An introduction to gamma-ray astrophysics

Andi Hektor
NICPB, Tallinn, Estonia
andi.hektor@cern.ch

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Outlines

- **Astrophysical sources of gamma-rays:** (Galactic and extragalactic) point sources and diffuse emission
- **Typical spectrum of common point sources:** pulsar, supernova remnant, active galactic nucleus etc
- Components and spectra of the diffuse emission
- **Beyond standard astrophysics:** Dark Matter & axion
- Annoying practicalities of experimental gamma ray astronomy
- **Gamma ray telescopes:** satellites (Fermi LAT) and Cherenkov telescopes

(1) Why are we interested in cosmic gamma rays?

- Astrophysical sources of gamma rays
- Exotic sources of gamma rays: Dark Matter and "New Physics"

(2) Cosmic production mechanisms of gamma rays

- Gamma ray as a messenger of non-thermal "violent" physics
- Astrophysical production mechanisms: (i) pion production and decay, (ii) inverse Compton production,
  (iii) bremsstrahlung and (iv) synchrotron production
- "New Physics" mechanisms: (i) annihilation or decay of Dark Matter and (ii) other exotics
- Energy spectrum of cosmic gamma rays
- Spatial distribution of cosmic gamma rays

(3) Gamma ray point sources

- Galactic: neutron stars, black holes, Central Black Hole
- Extragalactic: Active Galactic Nucleus

(4) Extended sources of gamma rays

- Galactic: Supernova Remnants, molecular clouds and diffuse gamma rays
- Extragalactic: galaxy clusters (are they?)
- “New Physics”: annihilation/decay of Dark Matter

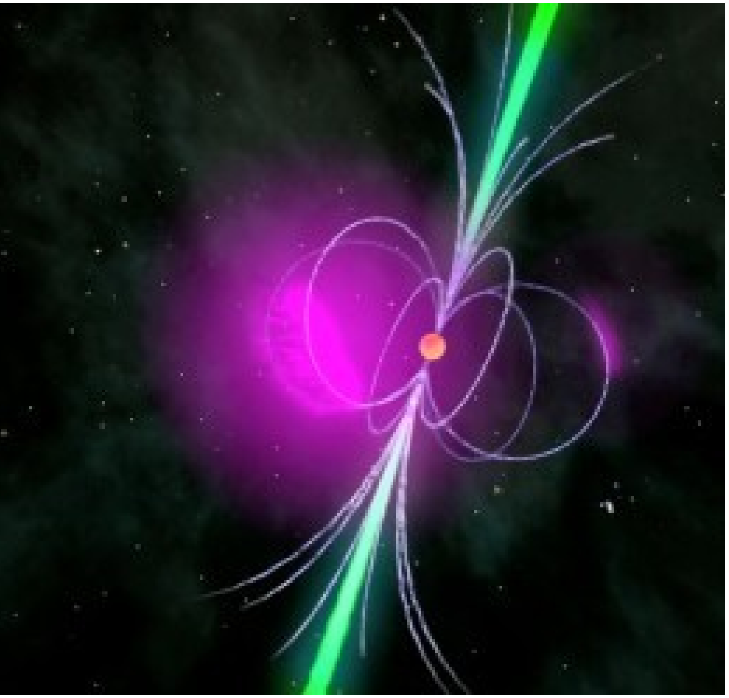
(5) Propagation of gamma rays

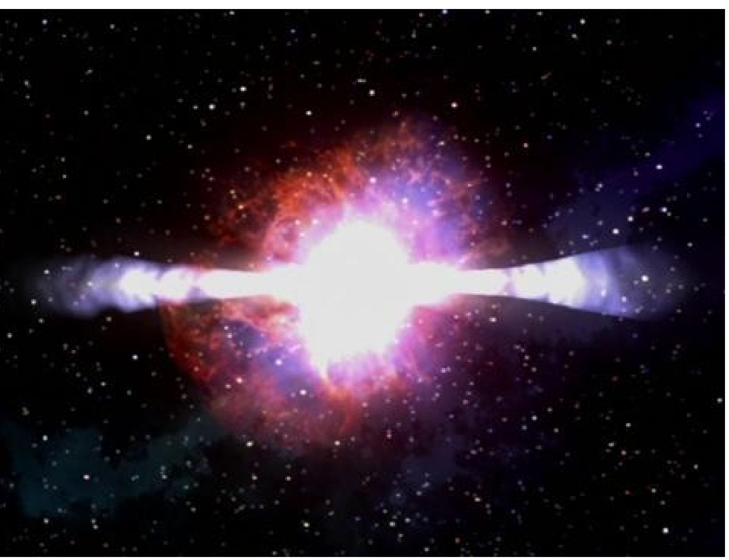
- Absorption mechanisms
- Transparency of the Galaxy
- Absorption in the cosmological scales, the cosmic "gamma ray window"

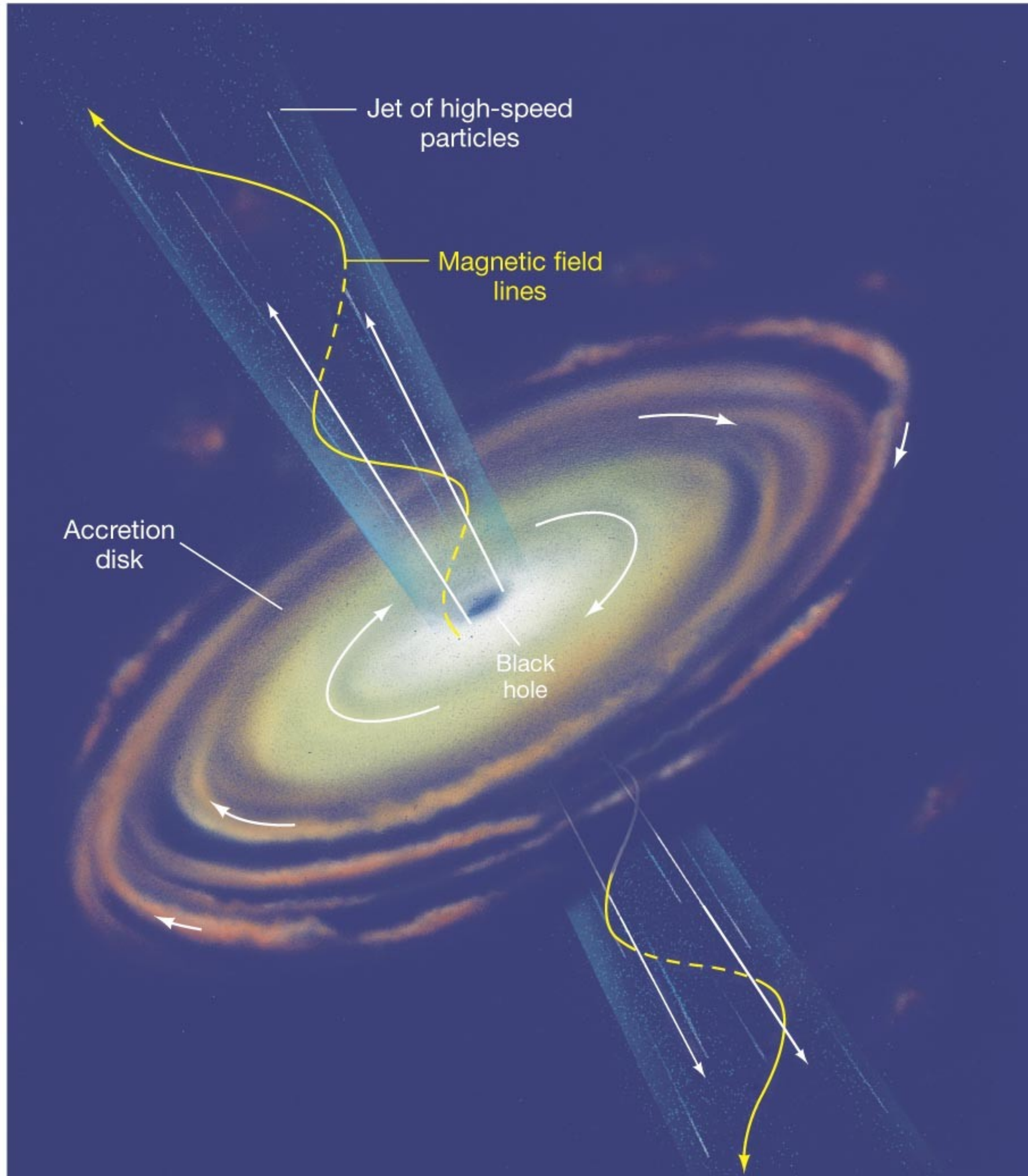
(6) Intro to gamma ray telescopes

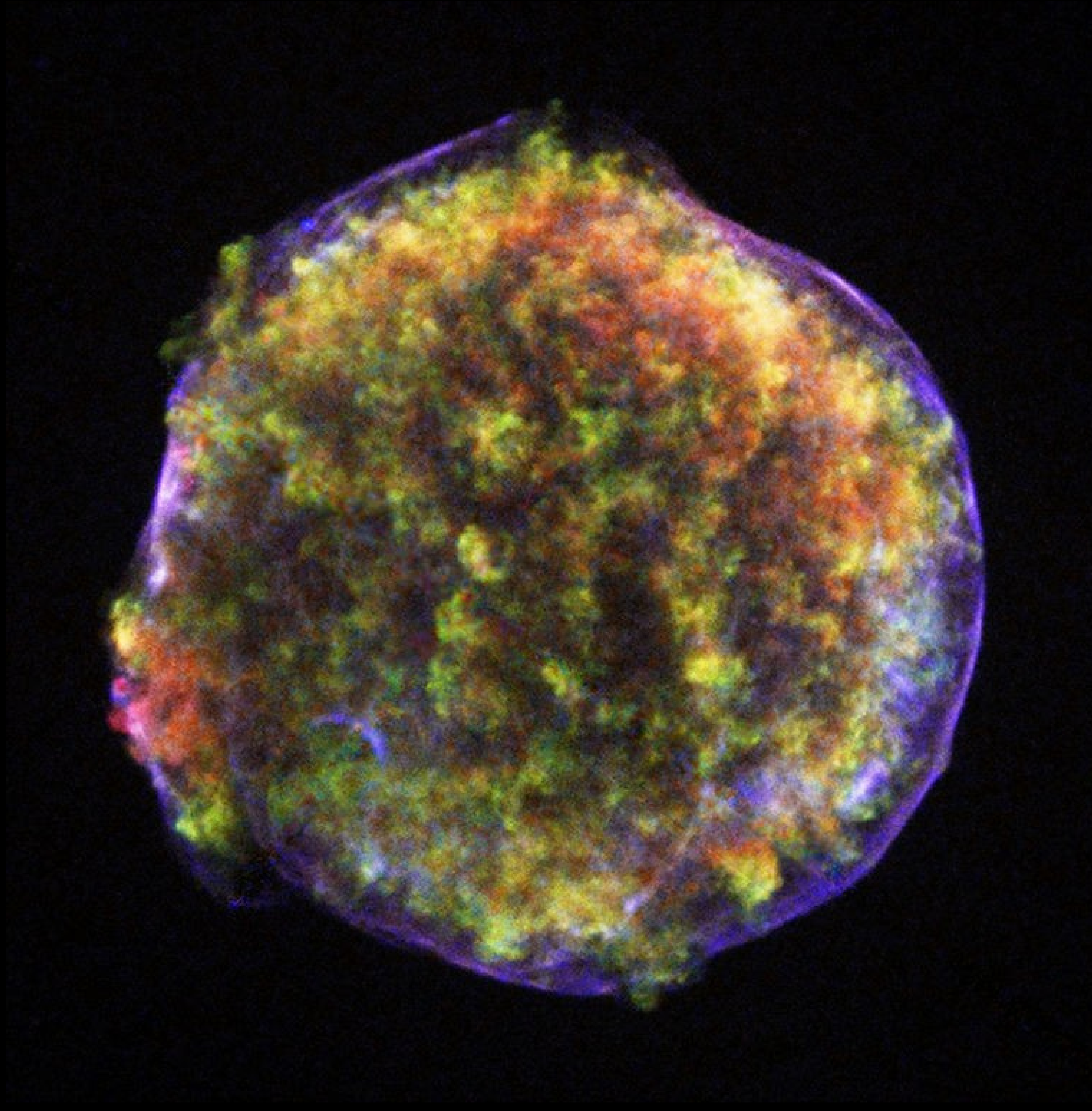
- Satellite telescopes: Fermi satellite
- Terrestrial telescopes: Cherenkov telescopes (MACIG, HESS, VERITAS, CTA)

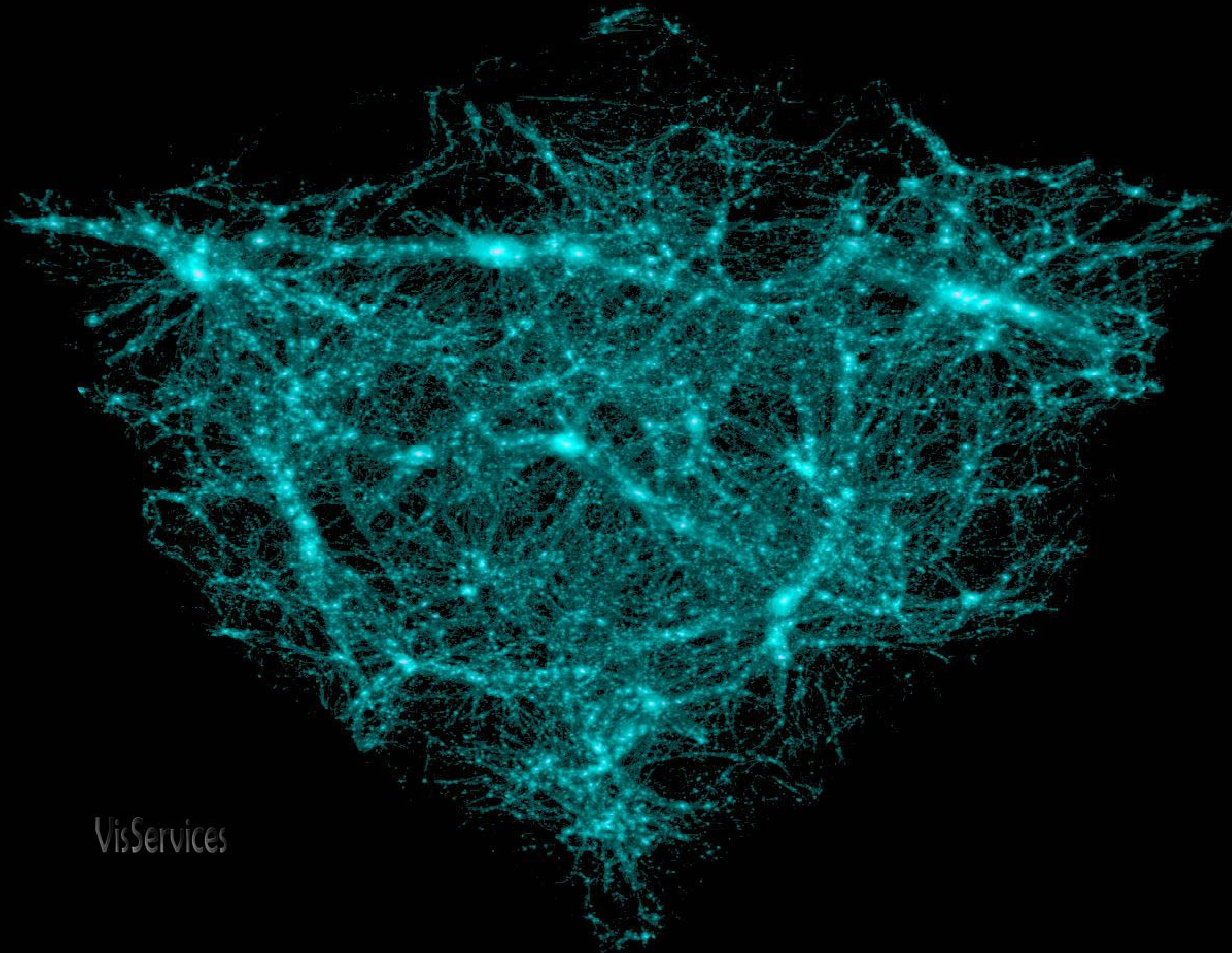
Why are we interested in γ-rays?






Jet of high-speed particles
Magnetic field lines
Accretion disk
Black hole




VisServices

Cosmic production mechanisms of gamma rays

Cosmic production mechanisms of gamma rays

- **Gamma ray as a messenger of non-thermal "violent" physics**
  – To produce a gamma ray, very energetic (charged) particles are needed. For example: E>GeV (inverse Compton, pi0 production, bremsstrahlung), E>TeV (synchrotron radiation)
- **Astrophysical production mechanisms**
  -- pion production and decay (cosmic rays + matter)
  -- inverse Compton production (cosmic rays + CMB/starlight/IR, pulsars)
  -- bremsstrahlung (cosmic rays + matter)
  -- synchrotron production (cosmic rays + magnetic fields)
- **"New Physics" mechanisms:**
  -- annihilation or decay of Dark Matter
  -- other exotics (cosmic strings etc)
- **Energy spectrum of cosmic gamma rays**
- **Spatial distribution of cosmic gamma rays**

Astrophysical production mechanisms

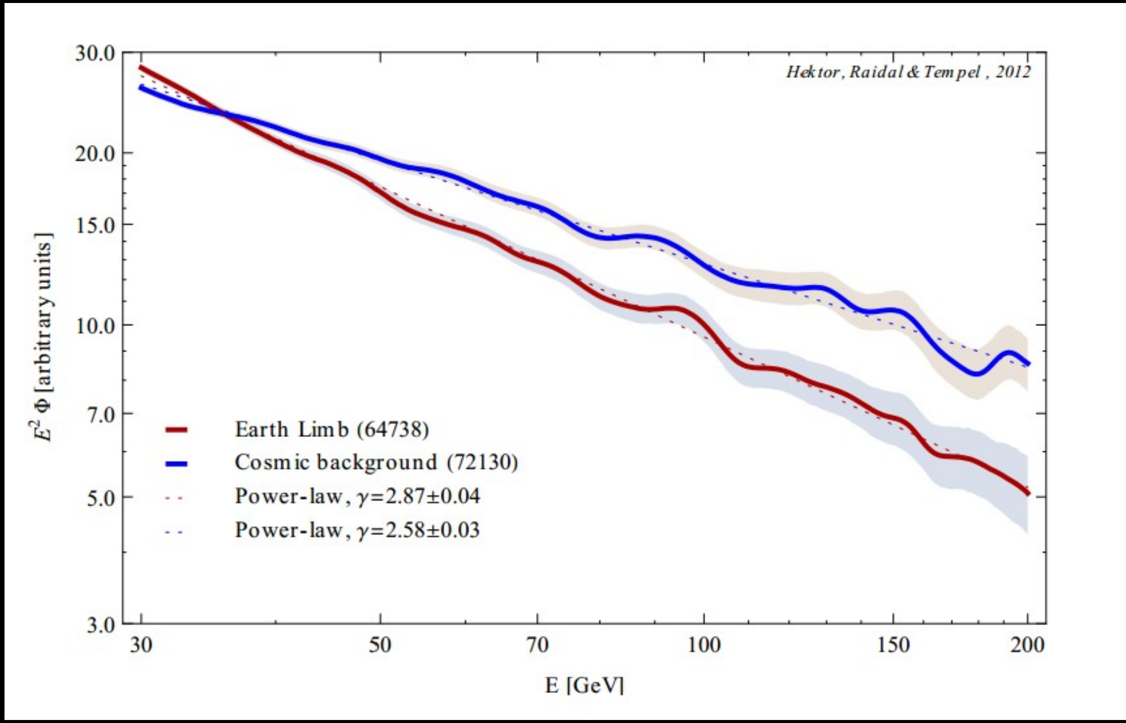
- pion production and decay (cosmic rays + matter)
- inverse Compton production (cosmic rays + CMB/starlight/IR)
- bremsstrahlung (cosmic rays + matter)
- synchrotron production (cosmic rays + magnetic fields)
- Pulsars: IC, syncrotron

To blackboard...

- ***pion production (pi0, pi+)***
- ***inverse Compton***
- ***bremsstrahlung (& synchrotron)***

Energy spectrum of gamma rays

- **Typical spectrum of gamma rays is power law!**



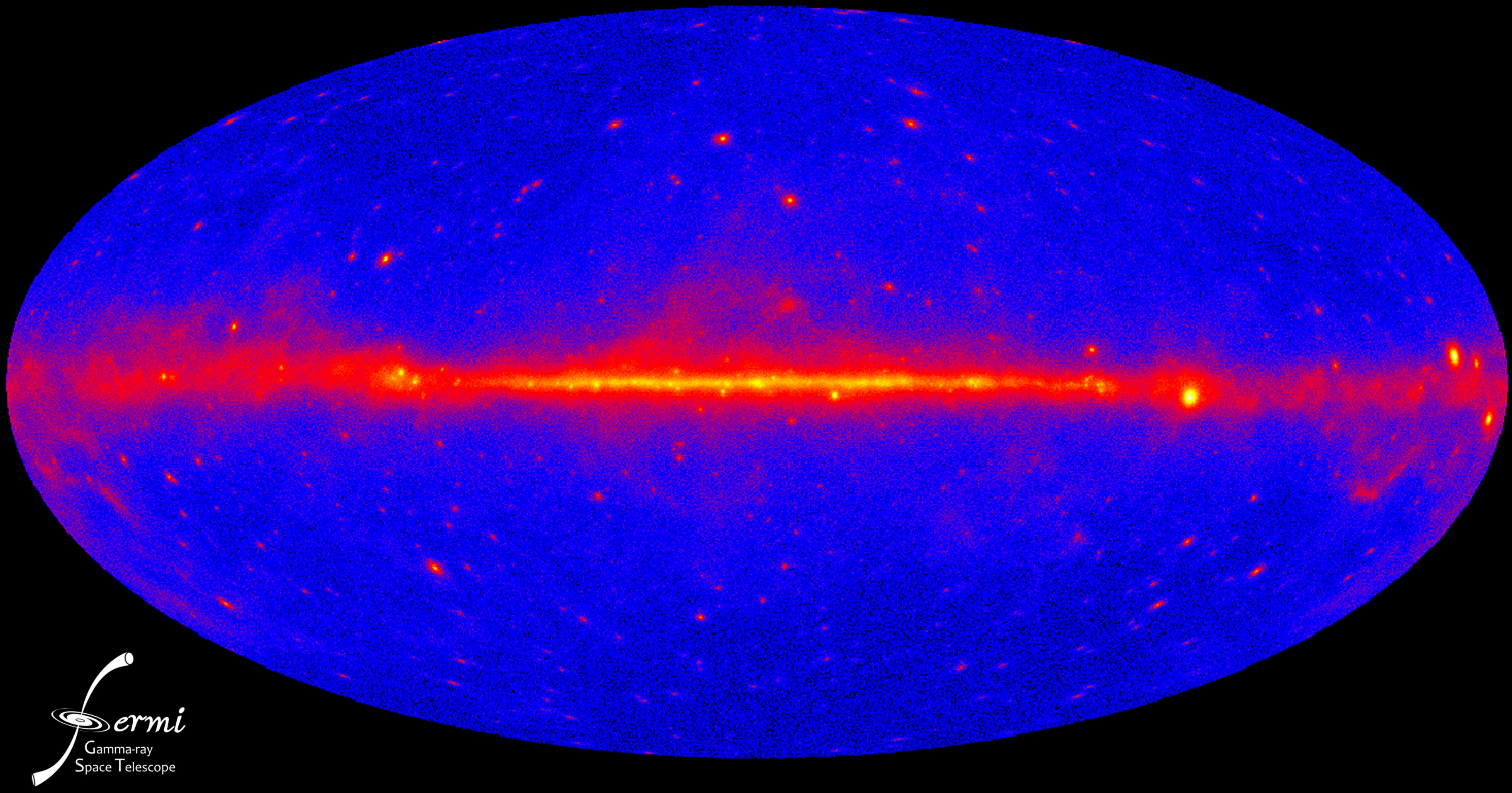
- **Why?**
  (i) Typical charged cosmic rays producing gammas have power law spectrum – the Fermi acceleration mechanism!
  (ii) Even if charged cosmic rays have initially non-power-law spectrum their spectrum is quickly converted to power law due to diffusion

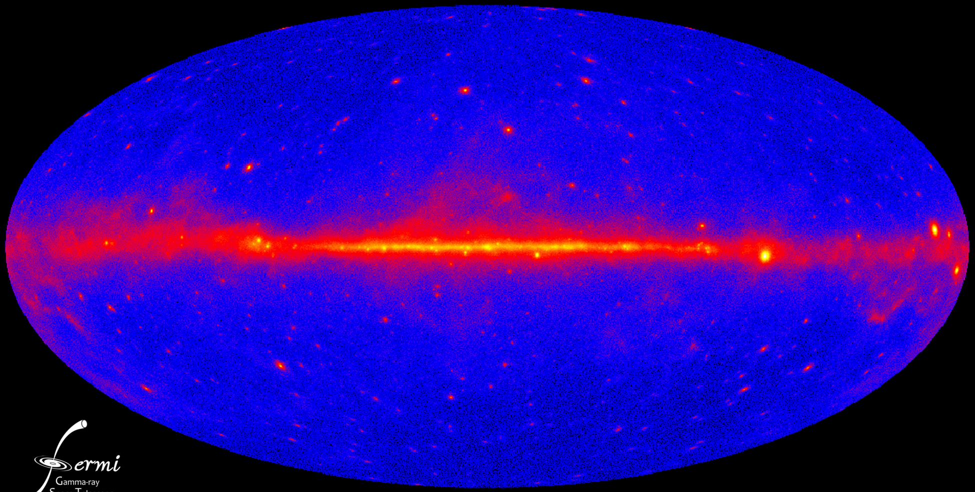
To blackboard...

– initial flux, Fermi mechanism

– diffuse flux, delta

Where do they come from?



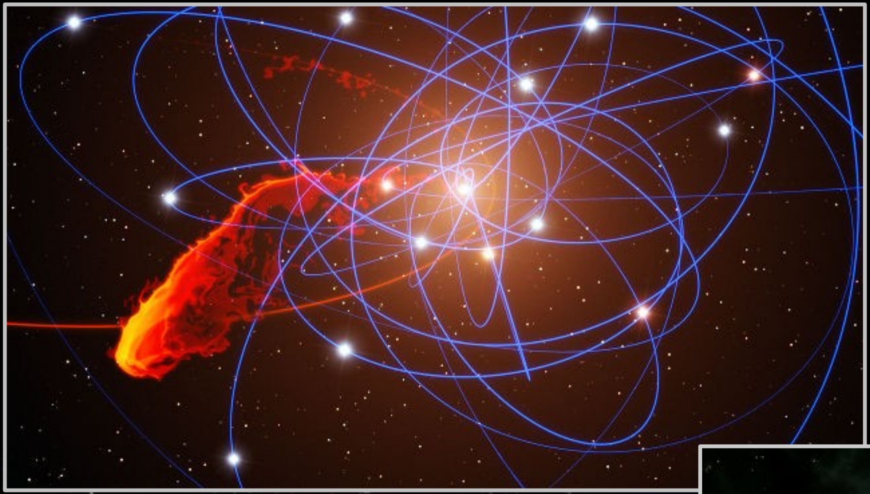


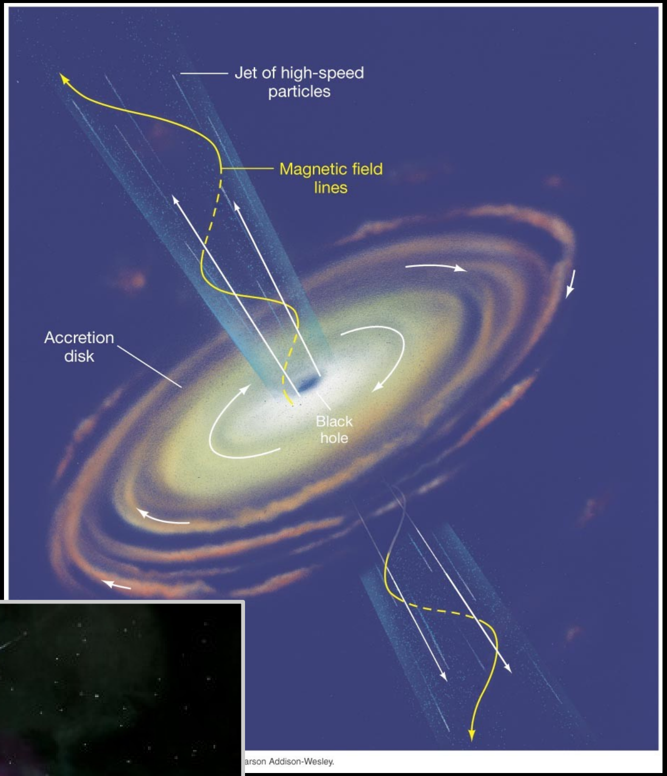
- **Two “type” of gamma rays:**
  (i) from “point” sources
  (ii) “diffusive” gamma rays
- **“Point” sources:**
  – true point sources, e.g. pulsars
  – extended sources, e.g. supernova remnants
- **“Diffusive” component**
  – true diffusive: interaction between the Galactic cosmic rays and matter (or CMB, interstellar starlight and IR)
  – unresolved point sources (Fermi LAT angular resolution ~ 0.1 deg)

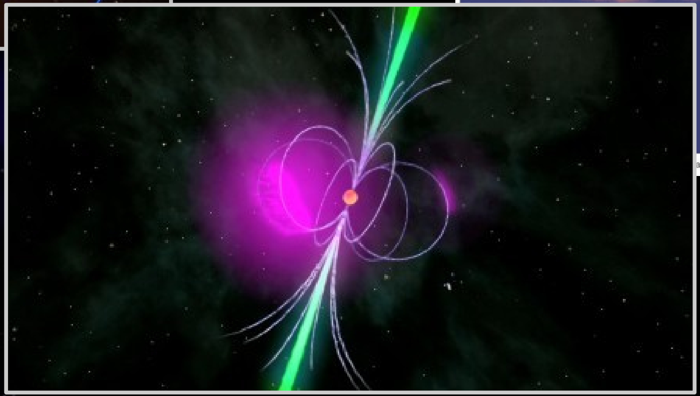
Gamma ray point sources

Gamma ray point sources

- Galactic: neutron stars, black holes, Central Black Hole
- Extragalactic: Active Galactic Nucleus





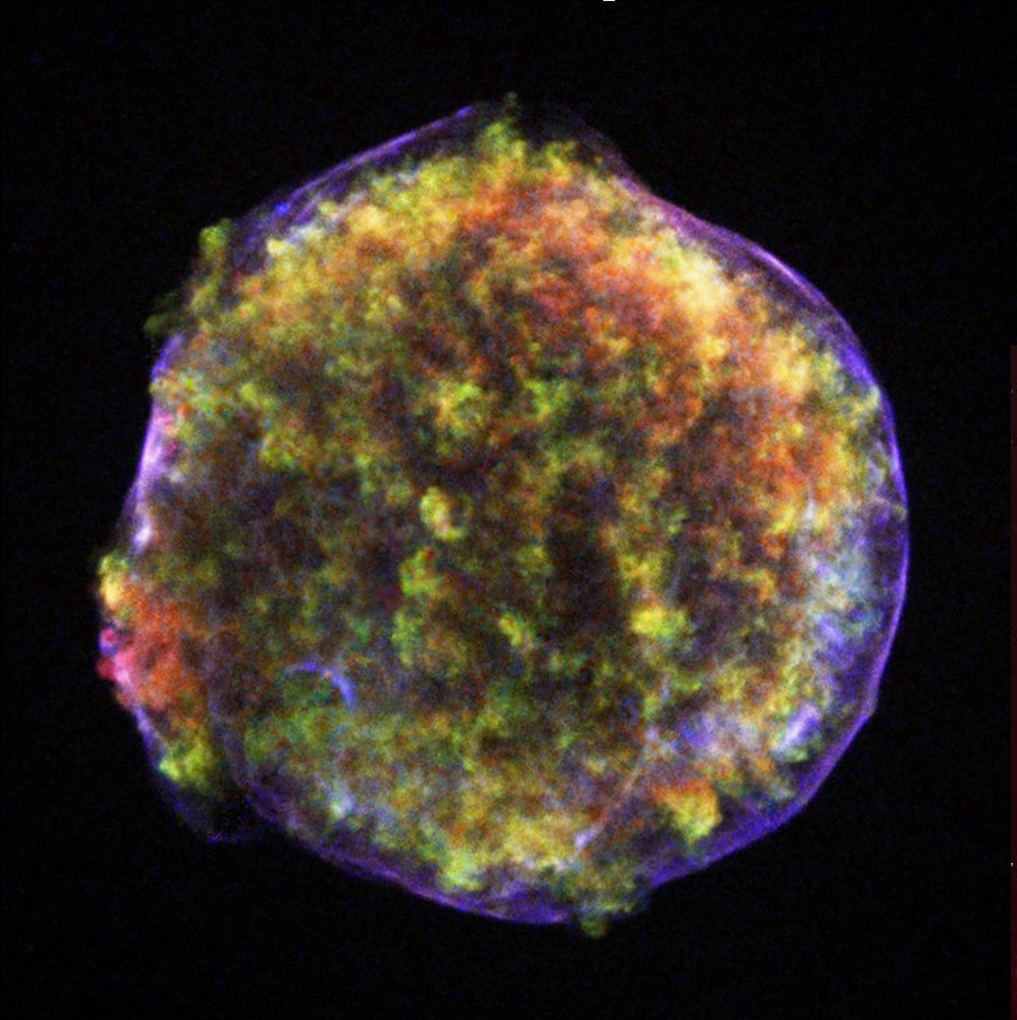


Extended sources of gamma rays

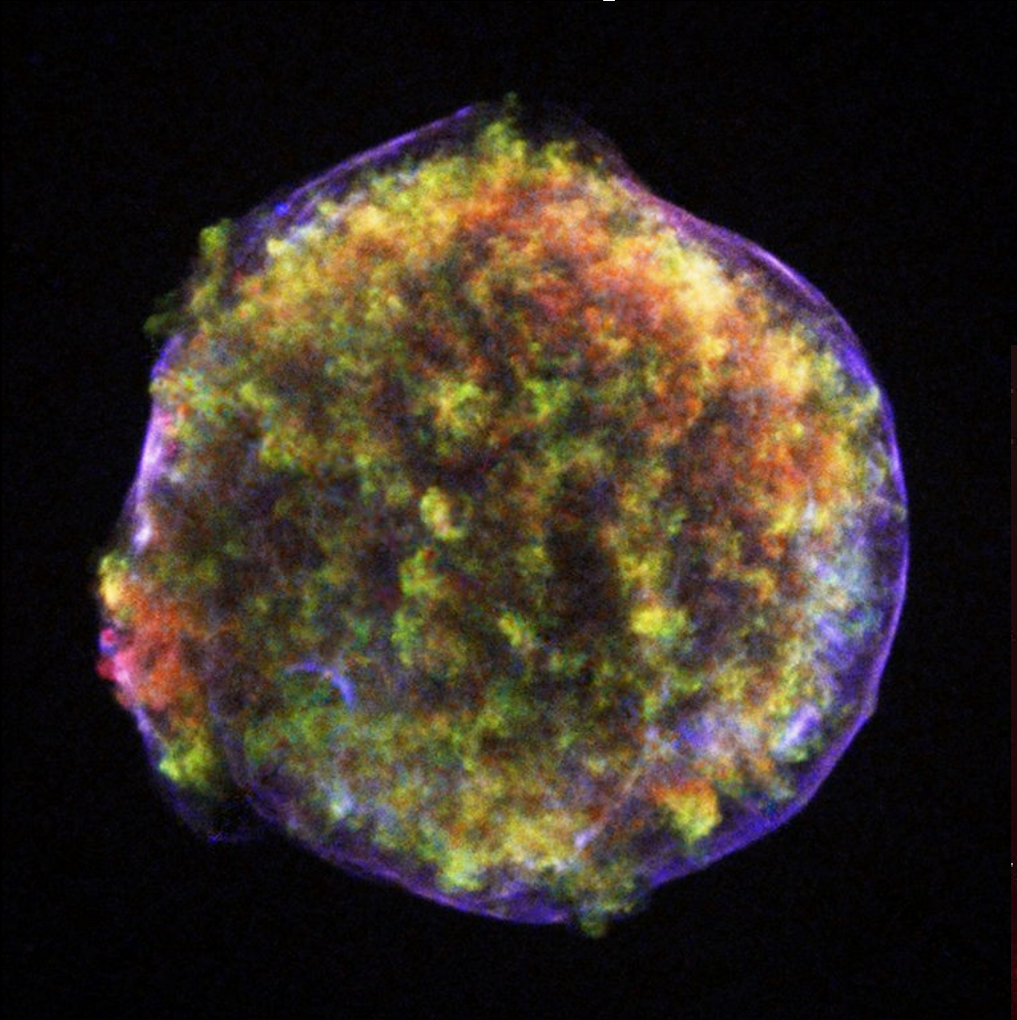
Extended sources of gamma rays

- Galactic: supernova remnants, molecular clouds and diffuse gamma rays
- Extragalactic: galaxy clusters (are they?)
- “New Physics”: annihilation/decay of Dark Matter

Supernova Remnants (SNR)

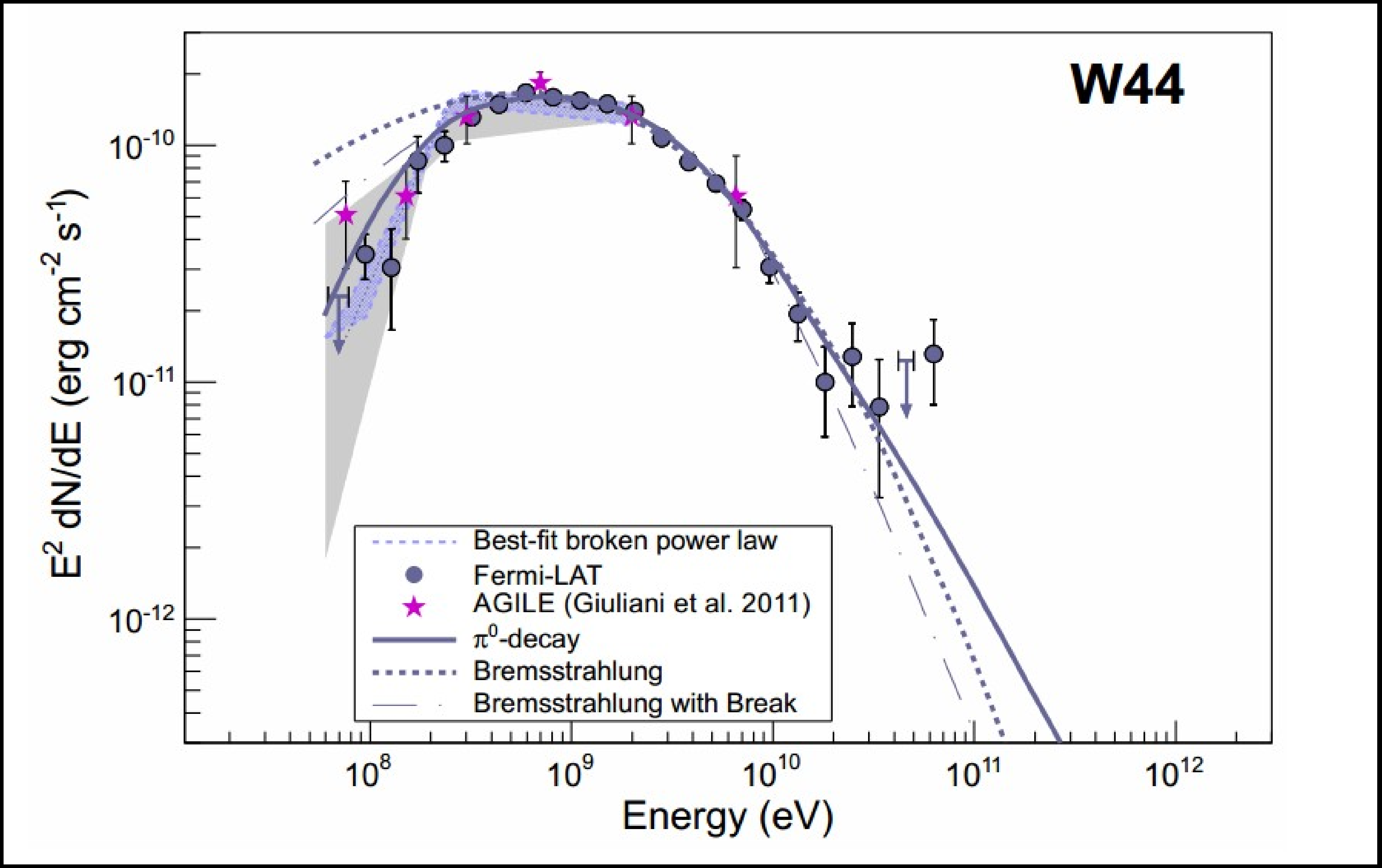


Supernova Remnants (SNR)



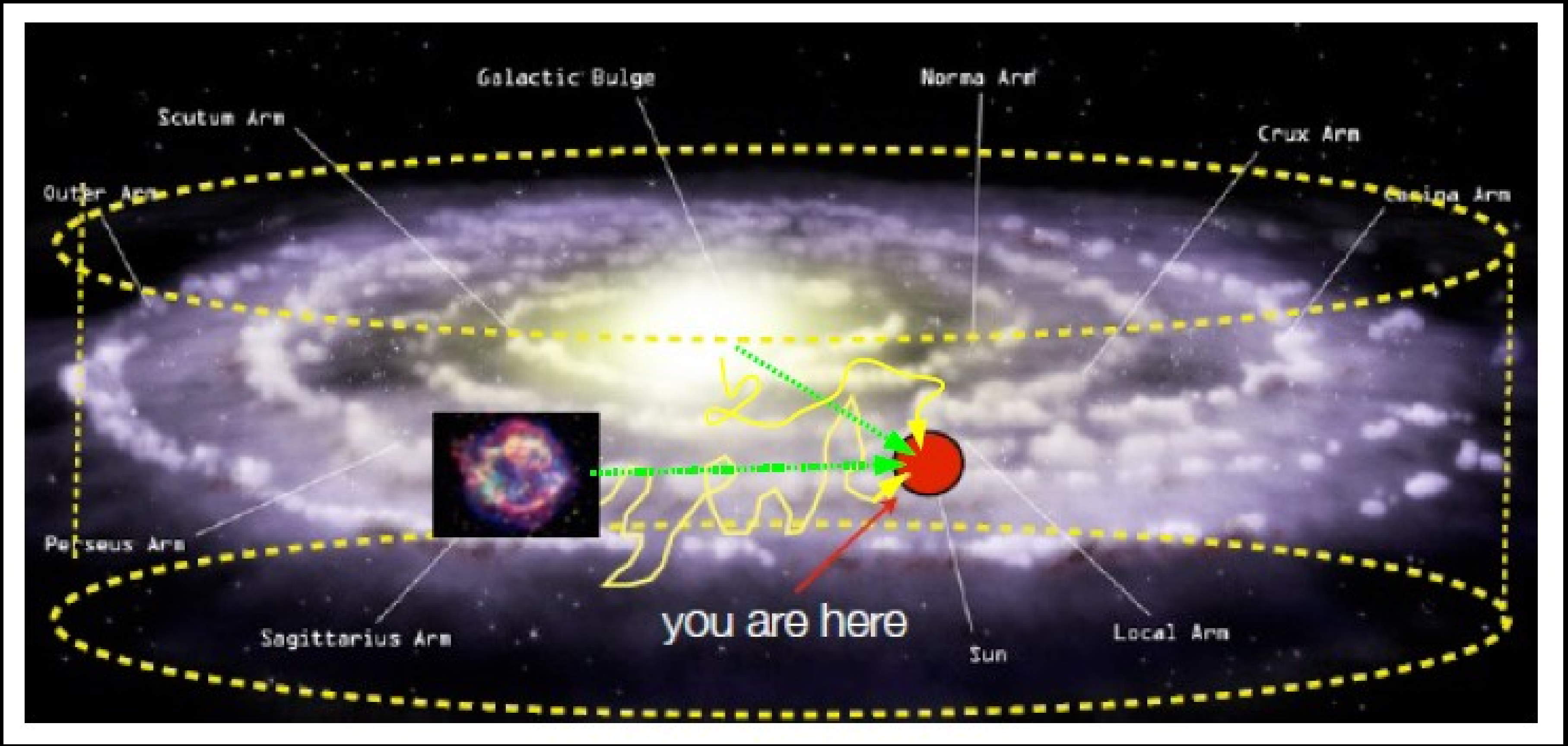
Tycho's supernova
(SN 1572)

Crab Nebula (M1,
NGC 1952, Taurus A)



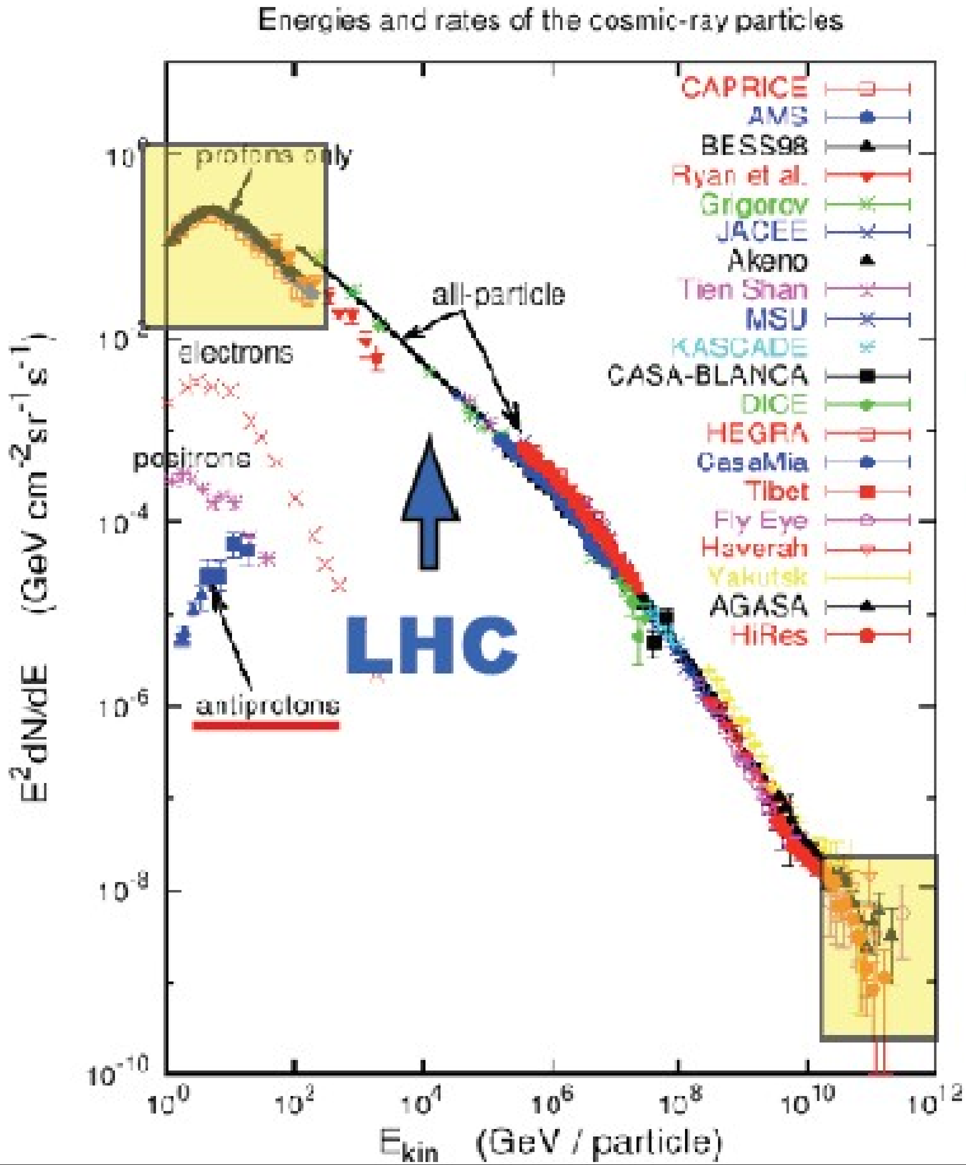
Detection of the Characteristic Pion-Decay Signature in Supernova Remnants, Fermi-LAT Collaboration (M. Ackermann et al), Science 339 (2013) 807

Diffuse gamma rays (from the Galaxy)



$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

$1/cm^2/s$



Ivo Karlović
2011 Davis Cup
~10^{12} GeV

$1/km^2/century$

To blackboard...

– diffusion versus direct propagation, Green's functions

Extragalactic extended sources: galaxy clusters (are they?)

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SEARCH FOR COSMIC-RAY INDUCED GAMMA RAY EMISSION IN GALAXY CLUSTERS

THE FERMI-LAT COLLABORATION: M. ACKERMANN[2†], M. AJELLO[3], A. ALBERT[4], A. ALLAFORT[5], W. B. ATWOOD[6], L. BALDINI[7], J. BALLET[8], G. BARBIELLINI[9,10], D. BASTIERI[11,12], K. BECHTOL[5], R. BELLAZZINI[13], E. D. BLOOM[5], E. BONAMENTE[14,15], E. BOTTACINI[5], T. J. BRANDT[16], J. BREGEON[13], M. BRIGIDA[17,18], P. BRUEL[19], R. BUEHLER[2], S. BUSON[11,12], G. A. CALIANDRO[20], R. A. CAMERON[5], P. A. CARAVEO[21], E. CAVAZZUTI[22], R.C.G. CHAVES[8], J. CHIANG[5], G. CHIARO[12], S. CIPRINI[22,23], R. CLAUS[5], J. COHEN-TANUGI[24], J. CONRAD[25,26,27,28,1], F. D'AMMANDO[29], A. DE ANGELIS[30], F. DE PALMA[17,18], C. D. DERMER[31], S. W. DIGEL[5], P. S. DRELL[5], A. DRLICA-WAGNER[5], C. FAVUZZI[17,18], A. FRANCKOWIAK[5], S. FUNK[5], P. FUSCO[17,18], F. GARGANO[18], D. GASPARRINI[22,23], S. GERMANI[14,15], N. GIGLIETTO[17,18], F. GIORDANO[17,18], M. GIROLETTI[29], G. GODFREY[5], G. A. GOMEZ-VARGAS[32,33,34], I. A. GRENIER[8], S. GUIRIEC[16,35], M. GUSTAFSSON[36], D. HADASCH[20], M. HAYASHIDA[5,37], J. HEWITT[16], R. E. HUGHES[4], T. E. JELTEMA[6], G. JÓHANNESSON[38], A. S. JOHNSON[5], T. KAMAE[5], J. KATAOKA[39], J. KNÖDLSEDER[40,41], M. KUSS[13], J. LANDE[5], S. LARSSON[25,26,42], L. LATRONICO[43], M. LLENA GARDE[25,26], F. LONGO[9,10], F. LOPARCO[17,18], M. N. LOVELLETTE[31], P. LUBRANO[14,15], M. MAYER[2], M. N. MAZZIOTTA[18], J. E. MCENERY[16,44], P. F. MICHELSON[5], W. MITTHUMSIRI[5], T. MIZUNO[45], M. E. MONZANI[5], A. MORSELLI[32], I. V. MOSKALENKO[5], S. MURGIA[5], R. NEMMEN[16], E. NUSS[24], T. OHSUGI[45], M. ORIENTI[29], E. ORLANDO[5], J. F. ORMES[46], J. S. PERKINS[16], M. PESCE-ROLLINS[13], F. PIRON[24], G. PIVATO[12], S. RAINÒ[17,18], R. RANDO[11,12], M. RAZZANO[13,6], S. RAZZAQUE[49], A. REIMER[50,5], O. REIMER[50,5,1], J. RUAN[51], M. SÁNCHEZ-CONDE[5], A. SCHULZ[2], C. SGRÒ[13], E. J. SISKIND[52], G. SPANDRE[13], P. SPINELLI[17,18], E. STORM[6], A. W. STRONG[53], D. J. SUSON[54], H. TAKAHASHI[55], J. G. THAYER[5], J. B. THAYER[5], D. J. THOMPSON[16], L. TIBALDO[5], M. TINIVELLA[13], D. F. TORRES[20,56], E. TROJA[16,44], Y. UCHIYAMA[57], T. L. USHER[5], J. VANDENBROUCKE[5], G. VIANELLO[5,58], V. VITALE[32,59], B. L. WINER[4], K. S. WOOD[31], S. ZIMMER[25,26,1], AND A. PINZKE[47†,60,1], C. PFROMMER[48,1]

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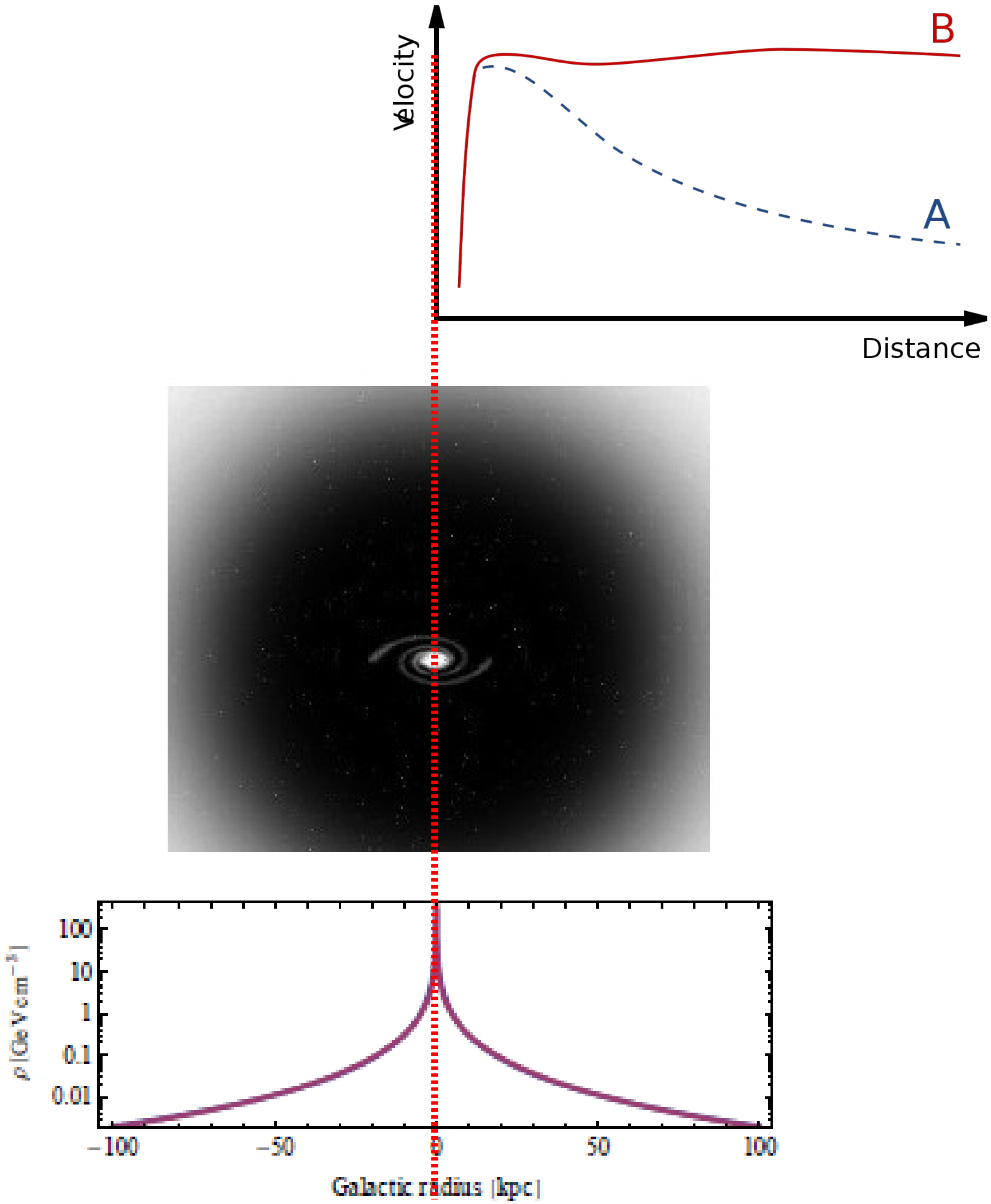
ABSTRACT

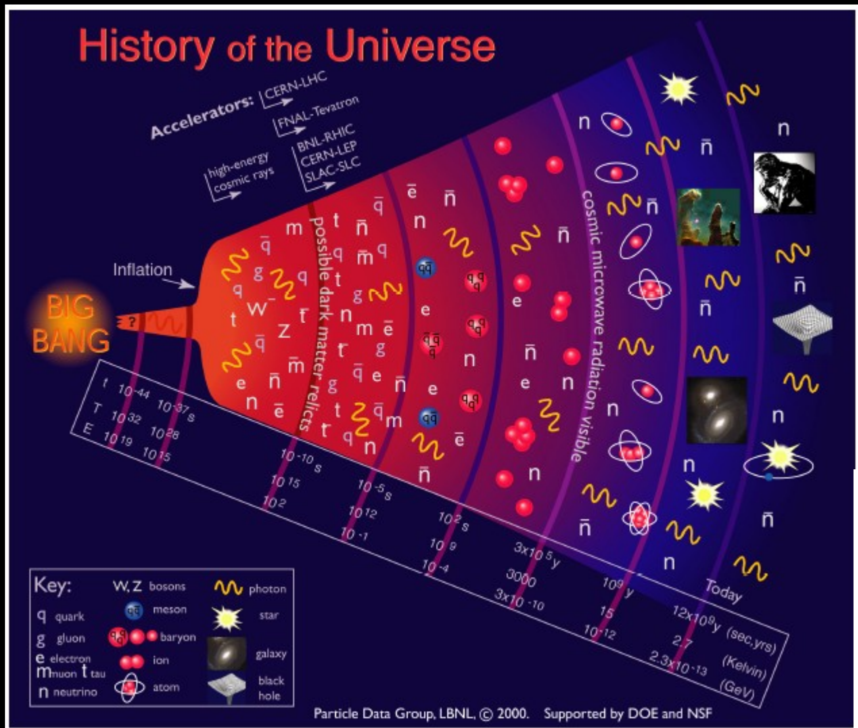
Current theories predict relativistic hadronic particle populations in clusters of galaxies in addition to the already observed relativistic leptons. In these scenarios hadronic interactions give rise to neutral pions which decay into γ rays that are potentially observable with the Large Area Telescope (LAT) on board the *Fermi* space telescope. We present a joint likelihood analysis searching for spatially extended γ-ray emission at the locations of 50 galaxy clusters in 4 years of *Fermi*-LAT data under the assumption of the universal cosmic-ray model proposed by Pinzke & Pfrommer (2010). We find an excess at a significance of $2.7\,\sigma$ which upon closer inspection is however correlated to *individual* excess emission towards three galaxy clusters: Abell 400, Abell 1367 and Abell 3112. We discuss these cases in detail and conservatively attribute the emission to unmodeled background (for example, radio galaxies within the clusters). Through the combined analysis of 50 clusters we exclude hadronic injection efficiencies in simple hadronic models above 21% and establish limits on the cosmic-ray to thermal pressure ratio within the virial radius, R_{200}, to be below 1.2-1.4% depending on the morphological classification. In addition we derive new limits on the γ-ray flux from individual clusters in our sample.

Subject headings: Gamma rays: galaxies: clusters; Galaxies: clusters: intracluster medium

Extended sources of gamma rays: annihilation or decay of Dark Matter

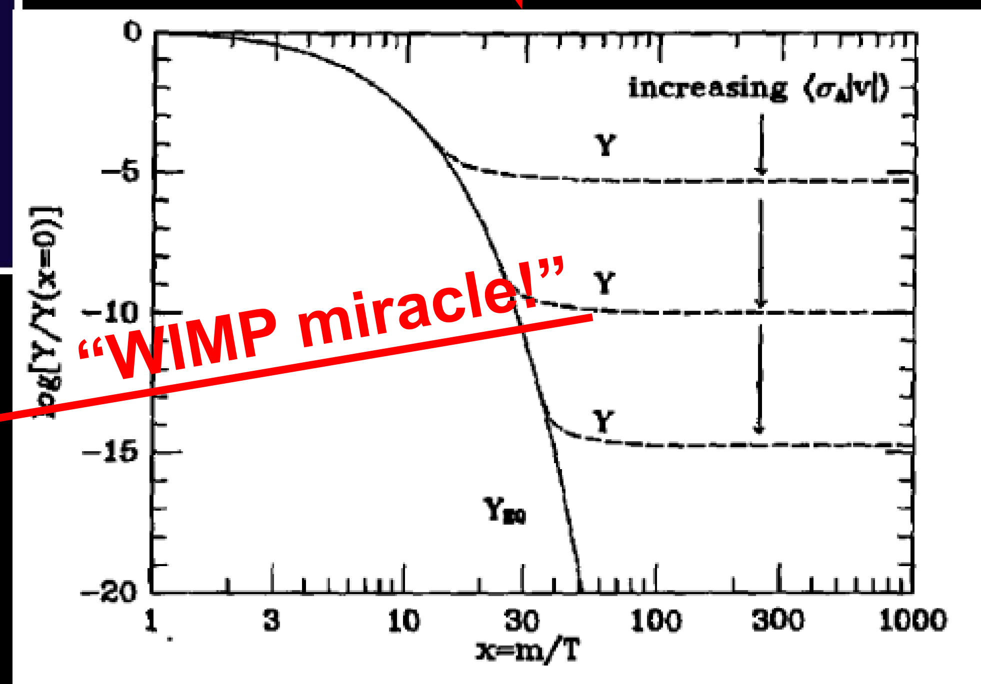

Velocity
B
A
Distance
100
10
1
0.1
0.01
ρ [GeV cm⁻³]
−100
−50
0
50
100
Galactic radius [kpc]

Thermal production of WIMPs

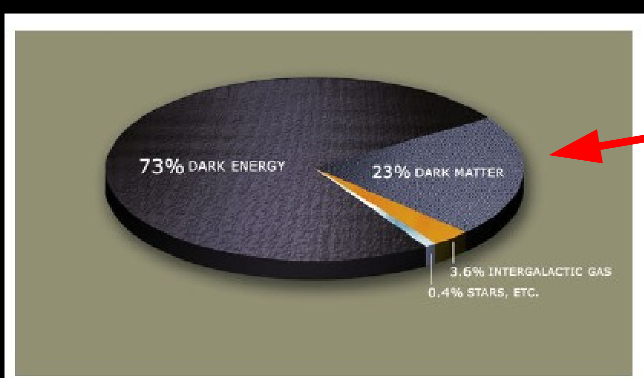


$$\Gamma \gtrsim H \Rightarrow \text{thermal equilibrium}$$

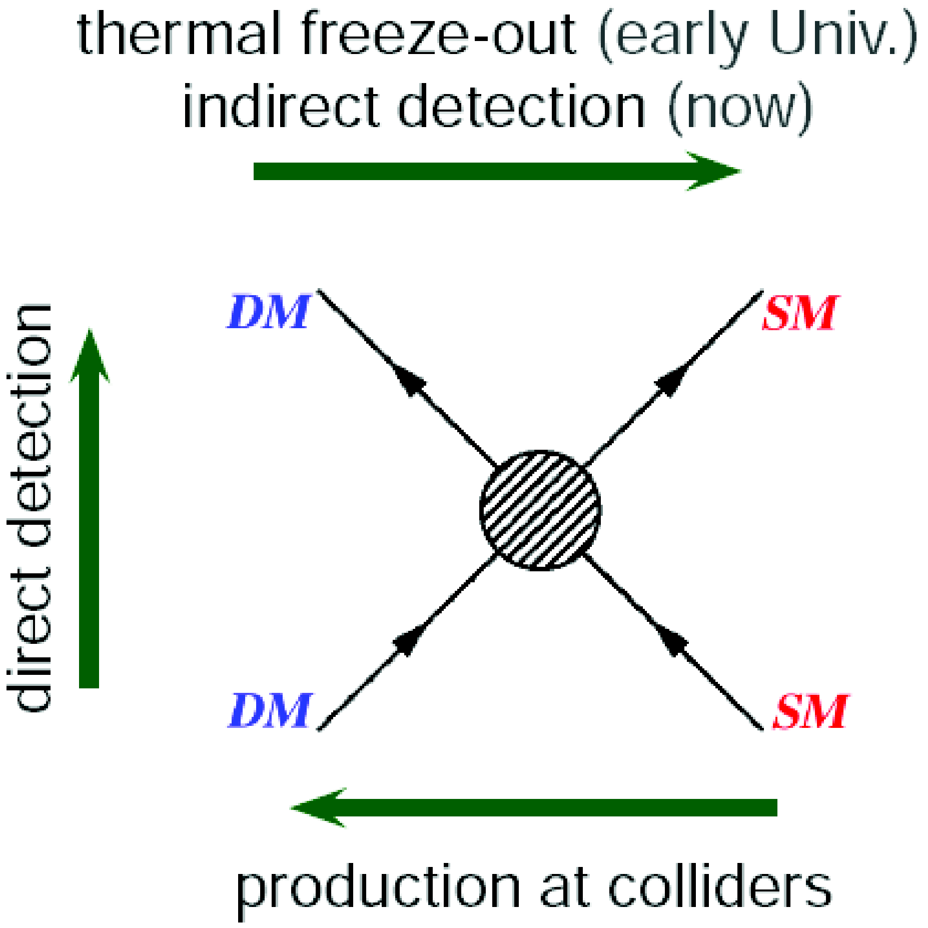
$$\Gamma \lesssim H \Rightarrow \text{decoupled evolution}$$



"WIMP miracle!"

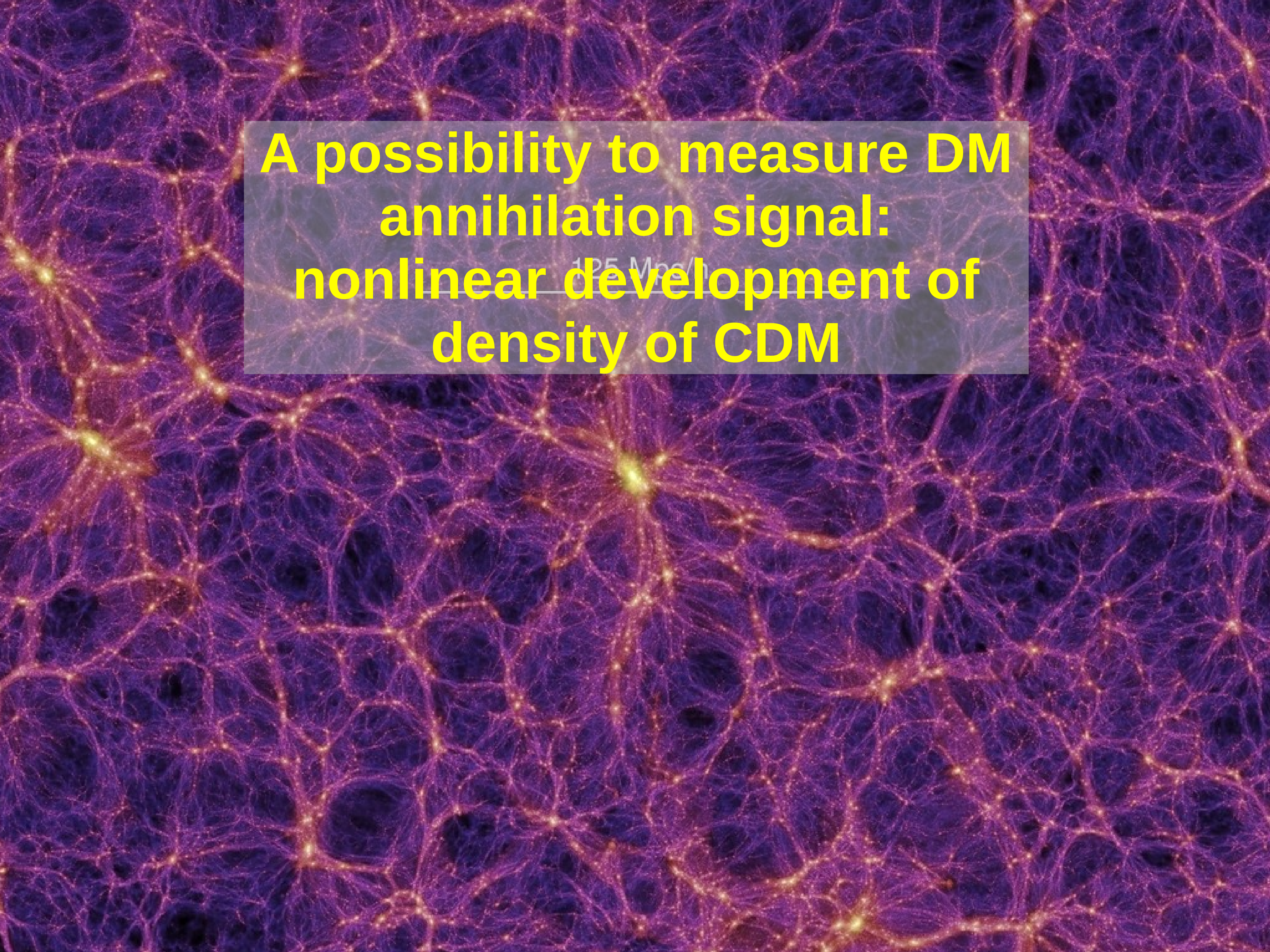


Why WIMP is so attractive?

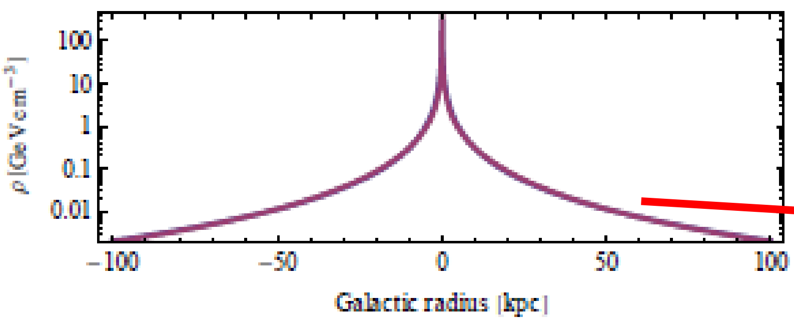


Many candidates waiting in particle physics – too many!

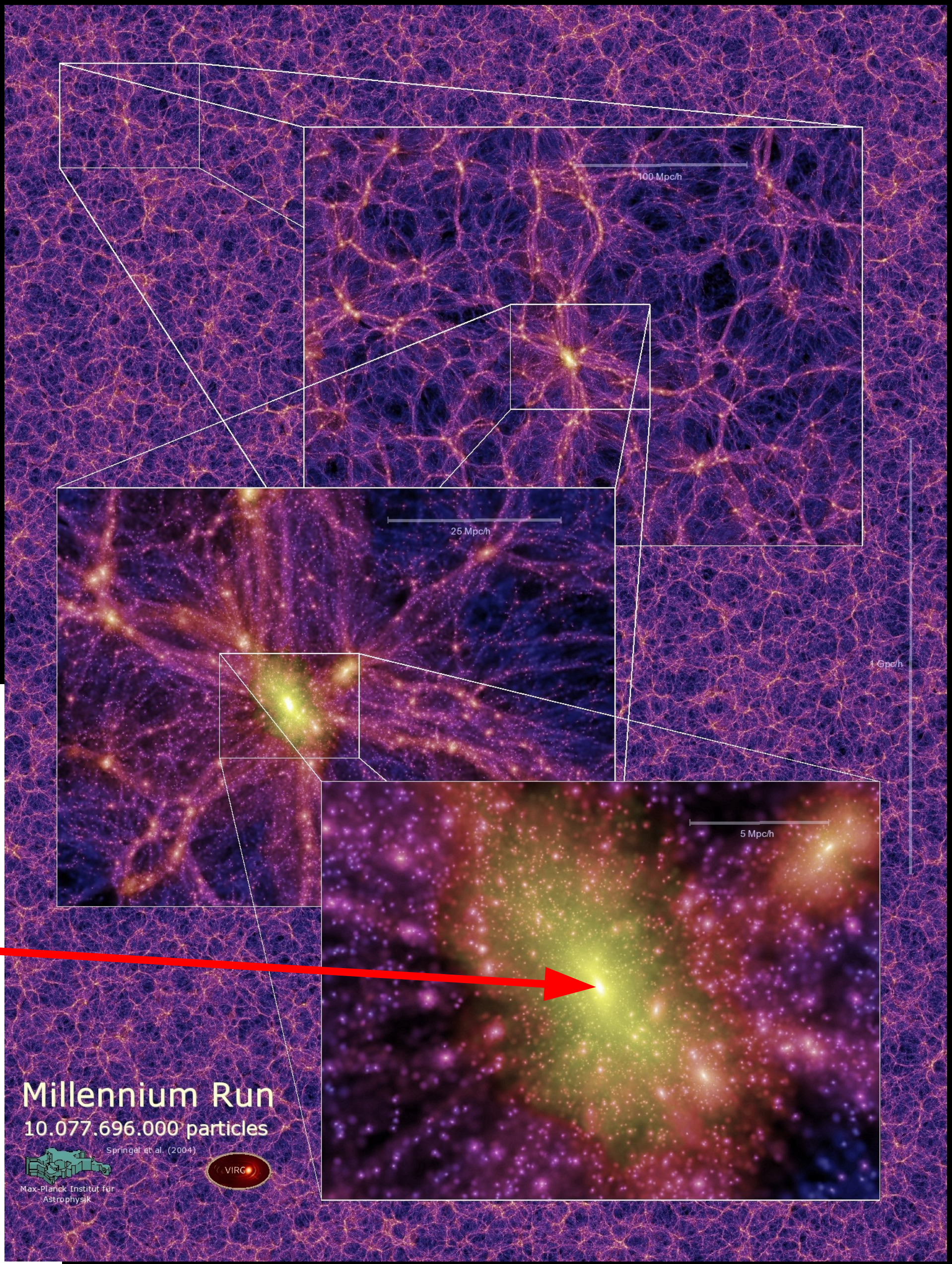
A possibility to measure DM annihilation signal: nonlinear development of density of CDM



Nonlinear development of density of WIMPs

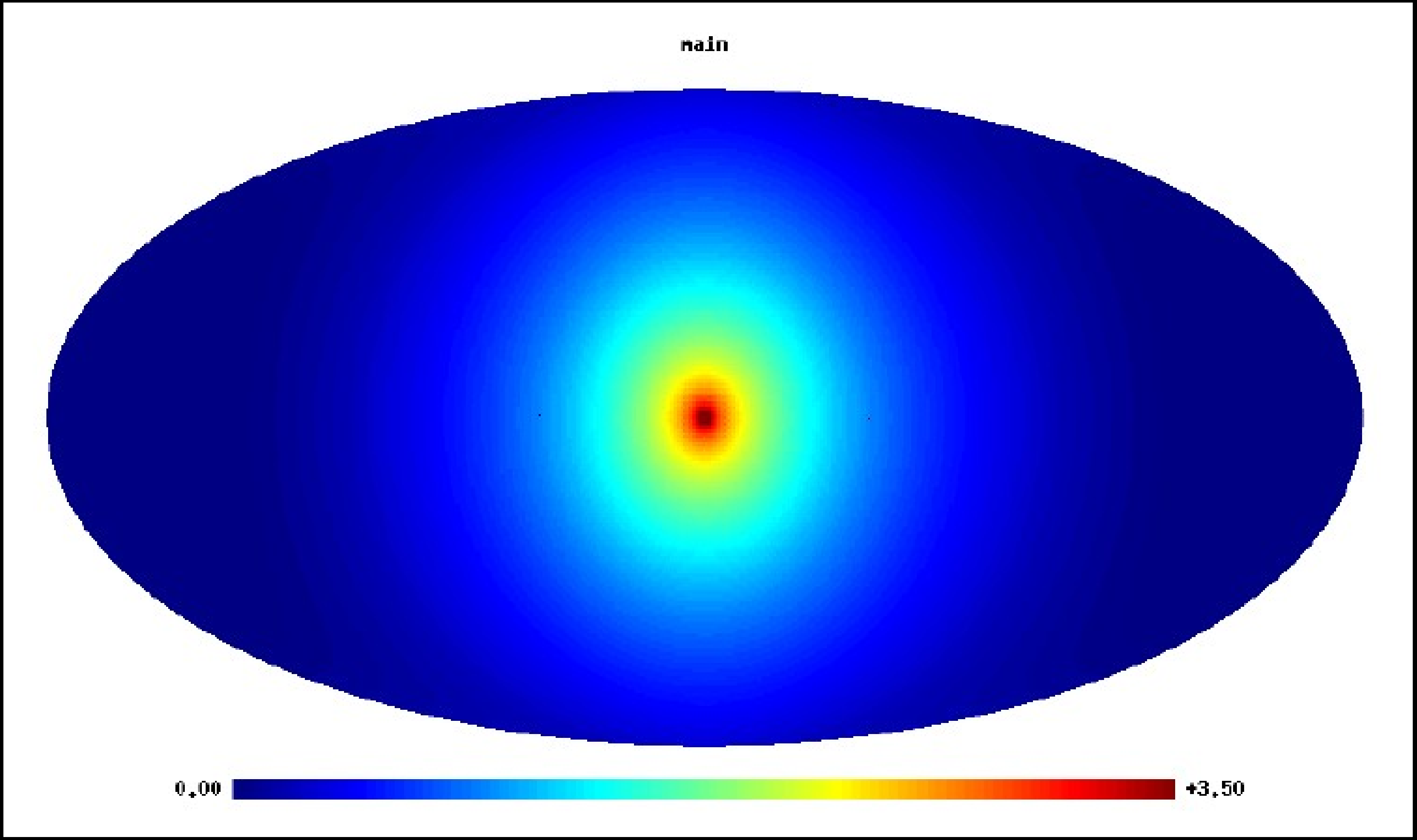


$$J_{\text{annih}} \propto \rho^2$$



Extended sources of gamma rays: annihilation or decay of Dark Matter in our Galaxy

Gamma-rays from DM annihilation: Galactic DM main halo



By Yuan et al [1203.5636]

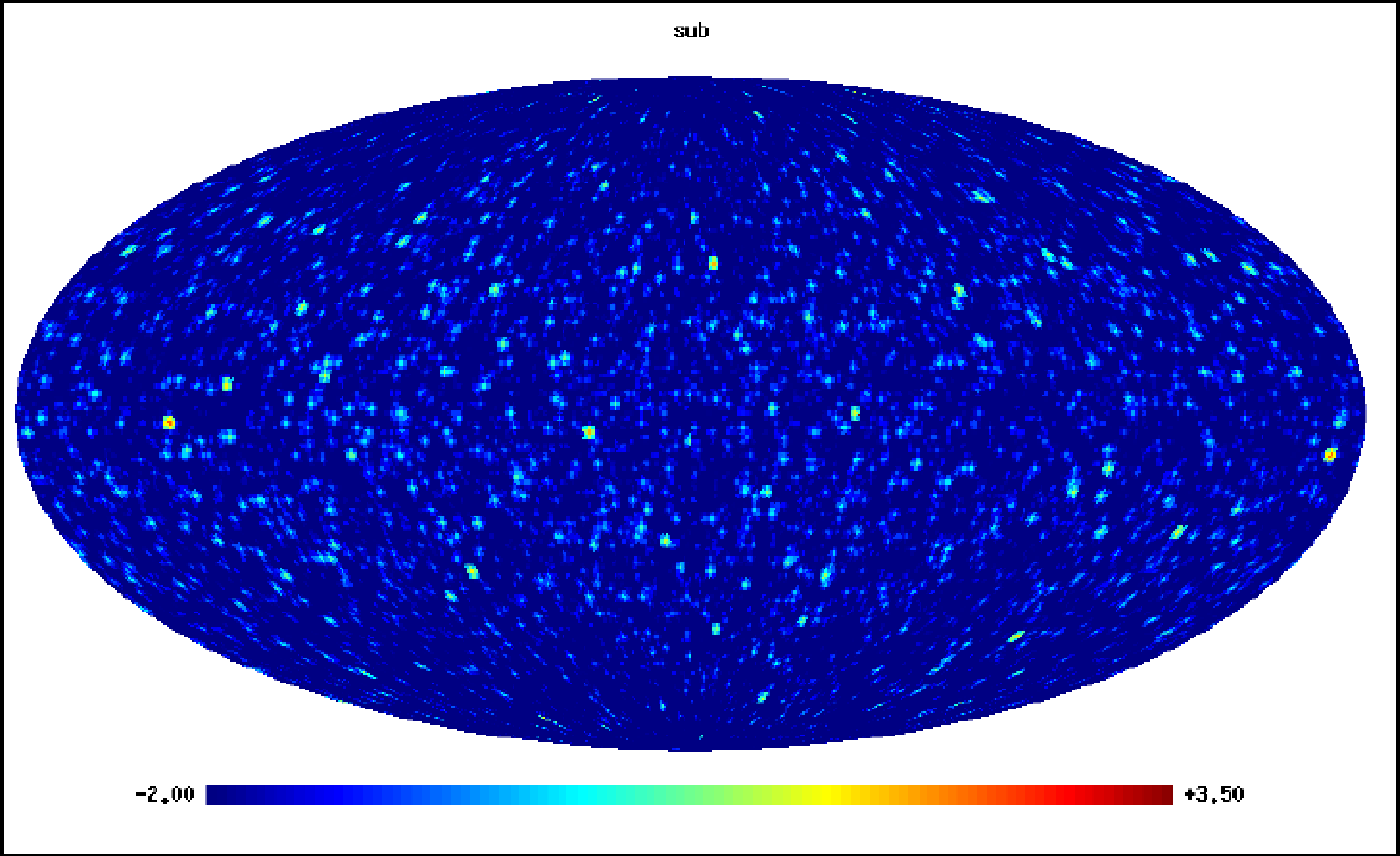
Gamma-rays from DM annihilation: Galactic DM main halo

J-factor

$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 J \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}, \qquad J = \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2 \qquad \text{(annihilation)}$$

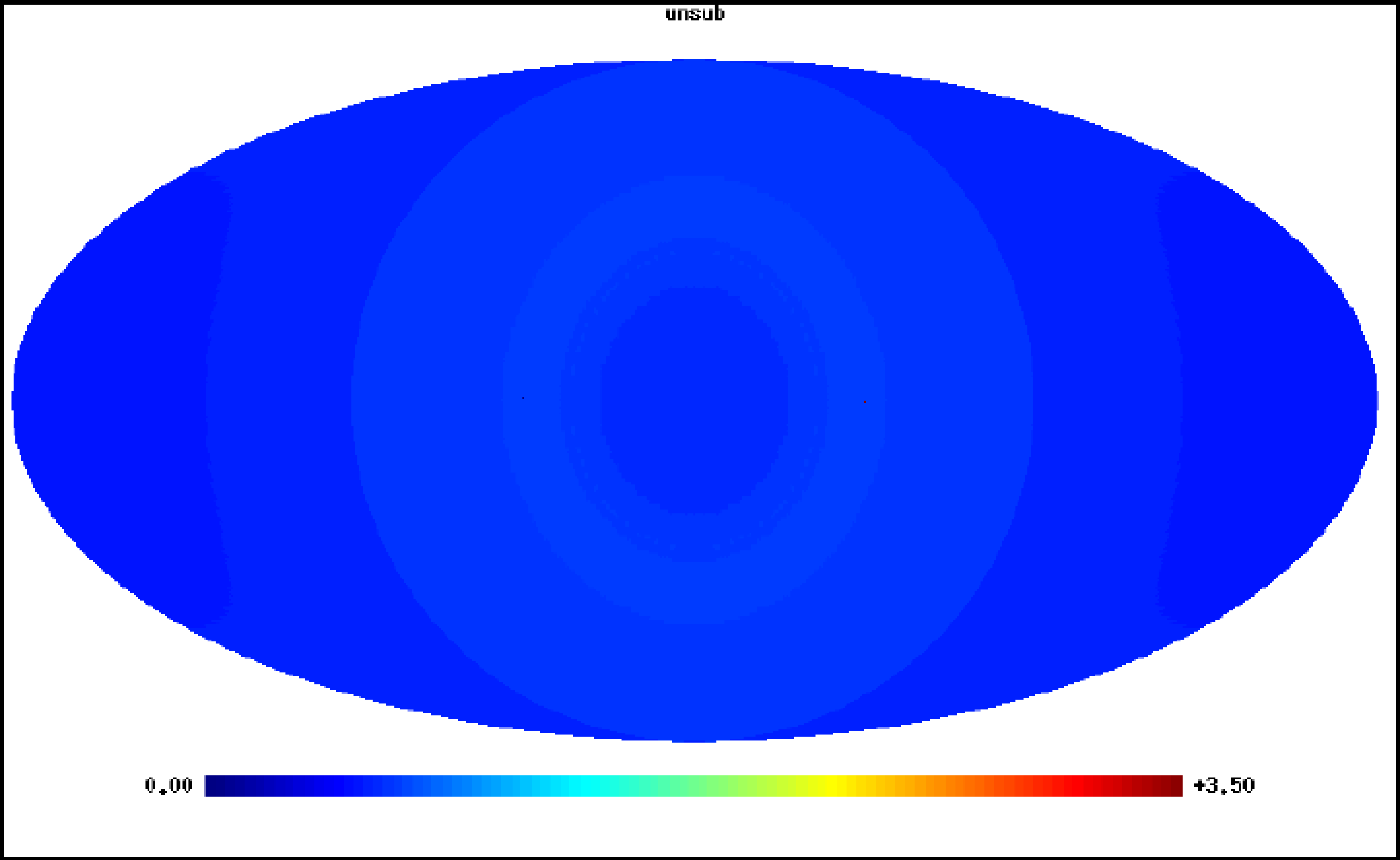
$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{r_\odot}{4\pi}\frac{\rho_\odot}{M_{\rm DM}} J \sum_f \Gamma_f \frac{dN_\gamma^f}{dE}, \qquad J = \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right) \qquad \text{(decay)}$$

Gamma-rays from DM annihilation: Galactic DM subhalos (resolved)



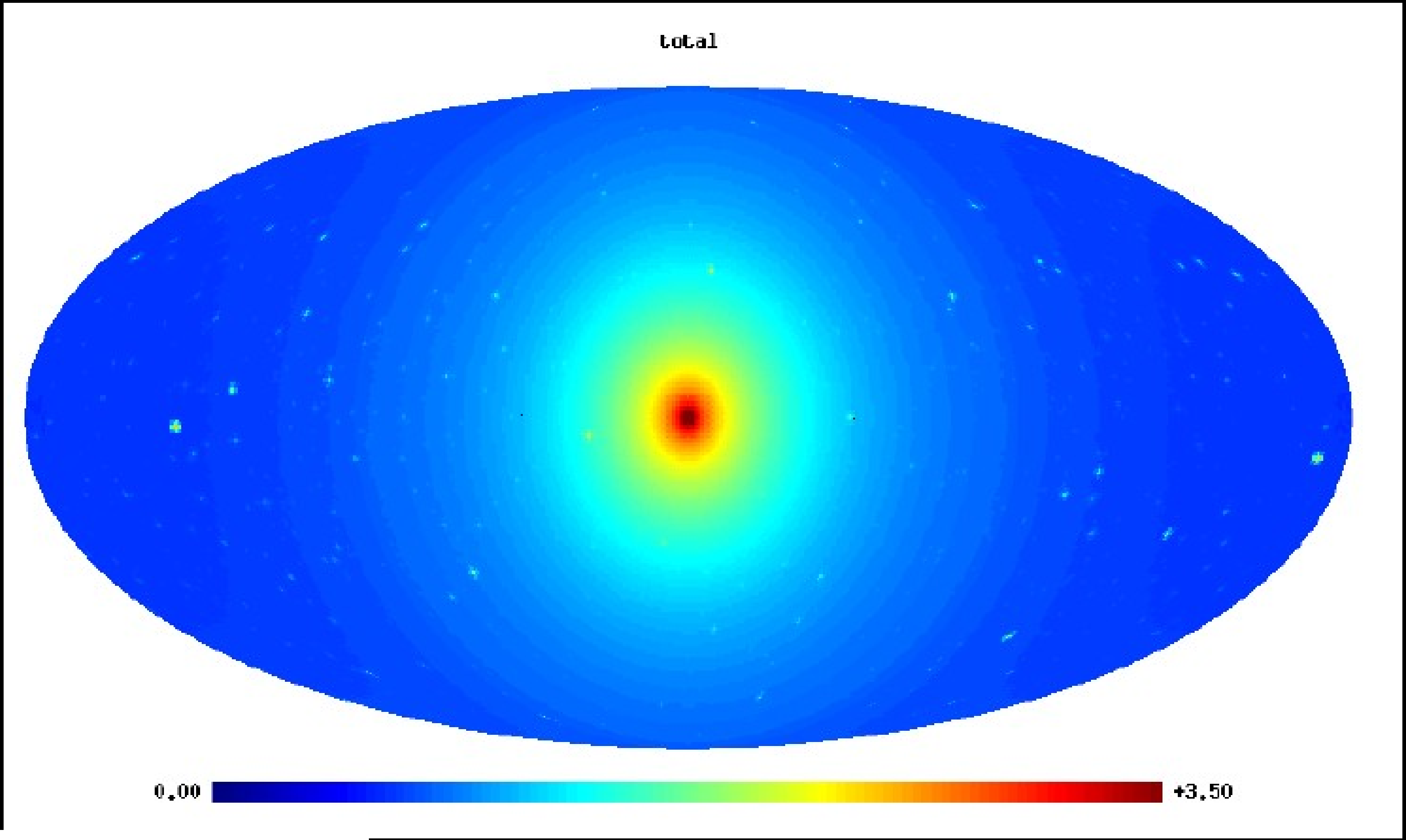
By Yuan et al [1203.5636]

Gamma-rays from DM annihilation: Galactic DM subhalos (unresolved)



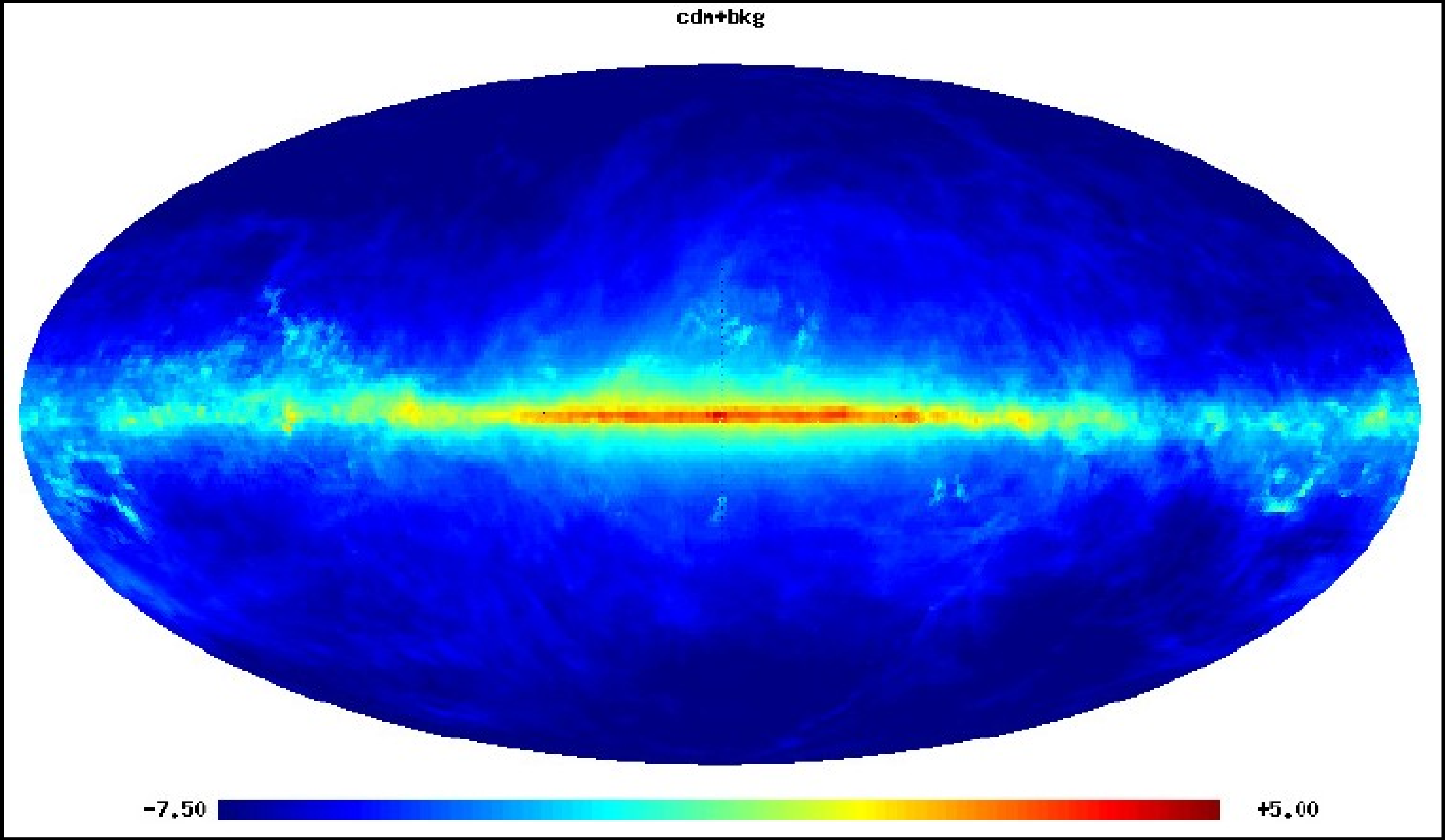
By Yuan et al [1203.5636]

Gamma-rays from DM annihilation: Galactic total



By Yuan et al [1203.5636]

Gamma-rays from DM annihilation:
DM annihilation + background (!)

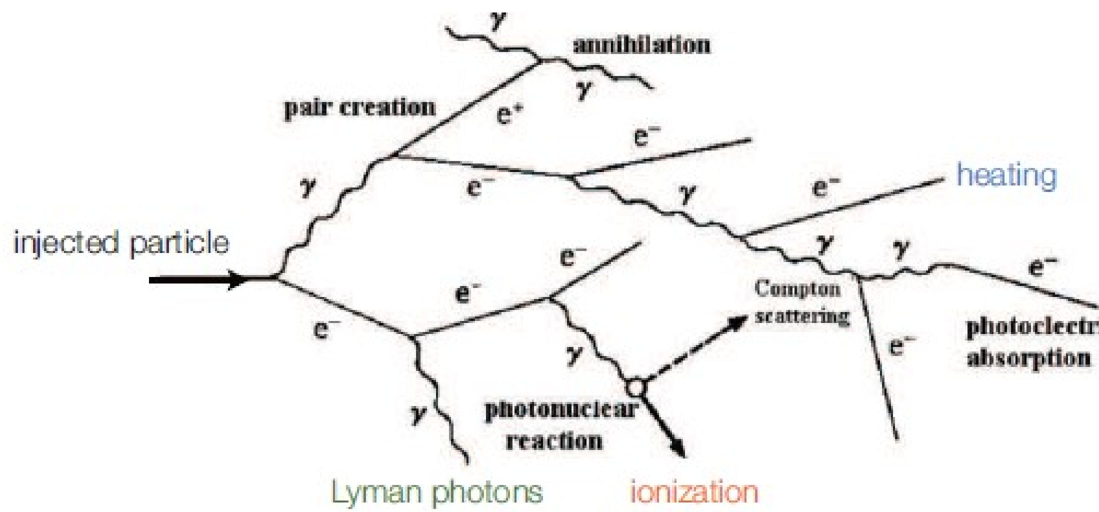


By Yuan et al [1203.5636]

Extragalatic sings of DM annihilation/decay

Cosmic rays in IGM influence free electron fraction (CMB) and temperature (21-cm)

- Electrons & positrons absorbed promptly due to IC from CMB
- Mean free path of γ-rays depends on energy
- Baryons are neglected usually



Galli et al [0905.0003], Slatyer et al [0906.1197], Huetsi et al [0906.4550], Evoli et al [MNRAS 422 (2012) 420]

Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT

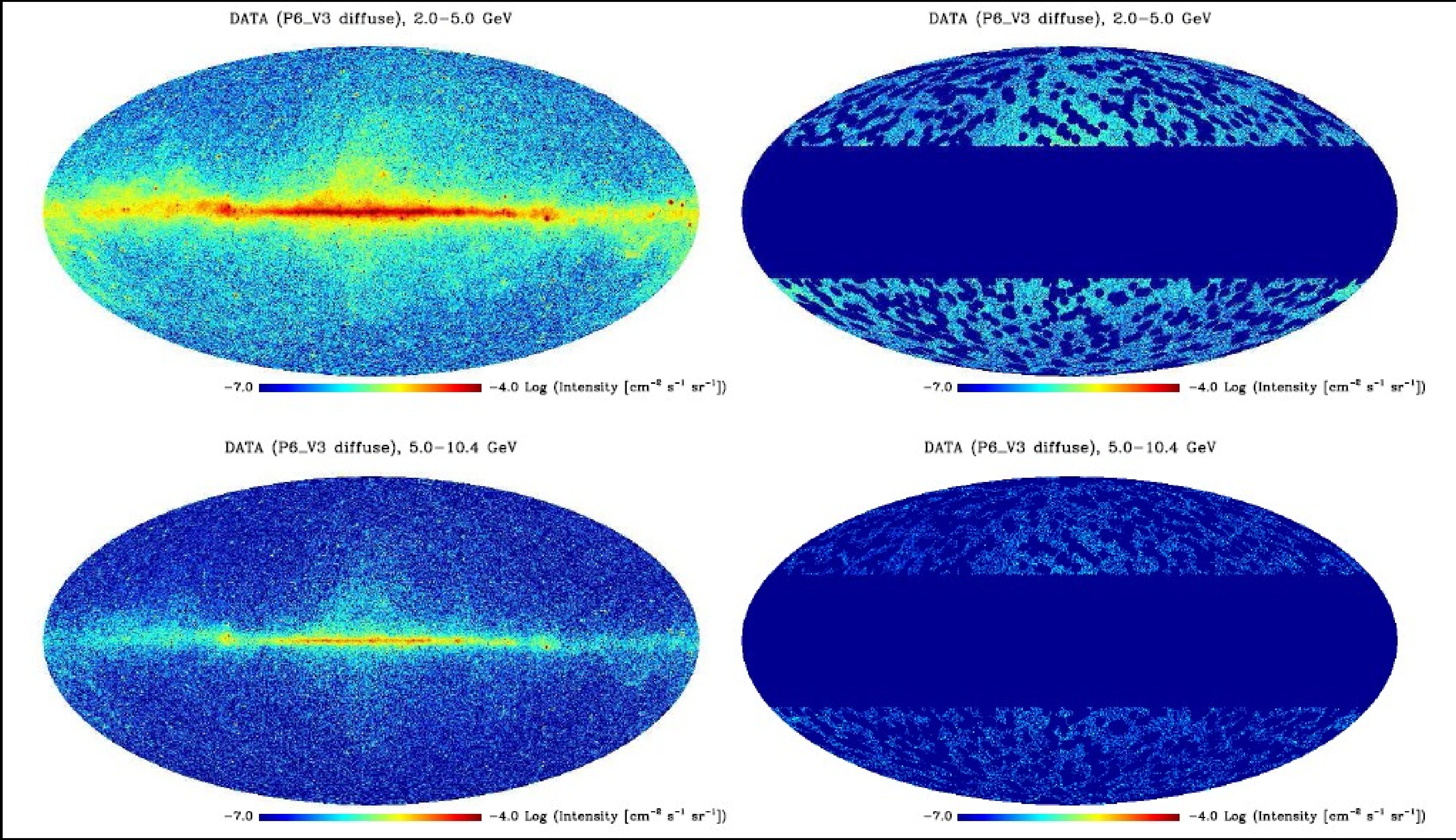
M. Ackermann,[1] M. Ajello,[2] A. Albert,[3] L. Baldini,[4] J. Ballet,[5] G. Barbiellini,[6,7] D. Bastieri,[8,9] K. Bechtol,[2] R. Bellazzini,[4] E. D. Bloom,[2] E. Bonamente,[10,11] A. W. Borgland,[2] T. J. Brandt,[12,13] J. Bregeon,[4] M. Brigida,[14,15] P. Bruel,[16] R. Buehler,[2] S. Buson,[8,9] G. A. Caliandro,[17] R. A. Cameron,[2] P. A. Caraveo,[18] C. Cecchi,[10,11] E. Charles,[2] A. Chekhtman,[19] J. Chiang,[2] S. Ciprini,[20,11] R. Claus,[2] J. Cohen-Tanugi,[21] J. Conrad,[22,23,24] A. Cuoco,[23,*] S. Cutini,[25] F. D'Ammando,[26,27] F. de Palma,[14,15] C. D. Dermer,[28] S. W. Digel,[2] E. do Couto e Silva,[2] P. S. Drell,[2] A. Drlica-Wagner,[2] R. Dubois,[2] C. Favuzzi,[14,15] S. J. Fegan,[16] E. C. Ferrara,[29] P. Fortin,[16] Y. Fukazawa,[30] P. Fusco,[14,15] F. Gargano,[15] D. Gasparrini,[25] S. Germani,[10,11] N. Giglietto,[14,15] M. Giroletti,[31] T. Glanzman,[2] G. Godfrey,[2] G. A. Gomez-Vargas,[32,33,34] T. Grégoire,[12,13] I. A. Grenier,[5] J. E. Grove,[28] S. Guiriec,[35] M. Gustafsson,[8] D. Hadasch,[17] M. Hayashida,[2,36] K. Hayashi,[30] X. Hou,[37] R. E. Hughes,[3] G. Jóhannesson,[38] A. S. Johnson,[2] T. Kamae,[2] J. Knödlseder,[12,13] M. Kuss,[4] J. Lande,[2] L. Latronico,[39] M. Lemoine-Goumard,[40,41] T. Linden,[42,†] A. M. Lionetto,[32,43] M. Llena Garde,[22,23] F. Longo,[6,7] F. Loparco,[14,15] M. N. Lovellette,[28] P. Lubrano,[10,11] M. N. Mazziotta,[15,‡] J. E. McEnery,[29,44] W. Mitthumsiri,[2] T. Mizuno,[30] C. Monte,[14,15] M. E. Monzani,[2] A. Morselli,[32] I. V. Moskalenko,[2] S. Murgia,[2] M. Naumann-Godo,[5] J. P. Norris,[45] E. Nuss,[21] T. Ohsugi,[46] A. Okumura,[2,47] M. Orienti,[31] E. Orlando,[2,48] J. F. Ormes,[49] D. Paneque,[50,2] J. H. Panetta,[2] D. Parent,[51] V. Pavlidou,[52] M. Pesce-Rollins,[4] M. Pierbattista,[5] F. Piron,[21] G. Pivato,[9] S. Rainò,[14,15] R. Rando,[8,9] A. Reimer,[53,2] O. Reimer,[53,2] M. Roth,[54] C. Sbarra,[8] J. Schmitt,[5] C. Sgrò,[4] J. Siegal-Gaskins,[3,52,§] E. J. Siskind,[55] G. Spandre,[4] P. Spinelli,[14,15] A. W. Strong,[48] D. J. Suson,[56] H. Takahashi,[46] T. Tanaka,[2] J. B. Thayer,[2] L. Tibaldo,[8,9] M. Tinivella,[4] D. F. Torres,[17,57] G. Tosti,[10,11] E. Troja,[29,58] T. L. Usher,[2] J. Vandenbroucke,[2] V. Vasileiou,[21] G. Vianello,[2,59] V. Vitale,[32,43,¶] A. P. Waite,[2] B. L. Winer,[3] K. S. Wood,[28] M. Wood,[2] Z. Yang,[22,23] and S. Zimmer[22,23]

(Fermi LAT Collaboration)

E. Komatsu[60,**]

[1]Deutsches Elektronen Synchrotron DESY, D-15738 Zeuthen, Germany
[2]W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
[3]Department of Physics, Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA
[4]Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy
[5]Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique, CEA Saclay, 91191 Gif sur Yvette, France
[6]Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy
[7]Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[8]Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
[9]Dipartimento di Fisica "G. Galilei", Università di Padova, I-35131 Padova, Italy
[10]Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy
[11]Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy
[12]CNRS, IRAP, F-31028 Toulouse cedex 4, France
[13]GAHEC, Université de Toulouse, UPS-OMP, IRAP, Toulouse, France
[14]Dipartimento di Fisica "M. Merlin" dell'Università e del Politecnico di Bari, I-70126 Bari, Italy
[15]Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70126 Bari, Italy
[16]Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Palaiseau, France

Angular power spectrum analysis



Cross-correlation analysis

Power spectrum tomography of dark matter annihilation with local galaxy distribution

Shin'ichiro Ando

GRAPPA Institute, University of Amsterdam, 1098 XH Amsterdam, The Netherlands

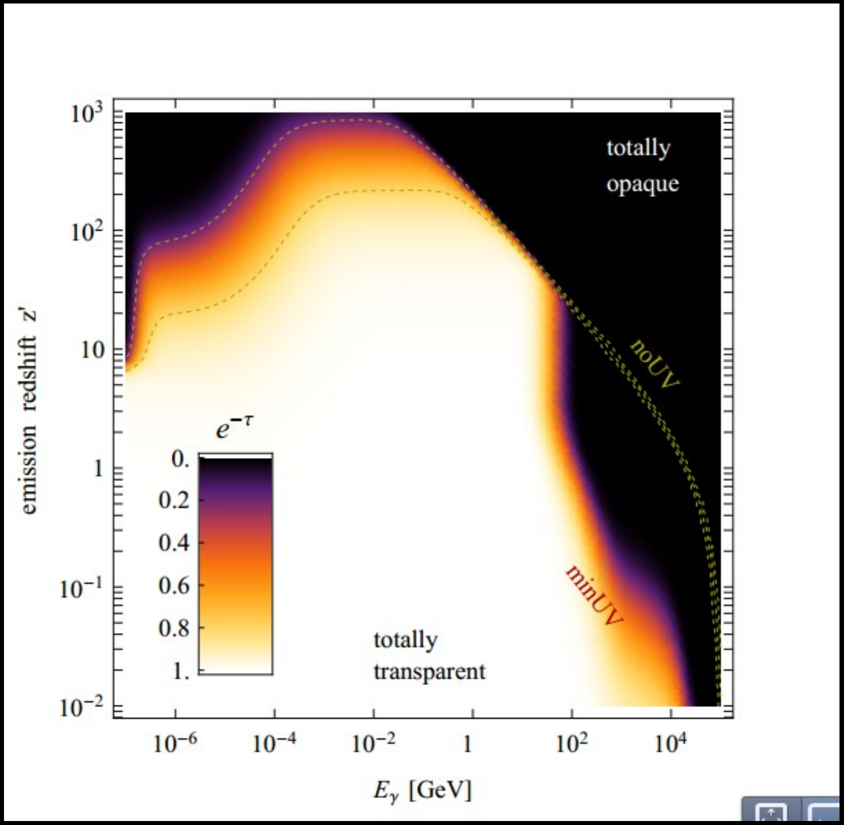
E-mail: s.ando@uva.nl

Abstract. Cross-correlating the gamma-ray background with local galaxy catalogs potentially gives stringent constraints on dark matter annihilation. We provide updated theoretical estimates of sensitivities to the annihilation cross section from gamma-ray data with Fermi telescope and 2MASS galaxy catalogs, by elaborating the galaxy power spectrum and astrophysical backgrounds, and adopting the Markov-Chain Monte Carlo simulations. In particular, we show that taking tomographic approach by dividing the galaxy catalogs into more than one redshift slice will improve the sensitivity by a factor of a few to several. If dark matter halos contain lots of bright substructures, yielding a large annihilation boost, then one may be able to probe the canonical annihilation cross section for thermal production mechanism up to masses of ~700 GeV. Even with modest substructure boost, on the other hand, the sensitivities could still reach a factor of three larger than the canonical cross section for dark matter masses of tens to a few hundreds of GeV.

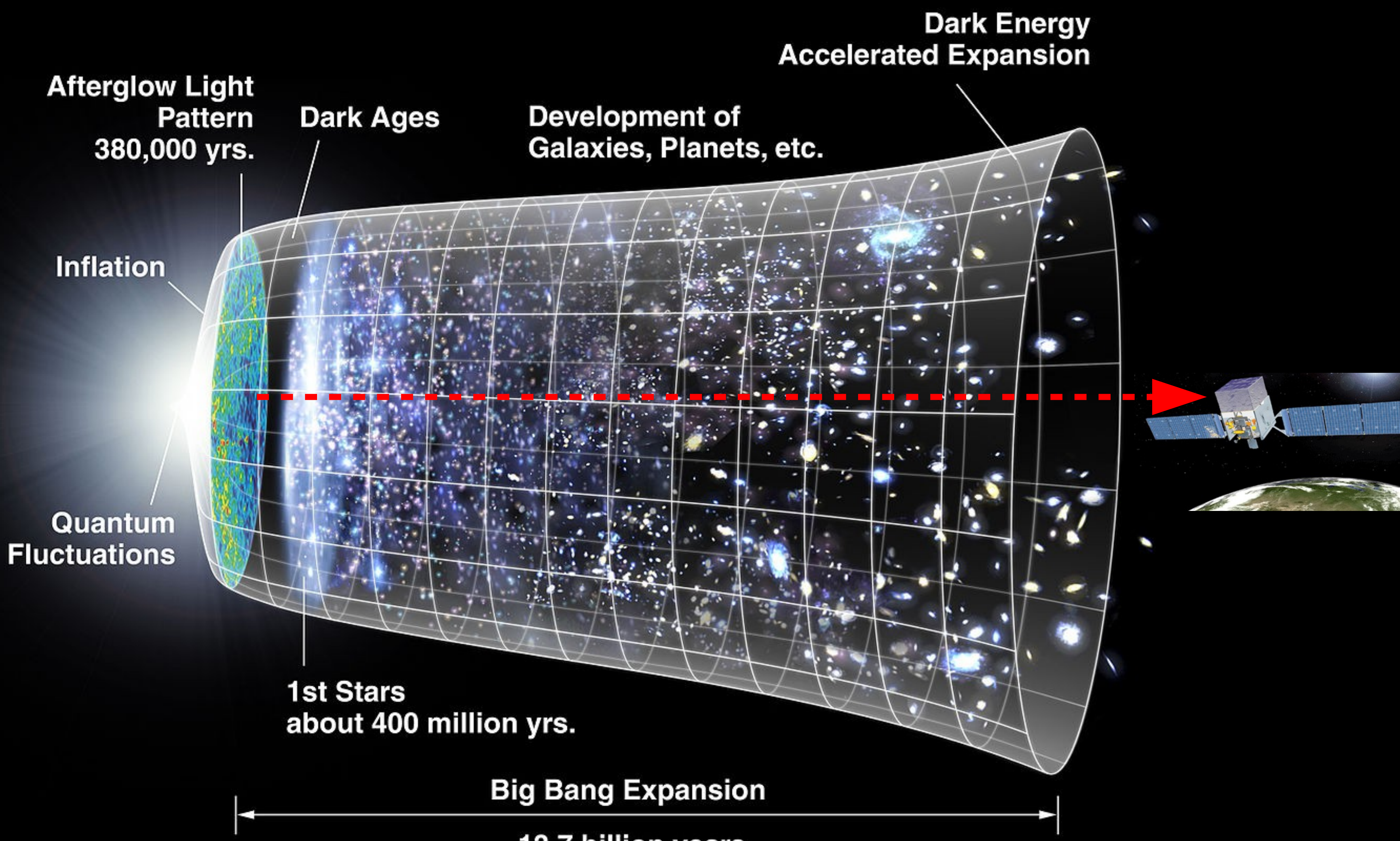
Propagation of gamma rays

Propagation of gamma rays

- Absorption mechanisms
- Galaxy is transparent!
- Absorption in the cosmological scales, the cosmic "gamma ray window"



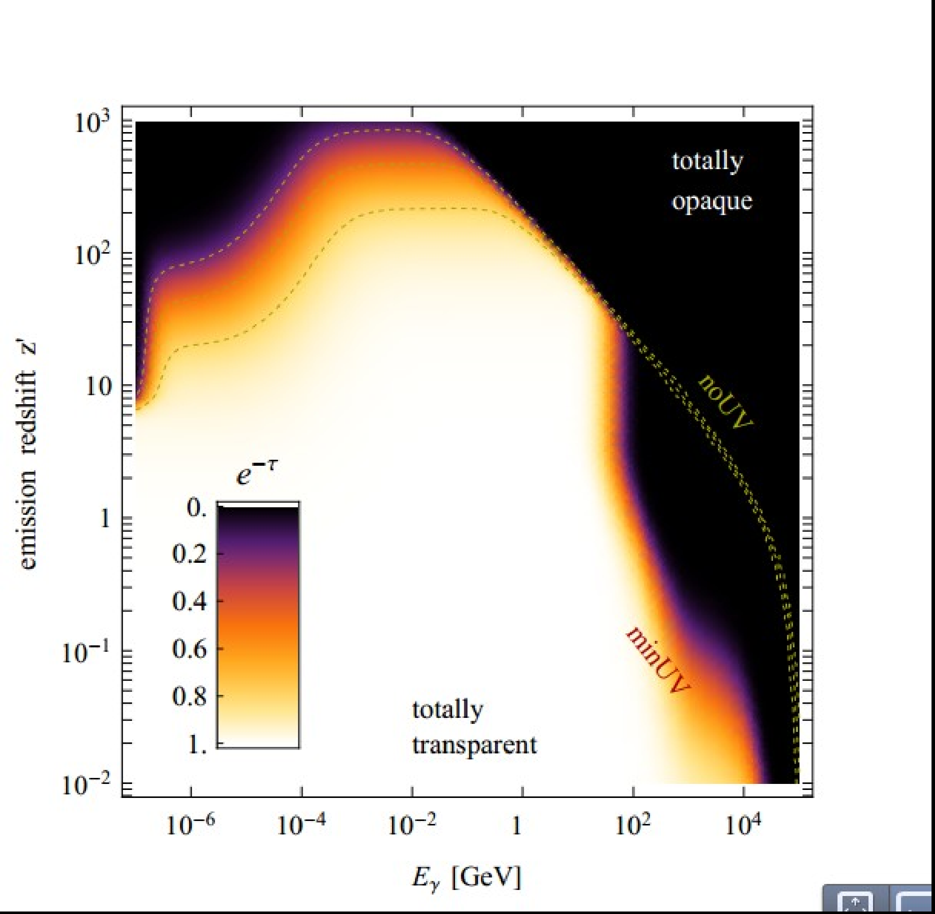
How transparent?



How transparent?

- pair production on baryonic matter
- photon-photon scattering on ambient Photon Background Radiation (PBR)
- pair production on ambient PBR

$$\tau(E_\gamma, z, z') = c \int_z^{z'} \mathrm{d}\tilde{z} \frac{\alpha(\tilde{\epsilon}, \tilde{z})}{H(\tilde{z})(1+\tilde{z})} \,,$$



How transparent?

PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

Marco Cirelli[a,b], Gennaro Corcella[c,d,e], Andi Hektor[f], Gert Hütsi[g], Mario Kadastik[f], Paolo Panci[a,h,i,j], Martti Raidal[f], Filippo Sala[d,e], Alessandro Strumia[a,e,f,k]

Abstract

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays in the Galaxy and beyond. For each DM channel, we present the energy spectra of $e^{\pm}, \bar{p}, \bar{d}, \gamma, \overset{(-)}{\nu}_{e,\mu,\tau}$ at production, computed by high-statistics simulations. We estimate the Monte Carlo uncertainty by comparing the results yielded by the PYTHIA and HERWIG event generators. We then provide the propagation functions for charged particles in the Galaxy, for several DM distribution profiles and sets of propagation parameters. Propagation of $e^{\pm}$ is performed with an improved semi-analytic method that takes into account position-dependent energy losses in the Milky Way. Using such propagation functions, we compute the energy spectra of $e^{\pm}, \bar{p}$ and $\bar{d}$ at the location of the Earth. We then present the gamma ray fluxes, both from prompt emission and from Inverse Compton scattering in the galactic halo. Finally, we provide the spectra of extragalactic gamma rays. All results are available in numerical form and ready to be consumed.

arXiv:1012.4515v4 [hep-ph] 21 Aug 2012

[a] *CERN Theory Division, CH-1211 Genève, Switzerland*
[b] *Institut de Physique Théorique, CNRS, URA 2306 & CEA/Saclay, F-91191 Gif-sur-Yvette, France*

Interim summary

- **Gamma ray is a messenger of non-thermal "violent" physics**
- **Astrophysical production mechanisms:**
  (i) pion production and decay, e.g. $p+p \to p+p+\pi^0$
  (ii) inverse Compton production (cosmic rays + CMB/starlight/IR, pulsars)
  (iii) bremsstrahlung (cosmic rays + matter)
  (iv) synchrotron production (cosmic rays + magnetic fields)
- **Gamma rays can hint "New Physics"**
  (i) annihilation or decay of Dark Matter
  (ii) other exotics
- **Energy spectrum of astrophysical gamma rays is (more-or-less) power law**
- **There exists gamma ray point (pulsar, AGN, SNR) and extended sources (diffuse, close by SNR, "DM annihilation/decay")**

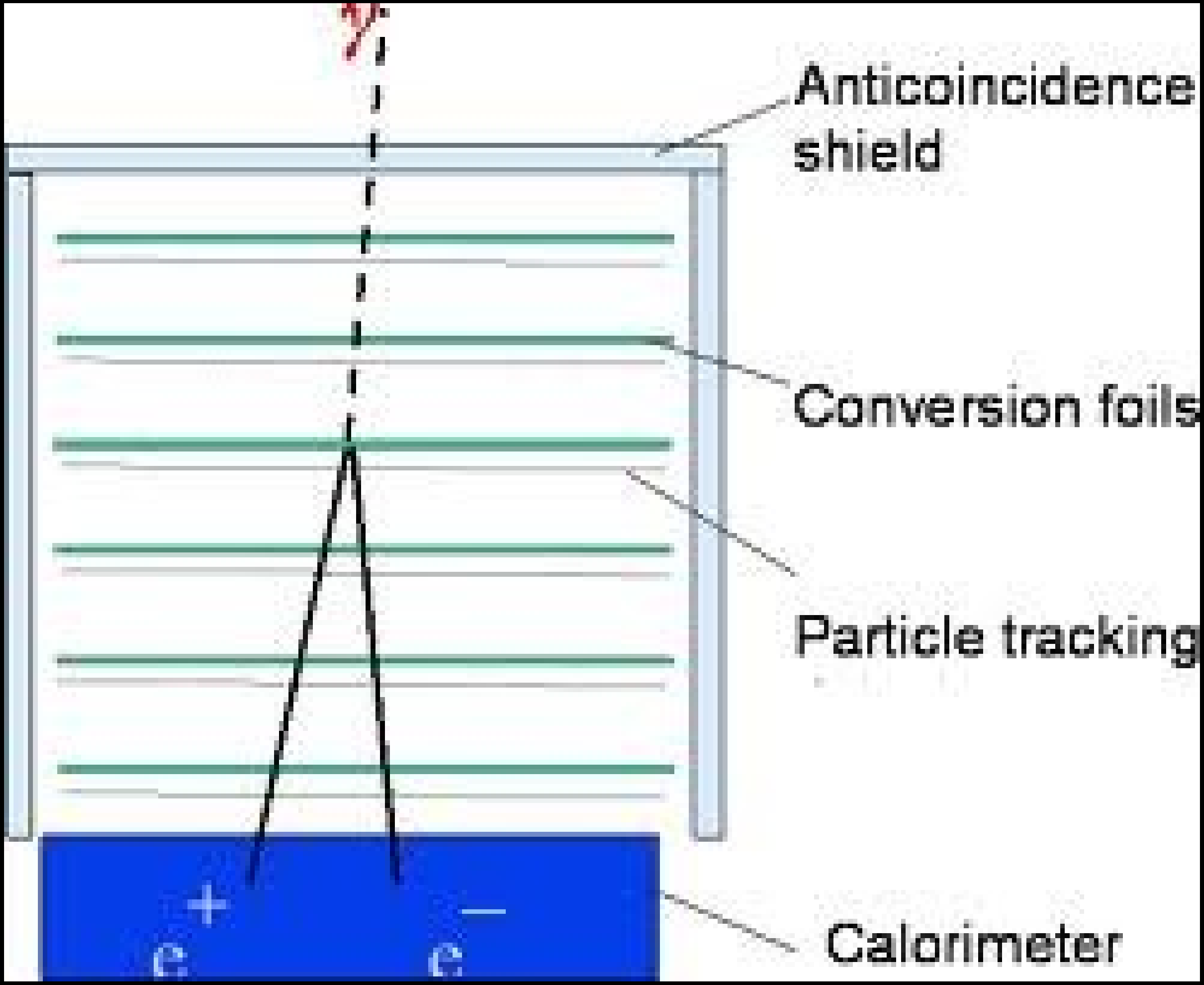
Intro to gamma ray telescopes

Intro to gamma ray telescopes

- Satellite telescopes: Fermi satellite
- Terrestrial telescopes: Cherenkov telescopes (MACIG, HESS, VERITAS, CTA)

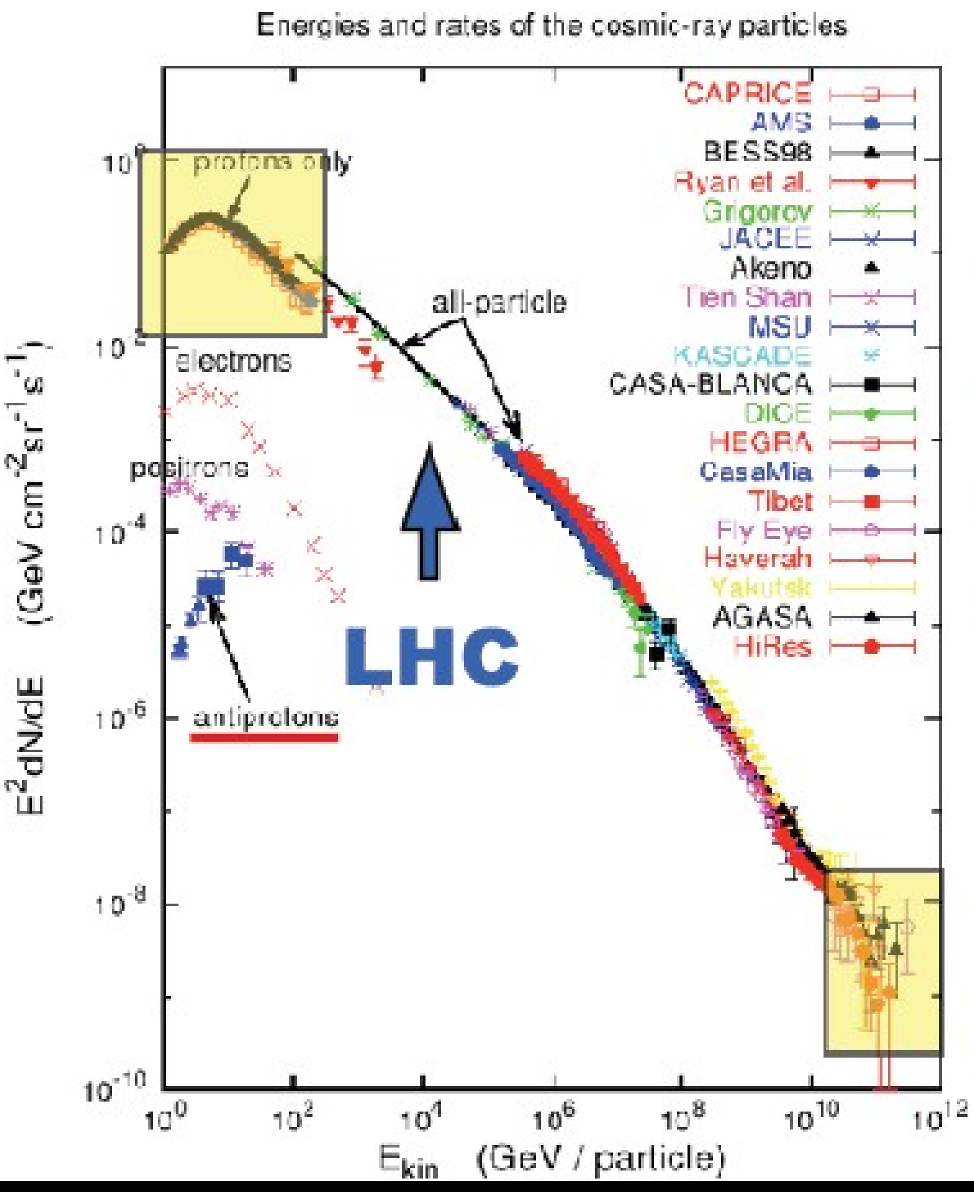
Fermi satellite

Fermi LAT,
a typical gamma ray detector



Charged cosmic rays are background for gamma rays!

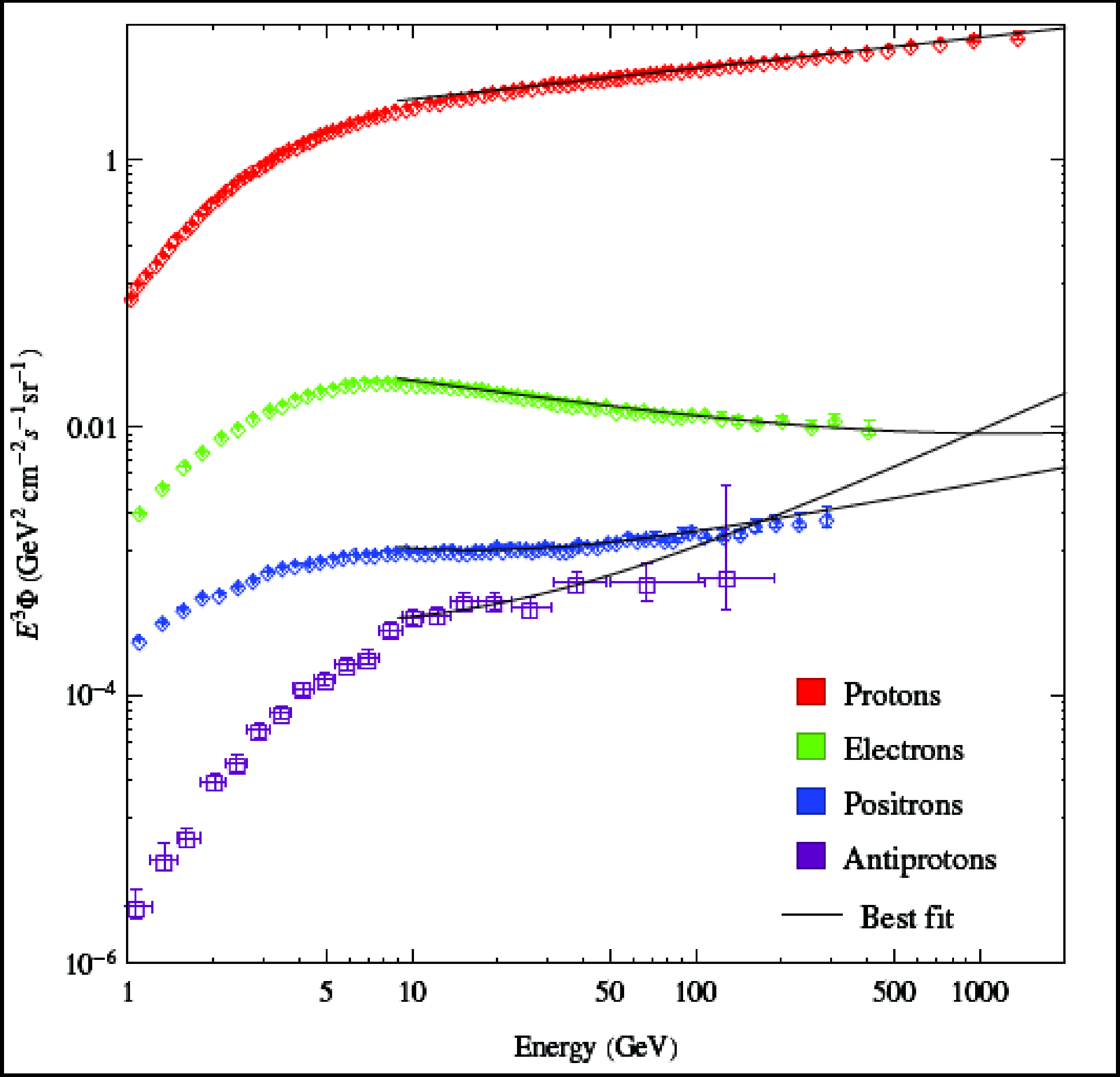
1/cm²/s



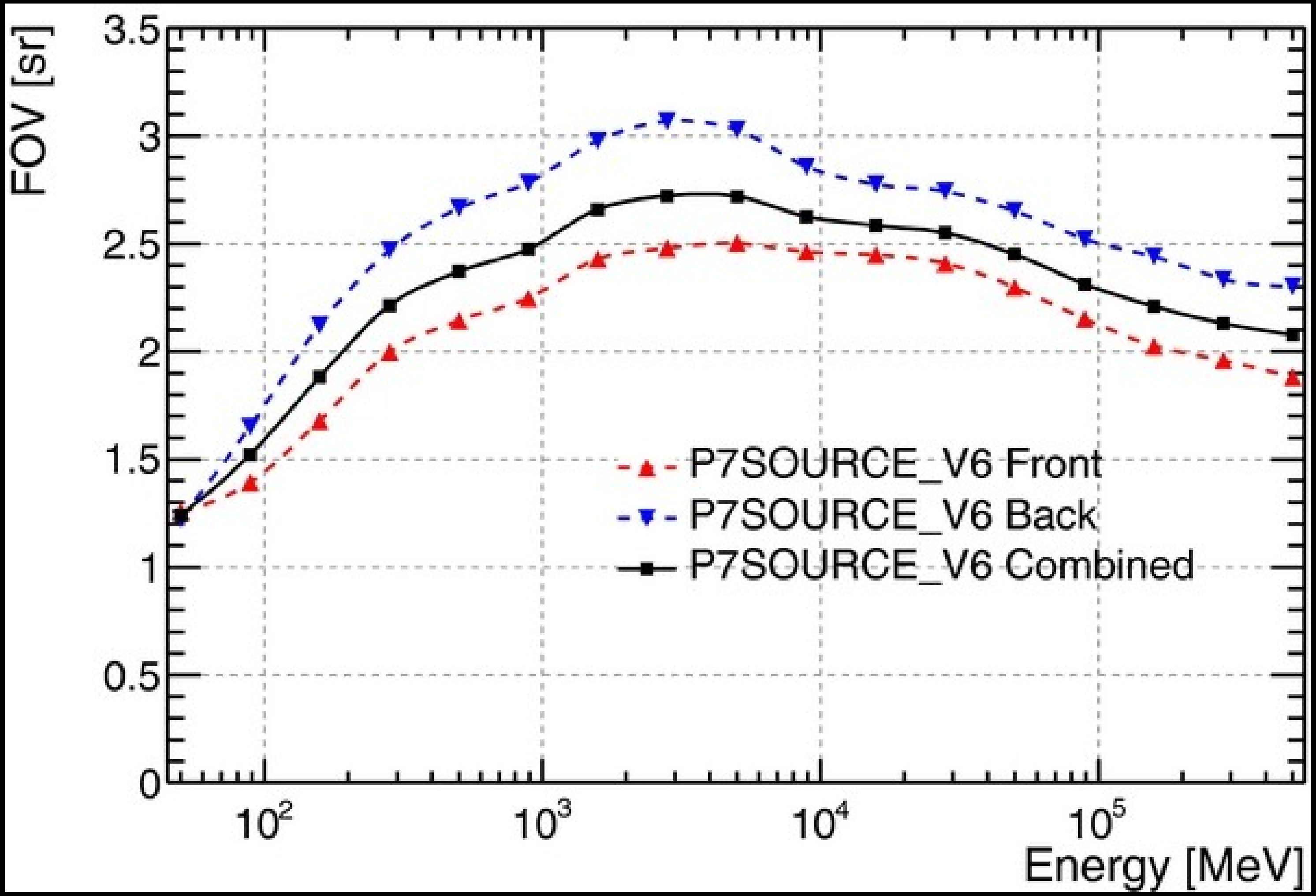
Ivo Karlović
2011 Davis Cup
~10^{12} GeV

1/km²/century

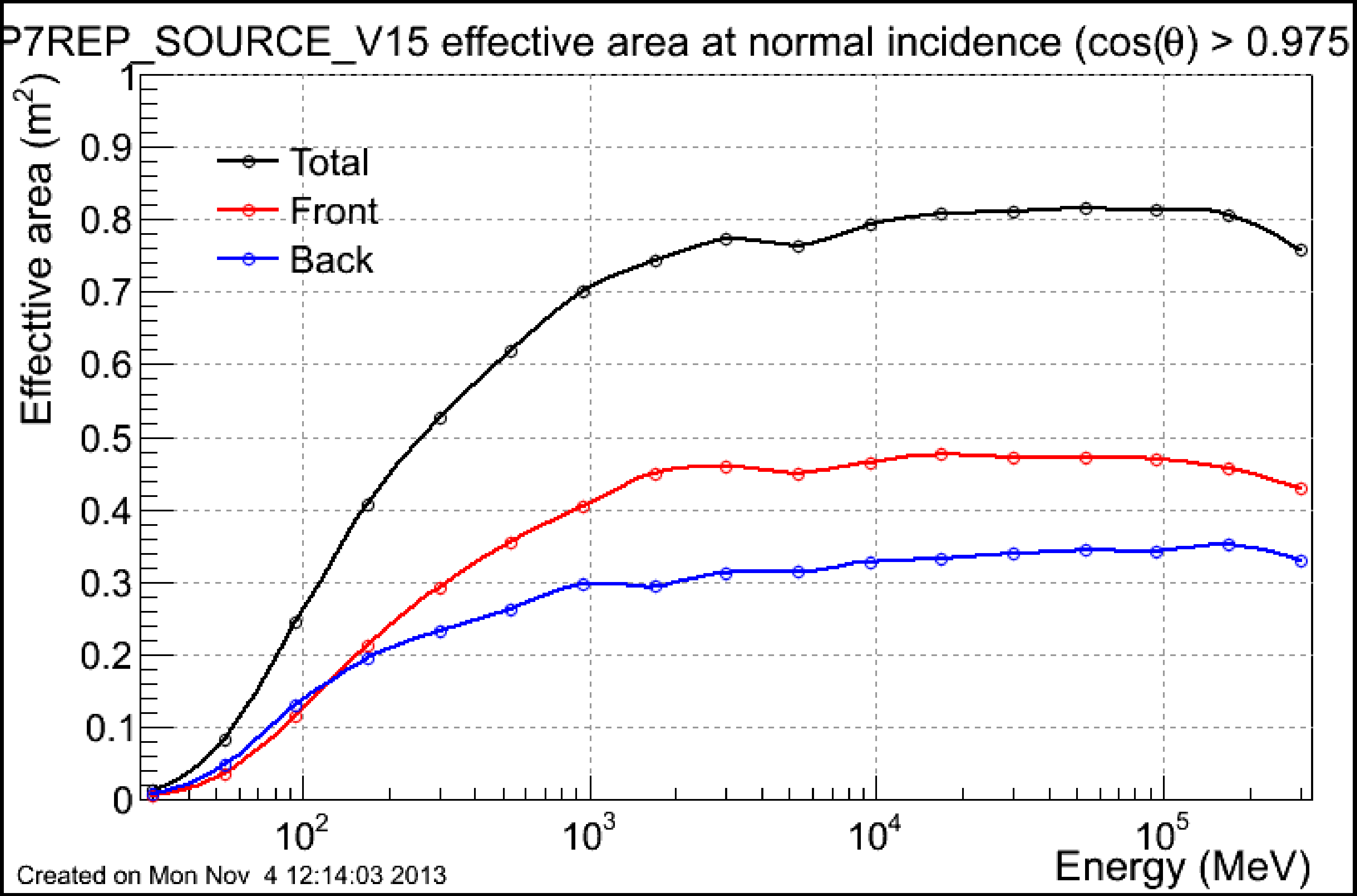
Charged cosmic rays are background for gamma rays!



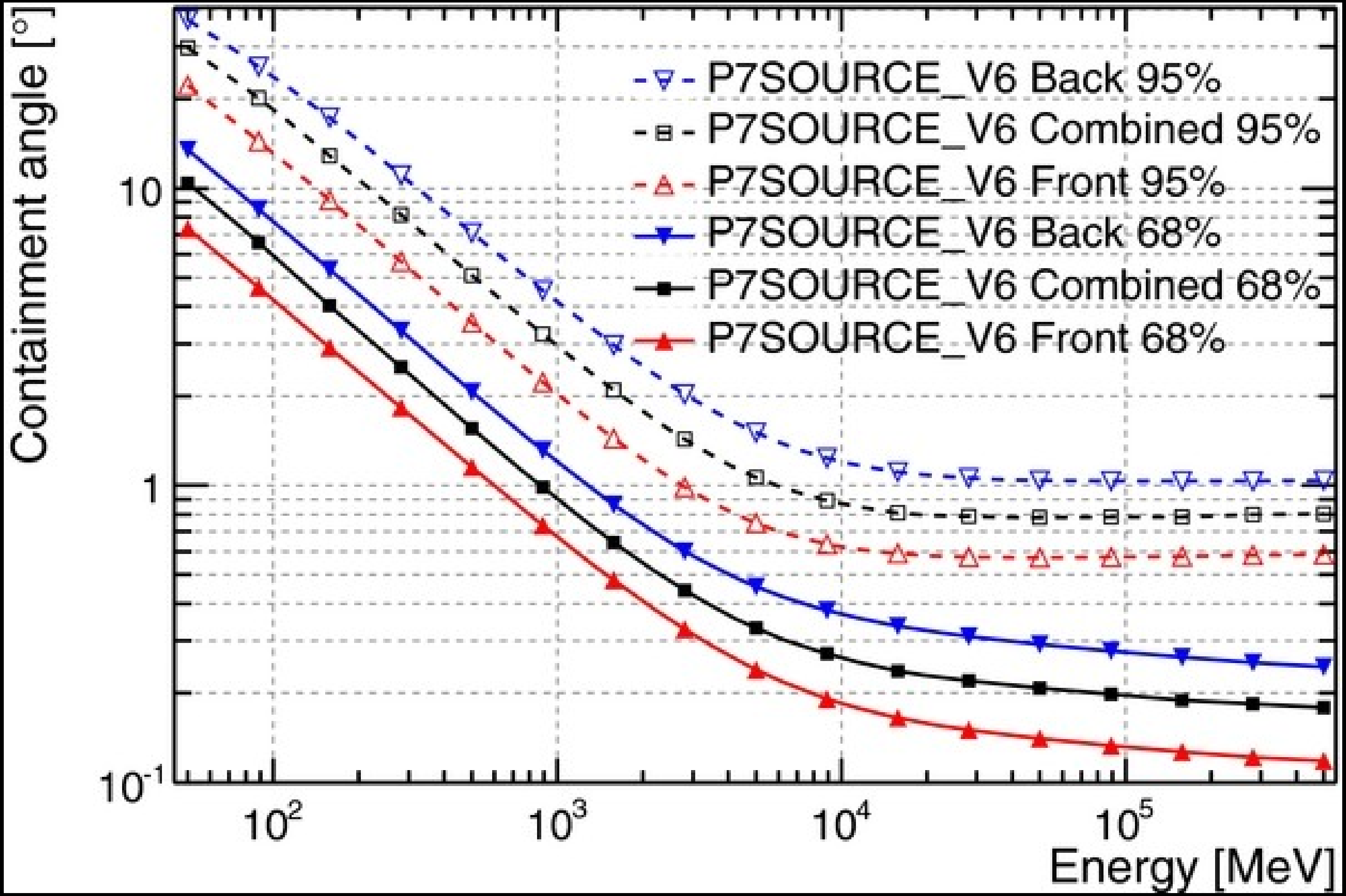
Parameters of the Fermi LAT: Field of View



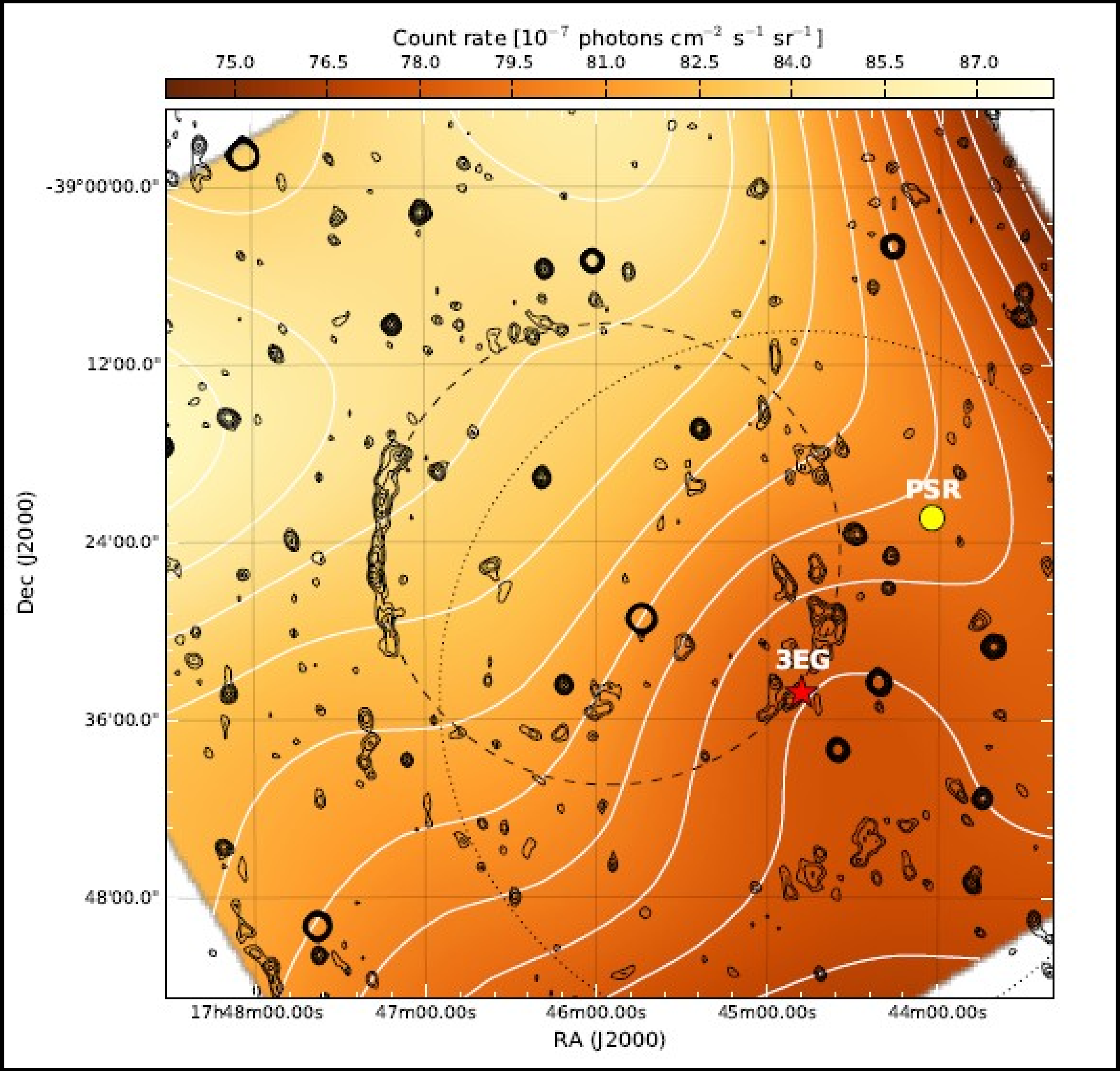
Parameters of the Fermi LAT: Effective Area



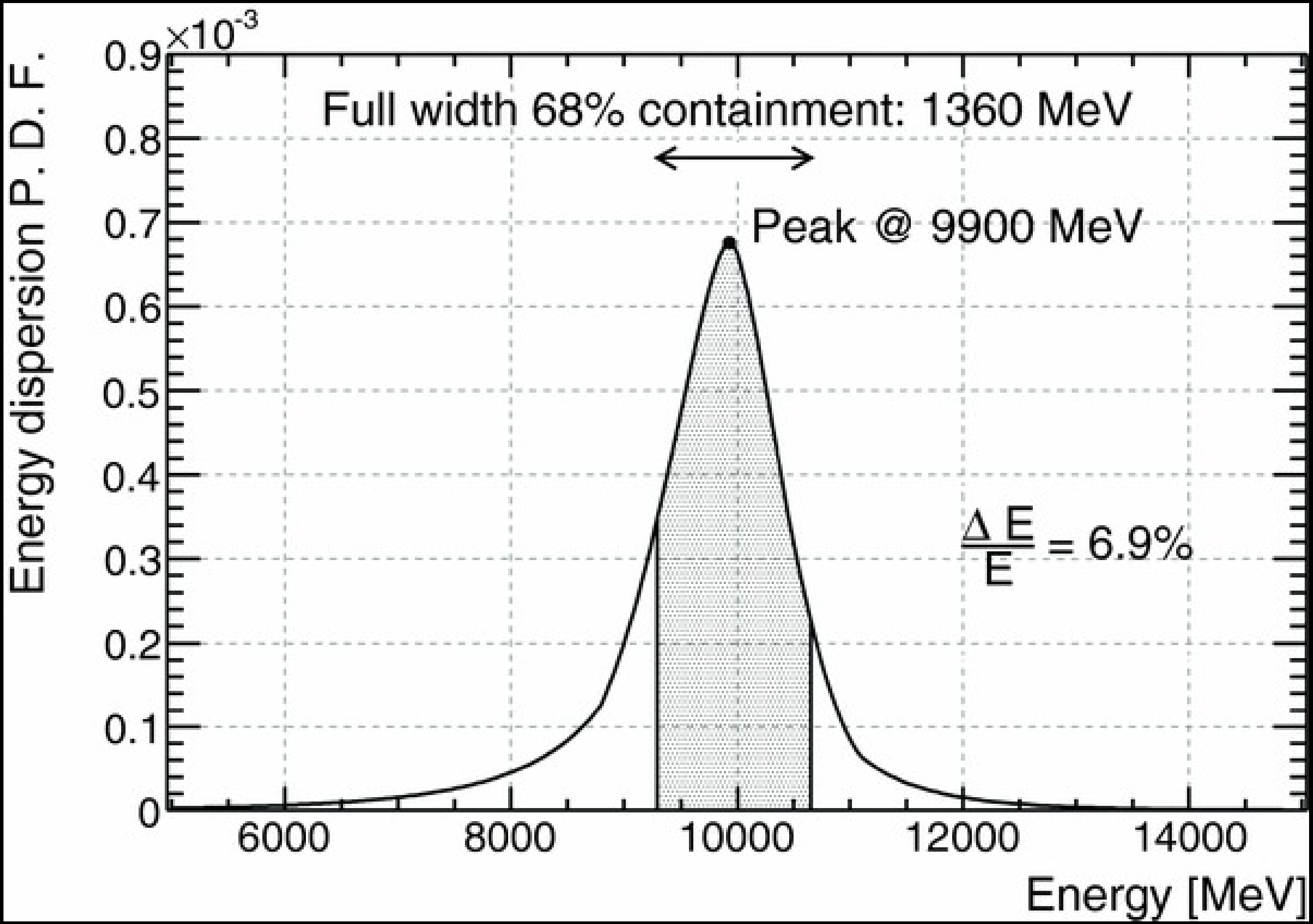
Parameters of the Fermi LAT: Point Spread Function



Parameters of the Fermi LAT: Point Spread Function



Parameters of the Fermi LAT: Energy Dispersion



Data system of the Fermi LAT

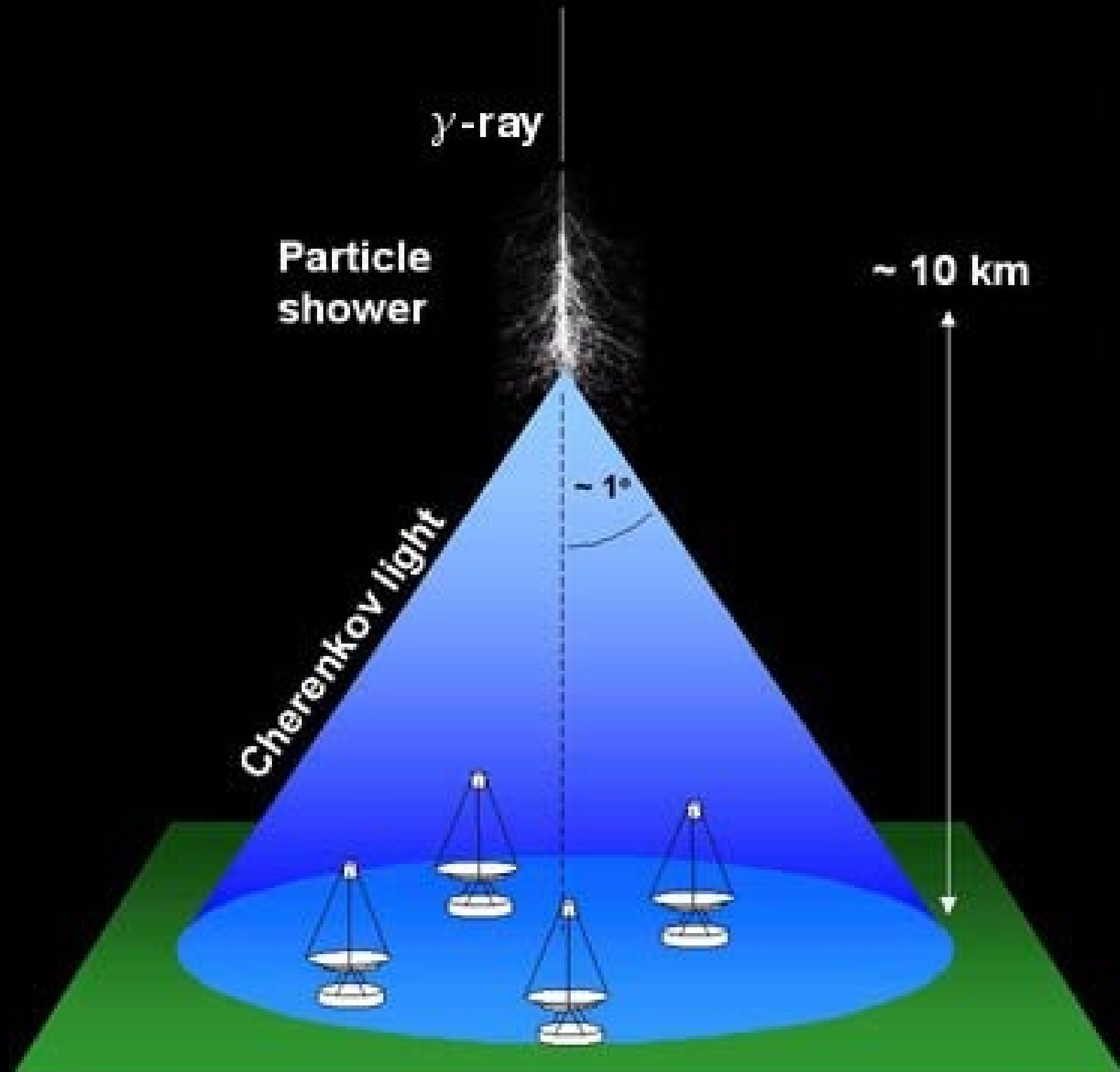
- Event-by-event data
- Data field: l, b, E, phi, type, zenith angle etc, time etc
- Amount of total data (~4 years): some Gigabytes
- The data is public
- A set of public (open source) analysis tools are available: Fermi Science Tools http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
- General web page of the Fermi Collaboration: http://www-glast.stanford.edu/

Catalogs of the Fermi LAT

- Second Fermi-LAT Point Source Catalog
- Second LAT AGN Catalog
- First Fermi-LAT Point Source Catalog
- First LAT AGN Catalog
- LAT Bright Source LIst
- LAT Bright AGN List
- First Catalog of LAT High-Energy Sources (> 10 GeV)
- First Catalog of LAT Gamma-ray Pulsars
- Catalog of Fermi-LAT Variable Sources
- Fermi-GBM Gamma-ray Burst Catalog (first 2 years)

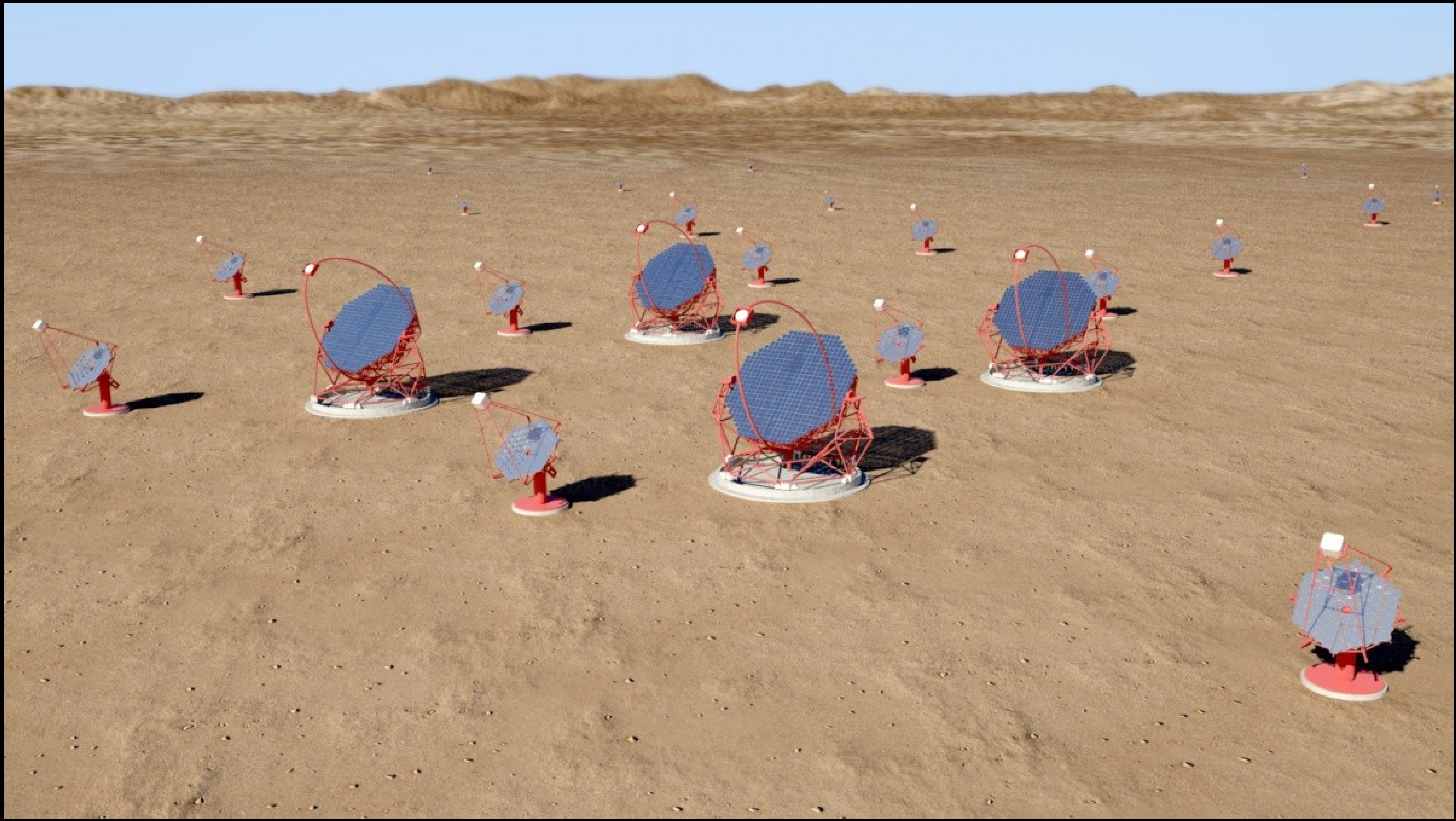
http://fermi.gsfc.nasa.gov/ssc/data/access/

Cherekov telescopes



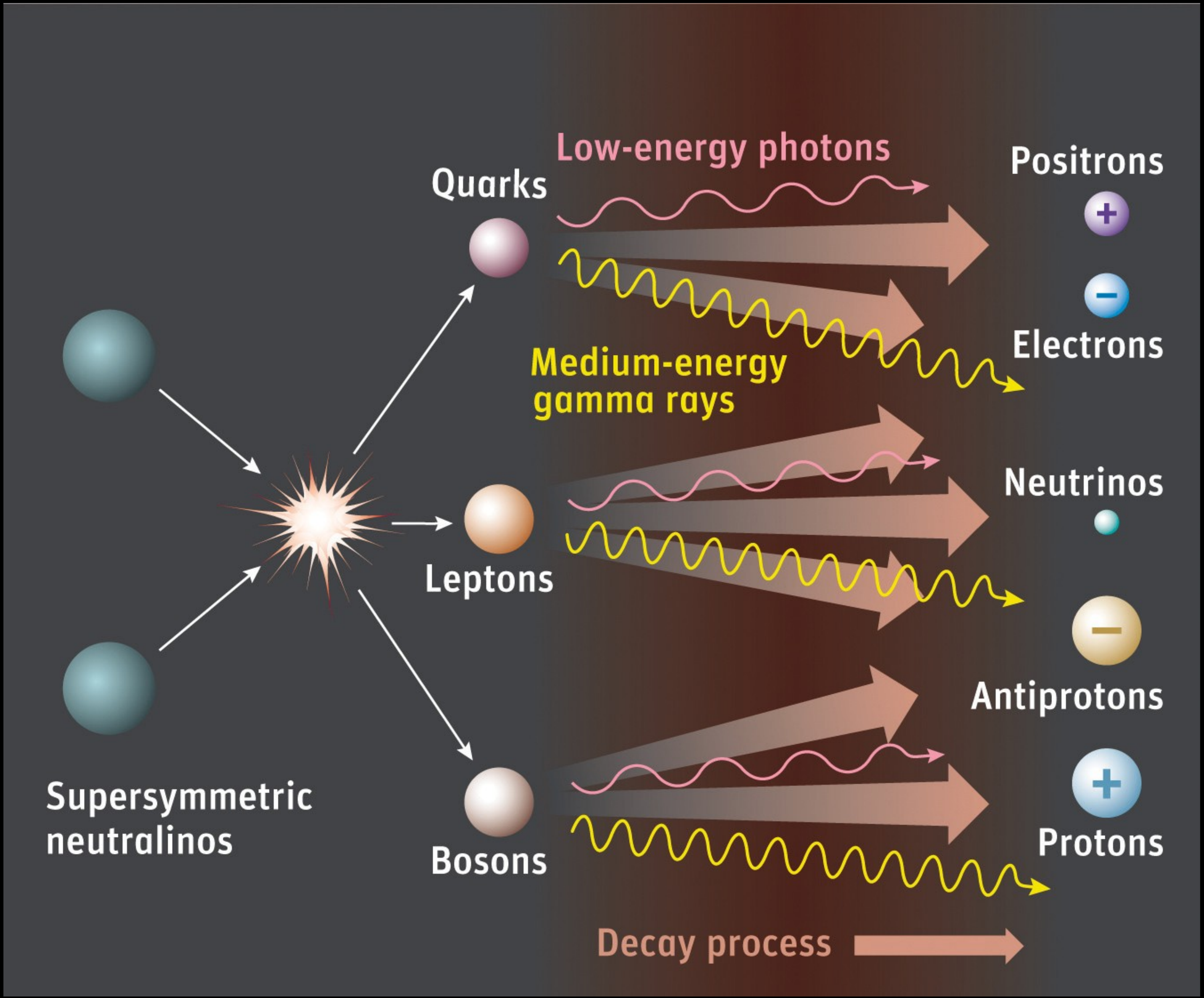
Cherekov telescopes: H.E.S.S.

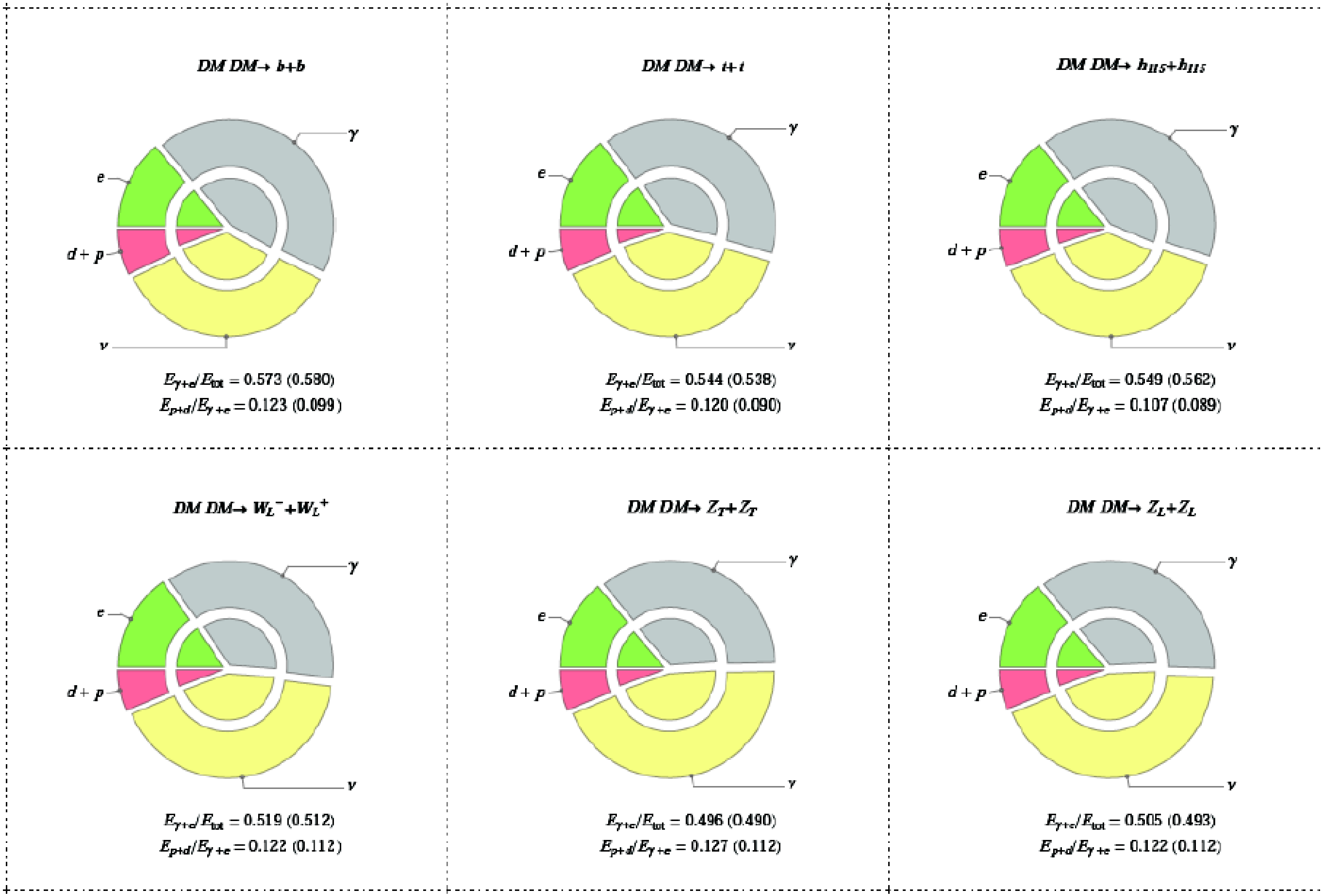
Next generation:
Cherenkov Telescope Array (CTA)

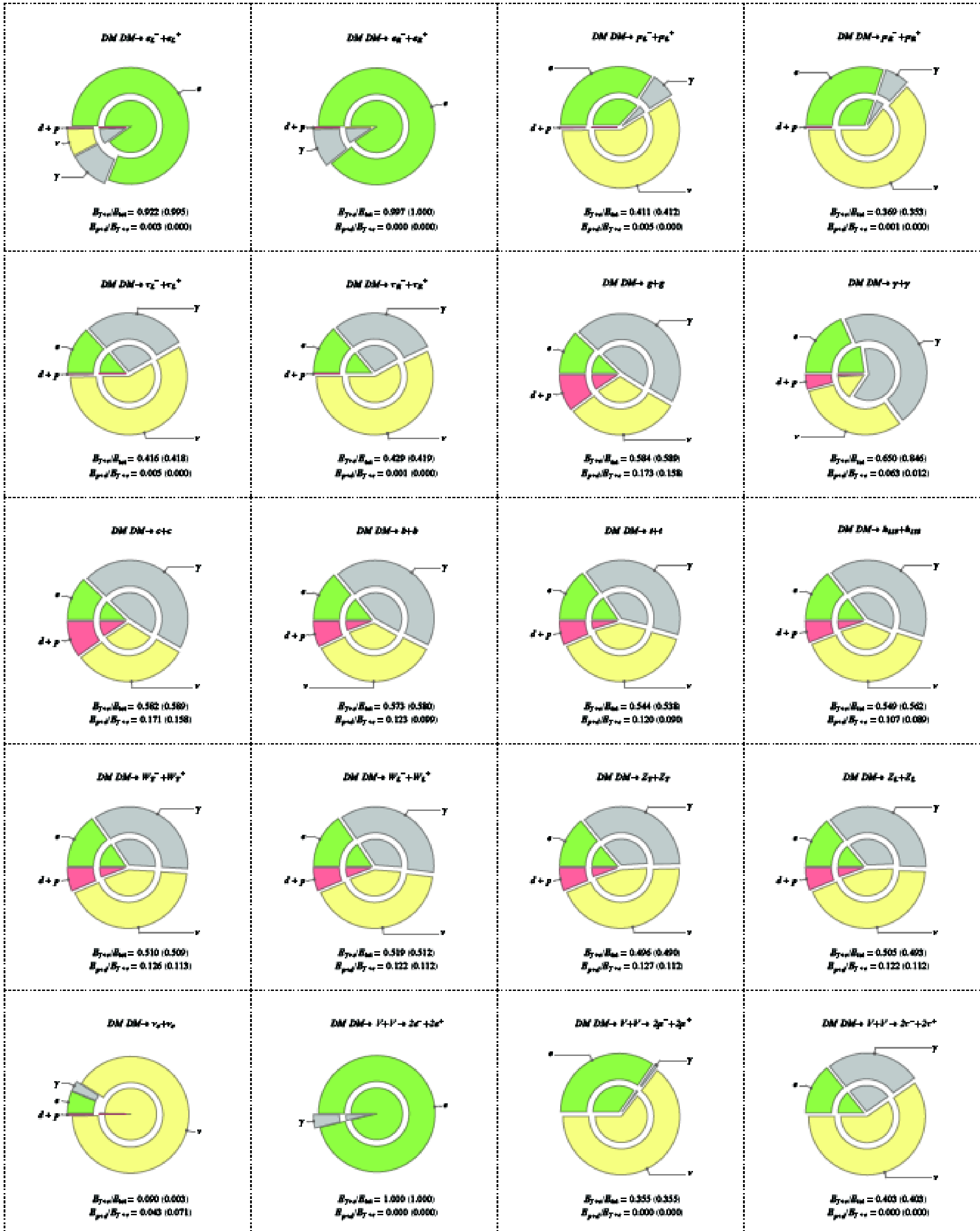



Thank you!
andi.hektor@cern.ch

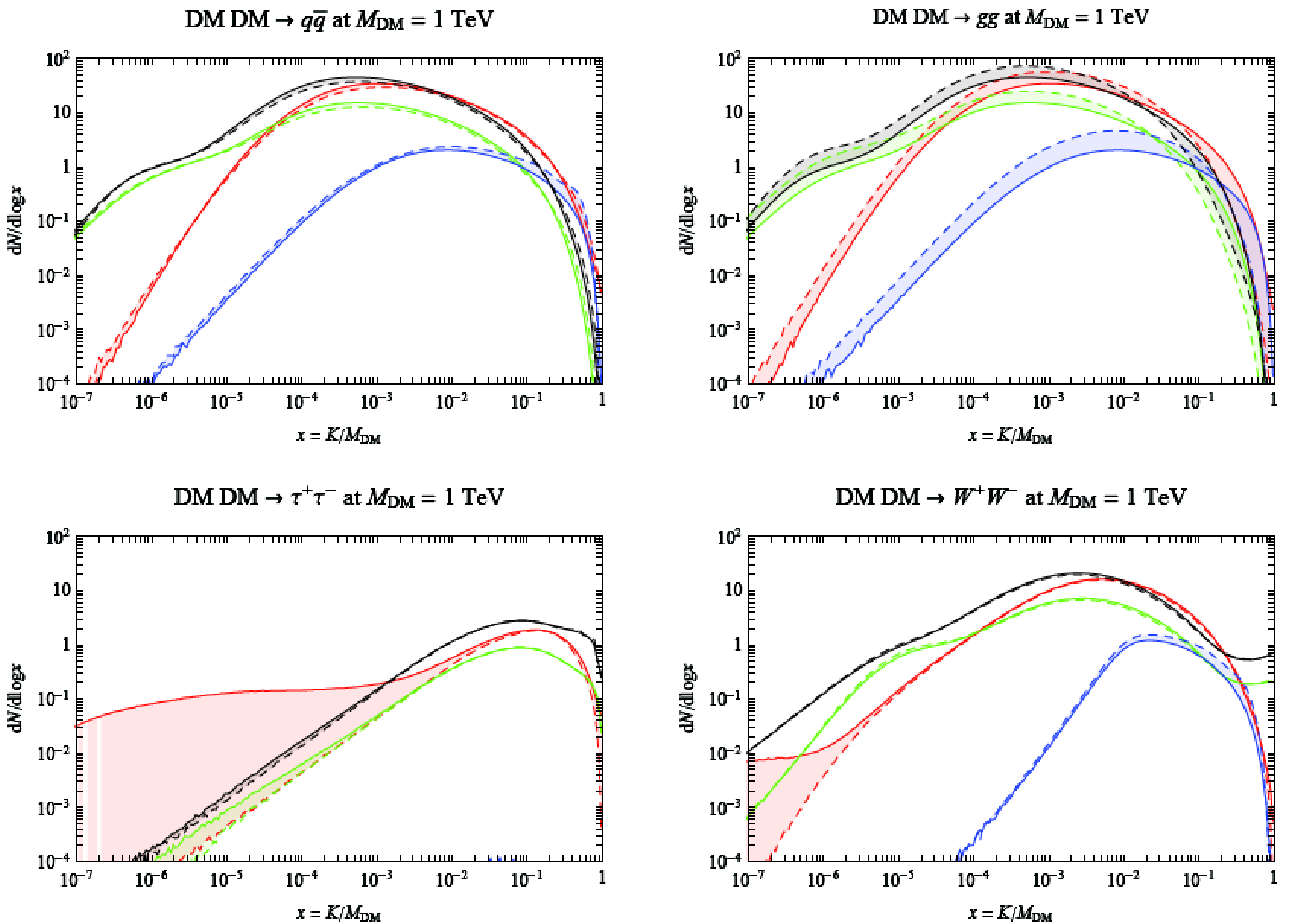
Bonus slaids


Low-energy photons
Quarks
Positrons
Medium-energy
gamma rays
Electrons
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Bosons
Protons
Decay process

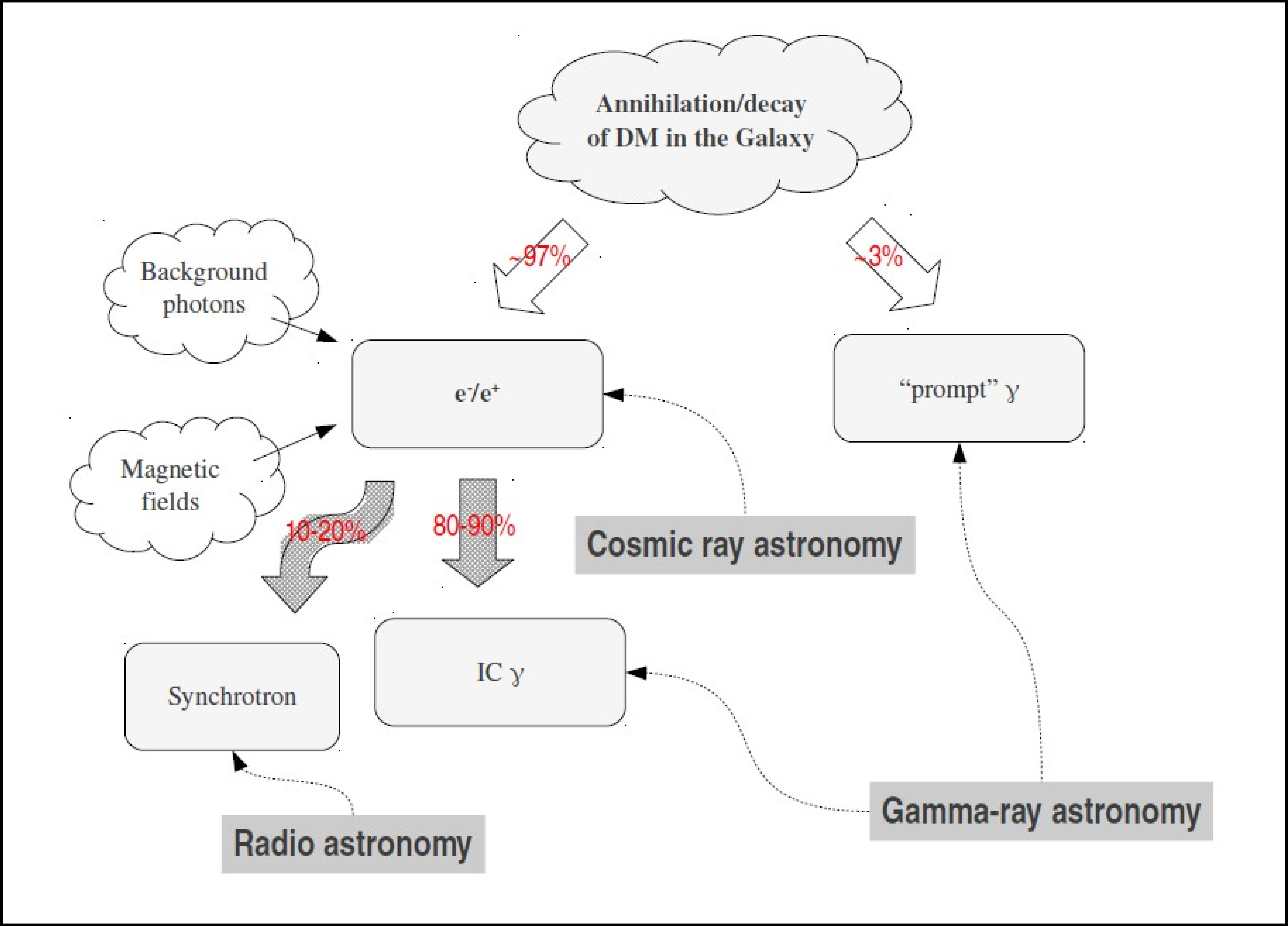

DM DM→ b+b
γ
e
d + p
ν
E_{γ+e}/E_tot = 0.573 (0.580)
E_{p+d}/E_{γ+e} = 0.123 (0.099)
DM DM→ t+t
γ
e
d + p
ν
E_{γ+e}/E_tot = 0.544 (0.538)
E_{p+d}/E_{γ+e} = 0.120 (0.090)
DM DM→ h_115+h_115
γ
e
d + p
ν
E_{γ+e}/E_tot = 0.549 (0.562)
E_{p+d}/E_{γ+e} = 0.107 (0.089)
DM DM→ W_L^-+W_L^+
γ
e
d + p
ν
E_{γ+e}/E_tot = 0.519 (0.512)
E_{p+d}/E_{γ+e} = 0.122 (0.112)
DM DM→ Z_T+Z_T
γ
e
d + p
γ
E_{γ+e}/E_tot = 0.496 (0.490)
E_{p+d}/E_{γ+e} = 0.127 (0.112)
DM DM→ Z_L+Z_L
γ
e
d + p
ν
E_{γ+e}/E_tot = 0.505 (0.493)
E_{p+d}/E_{γ+e} = 0.122 (0.112)



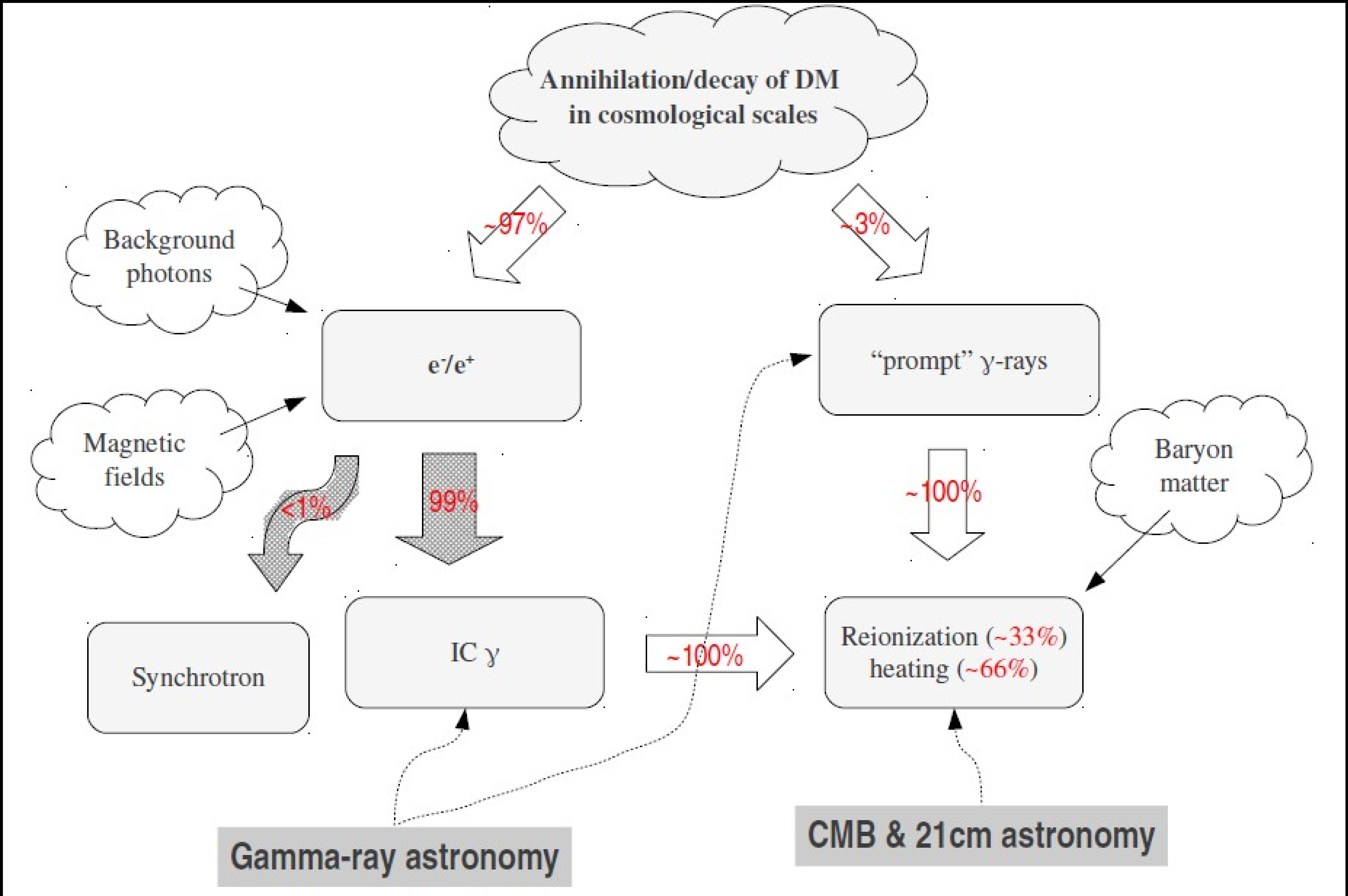
$DM\,DM \to e_L^- + e_L^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.922\ (0.995)$
$B_{p+d}/B_{\gamma+\nu} = 0.003\ (0.000)$
$DM\,DM \to e_R^- + e_R^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.997\ (1.000)$
$B_{p+d}/B_{\gamma+\nu} = 0.000\ (0.000)$
$DM\,DM \to \mu_L^- + \mu_L^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.411\ (0.412)$
$B_{p+d}/B_{\gamma+\nu} = 0.005\ (0.000)$
$DM\,DM \to \mu_R^- + \mu_R^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.369\ (0.353)$
$B_{p+d}/B_{\gamma+\nu} = 0.001\ (0.000)$
$DM\,DM \to \tau_L^- + \tau_L^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.416\ (0.418)$
$B_{p+d}/B_{\gamma+\nu} = 0.005\ (0.000)$
$DM\,DM \to \tau_R^- + \tau_R^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.429\ (0.419)$
$B_{p+d}/B_{\gamma+\nu} = 0.001\ (0.000)$
$DM\,DM \to g+g$
$B_{\gamma+\nu}/B_{\rm tot} = 0.584\ (0.589)$
$B_{p+d}/B_{\gamma+\nu} = 0.173\ (0.158)$
$DM\,DM \to \gamma+\gamma$
$B_{\gamma+\nu}/B_{\rm tot} = 0.650\ (0.846)$
$B_{p+d}/B_{\gamma+\nu} = 0.063\ (0.012)$
$DM\,DM \to c+c$
$B_{\gamma+\nu}/B_{\rm tot} = 0.582\ (0.589)$
$B_{p+d}/B_{\gamma+\nu} = 0.171\ (0.158)$
$DM\,DM \to b+b$
$B_{\gamma+\nu}/B_{\rm tot} = 0.573\ (0.580)$
$B_{p+d}/B_{\gamma+\nu} = 0.123\ (0.099)$
$DM\,DM \to t+t$
$B_{\gamma+\nu}/B_{\rm tot} = 0.544\ (0.538)$
$B_{p+d}/B_{\gamma+\nu} = 0.120\ (0.090)$
$DM\,DM \to h_{125}+h_{125}$
$B_{\gamma+\nu}/B_{\rm tot} = 0.549\ (0.562)$
$B_{p+d}/B_{\gamma+\nu} = 0.107\ (0.080)$
$DM\,DM \to W_T^- + W_T^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.510\ (0.509)$
$B_{p+d}/B_{\gamma+\nu} = 0.126\ (0.113)$
$DM\,DM \to W_L^- + W_L^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.519\ (0.512)$
$B_{p+d}/B_{\gamma+\nu} = 0.122\ (0.112)$
$DM\,DM \to Z_T+Z_T$
$B_{\gamma+\nu}/B_{\rm tot} = 0.496\ (0.490)$
$B_{p+d}/B_{\gamma+\nu} = 0.127\ (0.112)$
$DM\,DM \to Z_L+Z_L$
$B_{\gamma+\nu}/B_{\rm tot} = 0.505\ (0.493)$
$B_{p+d}/B_{\gamma+\nu} = 0.122\ (0.112)$
$DM\,DM \to \nu_e+\nu_e$
$B_{\gamma+\nu}/B_{\rm tot} = 0.090\ (0.003)$
$B_{p+d}/B_{\gamma+\nu} = 0.043\ (0.071)$
$DM\,DM \to V+V \to 2e^- + 2e^+$
$B_{\gamma+\nu}/B_{\rm tot} = 1.000\ (1.000)$
$B_{p+d}/B_{\gamma+\nu} = 0.000\ (0.000)$
$DM\,DM \to V+V \to 2\mu^- + 2\mu^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.355\ (0.355)$
$B_{p+d}/B_{\gamma+\nu} = 0.000\ (0.000)$
$DM\,DM \to V+V \to 2\tau^- + 2\tau^+$
$B_{\gamma+\nu}/B_{\rm tot} = 0.403\ (0.403)$
$B_{p+d}/B_{\gamma+\nu} = 0.000\ (0.000)$



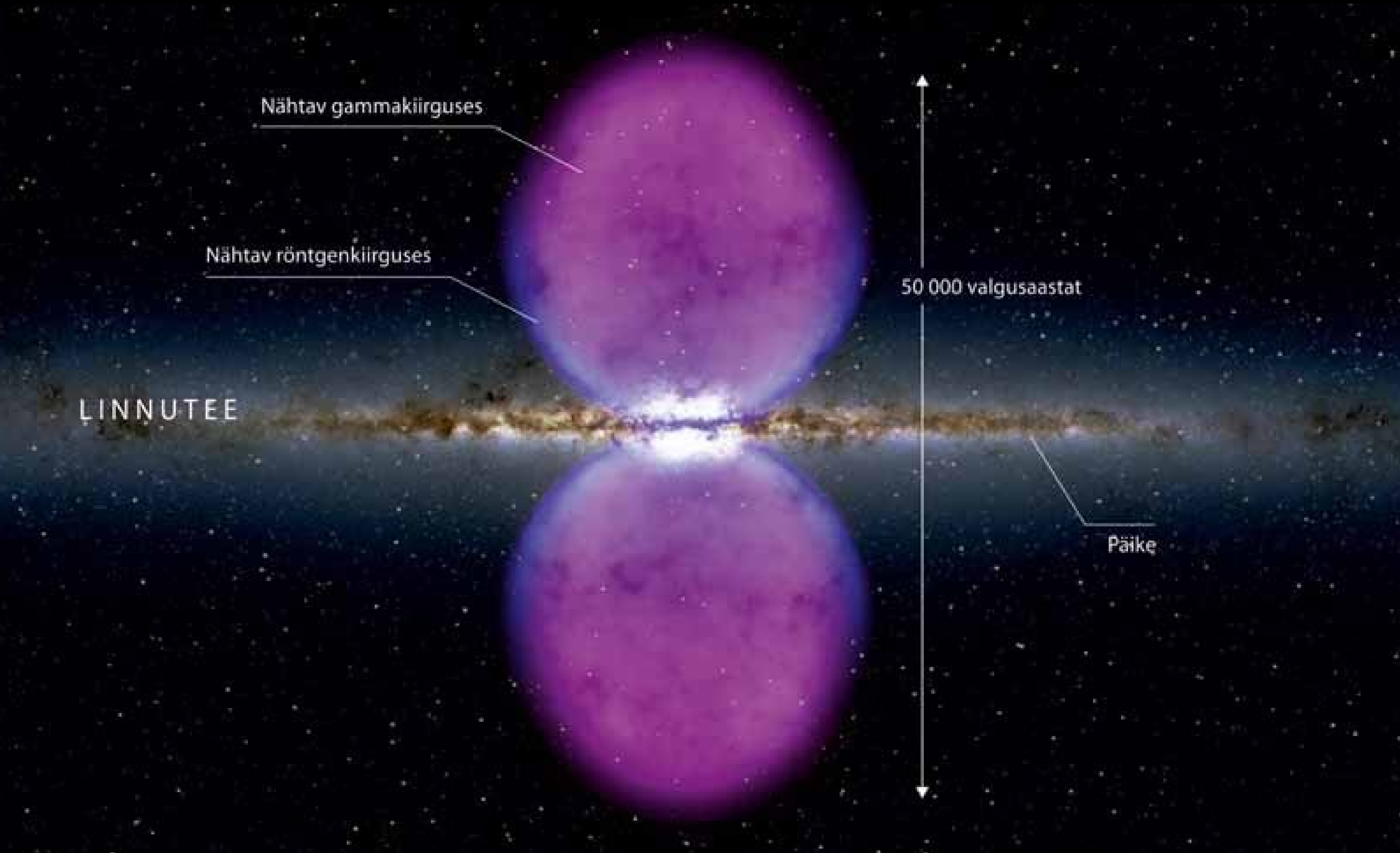
DM DM → $q\bar{q}$ at $M_{\rm DM}$ = 1 TeV
DM DM → gg at $M_{\rm DM}$ = 1 TeV
DM DM → $\tau^+\tau^-$ at $M_{\rm DM}$ = 1 TeV
DM DM → W^+W^- at $M_{\rm DM}$ = 1 TeV
$dN/d\log x$
$x = K/M_{\rm DM}$



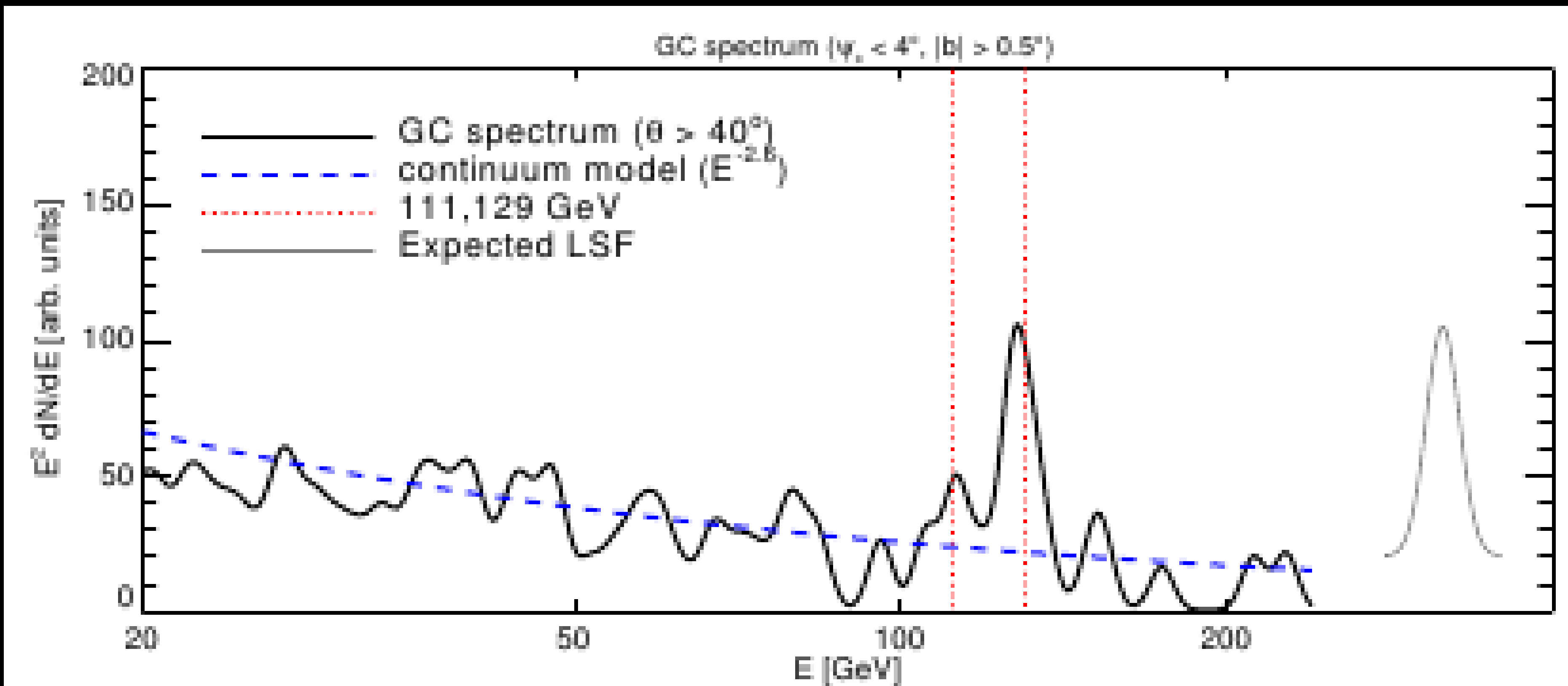
Annihilation/decay of DM in the Galaxy
~97%
~3%
Background photons
Magnetic fields
e^-/e^+
"prompt" γ
10-20%
80-90%
Cosmic ray astronomy
Synchrotron
IC γ
Radio astronomy
Gamma-ray astronomy

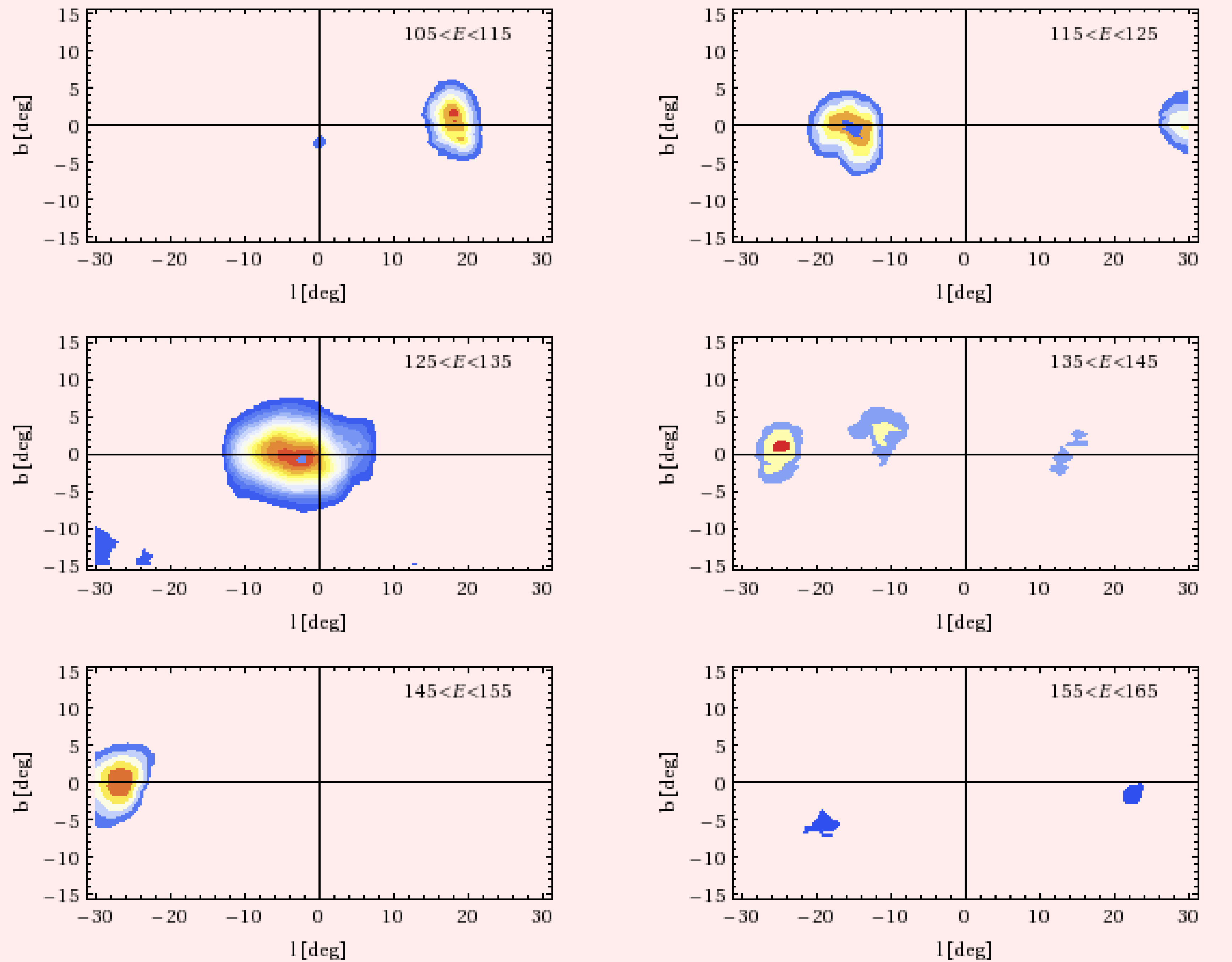

Annihilation/decay of DM
in cosmological scales
~97%
~3%
Background
photons
e^-/e^+
"prompt" γ-rays
Magnetic
fields
<1%
99%
~100%
Baryon
matter
Synchrotron
IC γ
~100%
Reionization (~33%)
heating (~66%)
Gamma-ray astronomy
CMB & 21cm astronomy

Some discoveries of Fermi LAT: "Fermi bubble"



Some discoveries of Fermi LAT:
"Fermi 130 GeV line"




105<E<115
115<E<125
125<E<135
135<E<145
145<E<155
155<E<165
b [deg]
l [deg]

Why a gamma ray line is so special?

- There is no “standard physics” giving a gamma ray lines!
- Lines are more visible over typical power-law like astrophysical background
- DM annihilation or decay can provide a gamma ray lines!