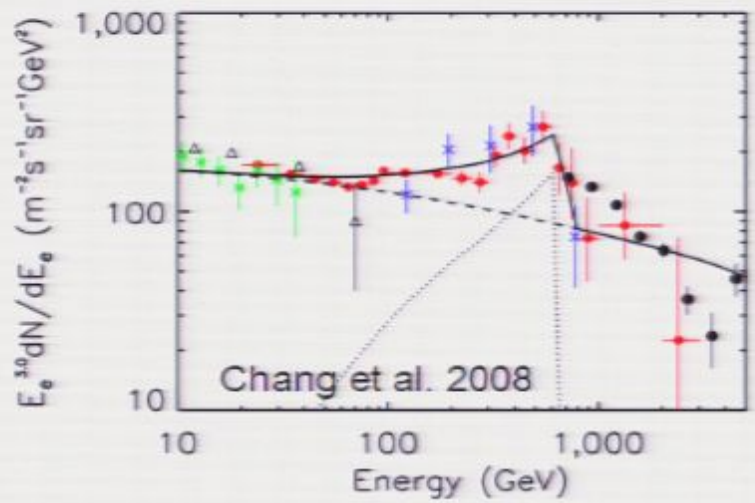


TABLE III: Possible combinations of multiple pulsars contributing to explain the PAMELA and the ATIC data. P/A refers to whether the pulsar dominantly contributes to the PAMELA or to the ATIC signal. E_{out} is the energy output in $e^{\pm}$ pairs in units of 10^{48} erg.

Name	P/A	Distance [kpc]	Age [yr]	E_{out} [ST]	E_{out} [CCY]	E_{out} [HR]	E_{out} [ZC]
J1918+1541	P	0.68	2.31×10^6	0.99	0.33	0.023	0.022
B0450+55	P	0.79	2.28×10^6	1.16	0.37	0.025	0.025
B0834+06	P	0.72	2.97×10^6	0.11	0.07	0.011	0.001
B1845-19	P	0.95	2.93×10^6	0.01	0.015	0.005	0.0002
B0919+06	A	1.20	4.97×10^5	0.158	0.178	0.010	0.016
B0355+54	A	1.10	5.64×10^5	1.366	0.677	0.022	0.121
B1055-52	A	1.53	5.35×10^5	0.82	0.49	0.017	0.075
J1849-0317	A	1.90	4.81×10^5	0.06	0.10	0.007	0.007
B1742-30	A	2.08	5.46×10^5	0.24	0.22	0.012	0.022

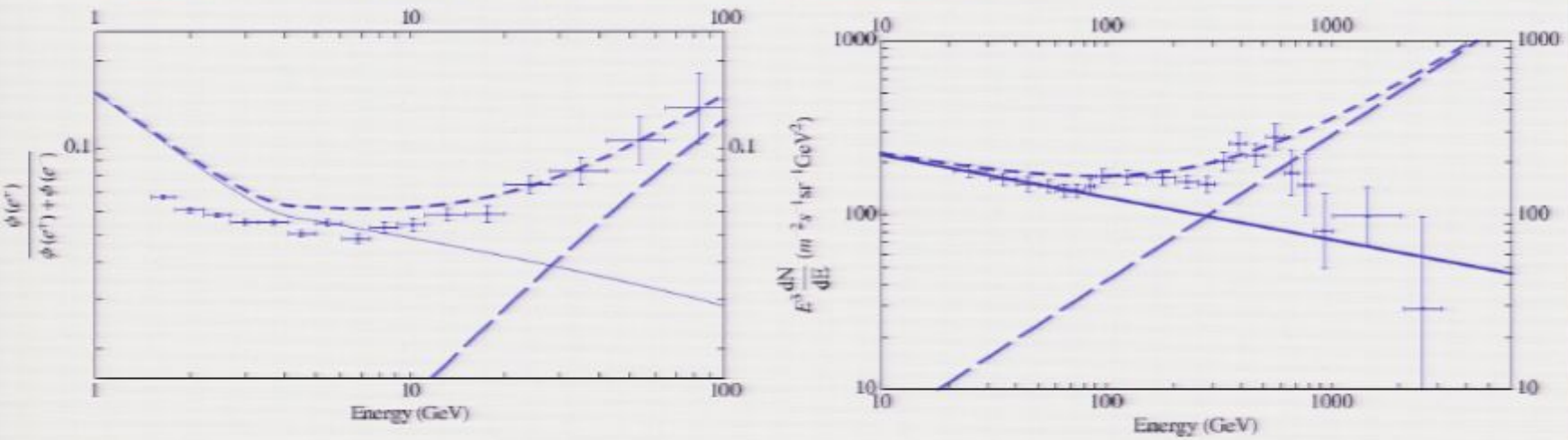
Or, a message from dark side?

- Neutralinos and Kaluza-Klein particles can annihilate to produce e^+,e^- pairs, but mass and branching ratio cross sections are not well defined
- Use the KK particle generator built into GALPROP to test the parameter space
  - Use isothermal dark matter halo model of 4 kpc scale height, local DM density of 0.43 GeV/cm^3 and a KK mass of 620 GeV
- Need an annihilation cross section rate of 1×10^{-23} cm^3/s
- Sharp upper energy cutoff is due to direct annihilation to e^+e^-
  - Delta function source spectrum
- Annihilation rate is about a factor of 230 larger than what is calculated for a thermal relic DM particle
  - Similar factor needed to explain the HEAT positron excess at 30 GeV
- Such large "boost" factors are the subject of much debate



Single Mechanism for Pamela and ATIC

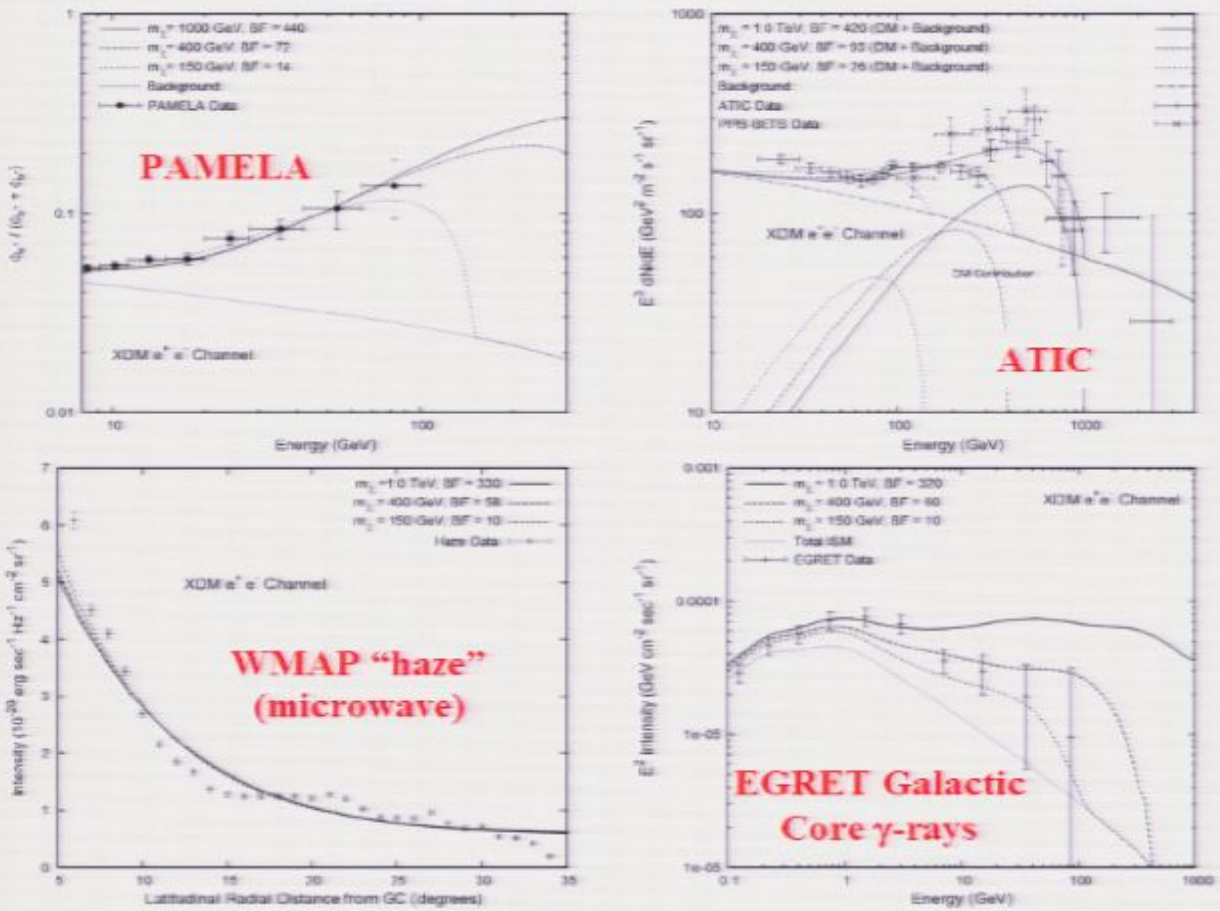
Cholis et al. (arXiv: 0811.3641v1), 2008



- A new power-law component of e+e− fit to the PAMELA excess is extrapolated to ATIC energies, assuming equal parts e+ and e−.
- The fact that the ATIC and PAMELA excesses are connected by such a generic argument suggests that <u>a single mechanism</u>, producing equal numbers of e+ and e−, explains both.

"Exciting" Dark Matter (XDM) annihilations

Cholis et al. (arXiv: 0811.3641v1), 2008



An intermediate light boson represses production of anti-protons.

Panels are for DM annihilation going to light boson → e^+e^-

Reasonable fit to PAMELA, ATIC & WMAP with particle mass of ~1 TeV and similar "boost factors".

Also predicts enhancement of GC gammas

What is next?

- Cosmic Ray Energetics And Mass (CREAM)
  - Cosmic ray composition to ~PeV in a series of Antarctic balloon flights
- A re-flight of ATIC has been proposed to NASA
  - Refurbish the ATIC-4 configuration with the 10-layer (22 Xo) calorimeter
  - Include a Boron doped plastic scintillator neutron detector for improved electron proton discrimination
    - May provide as much as a factor of 10 improvement
  - A space mission with a calorimeter deeper than Fermi and larger than ATIC could be the next step
- Cosmic Ray Electron Synchrotron Telescope (CREST)
  - ~10 TeV electrons by observing the characteristic linear trail of synchrotron gamma rays generated as the electron passes through the Earth's magnetic field
  - Antarctic balloon flight planned for December 2010
- General Anti-Particle Spectrometer (GAPS)
  - antideuterons < 300 MeV/n
  - Antarctic balloon flight planned for December 2014
- Alpha Magnet Spectrometer (AMS)
  - Search for dark matter by measuring positrons, antiprotons, antideuterons and γ-rays with a single instrument
  - Launch for ISS in September 2010

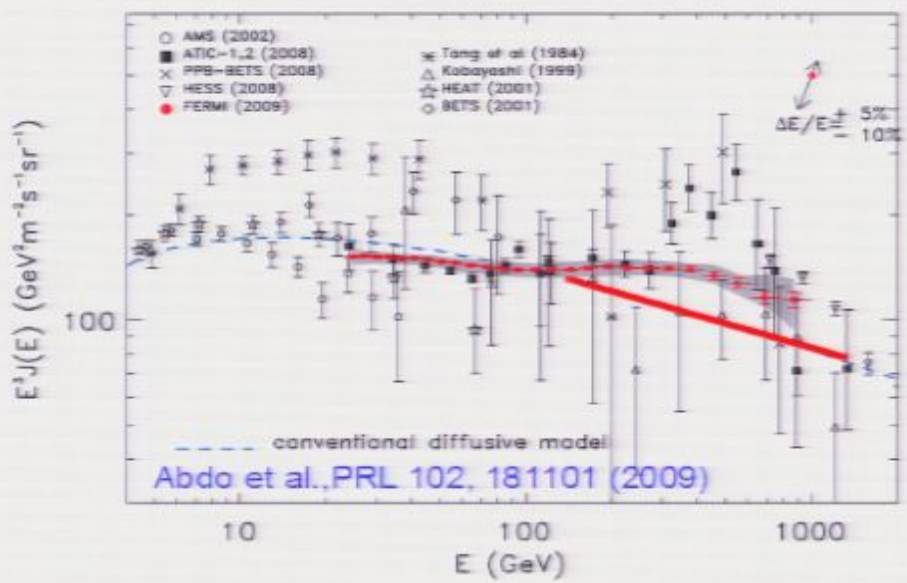
ATIC vs. Fermi

- ATIC BGO calorimeter
  - 18 - 22 Xo
  - fully contains the electron shower
  - energy resolution of ~2 %

- Fermi CsI calorimeter
  - **Thinner**, 8.6 Xo
  - showers are not fully contained
  - distribution of the reconstructed energy is asymmetric with a longer tail toward lower energies
  - **Poorer energy resolution** ~20%

Analysis method comparison

- ATIC analysis uses quantities measured during flight (e.g. atmospheric secondary gammas) to set selection cuts and determine background rates.
- In Fermi much of the electron identification and background rejection is based on simulations only.



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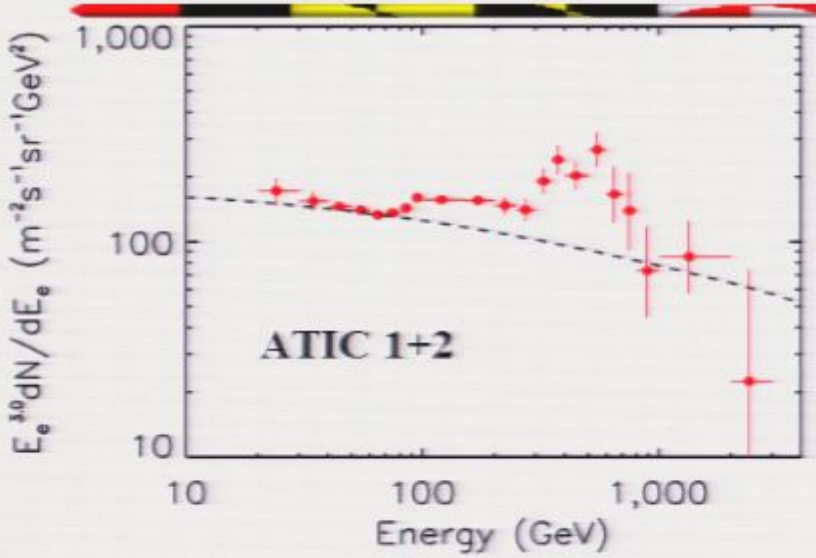

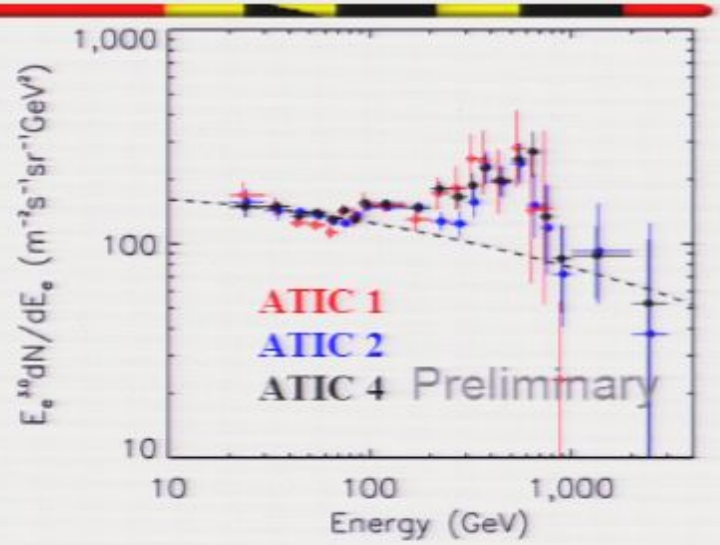

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Slide courtesy of J. P. Wefel