Fundamental physics with future γ-ray observatories

Abelardo Moralejo Olaizola

on behalf of the CTA consortium

γ-ray astronomy: techniques & bands

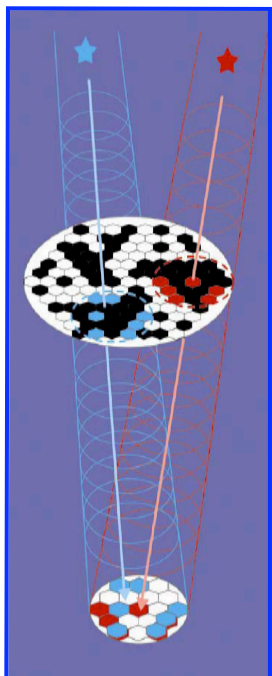
MeV GeV TeV

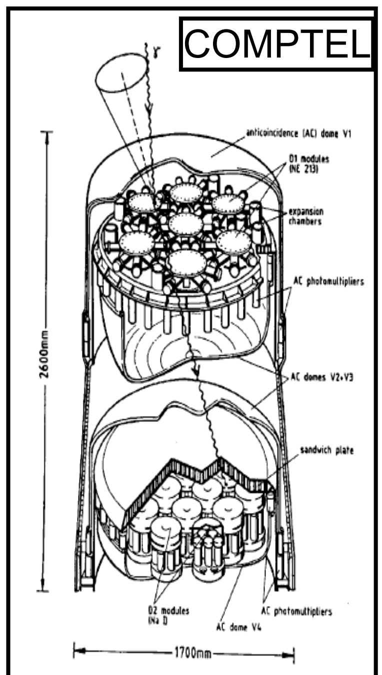
Coded masks, collimators
(e.g. INTEGRAL, Swift)

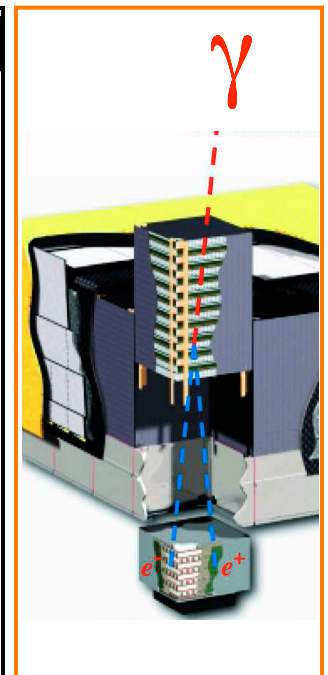
Pair conversion telescopes
(**Fermi-LAT**, AGILE)

Compton telescopes (CompTel)

Air shower (IACTs etc)







Next-generation instruments

Space-borne:

Science 333, July 2011

POLICYFORUM

ASTROPHYSICS

A Dark Age for Space Astronomy?

Horizon 2000 offers lessons to improve global planning and priority setting and to implement on-time, on-budget programs.

Roger-Maurice Bonnet[1*] and Johan A. M. Bleeker[2,3]

Artificial satellites have given astronomers access to hidden portions of the electromagnetic spectrum and dramatically changed our perception of the universe. Space-based astronomy remains an integral part of contemporary research, resting on powerful telescopes developed by major space agencies—the U.S. National Aeronautics and

LISA, and IXO. But JWST cost overruns cast doubts on the feasibility of developing WFIRST, LISA, and IXO within the decade (*6*, *7*).

In March 2011, ESA announced that IXO cooperation with NASA was no longer feasible because of incompatible schedules and budgets (*8*). All partners involved in merging the NASA Constellation-X and ESA X-ray Evolving Universe Spectroscopy (XEUS) projects into IXO, successful after a 10-year process, were put back where they started. A similar situation affects the

In the high-energy domain, no major x-ray and gamma-ray observatories will be available to replace XMM-Newton, Chandra, INTEGRAL, and Fermi (*1*).

at least from NASA / ESA / JAXA

Next-generation instruments

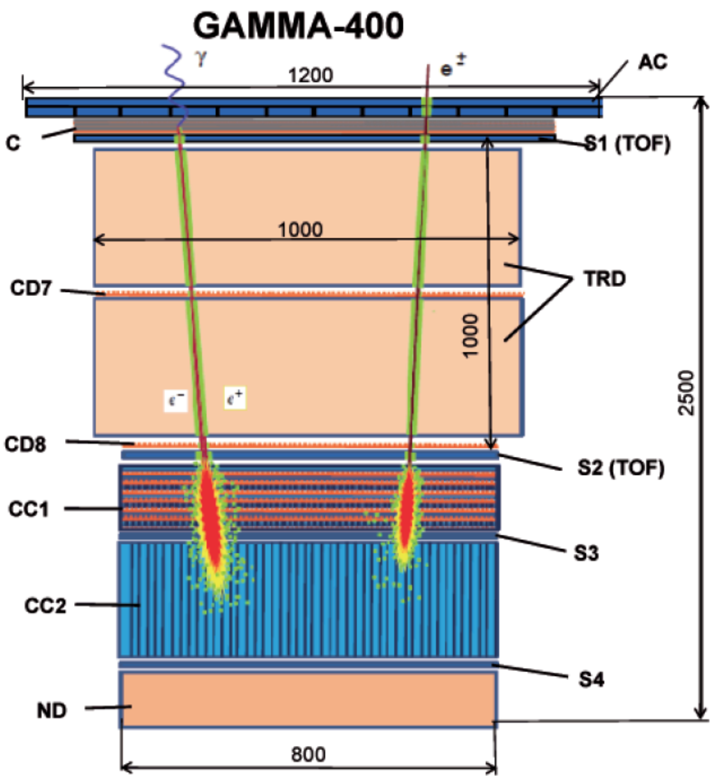
Space-borne:

- **Gamma-400:** pair-conversion space telescope Russian - Italian collaboration http://gamma400.lebedev.ru

- Smaller than Fermi-LAT, but better event reconstruction
- Launch expected for 2017 (Fermi operational at least until 2016)

Table 2. Comparison of the main characteristics of the GAMMA-400 and Fermi LAT gamma-ray telescopes

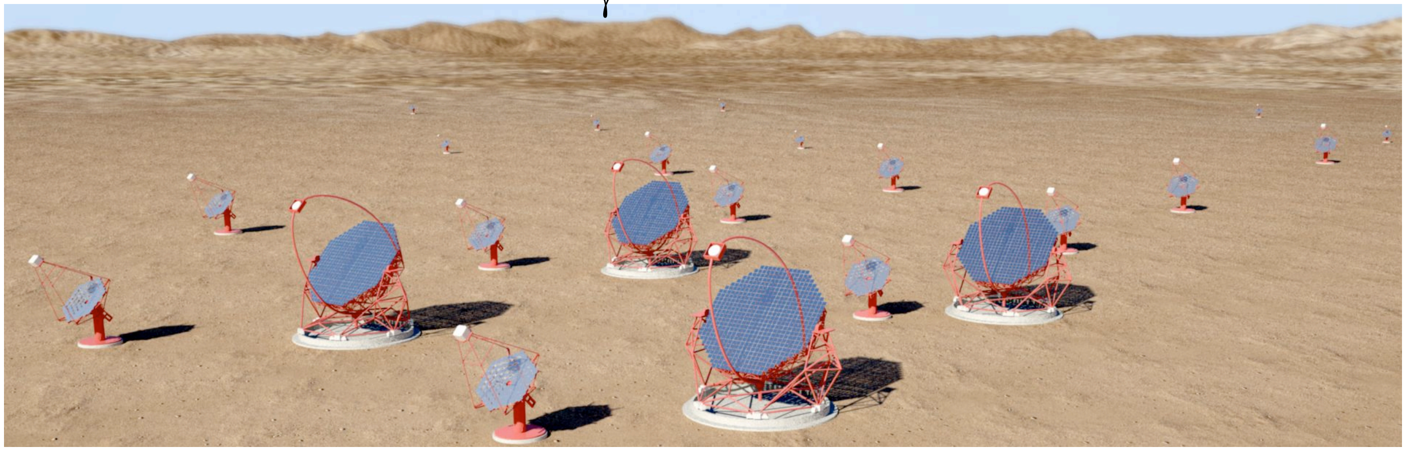
	Fermi LAT	GAMMA-400
Orbit, km	560	500–300 000
Energy range of gamma-ray detection	0.1–100 GeV	0.1–3000 GeV
Area of sensitivity, m^2	1.6	0.64
Coordinate detectors	Si (x, y) strips with a pitch of 0.22 mm (converter and tracker)	Si (x, y) strips with a pitch of 0.1 mm (converter)
Angular resolution ($E_\gamma > 100$ GeV)	0.05°	~0.01°
Calorimeter	CsI	BGO + Si strips
– thickness, r.l.	8.5	30.5
Energy resolution ($E_\gamma > 10$ GeV)	10%	~1%
Proton rejection factor	10^4	$\sim 10^6$
Sensitivity ($E_\gamma > 100$ MeV), photon/($cm^2 \cdot s$)	$\sim 5 \times 10^{-9}$	$\sim 2 \times 10^{-9}$



Next-generation instruments

Ground-based:

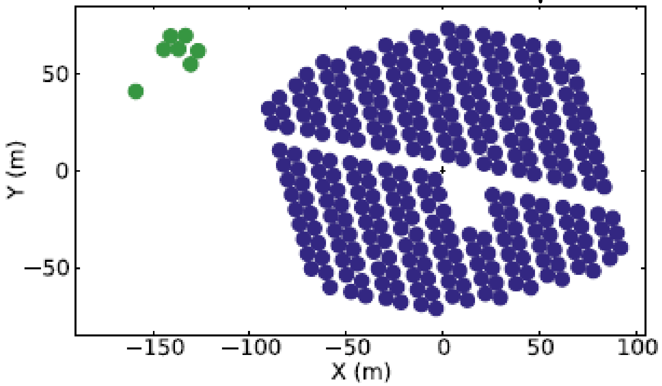
- **CTA:** atmospheric Cherenkov, E_γ>20 GeV



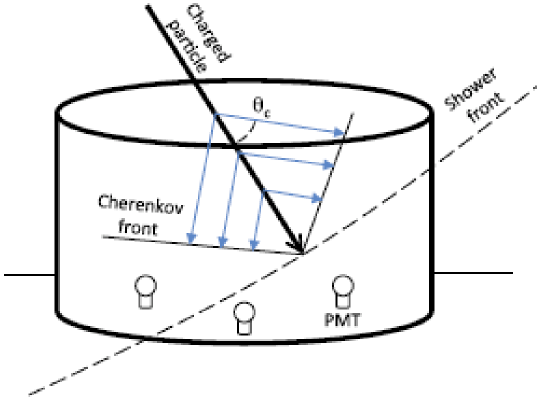
- **HAWC:** water Cherenkov, (mostly) E_γ> few 100 GeV

Only detects showers whose *particle* component reaches ground level ⇒

- Higher E- threshold
- Very high altitude site



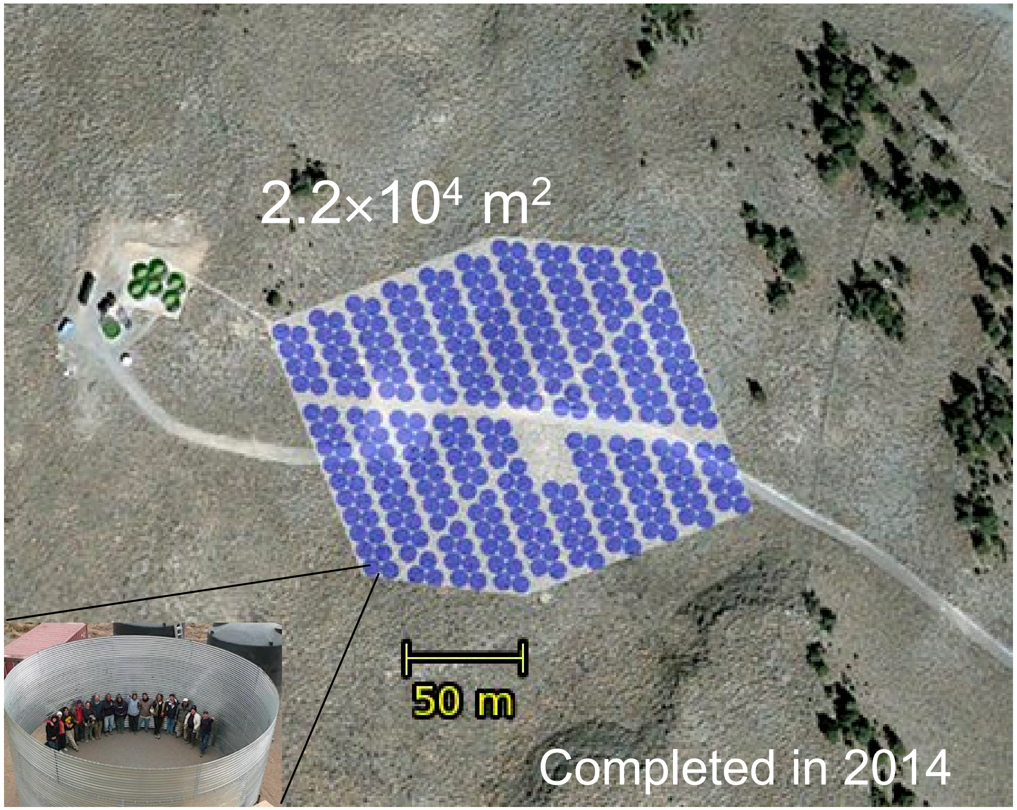
(a) HAWC tank layout.

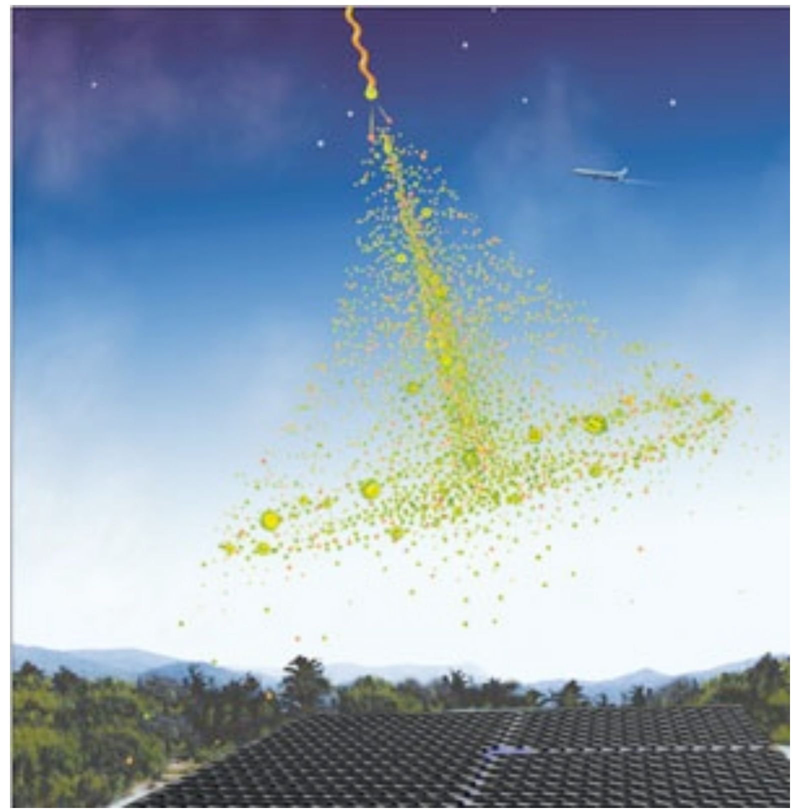


(b) Water Cherenkov Detection Principle.

HAWC http://hawc.umd.edu

- High-Altitude Water Cherenkov gamma-ray observatory
- 300 tanks of purified water (3 PMTs each), >50% coverage
- Located in Sierra Negra, Mexico, 4100 m a.s.l.



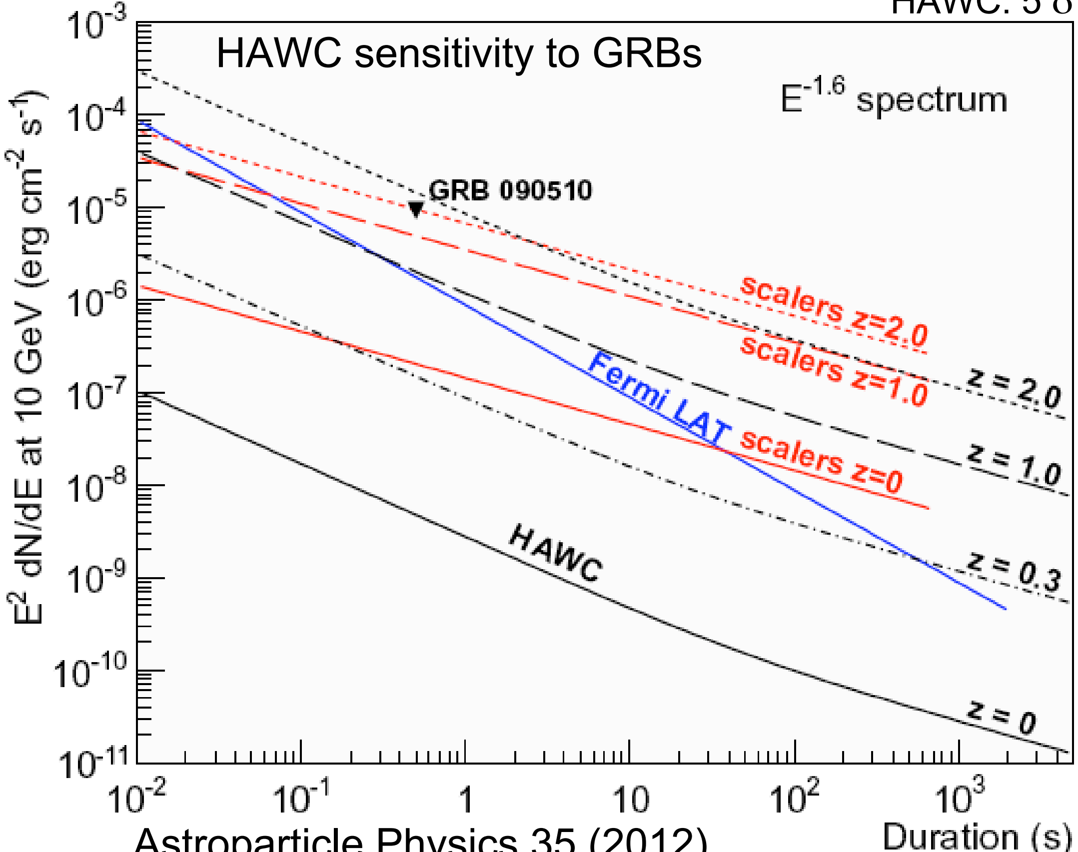


HAWC performance

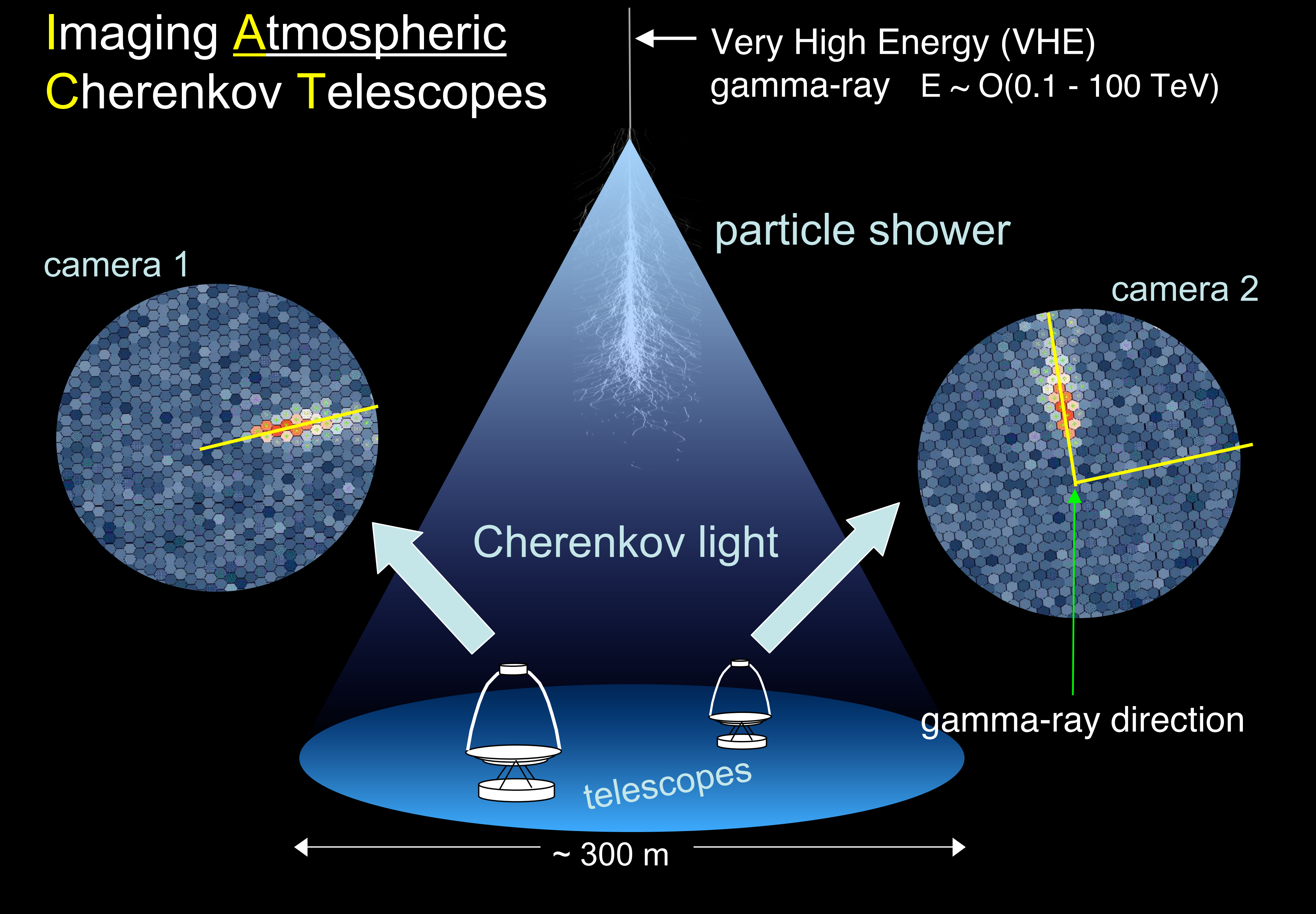
- Large field of view (2 sr):
  - many sources at a time → & GRBs !
  - Large-scale anisotropies
- Sensitivity ~10% of Crab Nebula (>1 TeV) in one year of running time. Above 10 TeV, better than current IACTs (50 h)
- Ang. res.: from 2º at threshold ↘ 0.1º above 10 TeV
- Spectral resolution: 100% ↘ 50%

(Fermi-LAT line: 1 photon above 10 GeV)

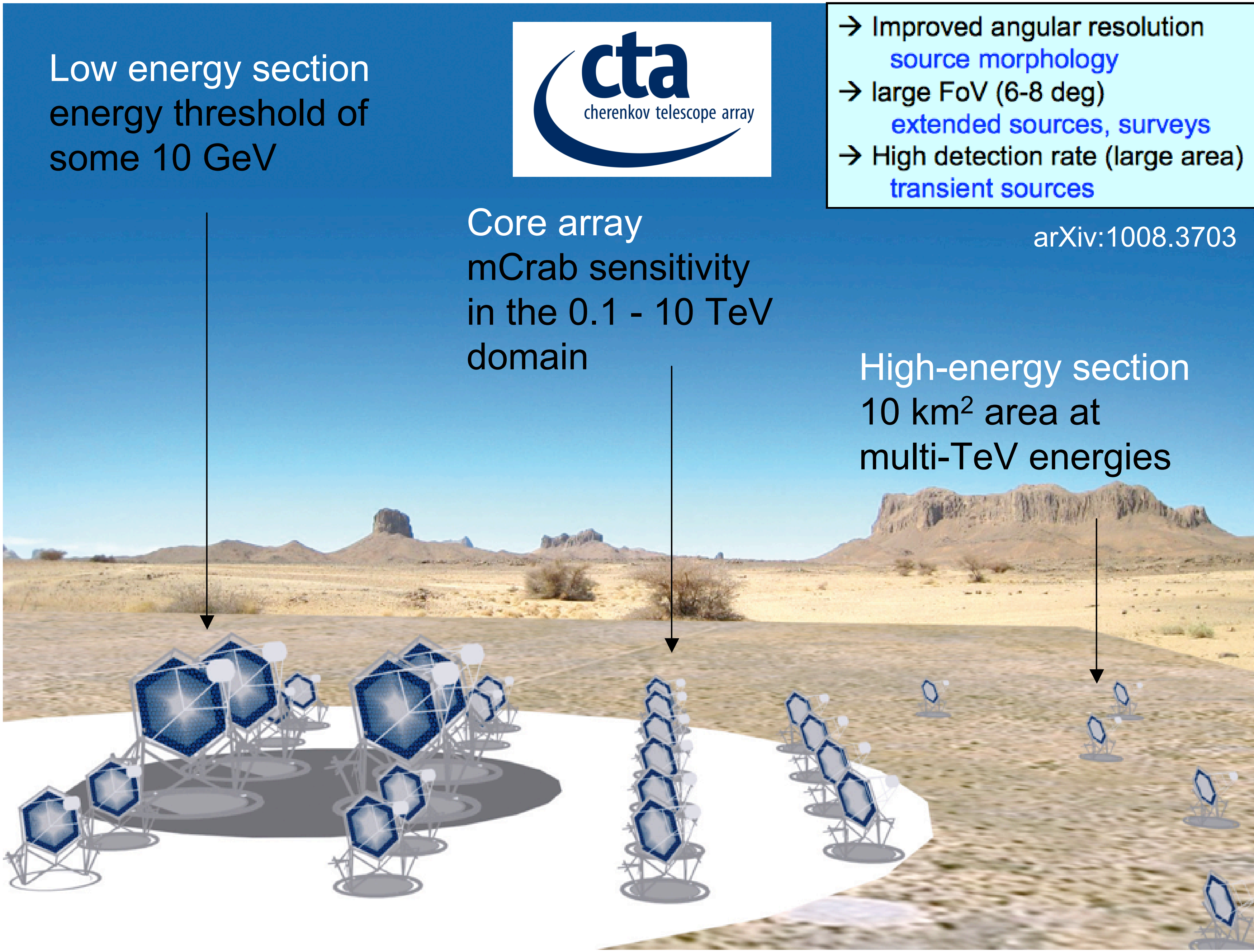
HAWC: 5 σ



Astroparticle Physics 35 (2012)


Imaging Atmospheric
Cherenkov Telescopes
Very High Energy (VHE)
gamma-ray E ~ O(0.1 - 100 TeV)
particle shower
camera 1
camera 2
Cherenkov light
gamma-ray direction
telescopes
~ 300 m

CTA:
the Cherenkov Telescope Array

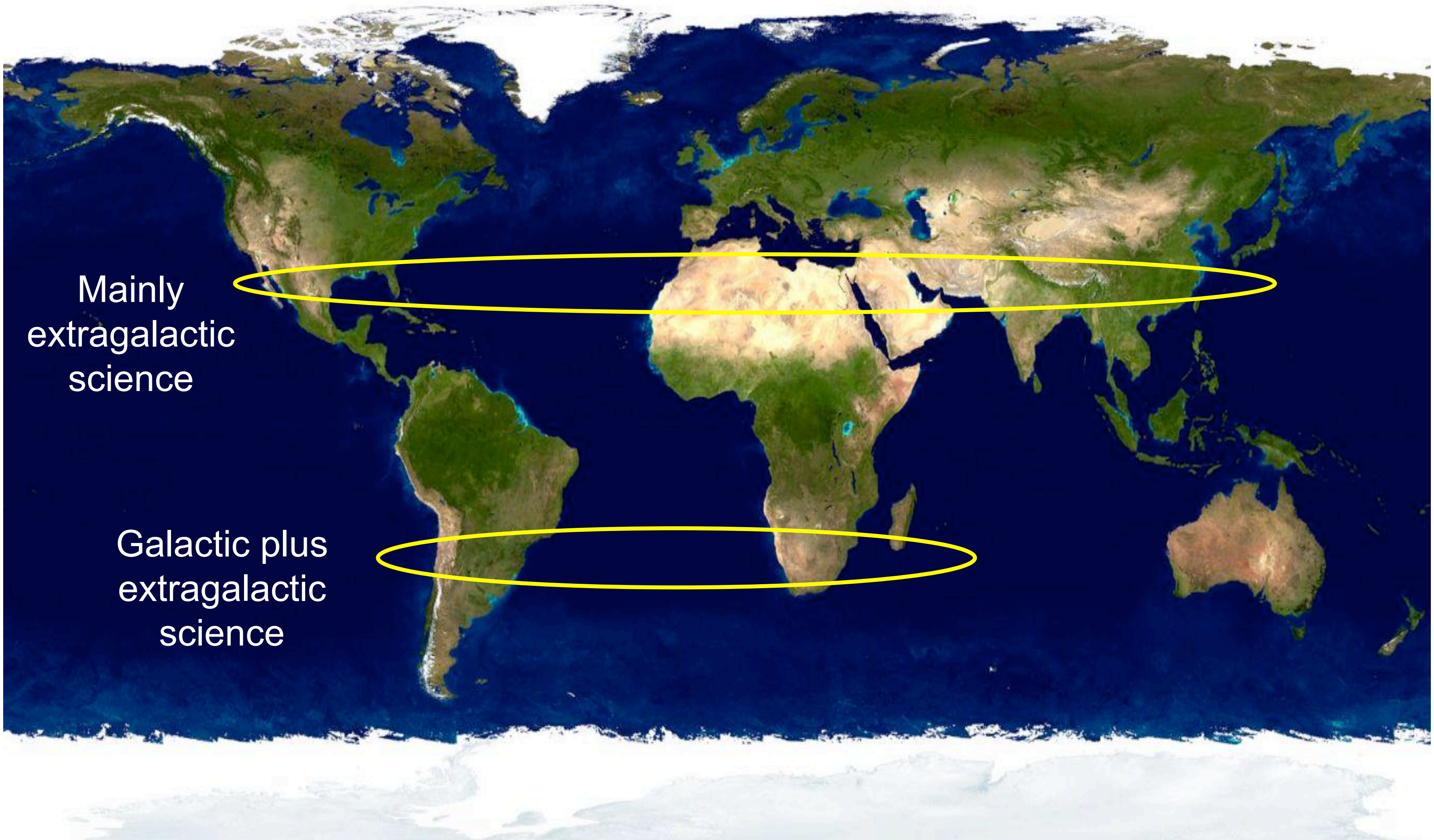


Low energy section
energy threshold of
some 10 GeV
cta
cherenkov telescope array
→ Improved angular resolution
source morphology
→ large FoV (6-8 deg)
extended sources, surveys
→ High detection rate (large area)
transient sources
arXiv:1008.3703
Core array
mCrab sensitivity
in the 0.1 - 10 TeV
domain
High-energy section
10 km^2 area at
multi-TeV energies

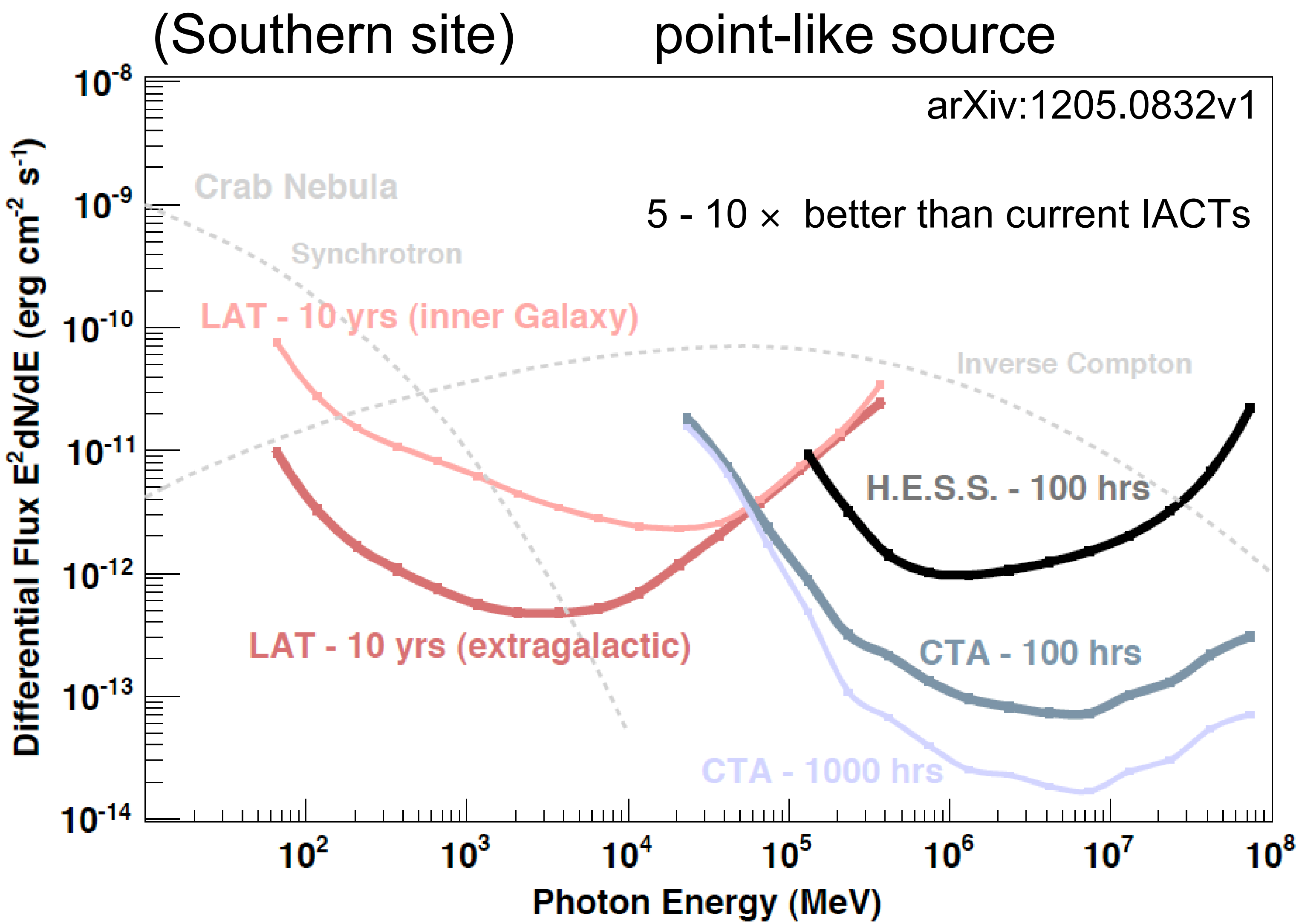
CTA

- A world-wide consortium of > 900 researchers
- FP7- supported Prep. Phase: Fall 2010 – Fall 2013
  - Technical design, sites, construction and operation costs
  - Legal, governance and finance schemes
  - Small + medium-sized telescope prototypes
- Aim for
  - start of deployment in early 2014
  - first data in 2016/17
  - base arrays complete in late 2018

CTA: two sites for all-sky coverage



CTA sensitivity



CTA sensitivity to transients

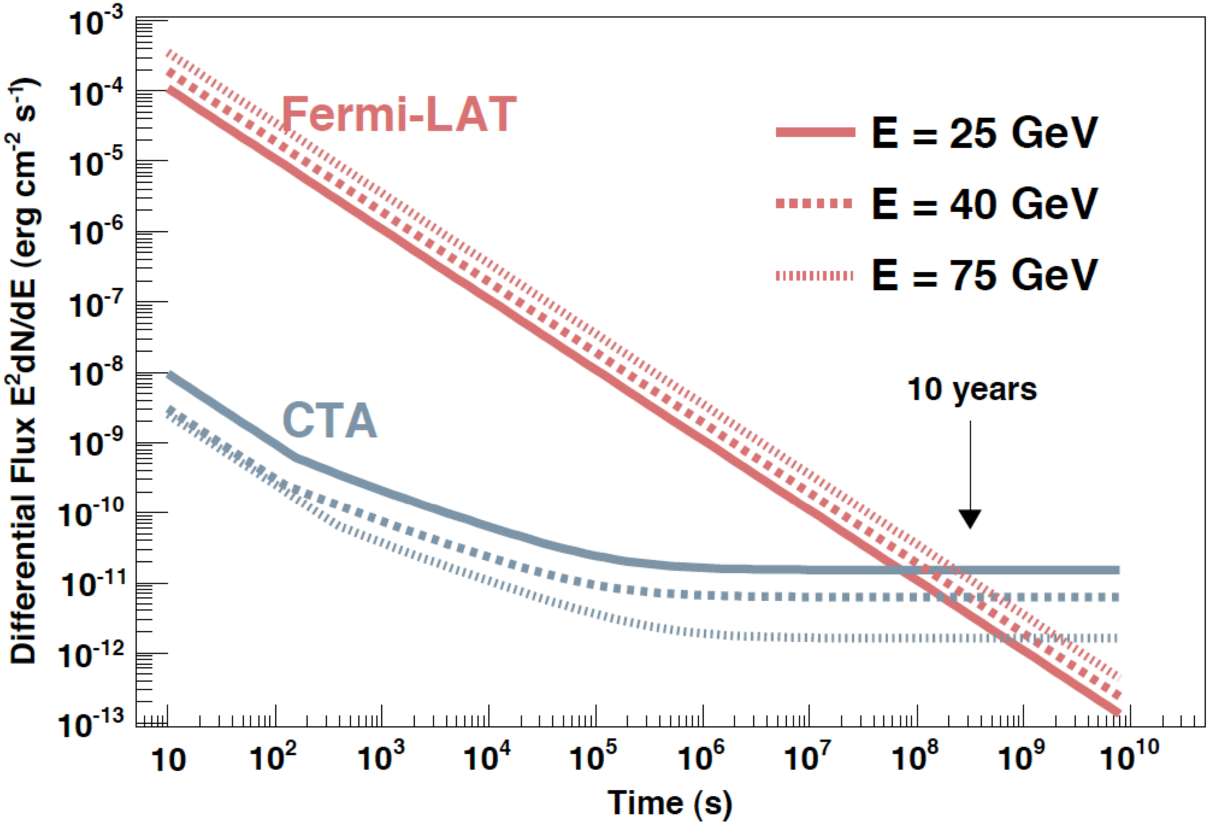
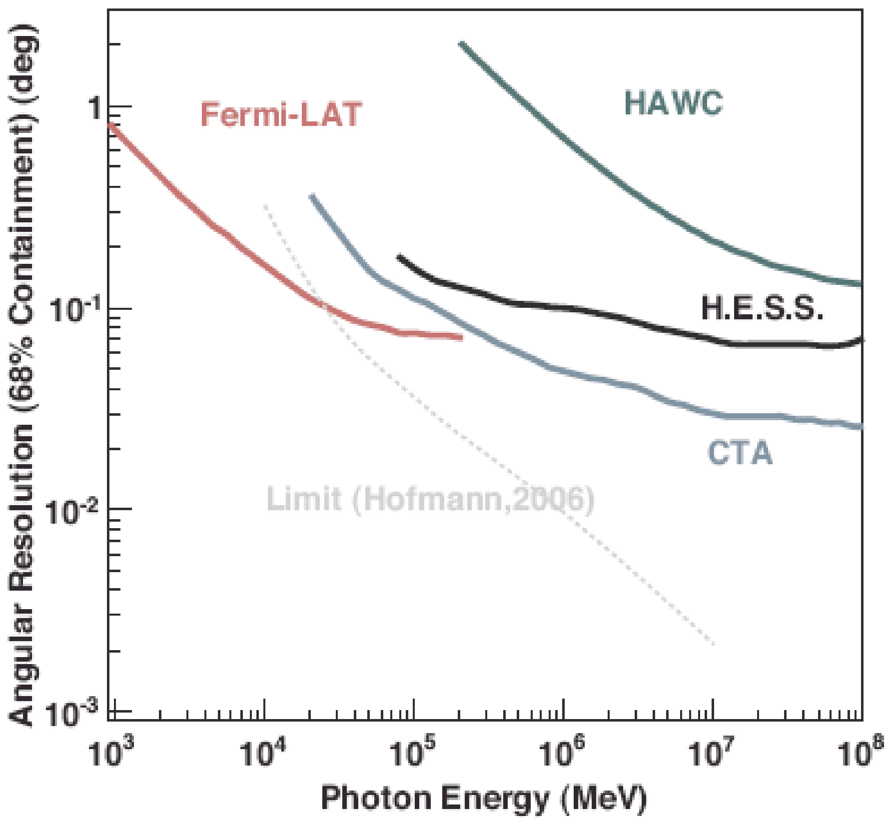


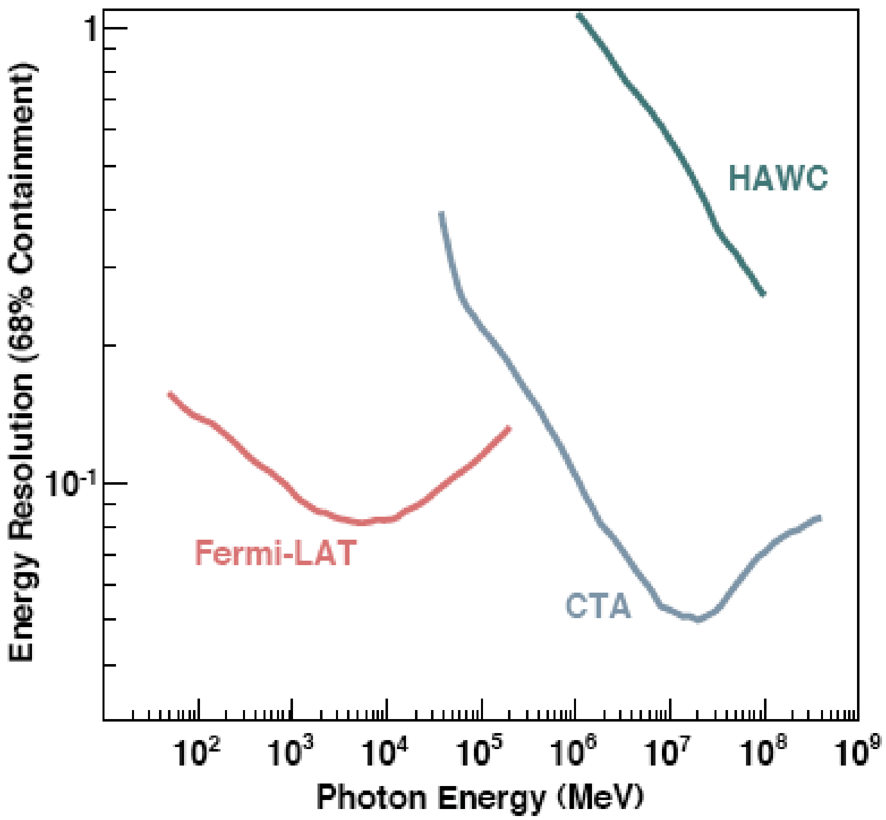
Figure 5: Differential sensitivity at selected energies as a function of observation time. These plots were generated for a detection significance of 5σ in the relevant energy bin and a minimum number of 25 events.

- *Fermi-LAT* limited by small collection area in overlapping E-range $\Rightarrow$ CTA up to $10^4\times$ better
- caveat: much smaller FoV!

Angular & spectral resolution

arXiv:1205.0832v1



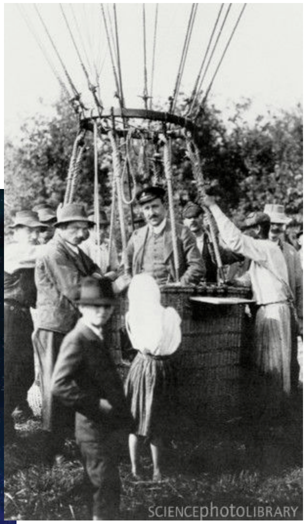


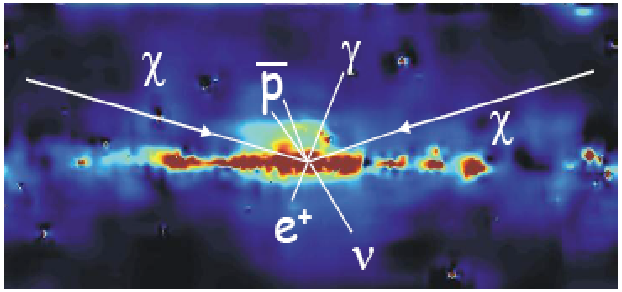
CTA main Science themes

- Understanding the origin of Cosmic Rays and their role in the Universe

- Understanding the nature and variety of particle acceleration around black holes

- Fundamental physics: indirect dark matter searches, tests of Lorentz invariance, axion-like particles, monopoles





Besides all of the above, CTA has high discovery potential due to the big leap in sensitivity

Astroparticle Physics CTA Special issue

(coming soon)

- Includes a section on DM and fundamental physics:

Dark Matter and Fundamental Physics with the Cherenkov Telescope Array

M. Doro[j,1], J. Conrad[g,h,1], D. Emmanoulopoulos[k], M. A. Sànchez-Conde[r], J.A. Barrio[a], E. Birsin[b], J. Bolmont[c], P. Brun[d], S. Colafrancesco[e], S. H. Connell[f], J.L. Contreras[a], M.K. Daniel[i], M. Fornasa[l,m], M. Gaug[j], J.F. Glicenstein[d], A. González-Muñoz[n,m], T. Hassan[a], D. Horns[o], A. Jacholkowska[c], C. Jahn[p], R. Mazini[q], N. Mirabal[a], A. Moralejo[n], E. Moulin[d], D. Nieto[a], J. Ripken[g], H. Sandaker[s], U. Schwanke[b], G. Spengler[b], A.Viana[d], H.-S. Zechlin[o], S. Zimmer[g], for the CTA collaboration.

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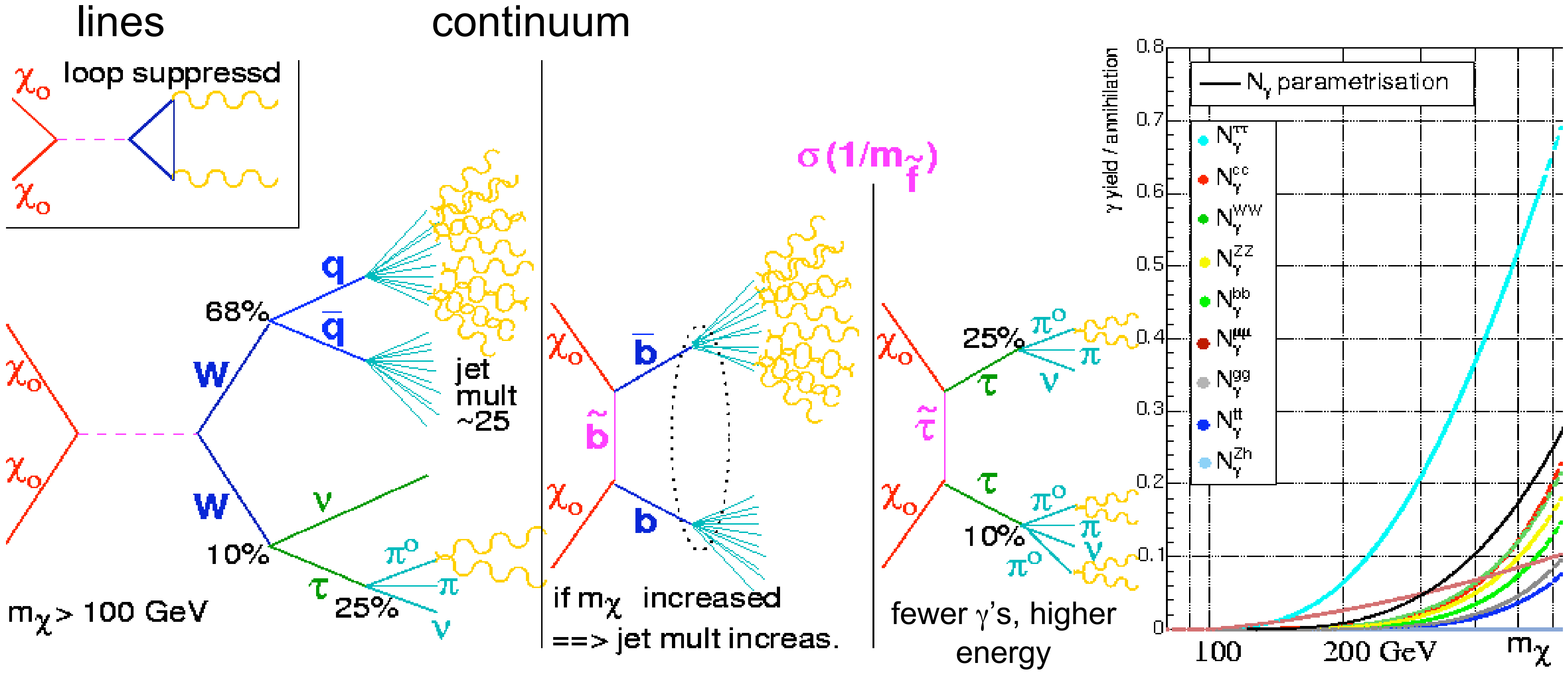
Indirect Dark Matter searches

VHE γ-rays from dark matter?

- Best scenario for IACTs (energy-wise): WIMP dark matter annihilation

(e.g. SUSY neutralinos)



The WIMP miracle

$$\chi\,\chi \xrightarrow{\langle \sigma v \rangle} \text{SM particles}$$

- If produced thermally, number of Dark Matter particles freezes out in early Universe when annihilation rate falls behind expansion rate

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \cdot \left(n_\chi^2 - n_{\chi,eq}^2 \right)$$

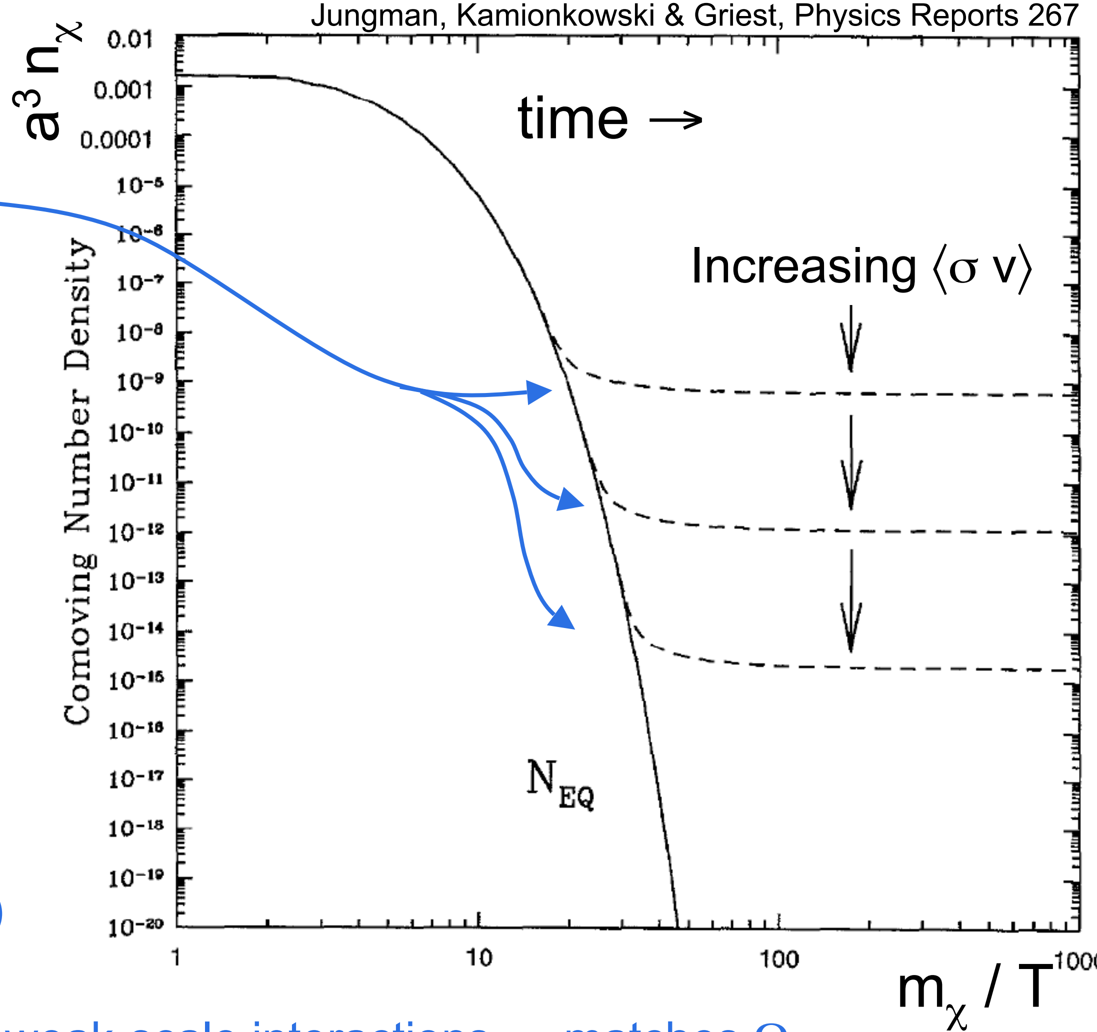
$$H = \dot{a}/a$$

$\Rightarrow$ Relic density *today*:

$$\Omega_\chi h^2 \approx \frac{3 \cdot 10^{-27}\, cm^3/s}{\langle \sigma v \rangle} \quad \sim O(0.1)$$

for weak-scale interactions $\Rightarrow$ matches Ω_{DM}

Jungman, Kamionkowski & Griest, Physics Reports 267



γ-ray flux from DM annihilation

- Expected γ-ray flux above *E₀*:

$$\Phi(> E_0, \Delta\Omega) = \Phi_\epsilon^{PP}(> E_0)\ J\left(\Delta\Omega\right)$$

  - Particle Physics factor:

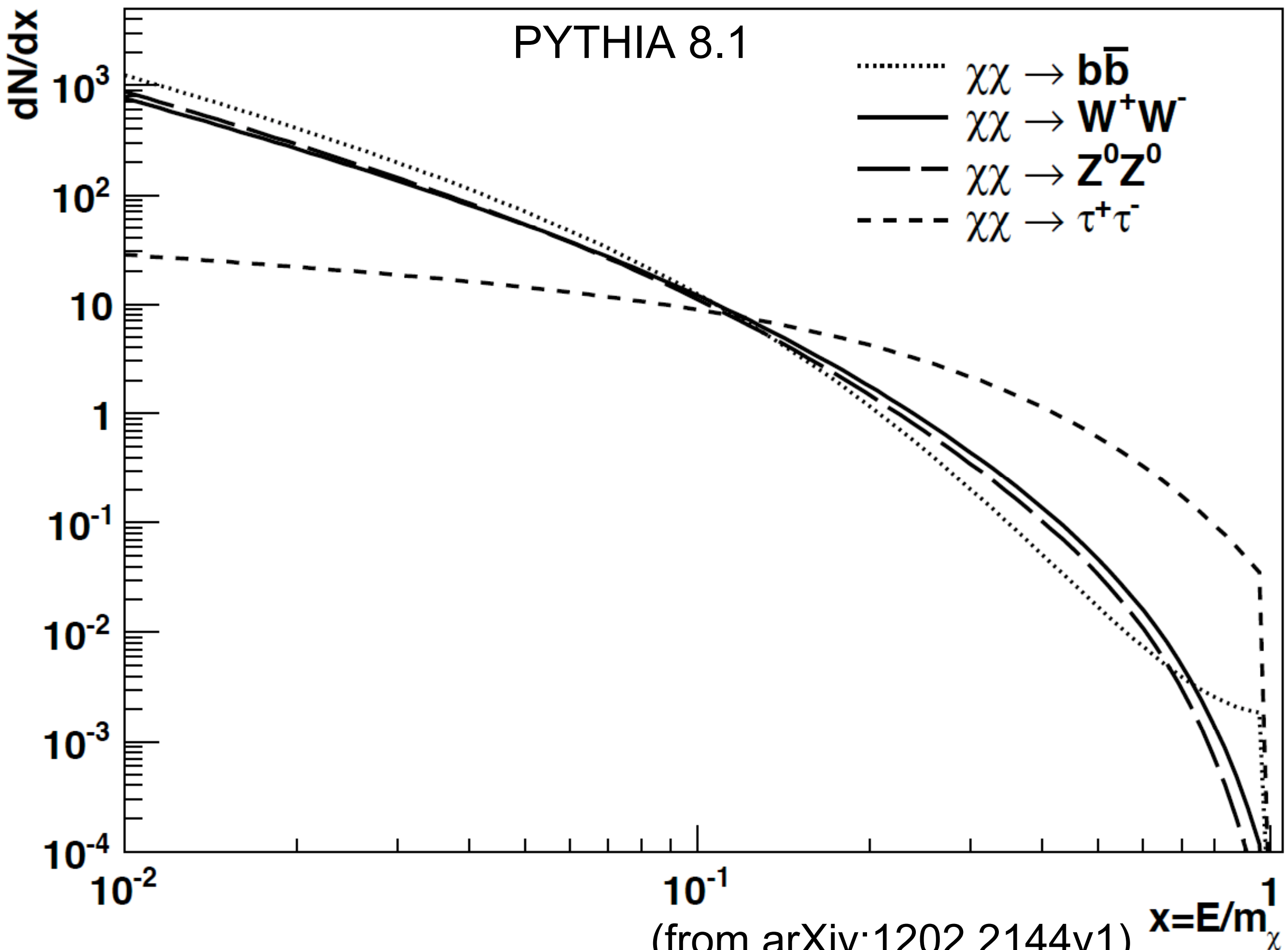
$$\boxed{\Phi_\epsilon^{PP}(> E_0) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_{i=1}^{n}B^i\frac{dN_\gamma^i}{dE}\ dE}$$

  - Astrophysics factor:

$$\boxed{J(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho^2(r(s,\Omega))\,ds\,d\Omega}$$

Example γ-ray spectra

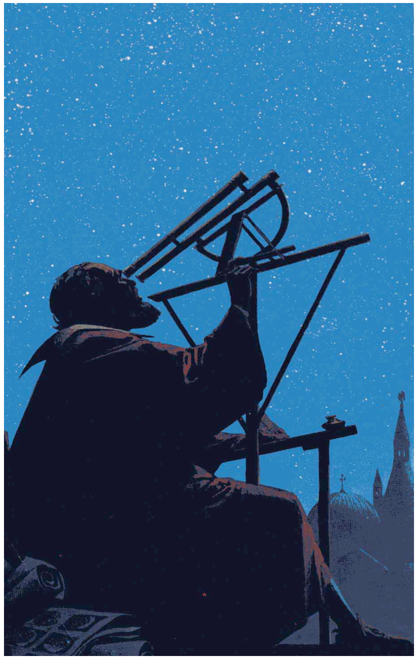
for different annihilation channels



(from arXiv:1202.2144v1)

Where to look?

- IACTs have limited FoV...
  - no all-sky search possible yet
  - with CTA, *all-sky* survey feasible - but with modest average exposure
  - Deep exposures achievable only for selected candidates



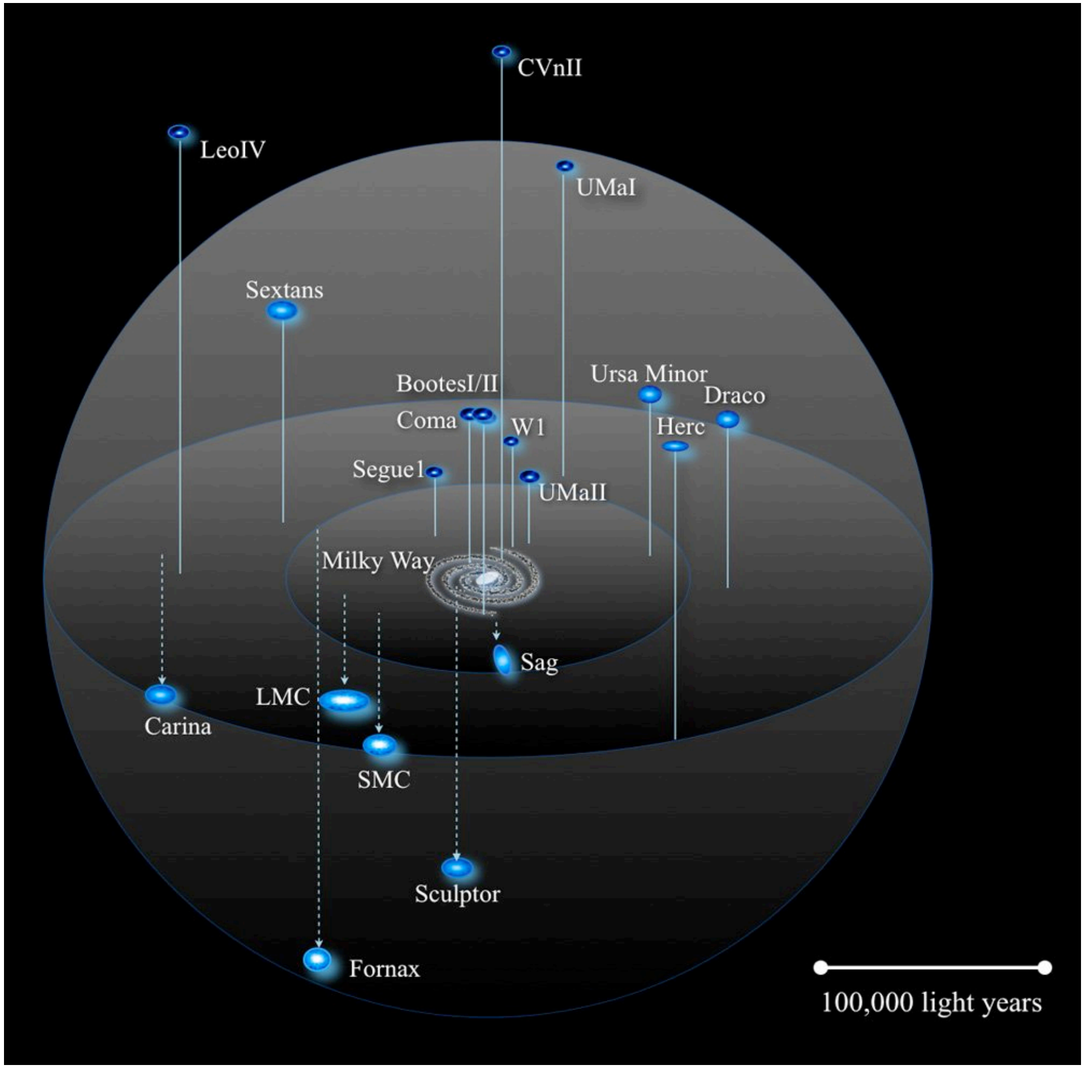
- Wish list for candidate sources:
  - **high ρ^2**
  - small distance
  - small apparent (angular) size
  - (if possible) no γ-rays from ordinary sources

Best candidates so far

- Dwarf spheroidal galaxies
- Galaxy clusters
- Galactic center & halo
- DM sub-halos?

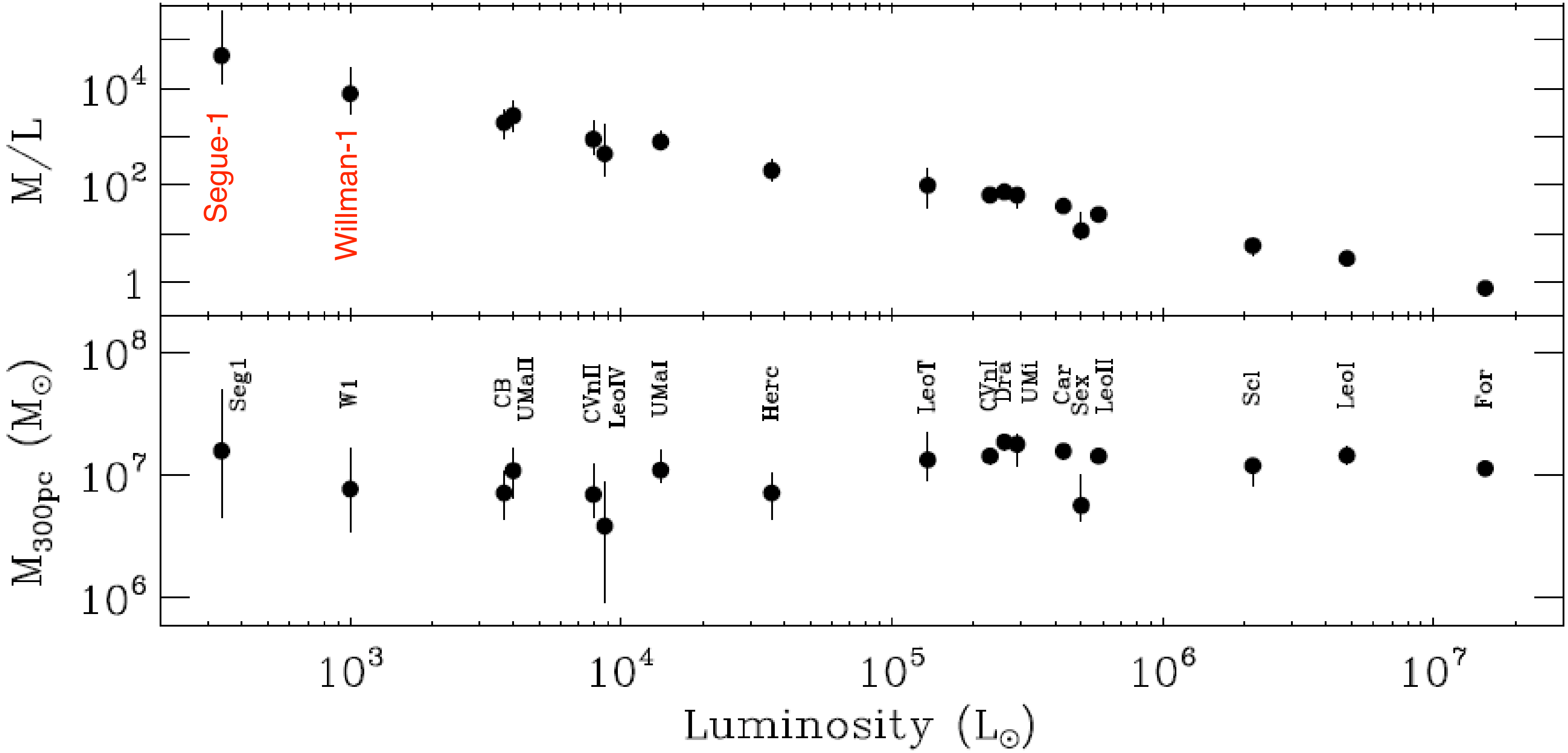
Dwarf spheroidal galaxies

- Small companion galaxies of the Milky Way
- Nearby, and large M/L ratio



Dwarf spheroidal galaxies

Geha et al, ApJ 692 (2009)



Dwarf spheroidals with CTA

- Existing limits will improve as expected from ~10-fold better sensitivity

- ...but still far from the expected ⟨σv⟩ values for thermally produced WIMPs (~ 3×10^{-26} cm^3 s^{-1})

ApP CTA special issue

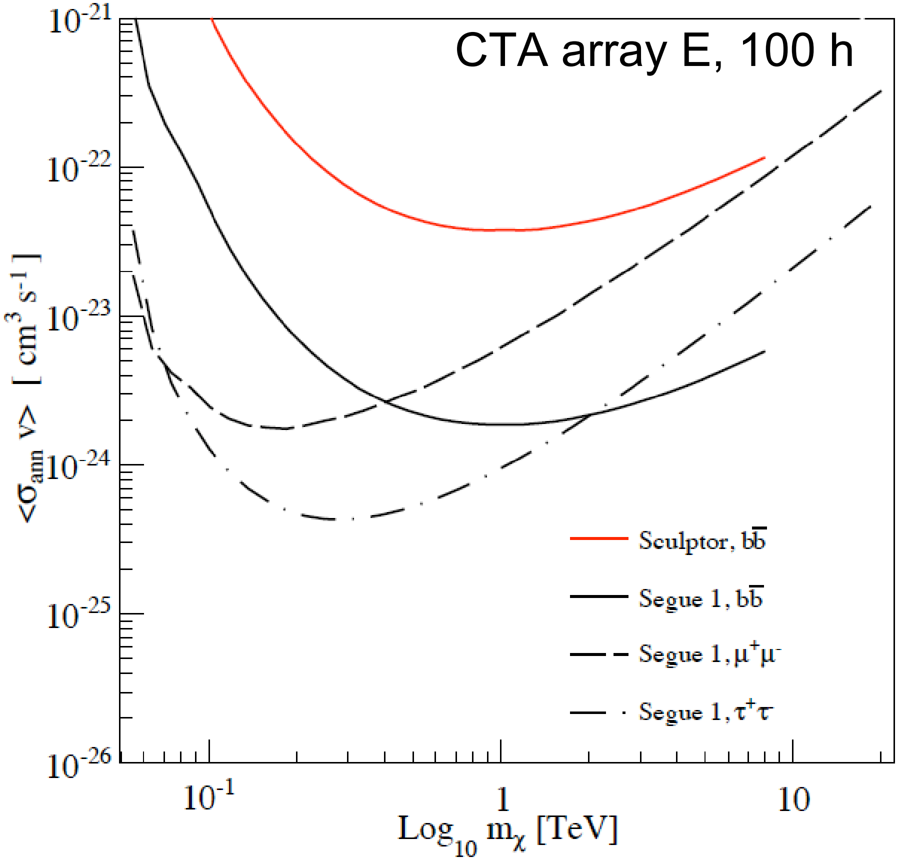


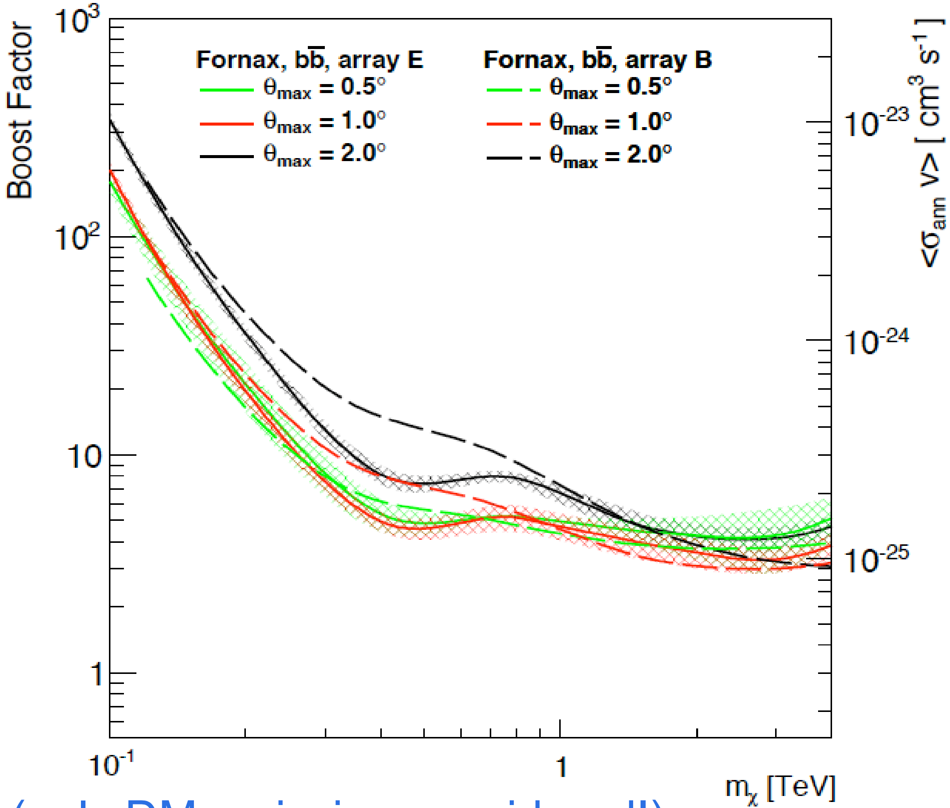
Figure 1.3: 95% C.L. sensitivity towards the Sculptor and Segue 1 dSphs for T_{obs} = 100 hours, assuming 100% branching ratio into $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$. The calculations are done for array E, a NFW profile and $\Delta\Omega = 1\times10^{-5}$ sr.

Galaxy clusters with CTA

- For best candidate (Fornax) predicted flux, for m_χ >0.3 TeV and $b\bar{b}$ channel, just 3-4 times lower than needed for detection

- *Might* constrain the case $\chi\,\chi \rightarrow \tau^+\tau^-$ but...

ApP CTA special issue



(only DM emission considered!)

Figure 1.7: Prospect of detection of DM-induced signal from Fornax for a DM particle annihilating into $b\bar{b}$ and 100 h integration time. The reference model is taken from Ref. [16] with substructure boost factor $B_F = 580$. Following the left-hand side vertical axis, the *additional* boost factor with respect to our model needed to have a 5σ detection is shown for different ROI. Following the

Galaxy clusters with CTA

- Disentangling DM from CR emission will be hard!

- Masking central part? $\Rightarrow$ less integrated flux, worse sensitivity

ApP CTA special issue

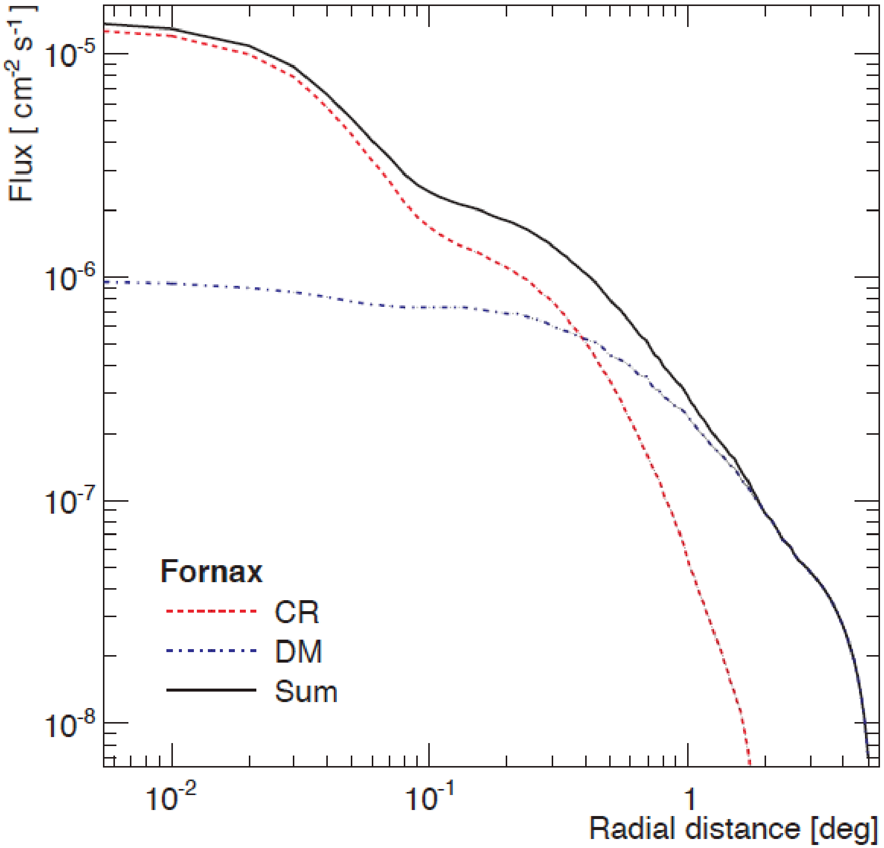
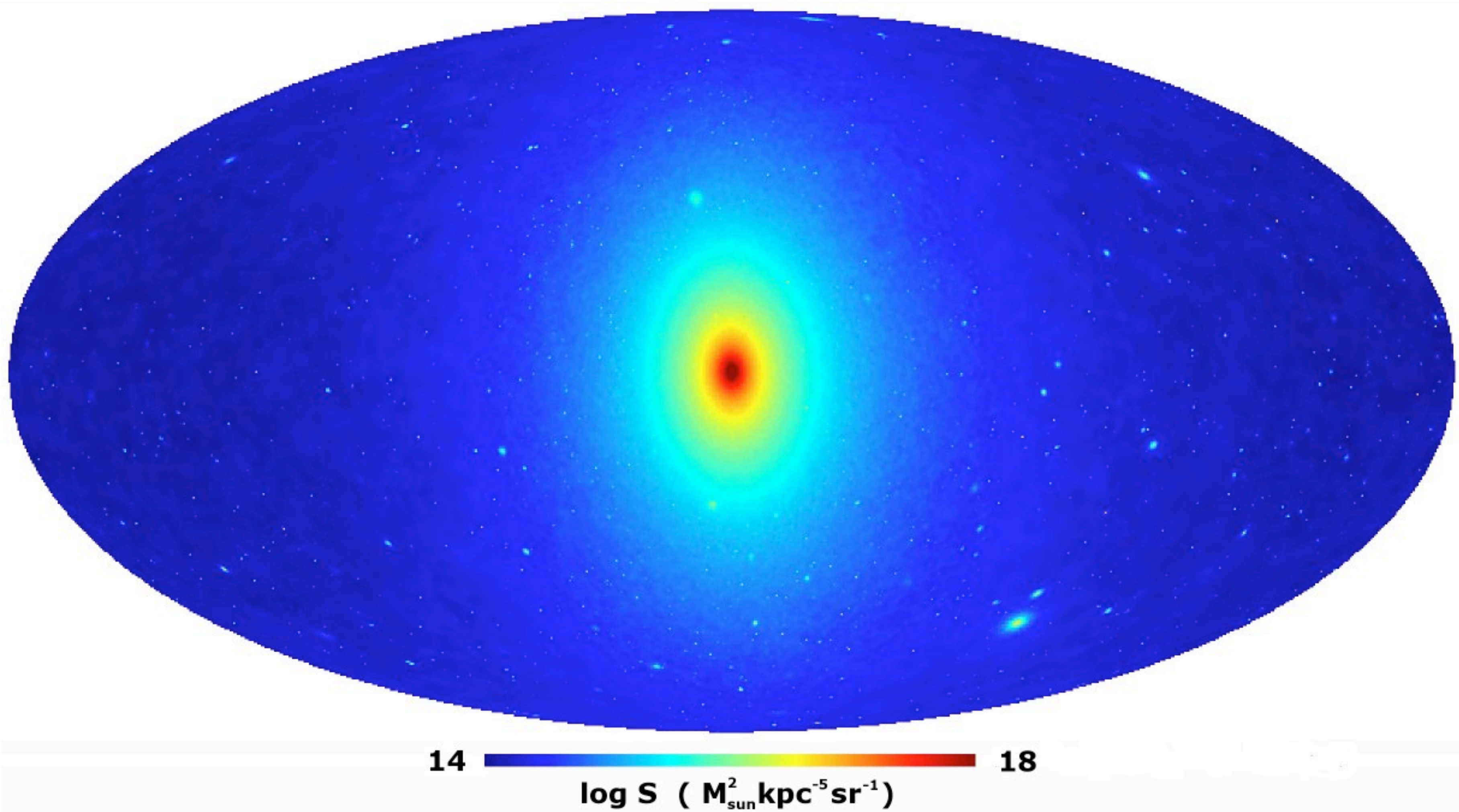


Figure 1.8: The surface brightness (above 1 GeV) of the gamma-ray emission from the Fornax cluster expected from CRs (red), DM (blue) and the sum of the two contributions (black).

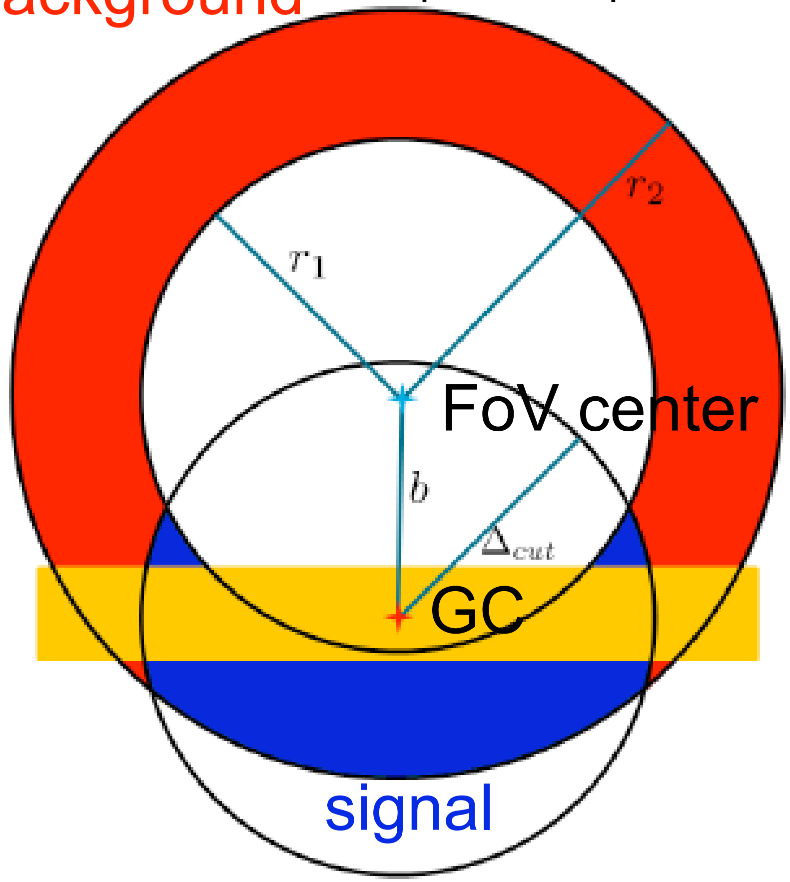
The Milky Way halo

Aquarius simulations http://www.mpa-garching.mpg.de/aquarius/



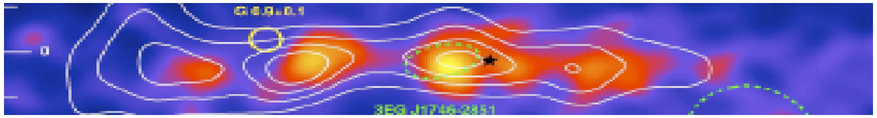
Surface brightness from DM annihilations

The Milky Way halo



Ring method

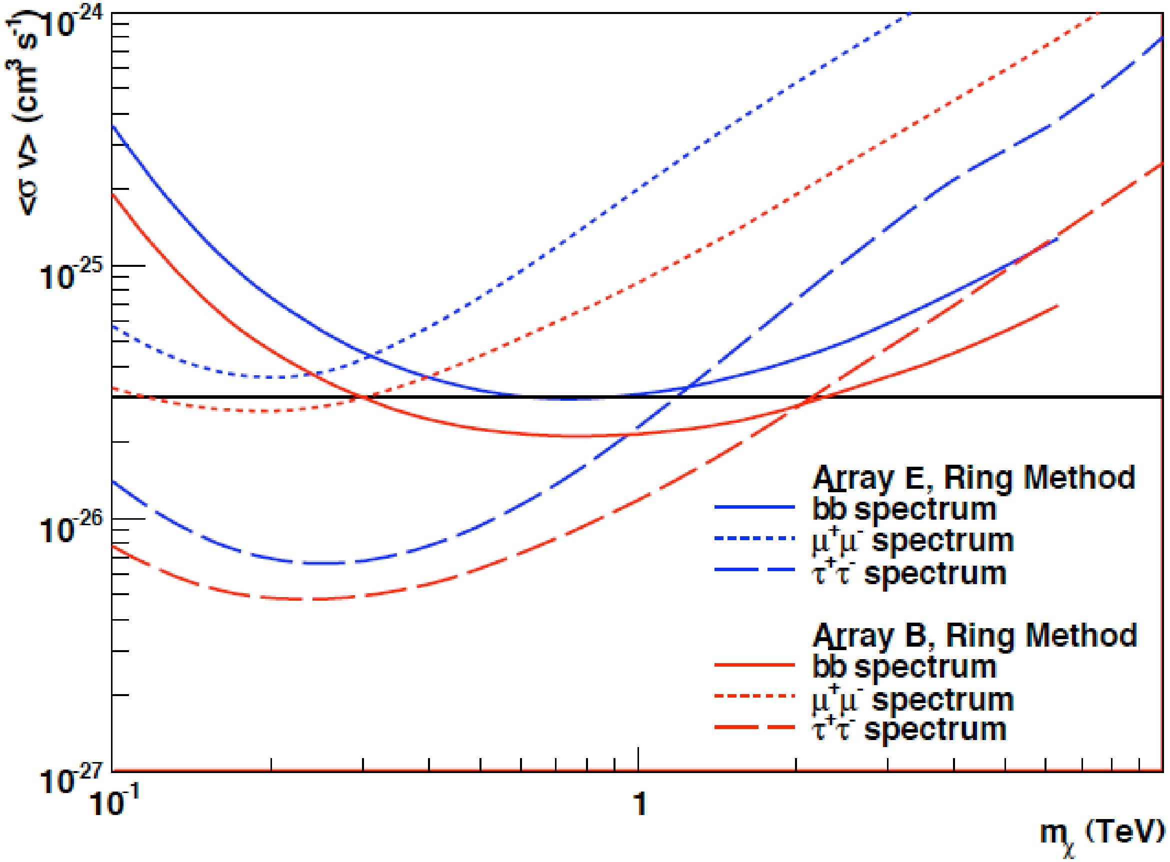
- Galactic Center (GC) and ridge too contaminated by other γ-ray sources



- ⇒ Study the MW halo excluding the centralmost part
- Need simultaneous view of *signal* and *background* regions ⇒ large FoV
- $r_1 \sim 0.5^{\circ}$ $r_2 \sim 2.5^{\circ}$

The Milky Way halo

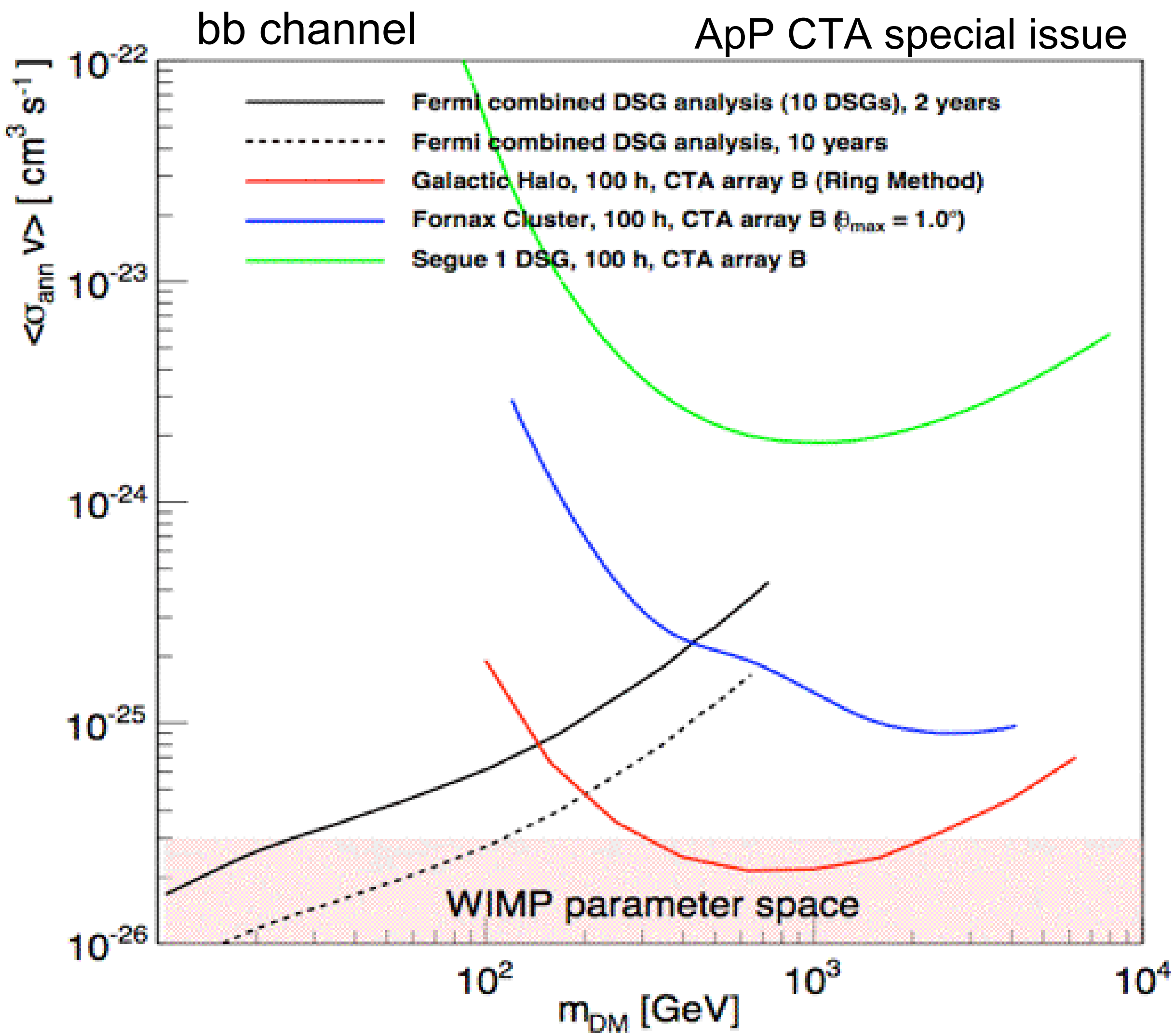
DM profile from Aquarius simulations



ApP CTA special issue

- The only target where the relevant $\langle\sigma v\rangle$ region can be probed by CTA with no extra “boost factor” needed

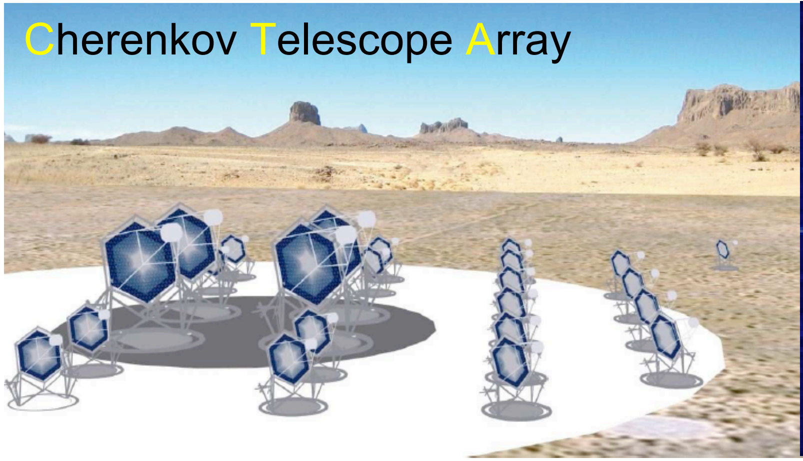
Comparison of targets

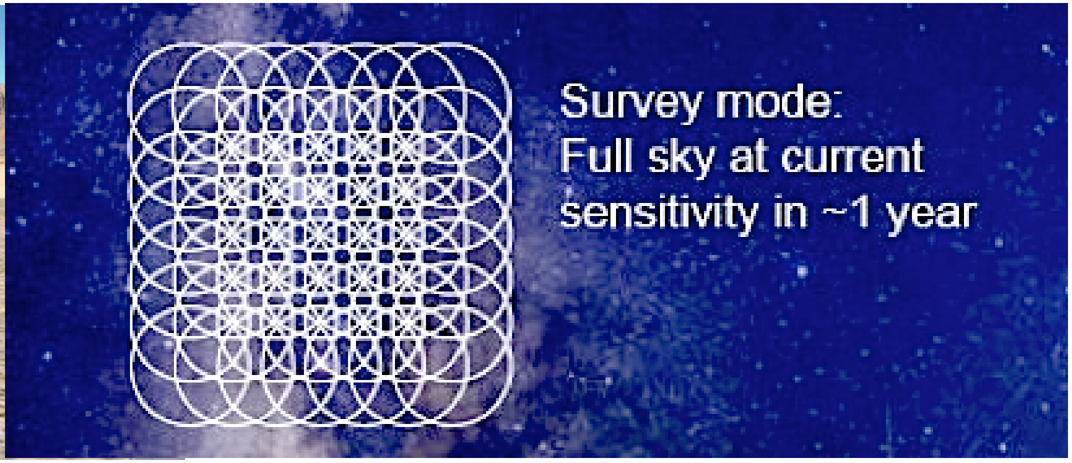


Besides known candidates...

CTA ⇒ first all-sky survey at ~TeV energies

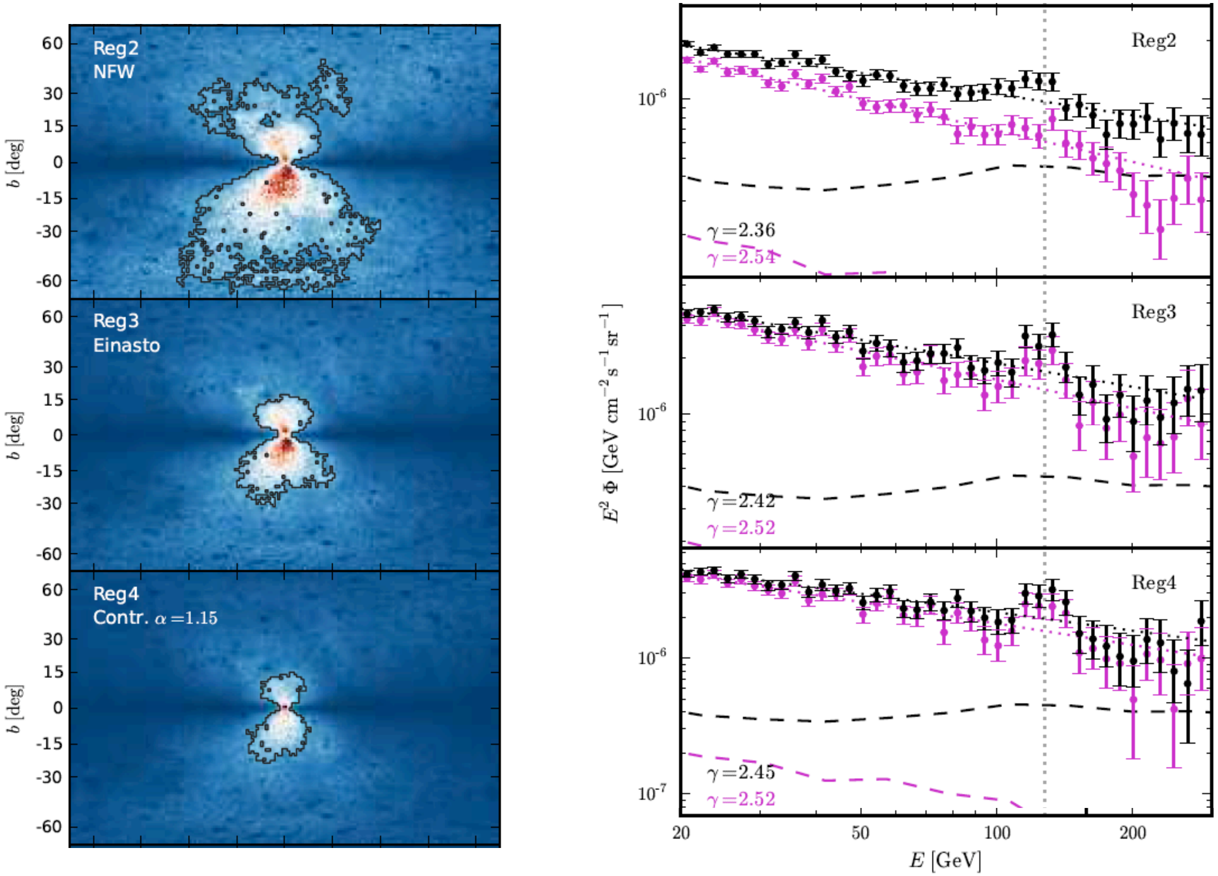
High discovery potential (e.g. DM sub-halos)





A γ-ray line at 130 GeV?

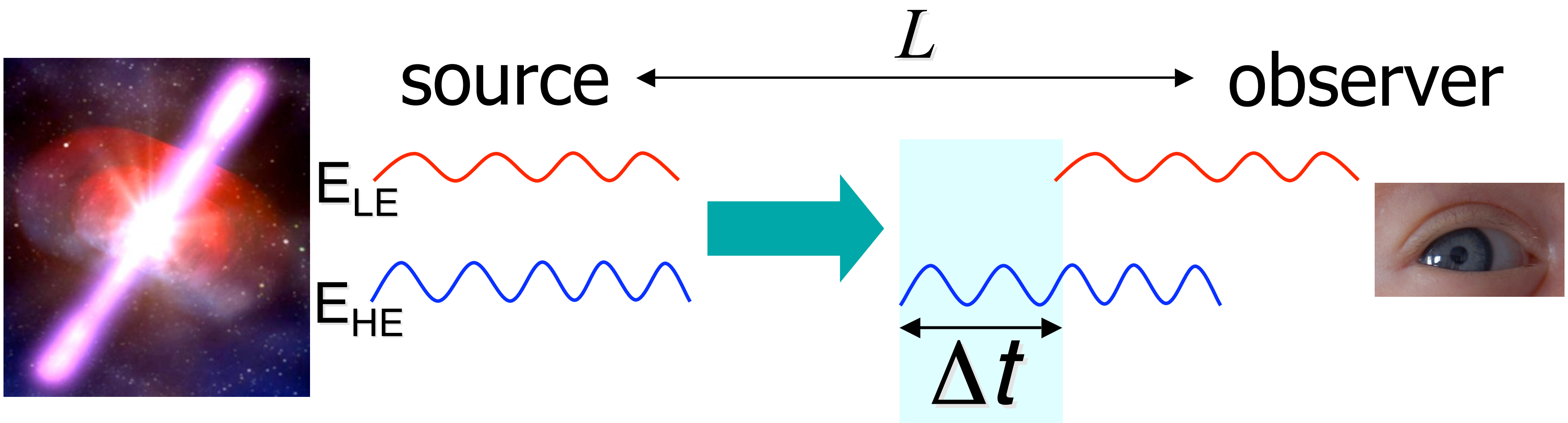
Weniger, arXiv:1204.2797v1



- hints of a line-like excess in public *Fermi-LAT* data of the MW halo, in a good E-range for CTA.
  Caveat! : *Fermi-LAT* collaboration finds no evidence (arXiv:1205.2739v1)

Tests of the speed of light

Tests of speed of light invariance



Some QG models predict

$$c' = c\left(1 - \frac{E}{M_{QG1}}\right)$$

or

$$c' = c\left(1 - \frac{E^2}{M_{QG2}^2}\right)$$

$$\Delta t \approx \frac{E_{HE}^n - E_{LE}^n}{M_{QG}^n} \frac{L}{c}$$

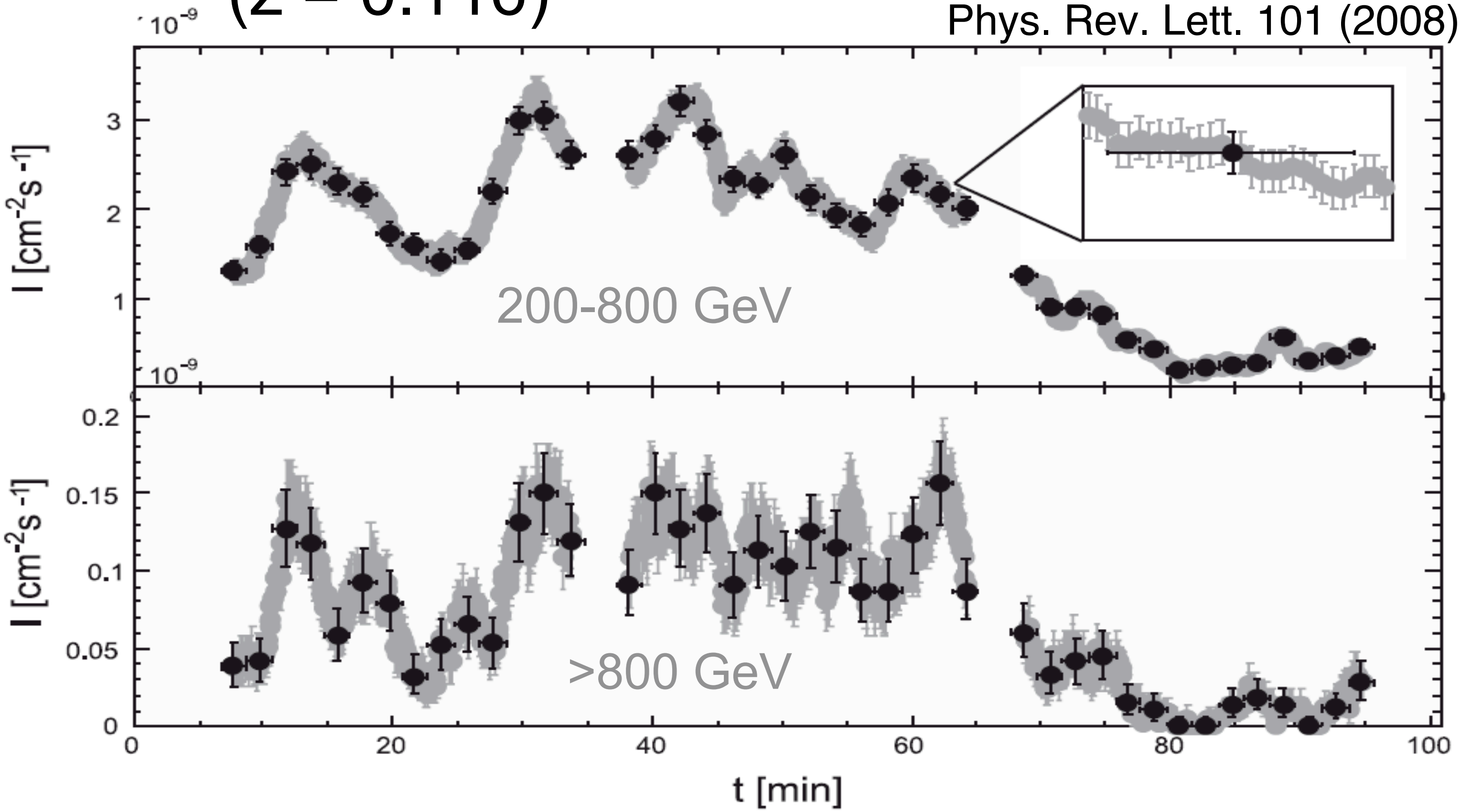
$n = 1 \text{ or } 2$

- Need fast-varying source (AGN flares, GRBs...)

HESS observations of PKS-2155 in 2006

(z = 0.116)

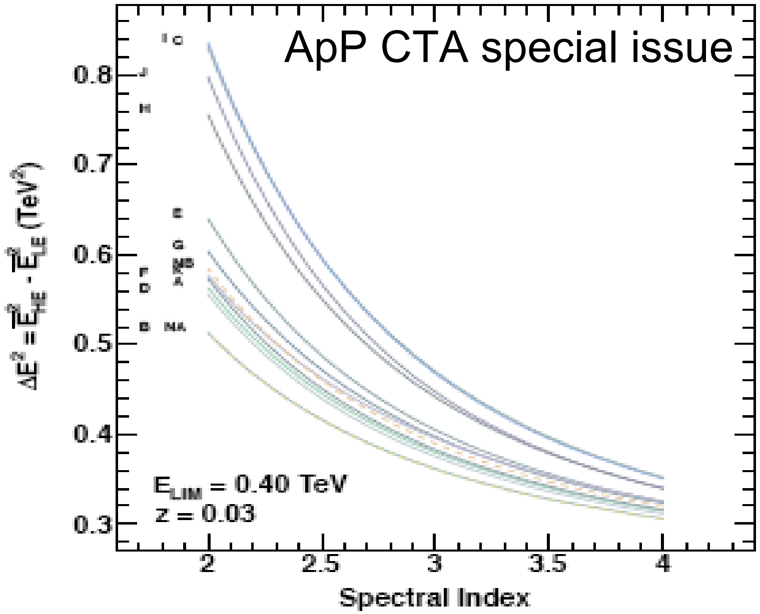
Phys. Rev. Lett. 101 (2008)

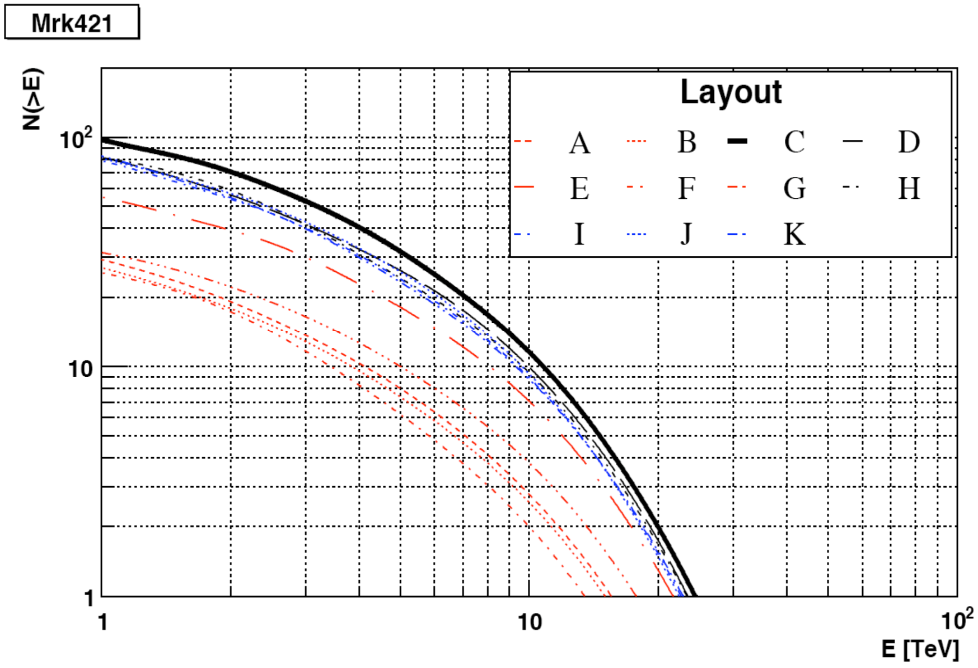


- No delay observed $\Rightarrow M_{QG1,\ 95\%CL} > 2.1 \times 10^{18}$ GeV

  (Astropart.Phys.34, 2011) $M_{QG2,\ 95\%CL} > 6.4 \times 10^{10}$ GeV

Tests of speed of light invariance with CTA



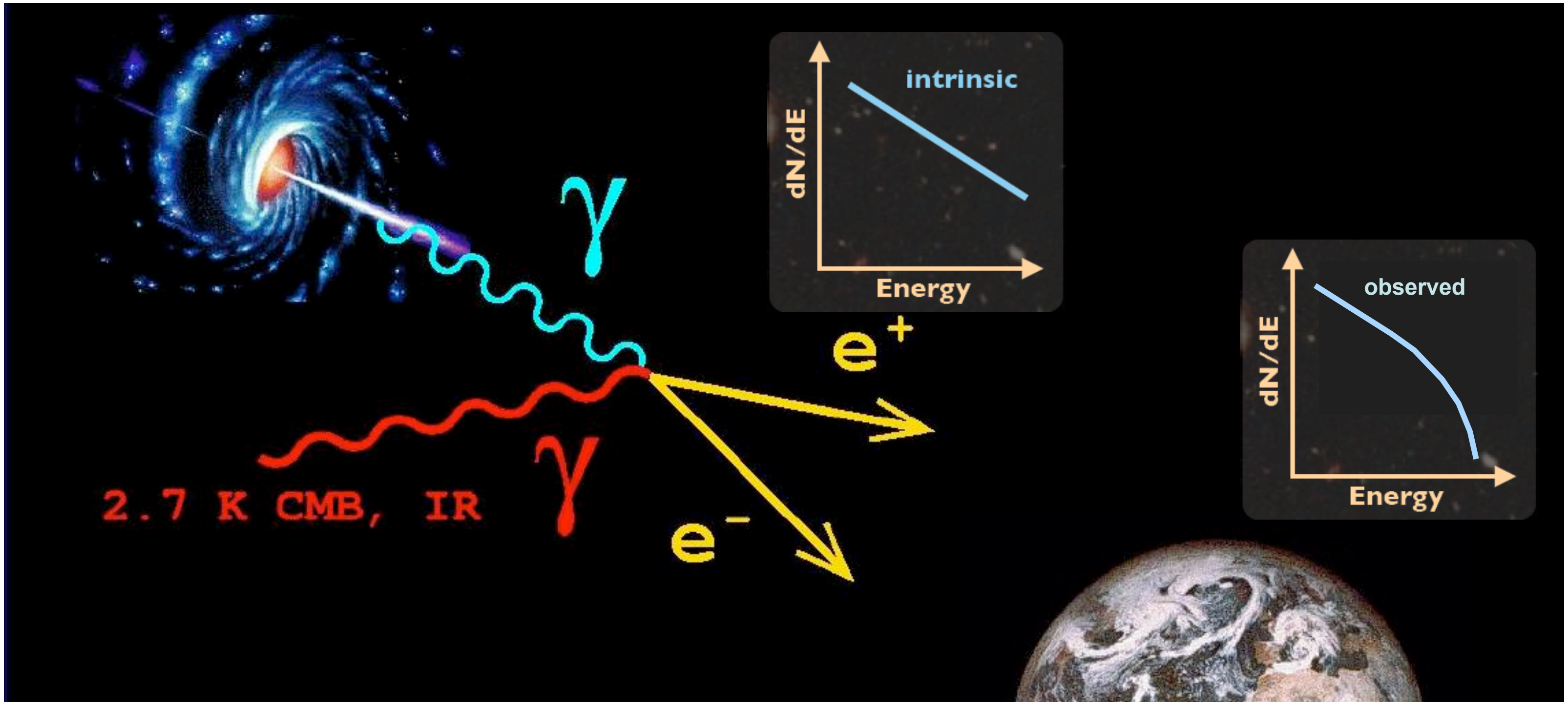


- CTA will benefit from large E- lever arm
- × 50 better limits expected for M_{QG2}
- Limit on M_{QG1} will exceed Planck mass

Search for axion-like particles (ALPs)

Extragalactic Background Light (EBL)

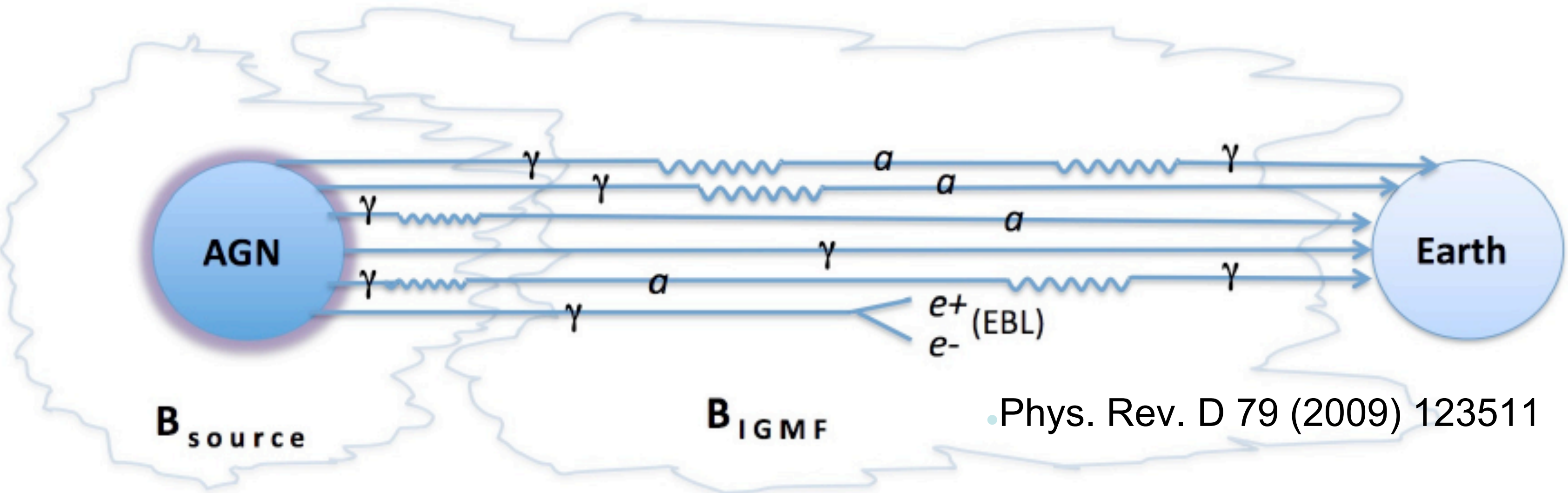
⇒ attenuation of γ-ray flux from distant sources



- Observed spectrum ≠ intrinsic spectrum
- Attenuation increases with E and (obviously) distance ⇒ "γ-ray horizon"

$\gamma \rightarrow$ ALP $\rightarrow \gamma$ conversions

- VHE photons above $E_{crit} = m^2 M / 2B$ $(M \equiv 1/g_{a\gamma})$ may couple to ultra-light ALPs ($m \sim 10^{-10}$ eV) in the presence of a B-field:



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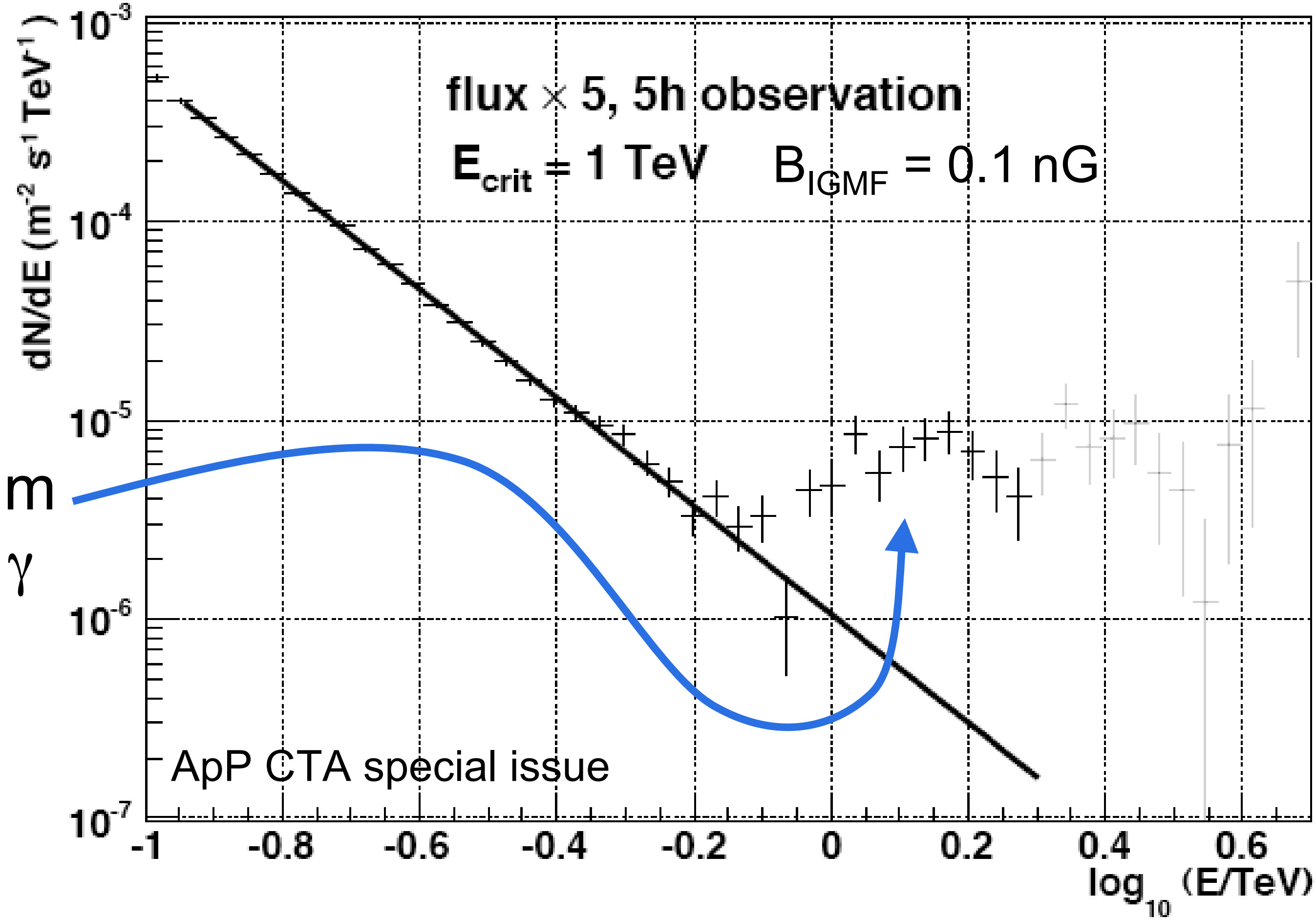
- This does not necessarily imply a reduction in flux:

ALPs would traverse the EBL unimpeded $\Rightarrow$ possible boost in observed γ-ray flux *w.r.t. expectation* (Phys. Rev. D 76)

Simulated ALP-boost for source at z = 0.43

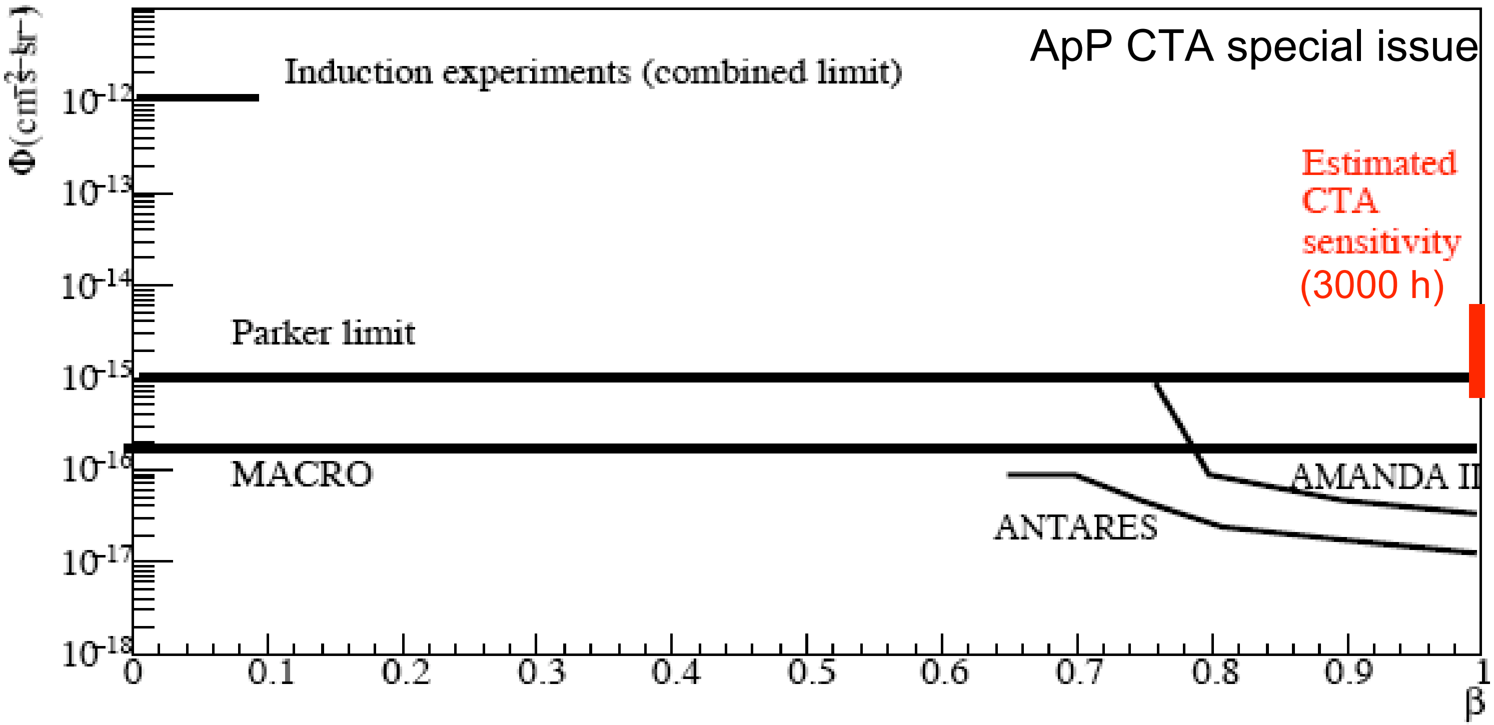
flux corrected for the EBL attenuation



unphysical spectrum (due to $\gamma \rightarrow$ ALP $\rightarrow \gamma$ conversions)

- If B_{IGMF} is ~ 0.1 nG, CTA can probe a region of *m vs.* $g_{a\gamma}$ allowed by CAST limits

Magnetic monopoles



- M >1 TeV monopoles with Lorentz factor > 10^3 would be detectable by CTA
- Expected limits worse than current limits from ν-telescopes (but is an independent test, and requires no dedicated observations)

Summary

- Future of gamma-ray astronomy seems bright (at least in the VHE range and above)
- CTA will improve sensitivity of current IACTs by a factor 5-10 and provide first sky survey in the VHE range: high discovery potential
- Indirect DM searches: observations of MW halo with CTA will probe the interesting $\langle\sigma v\rangle$ region (for $m_\chi > 300$ GeV)
- Observations with CTA *(et al)* can contribute to other Fundamental physics questions:
  - Tests of the invariance of the speed of light
  - Coupling of VHE photons to hypothetical axion-like particles
  - Magnetic monopoles