Positron Annihilations at the Galactic Center

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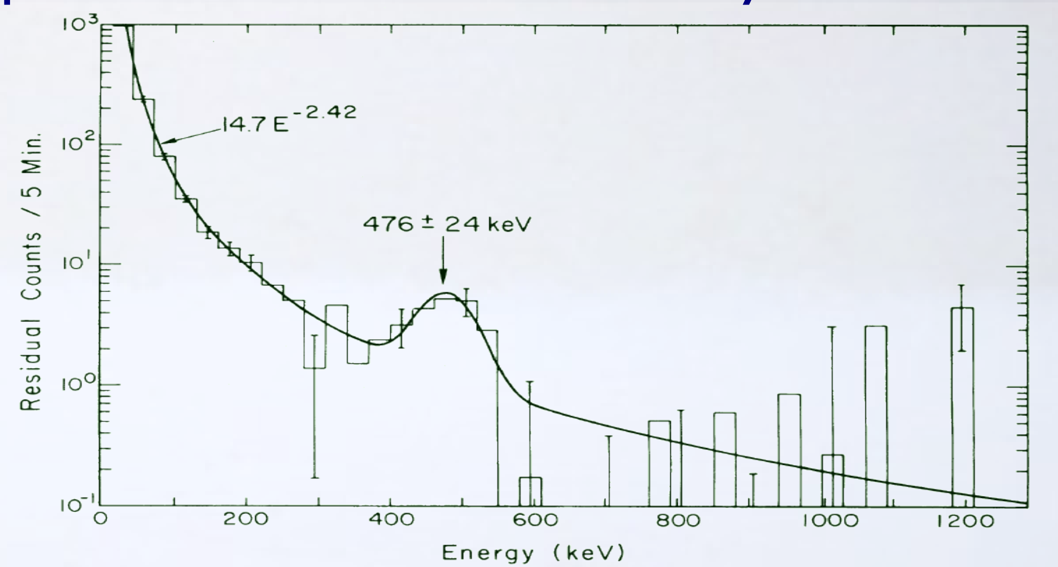
origin of positrons

- first gamma radiation spectral feature out of solar system

johnson haymes 1973



- cosmic rays produce energetic positrons

$p\ p \to p\ n\ \pi^+ \qquad \pi^+ \to \mu^+ \to e^+$

- β^+ isotopes from supernovae supply low energy positrons

^{56}Co, ^{26}Al, ^{44}Ti, ^{22}Na

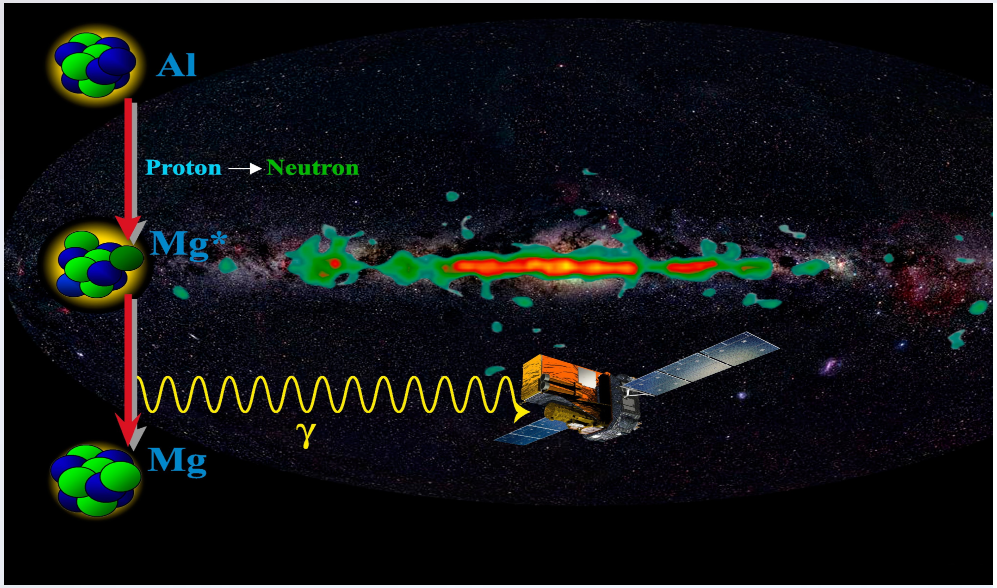
- pair production in compact objects (BHs, pulsars)

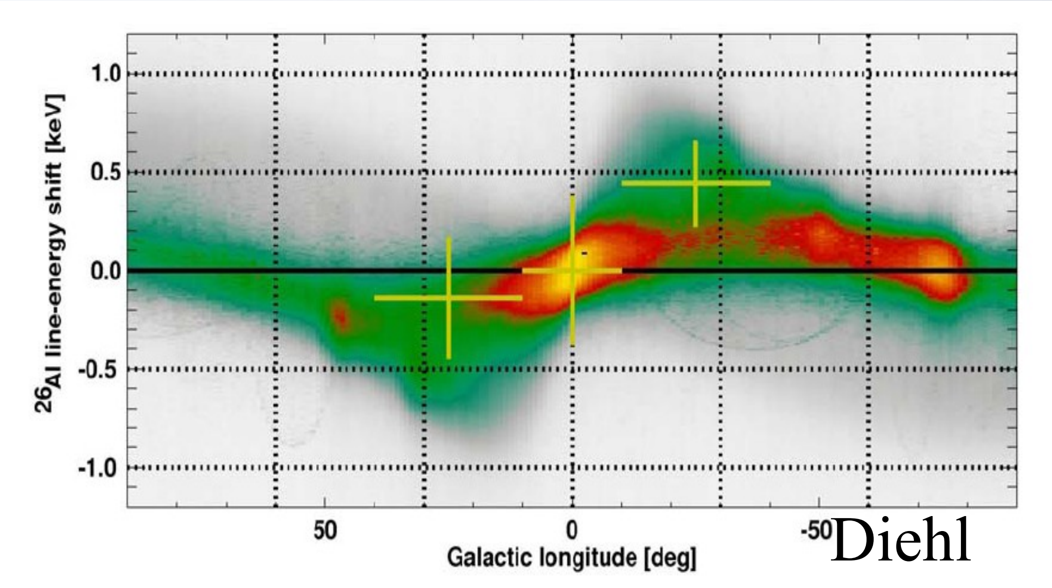
$\gamma^+\ N \to N\ e^+\ e^-$

- other more exotic mechanisms?

supernovae and ^{26}Al Line

1.809 MeV decaying Aluminium line



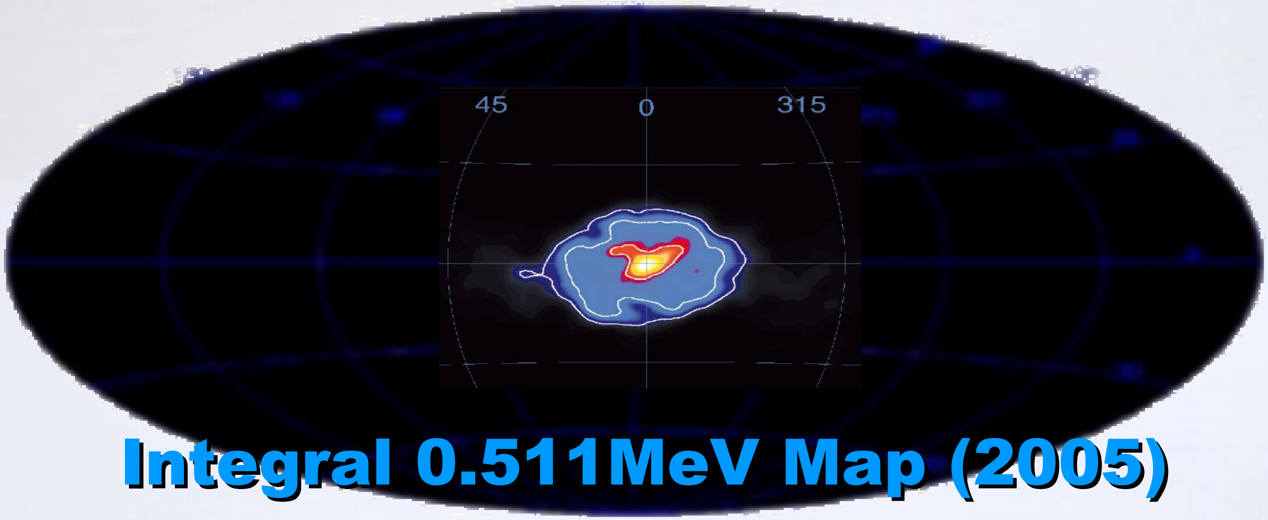


- traces a population of massive, young stars
- doppler shift due to differential rotation of the galaxy

- what about the distribution of positron annihilation line?

0.511 MeV annihilation line

- angular distribution: ~ 8° at FWHM (Knödlseder, 2005)

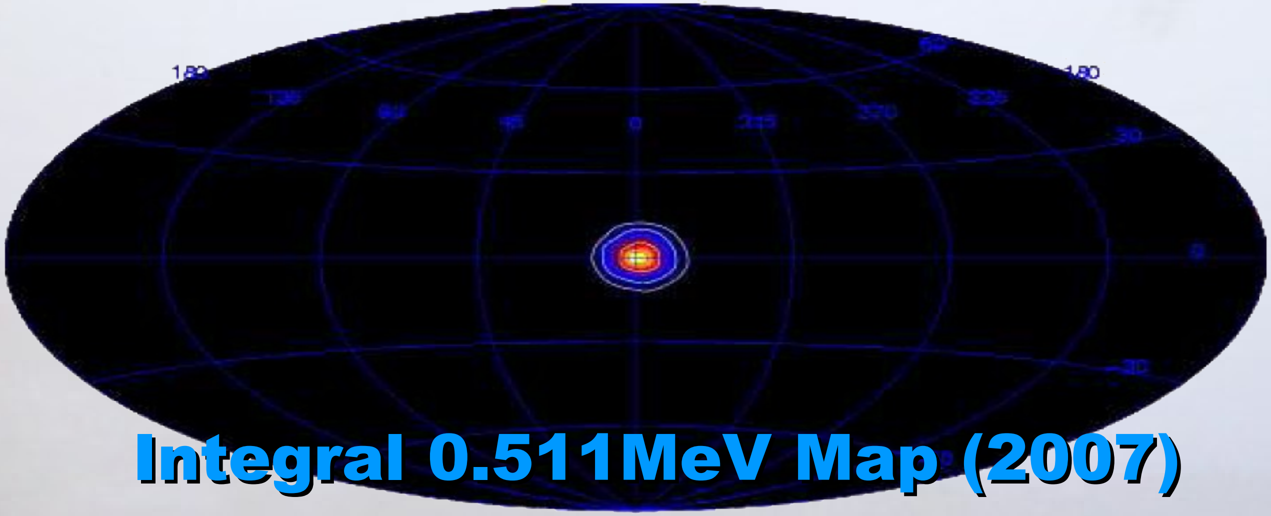


Integral 0.511MeV Map (2005)

- annihilation rate: ~10^{50} positrons/year

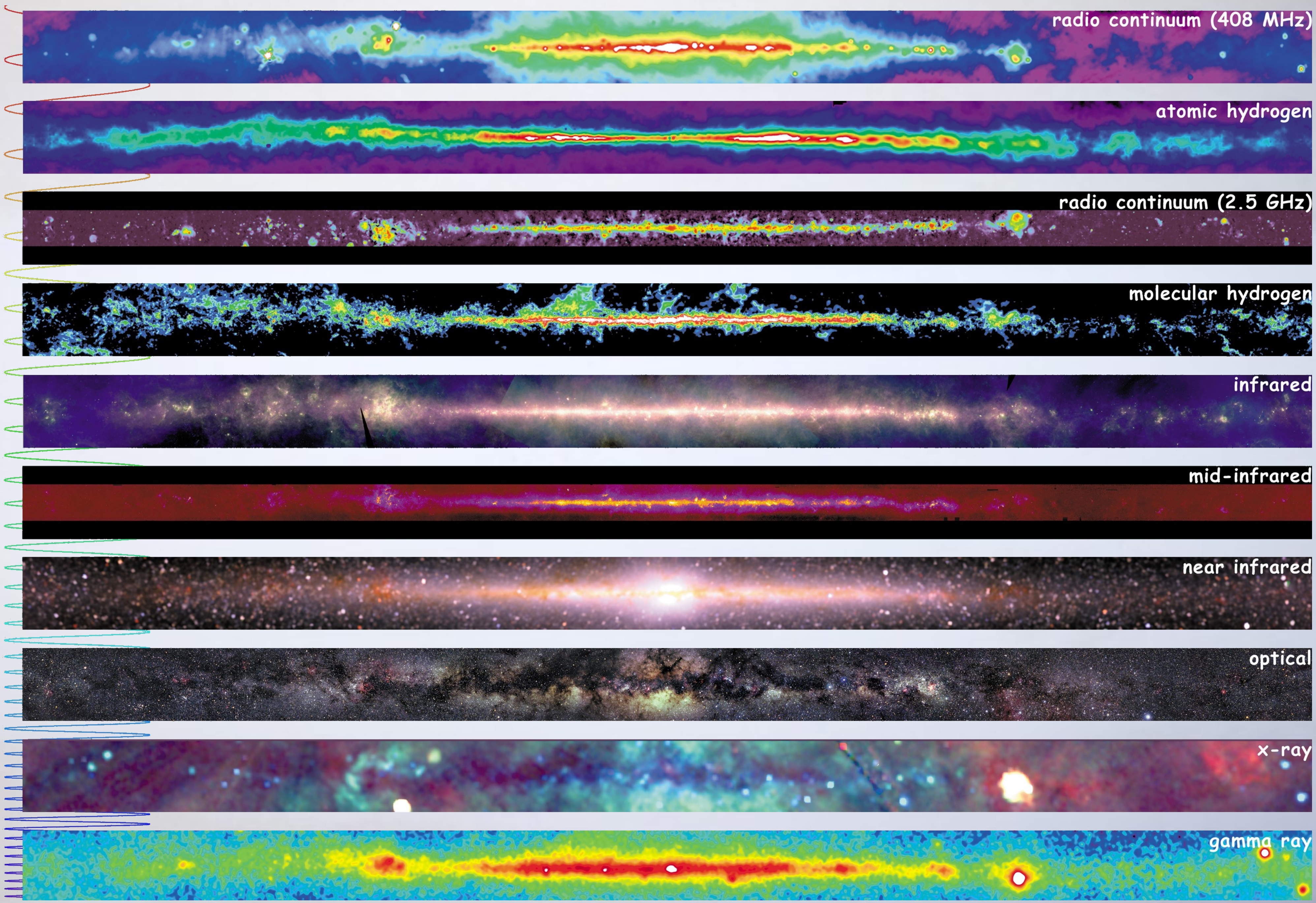
- 0.511 kev line flux: ~10^{-3} photons cm^{-2} s^{-1}

- angular distribution: ~ 6° at FWHM   (Weidenspointer, 2007)



Integral 0.511MeV Map (2007)

views of Milky Way



many models / studies on positrons

astrophysical scenarios

- *casse, cordier, paul and schanne, hypernovae/GRB*
- *bertone, kusenko, palomares-ruiz, pascoli and semikoz, GRBs*
- *milne, kurfess, kinzer and leising, SNe and positron annihilation*
- *prantzos, magnetic fields* - *guessoum jean prantzos, micro quasars*
- *totani, supermassive black hole Sgr A**
- *wang pun cheng, pulsar winds*
- *beacom and yüksel, inflight annihilation constraint on positrons* *...among many others ...*

exotic mechanisms

- *ferrer and vachaspati, superconducting cosmic strings*
- *frampton and kephart, primordial black holes*
- *picciotto and pospelov, unstable relics*
- *kasuya and takahashi, q balls*
- *kawasaki and yanagida, moduli decay* *....among many others ...*

dark matter inspired

- *boehm, hooper, silk, casse and paul, mev dark matter*
- *fayet, U-boson detectability, and light dark matter*
- *serpico and raffelt, primordial nucleosynthesis constraints on mev dm*
- *beacom, bell and bertone, gamma-ray constraint on mev dm*
- *ando and komatsu, ahn and komatsu, extragalactic mev dark matter*
- *oaknin and zhitnitsky, color superconducting dm, compact composite object dm*
- *cumberbatch silk starkman, difficulties in cco dm*
- *hooper and wang, axino dark matter*
- *pullen chary kamionkowski Wimps EGRET and positrons*
- *finkbeiner and weiner, XDM pospelov and ritz, ew scale WIMPS* *...among many others ...*

an exotic model: sccs

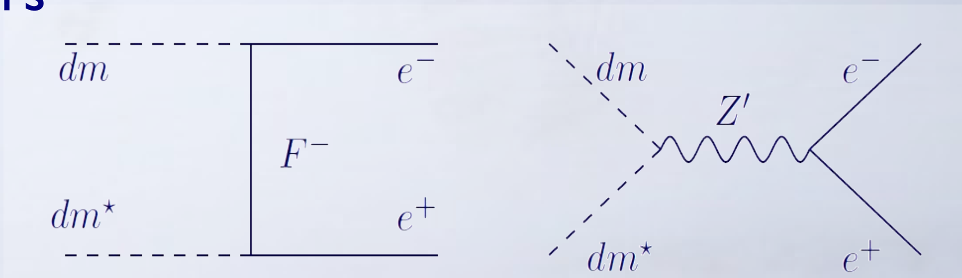
- tangle of superconducting strings frozen at the GC
- moving loops produce current through galactic magnetic fields
- zero modes of charged particles scatter out, once their enery exceed their rest mass
- positron flux depends on field strength and density of strings

ferrer vachaspati 2005 *ferrer mathur vachaspati starkman 2006*

light dark matter candidate: MeVdm

- light dark matter annihilates into e+ e- pairs
- dm^2 distribution in halo resembles observed 511 keV morphology

boehm, hooper, silk, casse, paul 2004



- proposed range is 1-100 MeV, in order to
- prevent production of particles other than e+e- pairs and energy losses are dominated by ionization (no sychrotron or breamsstrahlung)

exciting dark matter: xdm

- a WIMP candidate with an <u>excited state</u> 1-2 MeV above the ground state, which may be collisionally excited and de-excites by e+e- pair emission

finkbeiner and weiner, XDM
pospelov and ritz, ew scale WIMPS

dark anti-matter

- dark matter in the form of antimatter nuggets providing 511keV photons and more

oaknin and zhitnitsky, color superconducting dm, compact composite object dm

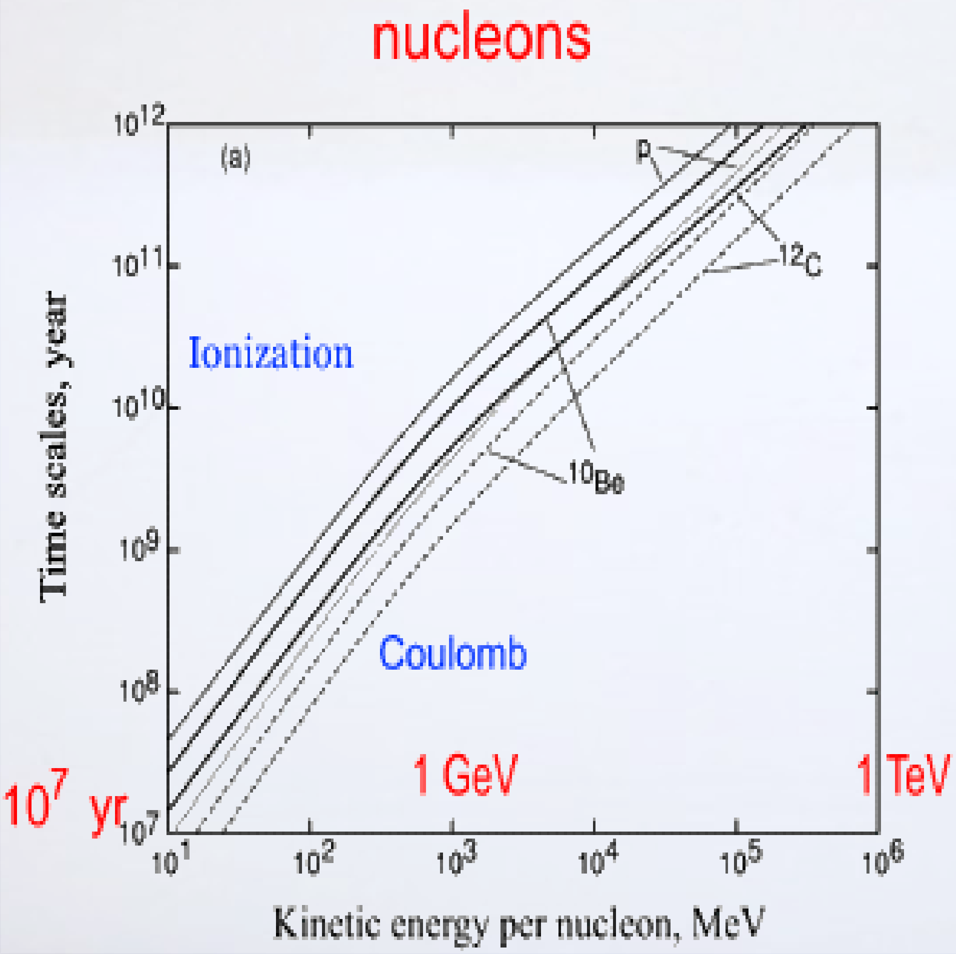
all these models need to be tested

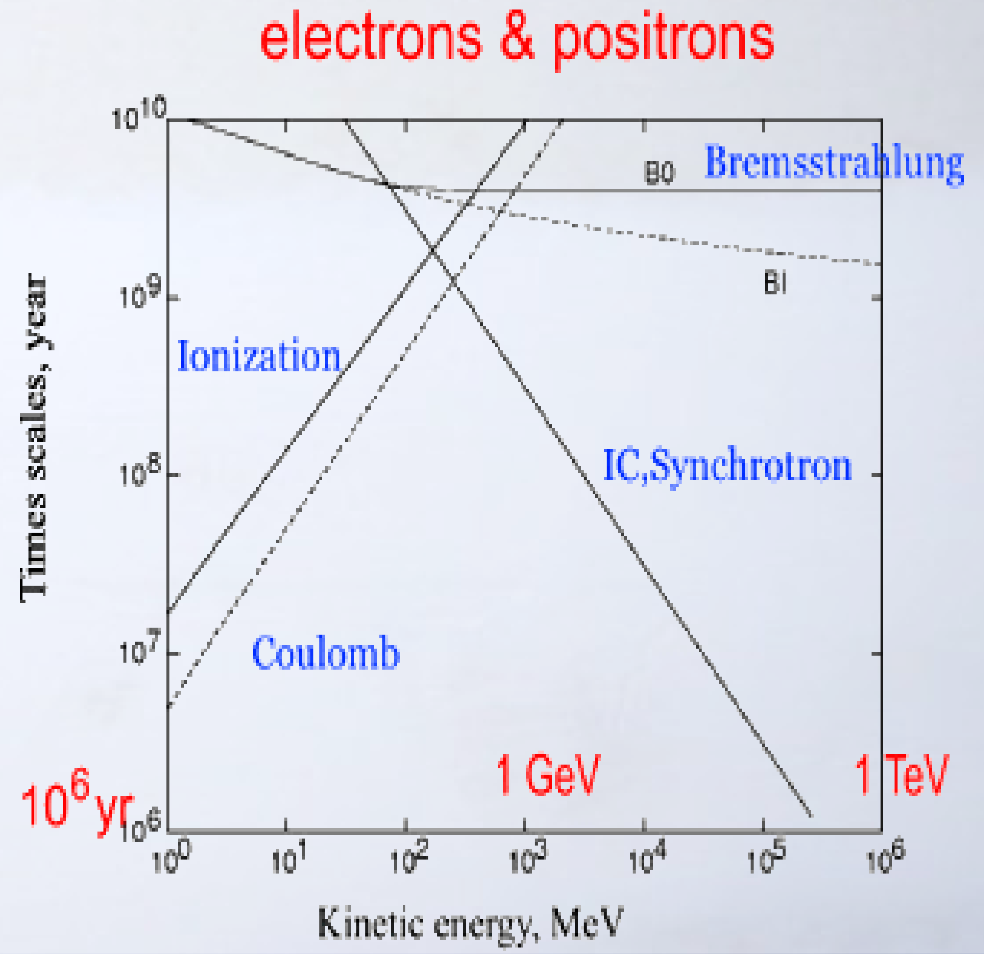
- energy scale of injected positrons can provide important clues about the underlying production mechanism

energy loss rate of charged particles

positron enery loss rate in neutral hydrogen medium:

strong moskalenko 1998



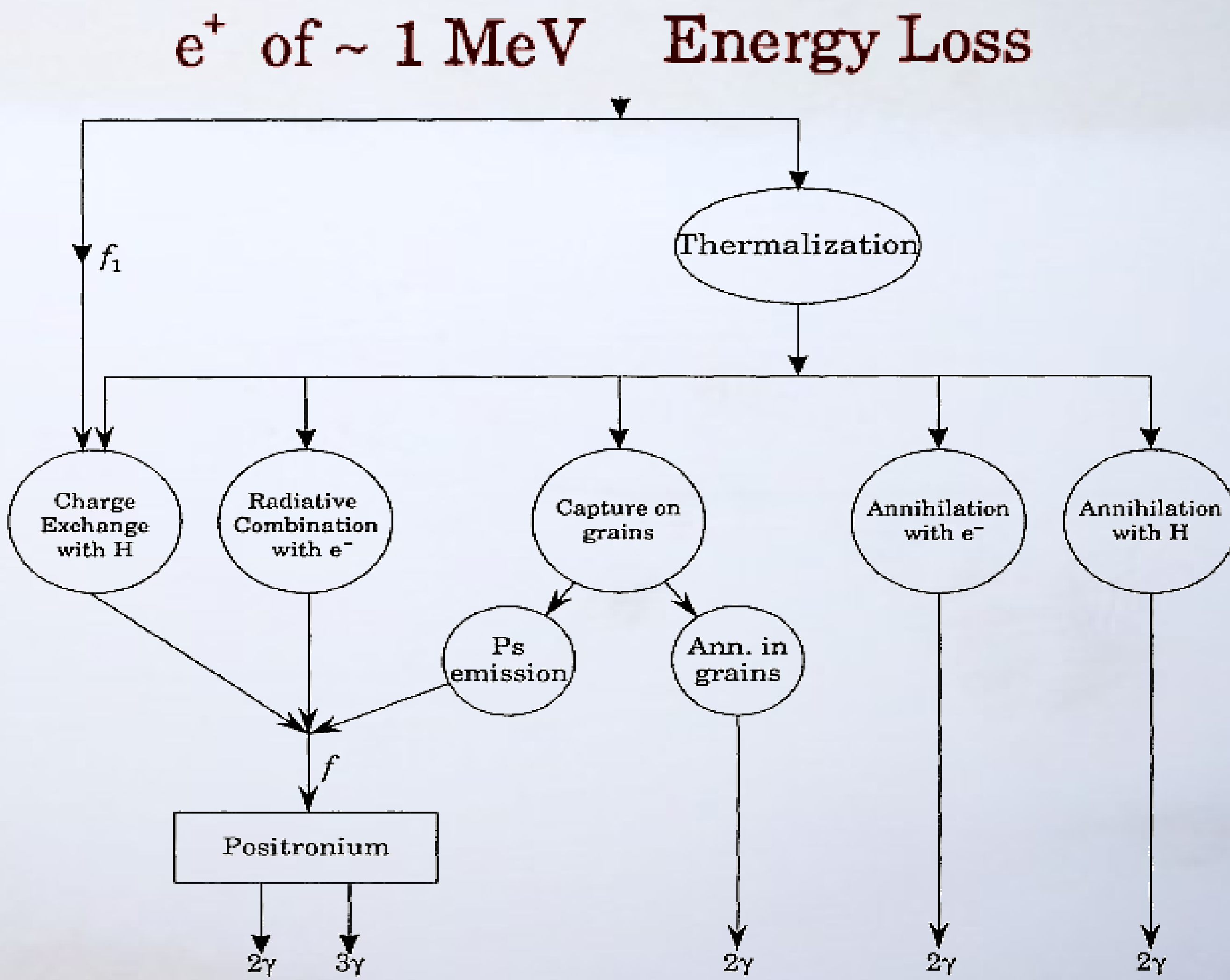


$$\left|\frac{dE}{dx}\right| \simeq \frac{7.6\times10^{-26}}{\beta^2}\left(\frac{n_{\rm H}}{0.1\ {\rm cm}^{-3}}\right)(\ln\gamma + 6.6)\,\frac{\rm MeV}{\rm cm}$$

annihilation of non-relativistic positrons

f: fraction of positrons forming positronium before annihilation

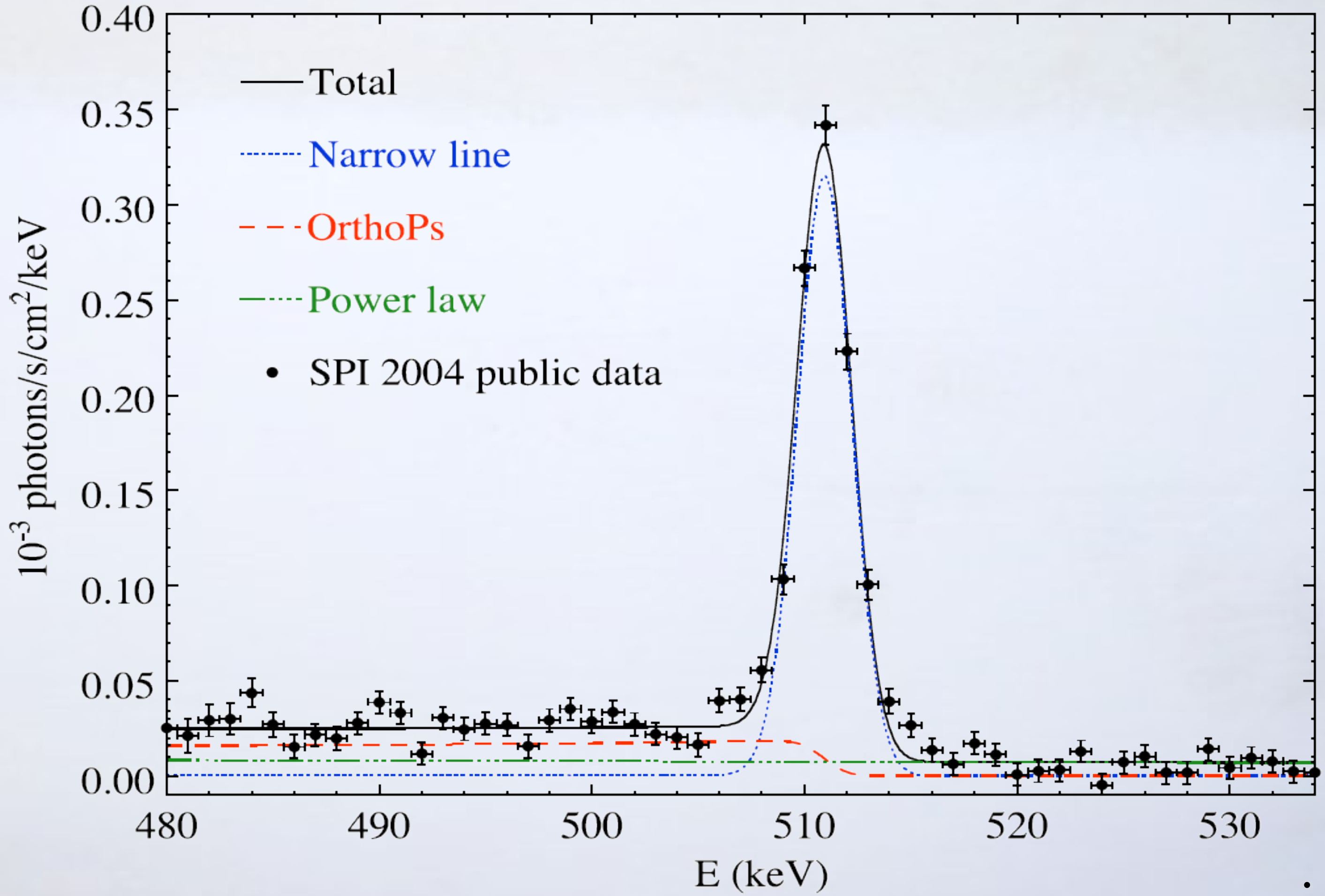
guessoum jean gillard 2005, guessoum ramaty lingenfelter 1991



annihilation of non-relativistic positrons

for each annihilated positron, number of photons produced:

2 (1 – ¾ f) → 2γ line 3 (¾ f) → 3γ continuum



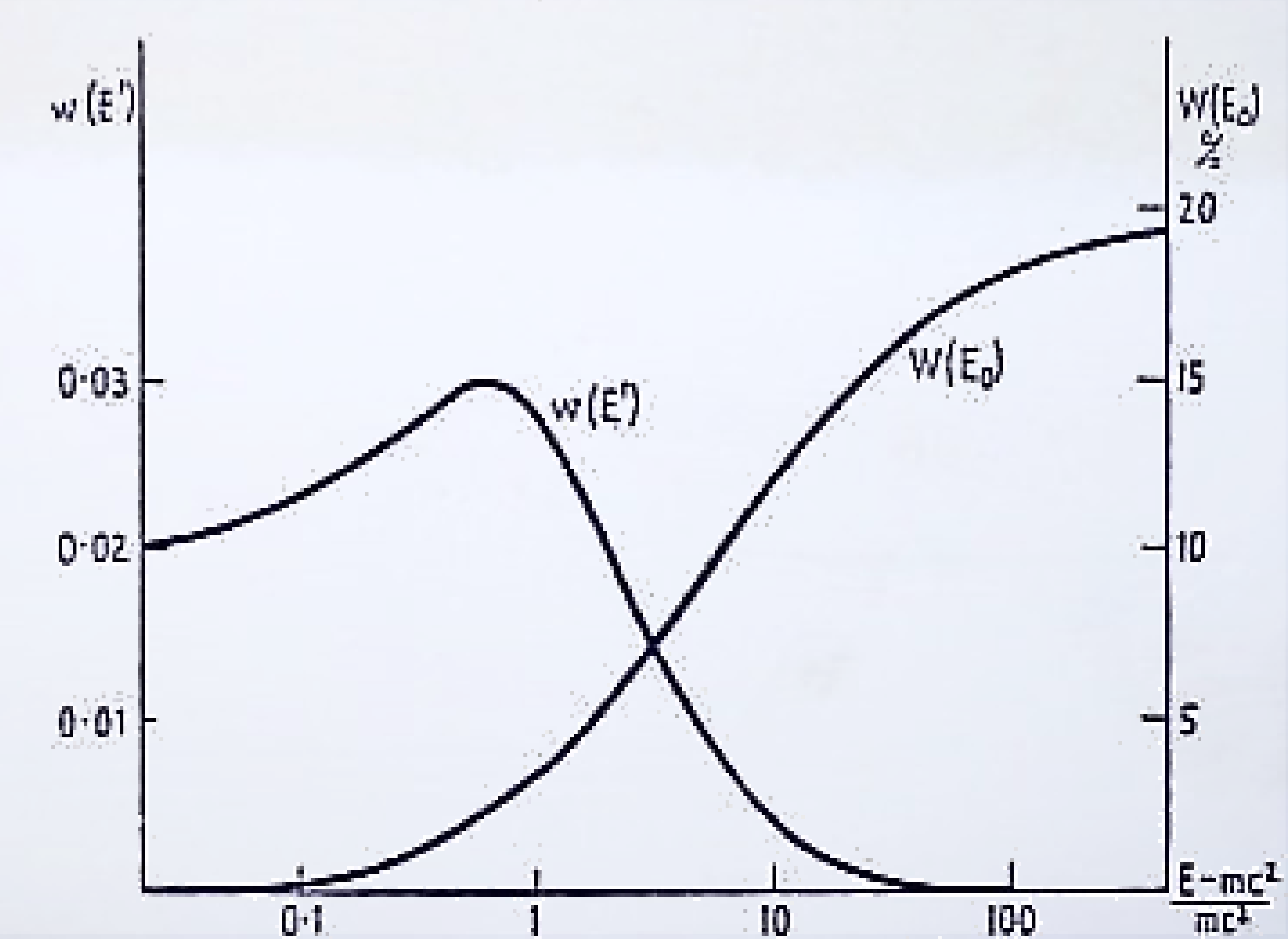
jean et al 2005

- line/continuum flux ratio suggests f ~ 1

inflight annihilations

- "up to 20% of ultra-relativistic positrons may annihilate inflight"

  heitler, quantum theory of radiation (1954)



- 1.4 % (5.5 %, 11 %) of positrons injected at 1 (3, 10) MeV may be annihilated in flight until they become non-relativistic

survival of positrons

- annihilation cross section calculated by Dirac, 1930

$$\sigma = \frac{\pi r_e^2}{\gamma + 1}\left[\frac{\gamma^2 + 4\gamma + 1}{\gamma^2 - 1} \ln(\gamma + \sqrt{\gamma^2 - 1}) - \frac{\gamma + 3}{\sqrt{\gamma^2 - 1}}\right]$$

- fraction annihilated when positrons travel by "dx"

$$\frac{dN(E)}{N(E)} = n_{\mathrm{H}}\sigma(E)dx = n_{\mathrm{H}}\sigma(E)\frac{dE}{|dE/dx|}$$

$$P_{E_0 \to E} = \frac{N(E)}{N(E_0)} = \exp\left[-n_{\mathrm{H}}\int_E^{E_0} \sigma(E')\frac{dE'}{|dE'/dx|}\right]$$

- P: terminal survival probability (positrons lost all their energy)

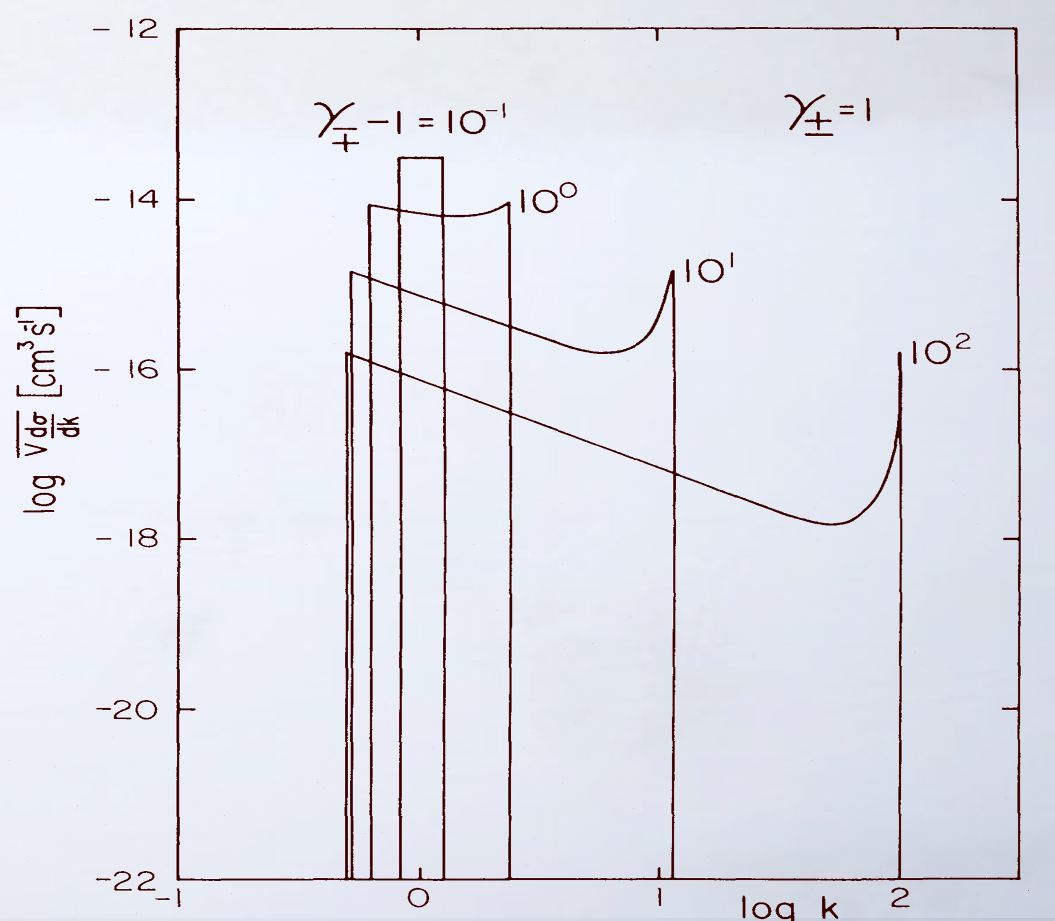
$$\frac{\Phi_{\mathrm{IA}}}{\Phi_{0.511}} = \frac{2(1 - P)}{2(1 - 3f/4)P} = \frac{1}{1 - 3f/4}\frac{1 - P}{P}$$

inflight annihilation photons

$$\frac{d\sigma}{dk} = \frac{\pi r_e^2}{\gamma^2\beta^2}\left(\frac{-(3+\gamma)/(1+\gamma)+(3+\gamma)/k-1/k^2}{[1-k/(1+\gamma)]^2}-2\right)$$

- the differential cross section is peaked at the endpoints
- as injected positrons lose energy, the low-energy peak remains below 0.511 MeV
- while the high-energy peak moves down slowly, producing a long tail

stecker 1969, svensson 1982, aharonian atoyan sunyaev 1982



$$\frac{d\Phi_{\rm IA}}{dk} = \frac{\Phi_{0.511}}{1-3f/4}\,\frac{n_{\rm H}}{P}\int^{E_0} P_{E_0\to E}\,\frac{1}{2}\,\frac{d\sigma}{dk}\,\frac{dE}{|dE/dx|}$$

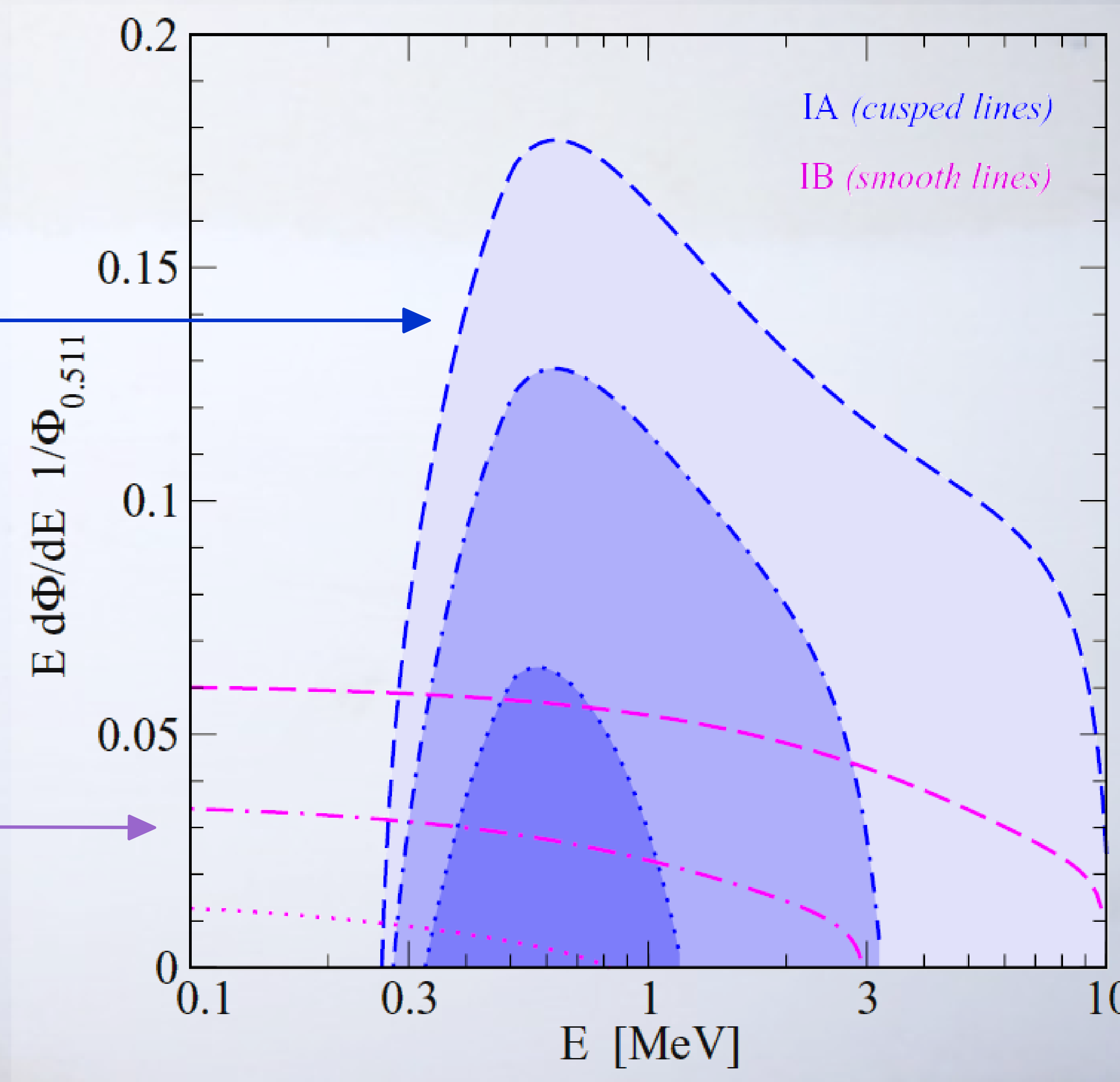
inflight annihilation spectrum

injection energy

1, 3, 10 MeV

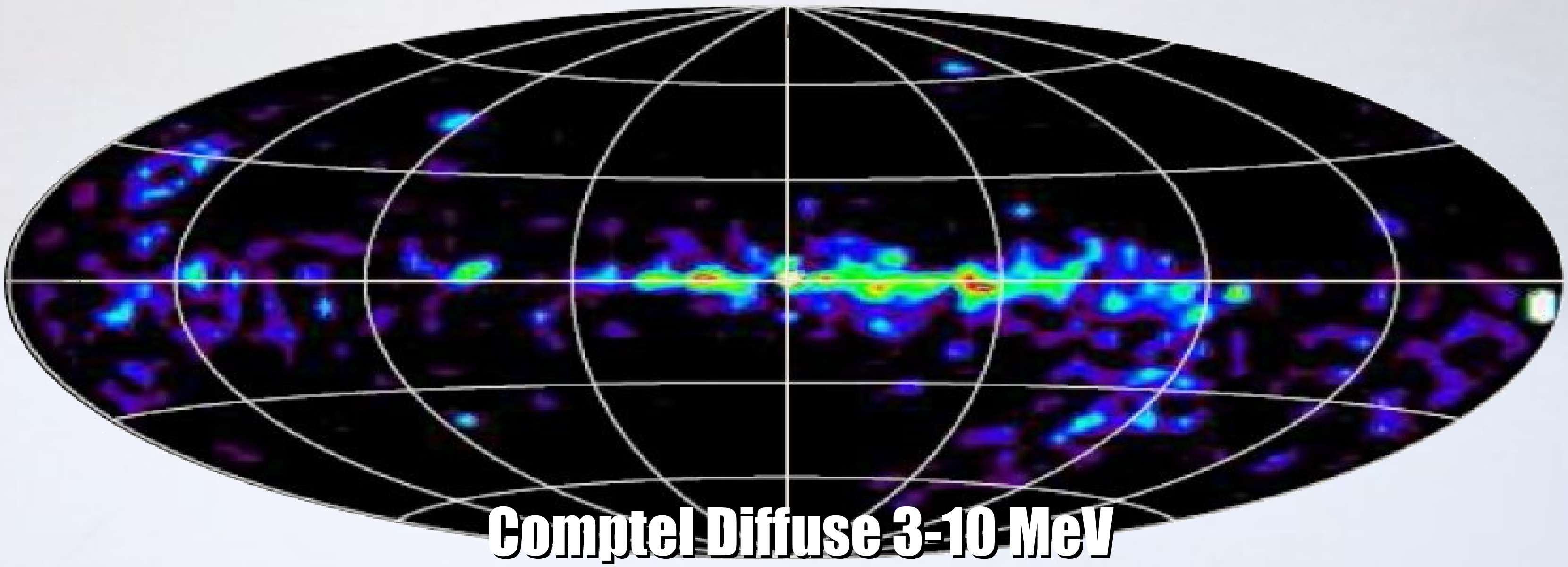
- inflight annihilation gamma ray spectrum

- internal bremsstrahlung gamma ray spectrum



beacom yüksel PRL 97, 071102 (2006)

power law fit to measured diffuse



- in the disk, diffuse flux can be approximated as:

$$\frac{d\Phi}{dE} = 0.013 \left(\frac{E}{\mathrm{MeV}}\right)^{-1.8} \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{MeV}^{-1}$$

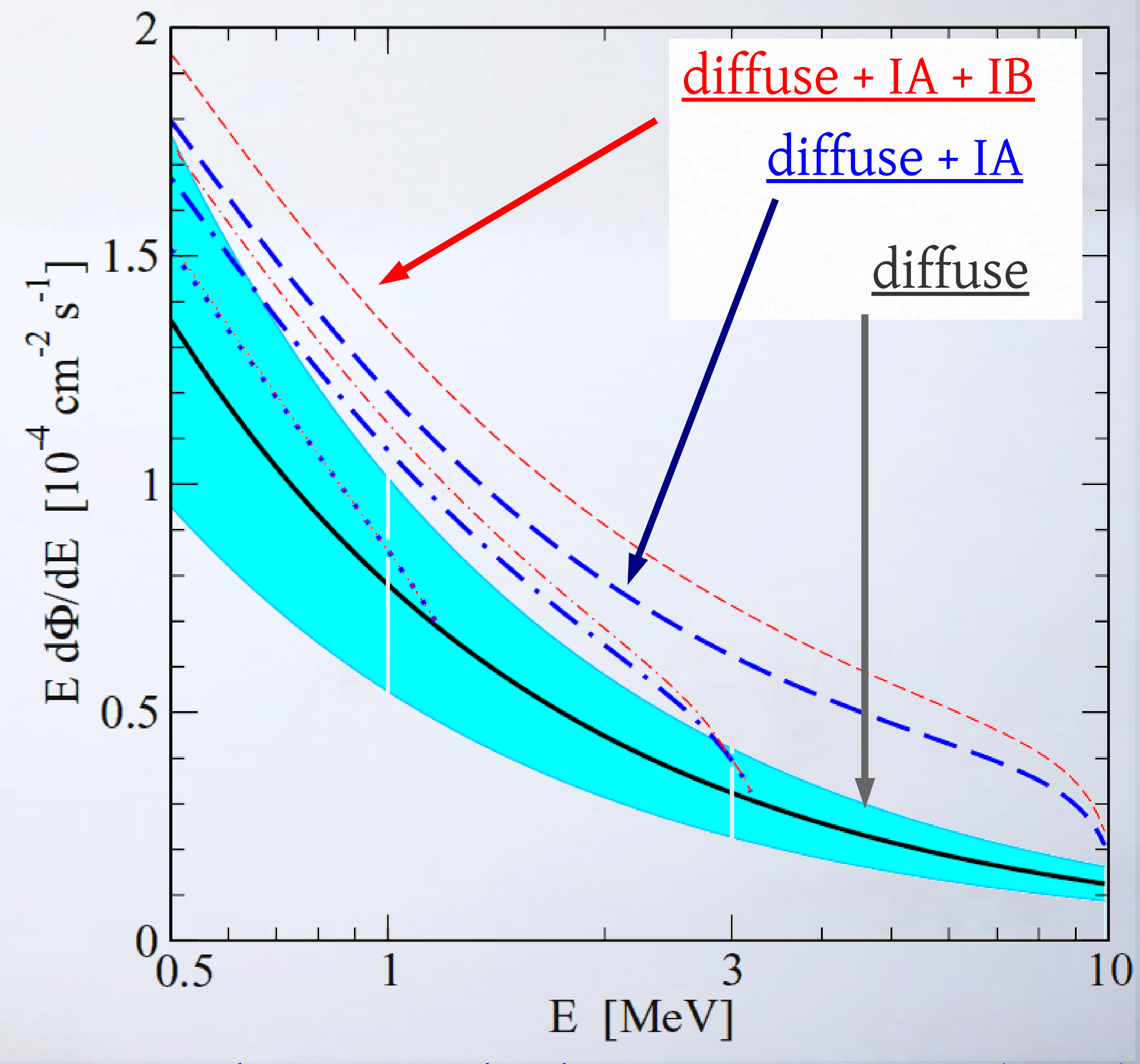
- agrees with diffuse flux below 1 MeV from INTEGRAL

strong et al 2005

constraints on positron injection energy

- compare diffuse flux to excess from inflight annihilations at the GC

- if positrons injected with energies over 3 MeV, the radiation from inflight annihilations would significantly exceed the diffuse gamma-ray flux observations



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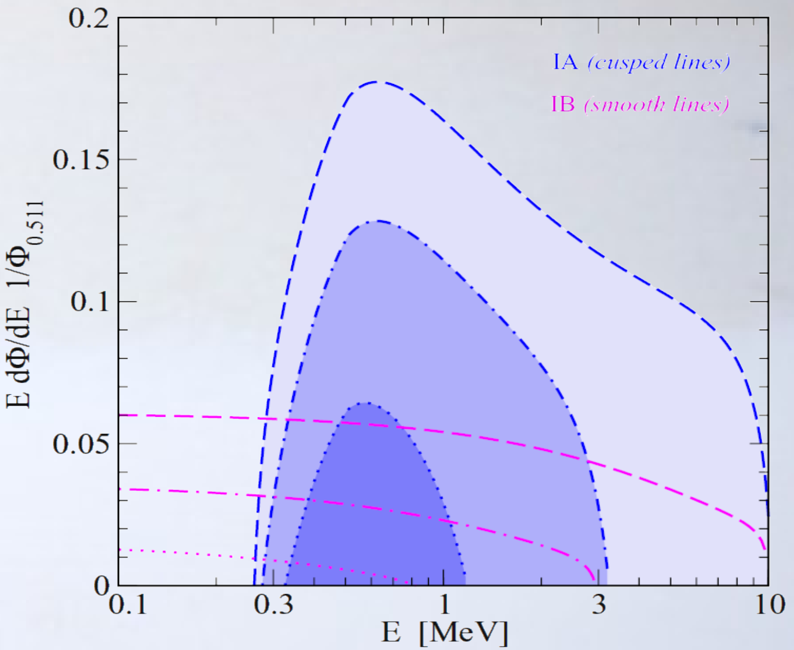
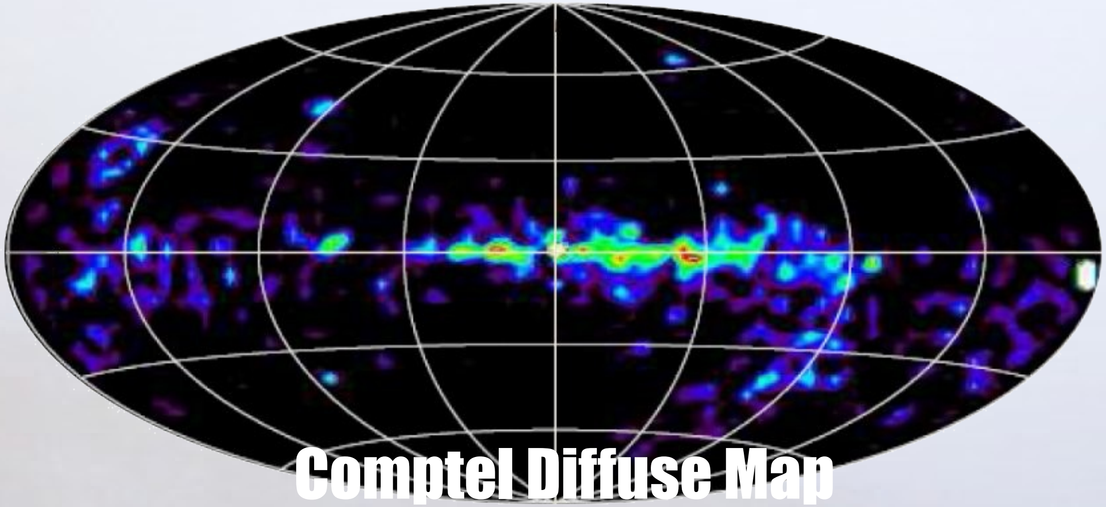
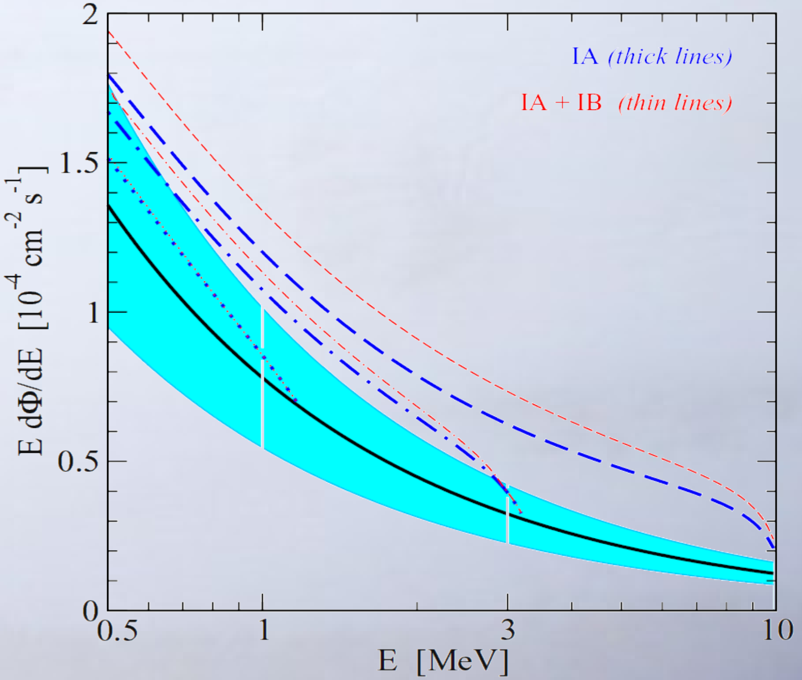
summary


Integral 0.511MeV Map (2007)


IA (cusped lines)
IB (smooth lines)
E dΦ/dE 1/Φ$_{0.511}$
E [MeV]
0.2
0.15
0.1
0.05
0
0.1
0.3
1
3
10


Comptel Diffuse Map


IA (thick lines)
IA + IB (thin lines)
E dΦ/dE [10^{-4} cm^{-2} s^{-1}]
E [MeV]
2
1.5
1
0.5
0
0.5
1
3
10