Gamma-ray astronomy and indirect searches for Dark Matter

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Séminaire LAPP – Annecy
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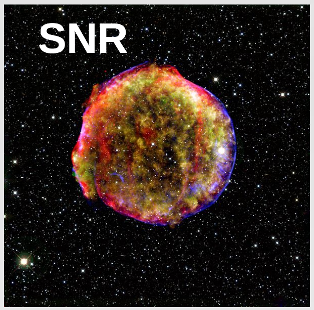
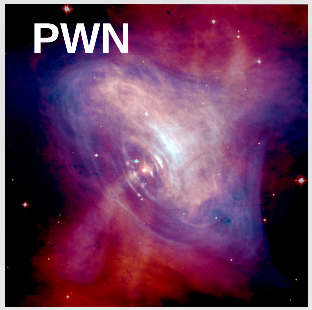
Outline

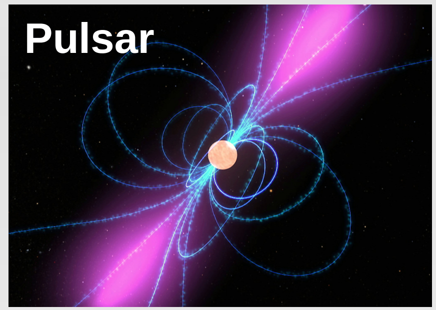
- γ-ray astronomy
- Current and future experiments
- Searches for new γ-ray emitters
  - CWB
  - Cluster of galaxies
  - Indirect search of Dark Matter
- Conclusion

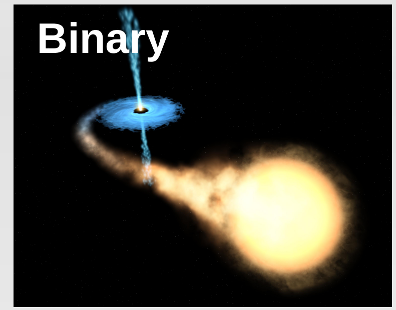
γ-ray astronomy : probing the non-thermal Universe

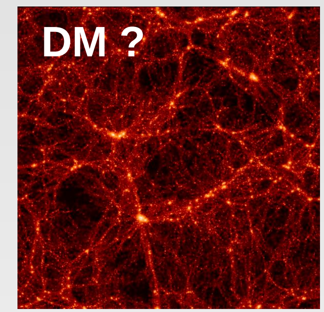
Galactic sources







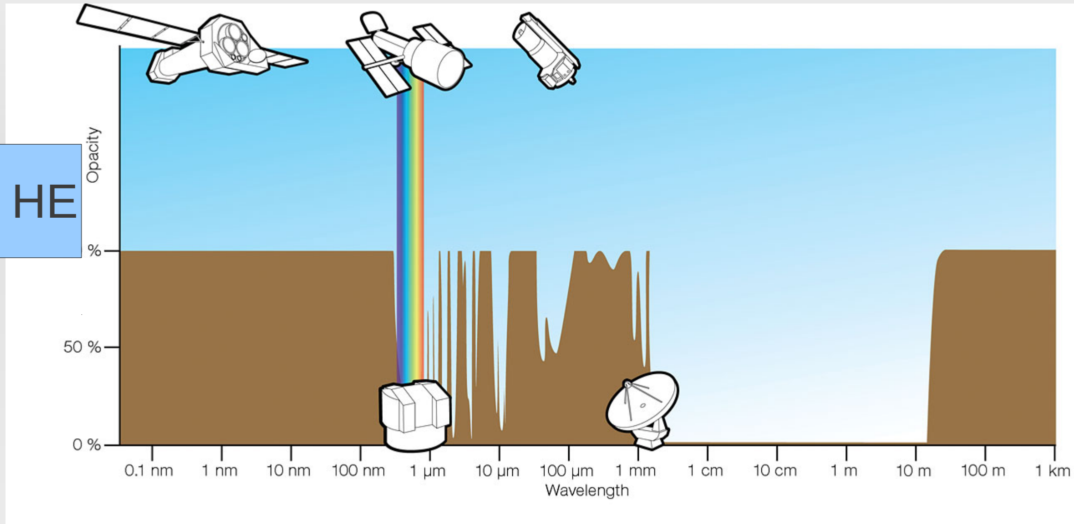


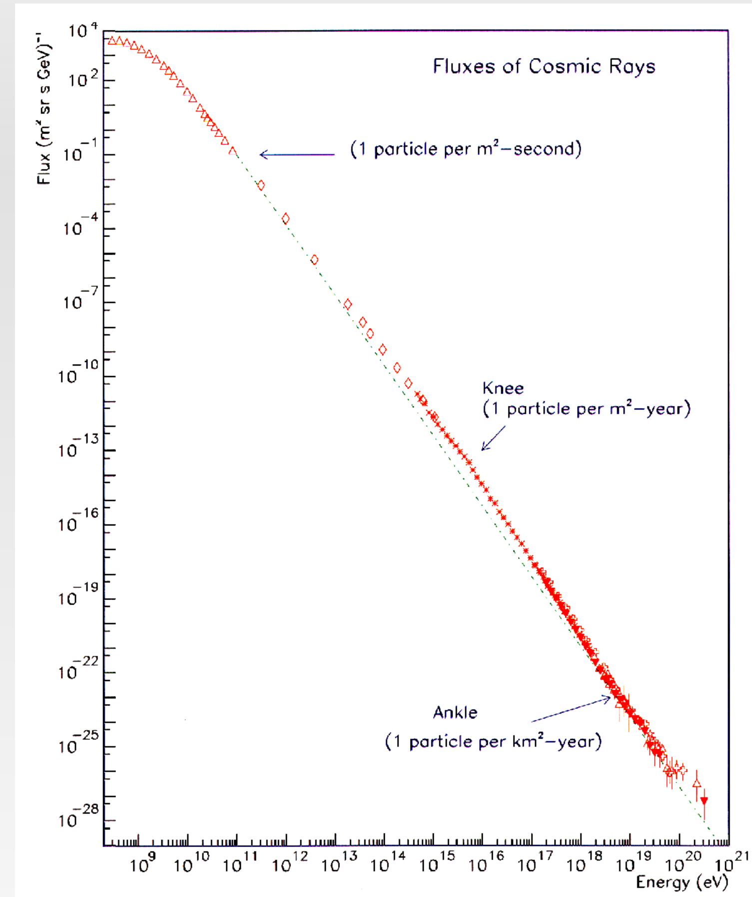


Extragalactic sources

Detecting γ-rays

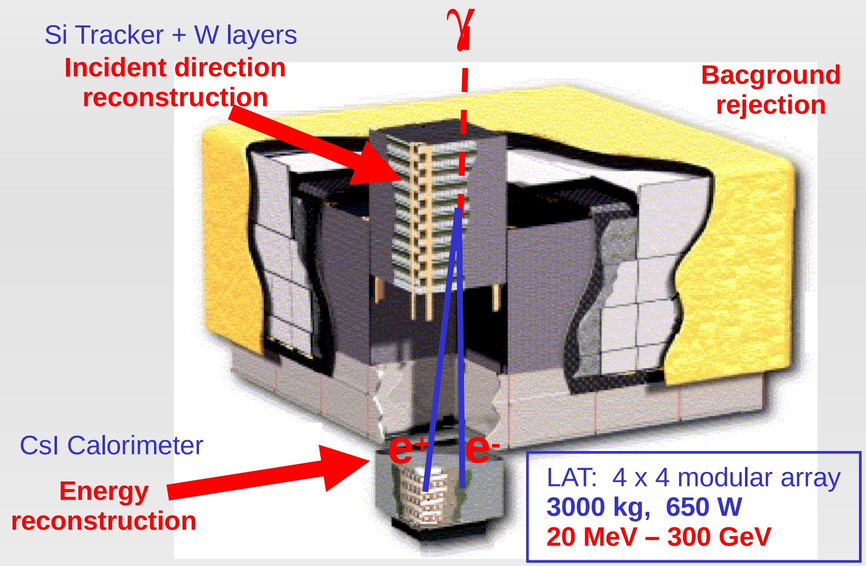
VHE, HE



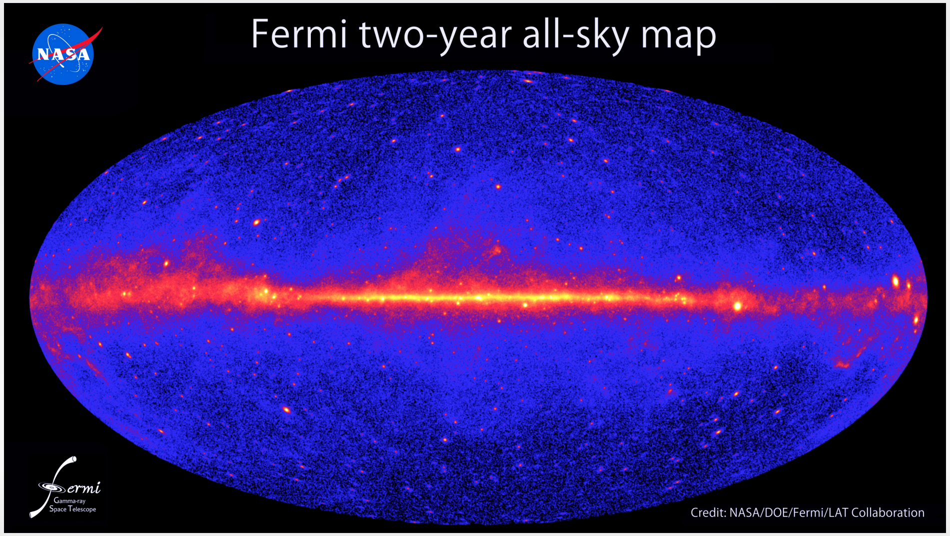


- Convention
  - HE : High Energy ($E \geq 100$ MeV)
  - VHE : Very High Energy ($E \geq 100$ GeV)
- γ-rays are not deflected by B → study of sources and production mecanisms
- Atmosphere is opaque to γ-rays
  - Satellite exp. for HE
  - IACTs for VHE (very low fluxes $10^{-(11\text{-}12)}$ ph cm^{-2}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

Detecting HE γ-rays : Fermi-Large Area Telescope



Credits : NASA, FSSC



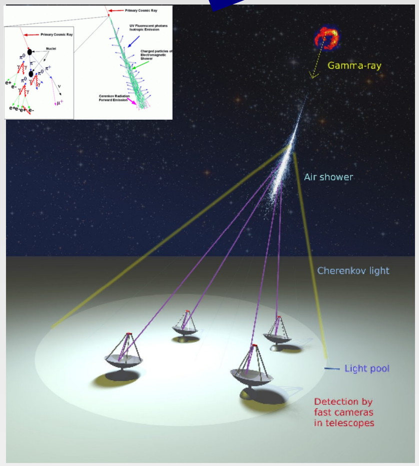
<u>A few numbers :</u>

Launched in 2008

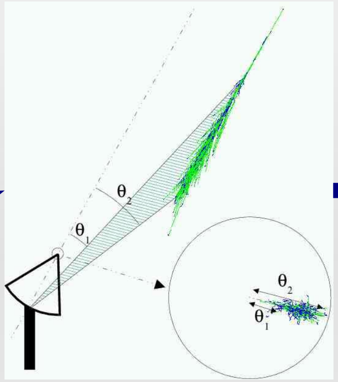
Energy range : 30 MeV to 300 GeV

2FGL : 1873 sources (594 unassociated)

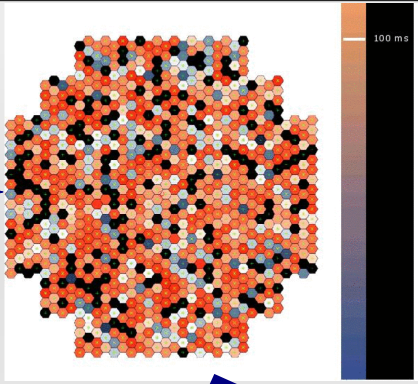
Detecting VHE γ-rays : IACTs principle



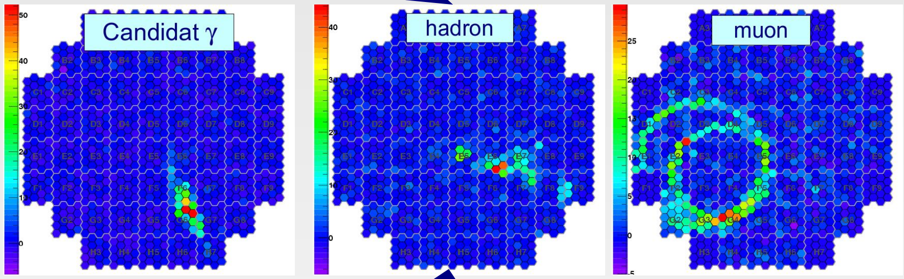
1) Cherenkov photons production.



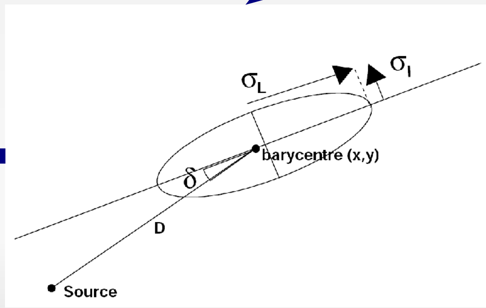
2) Shower development recorded in the focal plane.



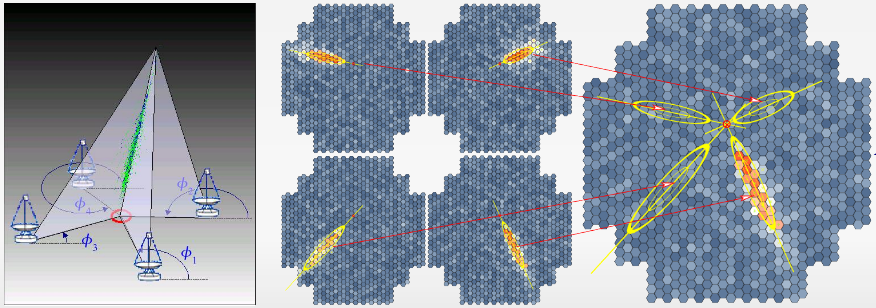
3) Ultra fast acquisition camera (~10ns).



4) Image based event selection / background rejection.

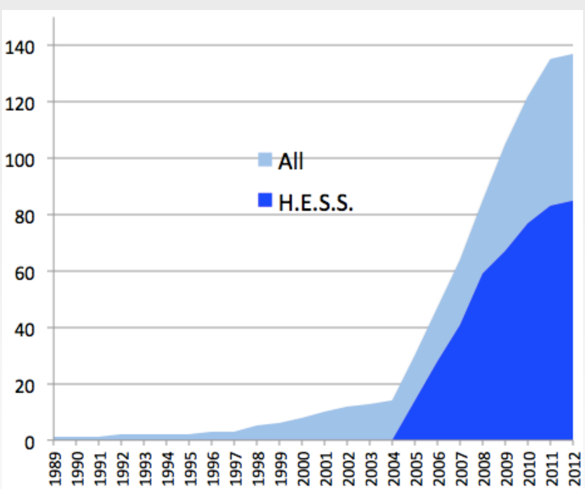


6) Image parameters reco.:E, (ra,dec)

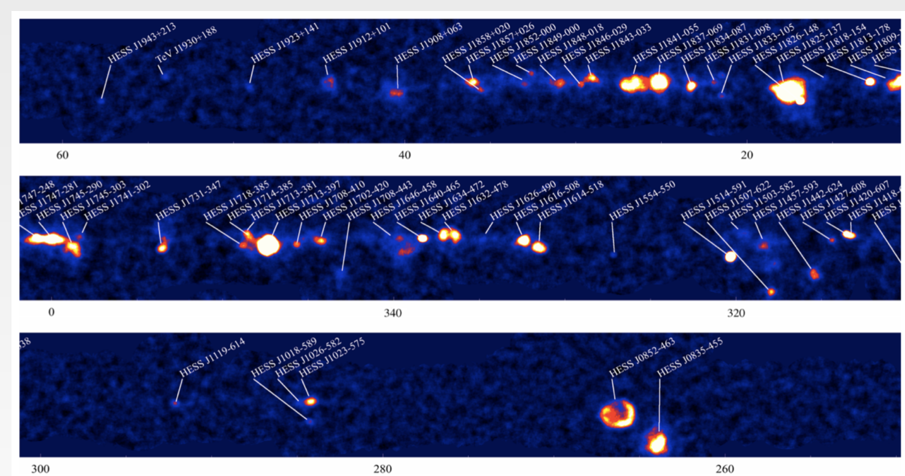


6) Multiple images recording : « stereoscopy »

H.E.S.S.

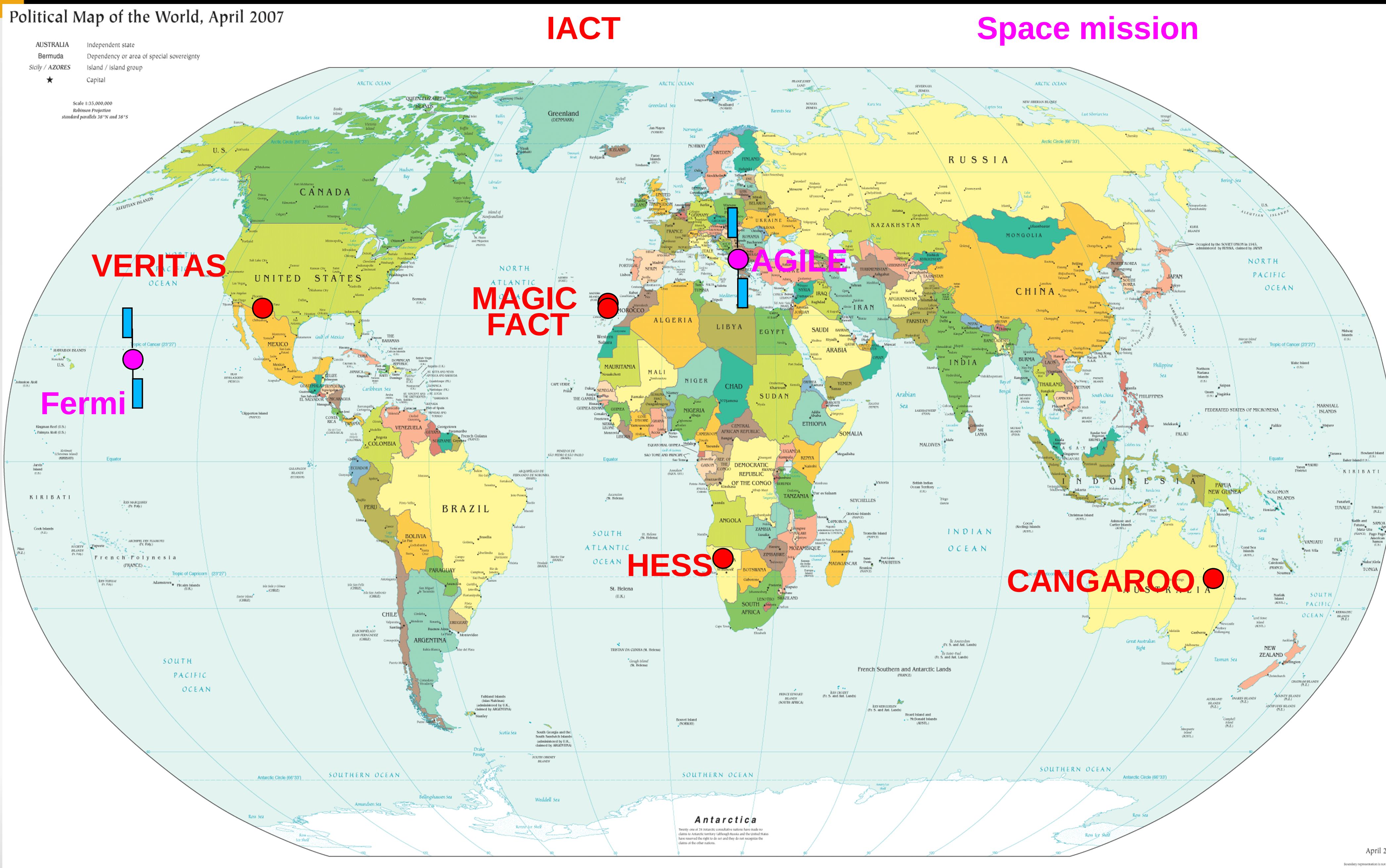


Nb of VHE sources vs time



H.E.S.S. view of the galactic plane

Census of γ-rays experiments

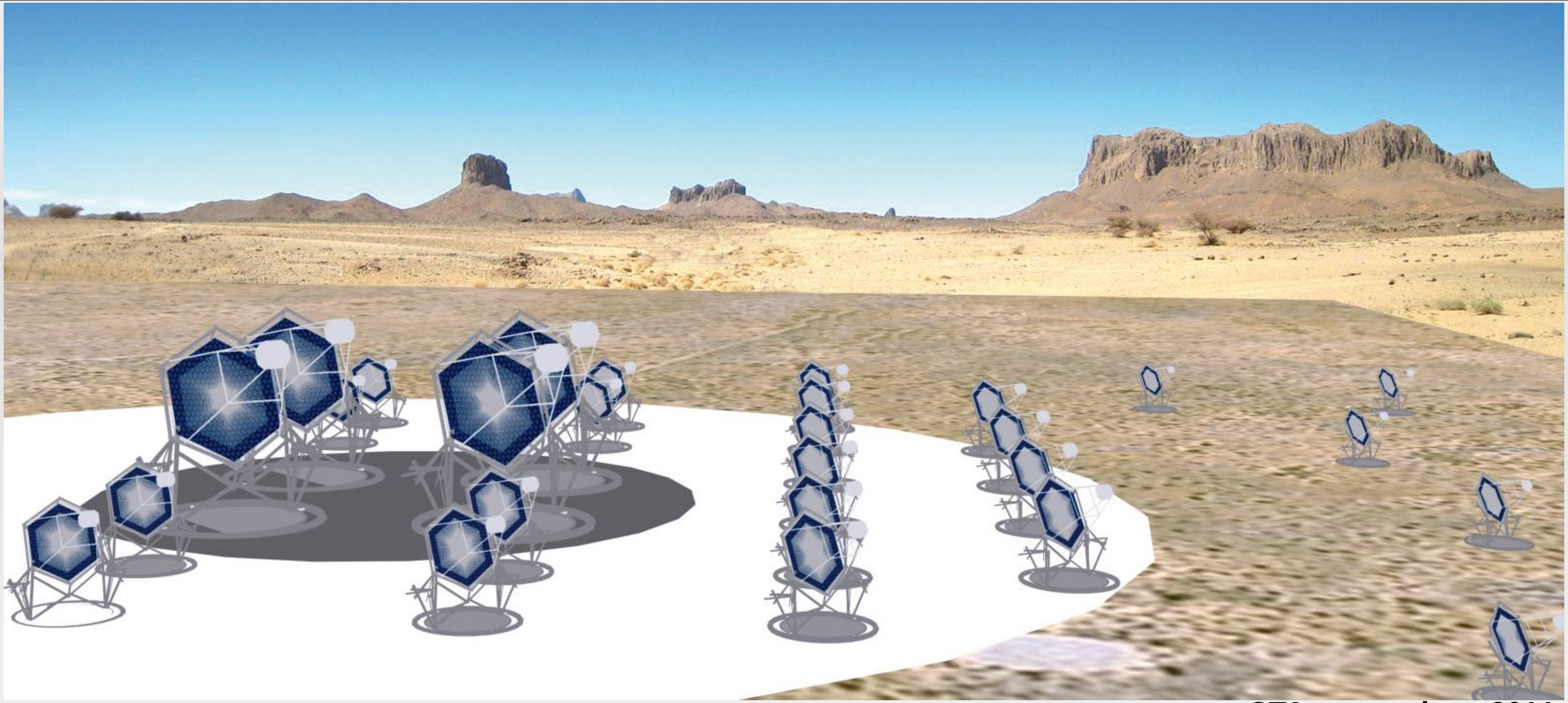


A step forward : H.E.S.S. phase 2

Since summer 2012 : additional telescope with a very large collection area

- Lower energy threshold (new class of sources ?)
- Faster mobility (GRB ?)

The future : CTA
Cherenkov Telescope Array



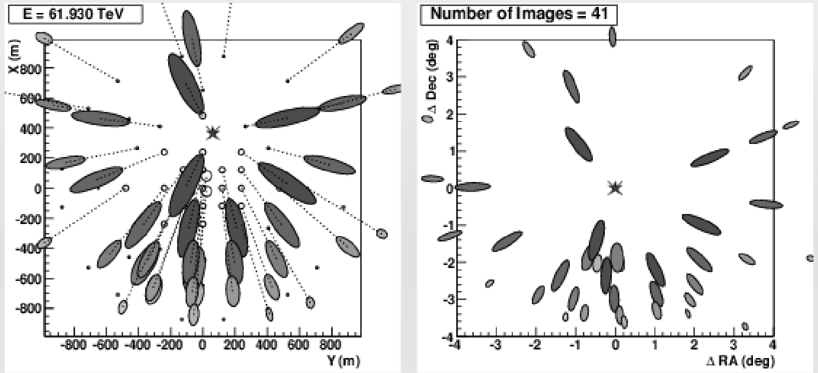
CTA consortium, 2011

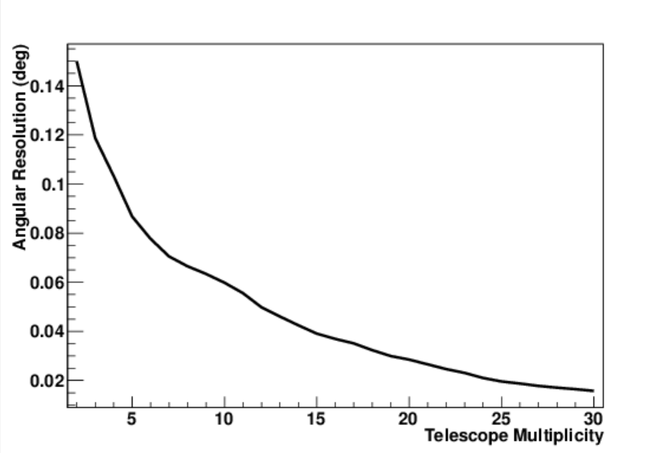
- 27 countries.
- > 700 scientists.
- 2 arrays : northern + southern.
- 3 types of telescopes.
- >1000 sources expected.
- ~ 1000h obs/y

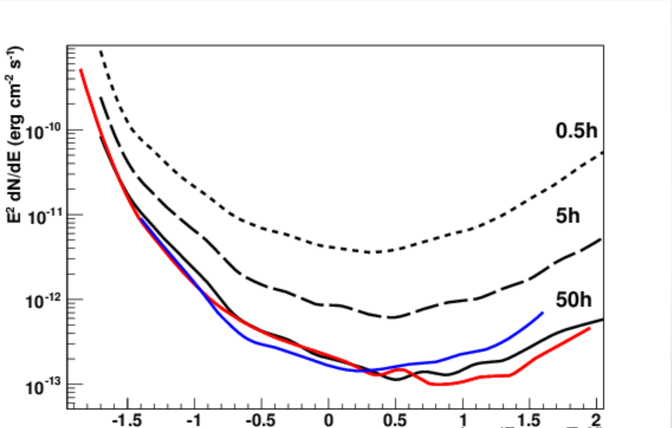
- Currently in the preparatory phase.
- Construction phase will start in 2013.
- 150 Meuros budget.
- First Cherenkov facility to operate as an observatory.

CTA : the "perfect" stereoscopic system

- The most advanced stereoscopic systems have only 5 (4) telescopes H.E.S.S. (VERITAS).
- CTA will have dozens, 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 (x 10),
  - ….





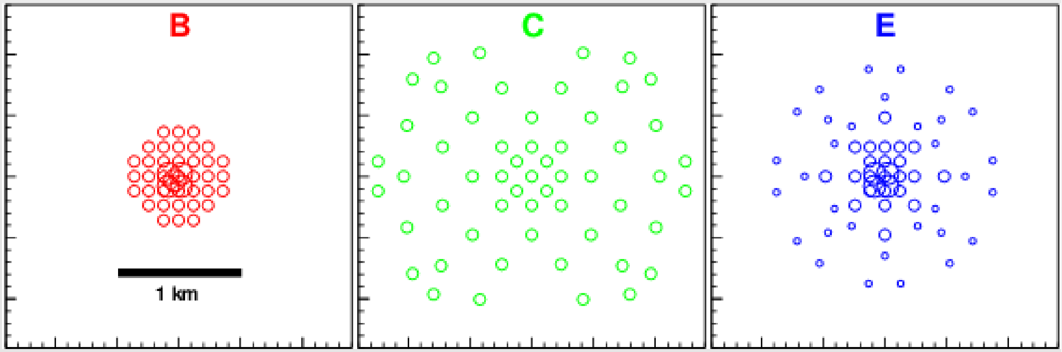


CTA consortium, 2011

CTA – still a lot of uncertainties...

- … on the site locations,
- … on the array design,
- … on the hardware solutions :
  - read-out electronics,
  - telescopes dish

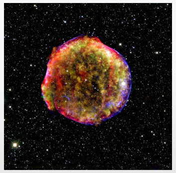
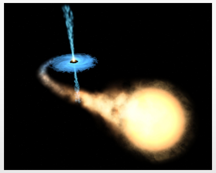
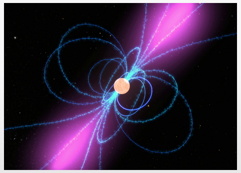
Lot of on-going work for the simulation Working Group !



CTA consortium, 2011

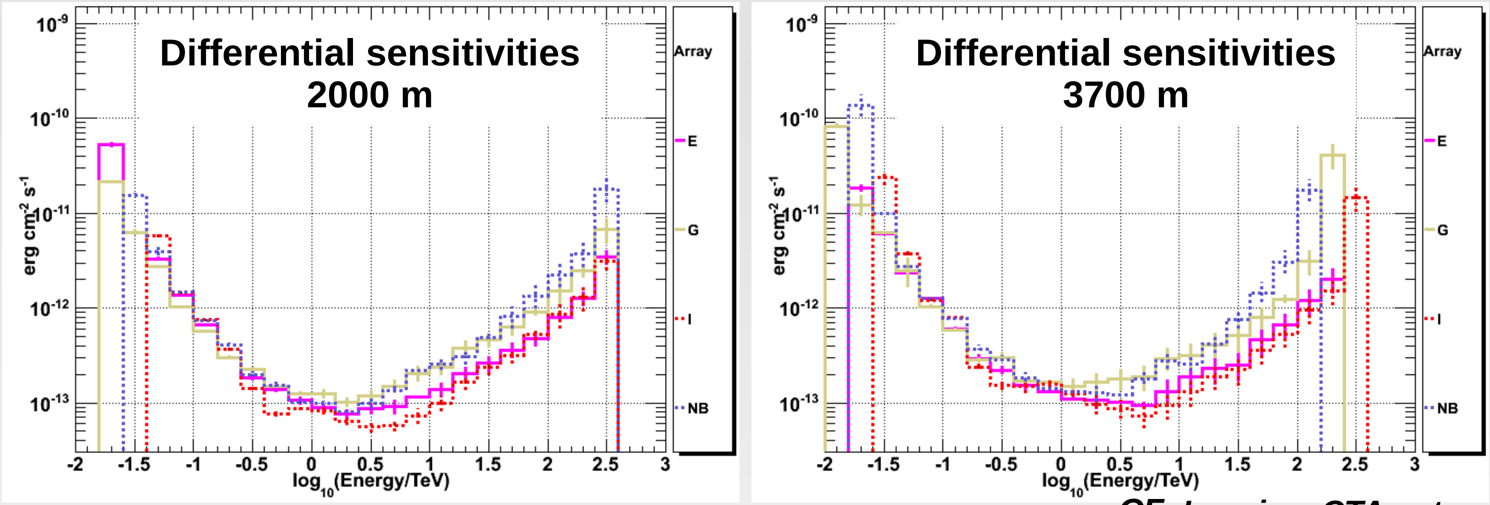
<u>3 potential array designs for CTA :</u>
B is optimized for the low energy range.
C is optimized for the high energy range.
E is a compromized design.

All of these choices being driven by an important number of scientific cases : galactic cosmic-rays origins, pulsars wind nebulae, supernova remnants, microquasars, binary systems, pulsar, active galaxies, gamma-ray bursts, **dark matter**, … for only ~1000h observations /y.

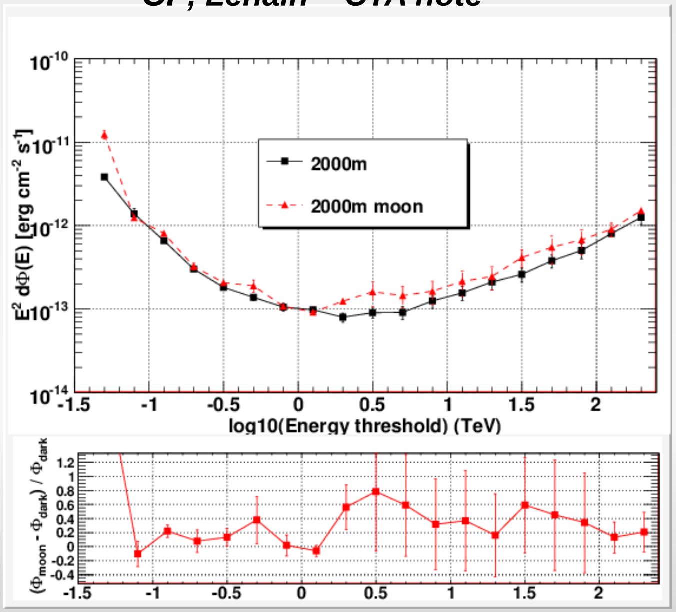
Improving performances

- Lowering the energy threshold : high altitude site
  - ~0.2 dex gain at low energy
  - comparable results at intermediate and high energies



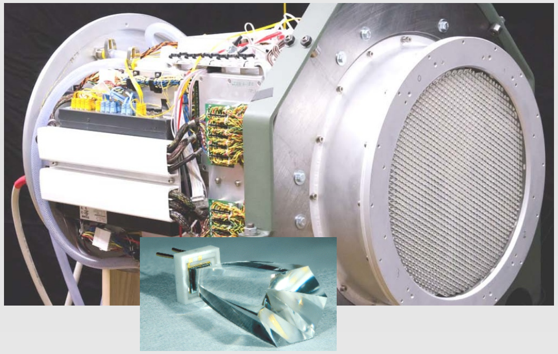
CF, Lenain – CTA note

- Increasing the duty cycle : observation under Moon light conditions
  - std NSB x4.5
  → 30 % of total obs. time gained
  Similar performances above 100 GeV



+ possibility to use **new photo-sensors**

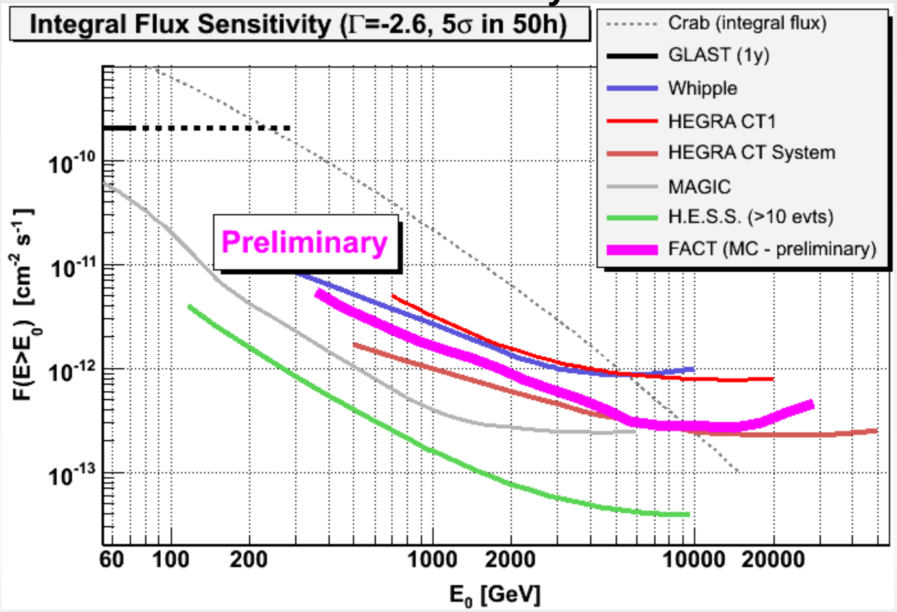
FACT – First G-APD Cherenkov Telescope



- Part of the DWARF project aiming for a continuous monitoring of AGN using an array of IACT spread over the World
- Small collaboration CH-Germany (5 institutes, 10 FTEs)

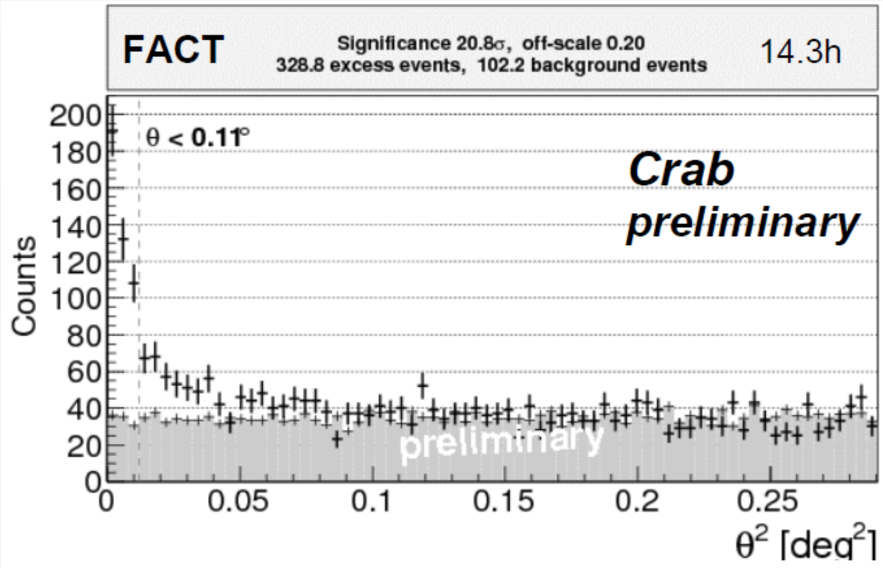
- CT3 from HEGRA with new mirrors
- G-APD camera
  - 1440 pixels (0.11°/pix) – 4.5°
  - PDE ~30-40 %
  - « High voltage » 70V
- Solid light concentrator
- First light : June 2011

2010 first sensitivity estimates

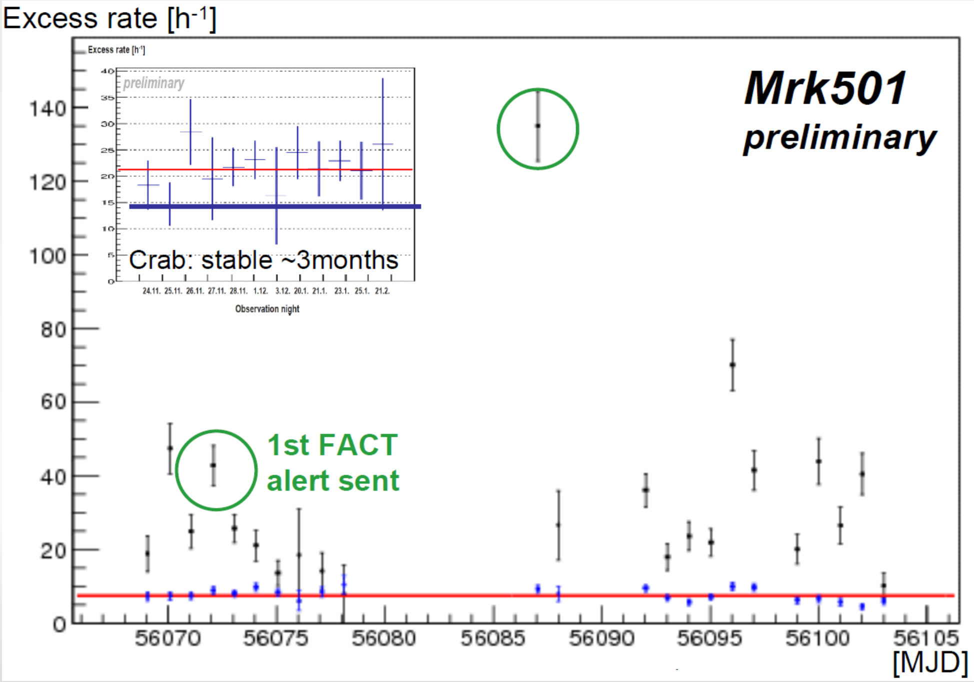


CF for the FACT Coll.

FACT – First results



- Crab detection ~5.5σ /√h (Li&Ma ; simple analysis)
- Detection of AGNs
  - Mkn421 : 24h, 6.6σ
  - Mkn501 : 35h, 38σ



Search for new γ-ray emitters

- CWB
- Cluster of Galaxies
- DM

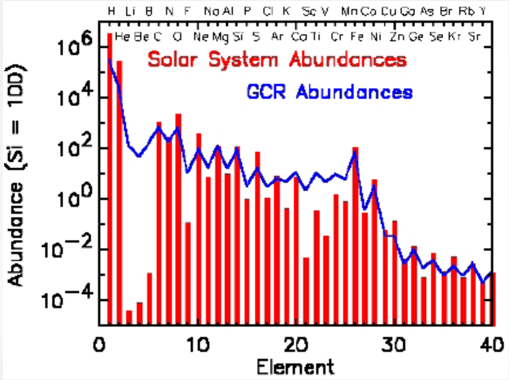
Colliding wind binaries :
a new class of γ-ray emitters ?

- Colliding wind binaries :
  - Binary system of 2 massive stars
  - Large mass loss rate in form of stellar winds

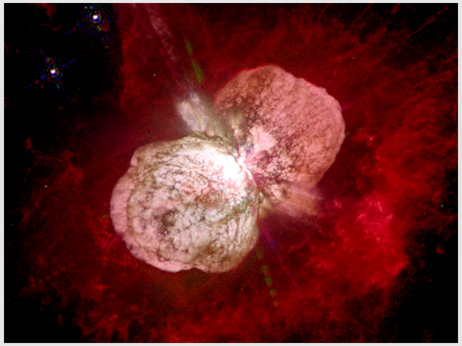
- Observations :
  - Synchroton emission observed in radio for ~20 systems
  - Hard X-ray emission from accelerated electrons observed in fewer systems

Credits : Parkin, Gosset

- Higher energies :
  - Early prediction for γ-ray emissivity by Eichler & Usov (1993) due to charged particles accelerated in the shock region.
  - CR abundances similar to massive stars composition
  - SNRs are primaries candidates for GCR sources, but γ-rays origin still under debate



First discovery at HE : Eta Carinae

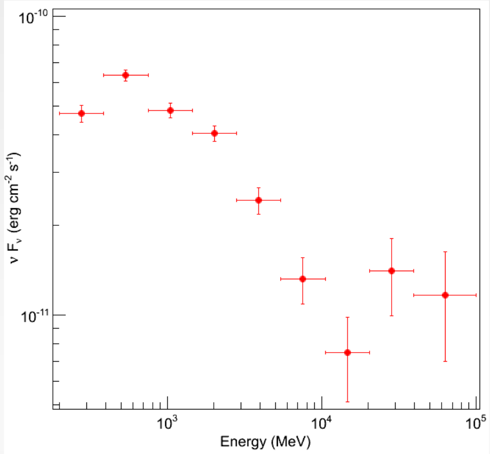


HST view of eta Carinae

eta Carinae binary system spredsheet

Parameter	Value	Reference
d	2.3 ± 0.1 kpc	Davidson & Humphreys (1997)
P	2024 ± 2 d	Corcoran et al. (2005)
i	$45°$	Okazaki et al. (2008)
e	0.9	Smith et al. (2004)
Φ	$27°$	Okazaki et al. (2008)
	0-$30°$	Parkin et al. (2009)
a	15.4 AU	Corcoran (2001)
M_A	$90\ M_\odot$	Hillier et al. (2001)
M_B	$30\ M_\odot$	Verner et al. (2005)
$\dot{M}_A$	$10^{-3}\ M_\odot yr^{-1}$	Hillier et al. (2001)
	$2.5\times10^{-4}\ M_\odot yr^{-1}$	Pittard & Corcoran (2002)
$\dot{M}_B$	$10^{-5}\ M_\odot yr^{-1}$	Pittard & Corcoran (2002)
	$1.5\times10^{-5}\ M_\odot yr^{-1}$	Parkin et al. (2009)
$V_{\infty,A}$	$500\ kms^{-1}$	Hillier et al. (2001)
$V_{\infty,B}$	$3000\ kms^{-1}$	Pittard & Corcoran (2002)

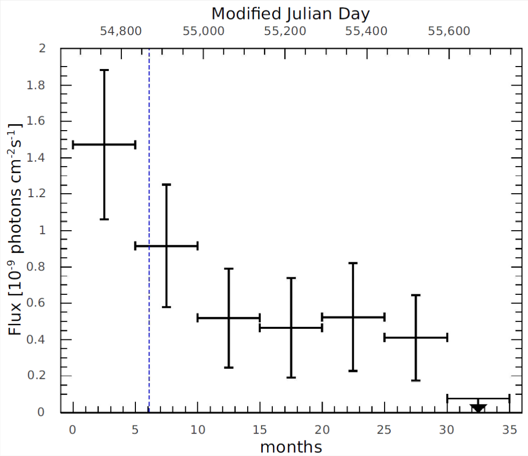
Eta Carinae SED
Fermi-LAT data



CF, Walter & Leyder 2011

← atypical γ-ray spectrum :
2 components, variation of the HE component over time related with geometry of the system →

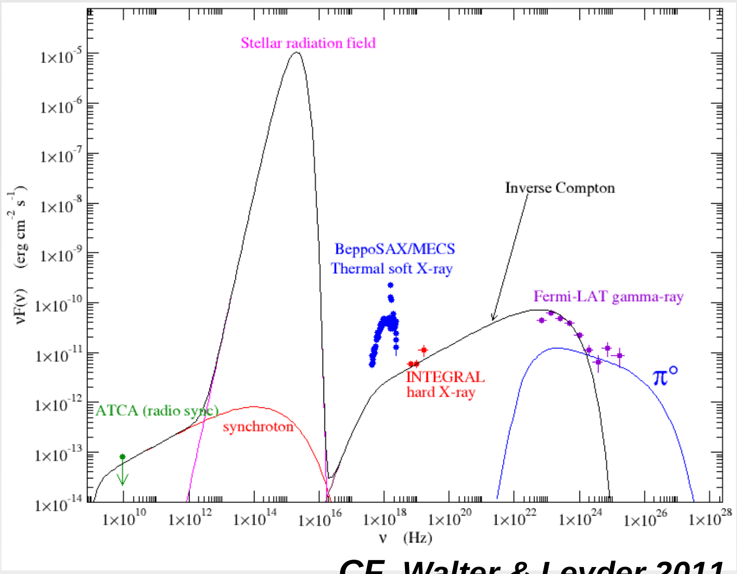
Eta Carinae lightcurve
Fermi-LAT data



Reitberger et al. 2012

Potential scenario for HE in eta Carinae

2 pop. of accelerated particles



CF, Walter & Leyder 2011

Energetics

- Wind momentum ratio : $\eta = \frac{\dot{M}_2 v_2^\infty}{\dot{M}_1 v_1^\infty} \approx 0.2$
- Wind fraction in CWB region ~10 %
- Mechanical energy available ~ $200L_{SUN}$
- Total interacting proton energy $E_p \sim 10^{40}$erg
  ↔ energy to sustain shock $E_p/t_{pp} \sim 10L_{SUN}$
  ↔ 5 % of shocked mechanical energy
  ↔ <1 % of total wind mechanical luminosity
- Integrated over massive star lifetime, CR acceleration efficiency to comparable SNRs

Population study ongoing

- Small but increasing number of systems display a hard X-ray components, but geometry/period seldom known
- Difficulties for LAT analysis due to strong galactic diffuse component

Implication

- Observed CRs composition close to massive stars
- CWB may have a significant contribution to galactic CRs

eta Carinae at VHE

- No detection at VHE, but (a posteriori) observations non optimal
  - Few data close to periastron
  - High E_{th}

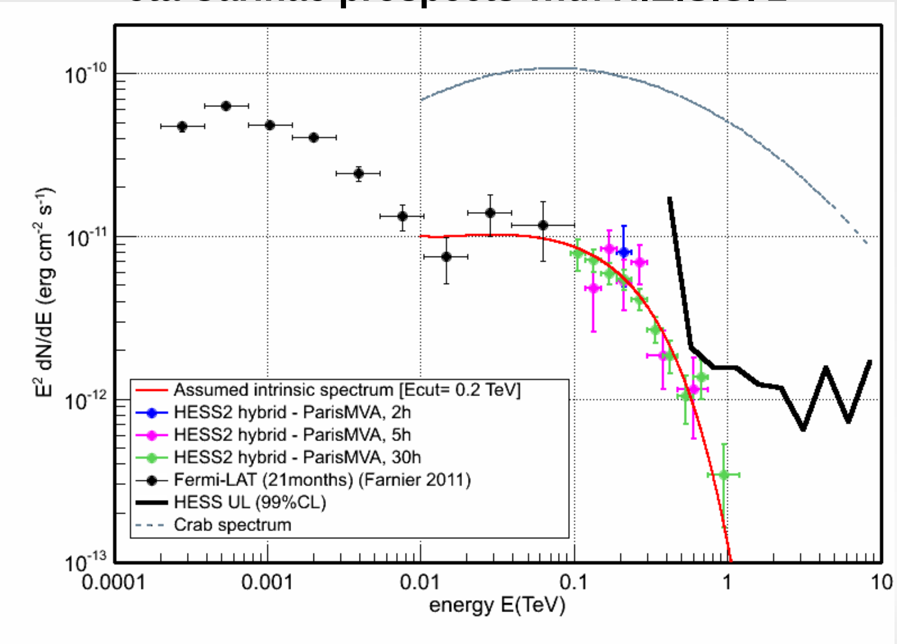
eta Carinae observations with H.E.S.S

Data Set	date	MJD	Phase	live time (hrs)
1	24.03.04	53088	0.12	1.4
2	11.02.05	53412	0.29	0.9
3	22.05.06 - 24.05.06	53877 - 53879	0.52	5.0
4	01.02.09 - 14.04.09	54863 - 54935	1.01 - 1.04	1.8
5	15.01.10 - 22.03.10	55211 - 55277	1.18 - 1.21	18.4
6	06.12.10 - 18.12.10	55536 - 55548	1.34 - 1.35	5.6
all	24.03.04 - 18.12.10	53088 - 55548	0.12 - 1.35	33.1

H.E.S.S Collab. 2012

- Good prospects with H.E.S.S. 2
- But difficult region : high NSB
- Observation in 2013 to understand the data
  Might reveal some suprises (fast variability bellow LAT threshold ?)
- Next periastron passage : summer 2014

eta Carinae prospects with H.E.S.S. 2

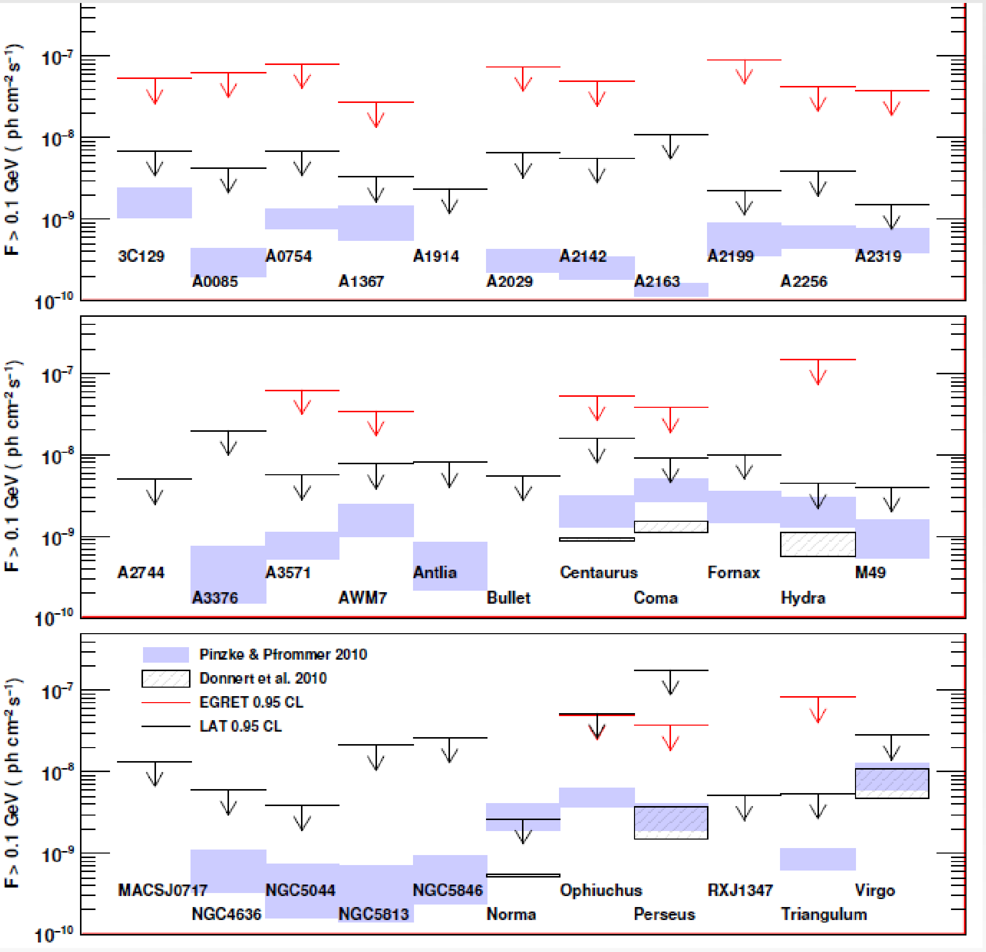


CF, Ohm, H.E.S.S. obs. proposal

Expected γ-ray emitter : cluster of galaxies

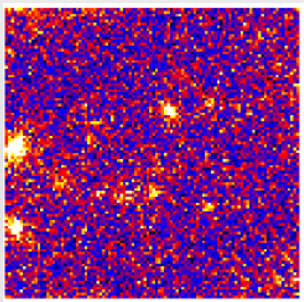
- NT component known through observation of diffuse radio emission →presence of relativistic e (secondary products of VHE p ?)
- But no detection at HE by Fermi-LAT
- HE flux UL of individual targets range between 7 to 140 x 10^{-10}ph/cm^2/s
- Fainter emissivity than expected from different models :
  - Wave shocks (hierarchical structure formation)
  - Injection of CR (SNR,AGN)
  - Central AGN feedback
  - ...
- Need to go deeper...

Fermi-LAT UL on 33 clusters of galaxies

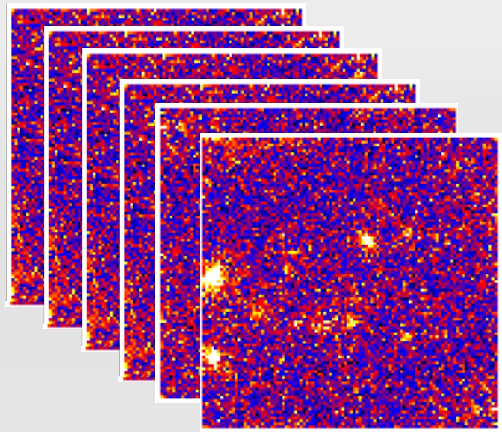


Fermi-LAT Coll., 2010

Stacking method

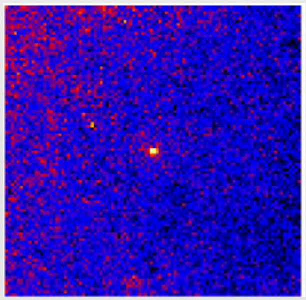


Single ROI with central source at the detection limit



Co-adding of multiple ROIs

Subtraction of 2FGL sources
Background fluctuations
« washed out »



Final stacked ROIs
central source clearly visible

<u>Additional cross-check with Monte-Carlo :</u>

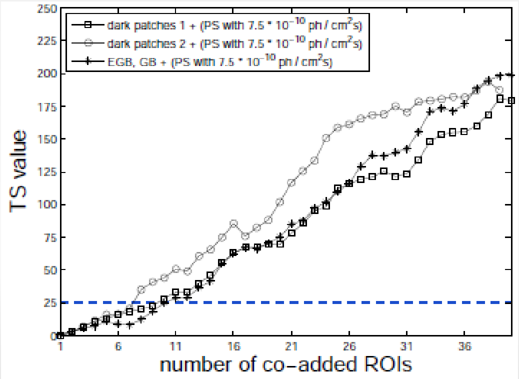
Bckg = true data

Central source = faint (well below detection threshold) PL source

Likelihood analysis of the final count map

Smooth development of the Test Statistic :
$TS = -2\ln(L_{Null}/L_{Alt})$

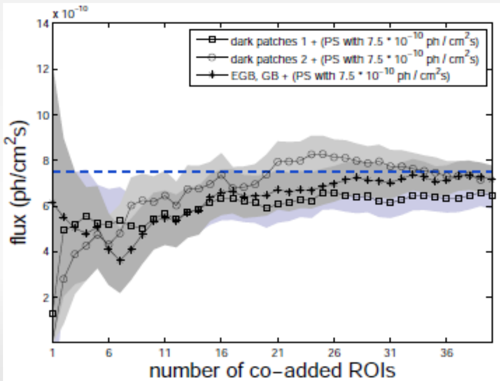
TS development of co-added ROIs



Maximum Likelihood fit of the final count map

Reconstructed flux compatible with simulated one

Flux determination



Huber, CF, et al. 2012

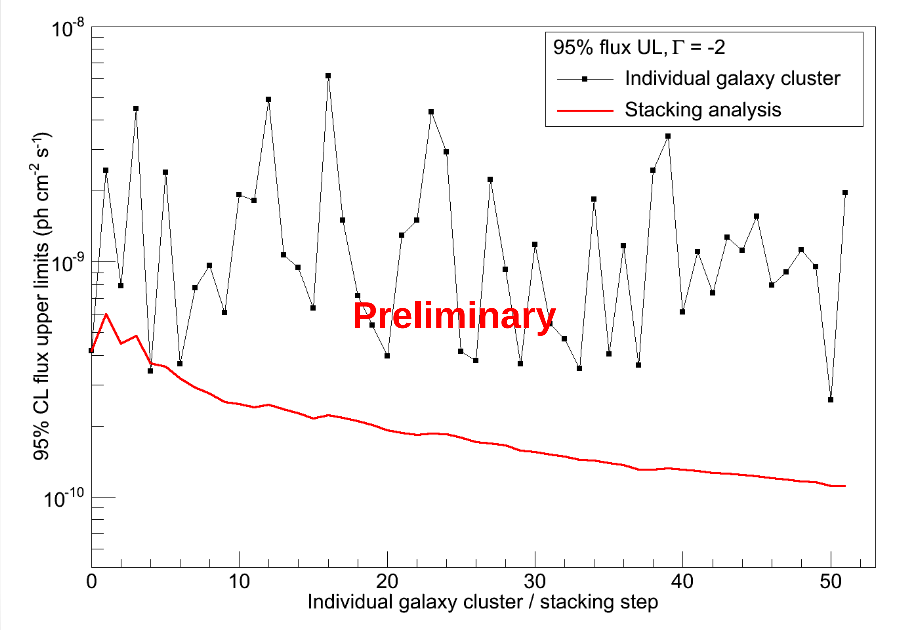
Stacking results on galaxy clusters

Data set

- 53 clusters (HIFLUGCS)
  |b|>25, 30<l<330 z<0.2 E>200 MeV T_{obs}~4 years of data
- HE emissivity UL from stacked sample ~1 x 10^{-10}ph/cm^2/s

Preliminary results on CR

- Population study (Cool-Core vs Non Cool-Core)
- Volume-averaged ratio of CR-hadron-to-thermal energy density < 3 % (vs 5-10 % from Fermi Coll. 2010)



Huber, Tchernin, Eckert, CF. et al., in prep.

A potential other source of γ-ray emission...

...annihilation of Dark Matter particles

DM in the Universe ?

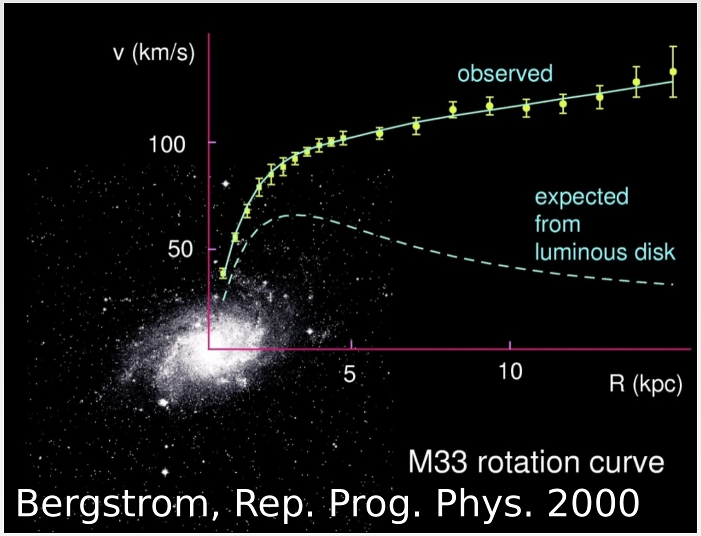
- We have proofs of its existence known for a long time
  - Mass estimation of cluster of galaxies – F. Zwicky 1933

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.”

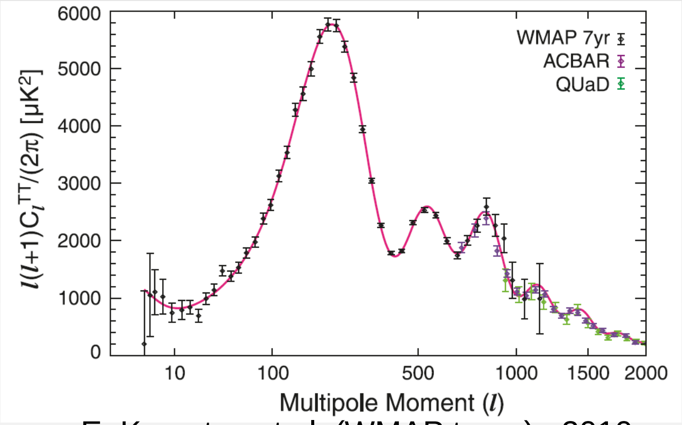
DM in the Universe ?

- We have proofs of its existence known for a long time
  - Mass estimation of cluster of galaxies – F. Zwicky 1933
  - Rotation curve of galaxies – V. Rubin 1962



DM in the Universe ?

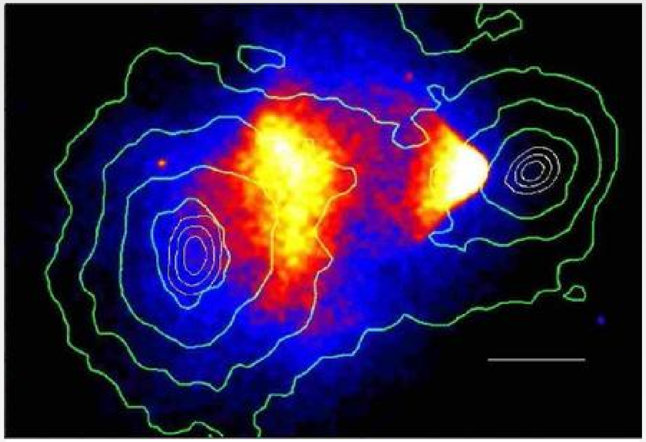
- We have proofs of its existence known for a long time
  - Mass estimation of cluster of galaxies – F. Zwicky 1933
  - Rotation curve of galaxies – V. Rubin 1962
  - CMB power spectrum



E. Komatsu et al. (WMAP team) , 2010

DM in the Universe ?

- We have proofs of its existence known for a long time
  - Mass estimation of cluster of galaxies – F. Zwicky 1933
  - Rotation curve of galaxies – V. Rubin 1962
  - CMB power spectrum
  - Bullet cluster observation

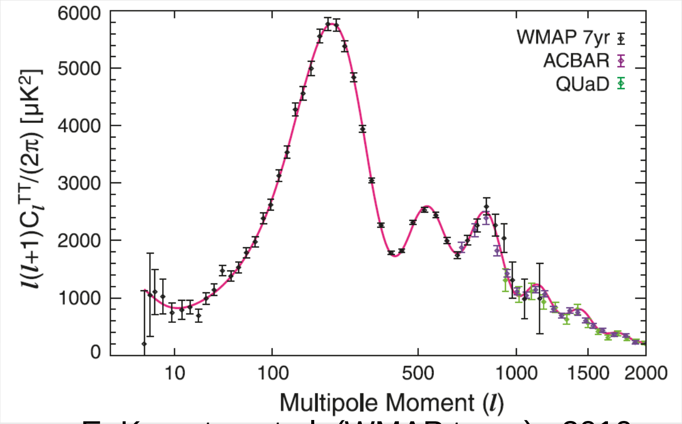


The bullet cluster, D. Clowe et al., 2006

(*cf.* new colliding cluster,Abell 2744, J. Marten et al., 2011)

DM in the Universe ?

- We have proofs of its existence known for a long time
  - Mass estimation of cluster of galaxies – F. Zwicky 1933
  - Rotation curve of galaxies – V. Rubin 1962
  - CMB power spectrum
  - Bullet cluster observation
  - …
- We know it can not be ordinary matter (CMB)
- Yet we have no clues on its nature.
  But we have strongly motivated candidates in form of Weakly Interacting Massive Particles (***WIMPs***).



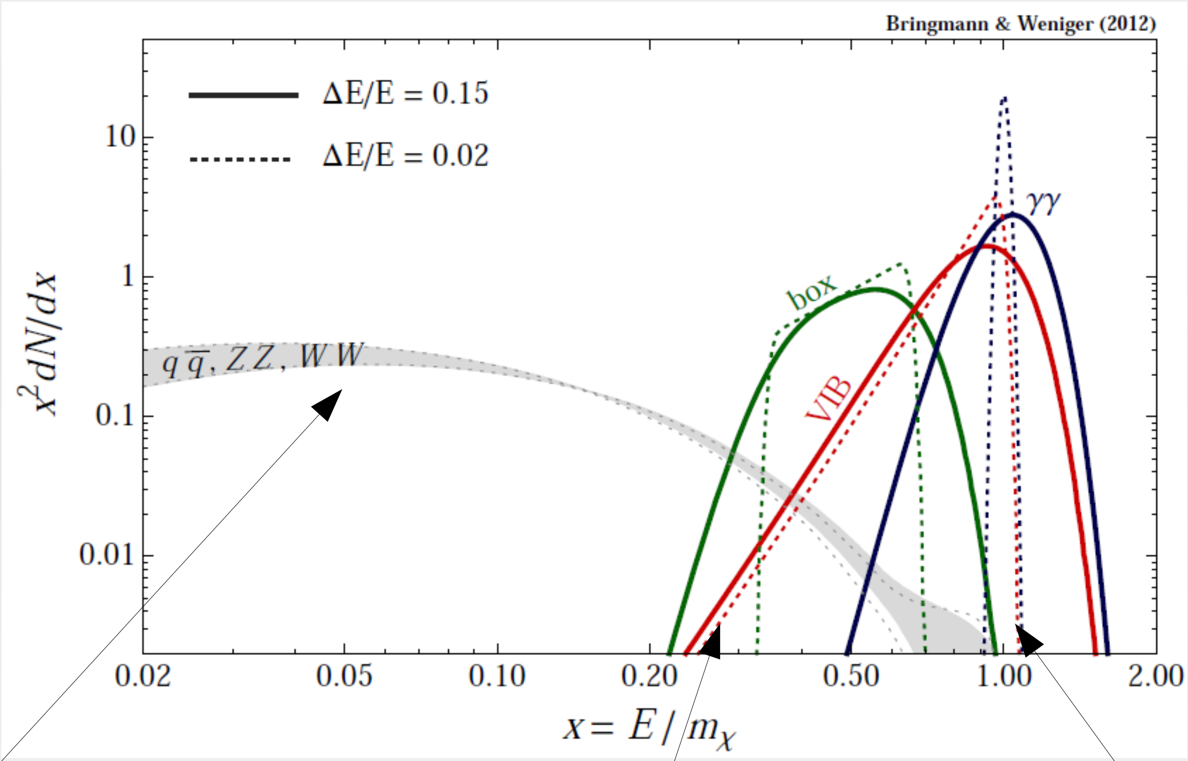
E. Komatsu et al. (WMAP team) , 2010

$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.003 \pm 0.01$$

$\Omega_\Lambda = 0.727 \pm 0.030$ $\boxed{\Omega_{CDM} h^2 = 0.1120 \pm 0.0056}$

$\Omega_B = 0.0455 \pm 0.0028$ $h = 0.704 \pm 0.025$

Various DM annihilation γ-ray spectra



Continuum emission
(« secondary photons »)

fragmentation of quarks / massive gauge bosons (via pi0 decay)

Virtual Internal Bremsstrahlung (VIB)

radiative correction to processes with charged final states

Generically suppressed by O(α)

Gamma-ray lines

from two-body annihilation into photons

Forbidden at tree-level, generically suppressed by O(α^2)

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,...

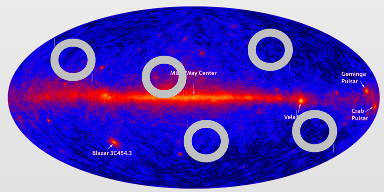
- Particle physic factor :
  - determine the nb of γ-ray produced per annihilation
    → spectral shape

Uncertainties :

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

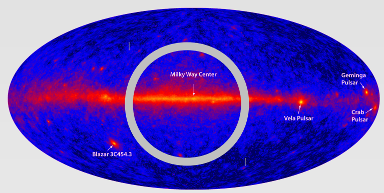
DM targets for indirect γ-ray searches

Dwarf galaxies



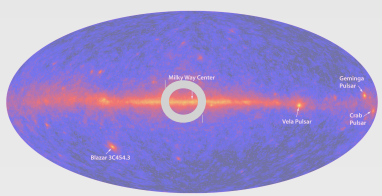
Pros: increasing number of objects, bckg free
Cons: amount of DM limited

Galactic Halo



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

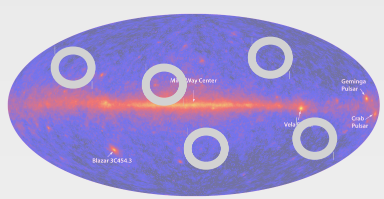
Galactic Centre



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

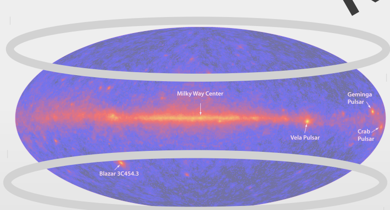
Not covered in this talk

Galaxy Clusters



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

Extragalactic

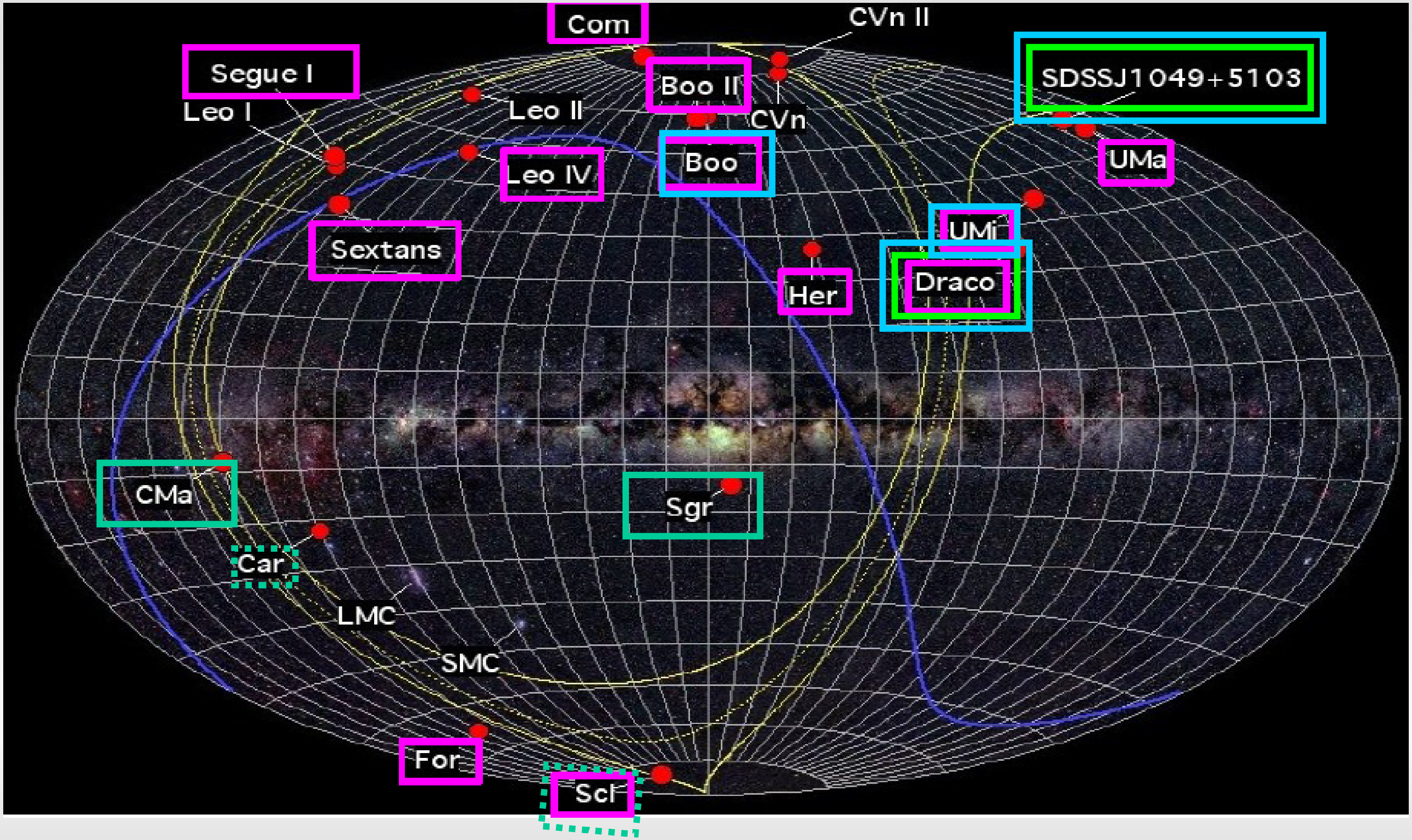


Pros: large integration region
Cons: low DM density, bckg

Dwarf spheroidal galaxies

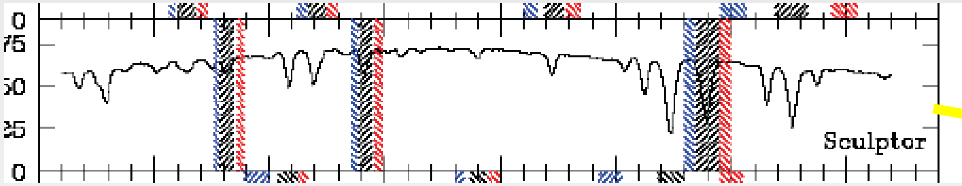
Dwarf galaxies probed in gamma-rays as in 2012

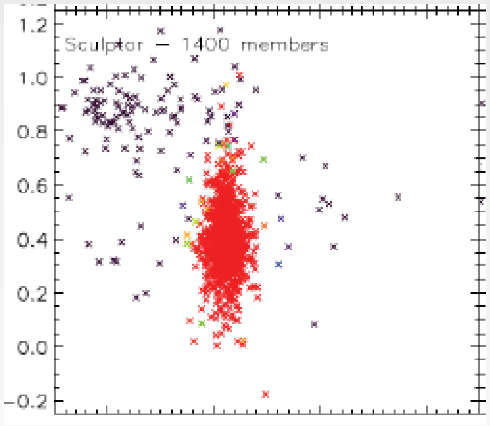
Fermi H.E.S.S. MAGIC Veritas

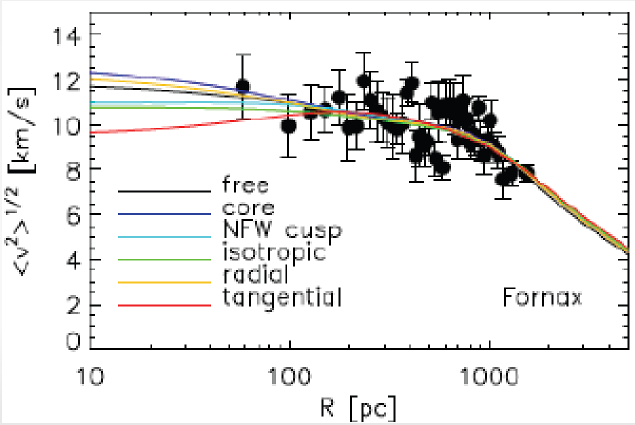


Why dwarf galaxies ?

- 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)



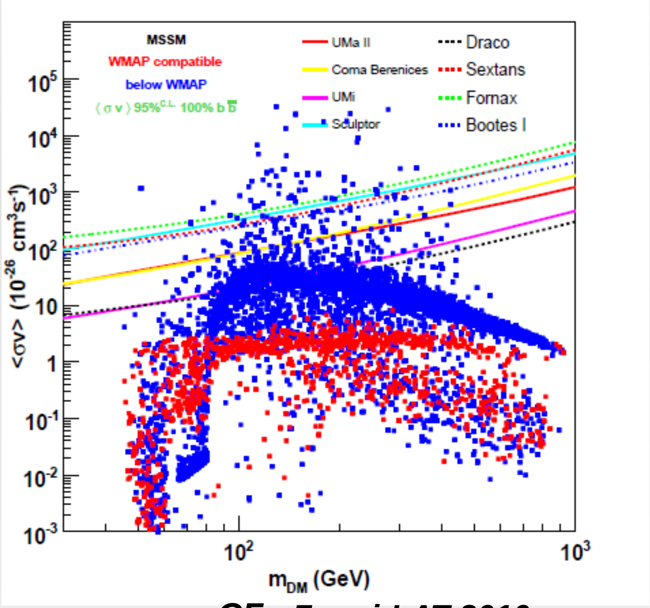




$<\sigma v>$ constraints from individual sources

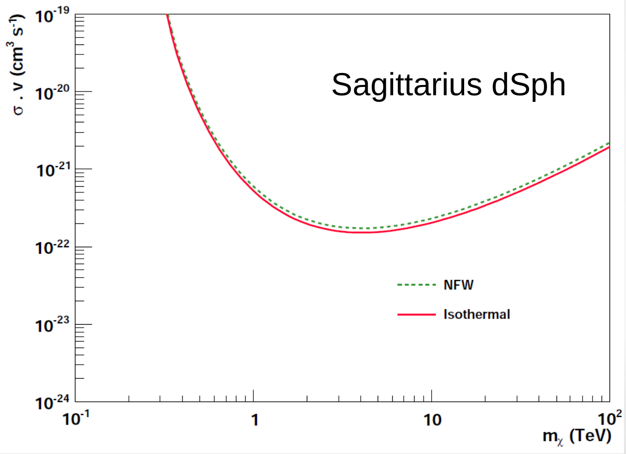
- Signal search : bckg (CR and/or γ-ray sources) modeling or subtraction
- Flux upper-limit determination
  $\Phi^{UL} = f(N_{obs}, A_{eff}, T_{obs}, \text{DM model}(m_{DM}))$
- Correspondance into
  $<\sigma v>^{UL} = f(\Phi^{UL}, \text{ DM model}(m_{DM}))$

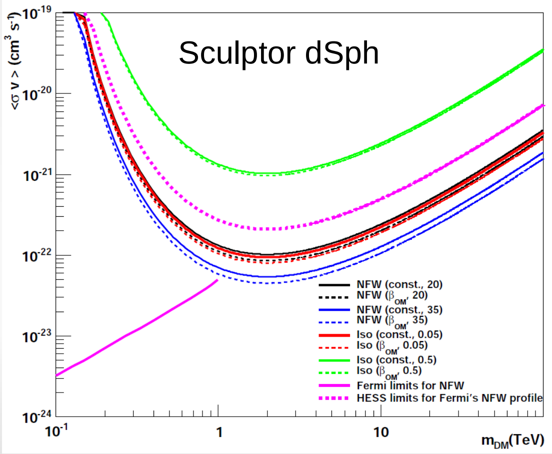
Fermi-LAT results

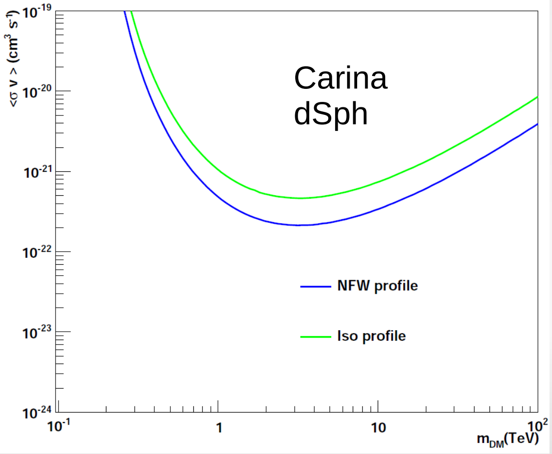


CF - Fermi-LAT 2010

H.E.S.S. results





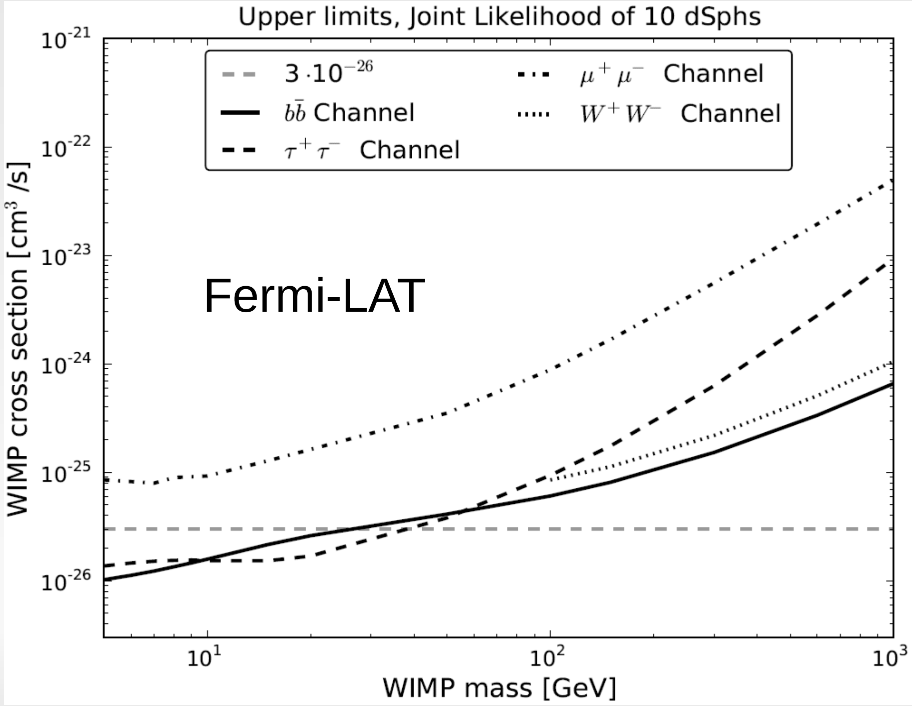


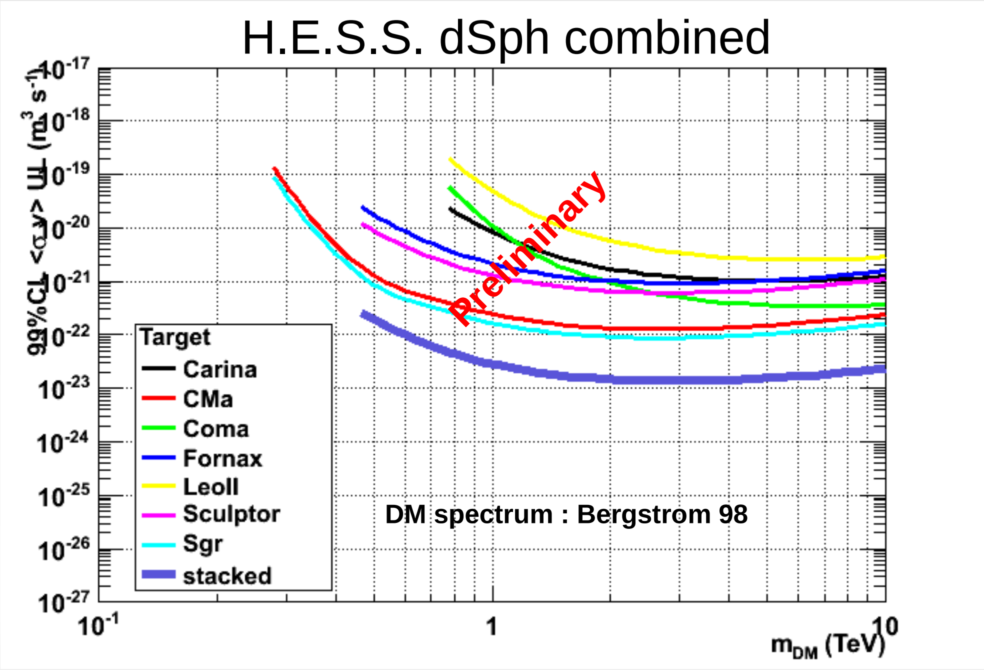
H.E.S.S. Coll, 2007-2011

dSphs combined analysis

Since DM profile is universal, observations of similar targets can be combined

- Work done by the Fermi-LAT collaboration on 10 dSphs, including J-factor uncertainties in the determination of <σv> upper-limits
- Similar work ongoing for H.E.S.S. observations with 7 dSphs



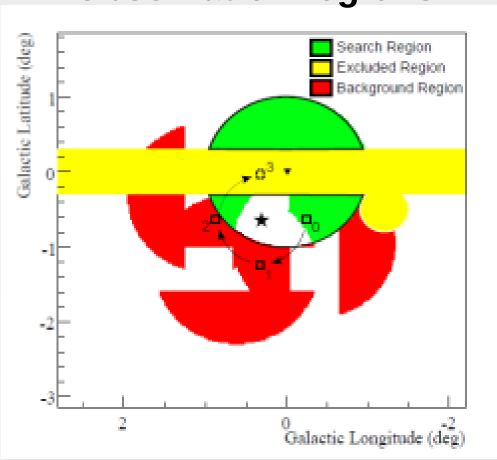


Fermi-LAT Coll, 2011

CF - H.E.S.S. Coll, in prep

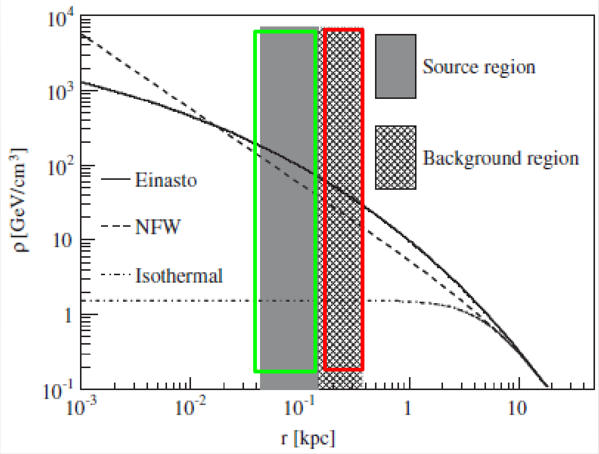
The Galactic halo with H.E.S.S.

Observation regions



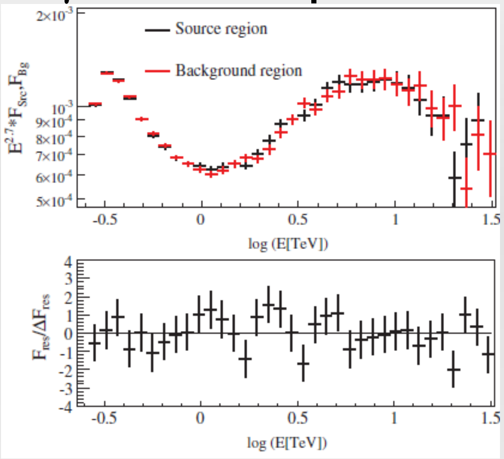
signal, bckg and excluded regions definition

DM density vs distance from the GC

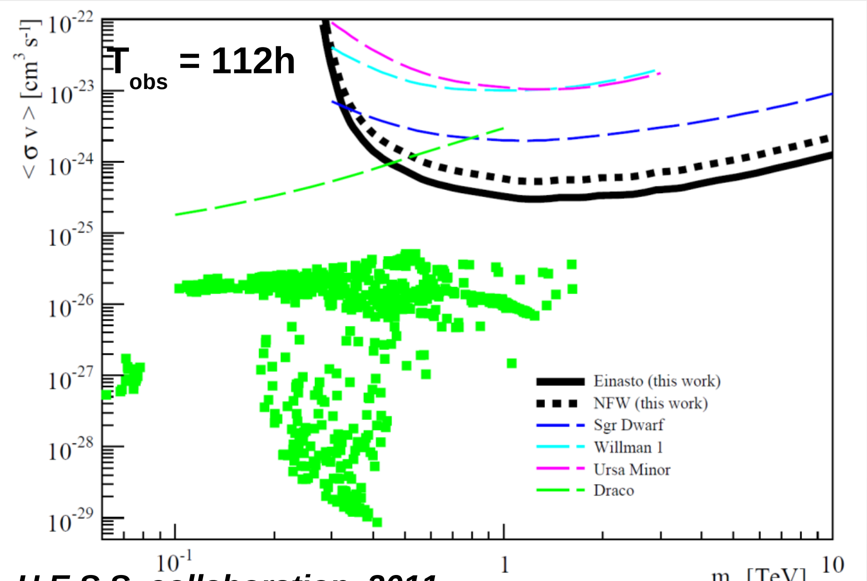


Corresponding DM densities

γ-like events spectrum



Observation results : no significant excess



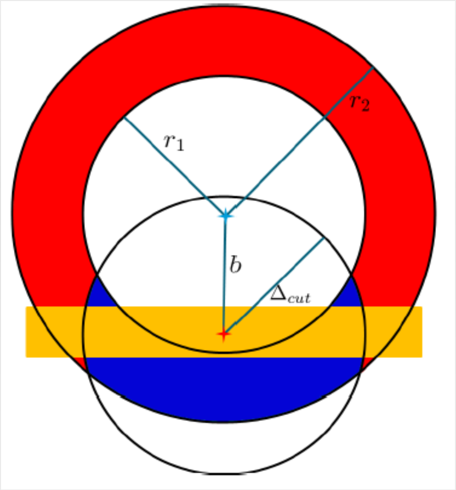
H.E.S.S. collaboration, 2011

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

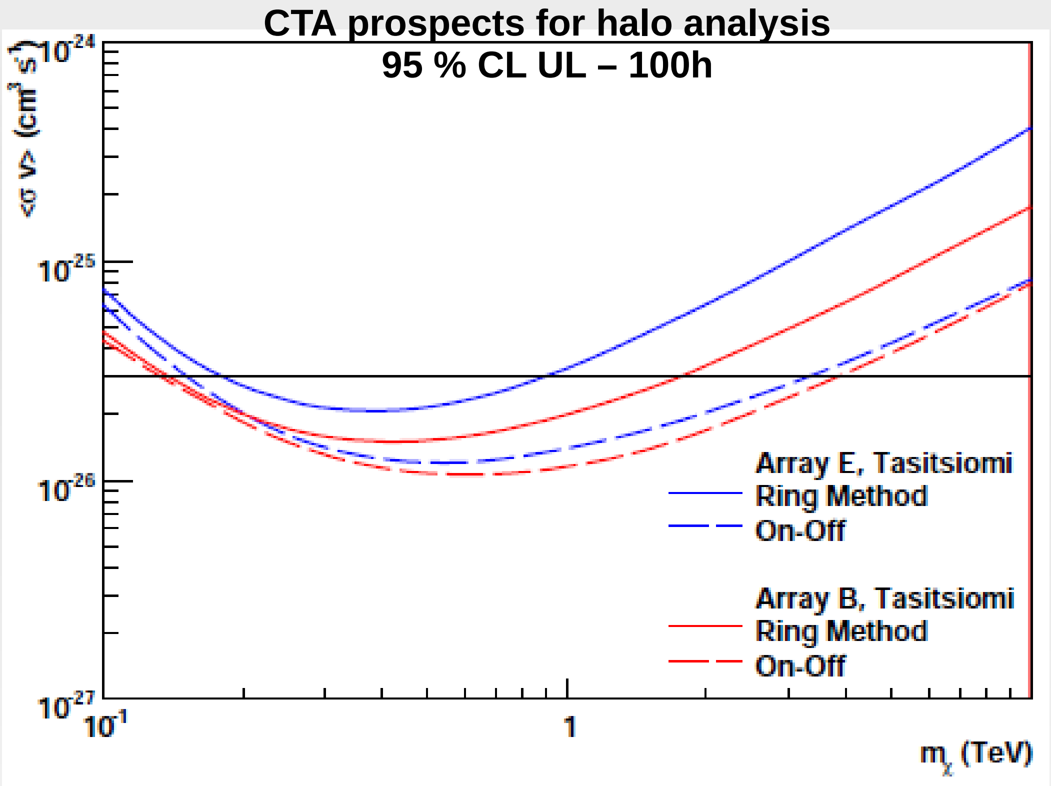
But still above viable DM models.

Better sensitivity is required.

Galactic halo with CTA – prospects



« Ring Method » to construct **signal** and **background** (**excluded**) regions



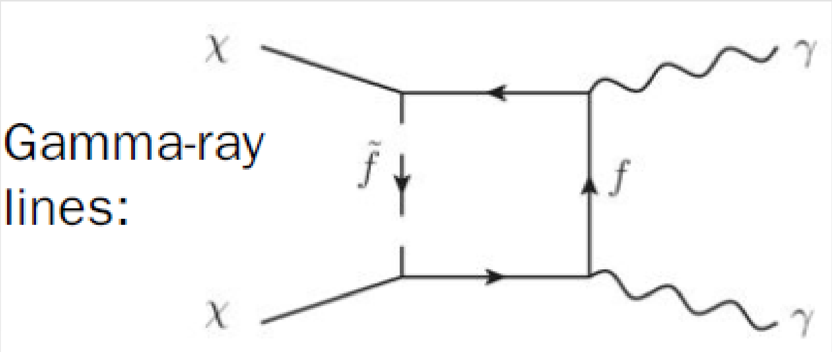
CTA consortium, in press

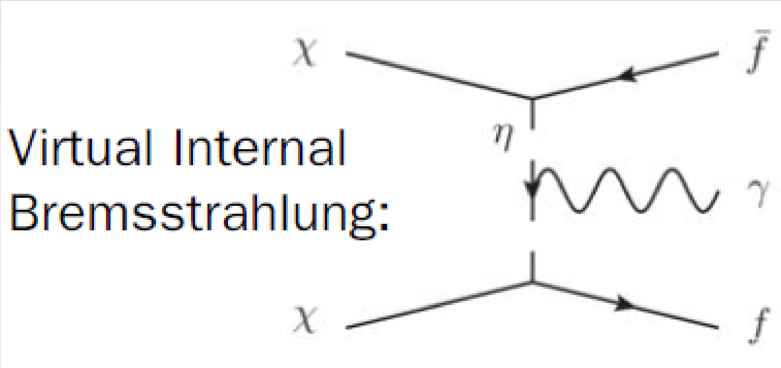
Simulations indicate that the Galactic halo is the most promising target for CTA to search for a continuum of γ-rays arising from DM annihilation.

In 100h of observations, CTA will probe SUSY models compatible with WMAP results thanks to better sensitivity and larger FOV.

Line-like signal from DM annihilation

- Search for a bump, sharp excess over the distribution of background events
- **Smoking gun** of DM since no other astrophysical sources are foreseen to mimic such signal



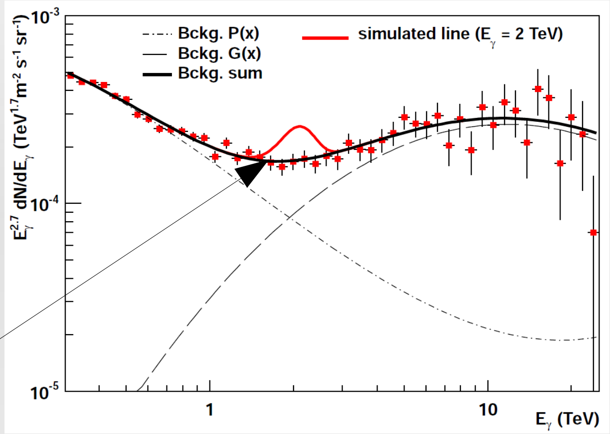


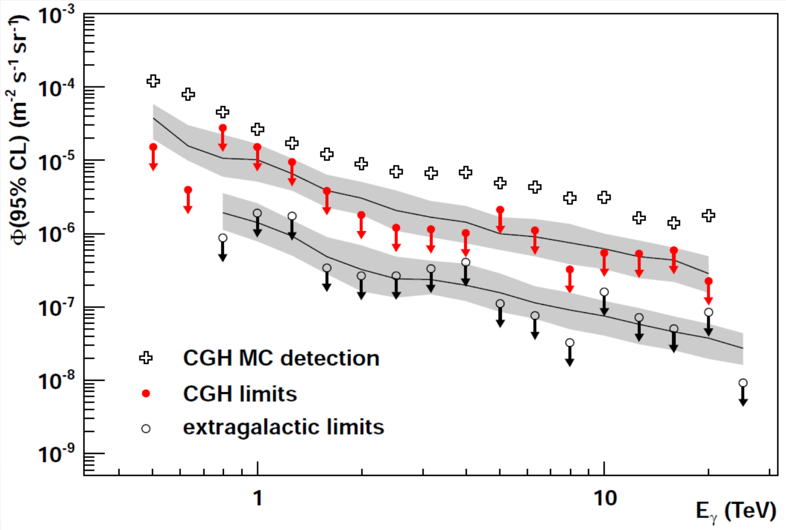
- Line arising from $\chi\chi \rightarrow \gamma X$ @ $E_\gamma = m_\chi \times [1 - m_X^2/4m_\chi^2]$, $[X = \gamma, Z, H]$
- Internal Bremsstrahlung :
  - Final state radiation
  - Virtual IB

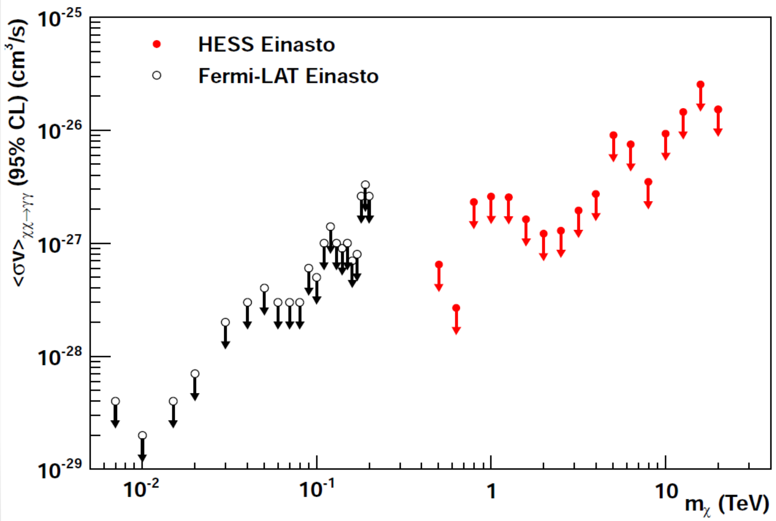
  is very model dependant, a broader feature

Line search with H.E.S.S.

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

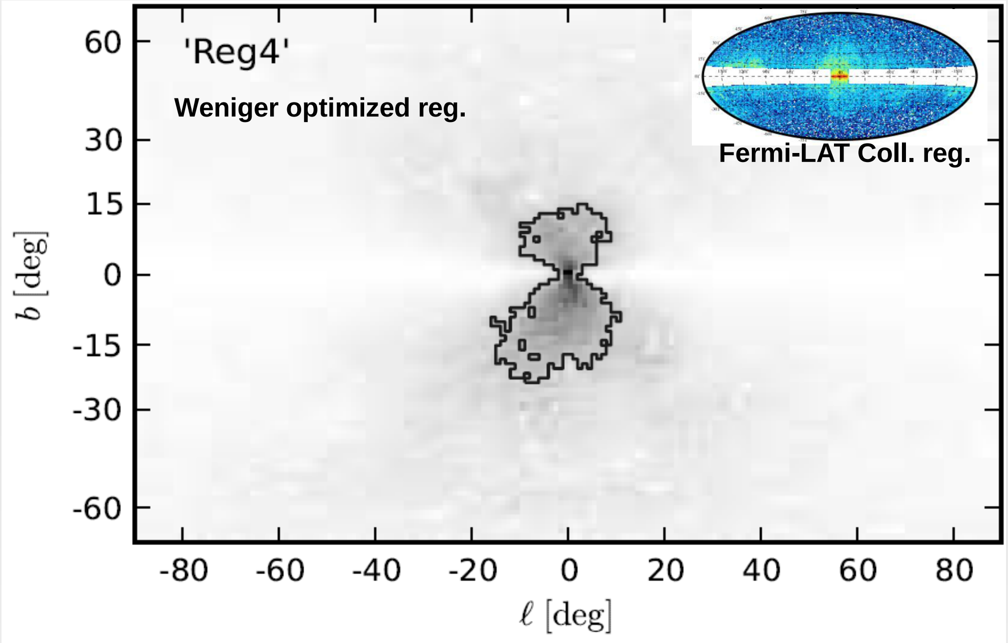


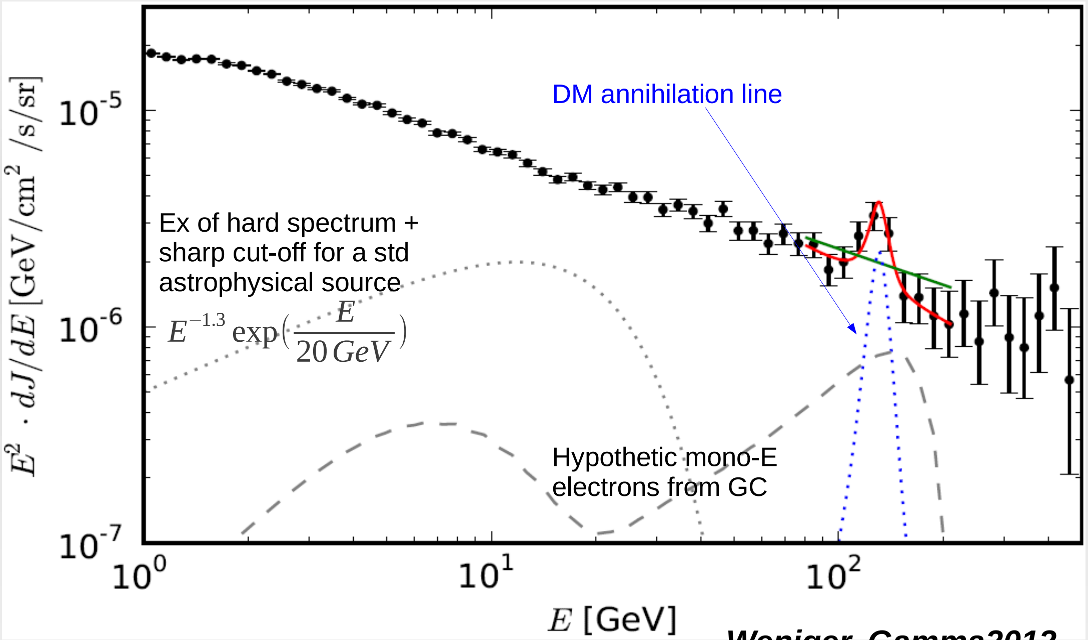




H.E.S.S. Coll. 2013, in press

Line search with Fermi-LAT





Weniger, Gamma2012

Spectral analysis of 43 months of Fermi-LAT data (with search region optimized S/B)
→ sharp spectral feature compatible with :

- an annihilation line for a DM particle of m_{DM}=130 GeV, 4.6σ (3.2σ) ***Weniger, 2012***
- Internal bremmstrahlung from a m_{DM}=149 GeV, 4.3σ (3.1σ) ***Bringmann et al., 2012***

Supported by spatial analysis + analysis of clusters of galaxies of Fermi-LAT data.

Su & Finkbeiner, 2012
Tempel et al., 2012

Is it really DM ?

- Several questions
  - Possible CR contamination ?
    Analysis of limb data are not able to confirm it nor rule it out
  - Deplacement of the signal w.r.t. Galactic centre ?
    Statistic limited, signal still compatible with (l=0,b=0)
  - Several lines ?
    Other lines are not significant
  - Lack of continuum ?
    Don't worry, theoreticians have found some ways out (see arXiv !!)
- Need confirmation
  - Fermi-LAT additional data ~ 2016 (a bit earlier with more advanced reconstruction algorithm)
  - Independant analysis

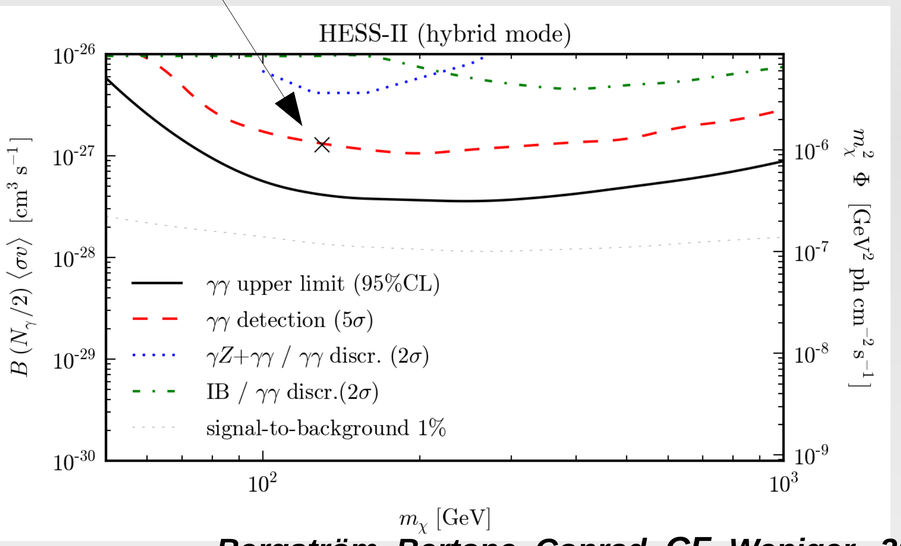
In a near future with H.E.S.S. 2

« Hybrid » mode observation : 5th large size tel. + ≥ 1 std tel.

- Lower energy threshold
- Improved sensitivity ≤ 500 GeV
- 5σ detection in 50h

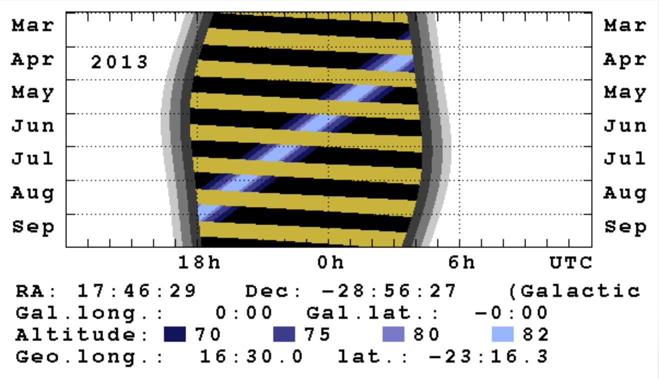
H.E.S.S. 2 can confirm (or rule out) the signal **by 2013 !**

Weniger signal



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

Galactic centre visibilty for H.E.S.S. In 2013



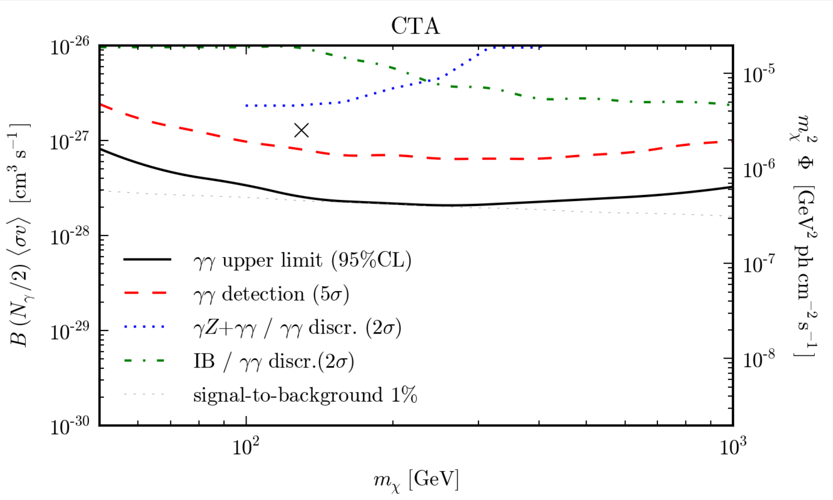
	Visibility during darkness (min) above altitude			
Month	70°	75°	80°	82°
March	216	48	0	0
April	1986	1602	1062	759
May	2553	1866	1113	789
June	2754	2001	1218	840
July	3186	2331	1395	978
August	2556	1920	1242	903
September	537	354	177	96
Total	13788	10122	6207	4365

CF, H.E.S.S. obs. poposal

Or next with CTA & Gamma400

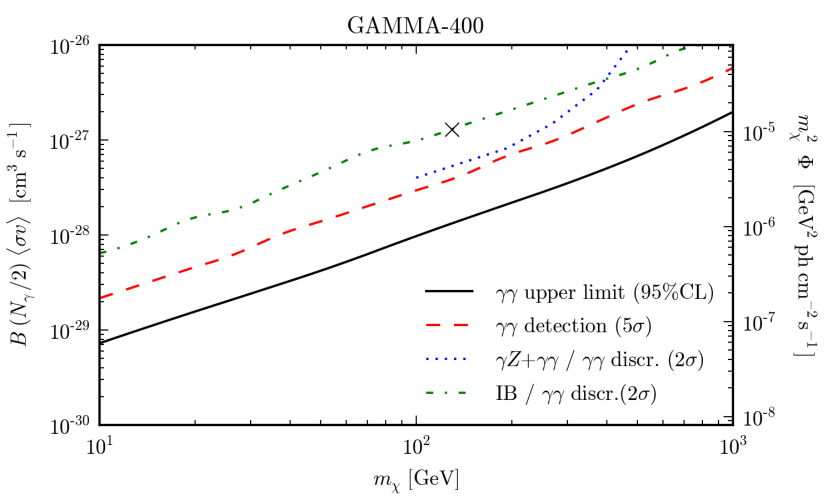
CTA expectations

- >5σ in 5h [syst. uncertainties]
- 1 vs 2 lines distinction reachable with additional time and refined analysis



Gamma400

- Russian satellite (2018) design « a la LAT » but with larger calorimeter (22 X_0)
- Better dE/E : 1.5 % @ 100GeV
- 1 vs 2 lines and line vs IB scenarios can be distinguished within 5y



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

Conclusions

- γ-rays probe the most extreme sources of the Universe.
- Current and near future experiments are transforming our vision :
  - Fermi-LAT proves is ability to detect a very large number of sources,
  - The future large ground based experiment, CTA, will increase the number of VHE sources by x10.
- With such sensitivities, new classes of γ-ray sources are likely to be discovered.
- Indirect searches for DM signal towards different targets already start to scratch SUSY parameter space with the right relic density
  - Collider experiments might be able to find new physic, but only observations of the Universe will allow to uncover the nature of DM.
- Do we have it already ? Stay tuned, confirmation will come soon !

Thanks for your attention !

Backups