The interstellar medium seen in gamma rays by *Fermi*

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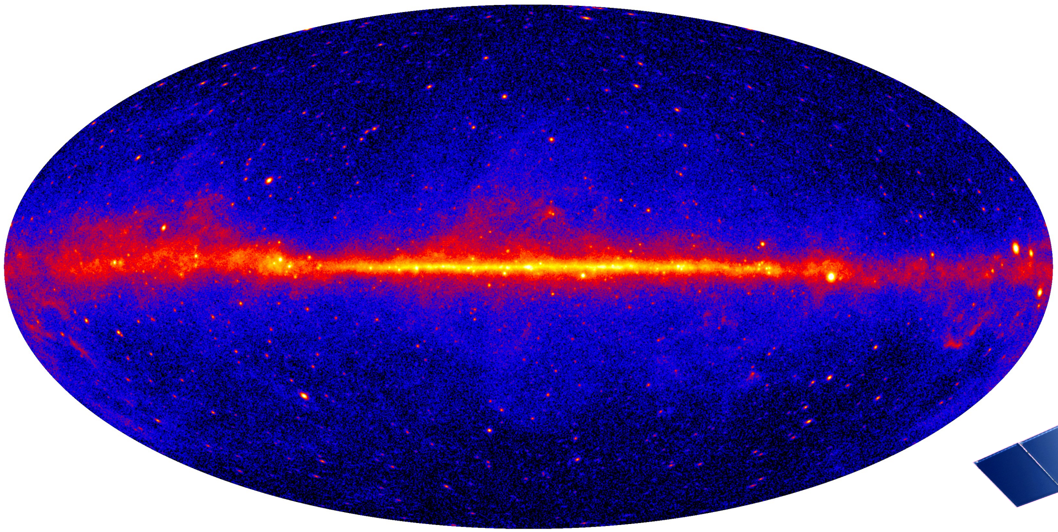
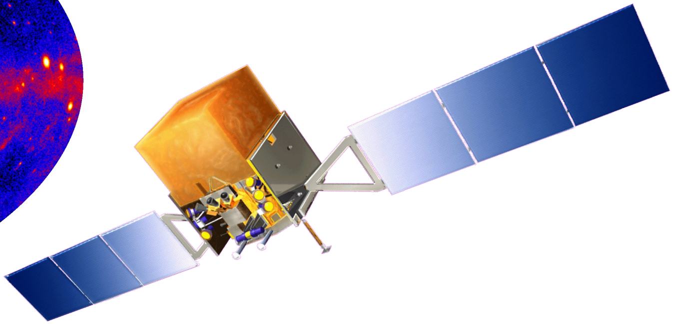
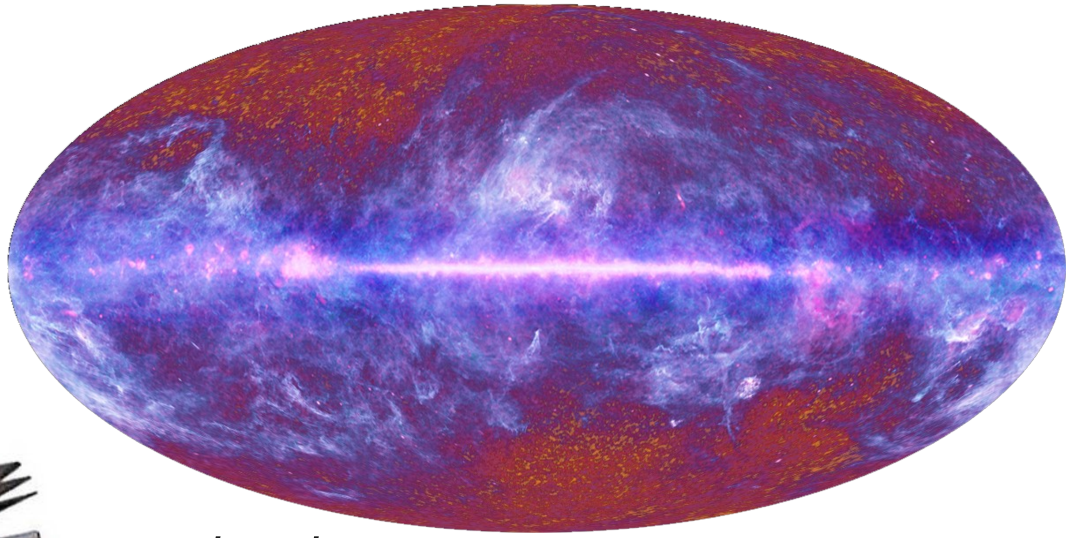
on behalf of the
***Fermi* LAT Collaboration**

Fermi vs *Planck*

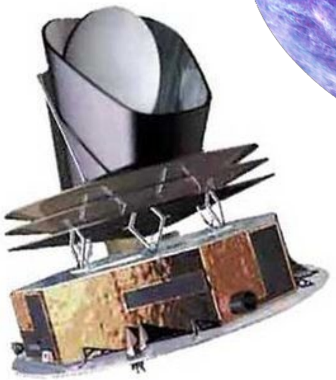


Fermi LAT
high-energy gamma rays
20 MeV – > 100 GeV



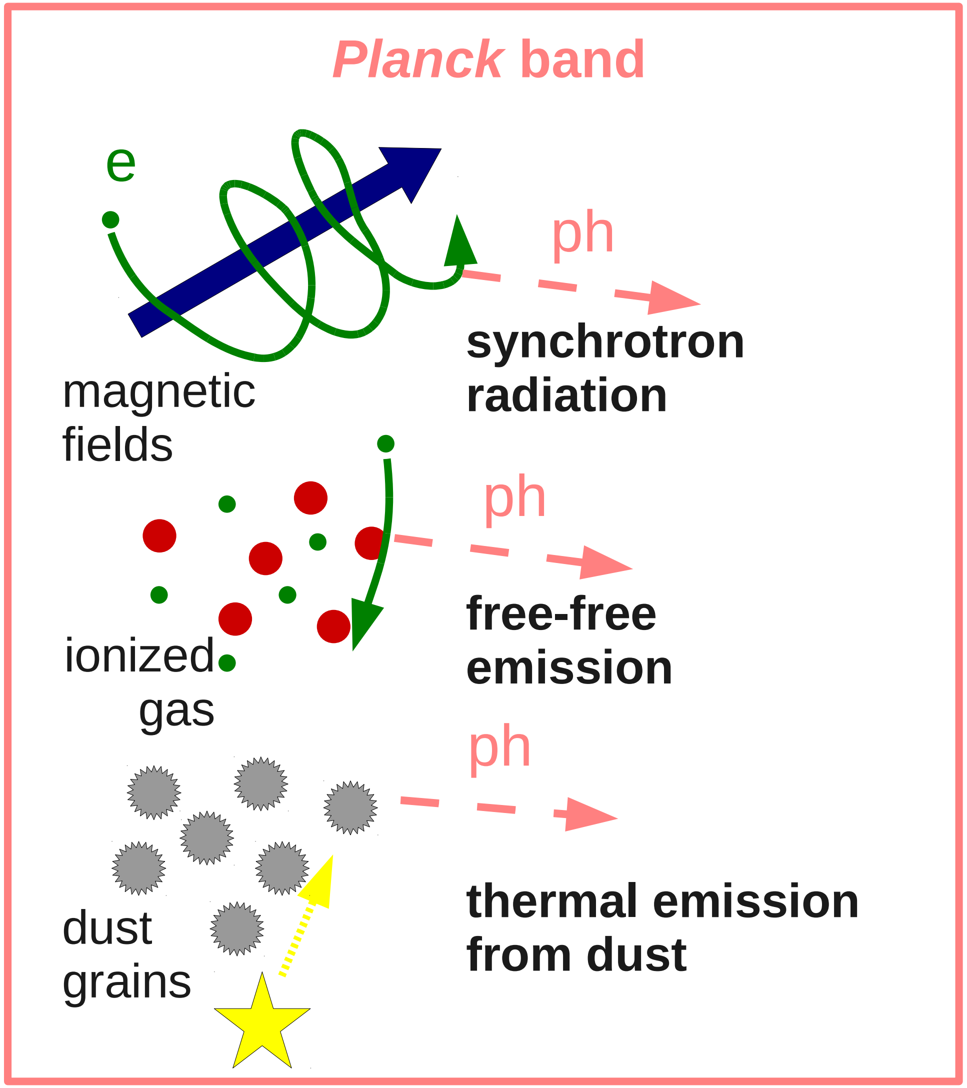


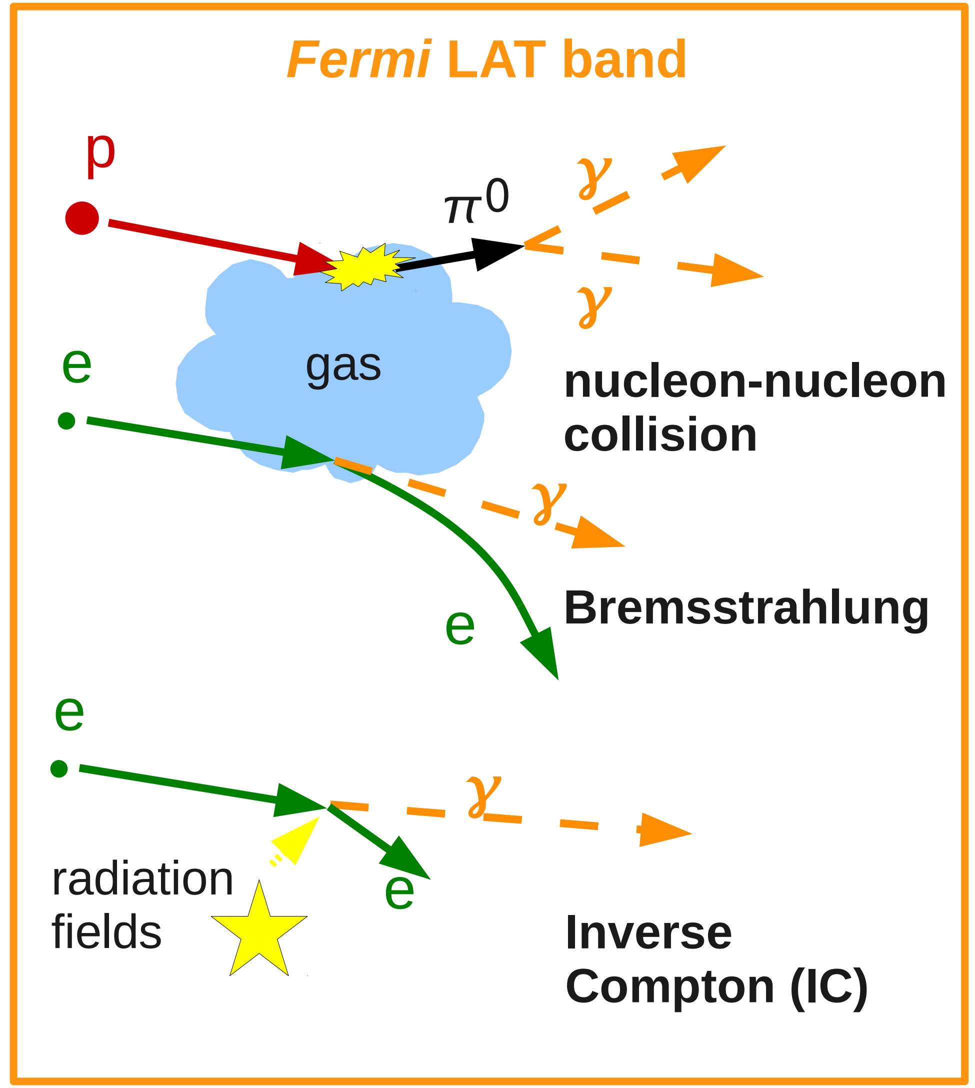
why do they look so much alike?



Planck
radio to sub-mm
30 GHz – 857 GHz

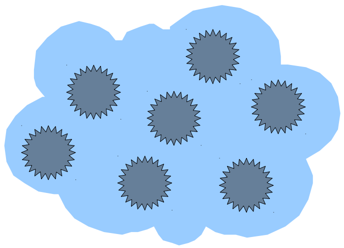
Interstellar emission from the Milky Way



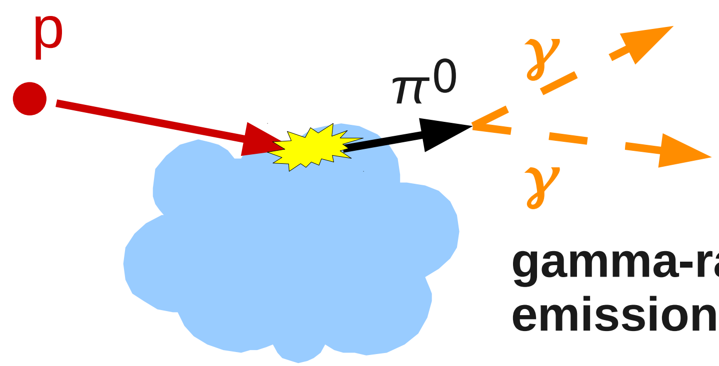


- also common source classes, e.g. AGN (see talk by P. Giommi)
- will concentrate on interstellar emission: gas and dust (for synchrotron/IC see talk by E. Orlando)

Dust and gamma-rays as ISM tracers



dust grains



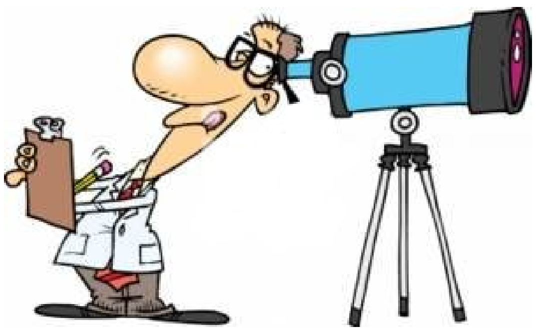
gamma-ray emission from gas

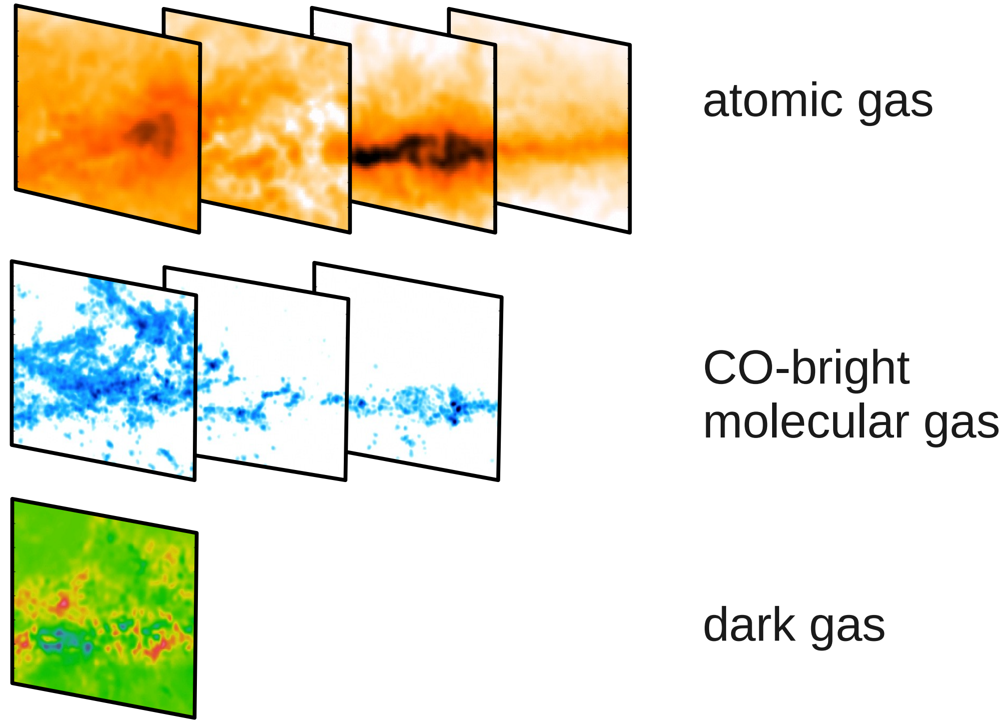
- trace the **total** column densities of the neutral ISM
  - none carry distance information (distribution in the Galaxy)
  - complement observations of specific lines from gas atoms/molecules
- for both *Fermi* and *Planck* direct interest + foregrounds

Outlook

- **the ISM seen in gamma rays**
  - facts and methods
  - the local ISM
- **atomic gas**
  - H I spin temperature and mass
  - constraints by *Fermi*
- **CO-bright molecular gas**
  - mass calibration in gamma rays
  - X_{CO} gradients in the Milky Way?
- **dark neutral gas**
  - gamma rays and dust vs. H I and CO
  - gamma-ray spectrum and mass

ISM studies with Fermi

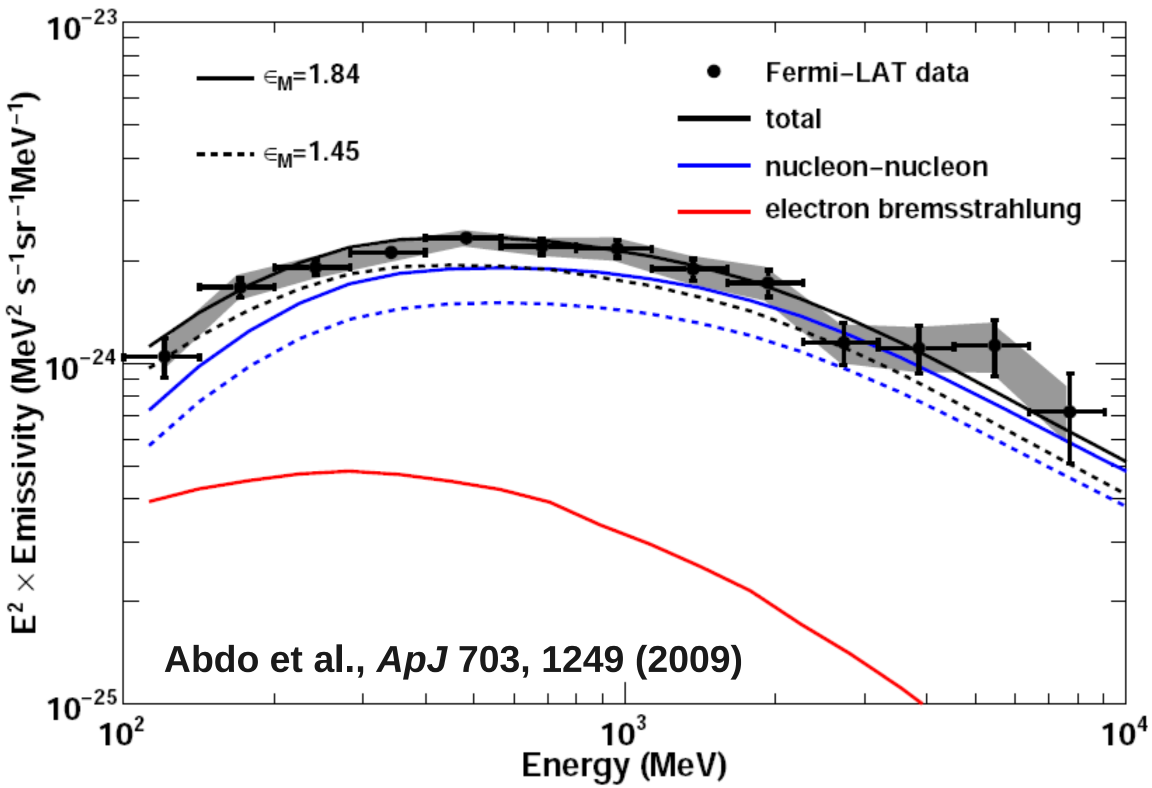




$$\int n_{ISM} \cdot n_{CR} \, dl$$

- gamma rays trace product of CR and ISM densities
- two complementary approaches
  - component separation → determine gas emissivity for different phases/regions
  - comparison between data and predictive models (GALPROP, see talk by E. Orlando)

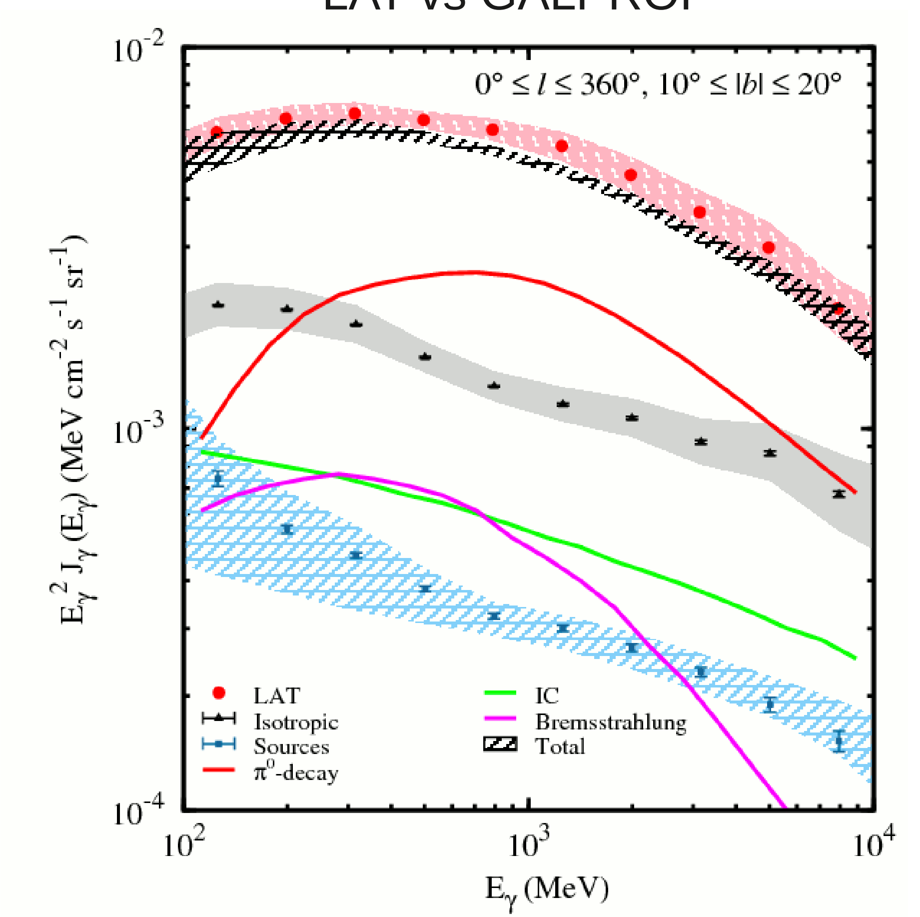
Gamma-ray emission from the local ISM



emissivity of local H I

Abdo et al., *Phys. Rev. Lett.* 103, 251101 (2009)

LAT vs GALPROP



- consistent with expectations based on CR spectra measured near the Earth
- basic emission processes understood

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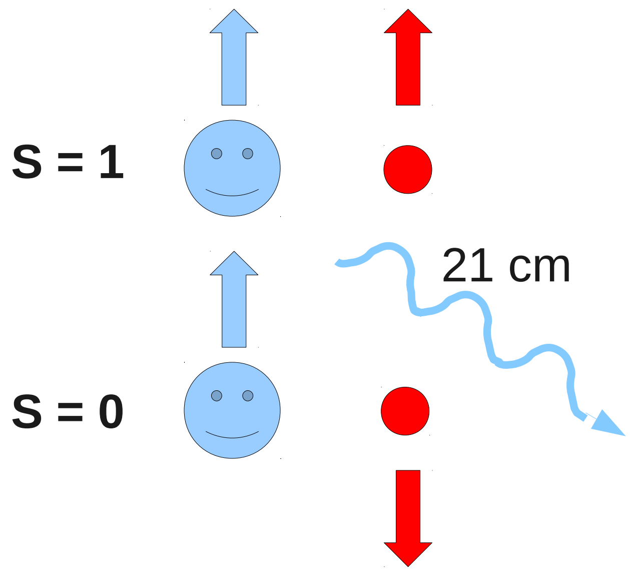
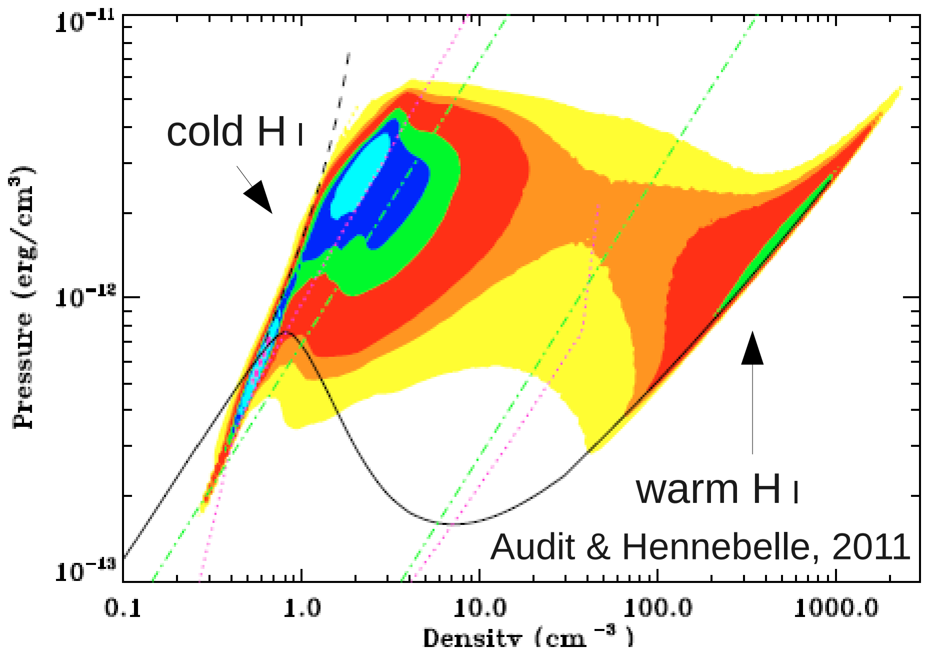
H I mass and spin temperature



$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\Delta E_{10}/kT_S}$$

- radiation transfer equation solvable only for **uniform spin temperature**
- often just assumed conventional value (in gamma rays 125 K)

$$N(\mathrm{H\,I}) = -C T_S \int \ln\left(1 - \frac{\Delta T_B(v)}{T_S - T_{\mathrm{bg}}}\right) \mathrm{d}v$$

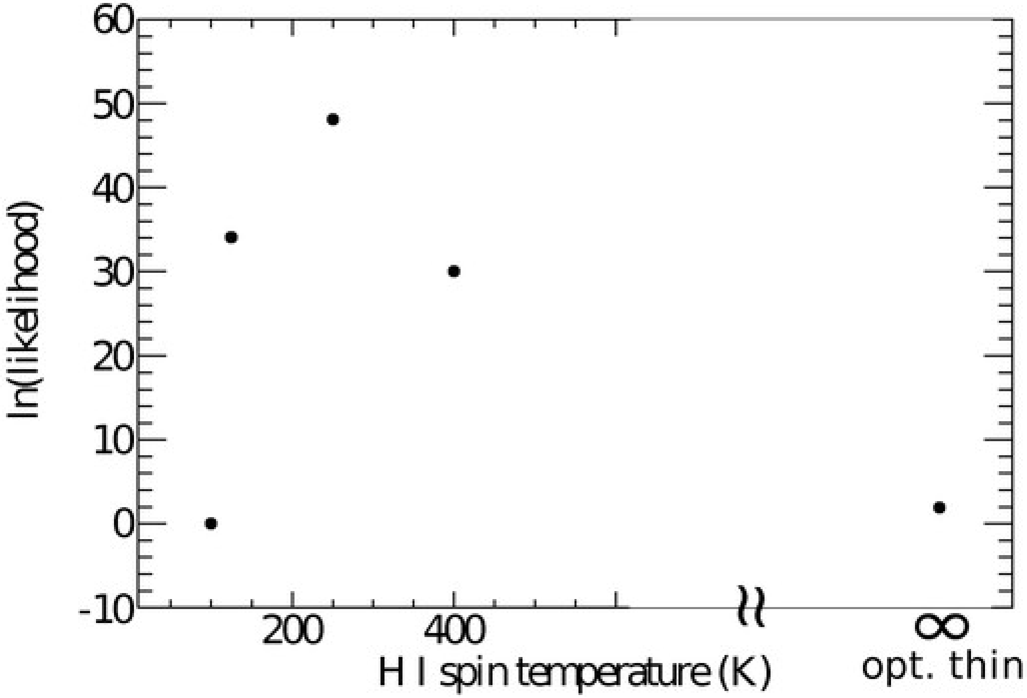


- not uniform
- large-scale effective spin temperature → blend of cold and warm medium

Gamma-ray observations of H I gas

- first recognized the importance of H I mass uncertainties in gamma
- gamma-ray observations capable of constraining large-scale effective Ts
- local/outer Galaxy
  - Ts of 150-400 K
  - ~ 80% warm gas, ~20% cold
  - consistent with radio

Ackermann et al., A&A 538, A71 (2012)



Cygnus region

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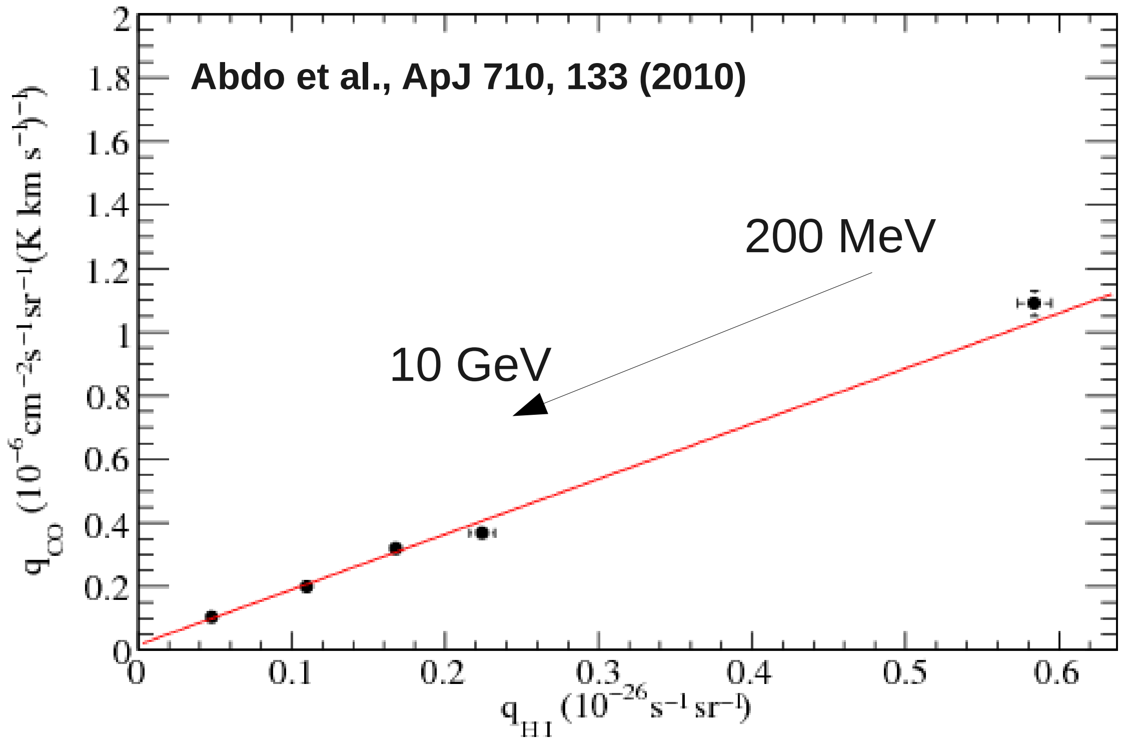
The mass of CO-bright molecular gas

- cold H_2 has no observable lines
- CO 2.6 mm line is a widely used surrogate
- only indirect tracer → need mass calibration $X_{CO} \equiv \frac{N(H_2)}{W_{CO}}$
- calibrate on gamma-ray emission from clouds assuming CR spectrum to be the same as in H I

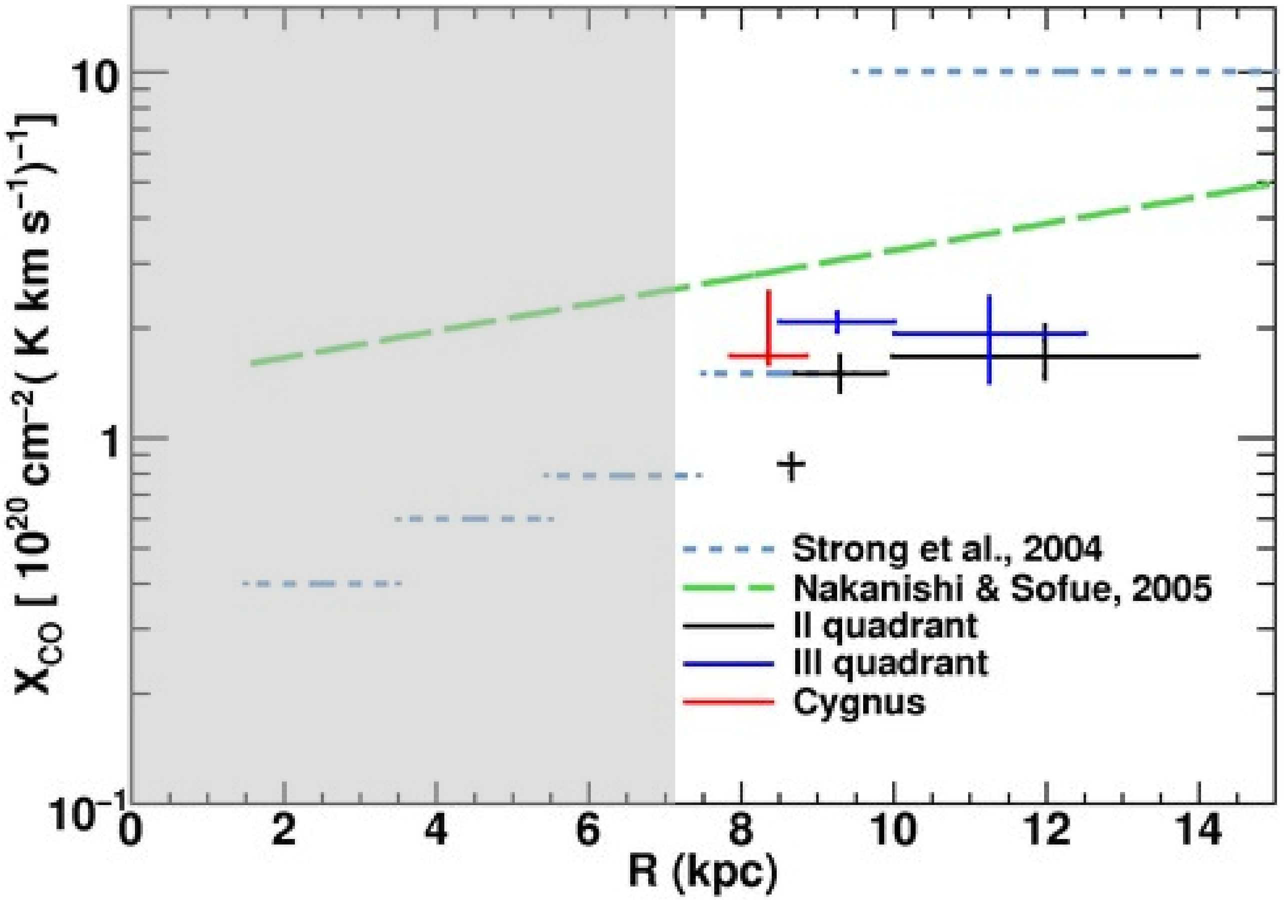
$$\begin{cases} q(H_2) = 2 \times \mathbf{q(H\,I)} \\ q(H_2) = X_{CO}^{-1} \times \mathbf{q(CO)} \end{cases}$$

$$\mathbf{q(CO)} = 2 \times X_{CO} \times \mathbf{q(H\,I)}$$

Cas/Cep/Pol complex



X_{CO} variations in the Milky Way?



Abdo et al., ApJ 710, 133 (2010)

Ackermann et al., ApJ 726, 81 (2011)

Ackermann et al., A&A 538, A71 (2012)

LT et al., Proceedings of 32nd ICRC (2011) arXiv:1110.6123

- no significant gradient with Galactocentric distance beyond solar circle
- drop for local clouds → intrinsic or sampling effect?
- drop for innermost few hundred pc of the Milky Way → breakdown of CO as H_2 tracer?

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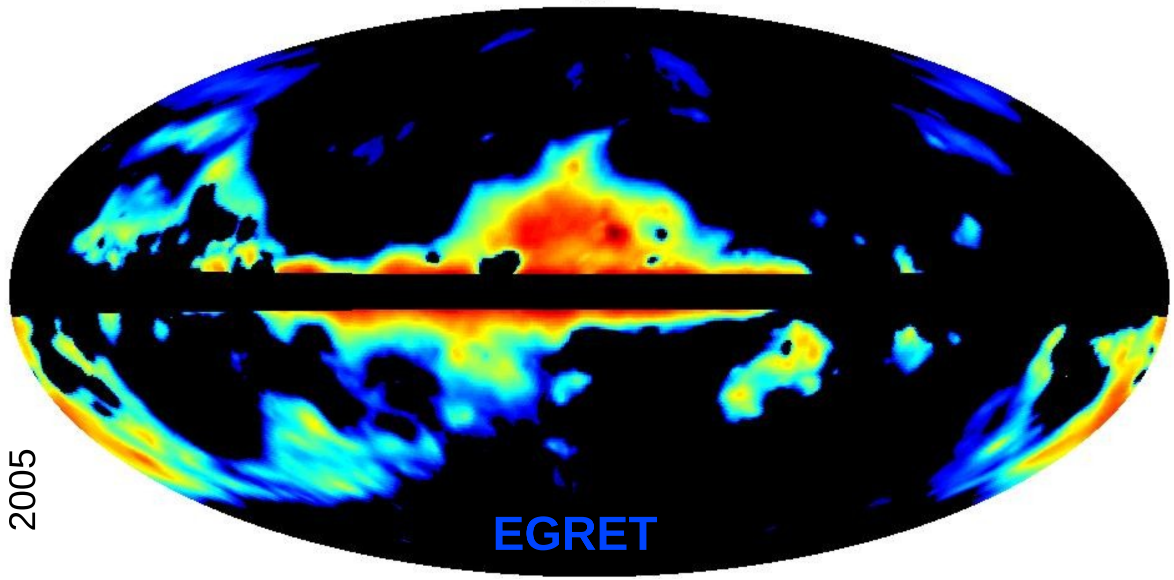
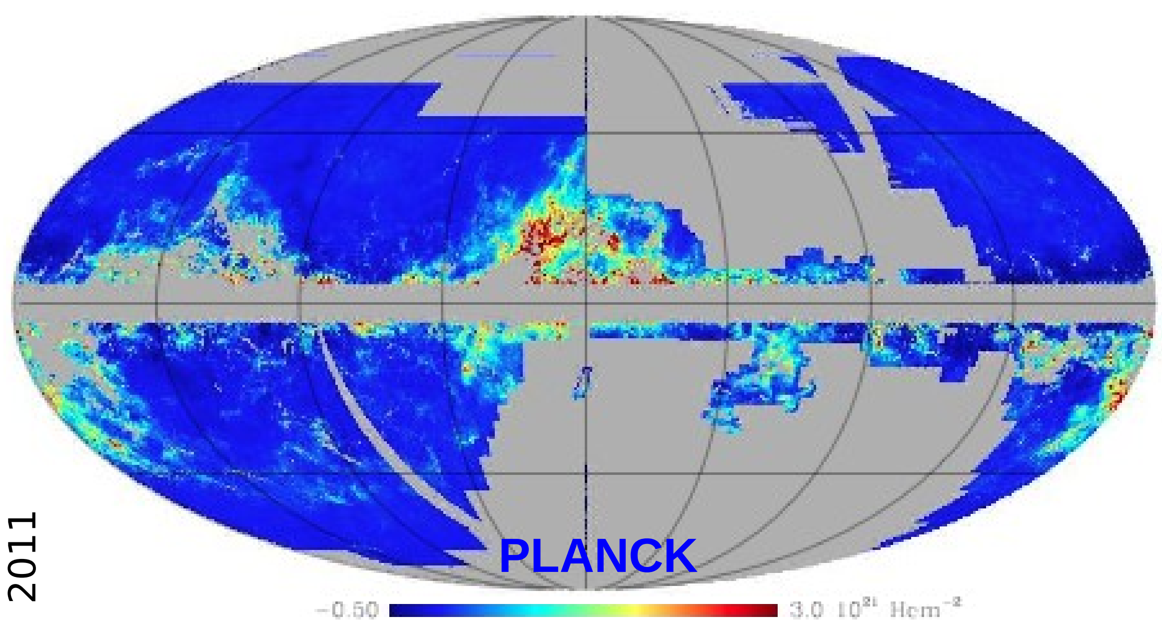
The “dark” gas

- correlated dust and gamma-ray excesses over linear combination of H I and CO → **dark gas**
  - neither H I nor CO are perfect tracers
- serious challenge for gamma-ray analyses
  - provisional (long-standing) solution: use dust residuals to trace dark gas

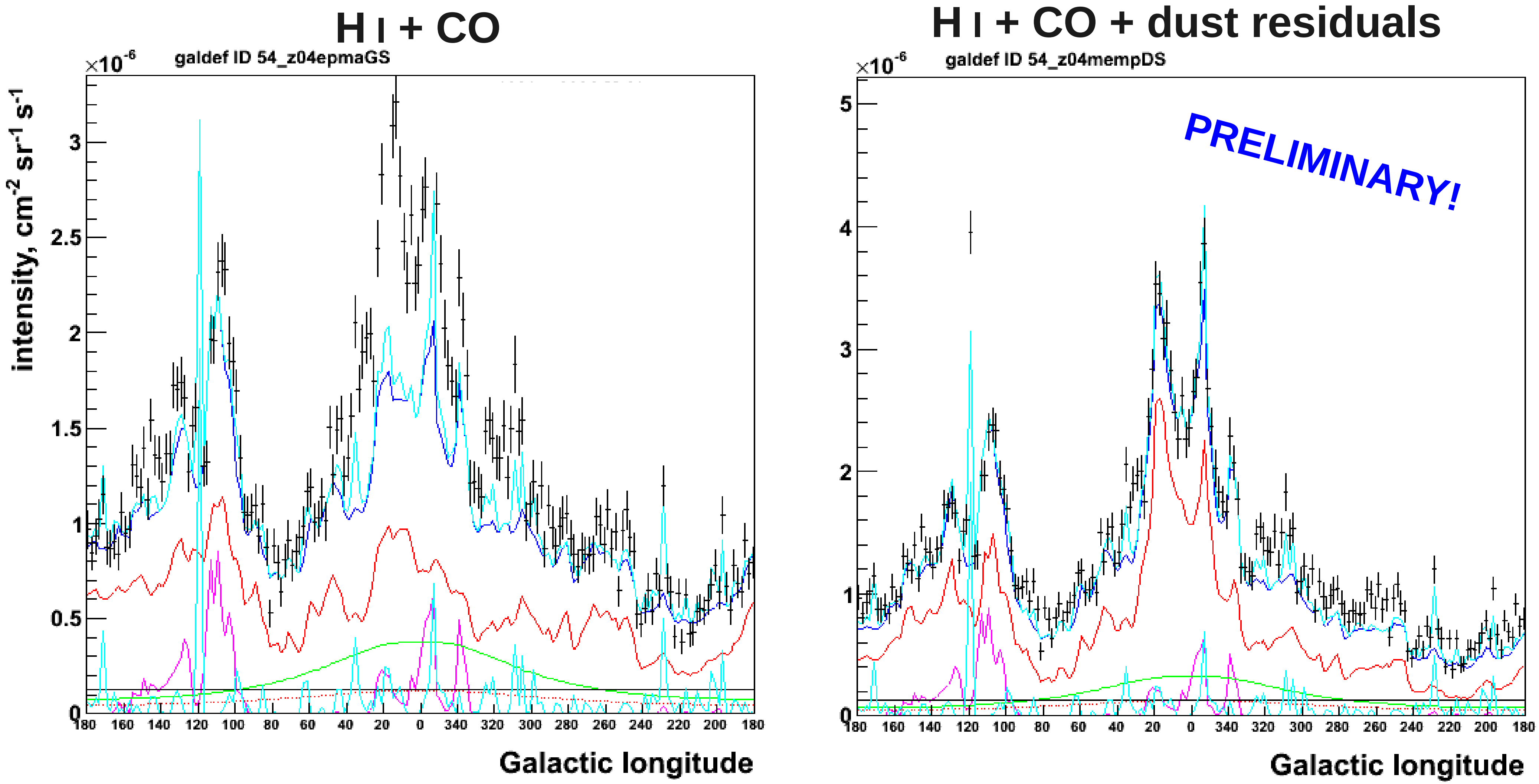
Grenier at al. 2005



Planck collaboration 2011



Fermi confirms the dark gas



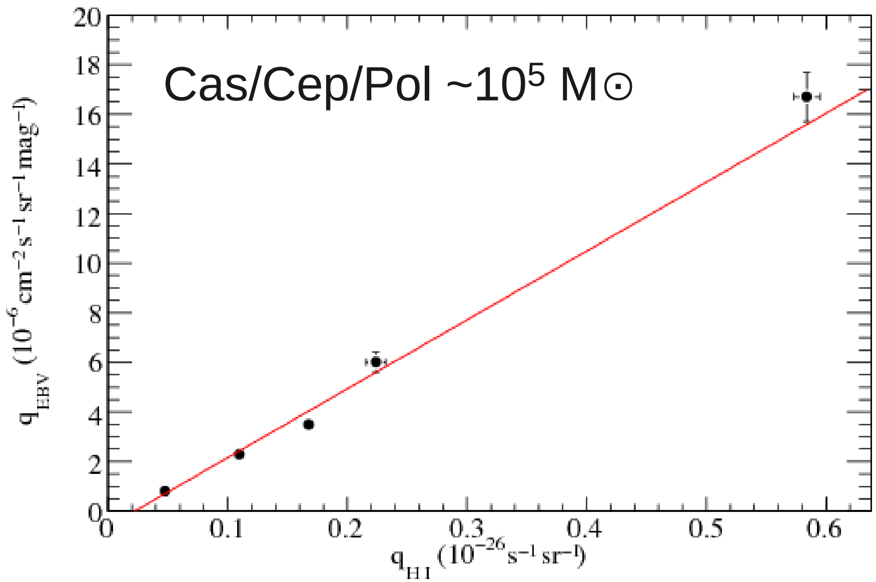
H I/H I + dark gas
H_2 (traced by CO)
H II
IC
total Galactic interstellar
isotropic
sources
total+sources

1.6 – 3.2 GeV
10° < |b| < 20°

Dark gas gamma-ray spectrum and mass

- LAT data confirm the presence of dark gas
- emissivity per dust residuals scales linearly with that per H atom over 100 MeV – 100 GeV
  - gamma rays from gas!
  - use for mass calibration
- 40-60% CO-bright mass from single cloud (10^4 M⊙) to large complex (10^6 M⊙)
- 118% for local clouds using dust only (Planck coll.)

Abdo et al., ApJ 710, 133 (2010)



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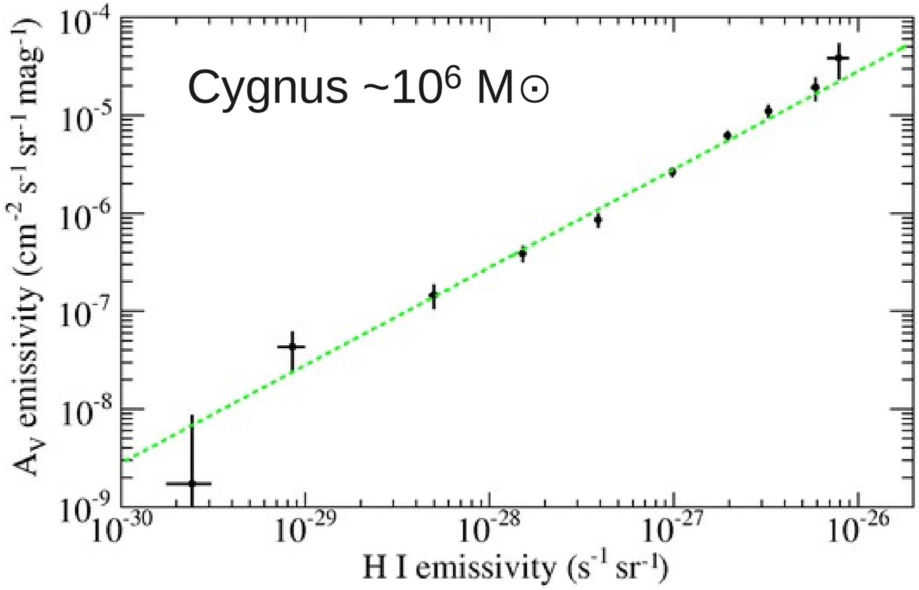


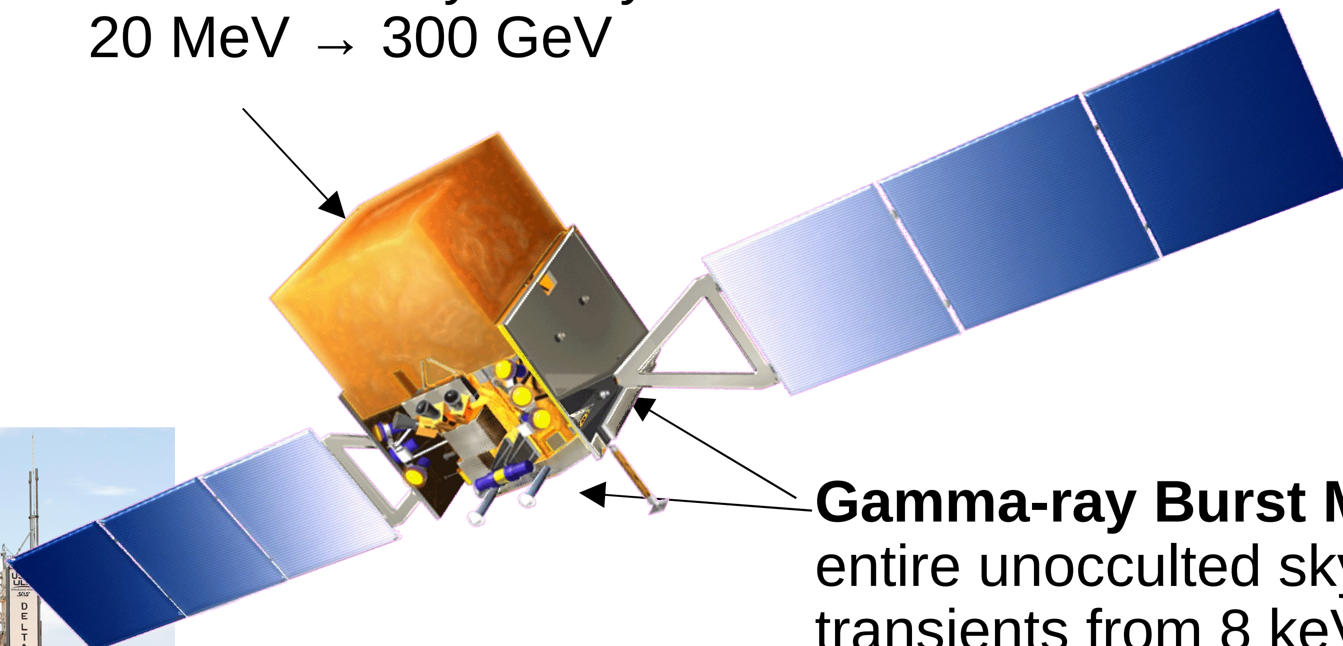
Final remarks

- interstellar gamma-ray emission is a valuable tracer of the neutral ISM
- recognized uncertainties due to H I optical depth
  - can constrain large-scale effective spin temperature
- measured X_{CO} for several cloud complexes
  - no significant gradients in the disc from local arm toward outer Galaxy
  - variations for local clouds and innermost Galaxy
- confirmed the presence of “dark” neutral gas
  - proved it has a gas spectrum in gamma rays
  - masses are comparable to those traced by CO
- more to come from *Fermi* and *Planck*

Backup slides

The *Fermi Gamma-ray Space Telescope*

Large Area Telescope (LAT)
20% of the sky at any instant
20 MeV → 300 GeV



Gamma-ray Burst Monitor (GBM)
entire unocculted sky
transients from 8 keV → 40 MeV

Launched from Cape Canaveral Air Station on 11 June 2008

nearly circular orbit 565 km, 25.6°

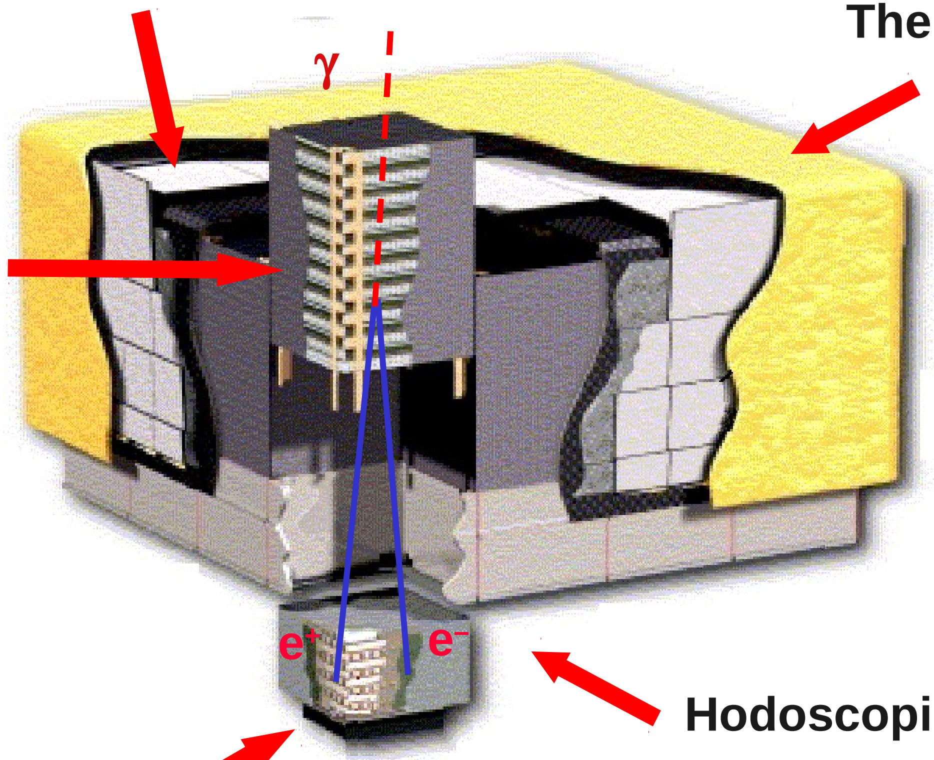
The Large Area Telescope

Anticoincidence Detector (ACD)
- segmented
- 0.9997 MIP efficiency

Pair-tracking Telescope
1.8 m x 1.8 m x 0.72 m

Thermal Blanket

Precision Si-strip Tracker + W Converters (TKR) :
- 12 planes 3% r.l. (FRONT)
- 4 planes 12% r.l. (BACK)
- 2 planes with no converter
- 0.9 M channels
- > 0.7 m^2 active Si

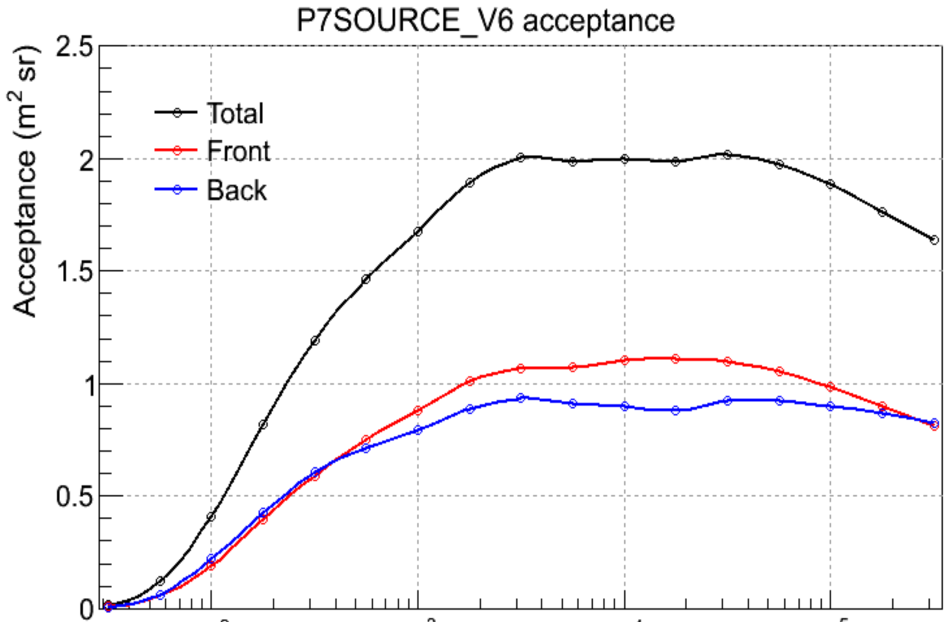


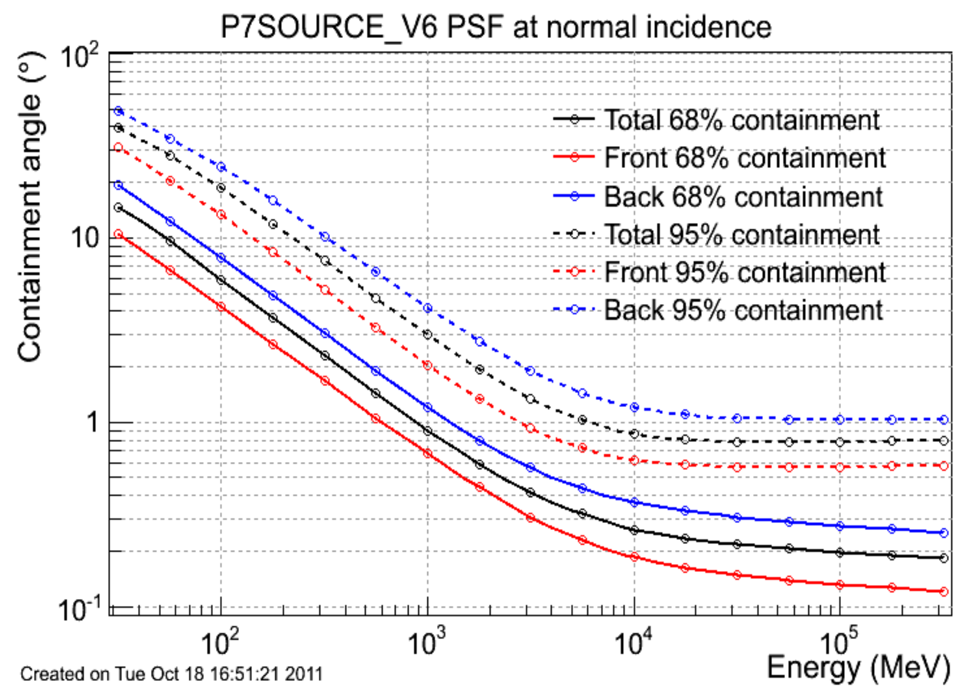
Hodoscopic CsI Calorimeter (CAL)
- 1536 logs
- 8.5 r.l. on axis

DAQ

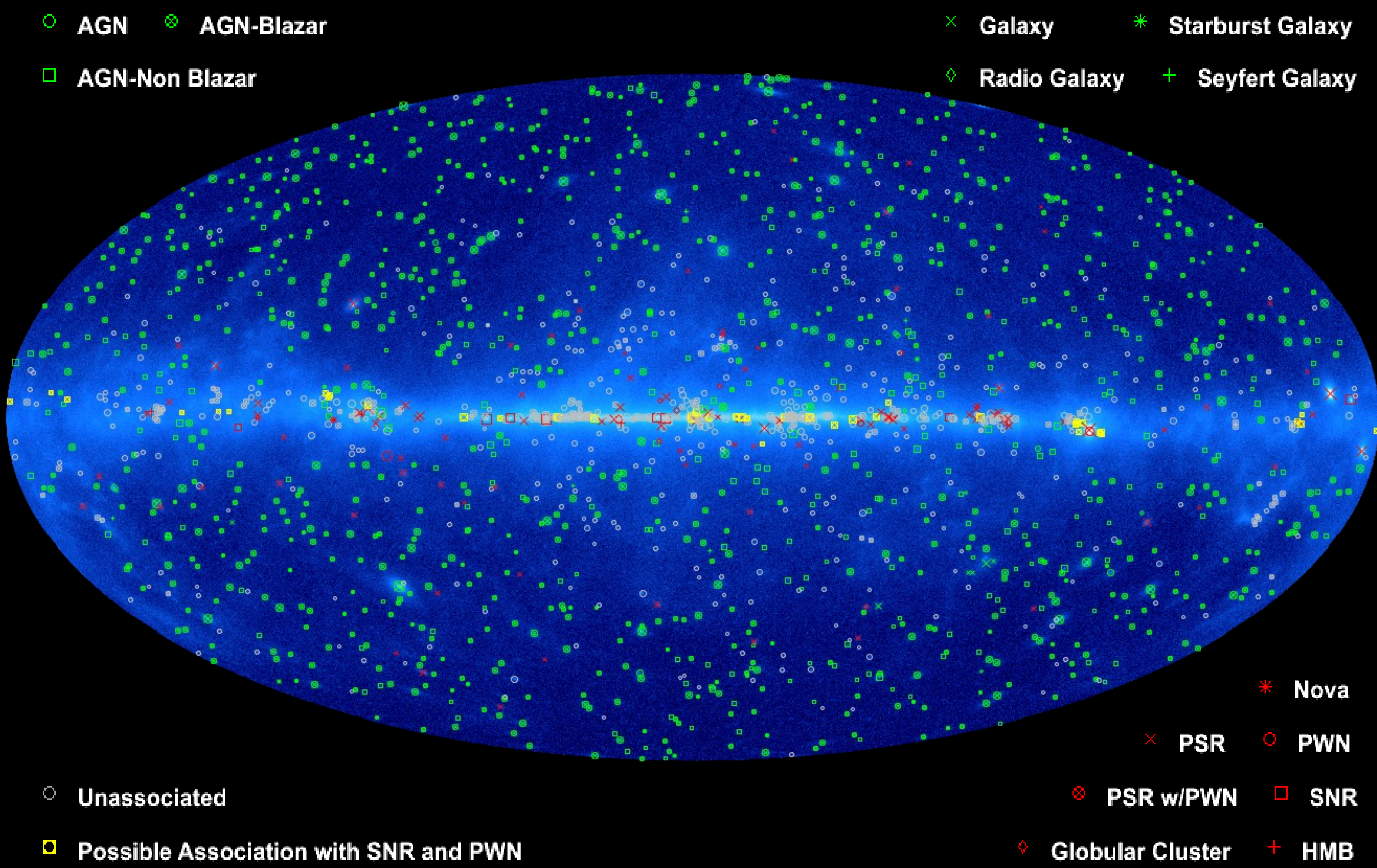
LAT instrument performance

- acceptance larger by > one order of magnitude w.r.t. predecessors
- PSF 68%: 5° → 0.2°
- energy resolution <15% for energies > 300 MeV





Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

Latitude profile outer Galaxy