

Astrofizyka cząstek

prof. dr hab. A.F.Żarnecki

Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład VI

- bezpośrednie poszukiwania ciemnej materii - uzupełnienie LUX
- pośrednie sygnały ciemnej materii: źródła i modelowanie
- detektor LAT na satelicie FERMI
- teleskopy promieniowania Czerenkowa

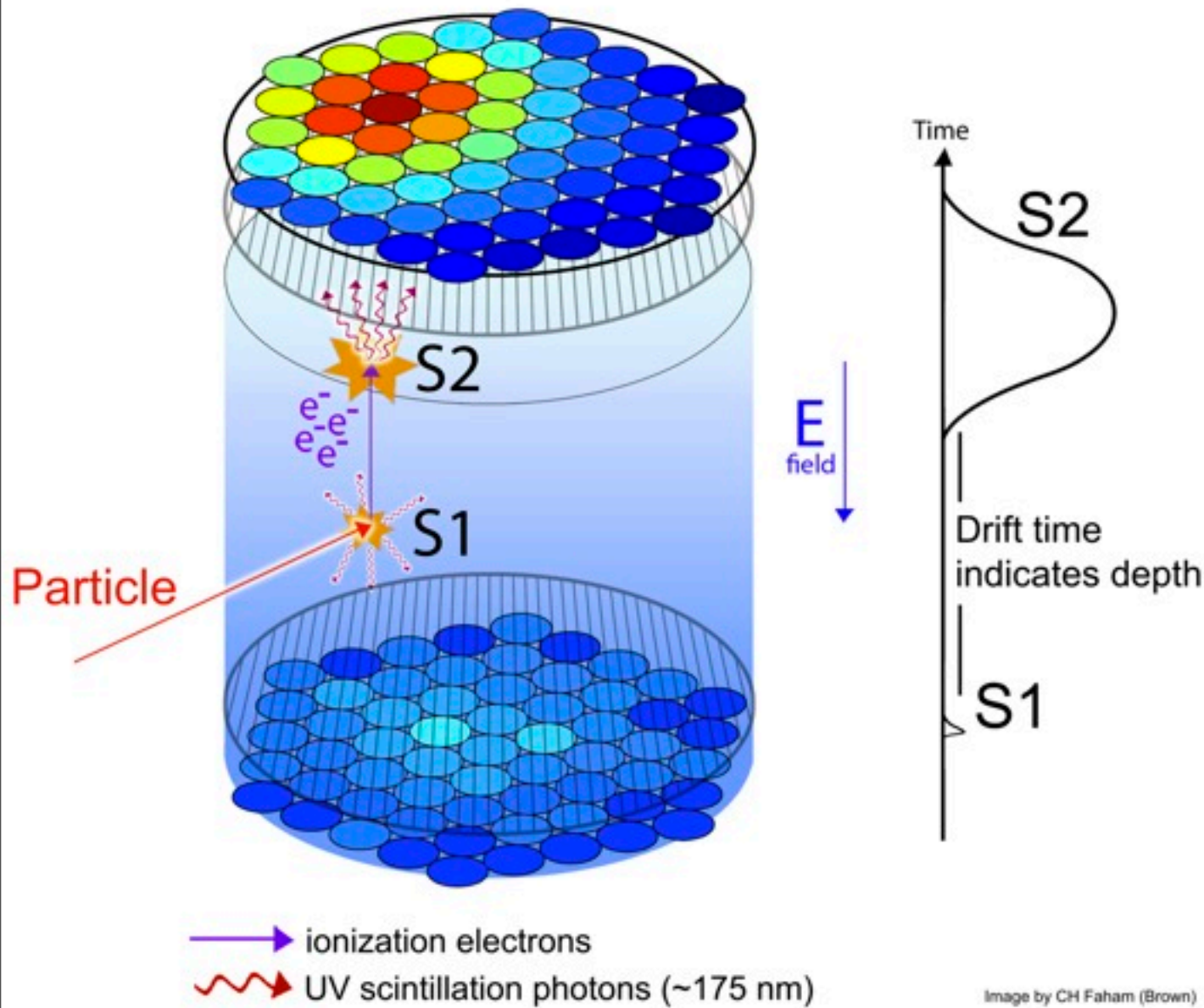
First results from the LUX Dark Matter Experiment

Cláudio Silva, LIP/UC Coimbra
on behalf of the LUX collaboration



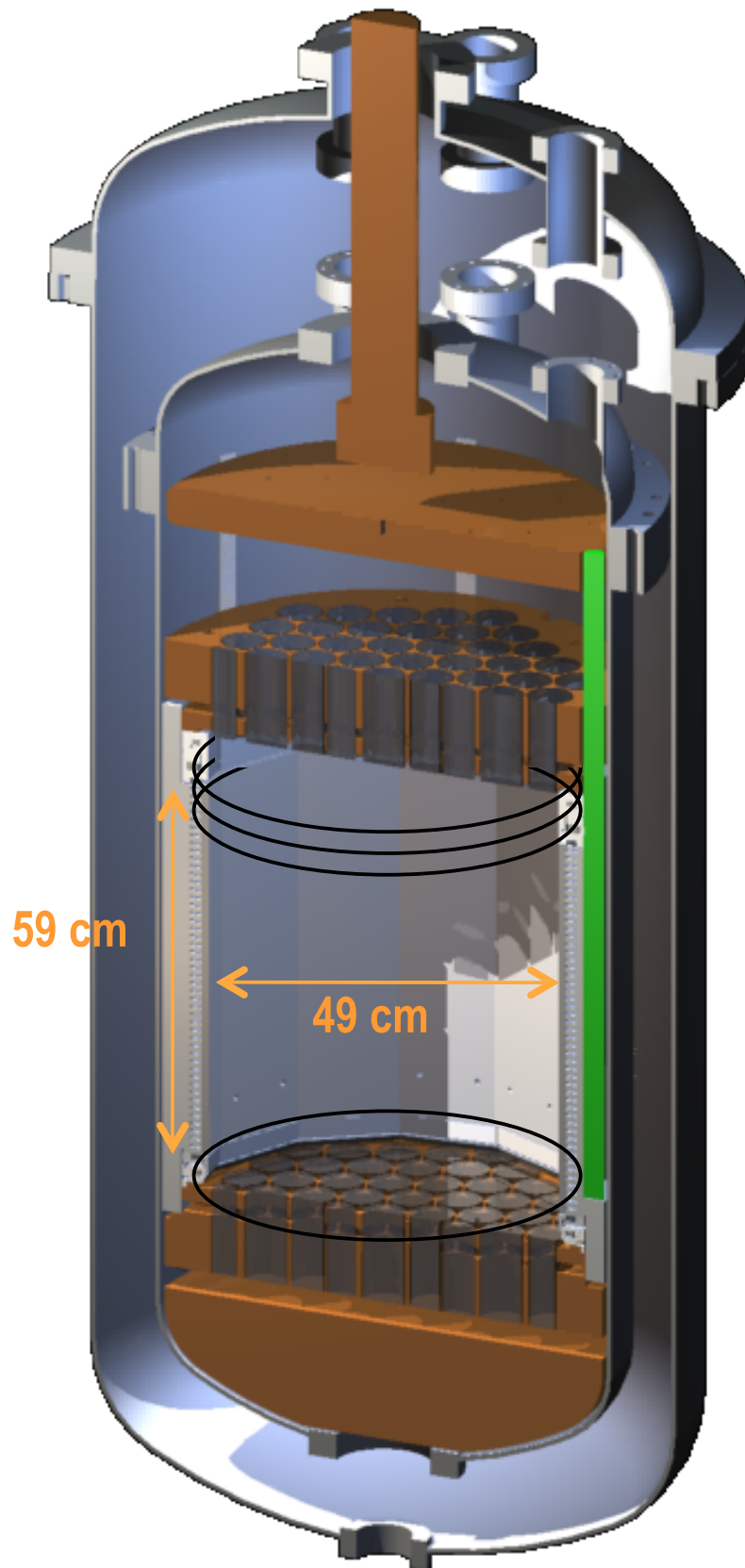
Rencontres de Moriond 2014
Electroweak Session
18th of March 2014



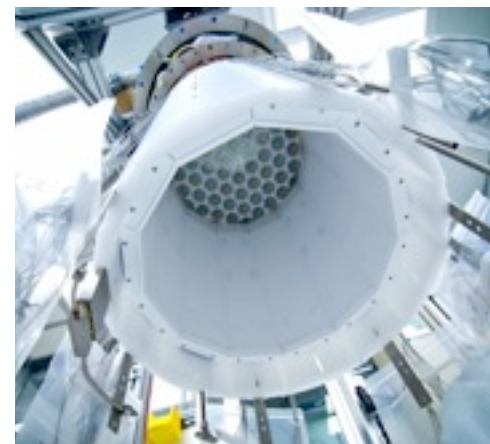


- Primary scintillation (**S1**)
- Secondary scintillation signal from electroluminescence after drift (**S2**)
- Position reconstruction
 - Z from time difference between S1 and S2 (1.51 mm/μs in LUX for a electric field of 181 V/cm)
 - XY reconstructed from light pattern observed in the top array.
 - Typical resolution of some mm.
- Reject gammas, betas by S2/S1 ratio
 - $(S2/S1)_{\gamma,e} > (S2/S1)_{WIMP}$

THE LUX DETECTOR

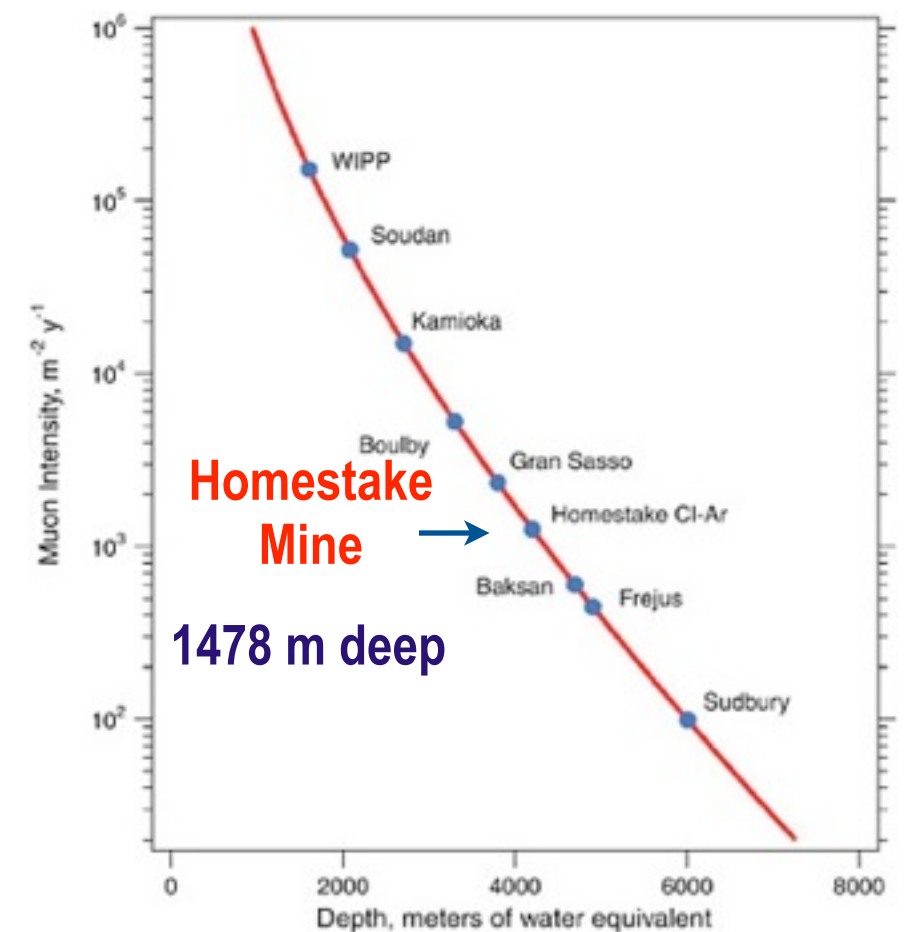
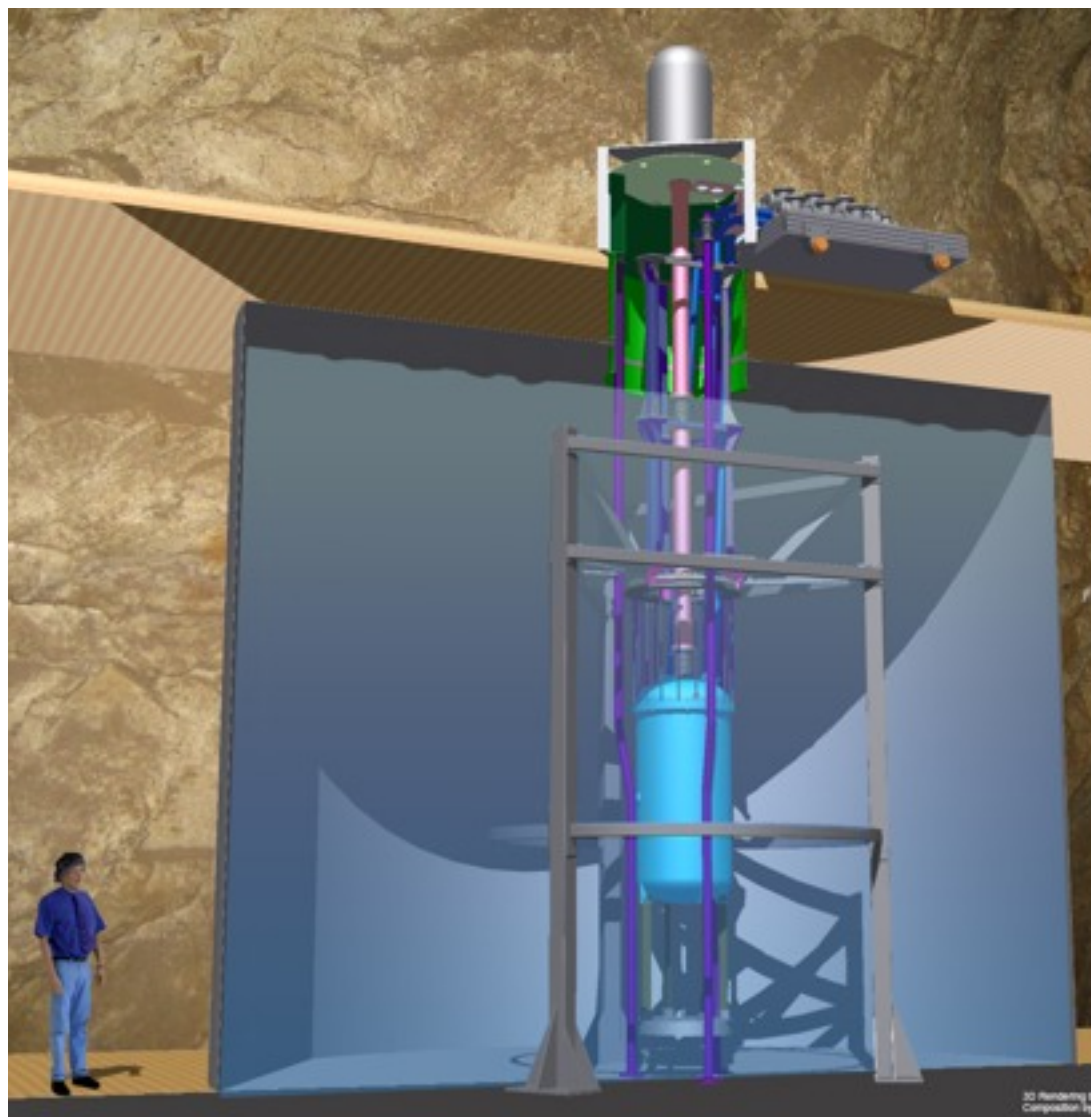


- **370 kg Liquid Xenon Detector (59 cm height, 49 cm diameter) in gas/liquid phases.**
 - 250 kg in the active volume
 - 118 kg in the fiducial volume
- **Construction materials chosen for low radioactivity: Ti, Cu, PTFE**
- **Viewed by 122 ultra low-background PMTs**
 - 61 on top and 61 on bottom
 - 12 mBq/PMT
- **Active region defined by PTFE**
 - High reflectivity for the VUV light - high light collection

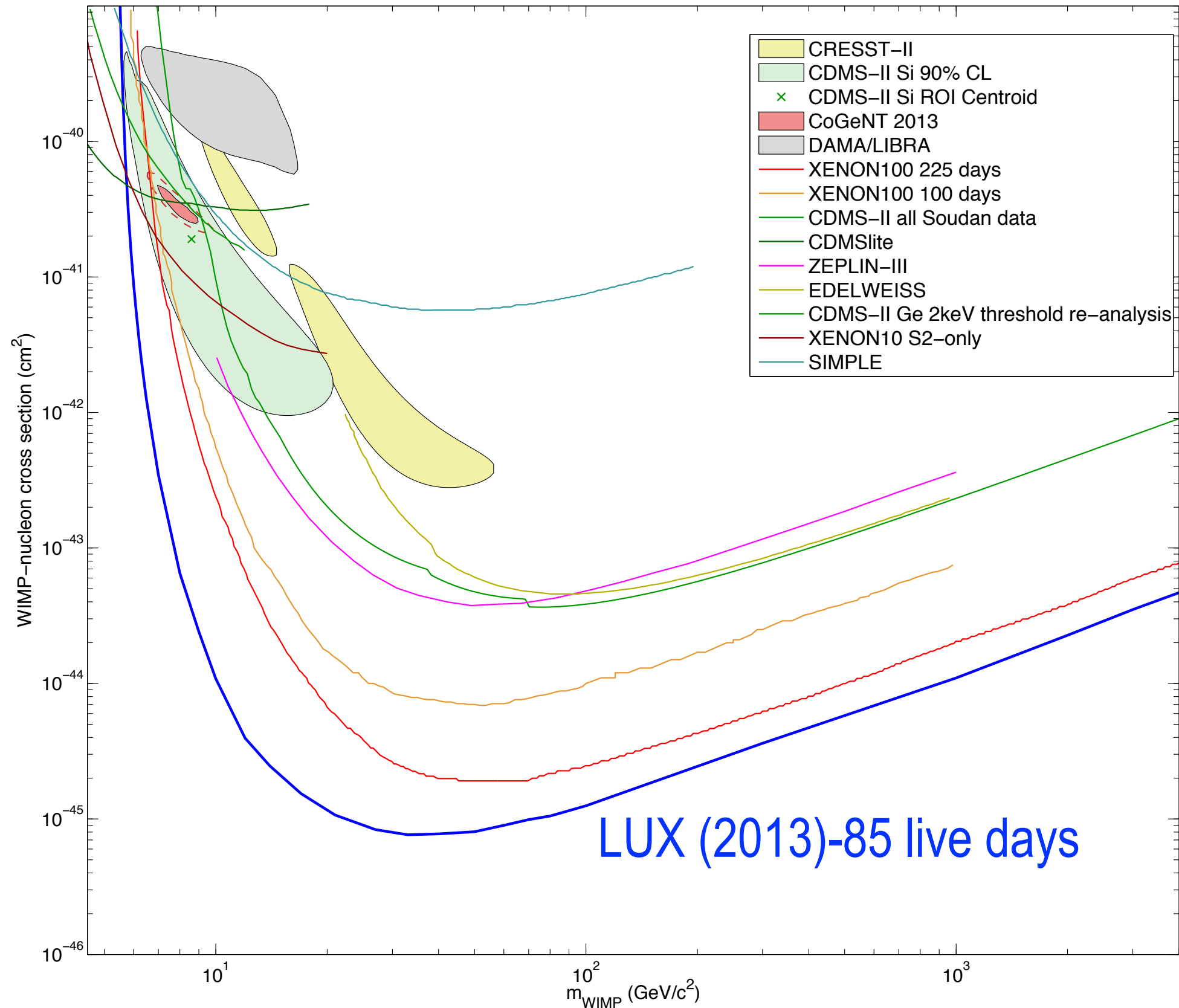


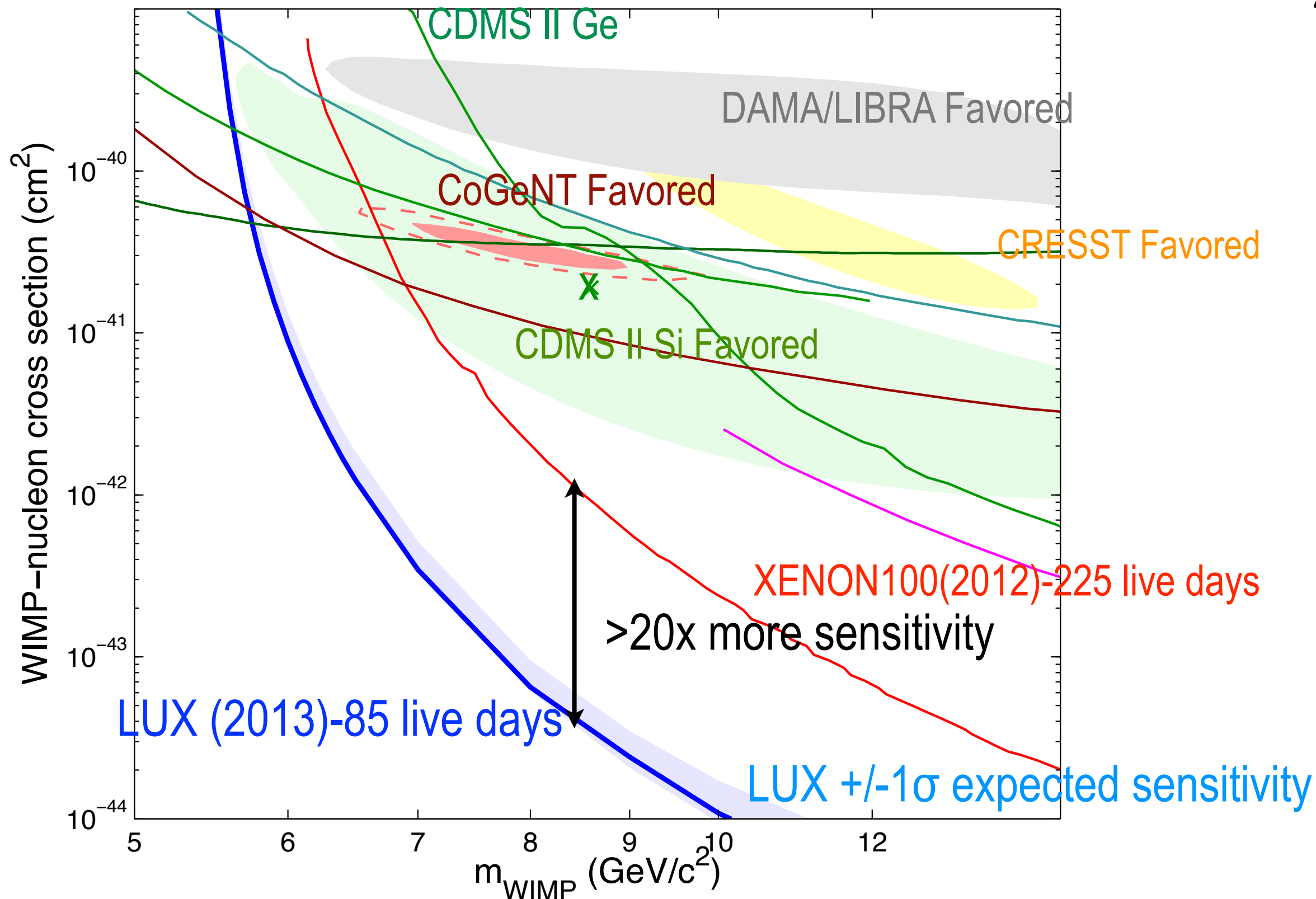
LUX AT SURF

- LUX operates 4850 feet (**1478 m**) underground at the Sanford Underground Research Facility (SURF), South Dakota, US
- Surrounded by a 7.6 m diameter water shield
- Background dominated by construction materials ...
 - **<2 background events per day in the central 118 kg target in the energy window of interest... and is decreasing.**

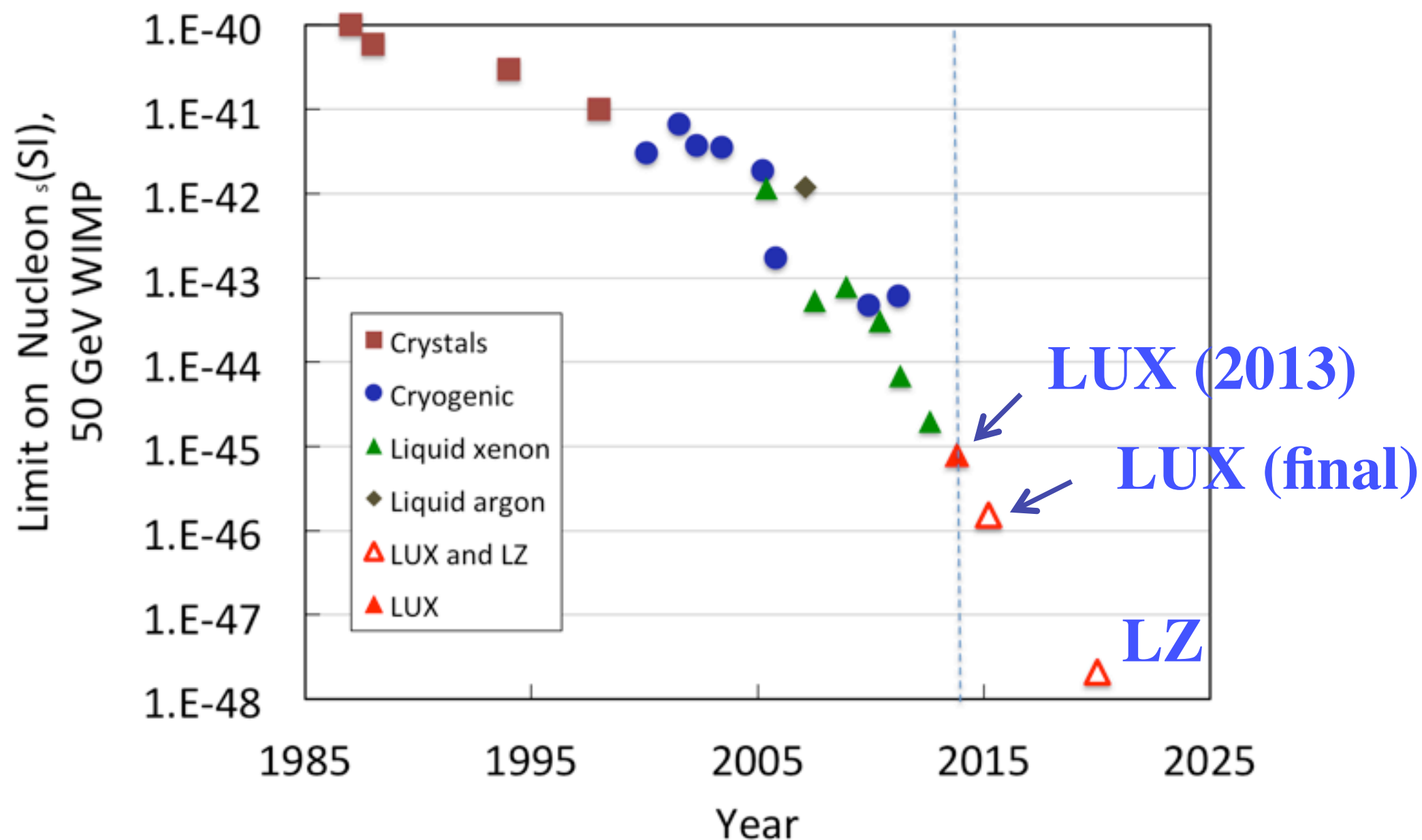


μ flux reduced by $\times 10^{-7}$
(compared to sea level)



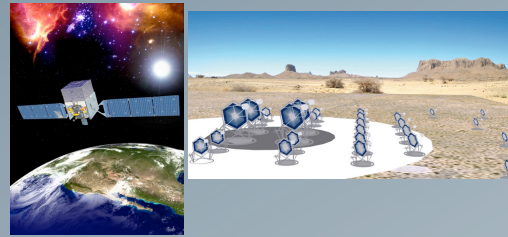


Favoured regions for low-mass WIMPs excluded



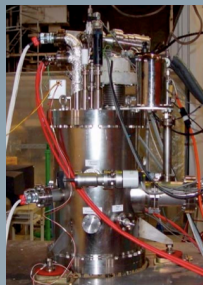
WIMPs do interact with the SM!

indirect detection



See also lectures by
A. Melchiorri, J. Conrad, D.
Boersma and F. Donato...

See
lectures by
J. Gascon



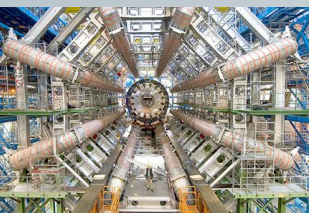
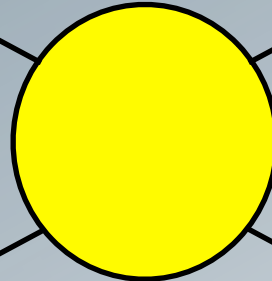
direct detection

χ

χ

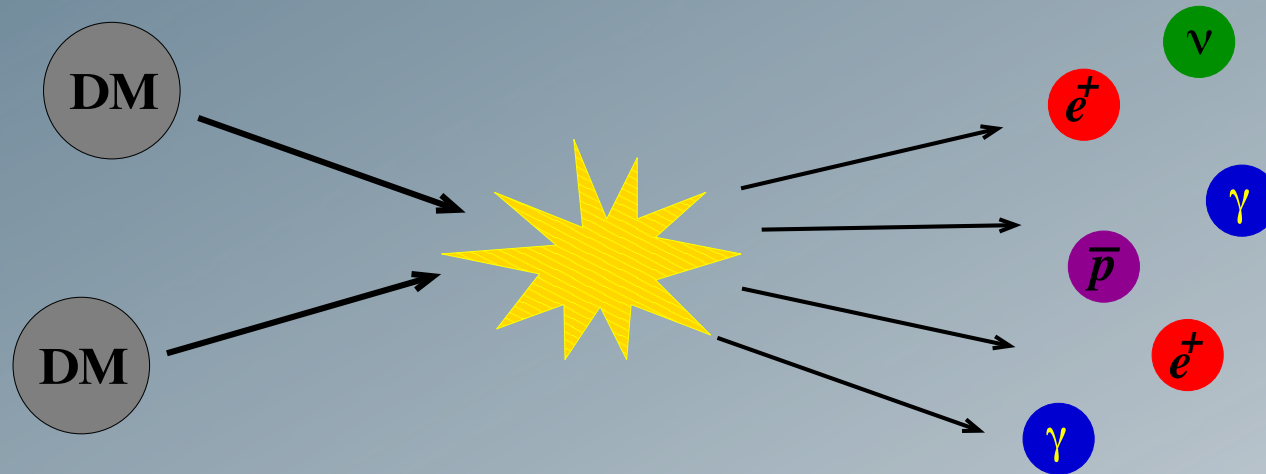
SM

SM



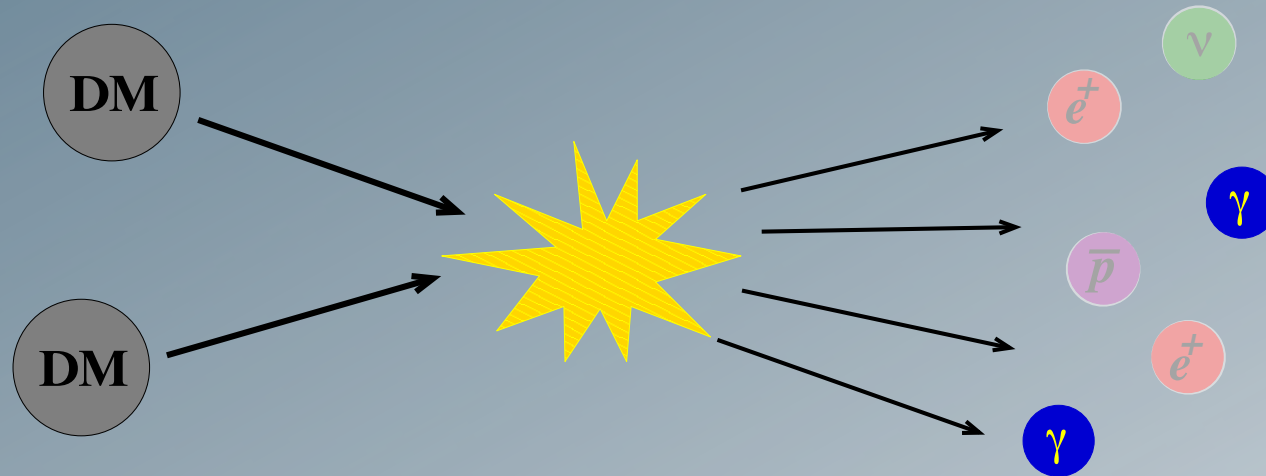
collider searches

Indirect detection in one slide



- DM has to be (quasi-)stable against decay...
- ... but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds
- The challenge: i) absolute rates
 $\rightsquigarrow$ regions of high DM density
 ii) discrimination against other sources
 $\rightsquigarrow$ low background; clear signatures

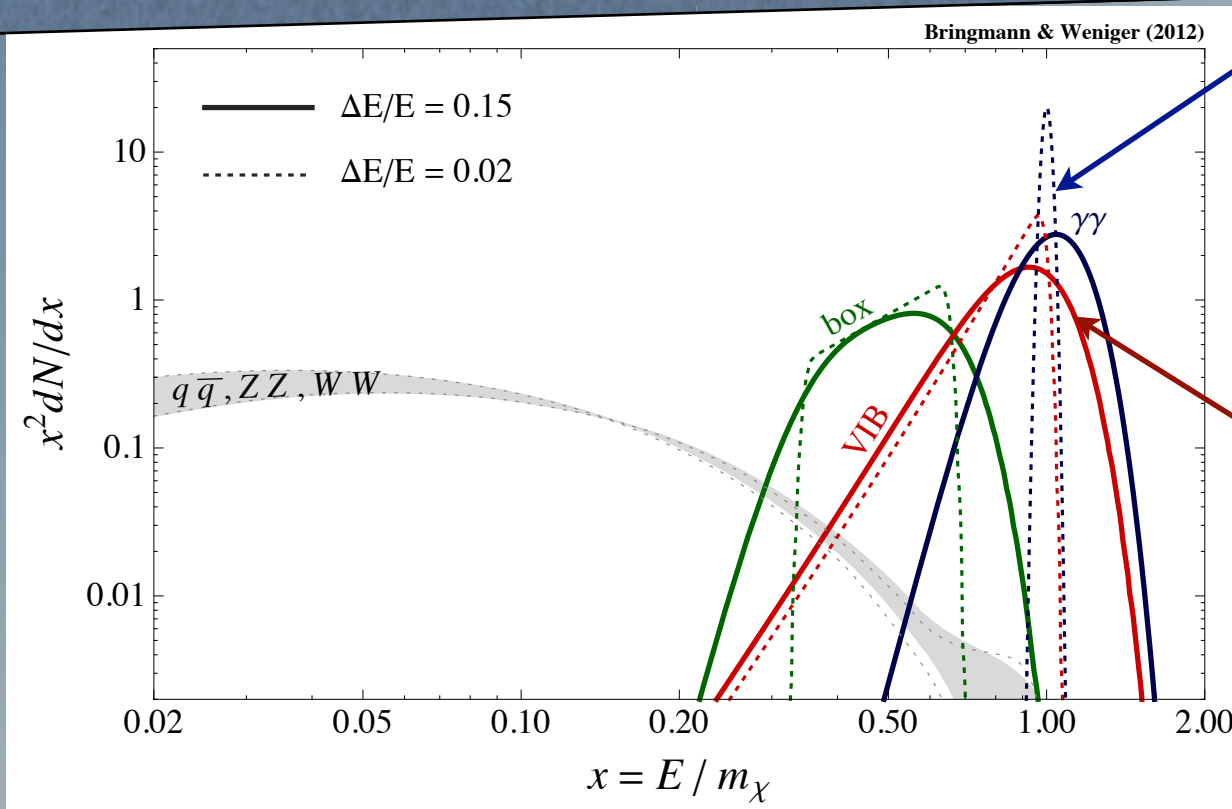
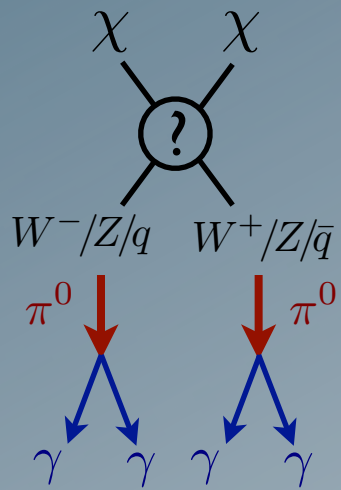
Indirect DM searches



Gamma rays:

- Rather **high rates**
- **No attenuation** when propagating through halo
- **No assumptions** about **diffuse halo** necessary
- **Point** directly to the **sources**: clear spatial signatures
- **Clear spectral signatures** to look for

Annihilation spectra



Monochromatic lines

$$\chi\chi \rightarrow \gamma\gamma, \gamma Z, \gamma H$$

$$\mathcal{O}(\alpha_{\text{em}}^2)$$

(Virtual) Internal Bremsstrahlung

$$\chi\chi \rightarrow \bar{f}f\gamma, W^+W^-\gamma$$

$$\mathcal{O}(\alpha_{\text{em}})$$

Secondary photons

- many photons but
- featureless & model-independent
- difficult to distinguish from astro BG

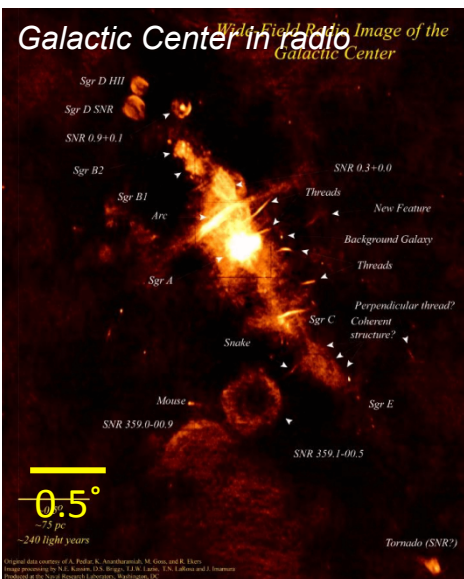
→ good constraining potential

Primary photons

- direct annihilation to photons
- model-dependent 'smoking gun' spectral features near $E_\gamma = m_\chi$

→ discovery potential

Dark matter targets

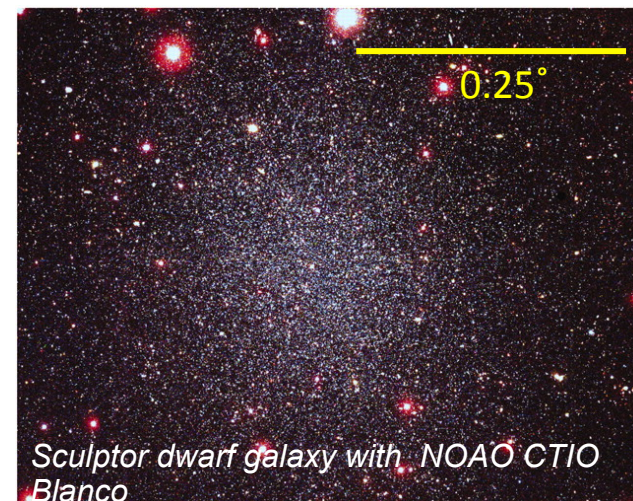


Galactic Centre

- ☐ Proximity (~8kpc)
- ☐ High (possibly) central DM concentration :
DM profile : core? cusp?
- ☐ High astrophysical background at TeV

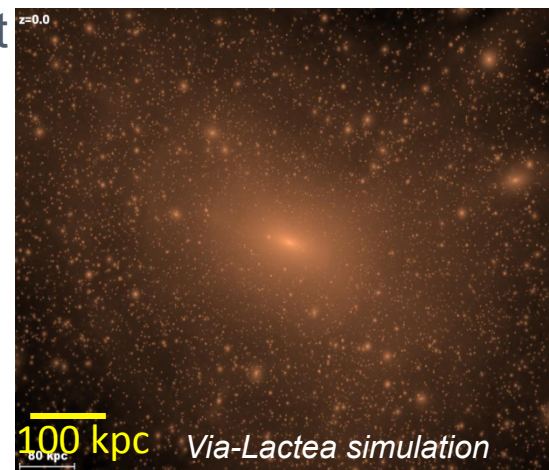
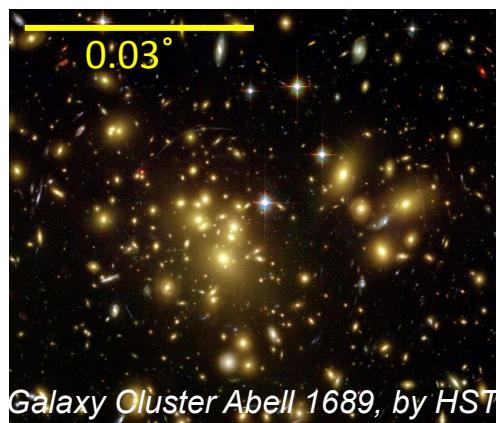
Dwarf galaxies of the Milky Way

- ☐ Many of them within the 100 kpc from Sun
- ☐ Extremely DM-dominated environment
- ☐ Potential low astrophysical background



Galaxy clusters

- ☐ High DM annihilation luminosity
- ☐ Substructures contribution to the overall DM flux
- ☐ Astrophysical background may be important



Substructures in the Galactic halo

- ☐ Low but clean signal
- ☐ Unknown location

Gamma-ray flux

The expected **gamma-ray flux** [$\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\psi) = \underbrace{\int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\text{l.o.s}} d\ell(\psi) \rho^2(\mathbf{r})}_{\text{astrophysics}} \underbrace{\left[\frac{\langle\sigma v\rangle_{\text{ann}}}{8\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \right]}_{\text{particle physics}}$$

for point-like sources:

$$\simeq (D^2 \Delta\psi)^{-1} \int d^3r \rho^2(\mathbf{r})$$

$\Delta\psi$: angular res. of detector

D : distance to source

angular information

+ rather uncertain **normalization**

$\langle\sigma v\rangle_{\text{ann}}$: total annihilation cross section

m_χ : WIMP mass ($50 \text{ GeV} \lesssim m_\chi \lesssim 5 \text{ TeV}$)

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

high accuracy

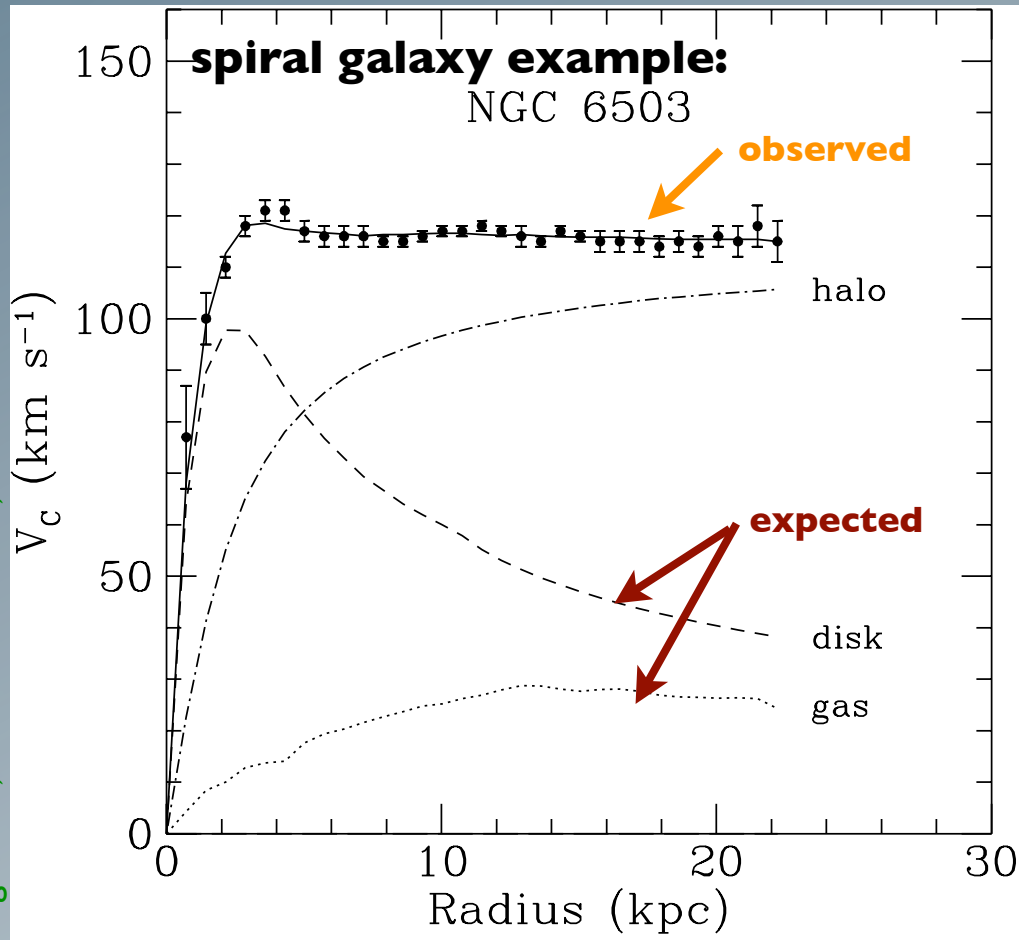
spectral information

Galactic rotation curves

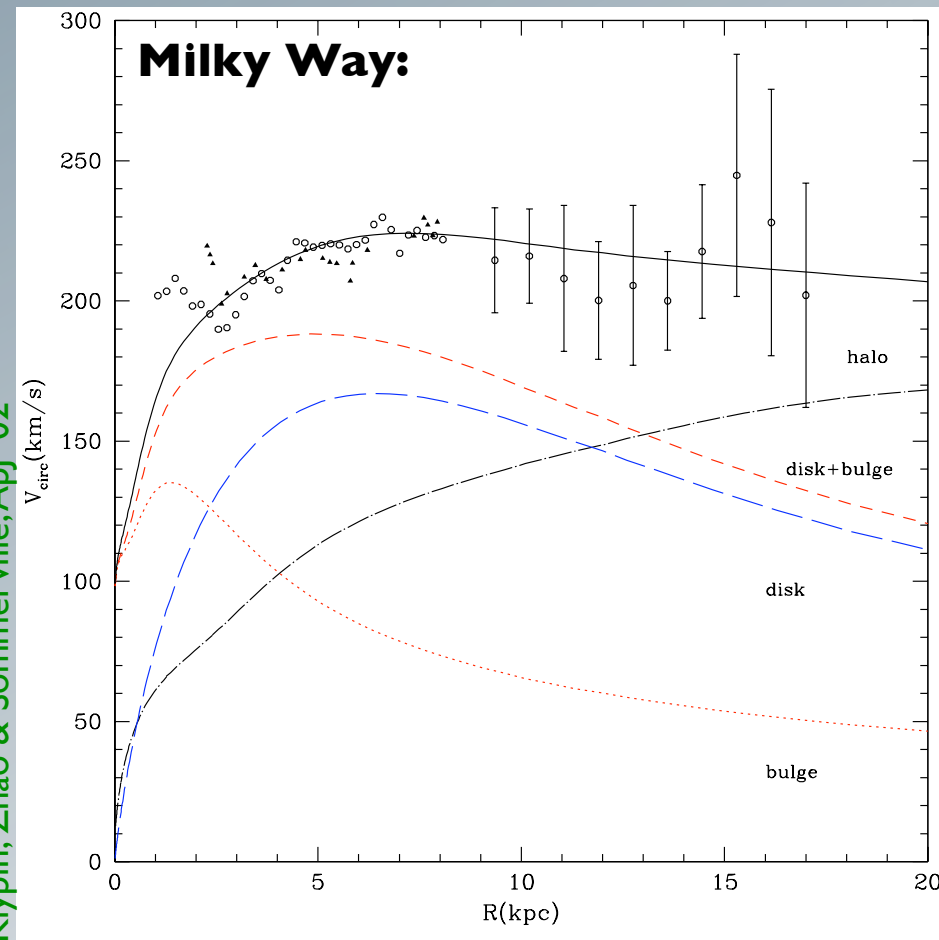
Standard Newtonian dynamics:

$$G_N m_{\odot} \frac{M(r < R)}{R^2} = m_{\odot} \frac{v^2}{R}$$

Begemann, Broeils & Sanders, MNRAS '91



Klypin, Zhao & Somerville, ApJ '02



➔ **Observational** determination of (inner) DM profile for MW ~ **impossible!**

Astrofizyka cząstek: wykład 6

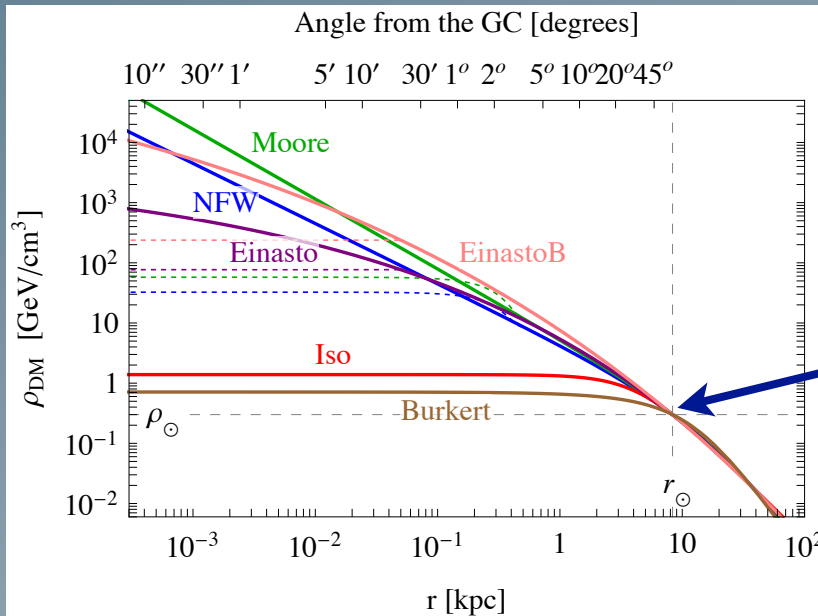
A.F.Żarnecki

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Torsten Bringmann, University of Hamburg

Indirect detection of dark matter - 14

Halo profiles (2)



- Large **uncertainties** “only” in the very **central** region.

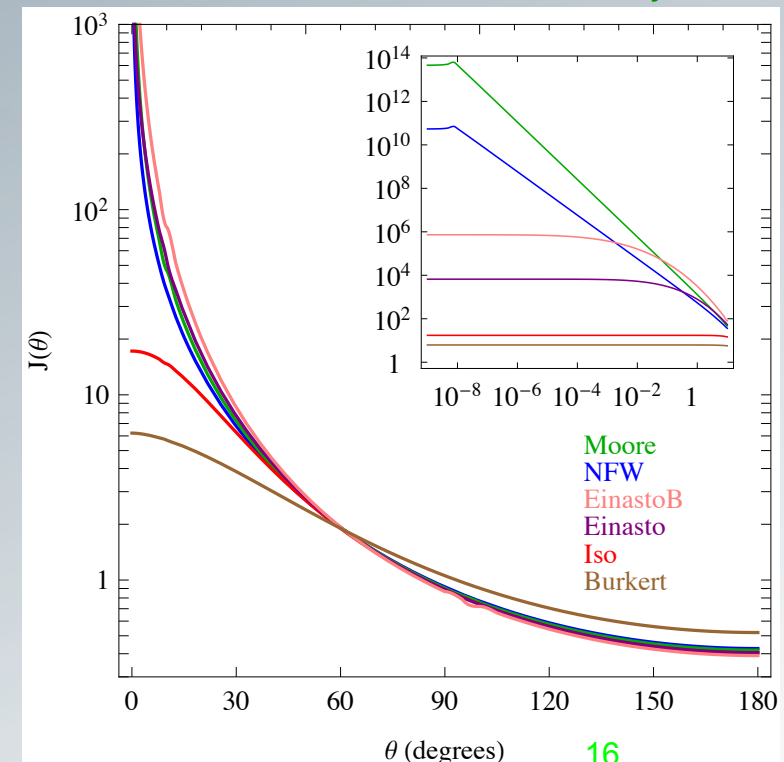
local DM density: $\rho_{\odot} \sim 0.4 \text{ GeV/cm}^3$

- Difference in annihilation flux several orders of magnitude for the **galactic center**

[NB: figure does not take into account **cut-off** due to **self-annihilation**!]

- Situation much better for e.g. **dwarf galaxies**

Cirelli et al., JCAP'11



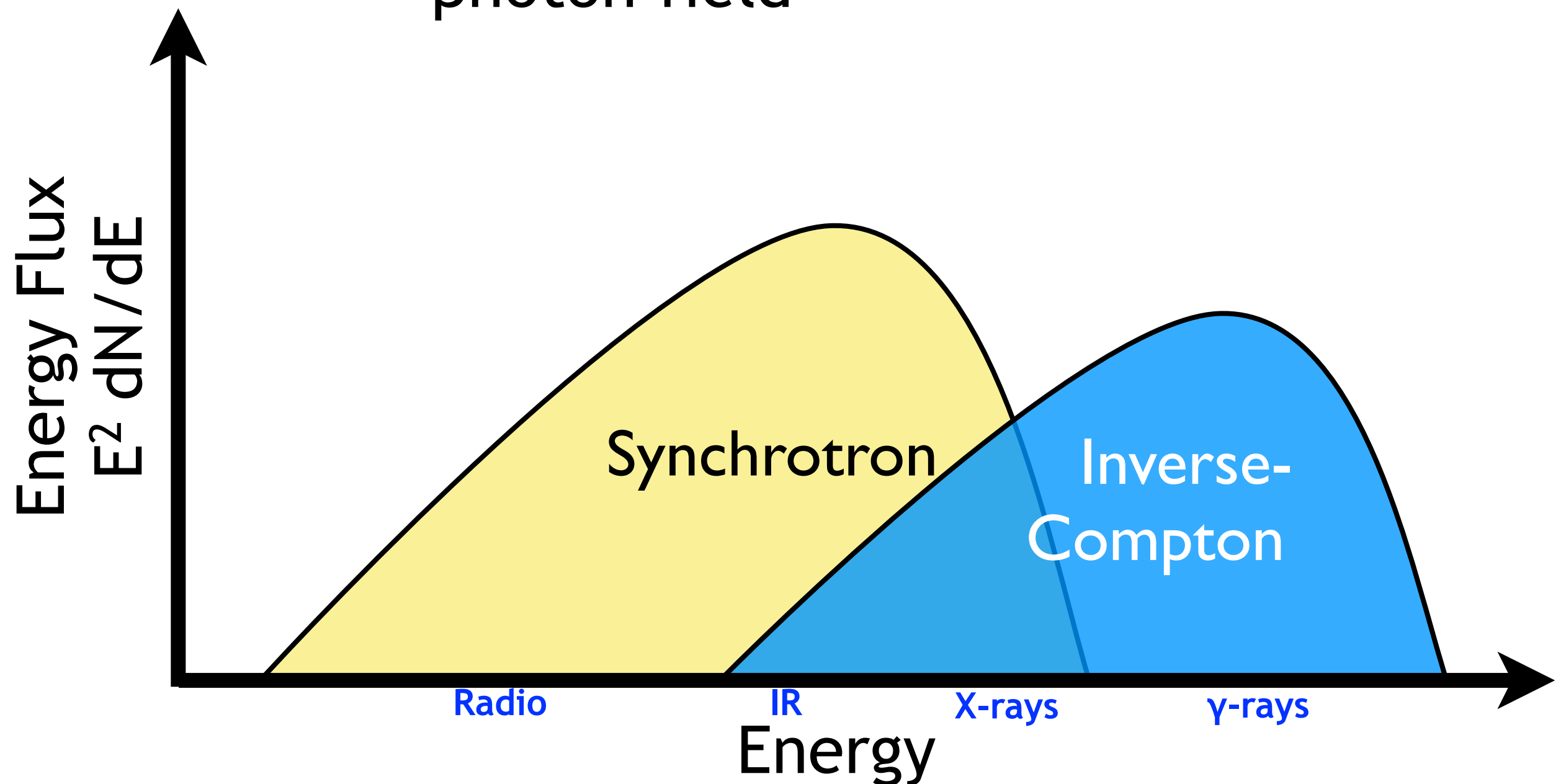
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Non-thermal Spectral Energy Distribution

Electron Population

+ B field
+ photon field

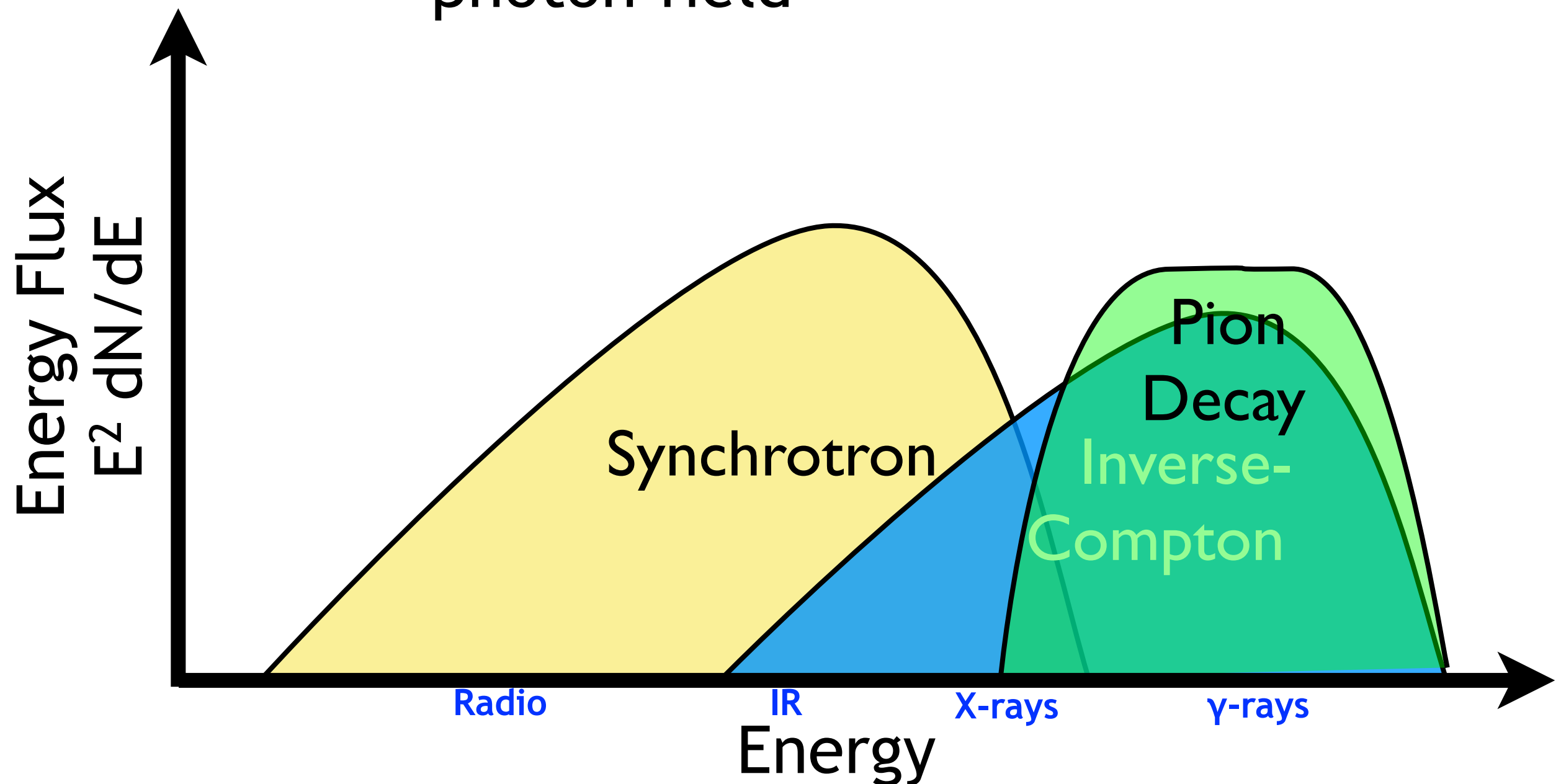
Proton Population



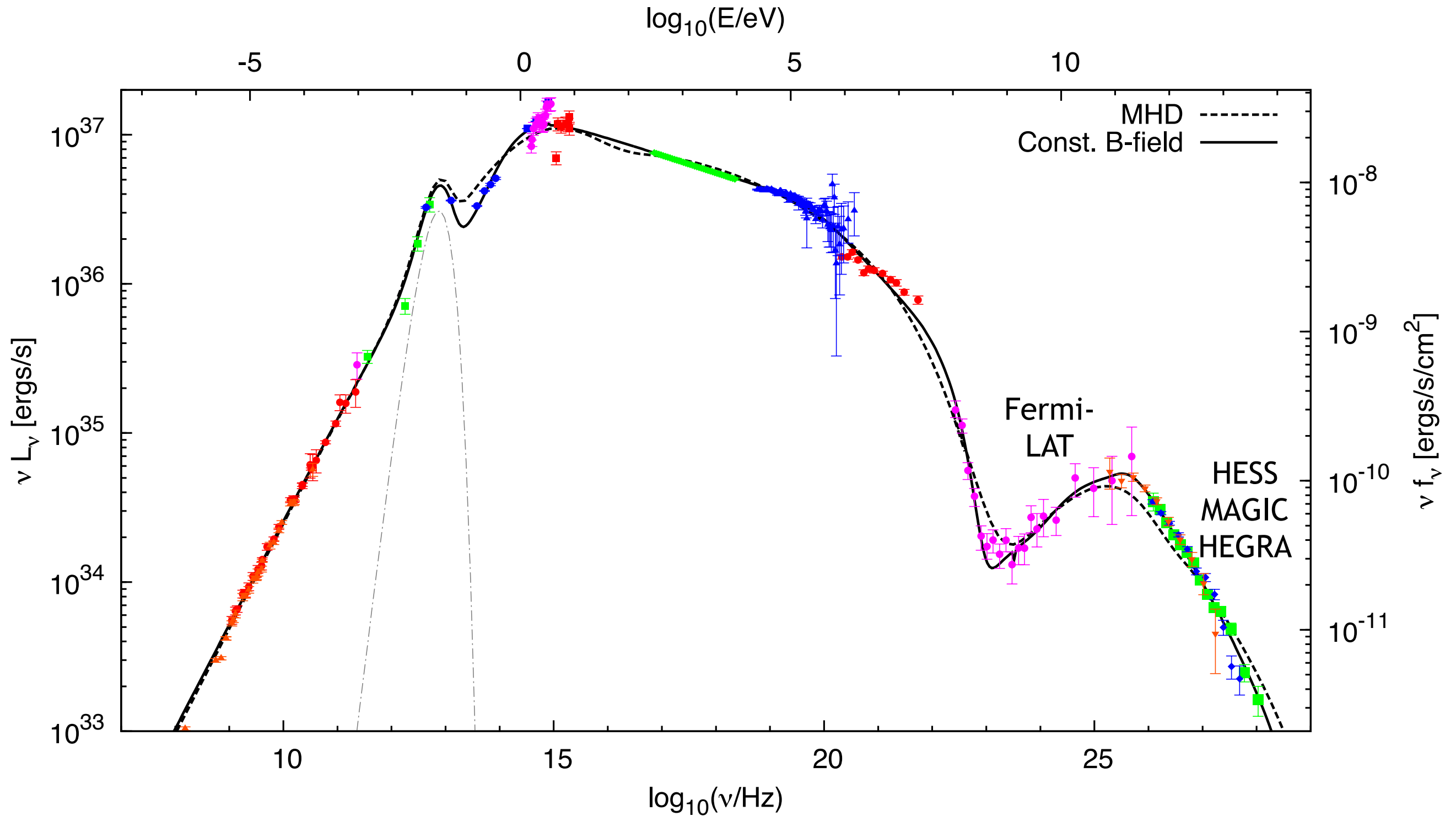
Non-thermal Spectral Energy Distribution

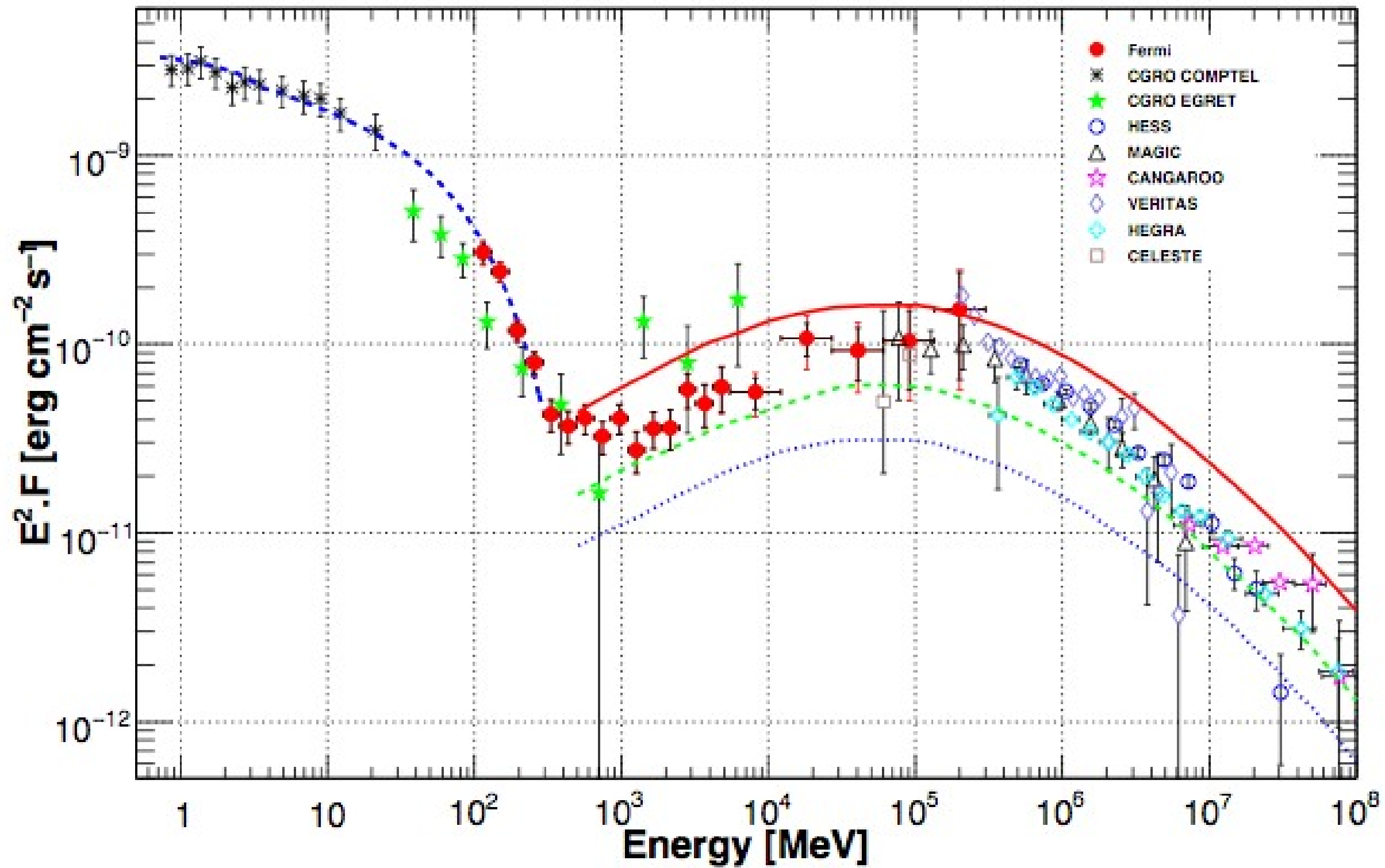
Electron Population
+ B field
+ photon field

Proton Population
+ target material

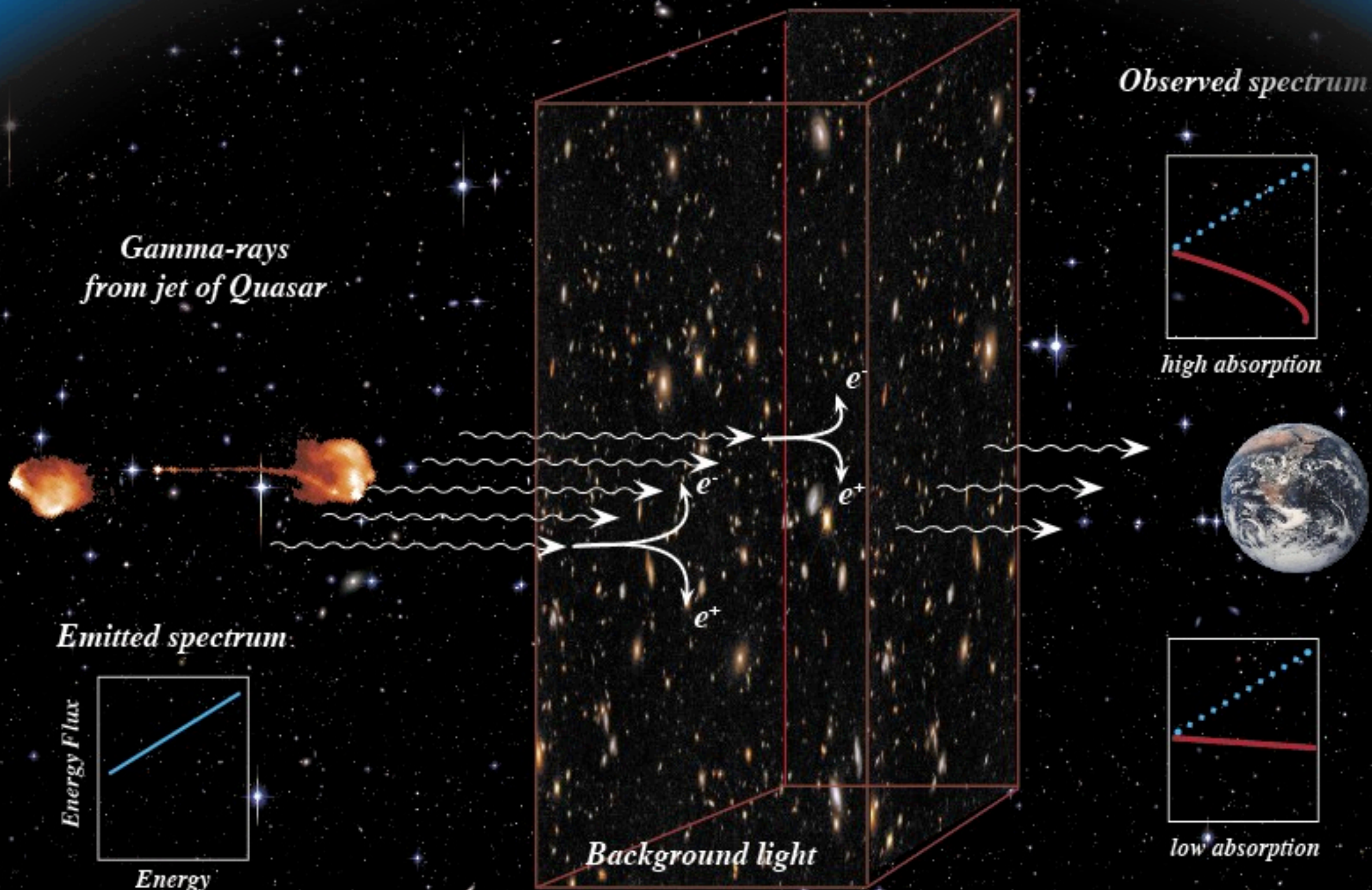


Spectral Energy Distribution of the Crab Nebula

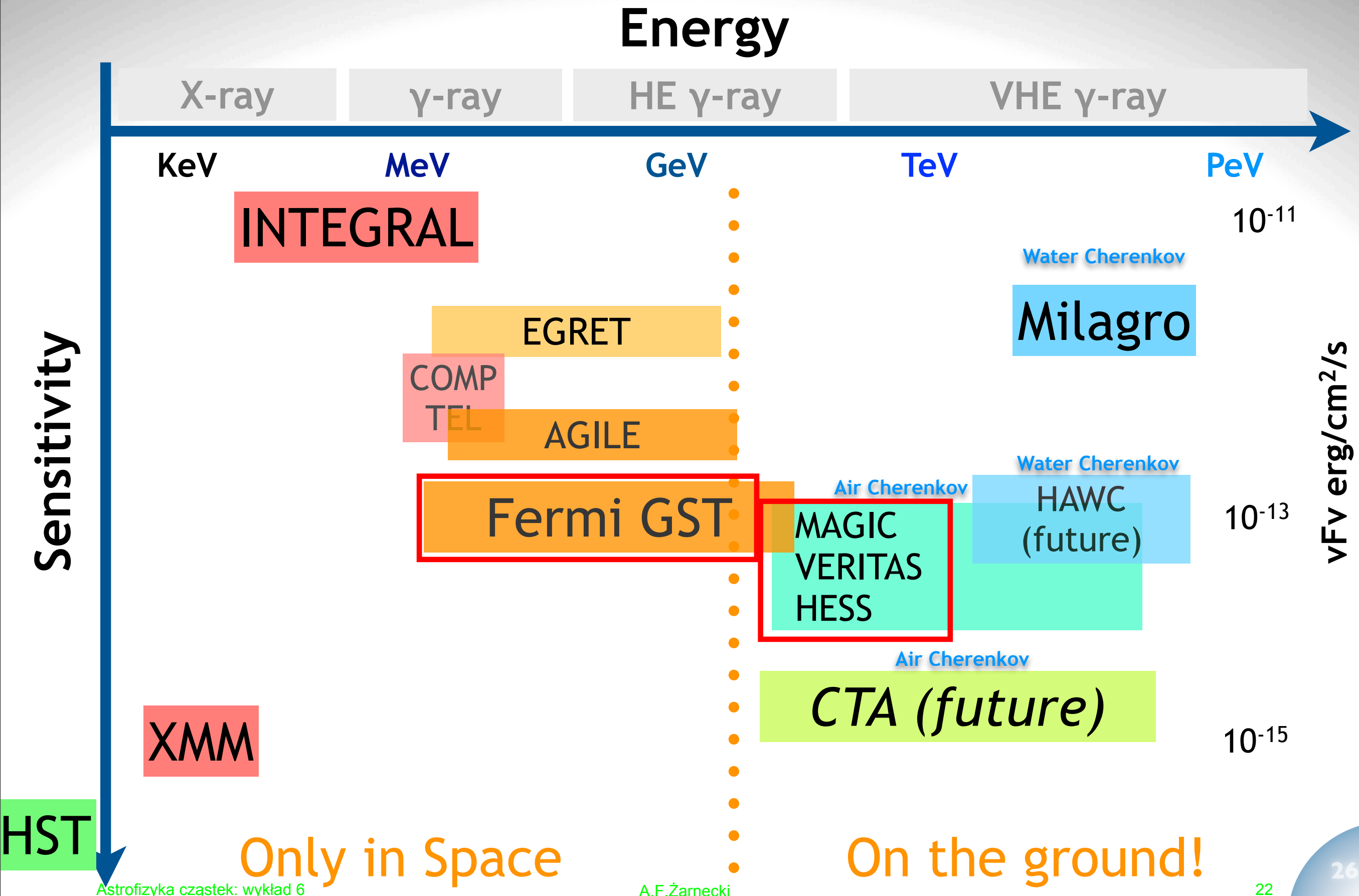




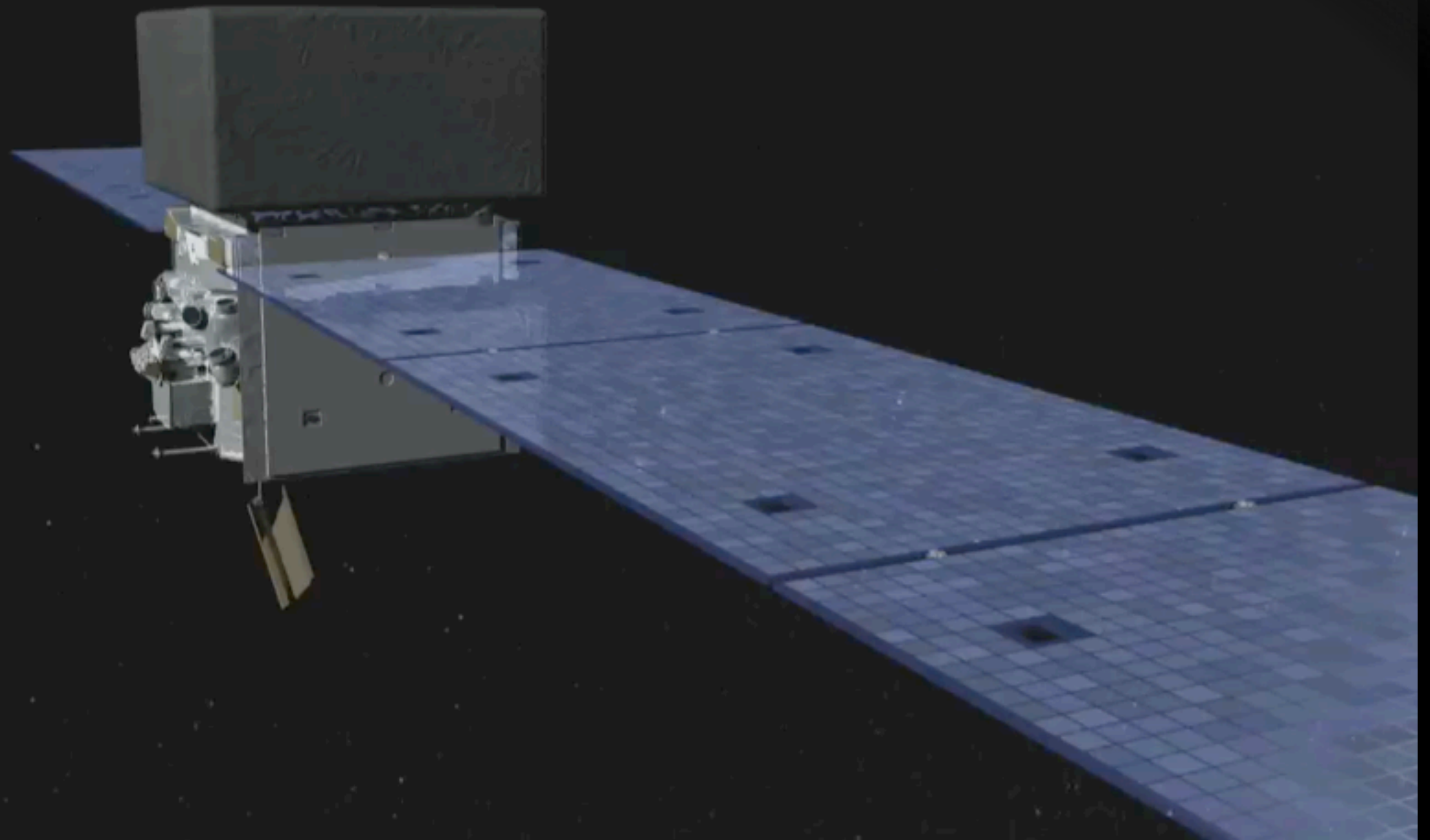
Gamma-ray Horizon



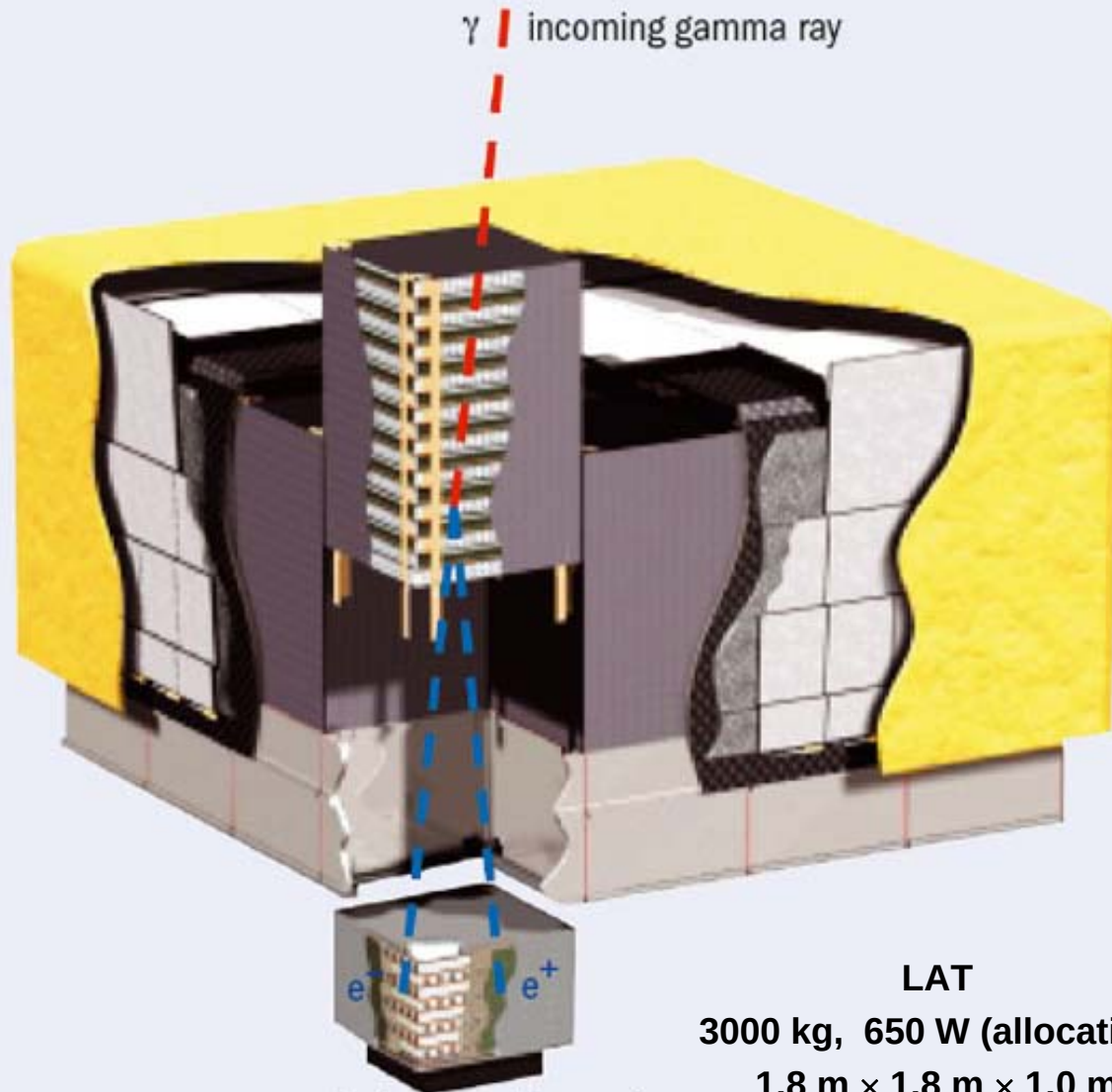
Some High Energy Instruments



Modern Generation: Fermi GST



Large Area Telescope



Astrofizyka cząstek i wykład 5

electron-positron pair

LAT
3000 kg, 650 W (allocation)
1.8 m × 1.8 m × 1.0 m
20 MeV – 300 GeV

A. F. Żarnowski

Tracker

γ direction and
identification

Calorimeter

γ energy
image particle
showers

Anti-coincidence detector

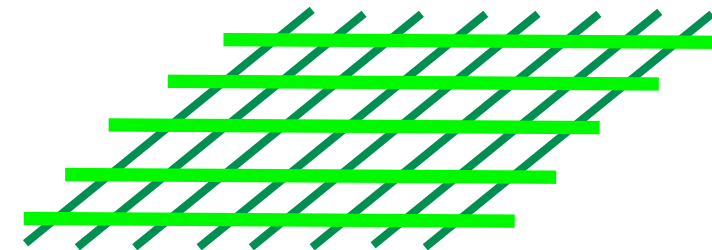
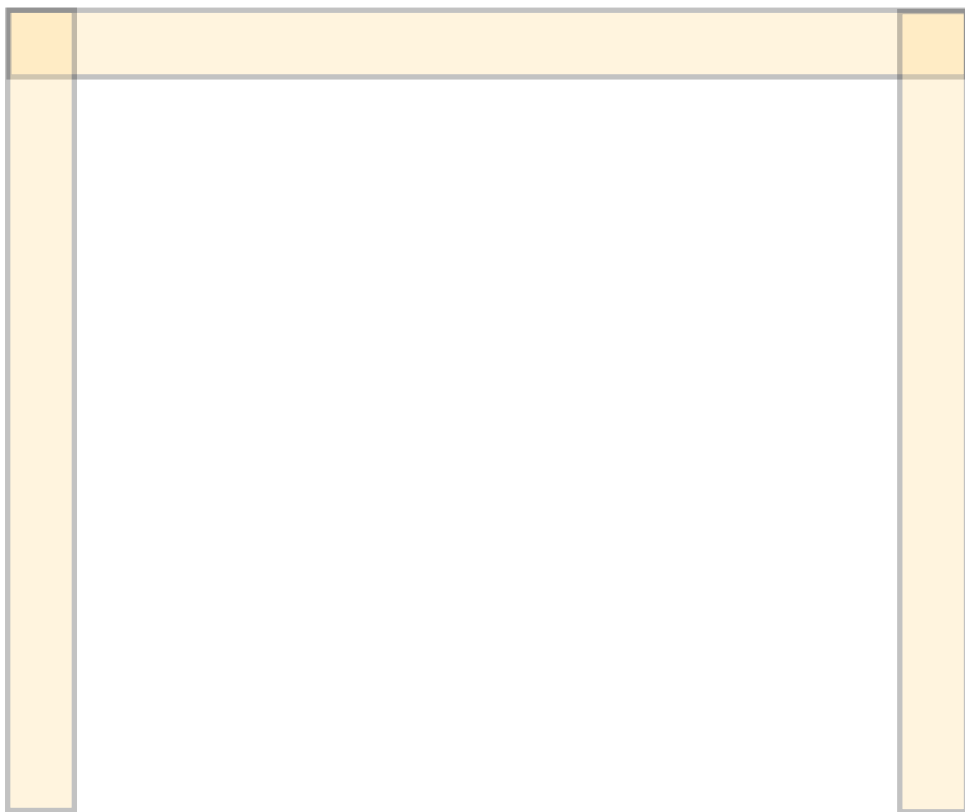
Background rejection

*segmentation reduces self-
veto at high energies*

Pair-conversion Details...

Anti-coincidence plastic scintillators

- ▶ generate light when a charged particle passes through them, but not a photon
- ▶ readout by PMTs
- ▶ provide anti-coincidence time veto for cosmic rays (reject 99.97%)



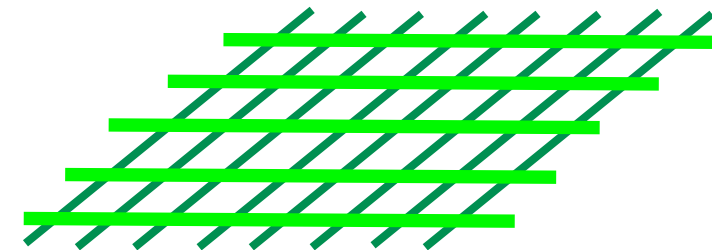
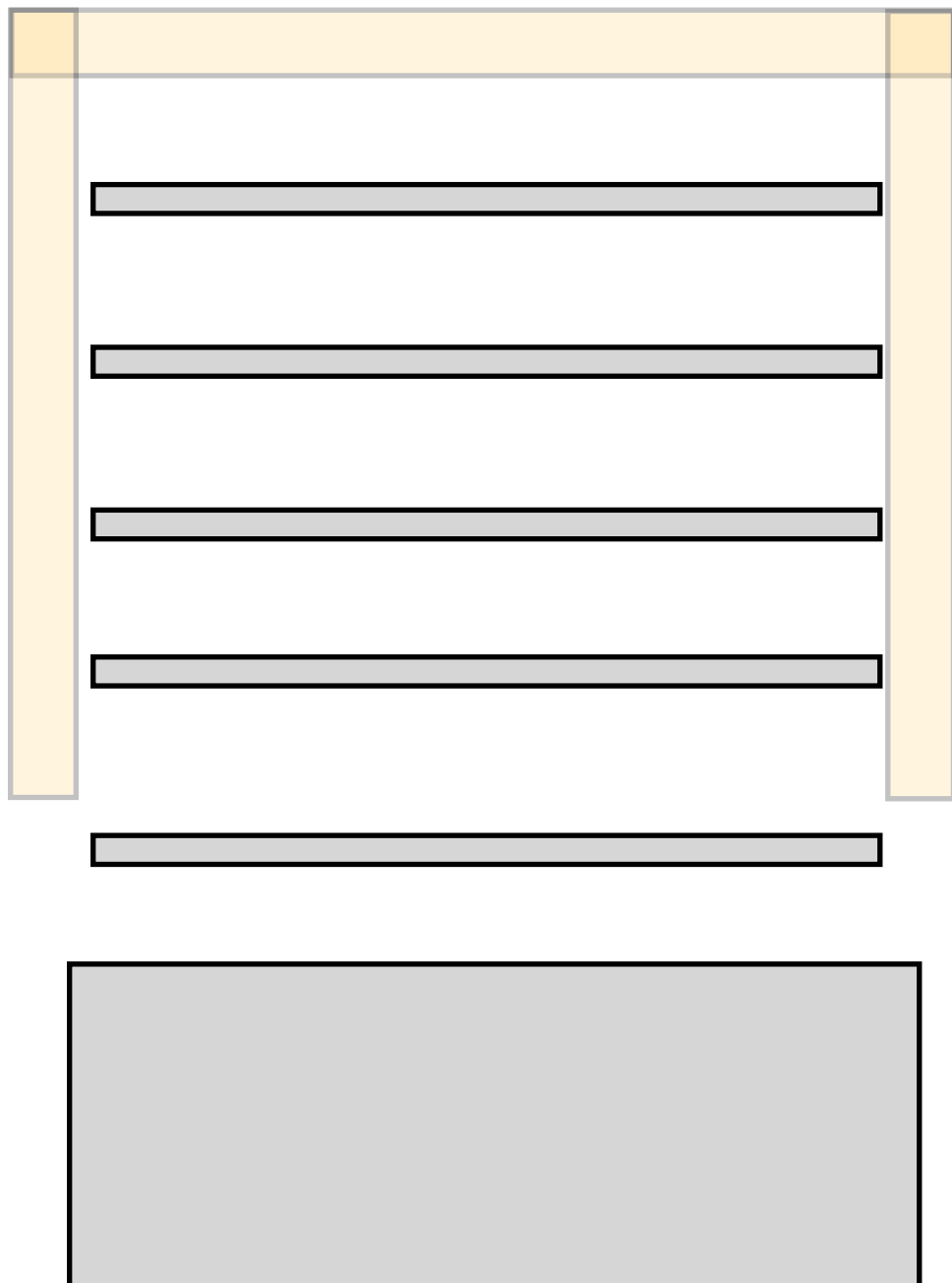
Pair-conversion Details...

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Layers of heavy material (tungston)

- ▶ provide target nuclei for pair production



Pair-conversion Details...

Anti-coincidence plastic scintillators

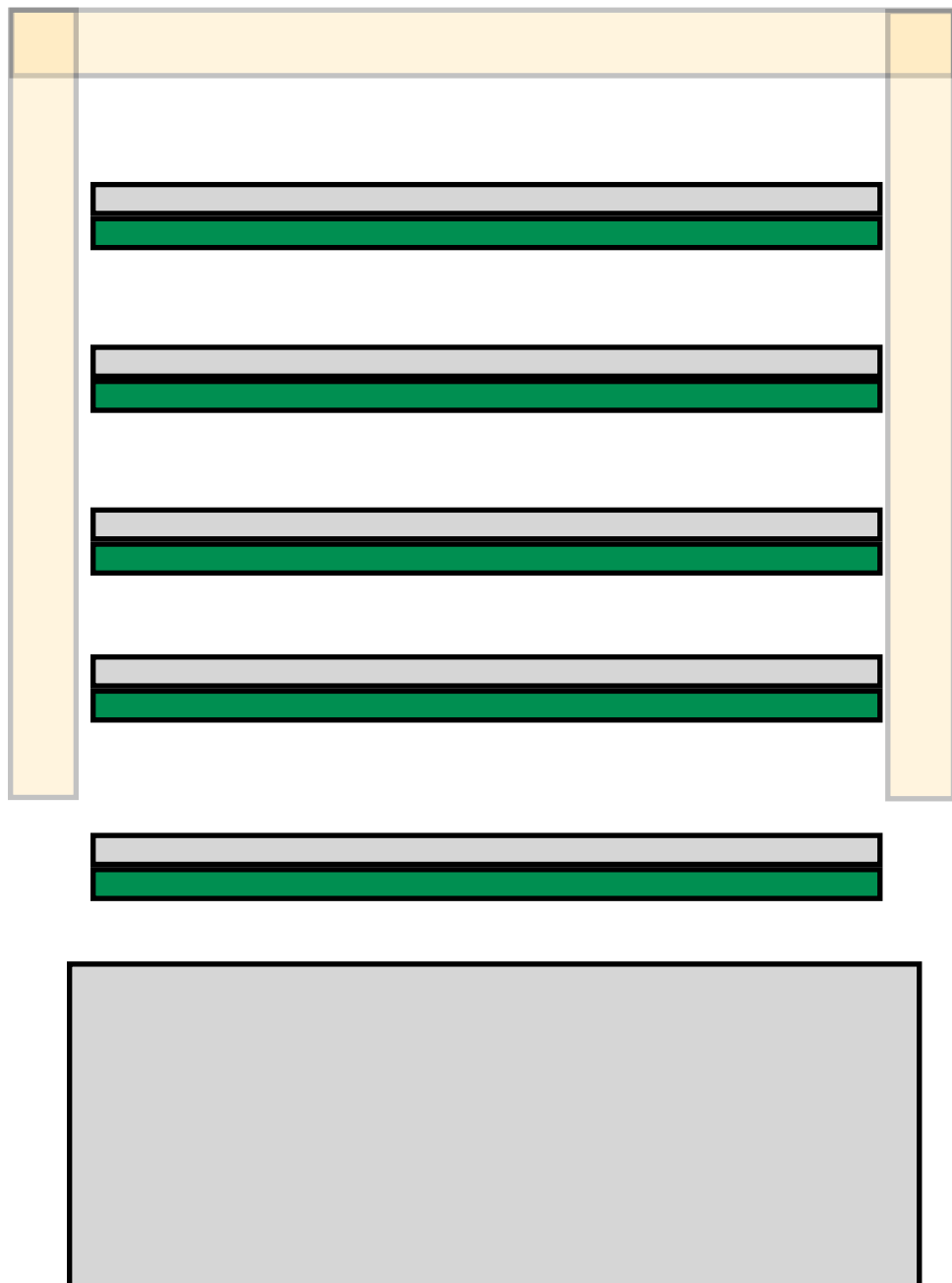
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Silicon tracker strips

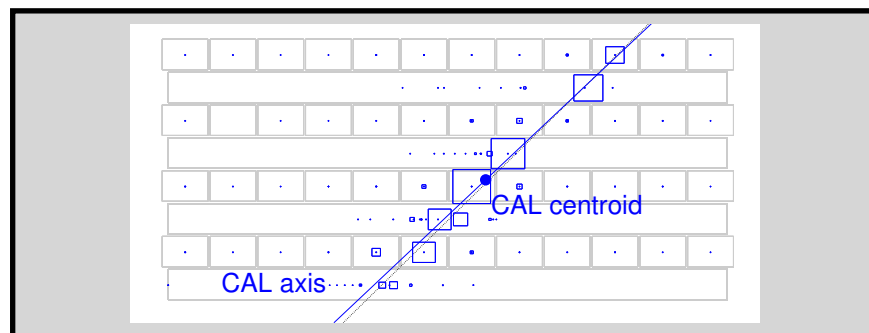
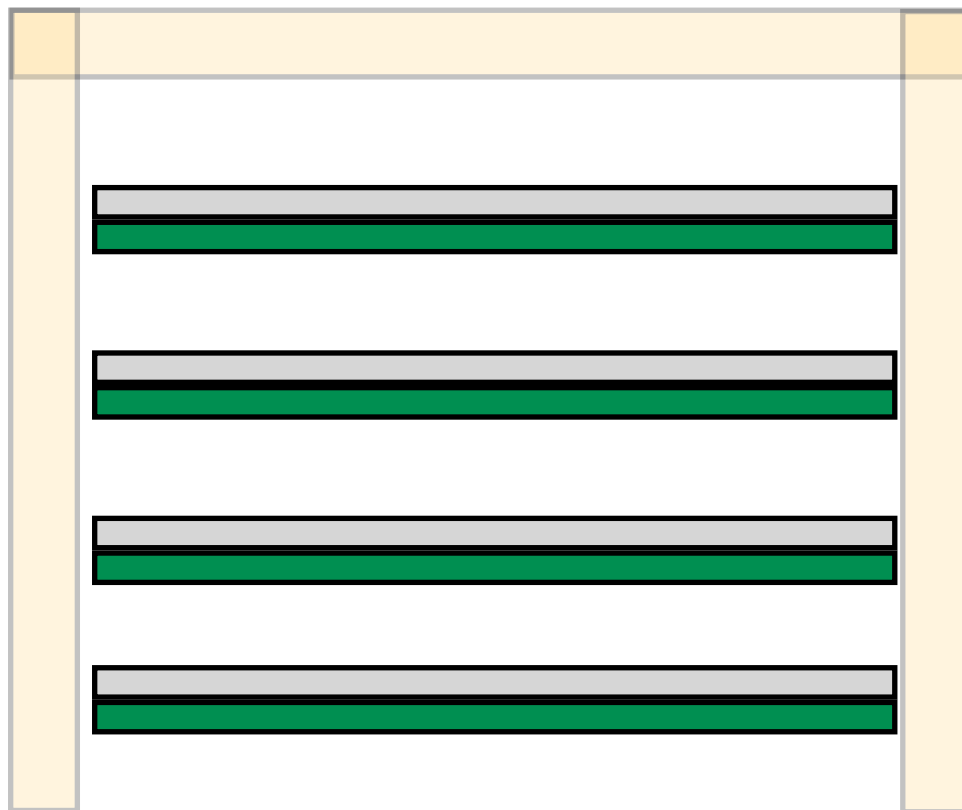
- ▶ between each tungston layer
- ▶ provide time and x or y position when particle ionizes atoms in the silicon
- ▶ alternating x and y strips give 2D position



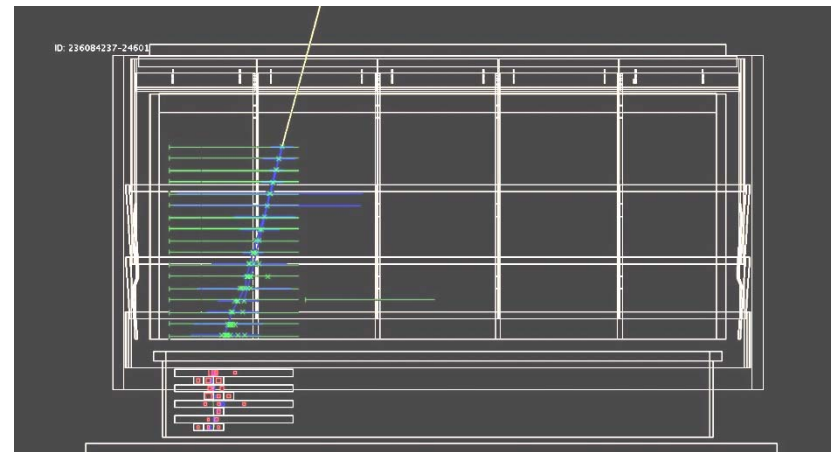
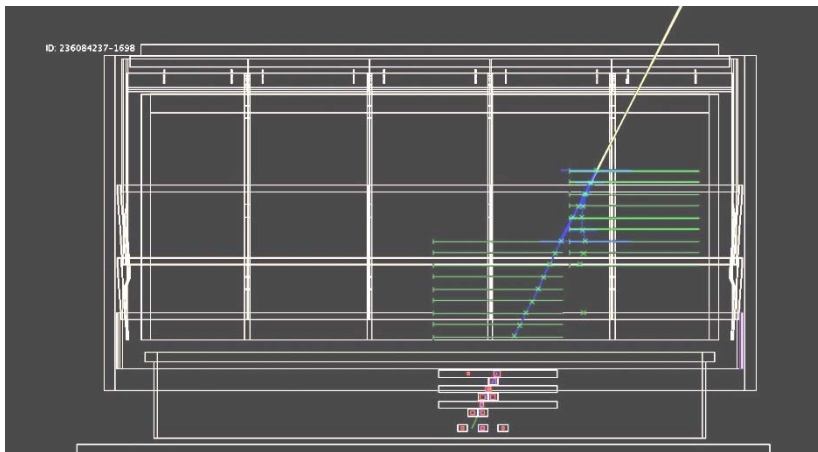
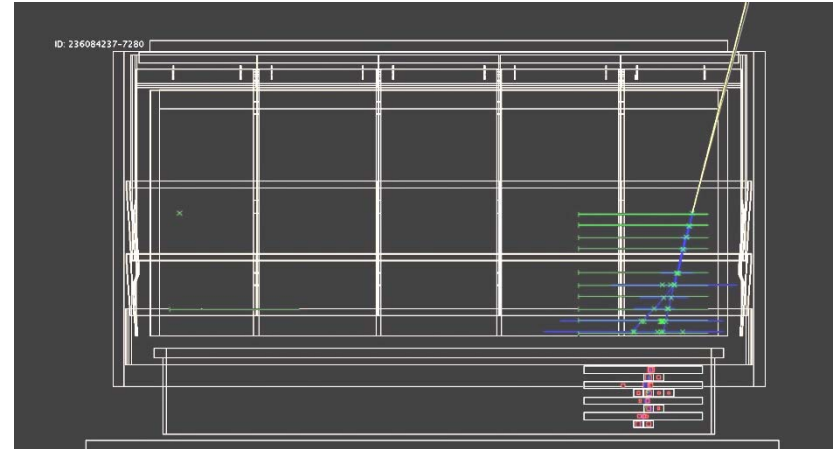
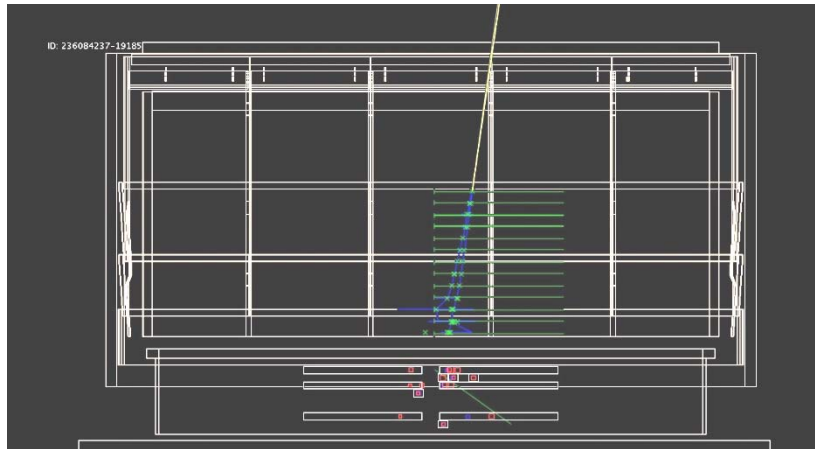
Pair-conversion Details...

Calorimeter

- ▶ 12 “logs” of CsI crystal scintillators in 8 layers per tower, alternating in X and Y directions (a hodoscope)
- ▶ logs are covered with a material that produces decreasing light along the length, to provide measure of position.
- ▶ photodiodes read out each “log”, providing full 3-D image of energy deposited
- ▶ above 3 GeV, showers no longer contained, 100 GeV half leak out

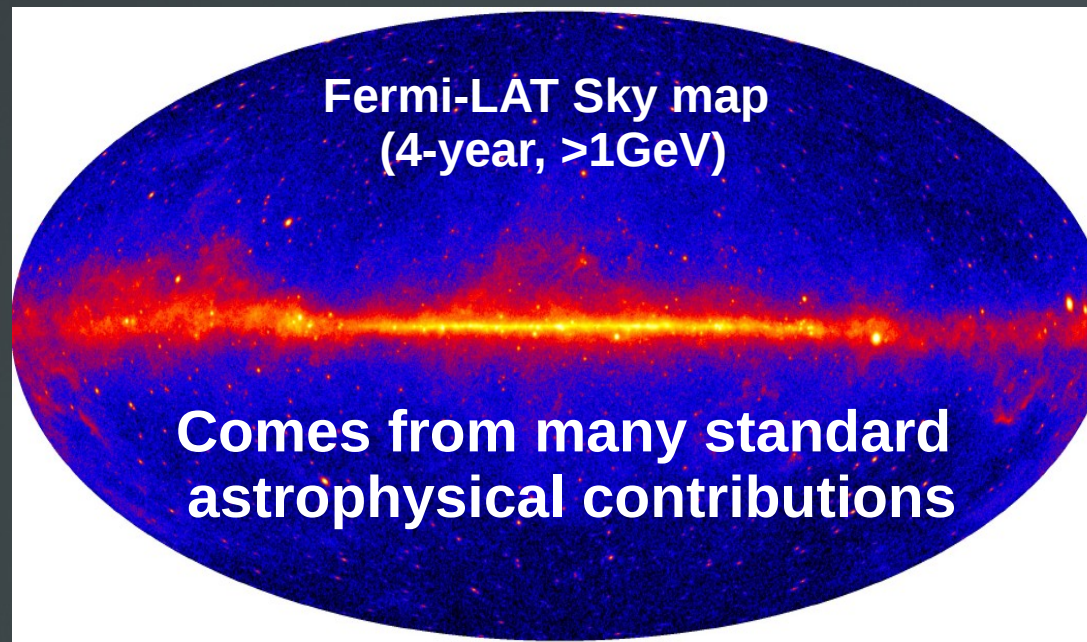
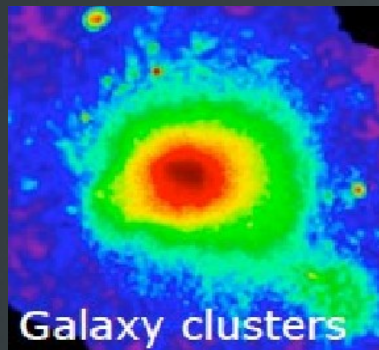
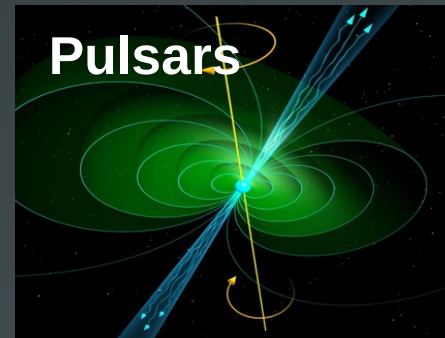


LAT Gamma Candidate Events

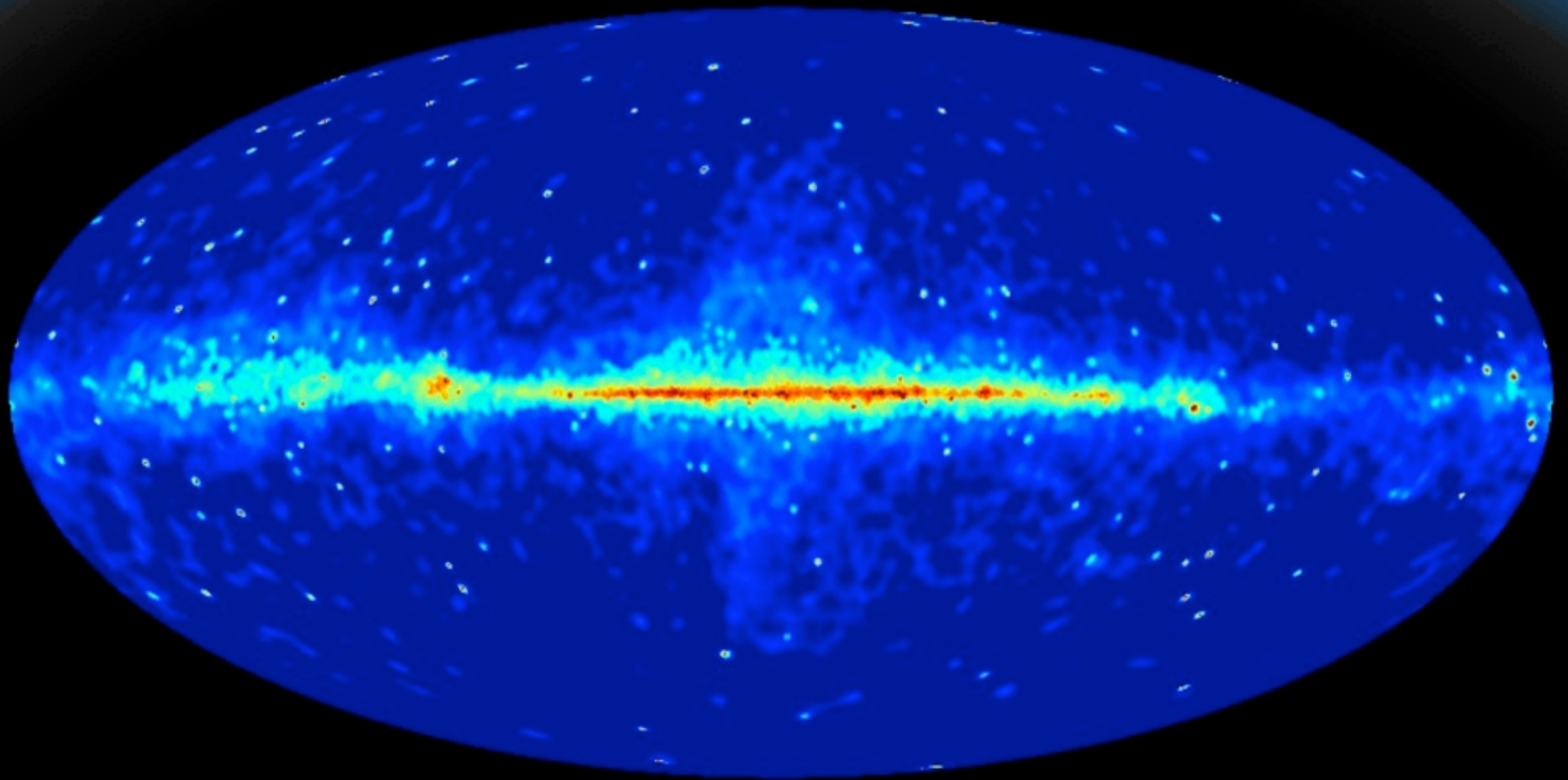


The green crosses show the detected positions of the charged particles, the blue lines show the reconstructed track trajectories, and the yellow line shows the candidate gamma-ray estimated direction. The red crosses show the detected energy depositions in the calorimeter.

The GeV-TeV Gamma-ray Sky



Fermi All-Sky, 3 Years

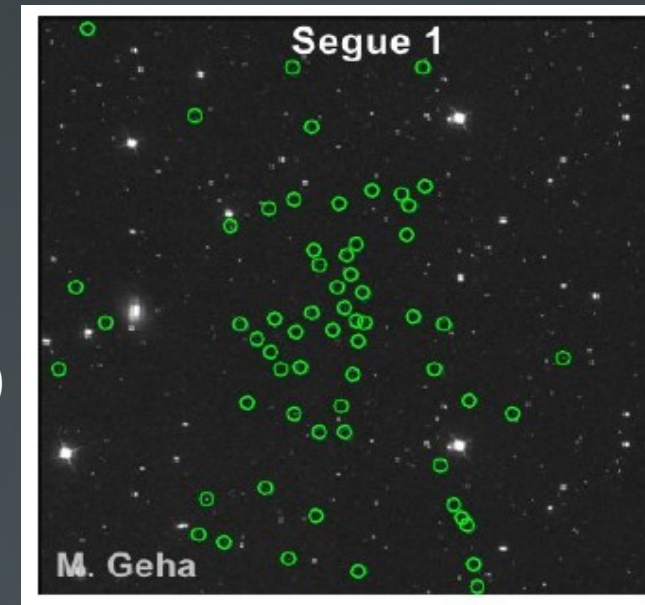


FERMI ($E > 10\text{GeV}$)

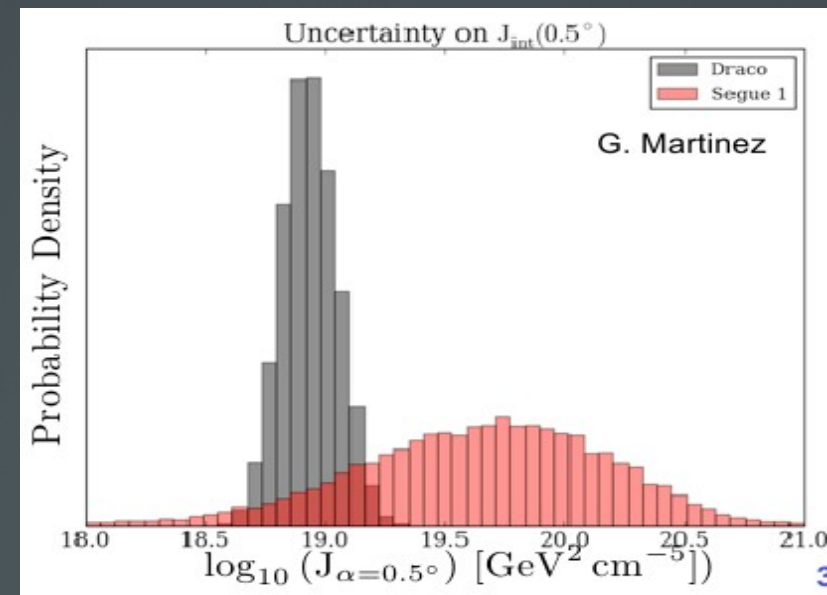
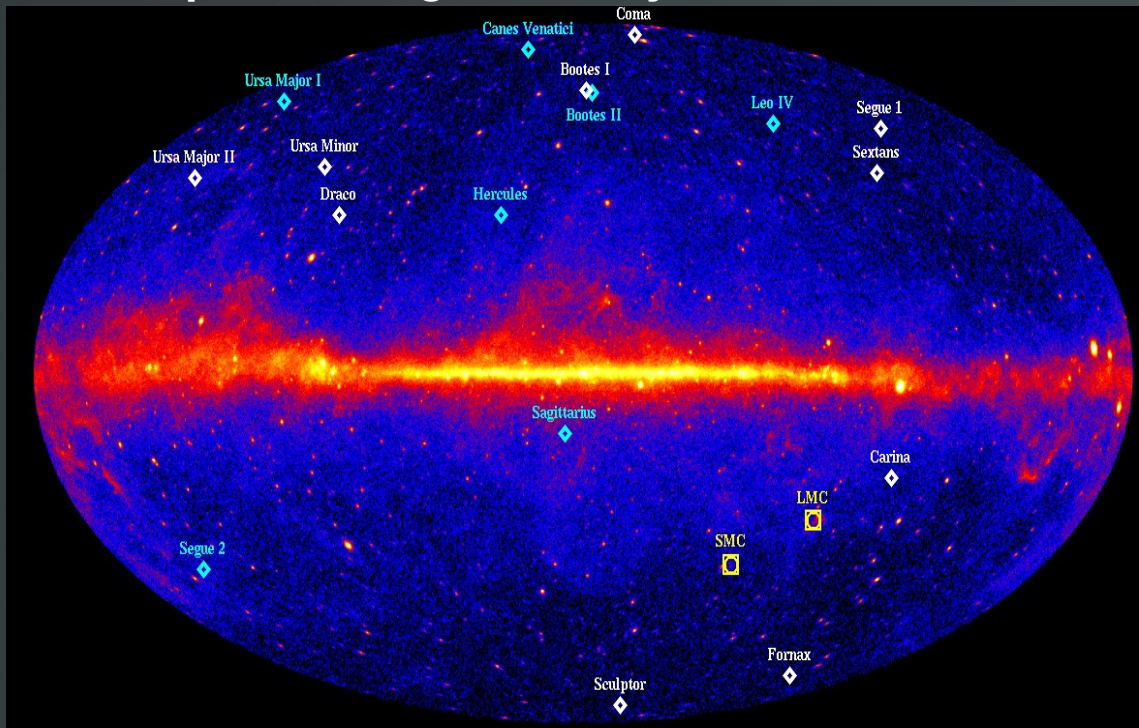
Search for DM in Dwarf Spheroidal Galaxies

dSphs are excellent DM targets of opportunity :

- Very large M/L ratios : ~ 10 to 1000 ($M/L \sim 10$ for Milky Way)
- Most of them are expected to be free from any other astrophysical gamma source and have low content in dust/gas, very few stars
- More promising targets could be discovered by current and upcoming experiments ! (SDSS, DES, PanSTARRS, ...)



Dwarfs probed in gamma-rays :

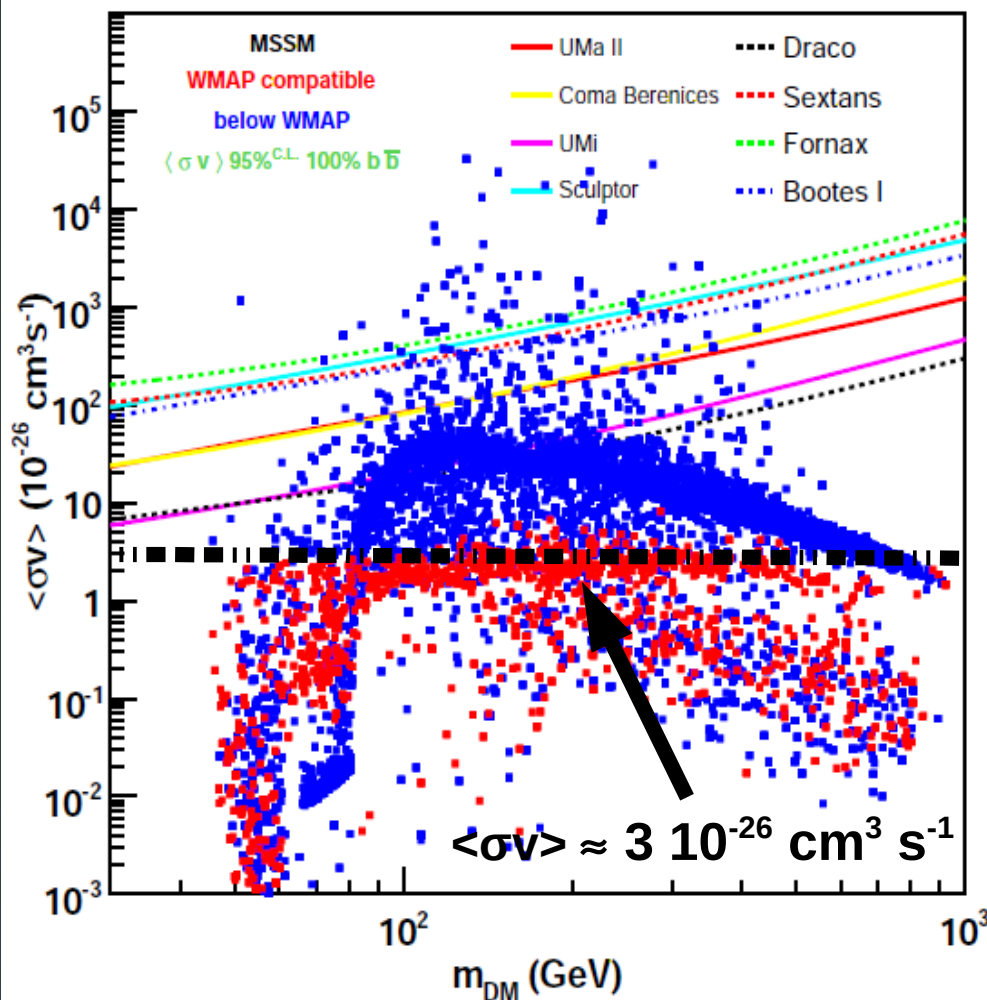


J-factors (DM signal) and their uncertainties can be calculated from stellar kinematical data of the dwarfs

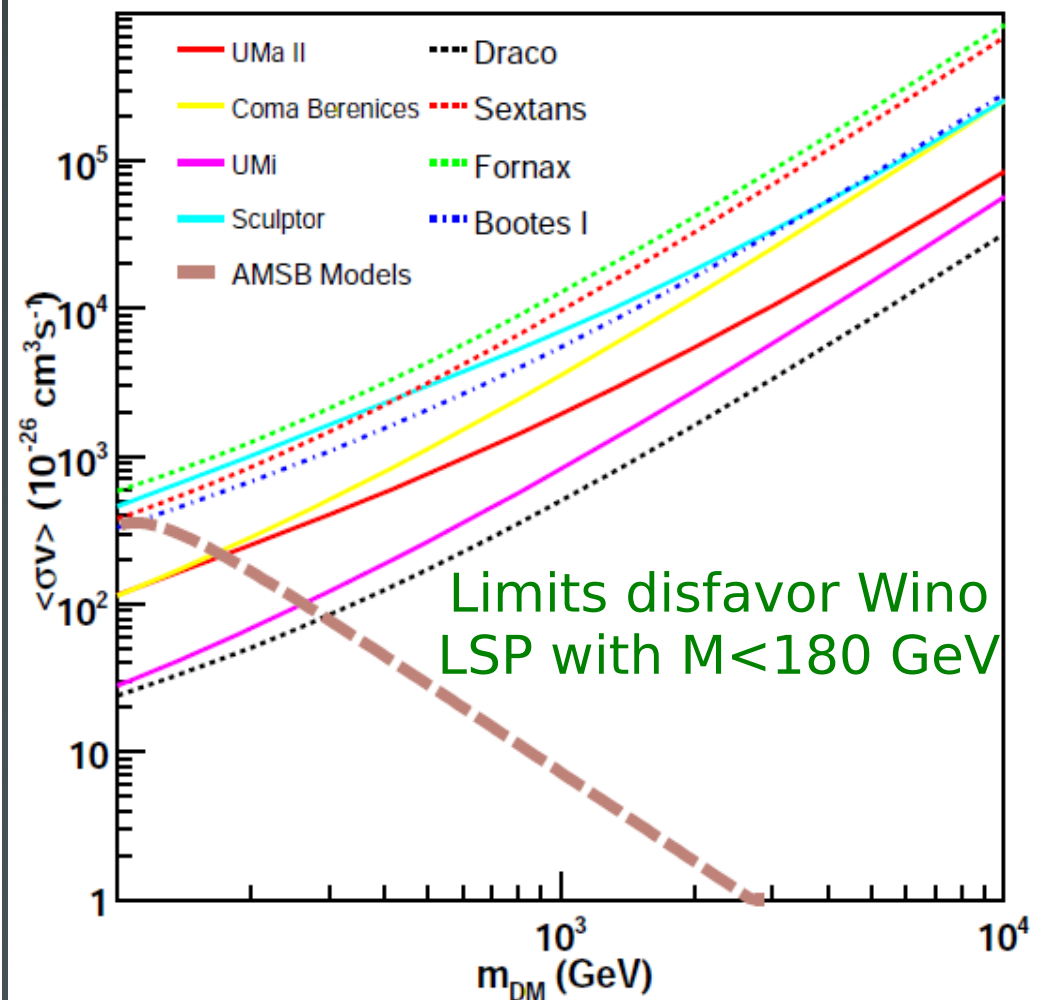
Step 1 : Search for DM in dSphs galaxies with Fermi

Select 10 dSphs with relatively large “astrophysical factor” J
(8 for individual study; +2 for stacking analysis)

« Constrained » MSSM



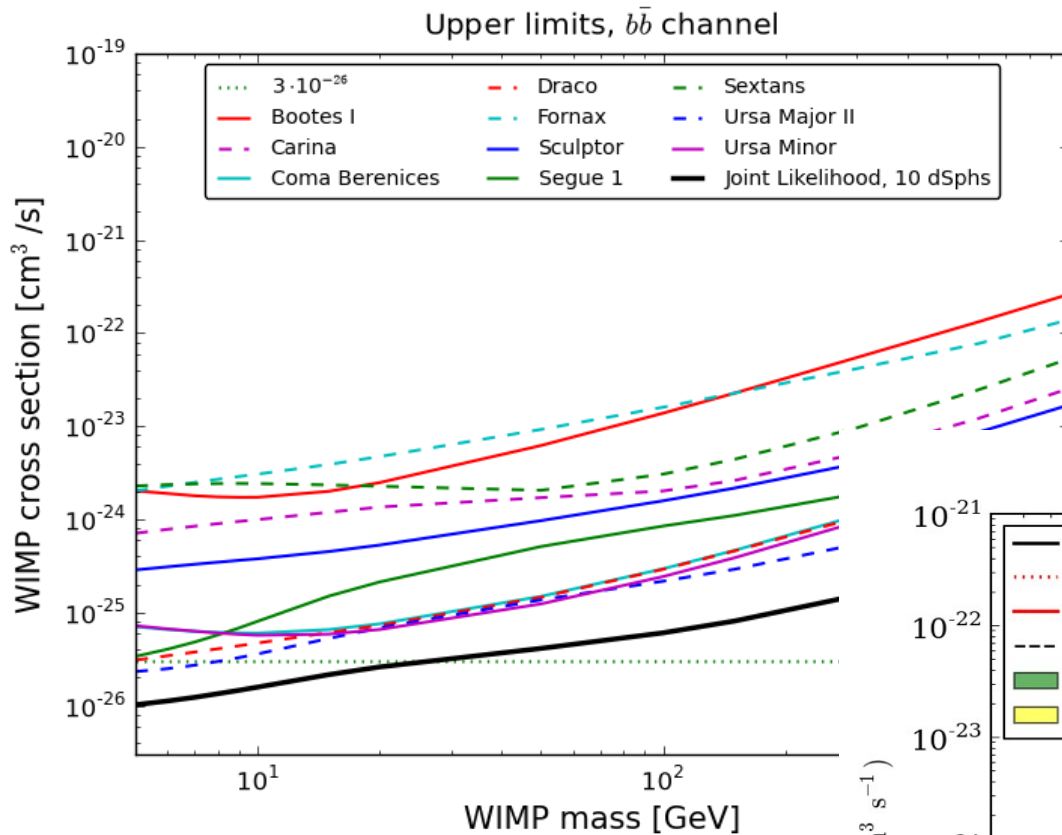
Anomaly mediated SUSY breaking



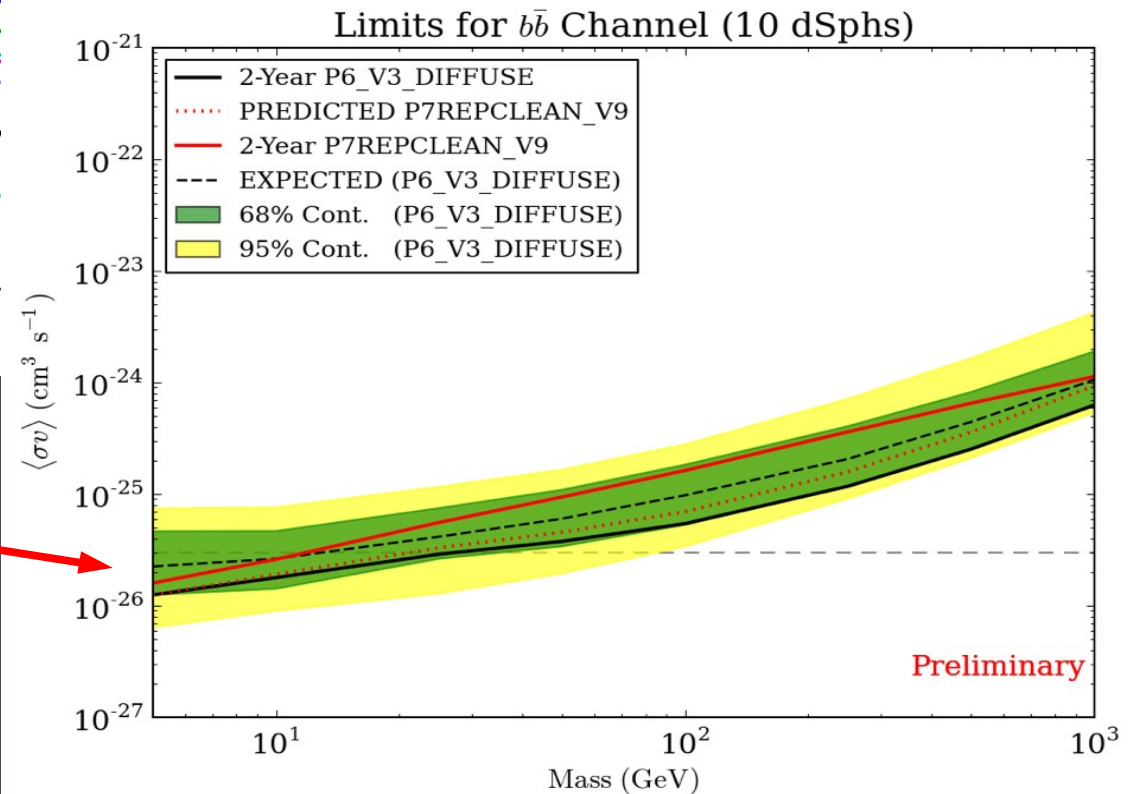
Fermi LAT Collaboration, ApJ 712 147 (2010)

Exclusion regions cutting into interesting parameter space for some WIMP models (NFW, no substructure).

Step 2 : Combining Fermi dSph limits (pass 7)



- Update analysis with an improved understanding of the instrument (reprocessed Pass 7)
- Leads to a statistical reshuffling of gamma-ray-classified events and higher limits.



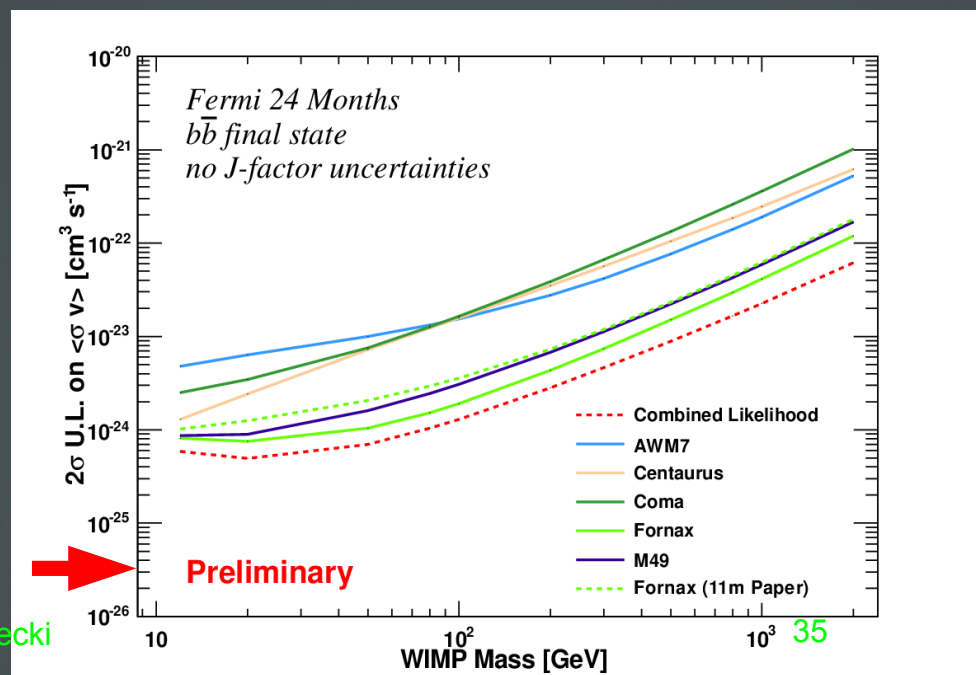
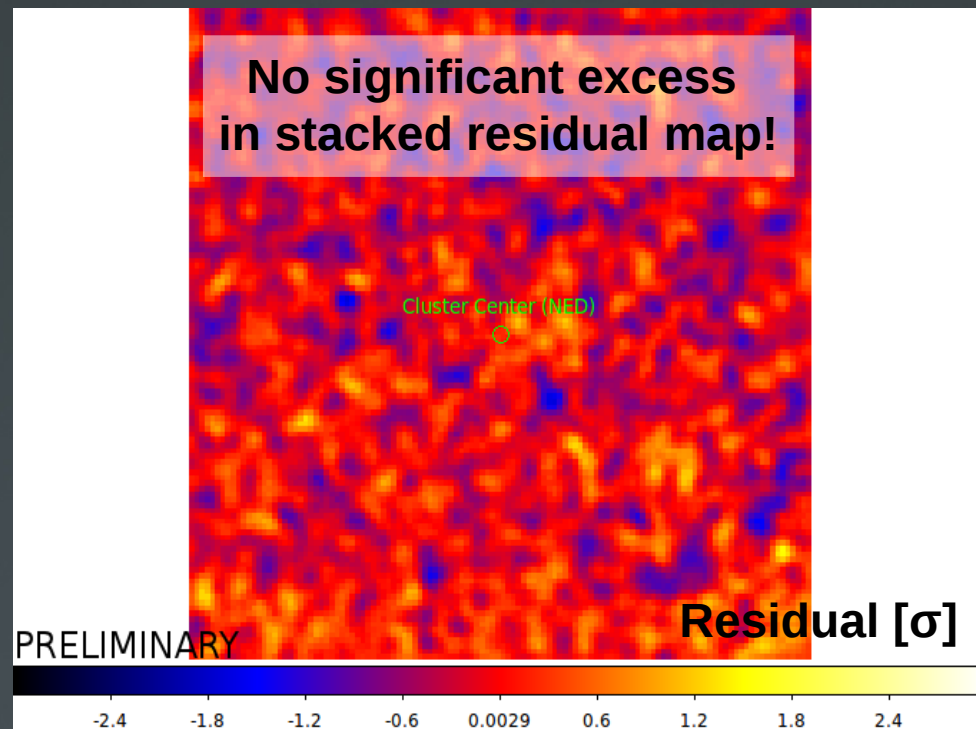
Both Pass 6 and Pass7 measurements lie within the 68% containment region of a statistical sample.

Preliminary

Clusters of galaxies

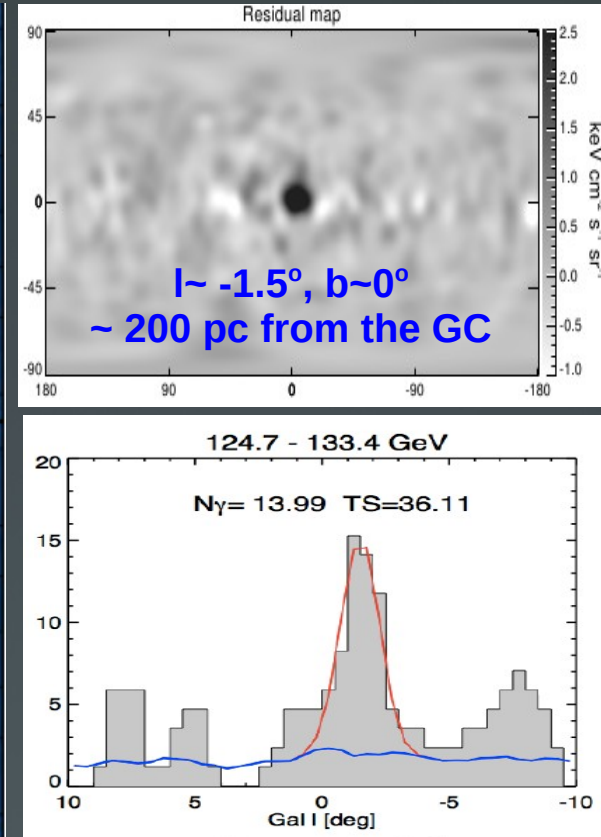
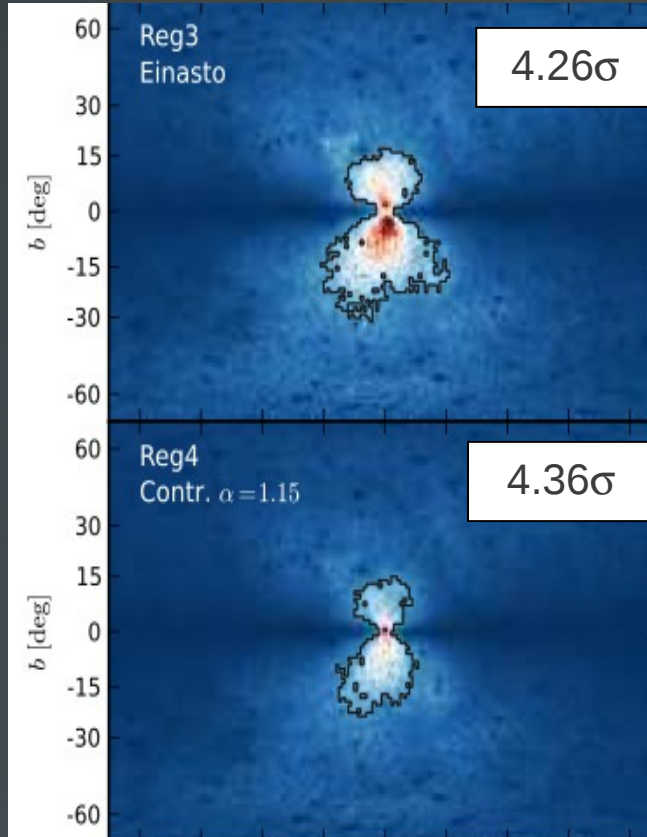
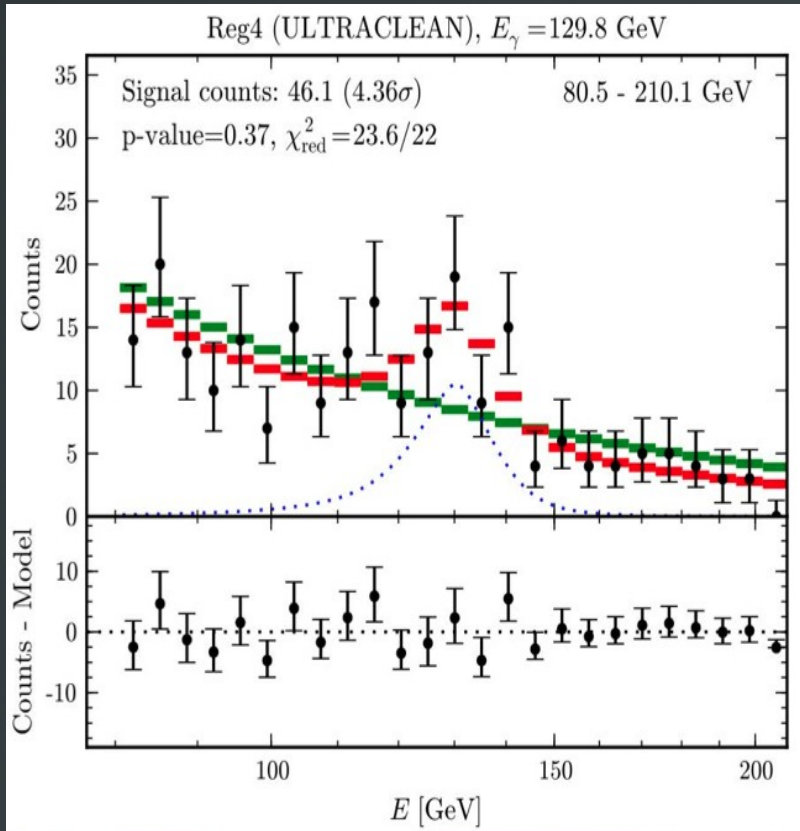
- Largest virialized and most massive structures in the universe :
 - Radio emission suggests rel. cosmic ray (CR) population
 - Lensing and X-Ray observations indicate large dark matter (DM)
- Data analysis :
 - 24 Months of Fermi-LAT data, p6v11 Diffuse class Events
 - Binned analysis, 10 deg ROI, 20 Energy bins from 200 MeV to 100 GeV
 - Clusters modeled as point sources !
- Combined Likelihood Approach :
 - In both cases, CR and DM have common parameter in all clusters (Annihilation cross section or decay time and maximum Injection efficiency)

No observational evidence for γ -rays so far.
A paper with details on careful modeling of clusters as extended sources considering both CR- and DM-induced γ -ray signals is in the works



Other Searches for Spectral Lines in Fermi data : Narrow Spectral Feature at 130 GeV

Bringmann+ [arXiv:1203.1312] , Weniger [arXiv:1204.2797] , Su+ [arXiv:1206.1616, 1207.7060] , ...



- Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC).
- Signal is particularly strong in 2 out of 5 test regions, shown above.
- Over 4σ local significance with $S/N > 30\%$, up to $\sim 60\%$ in optimized ROI.
- Some indication of double line (111 & 130 GeV).

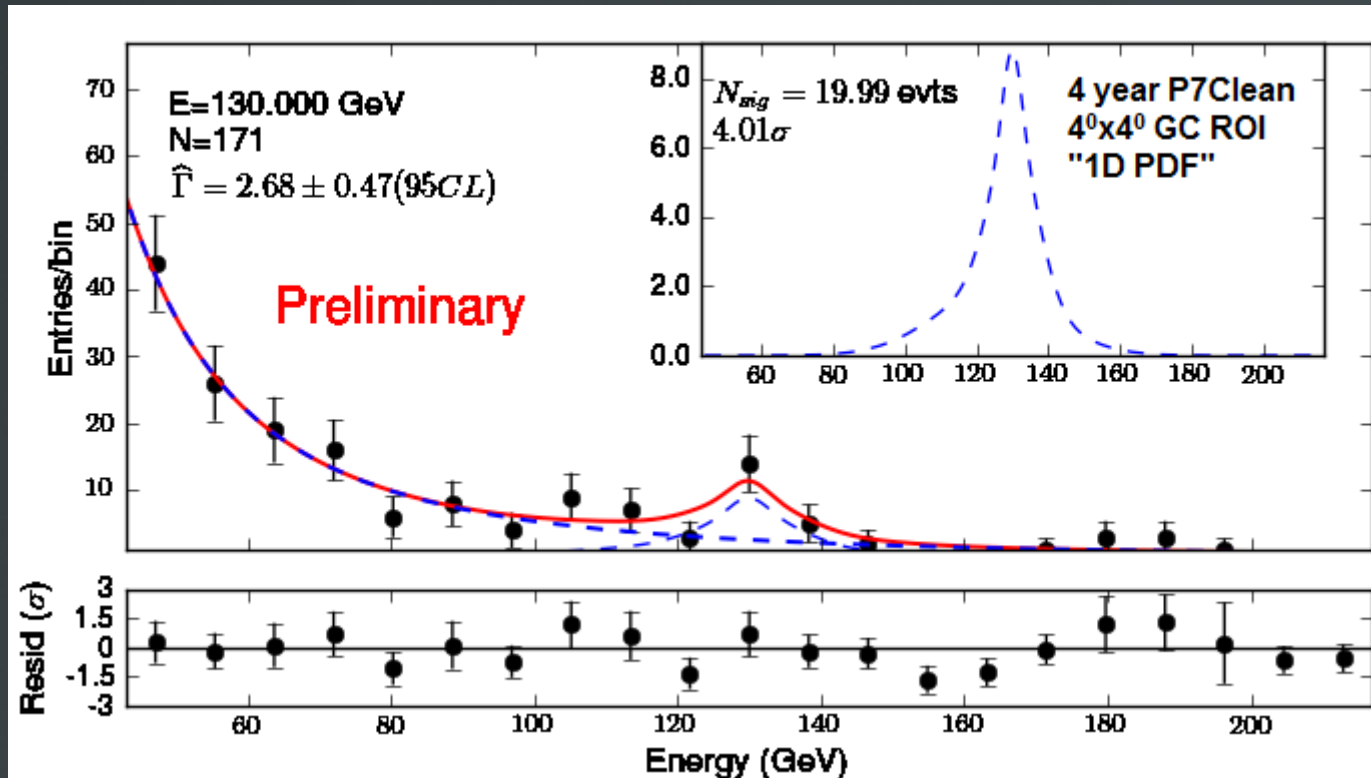
$$\chi\chi \rightarrow \gamma\gamma : m_\chi \sim 130 \text{ GeV} ; \langle \sigma v \rangle \sim 1.3 \times 10^{-27} \text{ cm}^3/\text{s}$$

$$\chi\chi \rightarrow Z\gamma : m_\chi \sim 144 \text{ GeV} ; \langle \sigma v \rangle \sim 3.1 \times 10^{-27} \text{ cm}^3/\text{s}$$

(Einasto DM profile)

Line-like Feature near 135 GeV

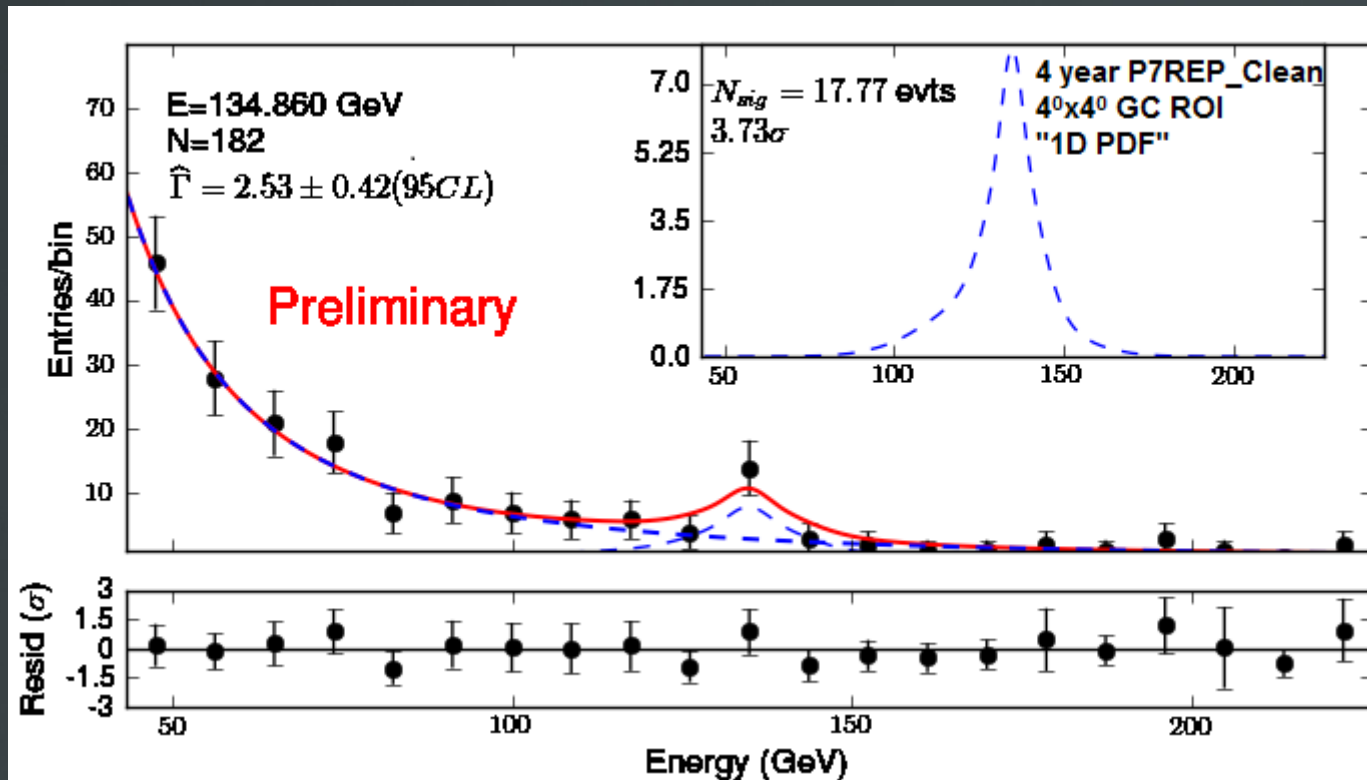
- Our blind search does not find globally significant feature near 135 GeV
 - Reprocessing shifts feature from 130 GeV to 135 GeV
 - Most significant fit was in R3, 3.17σ local ($\sim 1\sigma$ global)



- 4.01 σ (local) 1D fit at 130 GeV with 4 year unprocessed data
 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 1D PDF (no use of P_E)
- 3.73 σ (local) 1D fit at 135 GeV with 4 year reprocessed data
 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 1D PDF (no use of P_E)
- 3.35 σ (local) 2D fit at 135 GeV with 4 year reprocessed data
 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 2D PDF (P_E in data)

Line-like Feature near 135 GeV

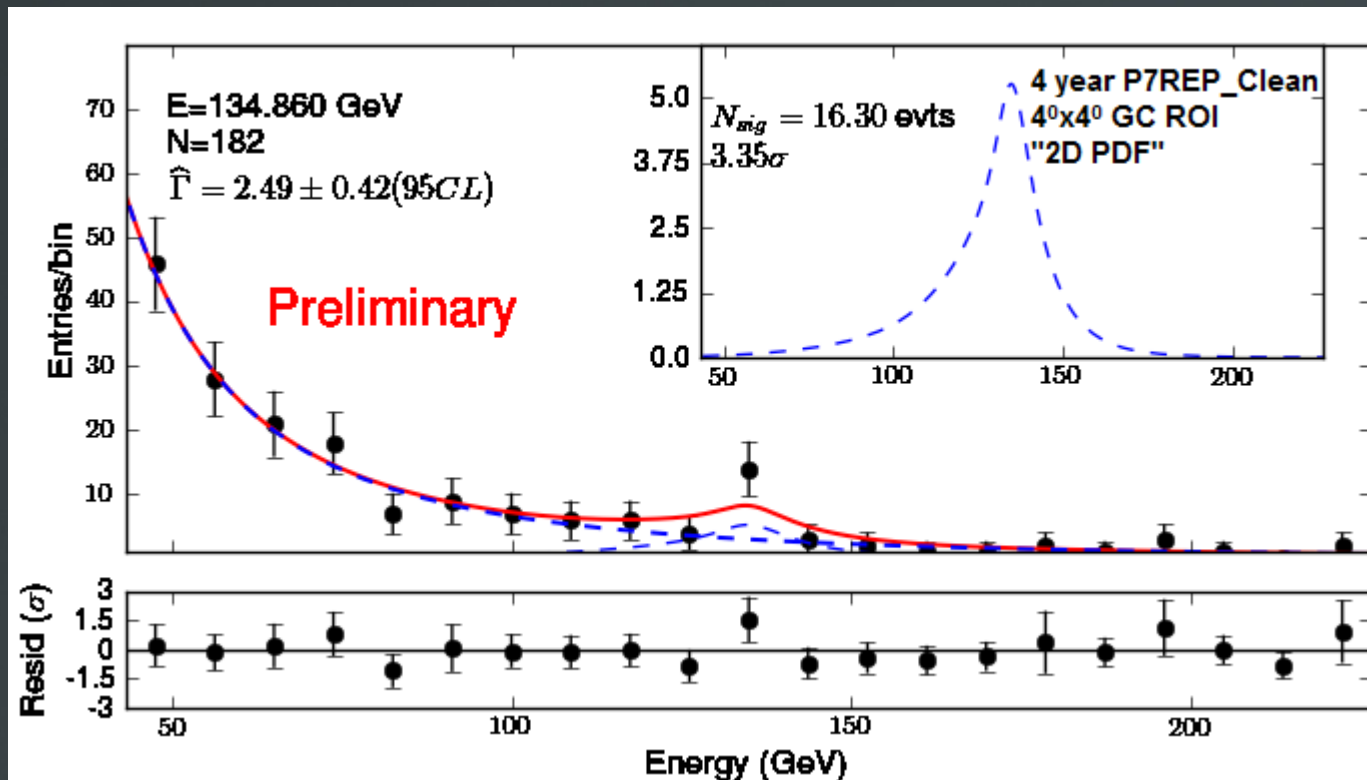
- Our blind search does not find globally significant feature near 135 GeV
 - Reprocessing shifts feature from 130 GeV to 135 GeV
 - Most significant fit was in R3, 3.17σ local ($\sim 1\sigma$ global)



- 4.01σ (local) 1D fit at 130 GeV with 4 year unprocessed data
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 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 2D PDF (P_E in data)

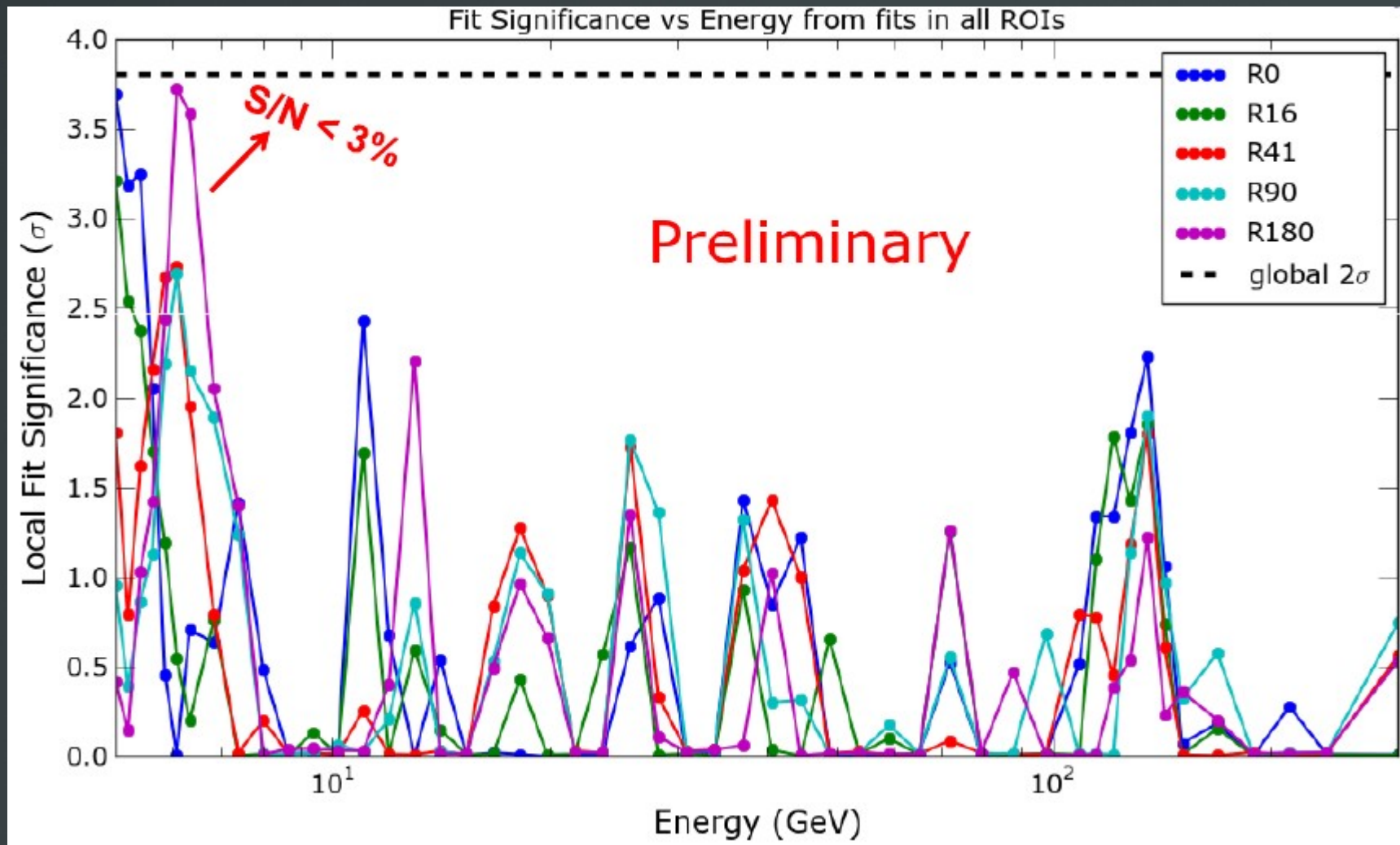
Line-like Feature near 135 GeV

- Our blind search does not find globally significant feature near 135 GeV
 - Reprocessing shifts feature from 130 GeV to 135 GeV
 - Most significant fit was in R3, 3.17σ local ($\sim 1\sigma$ global)



- 4.01σ (local) 1D fit at 130 GeV with 4 year unprocessed data
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- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
 - Look in $4^\circ \times 4^\circ$ GC ROI, Use 2D PDF (P_E in data)

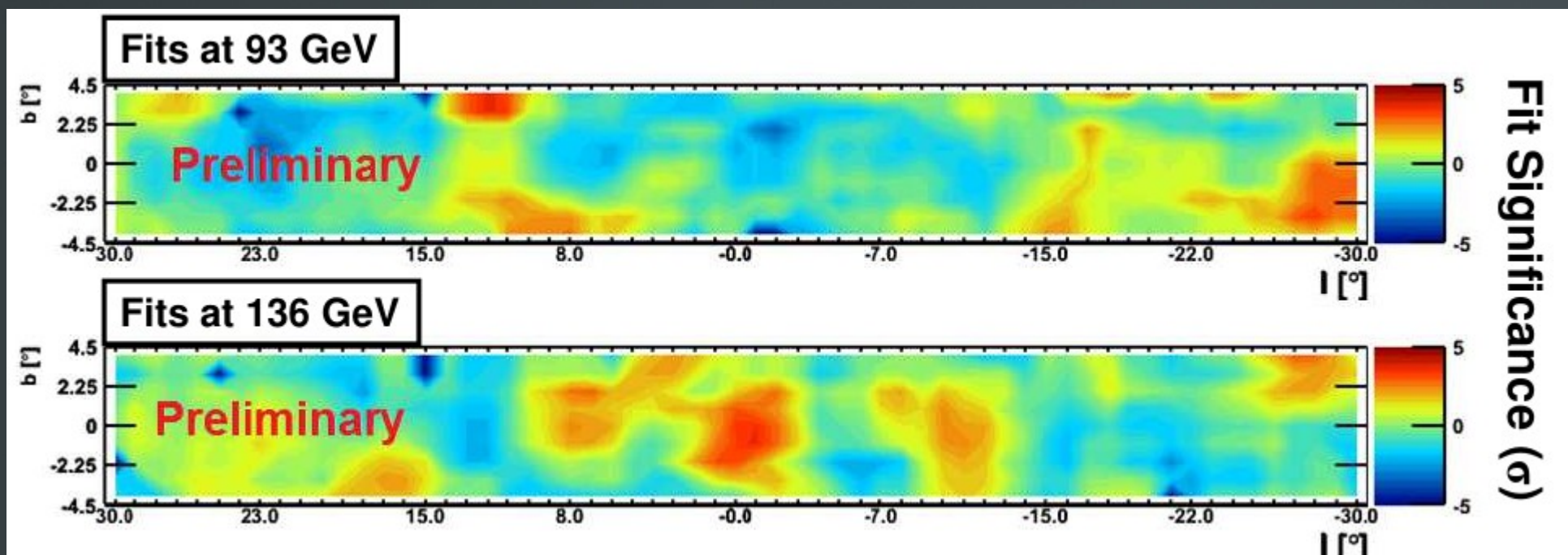
4 year Fermi-LAT Fermi-Line Search Results



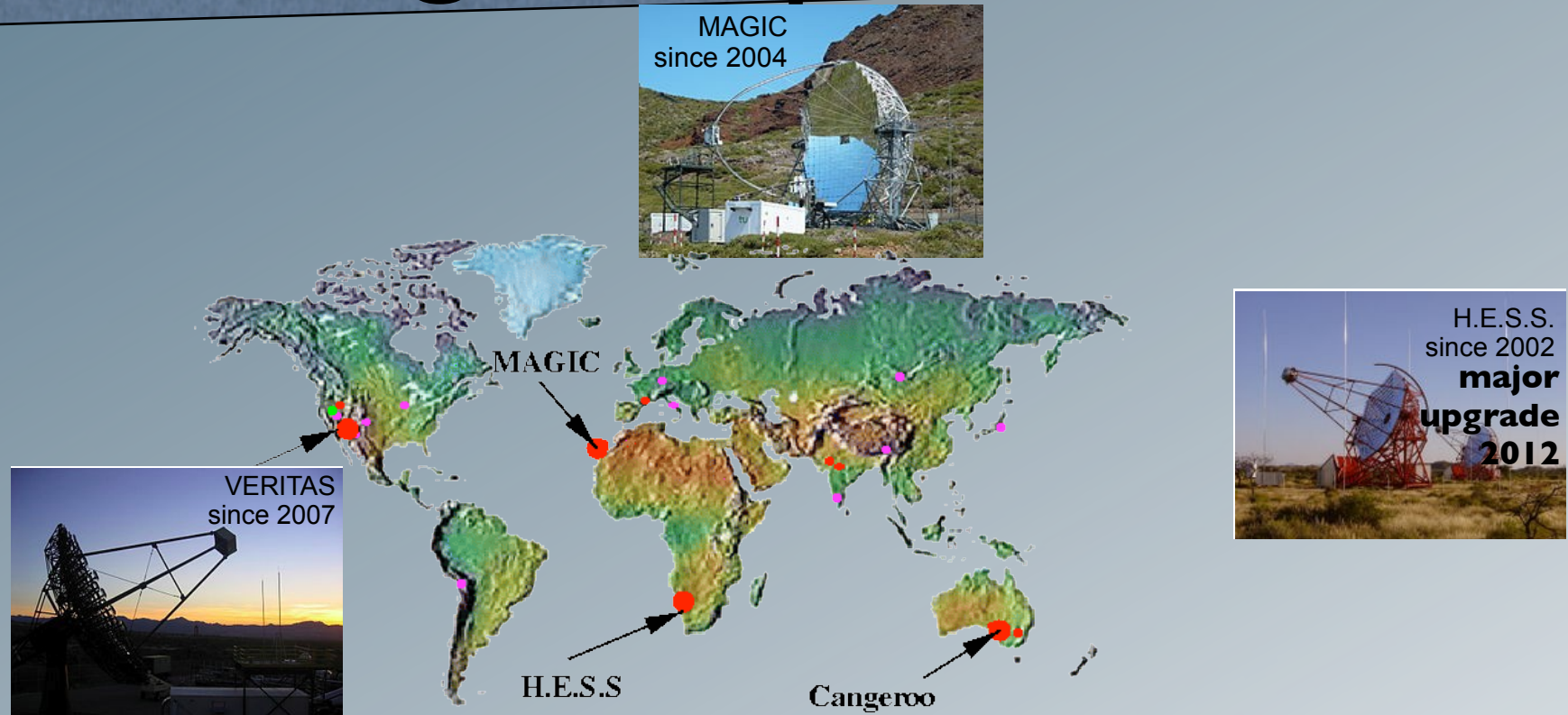
No globally significant lines found
Most significant fit was in R180 at 6 GeV, $\sim 2\sigma$ (3.7σ local)

Features in the Galactic Plane

- Fit in $4^\circ \times 4^\circ$ ROIs along the Galactic plane in 1° steps
 - Fit with “1D PDF”
 - To find where the counts are coming from
 - Allowed for negative fluctuations
- Find excess near ~ 135 GeV near GC
 - But find similar features at other energies along the GP
 - Some indication the 135 feature not smooth, but 2-3 smaller “hot spots”
 - Excess near 135 GeV is one of the largest and near GC, but is not otherwise unique



Operating and planned ACTs



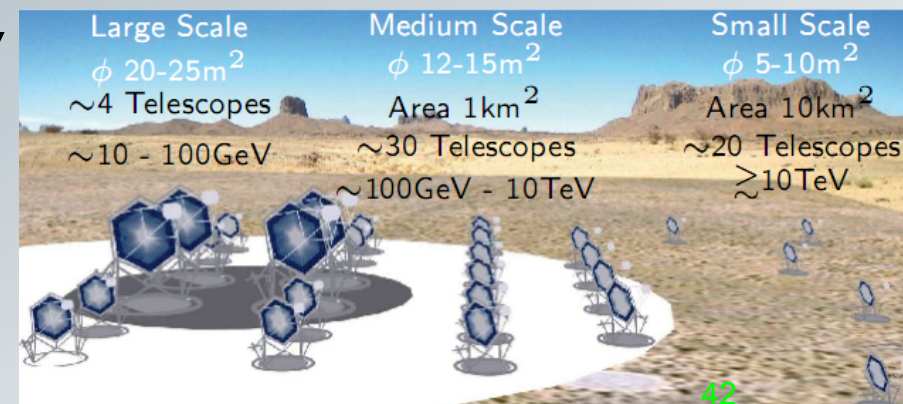
The Cherenkov Telescope Array

- planned **open observatory**, construction from 2015 ?
- ~10 times better sensitivity** than any existing instrument

Astrofizyka cząstek: wykład 6

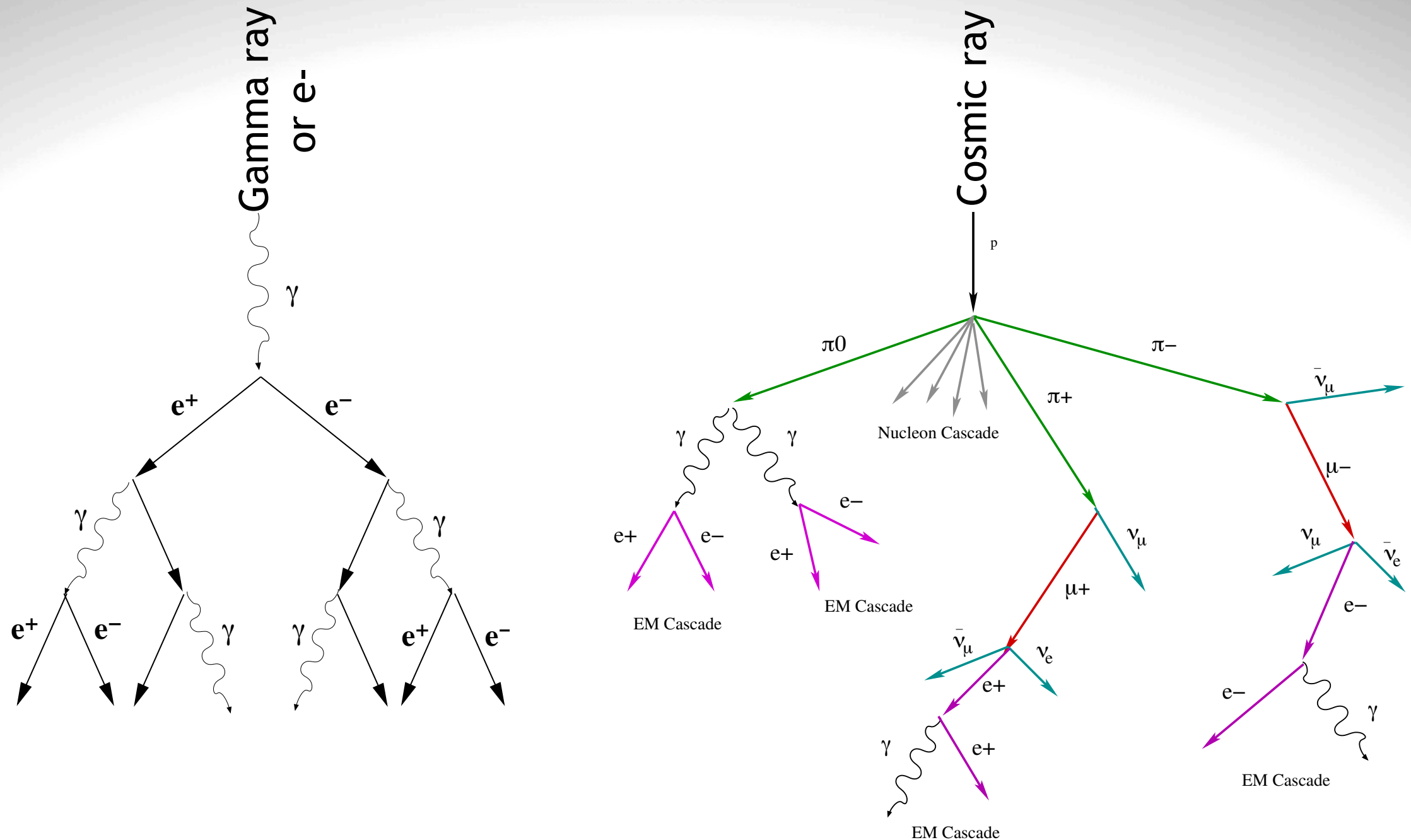
Torsten Bringmann, University of Hamburg

A.F.Żarnecki



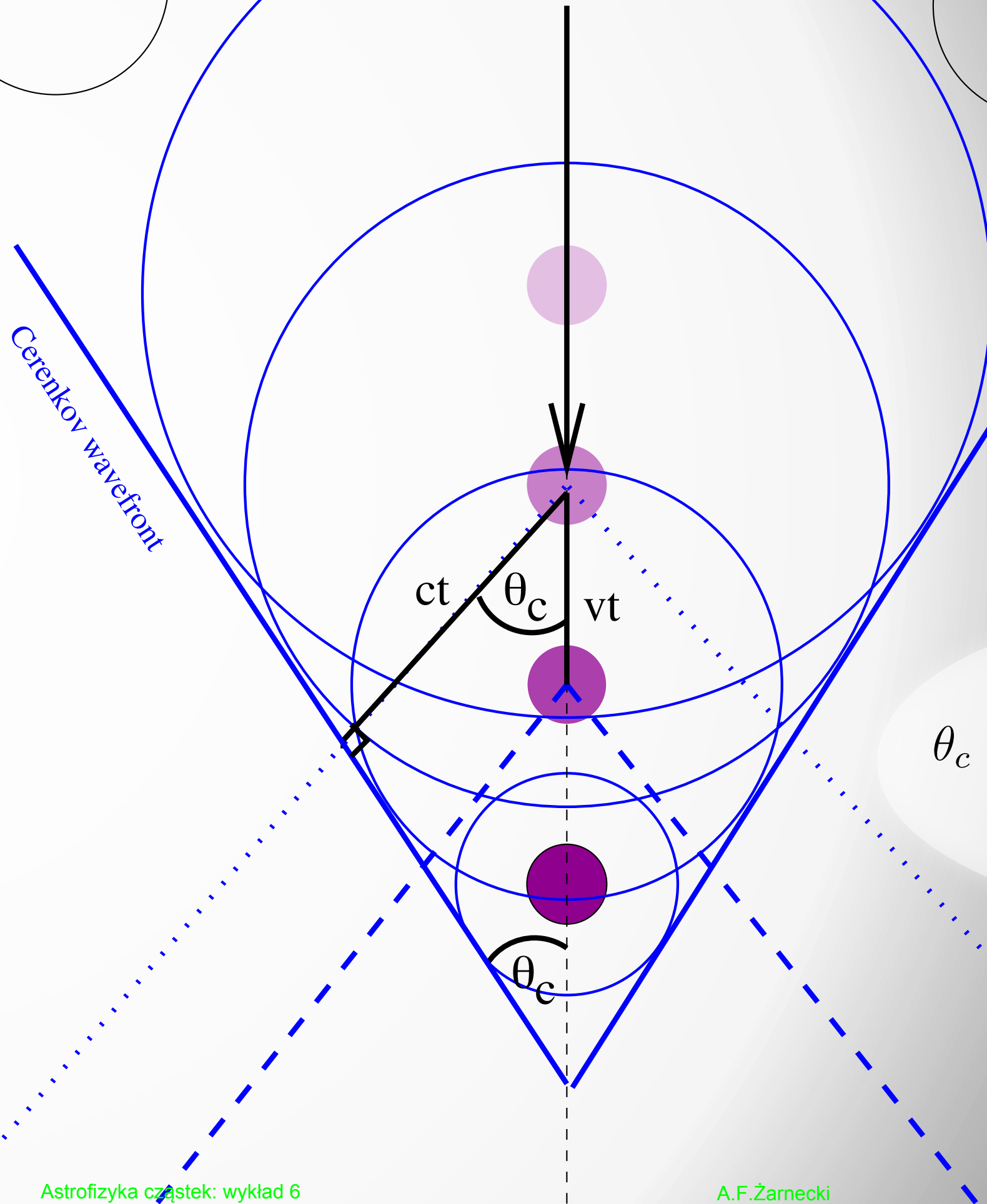
42

Recall: Air showers



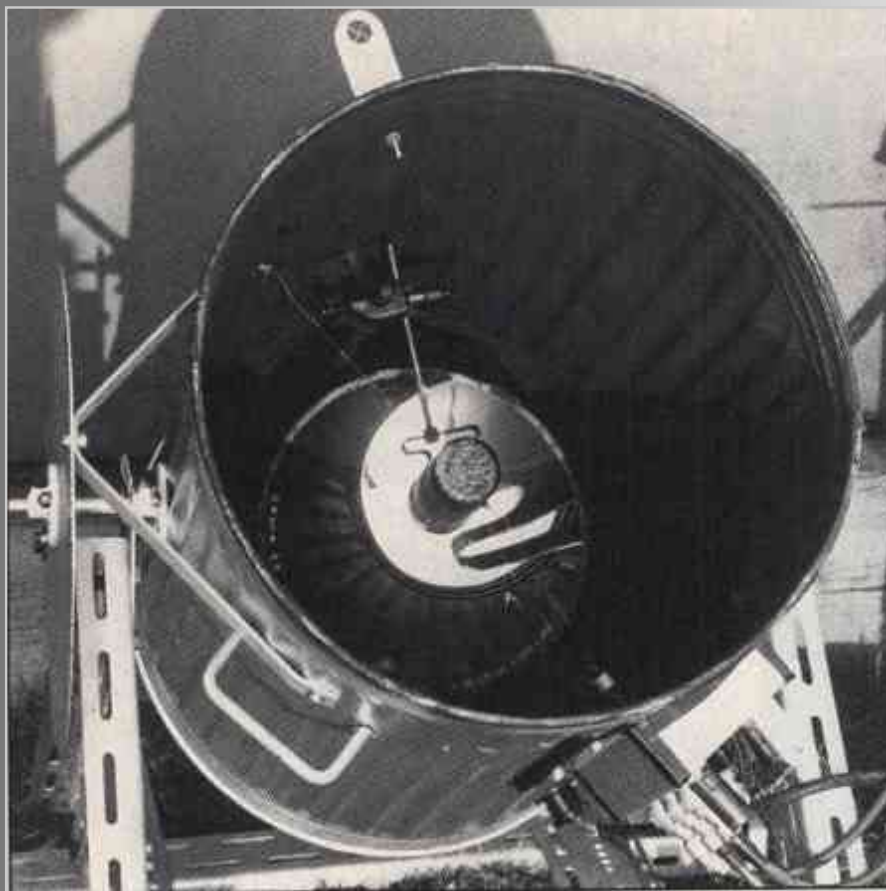
- Hadronic showers have larger transverse momentum, sub-showers that look like EM showers
- From Heitler Model of EM showers: max number of particles in shower is proportional to the incident energy

Cherenkov Radiation



$$\theta_c = \cos^{-1} \left(\frac{c_m t}{vt} \right) = \cos^{-1} \left(\frac{1}{\beta n} \right)$$

Detecting Cosmic Rays from Air Showers



yes, this is a trash can

February 21, 1953

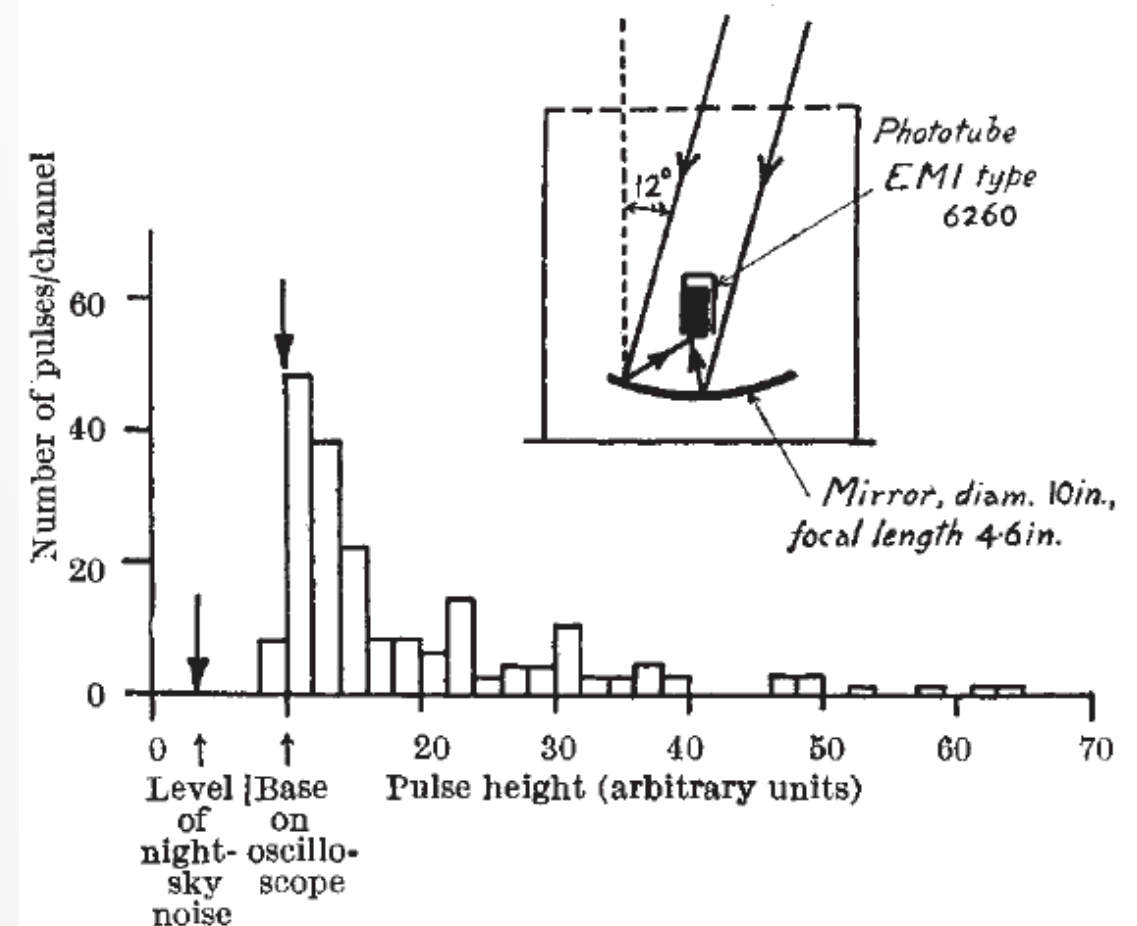
NATURE

Light Pulses from the Night Sky associated with Cosmic Rays

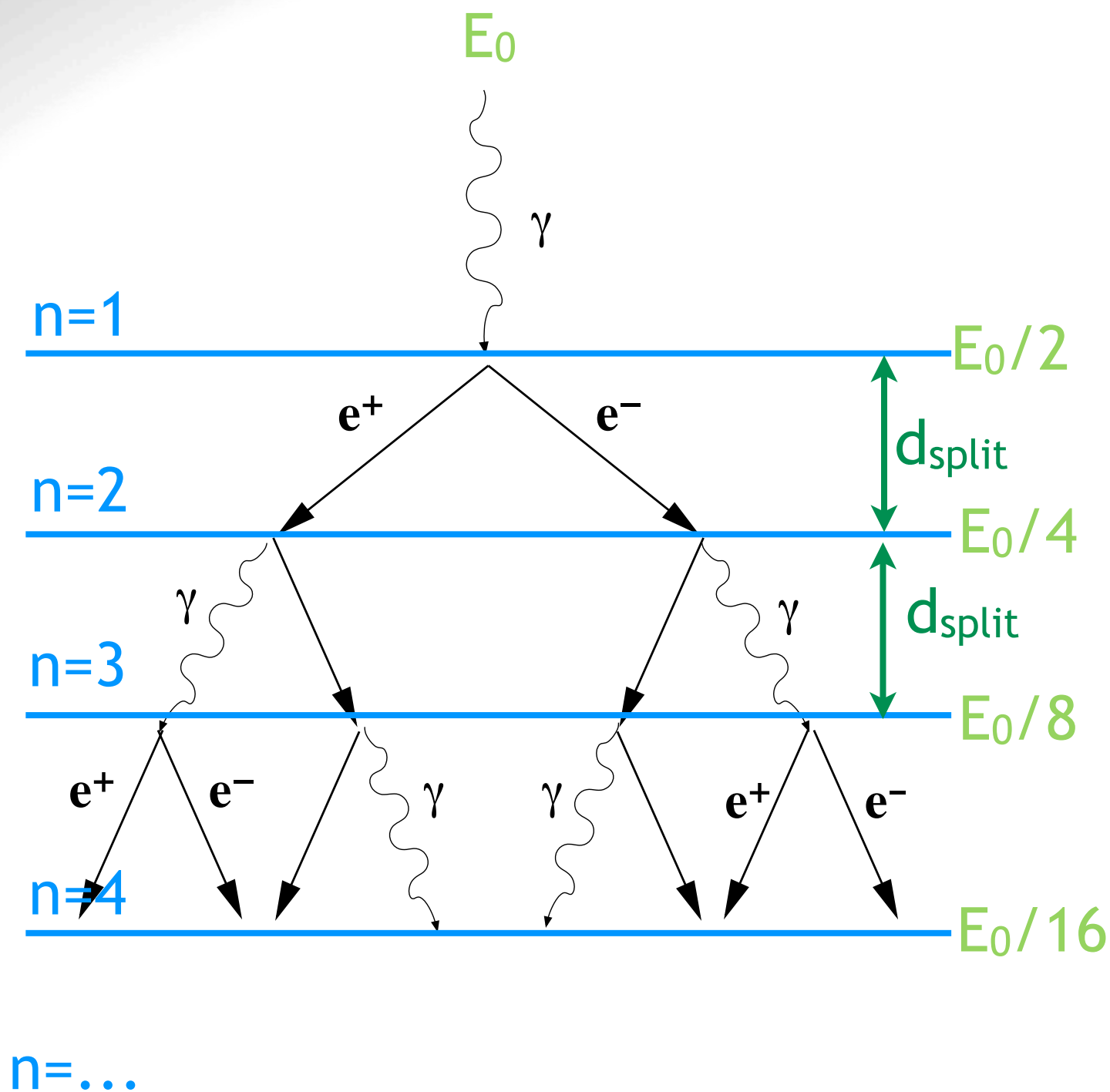
IN 1948, Blackett¹ suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation² produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

thank Mr. W. J. Whitehouse and Dr. E. Bretscher for their encouragement, and Dr. T. E. Cranshaw for the use of the extensive shower array.

W. GALBRAITH
J. V. JELLEY



Heitler Model



$$d_{\text{split}} = \ln 2 \lambda_r$$

= Distance over which electron loses half its energy via radiation

After n steps,

shower depth

$$x = n d_{\text{split}} = n \lambda_r \ln 2$$

total number of particles (e^+, e^-, γ)

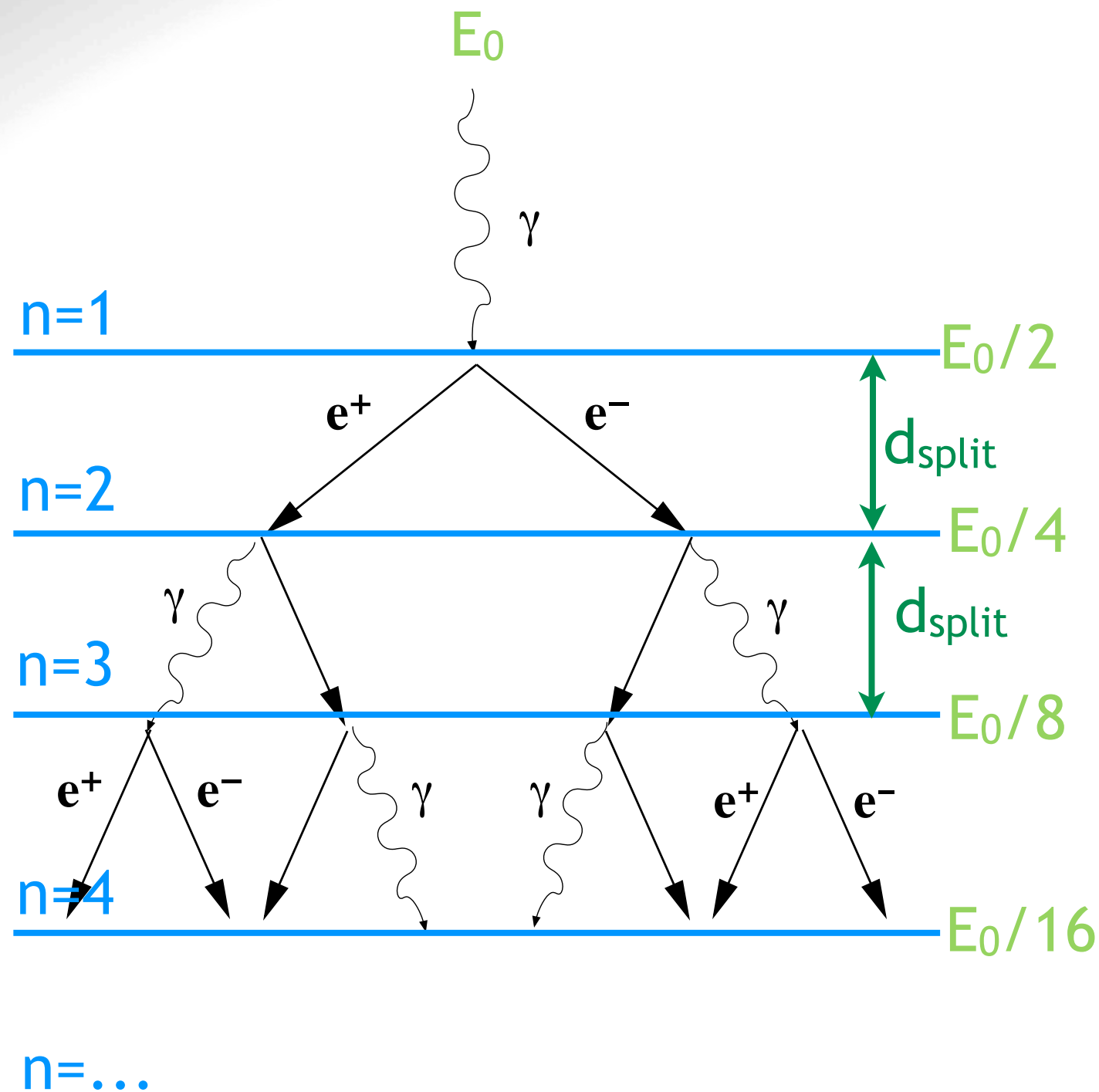
$$N = 2^n = e^{\frac{x}{\lambda_r}}$$

What is the maximum shower “size” (total number of particles)?

Occurs when all particles have $E = E_{\text{crit}}$

$$N_{\text{max}} = E_0 / E_{\text{crit}}$$

Heitler Model



$$d_{\text{split}} = \ln 2 \lambda_r$$

$$x = n d_{\text{split}} = n \lambda_r \ln 2$$

$$N = 2^n = e^{\frac{x}{\lambda_r}}$$

$$N_{\text{max}} = E_0 / E_{\text{crit}}$$

How deep is N_{max} ? When $n=n_{\text{crit}}$, all particles have E_{crit} :

$$N_{\text{max}} = 2^{n_{\text{crit}}}$$

$$\frac{E_0}{E_{\text{crit}}} = 2^{n_{\text{crit}}}$$

$$\ln \frac{E_0}{E_{\text{crit}}} = n_{\text{crit}} \ln 2$$

$$x_{\text{max}} = n_{\text{crit}} \lambda_r \ln 2$$

$$= \lambda_r \ln \frac{E_0}{E_{\text{crit}}}$$

Heitler Model

In Atmosphere:

- ▶ $\lambda_r \approx 40 \text{ g/cm}^2$
- ▶ $E_{\text{crit}} \approx 85 \text{ MeV}$
- ▶ total depth of atmosphere $\approx 1000 \text{ g/cm}^2$
- ▶ density profile:

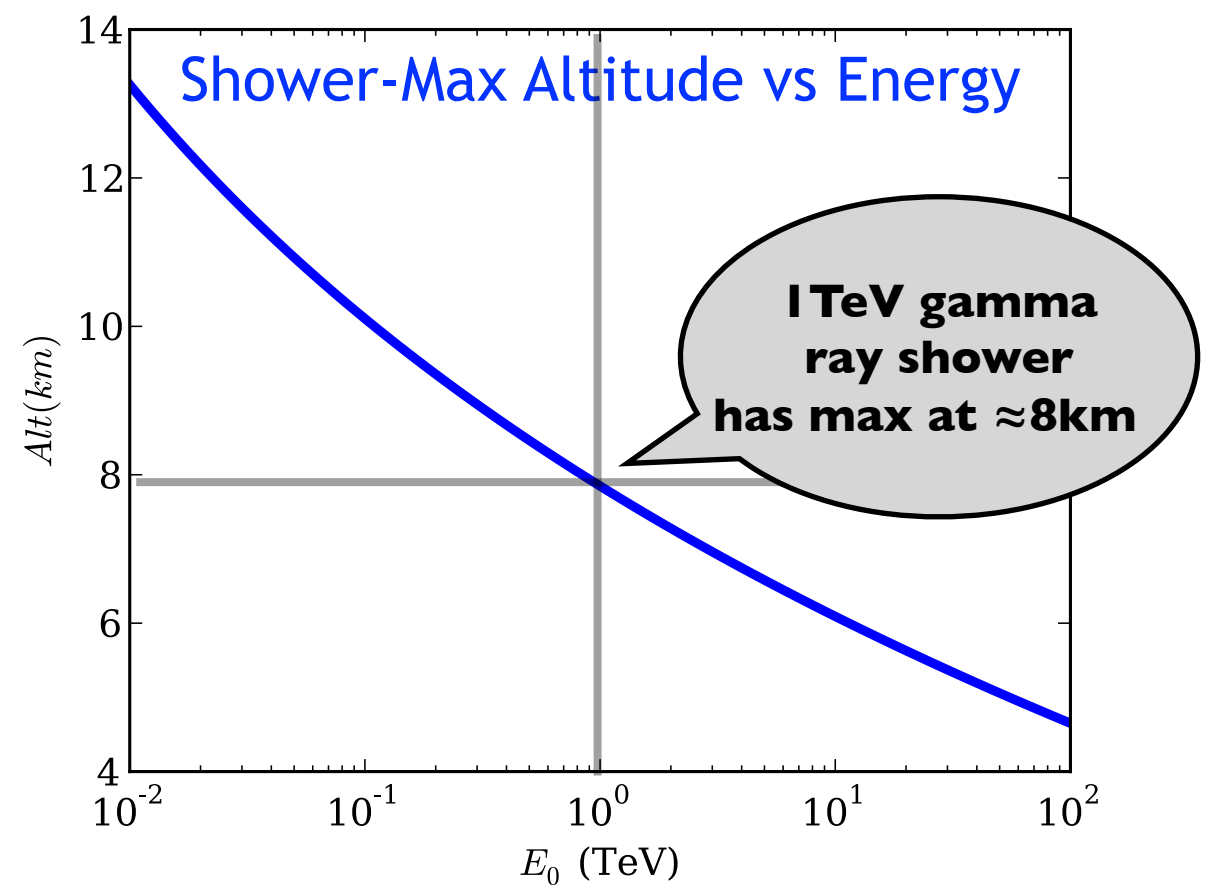
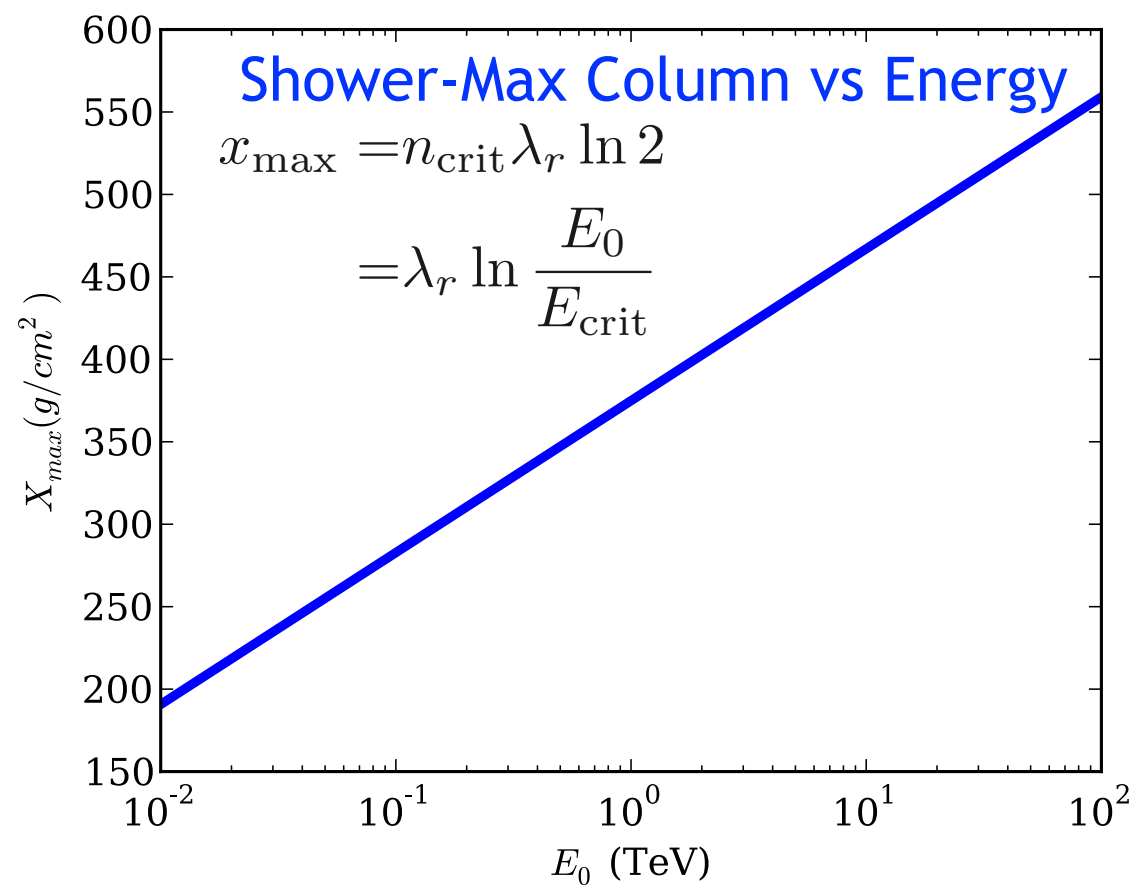
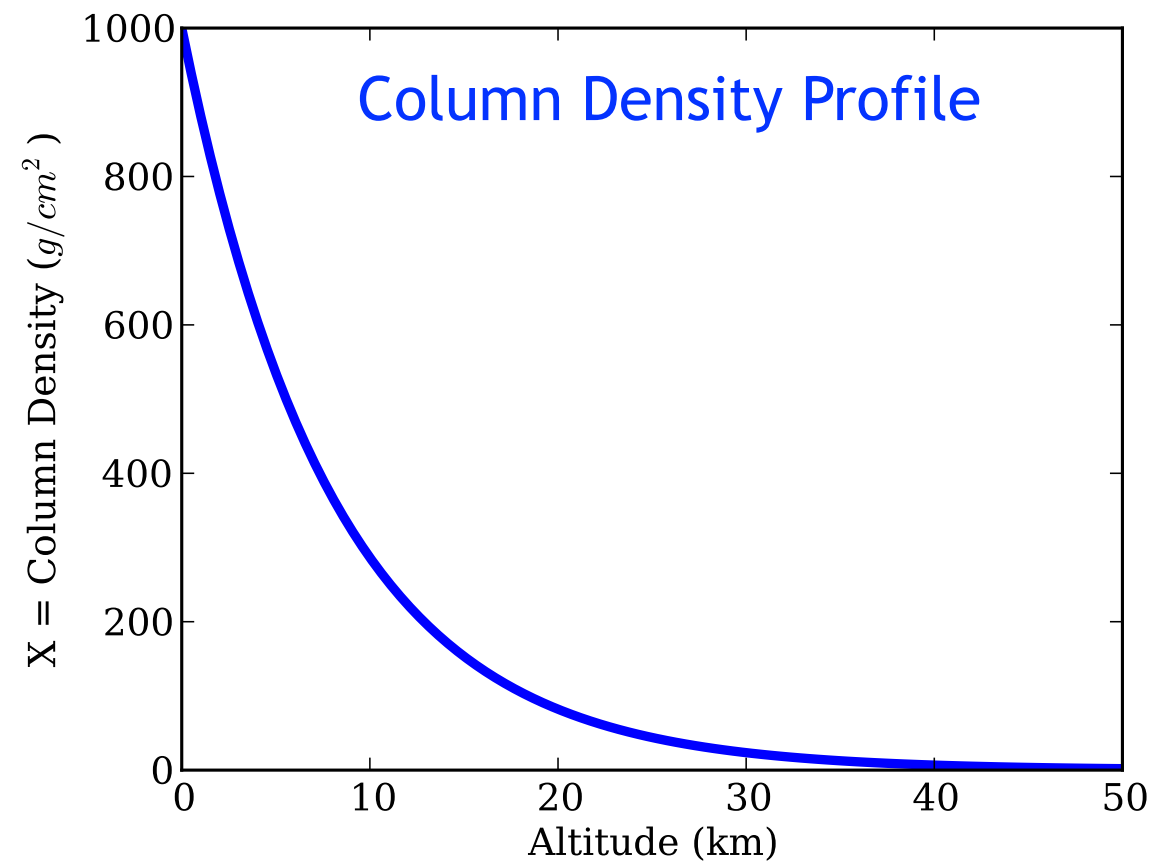
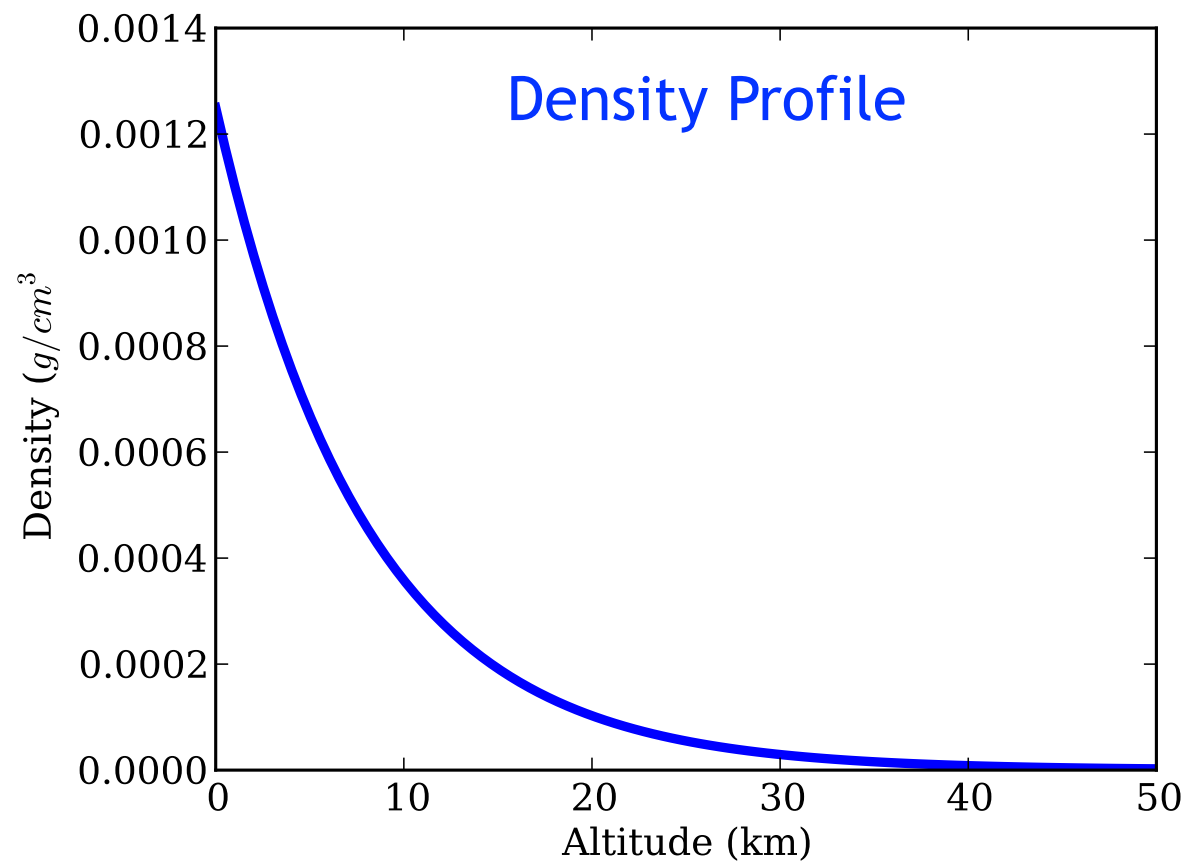
$$\rho = \rho_0 e^{-h/h_0}$$

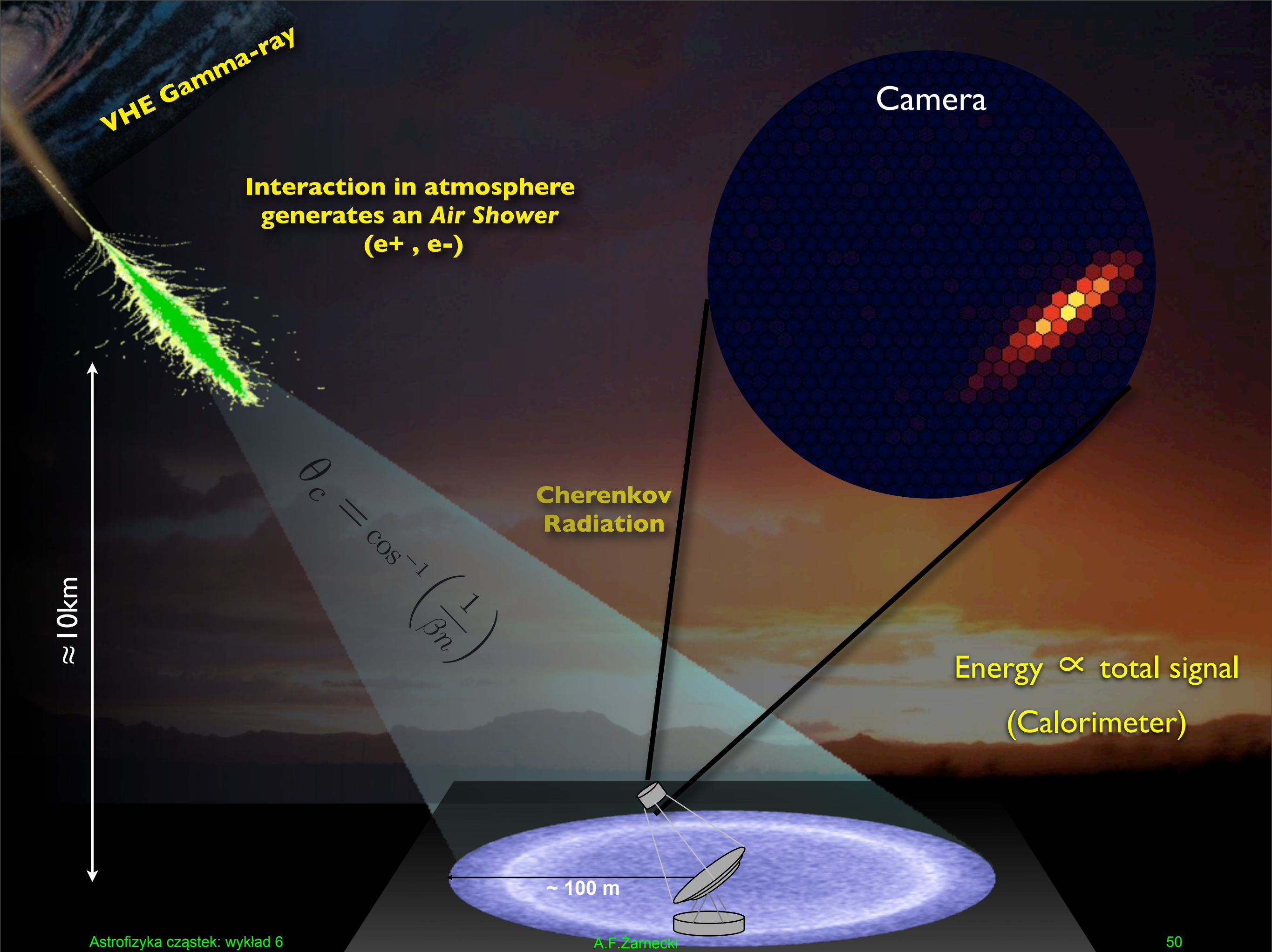
$$h_0 \simeq 8 \text{ km}$$

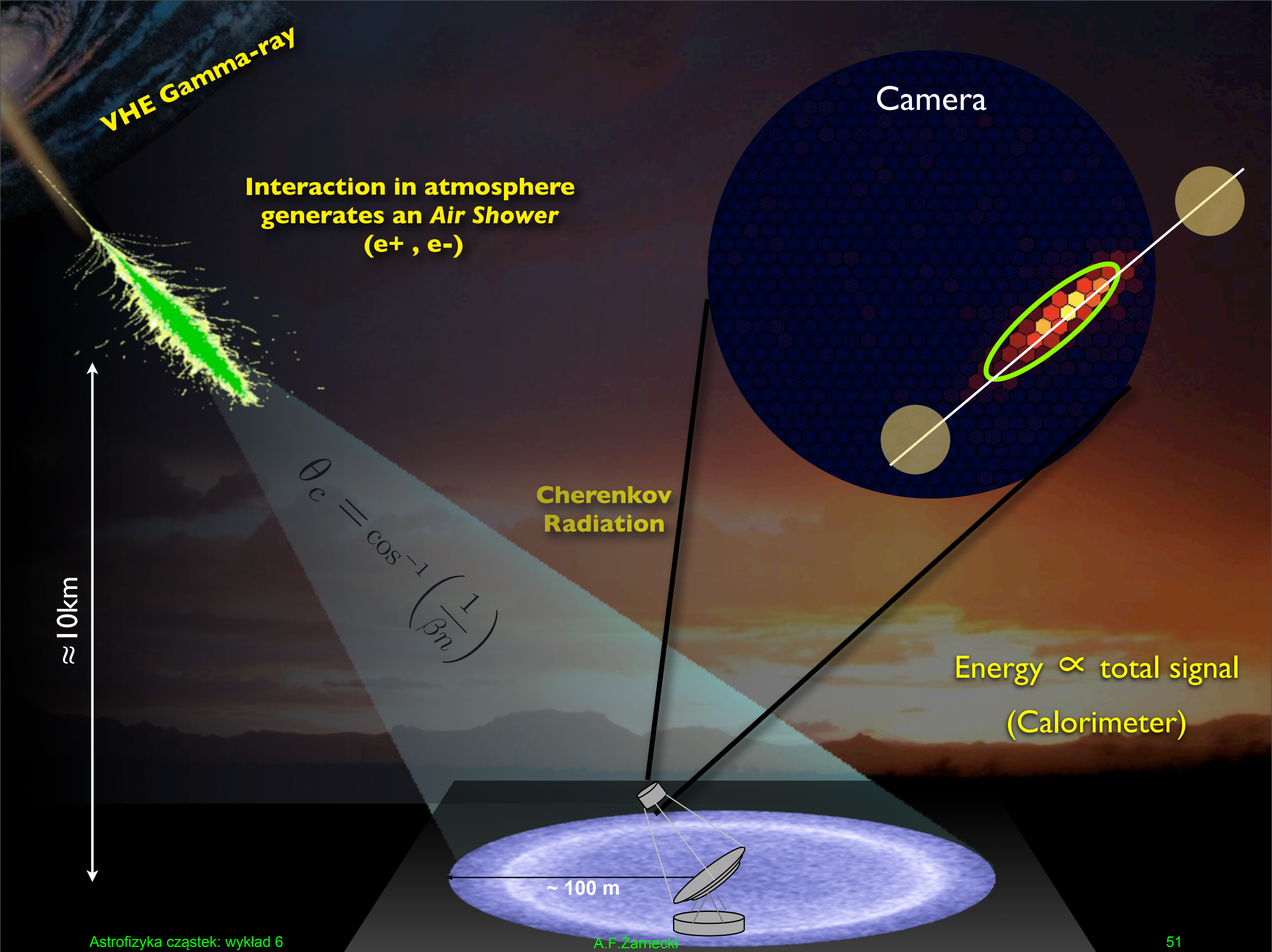
$$x \equiv \int_{\infty}^h \rho(h') dh'$$

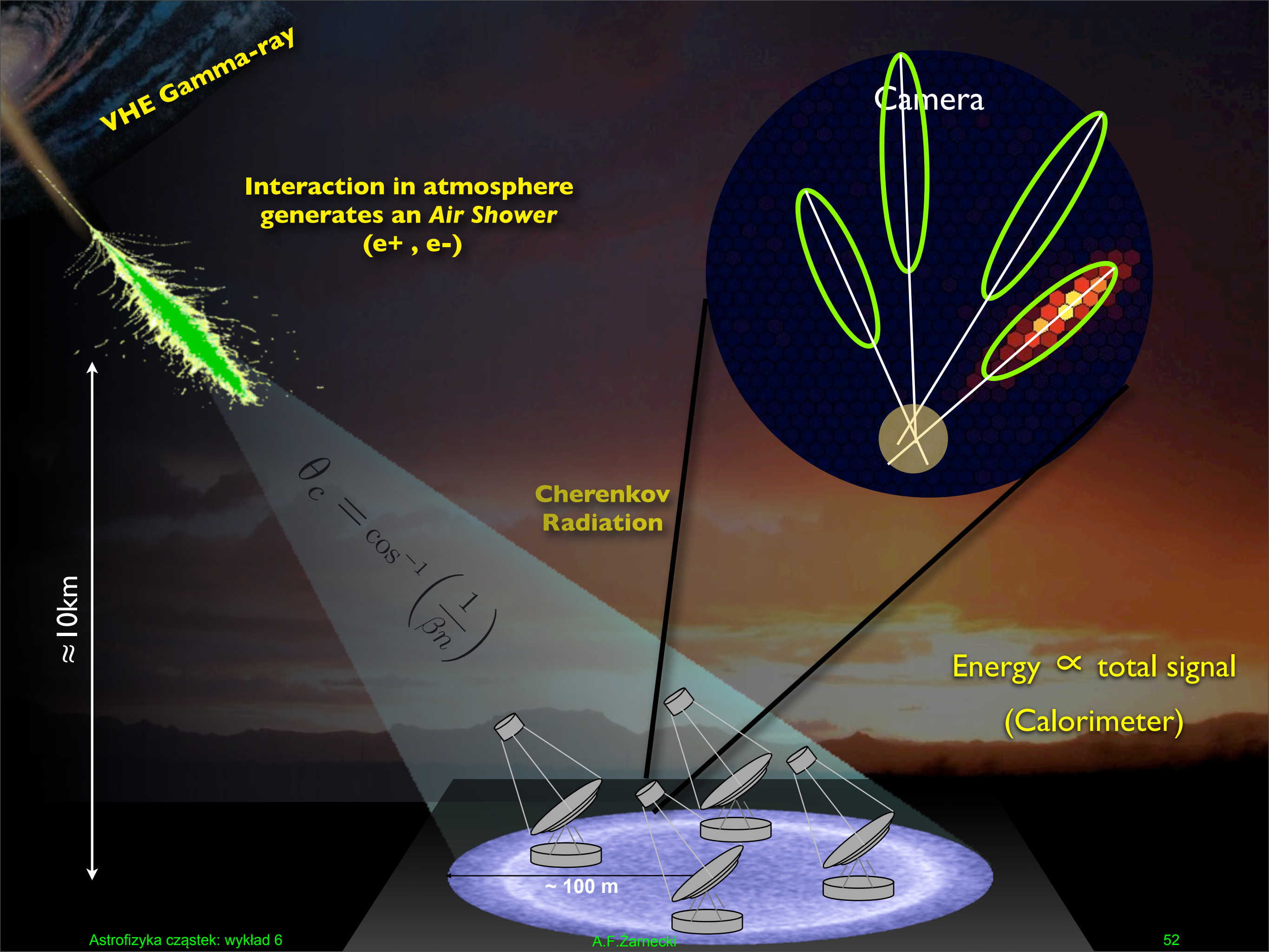
- therefore $\rho_0 \approx 0.00125$

- height of first interaction: $\approx 20 \text{ km}$









VHE Gamma-ray

Interaction in atmosphere
generates an Air Shower
(e+ , e-)

≈ 10km

$$\theta_c = \cos^{-1} \left(\frac{1}{\beta n} \right)$$

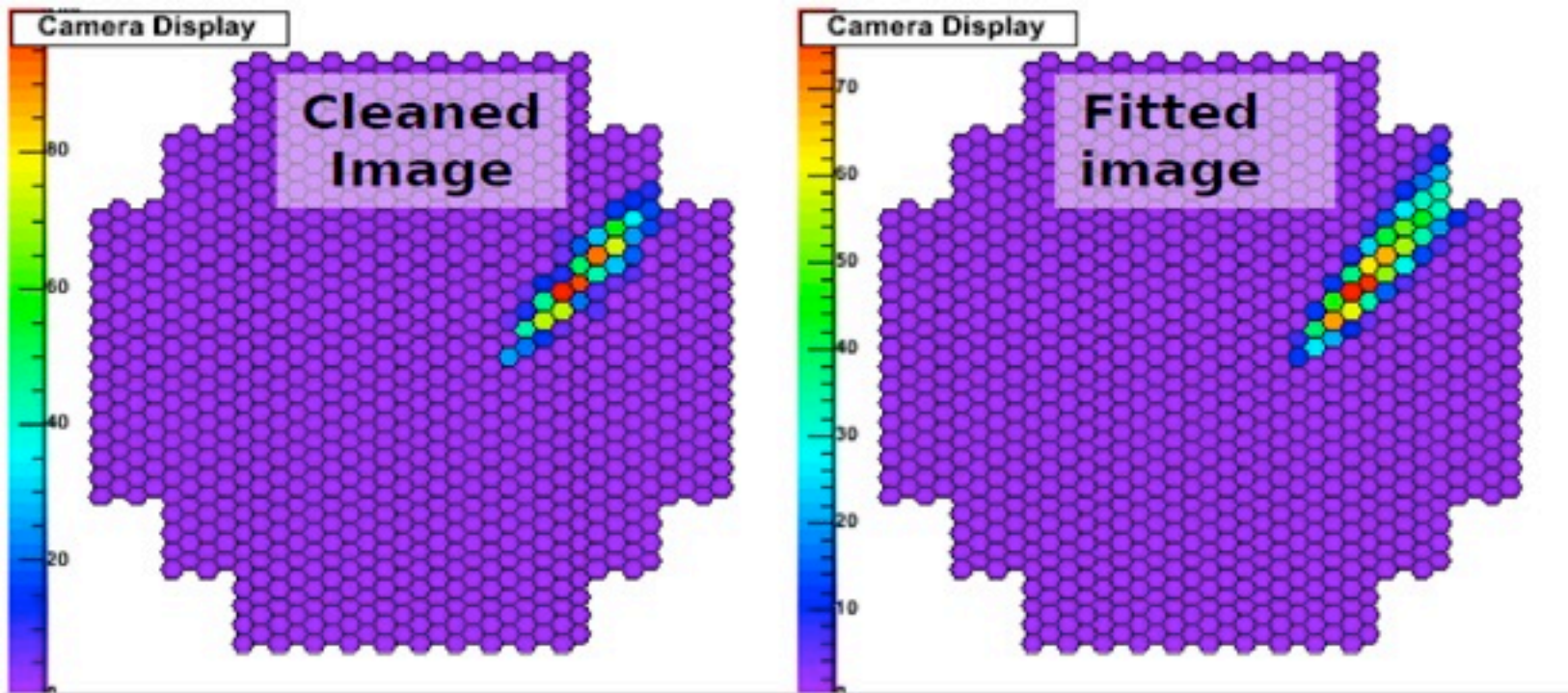
Cherenkov
Radiation

Camera

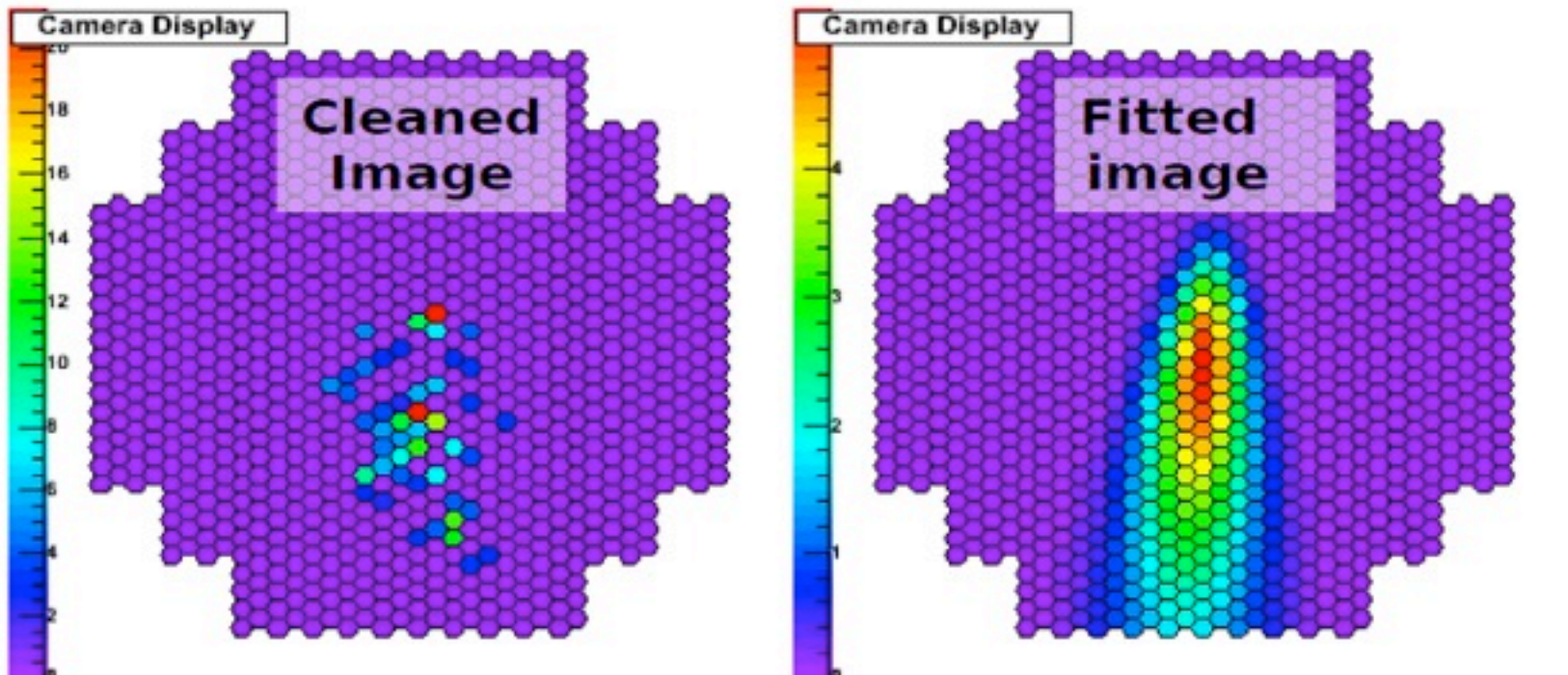
Energy ∝ total signal
(Calorimeter)

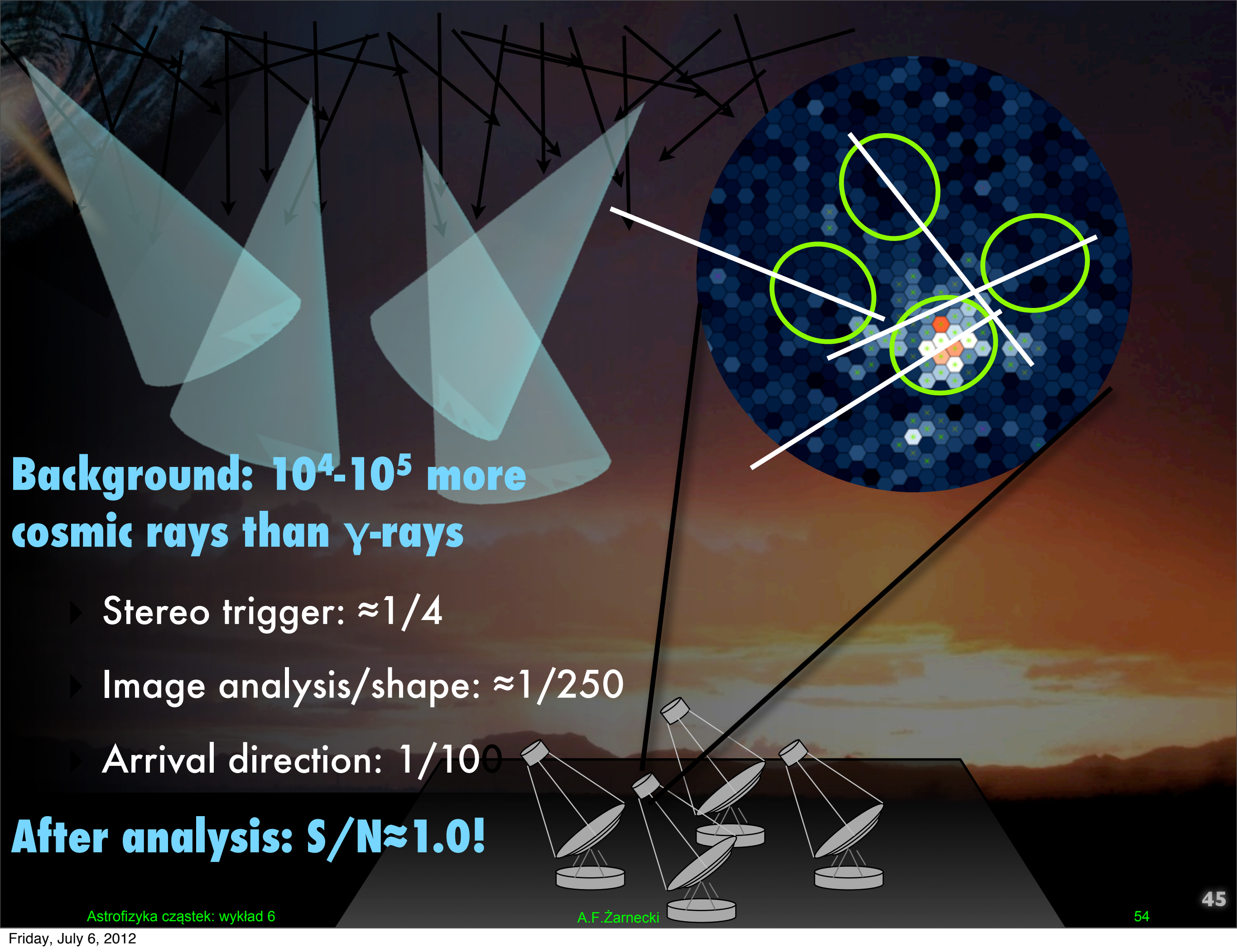
~ 100 m

Gamma Ray:



Hadron:



The background of the slide features a sunset sky. In the upper left, several overlapping light blue cones represent the fields of view of different detectors. Black arrows point downwards from the top, representing incoming cosmic rays. In the upper right, a circular inset shows a hexagonal grid representing a detector's surface. Four green circles highlight specific regions on this grid, with white lines intersecting them. In the lower right, a cluster of five satellite dishes is shown on a dark surface, with lines connecting them to the circular inset, indicating that the inset is a magnified view of the detector area.

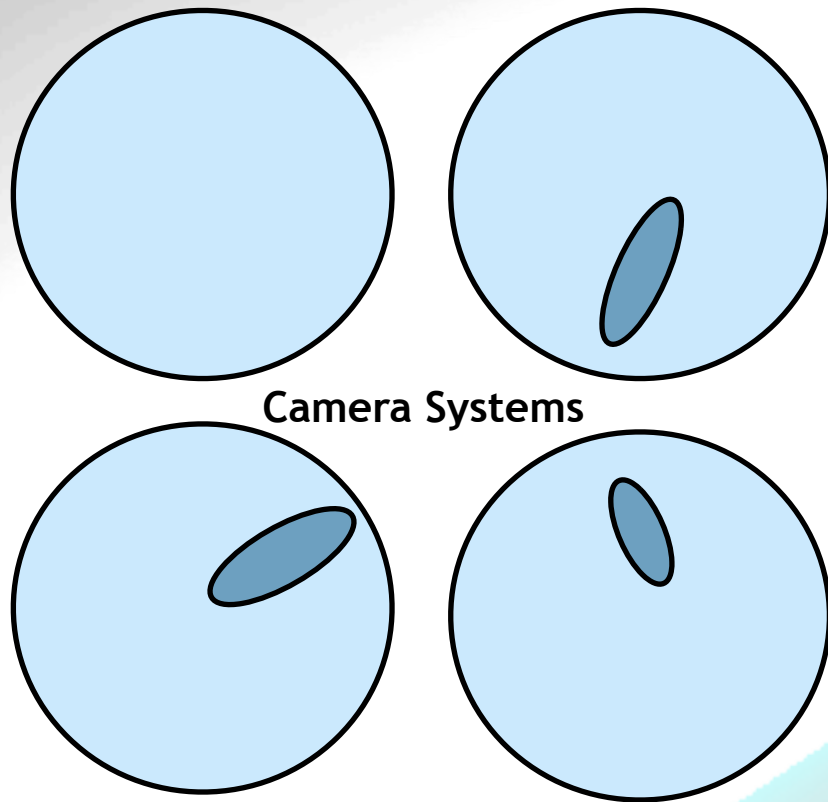
**Background: 10^4 - 10^5 more
cosmic rays than γ -rays**

- ▶ Stereo trigger: $\approx 1/4$
- ▶ Image analysis/shape: $\approx 1/250$
- ▶ Arrival direction: $1/100$

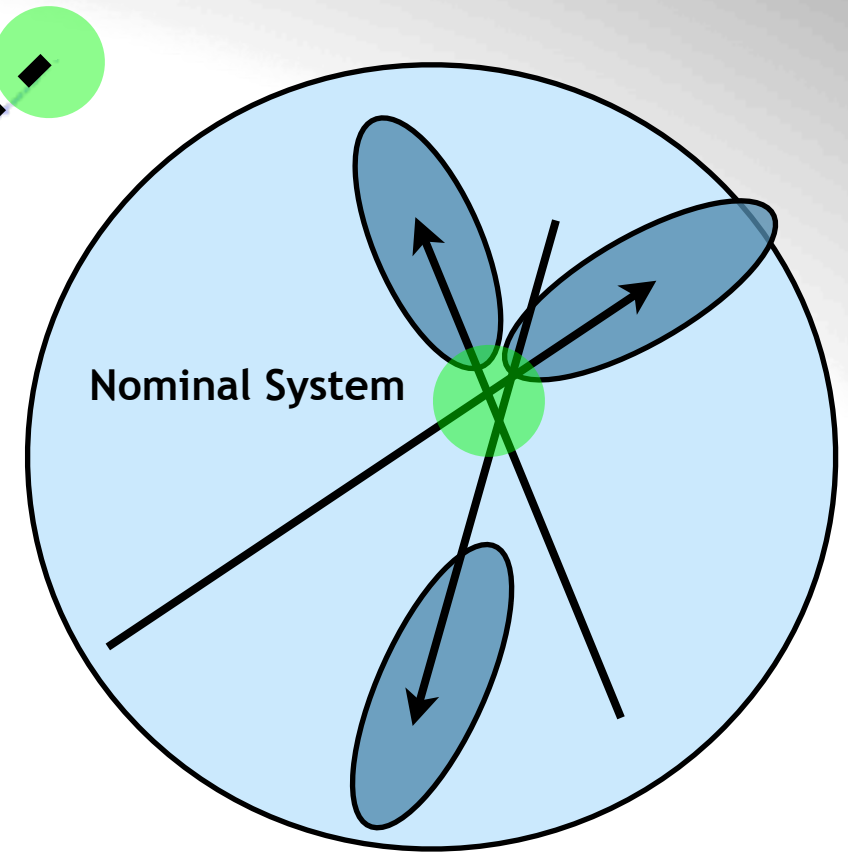
After analysis: $S/N \approx 1.0$!

Simple Stereo Reconstruction

Camera Systems



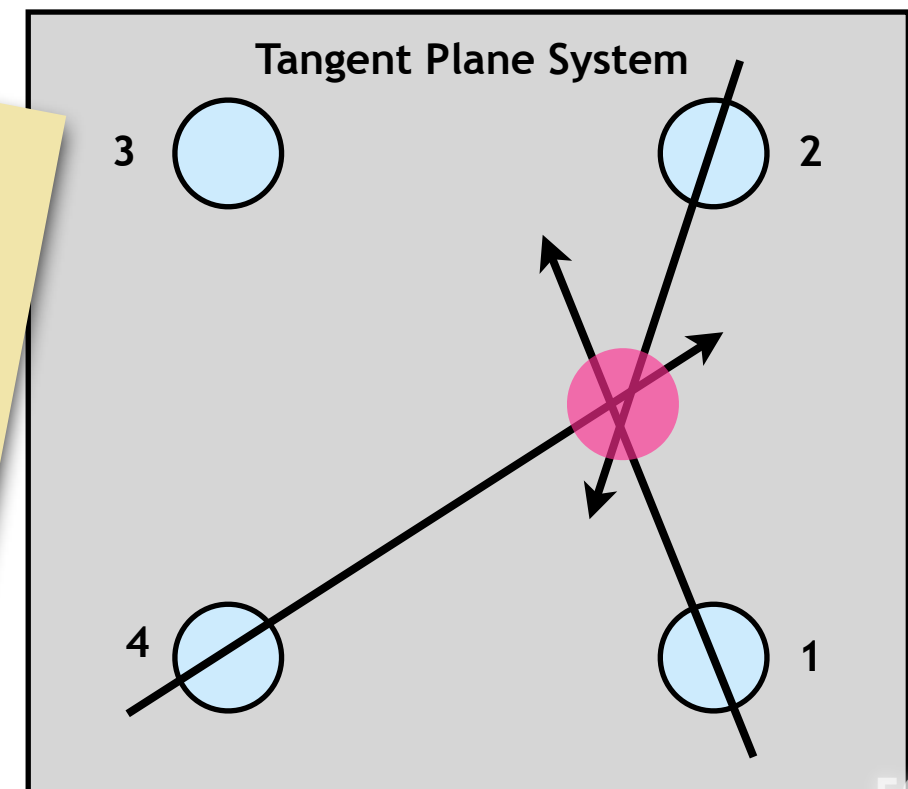
Nominal System



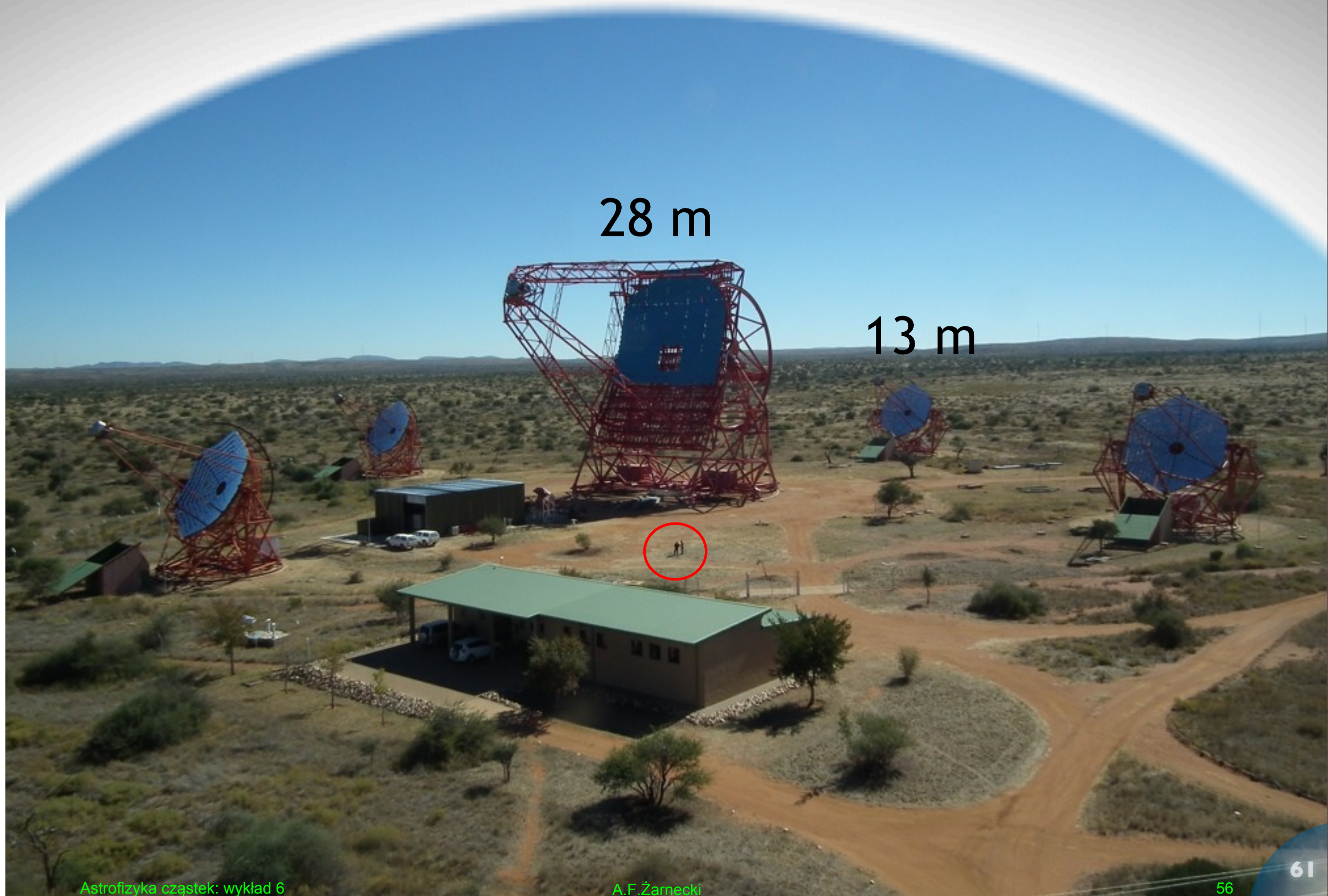
Physical Shower Parameters:

- Direction (RA, Dec)
- Core Position (X, Y)
- Energy
- X_{max} (depth in atmos.)
- lateral and longitudinal shower profile

Tangent Plane System



HESS-II: July 2012!



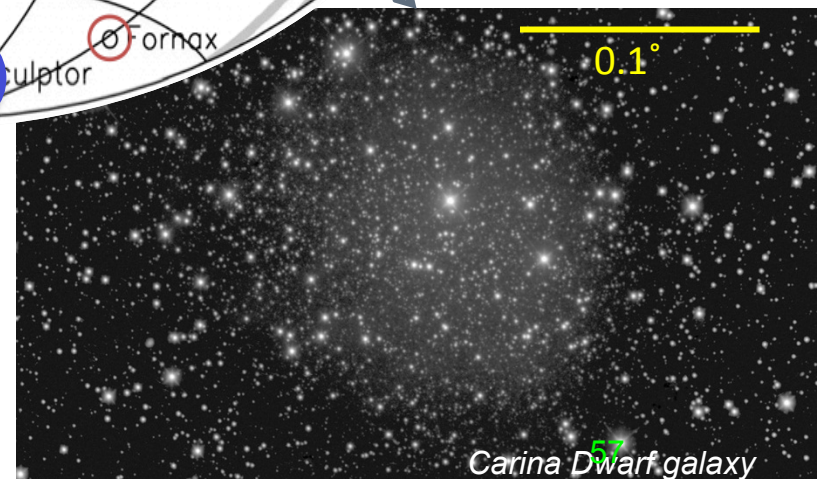
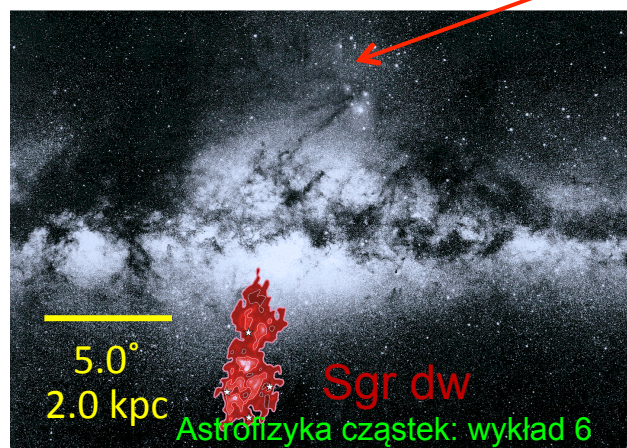
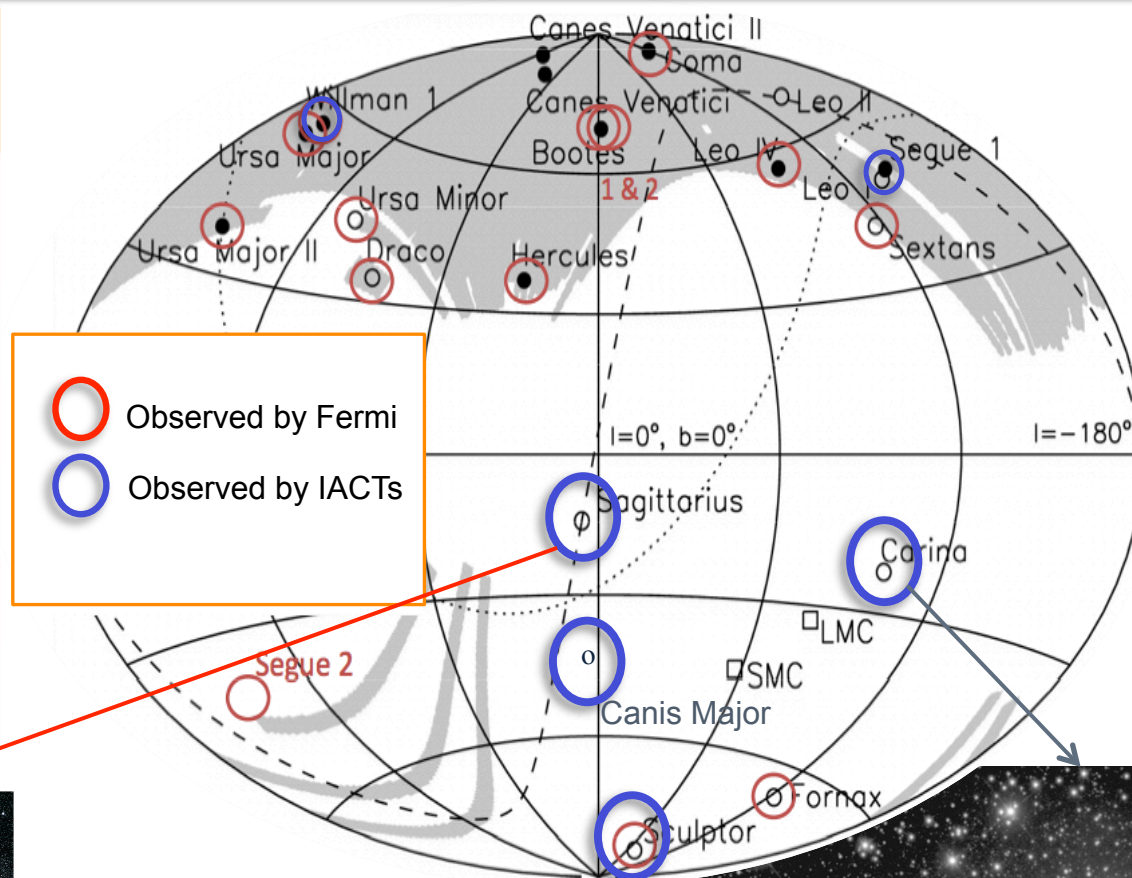
28 m

13 m

Dwarf galaxies of the Milky Way

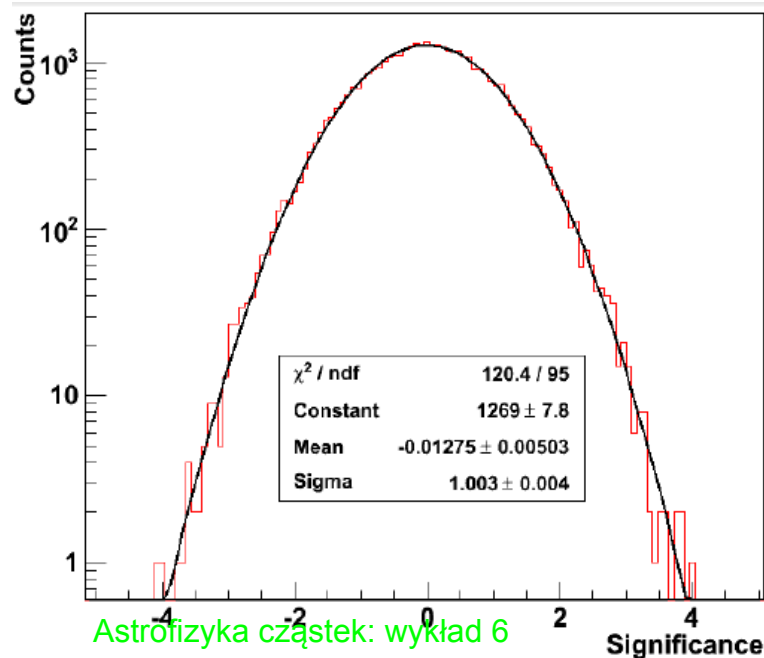
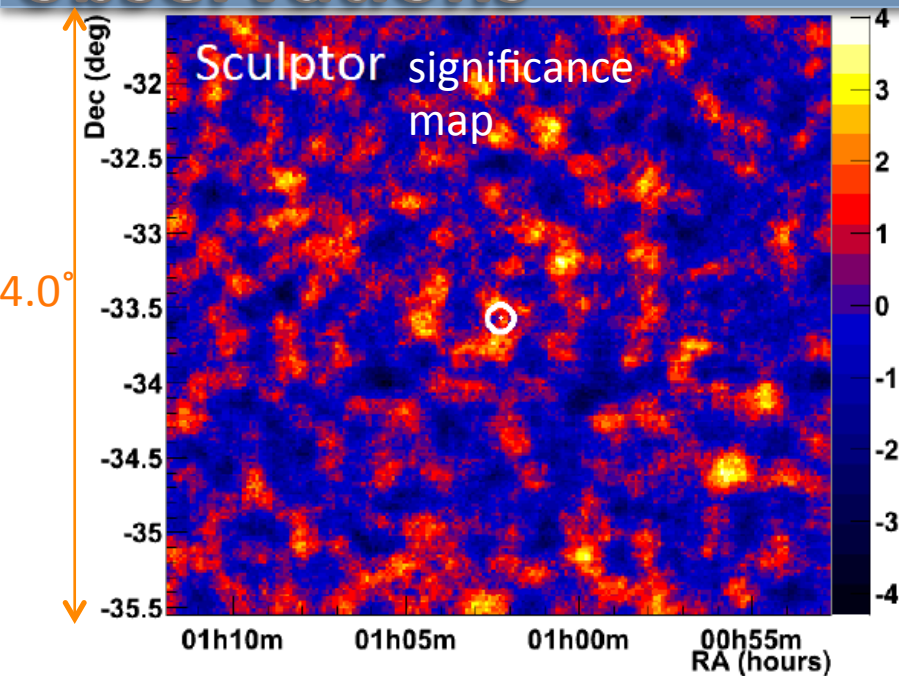
➤ Most DM-dominated systems in the Universe

Observed by HESS	d (kpc)	T _{obs} (h)
Sagittarius	24	11 (90)
Canis Major	8	10
Sculptor	79	11.8
Carina	101	14.8
Coma Be.	44	8.6
Fornax	140	6.1



A.F. Żarnecki

Example: Sculptor and Carina dataset and observations

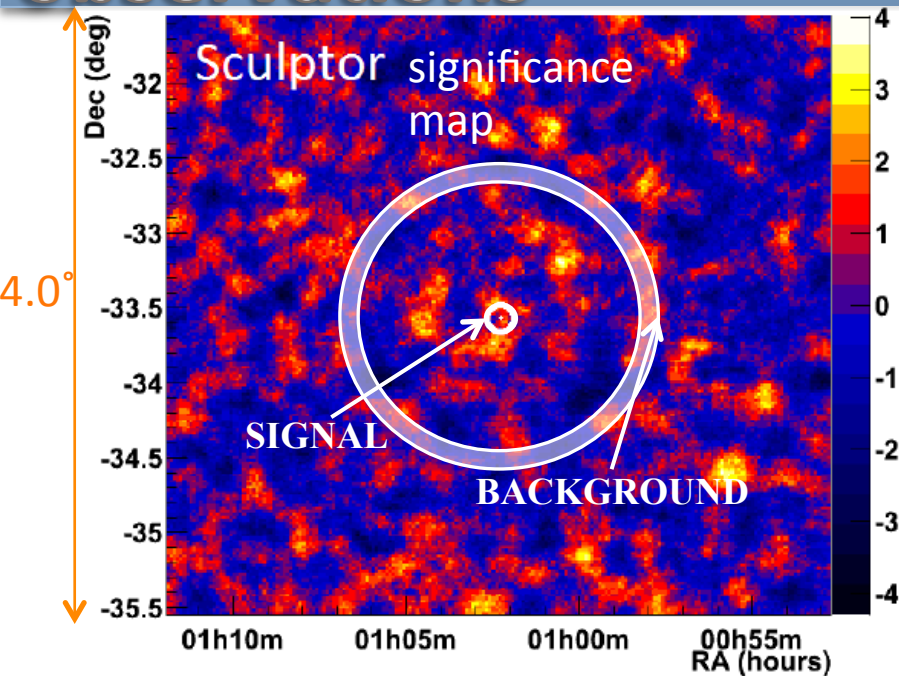


Galaxy	Sculptor	Carina
RA	01 ^h 02 ^m 19 ^s .2	06 ^h 41 ^m 36 ^s .0
Dec.	-33° 33' 00" 0	-50° 58' 12" 0
Distance (kpc)	79 $\pm$ 4	101 $\pm$ 5
Period	2008 Oct - Nov	2008 Jan - 2009 Dec
Hours Observed	11.8	14.8
$N_{\gamma, \text{tot}}^{95\% \text{ C.L.}}$	32.4	8.6

No significant gamma excess
at target position

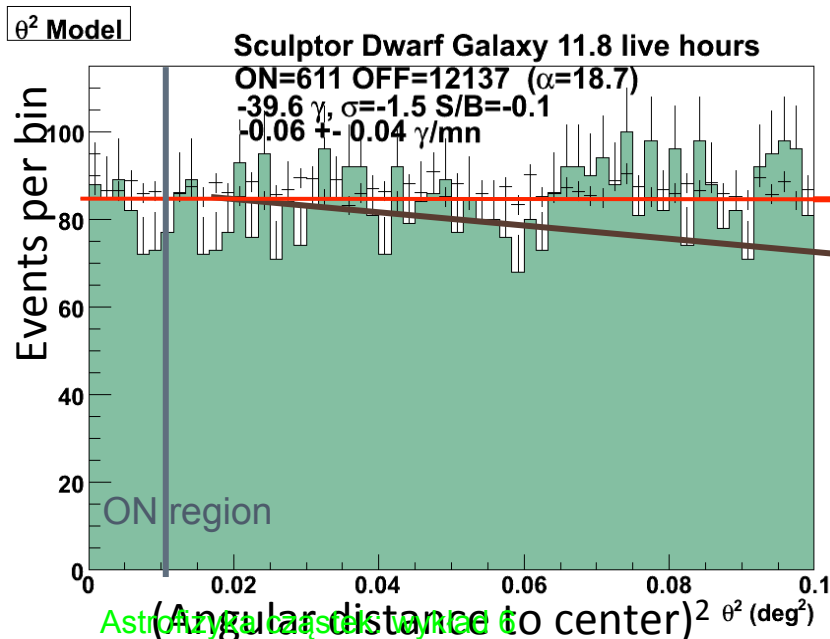
Abramowski et al. (H.E.S.S. collaboration), authors A. Viana & A. Charbonnier, Astroparticle Physics 34 (2011) 608

Example: Sculptor and Carina dataset and observations



Galaxy	Sculptor	Carina
RA	01 ^h 02 ^m 19 ^s .2	06 ^h 41 ^m 36 ^s .0
Dec.	−33° 33′ 00″.0	−50° 58′ 12″.0
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Period	2008 Oct - Nov	2008 Jan - 2009 Dec
Hours Observed	11.8	14.8
$N_{\gamma, \text{tot}}^{95\% \text{ C.L.}}$	32.4	8.6

No significant gamma excess at target position



Estimated background

Observed gamma-ray candidates

« Measured »:

Upper limit on the number of « true » gamma-rays

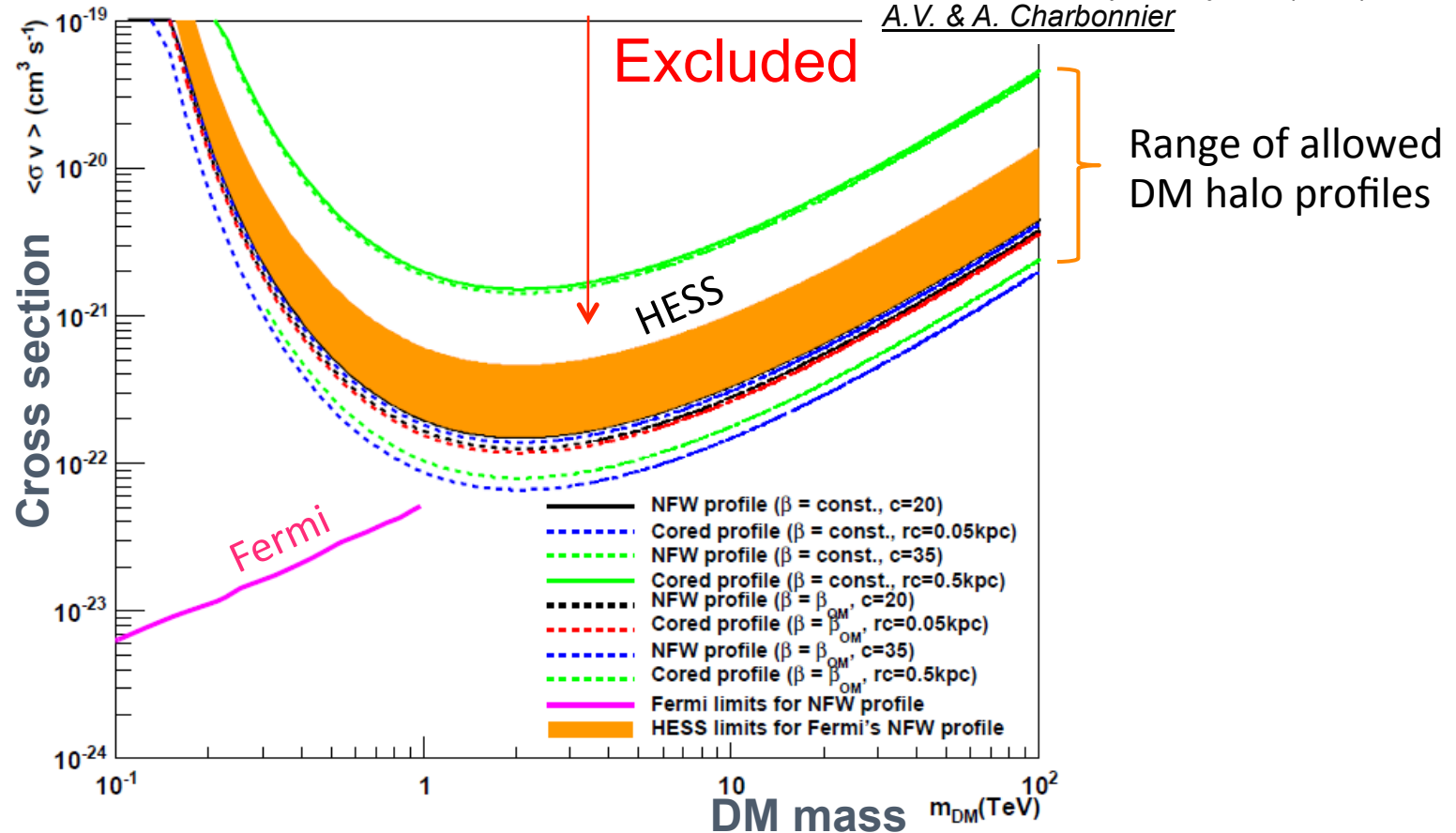
$N_{\gamma}^{95\% \text{ C.L.}}$

59

Exclusion curves: halo modeling dependence

Constraints on dark matter exclusion curve at 95% C.L.:

HESS coll., Astropart.Phys.34 (2011) 608, authors A.V. & A. Charbonnier



(a) Sculptor

- Various DM halo profile were studied in the case of Sculptor => helps to estimate the uncertainties due to the halo modeling
- Complementary constrains to Fermi limits

The MAGIC telescopes

Two Cherenkov telescopes 17m in diameter

2005: First telescope (mono)

2008: Faster readout

2009: Stereoscopic mode

2011-2012: Upgrades

- **MAGIC cameras:**

- Field of view: 3.5°
- 1039 pixels / camera
- DAQ: DRS4 at 2 GSample/s

- **Stereo Trigger**

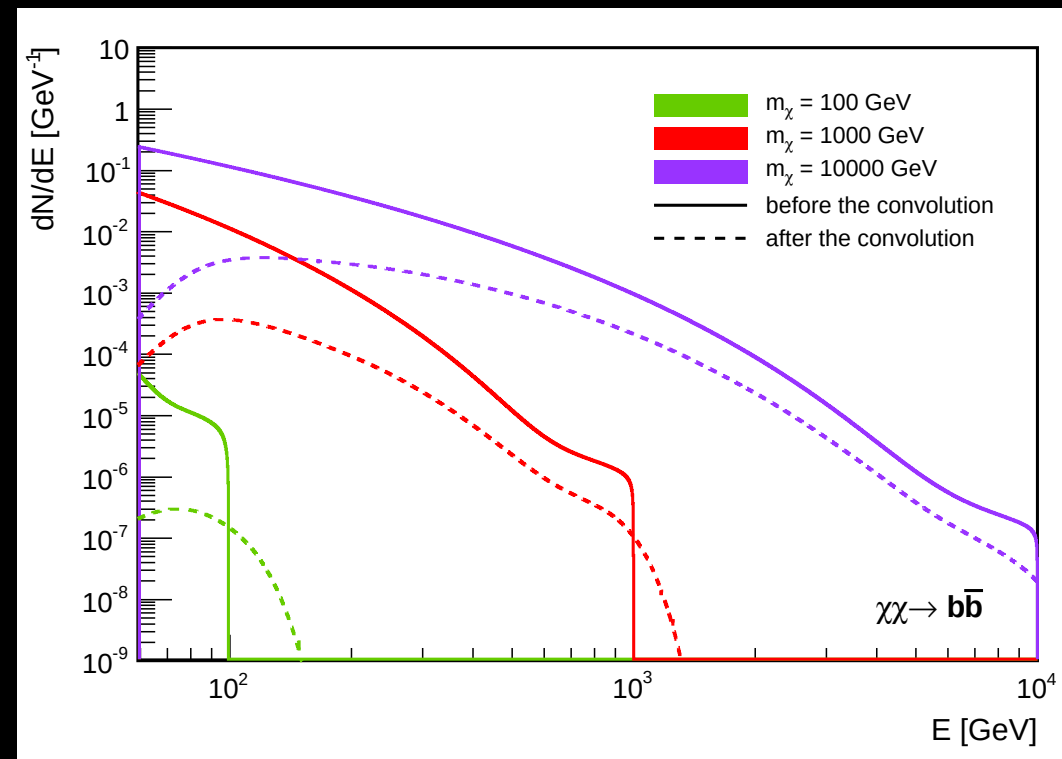
- Rate: ~ 300 Hz
- Energy threshold: ~ 50 GeV

Site: Canary Island of La Palma, 2200m asl



Dark matter models

- ★ **MAGIC response function**: calculated for each observation period separately
- ★ **Background spectral shape**: modeled from the Segue 1 observations
- ★ **Signal spectral shape**: few models of DM annihilation and decay:
 - ✦ Secondary photons
 - ✦ Monochromatic line
 - ✦ Virtual Internal Bremsstrahlung
 - ✦ Gamma-ray boxes
- ★ m_χ in the 100 GeV – 10 TeV (200 GeV – 20 TeV) range
- ★ BR = 100%
- ★ Einasto density profile
- ★ No boost factor



MAGIC mono results

✦ Galactic Center

(17 h): *Albert et al. ApJ Lett. 638 (2006) L101*

✦ Galaxy Clusters

Perseus cluster (25 h): *Aleksić et al. ApJ 710 (2010) 634*

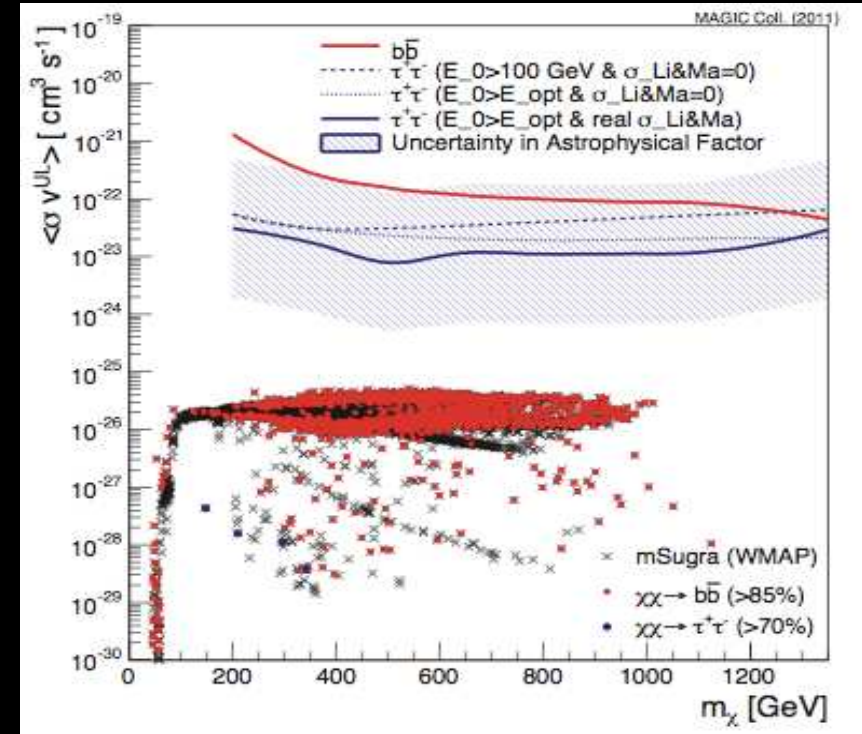
✦ Dwarf Spheroidals

Segue 1 (30 h): *Aleksić et al. JCAP 06 (2011) 035*

Willman 1 (16 h): *Aliu et al. ApJ 697 (2009) 1299*

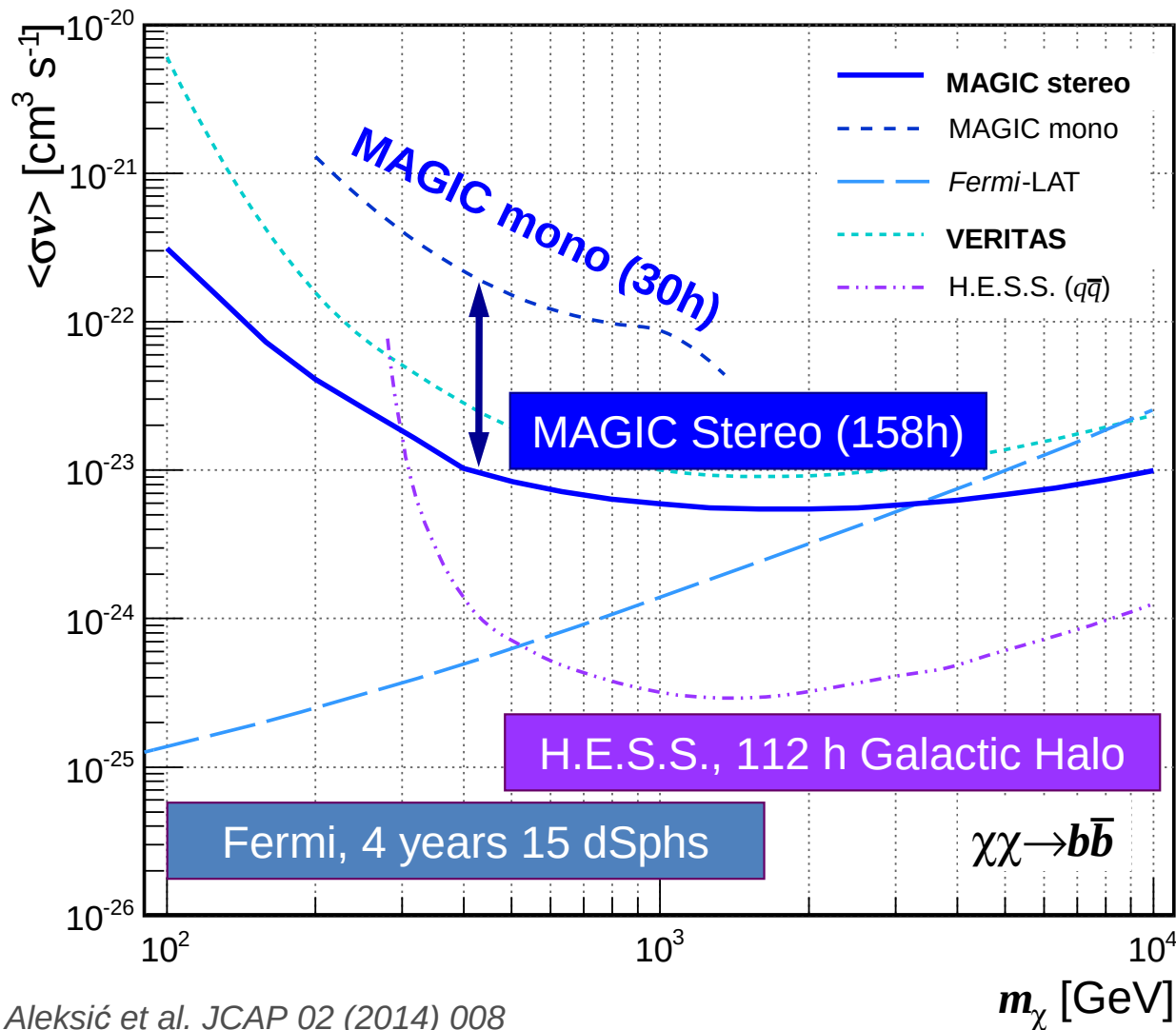
Draco (8 h): *Albert et al. Apj 679 (2008) 428*

Best MAGIC mono constraints are from Segue 1 observation



Secondary Photons

DM annihilation

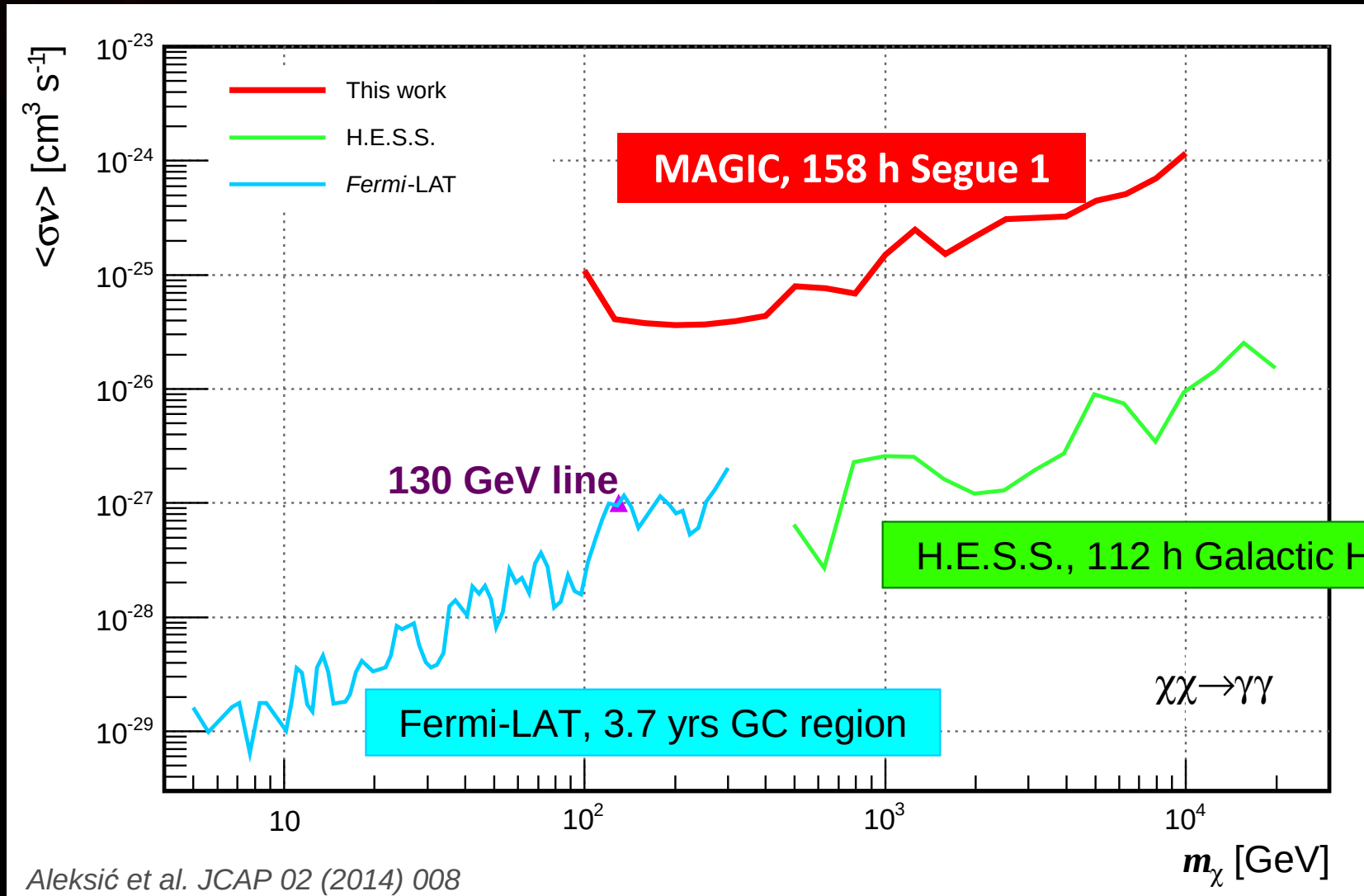


Aleksić et al. JCAP 02 (2014) 008

MAGIC provides the strongest limit above 3 TeV from dSphs

Monochromatic Line

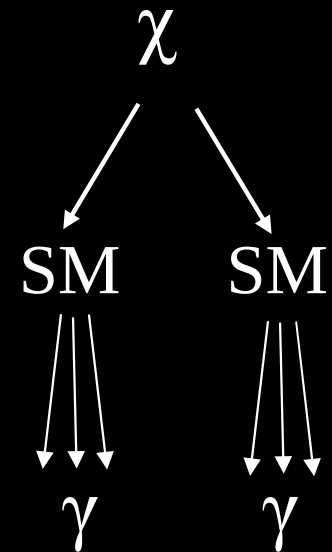
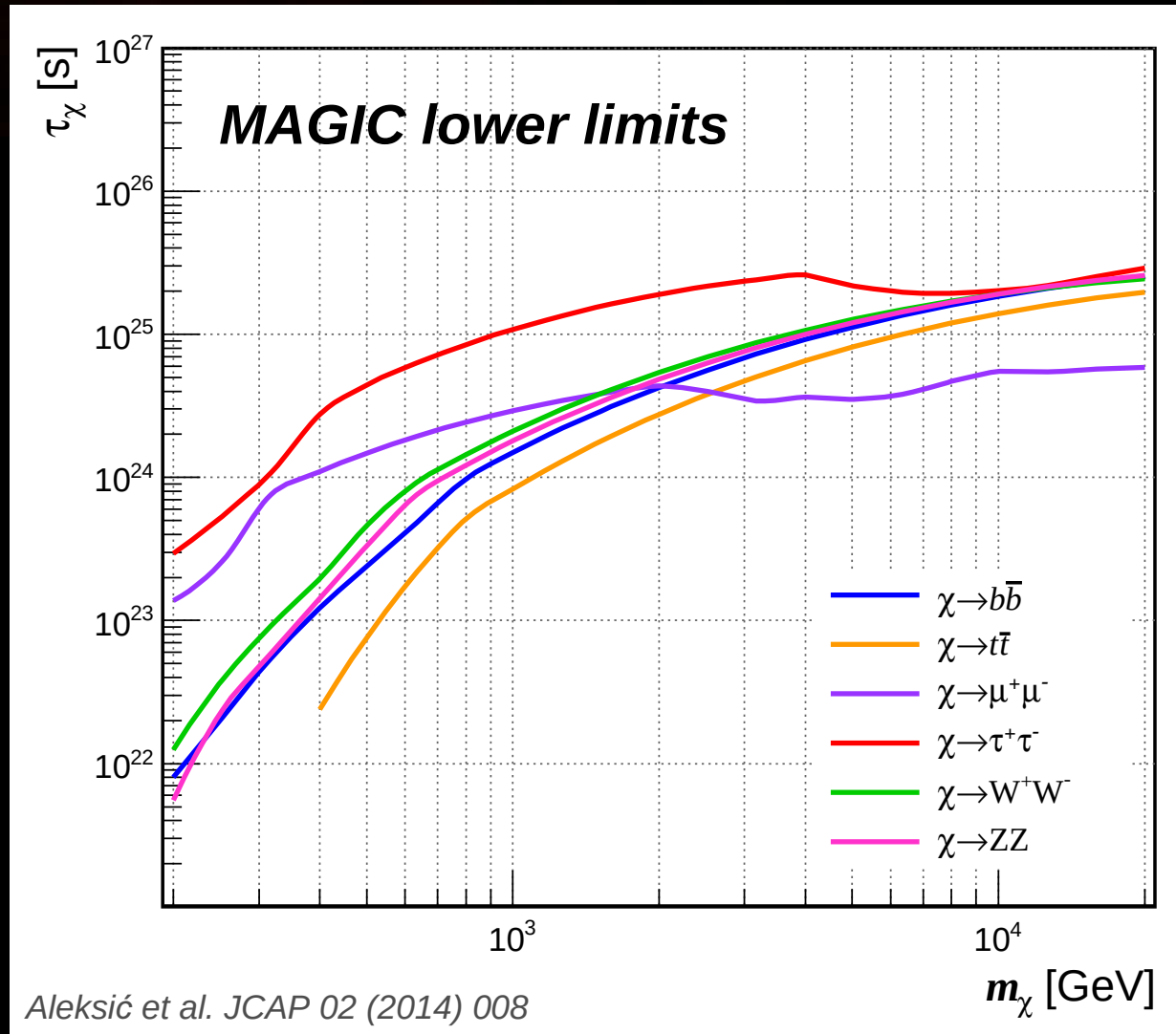
DM annihilation



Aleksić et al. JCAP 02 (2014) 008

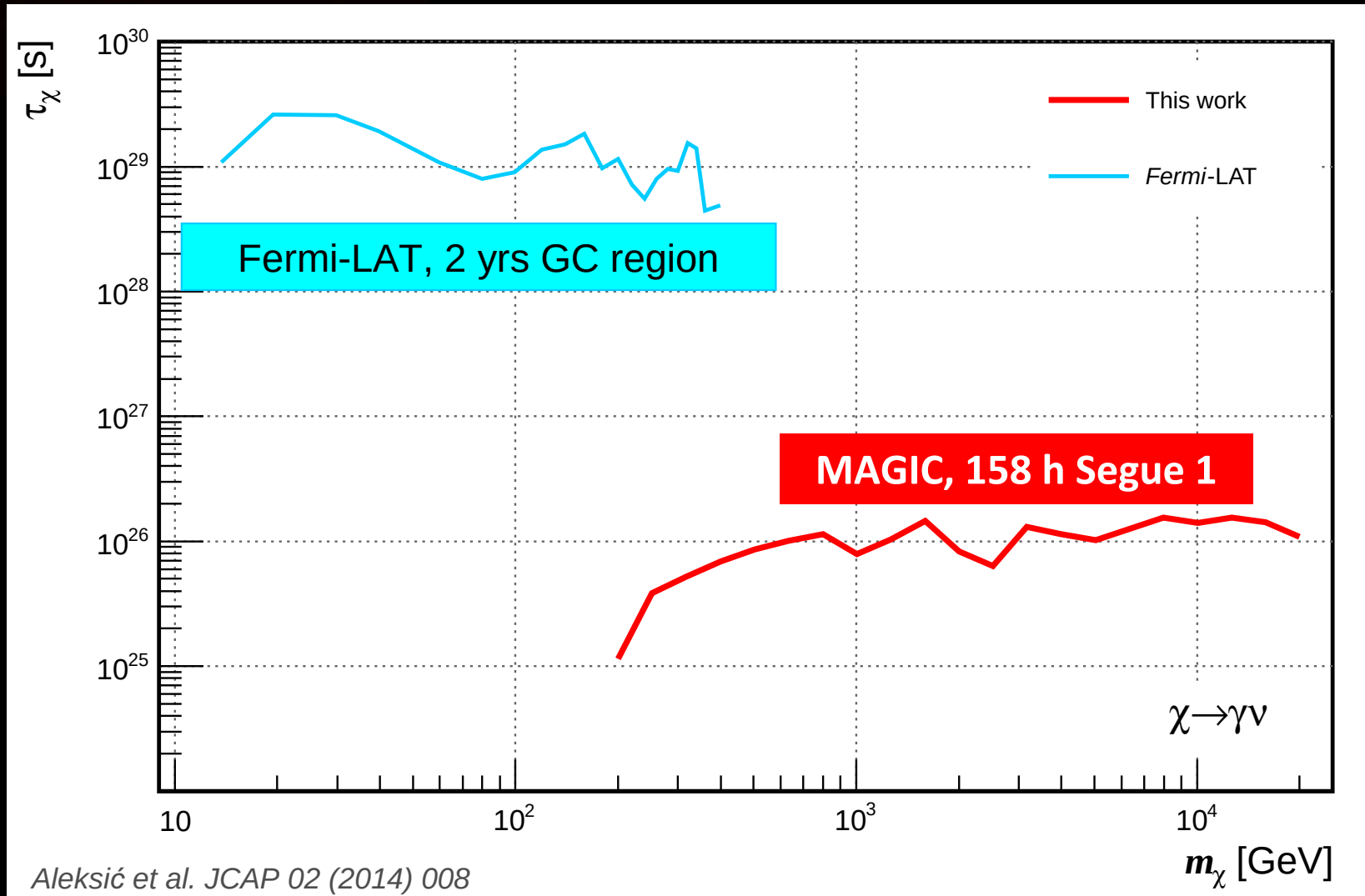
Secondary Photons

DM decay



Monochromatic Line

DM decay





Science-optimization under budget constraints:

- Array area increases with γ energy
- Mirror area decreases with γ energy

*Base budget (2006):
100 M€ capital inv. (S)
50 M€ capital inv. (N)*

few large telescopes
for lowest energies,
for 20 GeV to 1 TeV

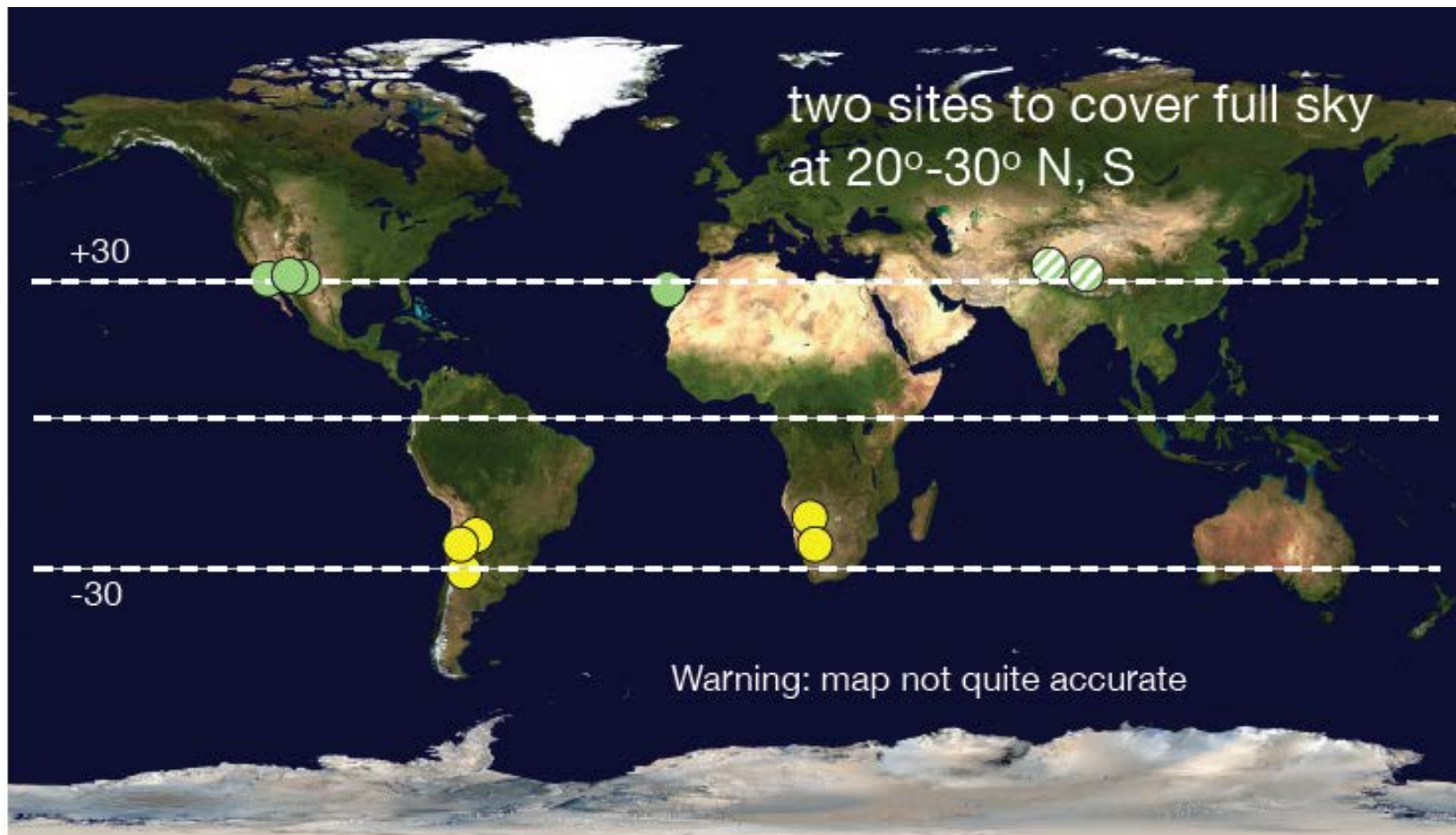
~km² array of
medium-sized
telescopes for
the 100 GeV to
10 TeV domain

large array of small
telescopes,
sensitive about few TeV
7 km² at 100 TeV

4 LSTs

~70 SSTs

~25 MSTs plus
~36 SSTs extension



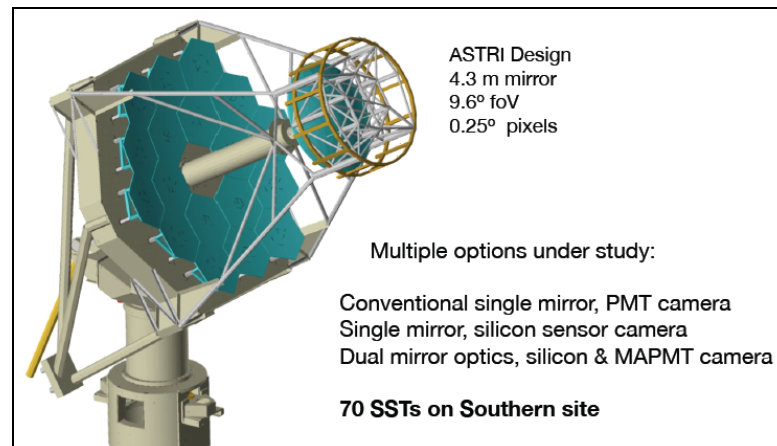
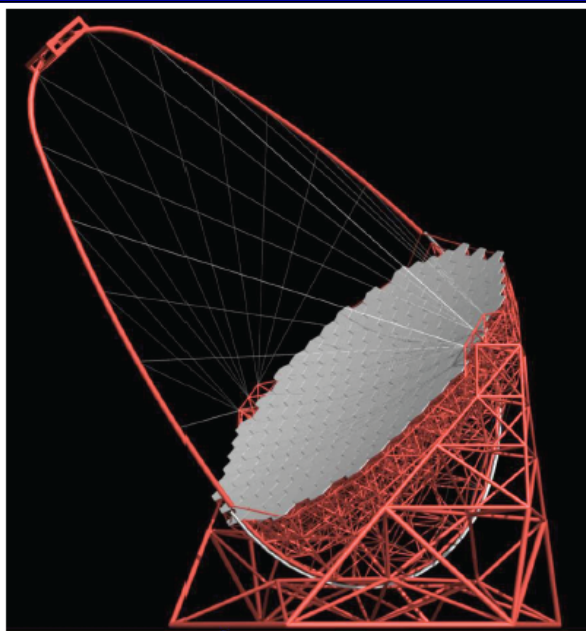
400 m² dish area
27.8 m focal length
1.5 m mirror facets

4.5° field of view
0.1° pixels
Camera Ø over 2 m

Carbon-fibre structure

Active damping
of oscillations,
active mirror control

4 LSTs on each site

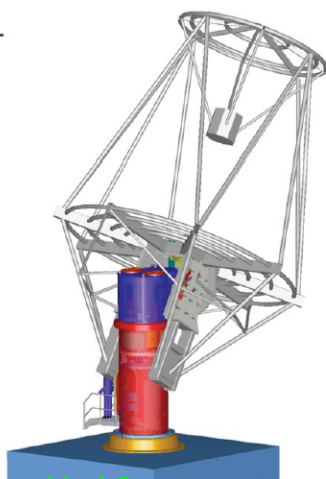


MEDIUM-SIZED DUAL MIRROR TEL. EXTENDING THE MST ARRAY

9.7 m diameter
50 m² dish area
5.6 m focal length

8-9° field of view
11000 x 0.07° pixels

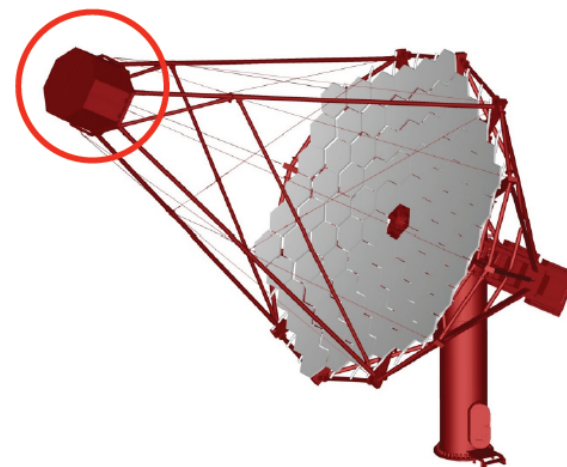
**Extend South array
by adding 36 SCTs
contributed mostly by US**

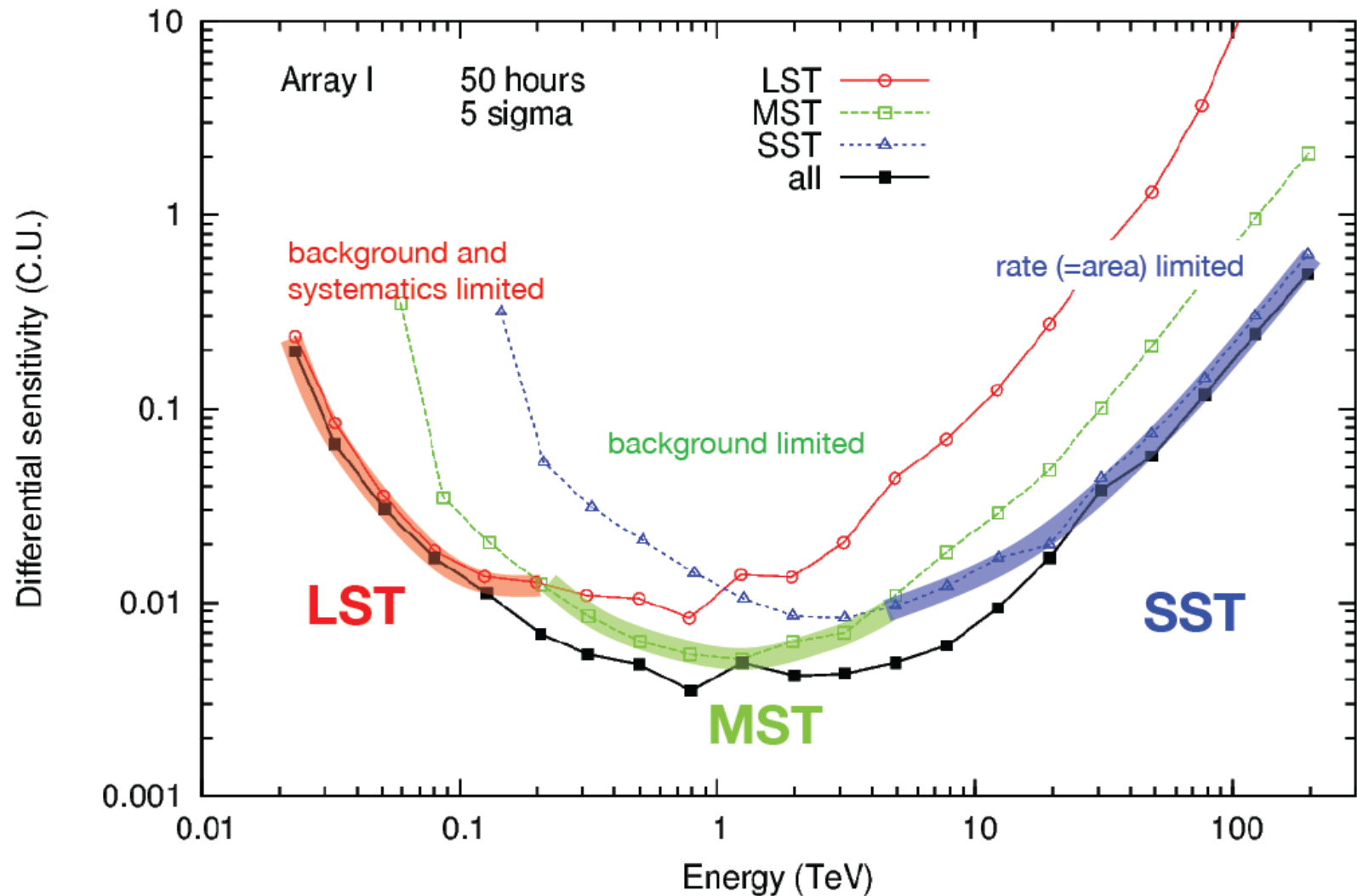


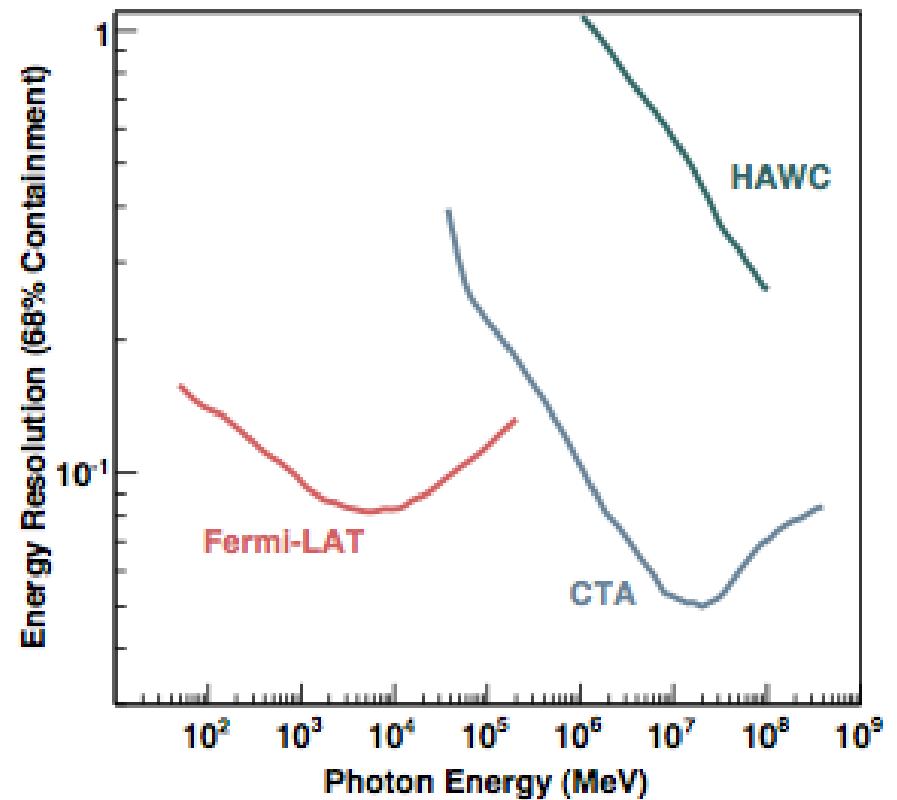
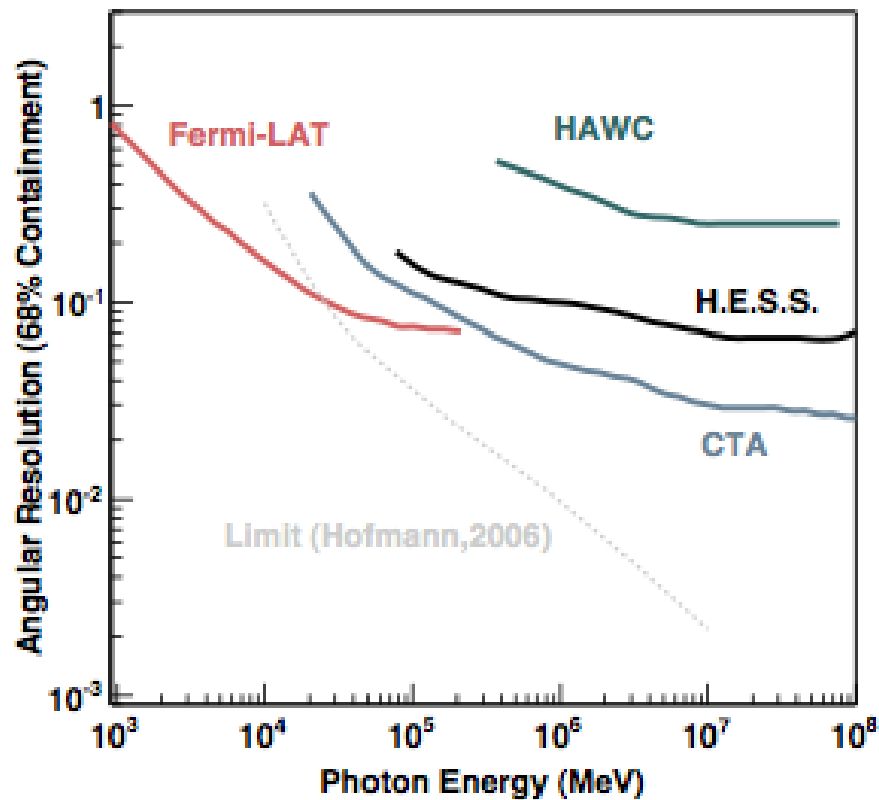
100 m² dish area
16 m focal length
1.2 m mirror facets

7-8° field of view
~2000 x 0.18° pixels

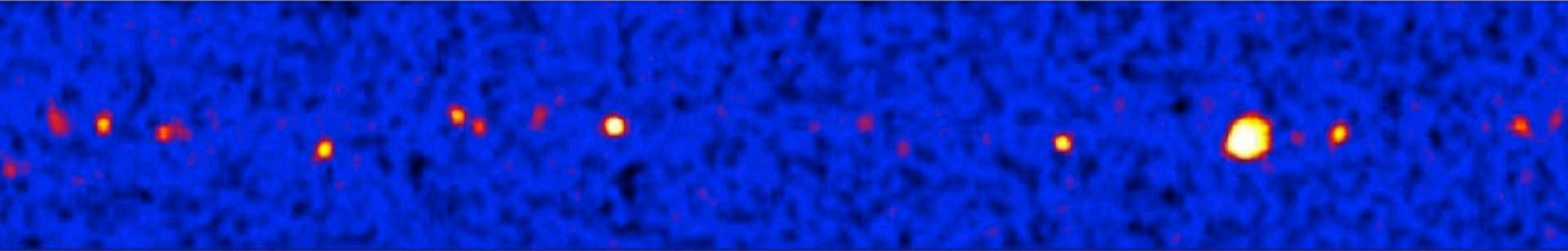
**25 MSTs on South site
15 MSTs on North site**



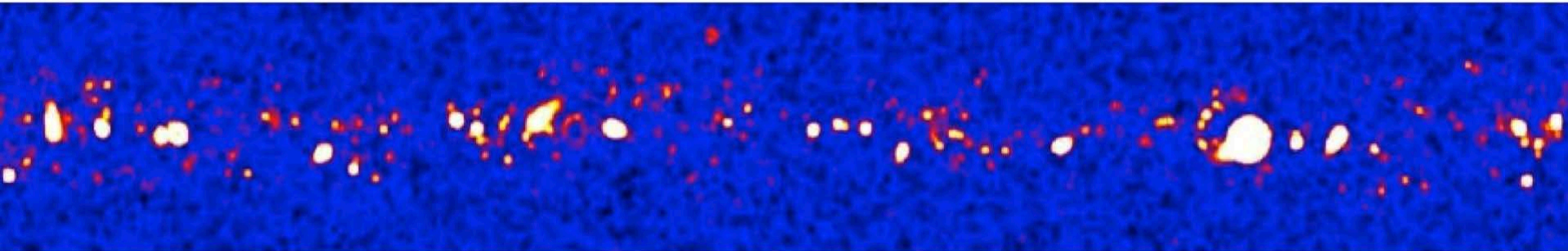




H.E.S.S.



CTA, for same exposure



expect ~1000 detected sources

Addressing key science questions

1. **Where and how are the bulk of CR particles accelerated in our Galaxy and beyond?** Understanding transitions in the CR spectra.
(one of the oldest surviving questions of astrophysics)
2. **How cosmic-rays propagate, interact, and heat the environment?** Which are the consequences from Galactic to cosmological scenarios?
3. **What makes black holes of all sizes such efficient particle accelerators?**
4. **What do high-energy gamma-rays tell us about the star formation history of the Universe, the structure of spacetime, or the fundamental laws of physics?**
5. **What is the nature of dark matter?** Can it be discovered via indirect searches? Can we map dark matter halos?
6. **Are there short-timescale phenomena at very high energies? Are GRBs gamma-ray emitter? Is there new Galactic phenomenology to uncover?**

