Fundamental Physics
with
VHE Cosmic Gamma Rays

DISCRETE'08, Valencia 16/Dec./2008

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IFAE

Outline:

0- Introduction

1- Cherenkov Telescopes

2- Dark Matter

3- Speed of light invariance

4- Outlook

0- Introduction

VHE Cosmic Gamma rays:

highest energy electromagnetic radiation from our Universe

Presently: Highest energy messengers detectable from our universe which:

- Are stable particles => cosmological distances

- Interact enough to be “easily” detected => modest and simple detectors

- Are not deflected by cosmic magnetic fields => allow to pinpoint and identify the source with high precision

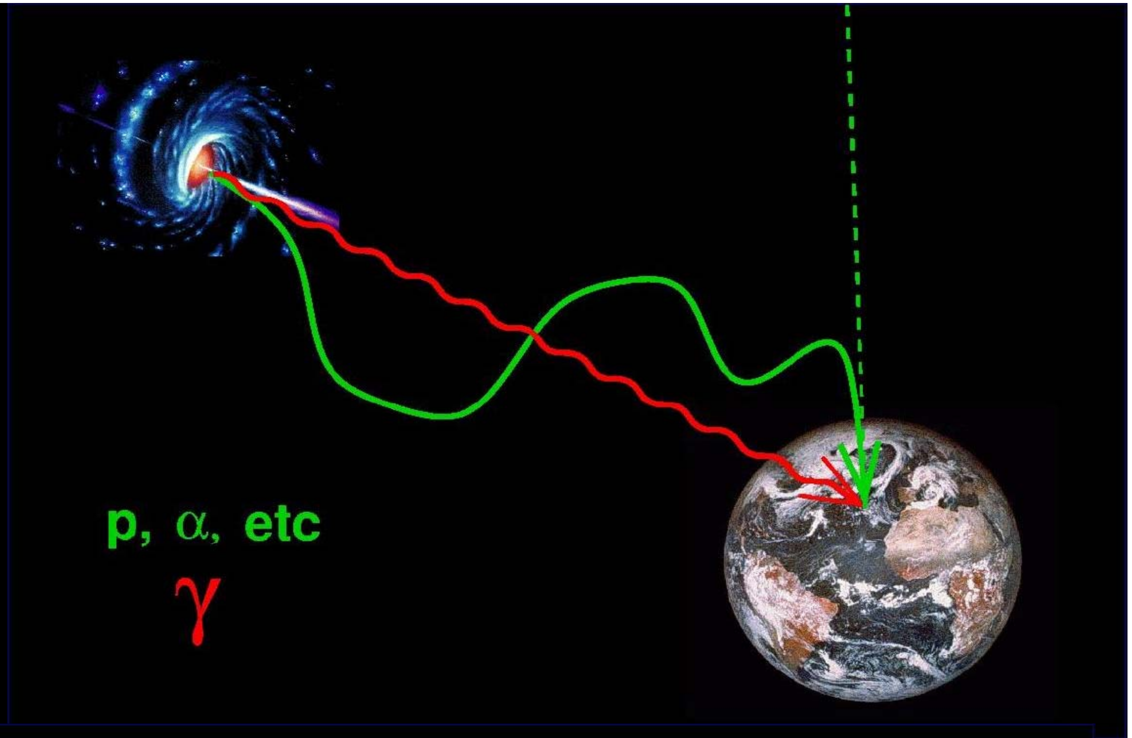
VHE Cosmic Gamma rays:

highest energy electromagnetic radiation from our Universe

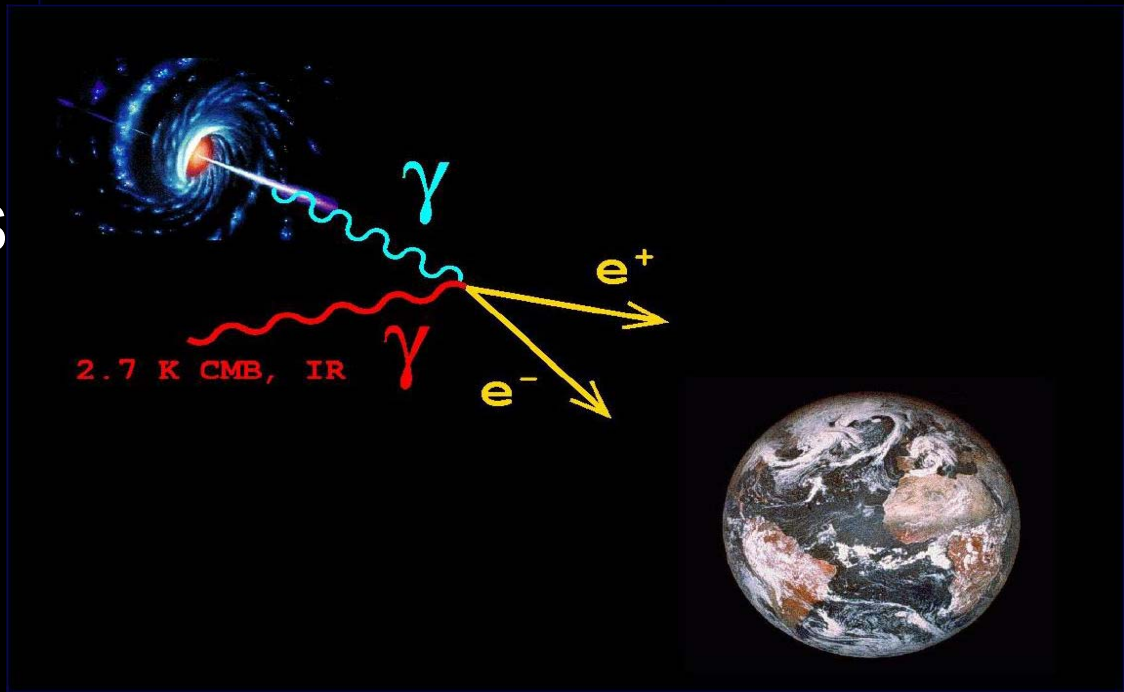
=> Highest energy **wide-open** window for the observation of our universe

VHE GAMMA-RAY <u>ASTRONOMY</u>

Source Studies



Propagation Studies

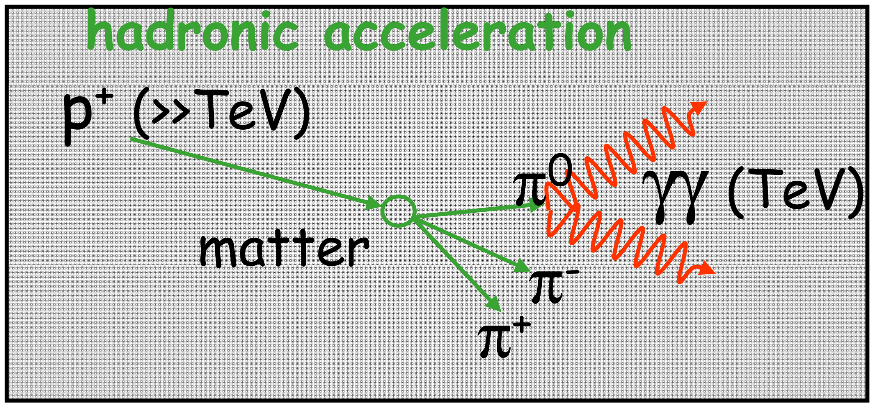


1) Study the source: production mechanisms

VHE gamma rays are produced in the most energetic and violent phenomena in the universe:

A) COSMIC ACCELERATORS

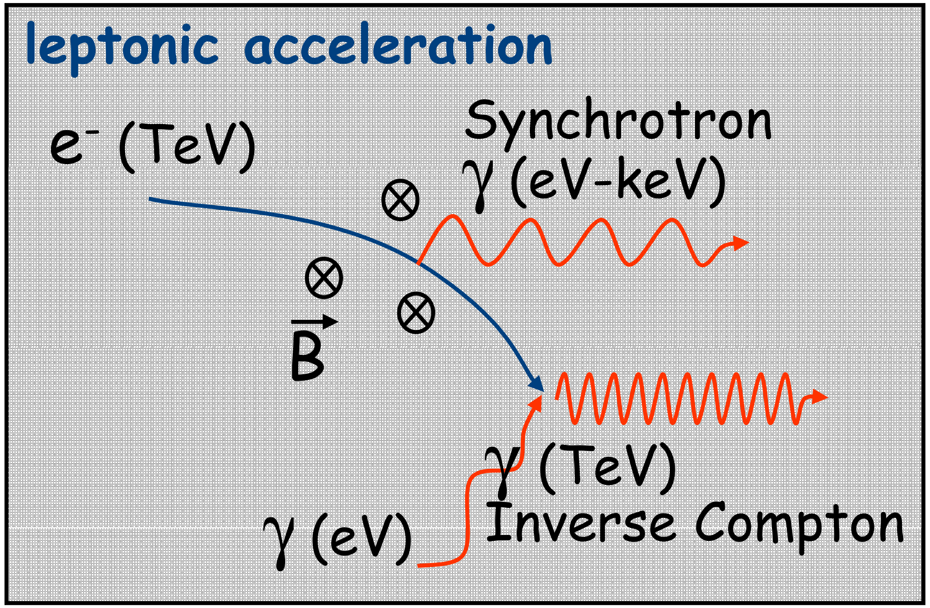
- Hadron accelerators: p X -> π -> gamma

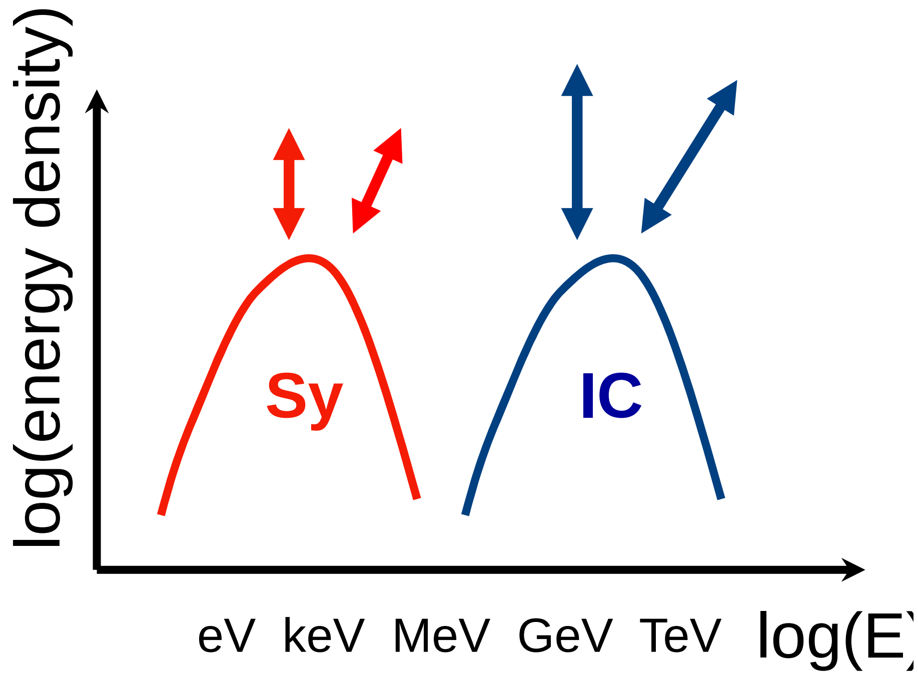


- Electron accelerators:

synchrotron: e B -> e gamma

+ inverse Compton: e gamma -> gamma e





B) HEAVY PARTICLE ANNIHILATION OR DECAY

Through the annihilation or decay of very massive or energetic objects:

dark matter, very massive particles at unification scales, relics of universe phase transitions, primordial black holes,…

=> Tool to search for new, massive, particles and objects.

2) Study the propagation in the cosmic medium

VHE gamma rays are, so far, the most energetic messengers reaching us through a determinable path: explore the structure of intergalactic medium:

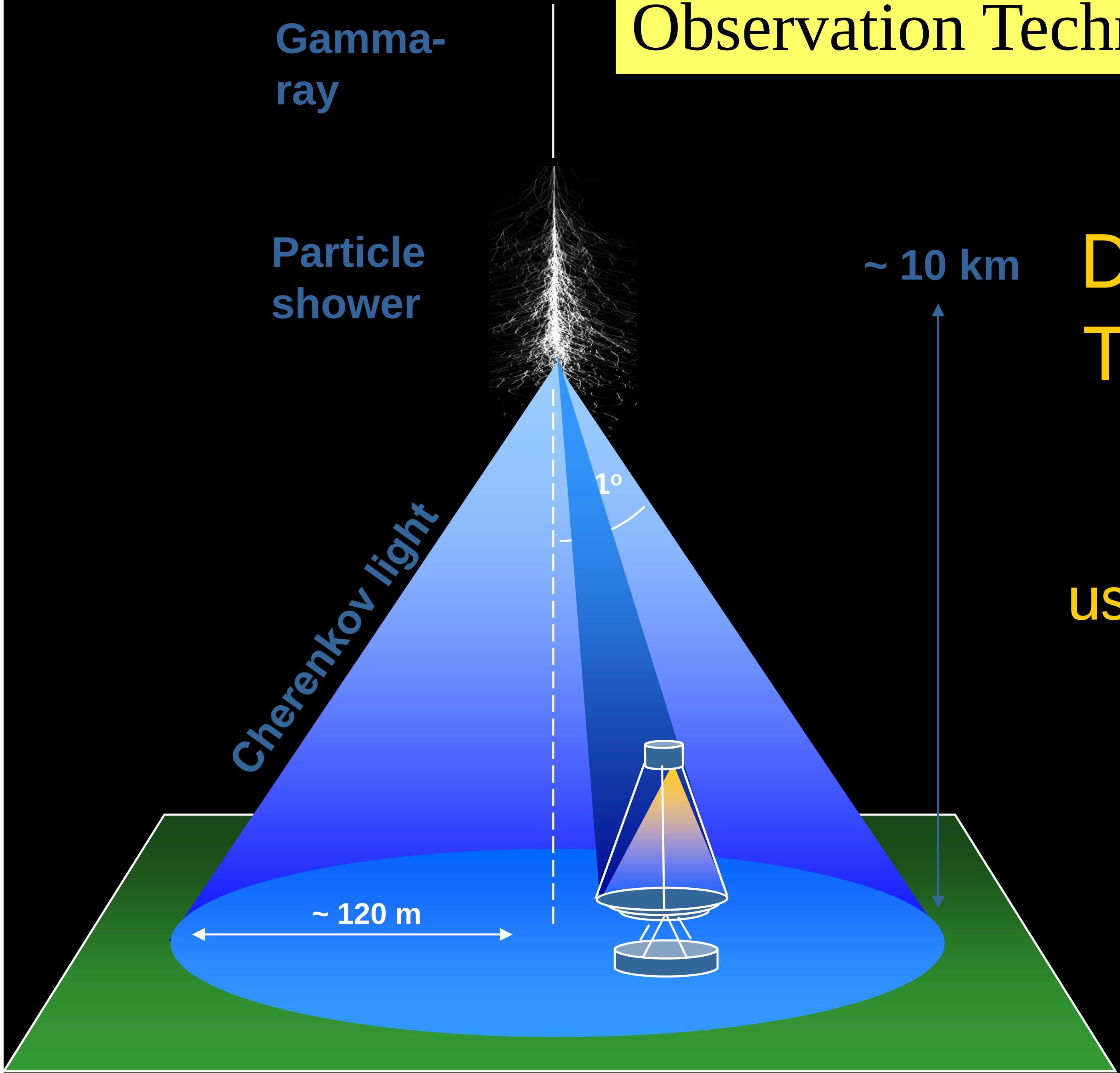
- at long distances: produced in sources at cosmological distances from us

- at the shortest distances: they explore space-time at the highest energies

=> they may allow us to address important questions in fundamental physics and cosmology

1- Cherenkov Telescopes

Observation Technique



Detection of TeV gamma rays

using Cherenkov telescopes

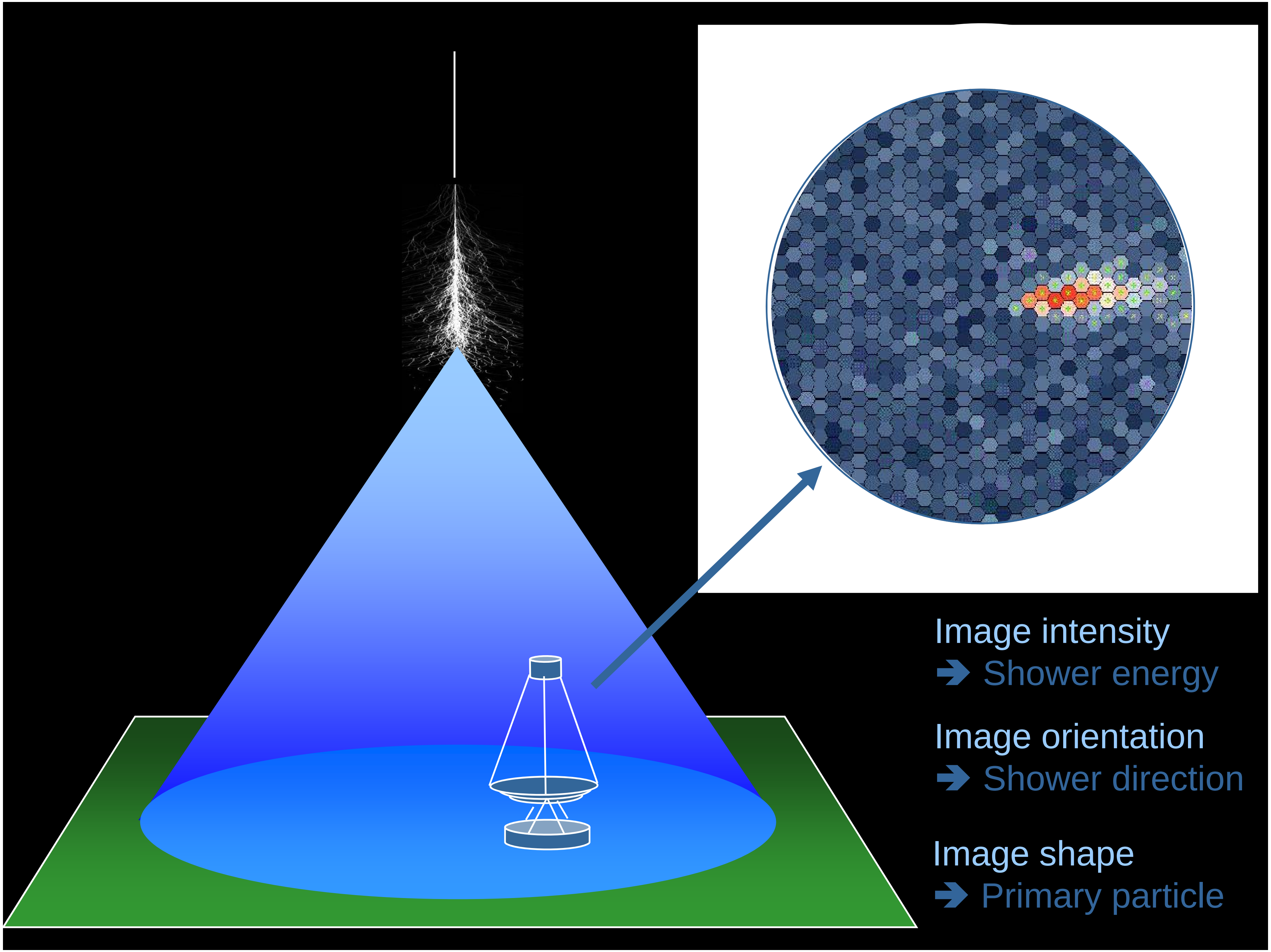
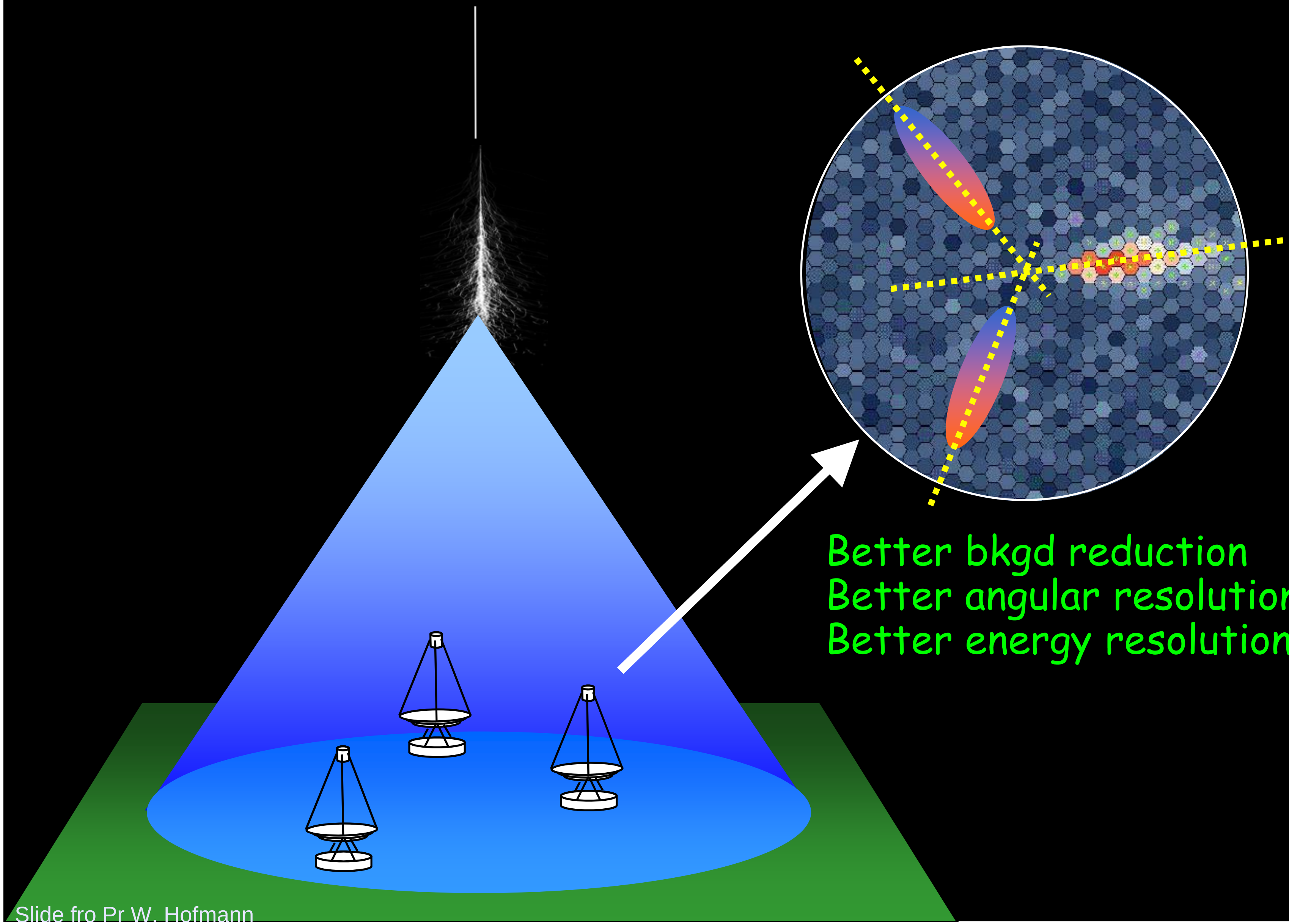


Image intensity
➔ Shower energy
Image orientation
➔ Shower direction
Image shape
➔ Primary particle

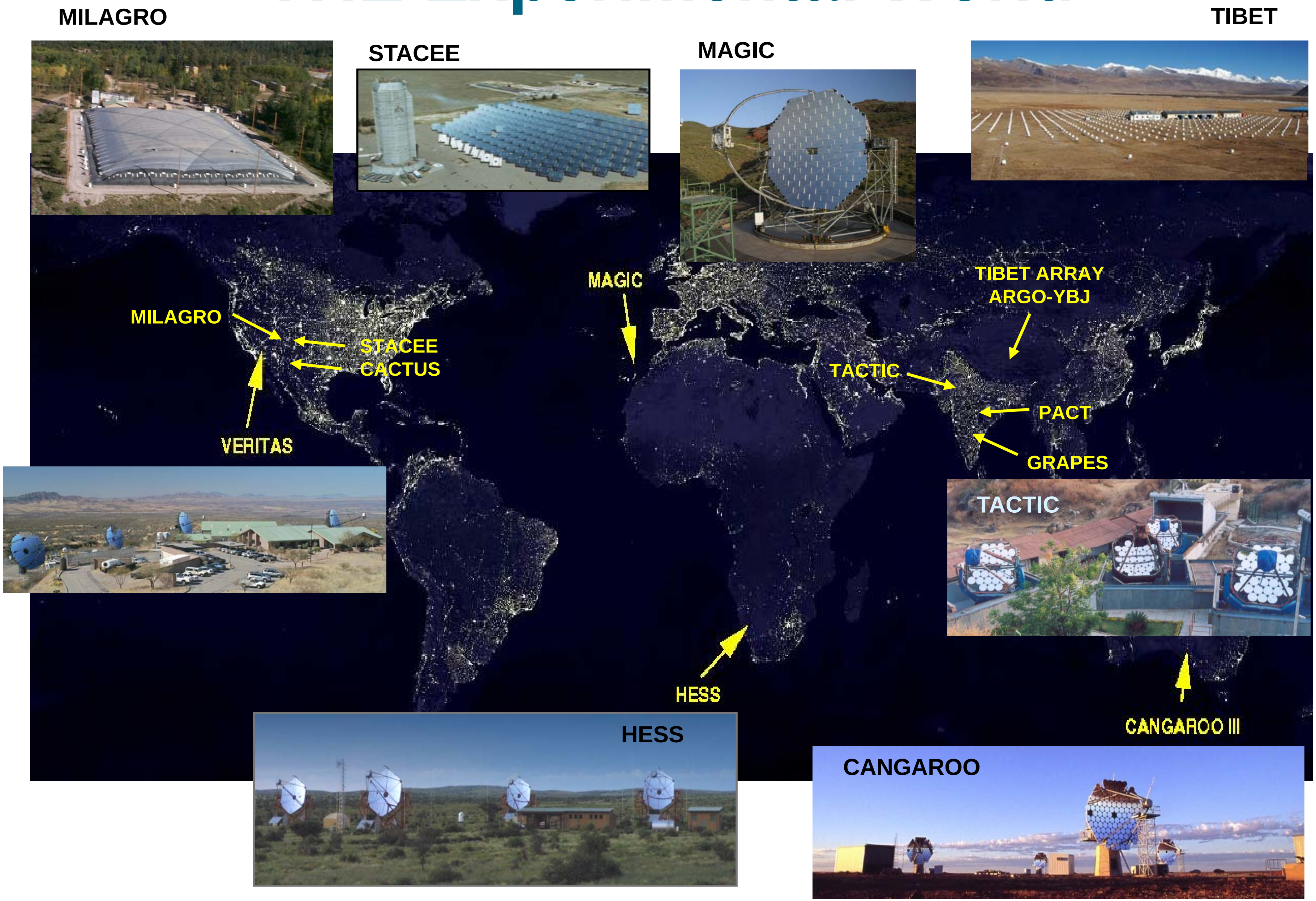
Systems of Cherenkov telescopes



Better bkgd reduction
Better angular resolution
Better energy resolution

Slide fro Pr W. Hofmann

VHE Experimental World



- Very special moment in VHE Cosmic gamma-ray observation:

  real revolution in consolidation of Cherenkov telescopes as astronomical instruments

  => transition from “HE experiments” to “telescopic installations”

  --> exploding interest in the astronomical community… !

- Big observational step in the last few years:

  - quantitative (x10 number of detected sources)
  - qualitative (extremely high quality => unprecedented detailed studies).

=> DOWN OF A GOLDEN AGE FOR CHERENKOV TELESCOPES !

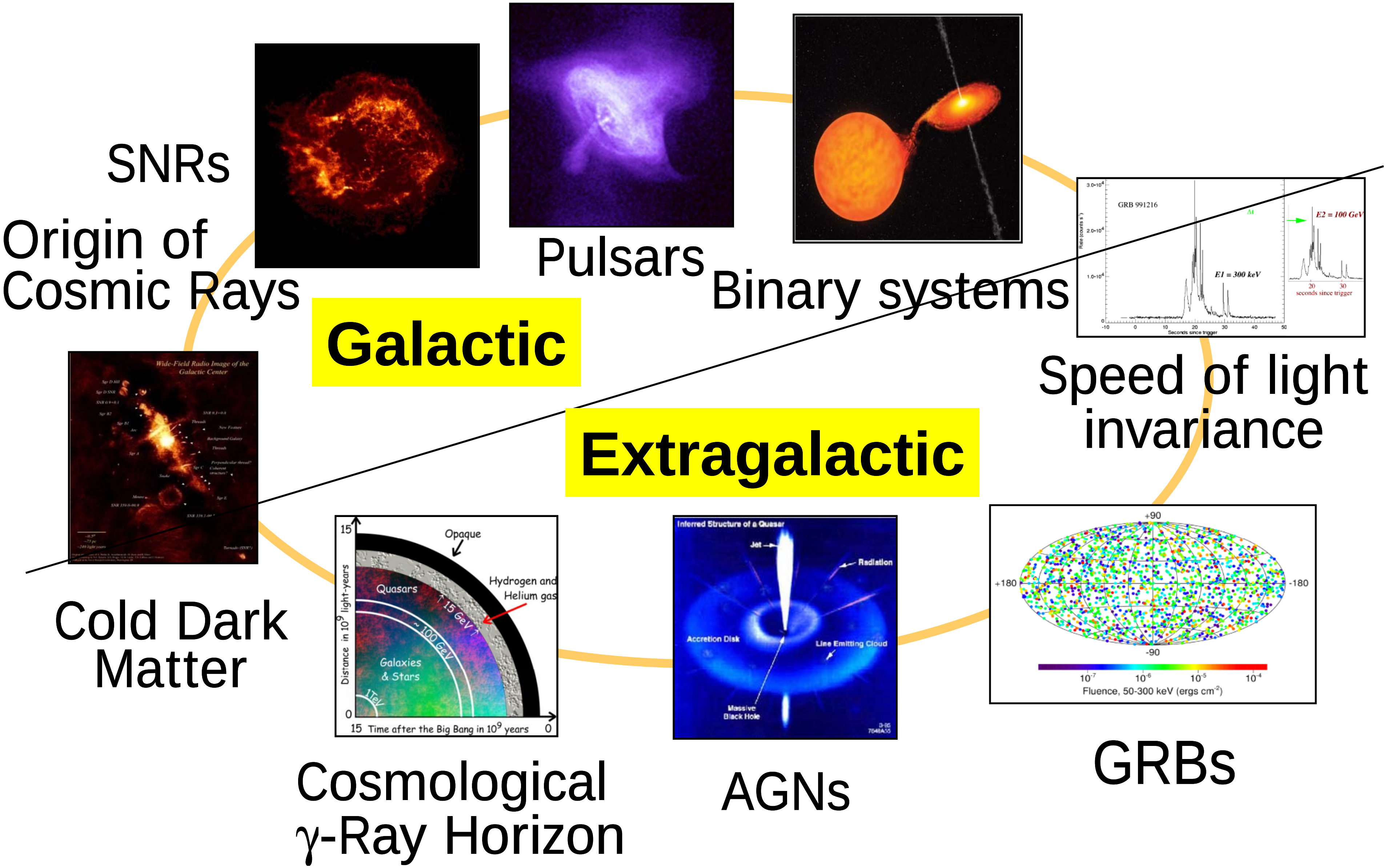
Gamma ray sources & their physics

Over 70 sources detected already (and increasing steadily...) :

- Supernova remnants
- Pulsar wind nebulae
- "Dark sources"
- Binaries
- Stellar winds
- Galactic center
- Active galaxies

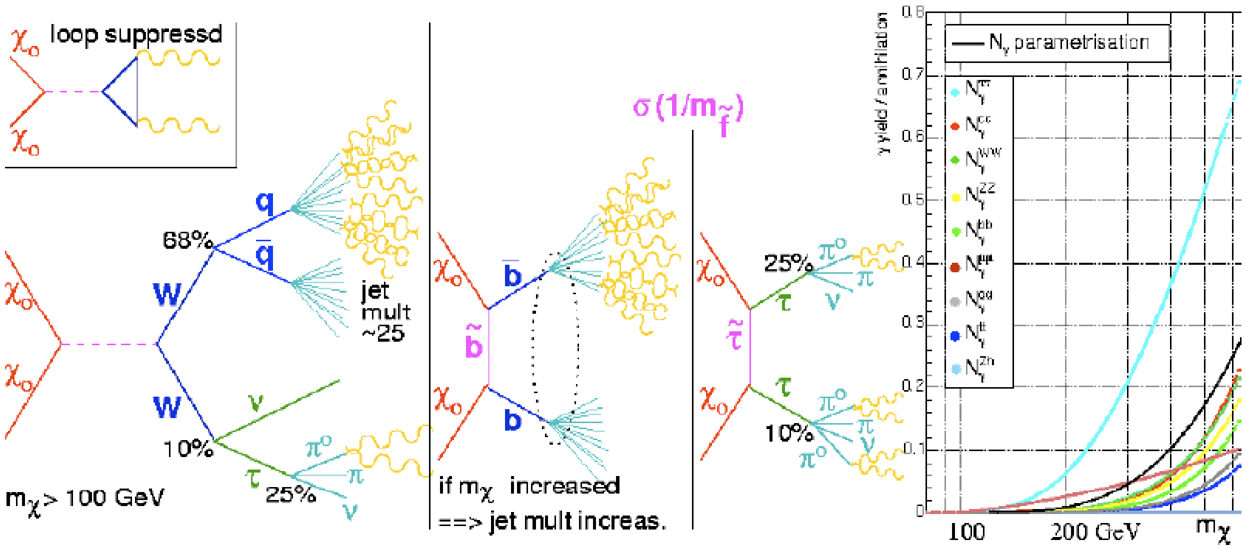
W. Hofmann

The VHE γ-ray Physics Program



2- Dark Matter

• Dark Matter annihilates producing gammas as secondary particles.

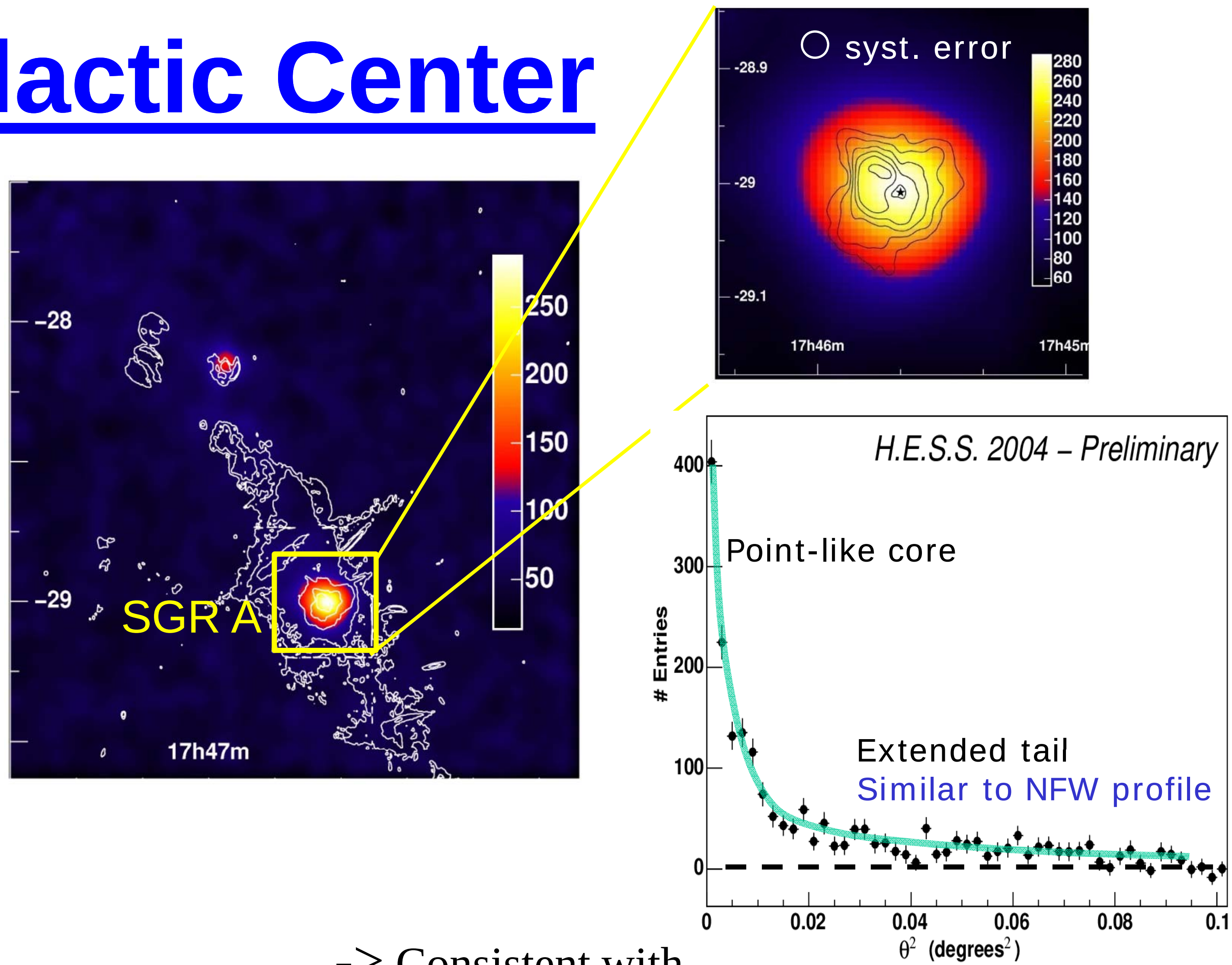


• Expected gamma flux proportional to $(\rho_{DM})^2 \times D^{-2} \times \sigma$

=> Most promising targets:

- Galactic Center,
- Dwarf Spheroidal Satellites (large M/L ratio),
- Subhalos,
- Microhalos,
- Intermediate Mass Black Holes (IMBH),
- Local Group Galaxies,
- Globular Clusters.

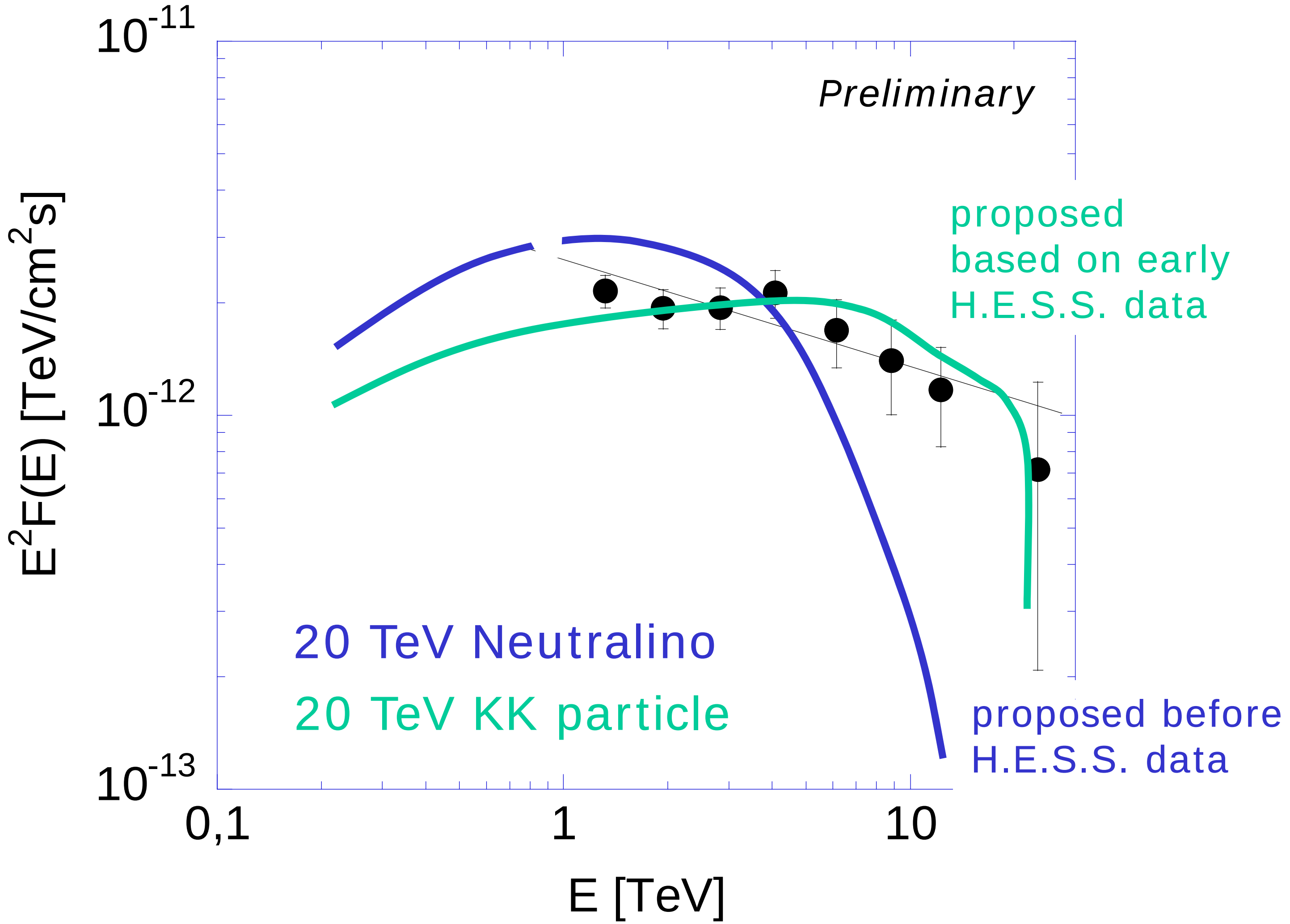
Galactic Center



-> Consistent with
SGR A* to 6'' and slightly extended.

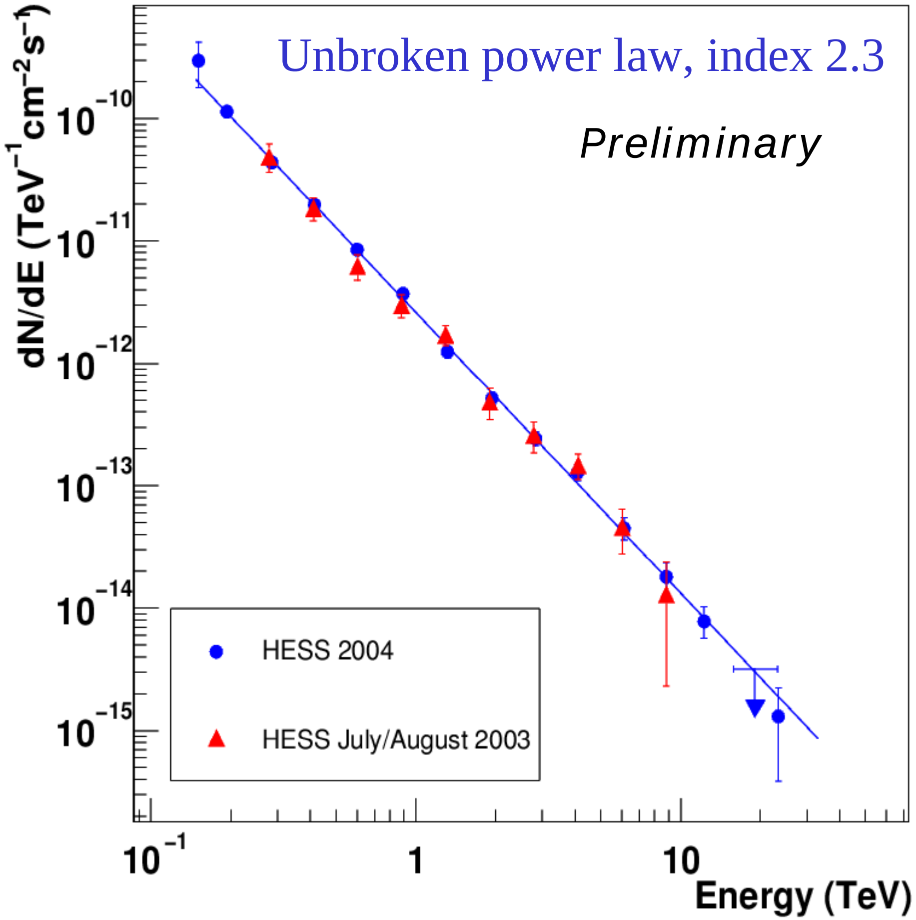
-> No significant variability from year to minute scales (in ~40 h obs. time distributed over 2 years)

Dark matter annihilation ?

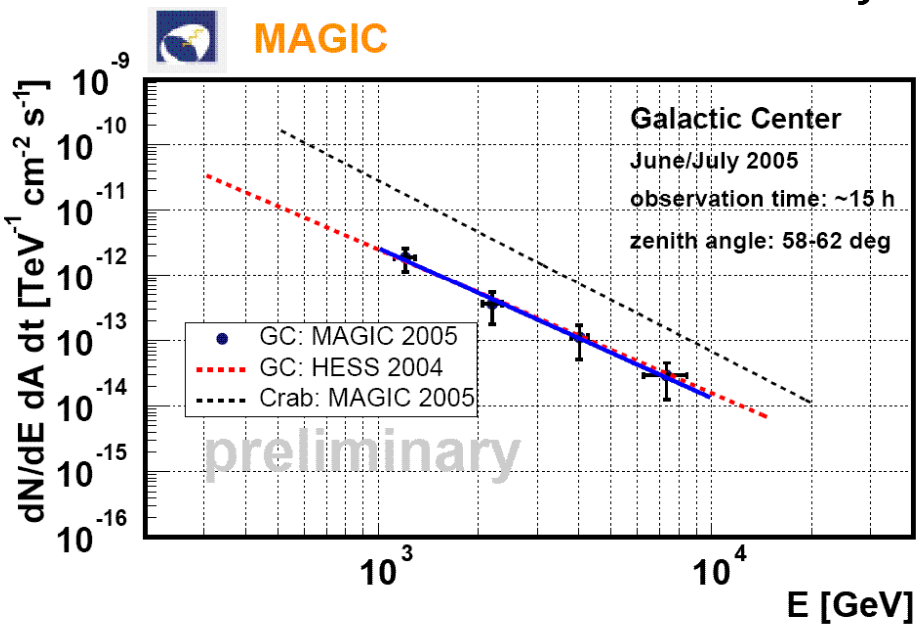


⏩ J. Ripken ICRC 2005

Gamma ray spectrum



Preliminary



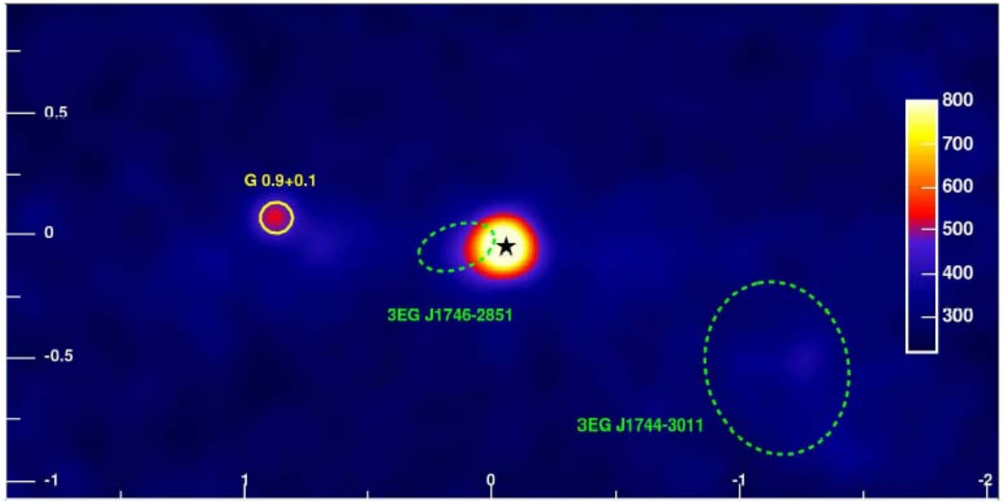
Good agreement between HESS and MAGIC (large zenith angle observation).

⇒**Very unlikely to be dark matter.**

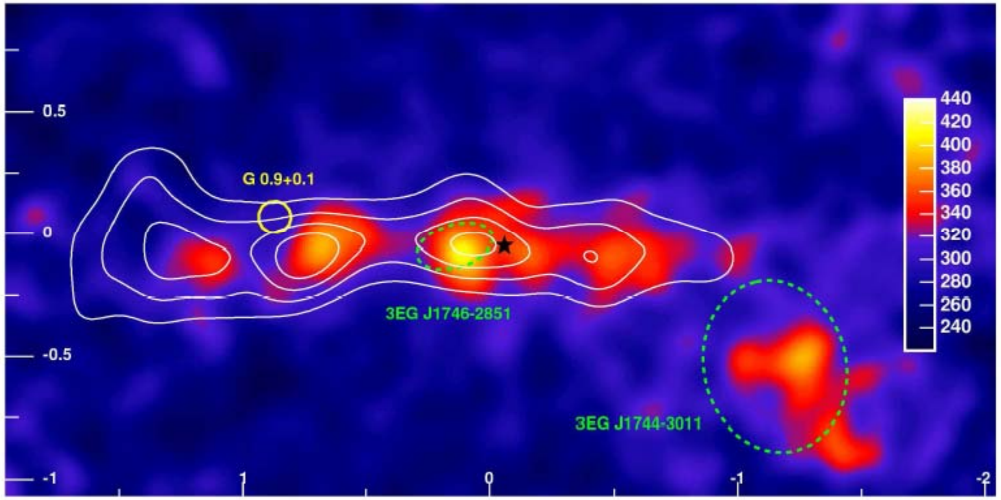
⇒**Presence of a strong gamma-ray source outshines any possible DM signal**

The Galactic Centre Ridge

HESS



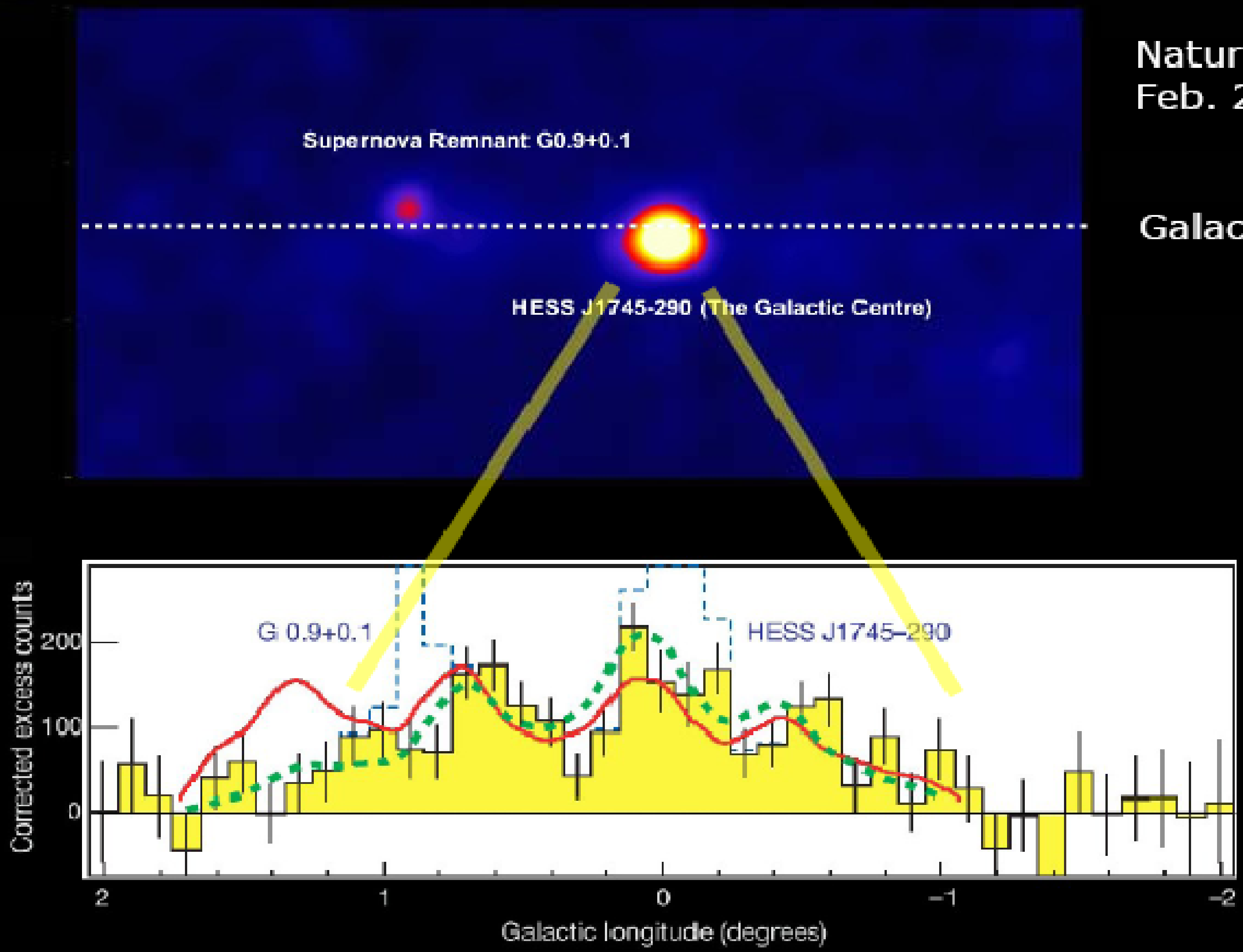
Galactic Centre gamma-ray count map



Same map after subtraction of two dominant point sources =>

Clear correlation with giant molecular clouds traced by their CS emission

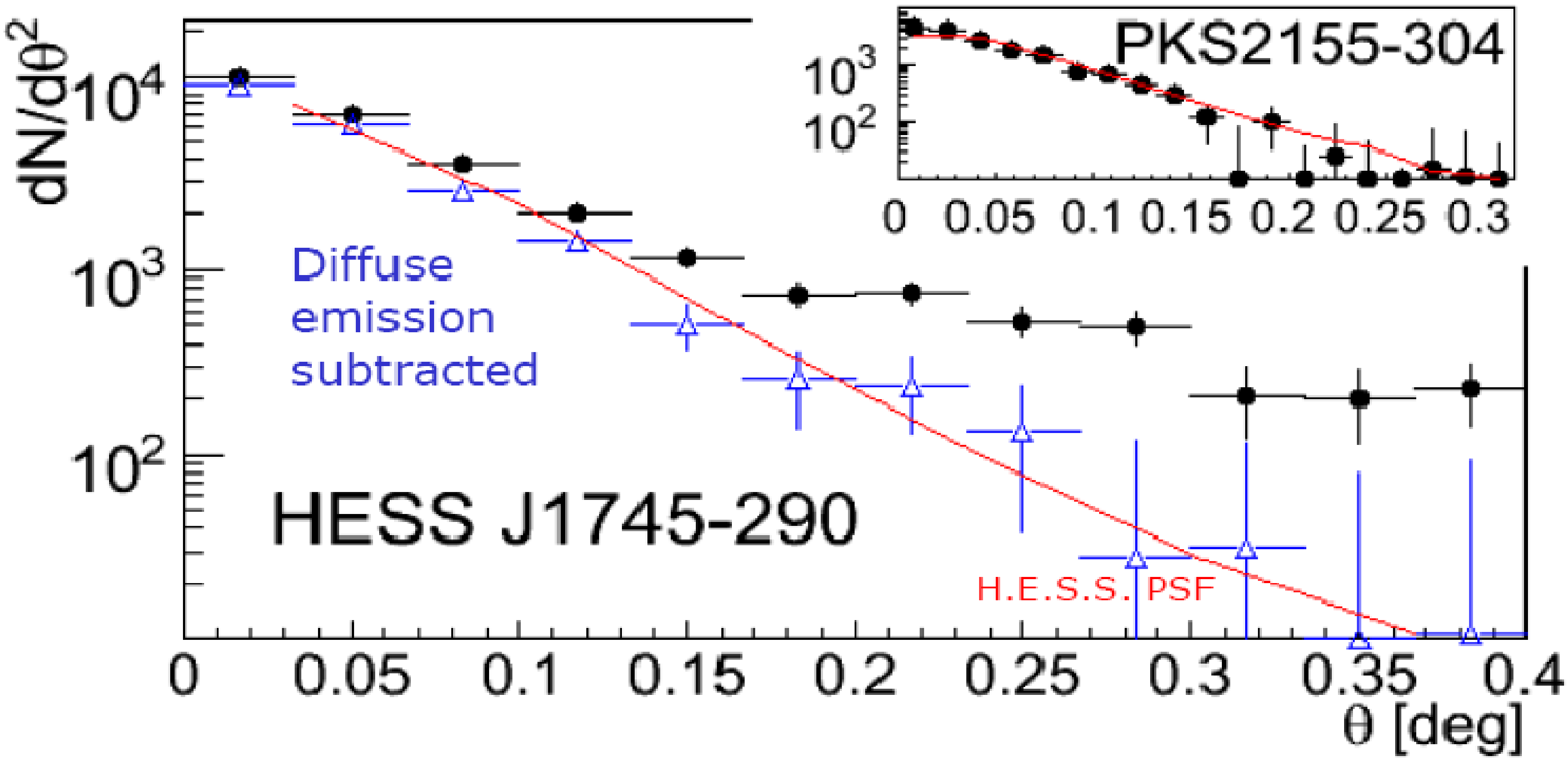
The center of our Galaxy



Nature
Feb. 2006

Galactic plane

Is it DM? ▶ Angular distribution



PRL, in press

• So far, efforts to detect DM annihilation with VHE gammas have been unsuccessful

but

It turns out that VHE gamma-ray astronomy provides probably the **best tool** to try to unveil the nature of DM:

- LHC -> may find candidates (SUSY, extra-dimensions,...) but cannot prove that they are the observed Dark Matter

- Direct searches (nuclear recoil) -> may recognize local halo WIMPs but cannot prove the nature and composition of Dark Matter on the sky.

- Indirect searches:
  * Charged particles -> may detect excesses but not map them into the gravitationally identified density profiles.
  * Neutrino telescopes -> may need many KM3 to reach the sensitivity attainable to VHE gamma ray installations.
  * Gamma satellites -> may have too limited lever arm to pinpoint DM spectral features.

• Note 1: Direct Searches and Indirect Searches look at different things:

- Direct searches: WIMP-hadron interaction -> interaction of Dark Matter with ordinary matter -> lose constraints -> impact on barionic compression.

- Indirect searches: WIMP-WIMP annihilation -> same process causing relic abundance -> cosmological constraints -> impact on fundamental cosmology

• Note 2: LHC (and ILC) reach limited to neutralino masses of <~300 GeV. Beyond that only ground based instruments will be able to provide additional constraints on SUSY parameter

-> the role of VHE gamma-ray astronomy for Dark Matter studies, even beyond the discovery, is **UNIQUE:**

”Gamma-ray observations provide the only avenue for measuring the dark matter halo profiles and illuminating the role of dark matter in structure formation”.

AGIS white book

- In addition, in the coming next few years:

  - LHC will have crutial information on particle candidates

  - Fermi (GLAST) may have found a plethora of “dark sources” already

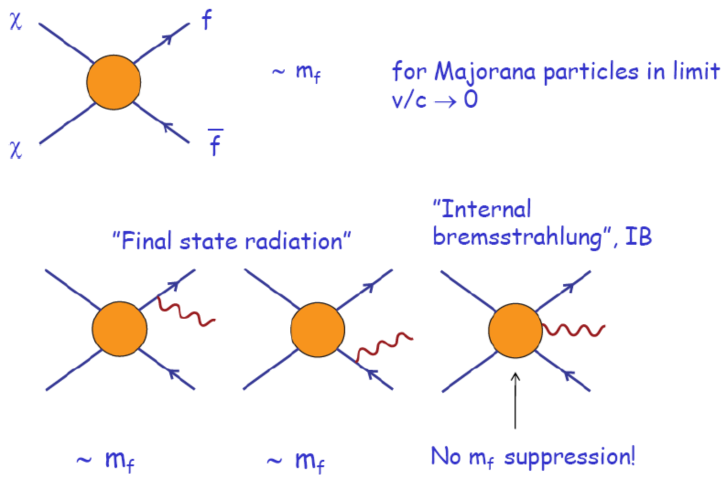
  - Astronomical surveys (SDSS, PanSTARRs, DES,...) will have identified a pretty large number of (nearby) objects with large mass/light ratio.

  - Improved calculations/simulations will allow more precise predictions.

Contribution of Internal Bremstrahlung

T.Bringmann, L.Bergstrom, J.Edsjo 2007

How to avoid helicity suppression
for Majorana particles



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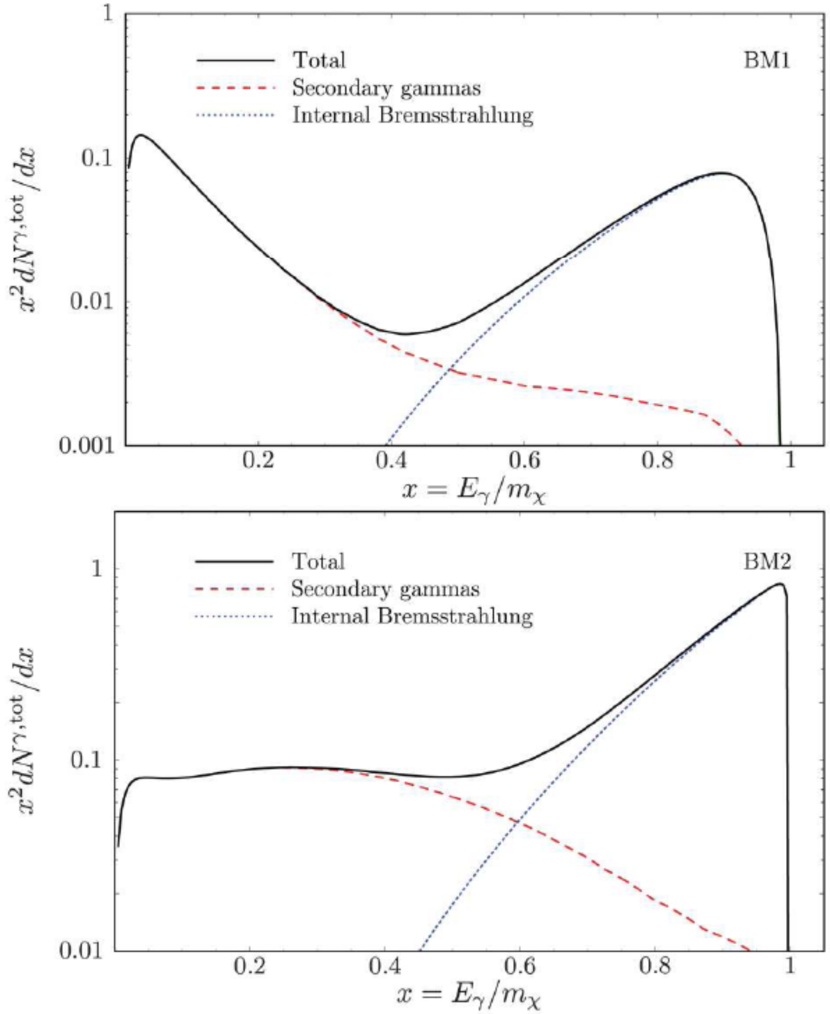
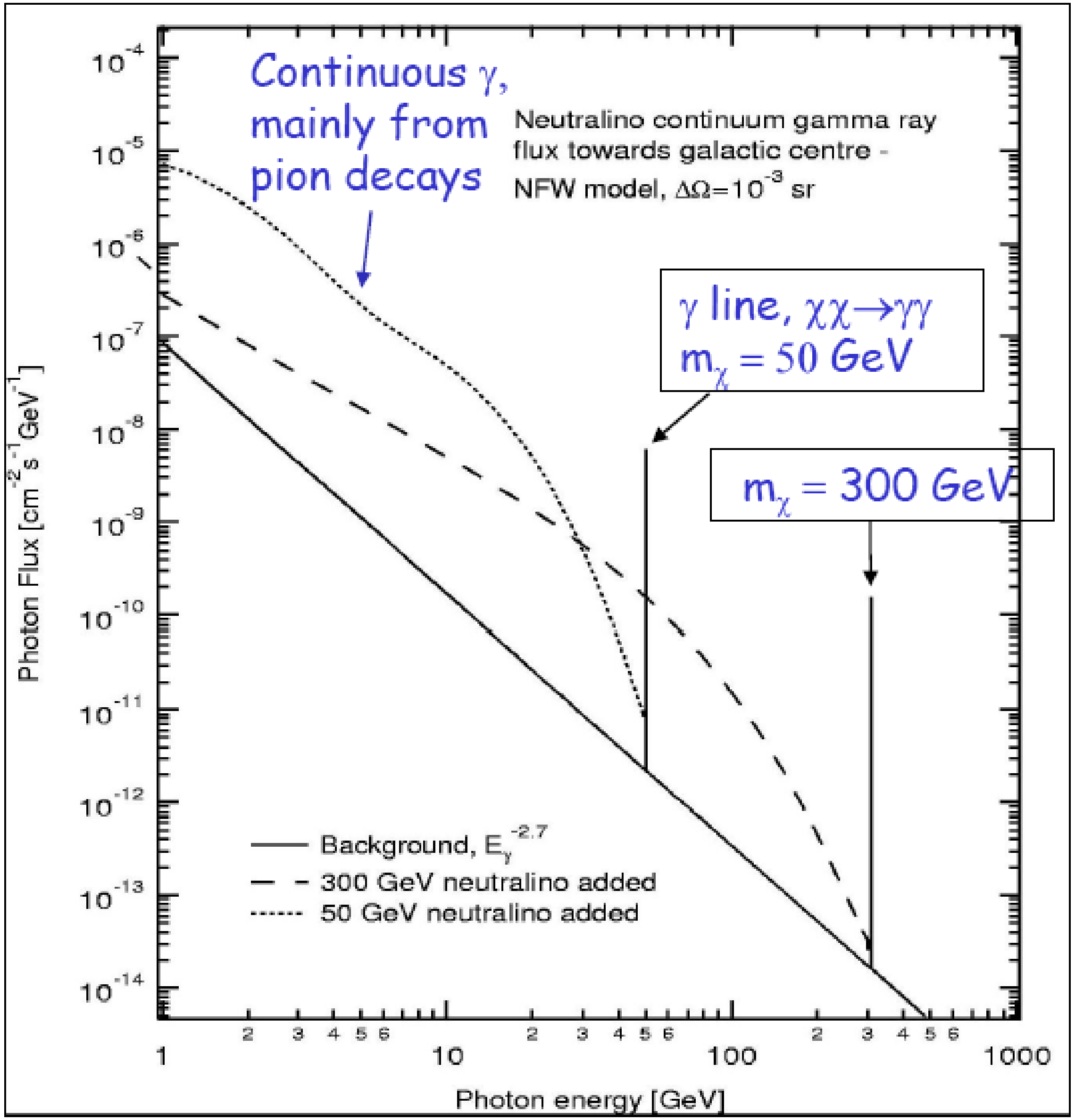
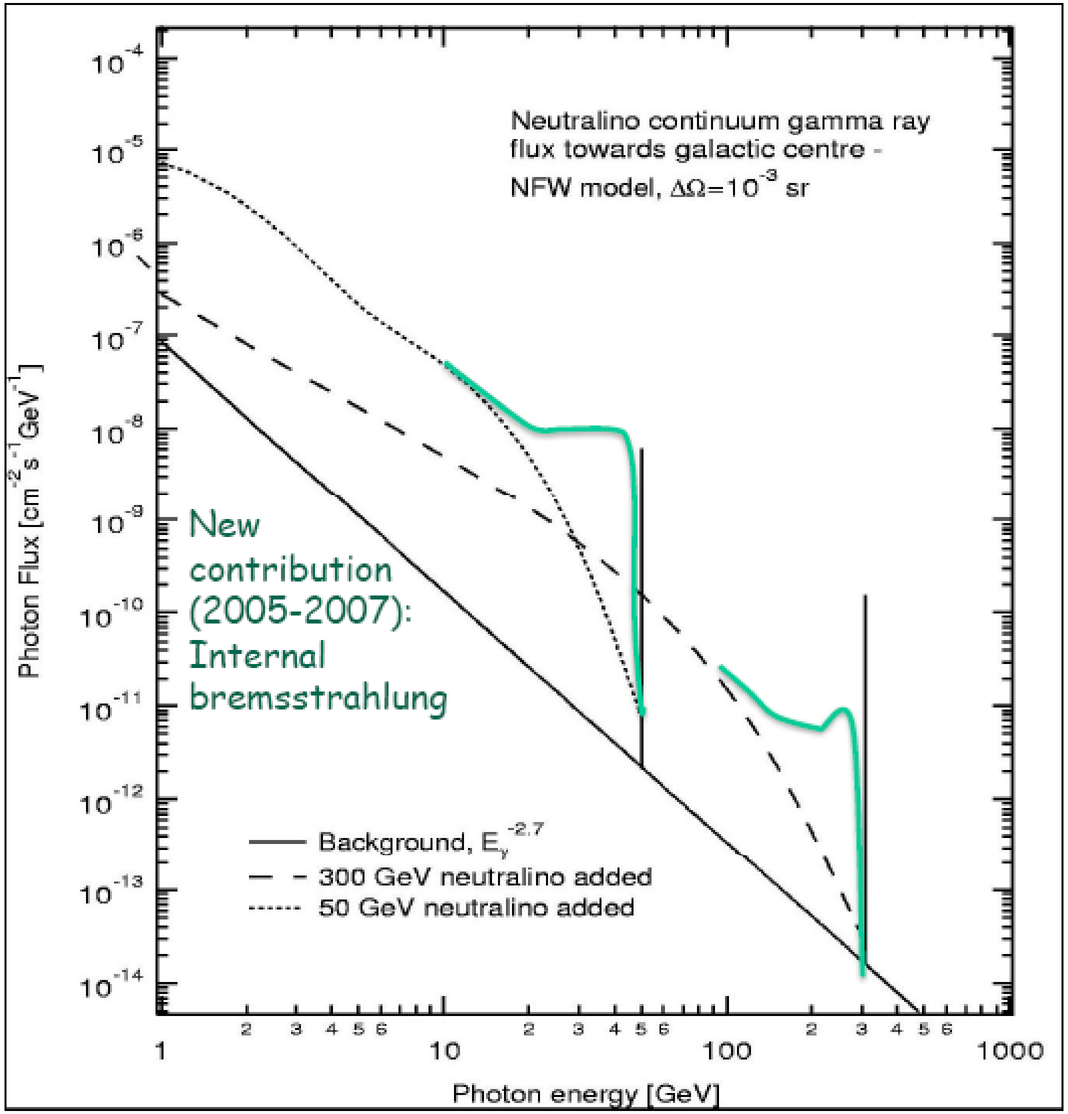


Figure 2: Continuum emission from neutralino annihilation from mSUGRA models.

Gamma-rays from DM annihilation



Gamma-rays



L.B., P.Ullio & J. Buckley 1998 T. Bringmann, L.B., J. Edsjö, 2007

Sommerfeld Enhancement for slow WIMPS (non-tidaly disrupted clumps)

M.Lattanzi and J.Silk 2008

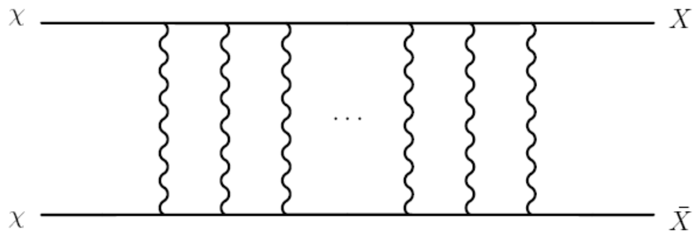


FIG. 1: Ladder diagram giving rise to the Sommerfeld enhancement for $\chi\chi \to X\overline{X}$ annihilation, via the exchange of gauge bosons.

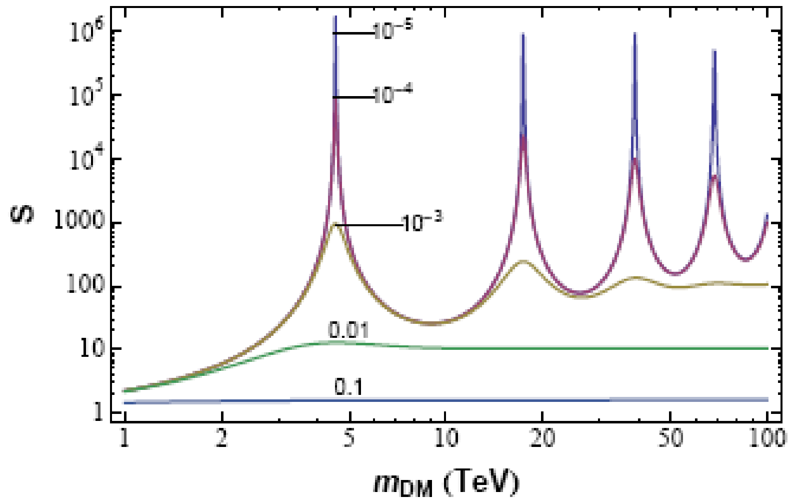


FIG. 2: Sommerfeld enhancement S as a function of the dark matter particle mass m, for different values of the particle velocity. Going from bottom to top $\beta = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$.

Or even:

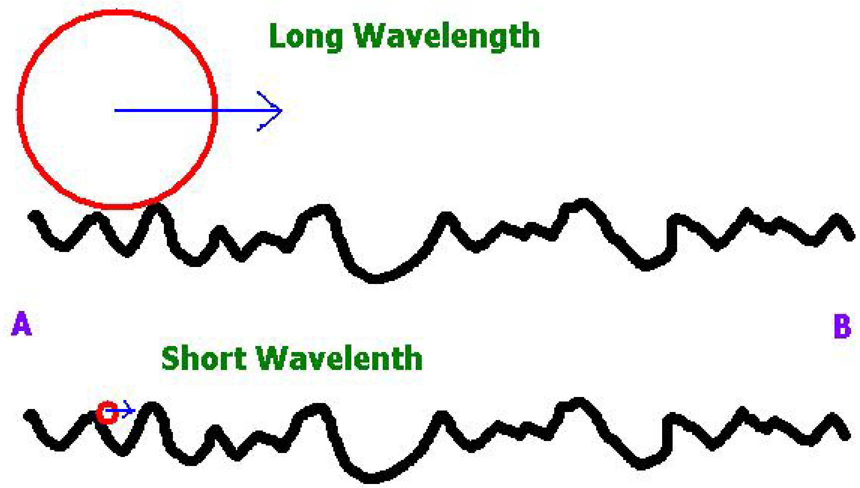
- The results of DAMA, PAMELA, ATIC, etc... might have been confirmed as DM signals.

=> there are very good prospects for VHE gamma ray astronomy playing a key role for the understanding of the nature, properties and distribution of Dark Matter in the next coming years.

3- Speed of light invariance

• Space-time at large distances is “smooth” but, if Gravity is a quantum theory, at very short distances it might show a very complex (“foamy”) structure due to Quantum fluctuations.

• A consequence of these fluctuations is the fact that the speed of light in vacuum may become energy dependent.



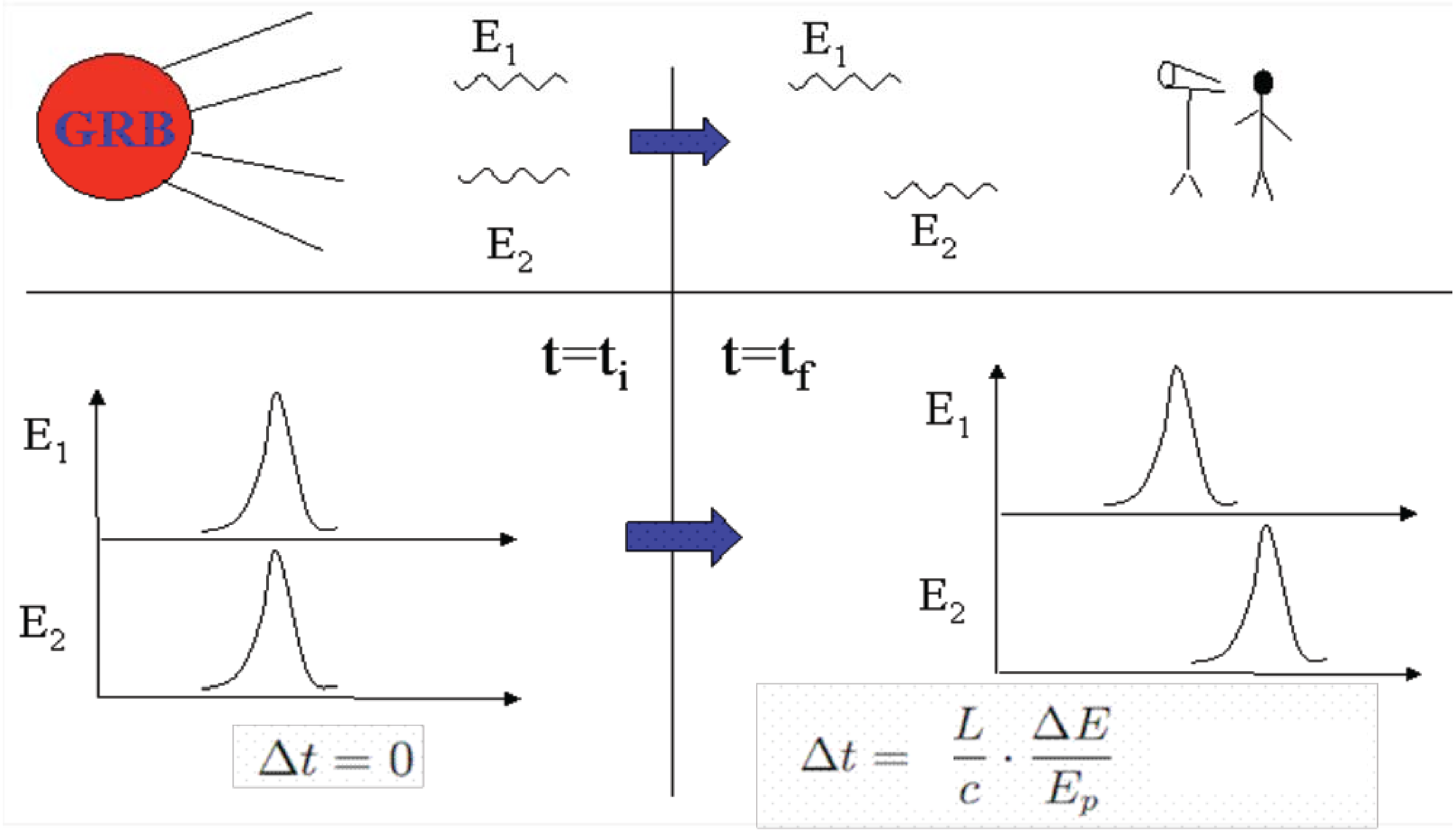
• The energy scale at which gravity is expected to behave as a quantum theory is the Planck Mass

$$E_{QG} = O(M_P) = O(10^{19})\ \mathrm{GeV}$$

- From a purely phenomenological point of view, the effect can be studied with a perturbative expansion. The arrival delay of γ-rays emitted simultaneously from a distant source should be proportional to the path L to the source and a the difference of the power *n* of their energies:

$$\Delta t \sim \frac{E^n - E_0^n}{E_{QG}^n} \frac{L}{c}$$

- The expected delay is very small and to make it measurable one needs to observe very high energy γ-rays coming from sources at cosmological distances which emit gammas with a sharp time structure


GRB
E_1
E_2
E_1
E_2
$t=t_i$
$t=t_f$
E_1
E_2
$\Delta t = 0$
E_1
E_2
$\Delta t = \frac{L}{c} \cdot \frac{\Delta E}{E_p}$

Results before MAGIC and HESS:

- Gamma rays of high energies (E)
- Cosmological distances (D)
- Short duration transients in time profiles

Pulsars, E up to 2GeV D about 10 kpc, (Kaaret, 1999)

$$M_{QG1} \geq 1.5 \times 10^{15} \text{ GeV}$$

AGNs, E up to 10 TeV D about 100s Mpc (Biller, et al, 1999)

$$M_{QG1} \geq 4 \times 10^{16} \text{ GeV}$$

$$M_{QG2} \geq 6 \times 10^{9} \text{ GeV}$$

35 GRBs, E up to MeV D beyond 7000 Mpc (Ellis, et al, 2005)

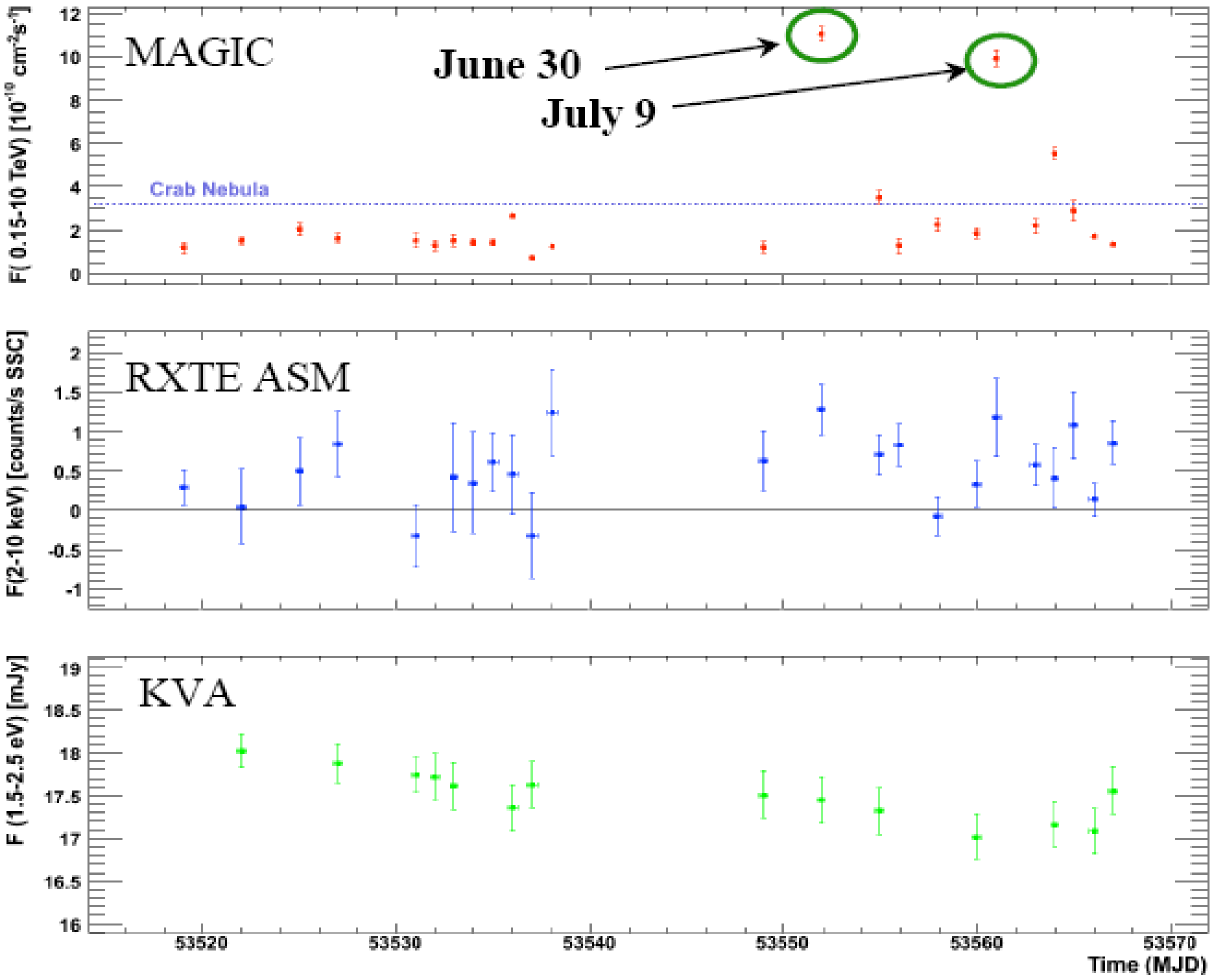
$$M_{QG1} \geq 0.9 \times 10^{16} \text{ GeV}$$

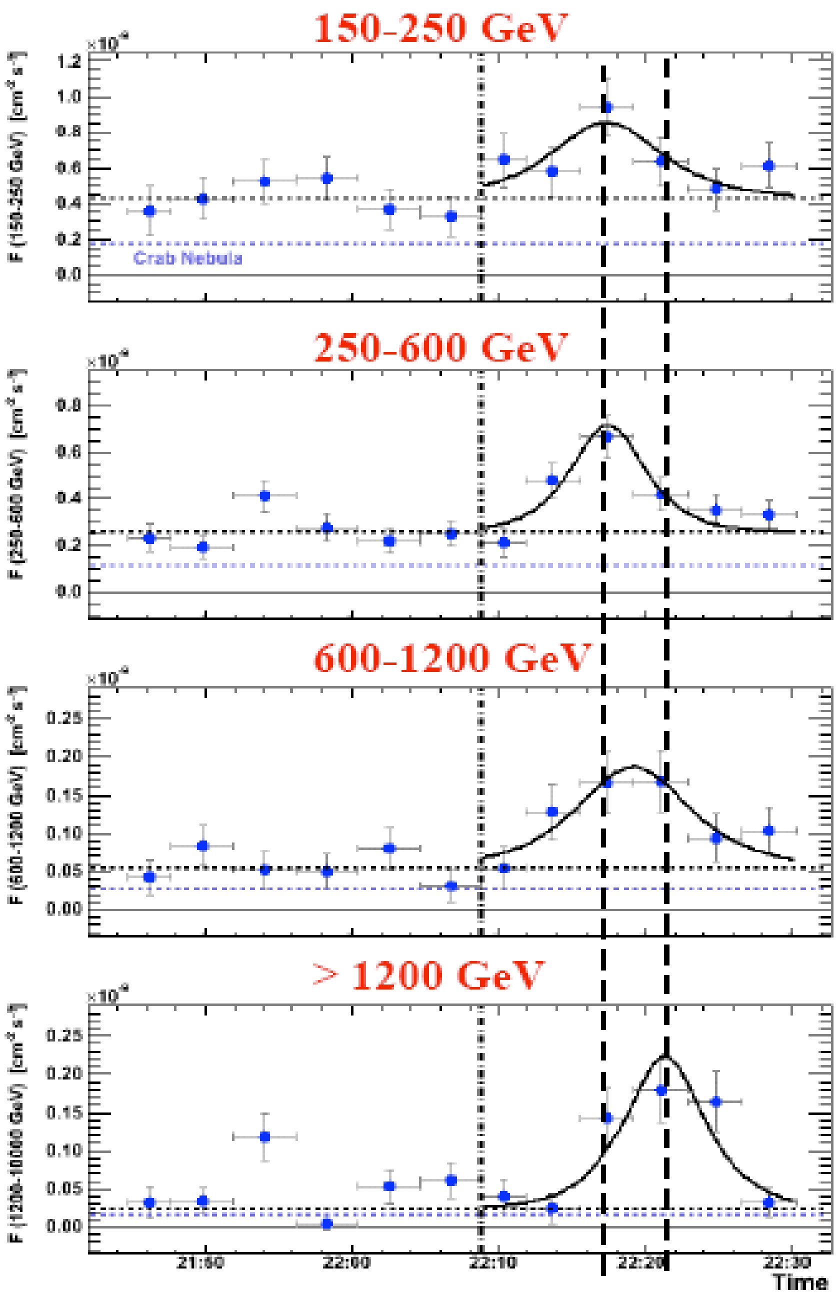
$$M_{QG2} \geq 6 \times 10^{5} \text{ GeV}$$

A.Sakharov 2007

MAGIC observation of Mkn 501 flare in 2005 (z=0.034)

2.1- Light curves (LCs): Gamma, X-rays, Optical





LCs for different energy ranges (4 min bins)

July 9

Flare is seen in all energy ranges

Astrophys.J. 669, 862 (2007)

MAGIC Results (ECF Method):

Linear

$$\tau_l \; = \; (0.030 \pm 0.012) \;\; \mathrm{s/GeV}$$

$$M_{\mathrm{QG1}} = 1.398 \times 10^{16} (1 \;\; \mathrm{s}/\tau_l)$$

$$M_{\mathrm{QG1}} = (0.47^{+0.31}_{-0.13}) \times 10^{18} \;\; \mathrm{GeV}$$

Quadratic

$$\tau_q \; = \; (3.71 \pm 2.57) \times 10^{-6} \;\; \mathrm{s/GeV^2}$$

$$M_{\mathrm{QG2}} = 1.182 \times 10^{8} (1 \;\; \mathrm{s}/\tau_q)^{1/2}$$

$$M_{\mathrm{QG2}} = (0.61^{+0.49}_{-0.14}) \times 10^{11} \;\; \mathrm{GeV}$$

95% CL

$$M_{\mathrm{QG1}} > 0.26 \times 10^{18} \;\; \mathrm{GeV}$$

$$M_{\mathrm{QG2}} > 0.27 \times 10^{11} \;\; \mathrm{GeV}$$

Phys.Lett B**668**, 253 (2008)

- Caveat:

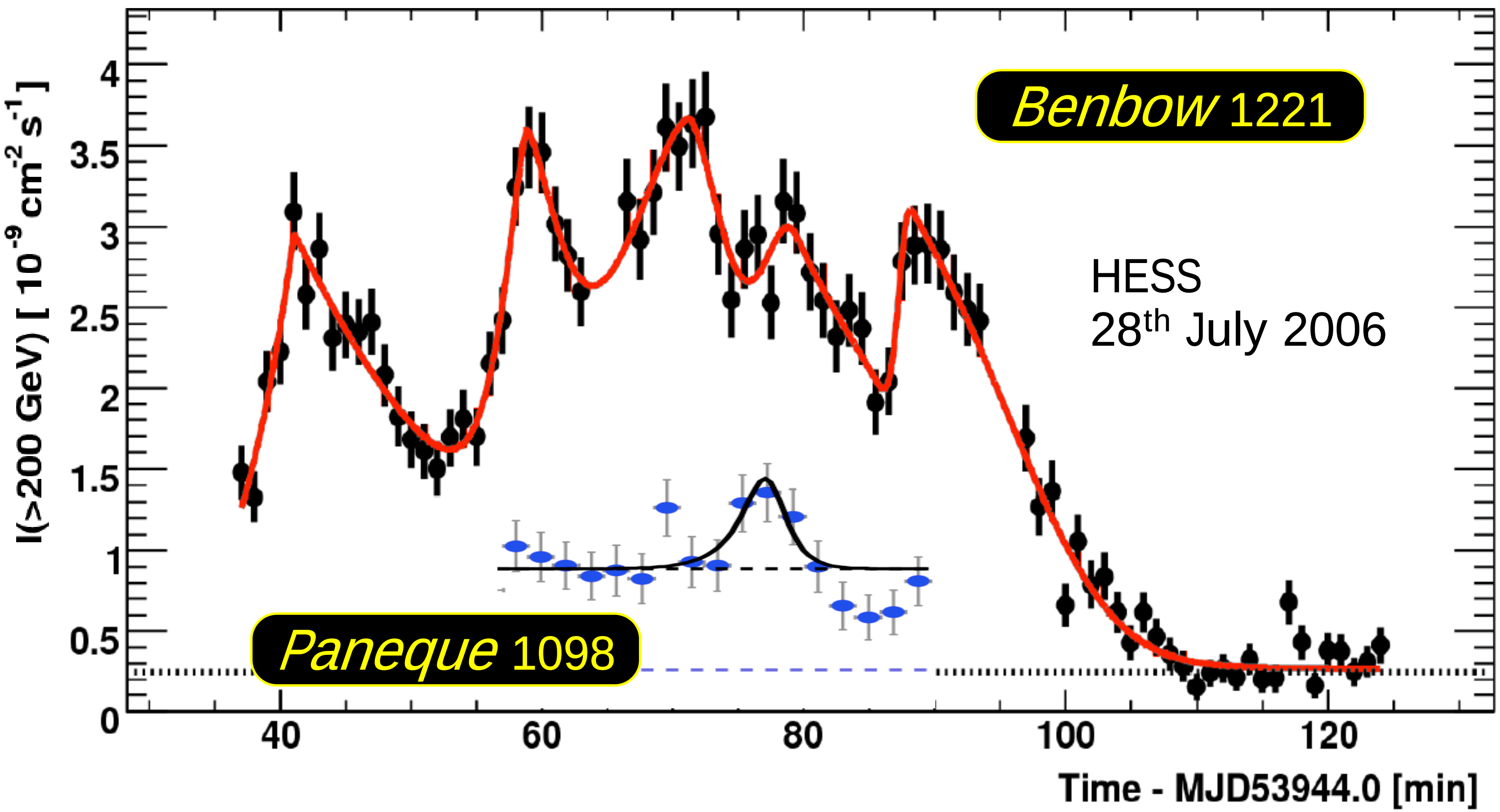
how to disentangle propagation delays from source-intrinsic delays ?.

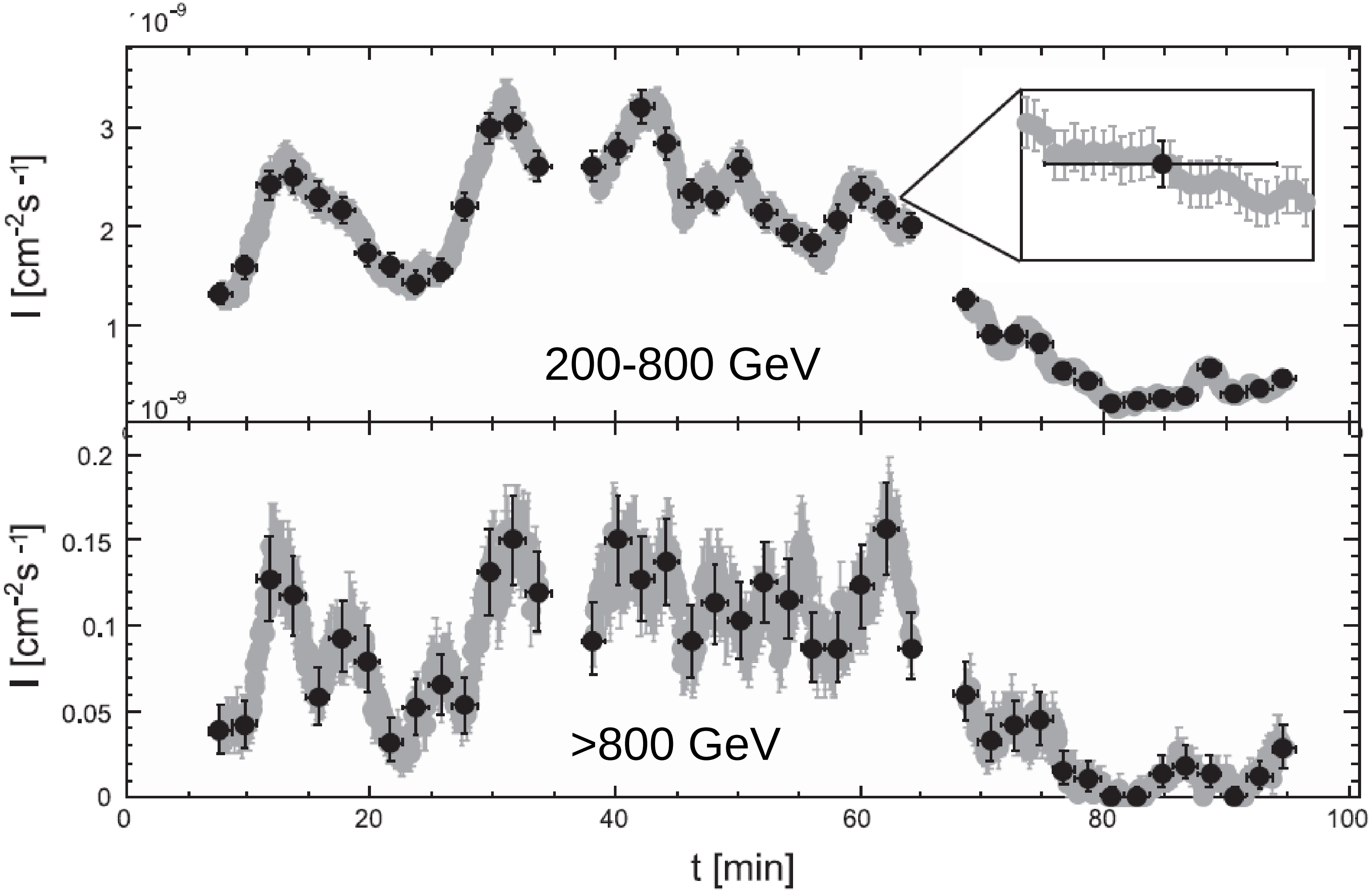
a) observe sources at different redshifts and check delay proportional to distance.

b) use geometrical time stamps (pulsars).

a) sources at different redshifts…

HESS observation of PKS 2155 flare in 2006
(z=0.116)

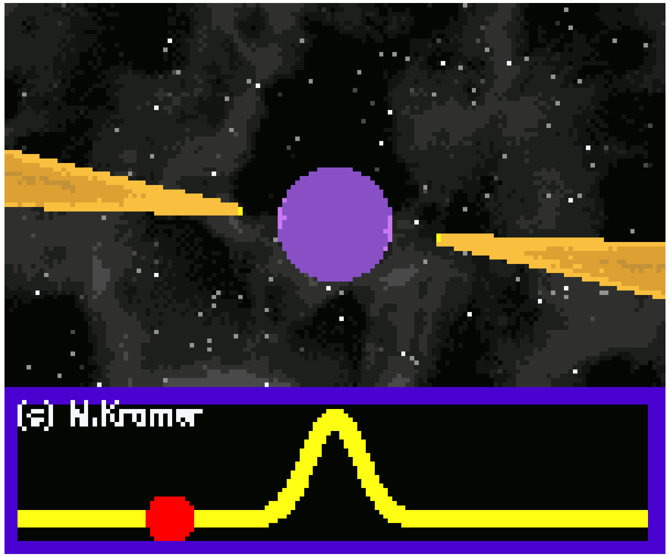




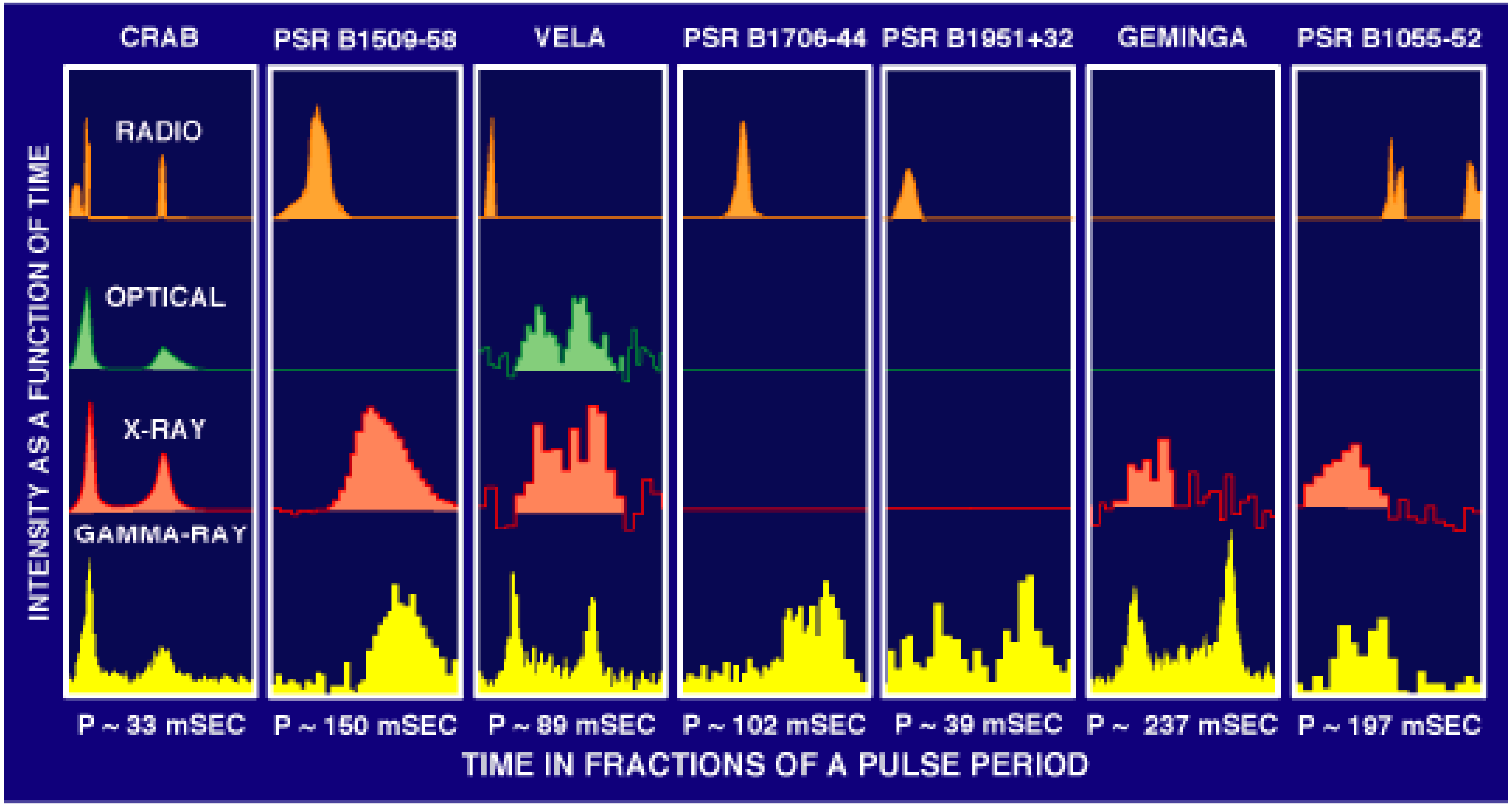
- No visible delay
- $M_{QG1} > 0.6 \times 10^{18}$ GeV
- Does not contradict MAGIC

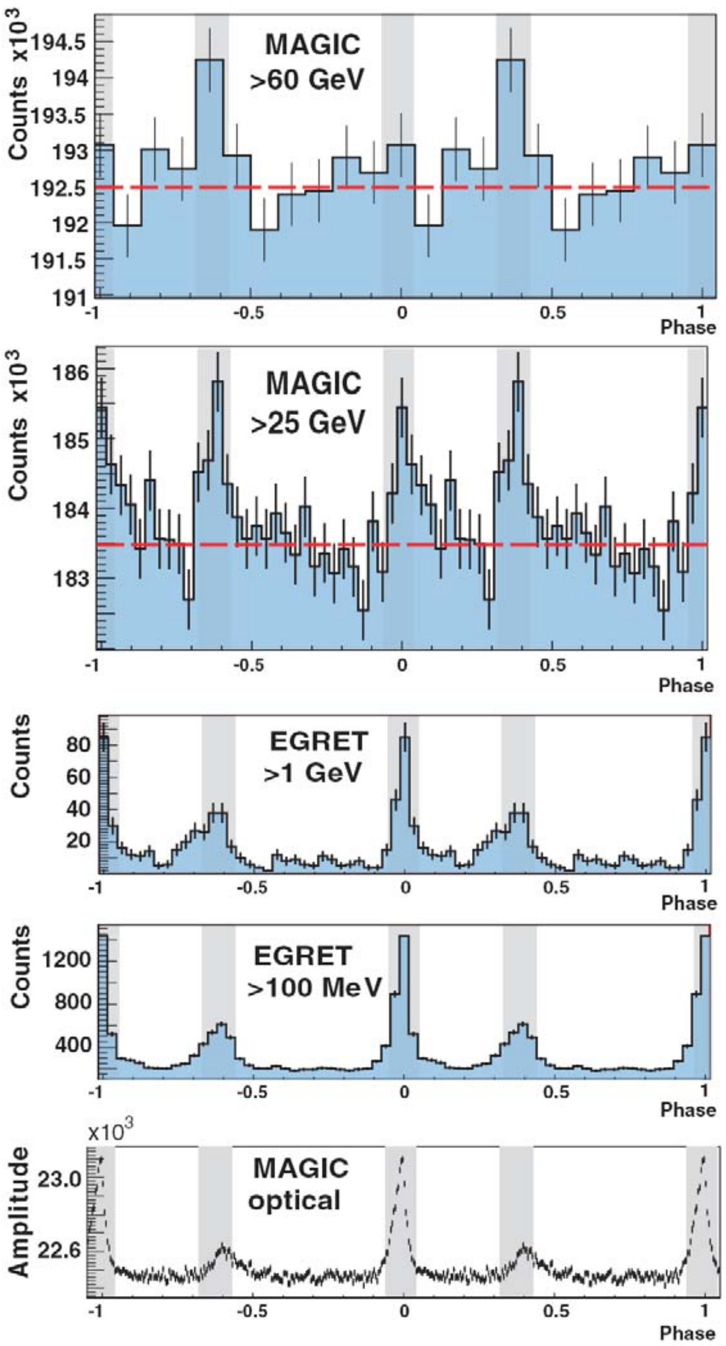
$$M_{\mathrm{QG1}} = (0.47^{+0.31}_{-0.13}) \times 10^{18}\ \mathrm{GeV}$$

b) geometrical time stamps…



EGRET Pulsars





2007-2008 MAGIC detection of the Crab Pulsar

Science 322 (2008) 1221

Detailed analysis ongoing.

What next ?.

- **GRBs:** (try to catch them at VHE)

  - Good timing, very large distance, low energies (-> linear term)

  - Better statistics are expected with GLAST.

  - A MAGIC detection around 100 GeV would probably yield to very good sensitivity to energy-dependent time delays.

- **AGNs:** (wait actively for next flare)

  - Bad timing, large distances, high energies (-> quadratic term)

  - Distance can improve with better sensitivity instruments, but paying the price of lower energies due to EBL. Timing can improve also with sensitivity.

- **Pulsars:** (try to observe them at VHE)

  - Very good timing, very short distance, low energies (-> linear term)

  - With better instruments the time resolution will improve and the detected energy might still increase a bit.

  - If GLAST and MAGIC pulse shapes are similar, a combined analysis may give competitive limits.

4- Outlook

Satellites

Fermi (GLAST)

- Major HE gamma-ray instrument.
- Thousands of new HE sources expected.
- LAT: coverage from 20 – 300 GeV.
- Launched in May 2008.
- Many discoveries and new results coming...

Cherenkov Telescopes - 1

MAGIC-II

- New, improved 17m telescope.
- Faster FADCs (up to 4Gsps) and a better high-QE camera.
- Factor 2-3 improvement in sensitivity.
- First light in 2009.

Cherenkov Telescopes - 2

HESS-II

- New 28m telescope.
- 2048 pixel camera.
- Lower energy threshold 40-50 GeV
- First light in 2010

The present generation of ground instruments may detect and study around 100 sources,

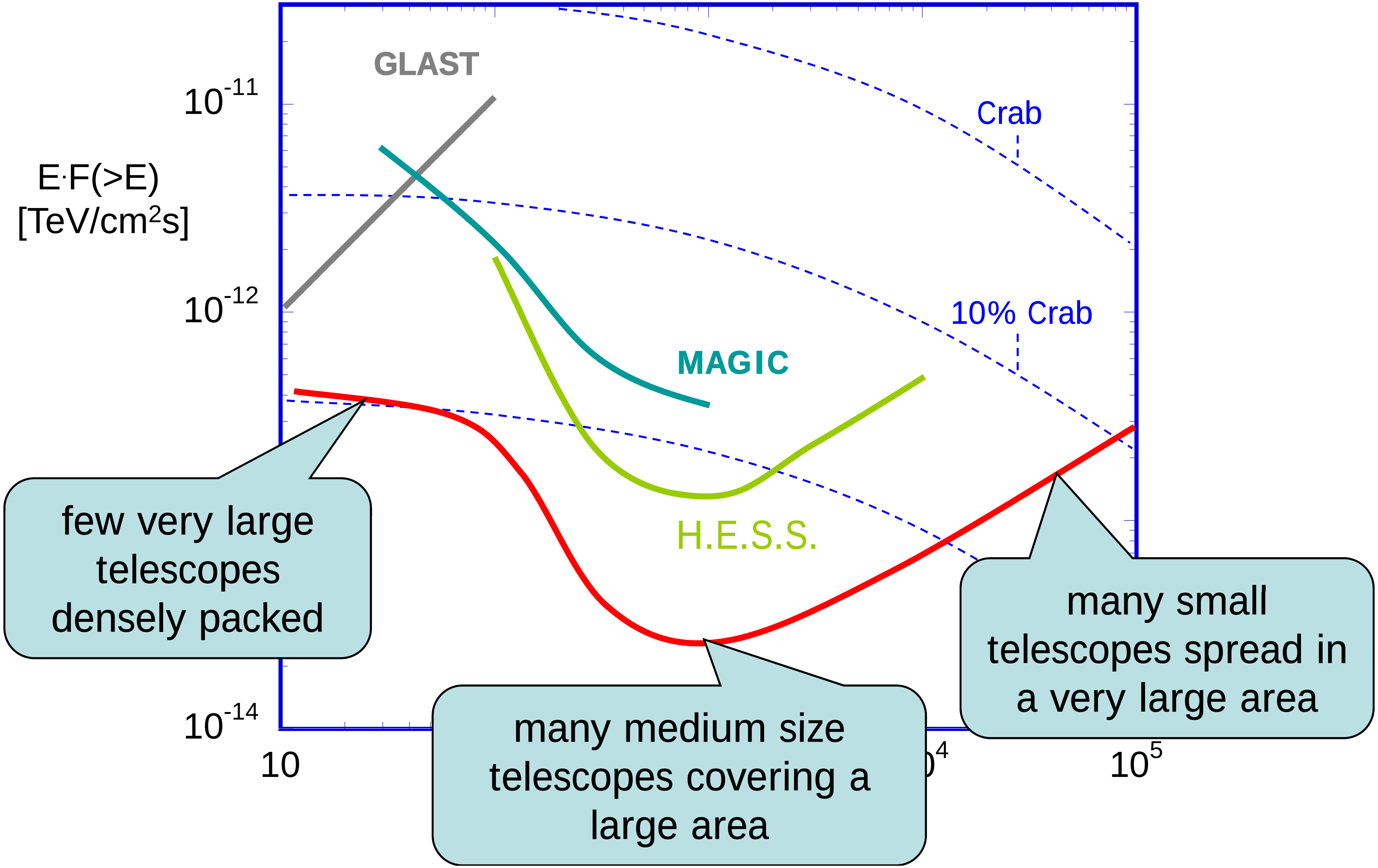
but a lot of physics potential still open…

What next ?

CTA

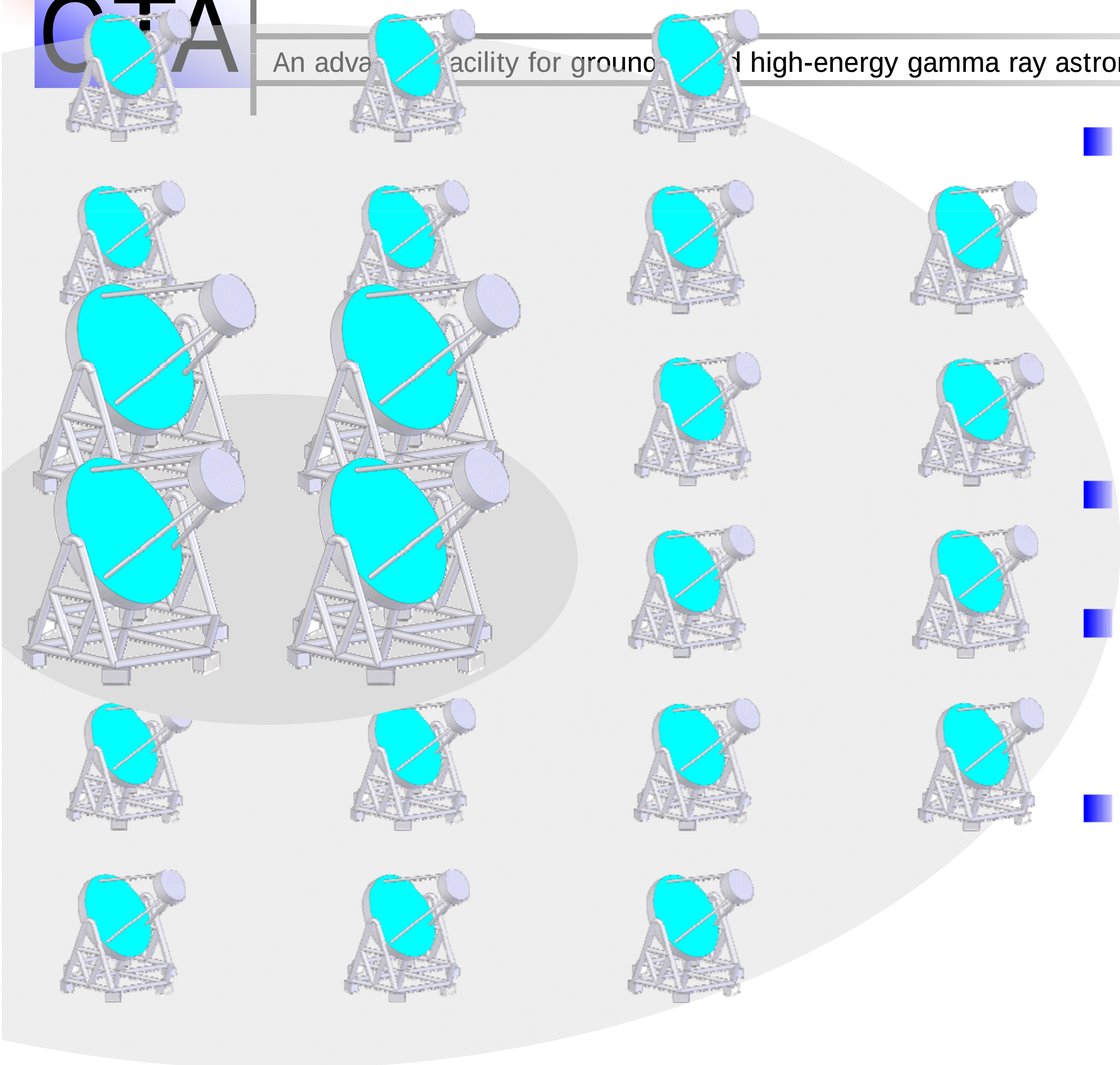
Possible CTA sensitivity

An advanced facility for ground-based high-energy gamma ray astronomy



CTA

An adva… acility for ground… high-energy gamma ray astronomy



Not to scale !

- Aims to explore the sky in the 10 GeV to 100 TeV energy range with ~10 better sensitivity and better energy and angular resolution.
- Builds on demonstrated technologies.
- Combines guaranteed science with significant discovery potential.
- Full sky coverage:

  South array ~100M€

  North array ~50M€

Status and Outlook

- ASPERA-ApPEC give full support to CTA in its roadmap.

- CTA also included in the ASTRONET roadmap.

- Recently included in the ESFRI updated roadmap.

2008 - 2010 -> Technical Design Report
2010 - 2012 -> Preparatory Phase (Array Prototyping)
2012 - 2017 -> Array Construction

partial operation could start already in 2012-2013

Summary:

- VHE gamma astronomy may play an UNIQUE role in the understanding of Dark Matter and other Fundamental Physics issues.

- VHE gamma astronomy is today in a golden age and the prospects for tomorrow and the near future are even more exciting…

stay tuned !.