AMS02, Fermi and Planck space experiments: an experimentalist perspective.

M. Incagli – INFN Pisa

Cortona (AR) – May 2014

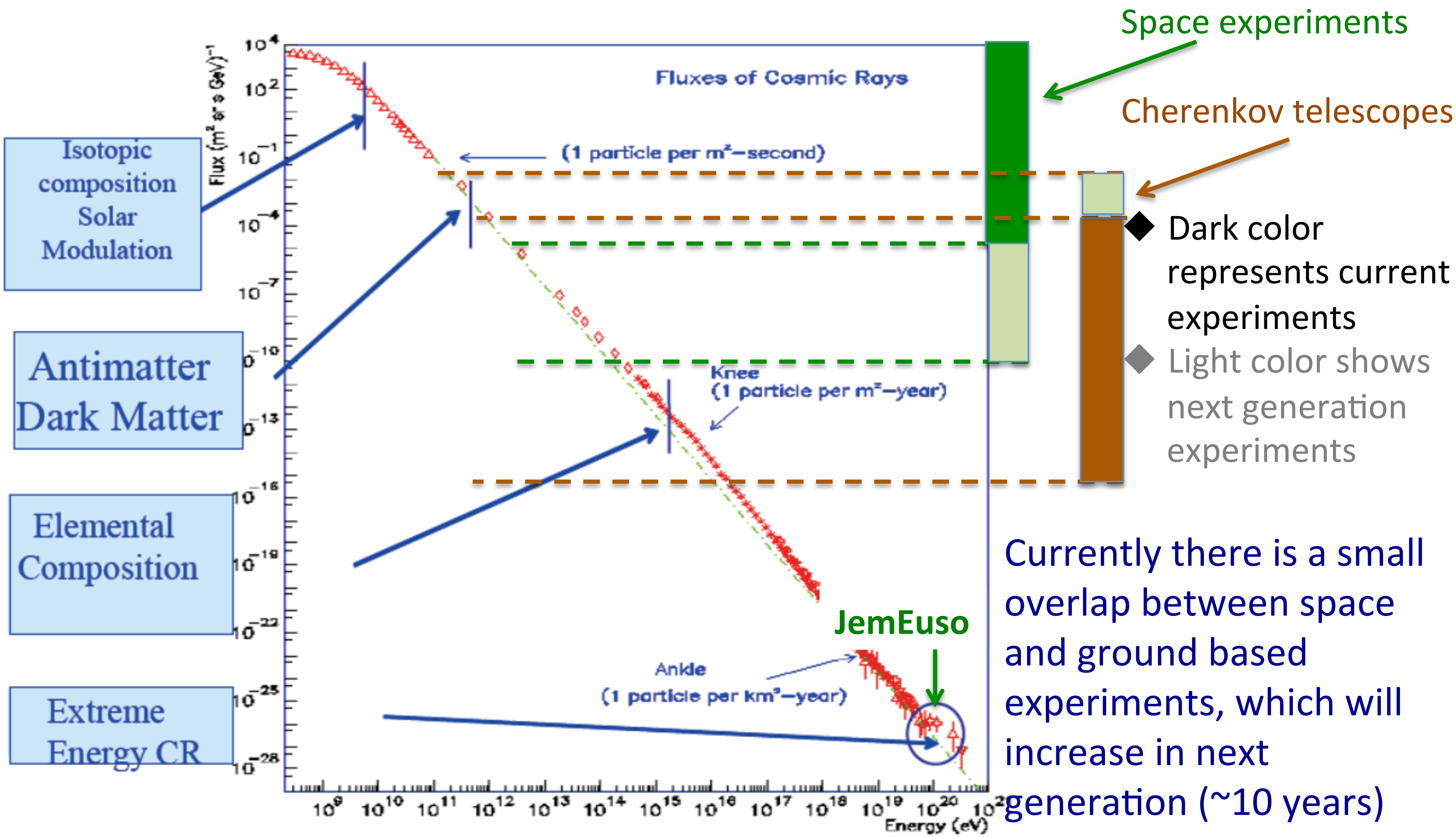
Outline

1. Detectors for Space Experiments
   - Why
   - How
   - Where (this is easy: in Space)
2. State of the arts experiments:
   - AMS02 : charged cosmic rays
   - Fermi : high energy (1-1000 GeV) photons
   - Planck : CMB

1. Detector for Space Experiments

- Building experiments is *an art*
- *Each apparatus is unique* – there are some standard *pieces* (tracker, calorimeter, ...) but each composition is a *delicate interplay between experimental goals, theory, personal attitude* ... and financing agencies!
- This is *even more true in Space Experiments*, which is a relatively young field of research
- In the first part of my talk, I will try to show the *philosphy* behind the experimental solutions that have been taken

Charged Cosmic Rays



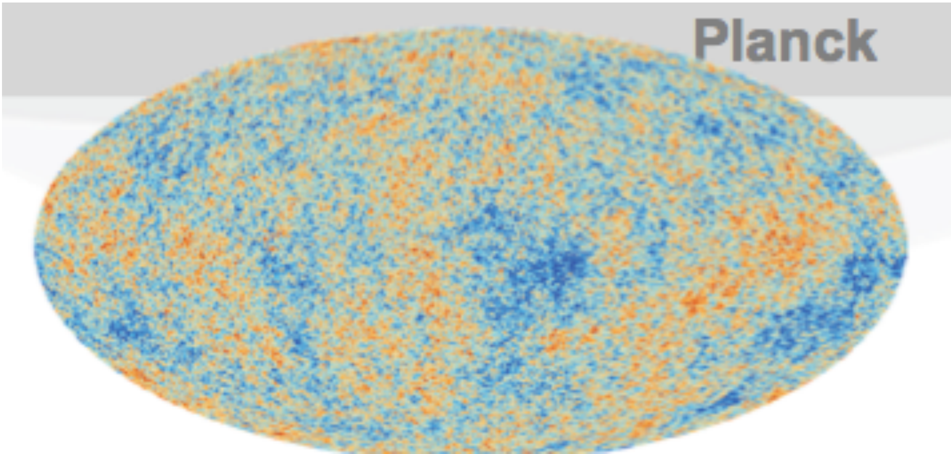
J. Cronin ,T.K. Gaisser & S.P. Swordy, Sci. Amer. 276 (1997) 44

- Dark color represents current experiments
- Light color shows next generation experiments

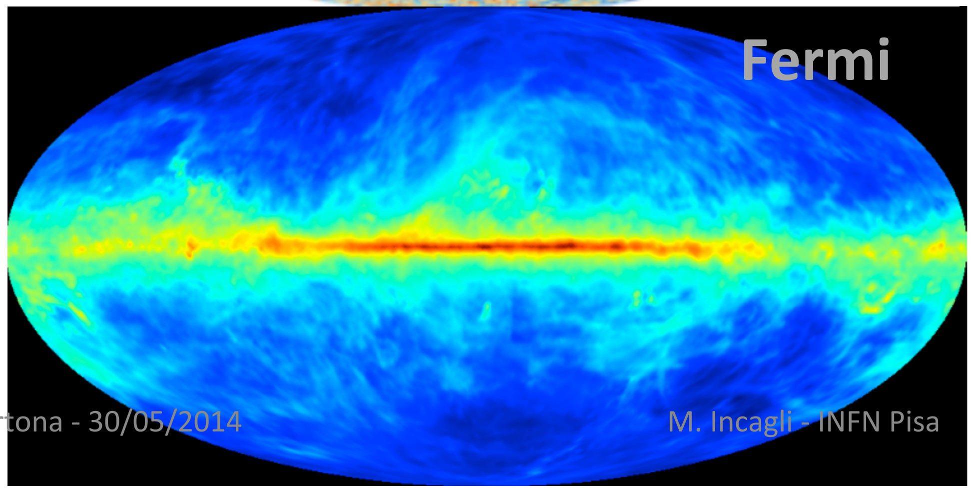
Currently there is a small overlap between space and ground based experiments, which will increase in next generation (~10 years)

Neutral Cosmic Rays

- Neutrinos, gravitational waves → not discussed here
- Photons → Multi-WaveLength search



30-1000 GHz → $\sim 10^{-4}$ eV



0.1-500 GeV → $\sim 10^{11}$ eV

Space experiments

- ✦ *Sensitive to "primary" component* (i.e. before interacting with earth atmosphere)
- ✦ A *higher precision on energy and on chemical composition* (Z, isotopes) can be reached
- ✦ With magnet → *sensitivity to anti-particles*
- ✦ Long period of continuos data taking
- – Limited mass
- – Limited geometrical acceptance
- – Large cost

High-energy space experiments

- High-energy: above 1-10 GeV
- Different *categories* of experiments are possible:

1. Magnetic spectrometer (*à la* AMS02)
2. Pair-conversion telescope (*à la* Fermi)
3. Cosmic Rays calorimeter (*à la* CREAM or ATIC, but also many new proposals: CALET, ISS-CREAM, GAMMA400, HERD, ...)

Spectrometers vs. calorimeters

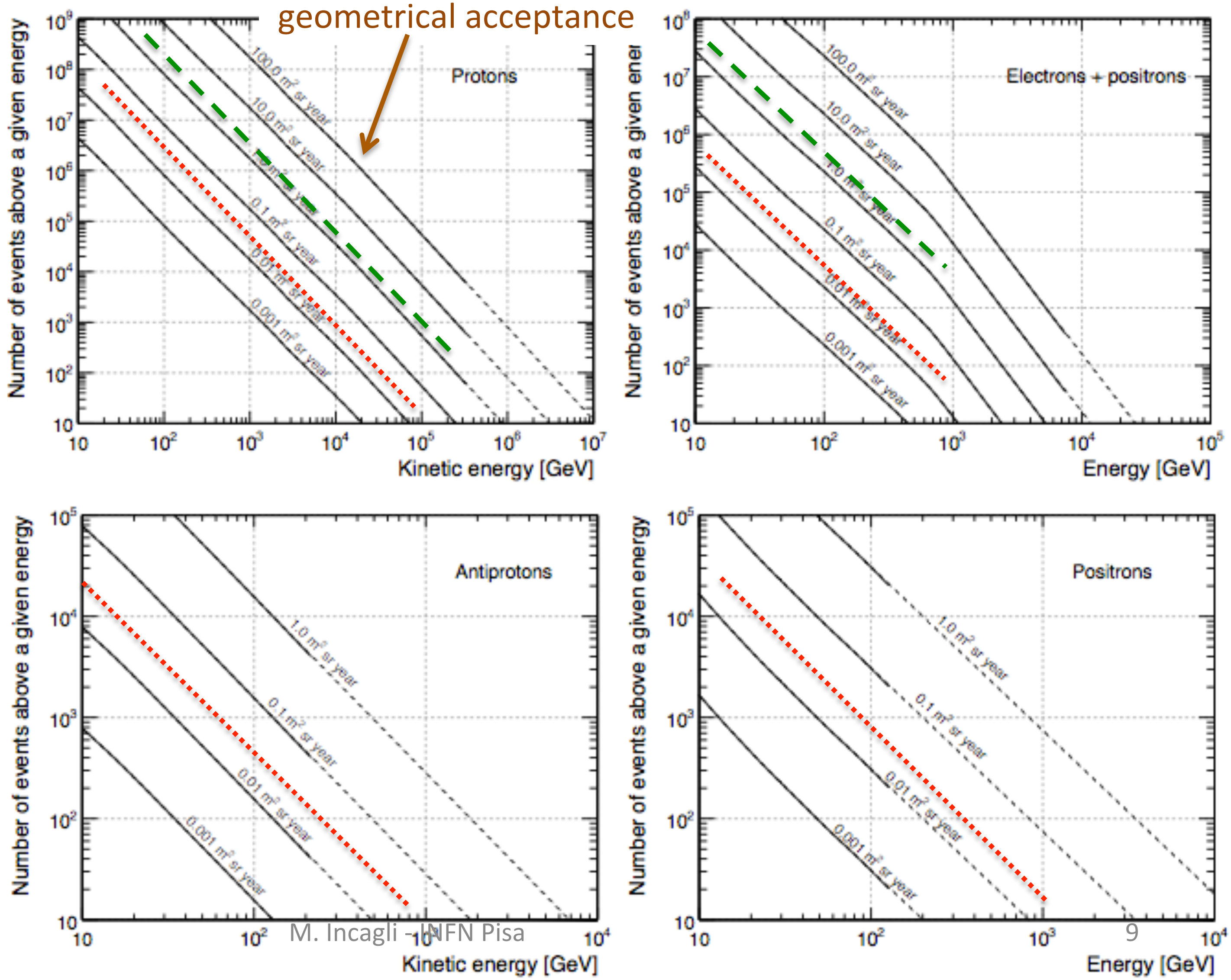
- *Spectrometers* : sign of the charge and momentum
  - **access to positrons and antiprotons**
  - access to CR isotopical composition
  - BUT: big magnets are heavy (permanent magnets) or hard to operate in space(superconducting magnets) → some R&D in progress
- *Pair-conversion telescope : gamma physics*
  - **dedicated tracking stage (>1X_0) in which $\gamma \to e^+e^-$**
  - much better Point Spread Function (PSF = angular resolution)
  - adds some complexity: reduce FOV or loose resolution
- *Calorimeters* discrimination of nuclei (Z measurement) and ep (electron-proton) separation
  - **maximum acceptance**
  - reach of high energies (~100-1000 TeV) for hadrons
  - precise (large statistics) measurement of $e^+ + e^-$ flux

Integral counts: fluxes rapidly decrease

lines: detector geometrical acceptance

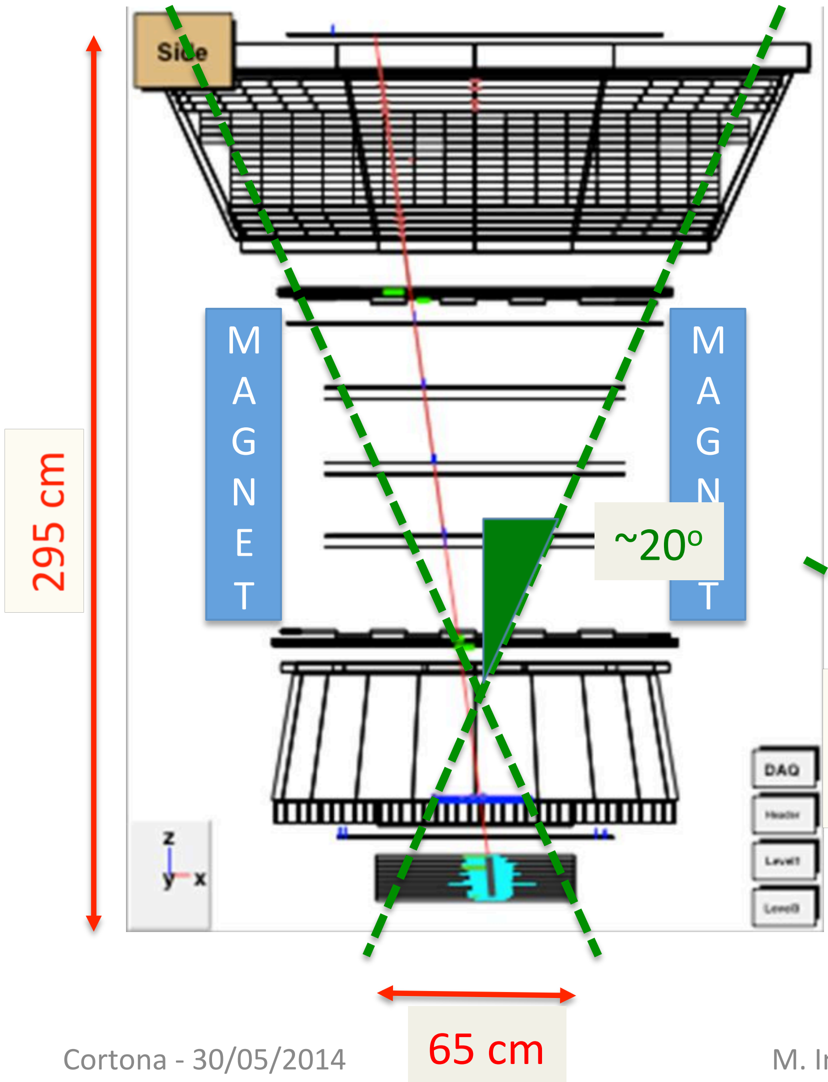
- - - Fermi

.... AMS02

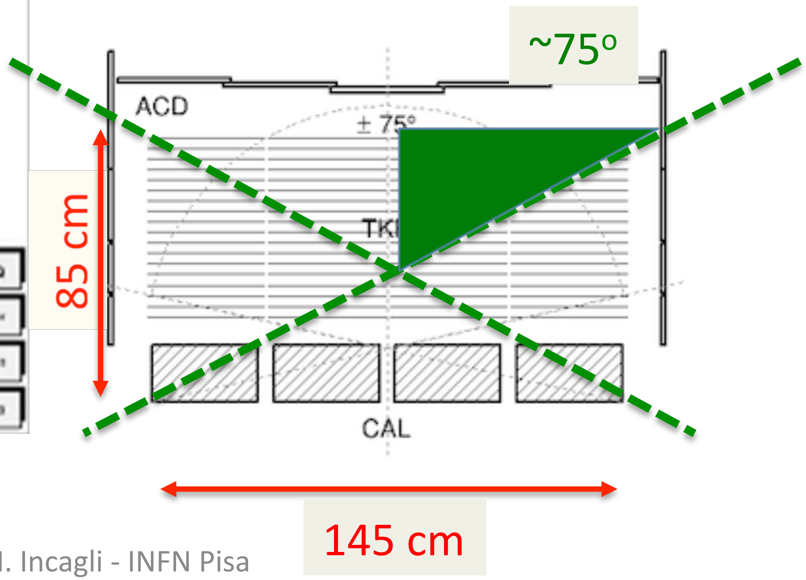


Magnet spectrometers only

Comparison AMS02-Fermi



- The 2 detectors in scale
- AMS02 maximizes redundancy, Fermi maximizes acceptance



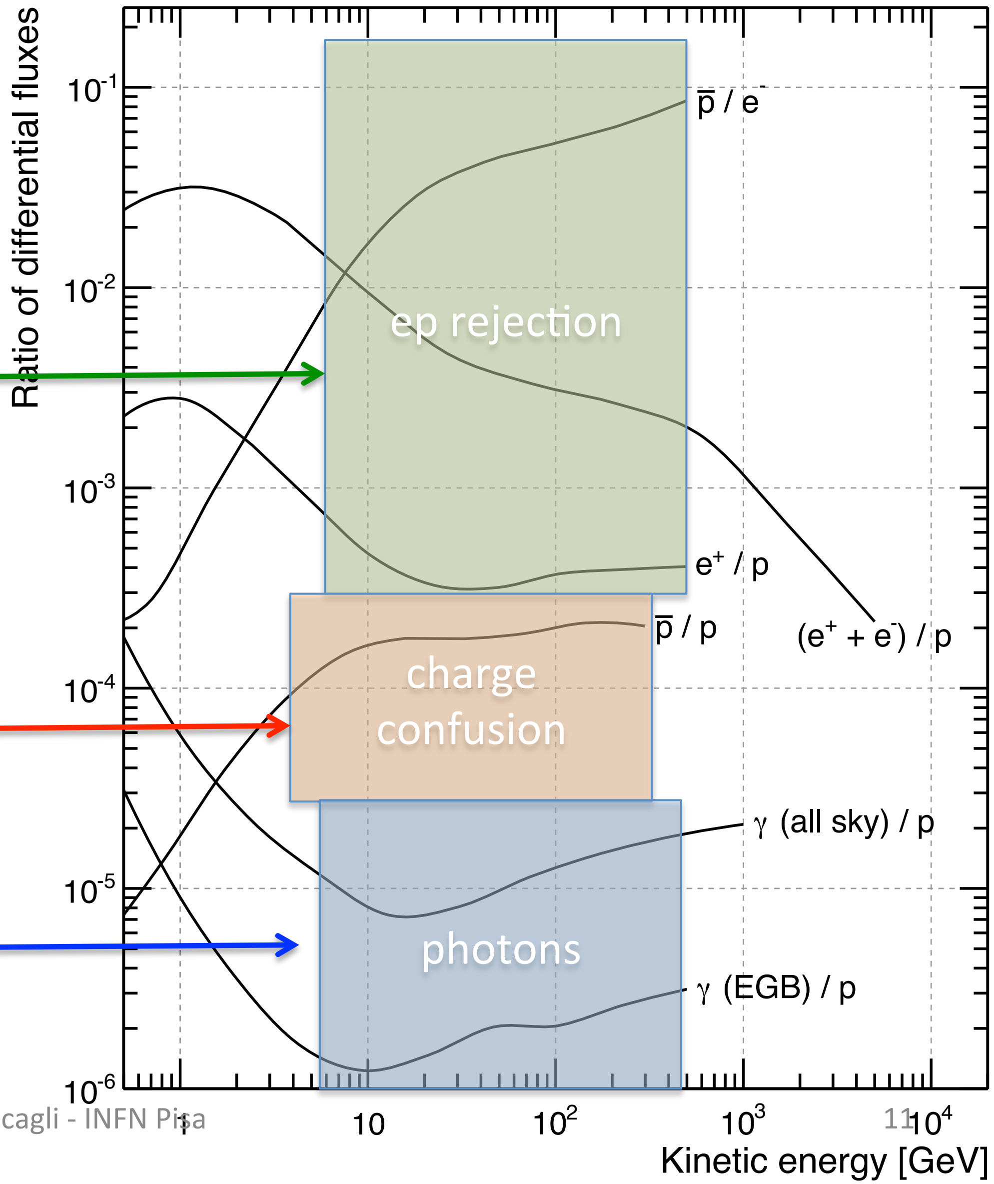
The issue of background

- But statistics is not the whole story:

✧ electrons (positrons) suffer from a proton background of 10^2 (10^4) times higher

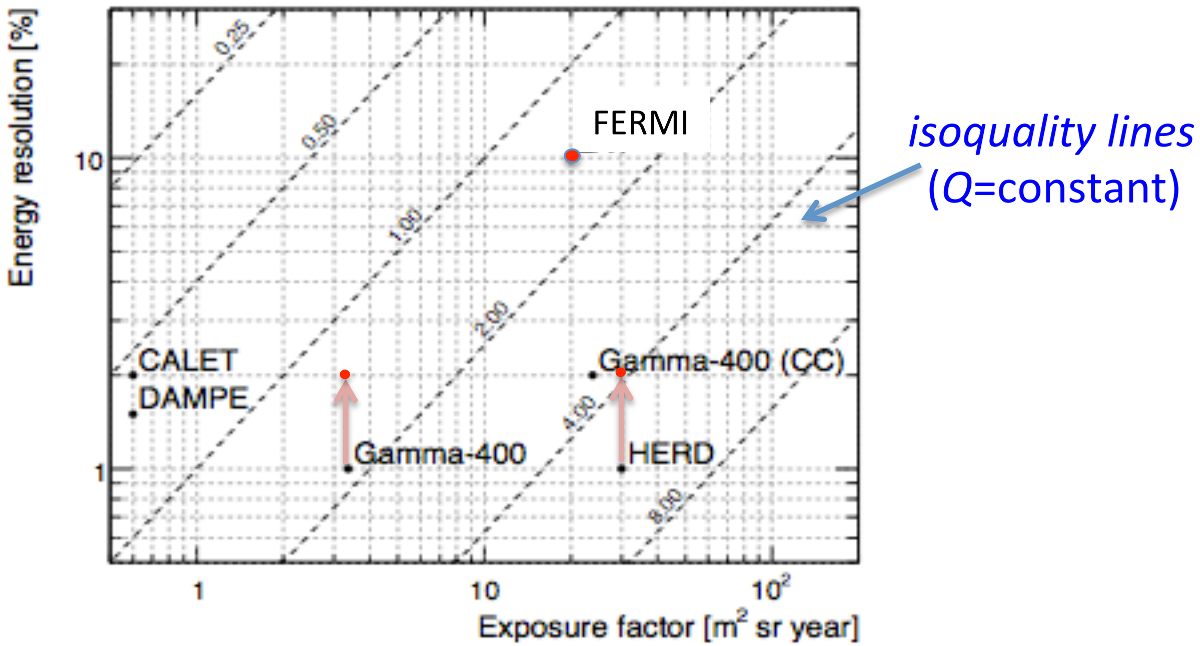
✧ proton background in anti-protons is ~10^4

✧ photons need rejection power of ~10^6



Many issues … I will discuss just one:
gamma line search

Gamma line sensitivity:
Fermi compared to next generation experiments



Credits to Luca Baldini (Fermi coll.) for the slide

- The basic figure of merit Q is

$$Q = \frac{n_s}{\sqrt{n_b}} \propto \sqrt{\frac{\mathcal{E}_f}{\sigma_E/E}}.$$

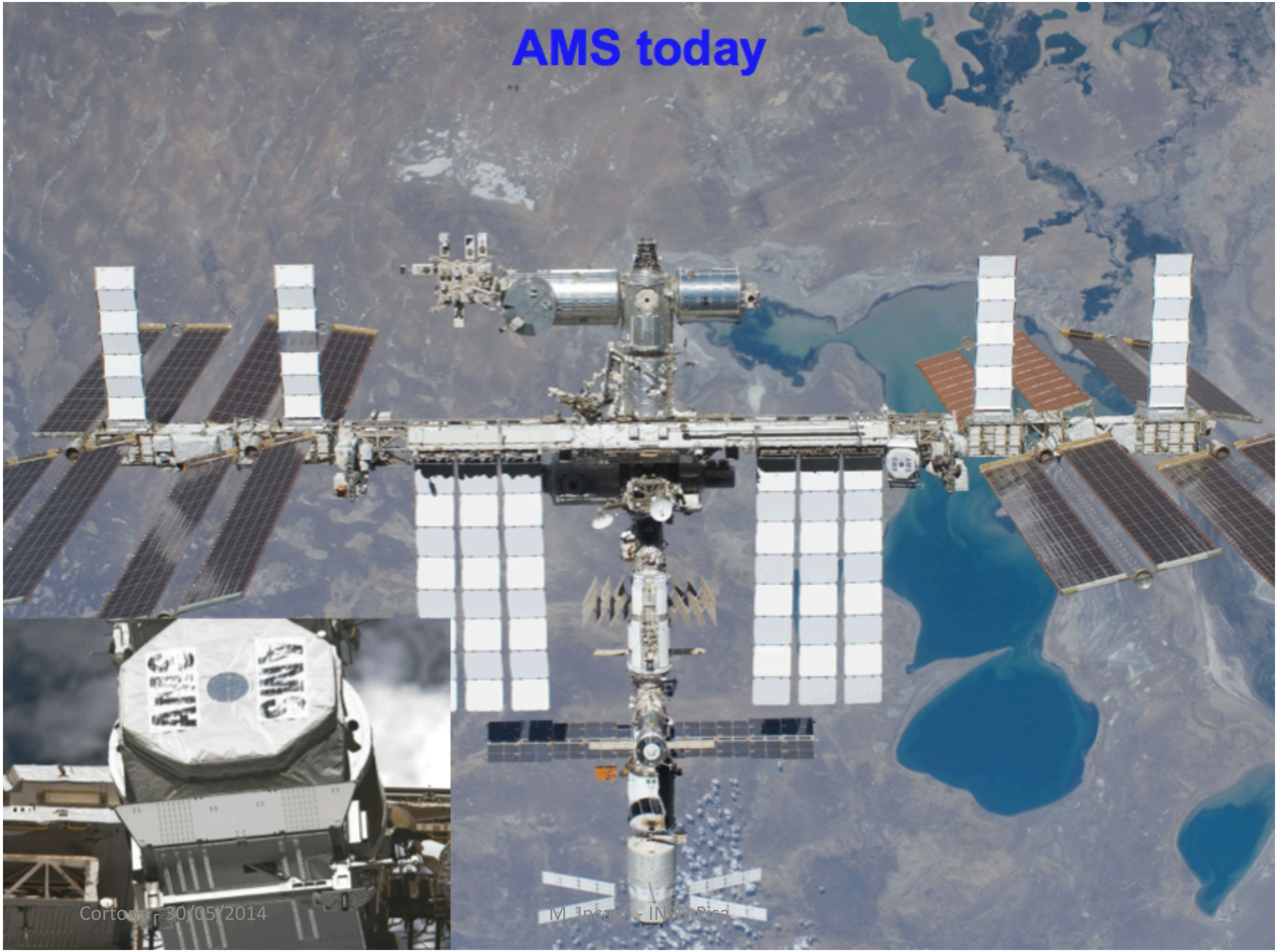
exposure factor

energy resolution

- Better energy resolution is good!
  - But only if you are not trading too much acceptance for that.

And now the 3 musketeers

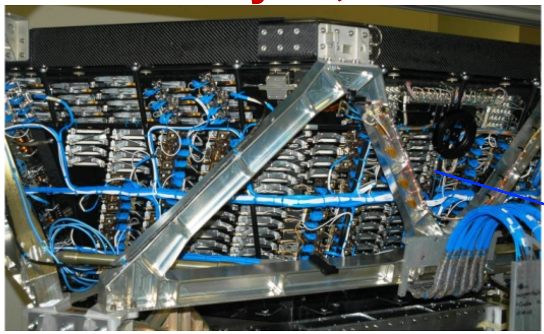
AMS today



AMS: A TeV precision, multipurpose spectrometer

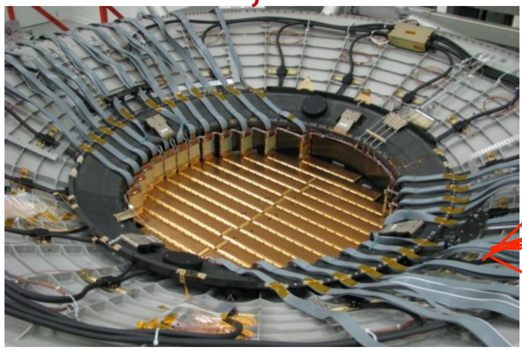
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TRD
Identify e^+, e^-

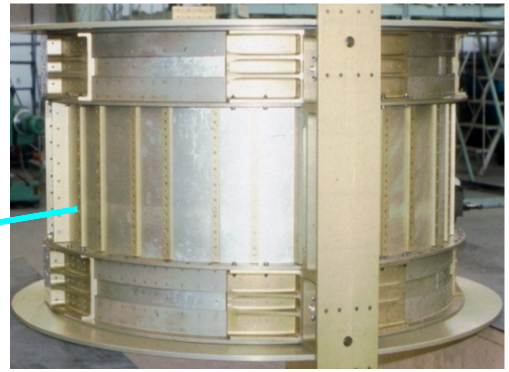


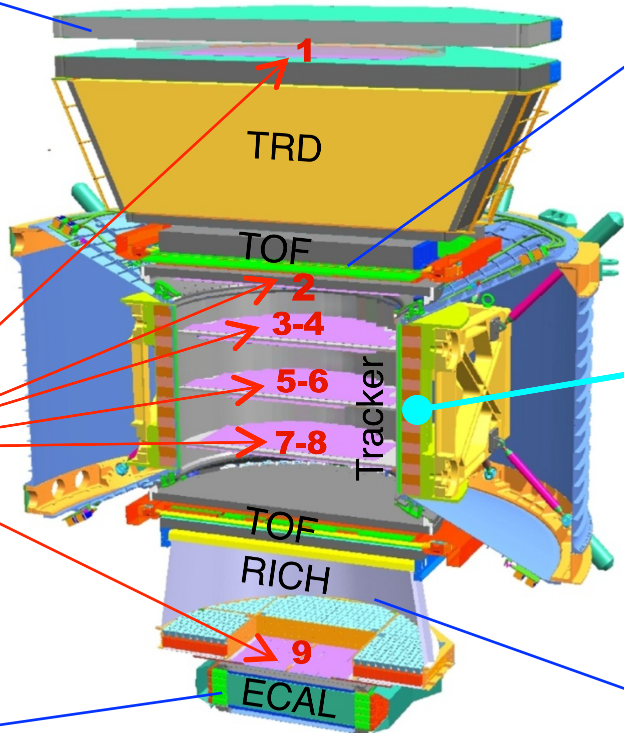
TOF
Z, E

Silicon Tracker
Z, P



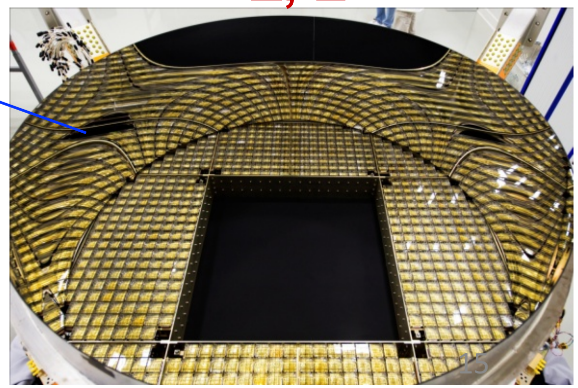
Magnet
±Z





ECAL
E of e^+, e^-, γ

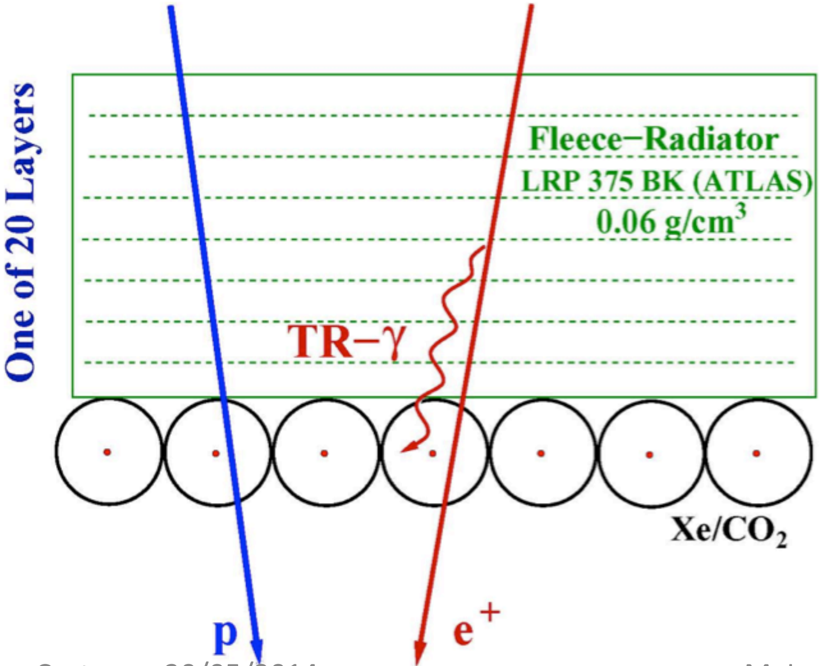
RICH
Z, E

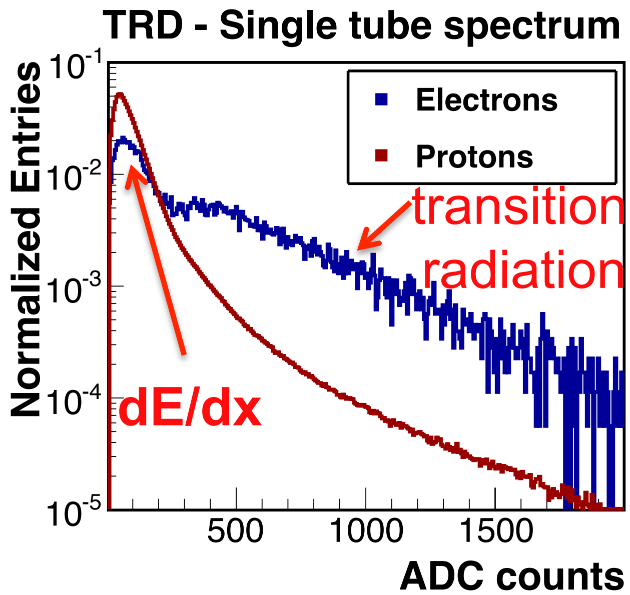


Z, P are measured independently by the Tracker, RICH, TOF and ECAL

AMS02 redundancy
Example 1: e/p rejection with TRD

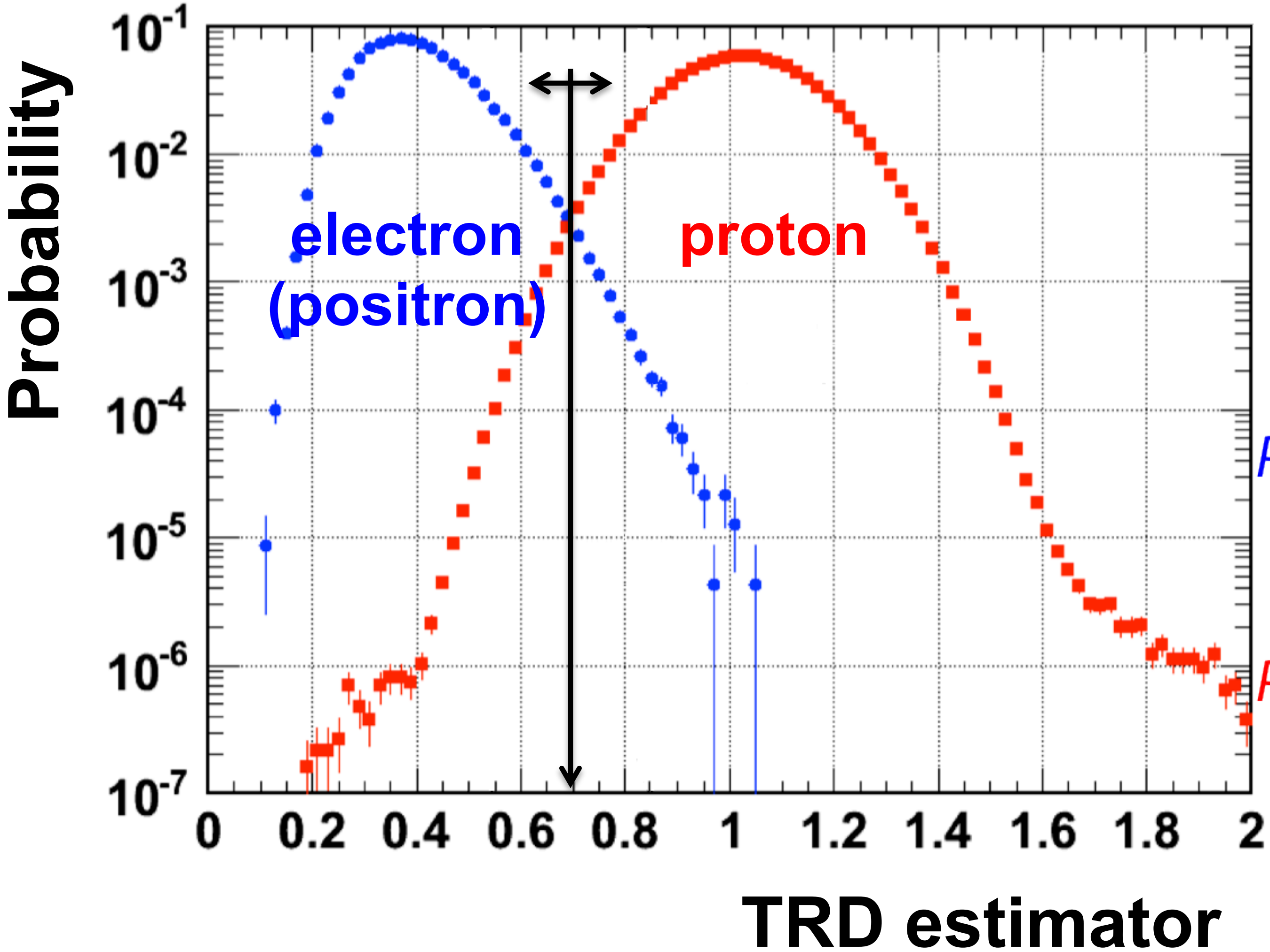
- electrons and protons are selected by looking at the *sign in the tracker and at ECAL shower shape*
- with this clean sample, *probability density functions* in each of the 20 TRD layers can be built from data





ep discrimination with TRD

TRD estimator = -ln(P_e/(P_e+P_p))



Normalized probabilities P_e and P_p

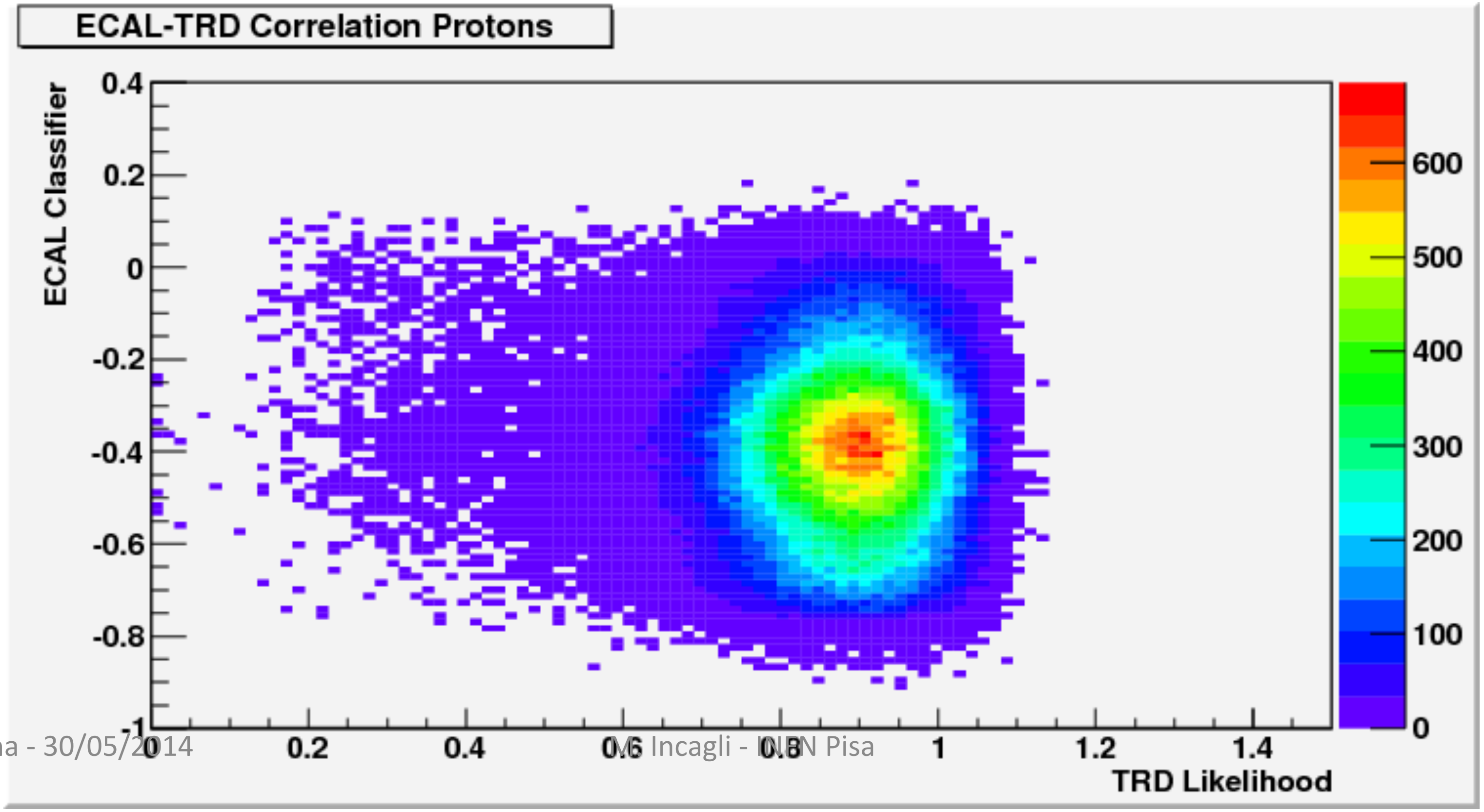
$$P_e = \sqrt[n]{\prod_{i}^{n} P_e^{(i)}(A)}$$

$$P_p = \sqrt[n]{\prod_{i}^{n} P_p^{(i)}(A)}$$

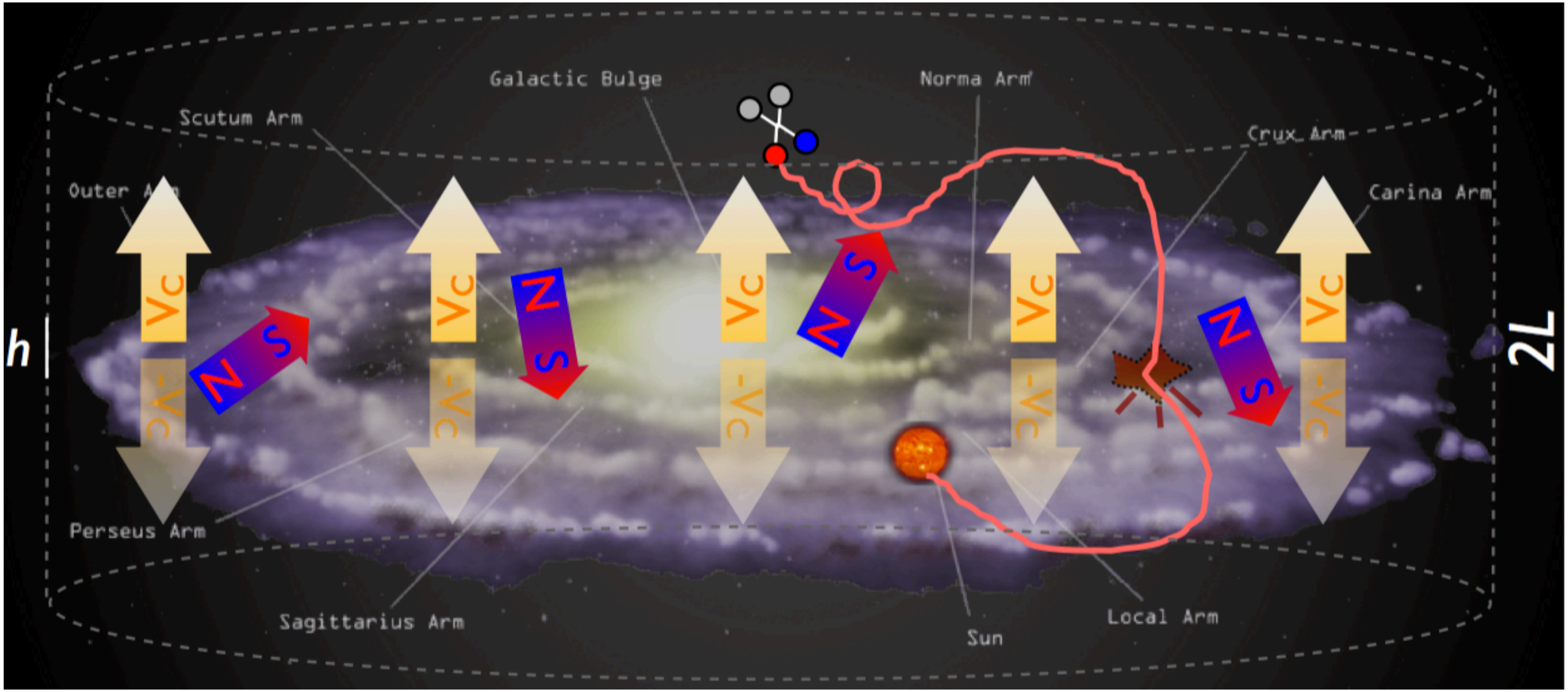
$P_e^{(i)}$ = electron pdf in layer *i* (total of 20 layers)

Are TRD and ECAL correlated?

- Correlation studied with pure (99.9%) primary proton beam of 400GeV/c at Cern SPS
- No sign of correlation observed

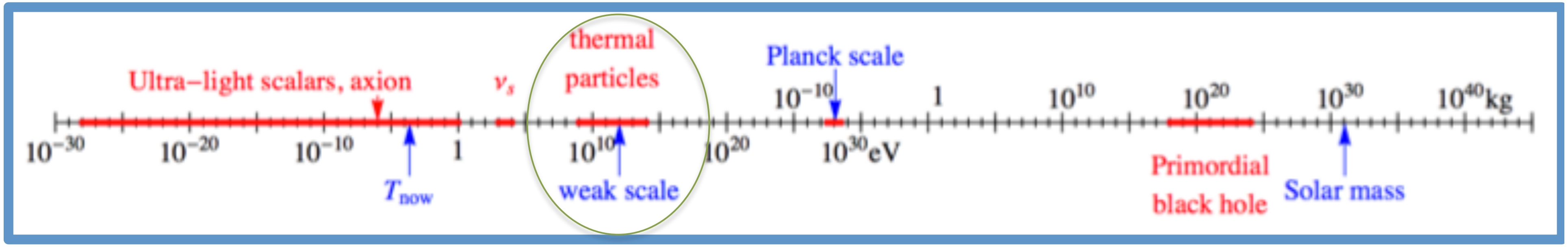


Physics case: Dark Matter indirect search



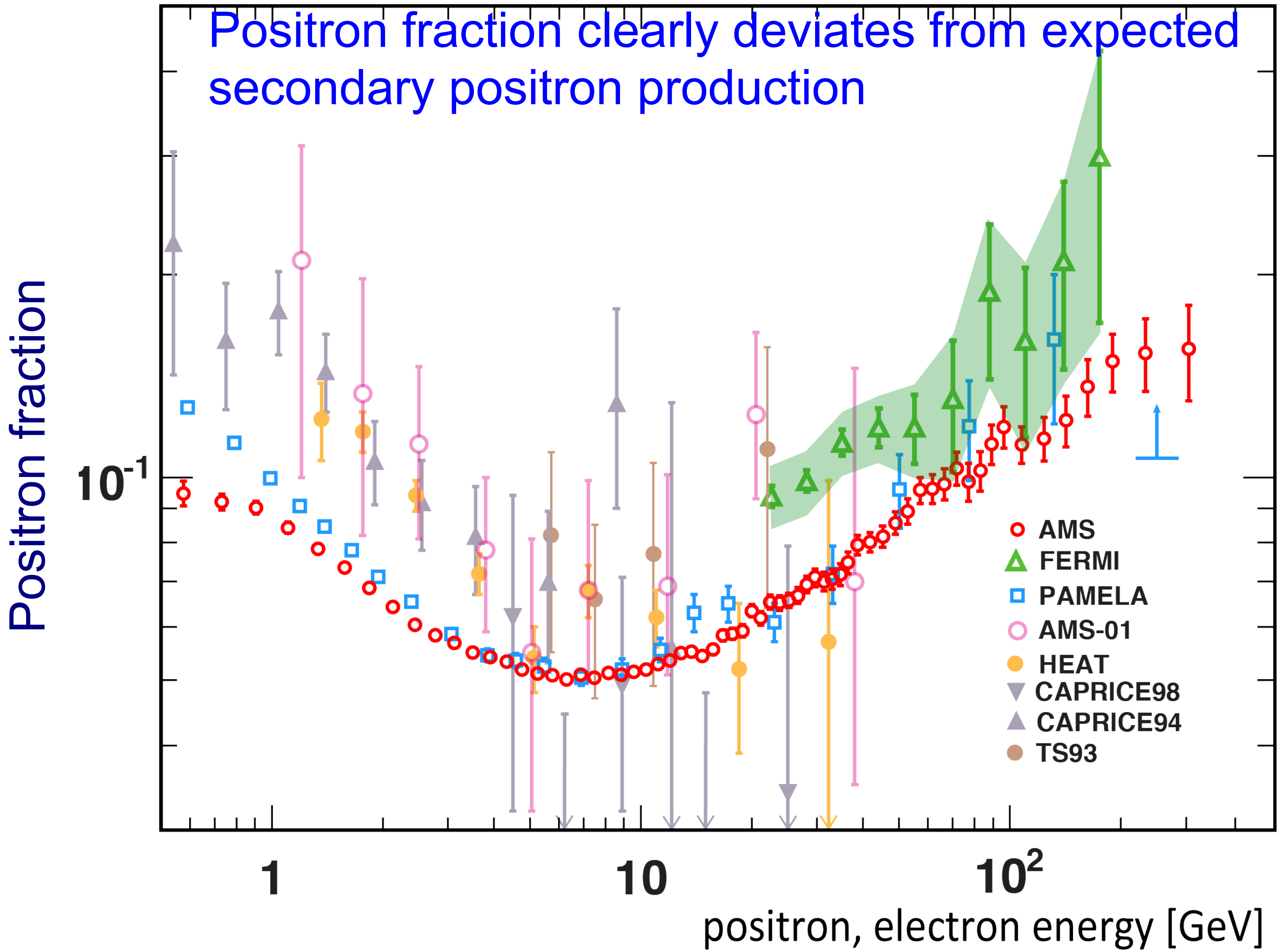
- DM annihilation → decay products, in particular anti-particles, observed by space experiments

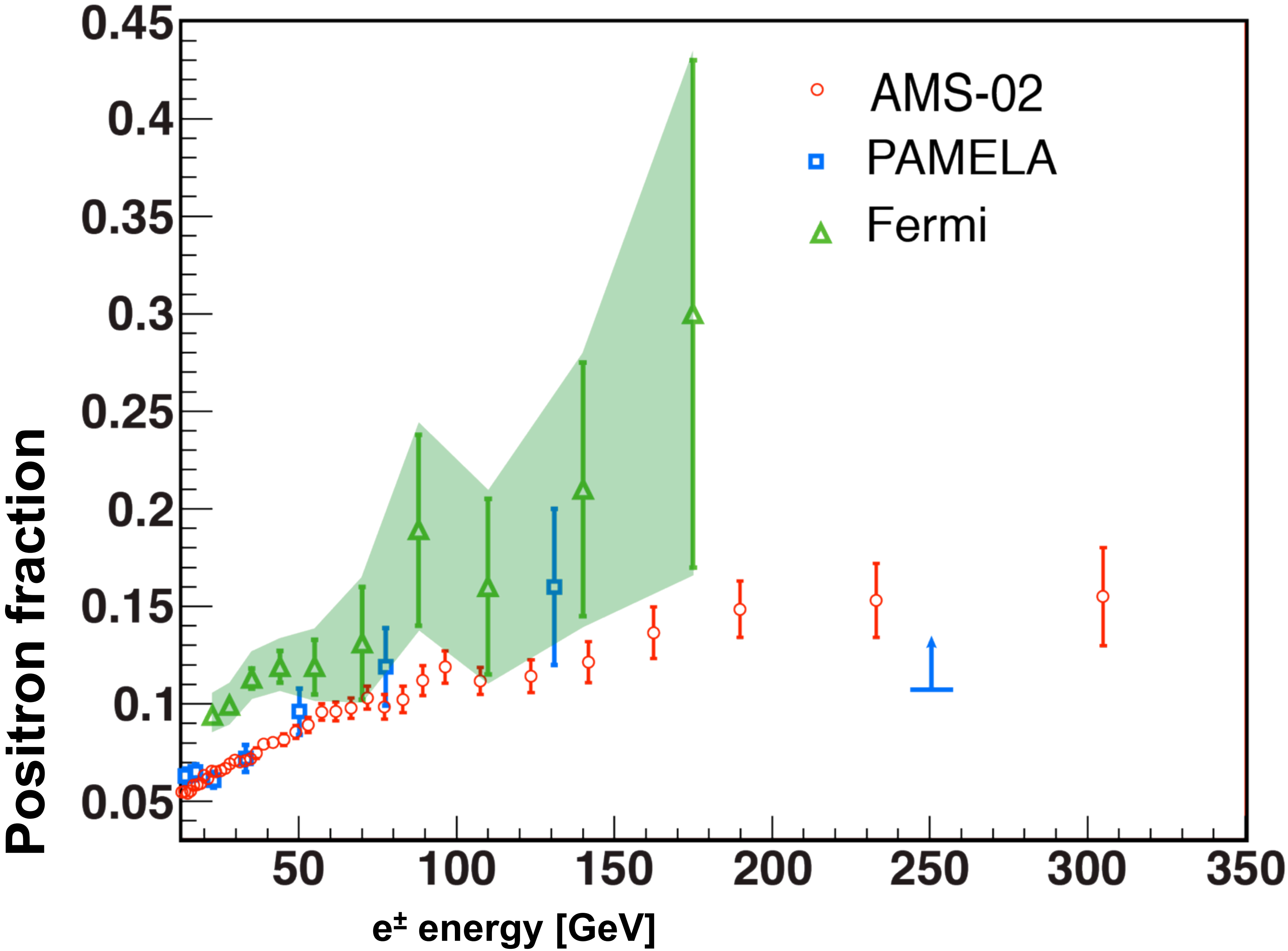
Dark Matter mass scale



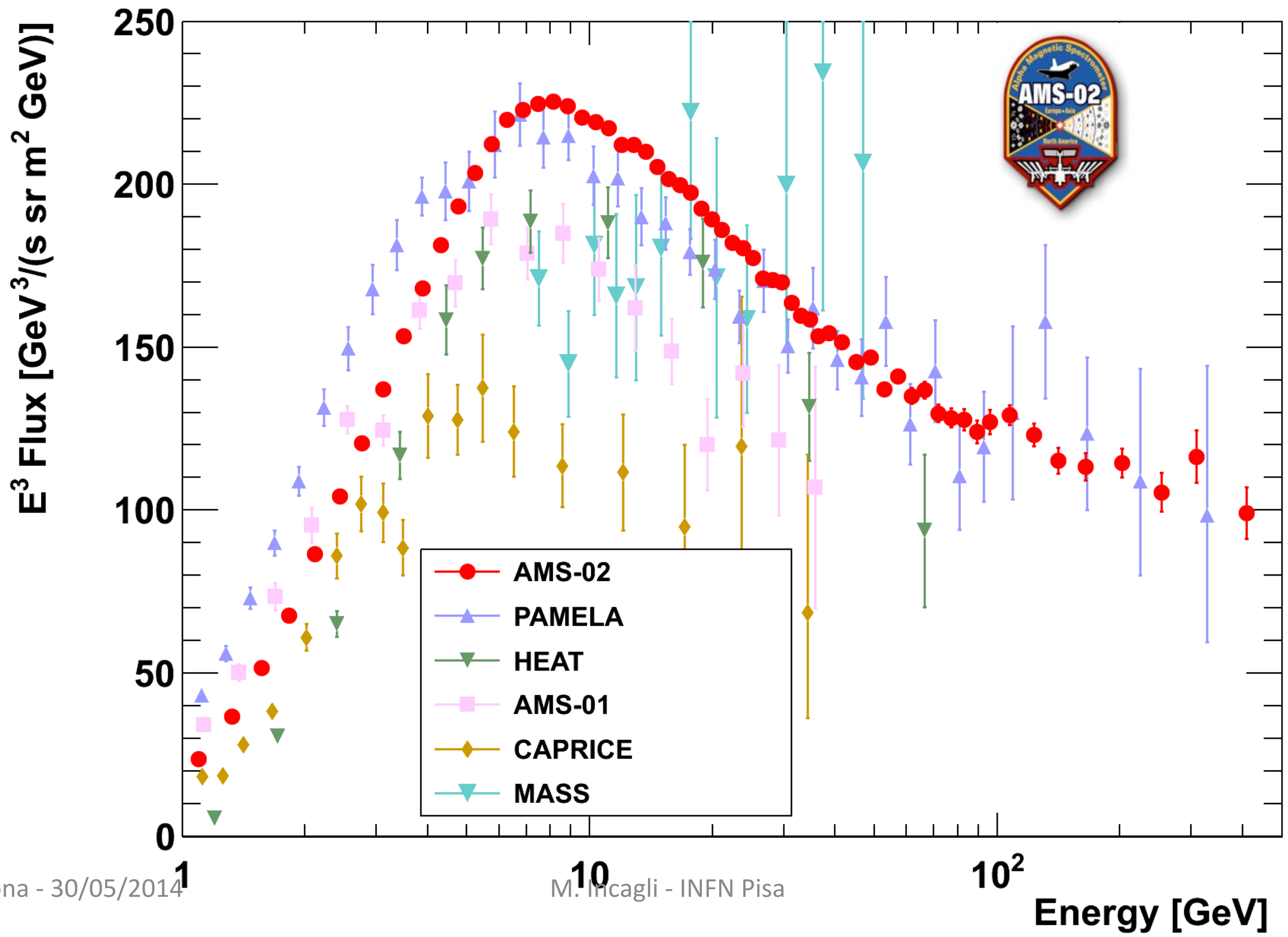
- Small problem: ~50 orders of magnitude to investigate!
- We "like" weak scale because it could solve, at the same time:
  - thermal cross section → $\sigma v \sim 10^{-26}\ cm^3 s^{-1}$
  - weak scale → supersimmetry

Hints of Dark Matter?



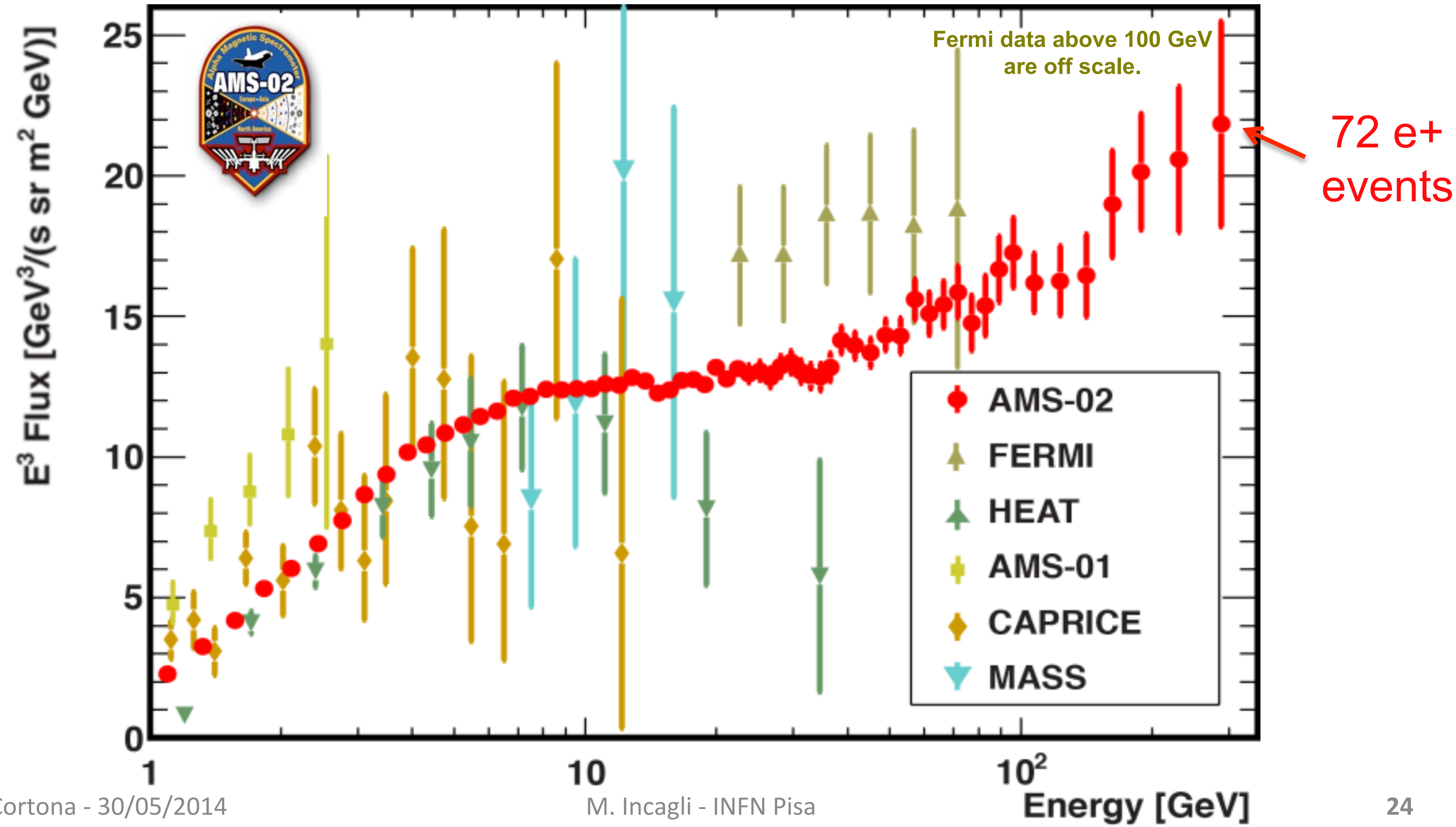

AMS-02
PAMELA
Fermi
Positron fraction
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
50
100
150
200
250
300
350
e± energy [GeV]

AMS-02 Electron Flux

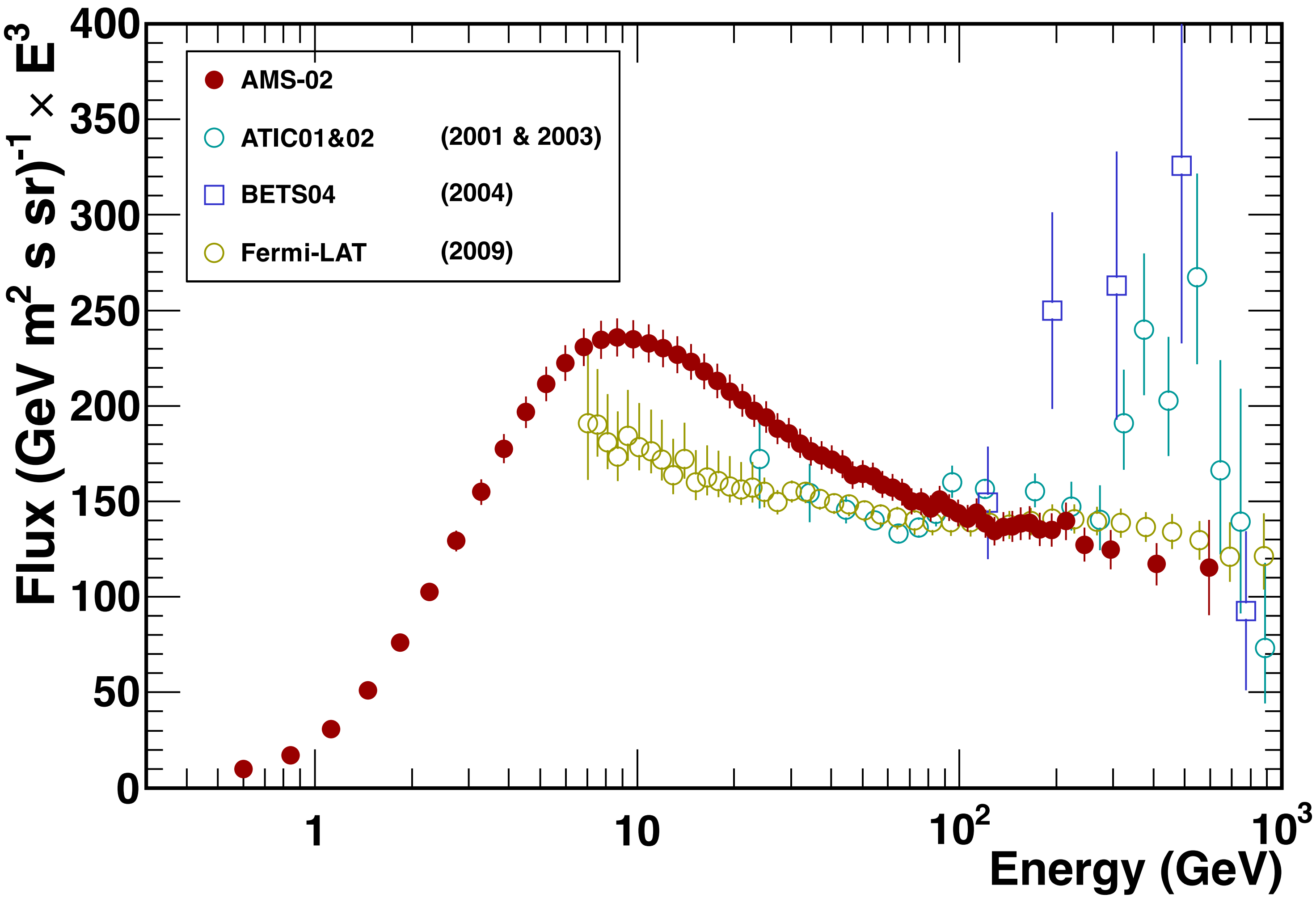


AMS-02 Positron Flux

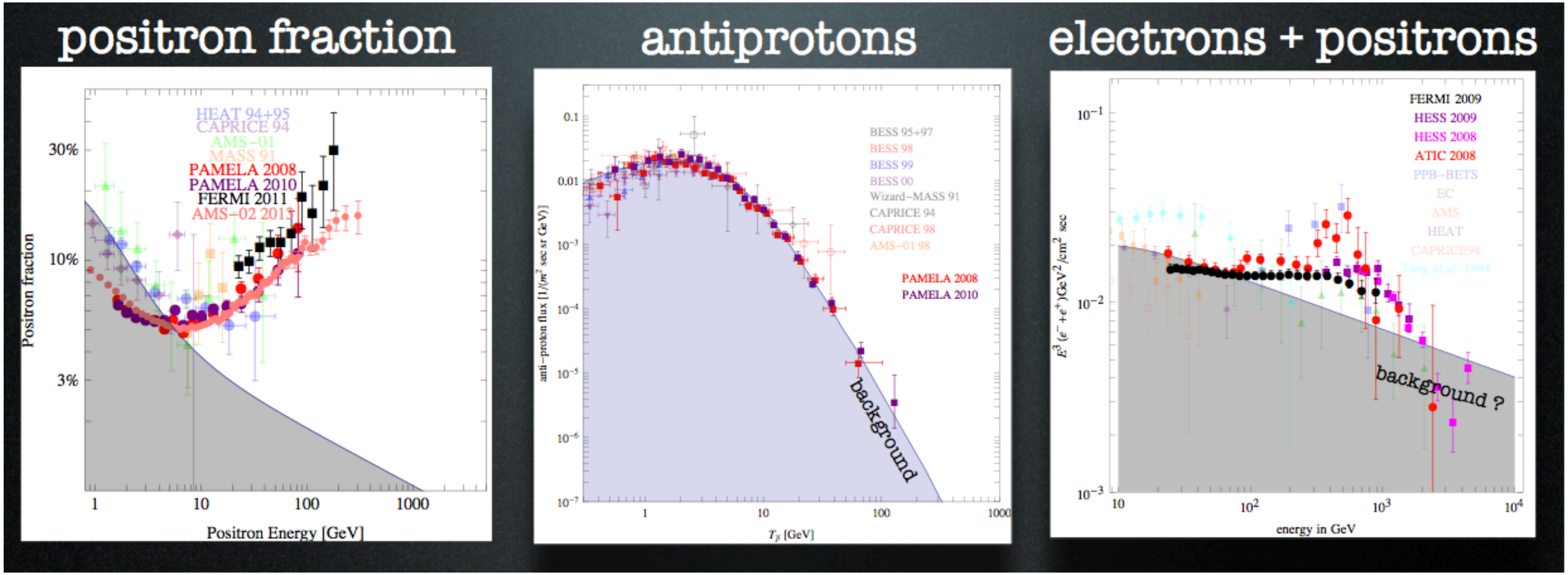
– The spectral index and its dependence on energy is clearly different from the electron spectrum.



The all electrons flux



Hints of Dark Matter?

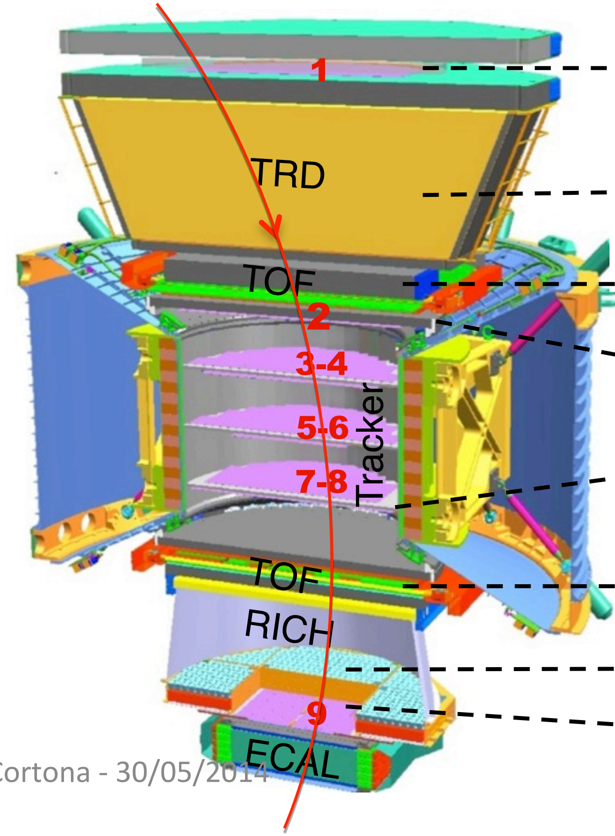


- Strong limits set by antiproton flux (PAMELA)
- Must invent *ad hoc* (not really "natural") theories
- AMS02 result on antiprotons eagerly expected
- It is important to constrain the background

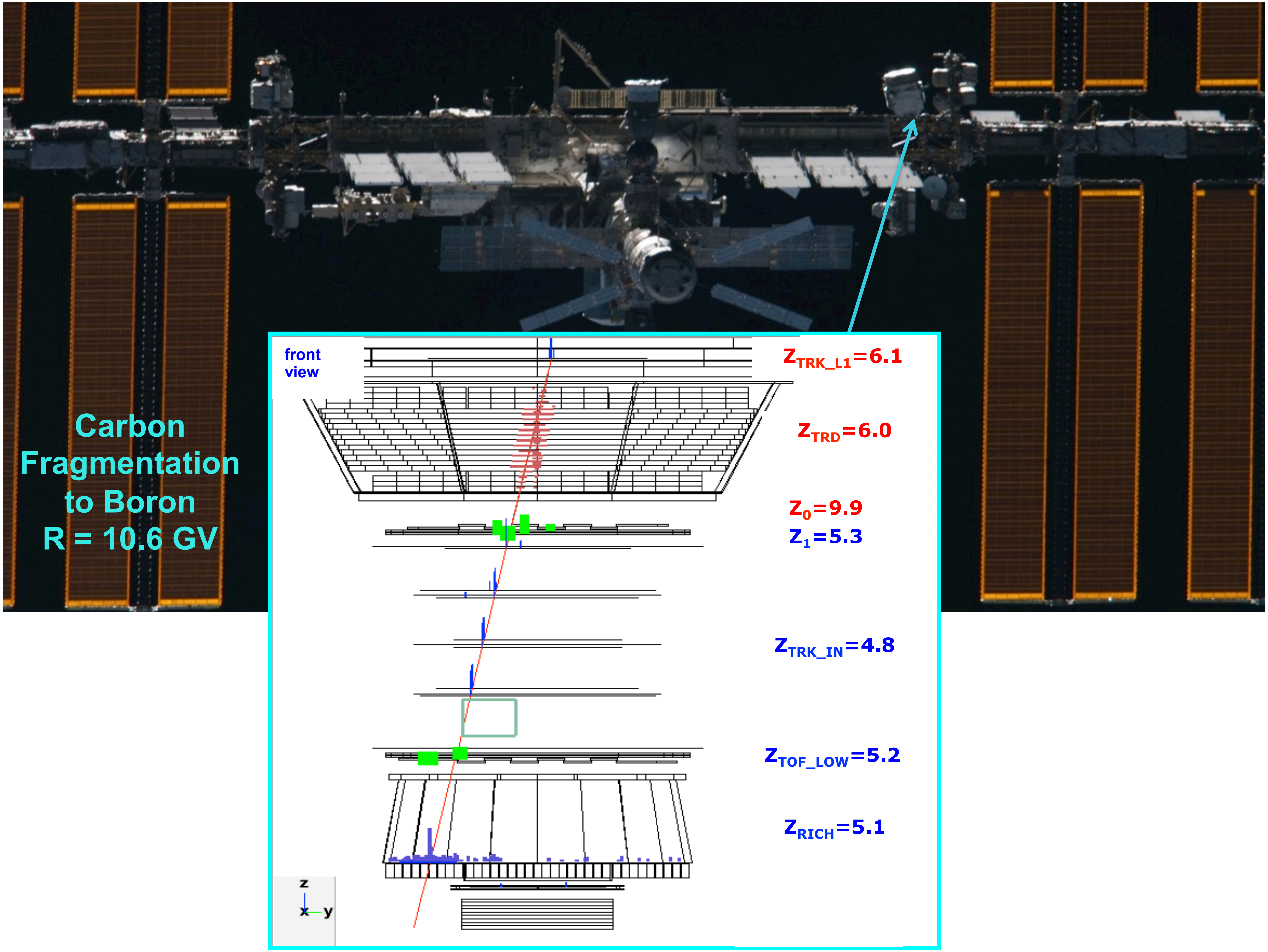
AMS redundancy
Example 2: Boron-to-Carbon ratio

- **Carbon : primary particle**
- **Boron : secondary particle produced in interactions of C with ISM (InterStellar Medium)**

AMS: Multiple Independent Measurements of the Charge (|Z|)

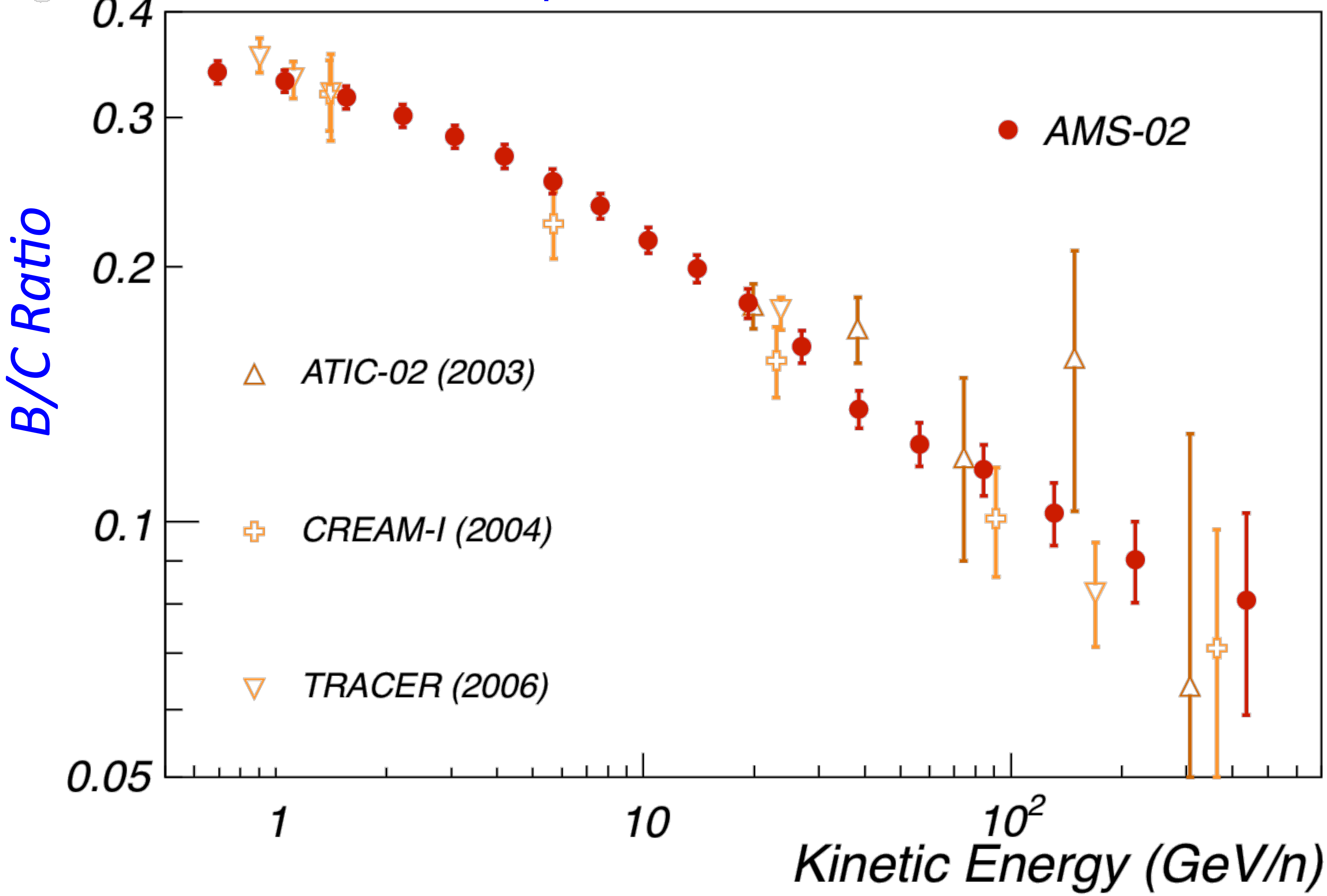


	Carbon (Z=6) ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30


Carbon
Fragmentation
to Boron
R = 10.6 GV
front
view
$Z_{TRK\_L1}=6.1$
$Z_{TRD}=6.0$
$Z_0=9.9$
$Z_1=5.3$
$Z_{TRK\_IN}=4.8$
$Z_{TOF\_LOW}=5.2$
$Z_{RICH}=5.1$
z
x
y

Boron-to-Carbon ratio

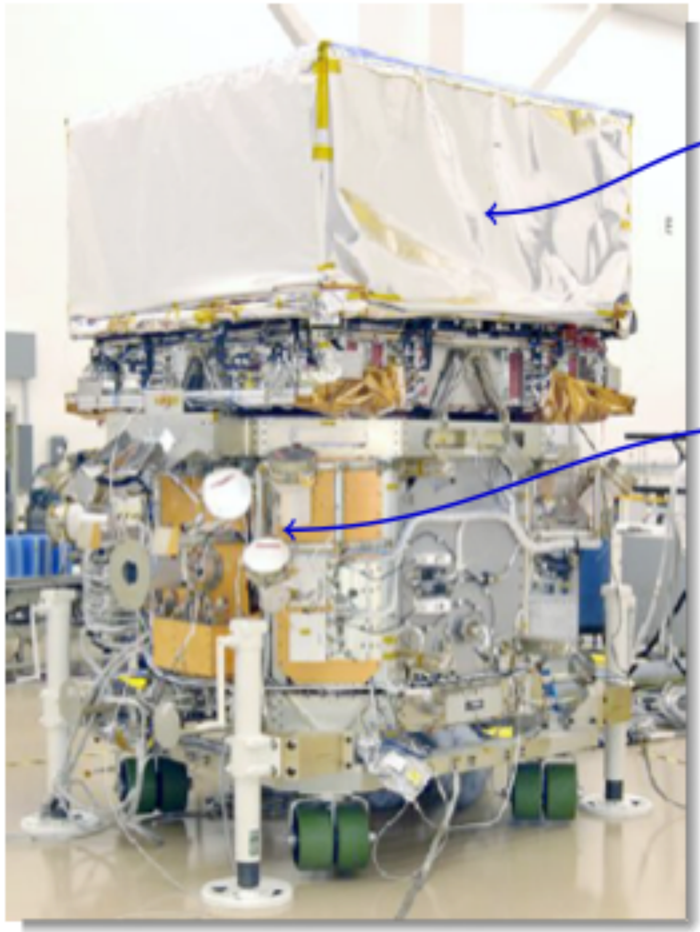
comparison with recent data



Future prospects

- final analyses (plots available 2° week of June):
  - total electrons < 700/1000 GeV
  - electron flux < 700 GeV
  - positron flux <500GeV
- Close to completion
  - proton flux <1.8TeV
- next in line:
  - He, B/C → end of the summer
  - fluxes of B, C, O → end of summer
  - light nuclei → ?
- mostly wanted: antiprotons ... no prediction;
  - hard, have to do it carefully!

Fermi

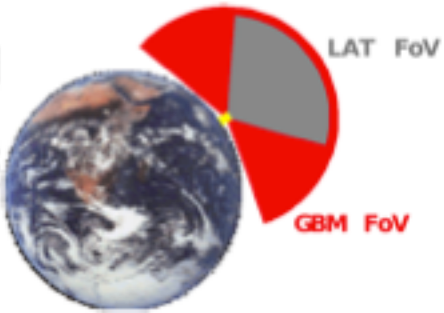


Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–300+ GeV.
- Sees 20% of the sky at any time (the full sky for half a hour every 3 hours).

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–30 MeV.



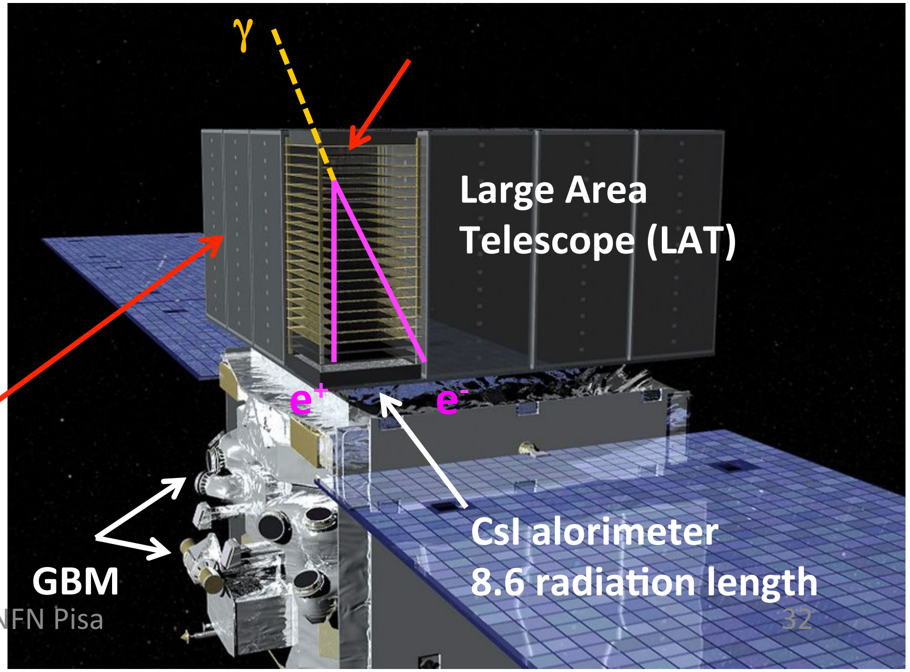
Fermi LAT

- Pair-conversion telescope
  - good background rejection due to "clear" γ-ray signature
  - (also sensitive to CR electrons)
- Tracker: pair conversion, tracking
  - angular resolution is dominated by multiple scattering below ~GeV
- Calorimeter: 8.6 X0 for perpendicular incidence
  - use shower profile to compensate for the leakage

Si Tracker
70 m^2, 228 μm pitch
~0.9 million channels

energy band: 20MeV to >300 GeV
effective area: >8000 cm2
FOV: >2.4 sr
angular resolution: ~0.1 deg
energy resolution: 5-10%

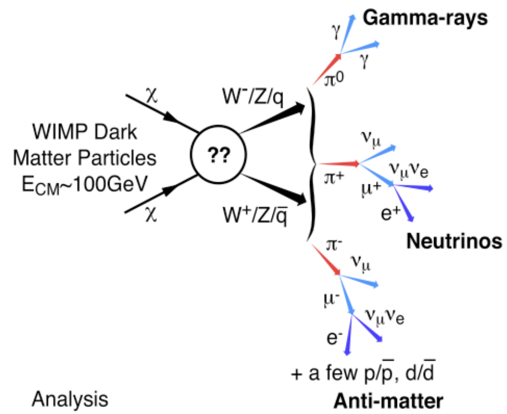
Anti-coincidence Detector
Segmented scintillator tiles



Dark Matter (DM) Search with γ-rays

(I will skip DM search from CR electron/positron)

- Gamma-rays may encrypt the DM signal



Gamma Ray Flux
(measured by Fermi-LAT)

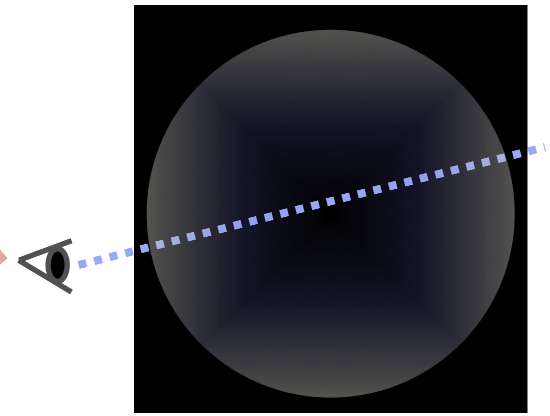
Particle Physics
(photons per annihilation)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

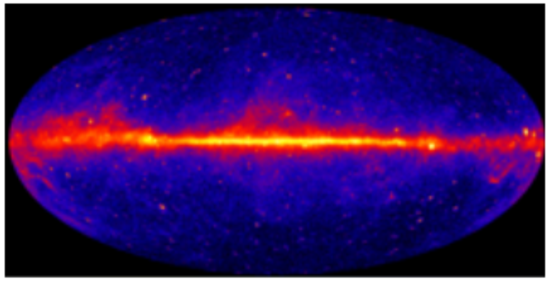
DM Distribution
(line-of-sight integral)



DM Search Strategies with γ-rays

- Spatial signature

Fermi-LAT data



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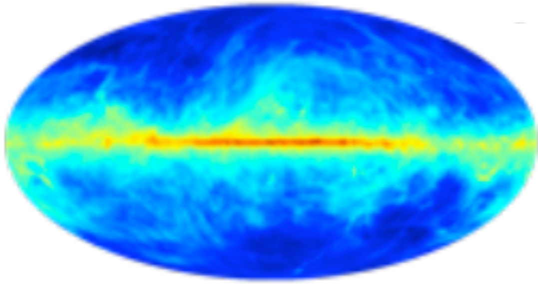
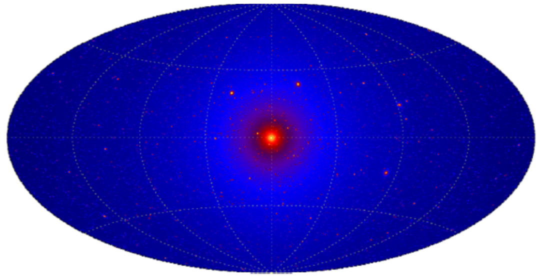
Galactic Diffuse, Sources, isotropic



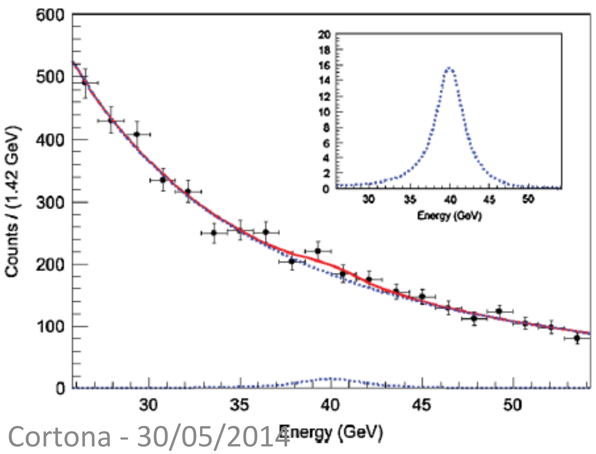
+

DM signal (e.g., MW halo)?



- Spectral signature

DM signal (e.g., line)?



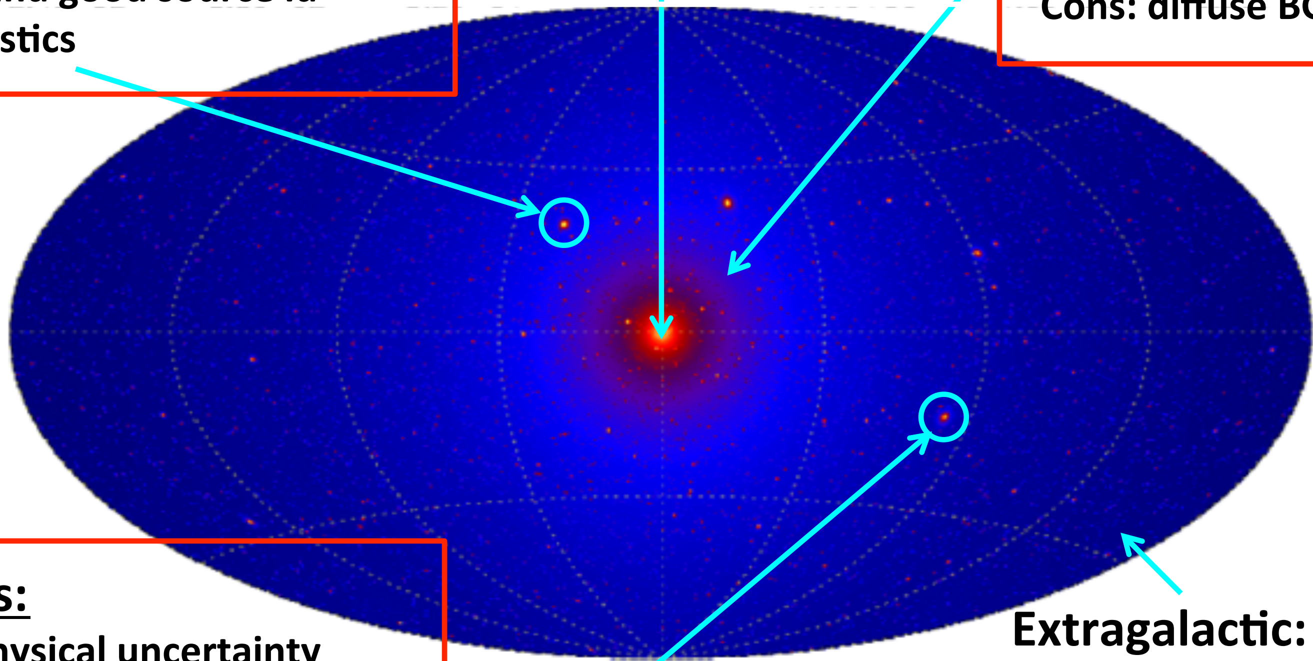
Good understanding of the Galactic diffuse emission and of the instrument is crucial

DM Search Strategies with γ-rays

Galactic Center:
Pros: Good statistics
Cons: confusion, diffuse BG

Satellites:
Pros: Low BG and good source id
Cons: low statistics

MW halo:
Pros: very good statistics
Cons: diffuse BG



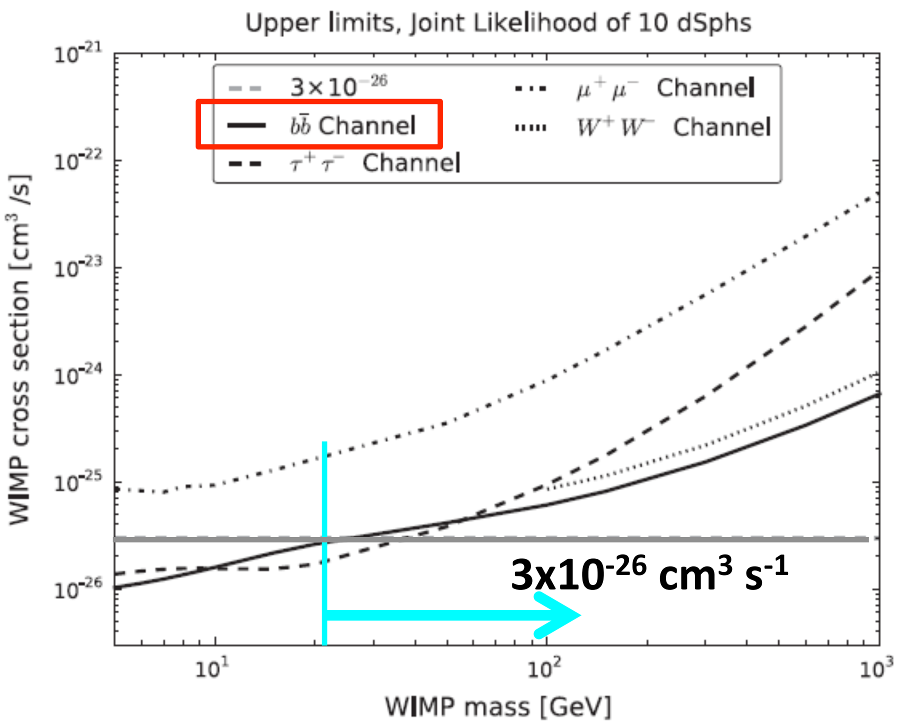
Spectral lines:
Pros: no astrophysical uncertainty (Smoking gun)
Cons: low statistics

Clusters:
Pros: low BG and good source id
Cons: low statistics, astrophysical uncertainties

Extragalactic:
Pros: very good statistics
Cons: diffuse BG, astrophysical uncertainties

1) Satellites: Dwarf galaxies

- Stacking analysis using 10 dSphs and 2 years data
  - conservative limit on DM cross section (no "boost factor")



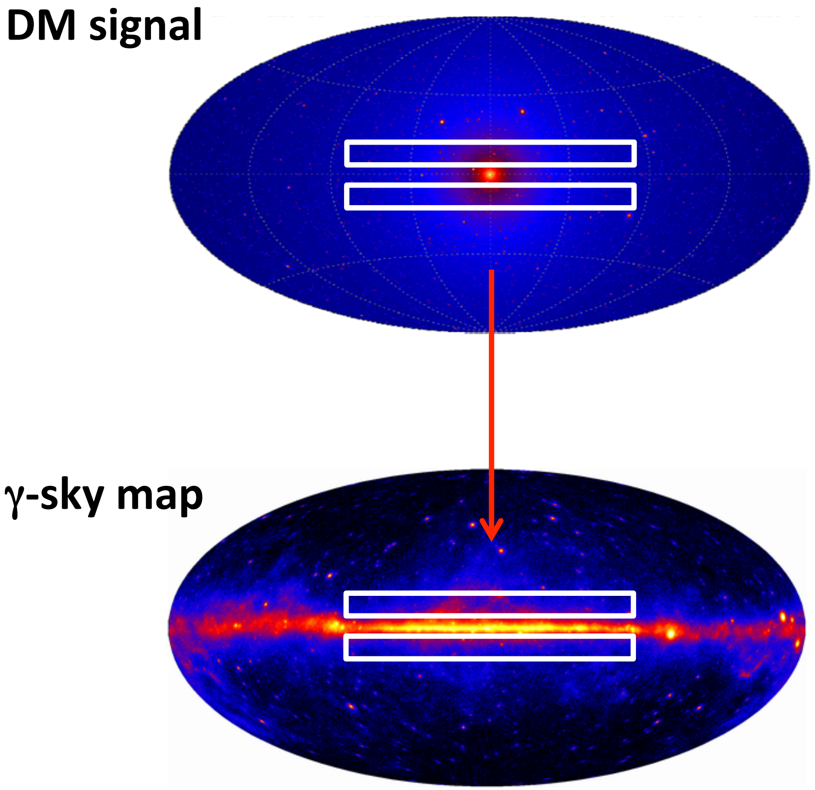
Name	l (degree)	b (degree)	d (kpc)	$\overline{\log_{10}(J)}$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}]$)	σ
Bootes I	358.08	69.62	60	17.7	0.34
Carina	260.11	−22.22	101	18.0	0.13
Coma Berenices	241.9	83.6	44	19.0	0.37
Draco	86.37	34.72	80	18.8	0.13
Fornax	237.1	−65.7	138	17.7	0.23
Sculptor	287.15	−83.16	80	18.4	0.13
Segue 1	220.48	50.42	23	19.6	0.53
Sextans	243.4	42.2	86	17.8	0.23
Ursa Major II	152.46	37.44	32	19.6	0.40
Ursa Minor	104.95	44.80	66	18.5	0.18

Ackermann+11, PRL 107, 241302

M_{WIMP}>=20 GeV to satisfy <σv>=3×10^{-26} cm^3 s^{-1}

2) Milky Way DM Halo

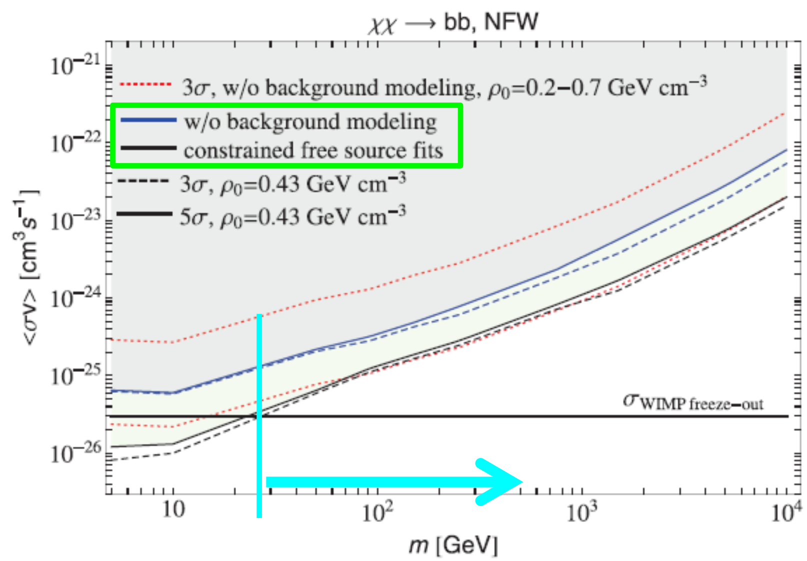
- Another recent and complementary DM search for MW halo
  - Search for continuous emission from DM annihilation/decay in the smooth MW halo

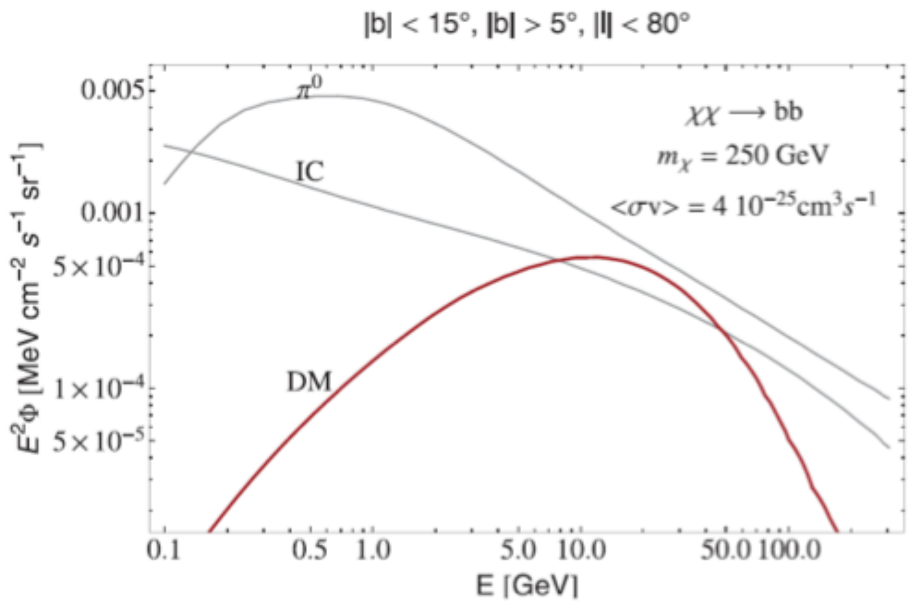


- **Analyze bands 5deg off the plane**
  - **decrease astrophysical BG**
  - **mitigate uncertainty from inner slope of DM density profile**
  - **fit DM source and astrophysical emission simultaneously**

Constraints on DM Model

- Modeling the astrophysical emission improves DM constraints
- w/ astrophysical BG, the limit constrains the thermal relic cross section for WIMP with mass > 30 GeV (comparable to dSphs)





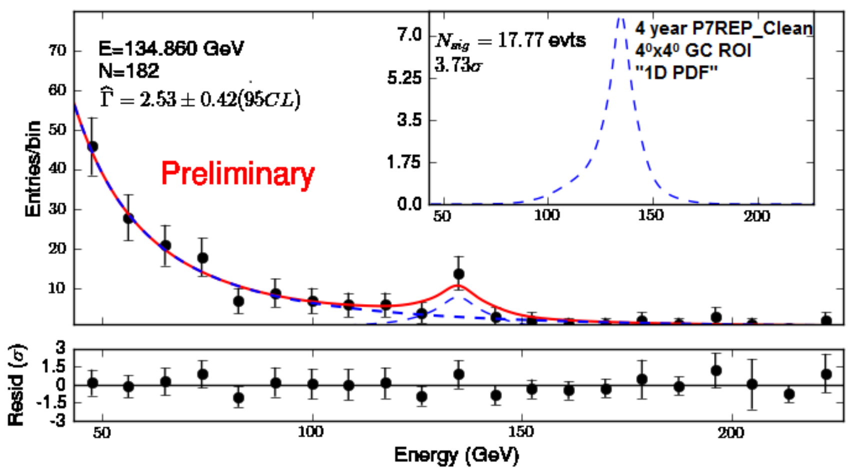
Ackermann+12, ApJ 761, 91

Gamma line search

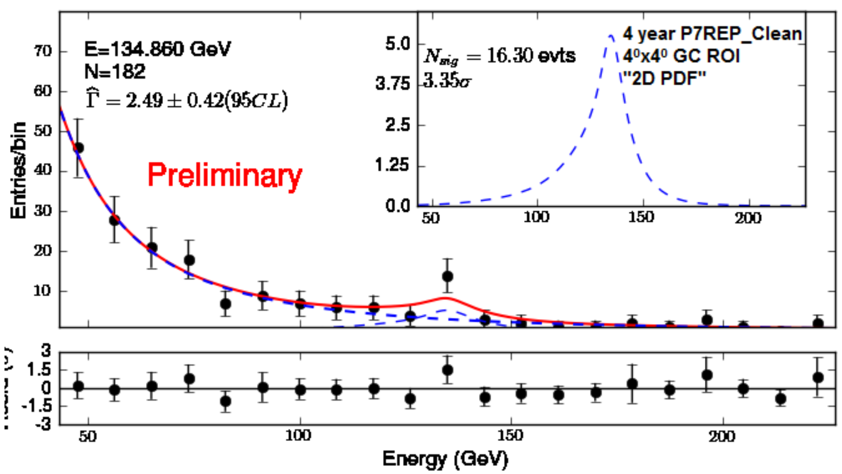
Evolution of line-like Feature near 135 GeV:

1. 1D PDF, reprocessed data (better energy calibration)
   – 3.7σ (local) at 135 GeV
2. 2D PDF, reprocessed data
   – 3.4σ (local) at 135 GeV (Energy dispersion in data is narrower than expected when P_E is taken into account)
   – <2σ global

1.



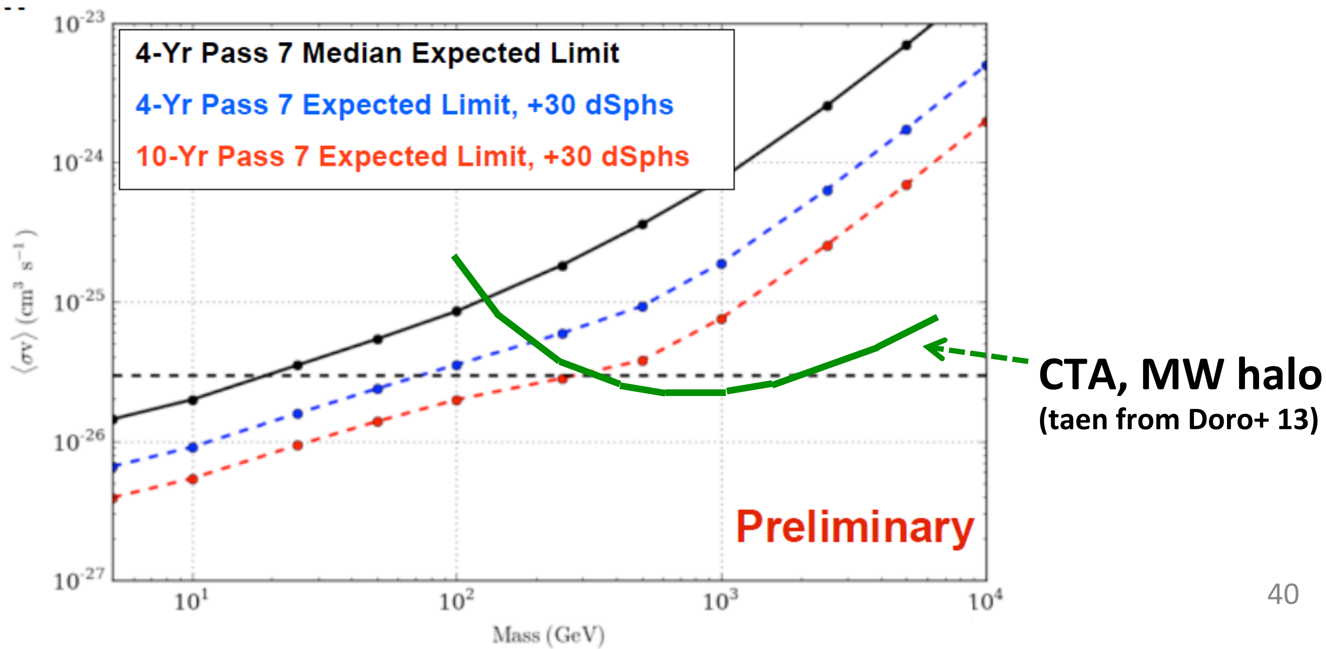
2.



4 year data - Look in 4x4deg^2 at GC

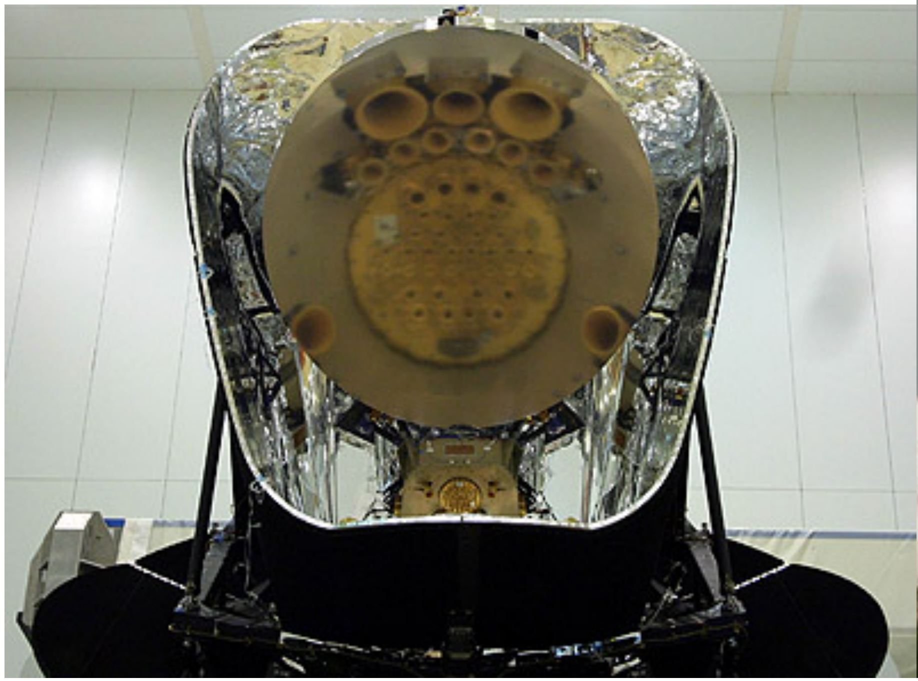
Fermi Future Prospects in DM search

- Dwarfs will remain a prime target (halo analysis: close match)
  - increased observation time
  - discovery of new dwarfs
  - sensitive to higher energies
- Next generation Cherenkov Telescope (e.g., CTA) will extend the limit to higher WIMP masses
- Extend significance of line search

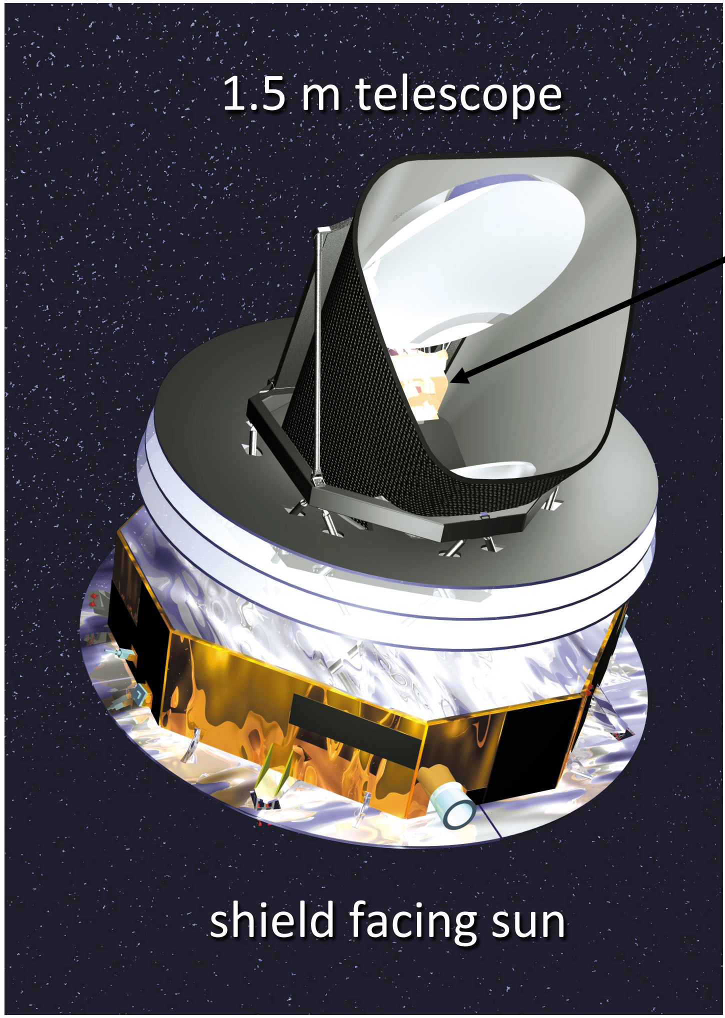


The Planck experiment

launch 14 May 2009



The Planck satellite



2 instruments:

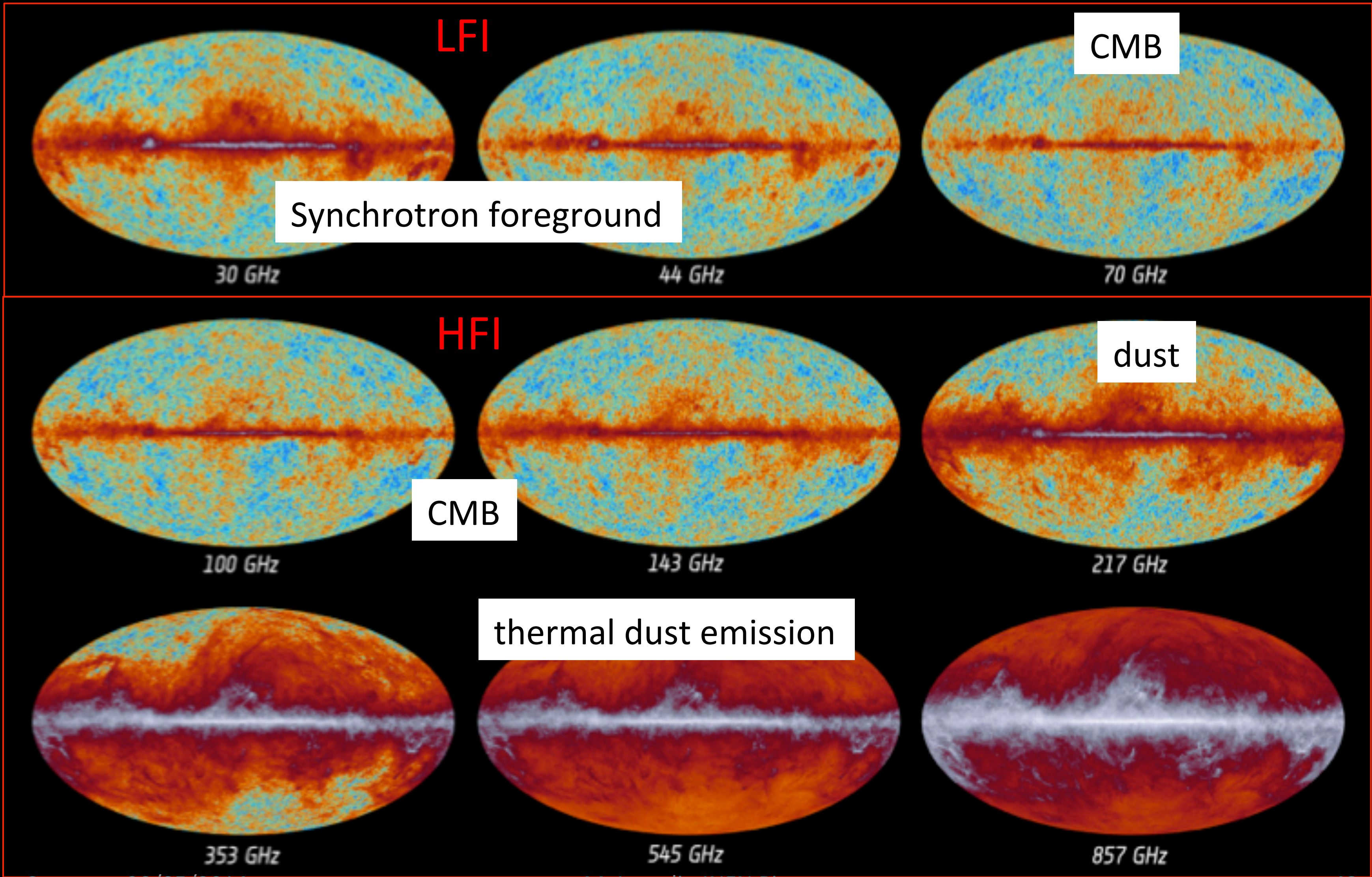
- LFI (led by Italy)
  - HEMTs (transitors)
  - cooled at 4K
  - sensitive to 30-100 GHz

- HFI (led by France/UK)
  - bolometer array
  - cooled at 0.1K
  - sensitive to 100-857 GHz

planck

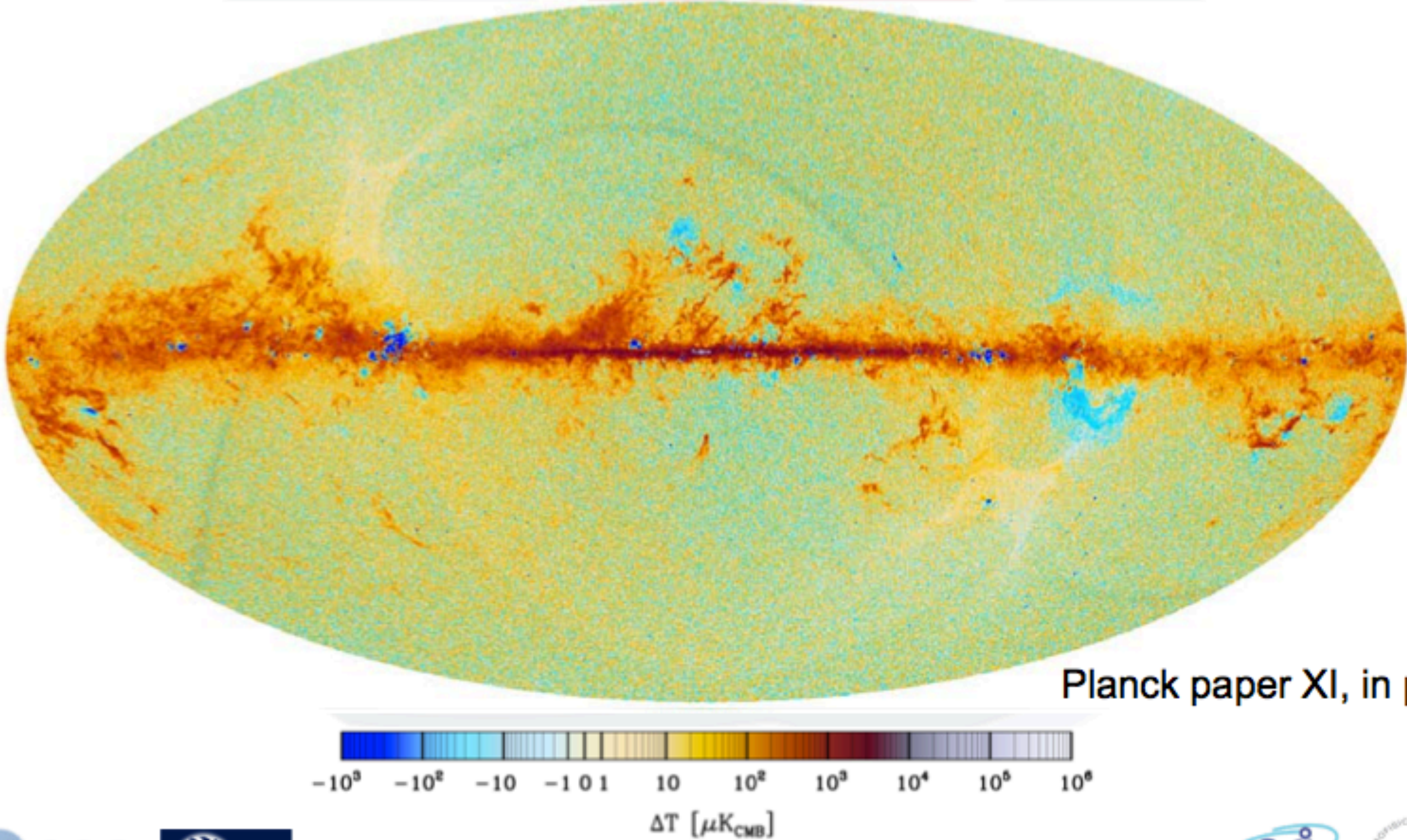
The sky as seen by Planck

esa



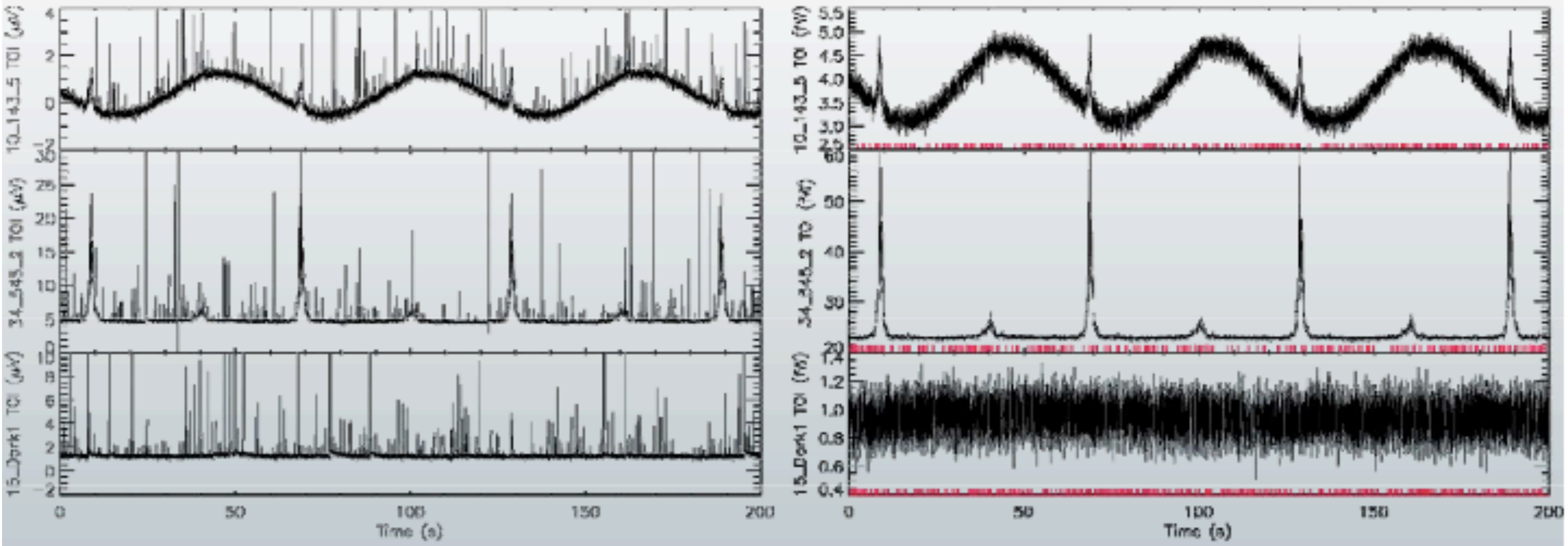
Consistency: HFI 100 GHz – LFI 70 GHz

Red is mostly CO, Blue is mostly free-free. CMB is gone!



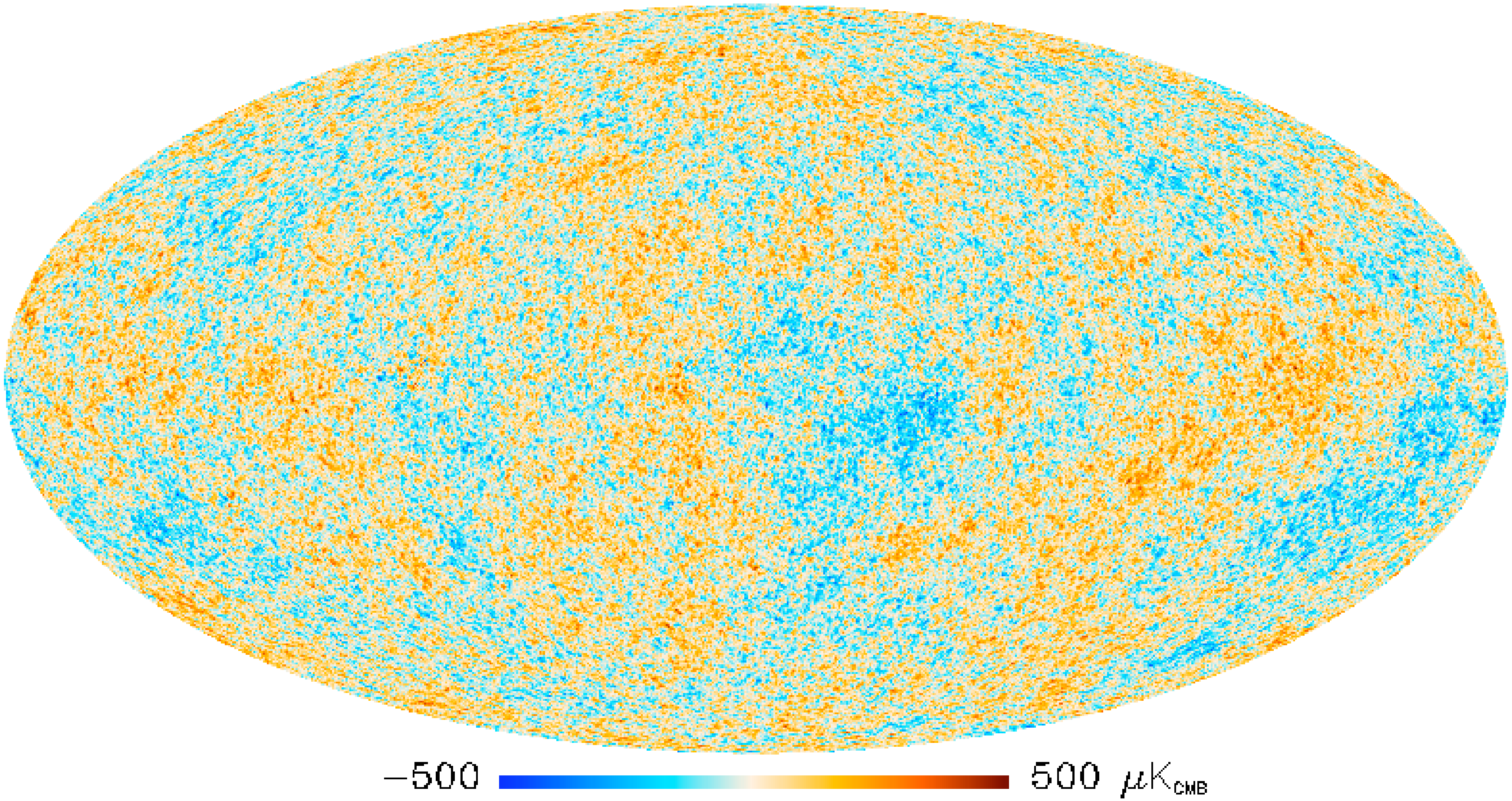
Planck paper XI, in prep.

following the time ordered data (TOI) processing



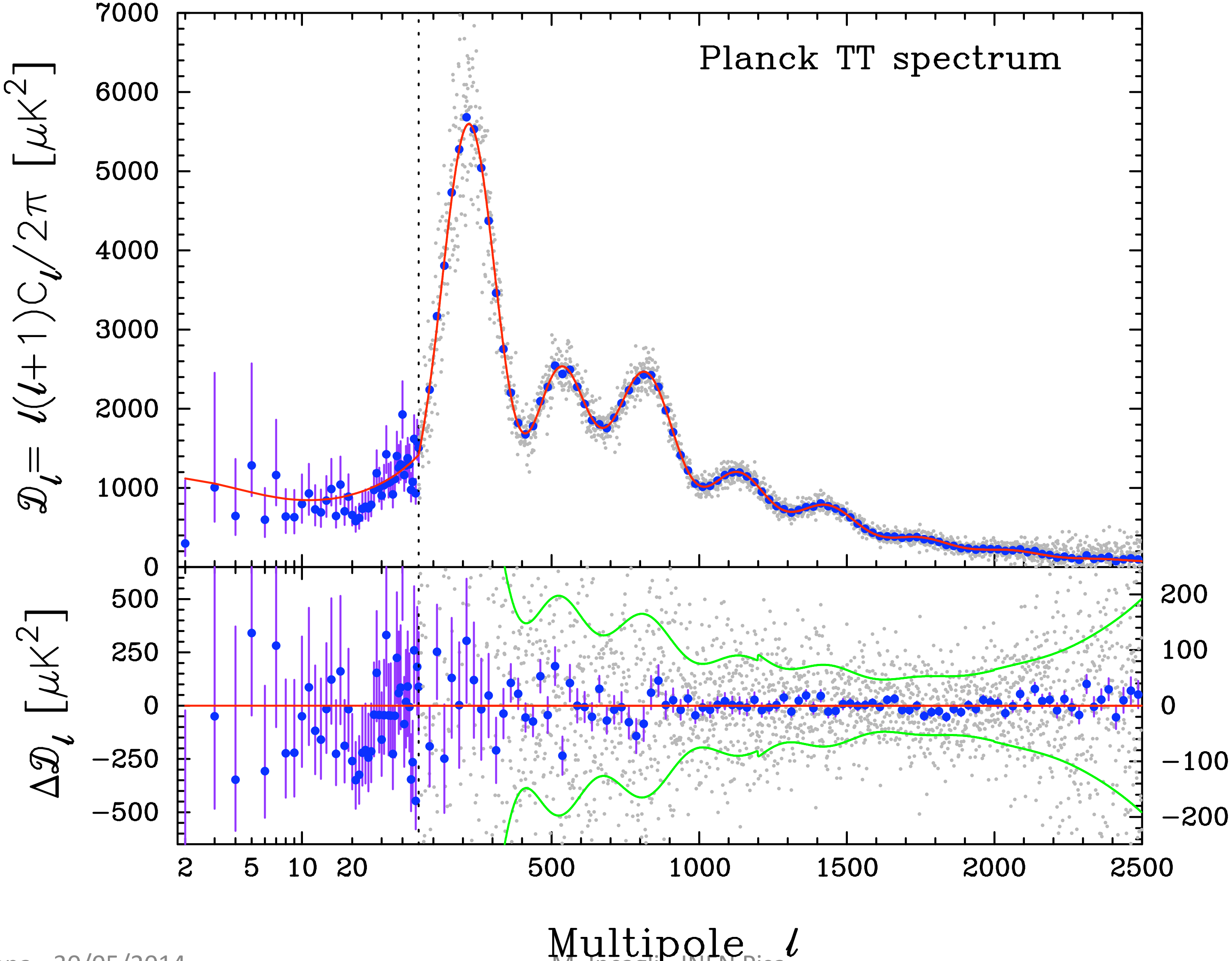
3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

The CMB map



Combined CMB map

ΛCDM is a very good fit
(→ Kunz presentation)



Conclusions

- Cosmic rays (CR) spans many orders of magnitude and flux → very different experimental techniques are required
- Space experiments are able to see "primary" cosmic rays → BUT limited geometrical acceptance
- The CR flux decreases very rapidly with energy → hard to reach energies above few TeV (electrons) or few hundred TeV (protons)
- The TeV energy range is particularly interesting for DM search (WIMP thermal cross section) → interest partially decreased after antiproton and gamma results