Fermi Gamma-ray Space Telescope

The interstellar emission from gamma rays to radio

ELENA ORLANDO

KIPAC

on behalf of the Fermi-LAT collaboration

Workshop on the Future of Dark Matter AstroParticle Physics

ICTP, Trieste

11 October 2013

Fermi Observatory

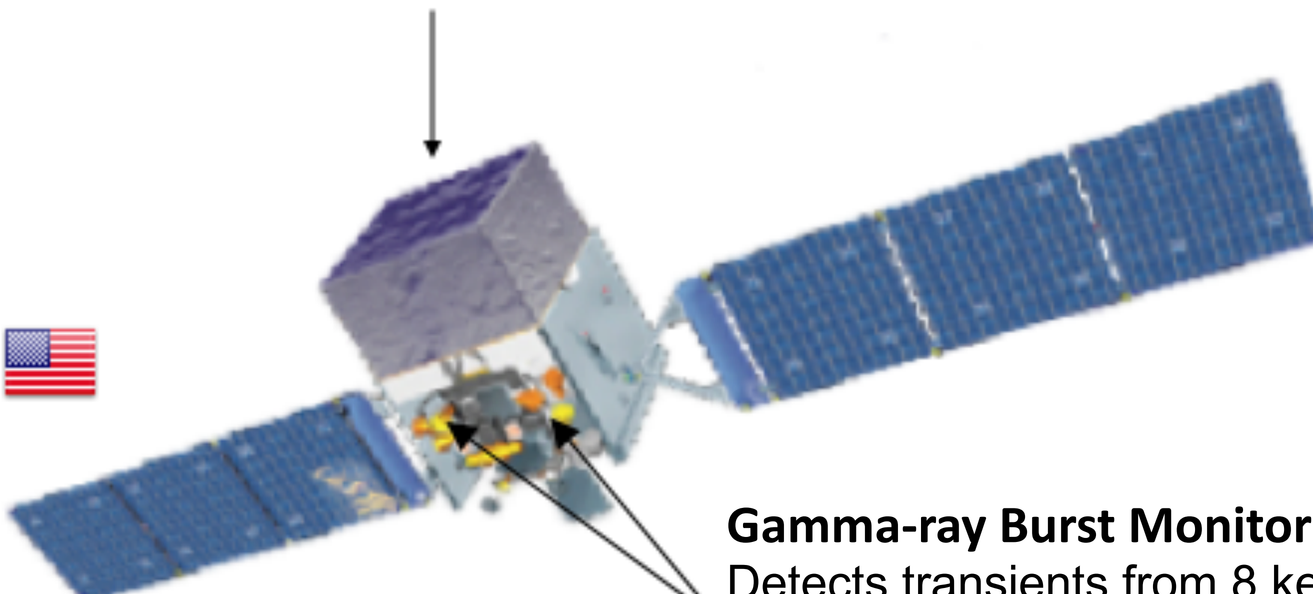
http://fermi.gsfc.nasa.gov/

Launch from Cape Canaveral 11 June 2008
Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination

See talk by Latronico

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - > 300 GeV

International collaboration



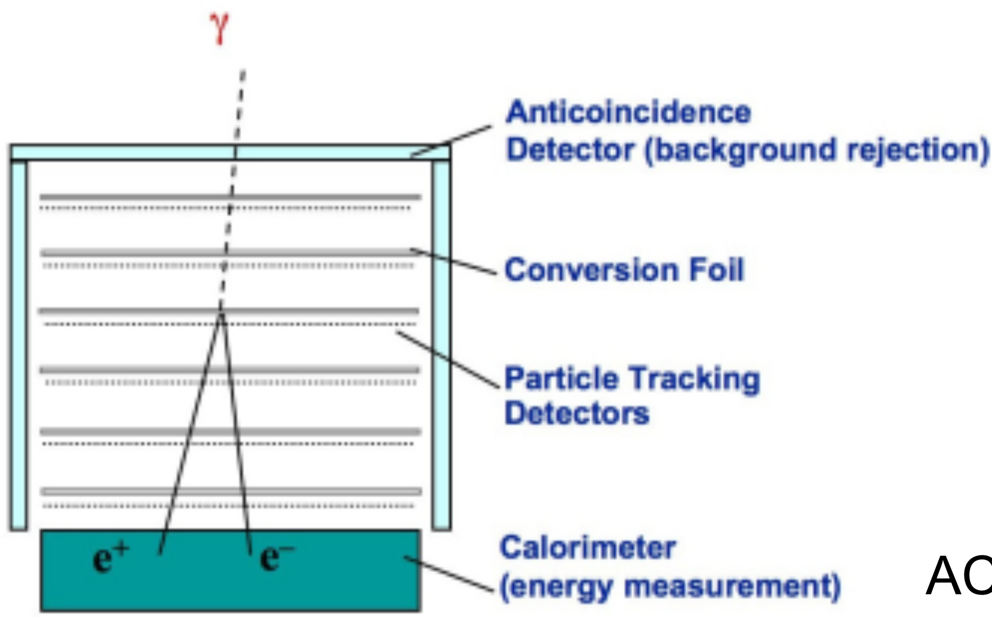
Gamma-ray Burst Monitor (GBM)
Detects transients from 8 keV - 40 MeV
12 NaI and 2 BGO detectors

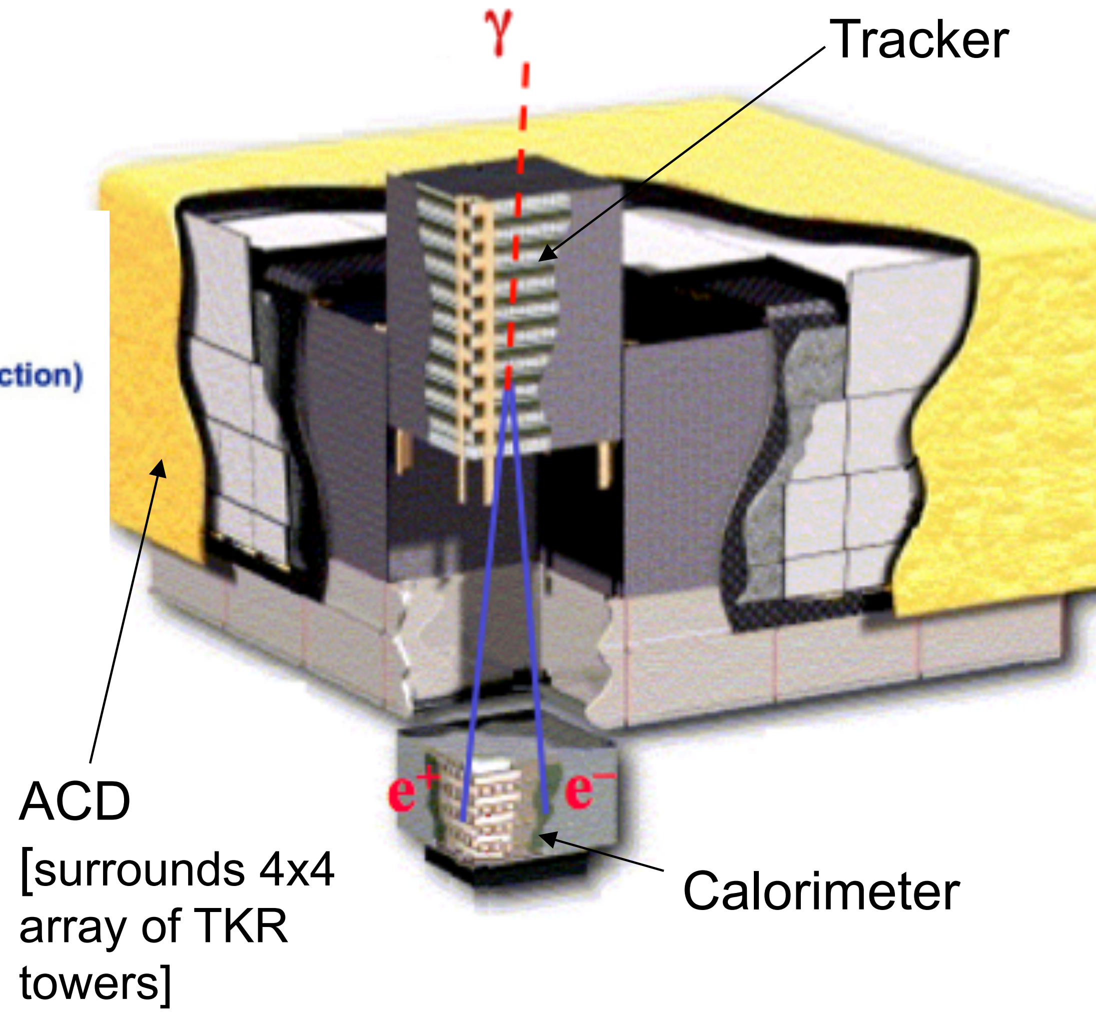
Large Area Telescope (LAT)

W. B. Atwood et al. 2009, ApJ, 697, 1071

See talk by Latronico

Pair conversion telescope

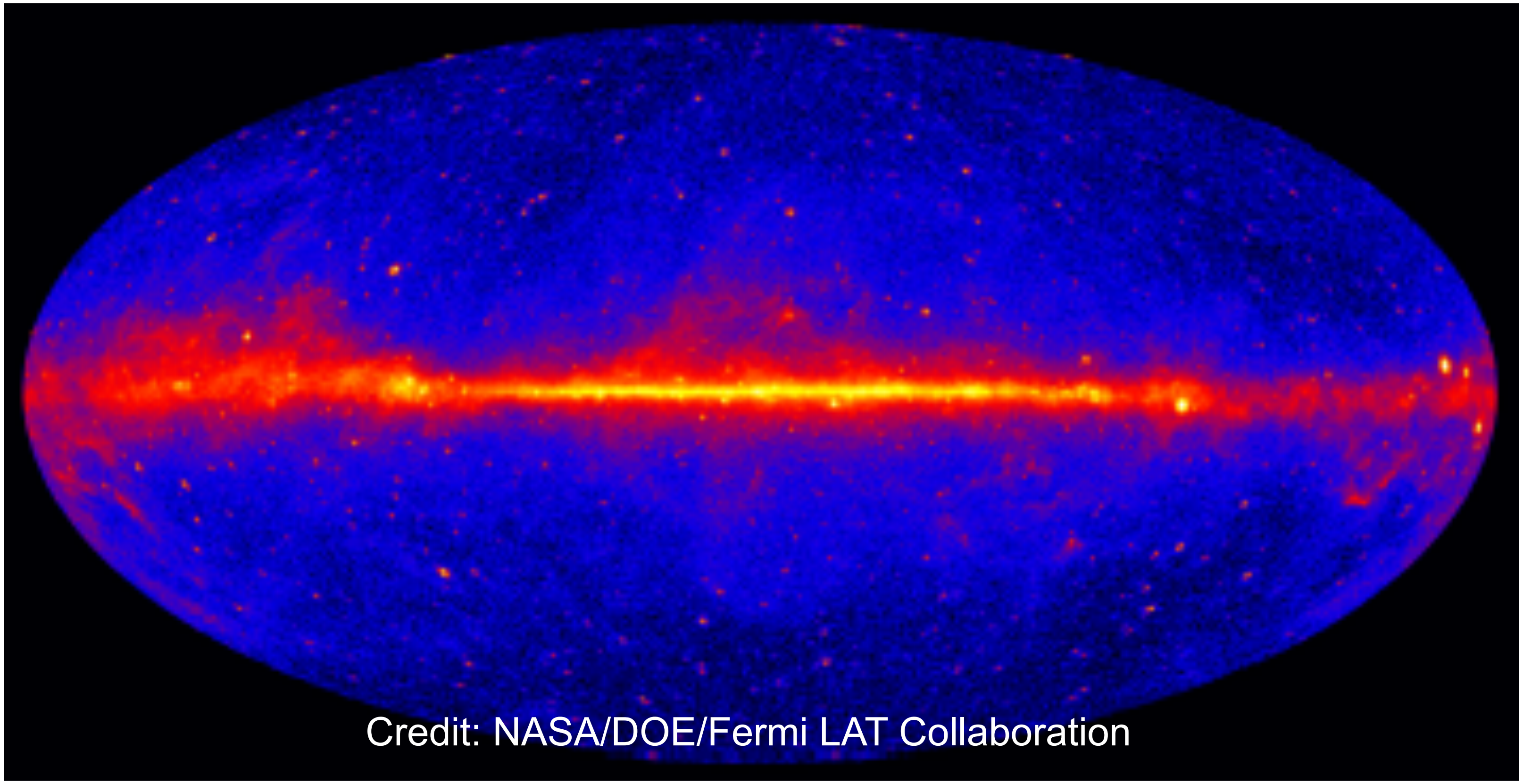




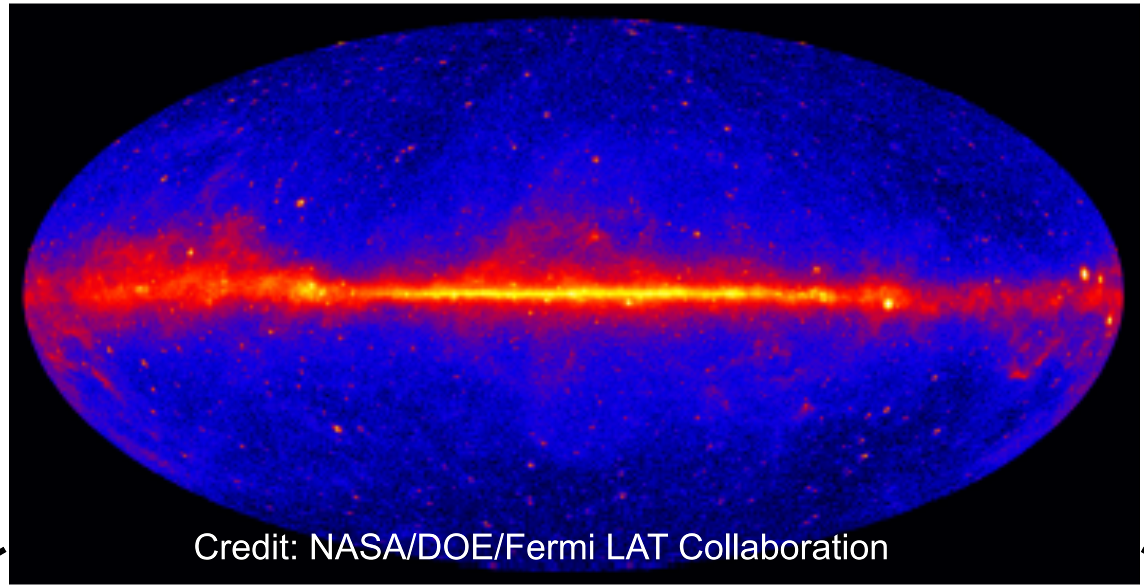
- **Anti-Coincidence Detector**: rejects charged particle, 89 plastic scintillator
- **Tracker**: 16 modules: tungsten conversion foils + silicon strip detectors in 36 layers
- **Calorimeter**: 16 modules: 96 Cesium Iodide crystals per module

The Fermi-LAT sky

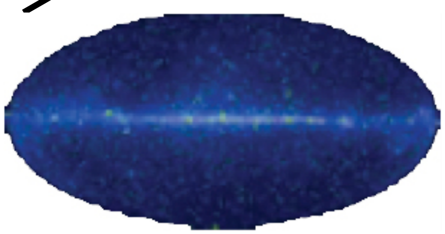
5-year Fermi-LAT data > 1GeV



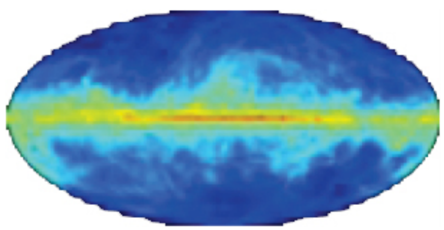
The Fermi-LAT sky



SOURCES



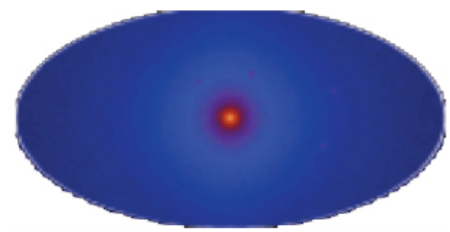
DIFFUSE



> 60%

ISOTROPIC

DARK MATTER?

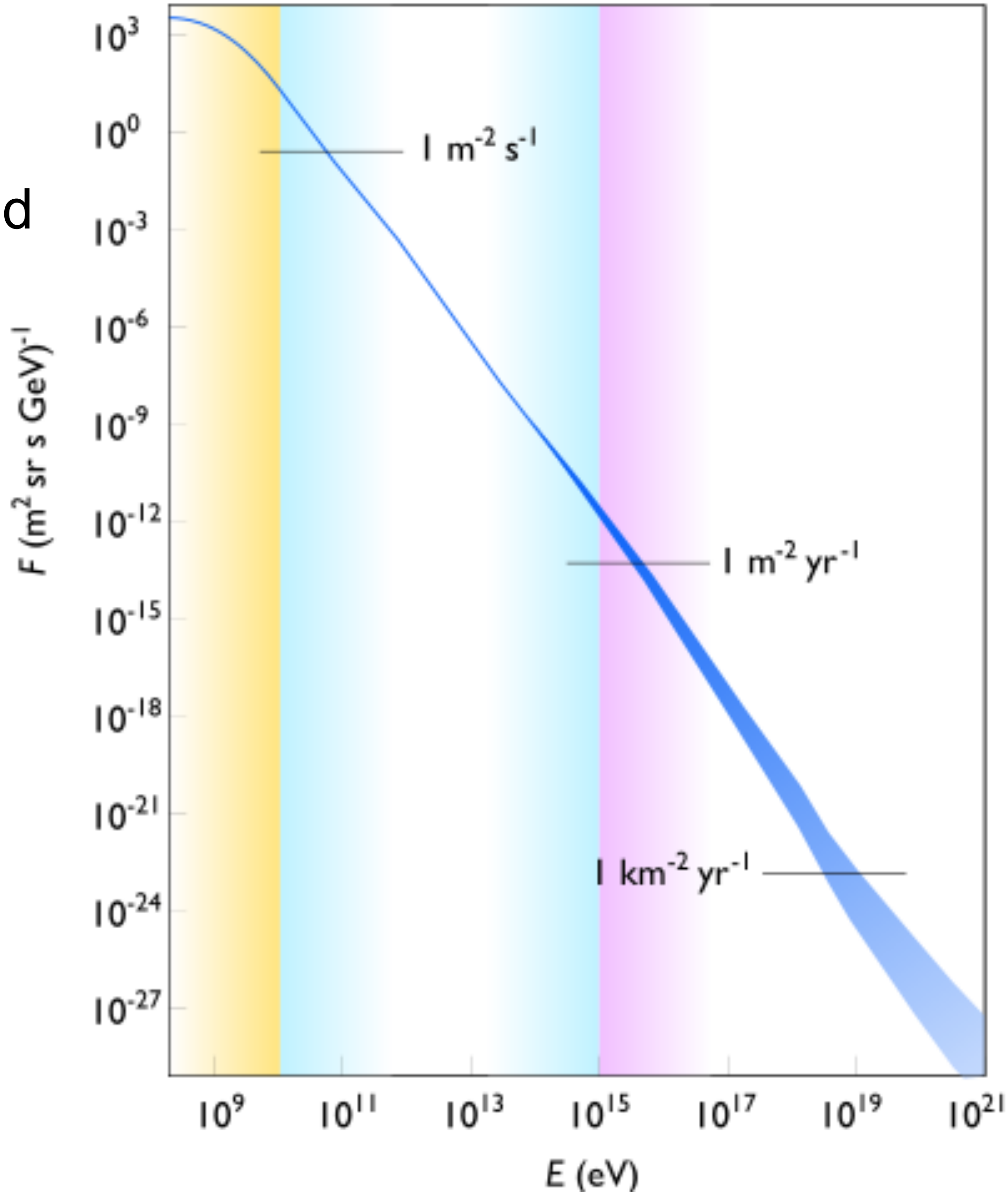


Diffuse emission needs to be accurately modeled to study the other components !

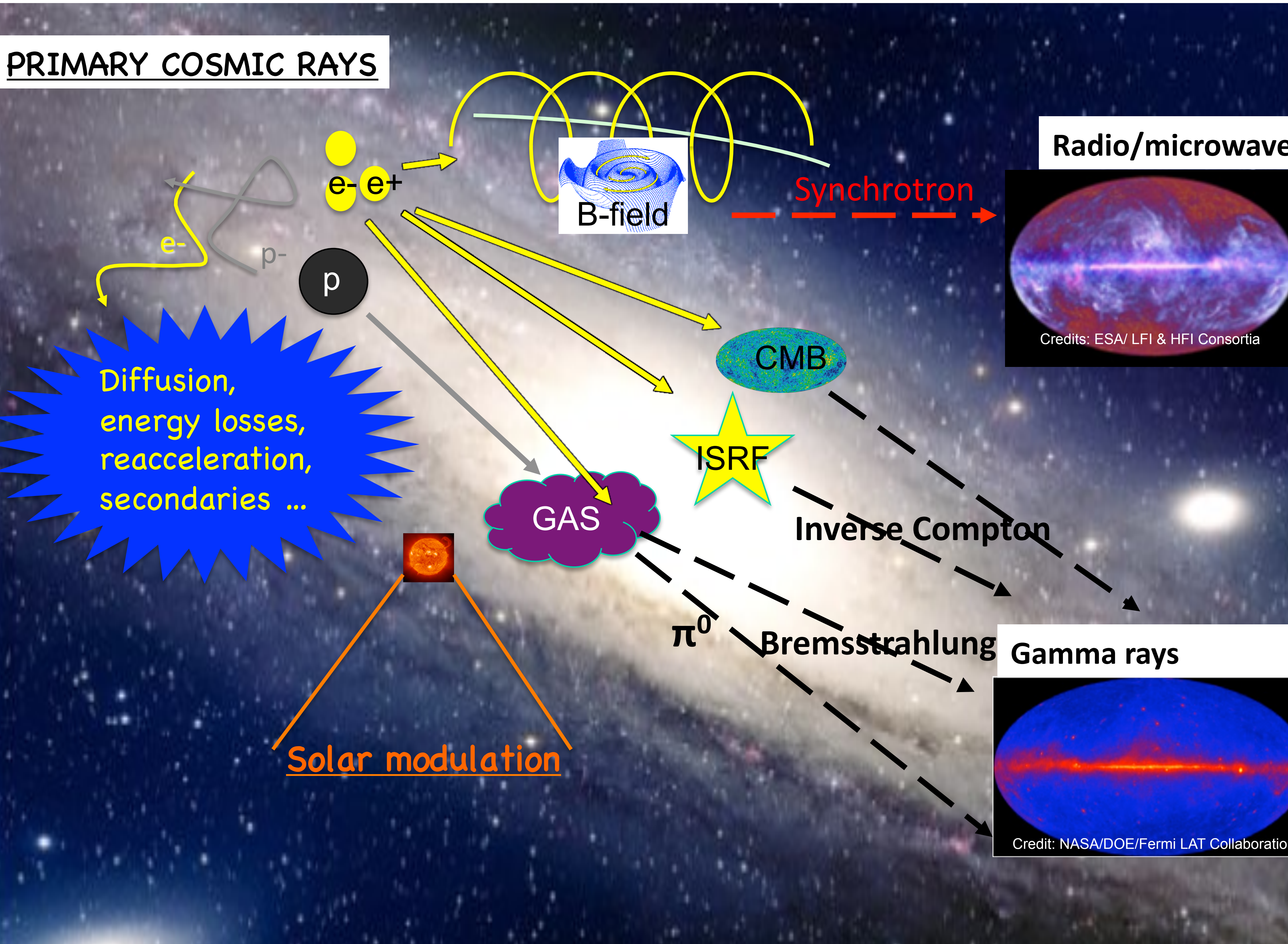
Cosmic Rays (CR)

Energetic charged particles

1% electrons
99% nuclei
- 89% protons,
- 10% helium,
- 1% heavier elements

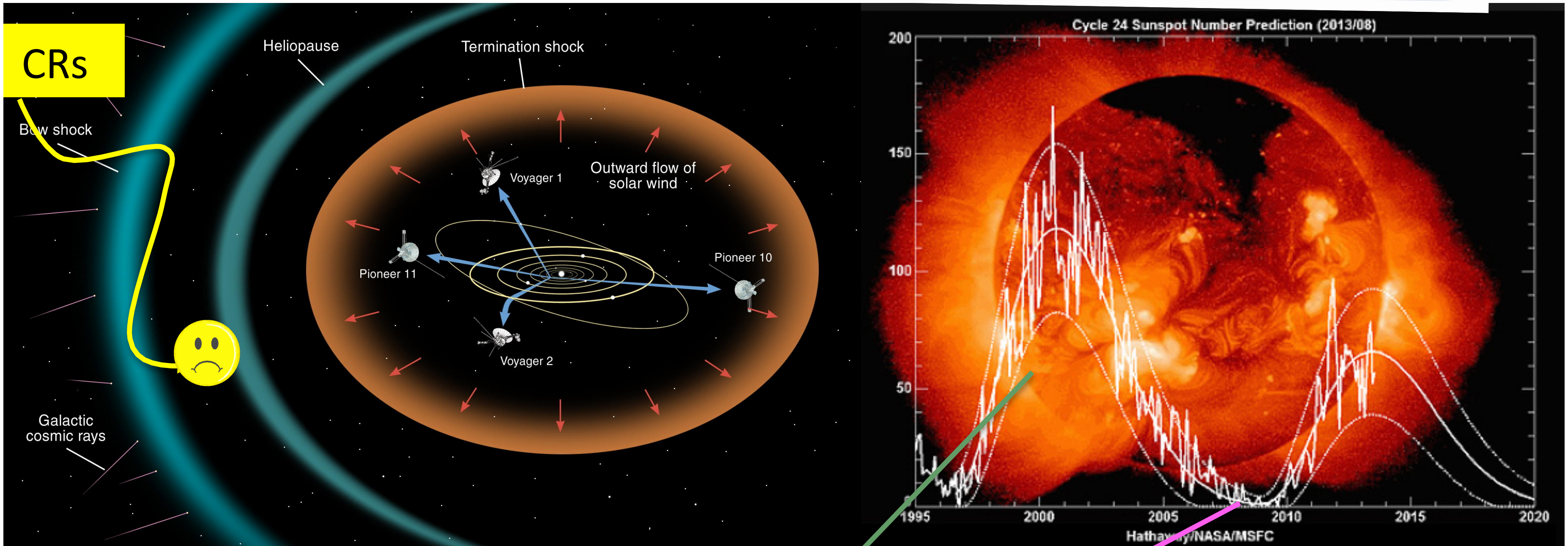


First discovery: 1912 by Victor Hess



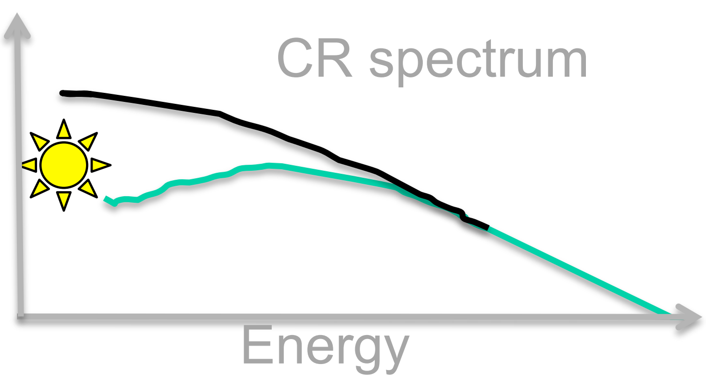
PRIMARY COSMIC RAYS
e- e+
e-
p-
p
B-field
Synchrotron
Radio/microwave
Credits: ESA/ LFI & HFI Consortia
CMB
ISRF
Diffusion,
energy losses,
reacceleration,
secondaries ...
GAS
Inverse Compton
π^0
Bremsstrahlung
Gamma rays
Credit: NASA/DOE/Fermi LAT Collaboratio
Solar modulation

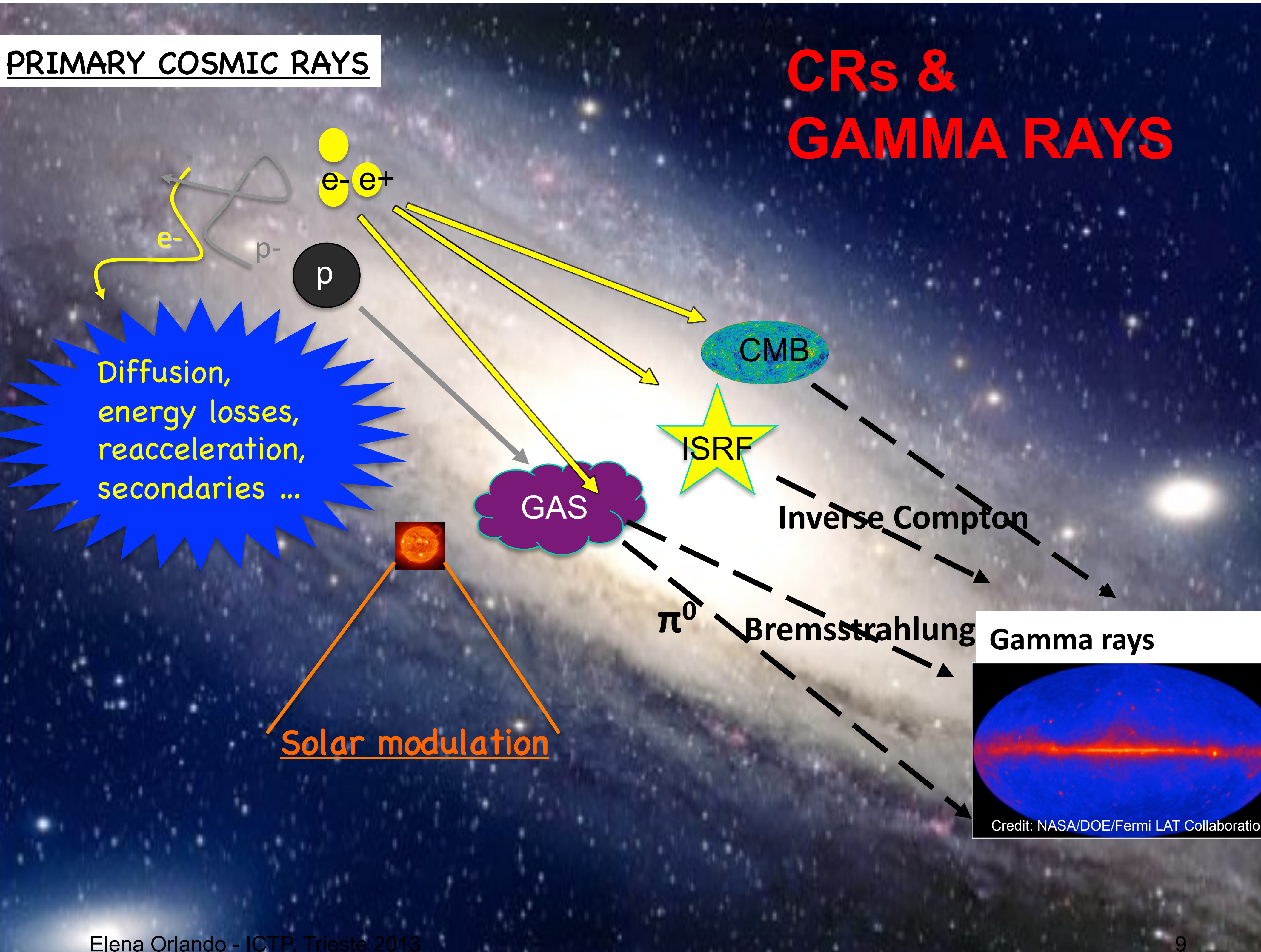
Solar modulation



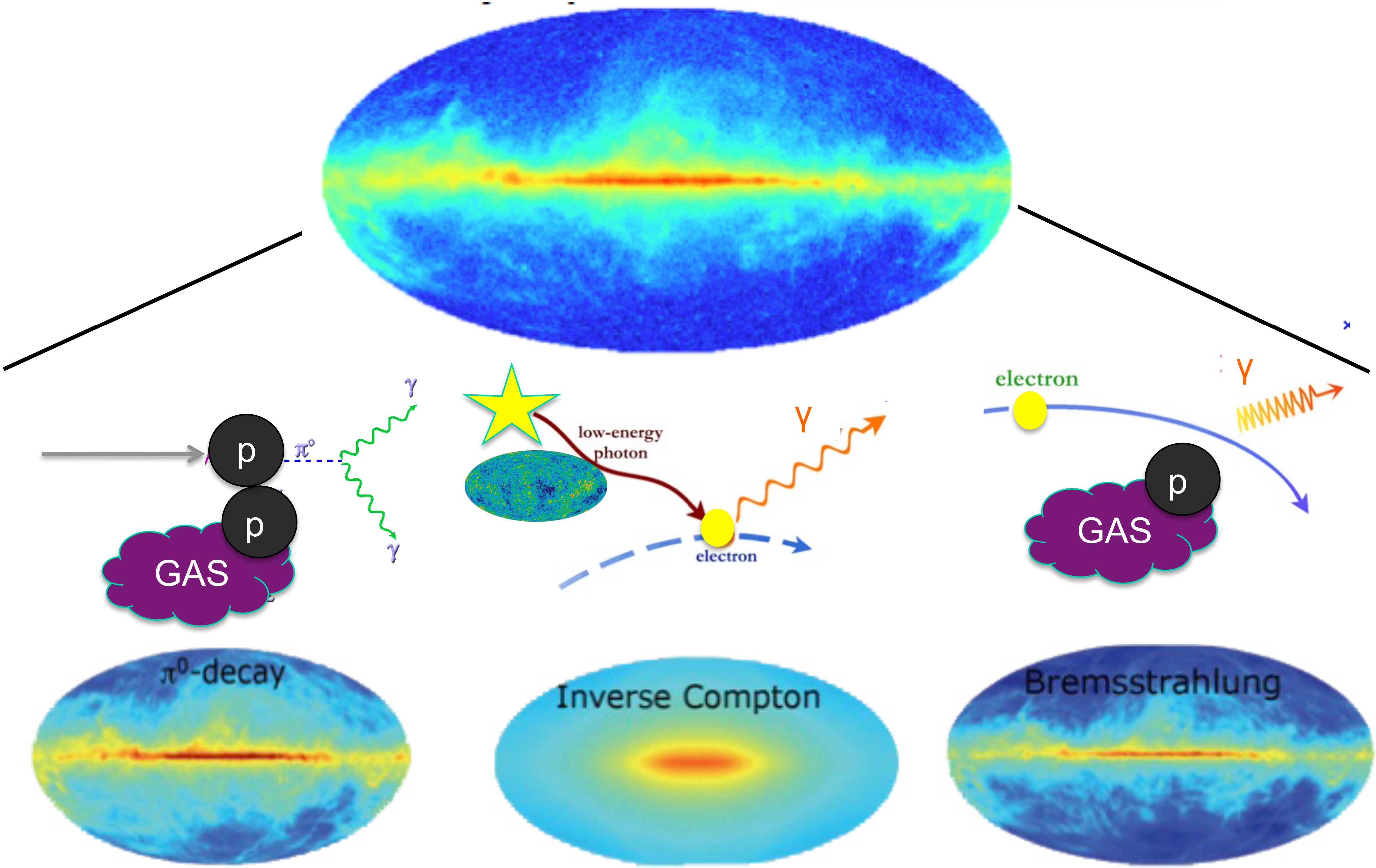
MAX solar activity -> MIN cosmic-ray flux

MIN solar activity -> MAX cosmic-ray flux

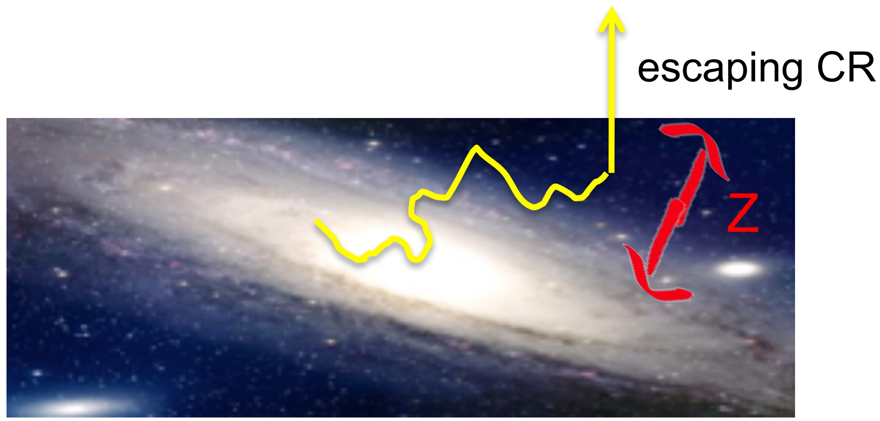



PRIMARY COSMIC RAYS
CRs & GAMMA RAYS
e- e+
e-
p-
p
Diffusion, energy losses, reacceleration, secondaries ...
CMB
ISRF
GAS
Inverse Compton
π0
Bremsstrahlung
Gamma rays
Credit: NASA/DOE/Fermi LAT Collaboratio
Solar modulation

Gamma-ray interstellar emission



Modeling diffuse emissions



Uncertainties:

Sources of CRs:
- Distribution of CR sources
- Injection spectra

Propagation:
- Energy losses, convection, reacceleration, halo size, diffusion coefficient

Modeling diffuse emission with GALPROP

THE TEAM:
I. Moskalenko and A. Strong (original developers),
S. Digel, G. Johannesson, E. Orlando, T. Porter, A. Vladimirov

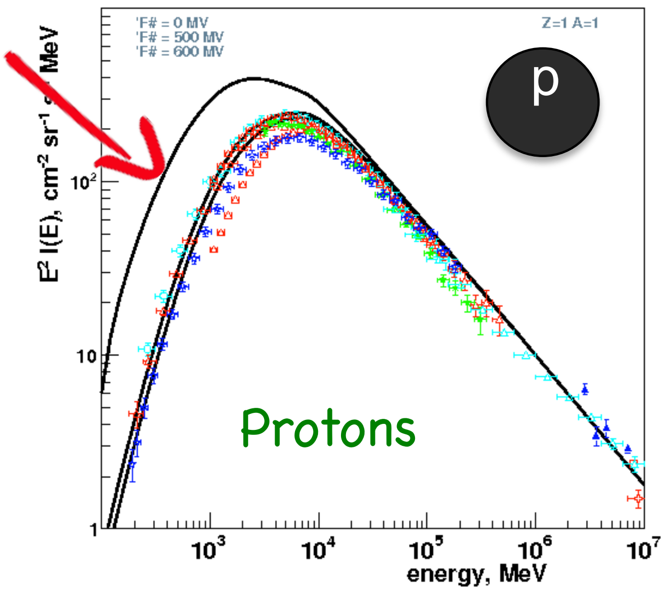
http://*galprop.stanford.edu*

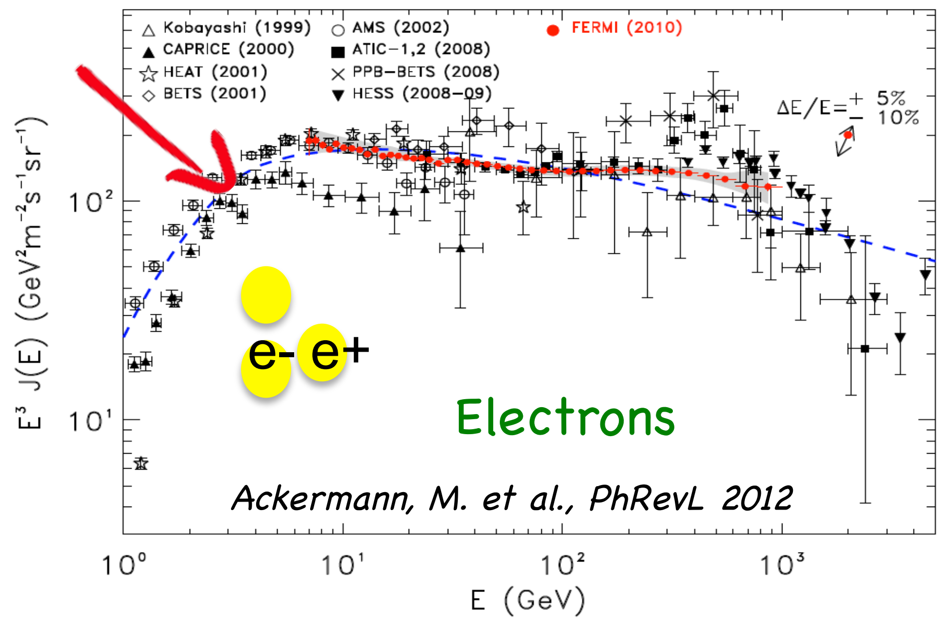
Solve transport equation (energy losses, diffusion, acceleration, convection, fragmentation, radioactive decay) for all CR species

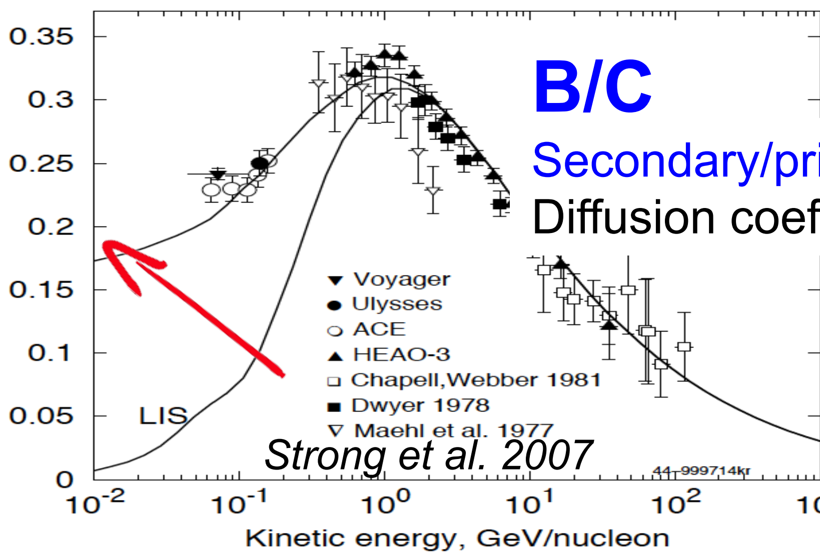
Goal : use all types of data in self-consistent way

Ingredients 1/3: CR measurements

Injected spectra adjusted to fit observations after propagation effects







B/C

Secondary/primary: Diffusion coefficient

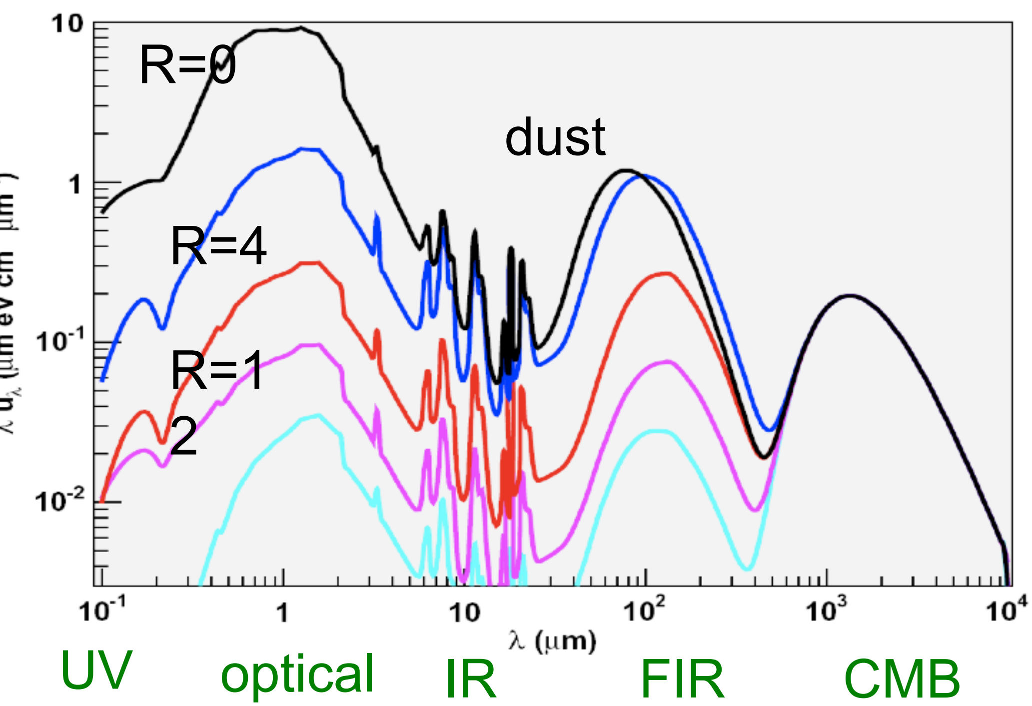
Interpretation of data is model dependent:

D ~ 10^{28} $(\rho)^{\delta}$ cm^2/s

with $\delta \approx 0.3$-0.6

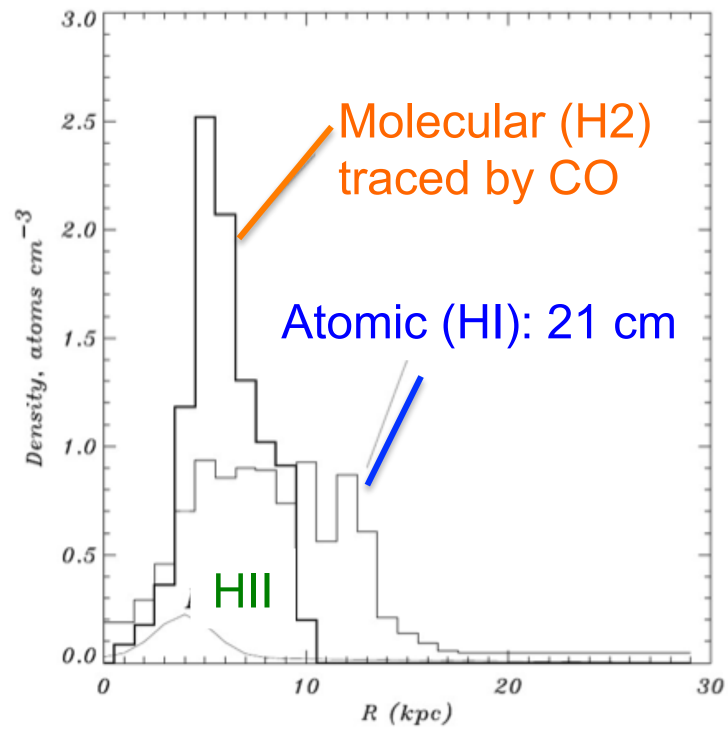
Ingredients 2/3: ISRF & ISM

Interstellar radiation field



Porter et al. 2008 ApJ 682

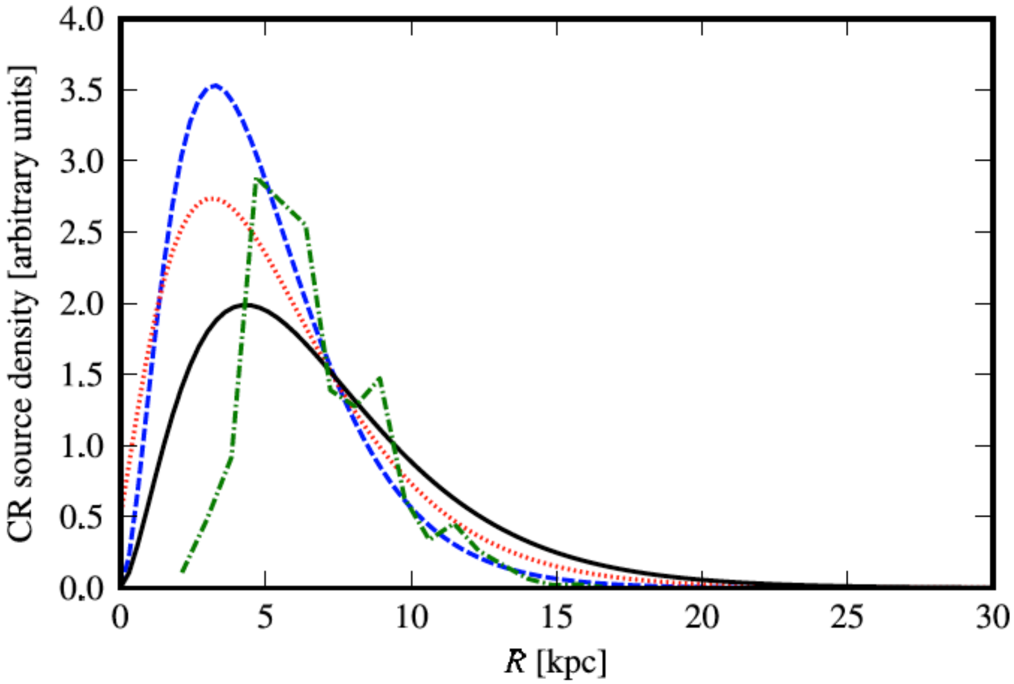
GAS



Best traced by dust

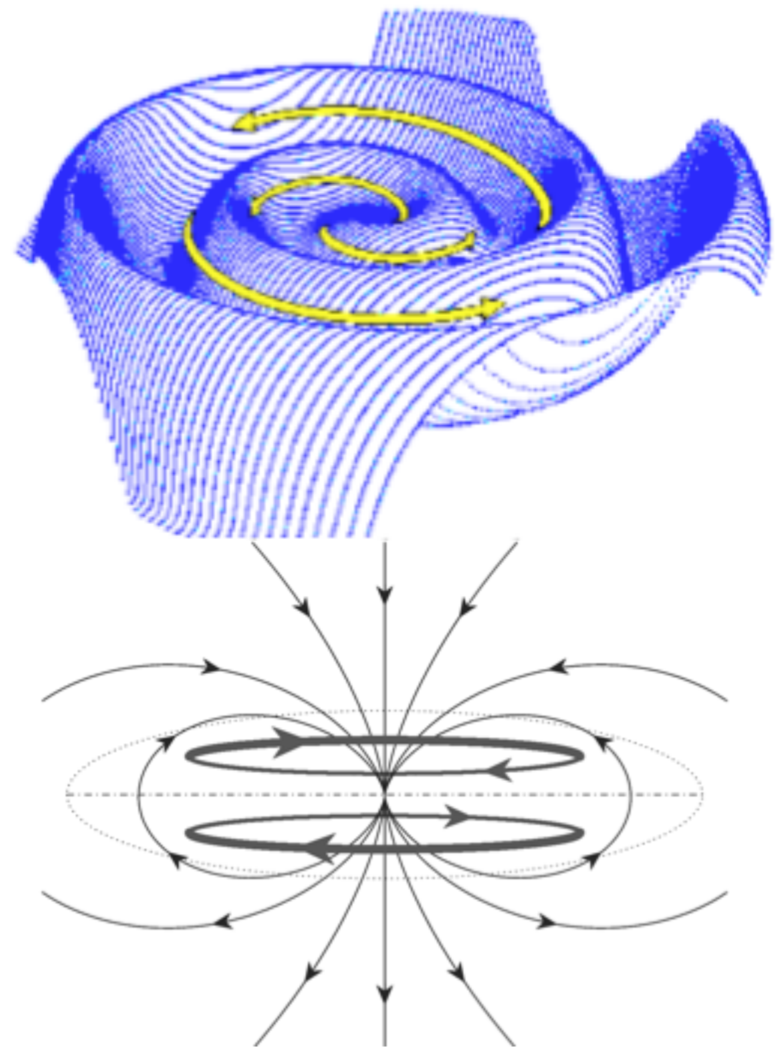
Ingredients 3/3: sources & B-fields

CR source distribution

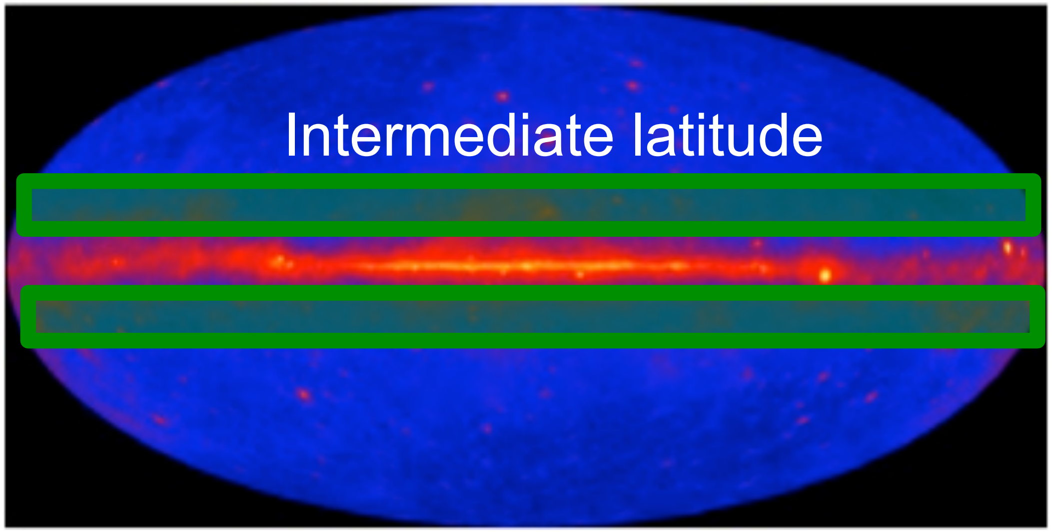


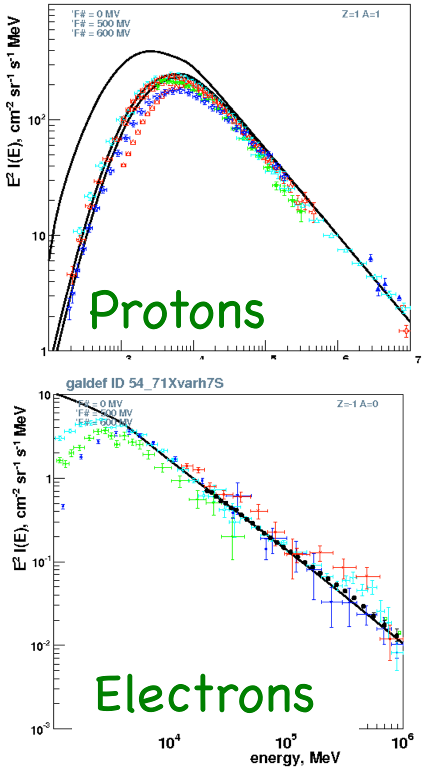
SNRs (Case & Bhattacharya 1998)
Pulsars (Lorimer et al. 2006)
Pulsars (Yusifov & Kucuk 2004)
OB stars (Bronfman et al. 2000)

2D or 3D B fields



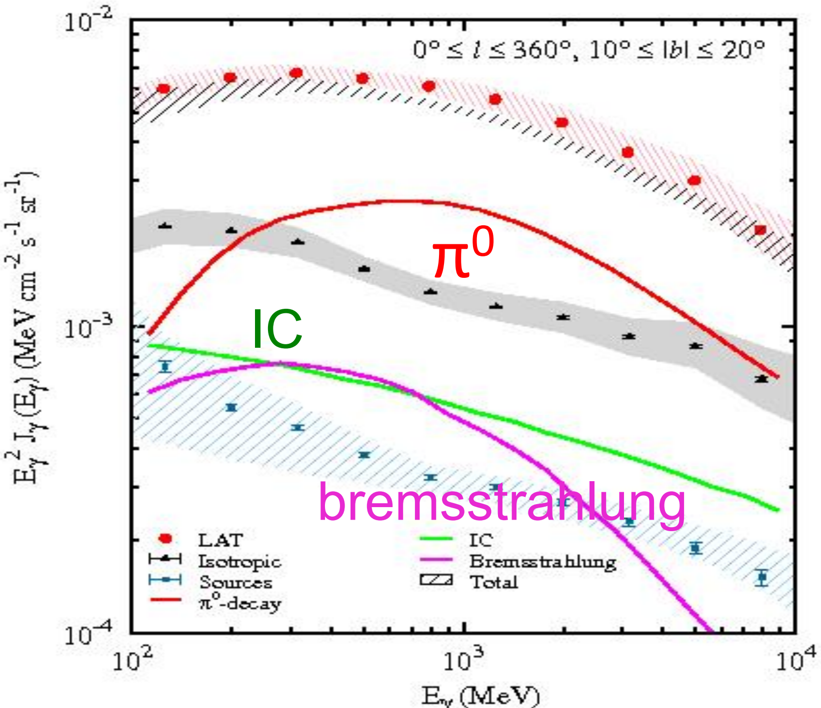
Diffuse γ rays with Fermi/LAT





Model based on local cosmic-ray spectra agrees with data !

Abdo et al. PhRevLett.103.251101



THE ASTROPHYSICAL JOURNAL, 750:3 (35pp), 2012 May 1 doi:10.1088/0004-637X/750/1/3

FERMI-LAT OBSERVATIONS OF THE DIFFUSE γ-RAY EMISSION: IMPLICATIONS FOR COSMIC RAYS AND THE INTERSTELLAR MEDIUM

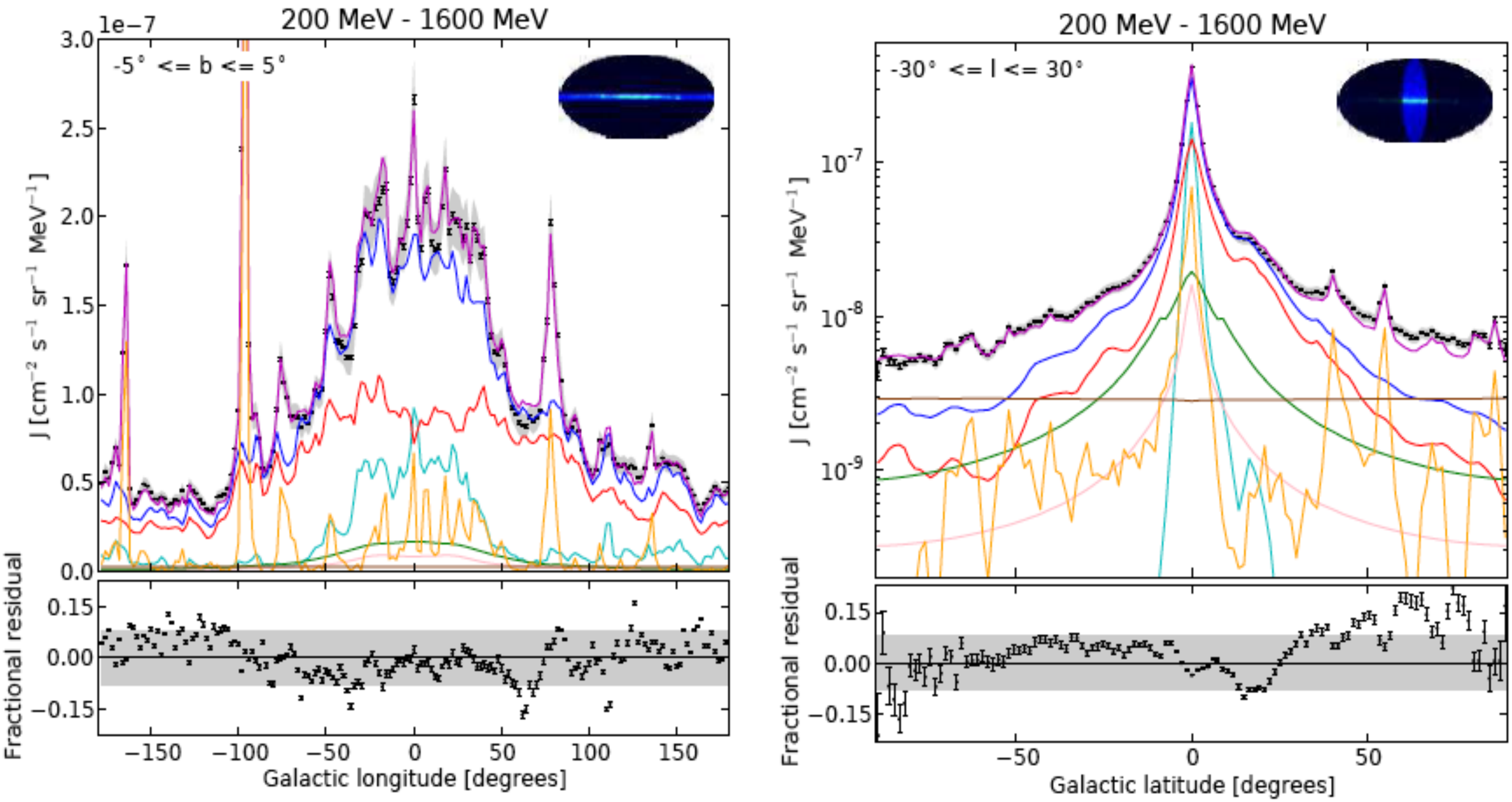
M. Ackermann[1], M. Ajello[2], W. B. Atwood[3], L. Baldini[4], J. Ballet[5], G. Barbiellini[6,7], D. Bastieri[8,9], K. Bechtol[2], R. Bellazzini[4], B. Berenji[2], R. D. Blandford[2], E. D. Bloom[2], E. Bonamente[10,11], A. W. Borgland[2], T. J. Brandt[12,13], J. Bregeon[4], M. Brigida[14,15], P. Bruel[16], R. Buehler[2], S. Buson[8,9], G. A. Caliandro[17], R. A. Cameron[2], P. A. Caraveo[18], E. Cavazzuti[19], C. Cecchi[10,11], E. Charles[2], A. Chekhtman[20,54], J. Chiang[2], S. Ciprini[11,19], R. Claus[2], J. Cohen-Tanugi[21], J. Conrad[22,23,55], S. Cutini[19], A. de Angelis[24], F. de Palma[14,15], C. D. Dermer[25], S. W. Digel[2], E. do Couto e Silva[2], P. S. Drell[2], A. Drlica-Wagner[2], L. Falletti[21], C. Favuzzi[14,15], S. J. Fegan[16], E. C. Ferrara[26], W. B. Focke[2], P. Fortin[16], Y. Fukazawa[27], S. Funk[2], P. Fusco[14,15], D. Gaggero[4], F. Gargano[15], S. Germani[10,11], N. Giglietto[14,15], F. Giordano[14,15], M. Giroletti[28], T. Glanzman[2], G. Godfrey[2], J. E. Grove[25], S. Guiriec[29], M. Gustafsson[8], D. Hadasch[17], Y. Hanabata[27], A. K. Harding[26], M. Hayashida[2,30], E. Hays[26], D. Horan[16], X. Hou[31], R. E. Hughes[32], G. Jóhannesson[33], A. S. Johnson[2], R. P. Johnson[3], T. Kamae[2], H. Katagiri[34], J. Kataoka[35], J. Knödlseder[12,13], M. Kuss[4], J. Lande[2], L. Latronico[36], S.-H. Lee[37], M. Lemoine-Goumard[38,56], F. Longo[6,7], F. Loparco[14,15], B. Lott[38], M. N. Lovellette[25], P. Lubrano[10,11], M. N. Mazziotta[15], J. E. McEnery[26,39], P. F. Michelson[2], W. Mitthumsiri[2], T. Mizuno[27], C. Monte[14,15], M. E. Monzani[2], A. Morselli[40], I. V. Moskalenko[2], S. Murgia[2], M. Naumann-Godo[5], J. P. Norris[41], E. Nuss[21], T. Ohsugi[42], A. Okumura[2,43], N. Omodei[2], E. Orlando[2,44], J. F. Ormes[45], D. Paneque[2,46], J. H. Panetta[2], D. Parent[47,54], M. Pesce-Rollins[4], M. Pierbattista[5], F. Piron[21], G. Pivato[9], T. A. Porter[2], S. Rainò[14,15], R. Rando[8,9], M. Razzano[3,4], S. Razzaque[47,54], A. Reimer[2,48], O. Reimer[2,48], H. F.-W. Sadrozinski[3], C. Sgrò[4], E. J. Siskind[49], G. Spandre[4], P. Spinelli[14,15], A. W. Strong[44], D. J. Suson[50], H. Takahashi[42], T. Tanaka[2], J. G. Thayer[2], J. B. Thayer[2], D. J. Thompson[26], L. Tibaldo[8,9], M. Tinivella[4], D. F. Torres[17,51], G. Tosti[10,11], E. Troja[26,57], T. L. Usher[2], J. Vandenbroucke[2], V. Vasileiou[21], G. Vianello[2,52], V. Vitale[40,53], A. P. Waite[2], P. Wang[2], B. L. Winer[32], K. S. Wood[25], M. Wood[2], Z. Yang[22,23], M. Ziegler[3], and S. Zimmer[22,23]

Studying systematics using GALPROP

128 MODELS (reacceleration): in agreement with CR data, varying CR source distribution, CR halo size, gas and compare with Fermi LAT data (21 months, 200 MeV to 100 GeV)

Results: profiles

Ackerman et al.2012 ApJ 750,3

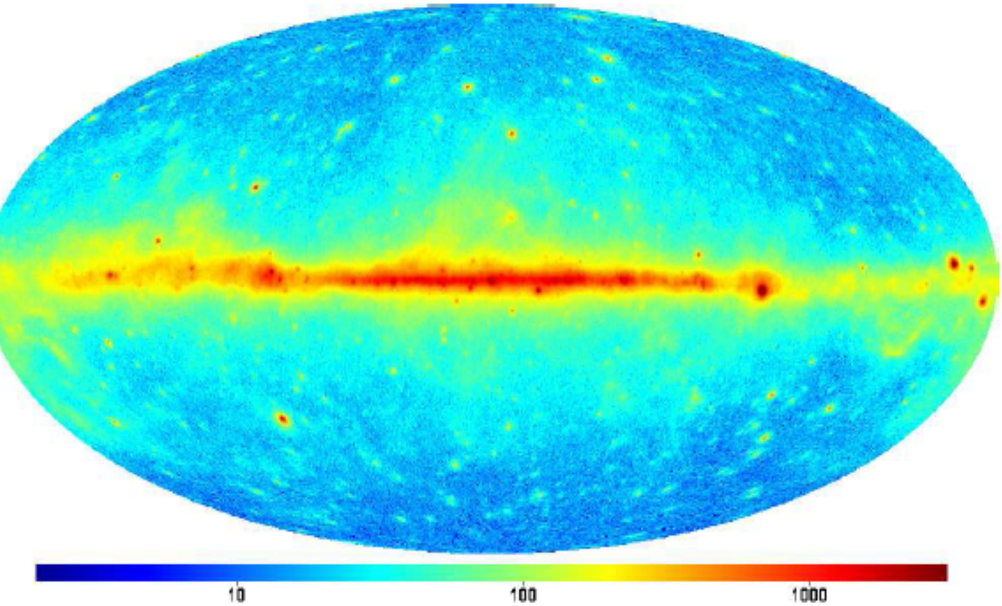


The physics of the interstellar emissions well understood and described.

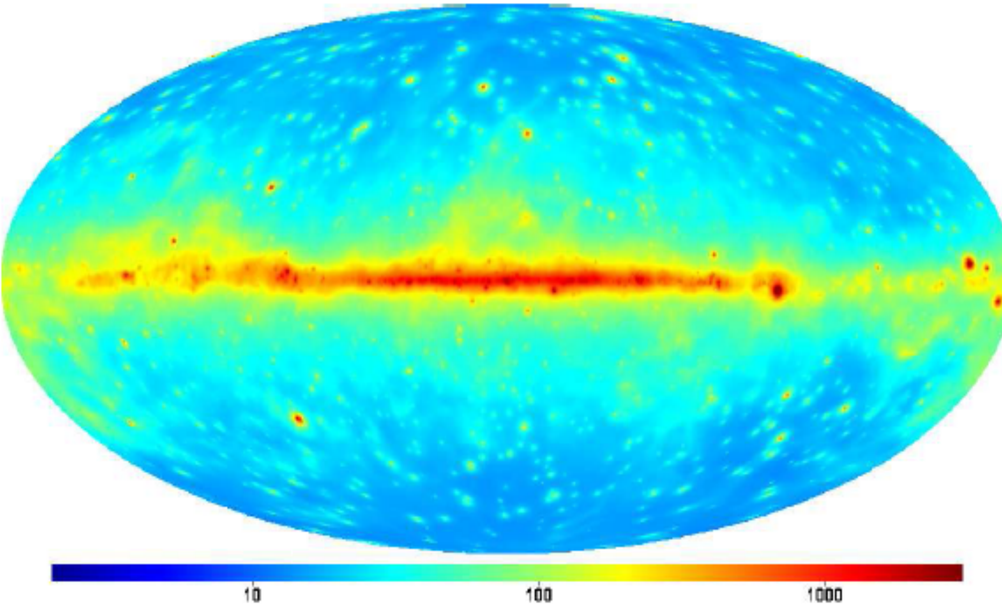
Results: all-sky

Ackerman et al.2012 ApJ 750,3

200 MeV – 100 GeV



data

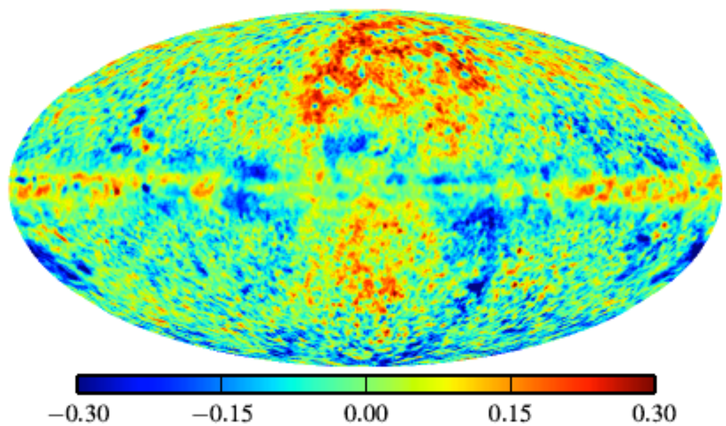


model

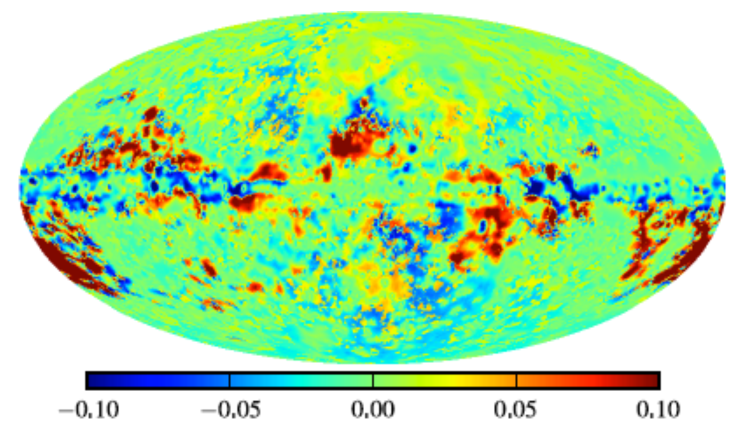
Residual maps

Ackerman et al.2012 ApJ 750,3

(model-data)/model



model 1 - model 2



Loop I, Fermi Bubbles and outer Galaxy show large residuals

All models are within 15% of data

BUT No single model gives best fit over all sky regions

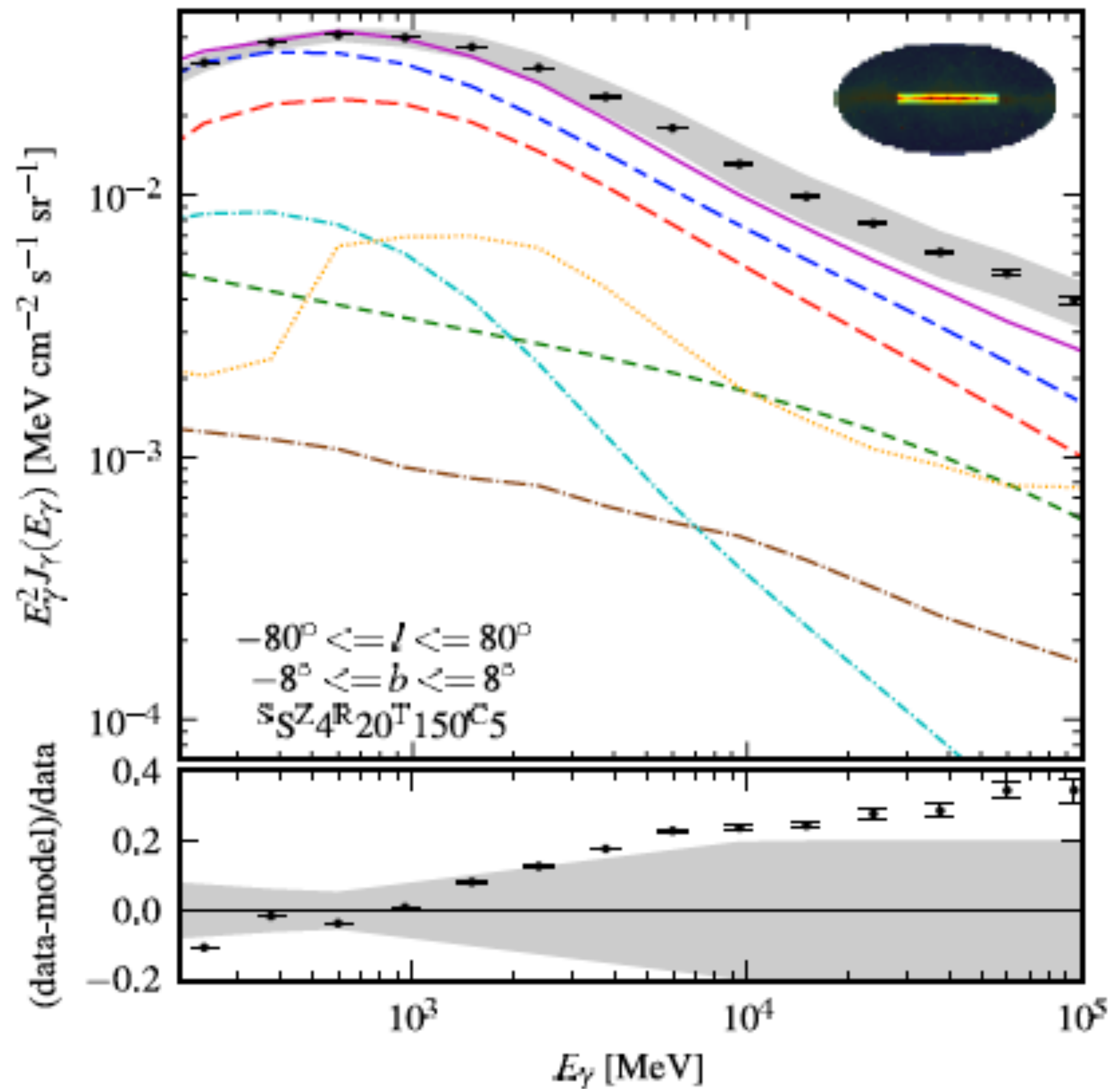
Models under-predict data in the outer Galactic plane

Larger Galactic halo size preferred

Inner Galaxy

Ackerman et al.2012 ApJ 750,3

See talk by Gomez



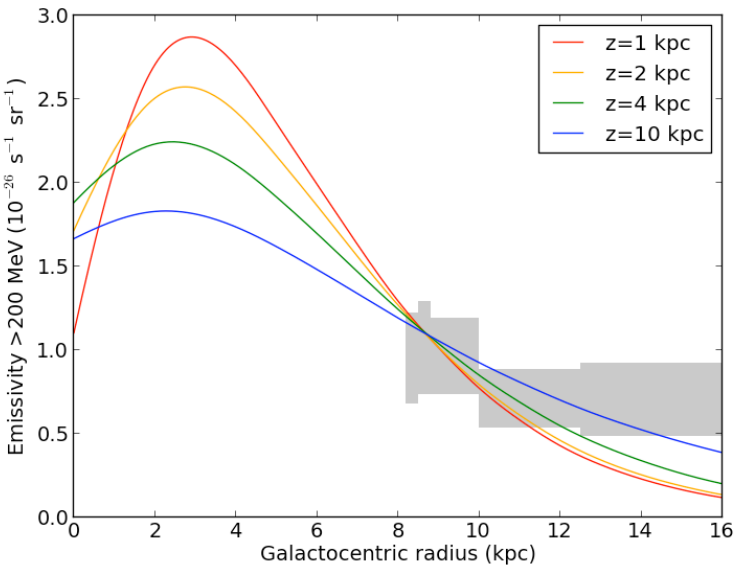
excess : unresolved sources, enhanced CRs … ?

Emissivity: outer galaxy

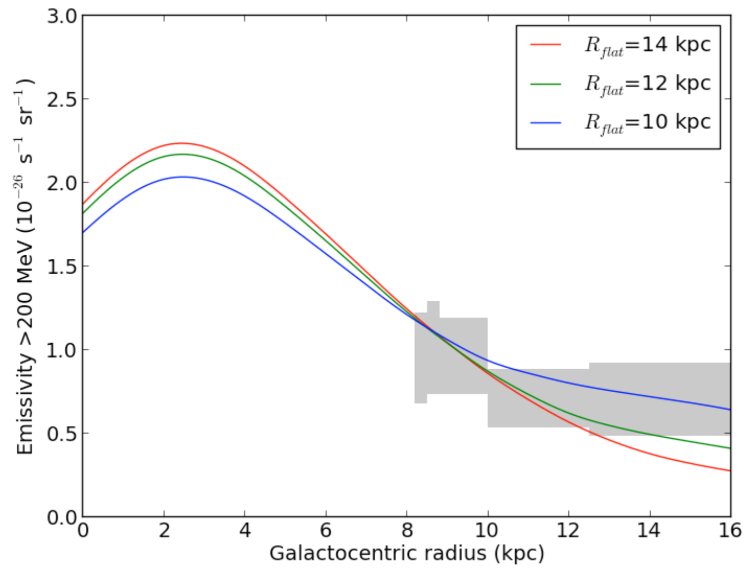
Abdo et al. 2010 ApJ 710,133
Ackermann et al. 2011 ApJ 726 81
Ackermann et al. 2012 A&A 538 A71

Gamma-ray emission rate per H atom

Varying halo size



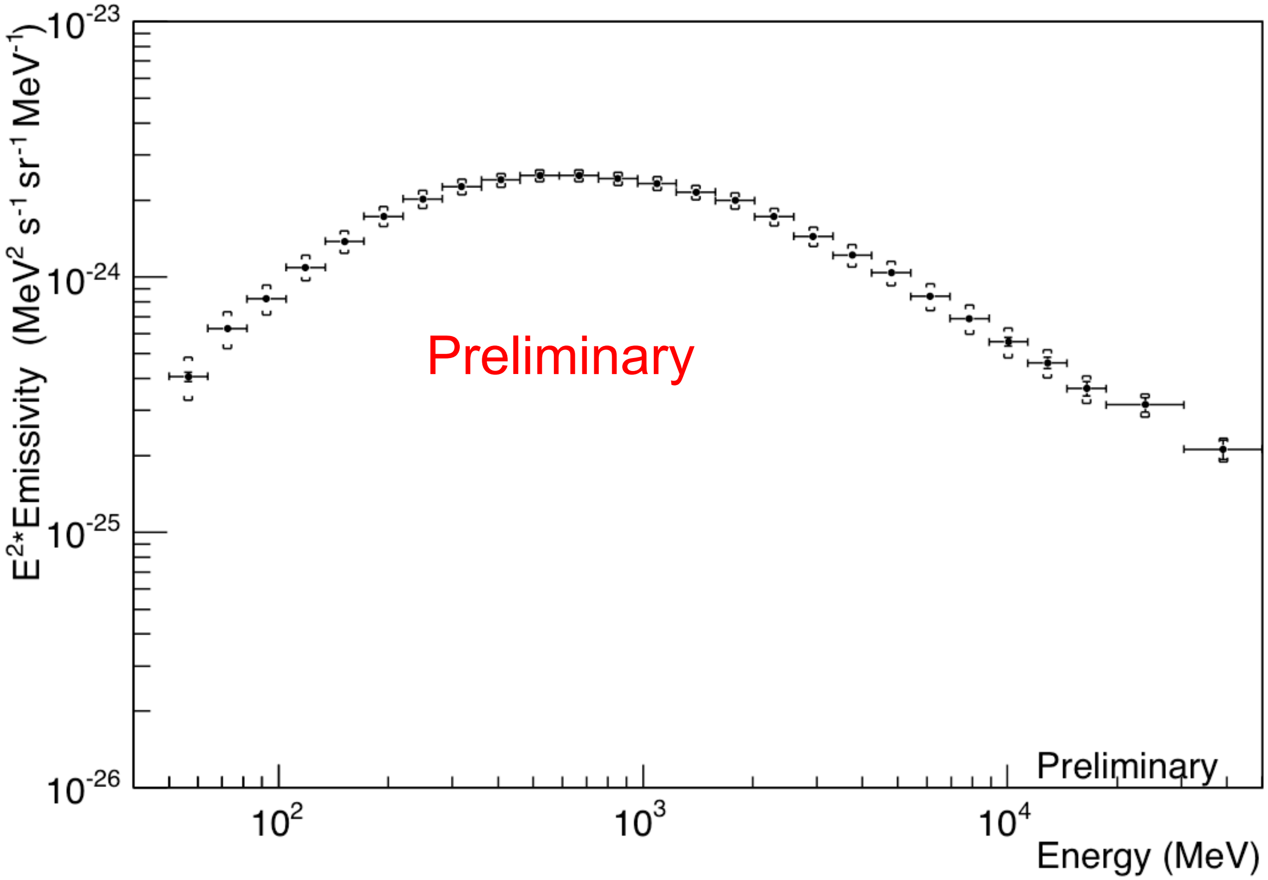
Varying CR source distribution



Models as usually assumed under-predict gamma rays in outer Galaxy !

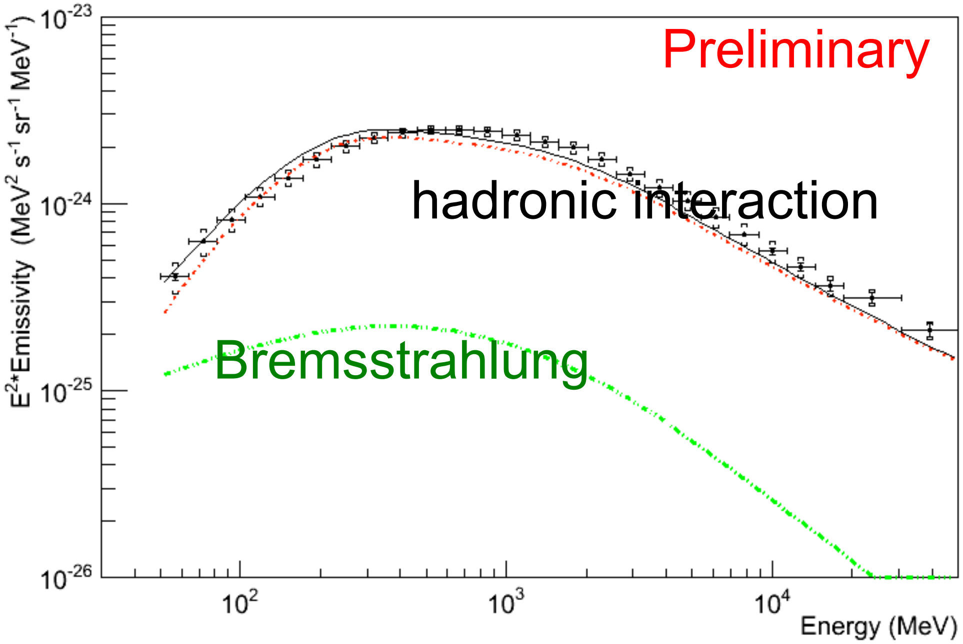
Local emissivity

|b|>10° probes gas within ~ 1 kpc from the Sun

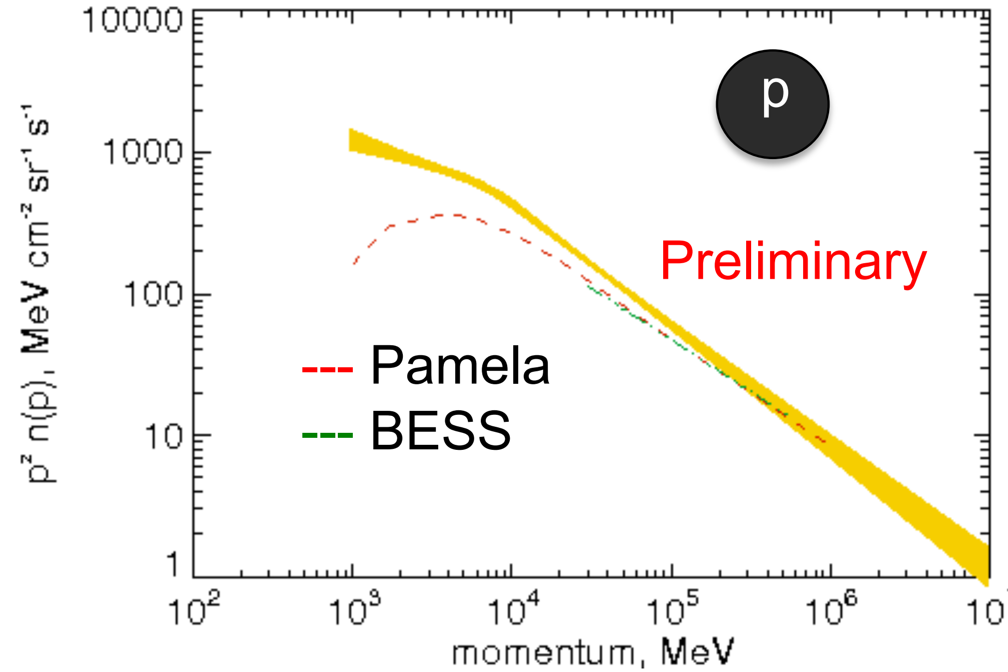


Casandjian, ICRC 2013

Local emissivity



Casandjian, ICRC 2013

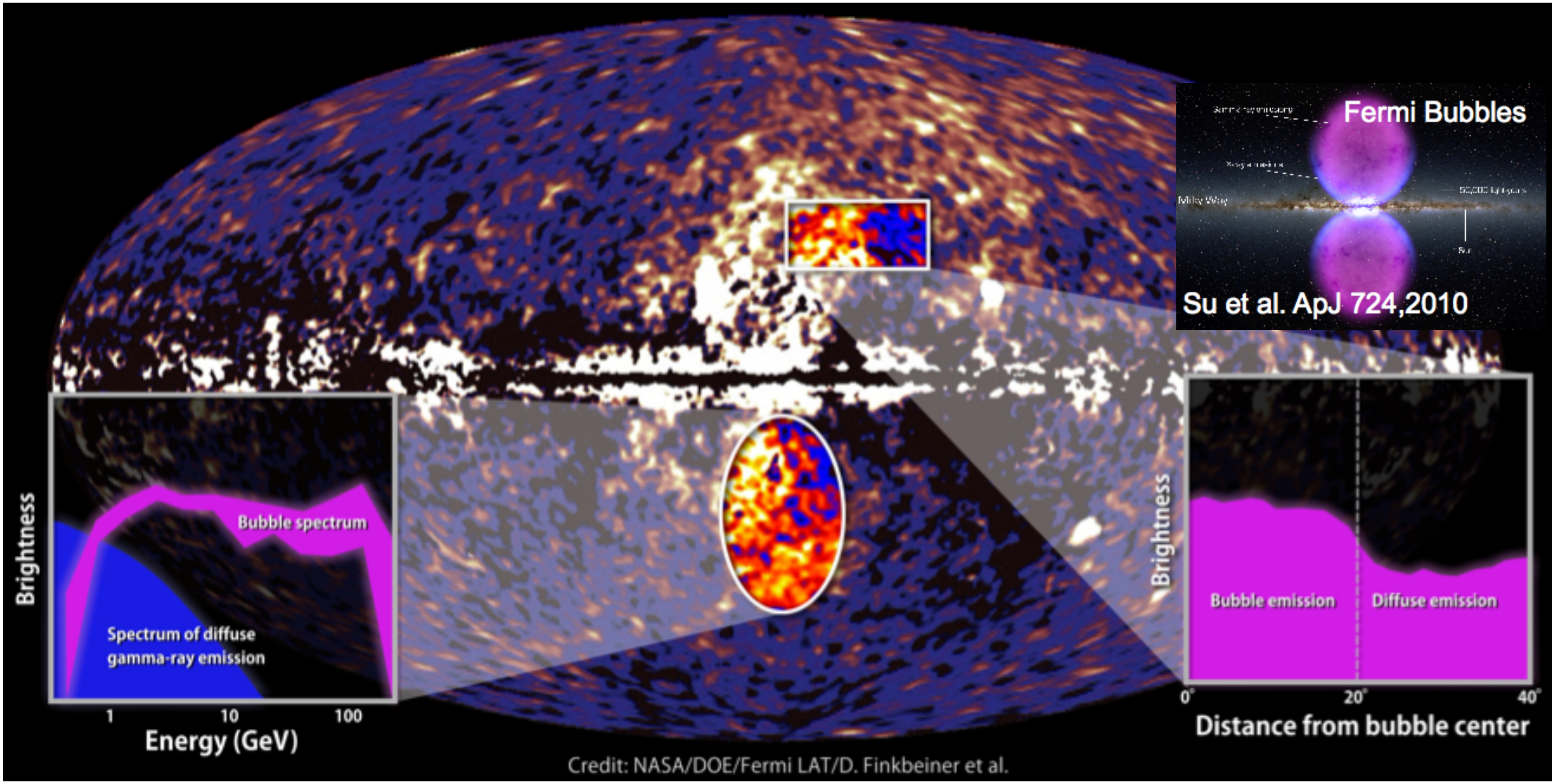


Strong, Fermi symposium 2012

Compatible with observed CRs including modulation!!!
20% uncertainty in hadronic production cross sections

The Fermi Bubbles

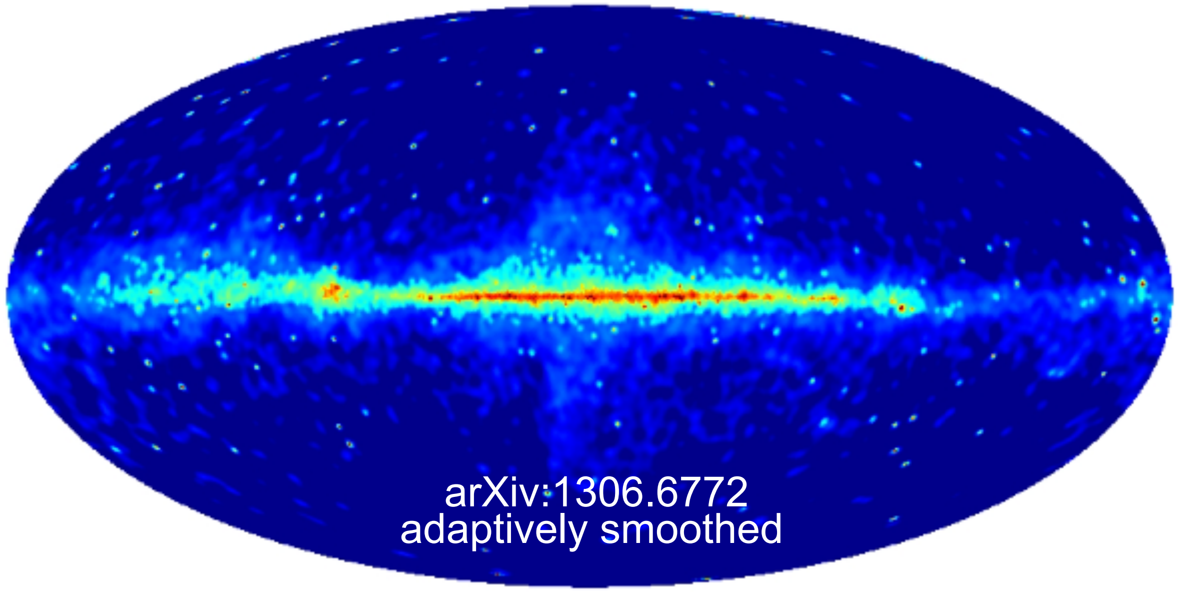
See talk by Su



NASA press release

The Fermi Bubbles

3 years, E>10GeV



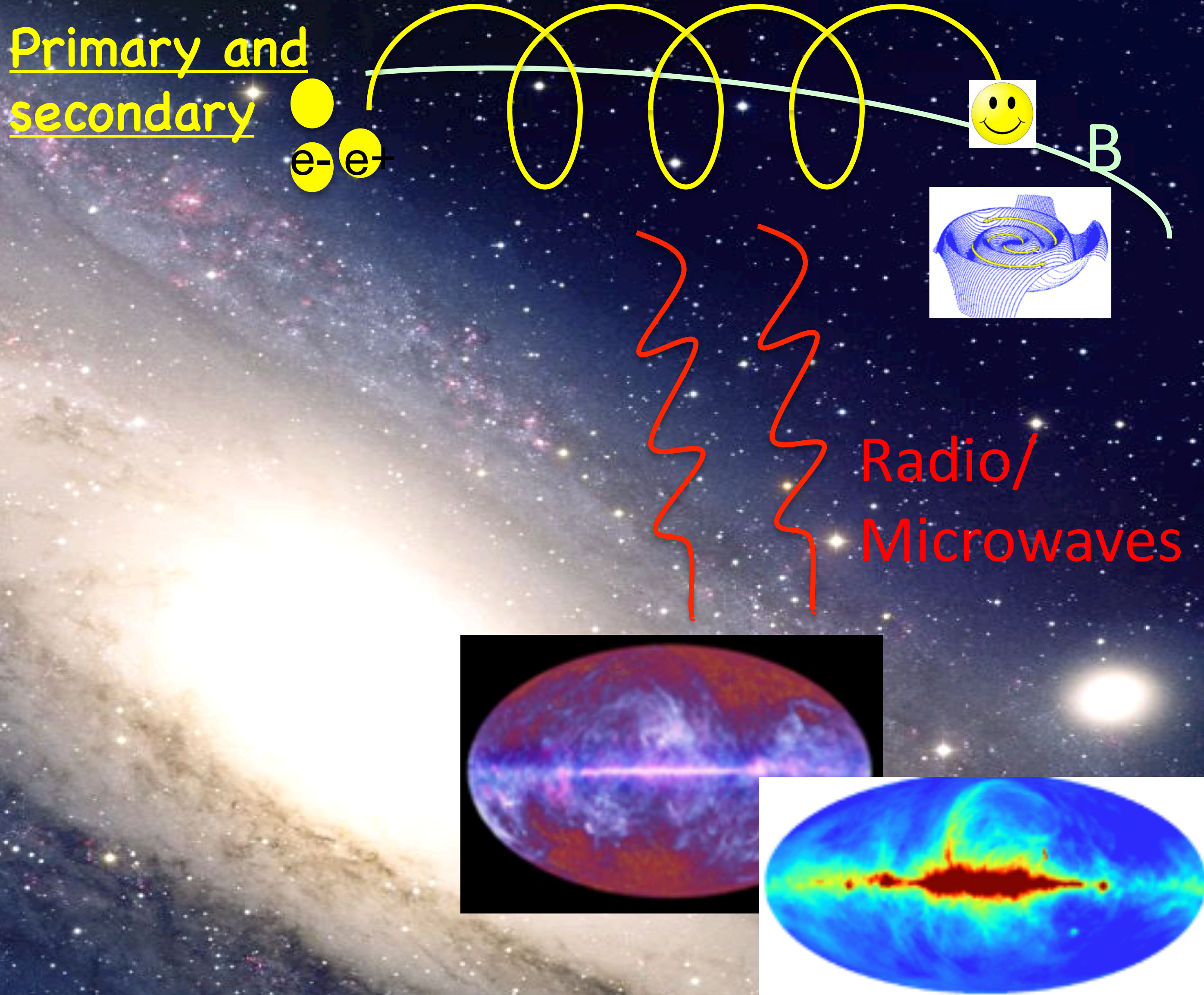
- Preliminary spectrum obtained with dedicated study of systematics

- Difficulties on disantangling Loop I and the bubbles

- Morphological study ongoing

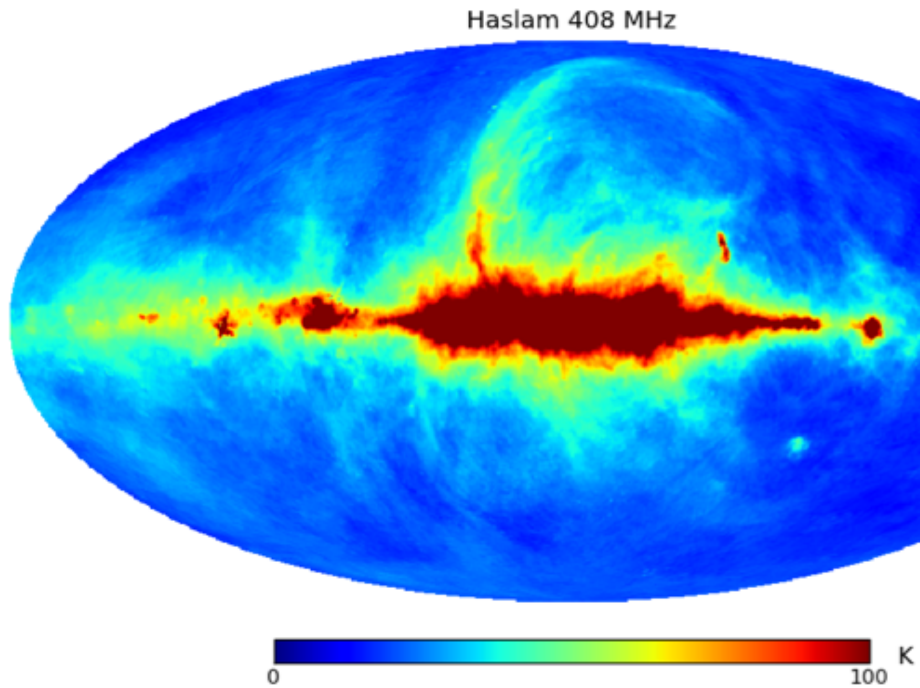
Franckowiak & Malyshev, ICRC 2013

CRs & RADIO



- Sy. spectral Index -> e^- spectral index
- Sy. Intensity -> B intensity and electron flux
- e^- 0.5 – 20 GeV -> 20 MHz – 100 GHz

CRs & synchrotron in radio



Additional constraints to :

- B-field
- CRe spectrum
- Propagation models
- CR source distribution
- Propagation halo size

New: Synchrotron modeling

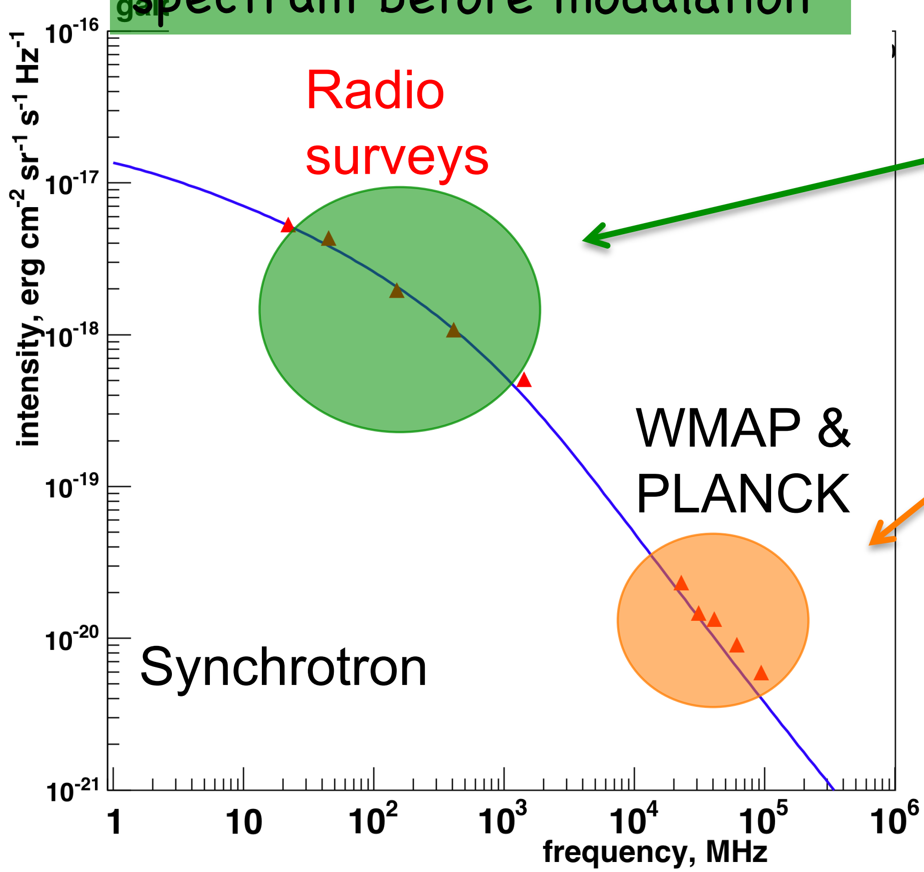
- 3D models of random and regular B-field
- Polarization

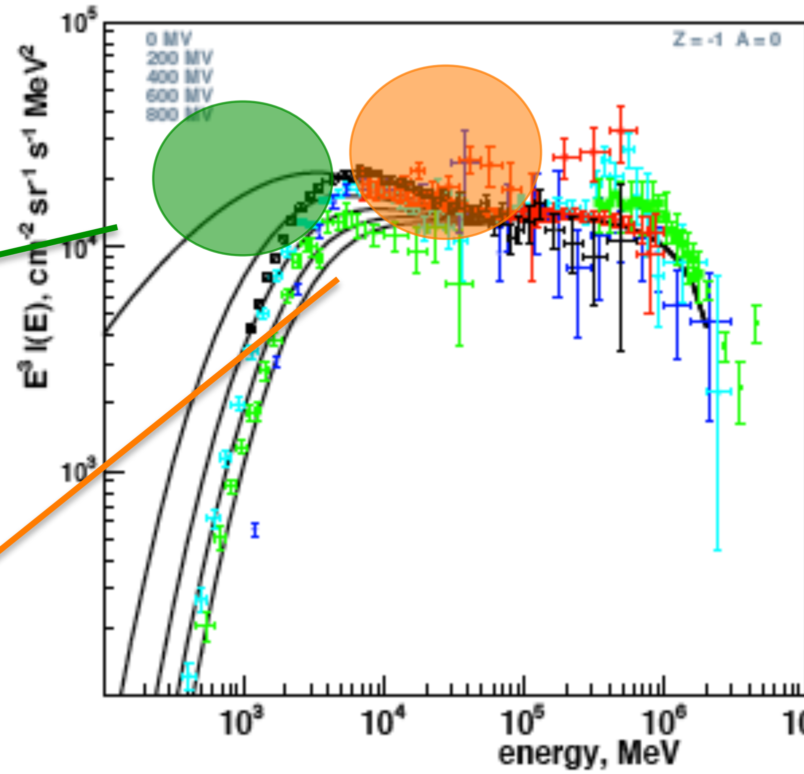
GALPROP improvements

First time models of total and polarized synchrotron emission in the context of CR propagation !

Strong, Orlando and Jaffe 2011, A&A 534, 54
Orlando & Strong 2013 MNRAS (arXiv1309.2947)

Constraints on leptons





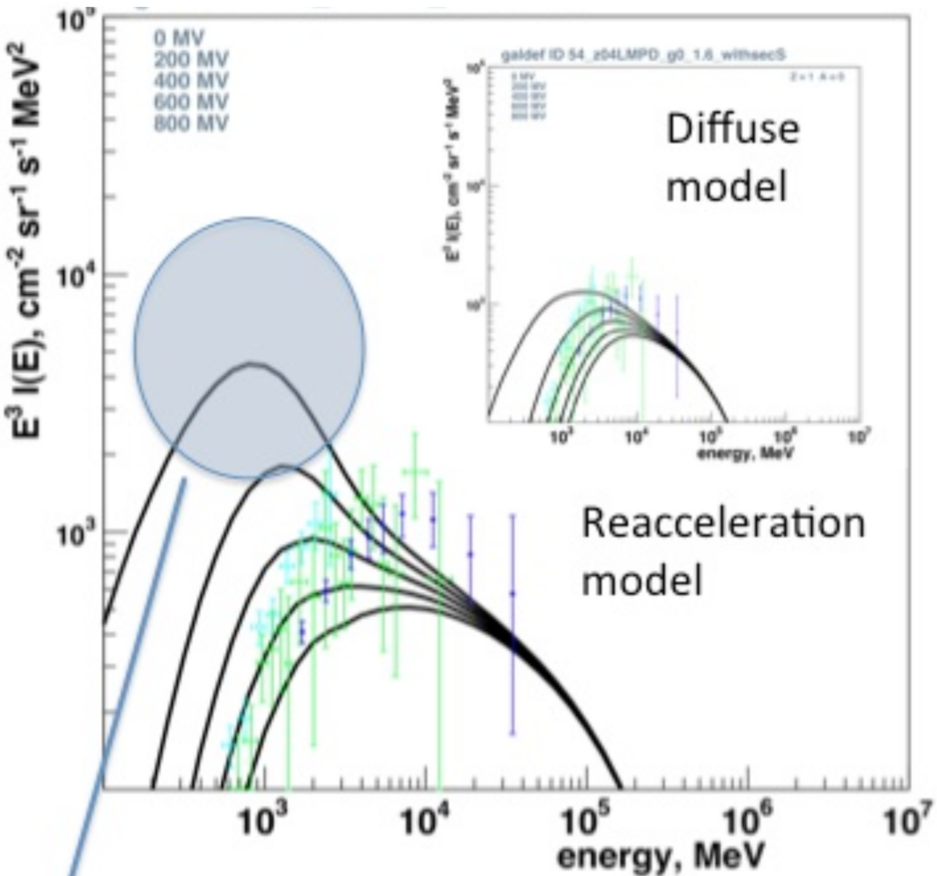
Probe of interstellar spectrum directly measured. Good determination of B field

Strong, Orlando and Jaffe 2011, A&A 534, 54

- Break in local interstellar electron spectrum from <2 to ~3 @ few GeV
- Injection spectrum < few GeV harder than 1.6

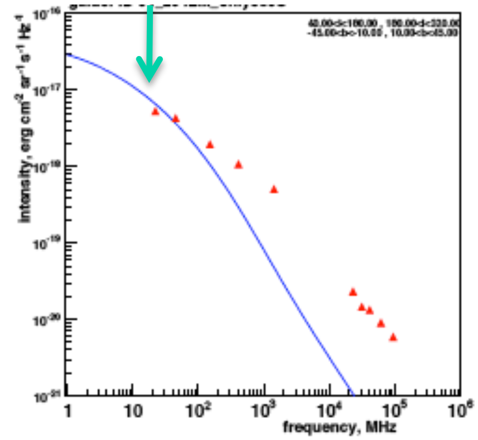
Testing models of propagation

POSITRONS (secondaries)

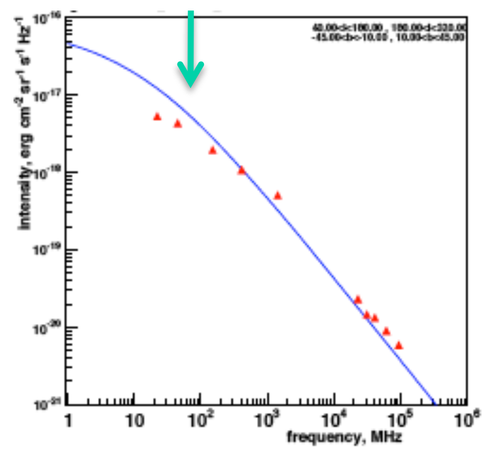


PEAK

PEAK (only secondaries)



Primaries+secondaries

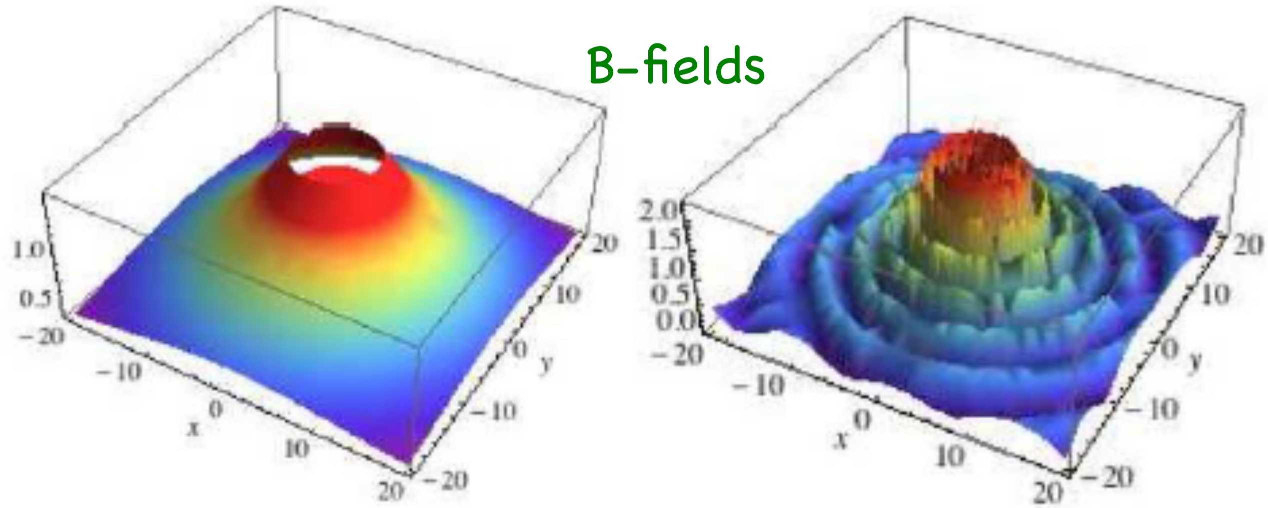


Strong, Orlando and Jaffe 2011, A&A 534, 54

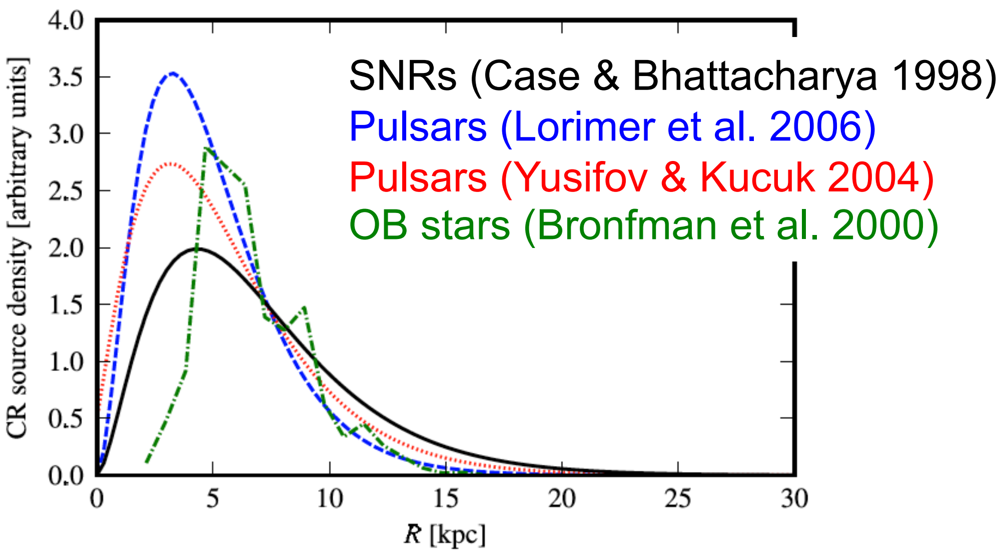
→ Standard reacceleration models hard to reconcile with synchrotron

Sensitivity to different parameters

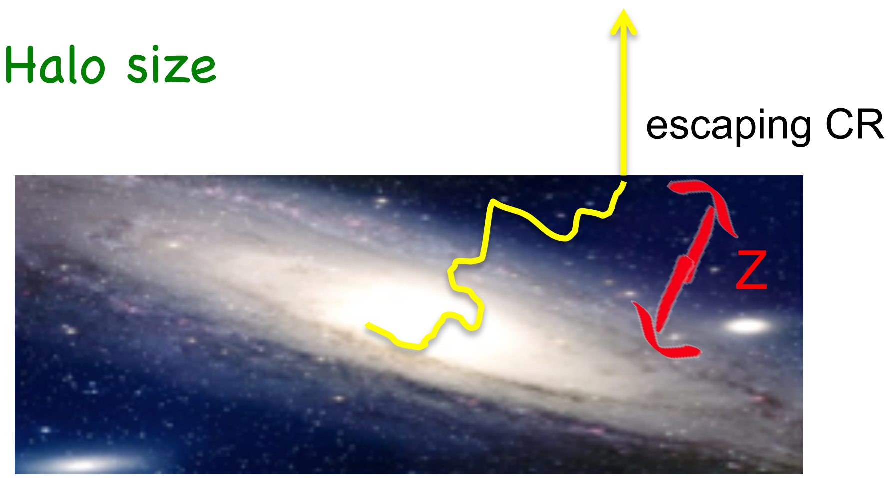
B-fields



CR source distribution



Halo size

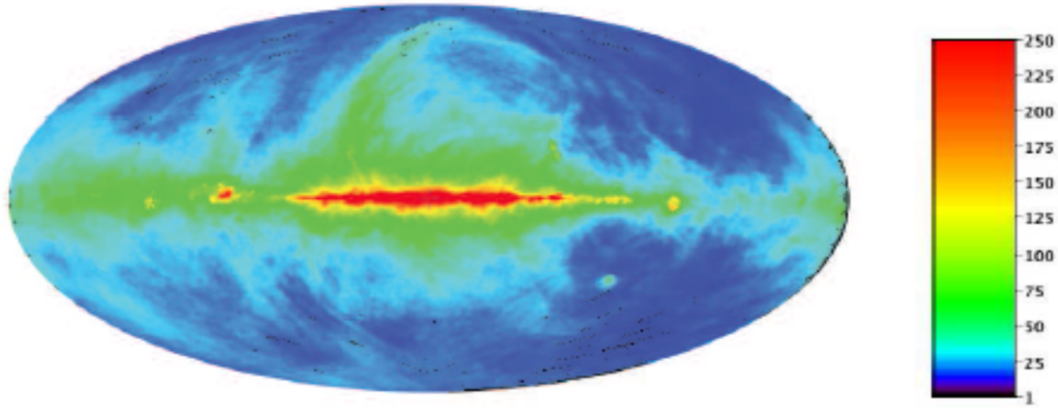


Orlando & Strong 2013 MNRAS (arXiv1309.2947)

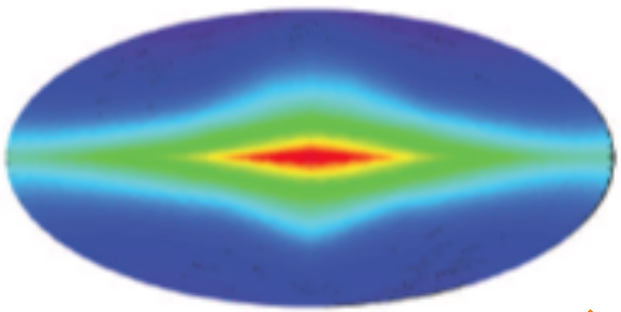
Some examples

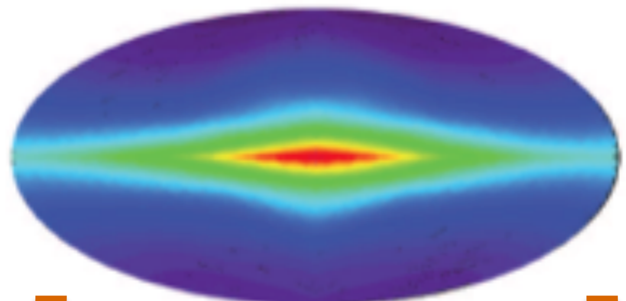
Orlando & Strong 2013 MNRAS in press (arXiv1309.2947)

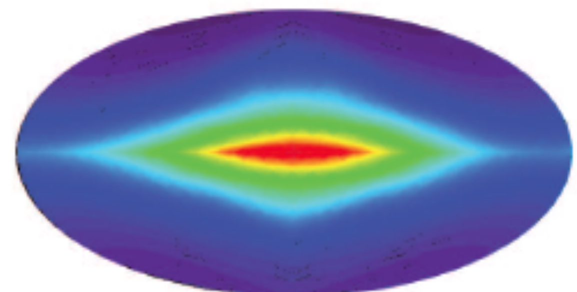
I @ 408 MHz



Same B-field models!







Z=10 kpc

Z=4 kpc

Strong 2010

Lorimer 2006

Different propagation halo size

Different CR source distribution

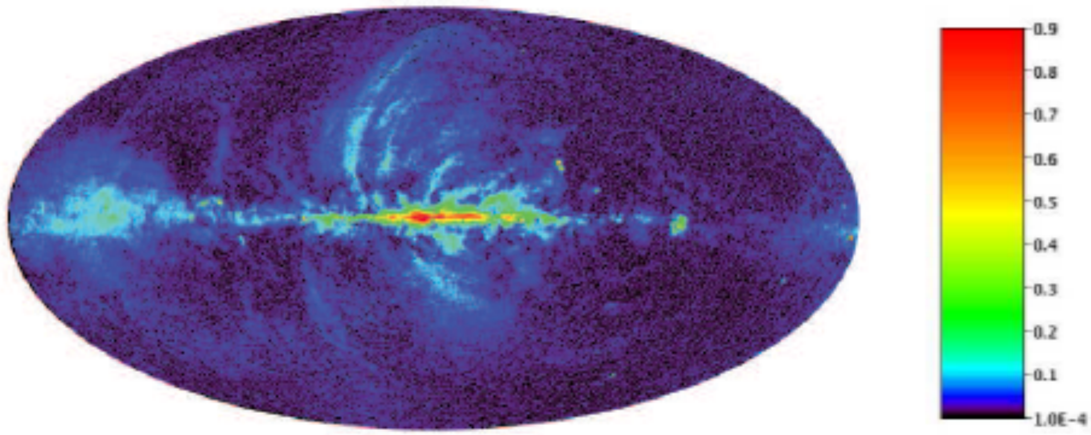
⇒ Larger Galactic halo size preferred

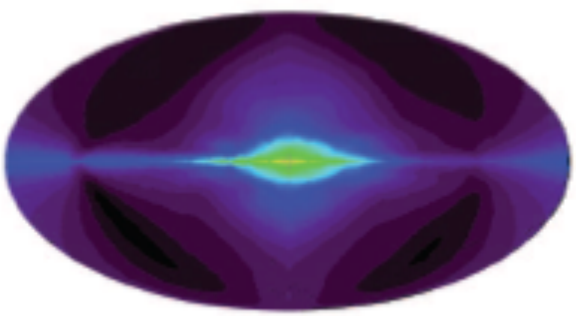
⇒ More CRs in the outer Galaxy preferred

Some examples

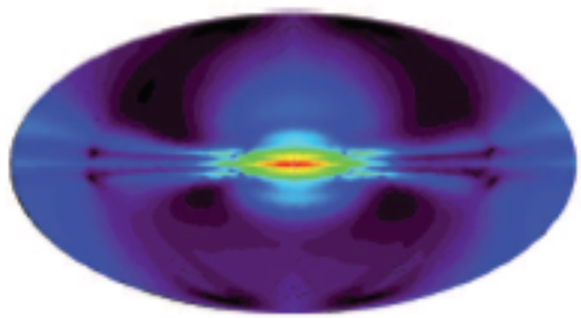
Orlando & Strong 2013 MNRAS in press (arXiv1309.2947)

P @ 23 GHz

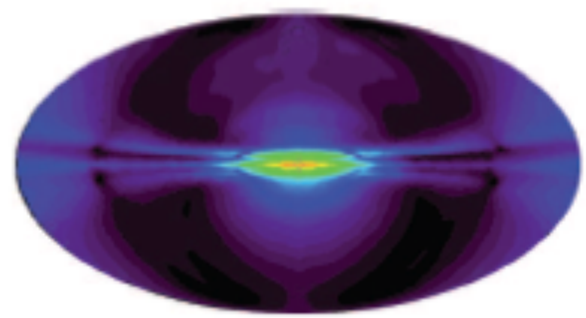




Sun 2008, 2010



Pshirkov, 2011 (ASS)



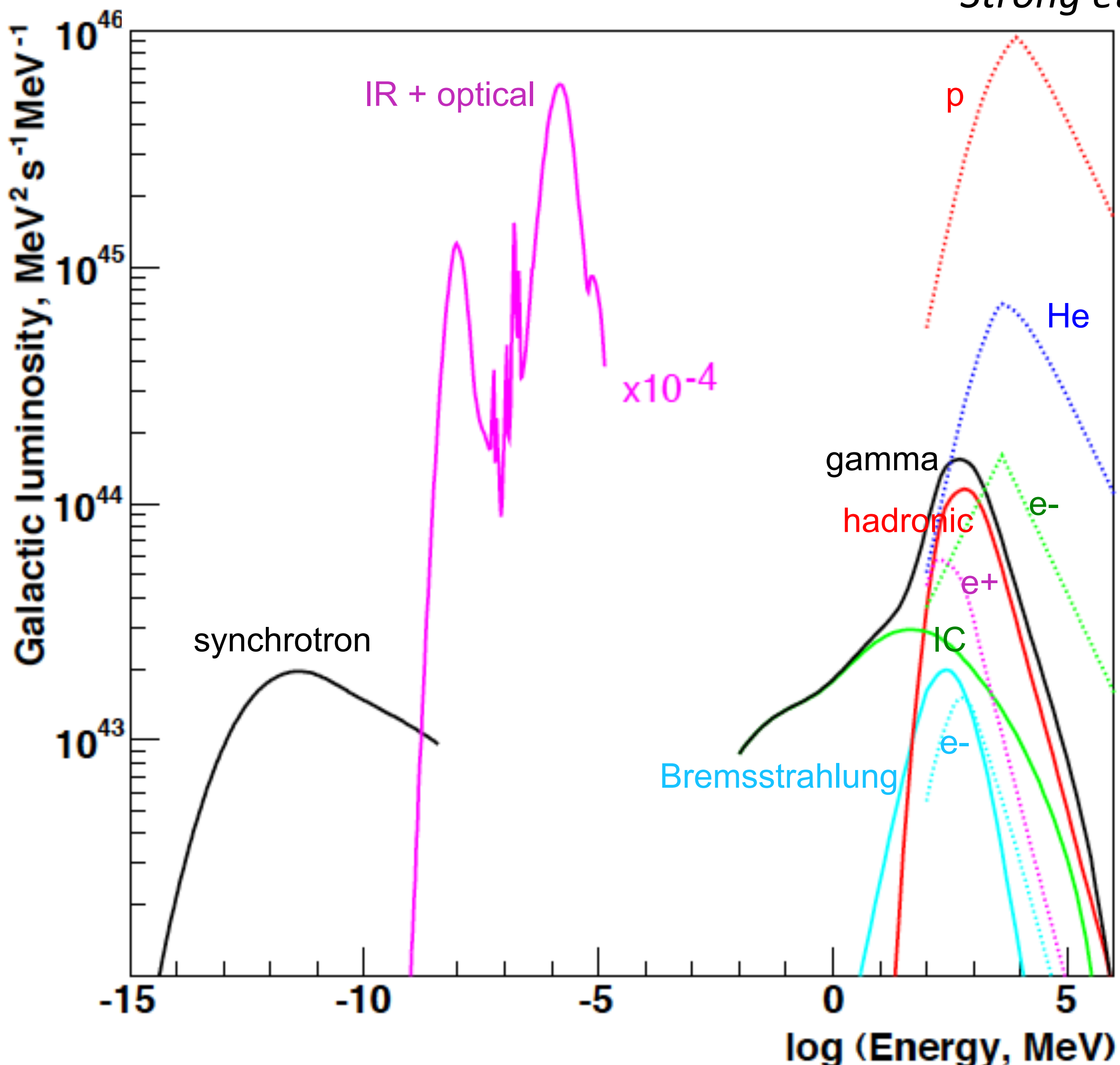
Pshirkov, 2011 (BSS)

Different B-fields

The big picture

Galaxy luminosity over 20 decades of energy

Strong et al. ApJ 2010



What did we learn so far?

- Interstellar emission mechanisms and their relation with CR are well understood

- CRs as locally measured reproduced reasonably well gamma-ray and synchrotron data
- Uncertainty in the interstellar emission model difficult to address and trivial for data interpretation (different propagation models and CR density through the Galaxy are still possible)

hints of:

- more CR than assumed in the outer Galaxy
- larger propagation halo size
- different CR propagation parameters

New CR measurements and multiwavelength observations will put more constraints!