CHERENKOV TELESCOPE ARRAY
CTA

Massimo Persic
INAF+INFN Trieste
for CTA Consortium
Merate, Oct 6, 2011

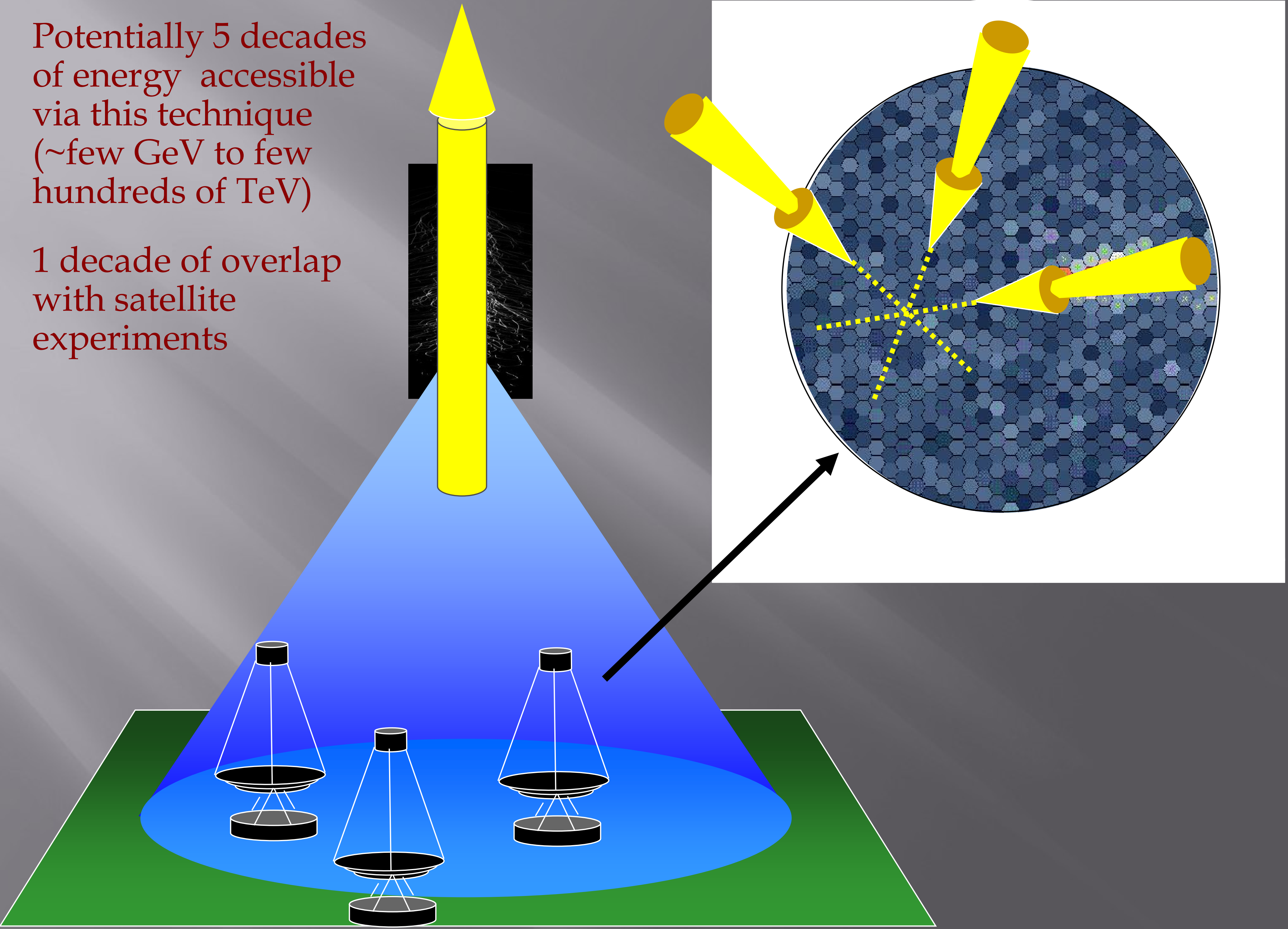
Outline

- Ground-Based gamma-ray astronomy
- Physics questions left by the current instruments
- The Cherenkov Telescope Array
  - Sensitivity Requirements
  - Current Status & Design Study, e.g.
    - Example MC simulation
    - Location Studies
- Possible Schedule
- CTA in Context
- Conclusions

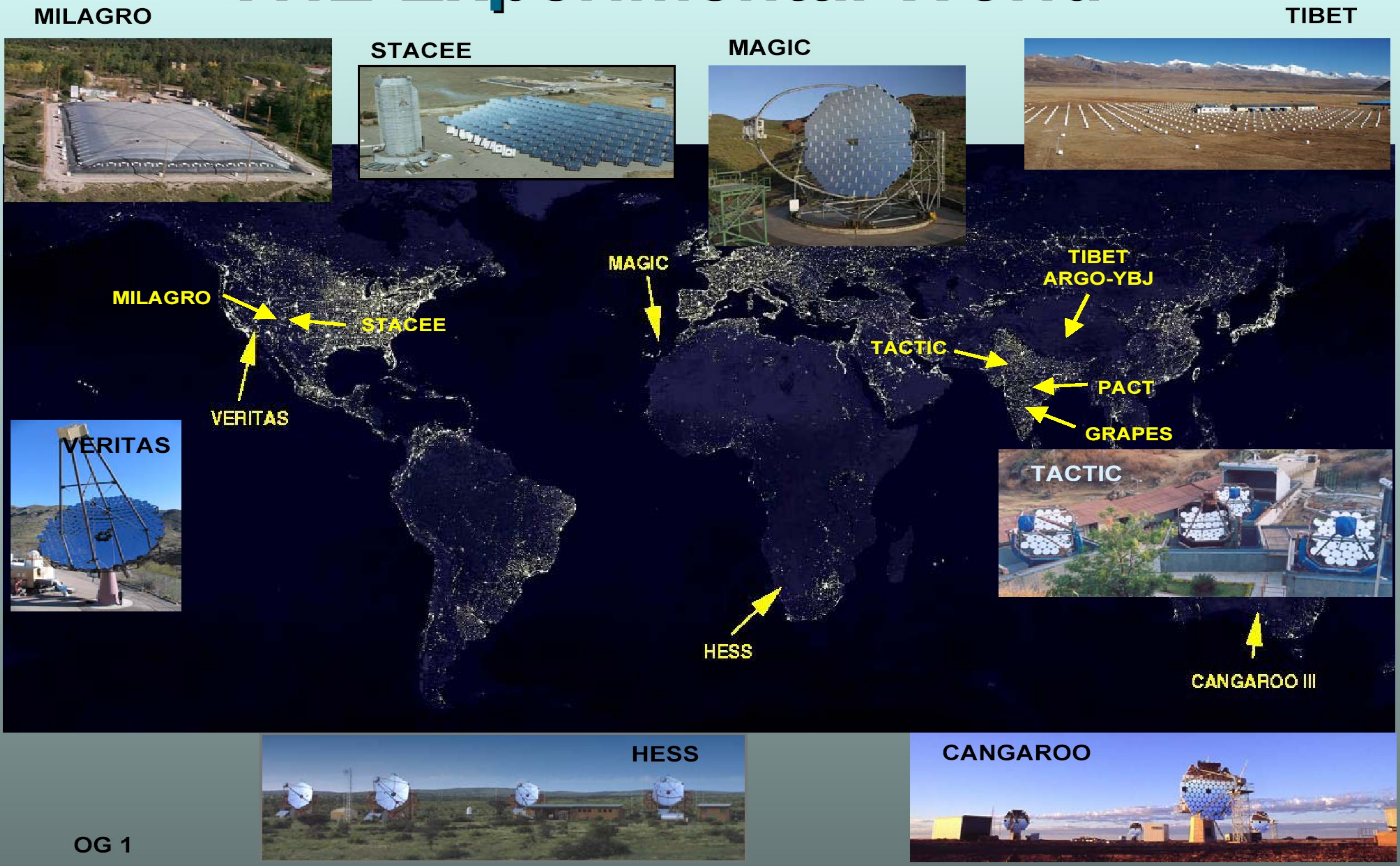
With slides from:
A.DeAngelis, G.Hermann, J.Hinton, W.Hofmann, M.Martinez, S.Nolan, S.Ritz, Th.Schweizer, M.Teshima, D.Torres

Potentially 5 decades of energy accessible via this technique (~few GeV to few hundreds of TeV)

1 decade of overlap with satellite experiments



VHE Experimental World



OG 1

VHE Experimental World

MILAGRO

STACEE

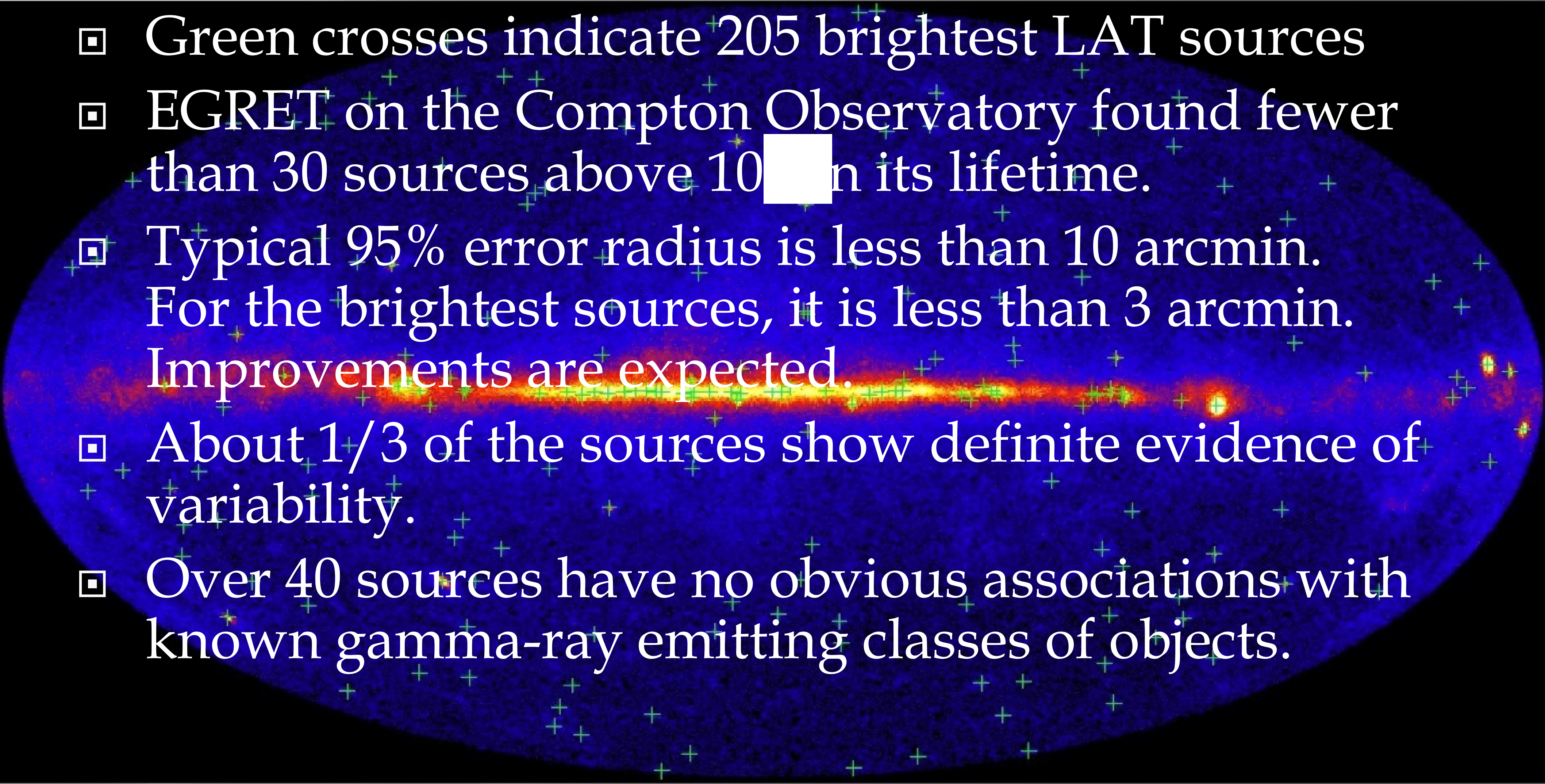
TIBET

Ground Based γ-ray Astronomy

H.E.S.S. II (1st light 2012)

MAGIC II (1st light 2009)

… and space (FERMI)



- Green crosses indicate 205 brightest LAT sources
- EGRET on the Compton Observatory found fewer than 30 sources above 10 n its lifetime.
- Typical 95% error radius is less than 10 arcmin. For the brightest sources, it is less than 3 arcmin. Improvements are expected.
- About 1/3 of the sources show definite evidence of variability.
- Over 40 sources have no obvious associations with known gamma-ray emitting classes of objects.

Current Status

The current generation of telescopes (H.E.S.S. / MAGIC / VERITAS) have detected >100 sources.

Several more with HESS2 / MAGIC2 / VERITAS

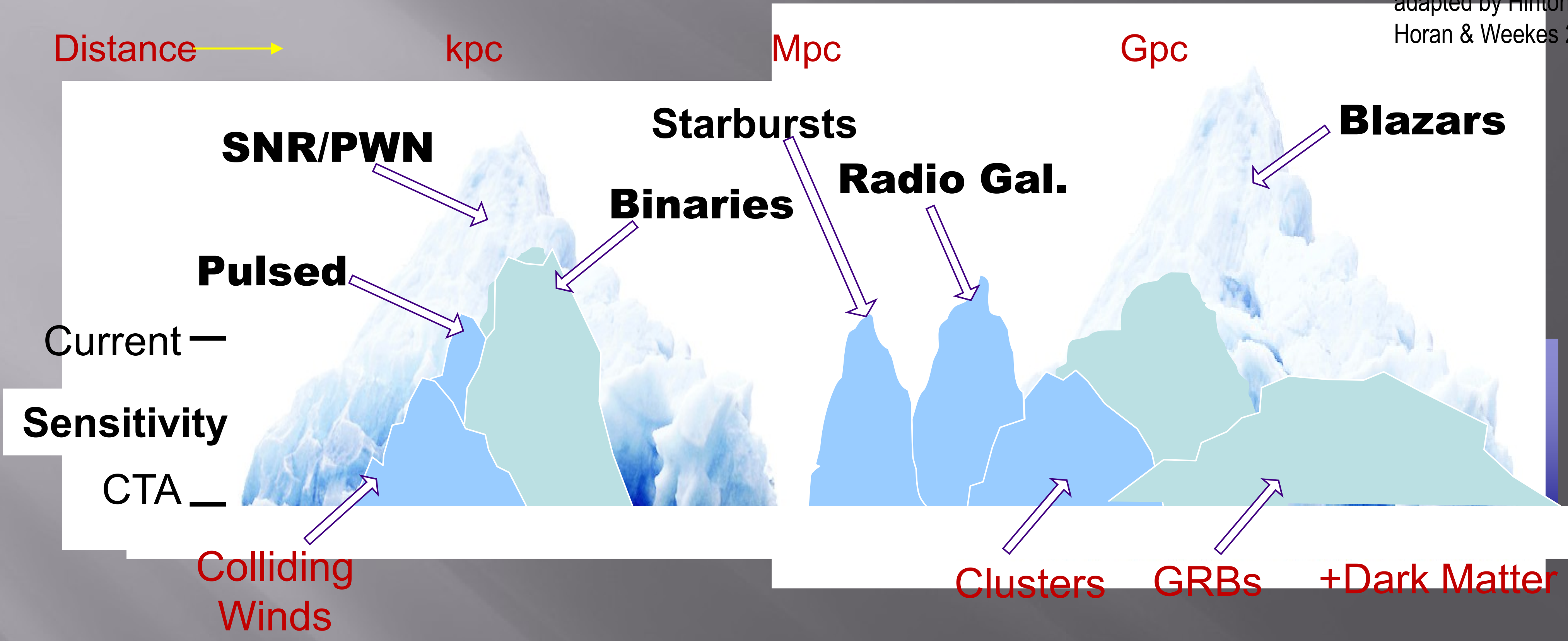
- ✸Stellar Winds
- ✸Supernova Remnants
- ✸Pulsar Wind Nebulae
- ✸Binary Systems
- ✸Molecular Clouds
- ✸Galactic Centre
- ✸No Counterpart/Dark

Sources

- ✸ AGN
- ✸Constraints on EBL
- ✸Constraints on QG
- ✸CR Electron Spectrum

Regular 70 GeV-20 TeV observations made with few % Crab sensitivity.

Science Potential



adapted by Hinton from Horan & Weekes 2003

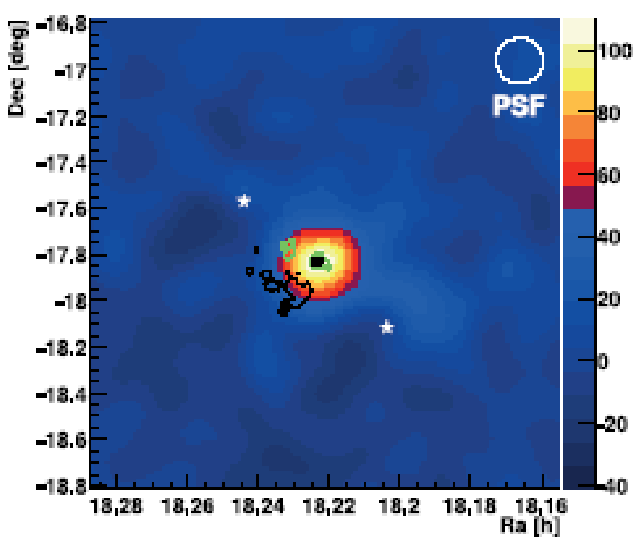
- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg
- What big science questions remain ?

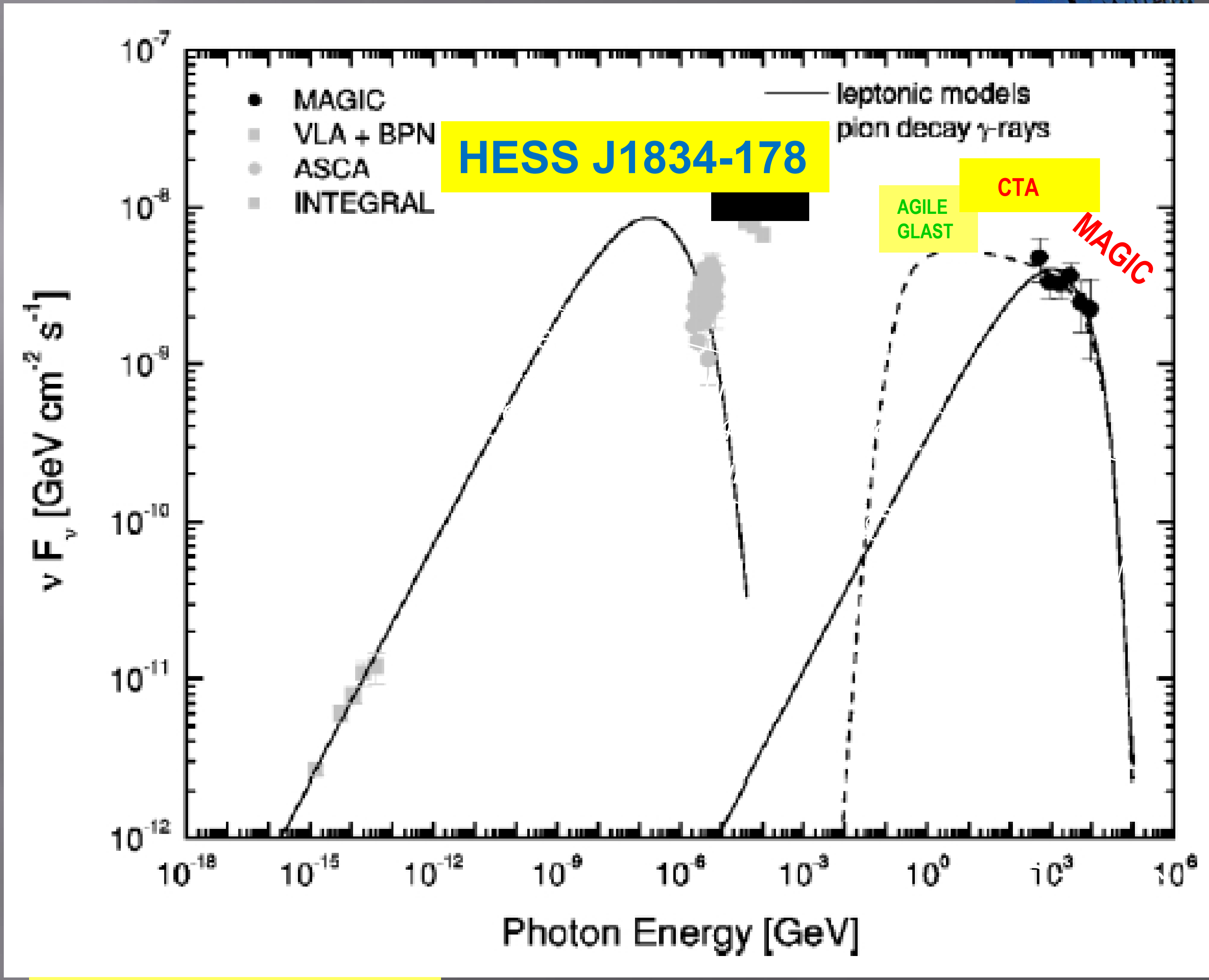
Big Science Questions

- Determine:
  - Origin of galactic cosmic-rays
  - Whether γ-ray binaries emit via wind/jet
- Study:
  - Star formation regions
  - Pulsars and PWN
  - Studying Physics of AGN Jets
- Constrain:
  - Extragalactic Background Light
  - Quantum Gravity Energy Scale
- Discover:
  - WIMP annihilation
  - NT view of cosmological structure formation
  - Dark sources / New source classes

Spectral modeling of SNRs ….

Spectral degeneracy at TeV energies





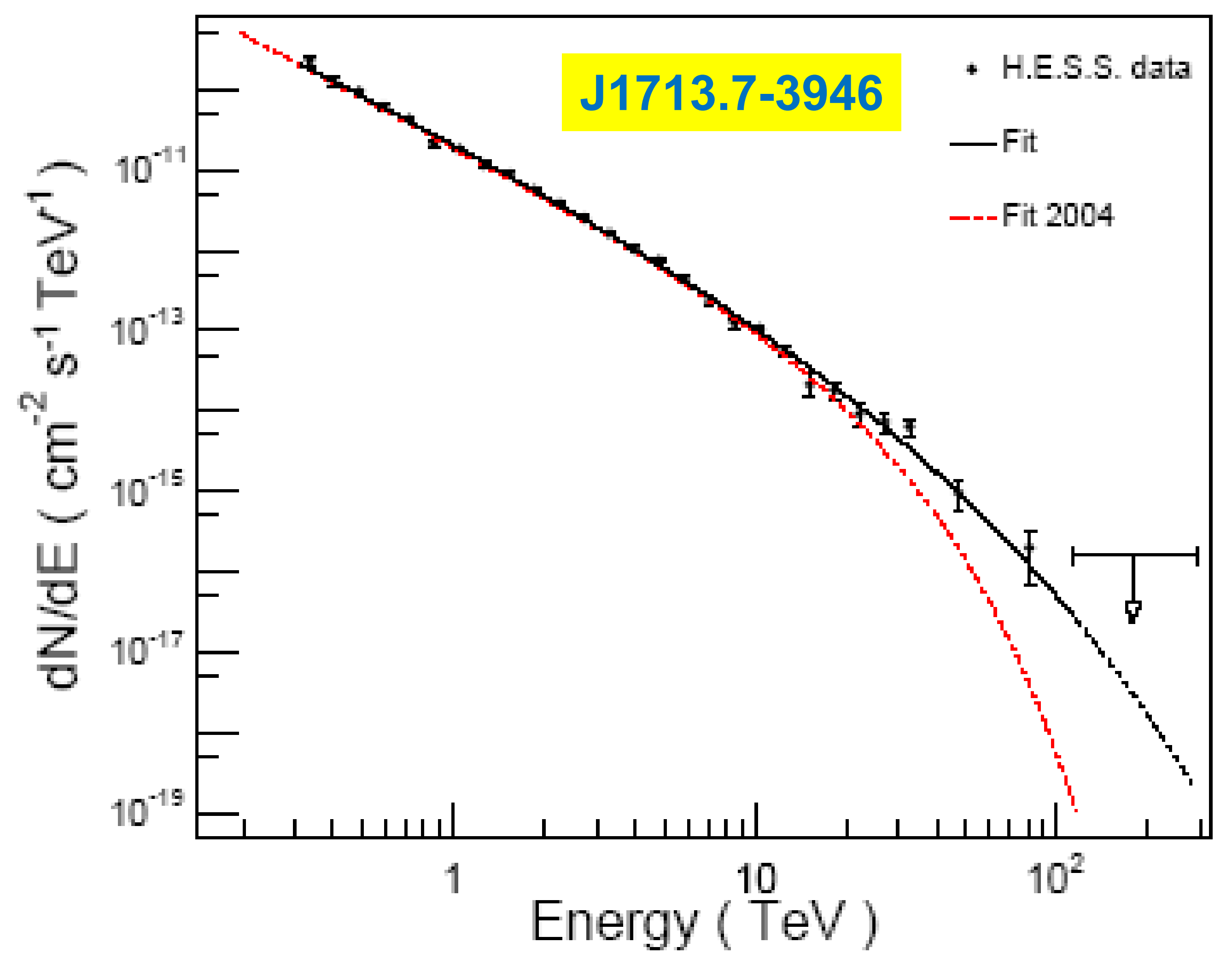
[redacted]

low E_{thr} (~10-30 GeV) to discriminate

VHE γ-rays: hadronic or leptonic ?

CTA → improved low-*E* coverage, solve spectral degeneracy

… and the origin of Galactic CRs



Leptonic:

$E_e \sim 20\ (E_\gamma)^{1/2}$ TeV
~ 110 TeV … but KN sets on ..
→ ~100 TeV

Hadronic:

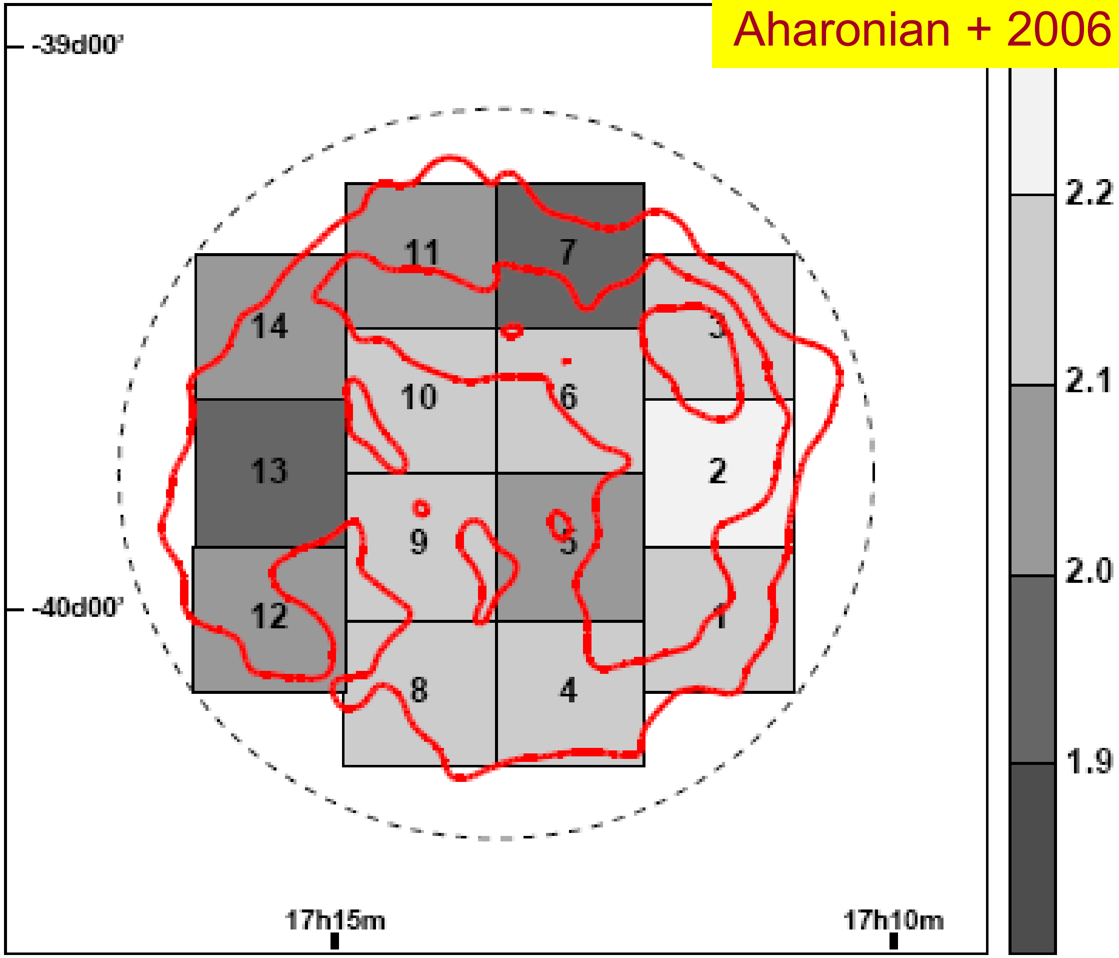
$E_p \sim E_\gamma / 0.15 \sim 30 / 0.15$ TeV ~
~ 200 TeV = $10^{5.3}$ GeV

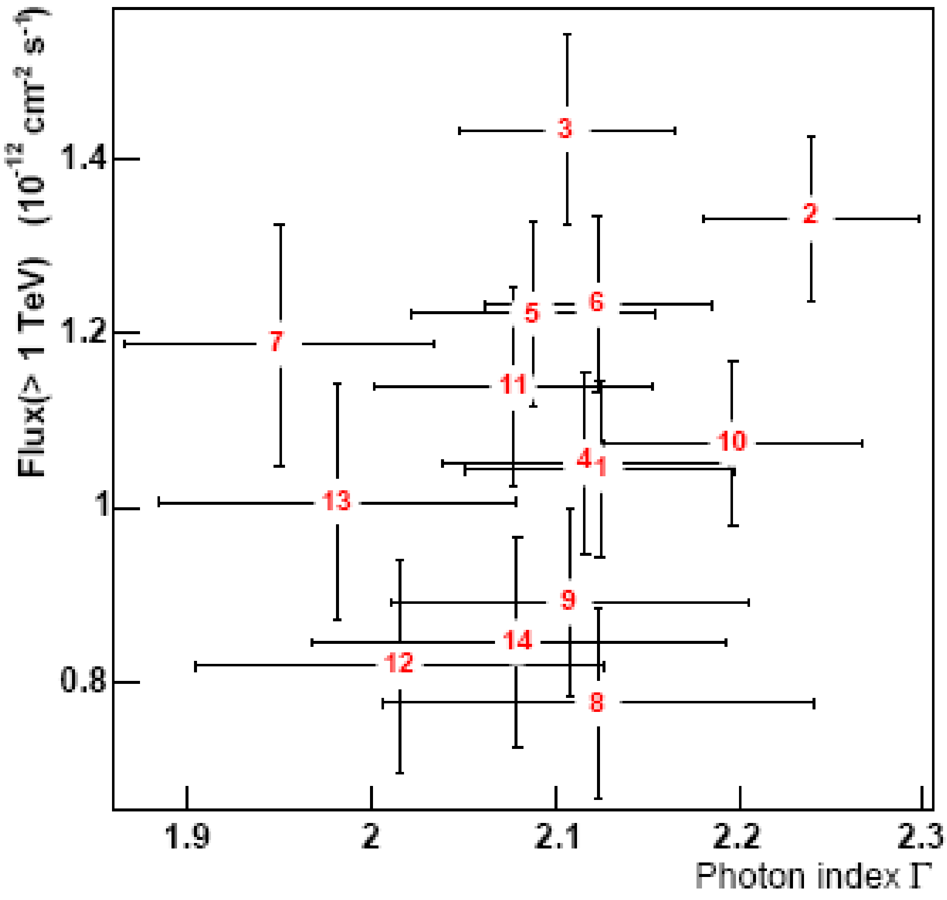
Importance of improving statistics: **3 years** of HESS data
1 year

CTA: improved statistics at E_γ > 100 TeV, to probe CR knee

Measurement of diffusion coefficient (cf. diffusion-loss equation)

Aharonian + 2006





- index $\Gamma \sim 2\text{–}2.2$ (strong NR shock)
- little variation across SNR

diffusion coefficient:
$\kappa(p) \propto A\, p^b$

CTA → spatially resolved spectroscopy

- young SNRs ($t < t_{cool}$ (p,e)):

CRp spectrum $\gamma = 1 + 2\alpha + b$

from VHE

from radio

$\kappa = p^b$ ... $b \sim 0.6$?
from secondary/primary ratio

→ measure $\kappa(p)$ as a function of p

… more in general:

COSMIC RAYS AND STAR FORMATION

CR – SN relation

- Fermi-I mechanism → SNRs
- SN rates, massive star formation

γ-ray (direct)

Test: $U_p \sim \frac{1}{4}\,(\nu \quad \tau \quad)\;(\eta\, E \quad)\; r^{-3}$

70 GeV-20 TeV

radio (indirect)
→ field-particles equipartition

observed

Milky Way normalization

observed

Arp 220	→	U_p	≈ 475	$\mathrm{eV\ cm^{-3}}$
NGC 253	→		125	
M 82	→		110	
Milky Way	→		1	
M31	→		0.3	
LMC	→		0.2	
SMC	→		0.1	

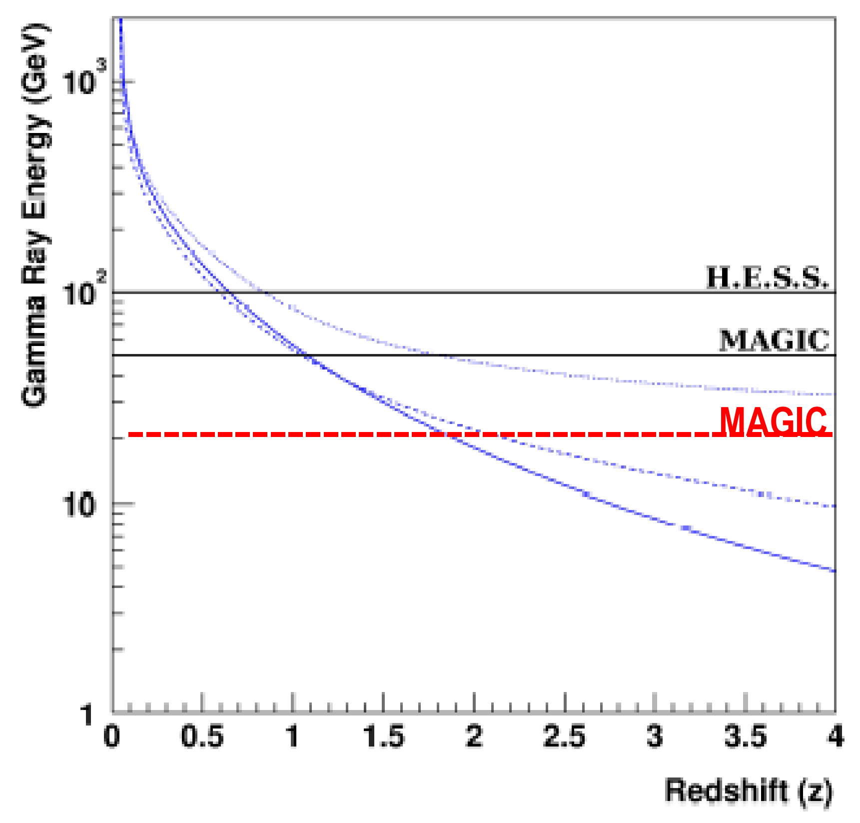
Early gals.:
→ high U_p
→ Gas heating
→ M_{jeans} affected?

CTA: more SF gals to be discovered ..

Gamma-Ray Bursts (GRBs)

CTA

- Most energetic explosions since Big Bang (10^{54} erg if isotropic)
- Astrophysical setting unknown (hypernova?)
- Emission mechanism unknown (hadronic vs leptonic, beaming, size of emitting region, role of environment, … …)
- Cosmological distances ($z >> 1$)
  → Missed *naked-eye* GRB 080319B (z=0.937)



CTA → low E_{thr} ~ 20 GeV
to see GRBs !!

GRBs

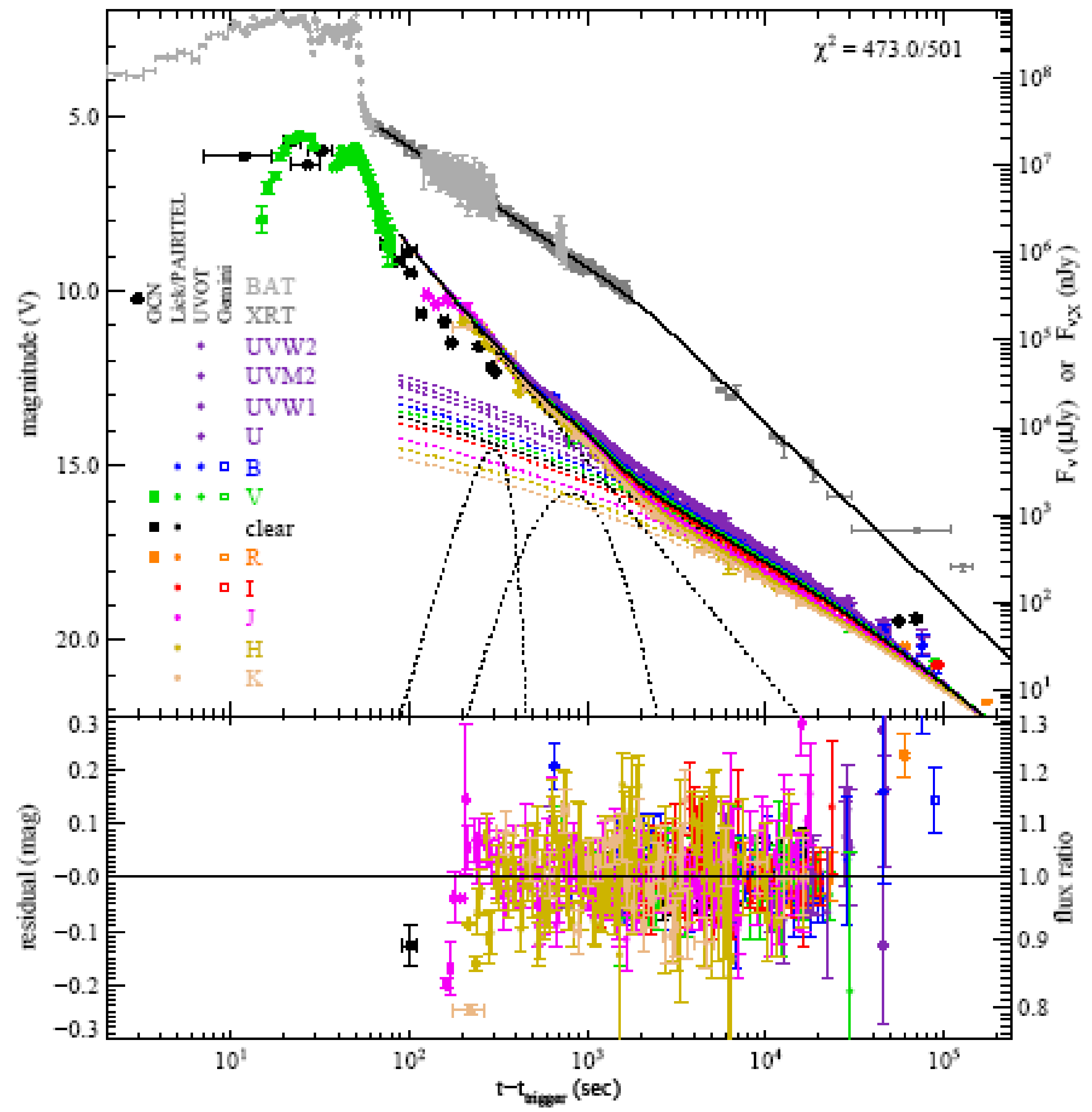
080319B → missed obs of "naked-eye" GRB

Intrinsically:
Nearby: z=0.937
Brightest ever observed in optical
Exceedingly high isotropic-equivalent in soft γ-rays

Swift/BAT could have observed it out to z=4.9
1m-class telescope could observe out to z=17

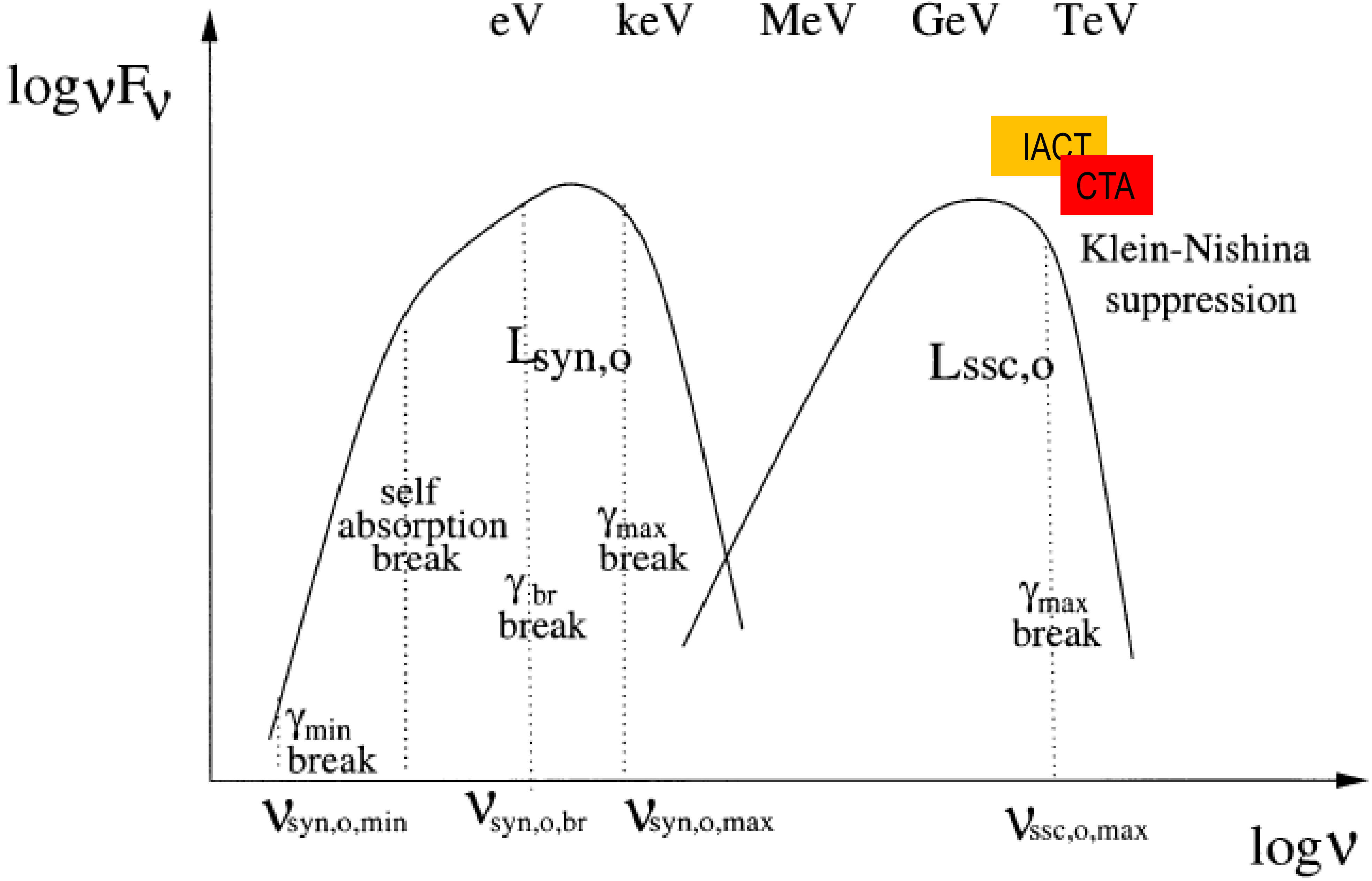
Missed by both AGILE (Earth screening) and MAGIC (almost dawn)

next BIG ONE awaited !!

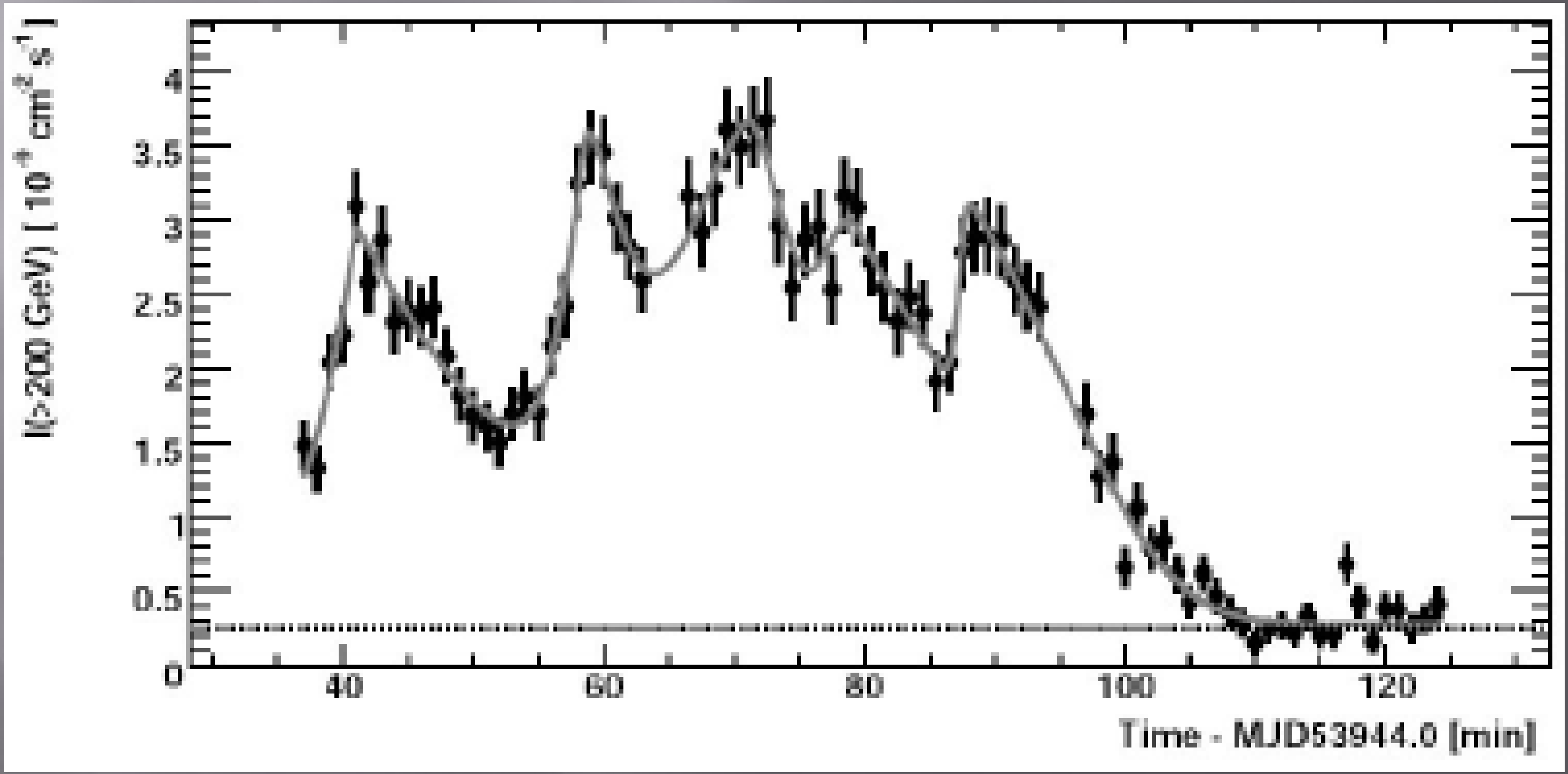


AGN

Quiescent states of low/intermediate-z blazars
High states of high-z blazar



Even more importantly, jet physics is challenged by extremly fast flares.
Timescales as short as 60 sec have been revealed.
Diameters implied are 100 times smaller than the Schwarzschild radius.
Radiating region cover a tiny fraction of jet cross-section.



Quantum gravity effects (involving GRBs)

Amelino-Camelia+ 1998

Stecker 2003

Search for dispersion of light from GRBs $\delta v \sim E/E_{QG}$

QG effect induced by deformed dispersion relation $c^2 p^2 = E^2[1 + f(E/E_{QG})]$

f(E_{QG}): model-dependent function of effective QG scale E_{QP}~E_P≈ 10^{19} GeV

If Hamiltonian eq. of motion: $\dot{x}_i = \partial H/\partial p_i$

→ energy-dependent velocities for massless particles $c + \delta v$

→ implications for EM signals from distant astrophysical sources

At $E \ll E_{QG}$: $c^2 p^2 = E^2 \left[1 + \xi E/E_{QG} + \mathcal{O}(E^2/E_{QG}^2)\right]$, with $\xi = \pm 1$ dependent on dynamical framework

Energy-dependent velocity $v = \dfrac{\partial E}{\partial p} \sim c\left(1 - \xi \dfrac{E}{E_{QG}}\right)$

→Vacuum responds differently to propagation of patricles of different *E* → cf. ordinary plasma

→'QG medium' to fluctuate on scale λ~ L_P≈10^{-33} cm on timescale t_P≈*h*/E_P → cf. thermal fluct's in plasma, *t*≈1/*T*

Time delay (w.r.t. ordinary case of *v*=*c*): $\Delta t \sim \xi \dfrac{E}{E_{QG}} \dfrac{L}{c}$ max. when E, L large and time structure δ*t* small

→ sensitivity factor $\eta \equiv |\Delta t^*|/\delta t$ (being $\Delta t^* \sim \pm E\,L/(c\,E_P)$ and δ*t* the time structure of the signal)

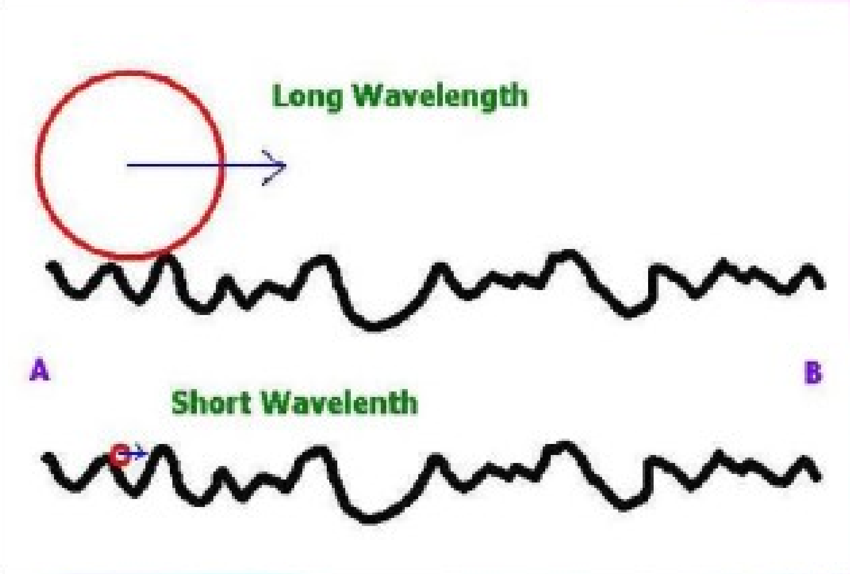
GRBs: δ*t* ~ 0.001 s, *L* ~ 5000 Mpc, *E* ~ 20 MeV → η~1

100 s 2 TeV

pulsars: δ*t* ~ µs, *L* ~ 3 kpc, *E* ~ eV → η~10^{-11}

SN Ia: δ*t* ~ ms, *L* ~ 5000 Mpc, *E* ~ eV → η~10^{-7}

Probing Quantum Gravity



$$E_{Pl} = \sqrt{\frac{\hbar c^5}{G}} \approx 1.22 \times 10^{19}\, GeV$$

If Gravity is a Quantum theory,
at a very short distance it may show a very complex "foamy" structure due to quantum fluctuation.

Use gamma ray beam from AGNs/GRBs
to study the space-time structure

Energy 1000GeV ~ $10^{-16} E_{Pl}$
Distance 100~1000Mpc ($10^{16\text{-}17}$sec)

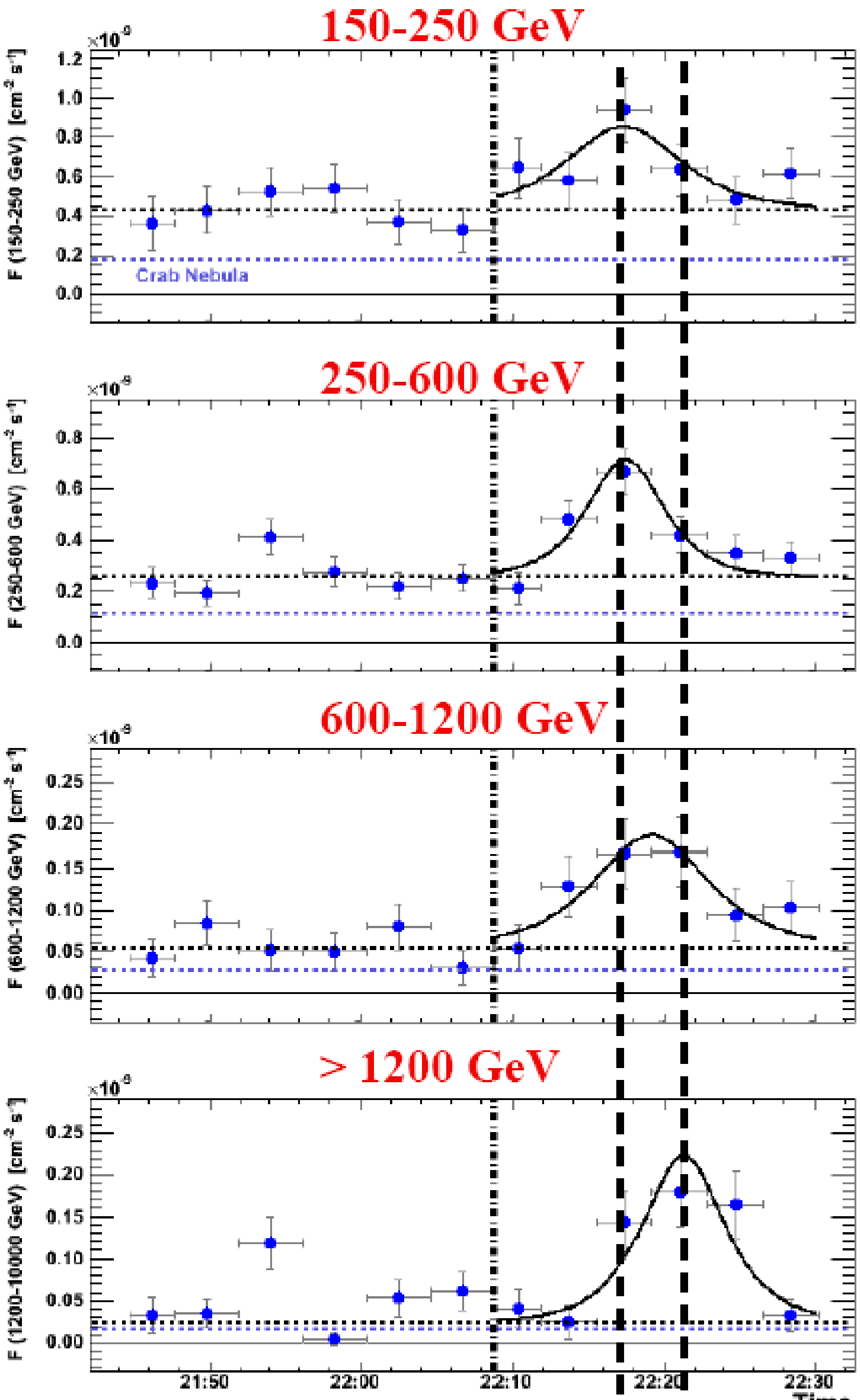
Visible time delay ~ 1 - 10 sec

Linear deviation:

$$\xi_1 < 0; \quad v = c\left(1 - \frac{E}{M_{QG1}}\right); \quad n(E) = 1 + \frac{E}{M_{QG1}}$$

Quadratic deviation:

$$\xi_1 = 0; \quad \xi_2 < 0; \quad v = c\left(1 - \frac{E^2}{M_{QG2}^2}\right); \quad n(E) = 1 + \frac{E^2}{M_{QG2}^2}$$


150-250 GeV

250-600 GeV

600-1200 GeV

> 1200 GeV

$E_{QG} \sim 0.05\ M_P$

IF

Photons at different energies were emitted simultaneously

and ∃ no conventional explanations →

$\Delta T = 4 \pm 1$ min; $\Delta E \sim 1$ TeV

$$\boxed{E_{QG} = \frac{L}{c} \cdot \frac{\Delta E}{\Delta t} = (0.6 \pm 0.2) \cdot 10^{17}\,\text{GeV}}$$

… in general:

$$V = c\,[1 +- \xi\,(E/E_{QG}) +- \xi_2\,(E/E_{QG})^2 +- \dots]$$

1st order $\Delta t \sim \xi \frac{E}{E_{QG}} \frac{z}{H_0} = \xi \frac{E}{E_{QG}} \frac{L}{c}$

MAGIC Mkn 501

$E_{QG} \sim 0.03\ M_P$

$E_{QG} > 0.02\ M_P$

HESS PKS 2155

$E_{QG} > 0.04\ M_P$

Whipple 1999, PRL 83(1999)2108

$E_{QG} > 0.005\ M_P$

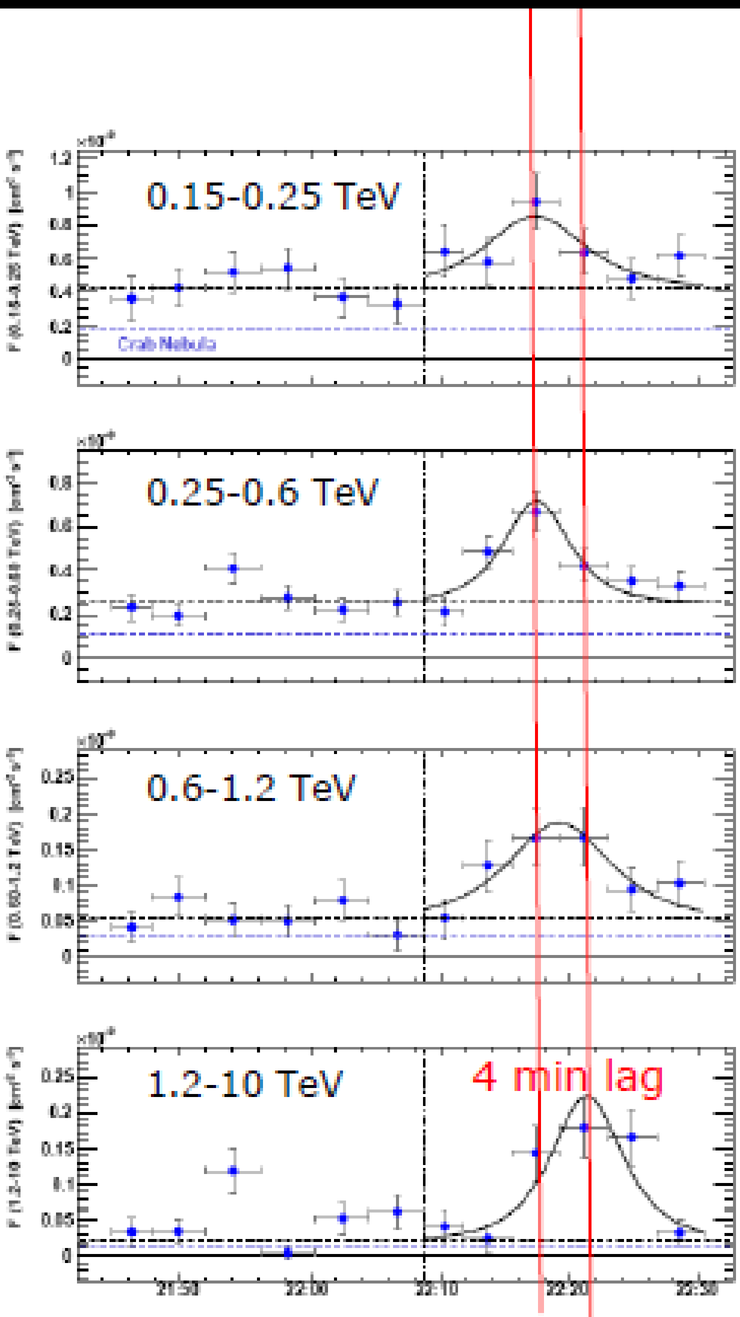
GRB X-ray limits:

$E_{QG} > 0.001 \dots 0.01\ M_P$

… but in most scenarios

$\Delta t \sim (E/E_{QG})^\alpha$, $\alpha > 1$

- ▶ VHE gamma rays even better
- ▶ Mrk 501: $E_{QG} > 3 \cdot 10^{-9}\ M_P$, $\alpha = 2$

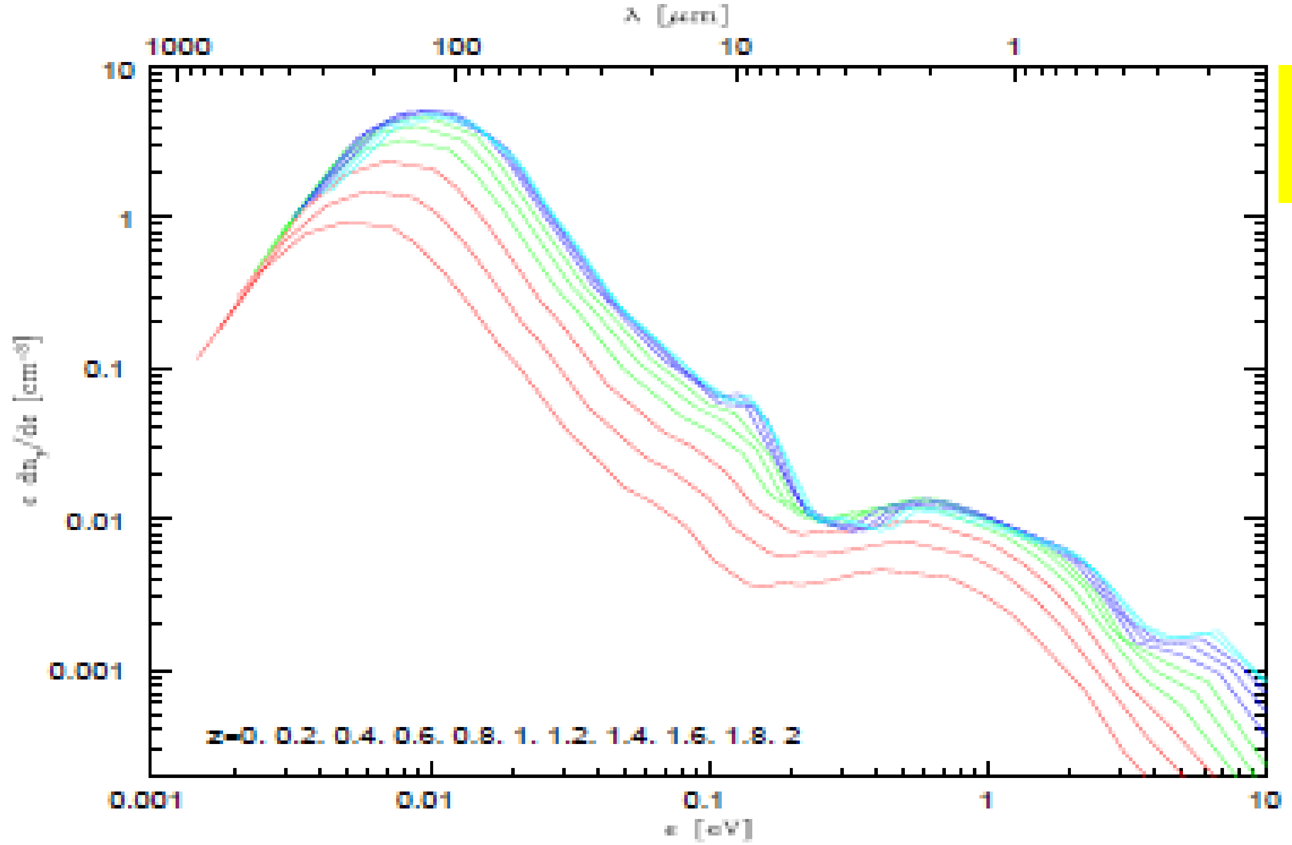


Mrk 501: Jul 9, 2005

Evolution of cosmic star formation rate

Distant sources suffer from extinction by pair creation along the los. Lowering the threshold allows to penetrate deeper into the universe.

This problem can be turned into an advantage, i.e. to probe the diffuse extragalactic radiation fields in situ. This provides a redshift-resolved determination of the radiative output at any cosmic epoch.



Franceschini et al. 2008

Galaxy Clusters

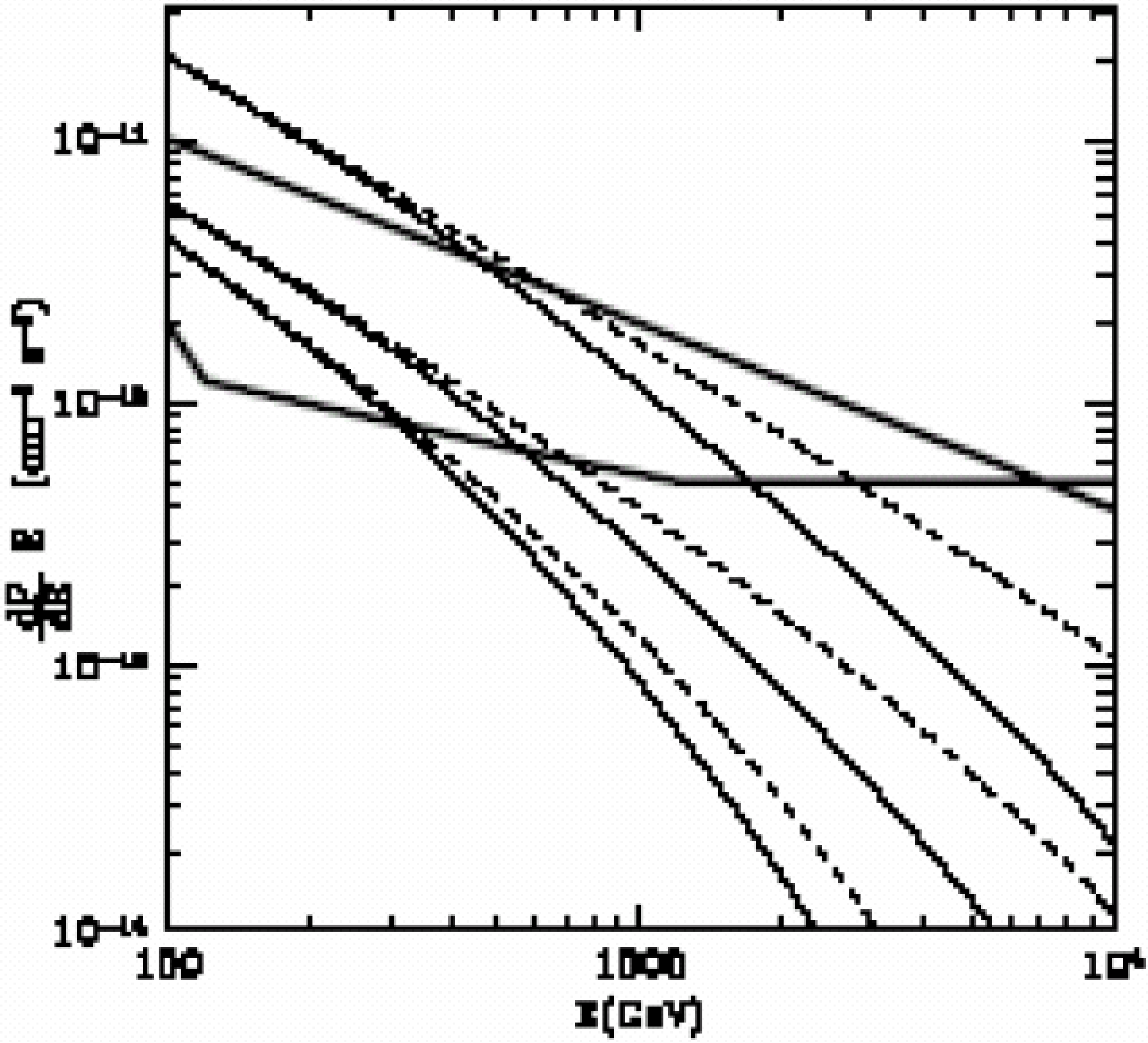
Clusters: channels of TeV emission

TeV sources in clusters:

→ pointlike: AGN
galaxies
→ diffuse: cluster formation (merging, accretion)
DM (diffuse, clumps)

Merger-generated shocks → $n(E_p) \propto E_p^{-\alpha}$
minor mergers (continuous accretion) lead to efficient particle acceleration (Gabici & Blasi 2003)

- pp interaction of CRp with ICp → $\underset{e^+e^-}{\pi^\pm};\ \underset{\gamma}{\pi^0}$ → diffuse emission from secondaries
- secondary electrons: synchrotron & Compton losses, Coulomb losses → continuity eq. → equilibrium particle spectrum (e.g., Rephaeli 1979)
- self-consistent modeling of cluster's complete NT SED (e.g.: Blasi & Colafrancesco 1999):
    - synchrotron from secondary electrons: radio (normalization!)
    - comptonized CMB photons from secondary electrons: UV, X-ray
    - bremsstr. from primary & secondary electrons: γ–ray
    - π^0 decay: γ–ray
- Cluster gas distribution: $n_H(r) \propto \left[1 + (r/r_0)^2\right]^{-3\beta/2}$, with $\beta \approx 0.7 - 1.1$



Simulation (Gabici & Blasi 2004):

- shock accel. efficiency η=0.05
- free-fall vel. of gas a virial radius: $v_{ff} = \sqrt{2GM}$
- cosmological baryon density: $\rho_b = \Omega_b \rho_{cr}$ with $\Omega_b = 0.02 h^2$.
- power converted at the shock into NT electrons

$$L^{acc} = \tfrac{1}{2} \eta \rho_b (1+z)^3 v_{ff} 4\pi r_v^2$$

Merger-related shock @ virial radius r_v~3Mpc.

Angular size $\theta \approx 1^{\circ} (\frac{D}{100 Mpc})$ comparable to (exceeding) IACT aperture.

→ Merger-related TeV emission from cluster unlikely to be observed by current IACTs.

Detectability maximized if:

point source $\theta \approx 1^{\circ} (\frac{D}{100 Mpc})$ → large distance
high flux ($\propto D^{-2}$) → low distance
high flux ($\propto \exp(-\tau_{\gamma\gamma}^{\mathrm{EBL}})$) → low distance
NT particles → radio halo, PL hard-X-ray spectral component
B_m likely lower than volume-averages indicated by Faraday measts
→ feasibilty of detectable VHE-γ emission enhanced

Dark matter

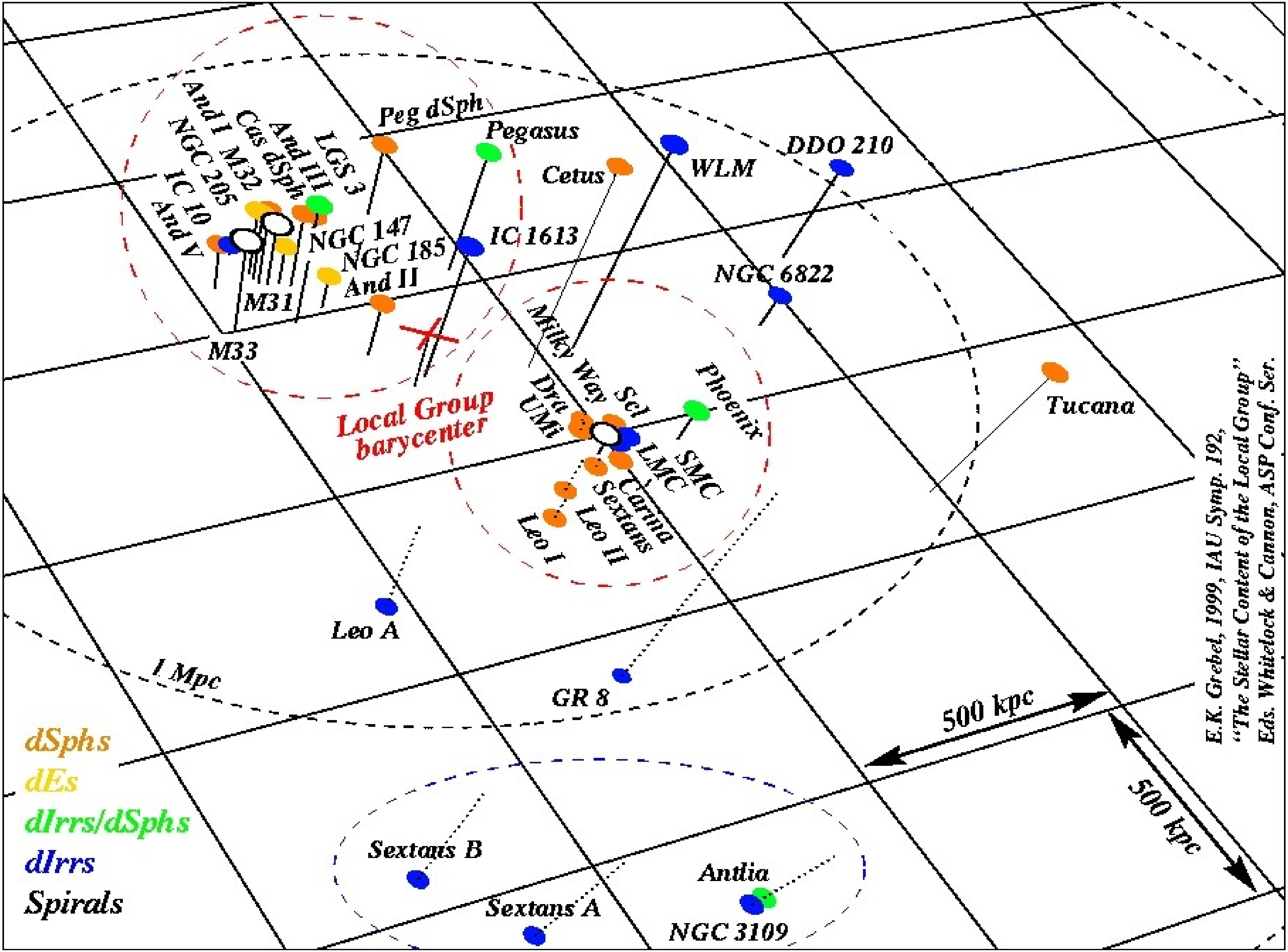
Bottom-up cosmology: small galaxies formed first, hence their density retains the cosmological density at the epoch of their turnaround ($\delta\rho/\rho \sim 1.8$).

Baryon infall: SF → SN expl. → winds → most of infalling baryons **lost** in small gals., but **retained** in bigger ones.

Smaller, denser gals. have little/no SF – bigger, less dense gals. do have strong SF.

→ dSph MW satellite best candidates

→ UFOs exciting candidates



E.K. Grebel, 1999, IAU Symp. 192,
"The Stellar Content of the Local Group"
Eds. Whitelock & Cannon, ASP Conf. Ser.

Draco dSph: modeling

d~80 kpc

Bergström & Hooper 2006

total DM annihil. rate

$$\Phi_A = \int_{r_{min}}^{r_a} dr\, 4\pi r^2 \frac{\langle\sigma_A v\rangle}{2} \left(\frac{\rho(r)}{m_\chi}\right)^2$$

$\langle\sigma_A v\rangle$, m_χ: **WIMP annihil. cross section, mass**

γ-ray flux

$$F_\gamma = \frac{\Phi_A N_\gamma}{4\pi D^2}$$

N_γ: **γ-rays / annihil.**

$$y = r/r_s$$

maximizes signal

cusped profile

$$\rho(r) = \frac{\rho_0}{y\,(1+y)^2}$$

$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{3m_\chi^2 D^2}\frac{\langle\sigma_A v\rangle}{2}\left[\frac{1}{(1+y_{min})^3} - \frac{1}{(1+y_a)^3}\right]$$

cored profile

$$\rho(r) = \frac{\rho_0}{(1+y)\,(1+y^2)}$$

$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{4m_\chi^2 D^2}\frac{\langle\sigma_A v\rangle}{2}\left[\frac{2+y_{min}+y_{min}^2}{1+y_{min}+y_{min}^2+y_{min}^3} + \arctan(y_{min}) - \frac{2+y_a+y_a^2}{1+y_a+y_a^2+y_a^3} - \arctan(y_a)\right]$$

γ-ray flux

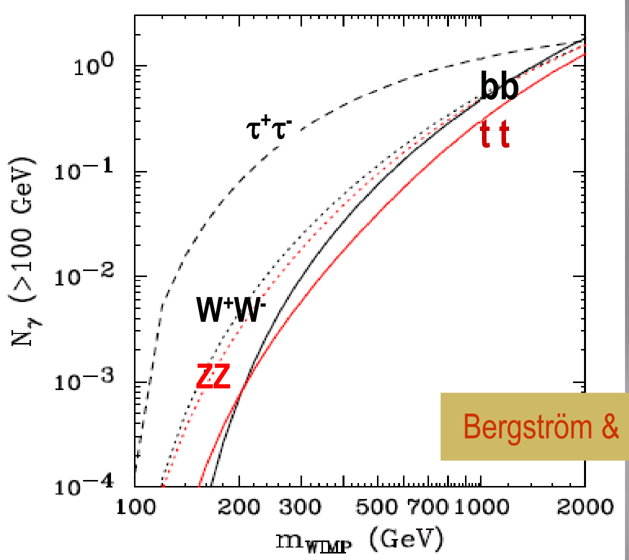
$$F_\gamma = \frac{\boxed{\rho_0^2 r_s^3} N_\gamma}{3\boxed{m_\chi^2} D^2}\frac{\boxed{\langle\sigma_A v\rangle}}{2} \times A$$

Profile Type	$A(r_a = r_s)$	$A(r_a \gg r_s)$
NFW	0.875	1.0
Core	0.160	0.323
Cusp, $\gamma = 1.1$	1.29	1.52
Cusp, $\gamma = 1.2$	2.16	2.63
Cusp, $\gamma = 1.3$	4.03	4.12
Cusp, $\gamma = 1.4$	11.1	12.5
Cusp, $\gamma = 1.45$	25.7	27.4

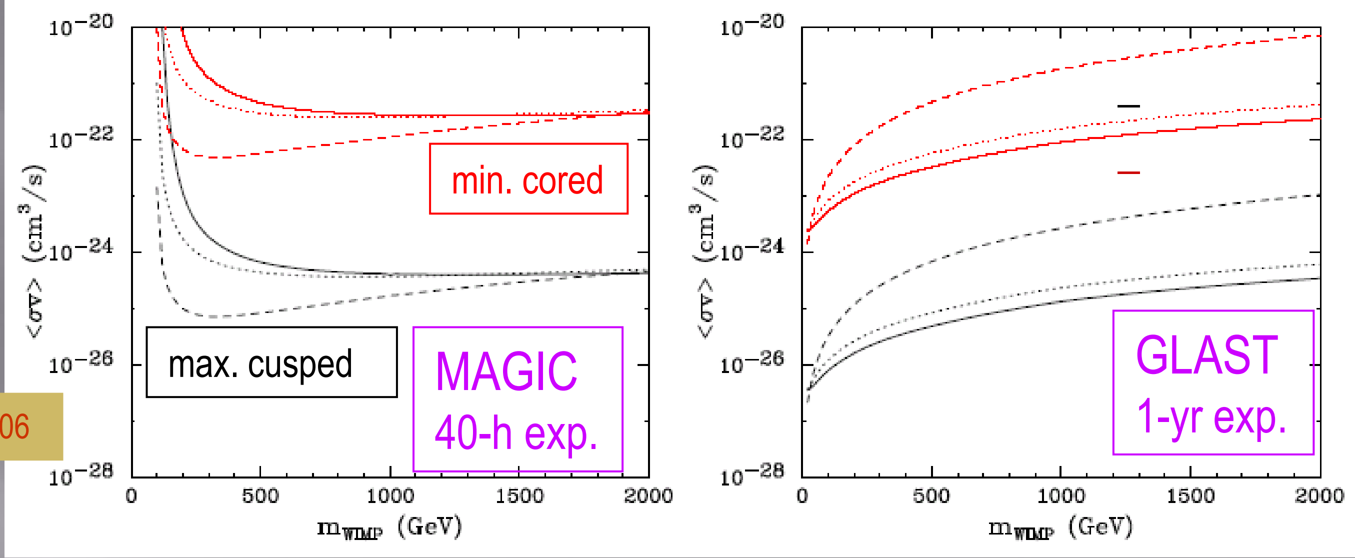
$r_s = 7 - 0.2$ kpc

[illegible] $= 10^7 - 10^9\ M_\odot\ \mathrm{kpc}^{-3}$

[illegible] $r_s^3 = 0.03 - 6\ M_\odot^2\ \mathrm{kpc}^{-3}$



Bergström & Hooper 2006

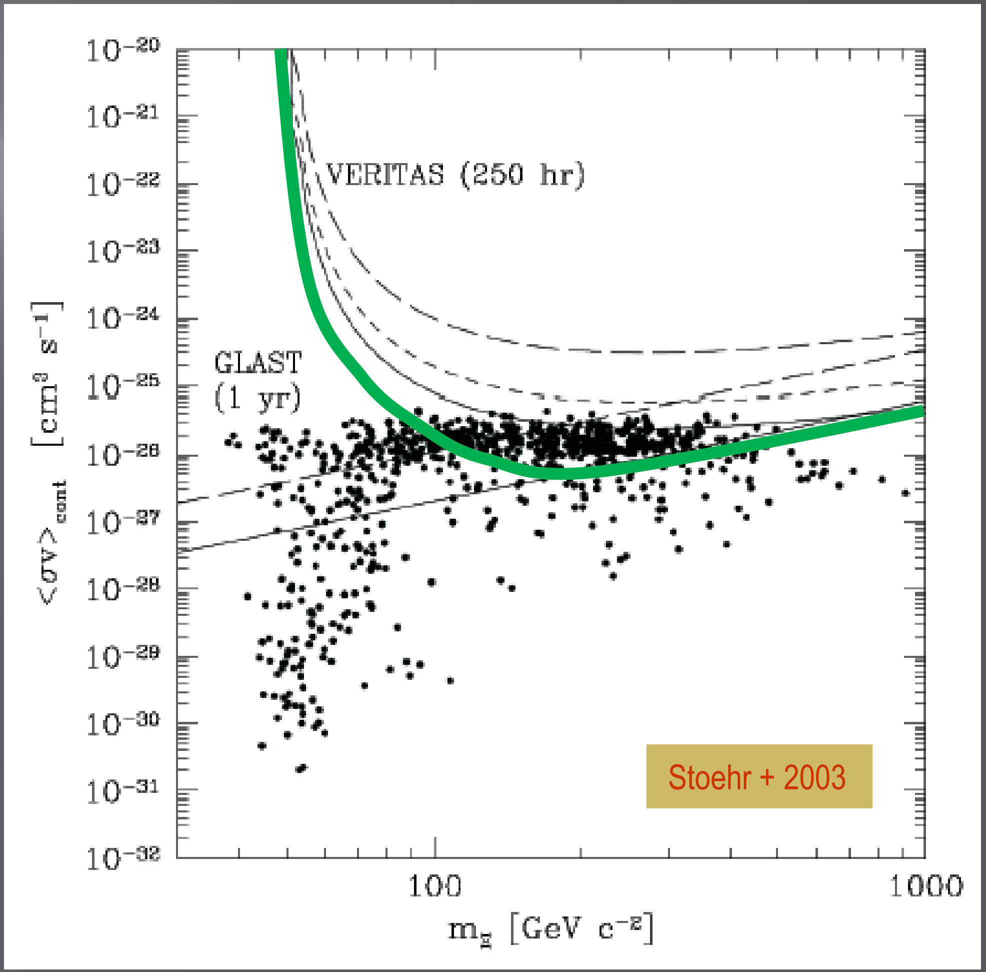


$$F^{\max}_{\gamma,\mathrm{NFW}} \approx 2.4\times 10^{-10}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \mathrm{cm^3s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\ \mathrm{cm^{-2}s^{-1}}$$

$$F^{\min}_{\gamma,\mathrm{NFW}} \approx 9.8\times 10^{-13}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \mathrm{cm^3s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\ \mathrm{cm^{-2}s^{-1}}$$

$$F^{\max}_{\gamma,\mathrm{core}} \approx 4.2\times 10^{-11}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \mathrm{cm^3s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\ \mathrm{cm^{-2}s^{-1}}$$

$$F^{\min}_{\gamma,\mathrm{core}} \approx 3.5\times 10^{-13}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot 10^{-26}\ \mathrm{cm^3s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\ \mathrm{cm^{-2}s^{-1}}$$



Stoehr + 2003

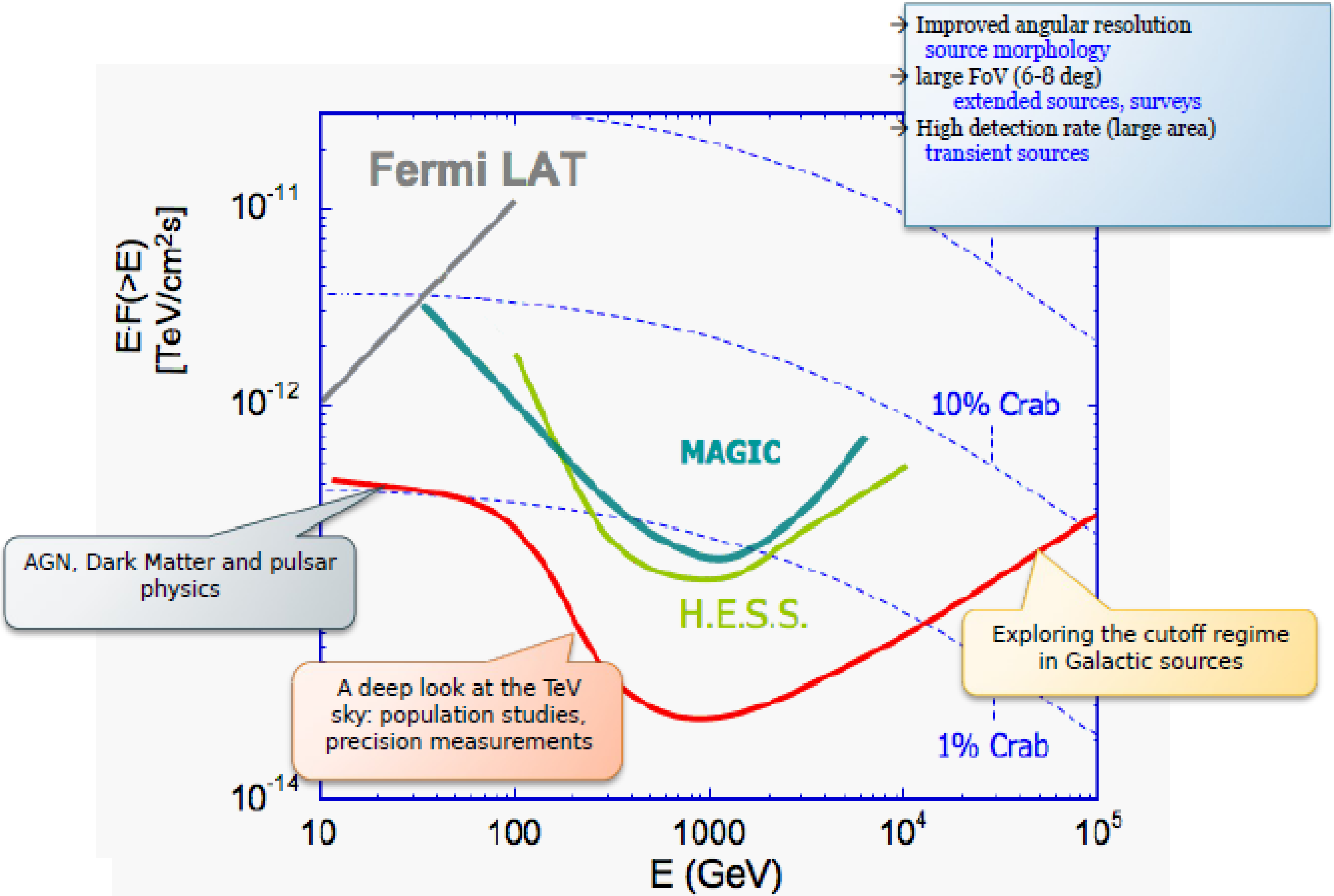
IACT neutralino detection:

$\langle\sigma_A v\rangle \geq 10^{-25}$ cm^{3}s^{-1}

CTA tech wish list

- Higher Sensitivity at TeV energies (x10)
  Deeper observations → More sources & more extended spectra
- Higher Detection Area
  Higher detection rates → Transient phenomena
- Better Angular Resolution
  Improved morphology studies → Structure of extended sources
- Lower Threshold (some 10 GeV)
  Pulsars, distant AGN, source mechanisms
- Higher Energy Reach (PeV and beyond)
  Cutoff region of galactic accelerators
- Wide Field of View
  Extended Sources, Surveys

CTA sensitivity



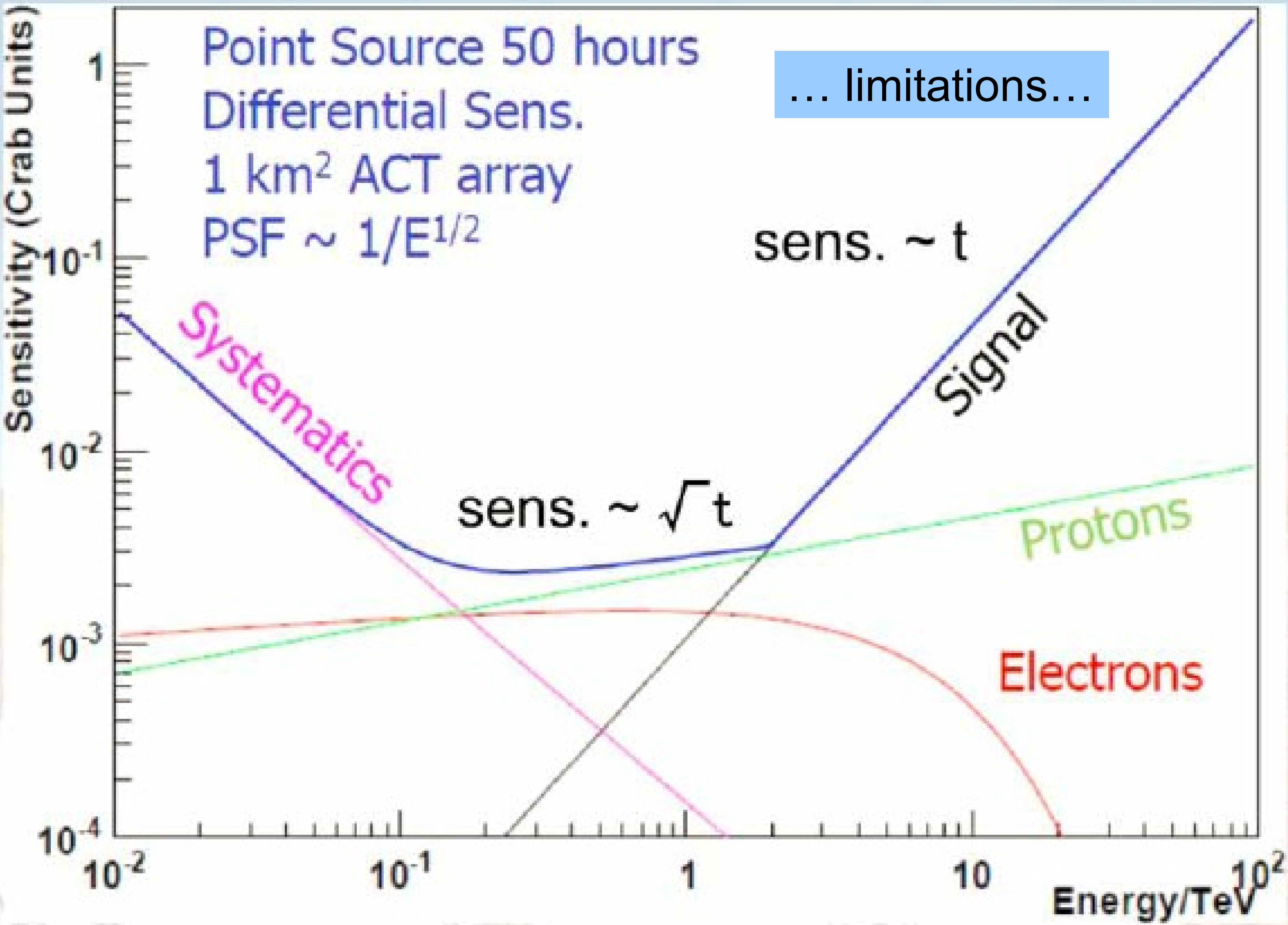
- → Improved angular resolution
  source morphology
- → large FoV (6-8 deg)
  extended sources, surveys
- → High detection rate (large area)
  transient sources

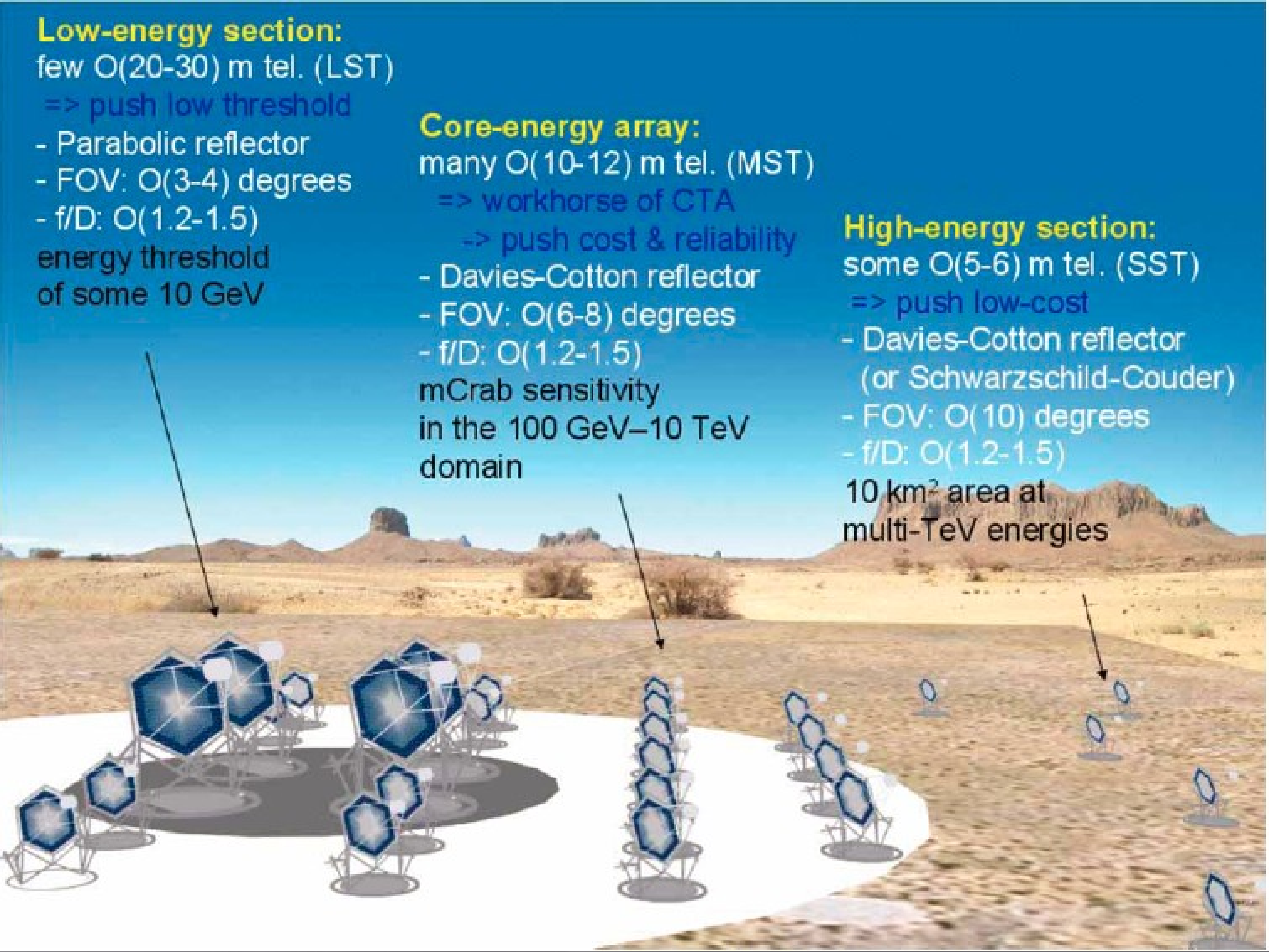
AGN, Dark Matter and pulsar physics

A deep look at the TeV sky: population studies, precision measurements

Exploring the cutoff regime in Galactic sources

… limitations…





Low-energy section:
few O(20-30) m tel. (LST)
=> push low threshold
- Parabolic reflector
- FOV: O(3-4) degrees
- f/D: O(1.2-1.5)

energy threshold
of some 10 GeV

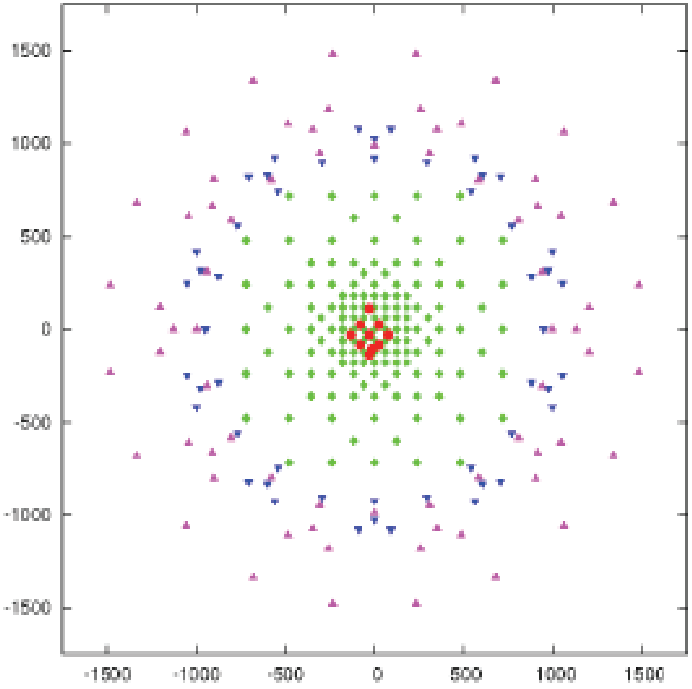
Core-energy array:
many O(10-12) m tel. (MST)
=> workhorse of CTA
-> push cost & reliability
- Davies-Cotton reflector
- FOV: O(6-8) degrees
- f/D: O(1.2-1.5)

mCrab sensitivity
in the 100 GeV–10 TeV
domain

High-energy section:
some O(5-6) m tel. (SST)
=> push low-cost
- Davies-Cotton reflector
  (or Schwarzschild-Couder)
- FOV: O(10) degrees
- f/D: O(1.2-1.5)

10 km^2 area at
multi-TeV energies

CTA considered arrays



From Padova 2008 CTA meeting, plot by Konrad.

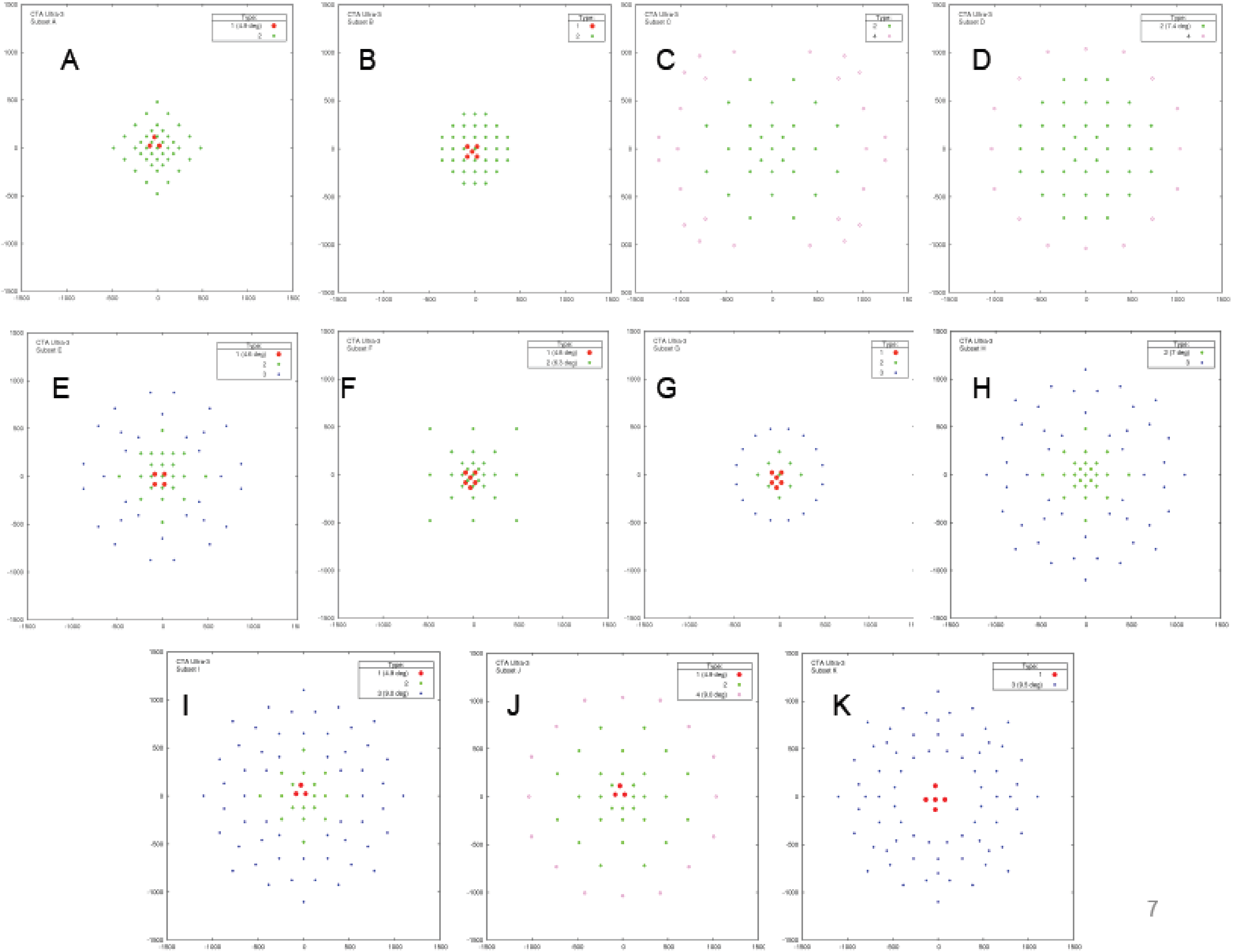
field of view

angular resolution

Types of telescopes:

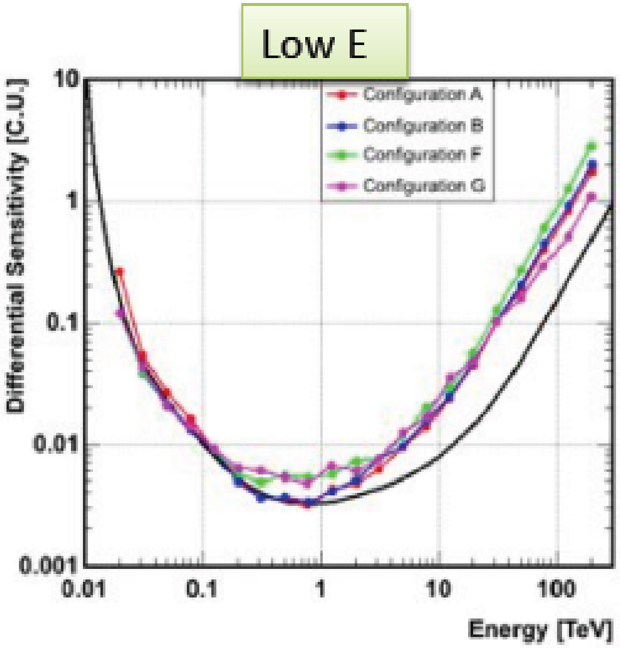
Area	Diameter	F.o.V.	Pixels	
412 m²	~ 23 m	5°	0.09°	(1)
100 m²	~ 11 m	8°	0.18°	(2)
37 m²	~ 7 m	10°	0.25°	(3)
100 m²	~ 11 m	10°	0.18°	(4)

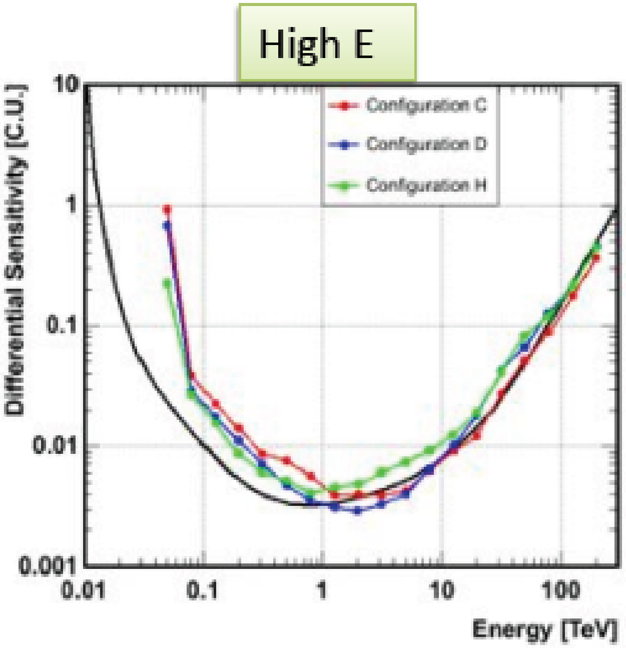
Configurations proposed with ~50 or more telescopes of 2-3 different types.

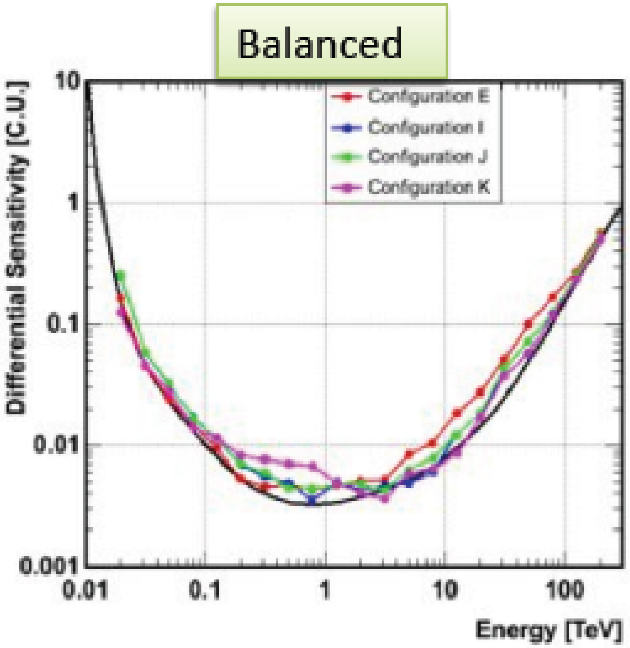

A
CTA Ultra-3
Subset A
Type:
1 (4.8 deg)
2
B
CTA Ultra-3
Subset B
Type:
1
2
C
CTA Ultra-3
Subset C
Type:
2
4
D
CTA Ultra-3
Subset D
Type:
2 (7.4 deg)
4
E
CTA Ultra-3
Subset E
Type:
1 (4.8 deg)
2
3
F
CTA Ultra-3
Subset F
Type:
1 (4.8 deg)
2 (8.3 deg)
G
CTA Ultra-3
Subset G
Type:
1
2
3
H
CTA Ultra-3
Subset H
Type:
2 (7 deg)
3
I
CTA Ultra-3
Subset I
Type:
1 (4.8 deg)
2
3 (9.6 deg)
J
CTA Ultra-3
Subset J
Type:
1 (4.8 deg)
2
4 (9.6 deg)
K
CTA Ultra-3
Subset K
Type:
1
3 (9.6 deg)
1500
1000
500
0
-500
-1000
-1500
-1500
-1000
-500
0
500
1000
1500

Grouping by similar sensitivities

Area	Diameter	F.o.V.	Pixels	
412 m^2	~ 23 m	5°	0.09°	(1)
100 m^2	~ 11 m	8°	0.18°	(2)
37 m^2	~ 7 m	10°	0.25°	(3)
100 m^2	~ 11 m	10°	0.18°	(4)


Low E

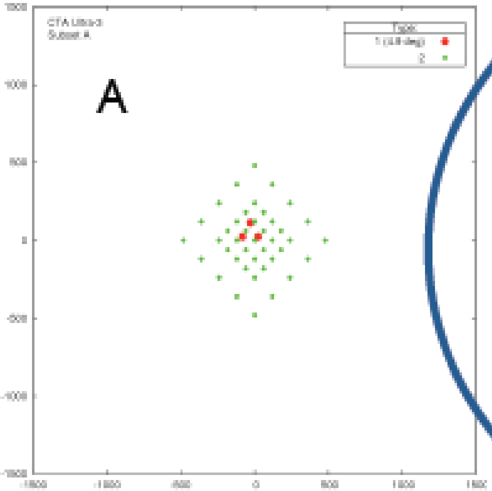

High E

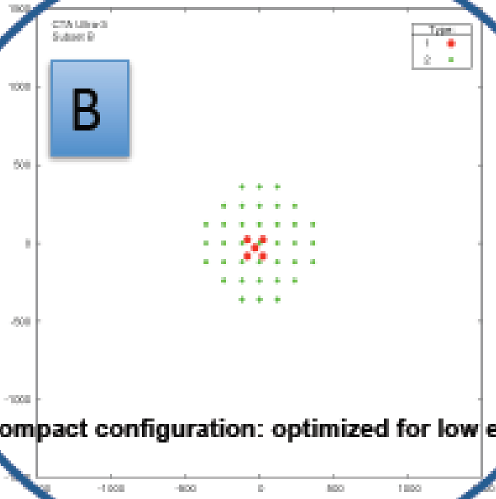

Balanced

Array	1	2	3	4
A	3 (4.9°)	41	-	-
B	5	37	-	-
F	6 (4.8°)	29 (6.3°)	-	-
G	6	9	16	-

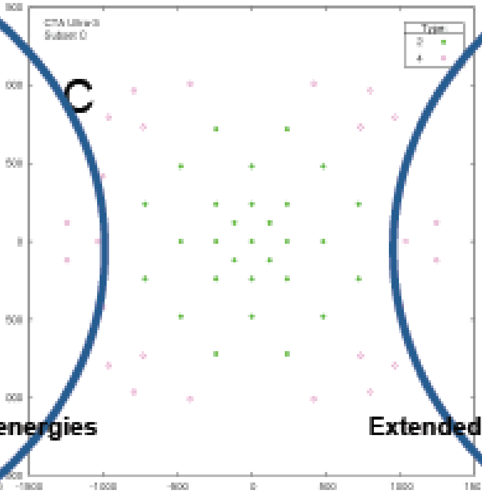
Array	1	2	3	4
C	-	29	-	26
D	-	41	-	16
H	-	25 (7°)	48	-

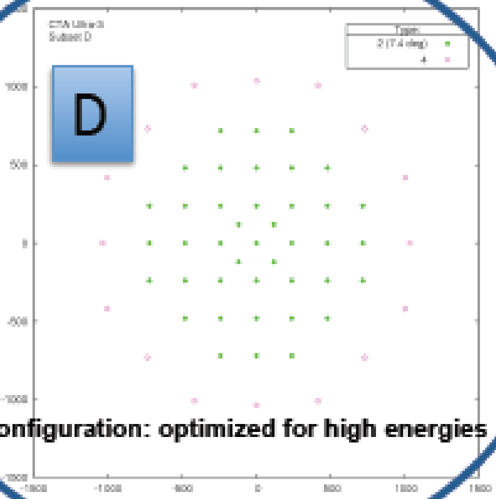
Array	1	2	3	4
E	4 (4.6°)	23	32	-
I	3 (4.9°)	18	56 (9°)	-
J	3 (4.9°)	30	-	16 (9°)
K	5	-	72	-



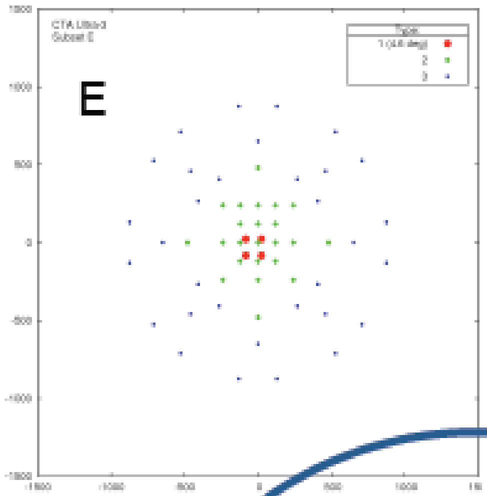


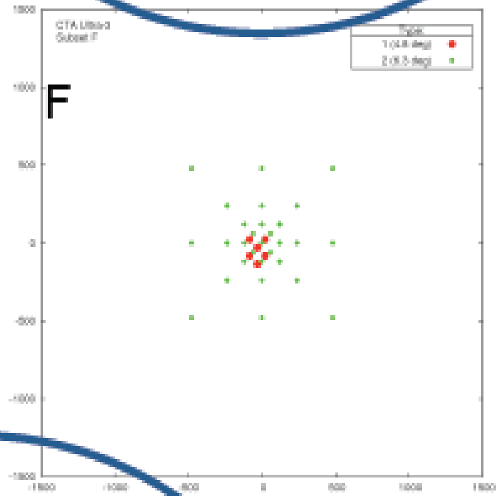
Compact configuration: optimized for low energies

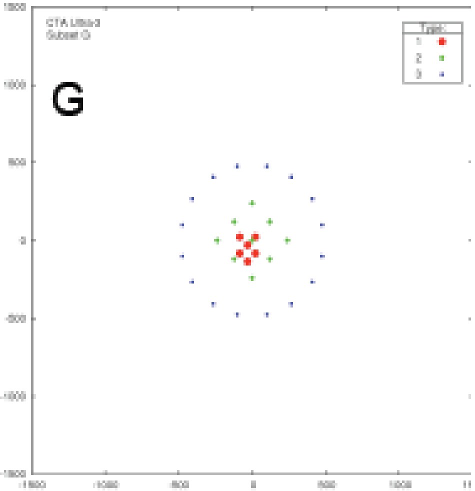


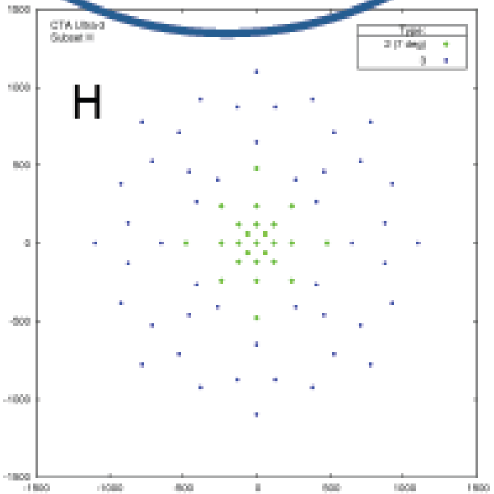


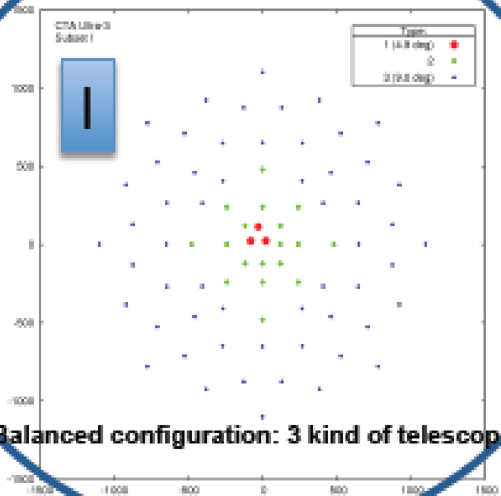
Extended configuration: optimized for high energies



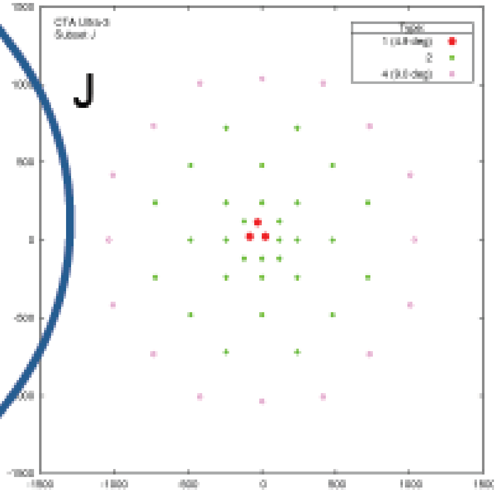


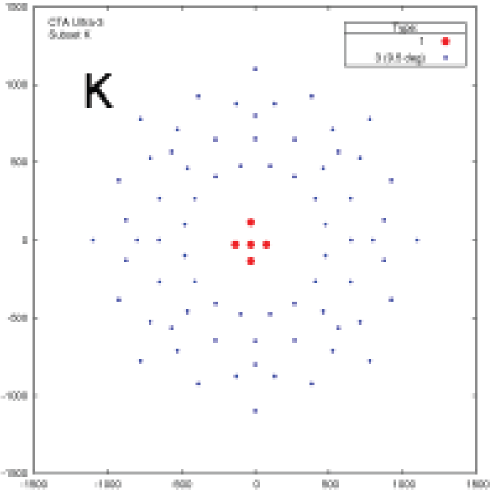




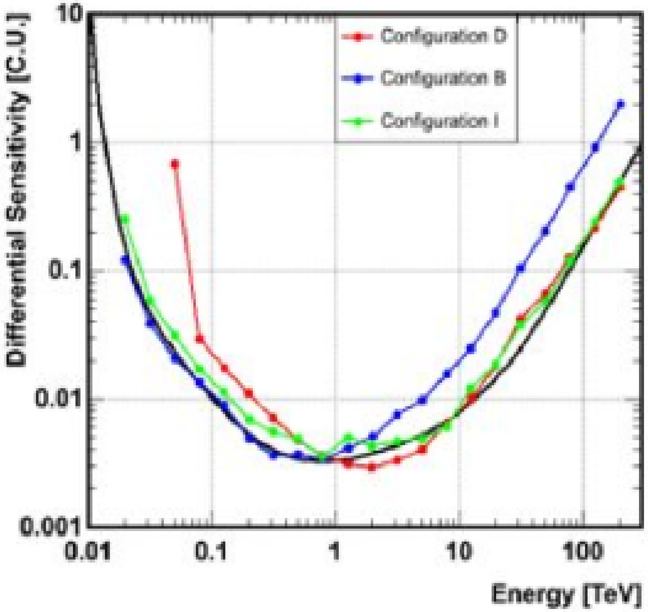


Balanced configuration: 3 kind of telescope



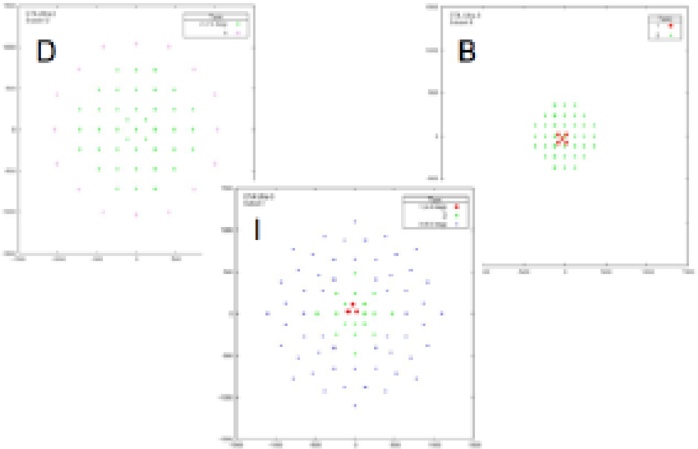


3 representative candidates for starters



Number of telescopes:

Array	1	2	3	4
D [HE]	-	41	-	16
B [LE]	5	37	-	-
I [wholeE]	3	18	56	-

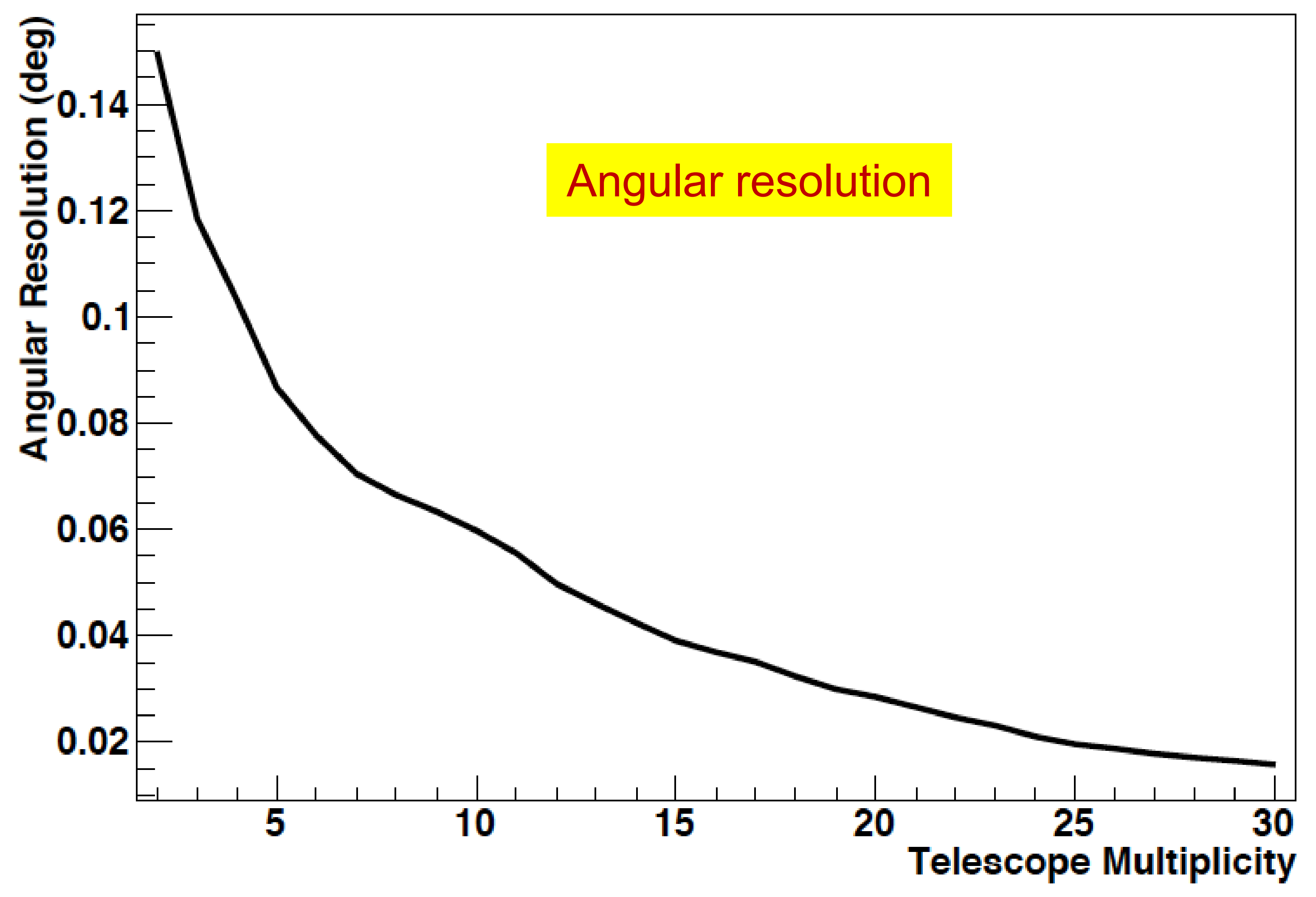


-B, D, I, not necessarily always better in every aspect with respect to their fellow members in their groups..

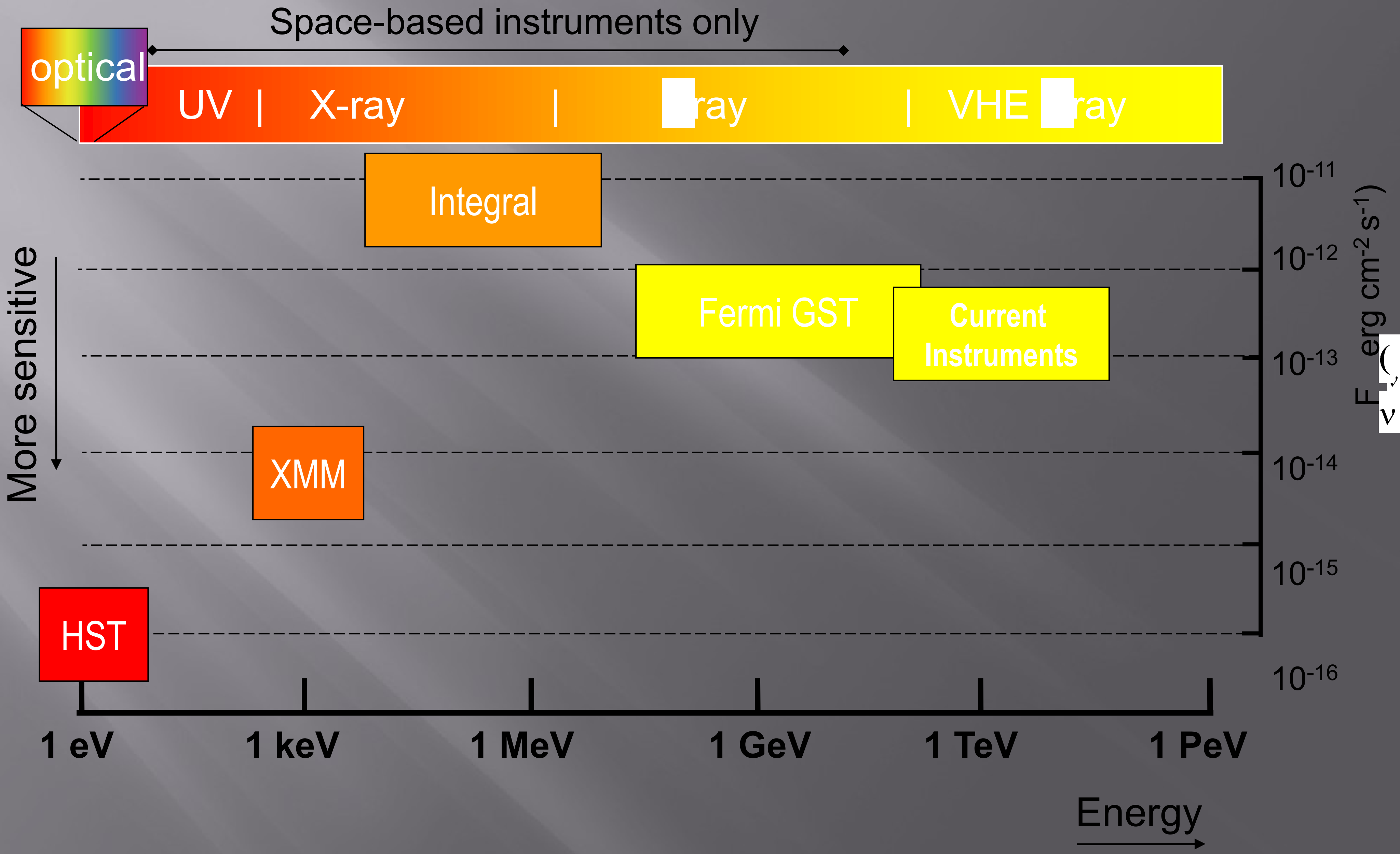
-..but differences within each group are (except a few cases) minimal in other aspects, and sensitivity alone is a good order parameter

B, D, I are best-sensitivity configurations in their corresponding groups (the PHYS-WP has been comparing these configurations thoroughly)

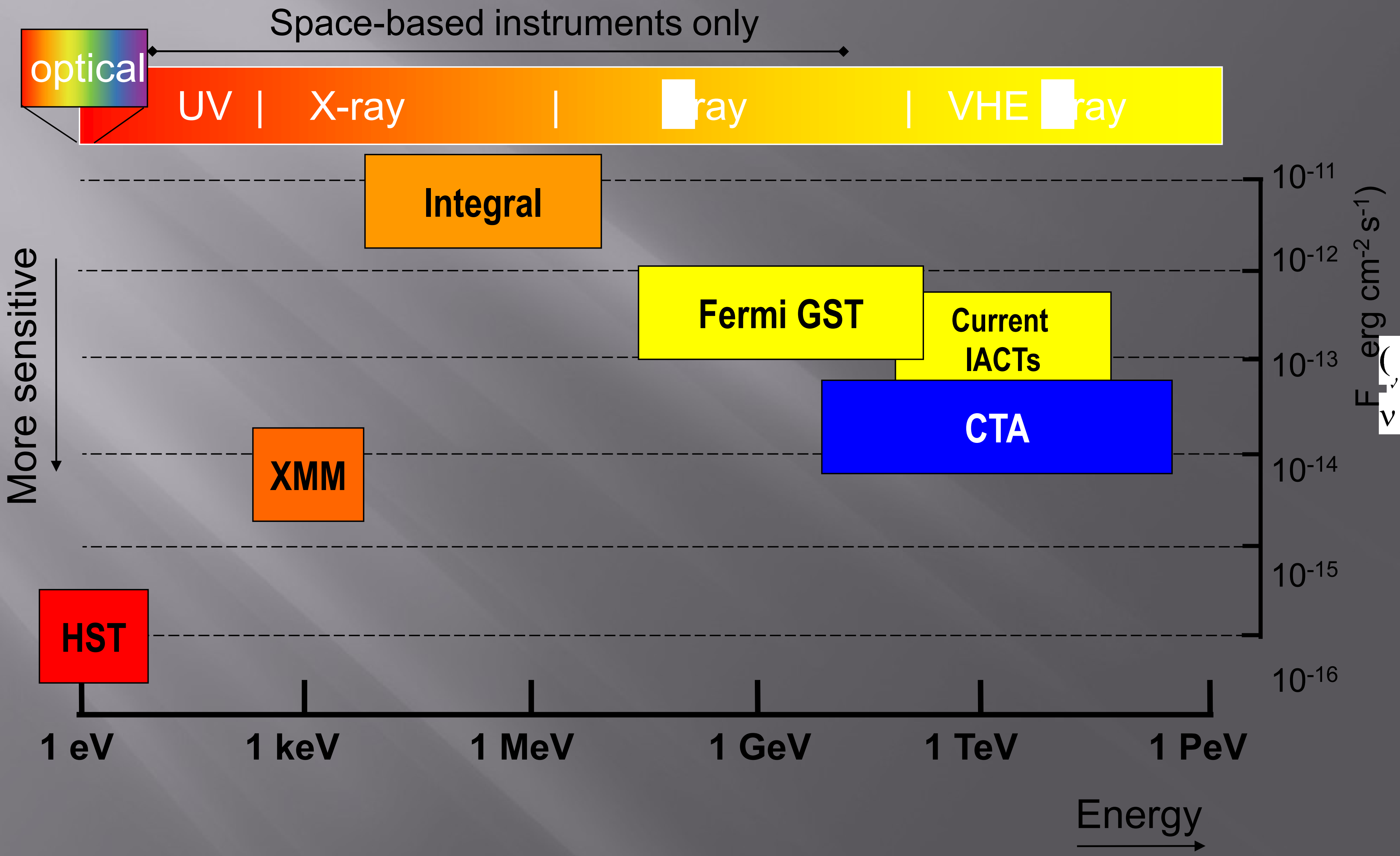
Basic message: CTA works!



CTA: In Context

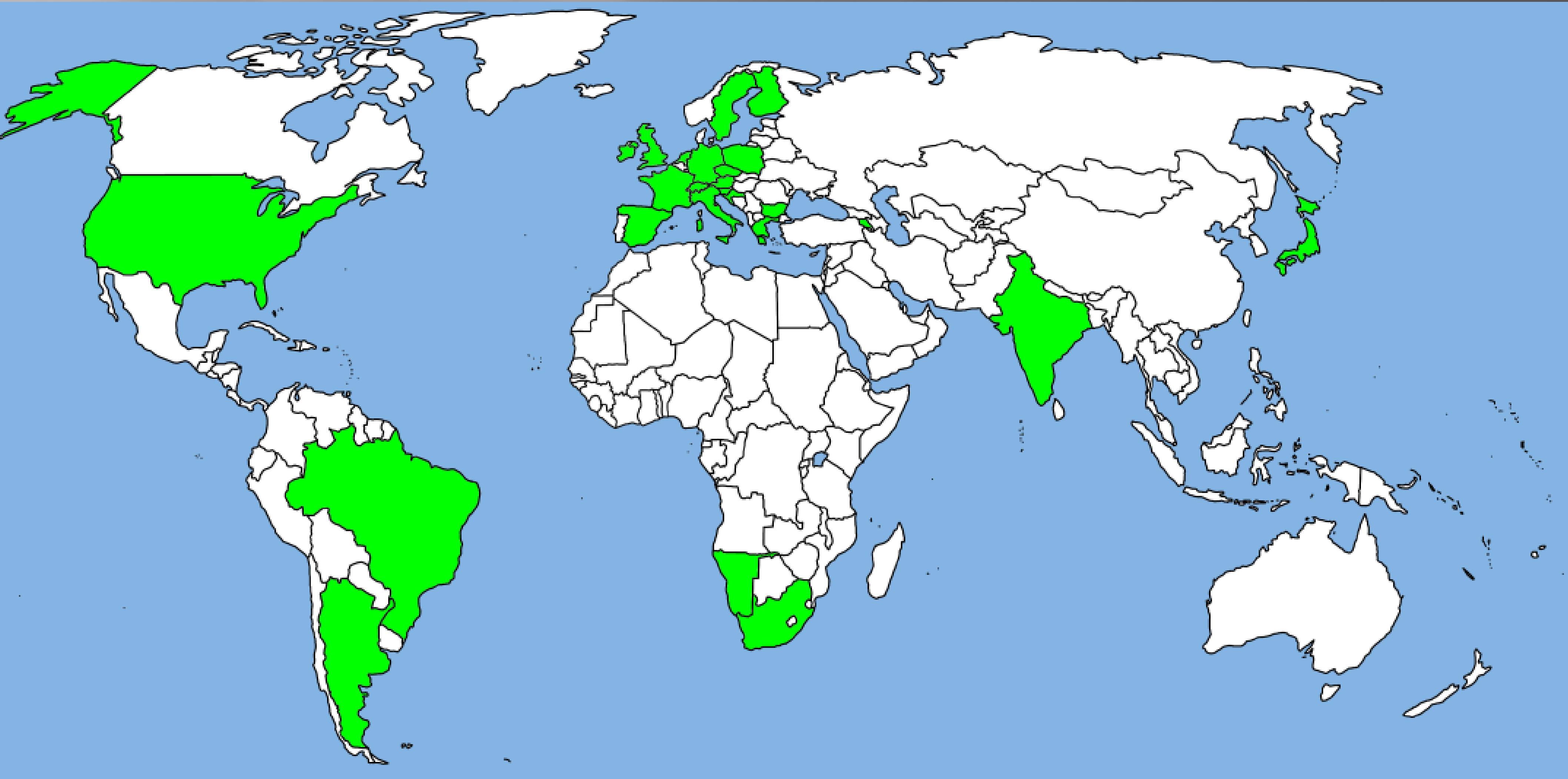


CTA: In Context

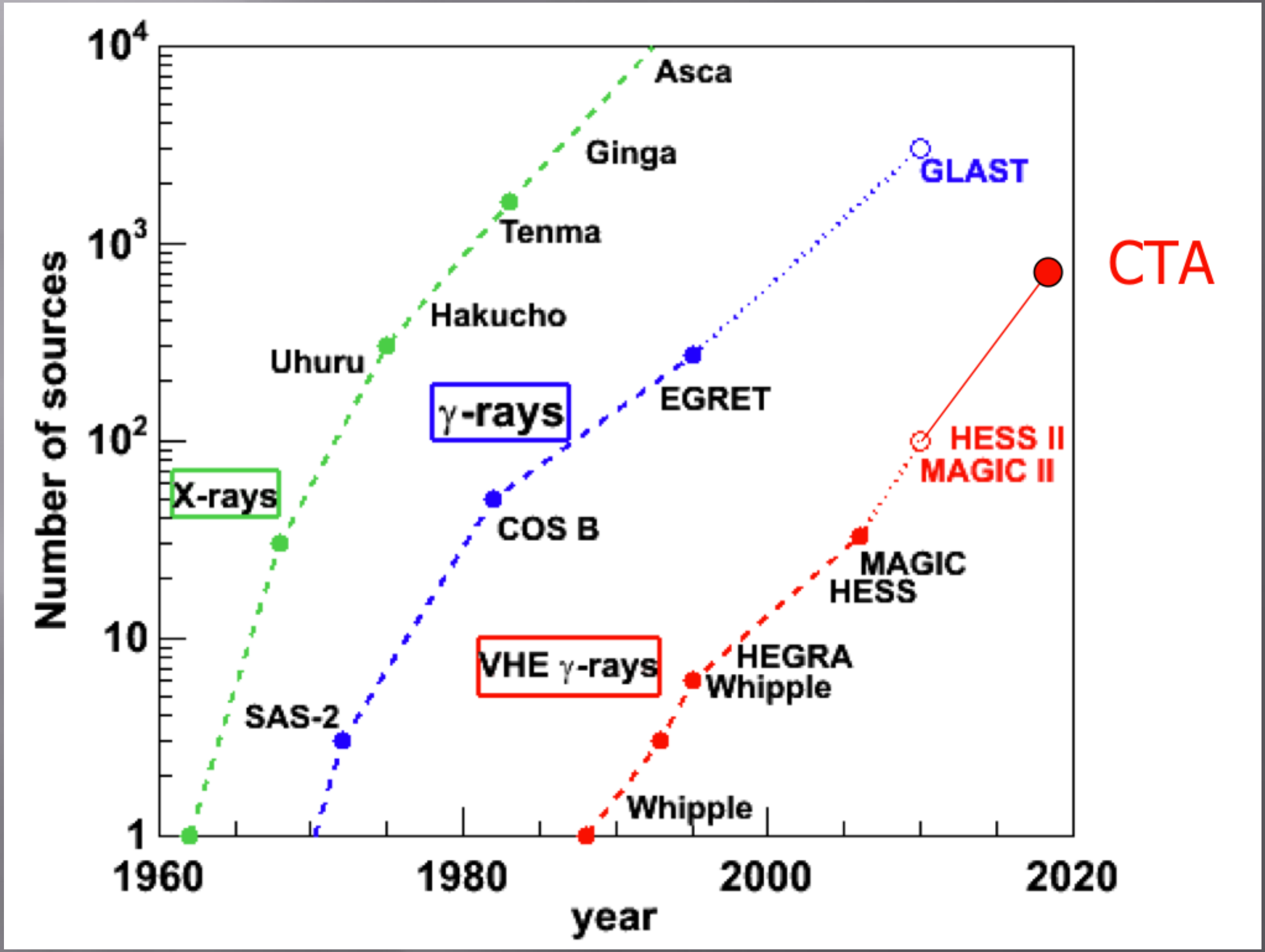


… by end of 2010

25 countries
132 institutes
734 people
(+27% compared to last meeting)
220 FTEs



The Future



10^4
10^3
10^2
10
1
Number of sources
1960
1980
2000
2020
year
X-rays
Asca
Ginga
Tenma
Hakucho
Uhuru
γ-rays
GLAST
EGRET
COS B
SAS-2
VHE γ-rays
CTA
HESS II
MAGIC II
MAGIC
HESS
HEGRA
Whipple
Whipple

CTA

That’s all folks!