UNIVERSITÄT BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Dark Matter – Experimental Searches

XVIII Frascati Spring School „Bruno Touschek“ – Spring 2016

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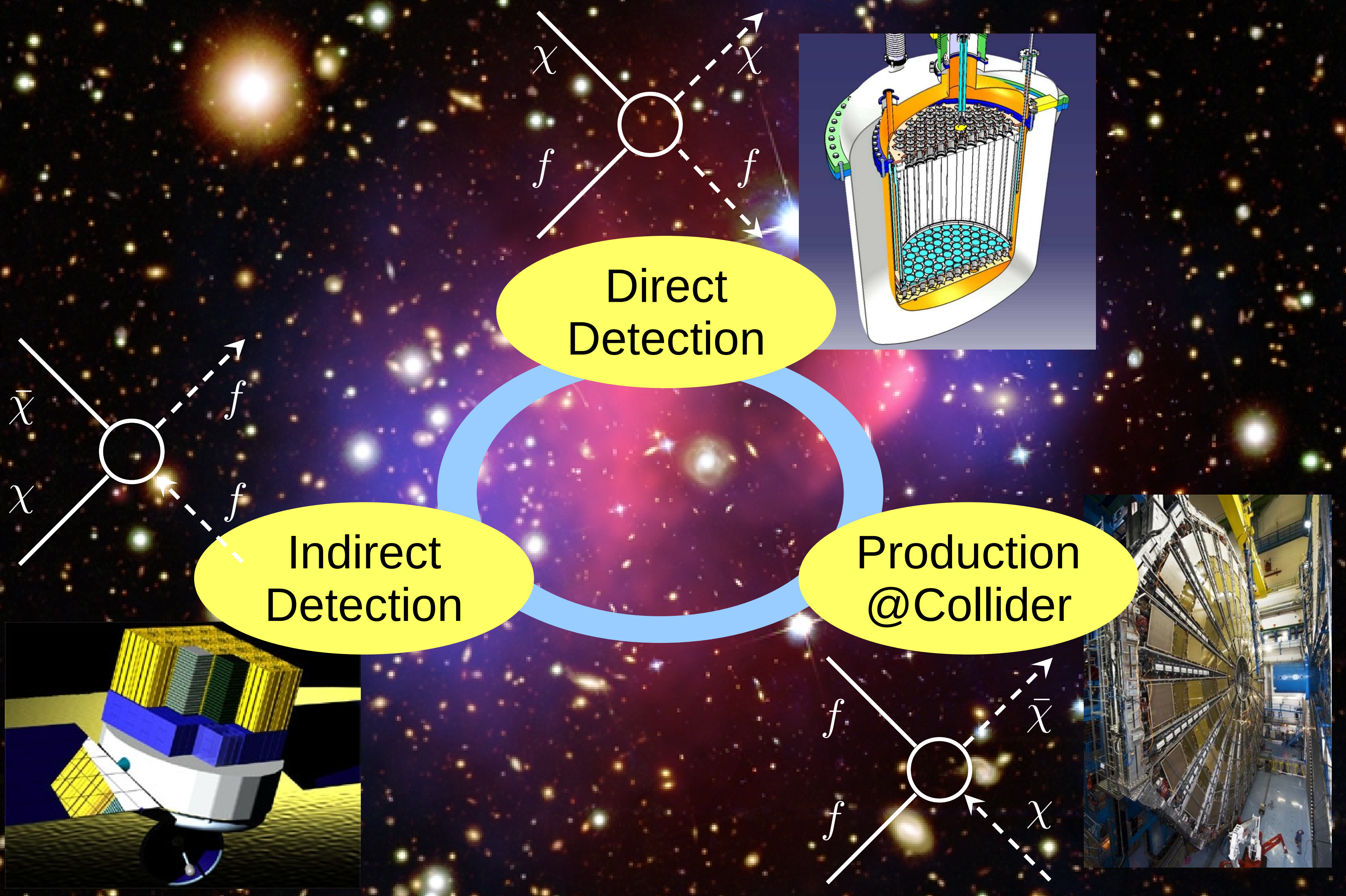
Content

Slides:
`http://www.lhep.unibe.ch/schumann/dm_2016.html`

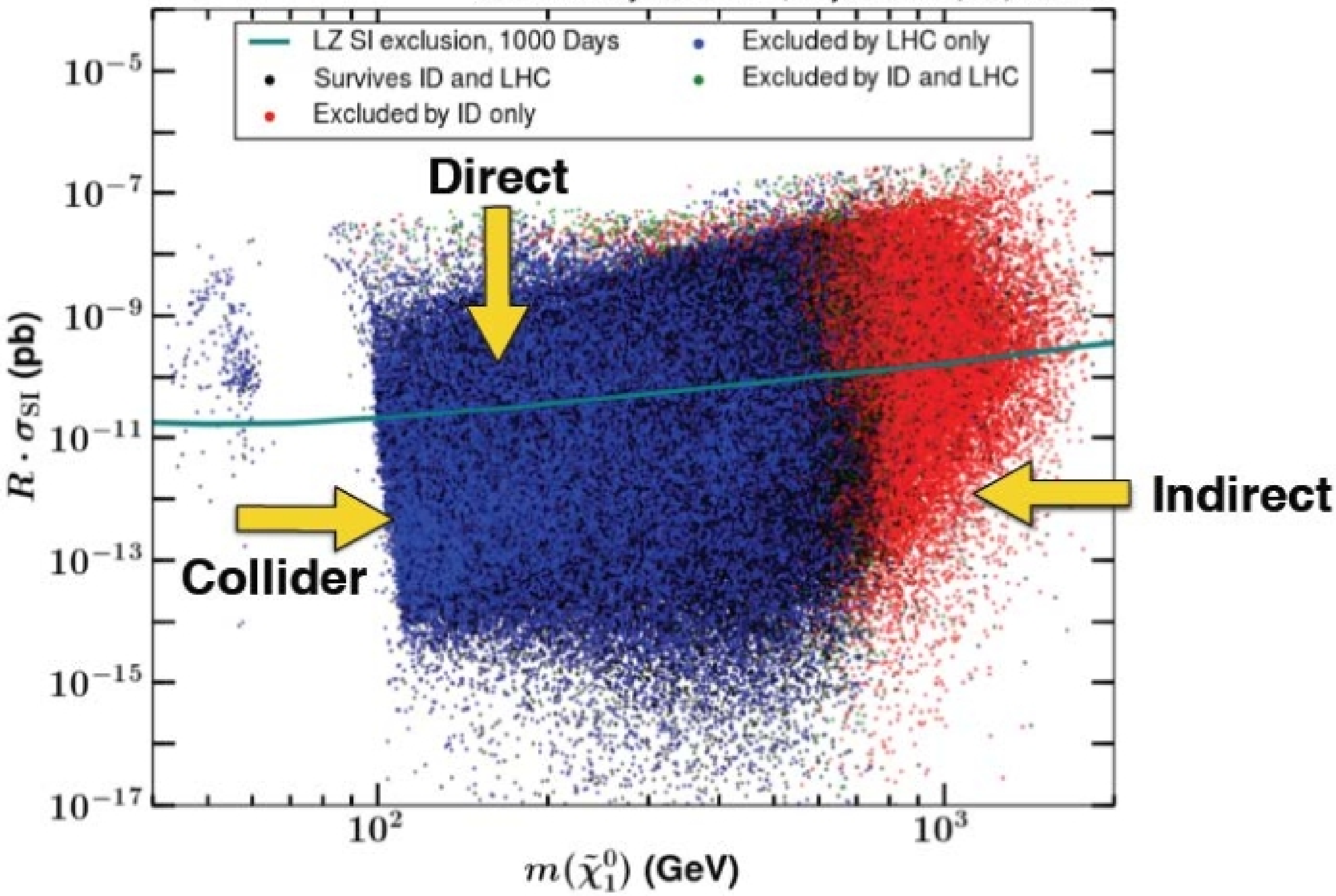
Dark Matter Search



Complementarity

here: in context of phenomenological minimal SUSY model (pMSSM): 19 parameters

Cahill-Rowley et al. 2015, Phys. Rev. D, 91, 055011

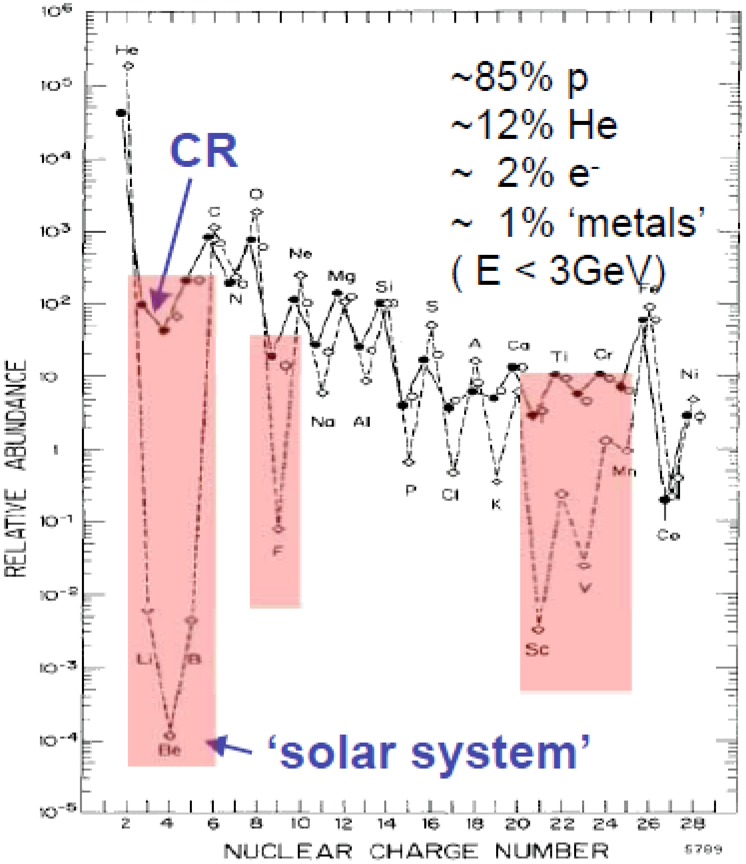


5 Indirect Dark Matter Detection

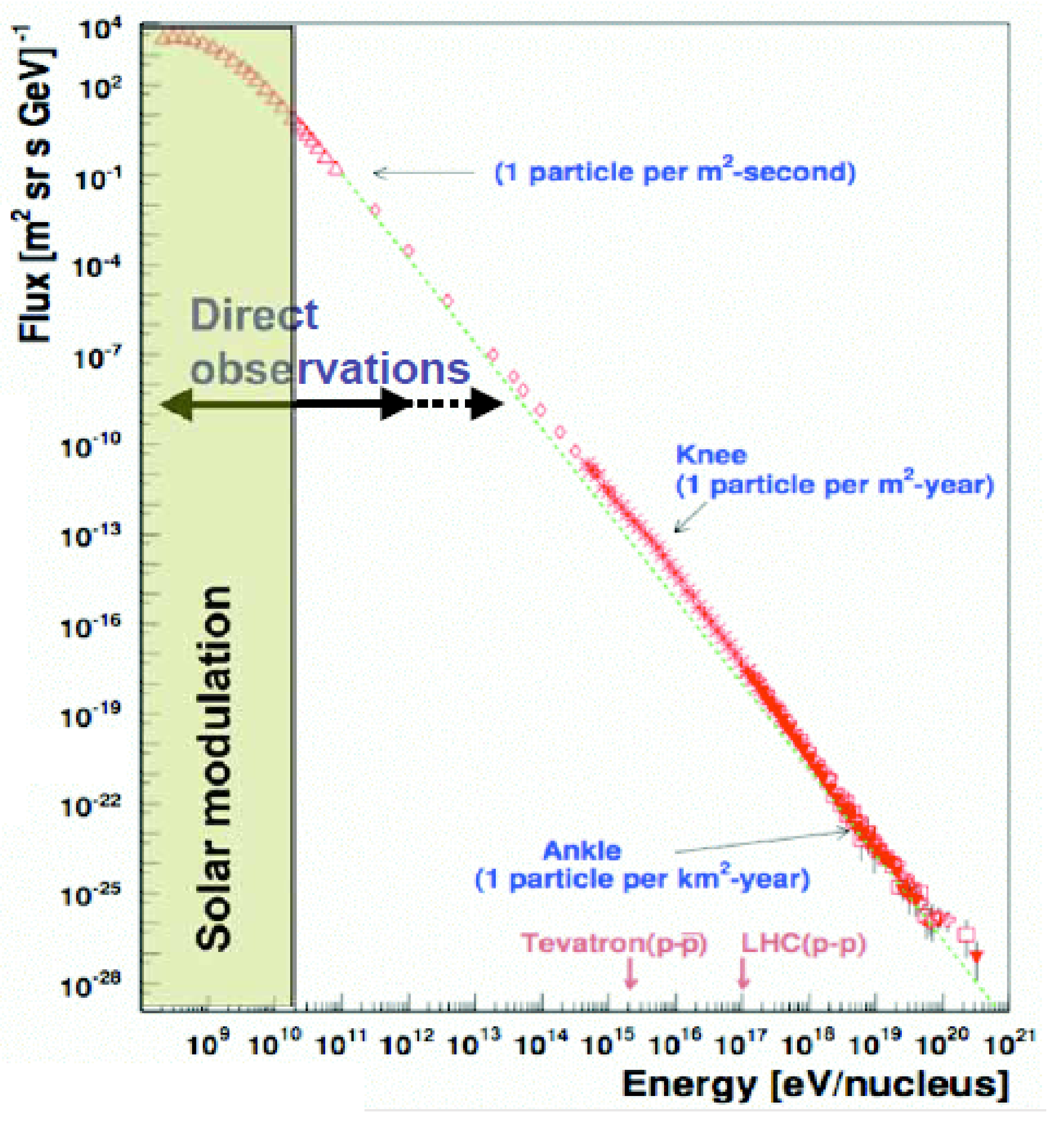
- What are cosmic rays?
  → number, spectrum, particles
- If dark matter particles annihilate somewhere in the Universe (Sun, Galactic Center, Dwarf Galaxies, …), we could detect the decay products in the cosmic rays:
  → positrons (Pamela/AMS-II)
  → gamma-rays (Fermi)
  → neutrinos (IceCube)

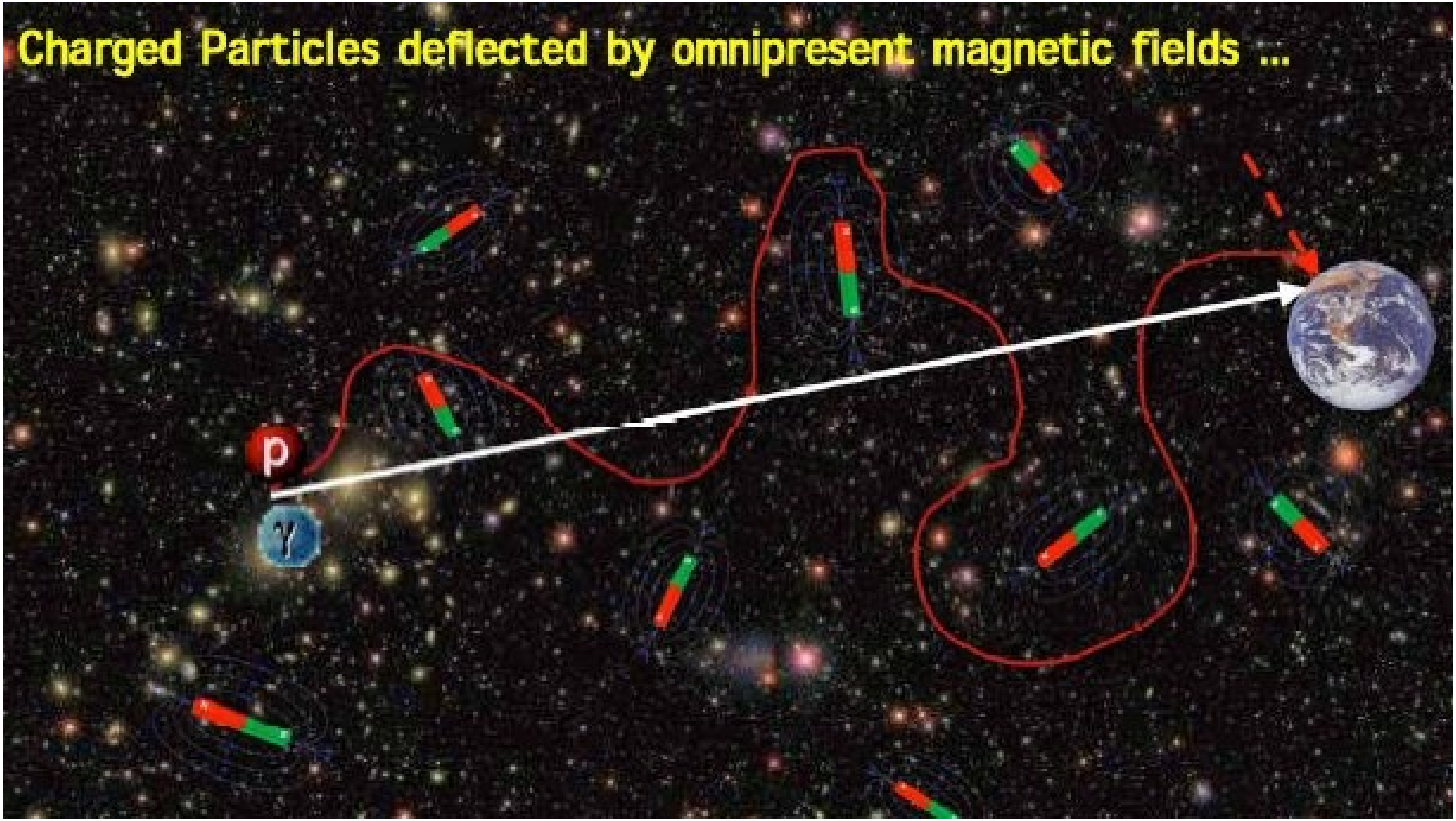
Cosmic Ray Abundance

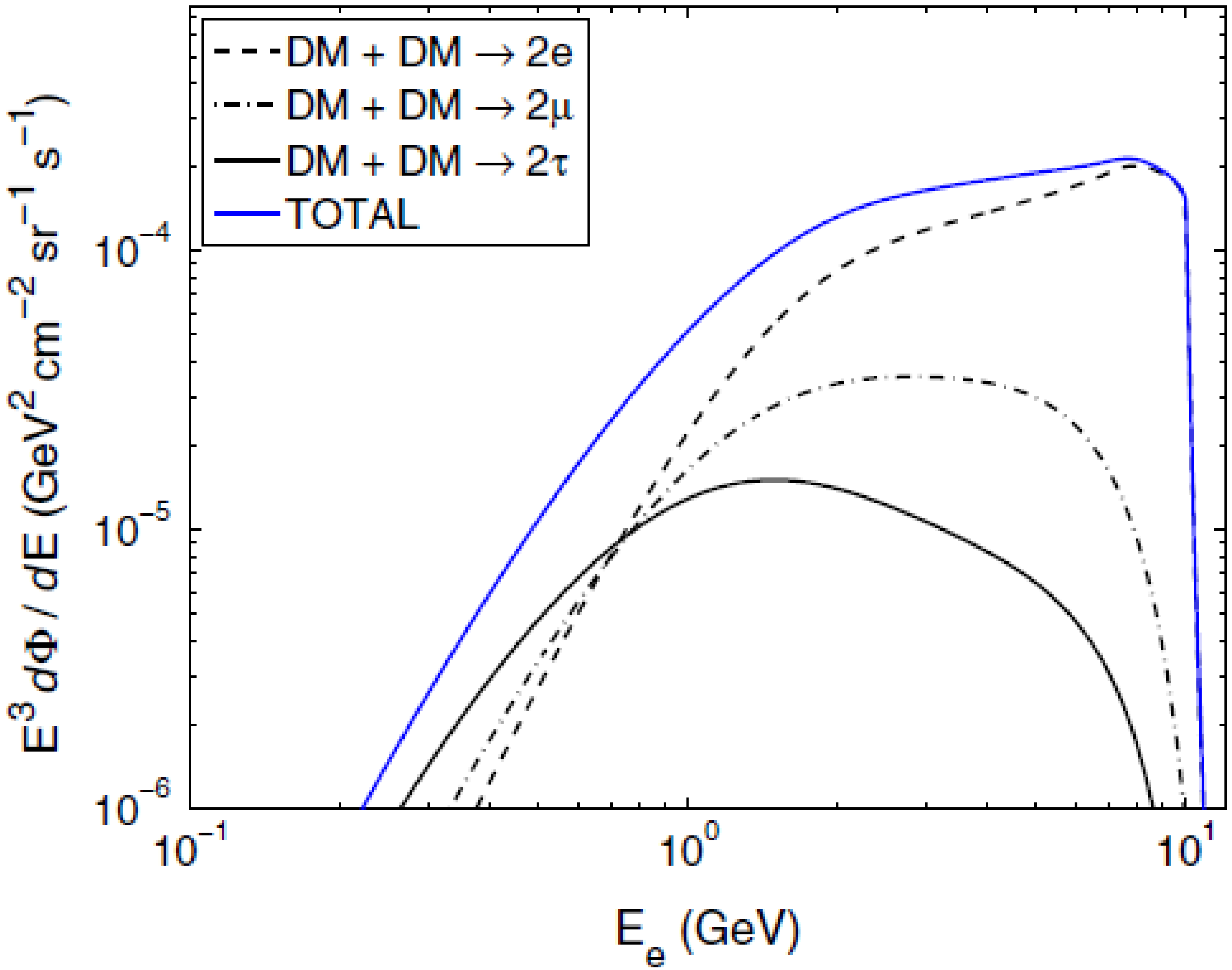
- Abundance in good agreement with observations of „metal ratios“ in interstellar metal
- odd/even structure is due to binding energy
- Large disagreement at some isotopes
  → too many cosmic rays or
  too little in solar neighborhood?



The Cosmic Ray Spectrum




Charged Particles deflected by omnipresent magnetic fields ...
p
γ

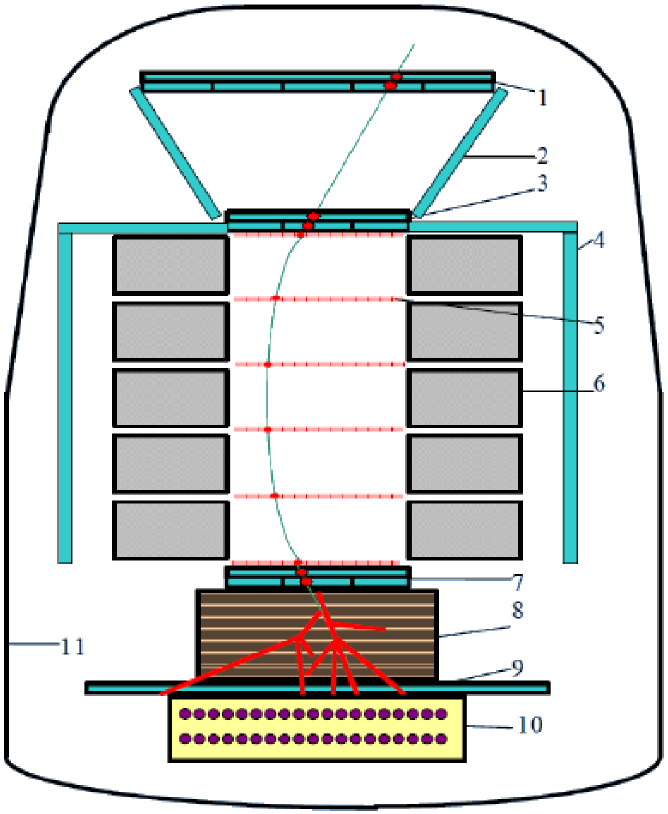


DM + DM → 2e
DM + DM → 2μ
DM + DM → 2τ
TOTAL
$E^3 d\Phi / dE$ ($GeV^2 cm^{-2} sr^{-1} s^{-1}$)
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^{0}
10^{1}
E_e (GeV)

PAMELA

Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics

launched 2006



1, 3, 7- TIME OF FLIGHT SYSTEM;
2, 4- ANTICOINCIDENCE SYSTEM;
5- SILICON STRIP TRACKER (SIX DOUBLE PLATES);
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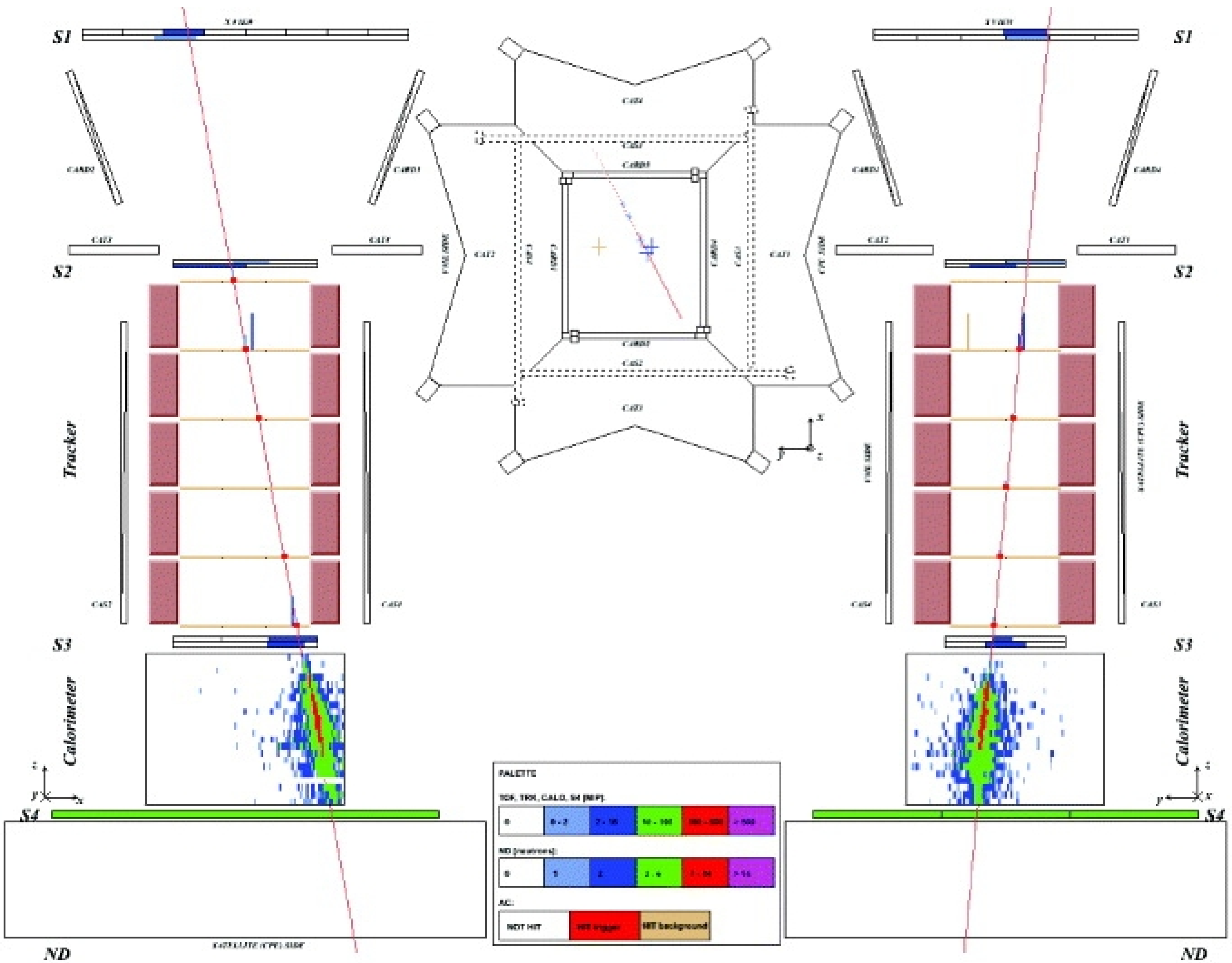
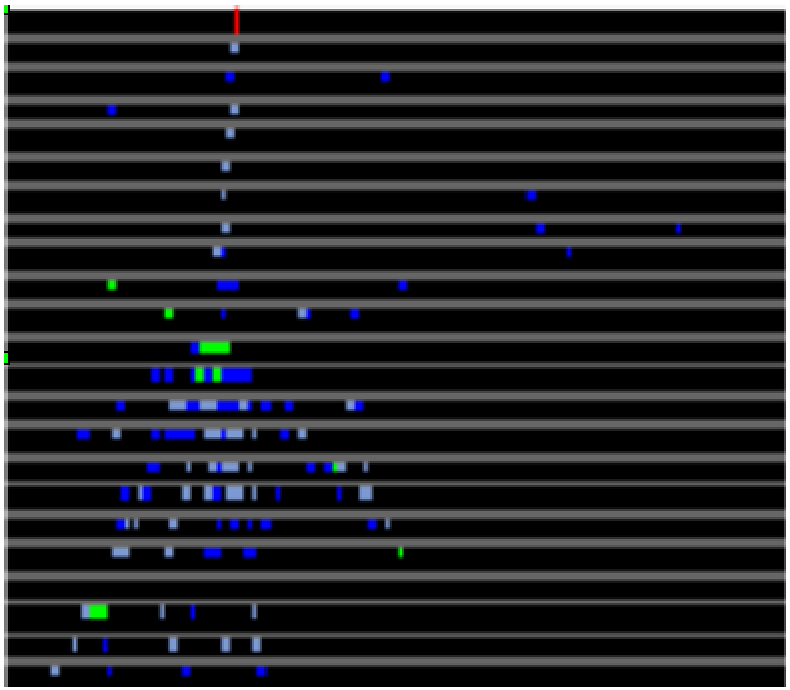
10- NEUTRON DETECTOR;
11- HERMOCONTAINER.

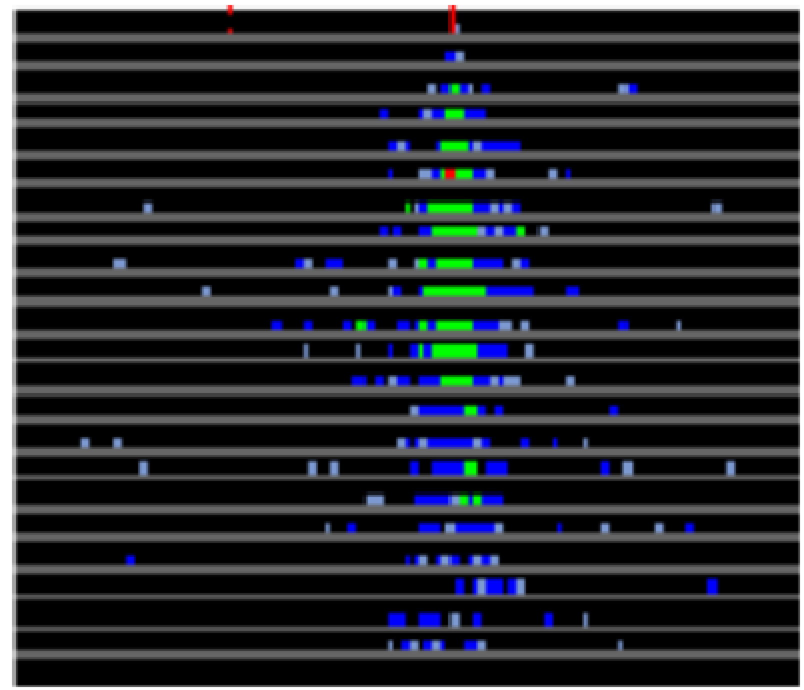
A 92 GeV positron



Sampling imaging Calorimeter



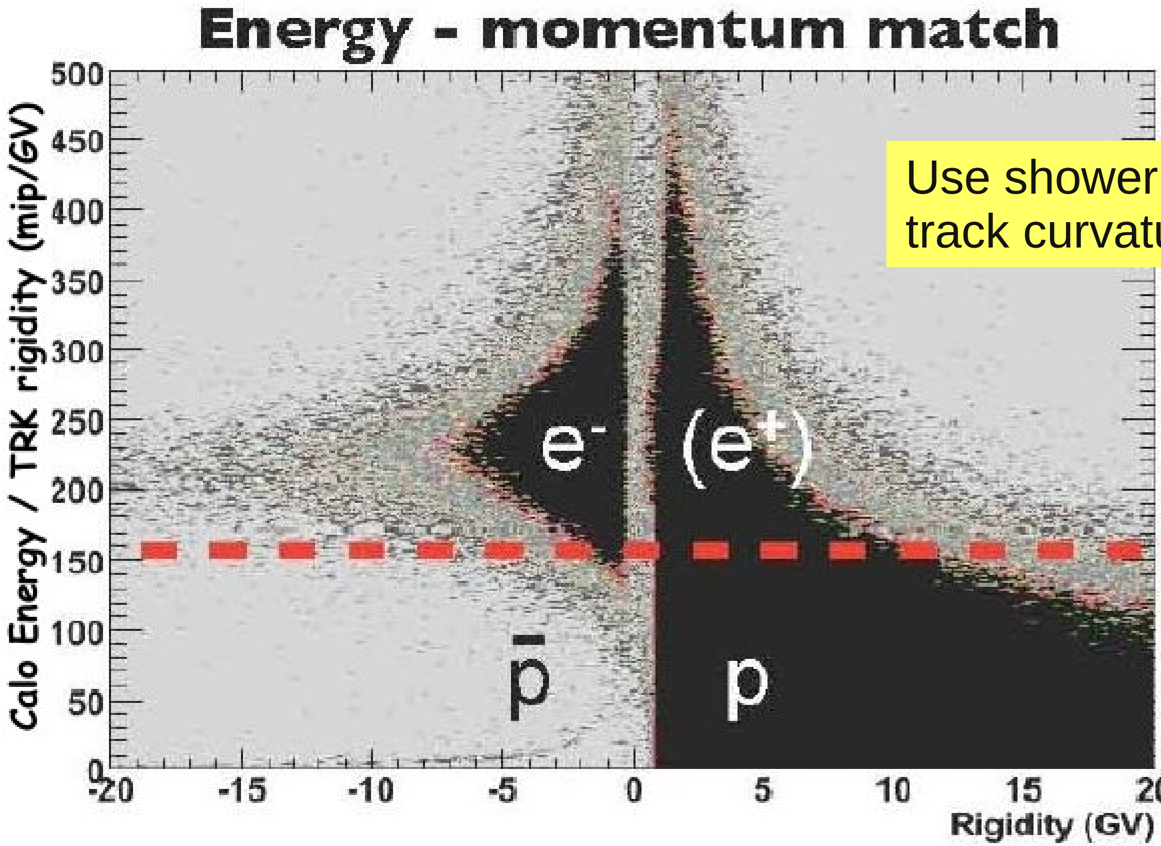
hadron (R=19GV)



electron (R=17GV)

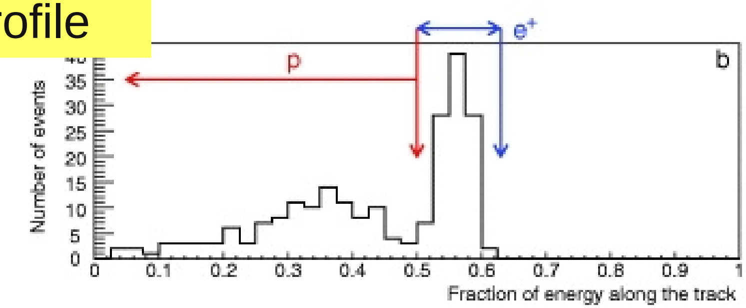
magnetic rigidity $R = pc / Ze = r_L B$

Positron Identification

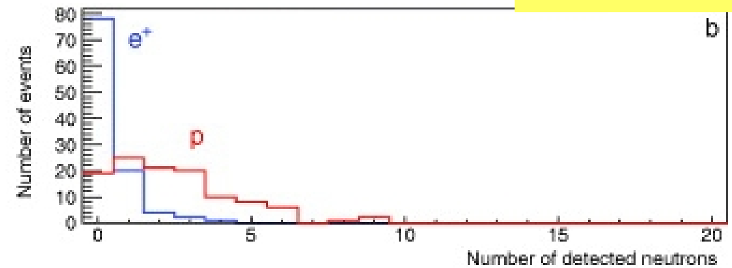


Use shower energy vs track curvature

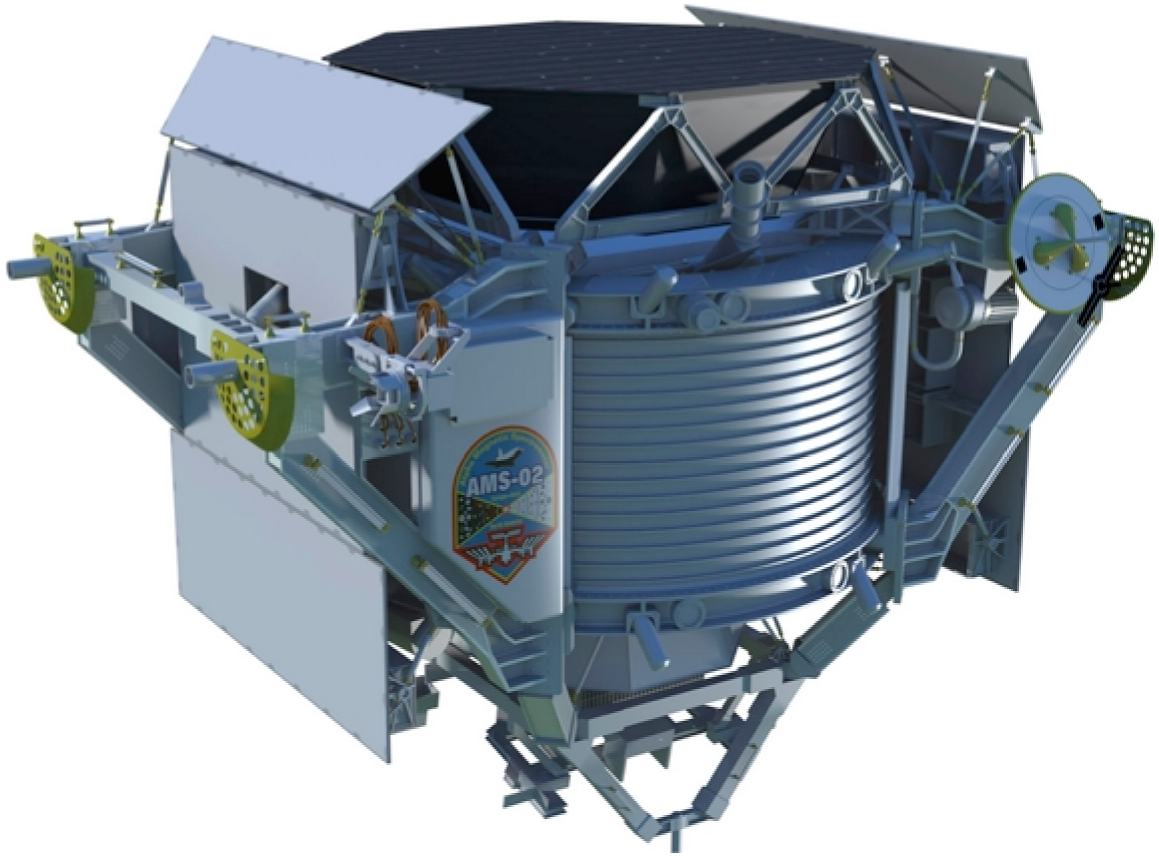
Use longitudinal shower profile

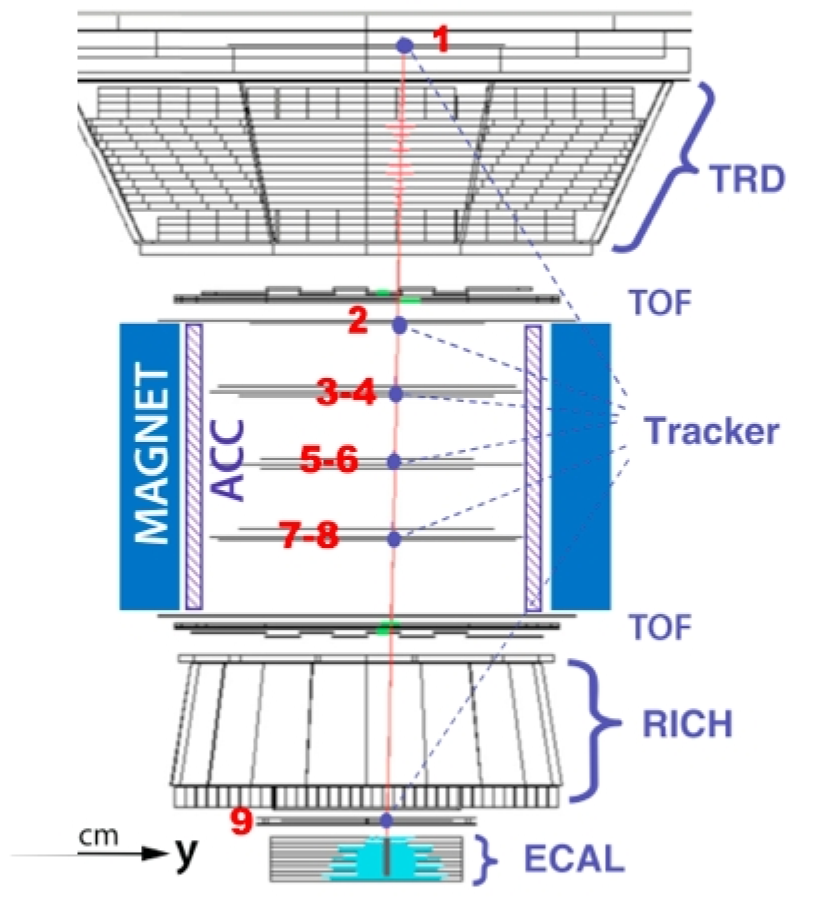


Neutron Multiplicity

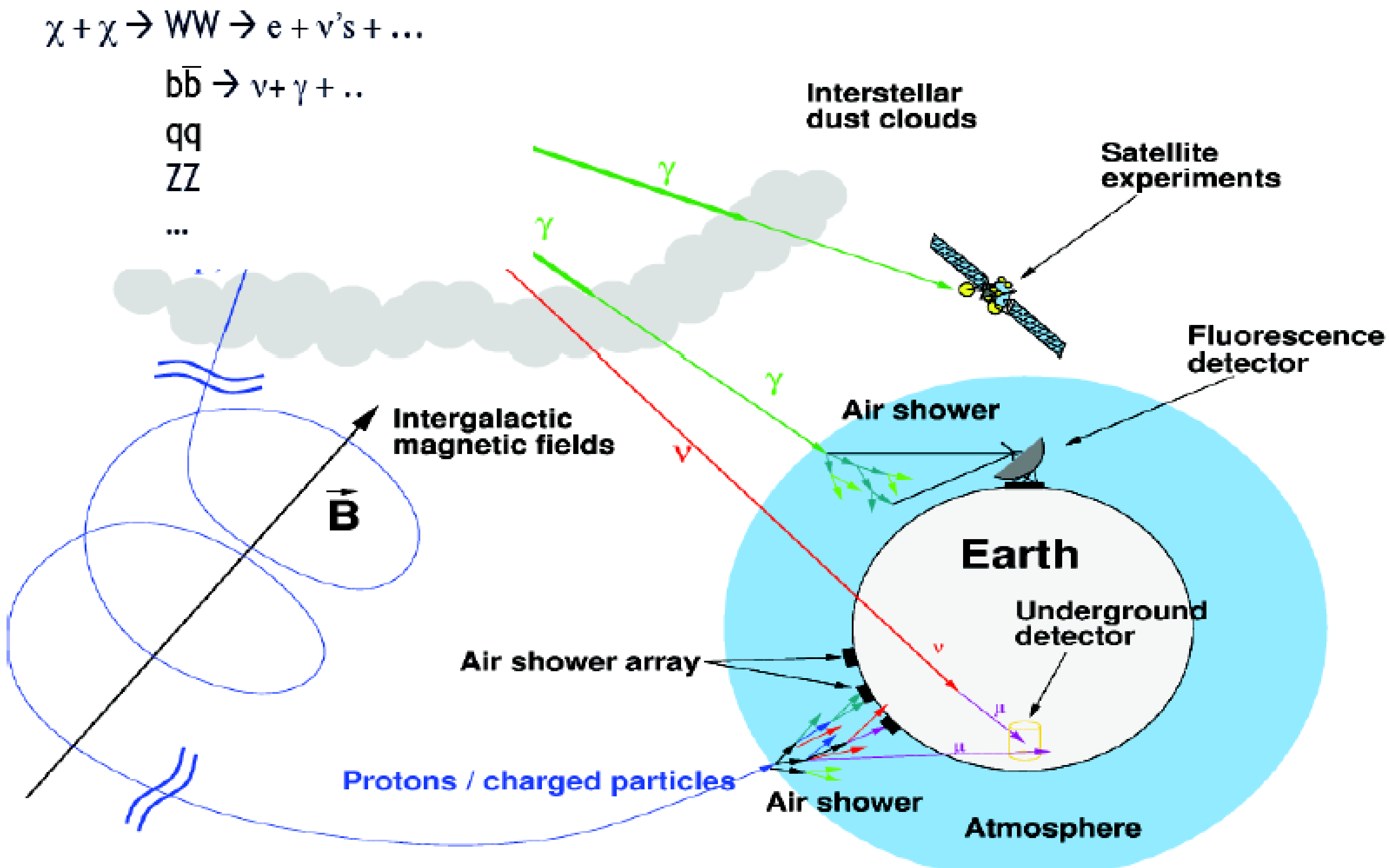


AMS-02 @ ISS



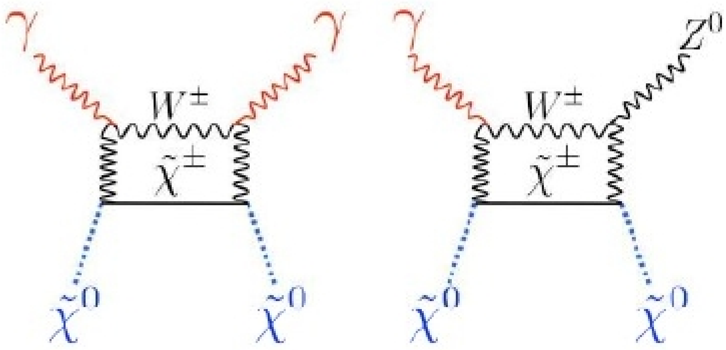


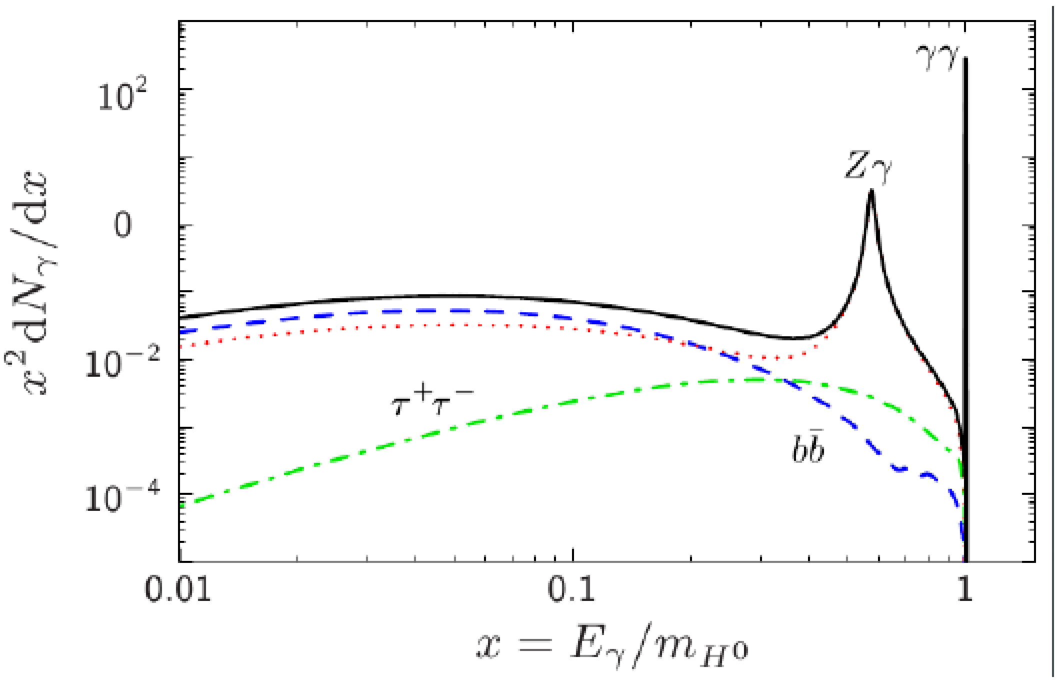
TRD: e^-/e^+ traversing the TRD produce X-rays, p/hadrons do not
RICH: measure particle velocity



$\chi + \chi \rightarrow WW \rightarrow e + \nu\text{'s} + \ldots$
$b\bar{b} \rightarrow \nu + \gamma + ..$
qq
ZZ
...
Interstellar dust clouds
Satellite experiments
γ
γ
γ
ν
Intergalactic magnetic fields
$\vec{B}$
Fluorescence detector
Air shower
Earth
Underground detector
Air shower array
Protons / charged particles
Air shower
Atmosphere

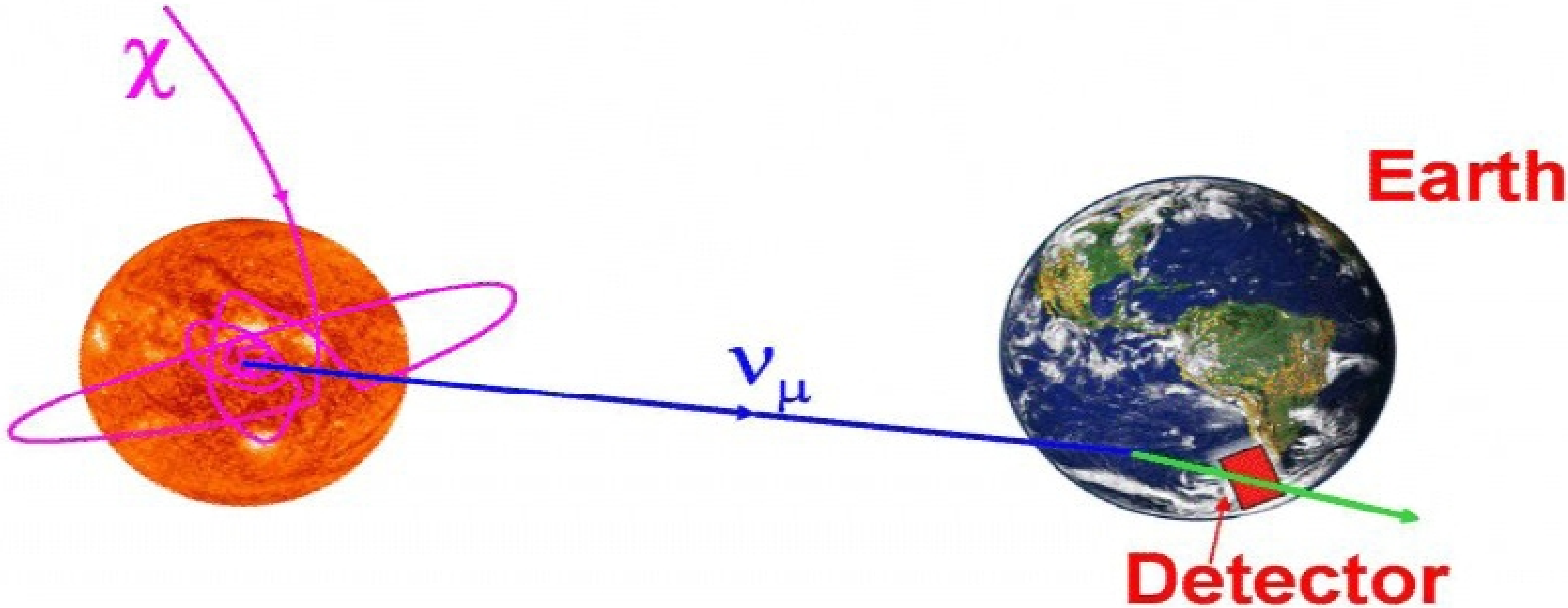
Gamma-Line: A smoking gun!



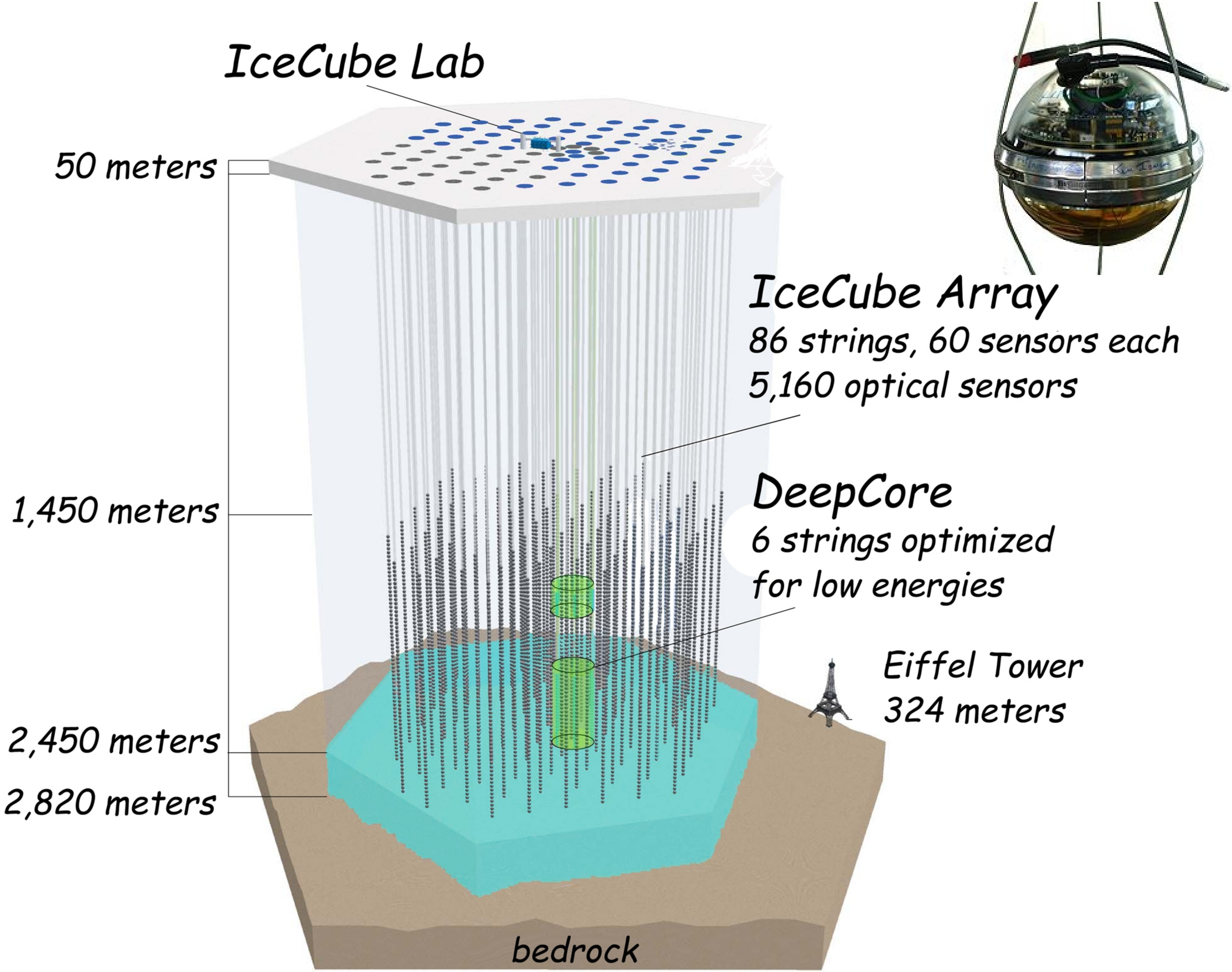


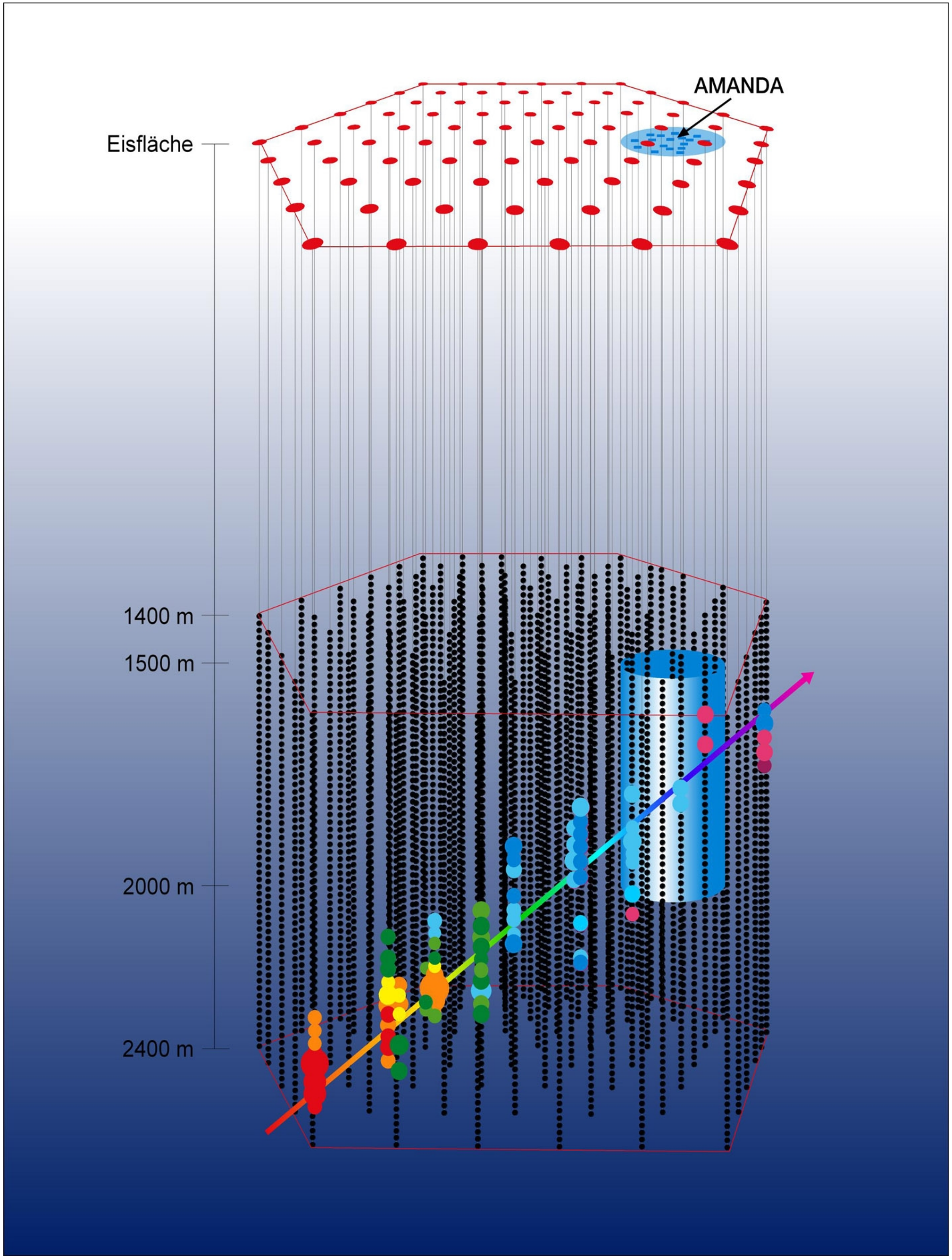
+ directly related to WIMP mass
+ sharp, distinct feature
+ at the relevant energies, astrophysics does not create lines

– does not happen at tree level (DM does not couple to gammas)
→ 2nd order process, rate is largely suppressed



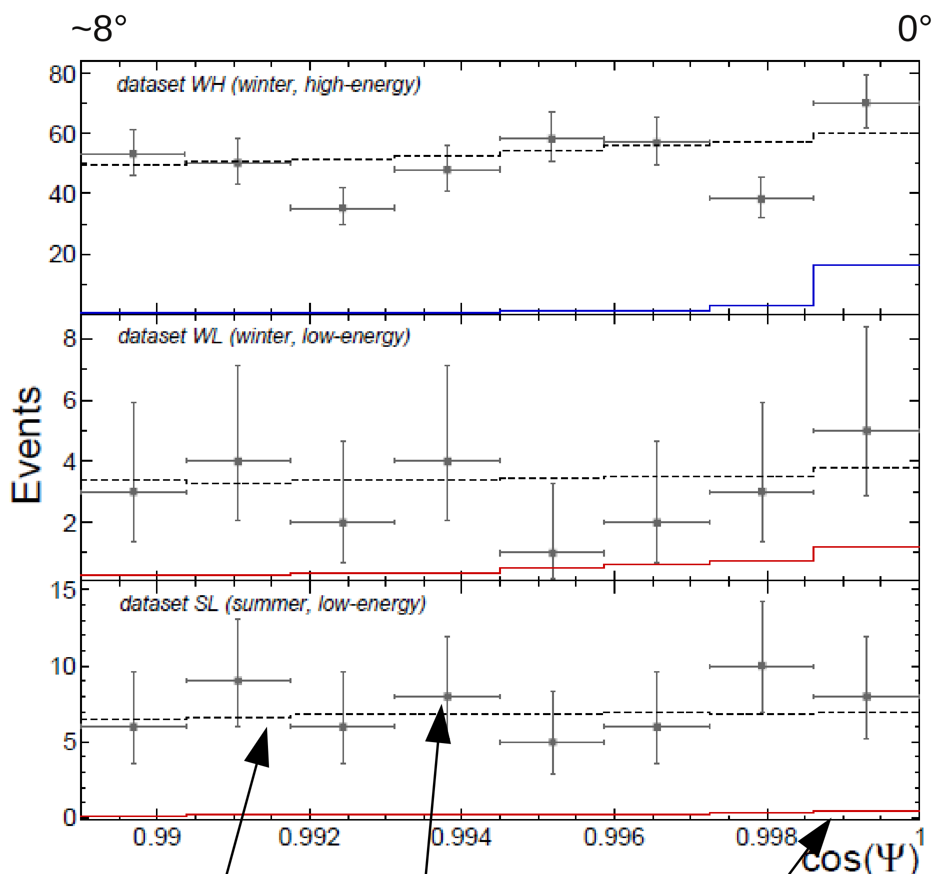
χ
Earth
ν_μ
Detector


IceCube Lab
50 meters
1,450 meters
2,450 meters
2,820 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
bedrock



AMANDA
Eisfläche
1400 m
1500 m
2000 m
2400 m

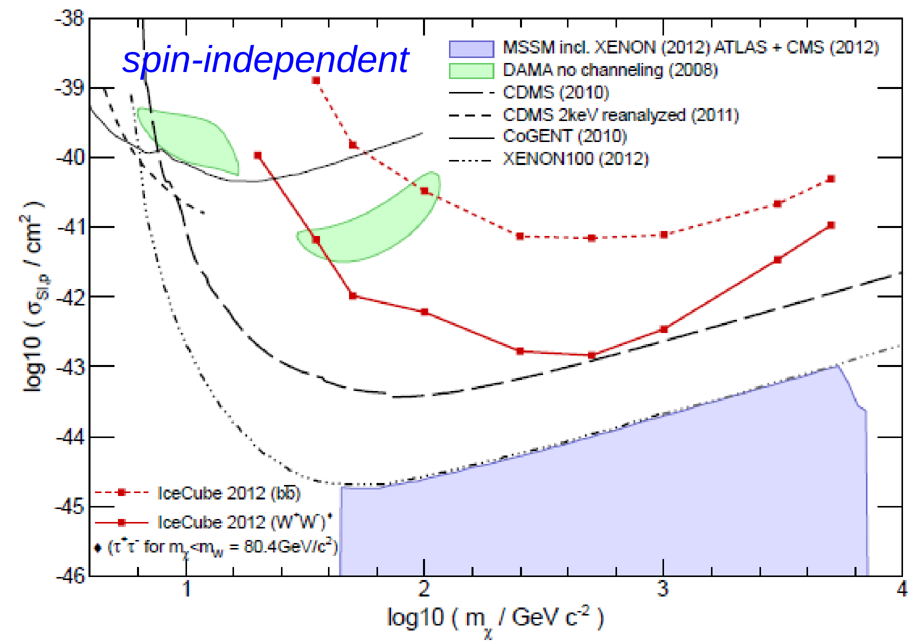
IceCube WIMP Limits

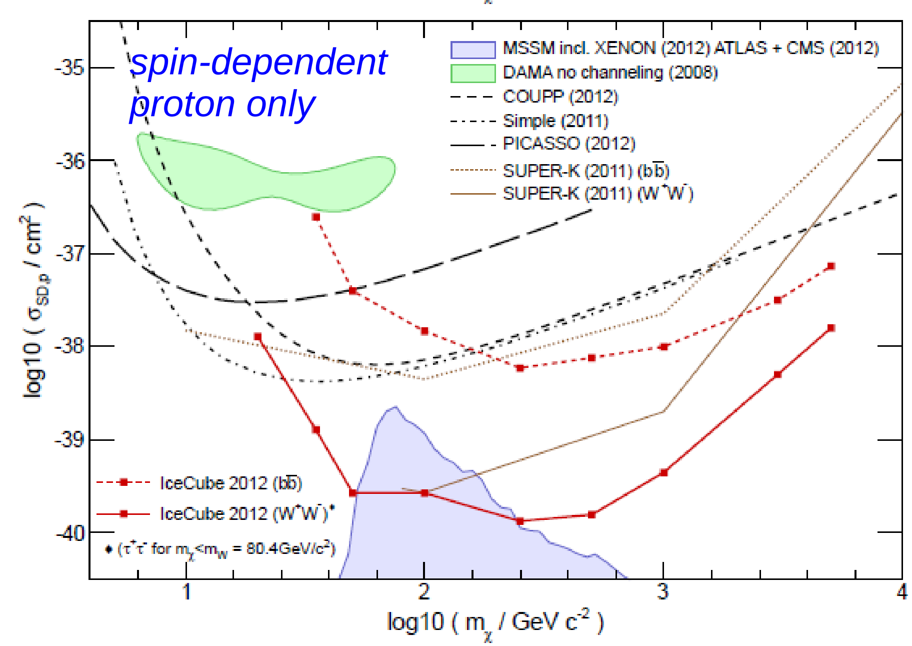


background from atmospheric μ and ν

measured data

simulated WIMP signal:
1 TeV/c², 50 GeV/c²
(scaled to 90% CL limit)





similar results from Super-K

6 The current dark matter landscape

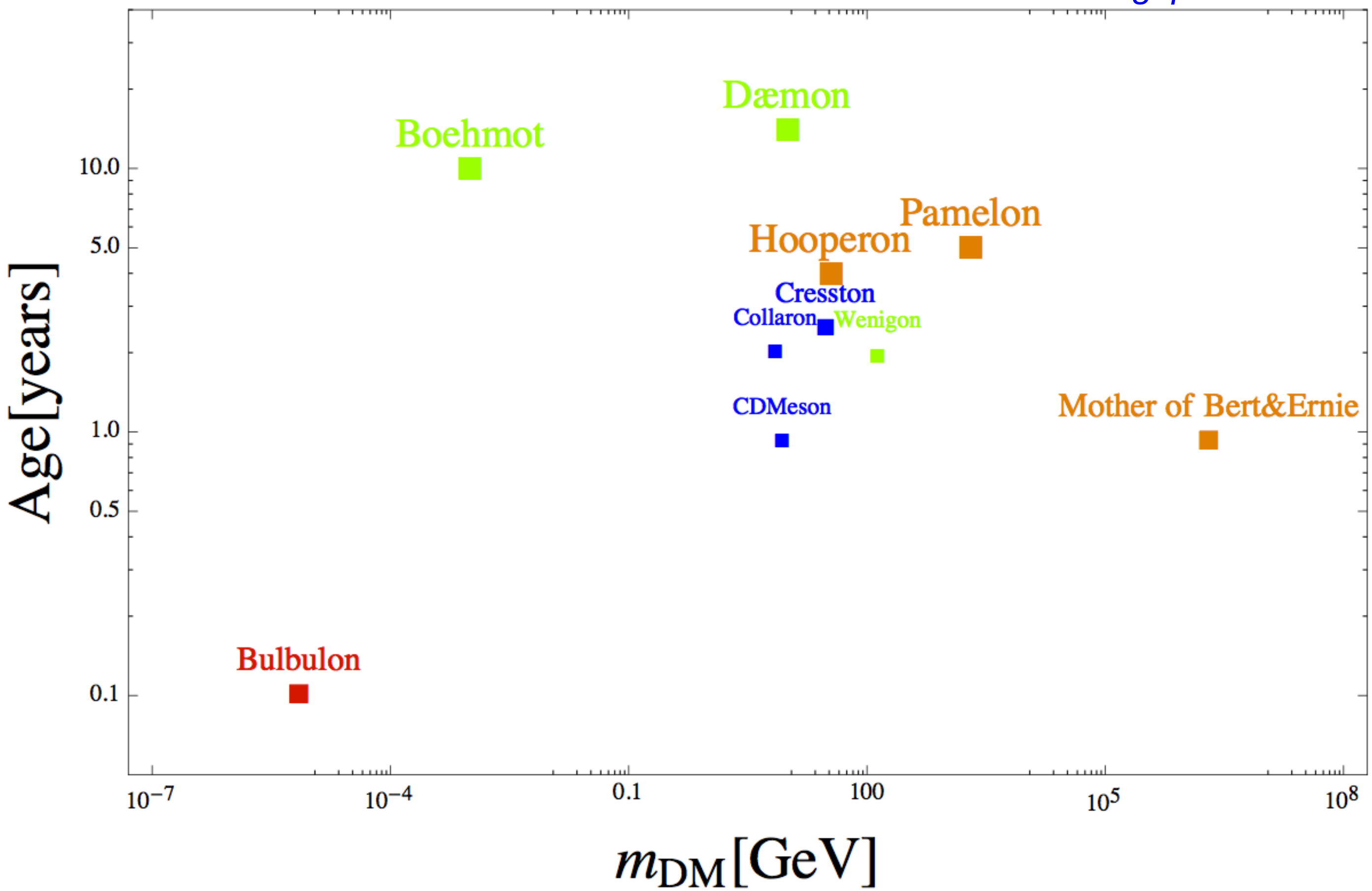
wrapping it all up...

At the moment, we have exclusion limits and conflicting detection claims (→ anomalies) at the same time

- Collider Seaches
  → no sign of dark matter yet → O. Buchmüller's lecture
- Indirect Detection
  → rising positron fraction?
  → galactic center excess?
  → a new X-ray line at 3.5 keV?
- Direct Detection
  → two anomalies,
  strongly challenged by various limits

Hints / Anomalies

from *resonaances.blogspot.com.br*



The graph shows the number of years the signal has survived vs. the inferred mass of the dark matter particle. The label's size is related to the statistical significance of the signal.

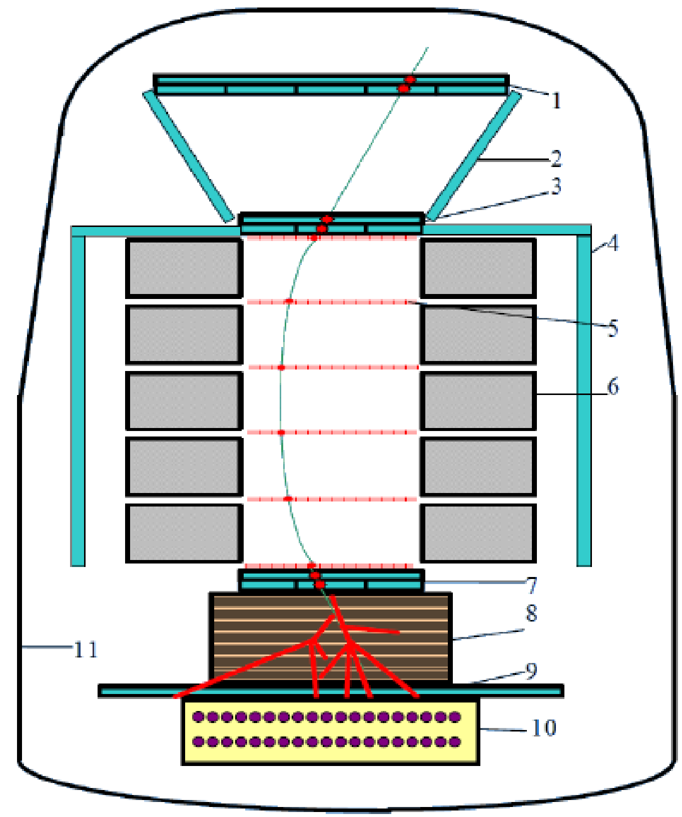
The colors correspond to the Bayesian likelihood that the signal originates from dark matter, from uncertain (red) to very unlikely (blue).

The masses of the discovered particles span impressive 11 orders of magnitude, although the largest concentration is near the weak scale (this is called the WIMP miracle).

Positrons – PAMELA

Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics

launched 2006



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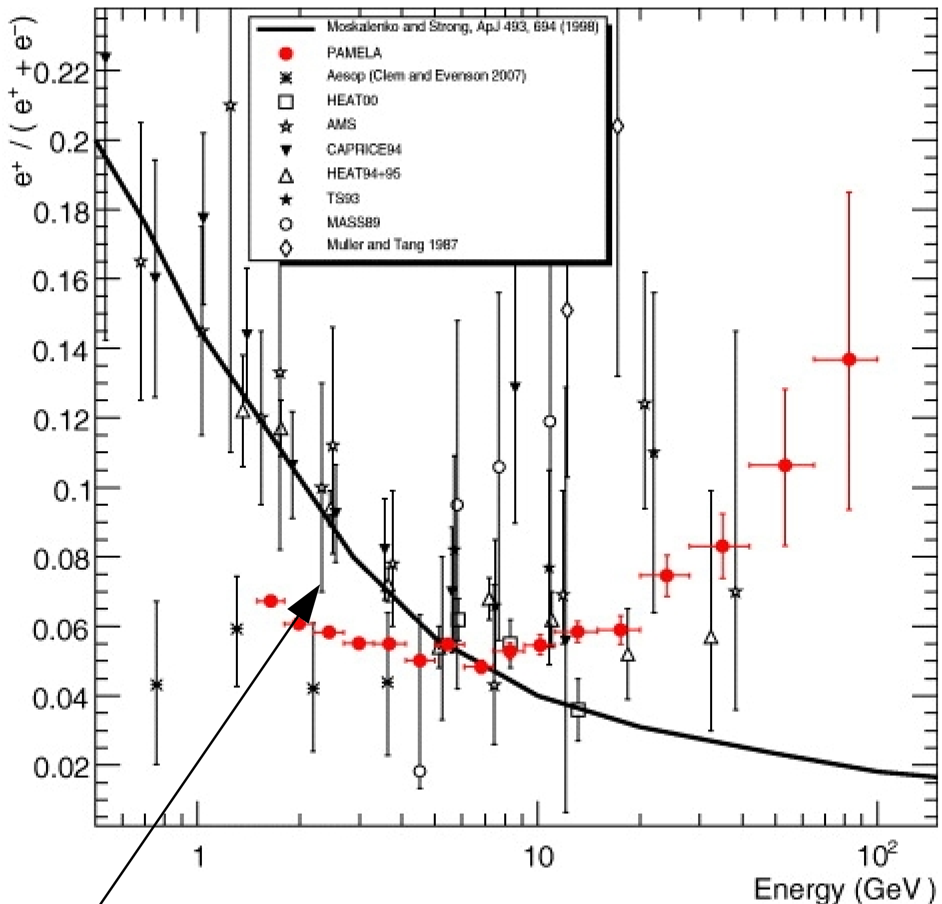
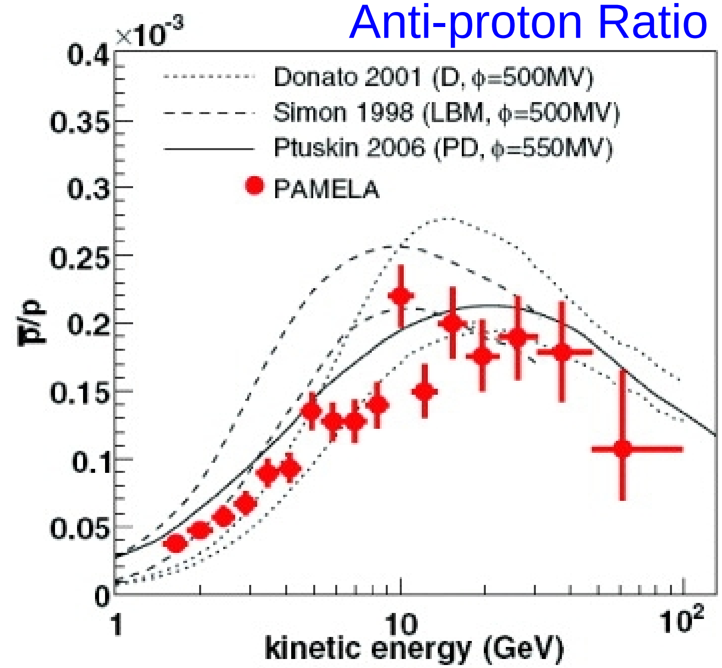
11- HERMOCONTAINER.

A rising positron fraction!!!

Positron Ratio



Anti-proton Ratio



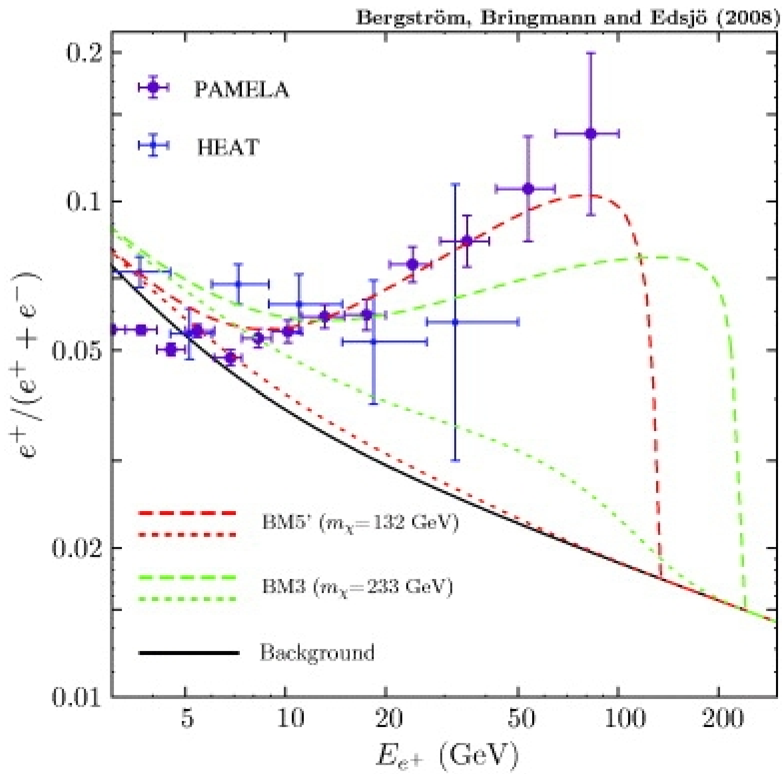
Measured anti-proton ratio in agreement with secondary production!
(also true for new AMS-02 data)

influence of sun
→ not accounted for
in the Galprop model

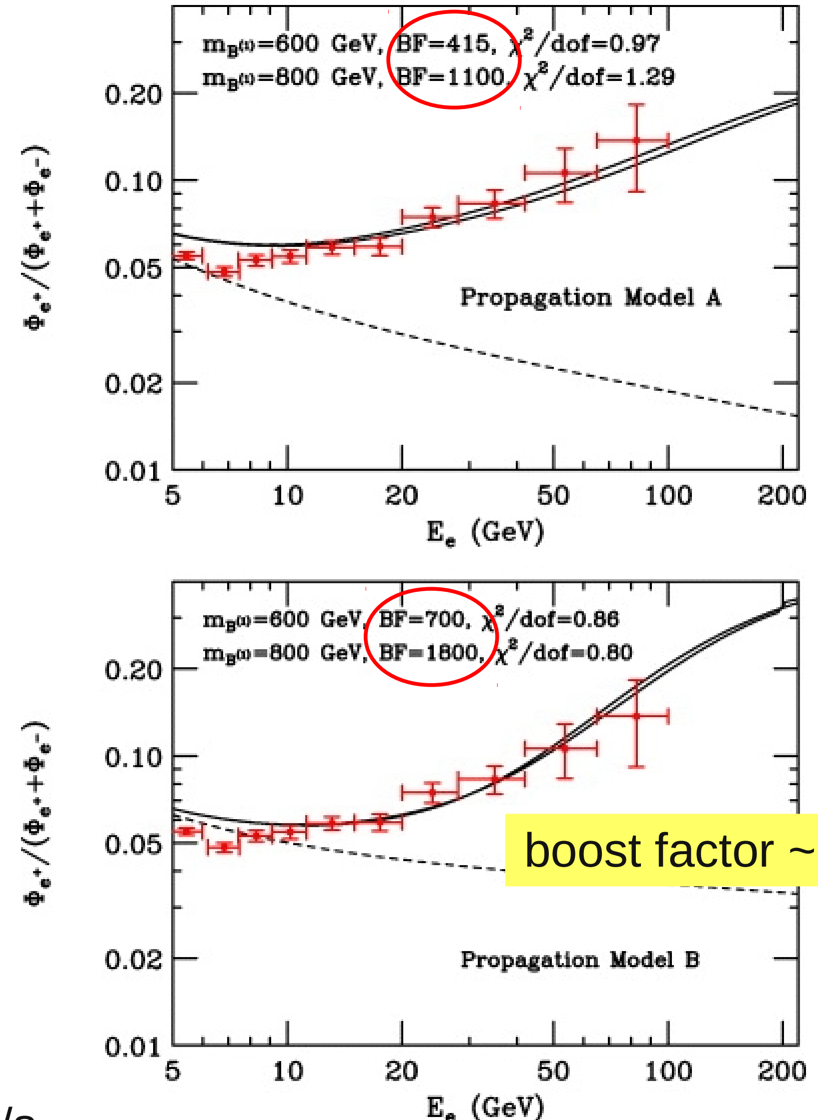
PAMELA does not have a TRD:
maybe some of the positrons are protons?
(There are 1000-10000 more p that e^+)
→ a proton contamination of 3 x 10^{-4}
could explain the rise

Dark Matter?

Neutralino Dark Matter



Kaluza-Klein Dark Matter



boost factor ~1000

- DM needs to be leptophilic
  (excess in e^+, not in p)
  → need to overcome helicity suppression
- radiative corrections might enhance the e^+ fraction
- WIMP miracle expects <σv> ~ 3 x 10^{-26} cm³/s,
  PAMELA would lead to <σv> ~ 10^{-23} cm³/s
  → need large boost factors!

How can we get Boost Factors?

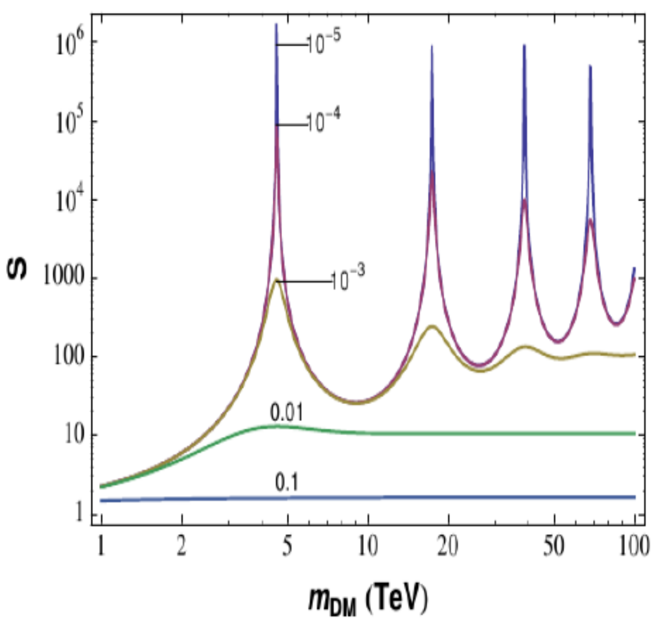
Astrophysics: local overdensity of dark matter in nearby sub-halos

Particle Physics: **Sommerfeld Enhancement**

$X + X \rightarrow f + f$

typically, the rate of the process is proportional to „flux x cross-section“

Sommerfeld: if the colliding particles attract each other, the rate is enhanced.
Classically: focusing effect and incresed velocity



$$\langle \sigma_{\text{ann.}} v \rangle = a + b\, v^2 + \cdots$$

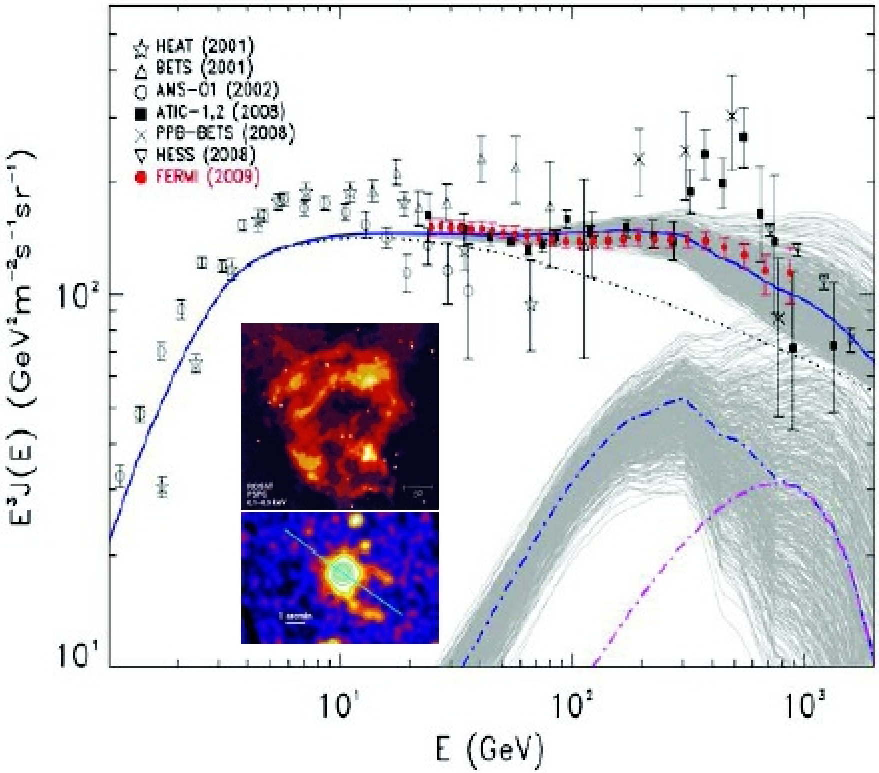
$$\sigma = \sigma_0 \cdot S_{\ell=0}$$

pure s-wave contribution, no enhancement

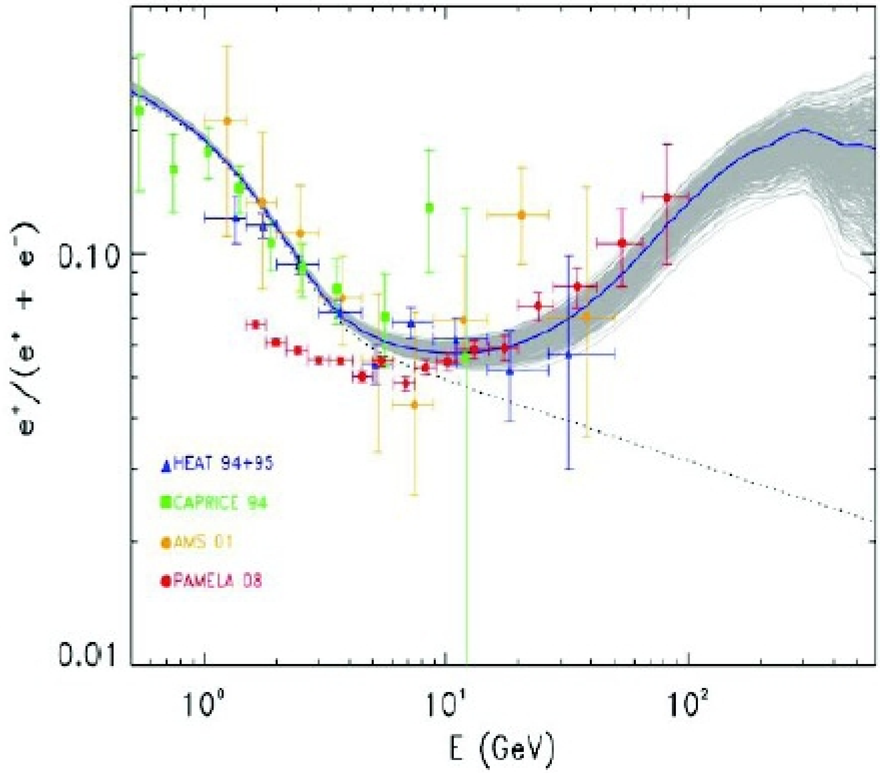
enhancement factor; can be very large

Or is it simply from nearby pulsars?

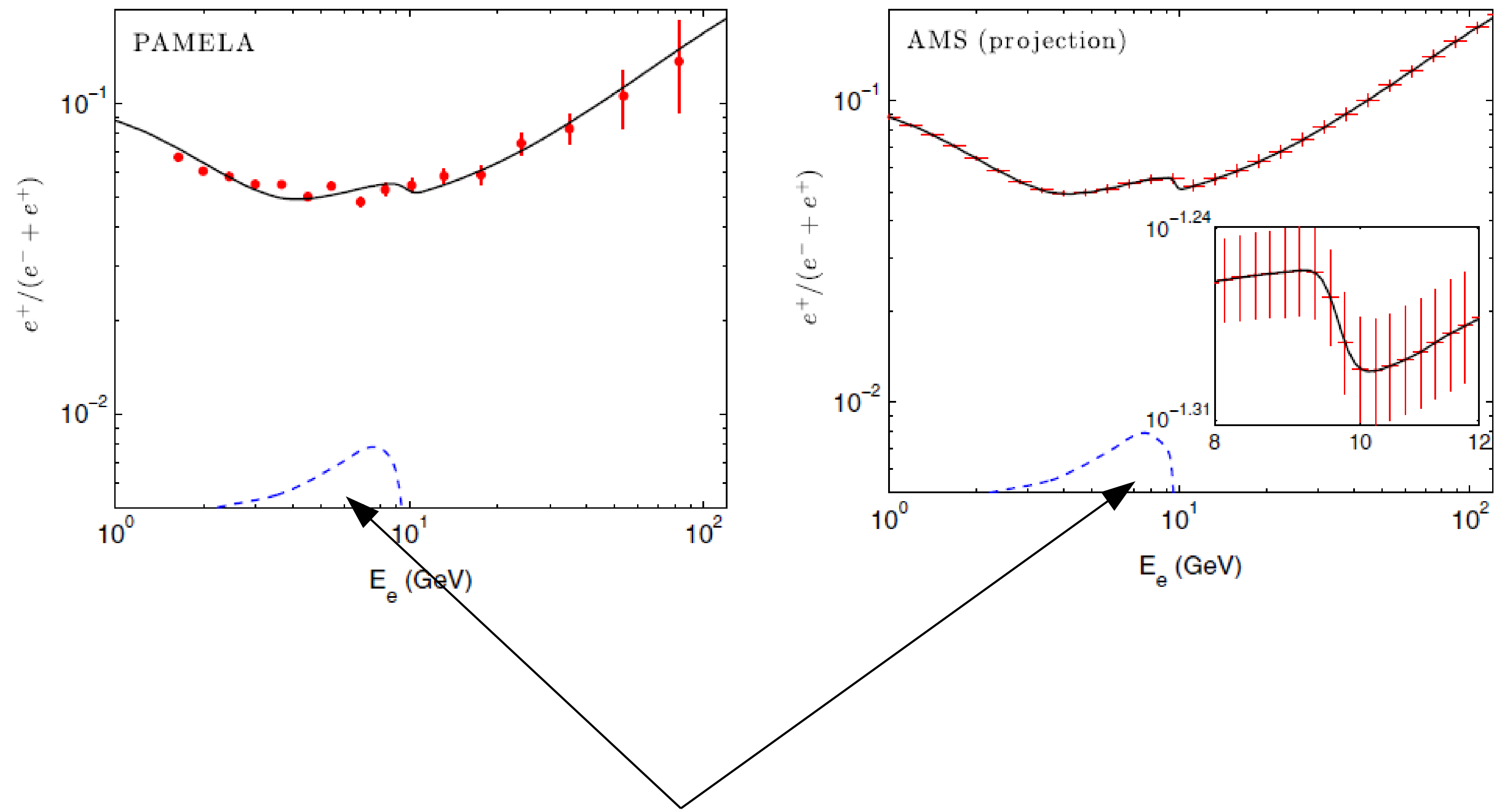
Protons



Positrons



Need better data...

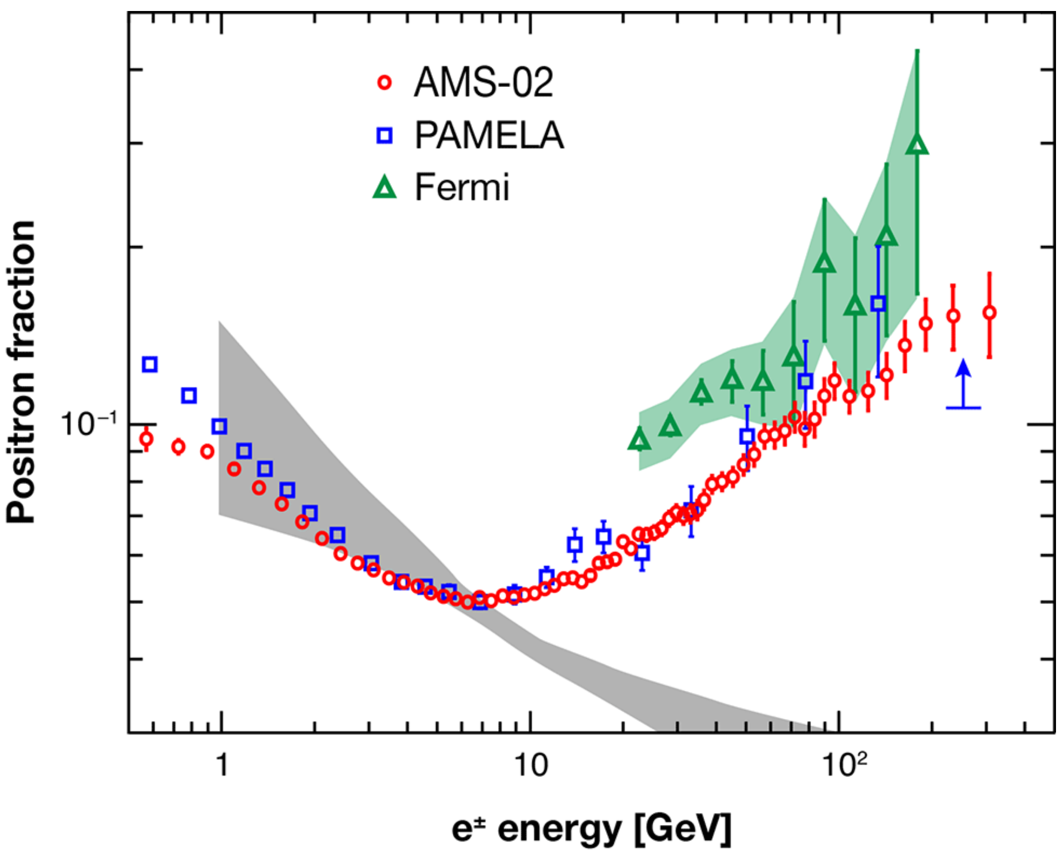


from a 10 GeV/c² KK WIMP annihilation

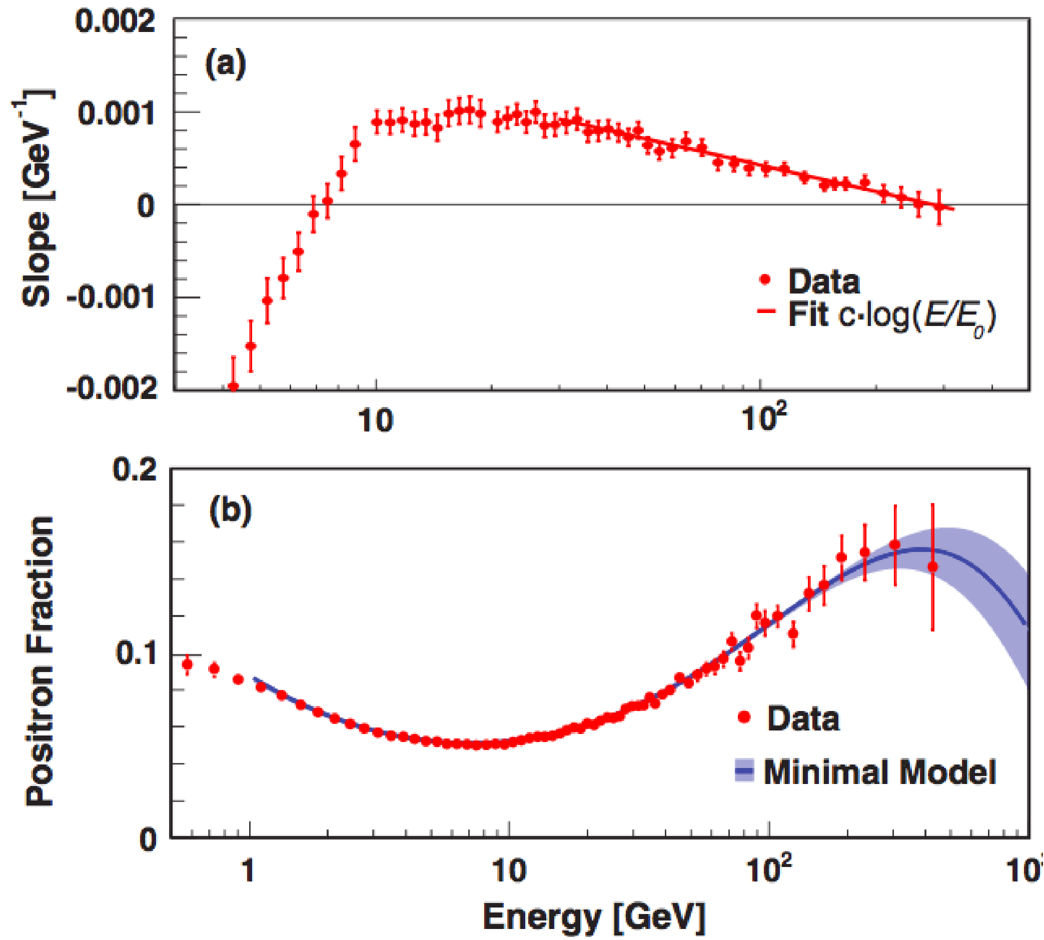

AMS @ ISS

AMS-02 result confirms PAMELA

2013



2014



– is the spectrum turning around??
– no features found in data!

Closing Thoughts: e^+ and $\bar{p}$

stolen from Pierre Salati, arXiv:1605.01218:

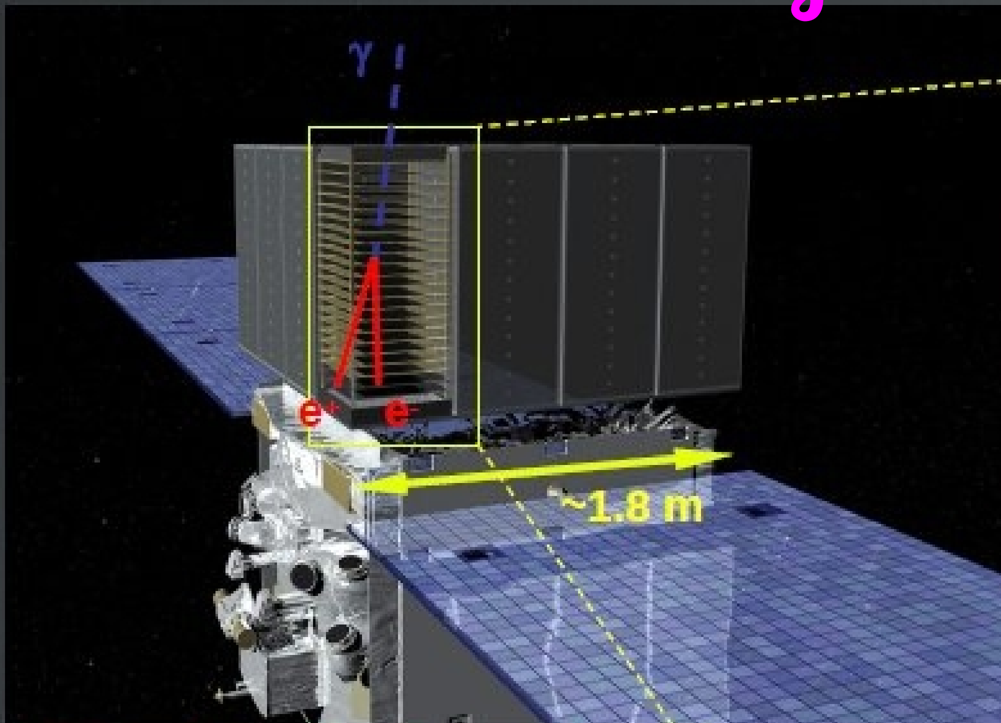
The [PAMELA] cosmic ray positron anomaly has been confirmed by the AMS-02 collaboration. It is difficult to explain this excess solely by DM annihilation. [...] The most plausible explanation has to be found in nearby pulsars.

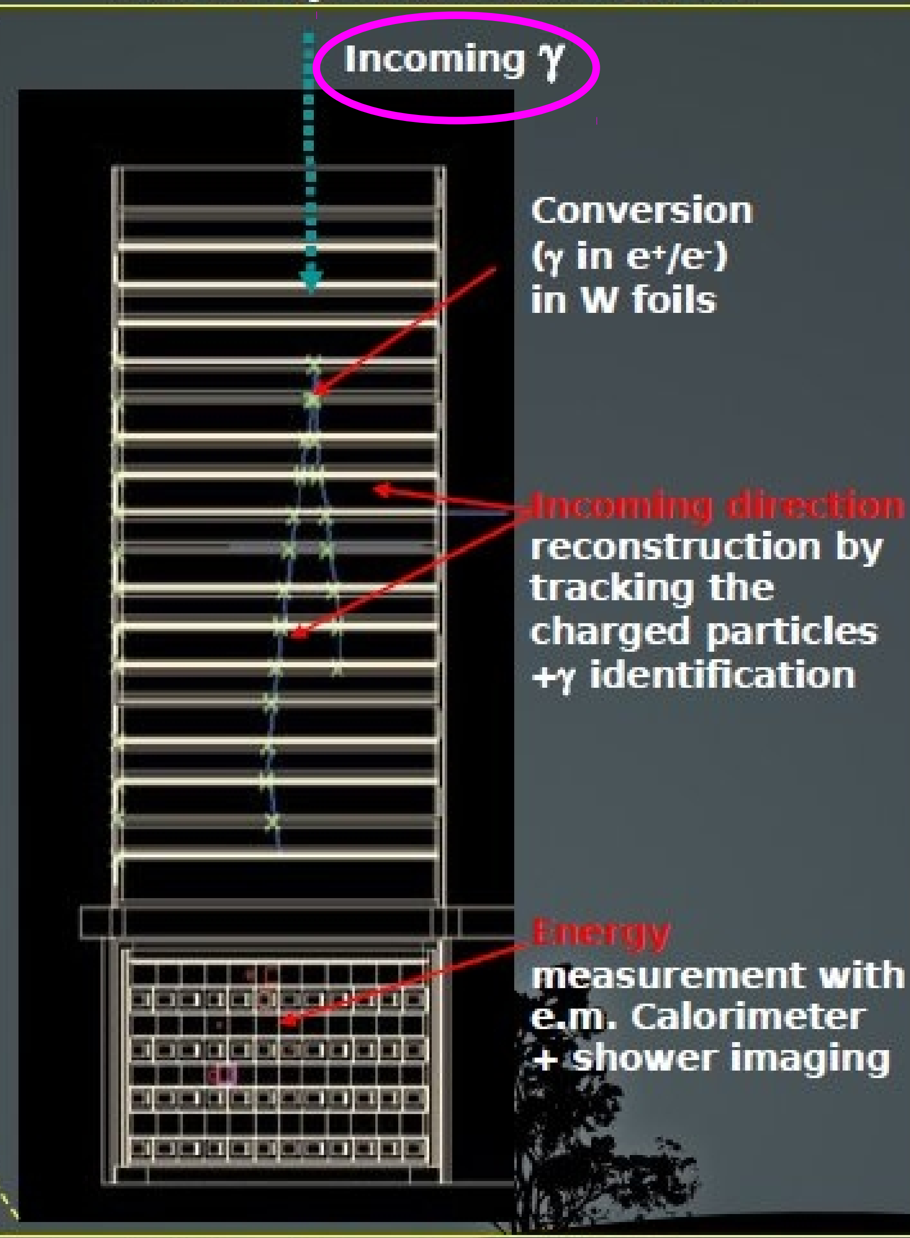
As regards antiprotons, the preliminary AMS-02 $\bar{p}/p$ ratio is compatible with a pure secondary component [=no DM], although the data are close to the upper edge of the expected background. To decide whether a DM signal is hidden, cosmic ray propagation needs to be better constrained and the antiproton production cross sections in pp and NN collisions should be more accurately measured.

FERMI – The LAT

γ-rays

Modular pair-conversion telescope
4 x 4 array of identical towers





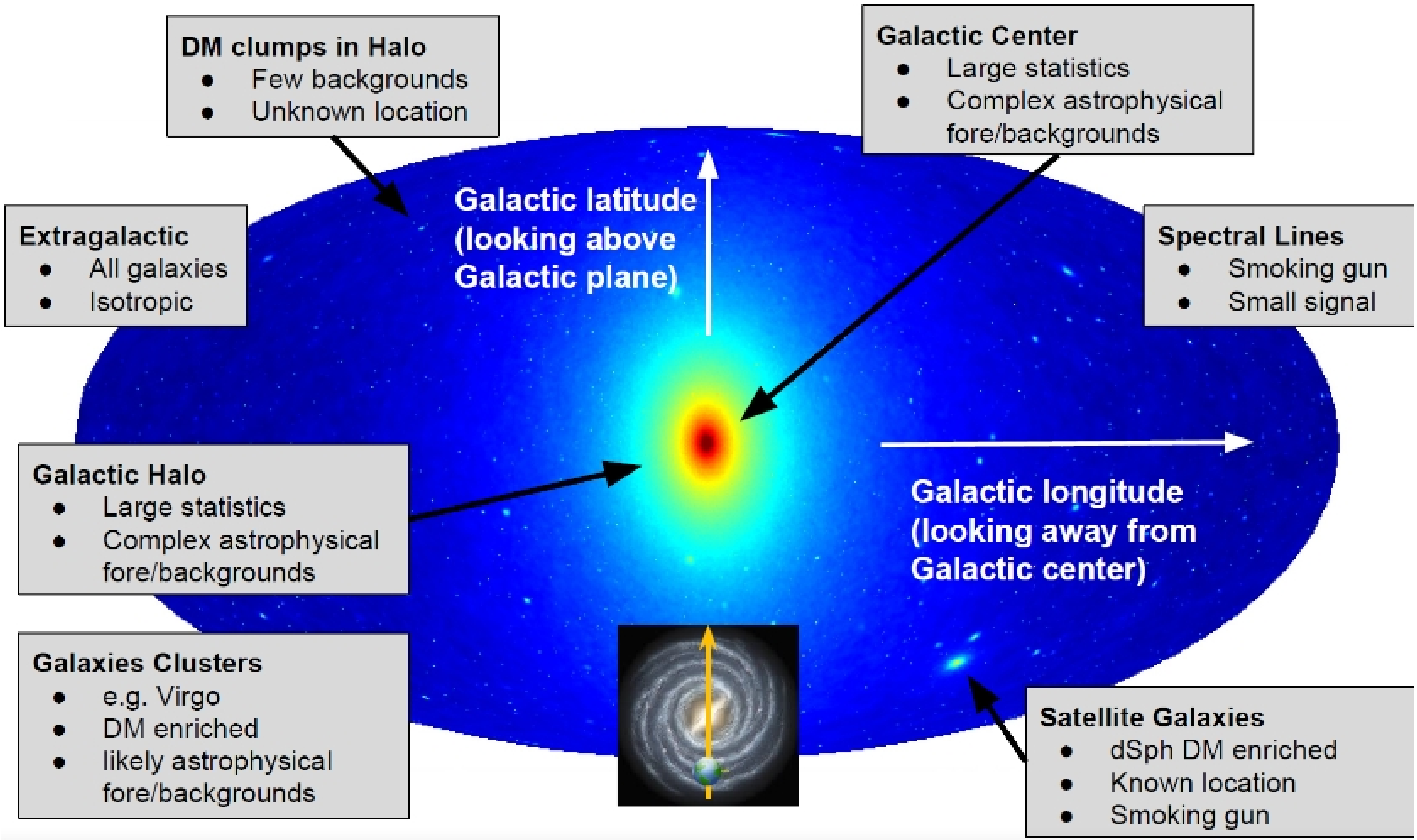
- **Precision Si-strip tracker :**
  Si-strip detector, W converter foils,
  80 m^2 of Si active area,
  1.5 radiation lengths on-axis.
- **Hodoscopic CsI calorimeter :**
  array of 1536 CsI(Tl) crystals in 8 layers.
  8.6 radiation lengths on-axis.
- **Segmented Anti-Coincidence Detector :**
  89 plastic scintillator tiles and 8 ribbons.
  charged particles veto (0.9997 average detection efficiency).

Fermi LAT Collaboration, APJ 697, 1071 (2009)

slide from E. Nuss

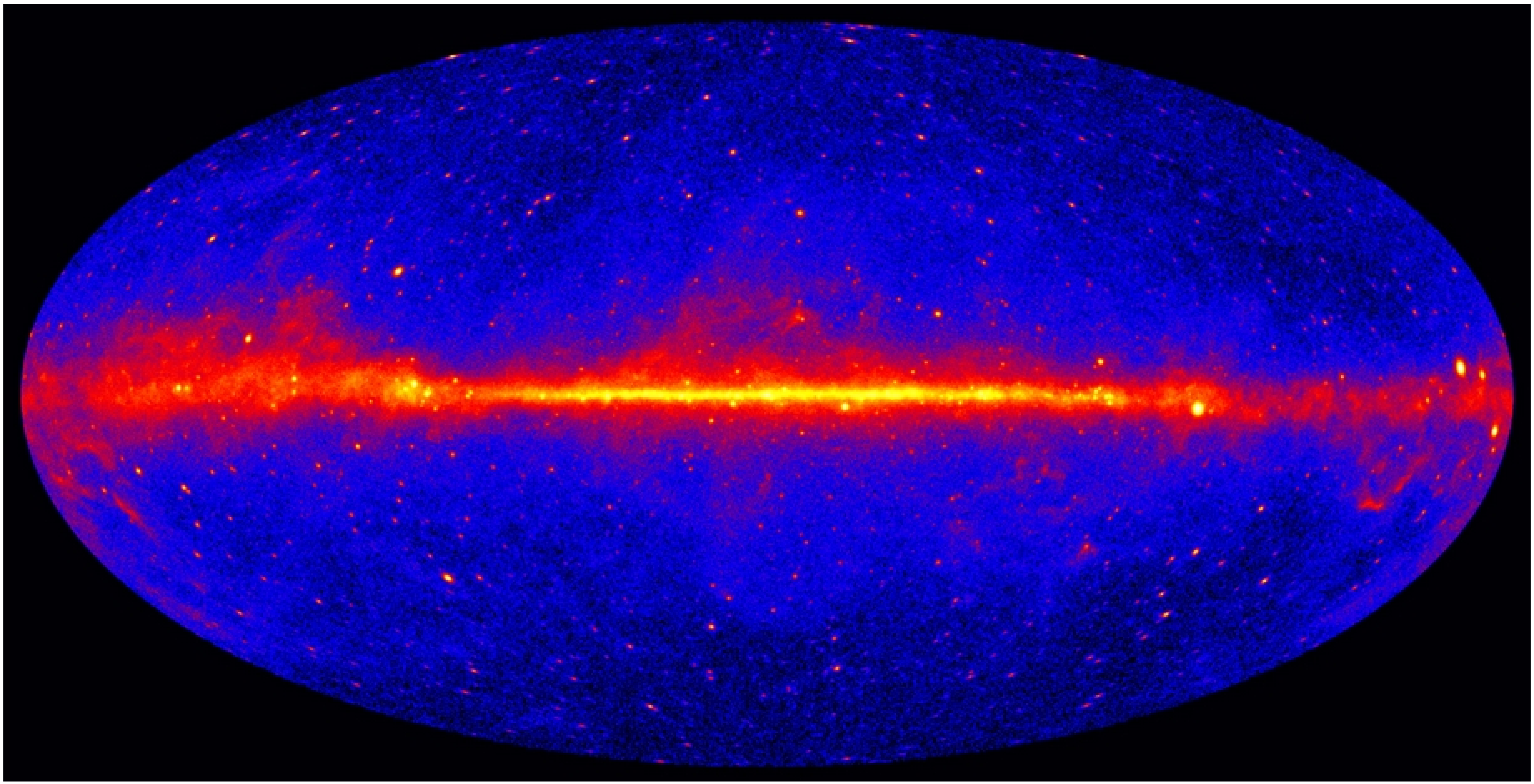
Where to search for gammas?

The dark matter Sky



slide from Olaf Reimer

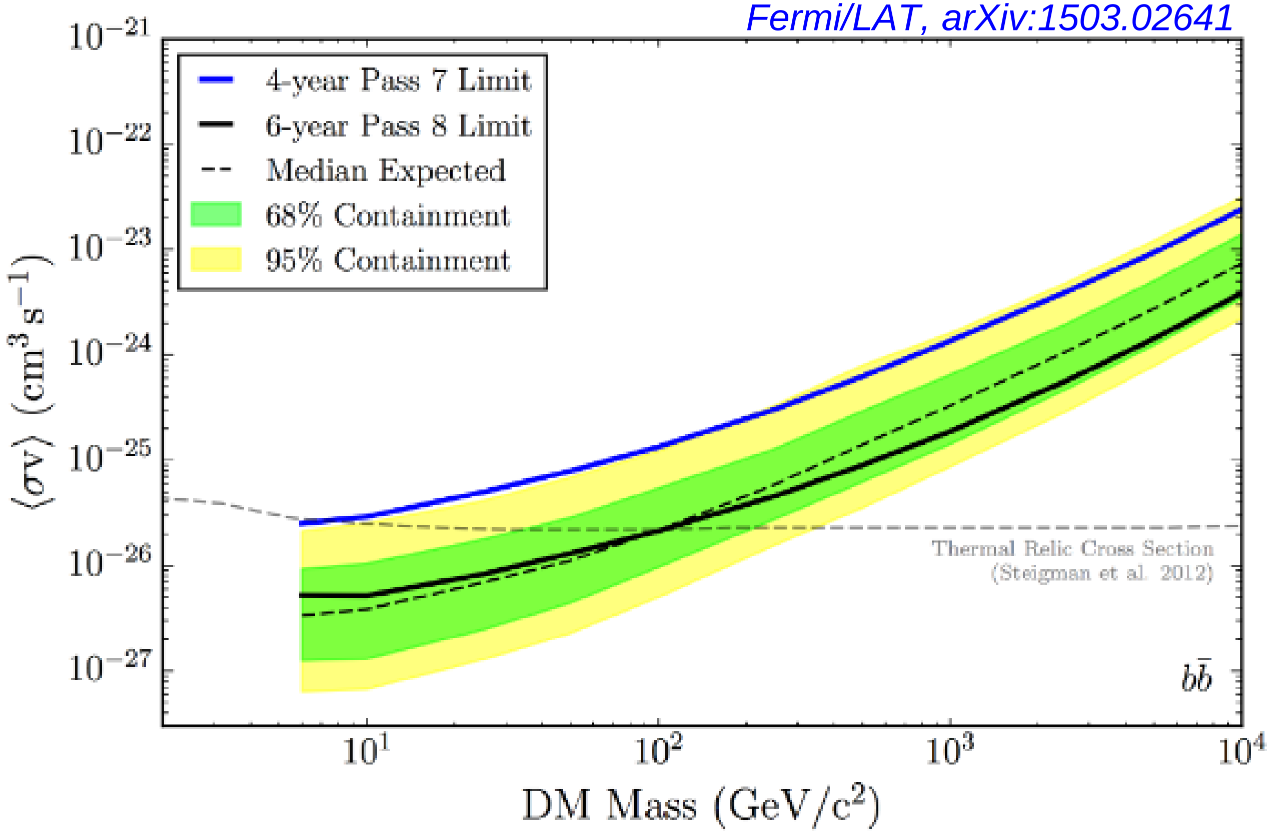
Fermi Gamma Sky



Dwarf Galaxies

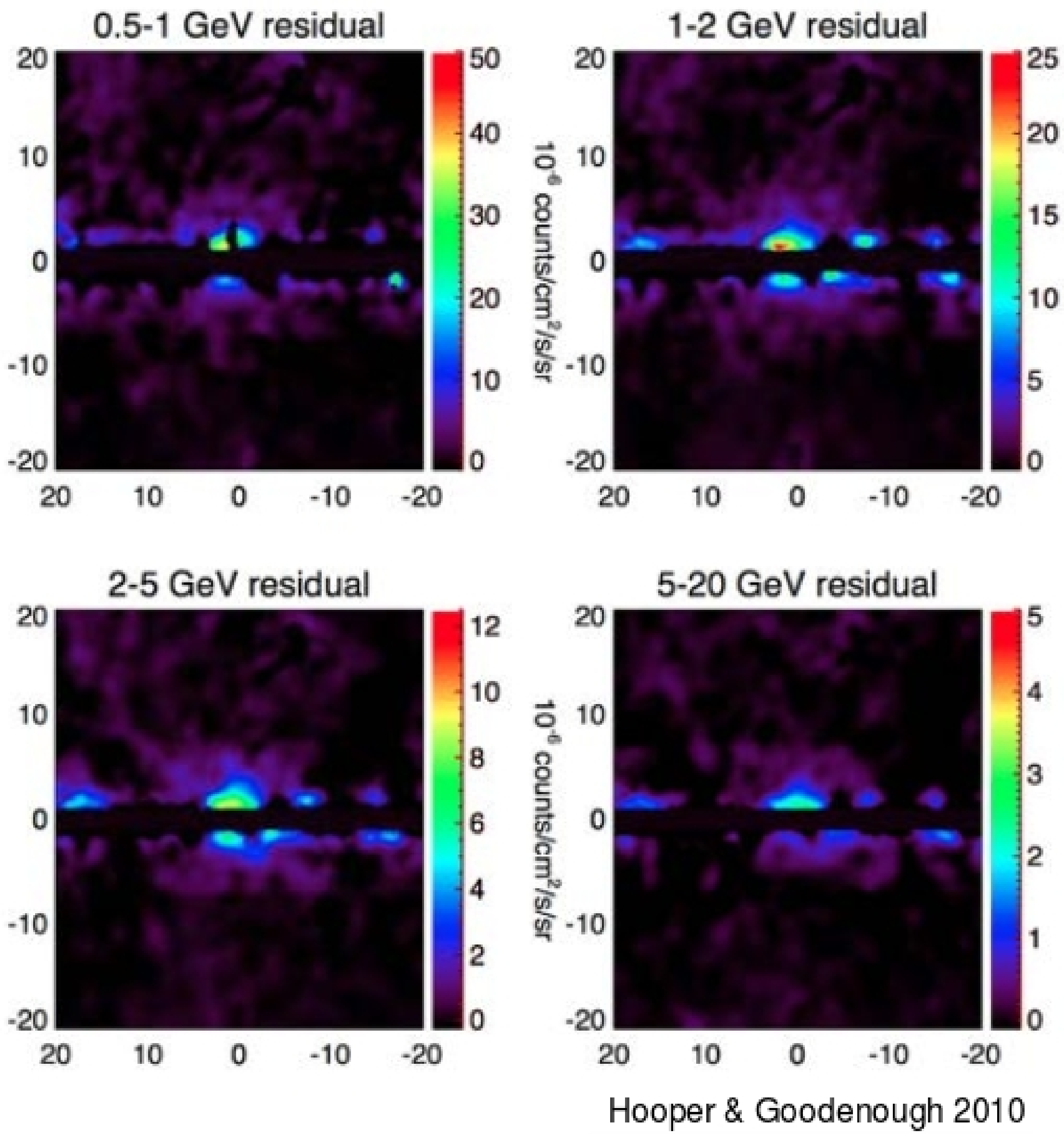
expect almost no background (DM only), but rather weak signal

Fermi/LAT, arXiv:1503.02641



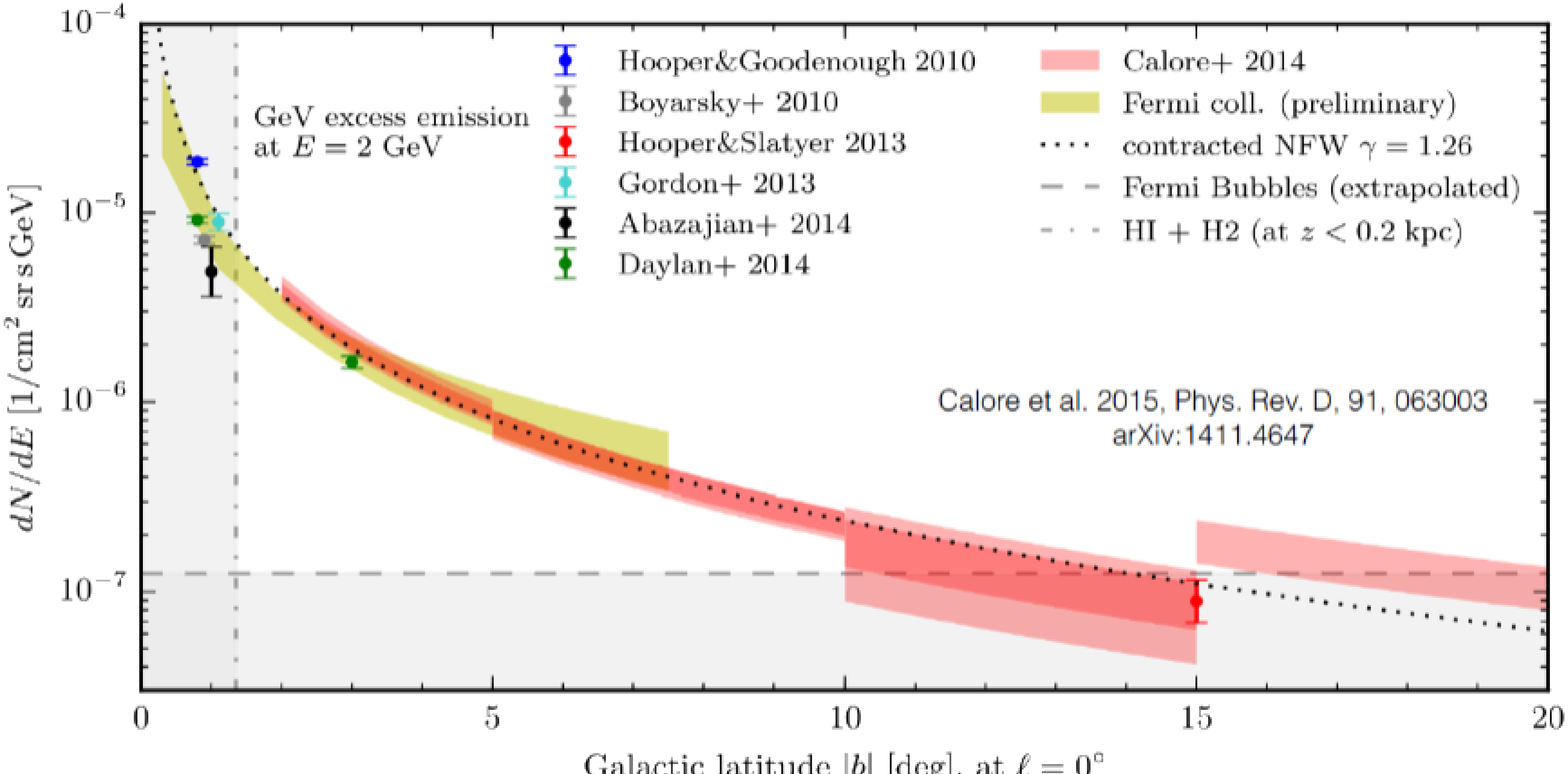
15 dSphs analyzed together, 6 year of Fermi data:
→ no indication of a signal

Galactic Center Excess



Galactic Center Excess

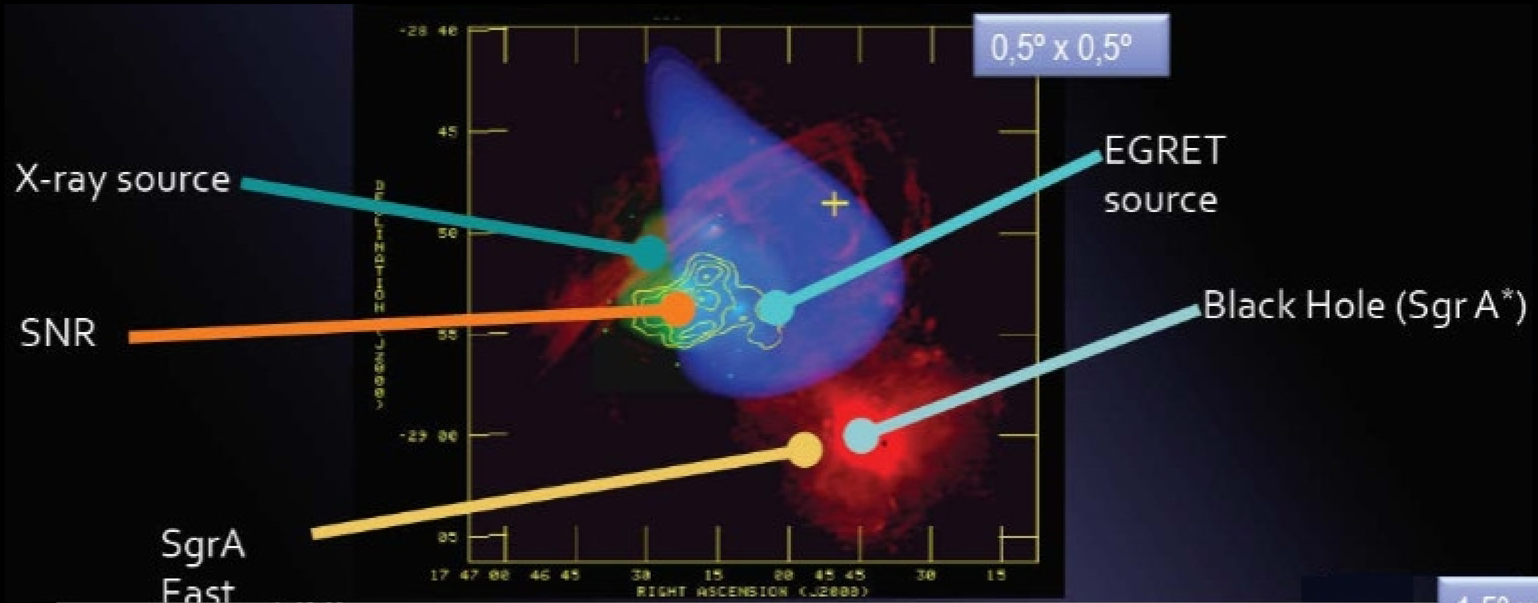
Many groups have reported a spatially extended excess of gamma-ray emission in the inner Galaxy peaking at ~2 GeV in E² dN/dE and consistent with a contracted NFW profile

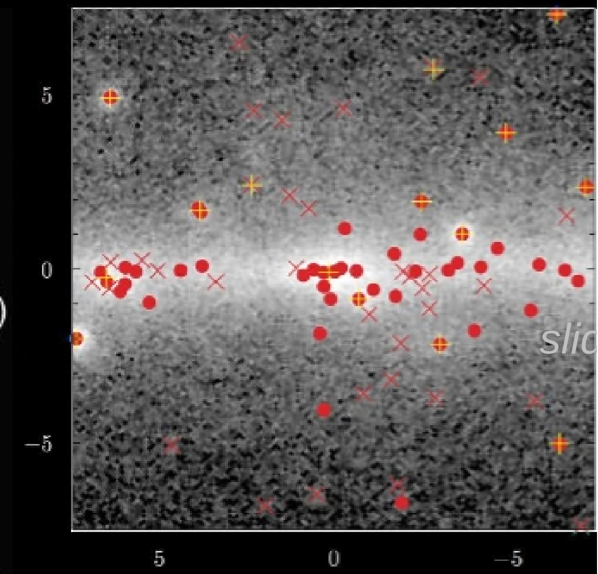


Spectrum, spatial profile, and inferred annihilation cross section are consistent with WIMP hypothesis within uncertainties — *can an astrophysical interpretation be excluded?*

slide from Olaf Reimer

Caveat: Modelling the diffuse astrophysical background is difficult





- GC is a crowded region
- modeling diffuse emission of all individual sources along line-of-sight is challenging
- what is the impact of astrophysical point sources?

slide from Olaf Reimer

X-ray line at 3.5 keV

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

[1402.2301]

We detect a weak unidentified emission line at E=(3.55-3.57)+/-0.03 keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01-0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is significantly detected in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the Chandra spectra of Perseus with the flux consistent with XMM (though it is not seen in Virgo)...

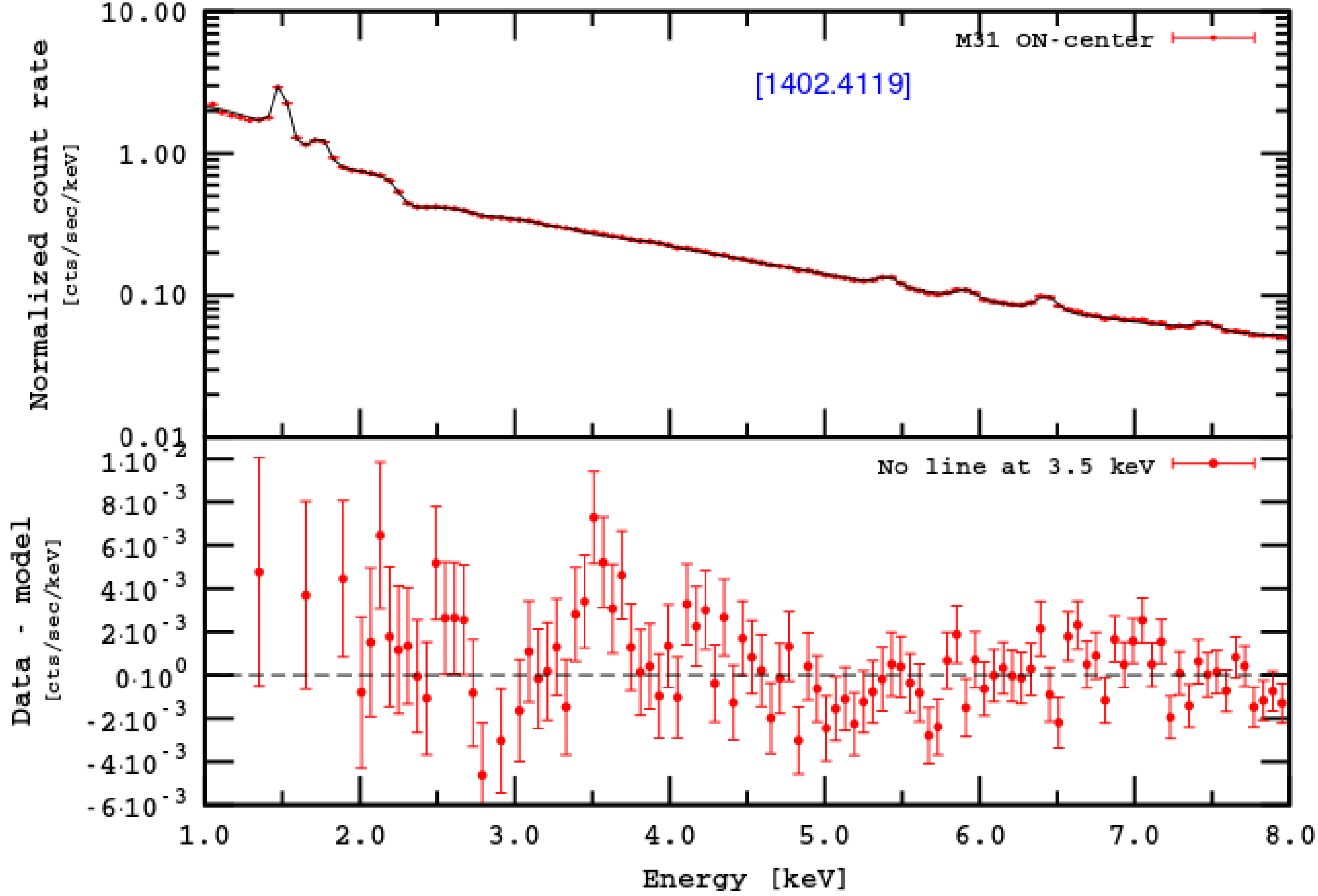
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switze

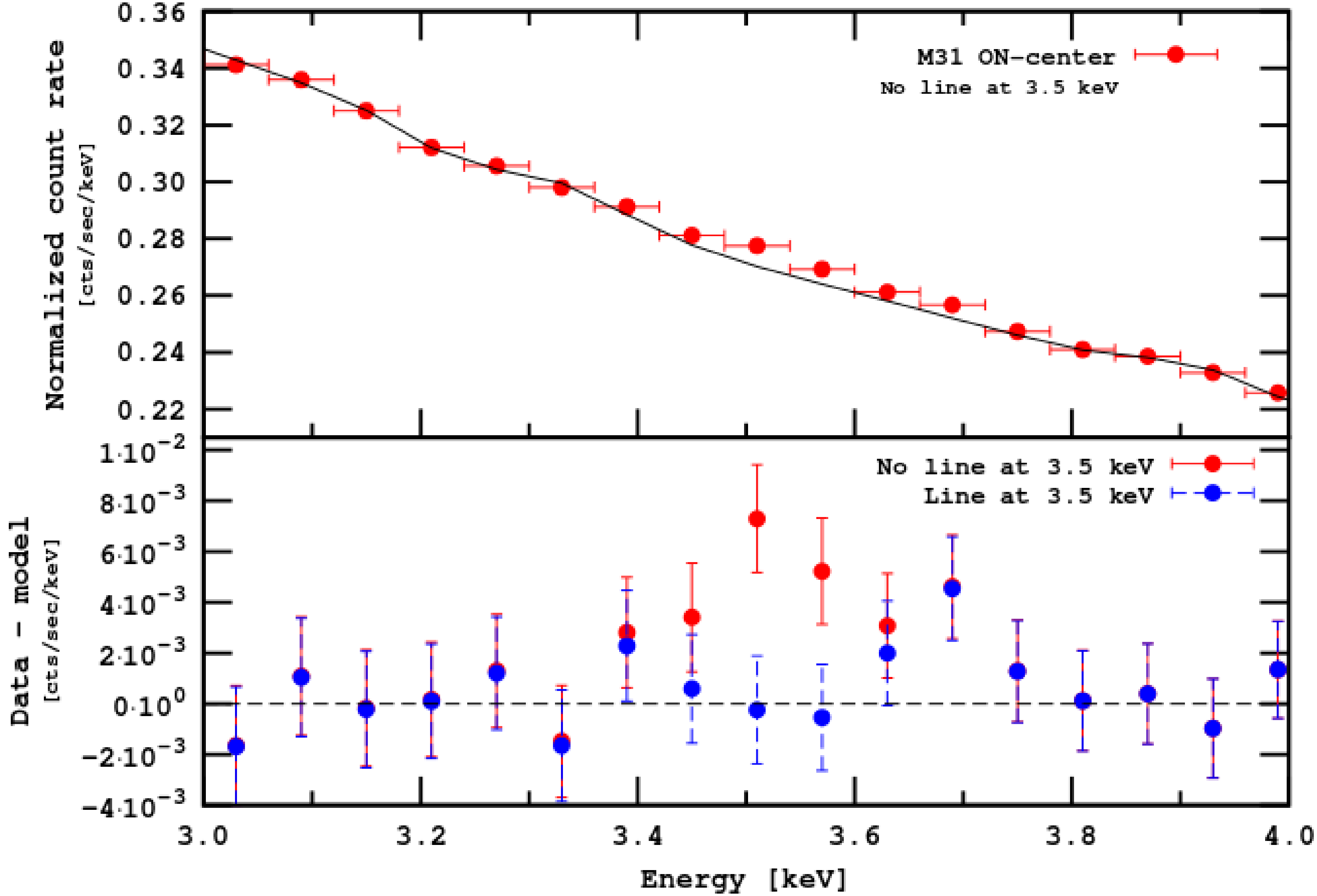
[1402.4119]

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset...

Andromeda Galaxy

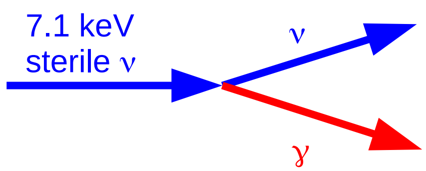


Andromeda Galaxy: Zoom



Possible new physics interpretations

- decaying gravitinos
- axino dark matter
- axions and ALPs
- light-nonthermal dark matter
- R-parity violating decays of keV sparticles
- sterile neutrinos



- millicharged dark matter
- eXciting dark matter
- etc etc etc

Or boring old things?
- unknown astrophysics
- atomic lines (known lines at 3.48 and 3.52 keV are included in fit)

No Conclusion yet

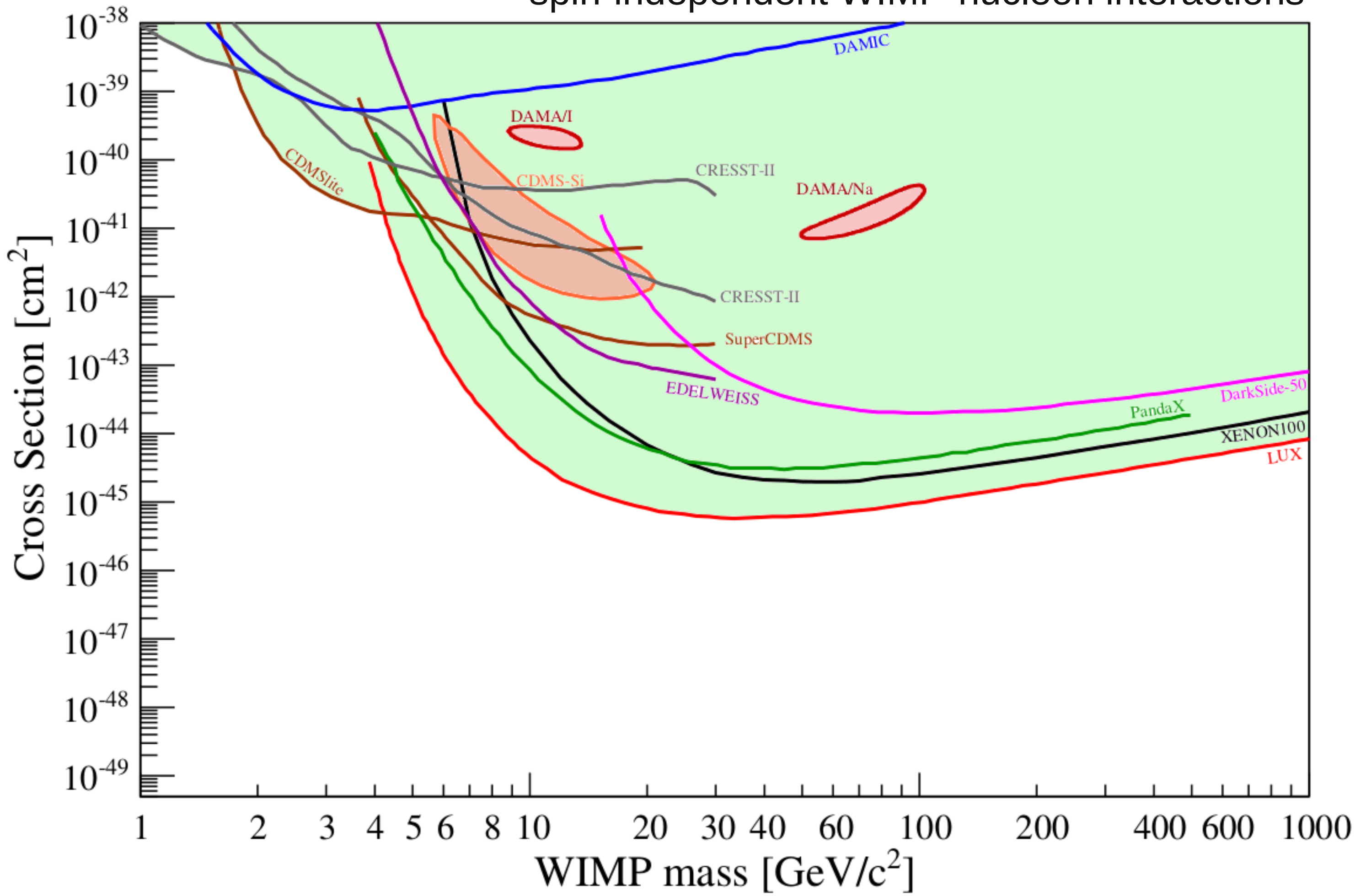
Target	Instrument	Significance (σ)	Reference
M31	XMM-Newton/MOS	3.2	Boyarsky 2014 1402.4119
Perseus Cluster (outskirts)	XMM-Newton/MOS XMM-Newton/PN	2.6 2.4	Boyarsky 2014 1402.4119
Perseus Cluster (center)	Chandra/ACIS	3.5	Bulbul 2014 1402.2301
Perseus Cluster (center)	Suzaku	3	J. Franse (TAUP 2015)
Galactic Center	XMM-Newton/MOS	5.7	Boyarksy 2014 1408.2503
73 Stacked Clusters (z<0.4)	XMM-Newton/MOS XMM-Newton/PN	5 4	Bulbul 2014 1402.2301
8 Stacked dSphs	XMM-Newton/MOS XMM-Newton/MOS	Non-detection	Malyshev et al. 2015 1408.3531
M31	Chandra/ACIS	Non-detection	Horiuchi et al. 2014 1311.0282
Blank Sky	XMM-Newton/MOS	Non-detection	Boyarsky 2014 1402.4119

Not a consensus, see, e.g., Jeltema & Profumo 2015, MNRAS, 450, 2143 (arXiv:1408.1699)

table from Olaf Reimer

Direct Detection

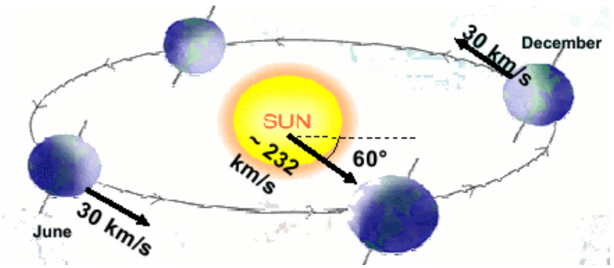
spin-independent WIMP-nucleon interactions



some results are missing...

The DAMA/LIBRA Modulation

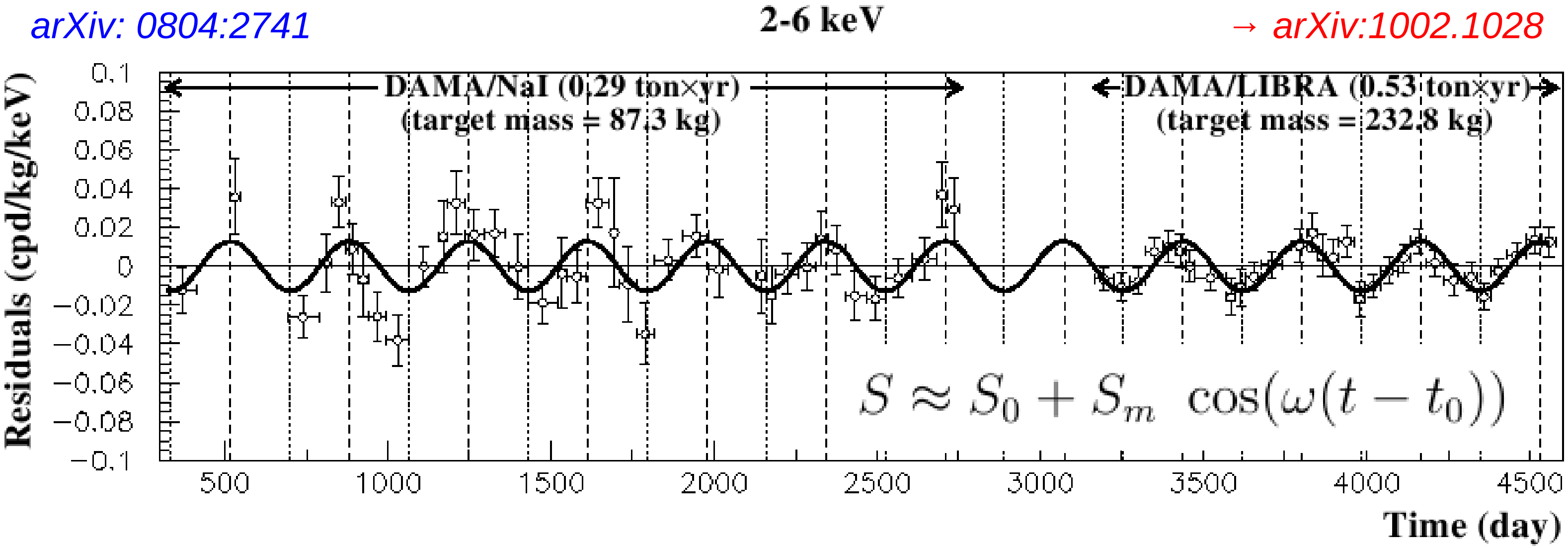
- DAMA: PMTs coupled to NaI Scintillators
  ➡ extremely low background necessary
- looks for annual modulation @ LNGS
- large mass and exposure: 0.82 ton years



- DAMA finds annual modulation @ 8.9σ
- BUT: result cannot be explained with standard neutralinos or KK Dark Matter, result in conflict with other experiments

arXiv: 0804:2741

→ arXiv:1002.1028

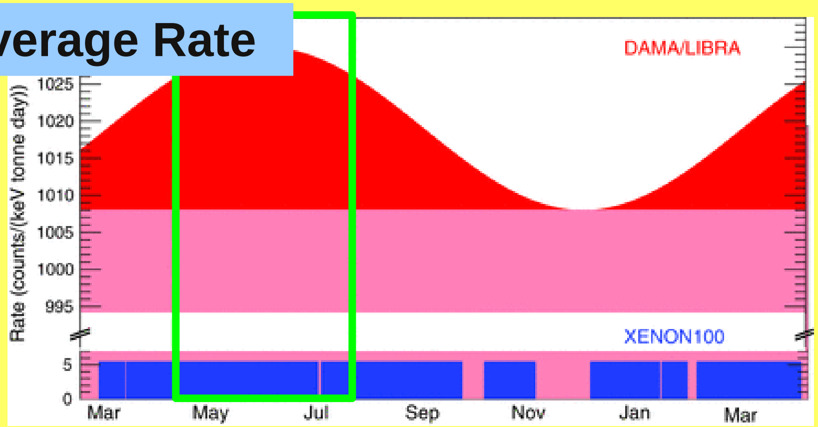


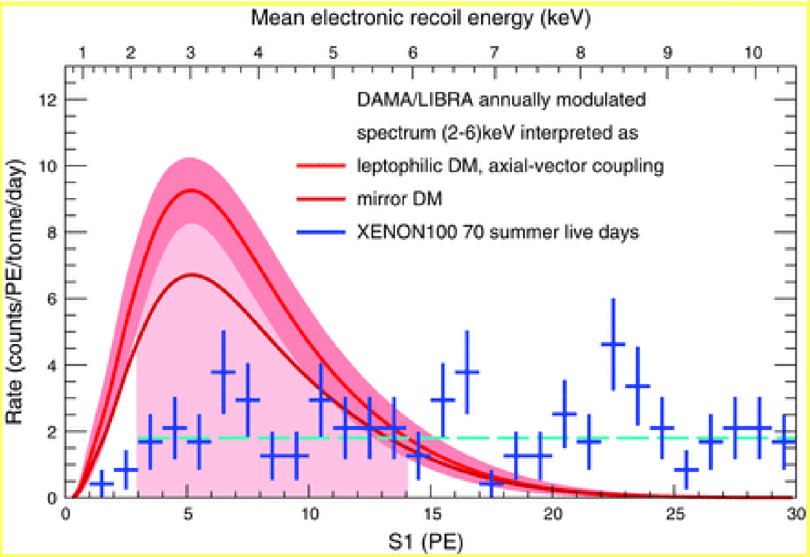
DAMA vs XENON

Science 349, 851 (2015)

PRL 115, 091302 (2015)

Average Rate





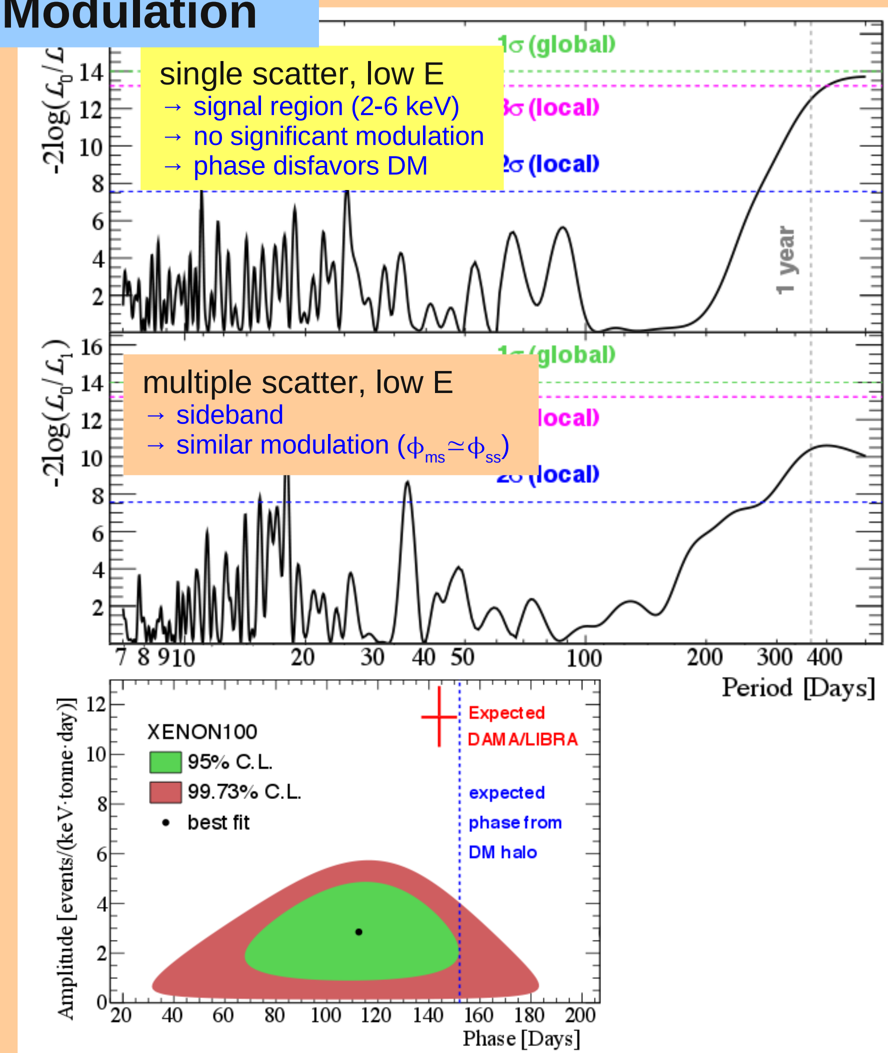
XENON100 excludes DAMA as being due to

– WIMP-e⁻ axial-vector couplings at **4.4σ**

– luminous dark matter at **4.6σ**

– mirror dark matter at **3.6σ**

Modulation



→ exclude DAMA/Libra as being induced by axial-vector WIMP-electron couplings at **4.8σ**

Modulation also directly tested by KIMS, CoGeNT, CDMS-II; upcoming: SABRE, DMIce/Anais

Upcoming NaI Projects

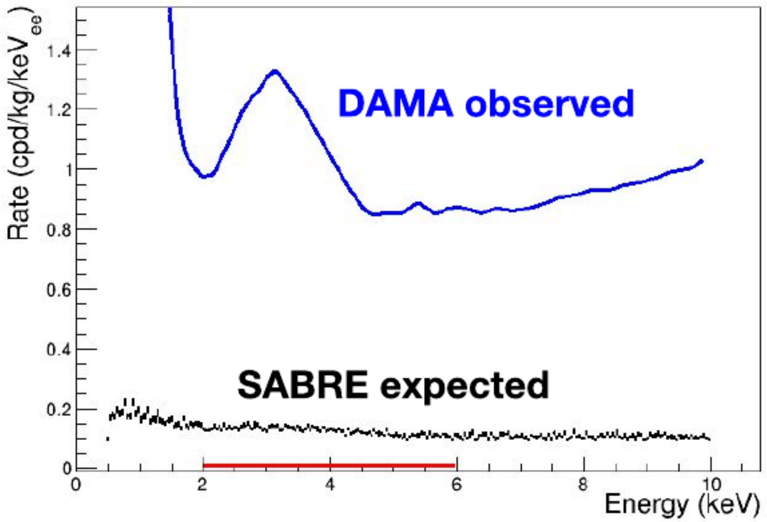
aim at testing the DAMA claim using the same target/detector
→ main challenges: crystal purity, low threshold, target mass

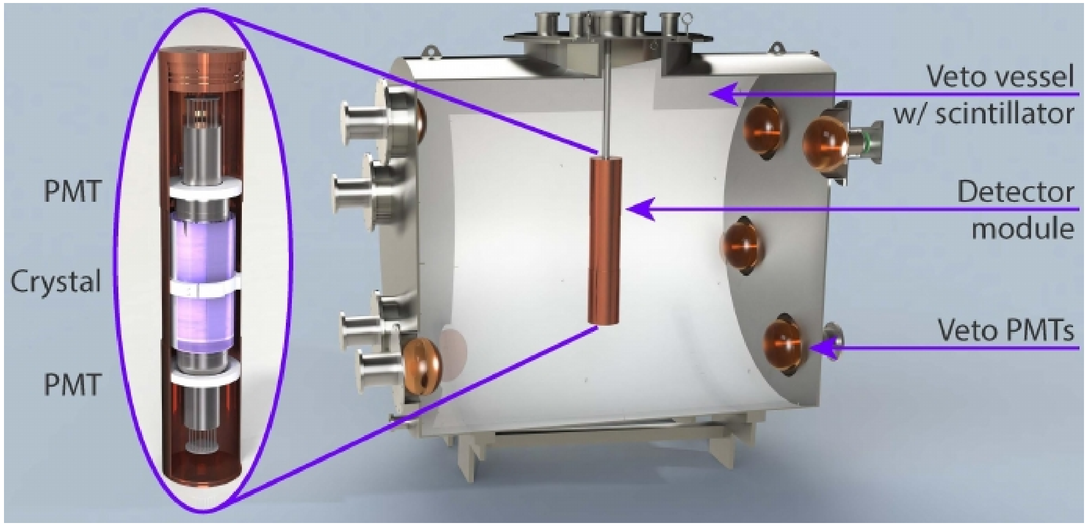
SABRE B. Suerfu (UCLA DM 2016)
*S*odium-iodine with *A*ctive *B*ackground *RE*jection

Strategy:

- lower background: better crystals ✓, PMTs
- liquid scintillator veto against ^{40}K (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- North (LNGS) and South (Australia)

- *Status*: tests with 5kg crystals ongoing at LNGS



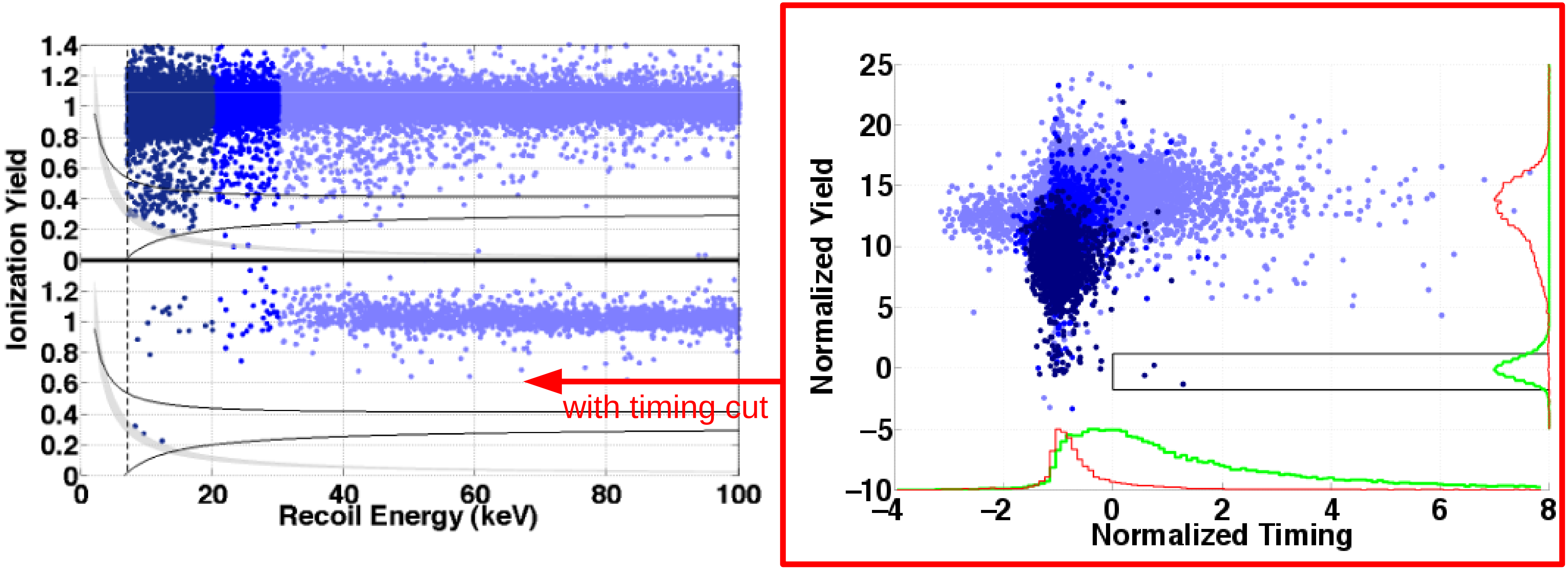


other: **DM-Ice + KIMS-NaI + ANAIS**
DM-Ice: 17 kg @ South Pole
arxiv:1602.05939

DM-Ice: 55kg @ Yangyang
KIMS: 52 kg @ Yangyang
ANAIS: 113 kg @ Canfranc
→ start data taking by June 2016
→ background 2-3x DAMA (no veto)

CDMS-II: Silicon Detectors

PRL. 111 (2013) 251301

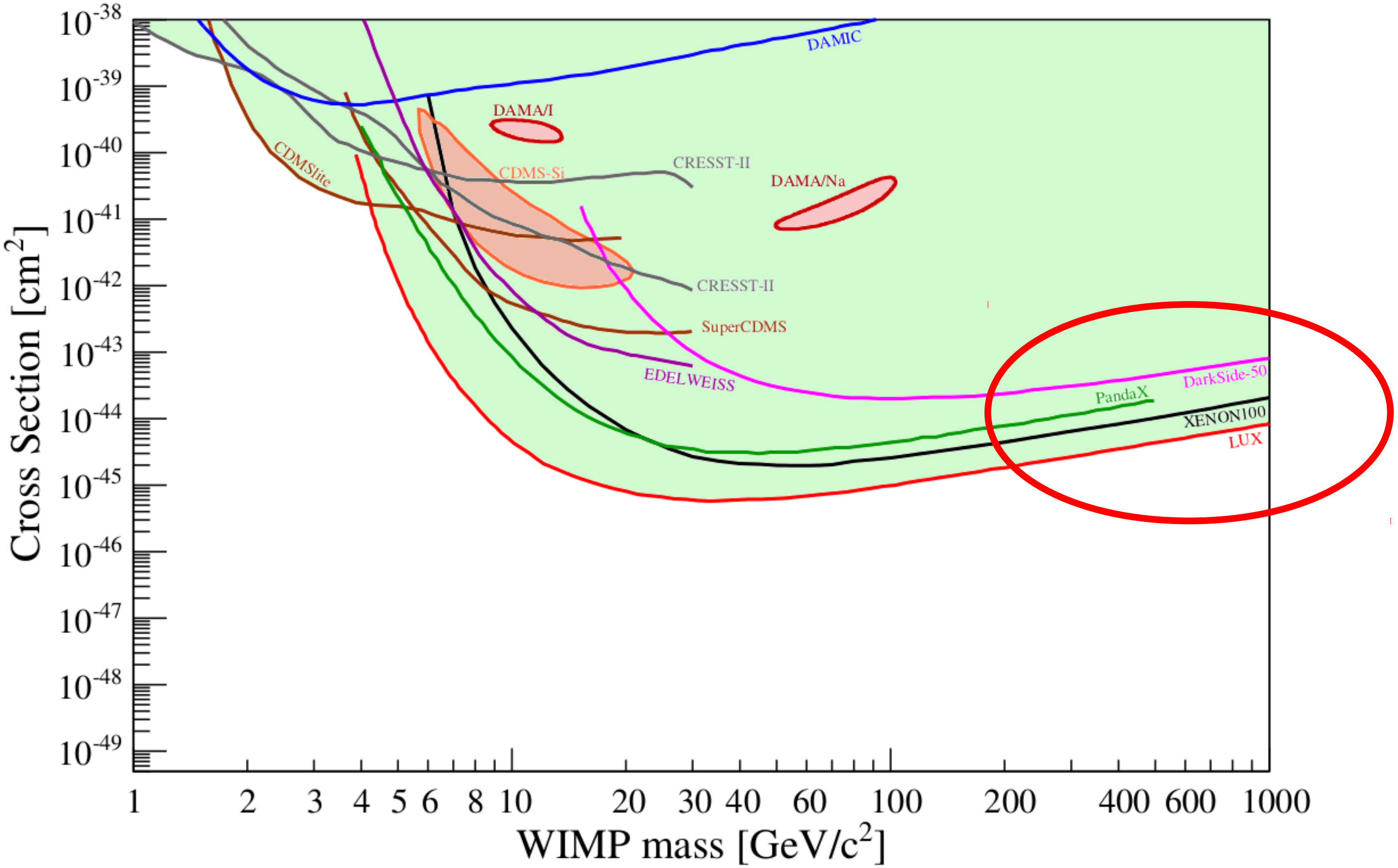


- 140 kg x days of data from cryogenic silicon detectors
- data acquired 2007-2008
- background prediction ~0.5 event
- blind analysis reveals **3 candidate events** (→ Poisson likelihood is 5.4%)

CDMS @ APS 2013:
„We do not believe this result rises to the level of a discovery, but does call for further investigation“

High WIMP-masses TPC dominated

≥4.5 GeV/c²



some results are missing...

Existing dual phase detectors

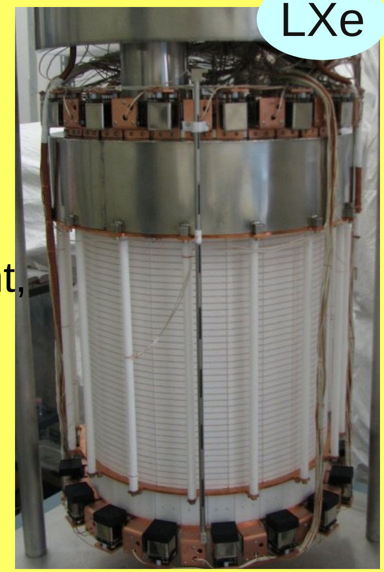
XENON100 @ LNGS (IT)

LXe

Astropart. Phys. 35, 573 (2012)

- **62 kg** LXe, 225×34kg exposure
- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, ...

- still running as testbench

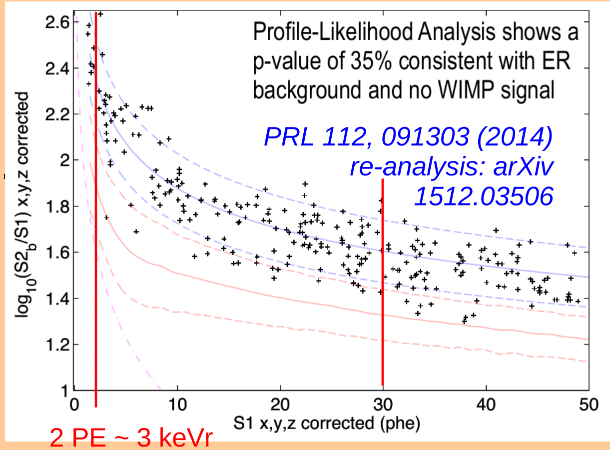


LUX @ SURF (USA)

LXe

NIM A 704, 111 (2013)

- best limit above ~6 GeV/c²
- **250 kg** LXe: 85d×118kg exp.
- high LY
- currently taking data



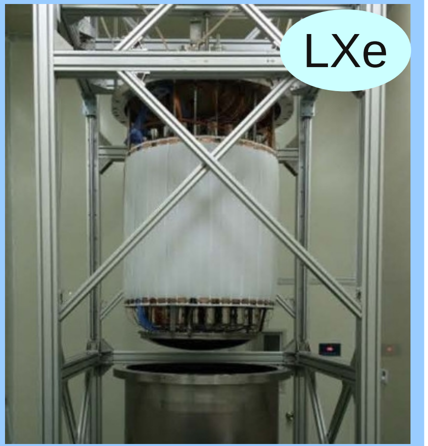
2 PE ~ 3 keVr

PandaX-II @ CJPL (CN)

LXe

arXiv:1602.06563

- the (currently) largest LXe TPC taking data
- new SS cryostat → lower radioactivity
- TPC: 60cm×60cm, **500 kg** target



First result from commissioning run

- 306 kg × 19d exposure; no signal excess

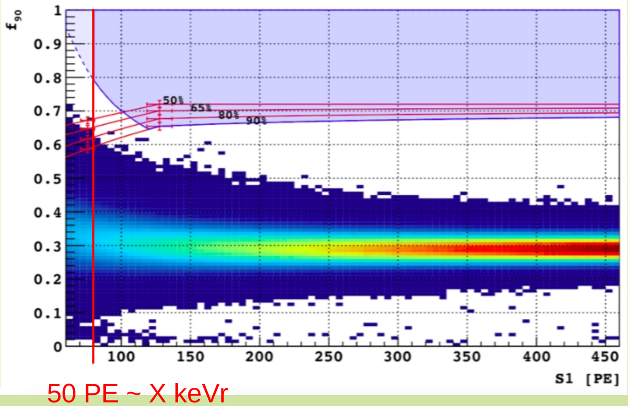
DarkSide-50 @ LNGS (IT)

LAr

arXiv:1510.00702

- **46 kg** ^{39}Ar-depleted LAr (factor 1400)
- 71d×37kg
- no event in search region
- taking data

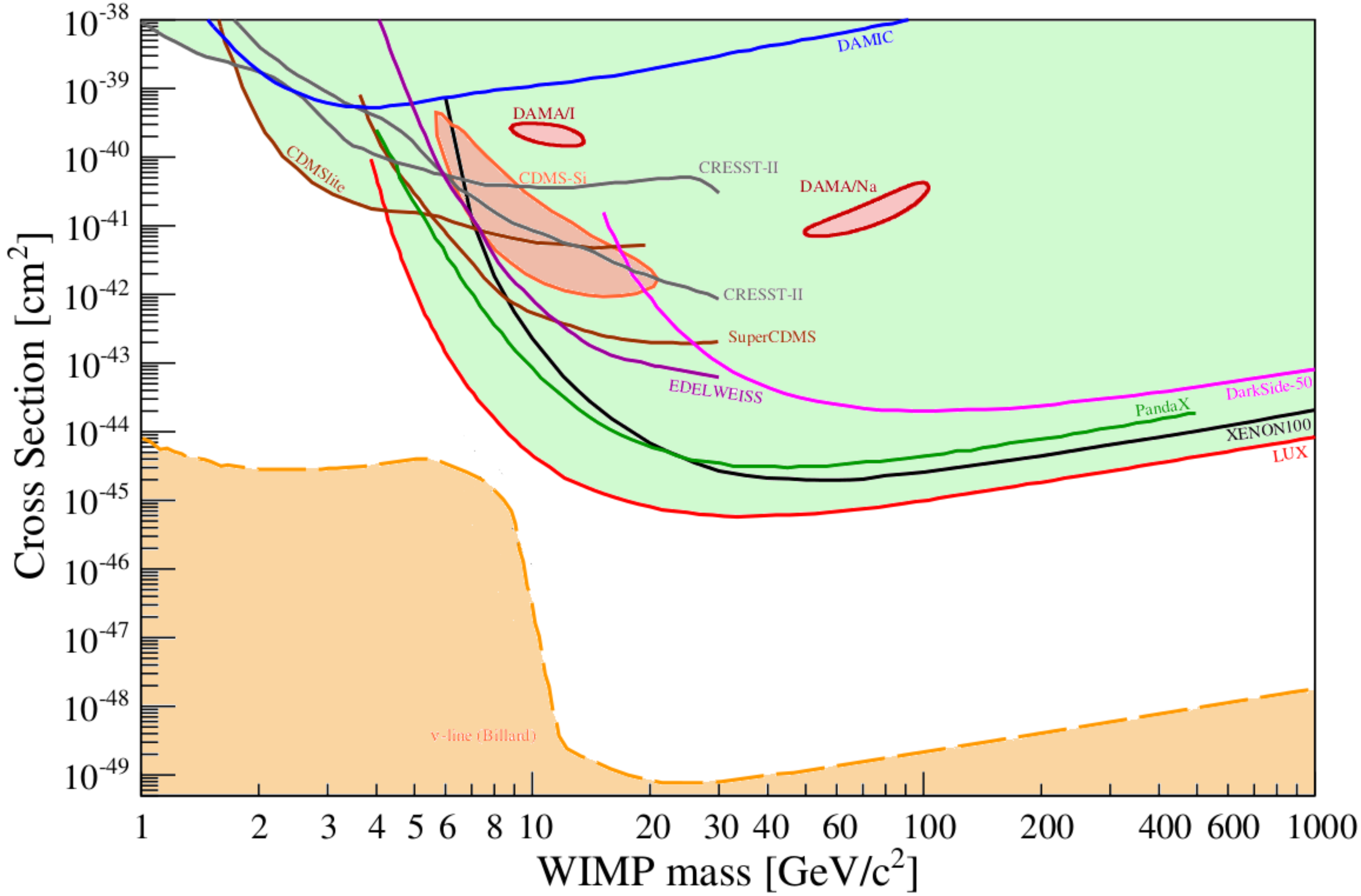
- proposal for DarkSide-20t



50 PE ~ X keVr

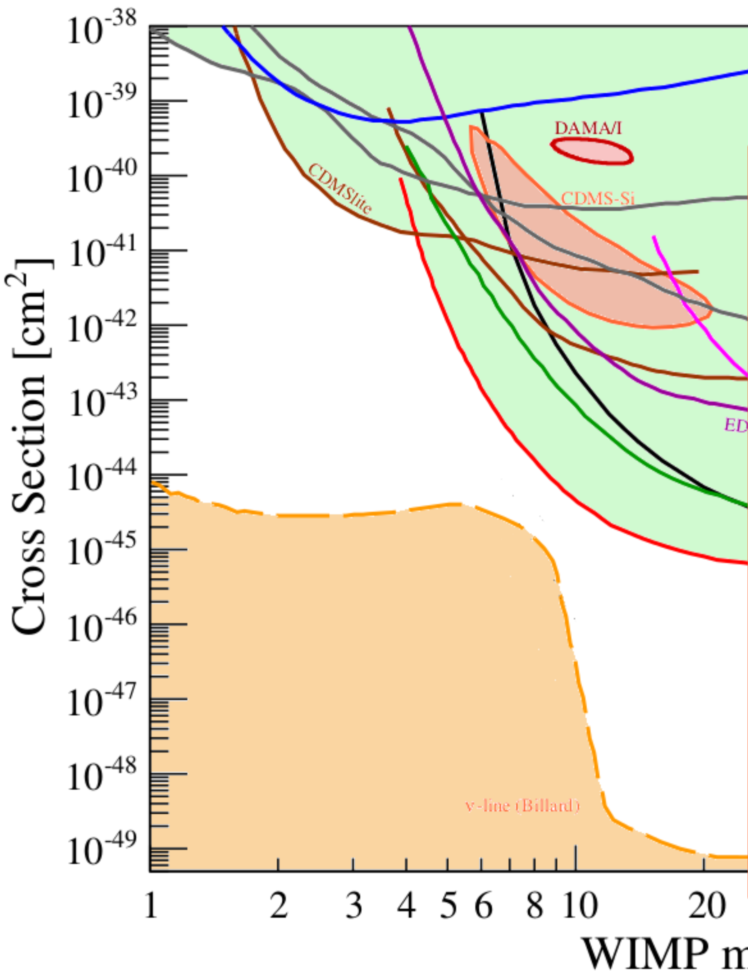
The ultimate limit for direct detection

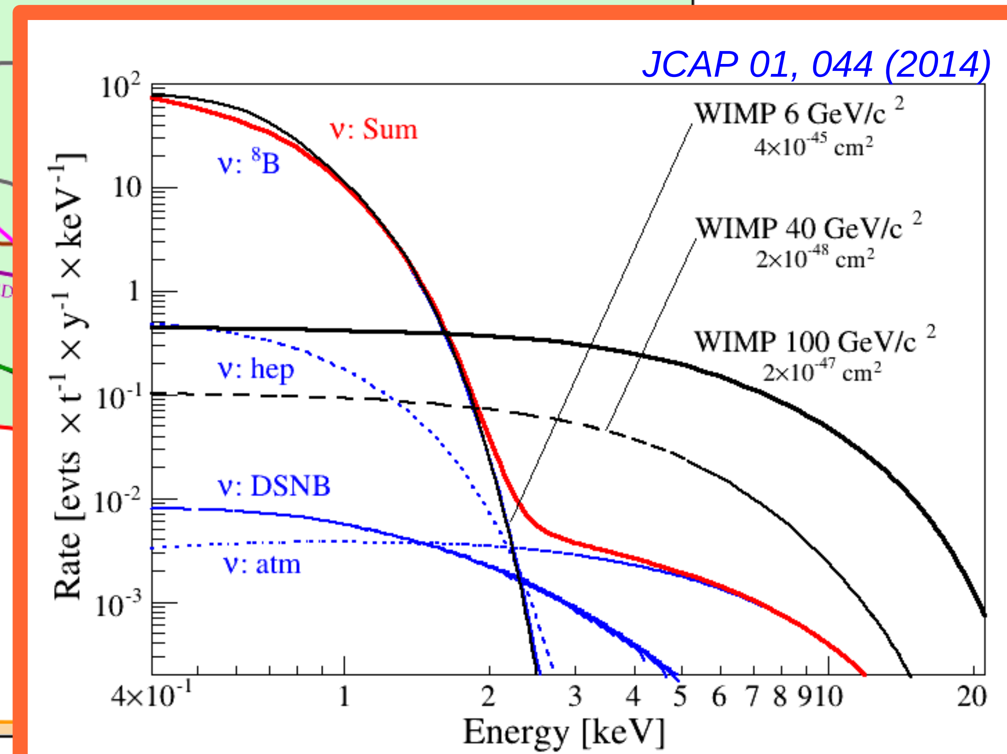
→ with directional information, it is in theory possible to go beyond...



The ultimate limit for direct detection

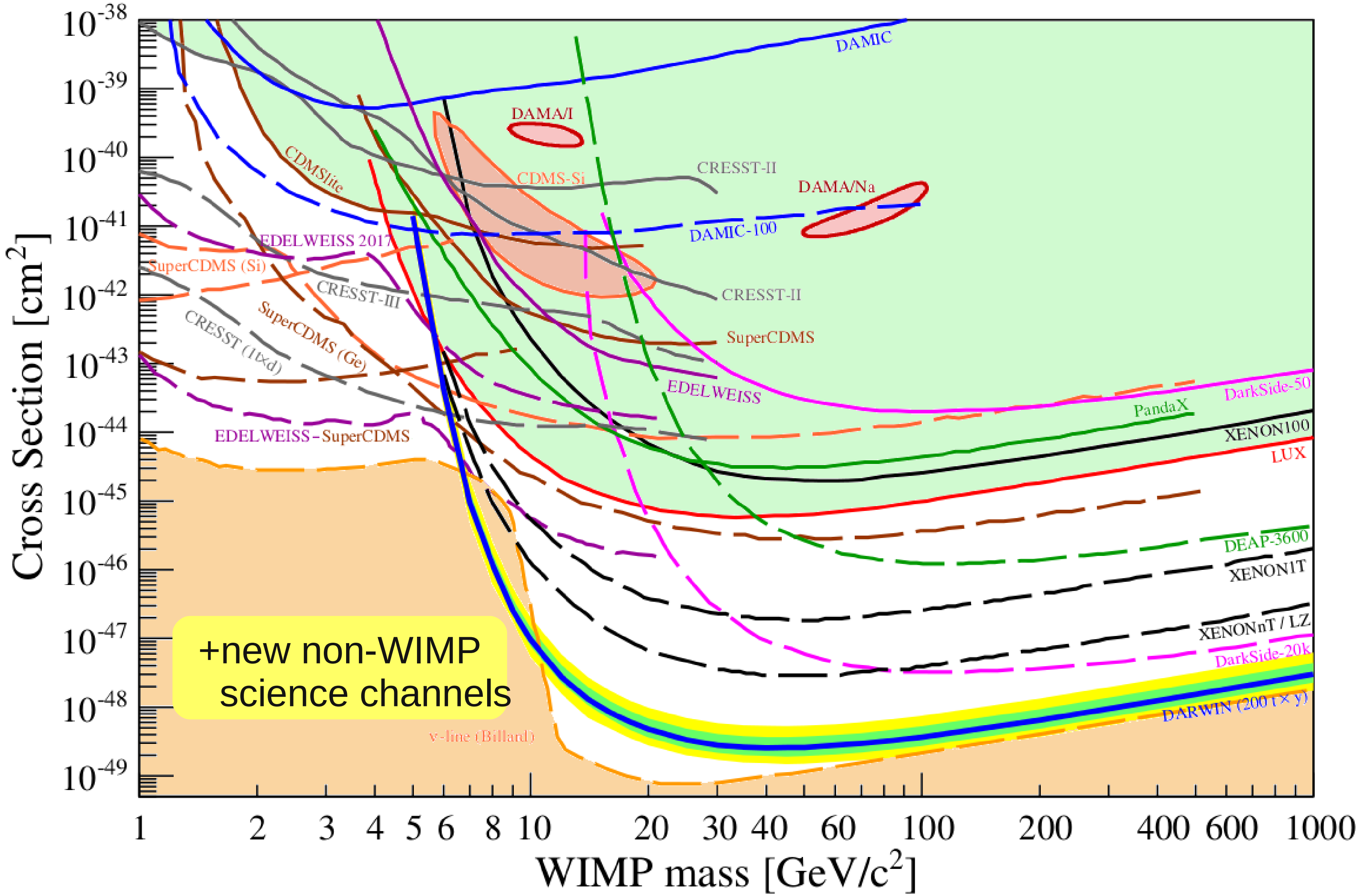
→ with directional information, it is in theory possible to go beyond...





Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection

The Future



Present

Future

contact: *marc.schumann@lhep.unibe.ch*