Search for fundamental physics with H.E.S.S. & CTA

Christian Farnier
Oskar Klein Centre – Stockholm University

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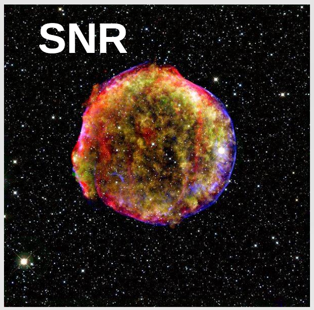
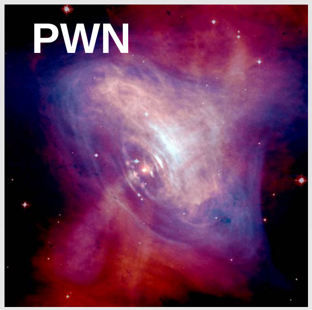
OUTLINE

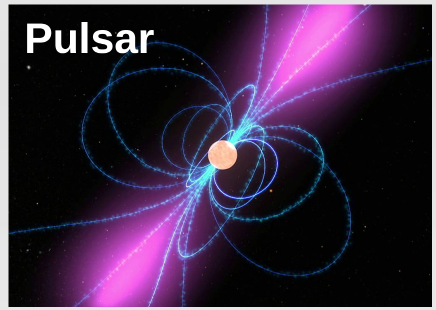
- VHE astronomy
- Imaging Atmospheric Cherenkov Telescopes
- Few results on the search for fundamental physics
- Conclusion

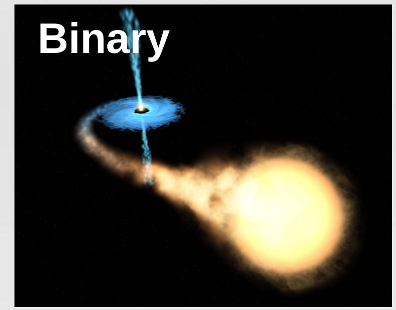
γ-ray astronomy : probing the non-thermal Universe

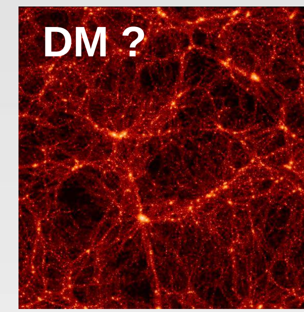
Galactic sources

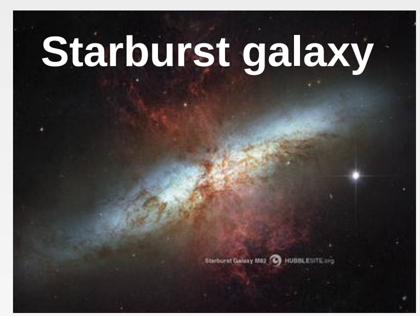






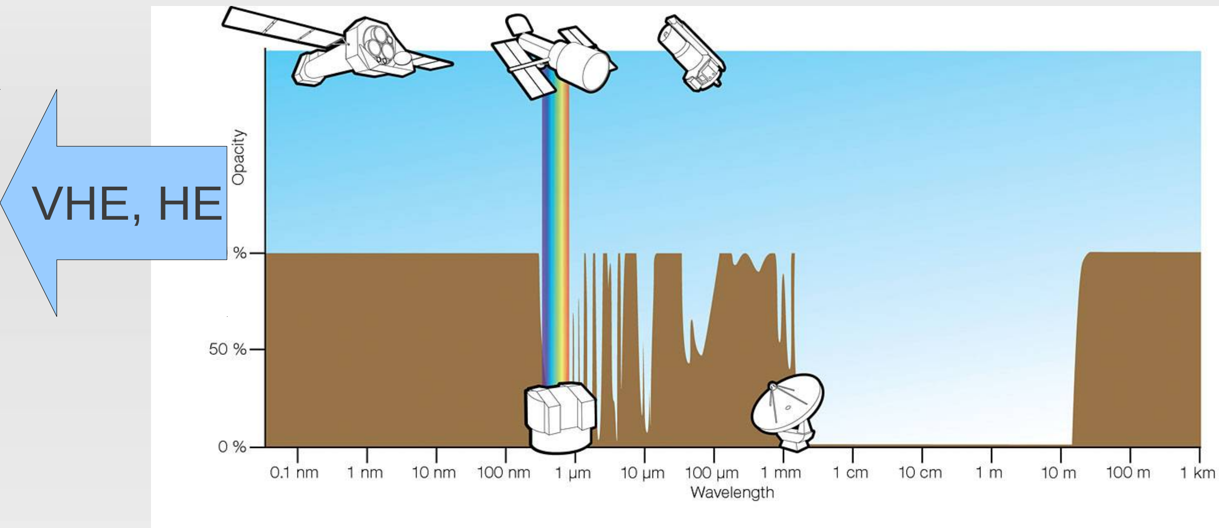


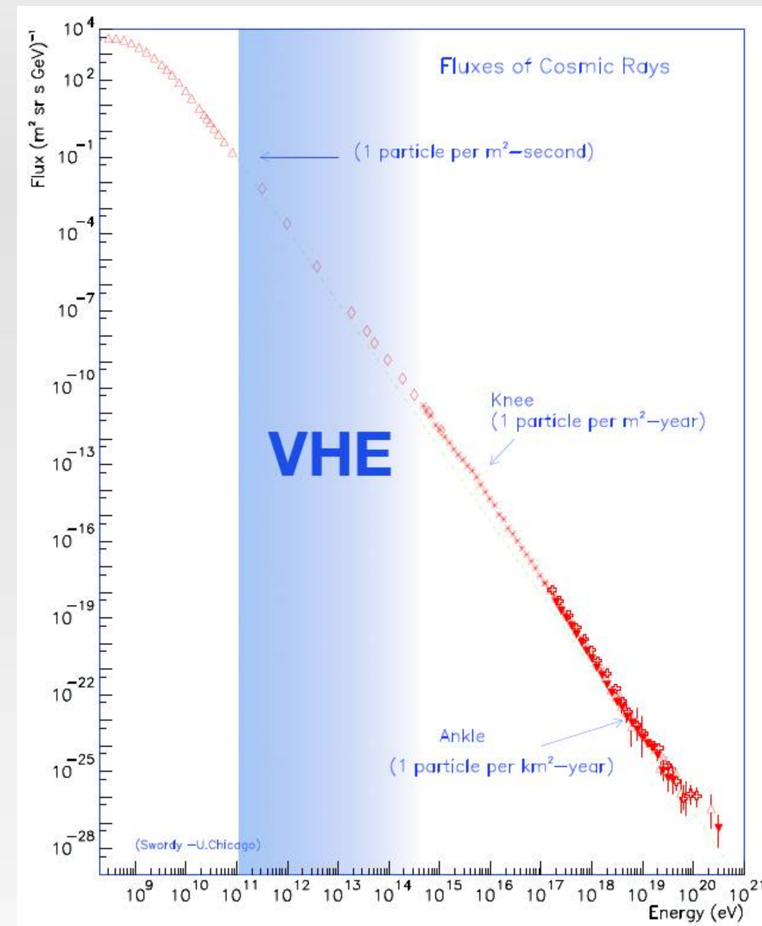




Extragalactic sources

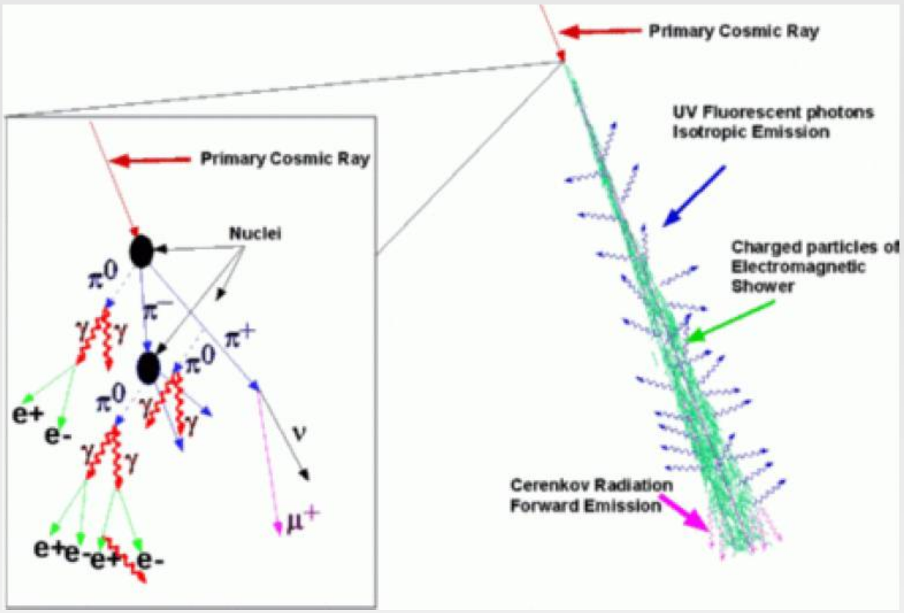
Detecting γ-rays

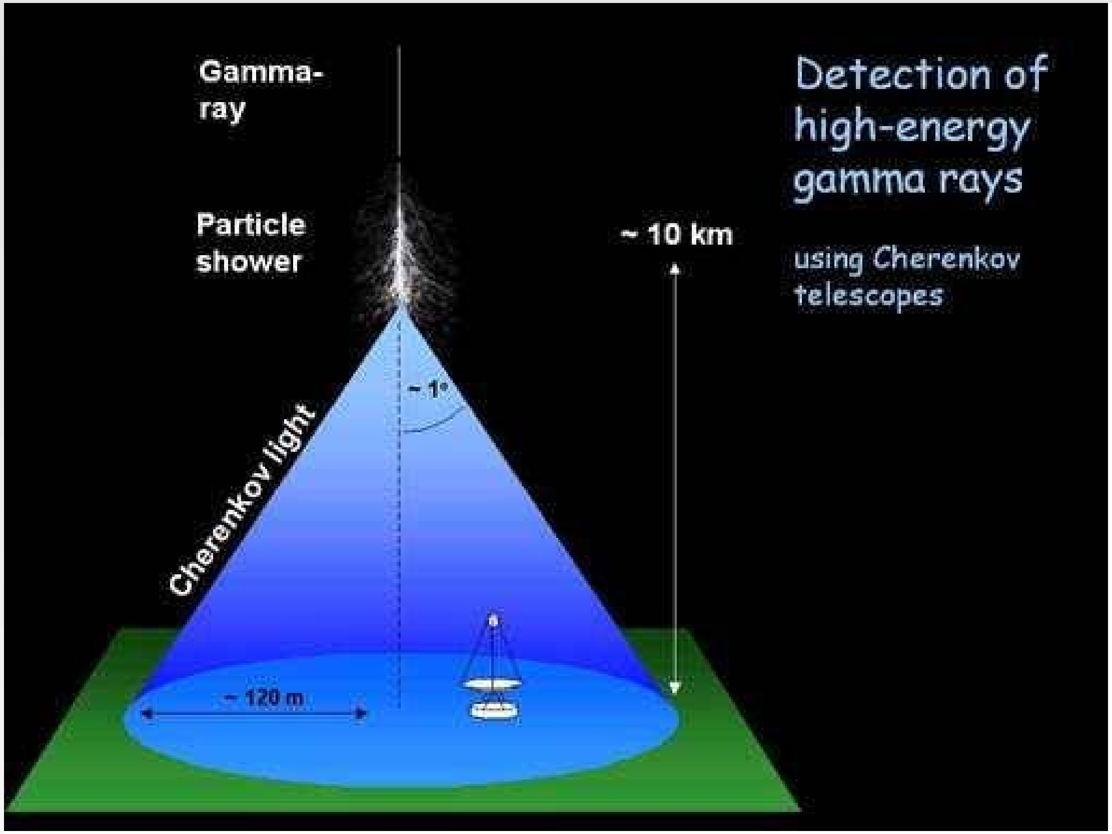




- Convention
  HE : High Energy (E ≥ 100 MeV)
  VHE : Very High Energy (E ≥ 100 GeV)
- γ-rays are not deflected by B → study of sources and production mecanisms
- Atmosphere is opaque to γ-rays
  Satellite exp. for HE
  IACTs for VHE (very low fluxes $10^{-(11\text{-}12)}$ ph cm^{-2} s^{-1})

Imaging Atmospheric Cherenkov Telescope (IACT) principle



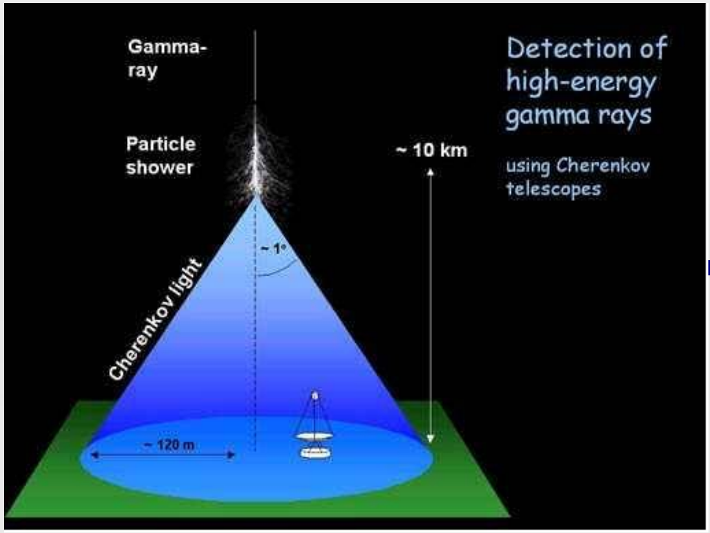


Backgrounds:

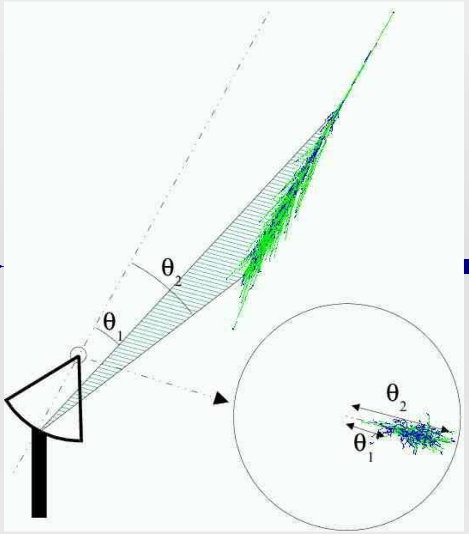
- the night sky (stars, Moon, …) : duty cycle ~1000h/y
- Charged cosmic rays (p,e,...) rate x10^5 higher than the brightest TeV γ-ray source.

Credits : W. Hofmann

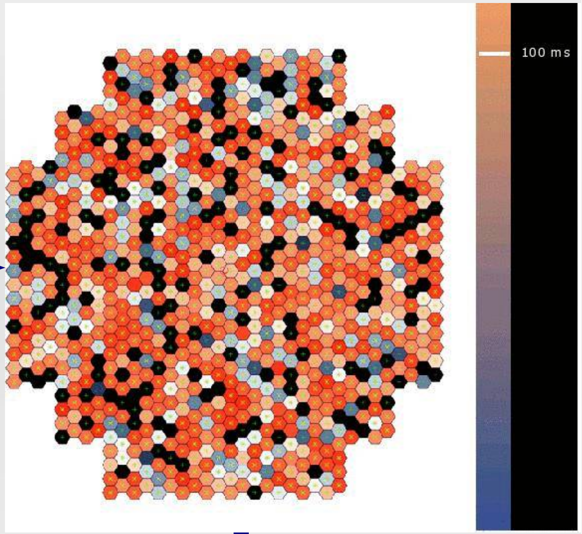
IACT principle (cntd)



Cherenkov photons production.



Shower development recorded in the focal plane.



Ultra fast (~10ns) acquisition camera.

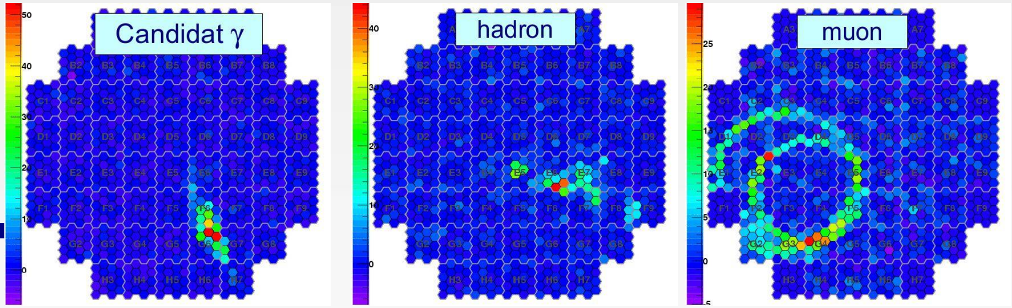


Image based event selection / background rejection.

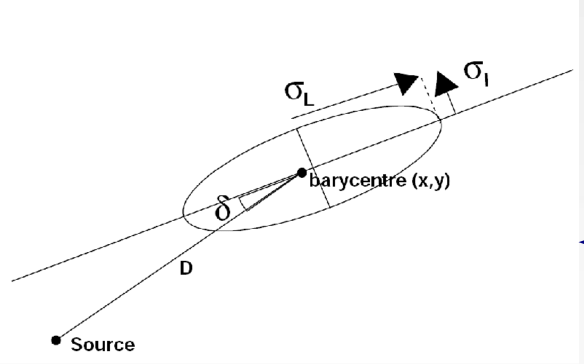
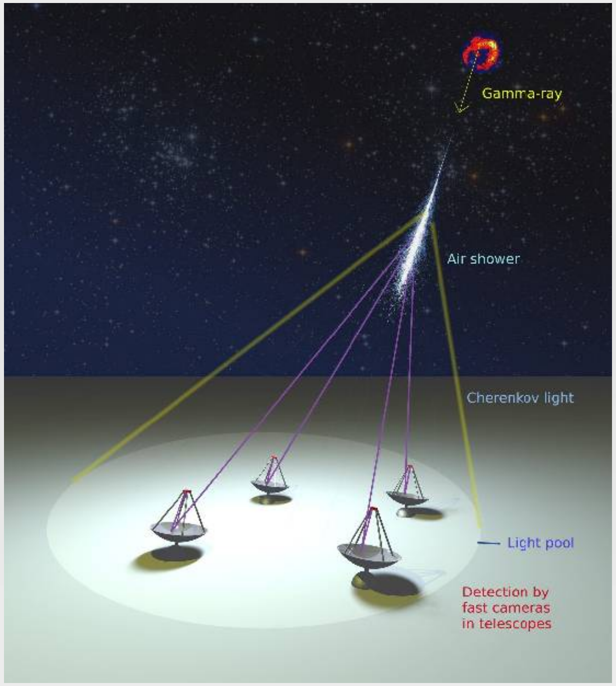
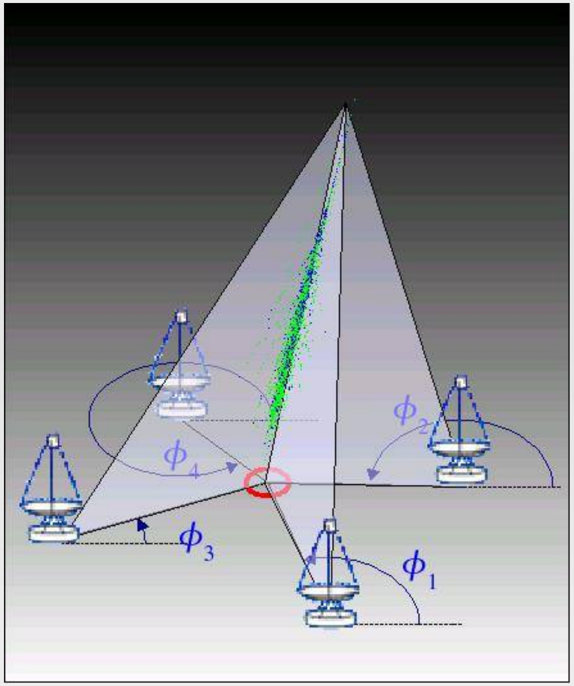
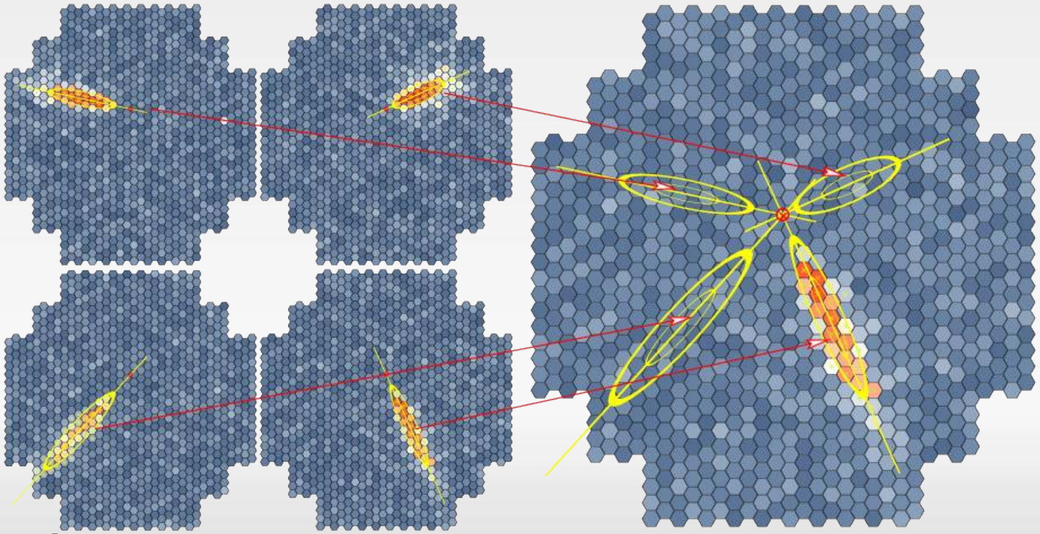


Image parameters reco. (direction, energy)

IACTs - Stereoscopic system







In the current experiments, up to 5 IACTs are put together, allowing to observe the same shower from several point of view.

Advantages :

- Improved bckg rejection (muons)
- Incoming direction degeneracy dispelled
- Improved angular resolution
- Improved energy resolution

+ new shower reconstruction algorithms developped based on intrinsic 3D shower properties.

Census of IACT experiments

The most advanced : H.E.S.S. 2

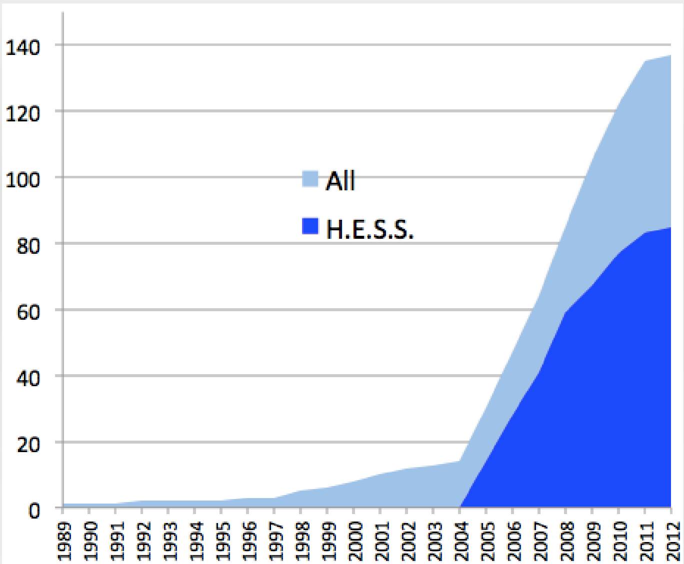
Phase 1 : 4x

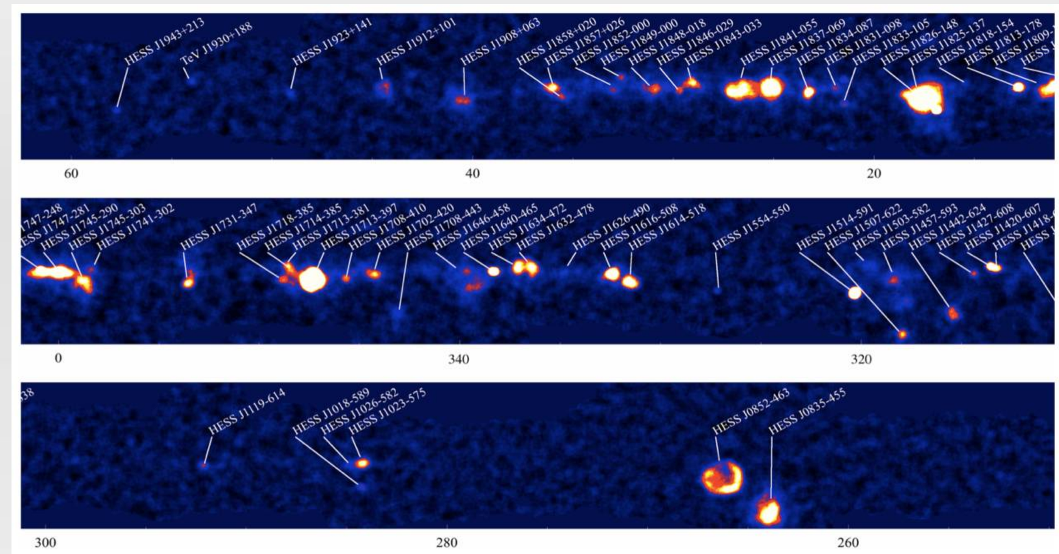
∅: 13m
Camera :1 ton, 960 PMTs
Begining of operation : 2004

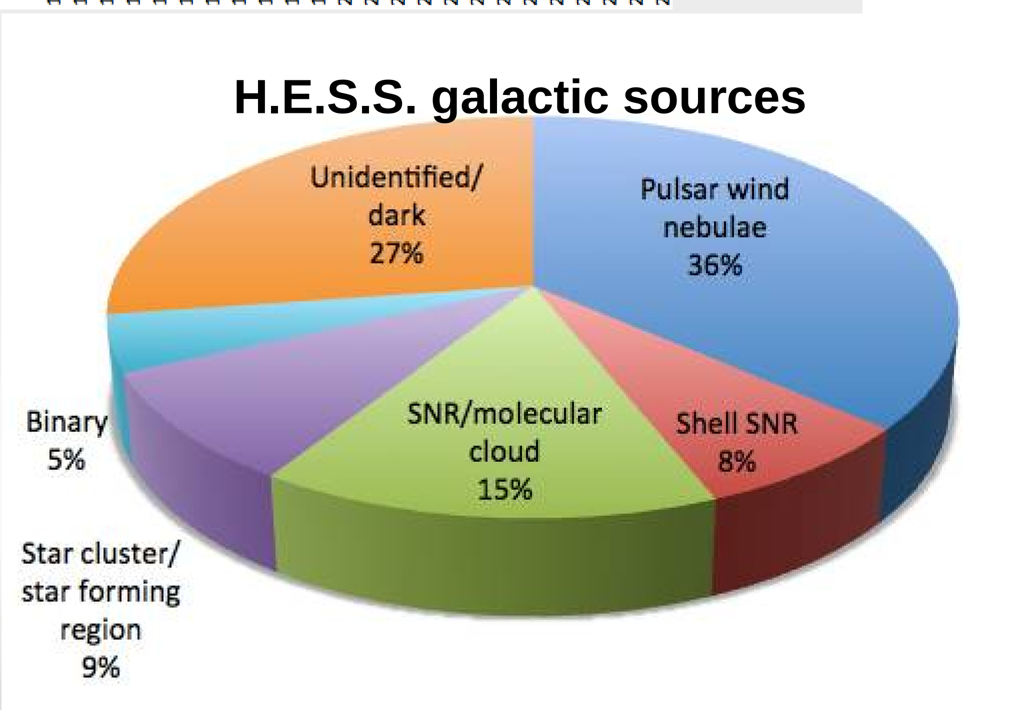
Phase 2 : + 1

∅: 28m
Camera :2 ton, >2000 PMTs
Begining of operation : 09/2012

H.E.S.S. astrophysical results

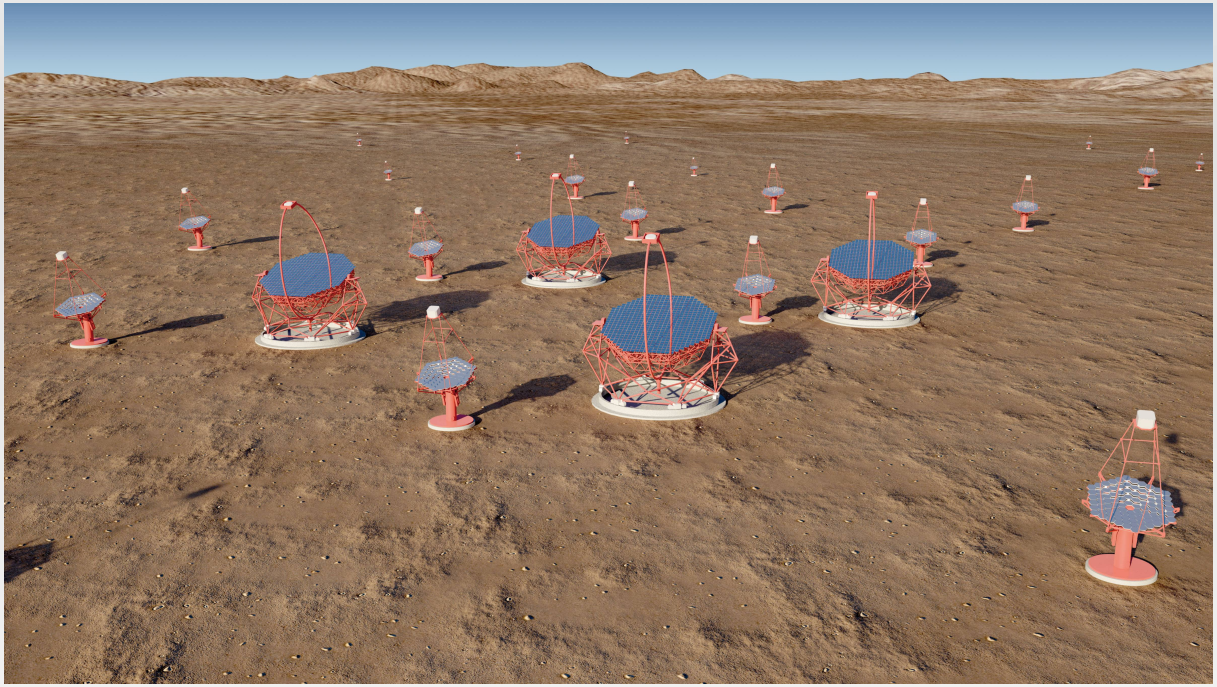


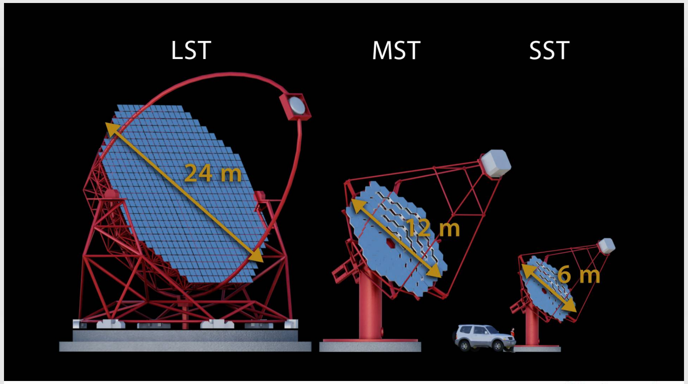


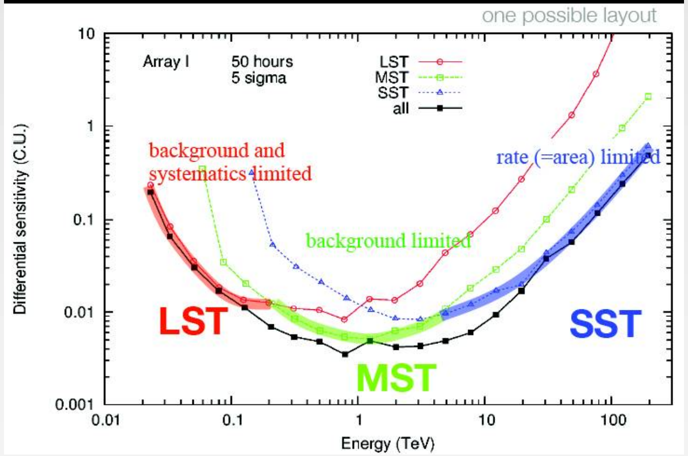


+ 19 extragalactic sources

CTA - Cherenkov Telescope Array





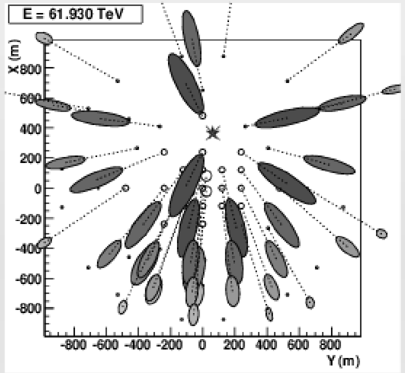


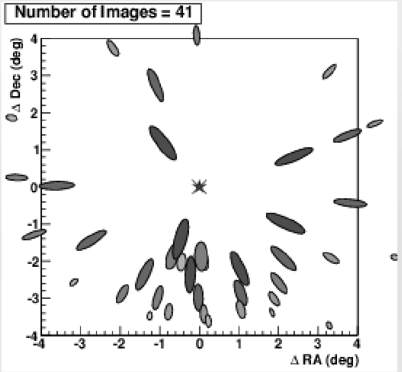
- 27 countries
- > 1000 scientists
- 2 arrays
- 3 types of telescopes

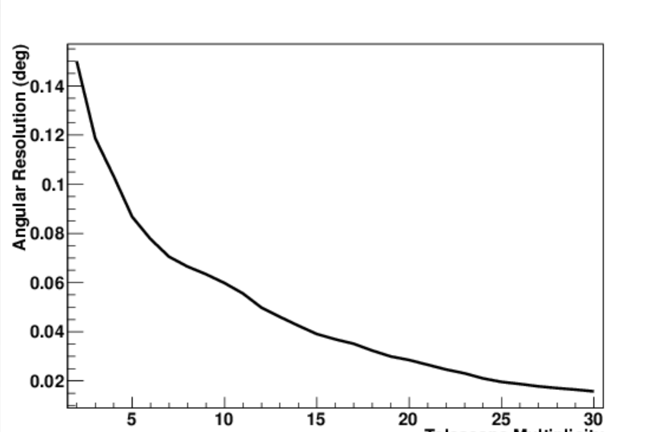
- Currently in the preparatory phase
- Construction phase will start in 2014
- >1000 sources expected
- ~ 1000h obs/y

CTA : the "perfect" stereoscopic system

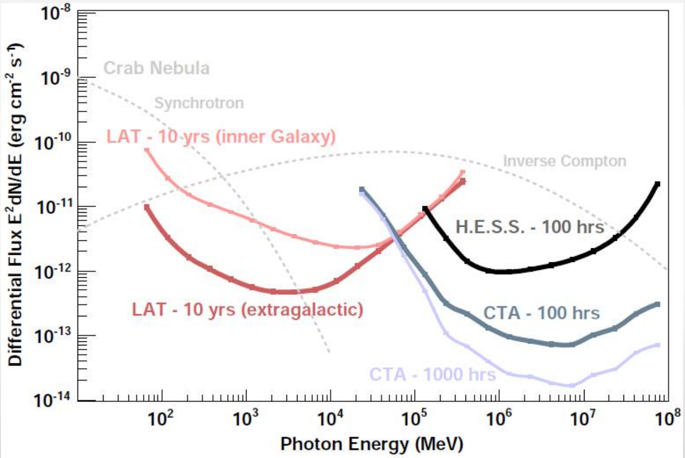
- The most advanced stereoscopic systems have only 5 (4) telescopes H.E.S.S. (VERITAS).
- CTA will have dozens (to cover an area O(km^2)), most probably of 3 (or 4) different sizes :
  - Large : 24m
  - Medium : 12m
  - Small : 6-8m
- Which will allow cover broader energy range and improve the performances :
  - Angular & energy resolutions,
  - Background rejection,
  - Sensitivity,
  - ….







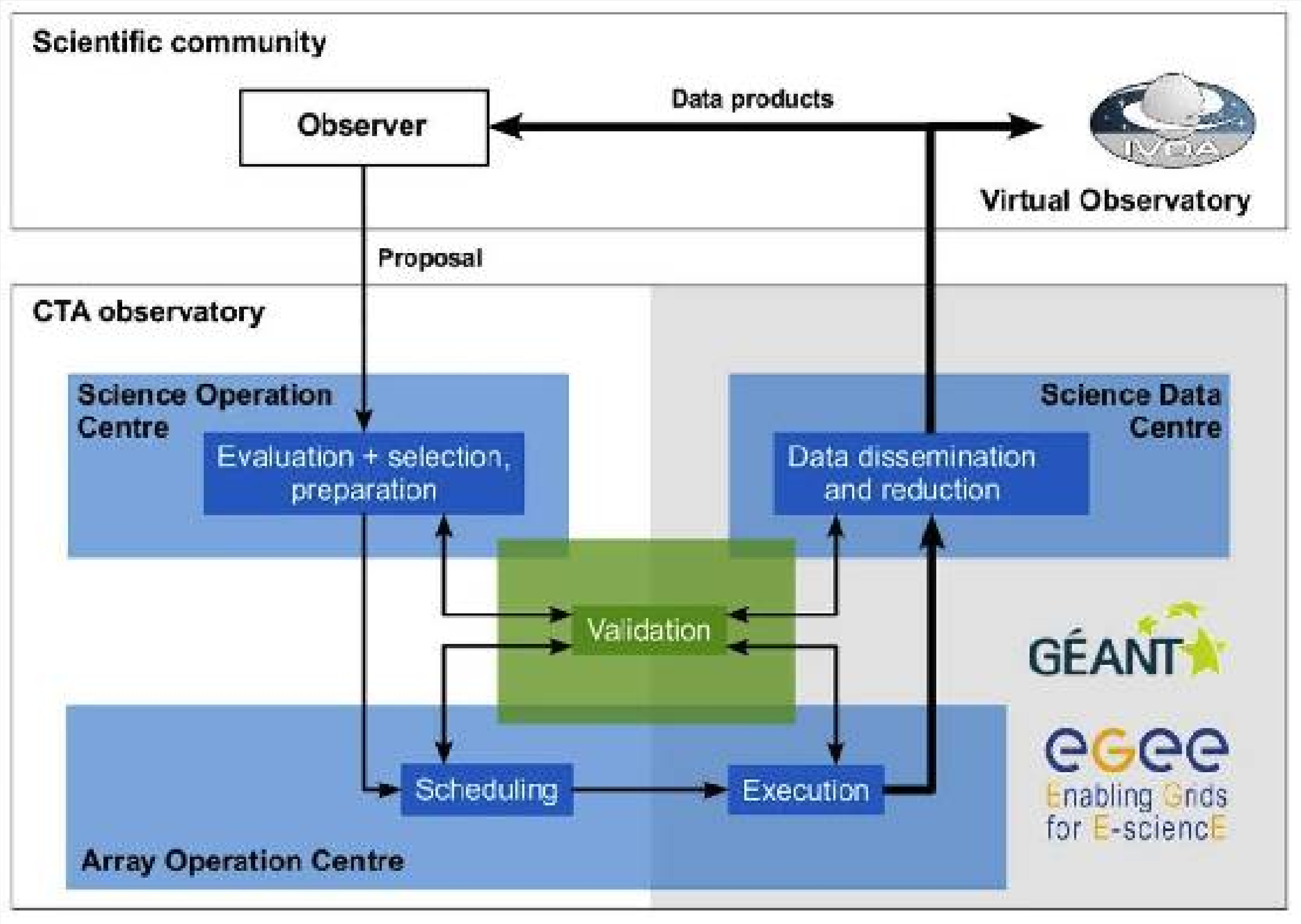
CTA consortium 2012



CTA observatory

First open observatory in the VHE domain

Large number of users from different fields of science



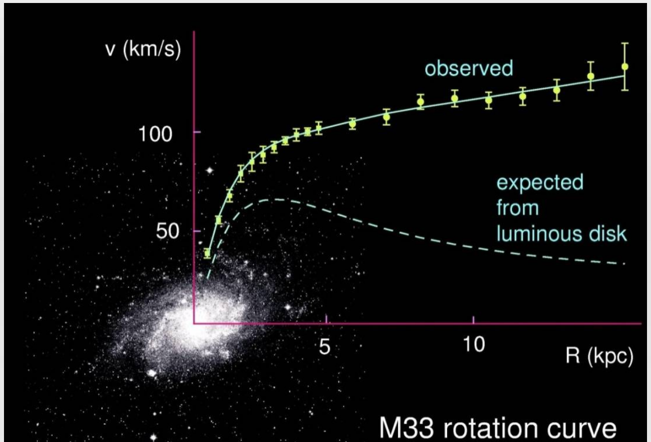
Some searches for fundamental physics :

1. Dark matter
2. Axion-like particles
3. Lorentz Invariance violation
4. Primordial black holes

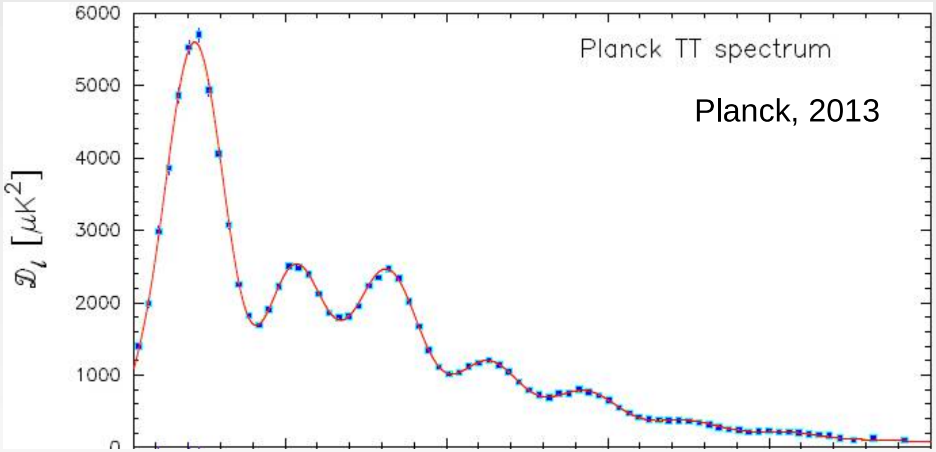
1. Dark matter in the Universe – really ?

Coma galaxy cluster

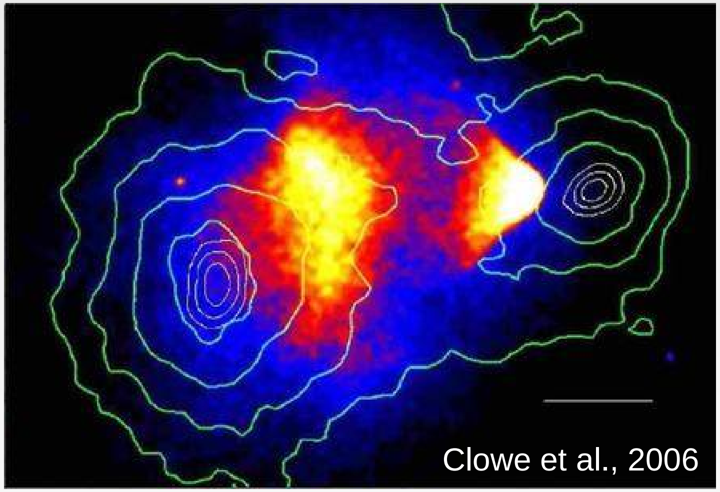
Fritz Zwicky, 1933: "If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter."



M33 rotation curve
Bergstrom, Rep. Prog. Phys. 2000



Planck, 2013



Clowe et al., 2006

YES ! At all scale.

γ-ray flux from WIMP annihilations

$$\Phi^{\gamma}_{WIMP}(E,\Psi) = J(\Psi) \times \Phi^{PP}(E)$$

$$J(\Psi) = \int_{los} dl(\Psi)\rho^2(l)$$

$$\Phi^{PP}(E) = \frac{1}{2}\frac{<\sigma v>}{m^2_{WIMP}}\sum_f \frac{dN_f}{dE} B_f$$

- Astrophysic factor :
  - determine the nb of annihilations
    → intensity of gamma-rays

Uncertainties :

  - density profile, diffusion, absorption,...

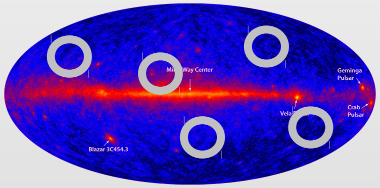
- Particle physic factor :
  - determine the nb of γ-ray produced per annihilation
    → spectral shape

Uncertainties :

  - cross section, mass, branching ratios,...

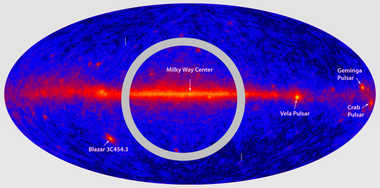
DM targets for indirect γ-ray searches

Dwarf galaxies



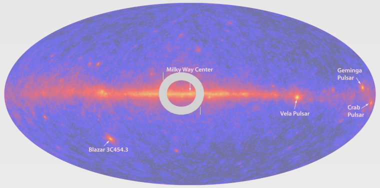
Pros: increasing number of objects, bckg free
Cons: amount of DM limited

Galactic Halo



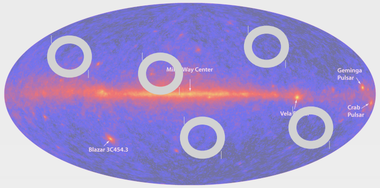
Pros: large integration region, DM profile well estimated
Cons: bckg

Galactic Centre



Pros: high DM density
Cons: large uncertainties, several std γ-ray accelerators

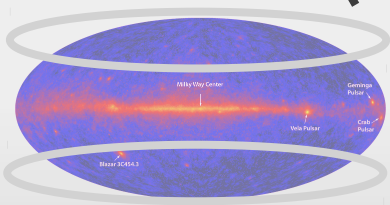
Galaxy Clusters



Pros: number of sources, large amount of DM
Cons: distance, bckg

Not covered in this talk

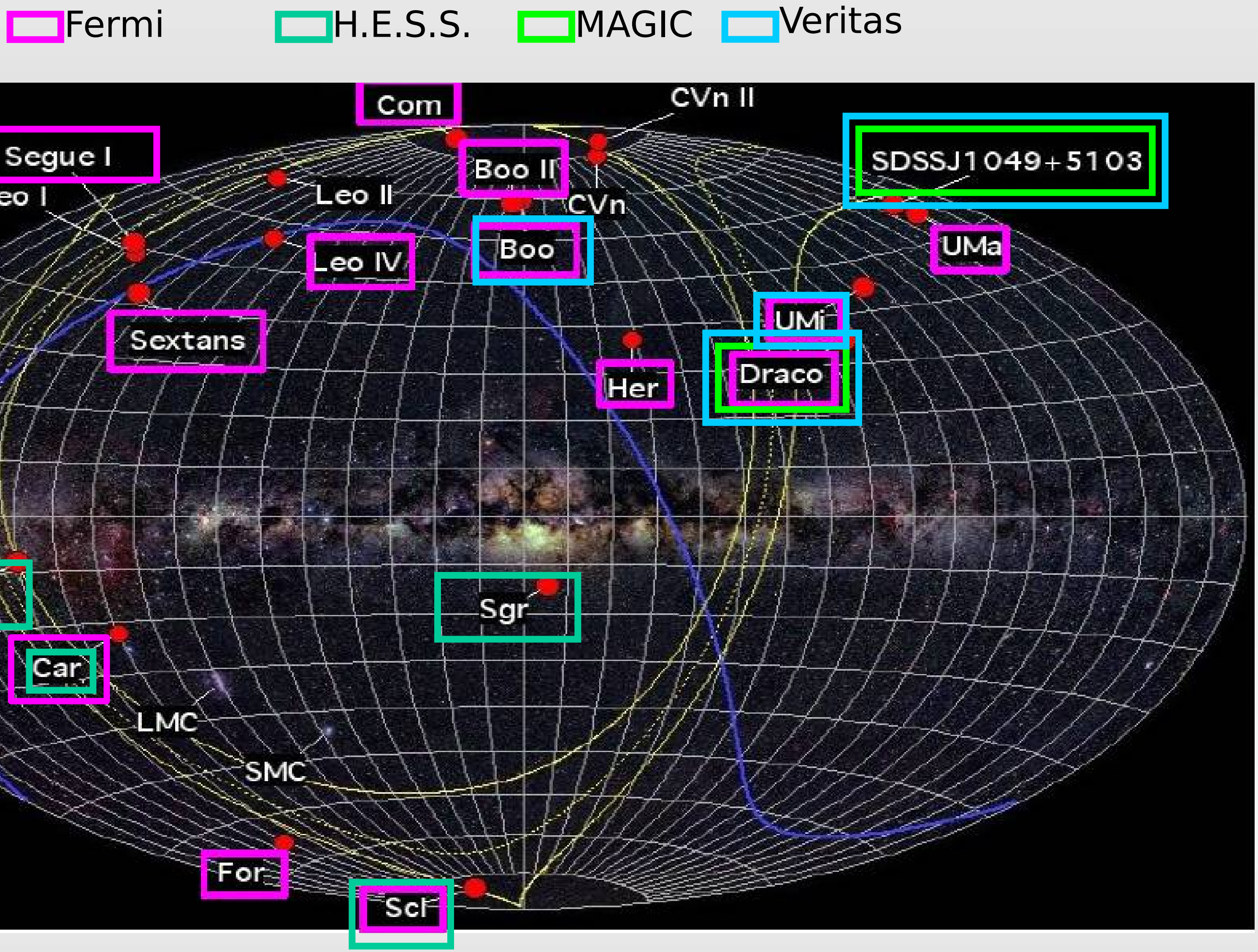
Extragalactic



Pros: large integration region
Cons: low DM density, bckg

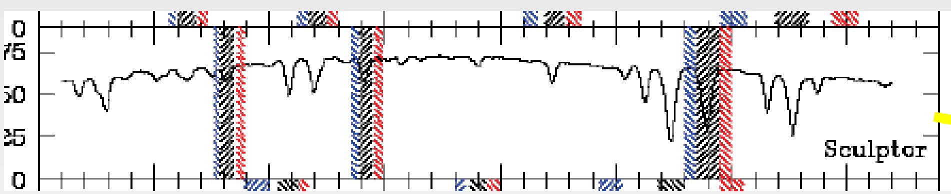
Dwarf spheroidal galaxies

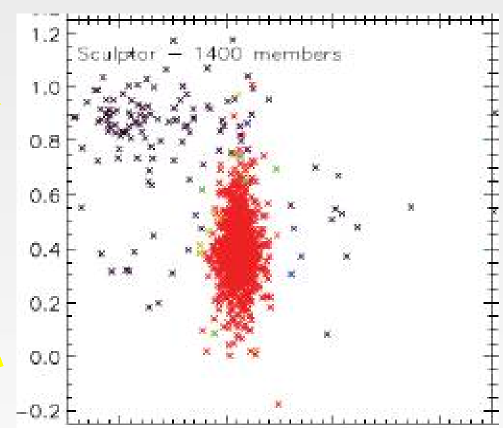
Dwarf galaxies probed in gamma-rays as in 2012

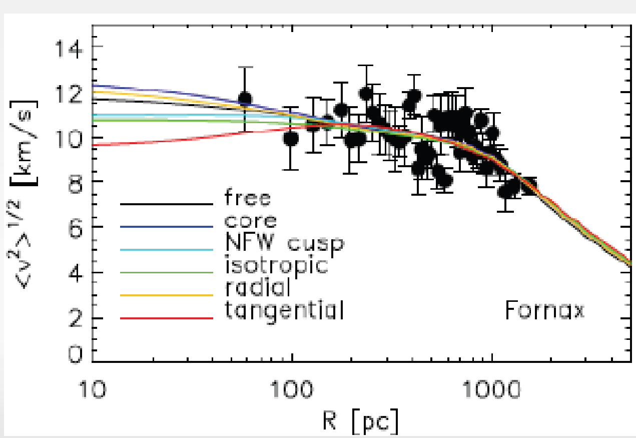


Why dwarf galaxies ?

- DM dominated (M/L ~ 10 – 100)
- Nearby (~100 kpc)
- Low background (ordinary matter content very low)
- Stellar velocities can be used to estimate DM density (error can be propagate to particle constraints)

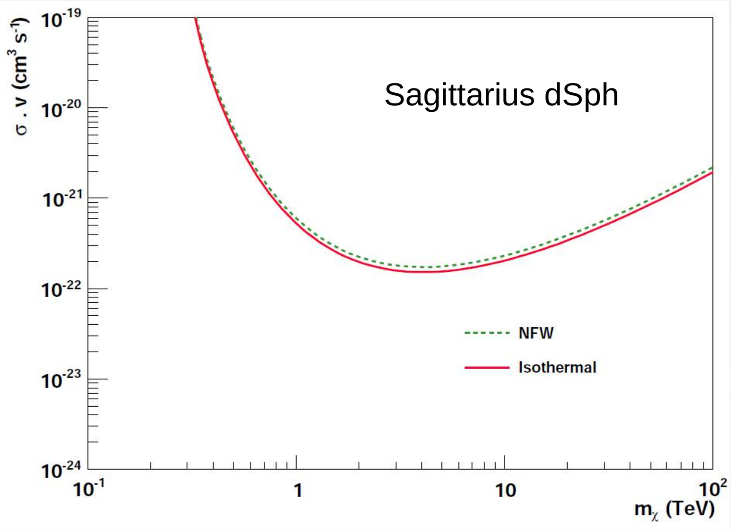


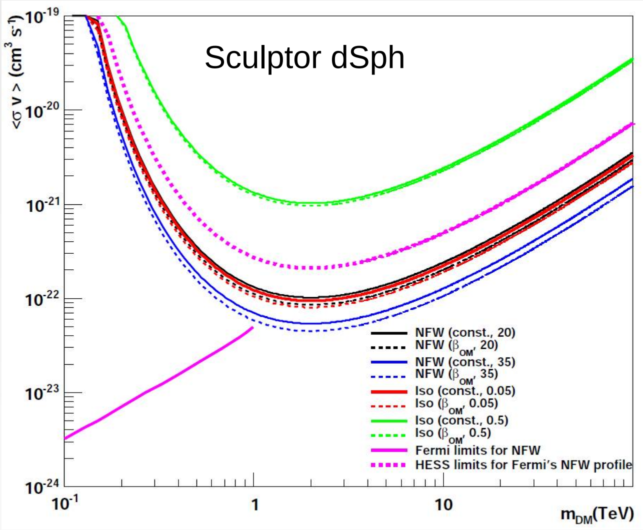


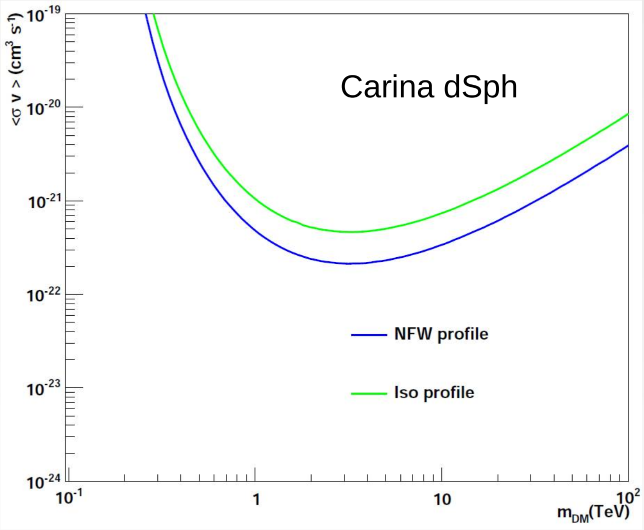


H.E.S.S. results

- Signal search : ON (target region) - OFFs (CR bckg determination)
- Flux upper-limit determination : $\Phi^{UL} = f(N_{obs}, A_{eff}, T_{obs}, \text{DM model}(m_{DM}))$
- Correspondance into annihilation cross-section :
  $<\sigma v>^{UL} = f(\Phi^{UL}, \text{DM model}(m_{DM}), J)$



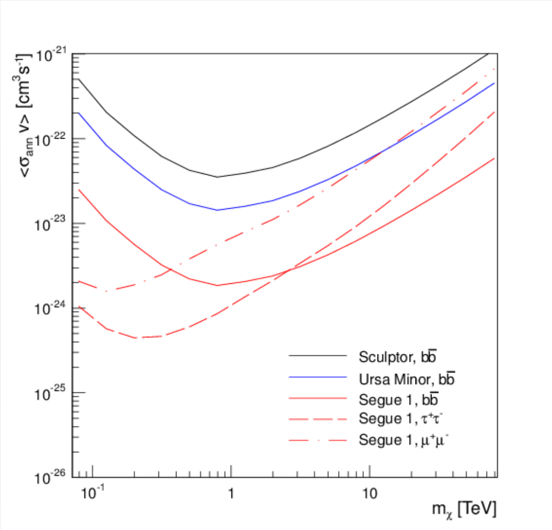




H.E.S.S. Coll, 2007-2011

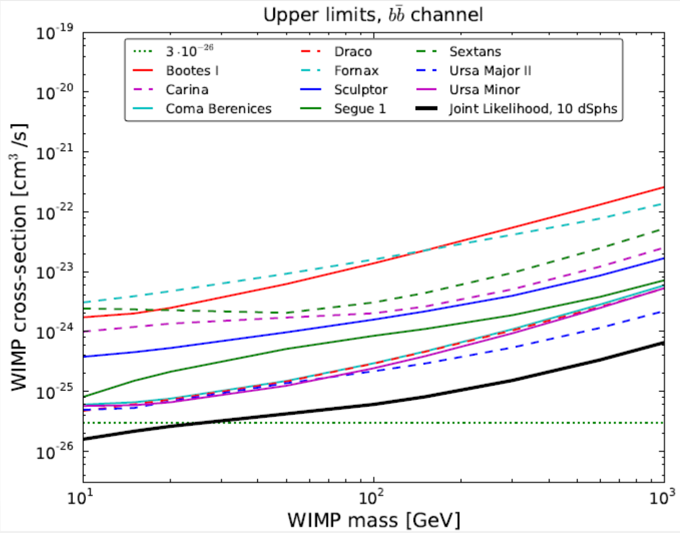
Prospects

- H.E.S.S. II and CTA will be more sensitive thanks to lower energy threshold
- Exemple :
  CTA – 100h
  Classical vs ultra-faint dSph



CTA consortium 2012

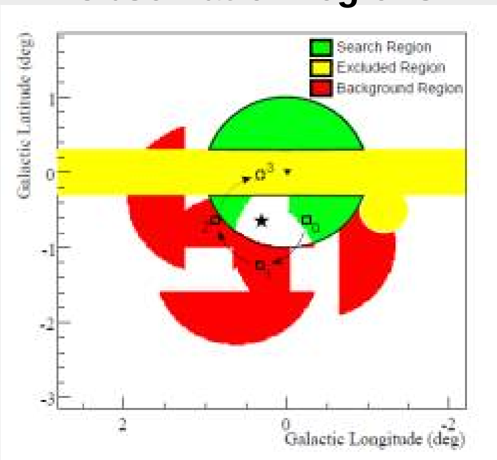
- Still above the thermal relic density
- But stacking will also improve our results, see Fermi-LAT results
  Similar analysis currently ongoing in H.E.S.S.



Fermi collab, 2011

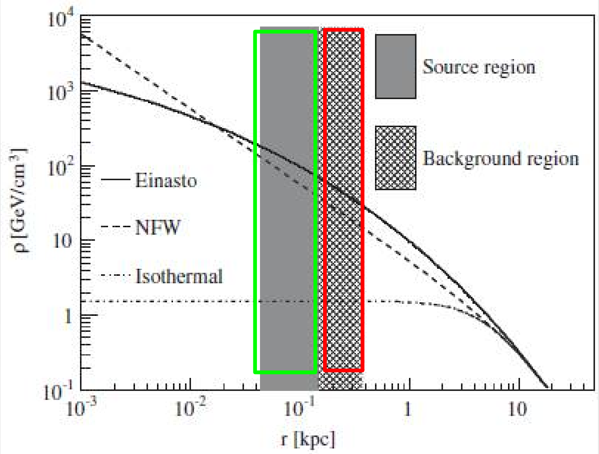
The Galactic halo with H.E.S.S.

Observation regions



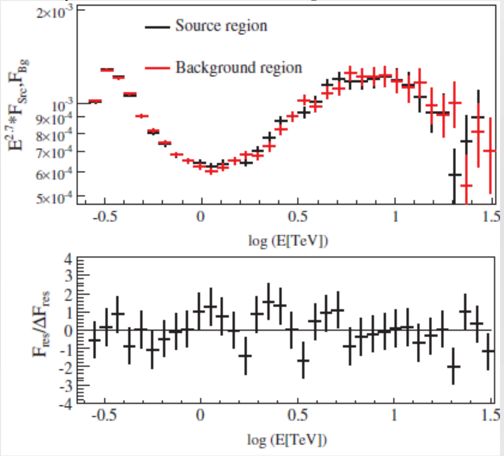
signal, bckg and excluded regions definition

DM density vs distance from the GC

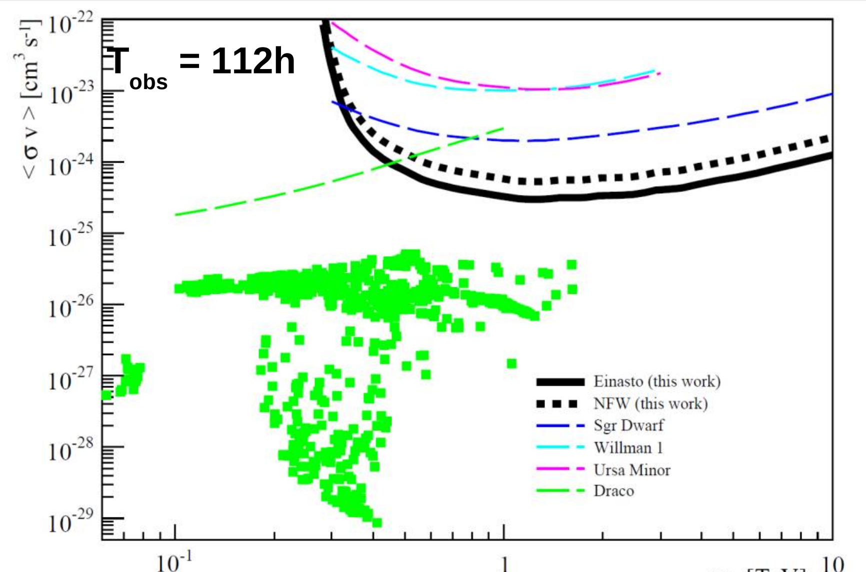


Corresponding DM densities

γ-like events spectrum



Observation results : no significant excess



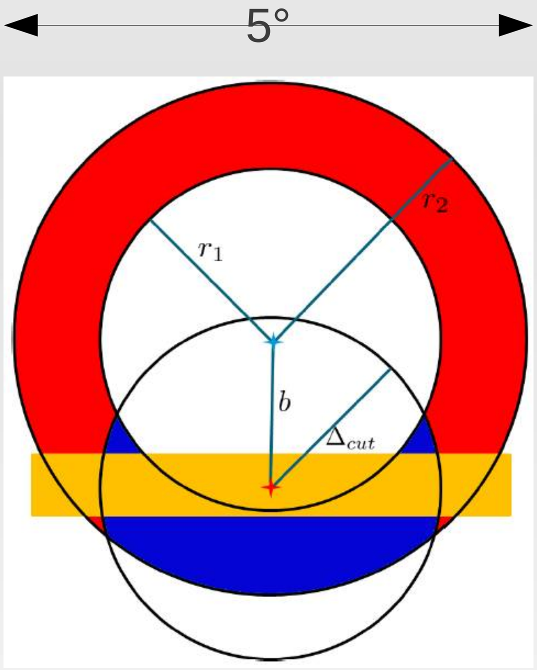
H.E.S.S. collaboration, 2011

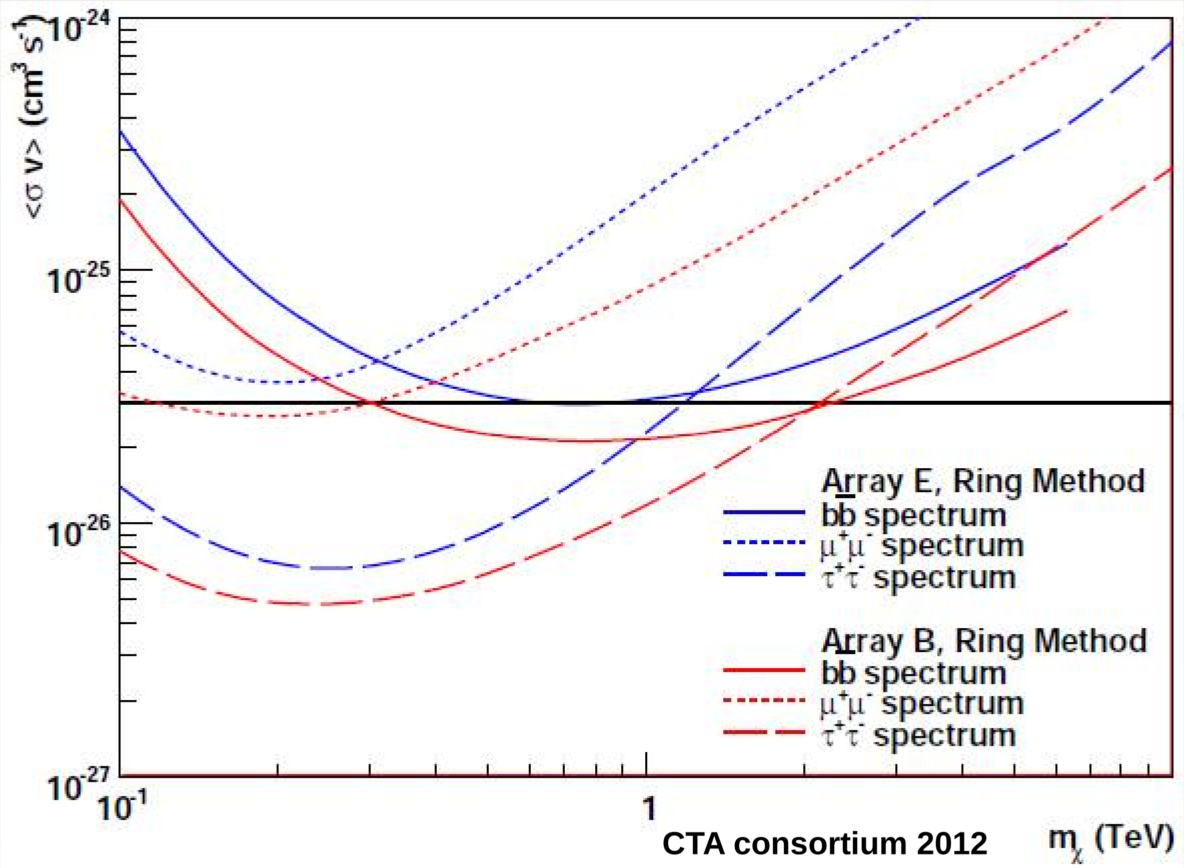
Most constraining results on the DM searches for large massive particles (m_{WIMP} ~ 400 GeV).

But still above viable DM models.

Better sensitivity is required.

CTA prospects

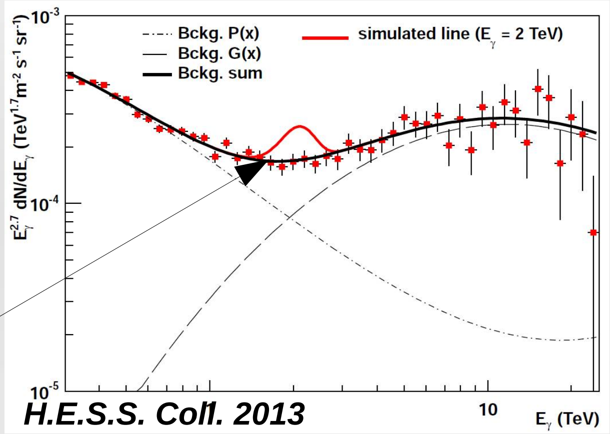


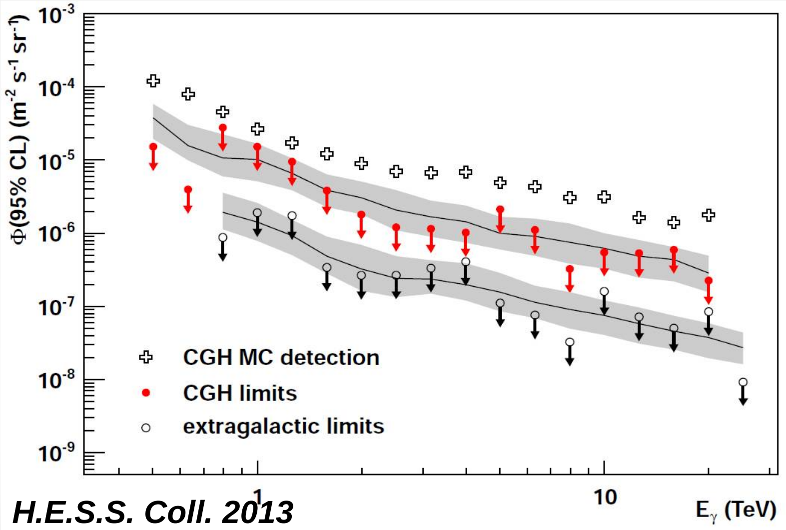


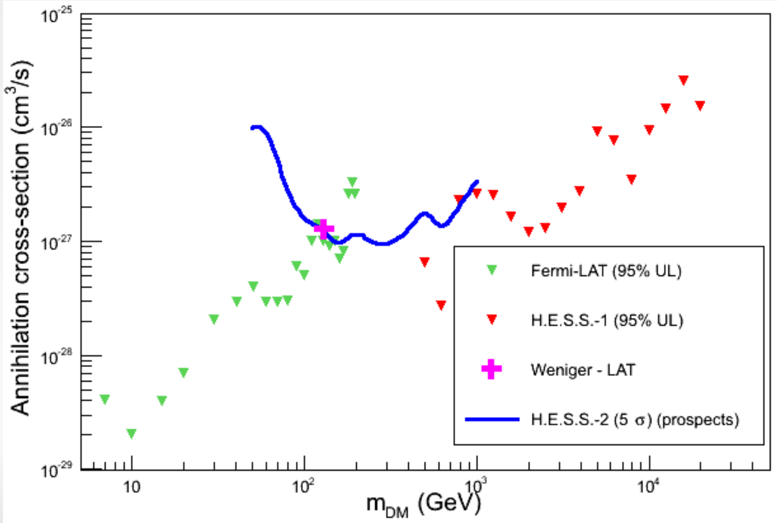
- Increased FOV → larger difference of DM content between ON and OFF regions
- Simulations indicates that the Galactic halo is the most promising location for CTA indirect DM search.
- In only 50h of observations, CTA will probe SUSY models compatible with WMAP results.

Line search with H.E.S.S.

- Integration region similar to halo analysis
- Data set :
    - 4-tel. events ($\Delta E/E$), 2004-2007 [112h] (E_{th})
- No OFF subtraction
    - Bckg (« g-like » CRs) spectrum fitted
- Profile likelihood search of a line-like signal on top of background
- H.E.S.S. II prospects





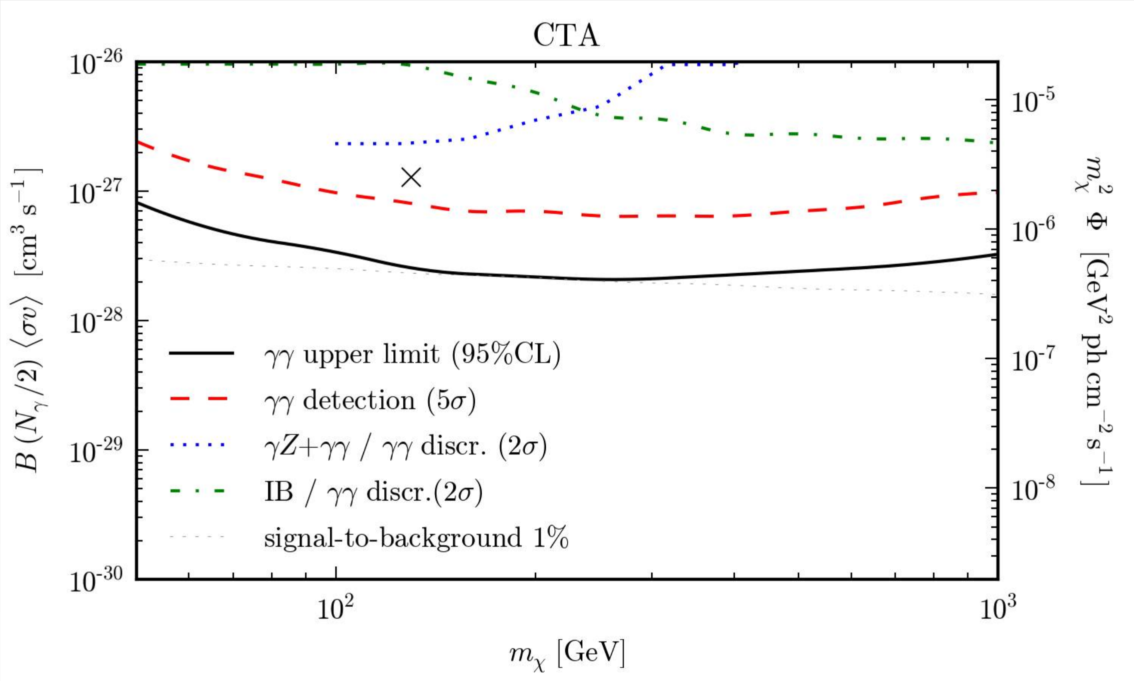


HESS coll. 2013
Bergström, Bertone, Conrad, CF, Weniger, 2012

And next with CTA

CTA expectations

- Confirmation of Weniger (2012) line >5σ in 5h [syst. uncertainties]
- 1 vs 2 lines distinction reachable with additional time and refined analysis



Bergström, Bertone, Conrad, CF, Weniger., 2012

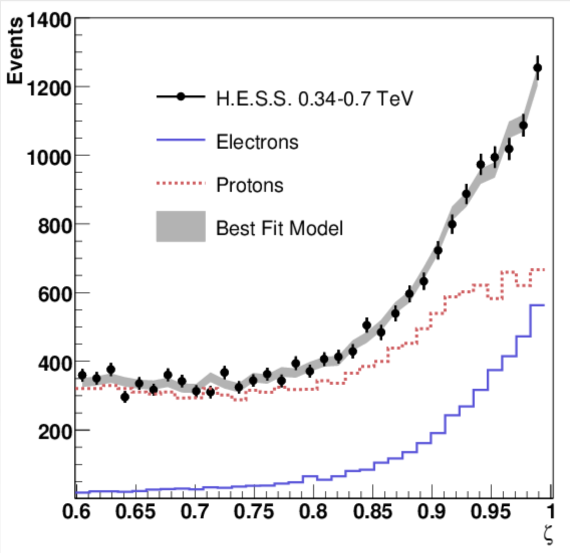
Not only gamma-rays !

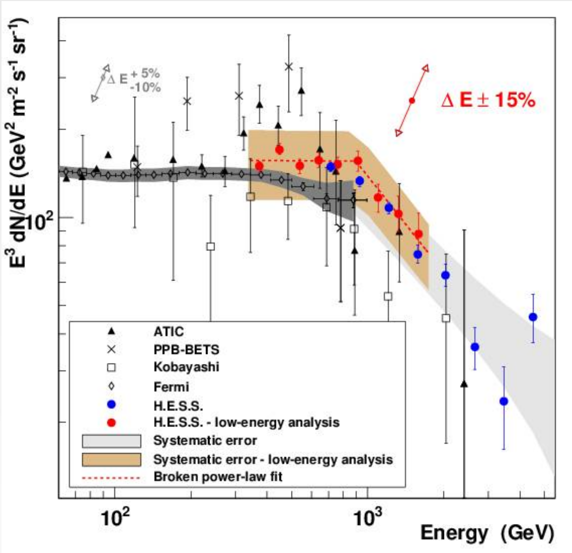
Search for electrons (+positrons)

- Extragalactic regions (low gamma-ray content)
- Large collection area and exposure time

Analysis and results

- Electron identification from simulations + Random Forest
- Power-law + break @ 1 TeV





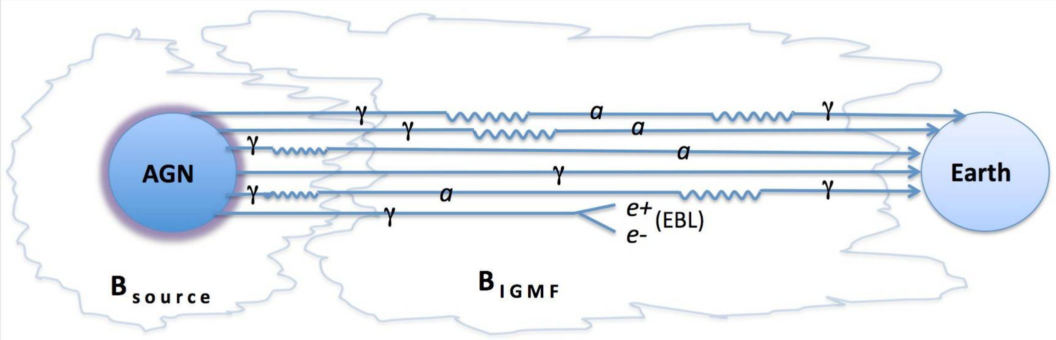
Disproved ATIC peak
and its DM interpretation

H.E.S.S. coll., PRL 2008 & A&A 2009

2. Axion-like particles

Same phenomenology as true axion (Peccei & Quinn, 76) but m_a and $g_{\gamma a}$ unrelated

γ/ALP oscillations in external magnetic field...

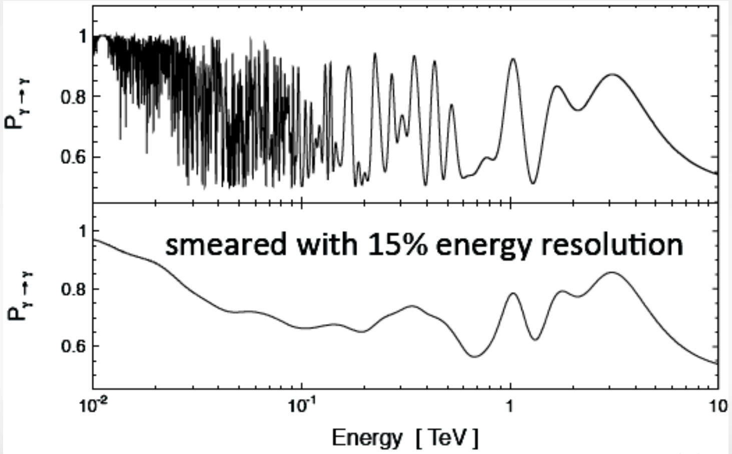


...possible modification of opacity of the Universe to TeV gamma-rays.

Important for very distant sources detected in gamma-ray.

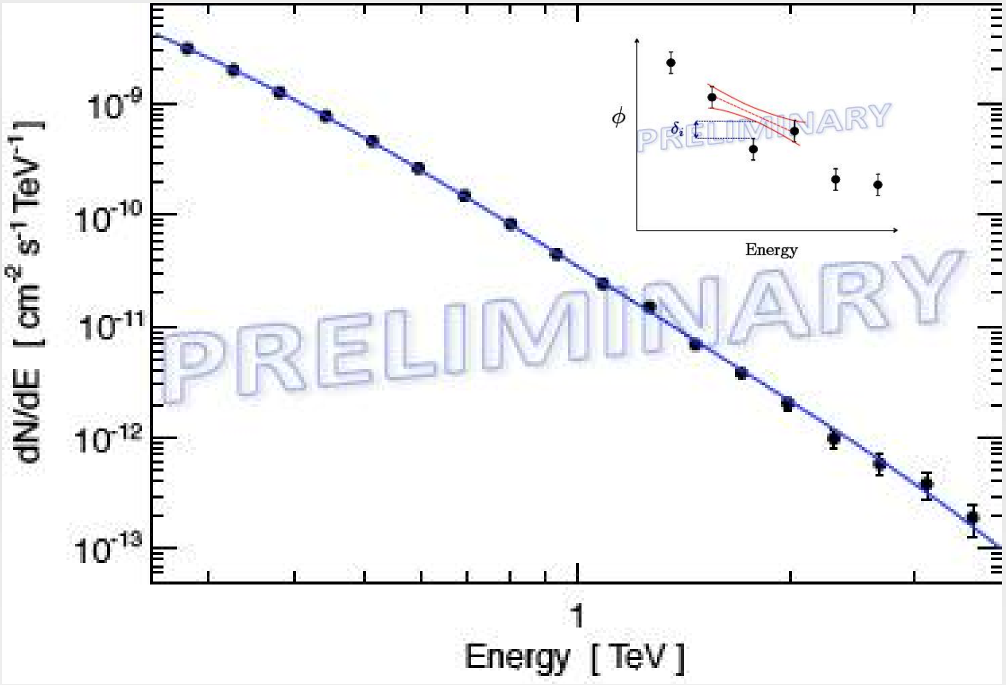
Conversions γ/ALP introduce irregularities in gamma-ray spectrum

- amplitude driven by $g_{\gamma a}$
- location driven by m_a



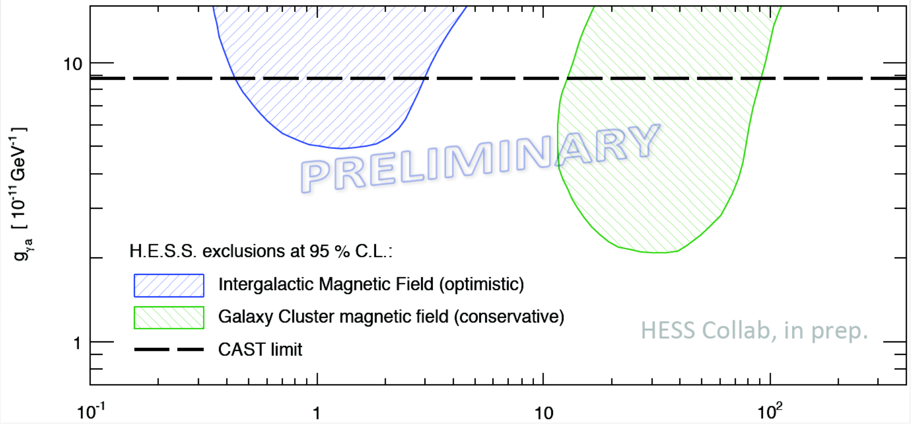
Wouters & Brun, PRD, 2012

Axion-like particles
H.E.S.S. results



- Search for irregularities in PKS2155 flare spectrum
- Look for anomalous deviations in triplet of successive bins
- Statistical analysis on MC

	B	L	L/s
Cluster magnetic field	1 µG	370 kpc	37
IGMF	1 nG	478 Mpc	505



L ↔ size of conversion domain
s ↔ coherence length

H.E.S.S. collab. submitted

3. Lorentz Invariance Violation

Motivation

- Test LI predicted to be violated @~Planck scale in some QG theories
  → absence of LIV can help discards models

Speed of light dispersion

$$c' = c\left(1 \pm \zeta \frac{E}{E_P} \pm \xi^2 \frac{E^2}{E_P{}^2}\right)$$

Context

- Consider 2 photons of ≠ E_1, E_2 emitted at same time but observed at t_1 and t_2

$$\frac{\Delta t}{\Delta E} \approx \frac{\zeta}{E_P H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

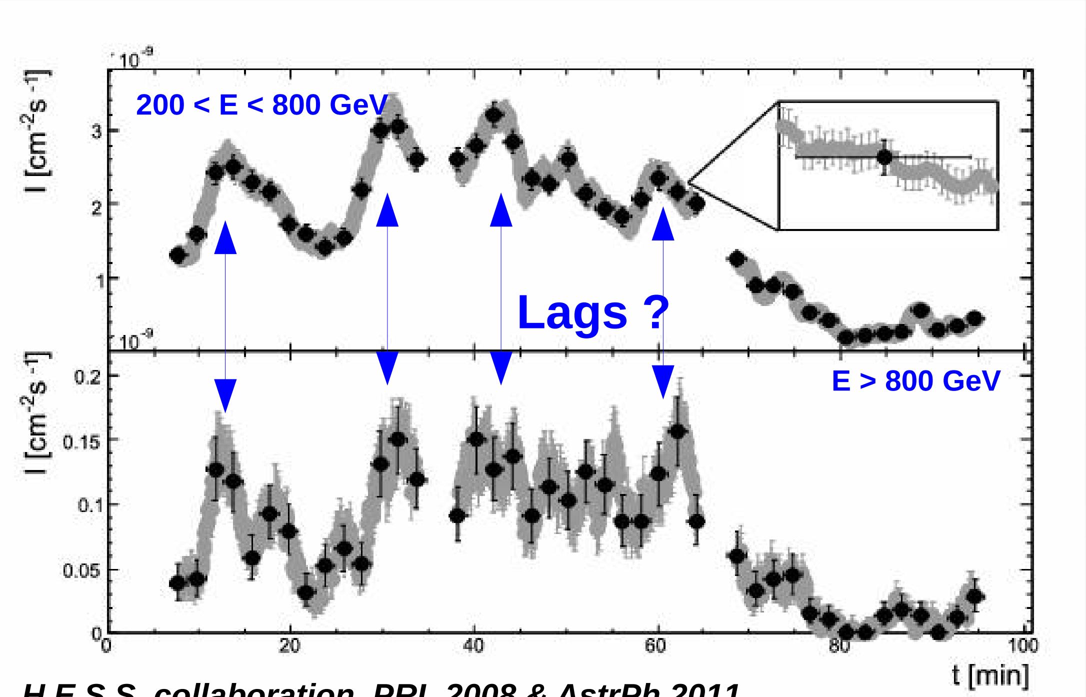
$$\frac{\Delta t}{\Delta E^2} \approx \frac{3\xi}{2 E_P{}^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

- Small effect can add up over cosmological distances and lead to signficant delays
  → use of variable and distant sources (GRBs, AGN flares)

Lorentz Invariance Violation H.E.S.S. results

PKS2155 exceptional flare of 2006

- Signal dominated (300σ)
- High flux variability
- No spectrum variability
- z=0.116



H.E.S.S. collaboration, PRL 2008 & AstrPh 2011

Results (from event-by-event likelihood analysis ***[H.E.S.S., Astr.Ph 2011]***):

- No significant lags → 95%CL UL on QG scale

Linear term : $E^{l}_{QG} > 2.1\times10^{18}$ GeV

Quad. Term : $E^{q}_{QG} > 0.6\times10^{11}$GeV

→ Best limits with AGN

Lorentz Invariance Violation Prospects : H.E.S.S.II & CTA

H.E.S.S. II

- Increased energy range to lower energy (E_{th} ~ 30GeV)

  → bigger lever arm for ΔE
- Faster repositioning of the large size telescope
  → Observation of GRBs at VHE ?

CTA

- Increased energy range (both side)
- x10 better sensitivity & pointing modes dedicated to transient source detection

  → AGN population study (better understanding of source effect – time-dependant model)

Pulsars

- VERITAS detection of Crab pulsar @ 200GeV. More to come ?
  + pulsars are perfect astronomical clocks
  - nearby object

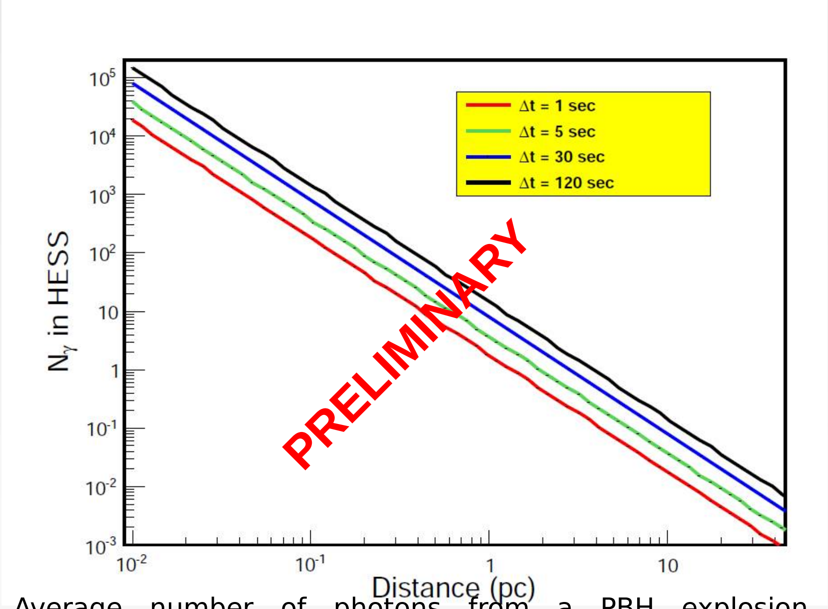
4. Primordial black holes

PBH as source of gamma-rays

- BH created in the early Universe
- Evaporation through Hawking's radiation
- Lifetime is related to M_{PBH} (sensitive to M_{PBH} $O(10^{14}g)$)
- Progenitor for some GRBs ?

Gamma-ray search

- Hypothesis : BH atmosphere negligible (otherwise strong energy cut off)
- Evaporation is a runaway process : burst of gamma-rays expected in final stage
- Search for number $N = \partial\rho/\partial t \times V_{eff}$ of events in time window Δt within the HESS PSF



Average number of photons from a PBH explosion detectable by H.E.S.S. as a function of the distance to the burst, for several values of the remaining time before explosion Δt.

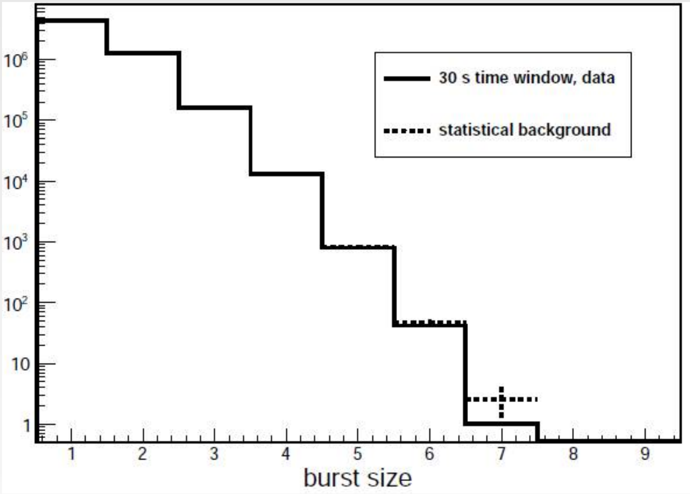
Primordial black holes

Method

- Search for correlated events in space and arrival time
- Background estimates through « scrambling »

Data set

- 2004-2012 (~2600h)
- Events within 2deg of camera FOV
- PSF=0.1deg



Results

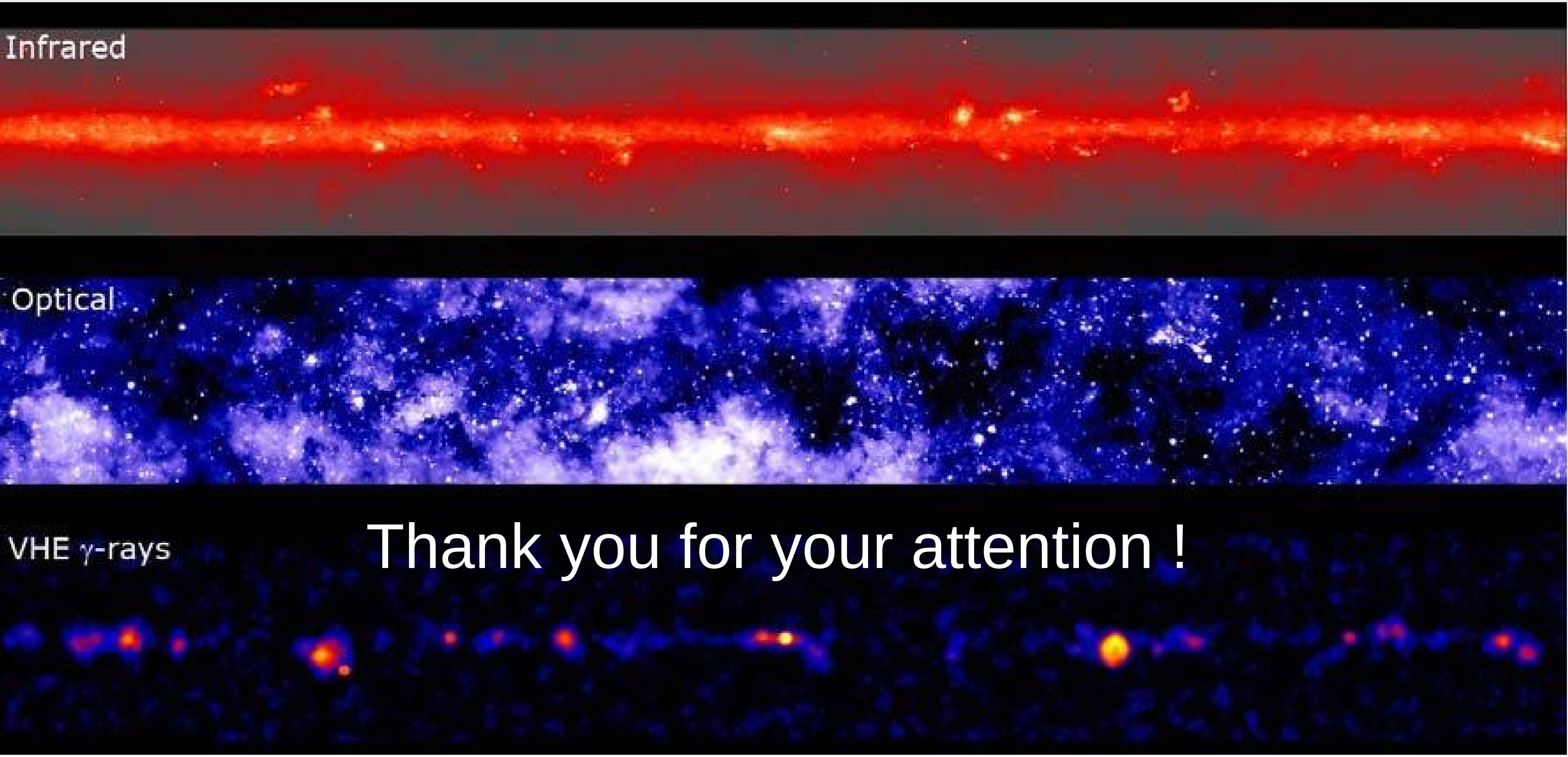
- No significant deviation from bckg expectation
  → 95 % CL UL : $\partial\rho/\partial t < 1.4 \times 10^4\ pc^{-3}y^{-1}$

Prospects

- Thanks to lower energy threshold H.E.S.S.II and CTA will allow to probe models PBH with atmosphere

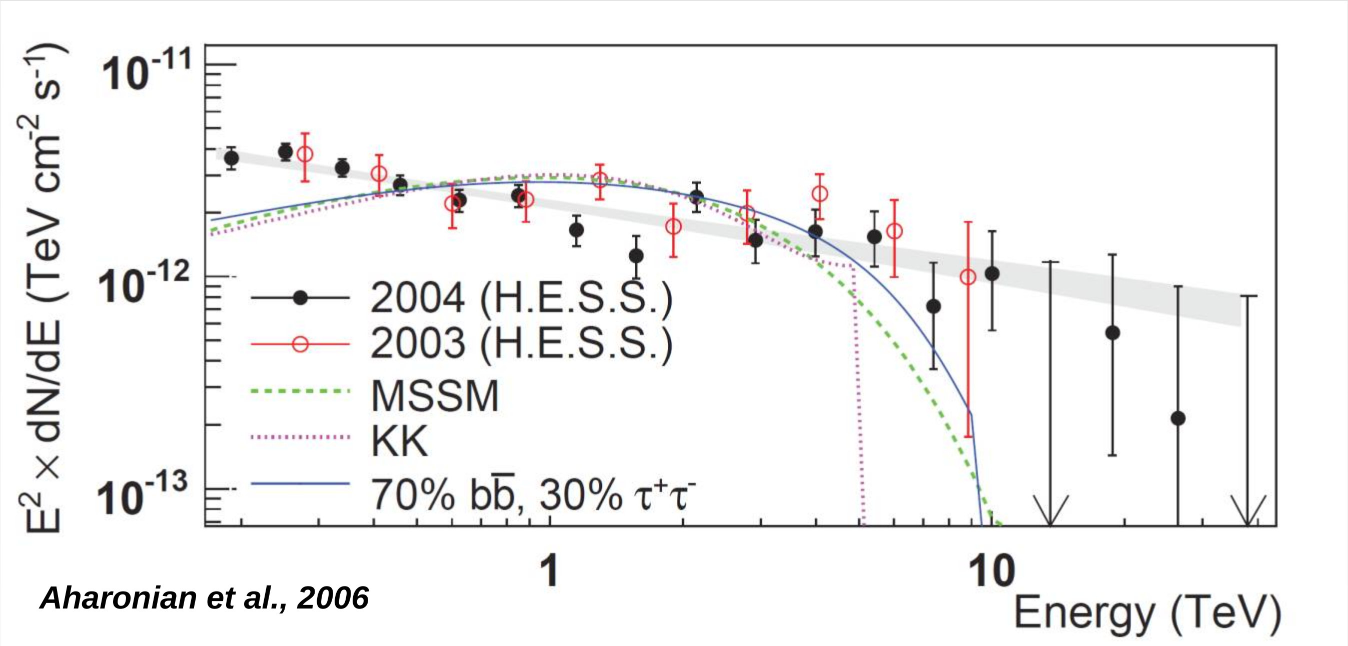
Conclusions

- IACT experiments have entered into a new era :
  - Already >140 sources detected @ VHE
  - H.E.S.S. II has been inaugurated 1 year ago, new results are soon to come
  - The CTA observatory, will enlarge this window of the Universe recently opened and allow to discovered ~10 times more sources
- IACTs are multi-purpose, multi-channel experiments
- They can bring a lot of new information to questions of fundamental physics



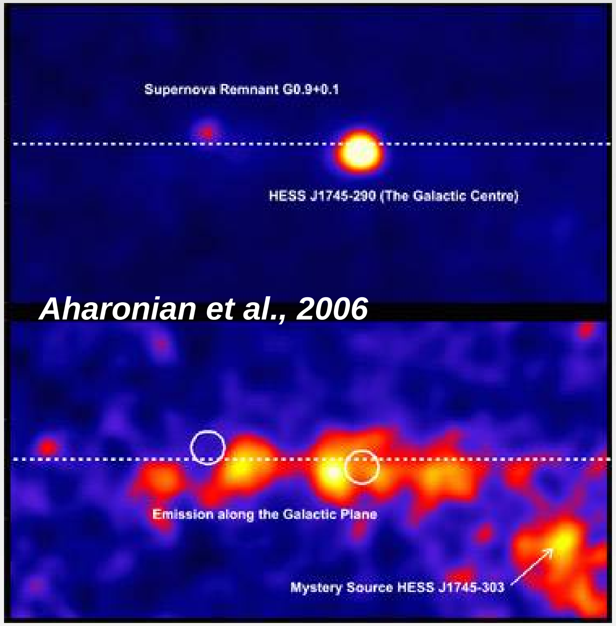
Thank you for your attention !

H.E.S.S. view of the GC



Aharonian et al., 2006

H.E.S.S. view of the GC



After point-like sources removal

DM interpretation unlikely both from the signal morphology and its spectral shape.
DM signal search difficult due to the observed emission.