The future of very high energy gamma ray astronomy

From HESS to CTA

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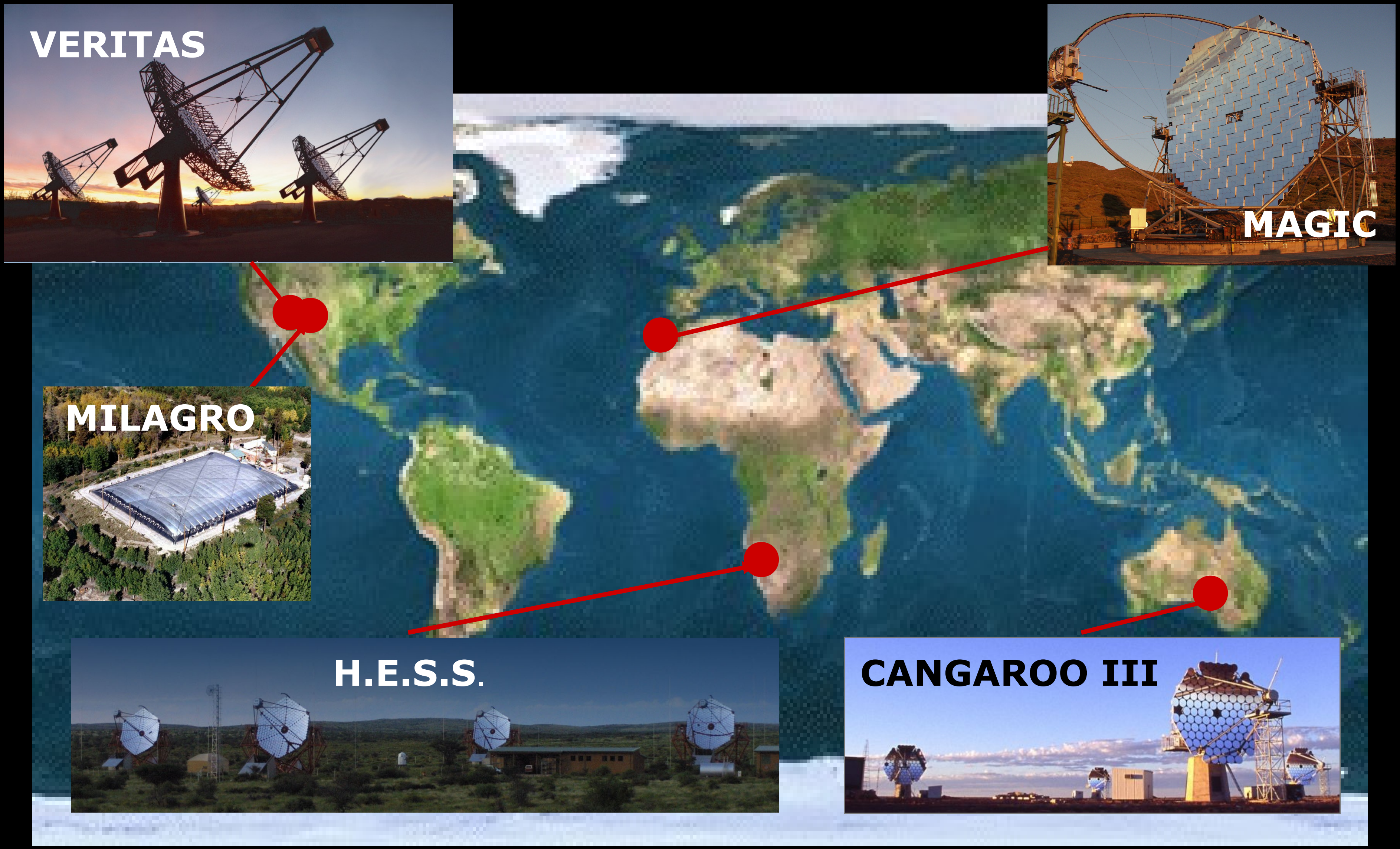
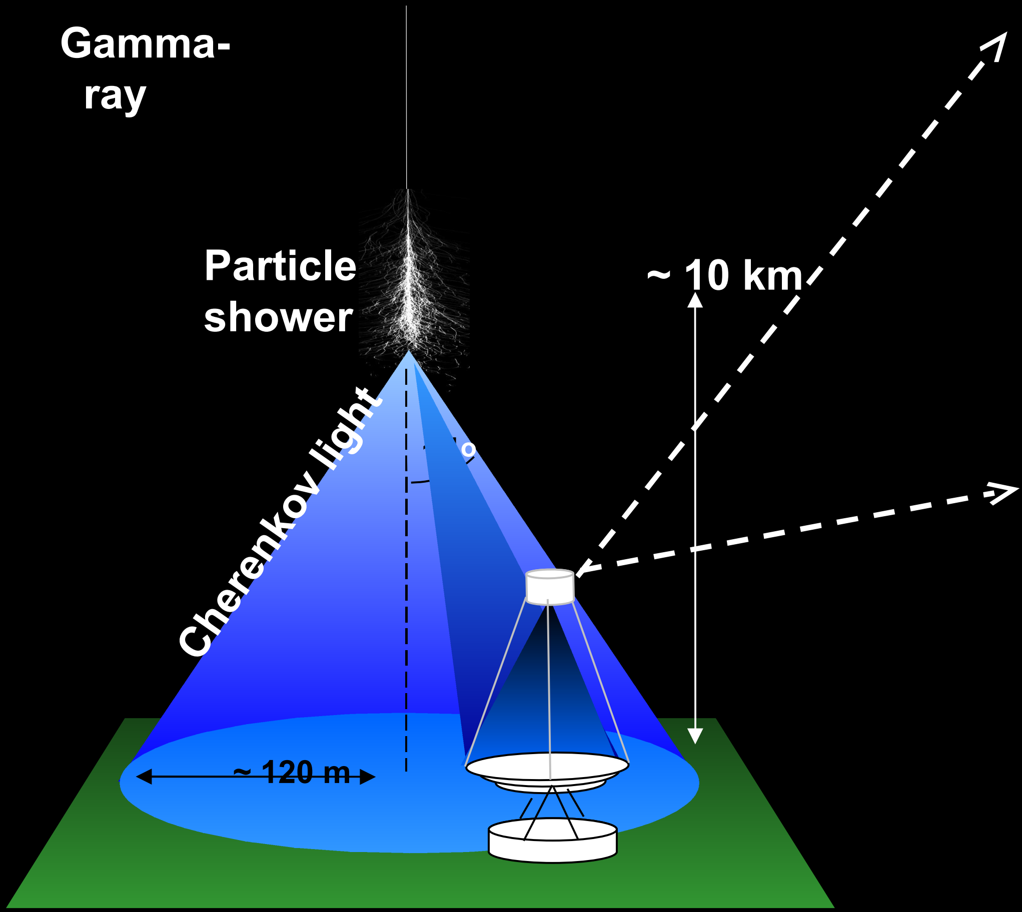
Outline

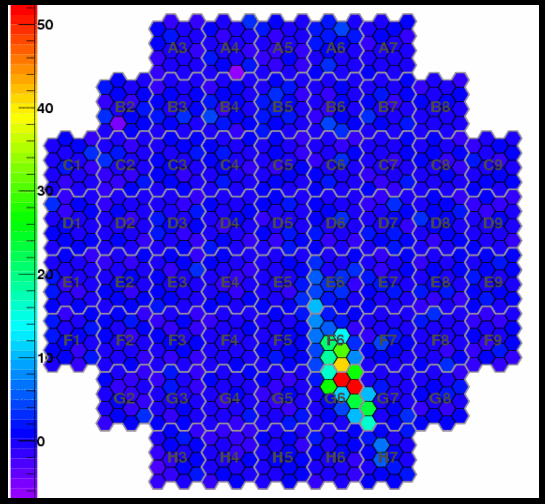
- Status of VHE γ ray astronomy
- Recent results on DM search with HESS
- The CTA concept
- Dark matter, from HESS to CTA
- The CTA consortium and design study

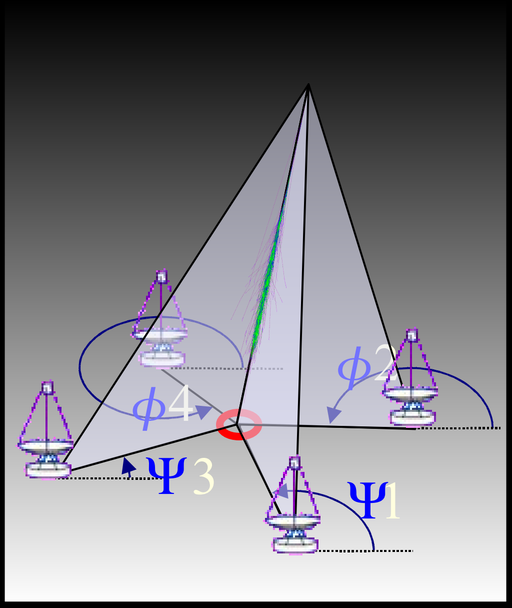
Ground-based VHE gamma-ray instruments



Imaging atmospheric Cherenkov telescopes







- brief flash ~3 ns
- **steroscopy**:
  improved gamma ray reconstruction
  muon background rejection

High Energy Stereoscopic System

located in Namibia, latitude=-23°, altitude=1800 m
4 telescopes, 107 m^2 each
cameras 960 PMT
FOV= 5°
trigger threshold=100GeV
installed: january 2004

installation of 5th telescope in 2011
mirror: 600m^2, 2048 PMT, FOV=3.5°, trigger threshold=20 GeV

Major Atmospheric Gamma-ray Imaging Cherenkov

located in La Palma (Canaries Islands),
latitude=+29^o, altitude=2225 m
mirror: 234 m^2
camera 534 PMT
FOV=3.5^o

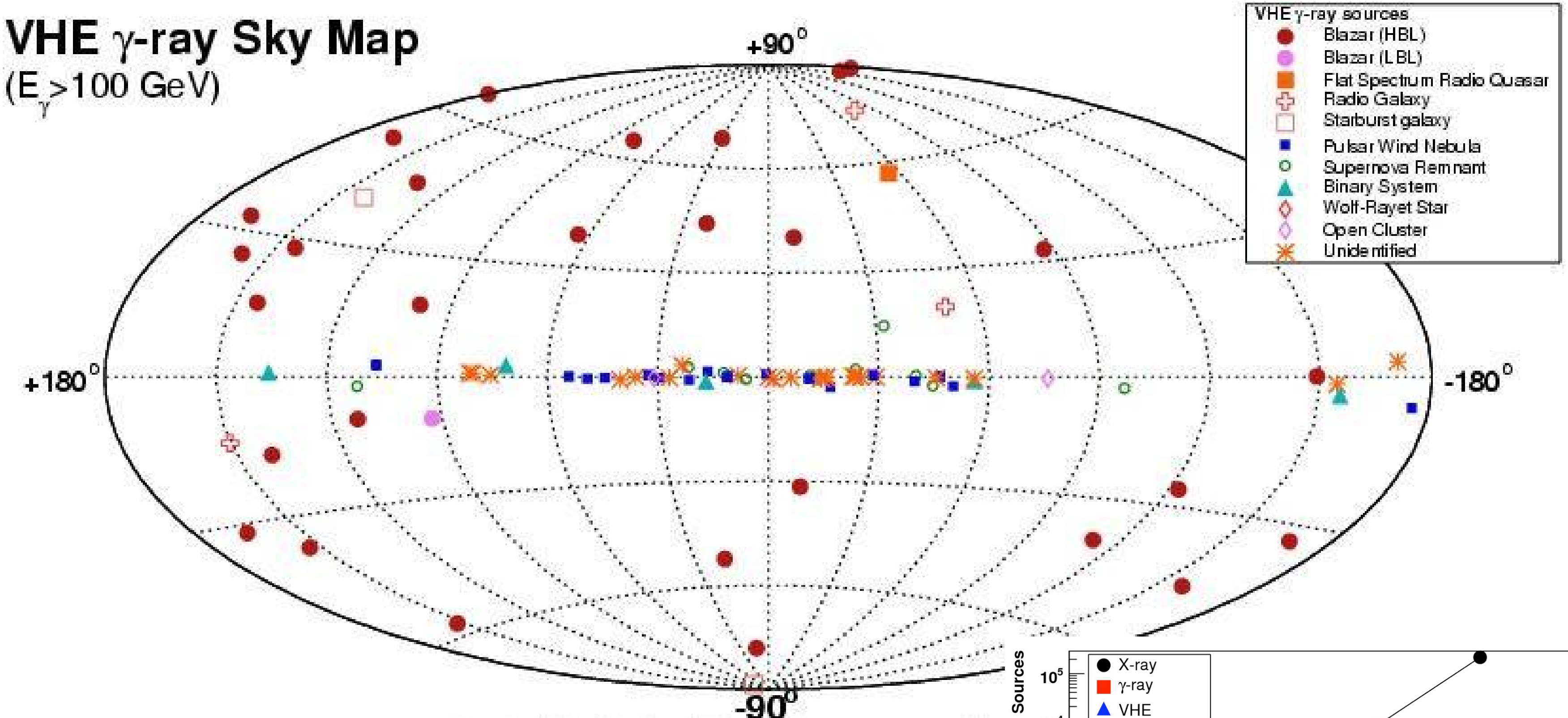
trigger threshold=60 GeV
installed late 2004
installation 2nd telescope in 2009
mirror 234m^2, 1099 PMT

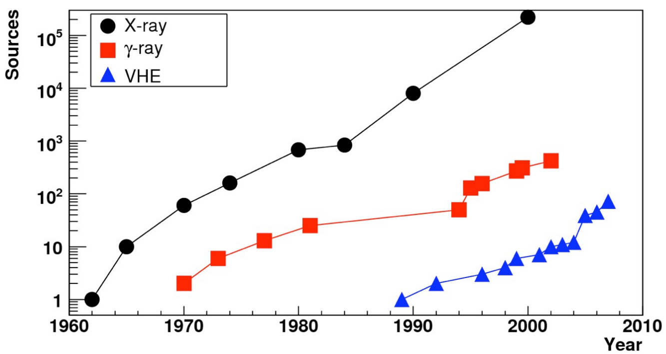
Very Energetic Radiation Imaging Telescope Array System

origin: Whipple collaboration (10 m, late 80s)
located in Arizona, latitude=+32^o, altitude=1275 m

4 telescopes, 106 m^2 each
cameras 499 PMT
FOV=3.5^o
trigger threshold=100 GeV
installed in april 2007

Status of VHE gamma-ray astronomy



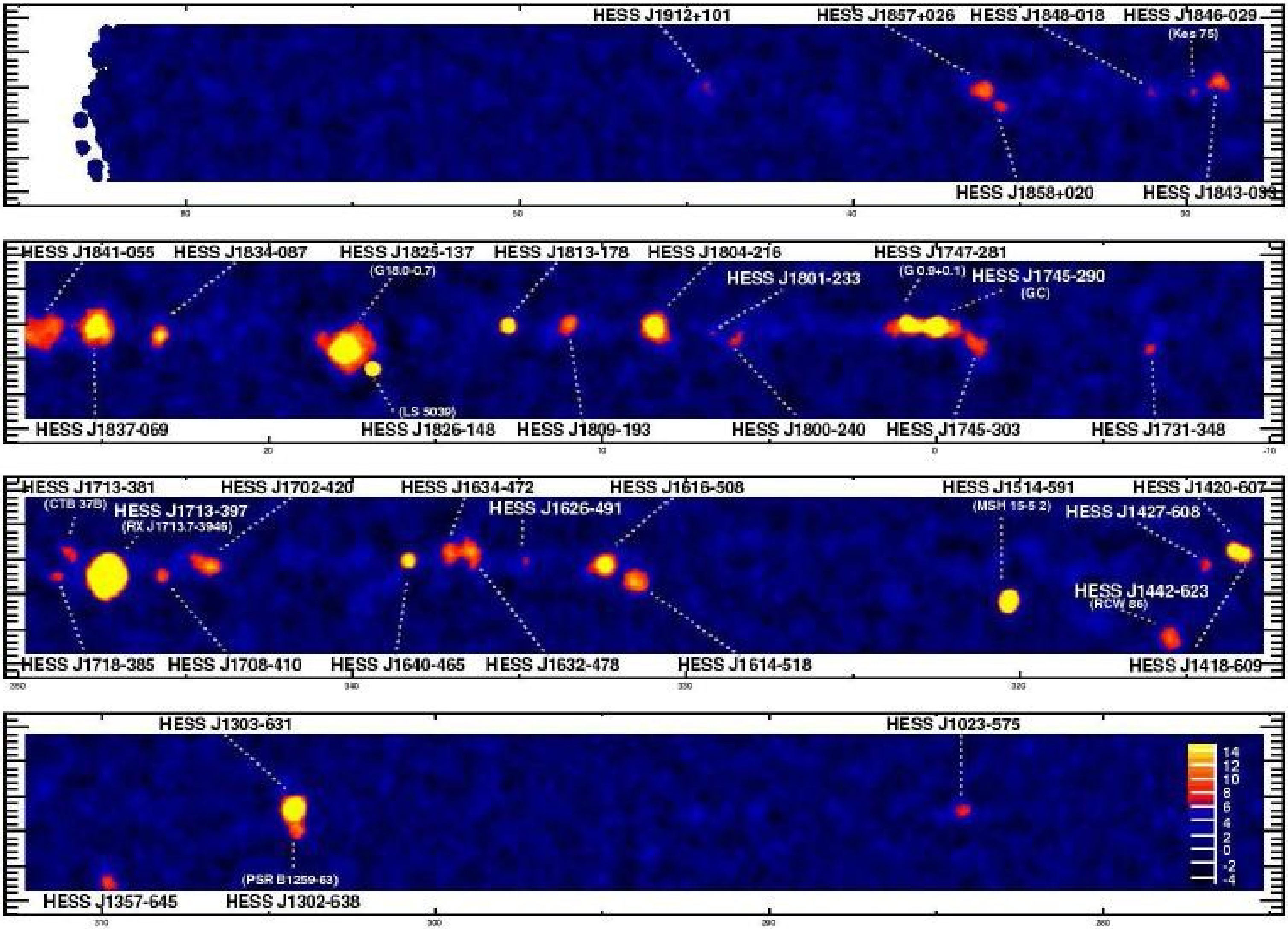


The VHE gamma-ray sky (March 2010)

http://www.mppmu.mpg.de/~rwagner/sources/

~100 sources (60 galactic)

The H.E.S.S. survey of the Galactic plane



Indirect dark matter search strategy

WIMP annihilation flux into γ rays observed in solid angle $\Delta\Omega$:

$$\frac{d\phi_\gamma}{dE} \propto \boxed{\left[\frac{dN_\gamma}{dE}\left(\frac{<\sigma v>}{3\ 10^{-26}\, cm^3/s}\right)\left(\frac{1\,\mathrm{TeV}}{\mathrm{M}_\chi}\right)^2\right]} \boxed{\left[\bar{J}(\Delta\Omega)\,\Delta\Omega\right]} \qquad \Delta\Omega_{\mathrm{HESS}} = 10^{-5}\ \mathrm{sr}$$

particle model

f : dark halo model

- dNγ/dE given by selected particle models:
  - neutralinos (MSSM)
  - U Extra Dimensions (*Servant, Tait 2003*) boson B

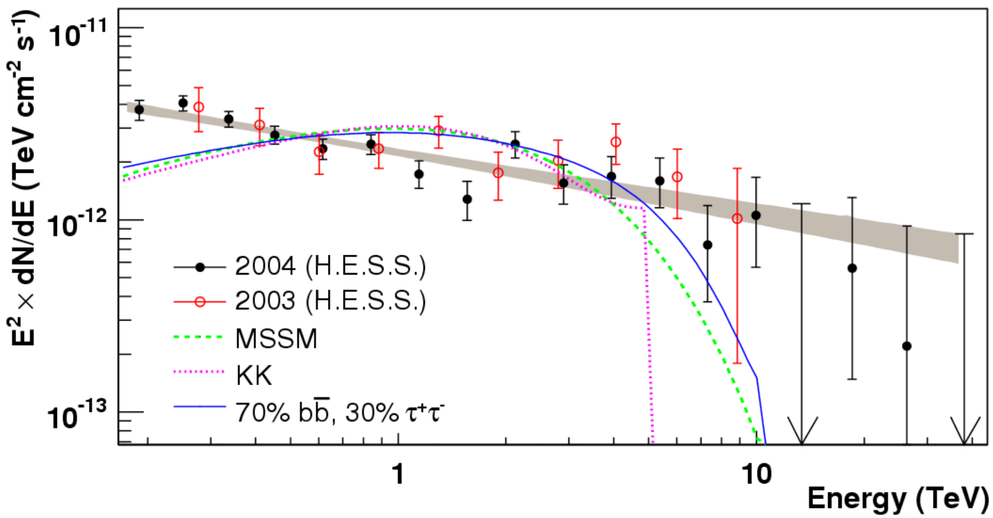
- Astrophysical factor: $f^{AP} = \bar{J}\Delta\Omega \propto \int_{l.o.s} \rho_{DM}{}^2 dl$

  $\Rightarrow$ dense targets

Observed by HESS: Galactic Center
nearby dwarf galaxies, globular clusters
center of galaxy clusters (M87..)
searches for clumps, IMBH

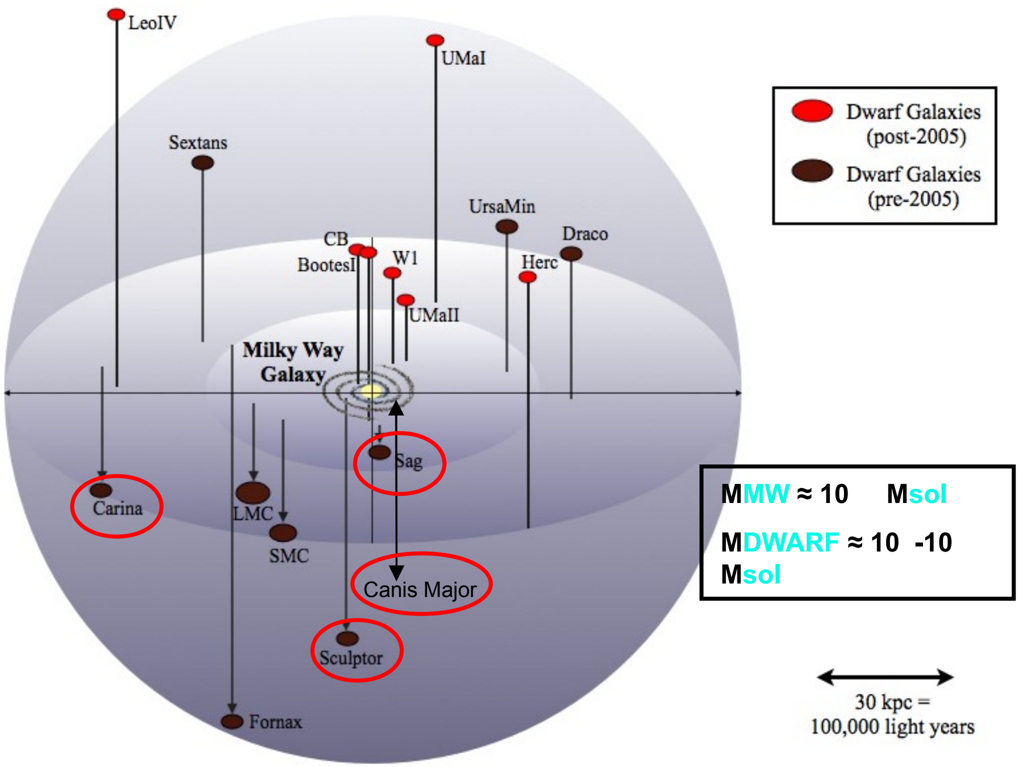
Overview of HESS DM searches

- Galactic Center
  - limits on <σ v> at the level of 10^{-24} cm^3 s^{-1}
  - *F.Aharonian et al., Phys.Rev. Letters, 97, 221102 (2006)*



- IMBH
  - strong constraints provided these objects exist
  - *F.Aharonian et al, Phys.Rev D 78, 072008 (2008)*
- High energy electrons (ATIC/PAMELA signal)
  - *F.Aharonian et al, A & A, 508, 561 (2009)*
- Dwarf galaxies

Dwarf spheroidal galaxies

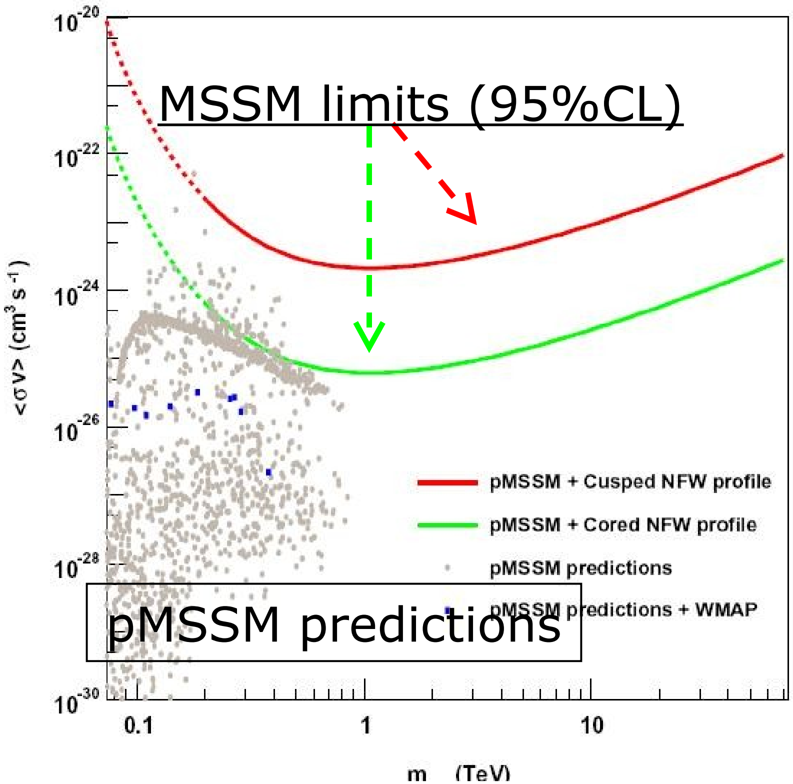


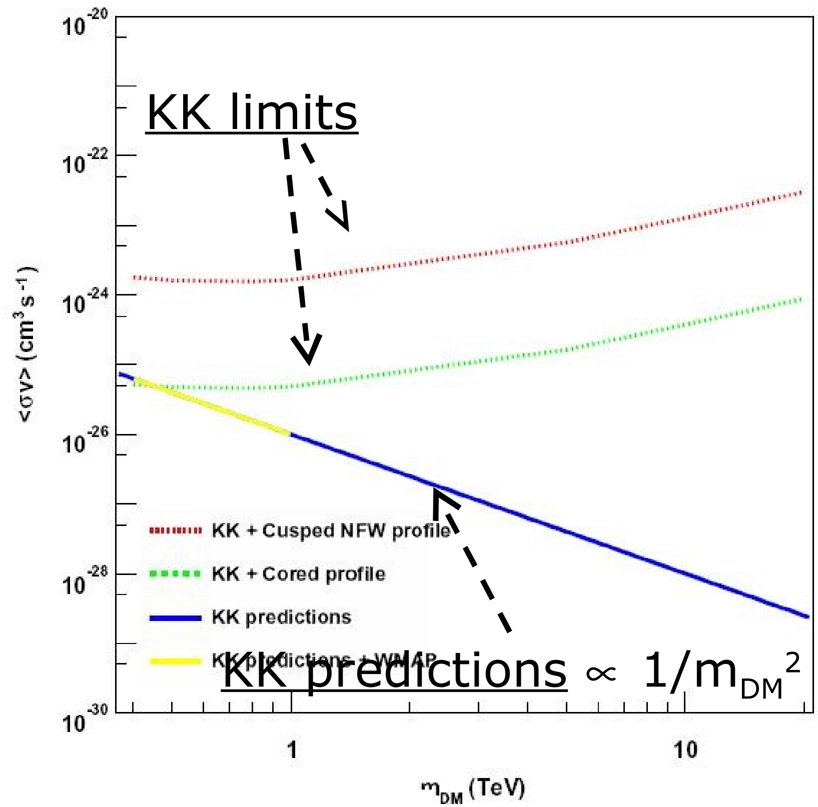
MMW ≈ 10 Msol

MDWARF ≈ 10 -10 Msol

- dark matter dominated
- data on surface brightness, velocity dispersion, globular clusters for most of them $\Rightarrow$ **galactic structure well modelled**
- mass range $10^7 - 10^9\ M_\odot$
- observed by HESS: Sagittarius, Canis Major, **Carina**, **Sculptor**

Sgr dwarf: exclusion plots





- nearby galaxy (24 kpc), in interaction with Milky Way
- galactic modeling difficult (tidal stripping)

$$\frac{\bar{J}_{\rm Sgr}}{\bar{J}^{\rm GC}_{\rm NFW}} = 0.07 - 2.6$$

min

-

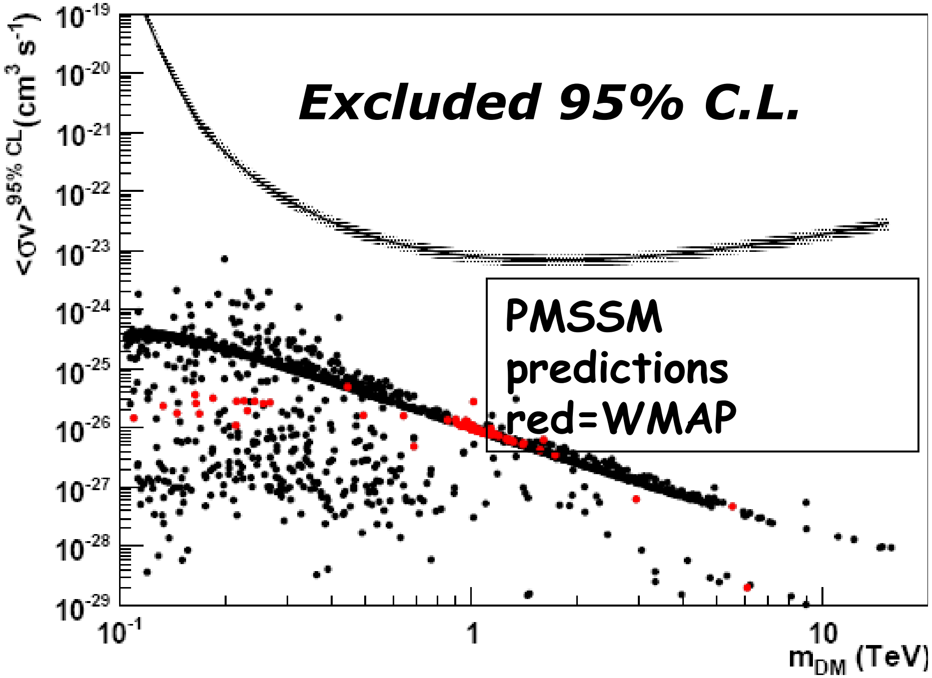
<σ v> ≈ 5 10 cm s (MSSM, NFW profile)

- *F.Aharonian et al, Astropart.Physics 29,55(2008)*

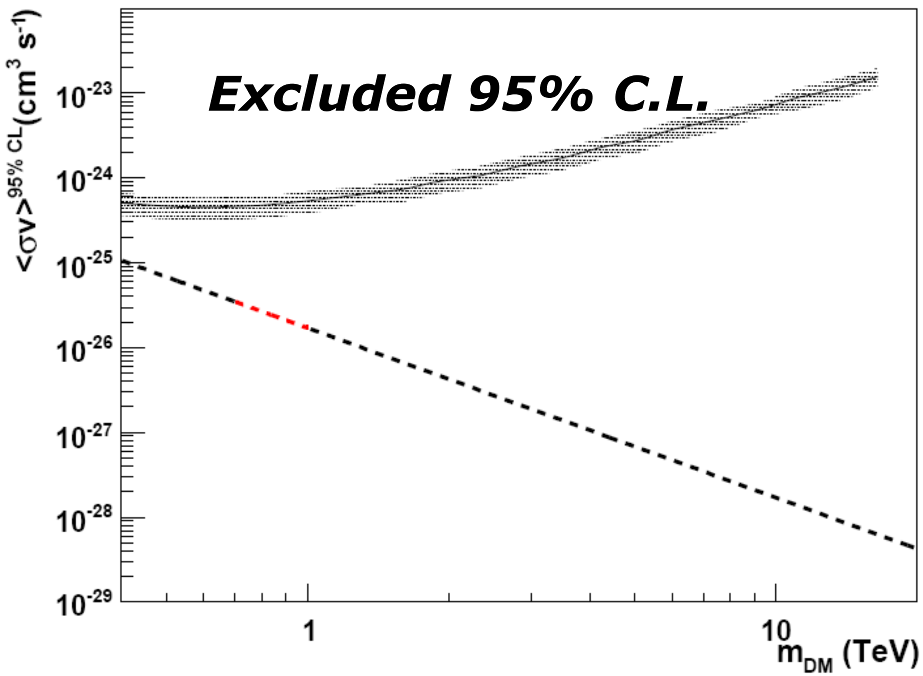
  F. Aharonian et al, Astropart. Physics 33,274 (2010)

Canis Major: exclusion plots

MSSM limits



Kaluza-Klein UED



- overdensity discovered 2004, nearby (7 kpc)
- status as a dwarf galaxy disputed
- halo modeling based on galaxy formation theory

min

-

<σ v> ≈ 5 10 cm s (MSSM)

- *F. Aharonian et al, ApJ 691, 175 (2009)*

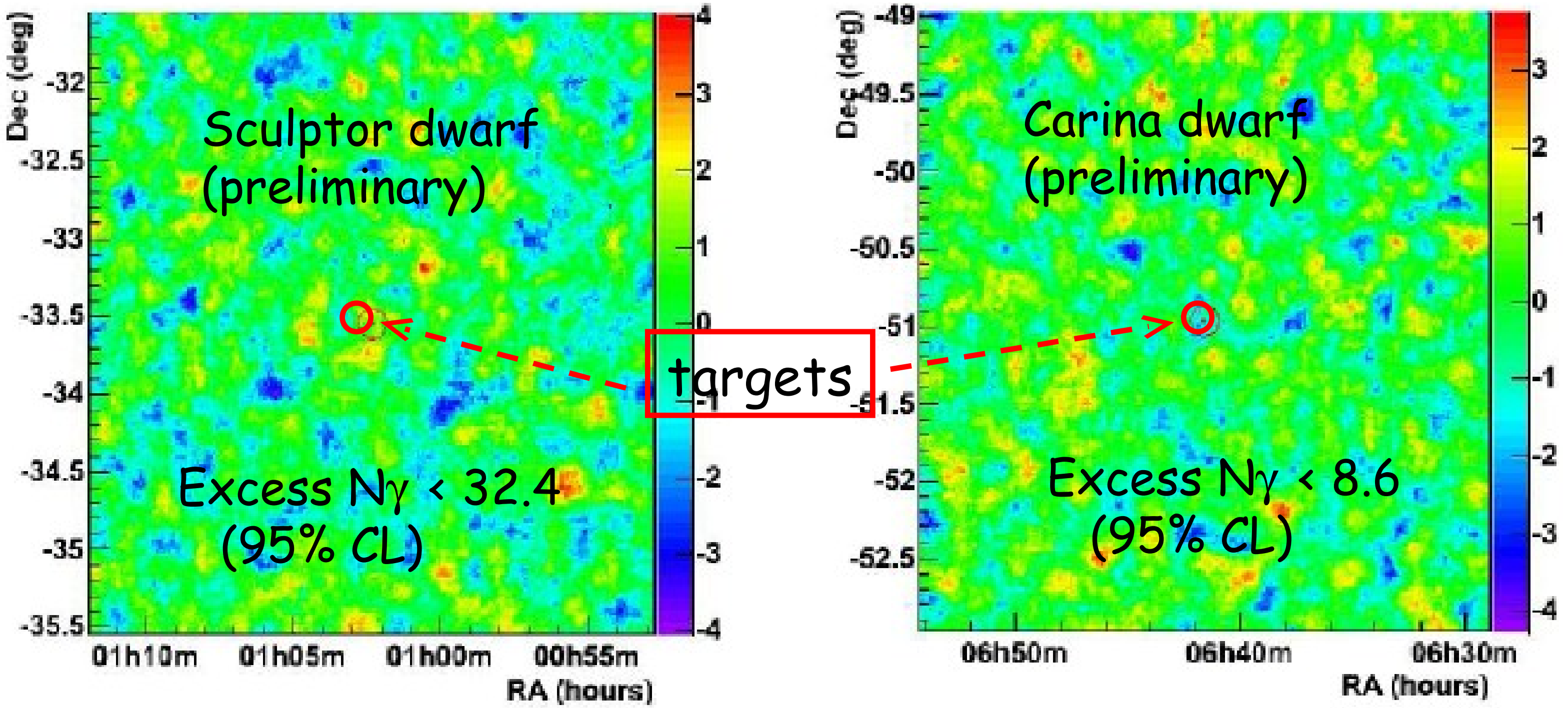
$$\frac{\bar{J}_{\mathrm{CMa}}}{\bar{J}^{\mathrm{GC}}_{\mathrm{NFW}}} \approx 0.2$$

with the assumption $M_{CMa} = 3\ 10^8\ M_{sol}$

HESS observations towards Carina/Sculptor

- data taken in 2008 (Sculptor) and 2008-2009 (Carina)

	distance (kpc)	t observation	<zenith angle>	Eff threshold (GeV)
Carina dwarf	101	14.8 h	34 °	320
Sculptor dwarf	79	11.8 h	14°	220



DM modeling of Sculptor and Carina

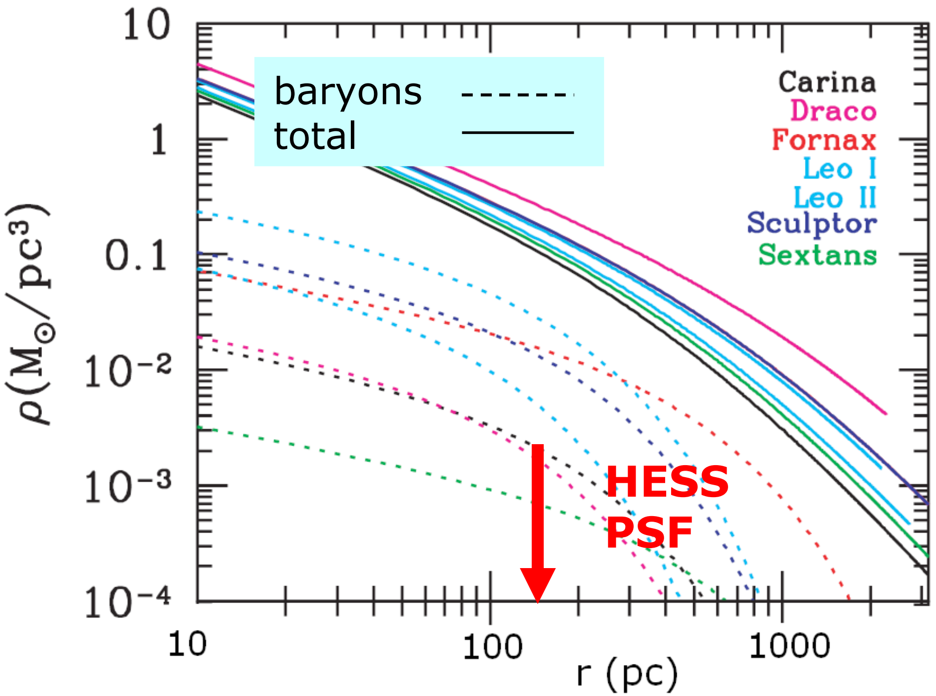
- 2 halo profiles: $\rho_{\mathrm{NFW}} = \frac{\rho_o r_S}{r} \frac{1}{(1 + r / r_S)^2}$ NFW

  $\rho_{\mathrm{core}} = \frac{\rho_c r_c^2}{r^2 + r_c^2}$ core

- models parameters fitted to velocity dispersion and luminosity profile data.
- models taken from publications:
  - Sculptor: G. Battaglia thesis (2007)
    Battaglia et al , (2008)
  - Carina: Gilmore et al (2007)
    Walker et al (2007)
- Astrophysical factors $\bar{J}$

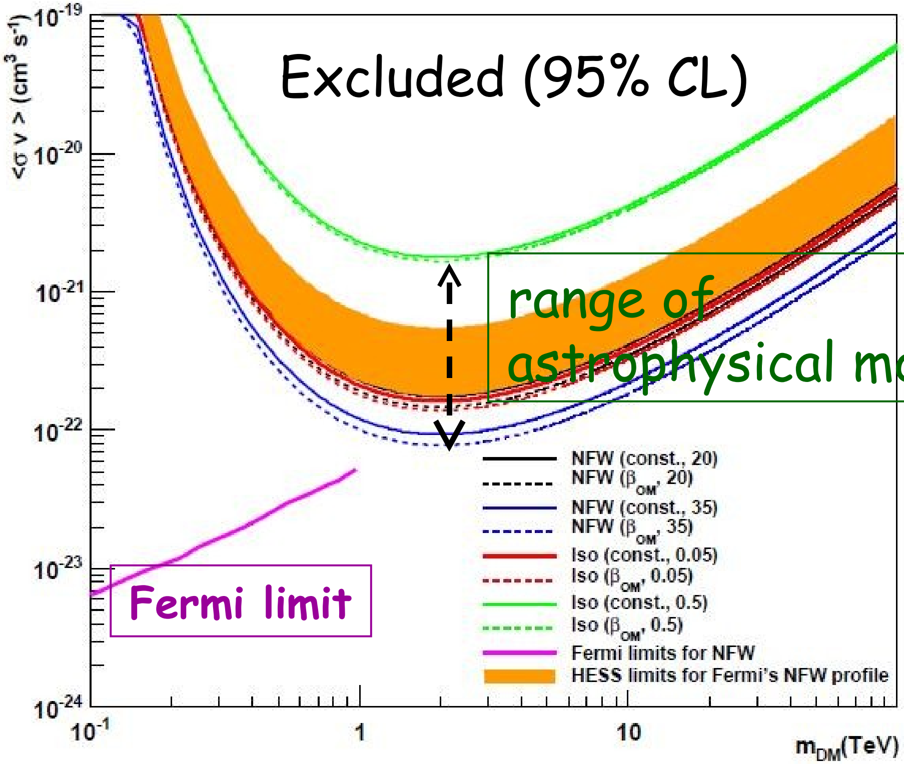
$$\frac{\bar{J}_{\mathrm{Sculptor}}}{\bar{J}^{\mathrm{GC}}_{\mathrm{NFW}}} = (0.2 - 2.3) \cdot 10^{-2}$$

$$\frac{\bar{J}_{\mathrm{Carina}}}{\bar{J}^{\mathrm{GC}}_{\mathrm{NFW}}} = (0.7 - 1.5) \cdot 10^{-3}$$

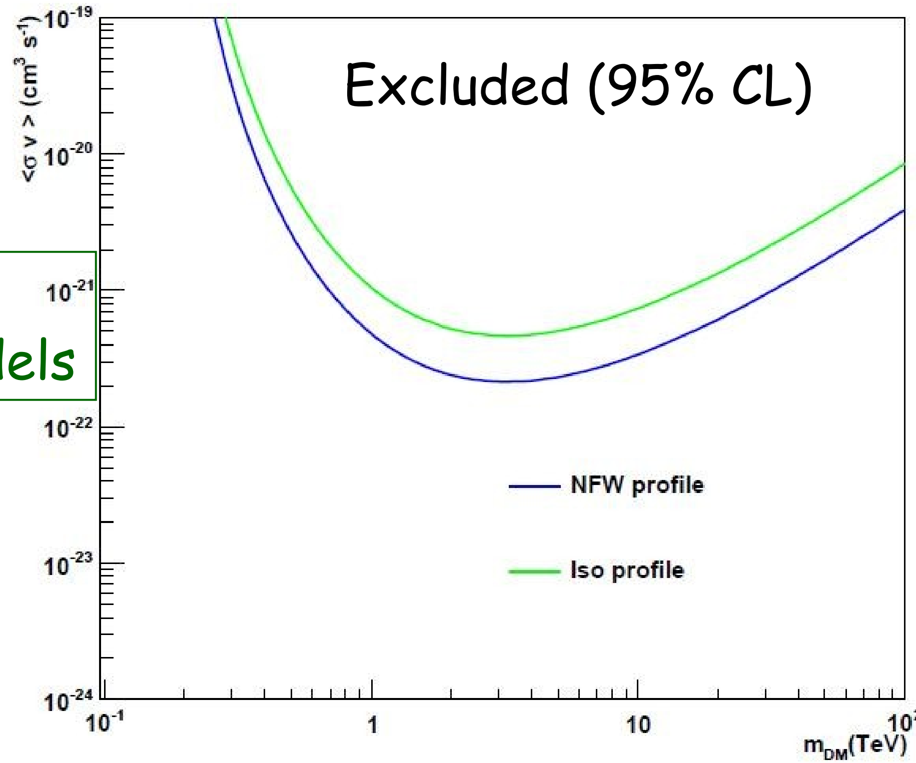


Sculptor and Carina: exclusion limits (MSSM)

Sculptor dwarf



Carina dwarf



– Constraints on MSSM models at the level of

$\langle \sigma v \rangle_{min}$ = 5 10 cm s

–

Signal boosts

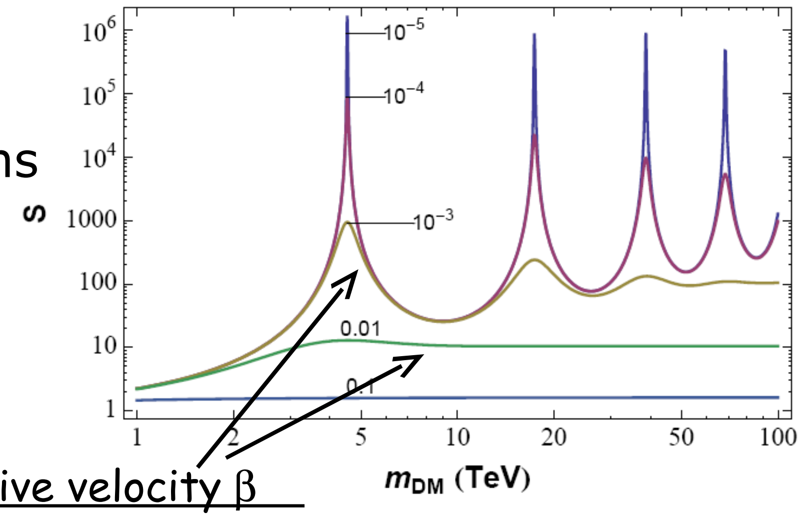
- astrophysics:
  - « clumps »: few % enhancement for Carina/Sculptor

- particle physics:
  - Sommerfeld effect:
    - effective low velocity dispersions

$$\beta = \frac{v}{c} \ll \alpha_2 \approx 0.03$$

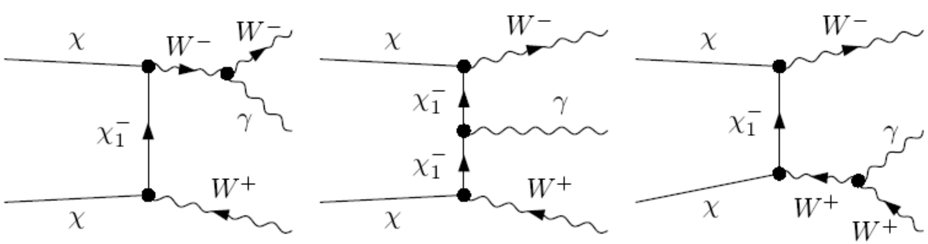
    - resonances at:

$$M_\chi = \frac{M_Z}{\alpha_2} n^2 = 4.45 n^2 \text{ TeV}$$



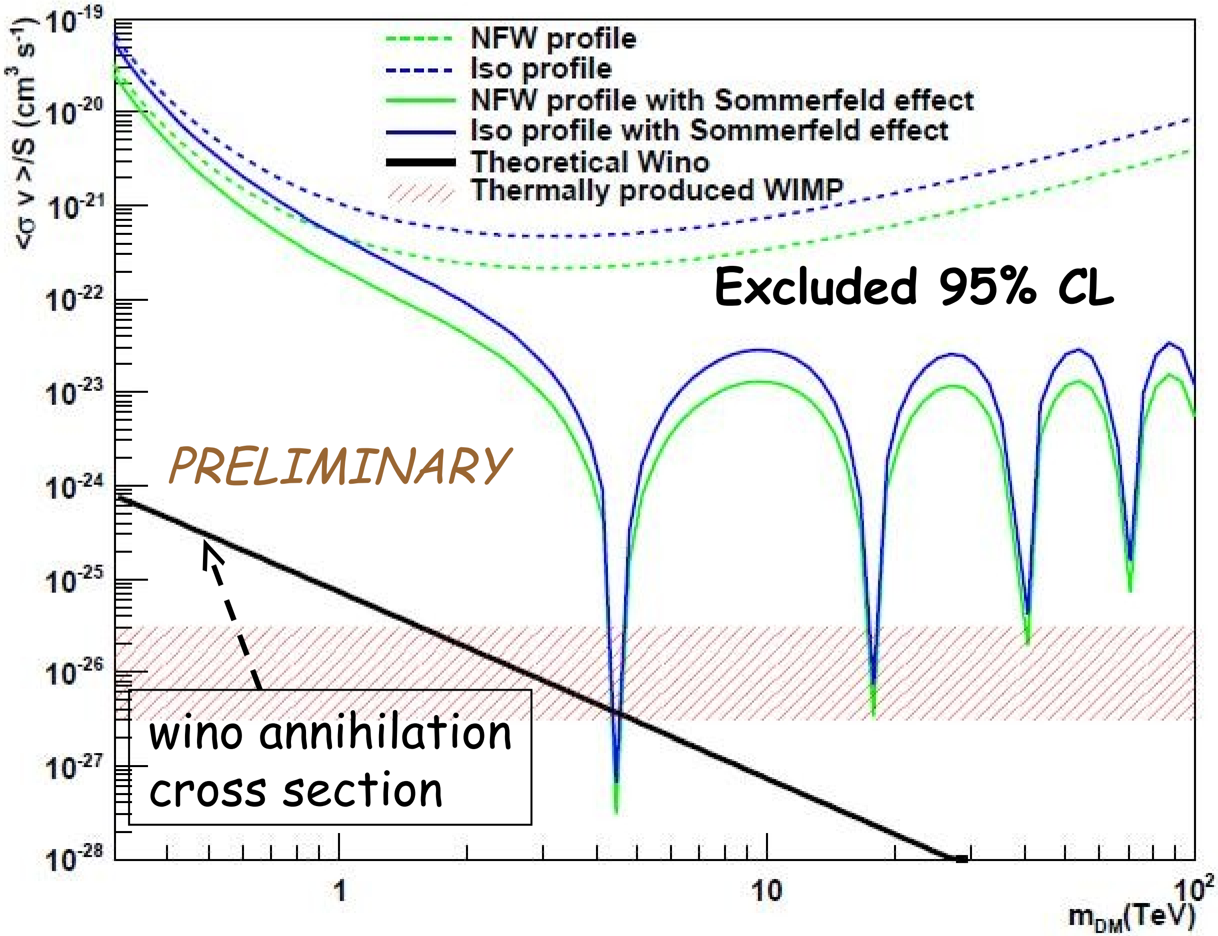
  - Internal Brehmstrahlung
    - annihilation to W^+W^-, $f\bar{f}$

(χ heavy higgsino-like)



FSR IB

Carina dwarf : Sommerfeld effect



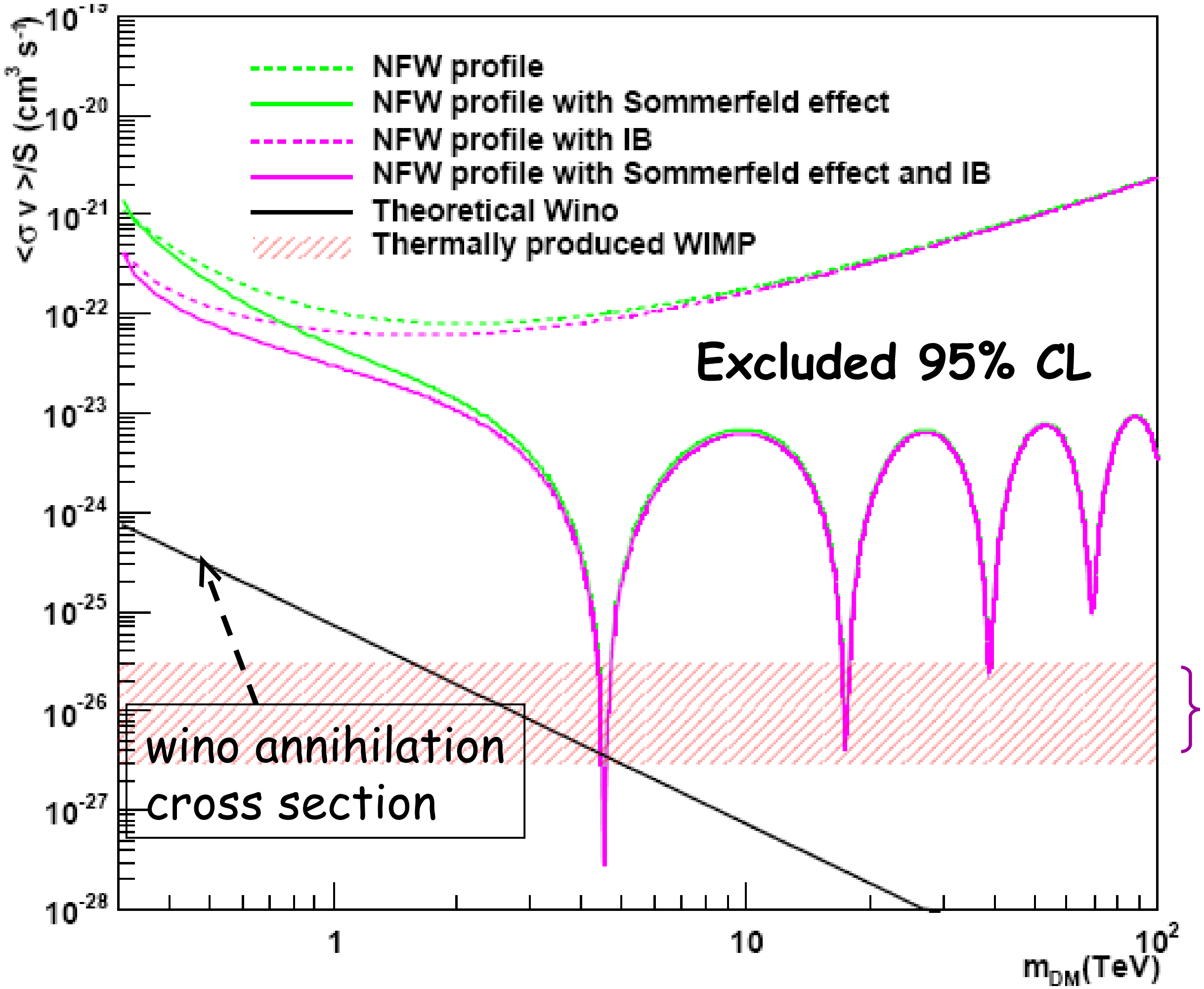
- dispersion velocity σ = 7.5 km/s
- $\beta \sim 2\ 10^{-5} \ll \alpha_2 = 1/30$

$\Rightarrow$ Sommerfeld boost expected to be important for models with pure wino χ

} thermal wimp annihilation cross section

- some models excluded near $M\chi \approx$ 4.5 TeV

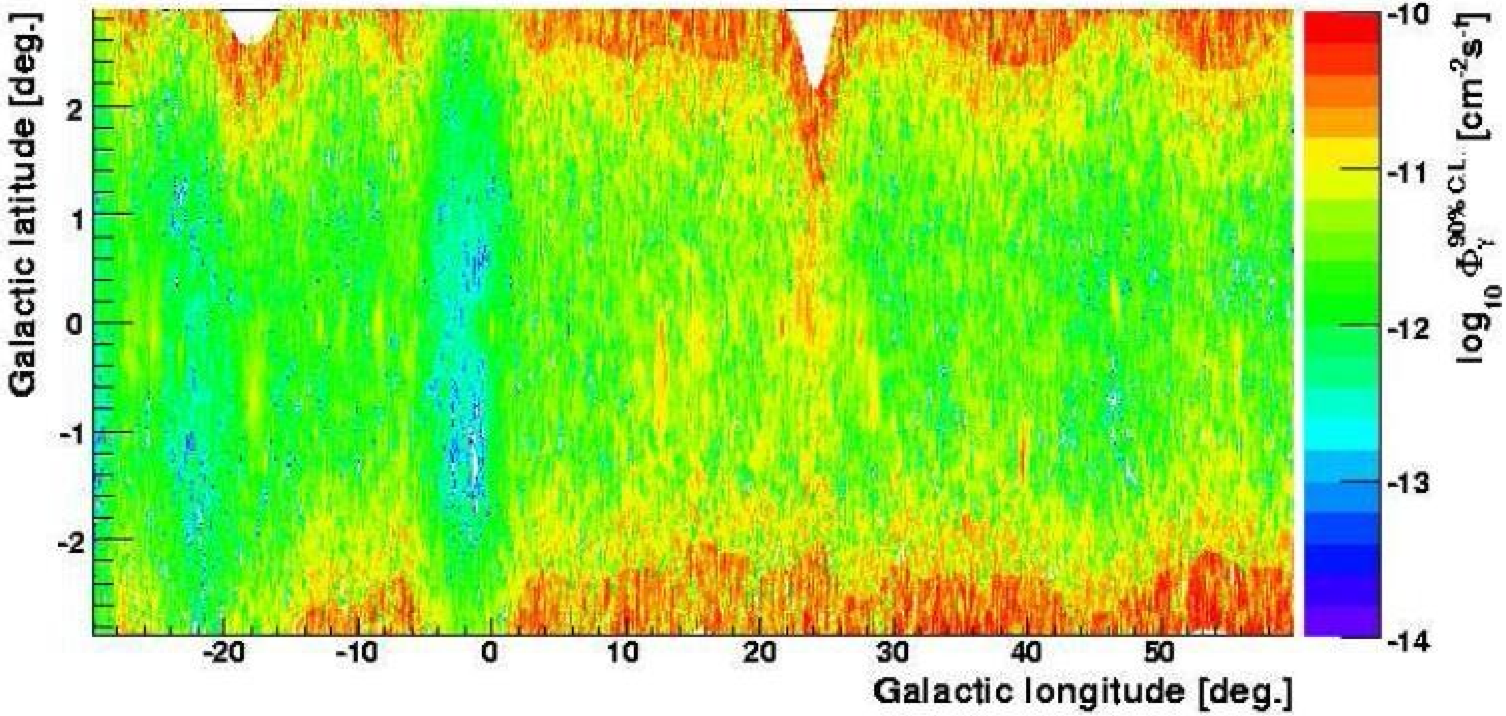
Sculptor dwarf: enhancements from IB and Sommerfeld effect



- dispersion velocity σ = 10 km/s
- Sommerfeld boost also expected to be important for models with pure wino χ
- effect of IB important for M_χ < 1 TeV

} thermal wimp annihilation cross section

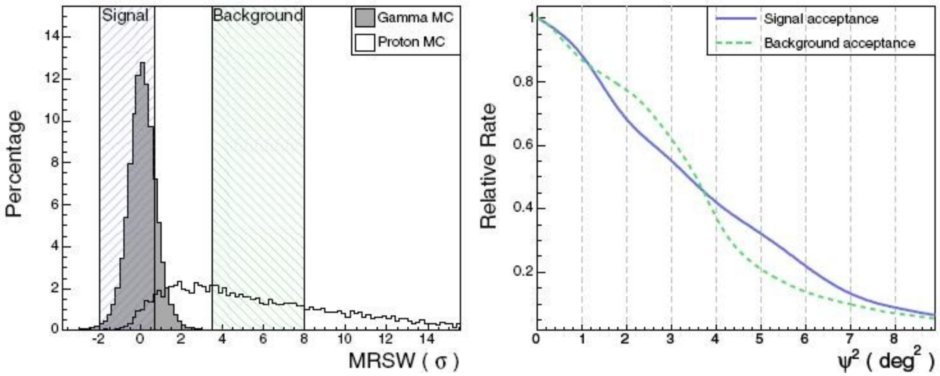
Galactic plane flux sensitivity map (HESS)



- from HESS galactic survey (2004-2007)
- $|b| \leq 3^o$, $-30^o \leq l \leq 60^o$
- map divided into $0.02^o \times 0.02^o$ bin
- smoothed to a $0.1^o \times 0.1^o$ resolution (HESS)

Galactic plane sensitivity map (2)

- in each bin (b,l) of the map, get N_γ (γ candidates)/ N_{hadr}
- outside sources, N_γ is dominated by fake gammas
- background B estimated by the « template method »



(from Berge et al 2007)

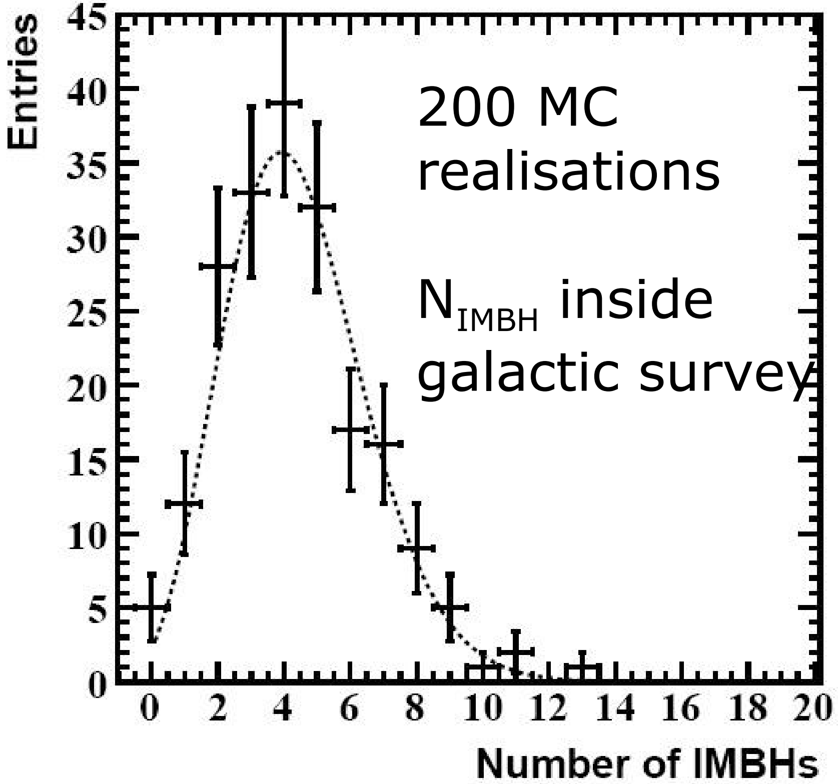
- N_γ compared to B $\Rightarrow$ 90% C.L. upper limit on signal S_{90}
- Φ_{90} obtained from S_{90} by

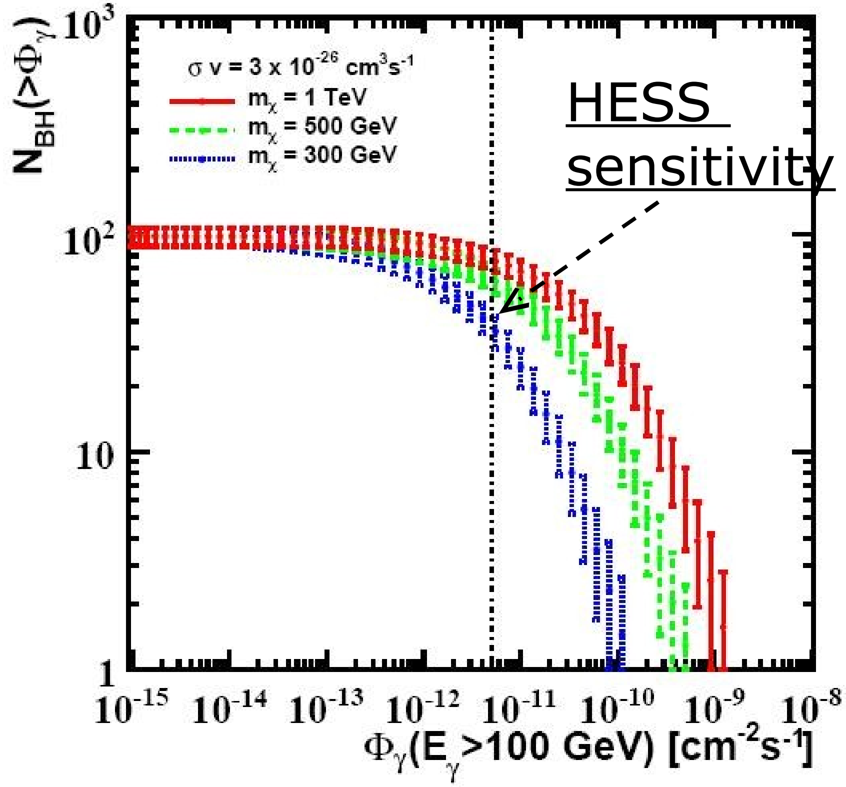
$$\phi_{90}(b,l) = \frac{S_{90}(b,l)\int_{E_{\min}}^{M_{DM}} \frac{dN}{dE}dE}{T_{obs}(b,l)\int_{0}^{M_{DM}} A_{eff}\frac{dN}{dE}dE} \quad (E_{\min} = 100GeV)$$

- Assumes dN/dE from $\chi\chi \rightarrow bb$ (not sensitive to this assumption)

M_χ = 500 GeV

Dark matter annihilation around IMBH





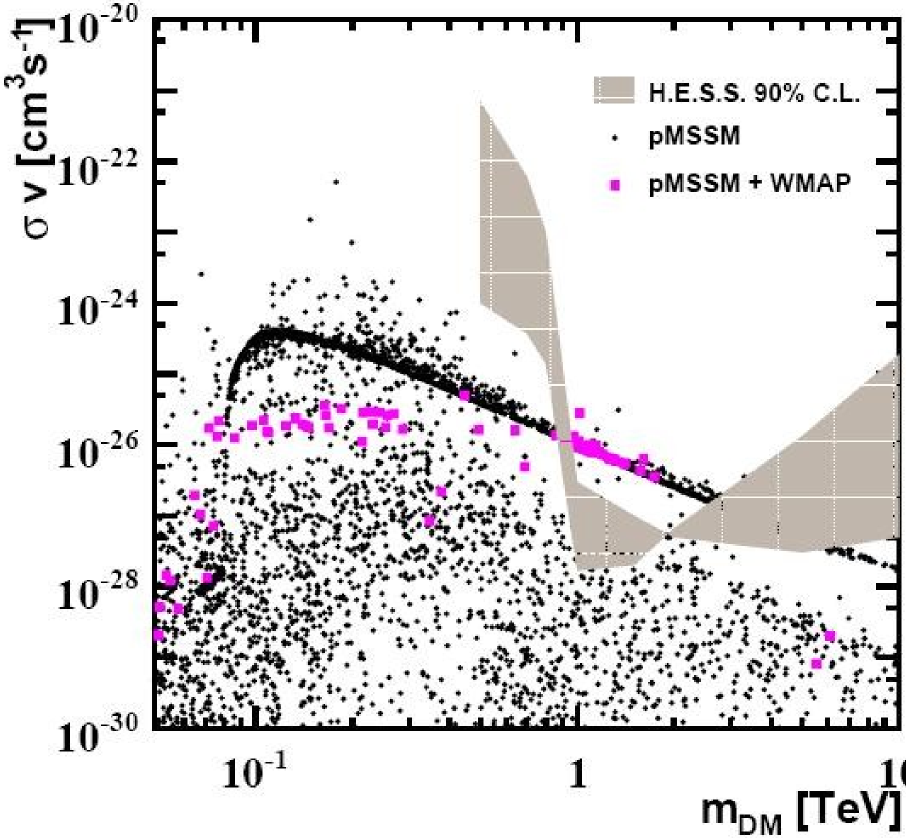
— « scenario B » of *Bertone, Zentner, Silk 2005*

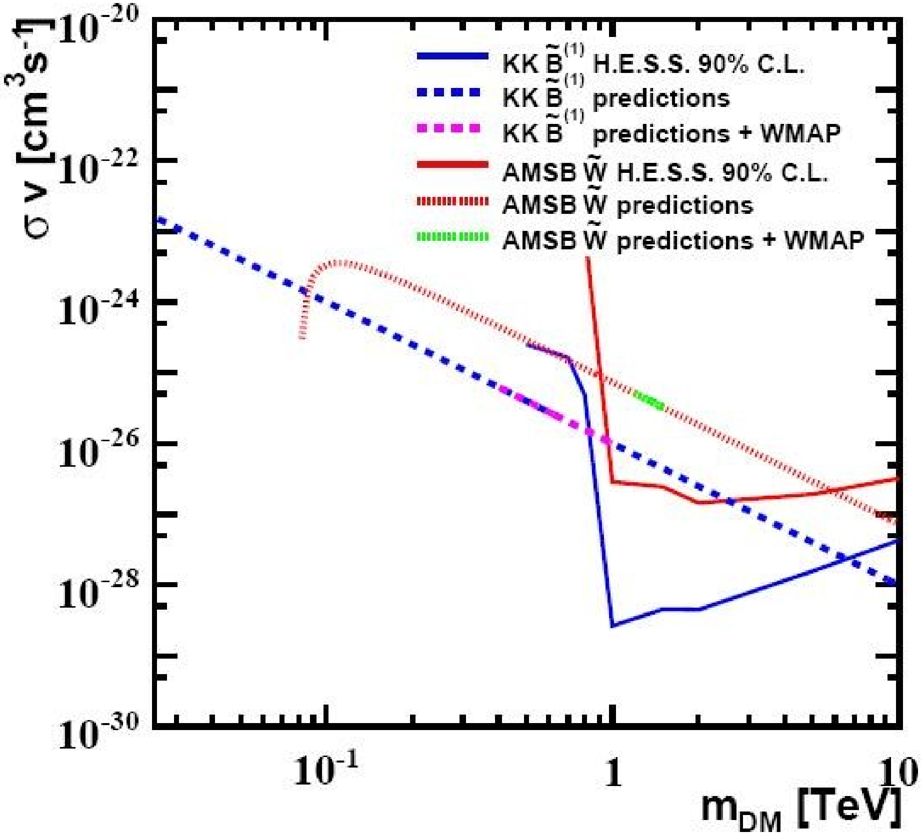
— collapse of a primordial cloud of gas ~10^5 M_{sol} into ~4 10^4 M_{sol} Intermediate Mass Black Hole

— 101±22 IMBH in MW (4.3±2.3 in Hess galactic survey)

— very luminous (due to the DM spike around BH)

HESS IMBH limits (scenario B)

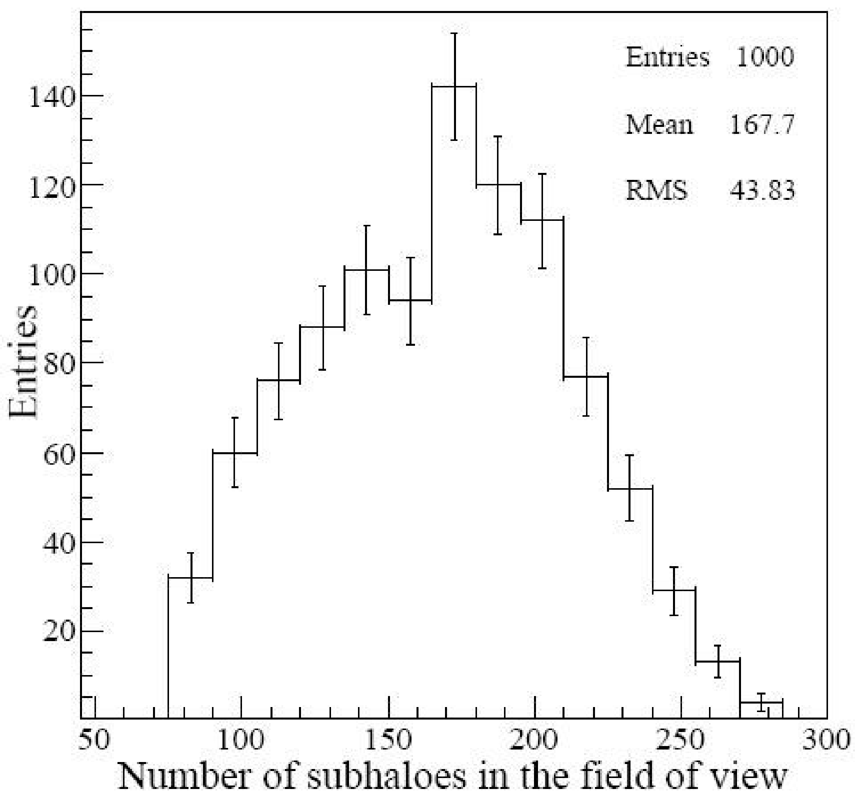


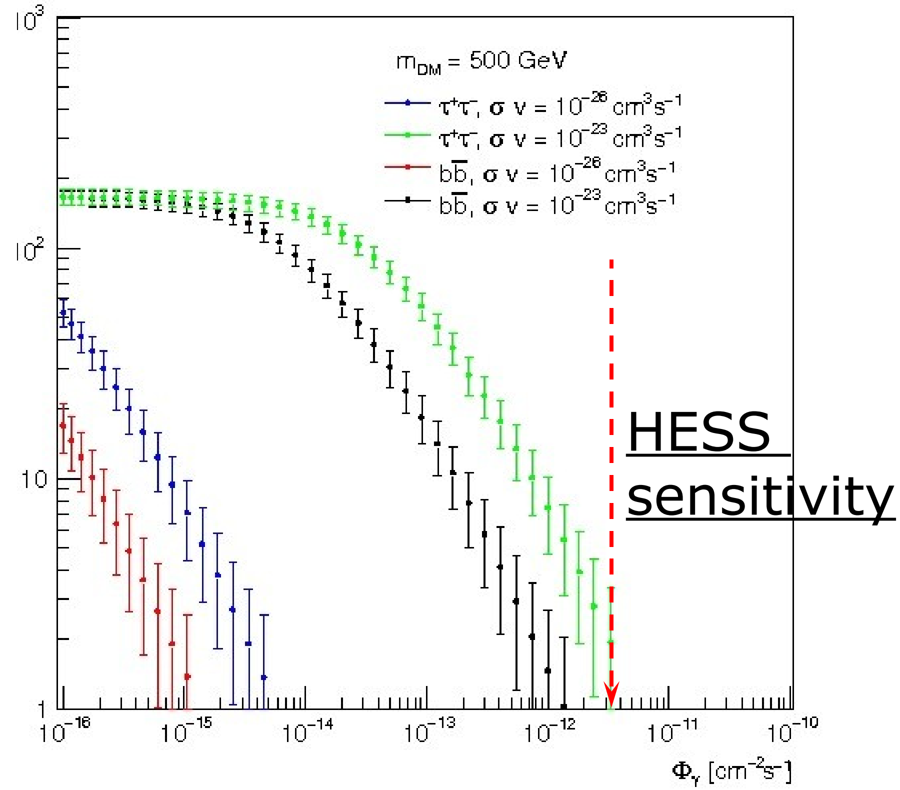


— for each m_{DM}, decrease $<\sigma\ v>$ until $N_{IMBH} < 2.3$

F.Aharonian et al (HESS)+Bertone,PRD 78 (2008), 072008

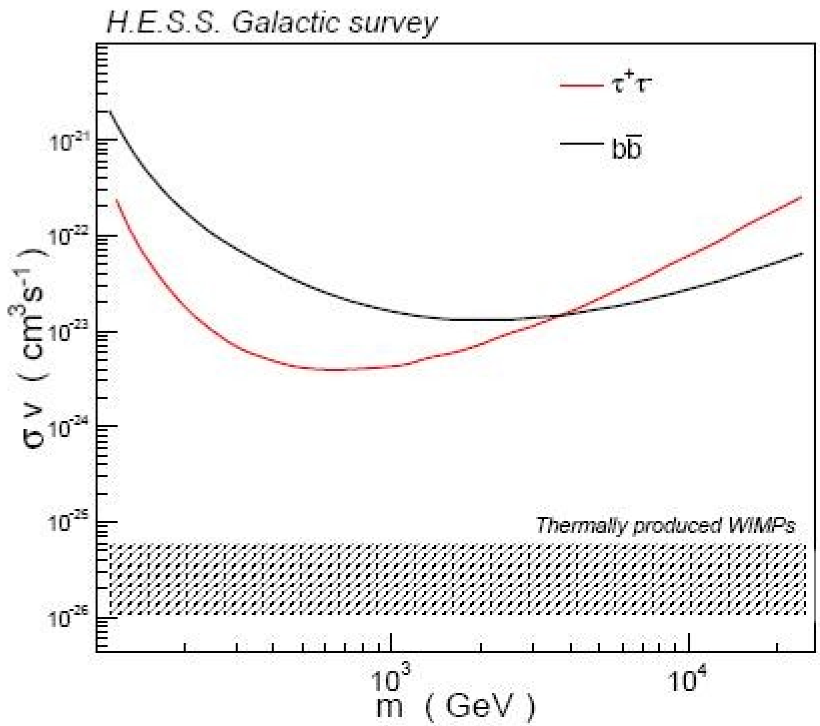
Dark matter clumps

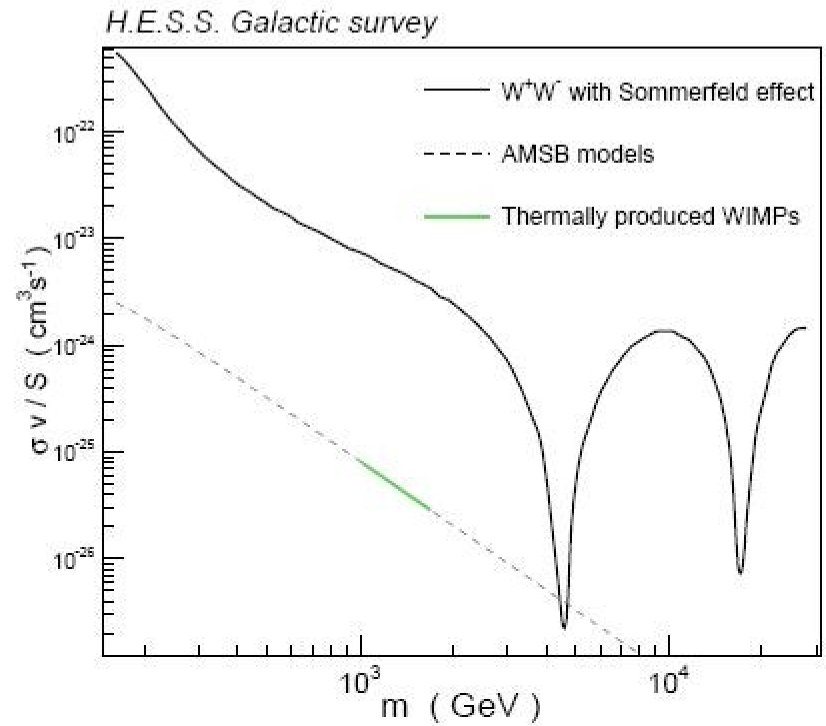




- clumps from ViaLacteaII (*Diemand, Kuhlen, Madau, 2008*)
- ~10^4 resolved halos in MW (M>10^5 M_{sol})
- 10^3 random realizations (rotate the observer position @8.5 kpc)
- 168±44 clumps inside HESS galactic survey

HESS clump limits

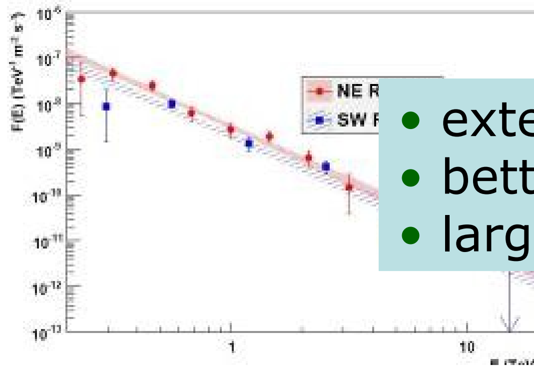


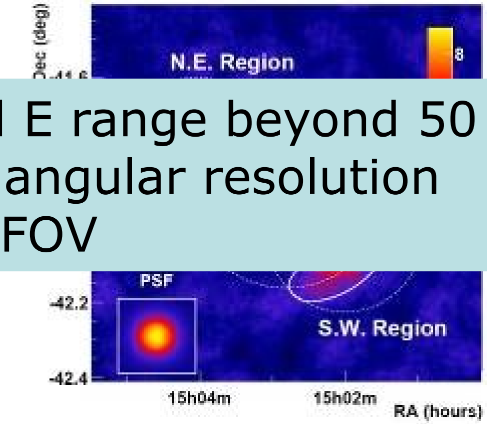


- use the HESS Galactic plane sensitivity map
- 90% C.L. limits comparable to Sgr dwarf, Galactic Center
- *P.Brun,E.Moulin, J.Diemand, J-F.G, submitted to PRD (2010)*

«Wish list» of the VHE astrophysicist

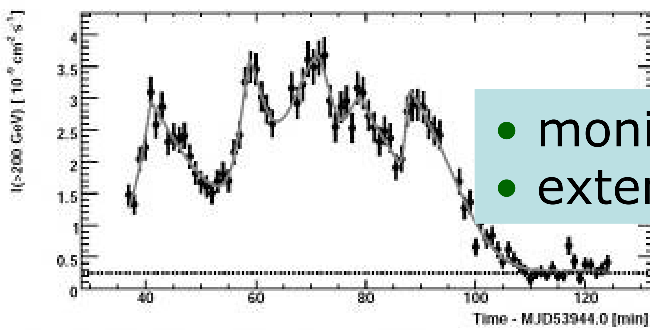
— Galactic sources





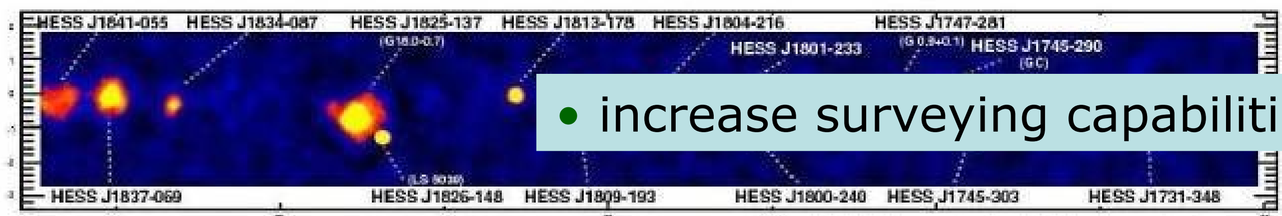
- extend E range beyond 50 TeV
- better angular resolution
- larger FOV

— AGN



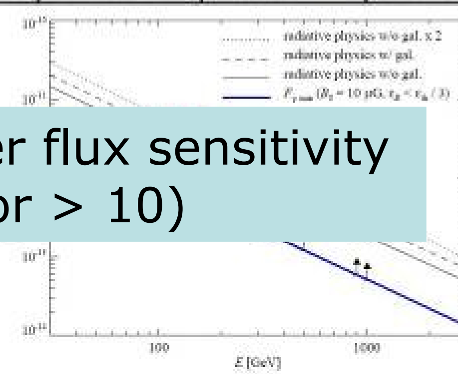
- monitor many objects simult.
- extend E range under 50 GeV

— Surveys



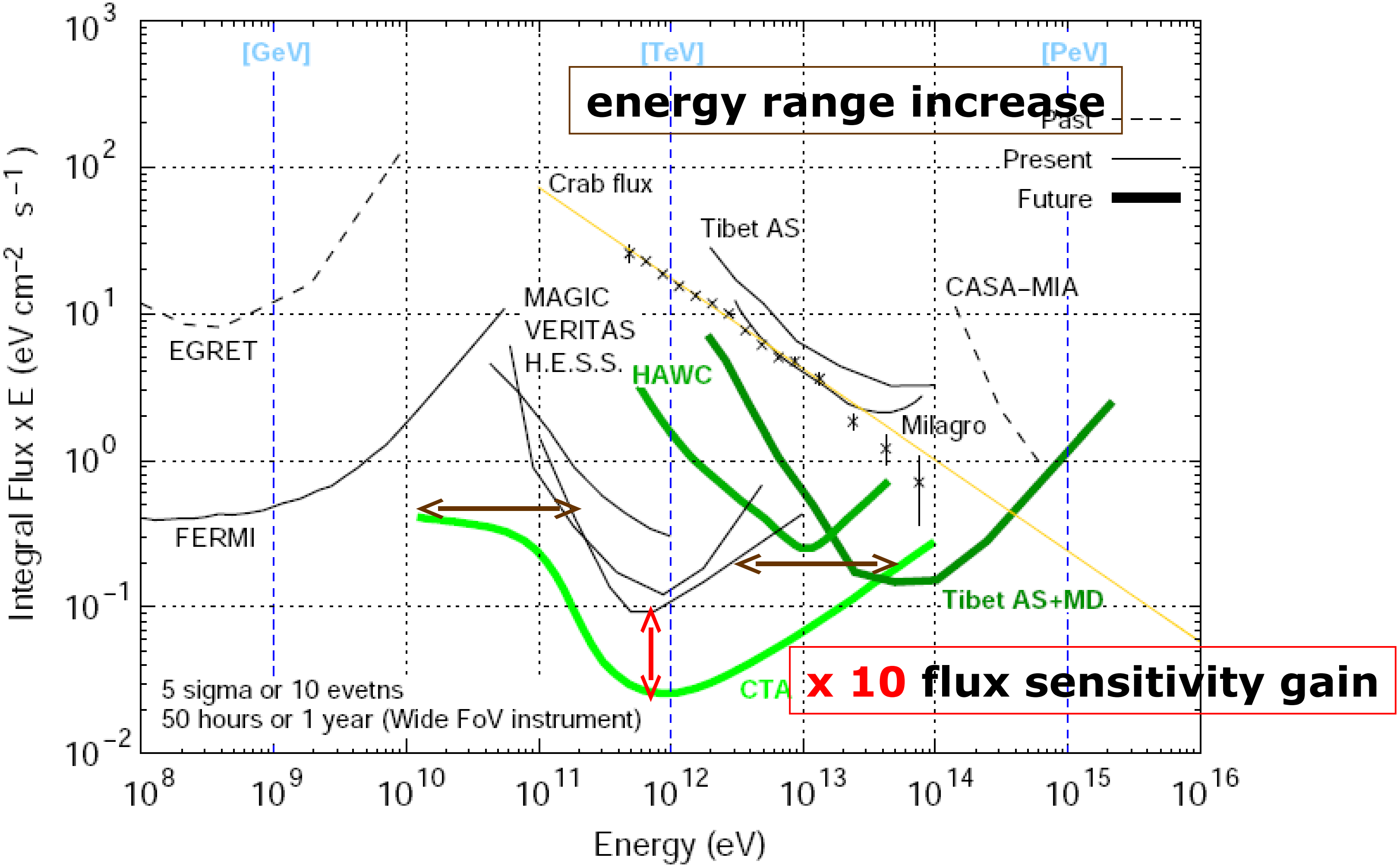
- increase surveying capabilities

— New physics
  – clusters/extended sources
  – dark matter and astroparticle physics



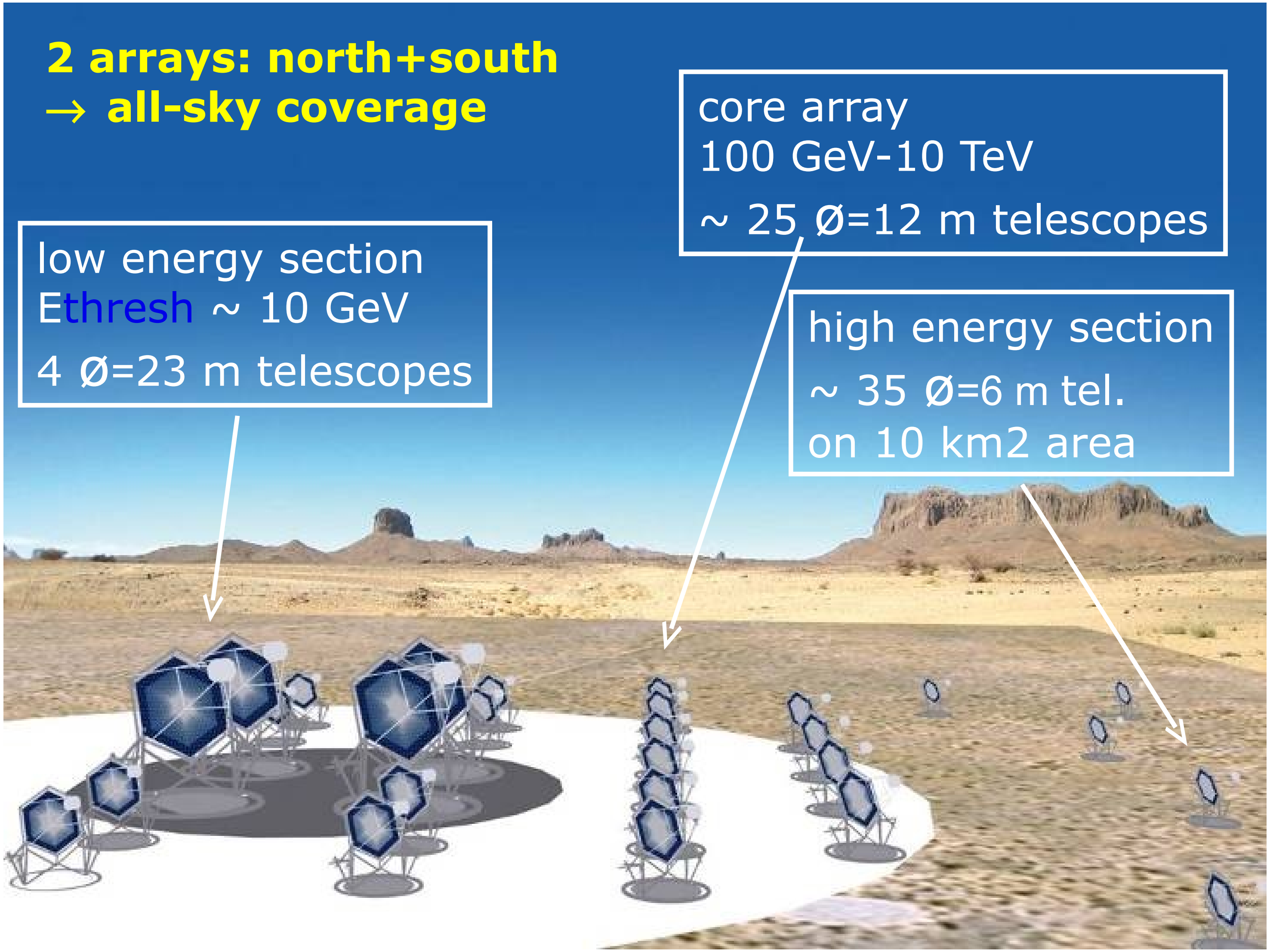
- better flux sensitivity (factor > 10)

CTA expected sensitivity

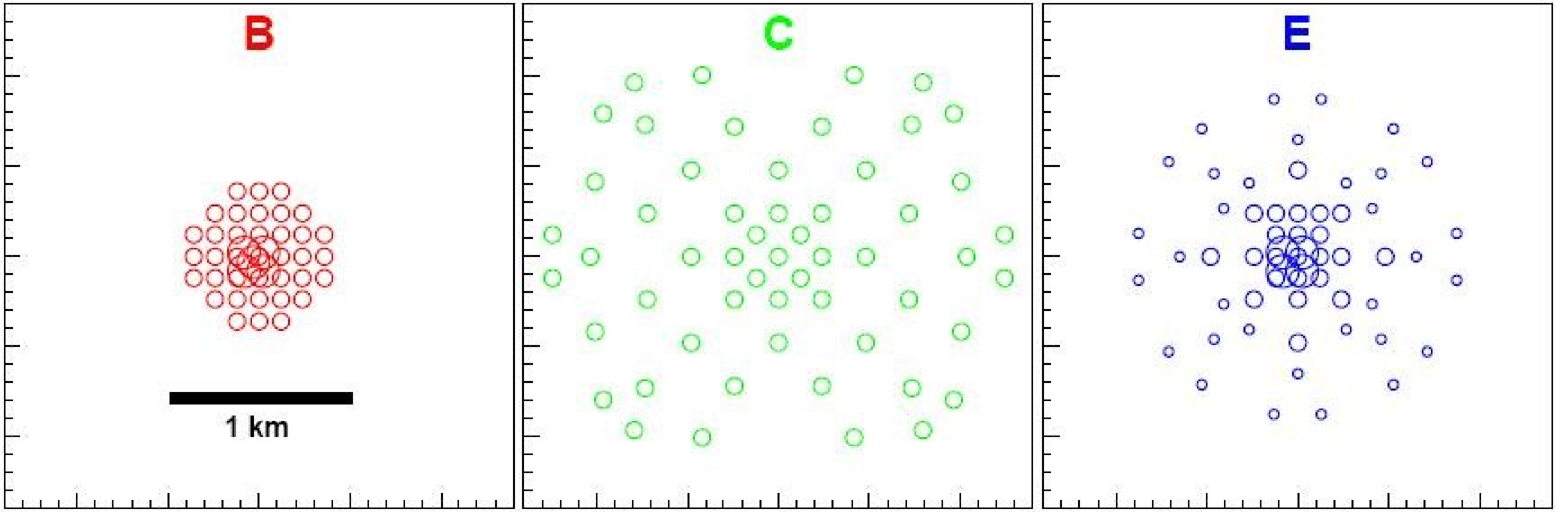


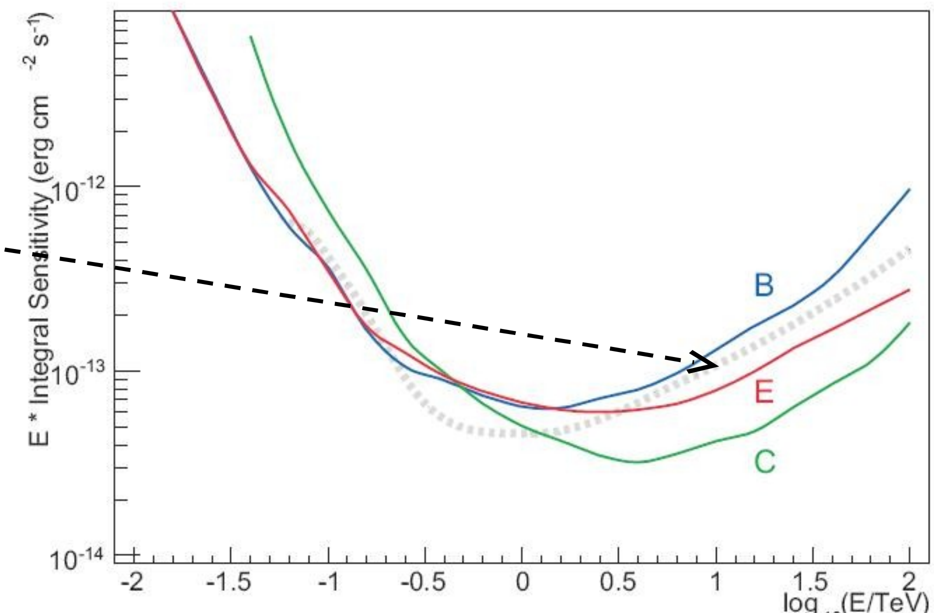
from Amenomori et al (ICRC2009)

The CTA concept



CTA: array design

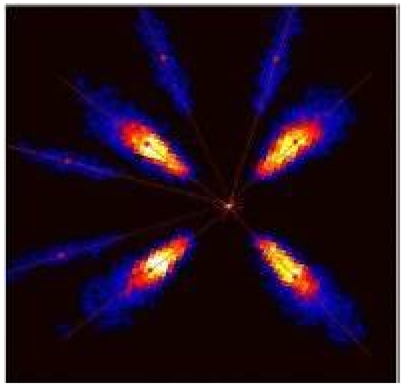


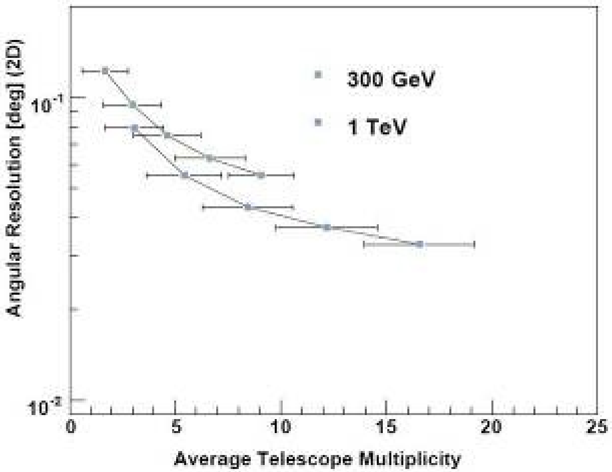


target performances

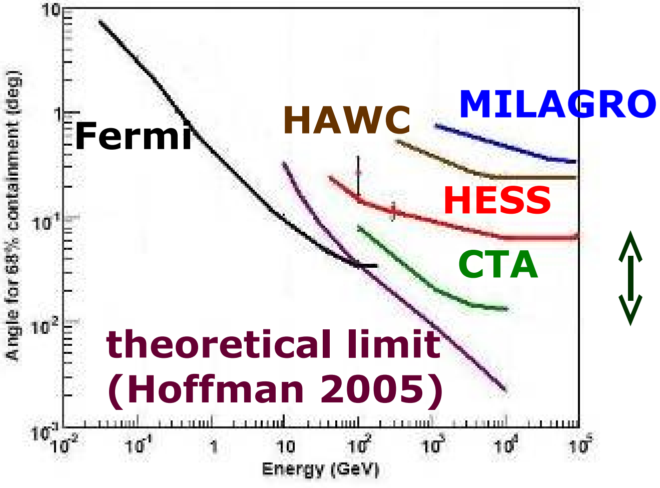
Performances: angular resolution

- Angular resolution improves as more telescopes used in reconstrution





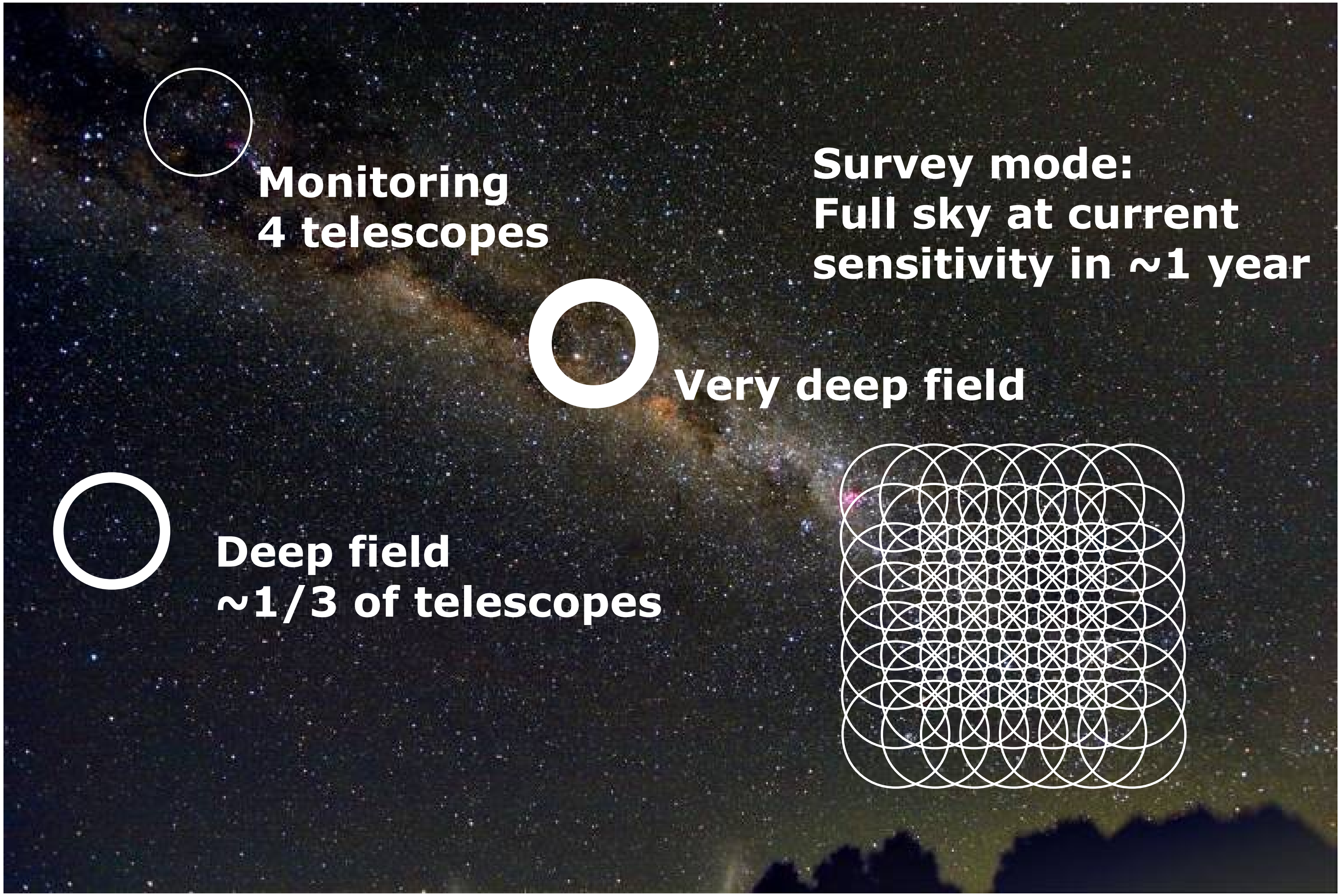
- Angular resolution closer to theoretical limit



factor **3** improvement

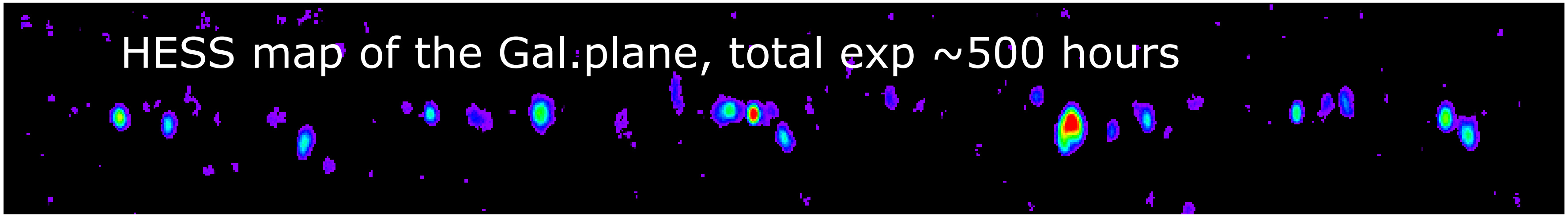
S.Funk, J.A. Hinton, arXiV0901.2153

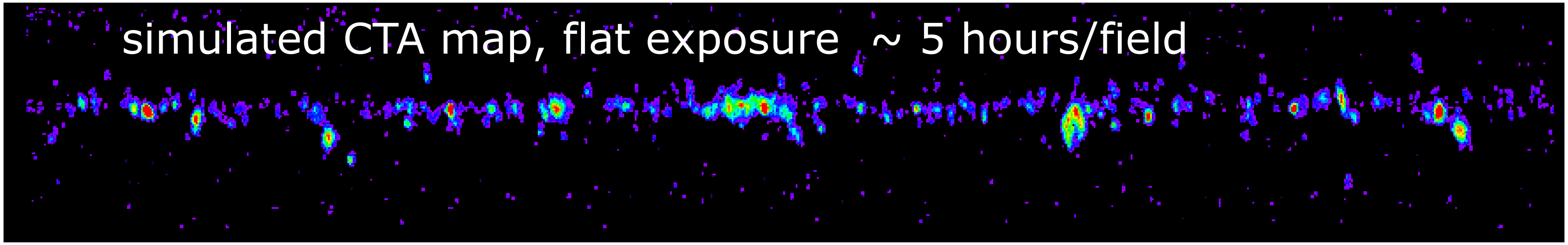
CTA operation modes



Expectations for Galactic plane survey

Funk,Hinton,Hermann,Digel, arXiV0901.1885



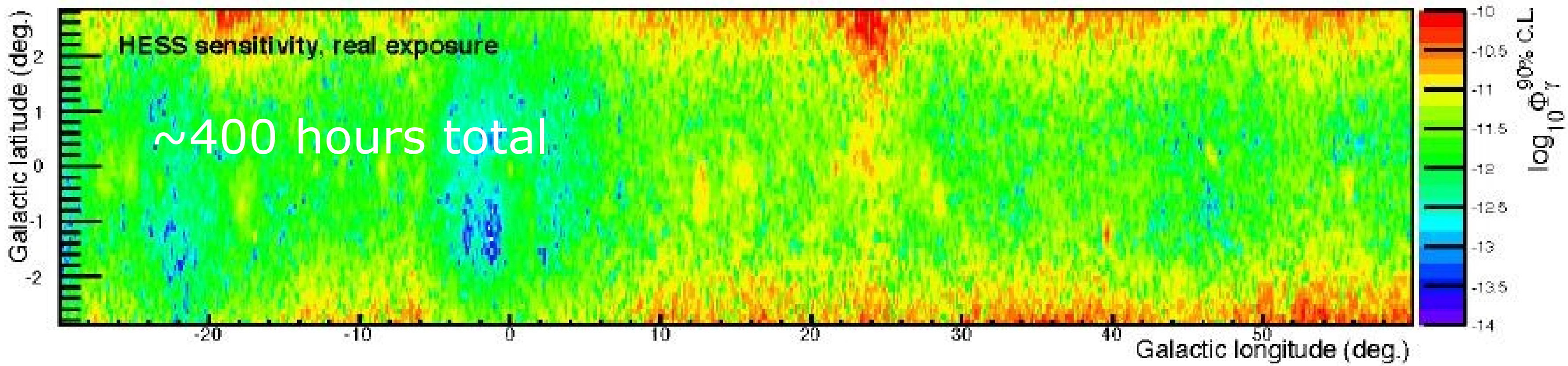


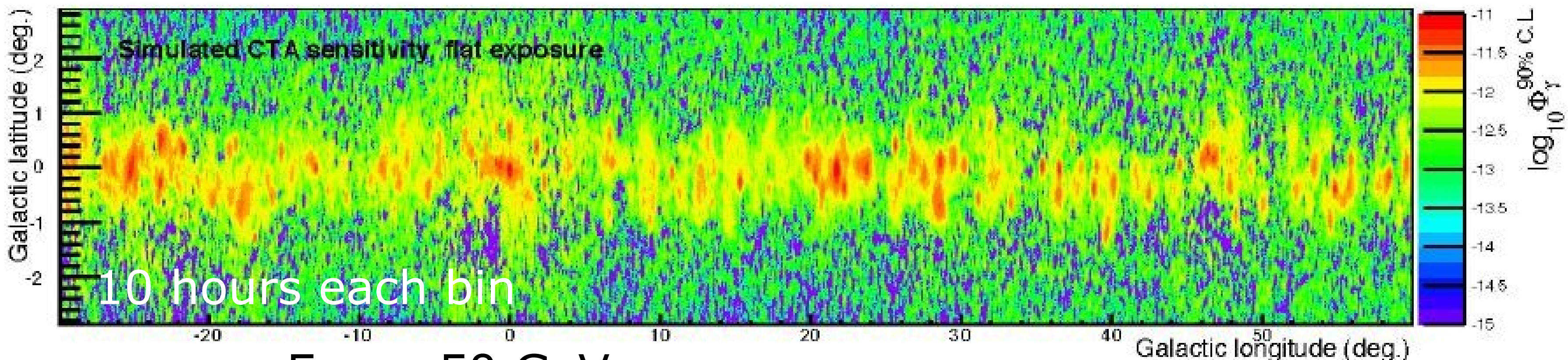
- assumes
  - x 2 improvement in hadron rejection
  - x 2 gain in angular resolution
  - x 10 gain in effective area

⇒ overall increase in sensitivity of ~ 9

- expect ~ 300 sources in -30 deg≤ l ≤ 30 deg.

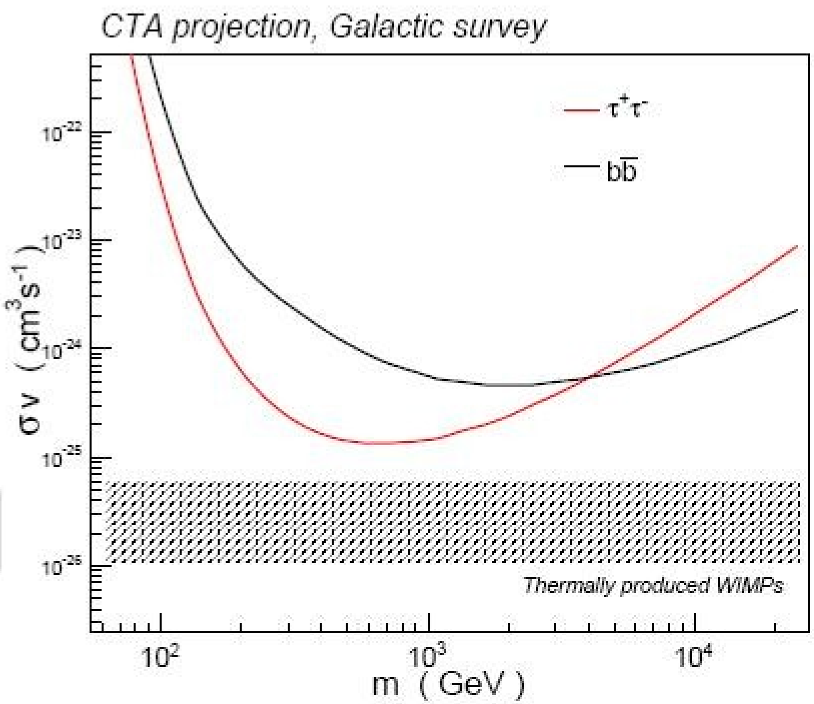
Galactic plane sensitivity (CTA)

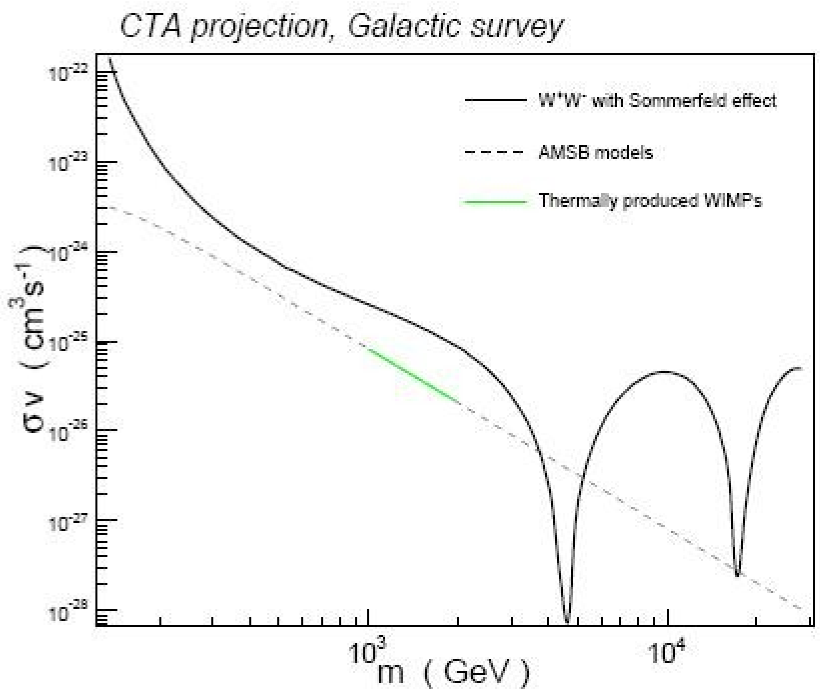




- assume E_{min} = 50 GeV
- 500 GeV WIMP annihilating to bb
- x10 gain in effective area, x2 gain in hadron rejection
- reaches 10^{-13} cm^{-2} s^{-1} sensitivity, except on new sources

CTA clump limits (Galactic plane)

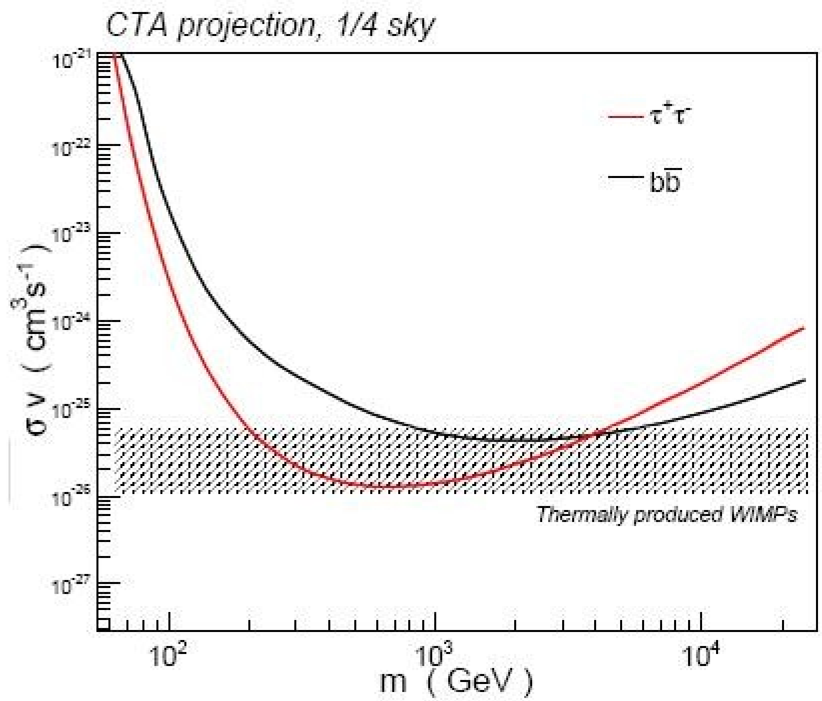


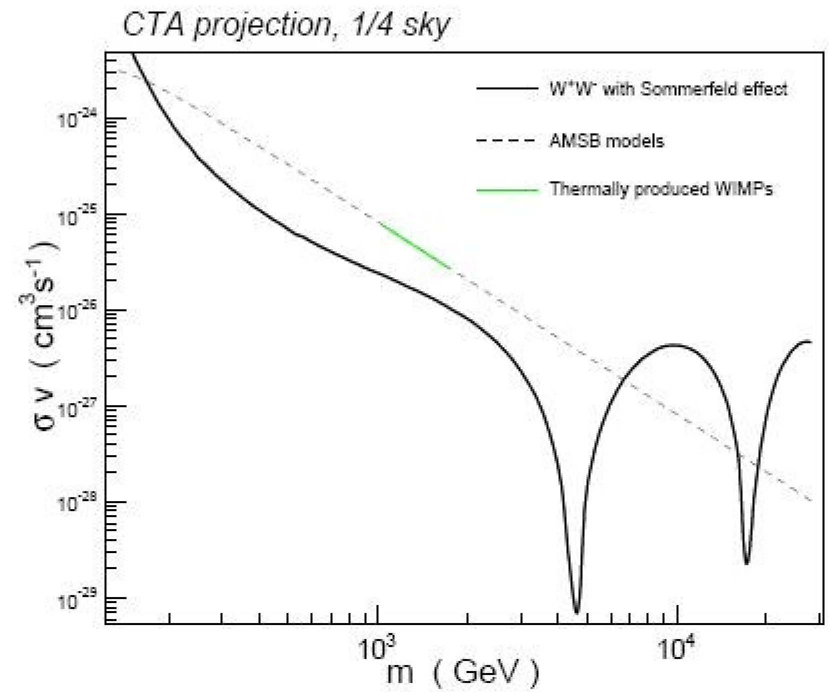


P.Brun, E.Moulin,J.Diemand, J-F.G, PRD sub. (2010)

- 90% C.L. limits improved by an order of mag/ HESS
- interesting <σ v>s not reached

CTA clump limits (1/4 sky)



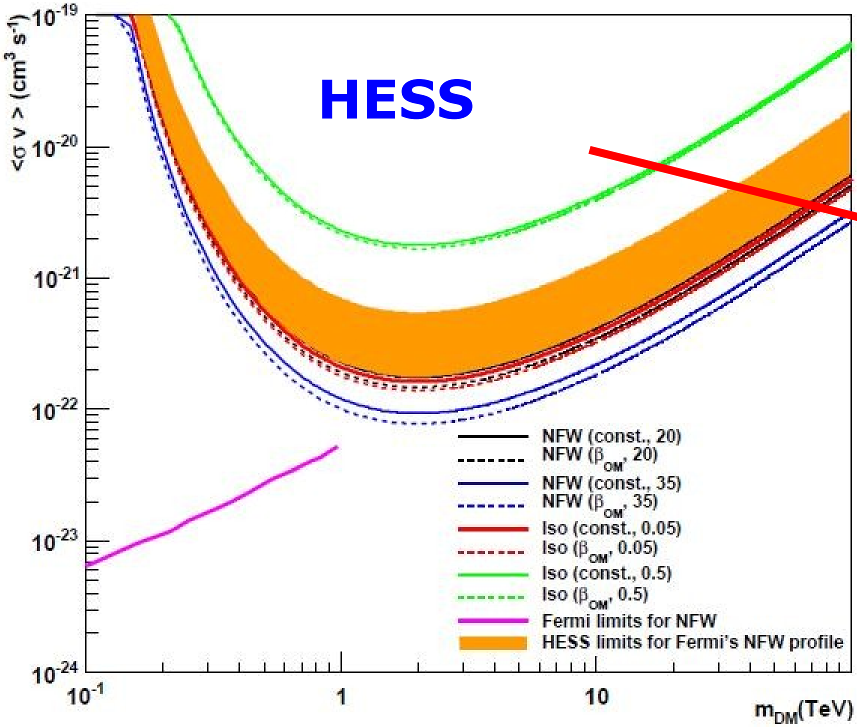


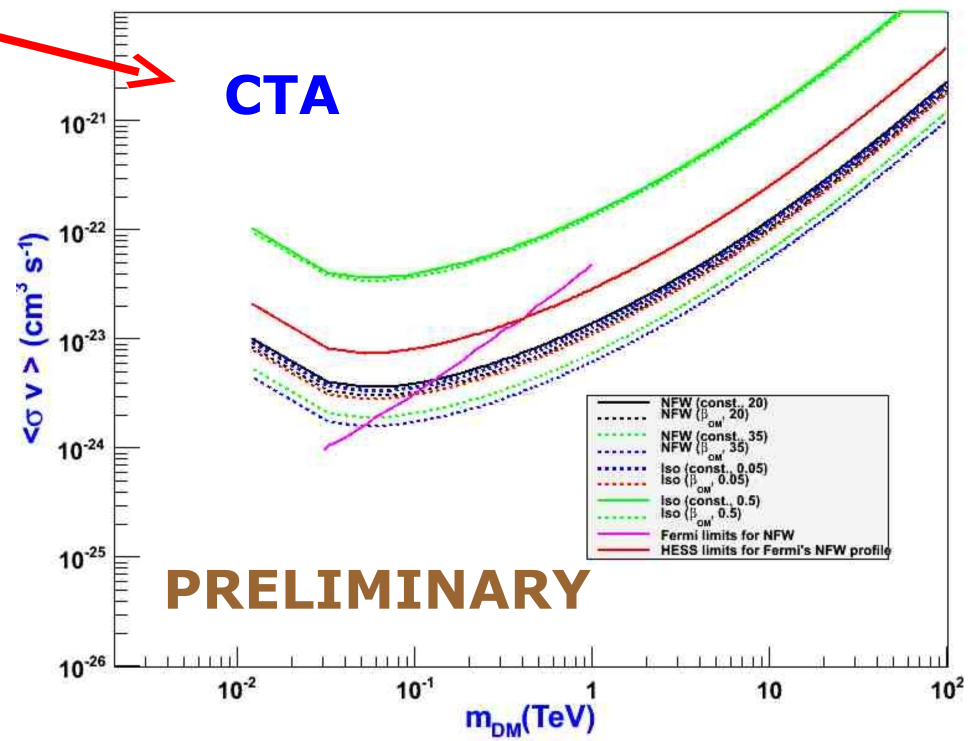
P.Brun, E.Moulin,J.Diemand, J-F.G, PRD sub. (2010)

- 1/4 survey in ~6 years
- assume 5 10^{-13} $cm^{-2}s^{-1}$ sensitivity (5 hour/bin)
- number of subhalos: 3907±324
- thermal WIMPs region reachable

Sculptor dwarf, extrapolation to CTA

- 11.8 hours (as in HESS)
- trigger effective area
  CTA array C (optimistic @ low E)



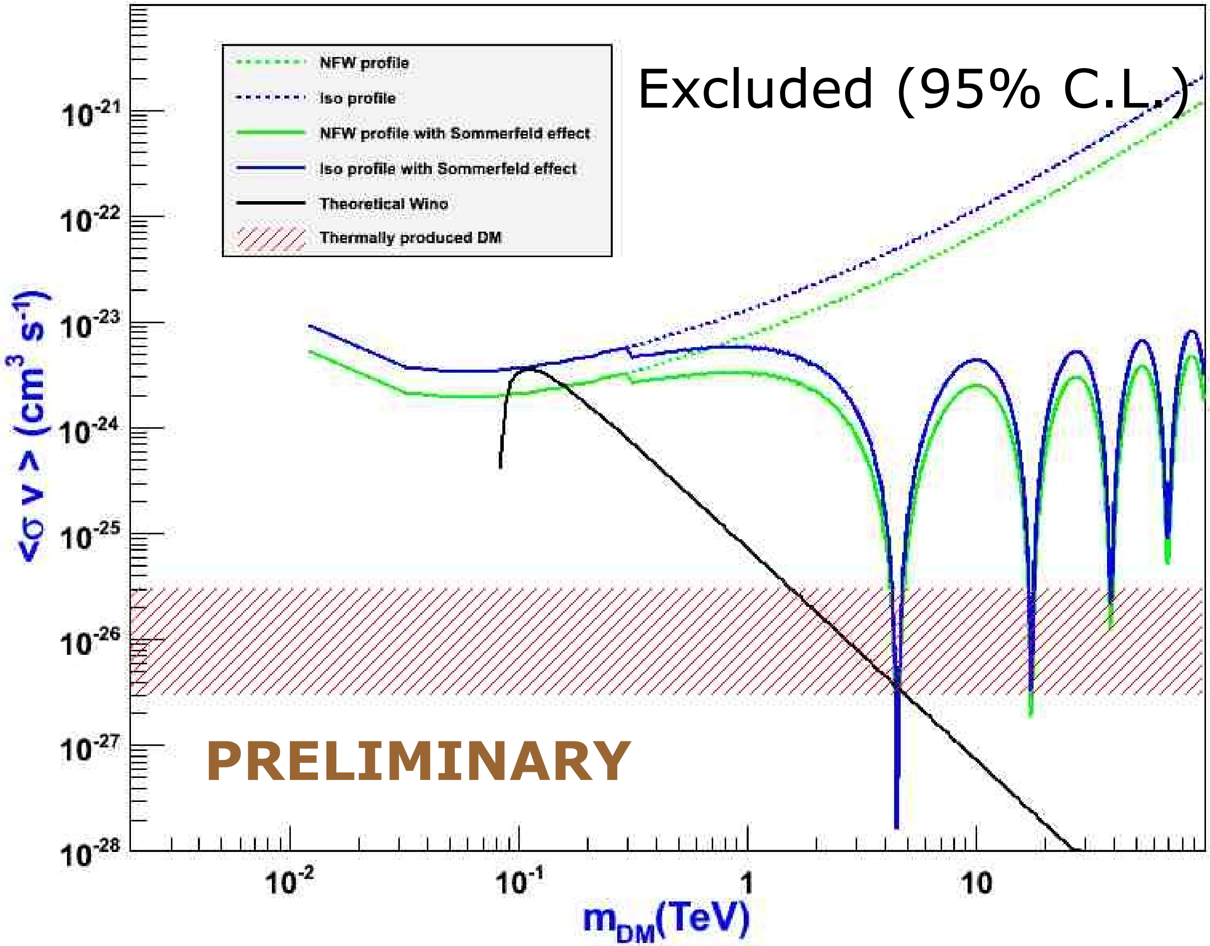


- limits improved by ~10
  (high MDM)
- limits comparable to Fermi
  (low MDM)
- factor ~10 above thermal WIMPS

A. Viana (IRFU)

Sculptor dwarf (CTA)

Sculptor, 11.8 hours, extrapolated to CTA

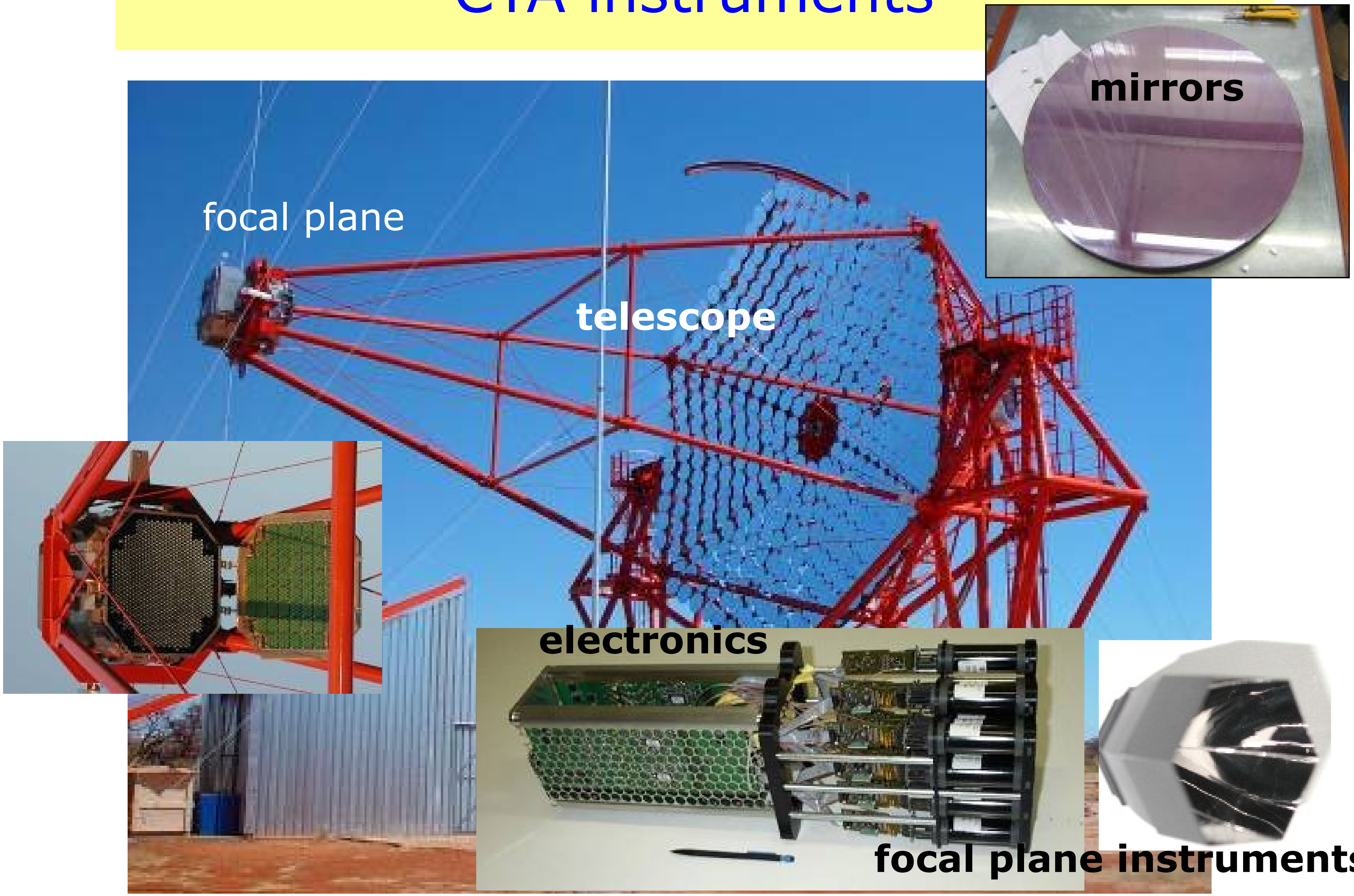


A.Viana (IRFU)

The CTA consortium

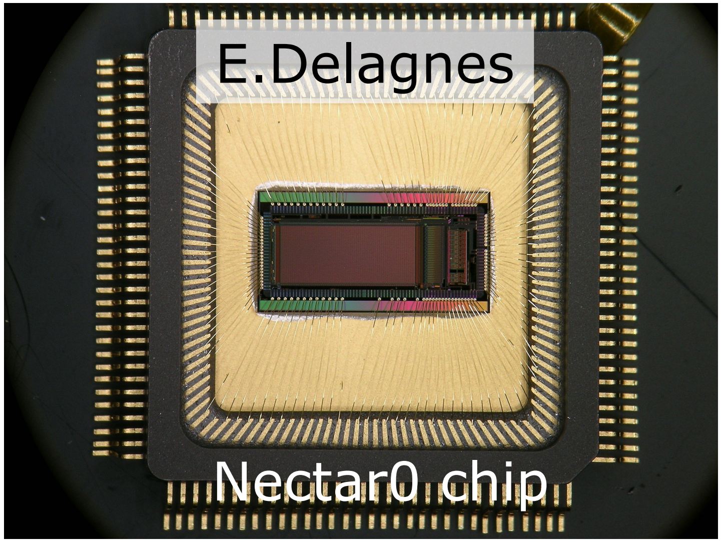
- Aims:
  - select the appropriate sites
  - reduce production costs of telescopes, sensors, electronics etc (technology already proven with HESS, MAGIC,VERITAS).
  - improve reliability of components and systems
  - prepare the construction of the observatories
- 25 countries (France, Germany, Spain, Poland, Italy, +USA, Japan)
- ~ 685 physicists+engineers (220 FTE)
- spokespersons: W.Hoffman (MPIK Heidelberg)
  M.Martinez (IFAE, Barcelone)
- merged with competiting project AGIS in 2010
- design study started in 2008 (Barcelona meeting)
- Concept design report published in August 2010
- in prep. phase of the FP7 since October 2010

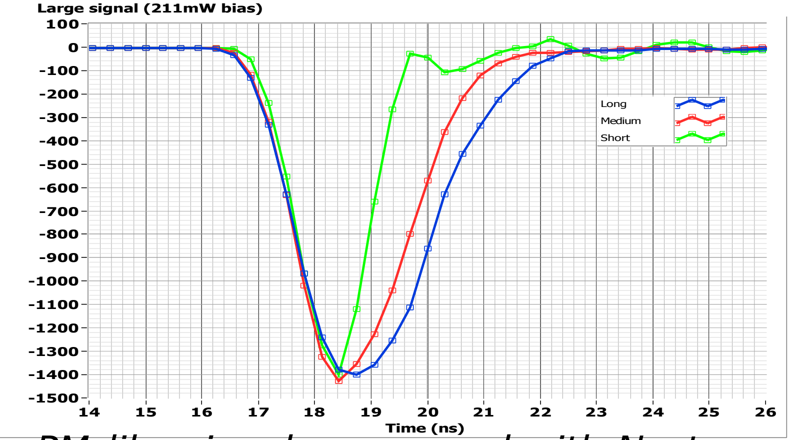
CTA instruments



CTA Design study at IRFU-Saclay

- telescope design (medium/large)
- mirrors
- electronics
- site development/ energy management

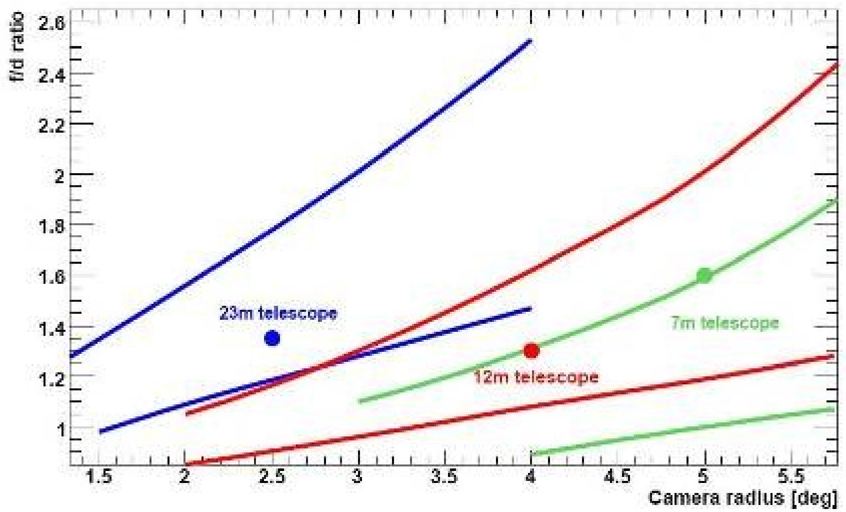




PM-like signals measured with Nectar

Requirements for telescopes

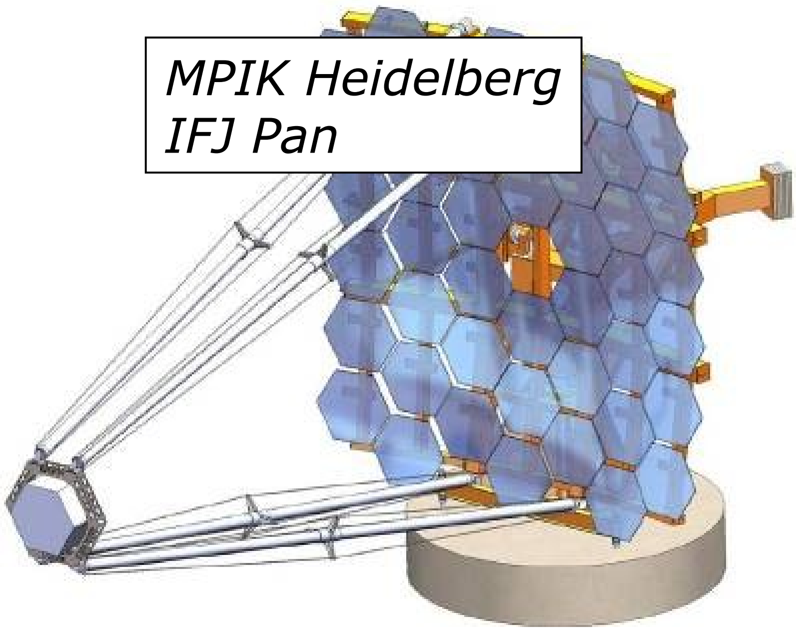
— dish ø=6 m (small) ø=12 m (medium) ø=23 m (large)
— dish shape spherical (Davies-Cotton): S+M, parabolic (L)
— f/d = 1.4 (M) and 1.2-1.4 (L)



P.Colin

— Camera Field of View: 8° (M), 5° (L)
— Number of pixels in camera ~ 1500 (M), ~2500 (L)
— Camera weight: 2.5 tons (M), 2 tons (L)

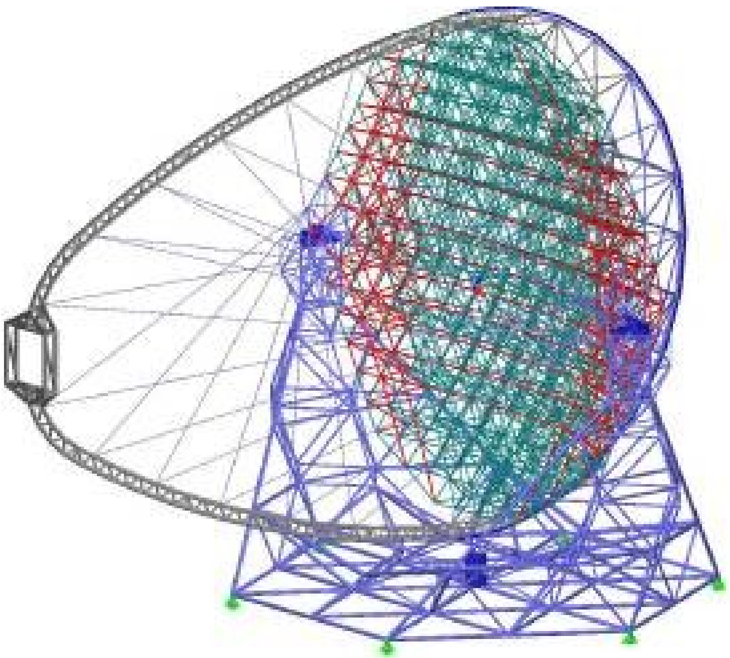
Small size telescope



- 2 options:
  - (baseline) 6 meter dish, camera 9 deg FOV, 1300 PMT
  - 2 mirror design, primary mirror 3.5 m, camera 8 deg FOV, 1600 pixels MAPMT or SiPM

23-meter class telescopes

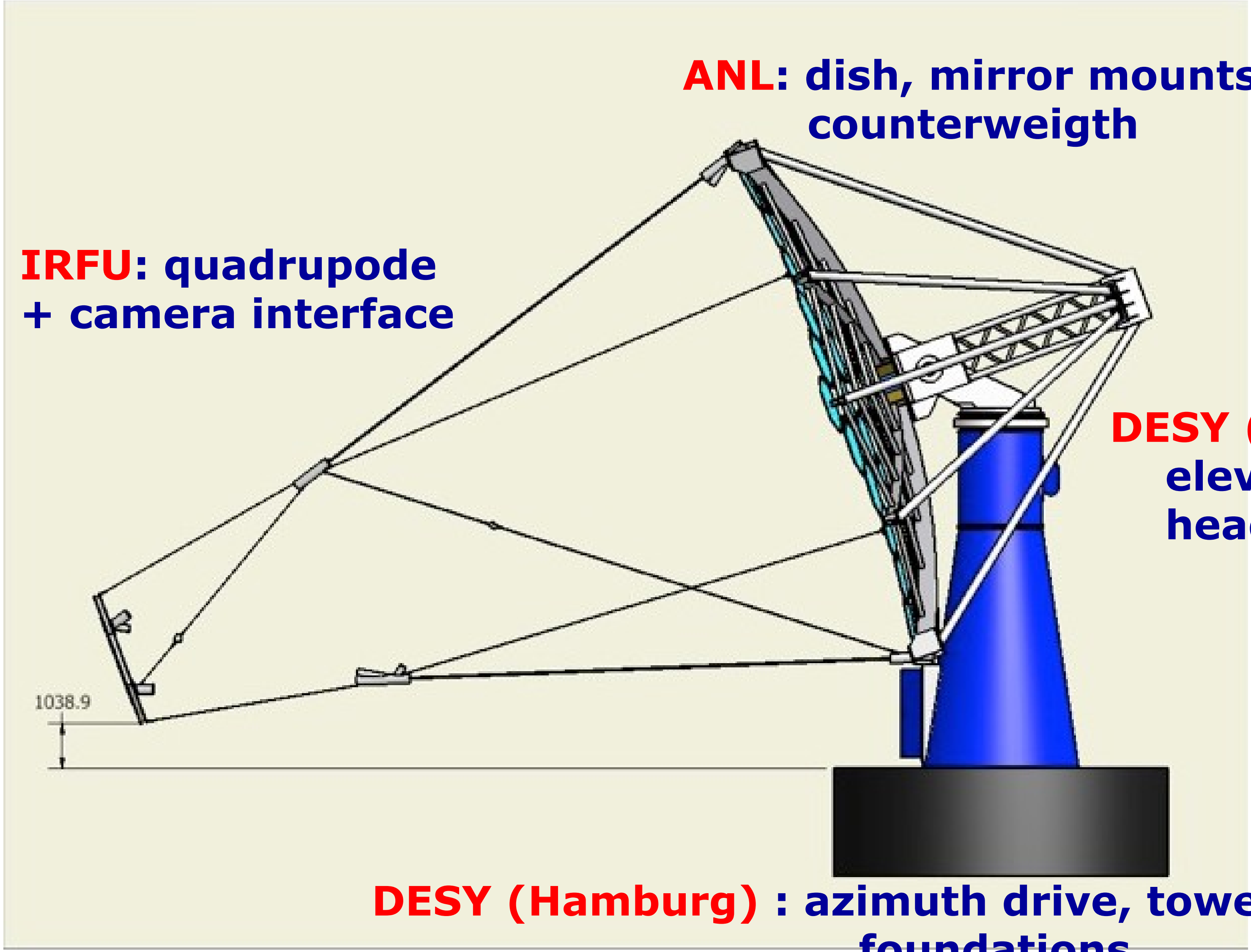
– possible design: extrapolate from MAGIC 17 m telescopes



MERO (company) design
MPI-P Munich, LAPP Annecy

12-meter class telescopes

- previous designs: HESS, VERITAS OK
- CTA DS focused on
  - cost reduction,
  - improvement of reliability ..
- Alternative: dual mirror design (AGIS)



— MST prototype to be built in Berlin (2011-2012)

Site of 12 m telescope prototype in Adlershof


The south side of BESSY GmbH


The location of MST prototype

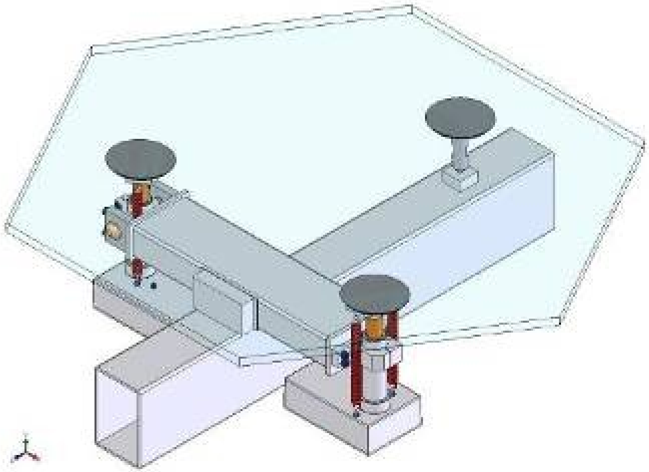
Berlin suburb, close to Humboldt Univ.


The University complex in the immediate neighborhood


The Erwin Schrödinger cafeteria

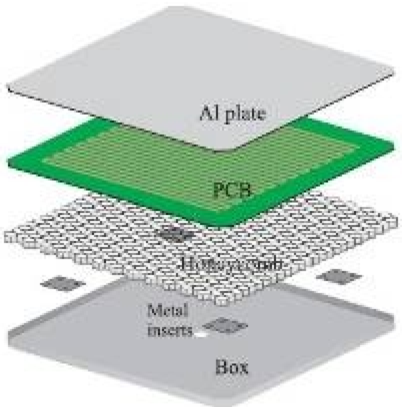
Mirror specifications

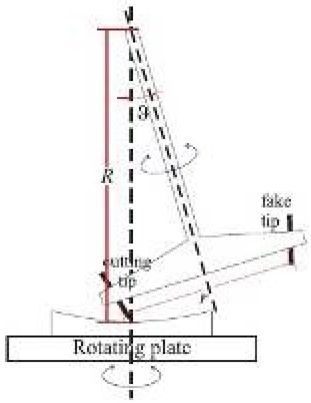
- hexagonal
- size: 1200 mm ± 2 mm flat to flat (MST prototype)
- weight < 35 kg/m^2 (including AMC and fixations)
- reflectance > 80% (300-600 nm)
- spot size < 1mrad (68% containment
- spherical with radius 30-40 m (MST), aspherical (LST)

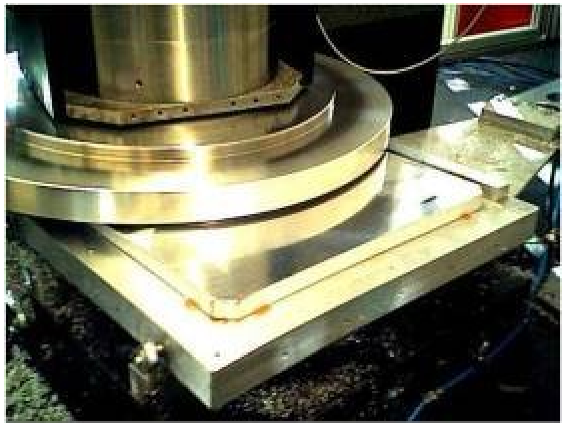


Mirror developpement (1)

- MAGIC I-II aluminium mirror (INFN Padova)
  - diamond milling



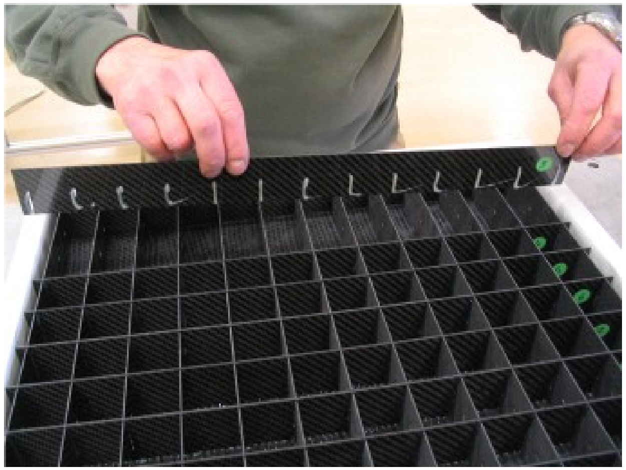


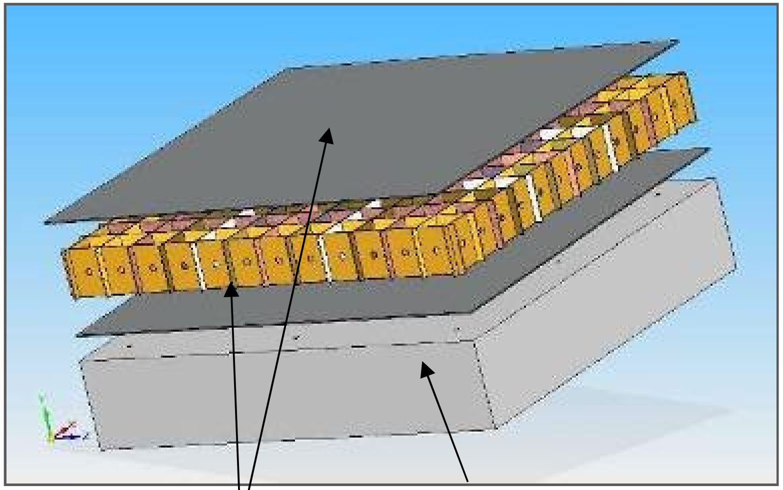


- MAGIC II glass mirrors (INAF, Mediolario)
  - produced by the « cold slumping » technique.

Mirror developpement (2)

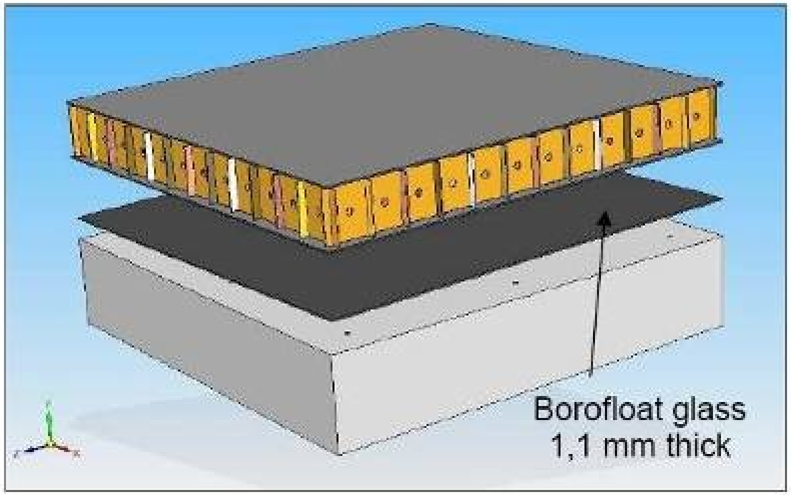
— Carbon/glass fiber composite mirrors (IRFU-Saclay, IFJ Cracow, SRC Warsaw)



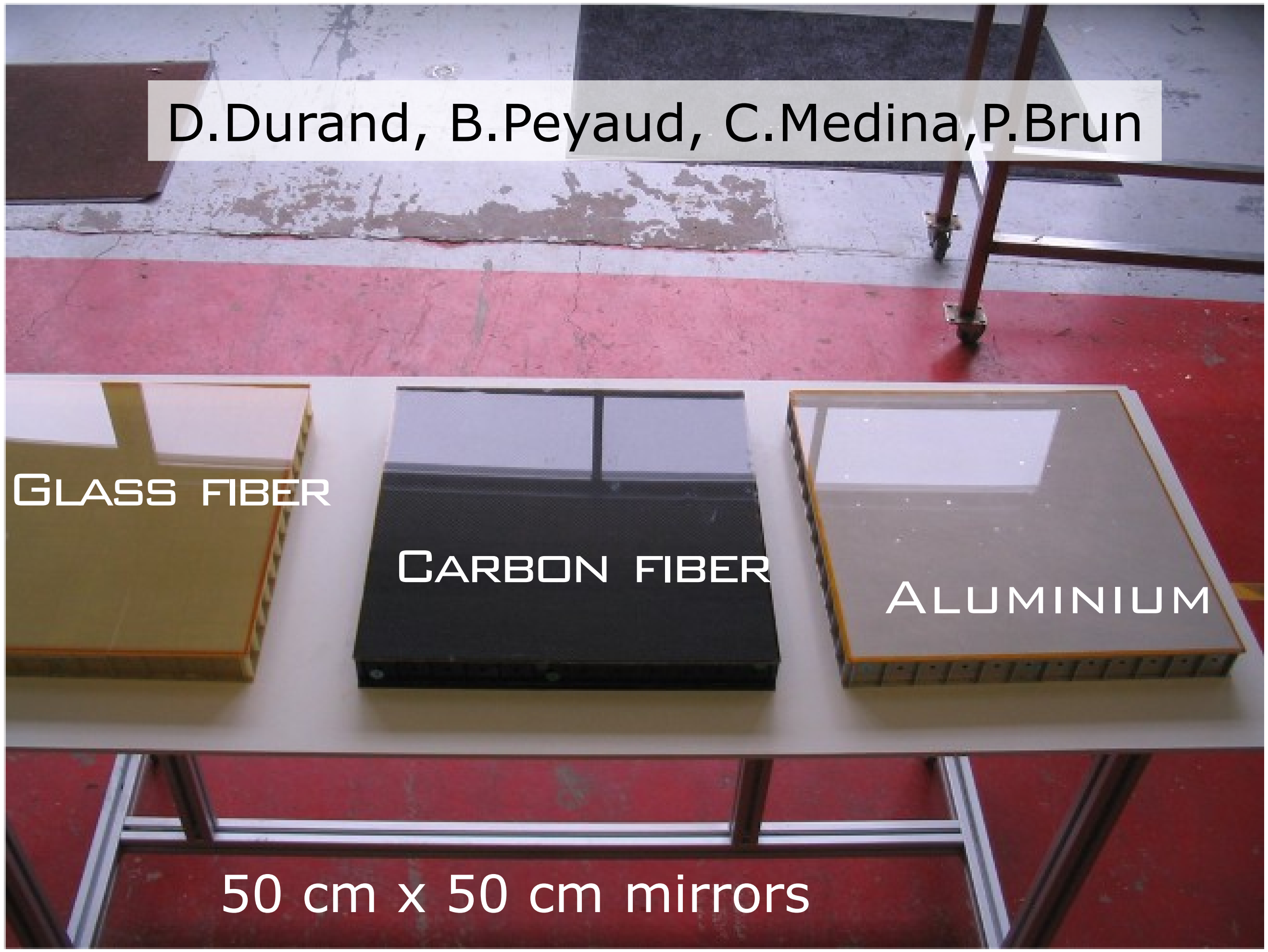


MOLD WITH SUCTION

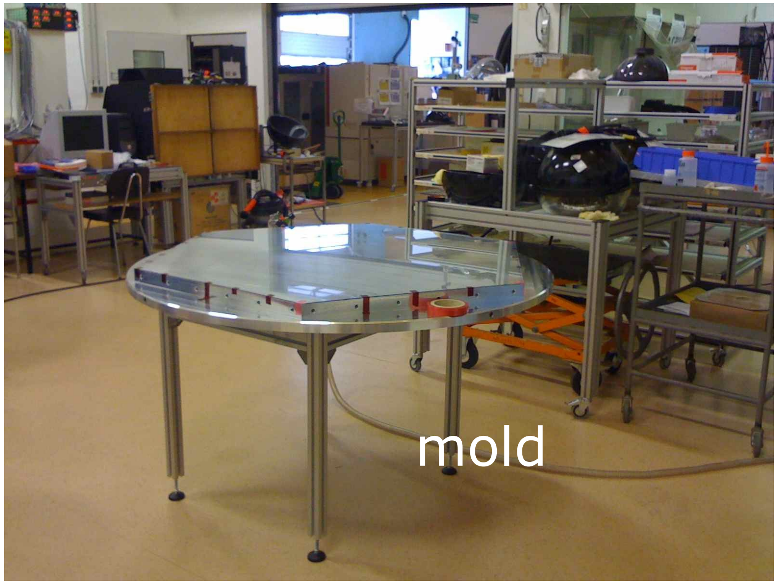
CARBON SHEETS 1.5 MM THICK

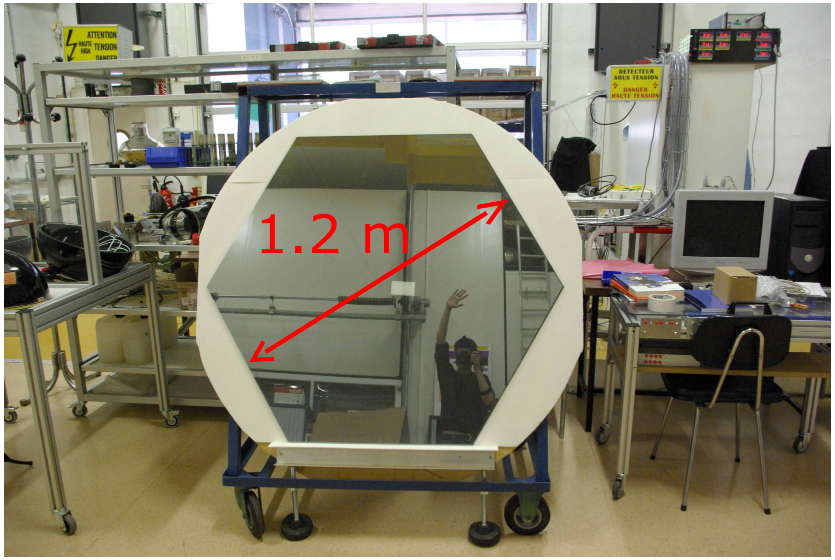


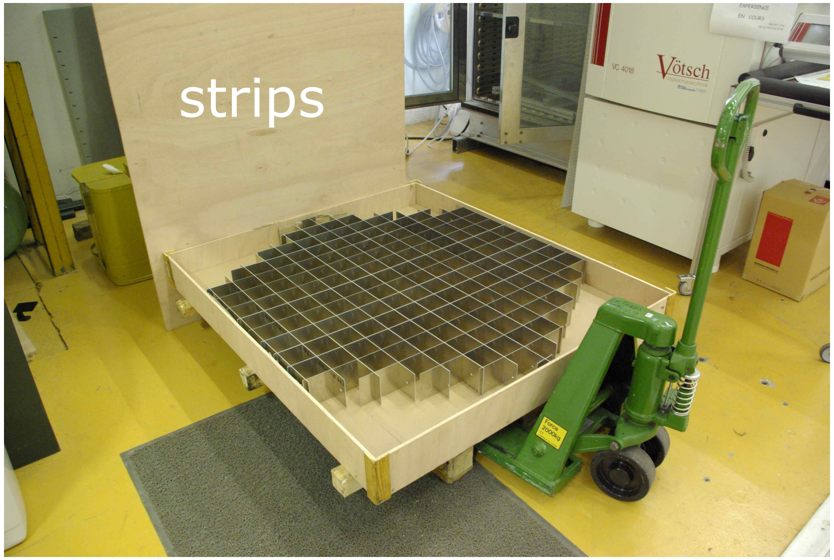
Mirror R&D at IRFU-Saclay



Design of large mirrors at IRFU







Summary and prospects

- Present Cherenkov Telescope arrays lack a few order of magnitude to be sensitive to « natural » WIMP models.
- New clump-based limit with HESS galactic plane at the level of $<\sigma v> \sim 10^{-23}$ $cm^{-2}s^{-1}$
- CTA will be the major observatory in VHE gamma ray astronomy in the 2020s with both guaranteed astrophysics and a significant discovery potential.
- CTA could discover a few DM clumps in a 1/4 sky survey
- The CTA design study is aiming at reducing costs and improving reliability of instruments and systems.

  It is on-going, with significant advances in mirror technology, telescope design (MST), electronics.
- The FP7 prep. phase for the CTA has just started in October 2010 for 3 years.

Backup slides

Bounds on the quantum gravity scale

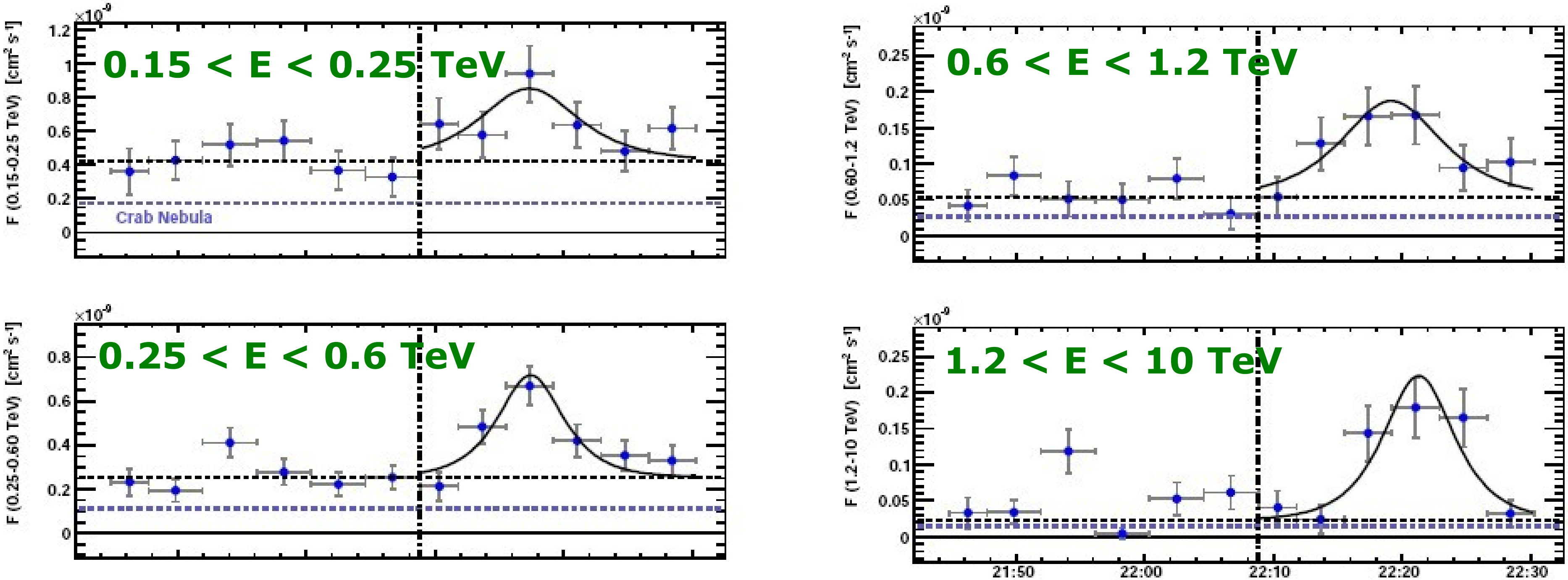
- At the quantum gravity scale, photons and neutrinos expected to experience a non-trivial refractive index in vacuum.
- Parametrization: $v = 1 - \xi\left(\frac{E}{M_1}\right)$ $\left(v = 1 - \xi\left(\frac{E}{M_2}\right)^2\right)$

  with $M_{1,2} \sim M_{Planck}$
- One expects a time difference for photons of different energies emitted at the same time.
- Sensitivity to M_1 (M_2): $M_1 \approx \frac{L\,\Delta E}{c\Delta t_{burst}} \approx 10^{15}\,GeV\left(\frac{L}{500\,Mpc}\right)\left(\frac{\Delta E}{1\,GeV}\right)\left(\frac{60\,s}{\Delta t_{burst}}\right)$
- Pulsar observed at GeV energies, L~1kpc, Δt ~1 ms

  $M_1 \sim 10$ GeV
- AGN with Cerenkov telescopes, z~0.1, Δt~1mn, E~1 TeV,

  $M_1 \sim 10$ GeV

Mkn501 (MAGIC)



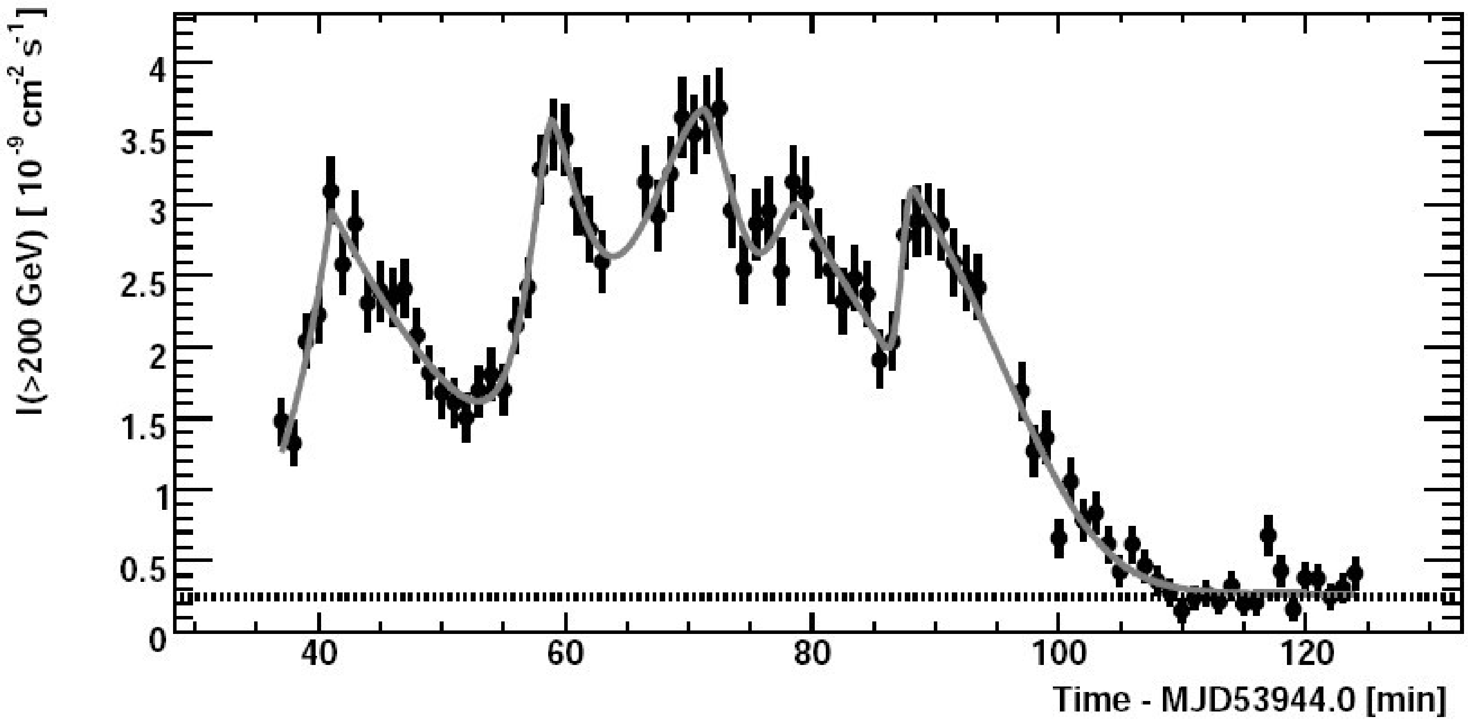
- blazar at z=0.034 (L~170 Mpc)
- large flare (~3.5 Crab units) on 9/07/2005
- flux-doubling time ~2 minutes
- time of maximum energy dependent: $t_{max}(> ١.٢\,\mathrm{TeV}) - t_{max}(< ٠.٦\,\mathrm{TeV}) = ٤ \pm ١\,\mathrm{minute}$

limits on quantum gravity scale: M > 0.26 10 GeV (95%CL)

Albert et al (MAGIC) ApJ,669,862 (2007)

Albert et al (MAGIC)+J.Ellis et al. (arXiv:0708.2889, 2007)

AGN physics: PKS2155-304 (H.E.S.S)

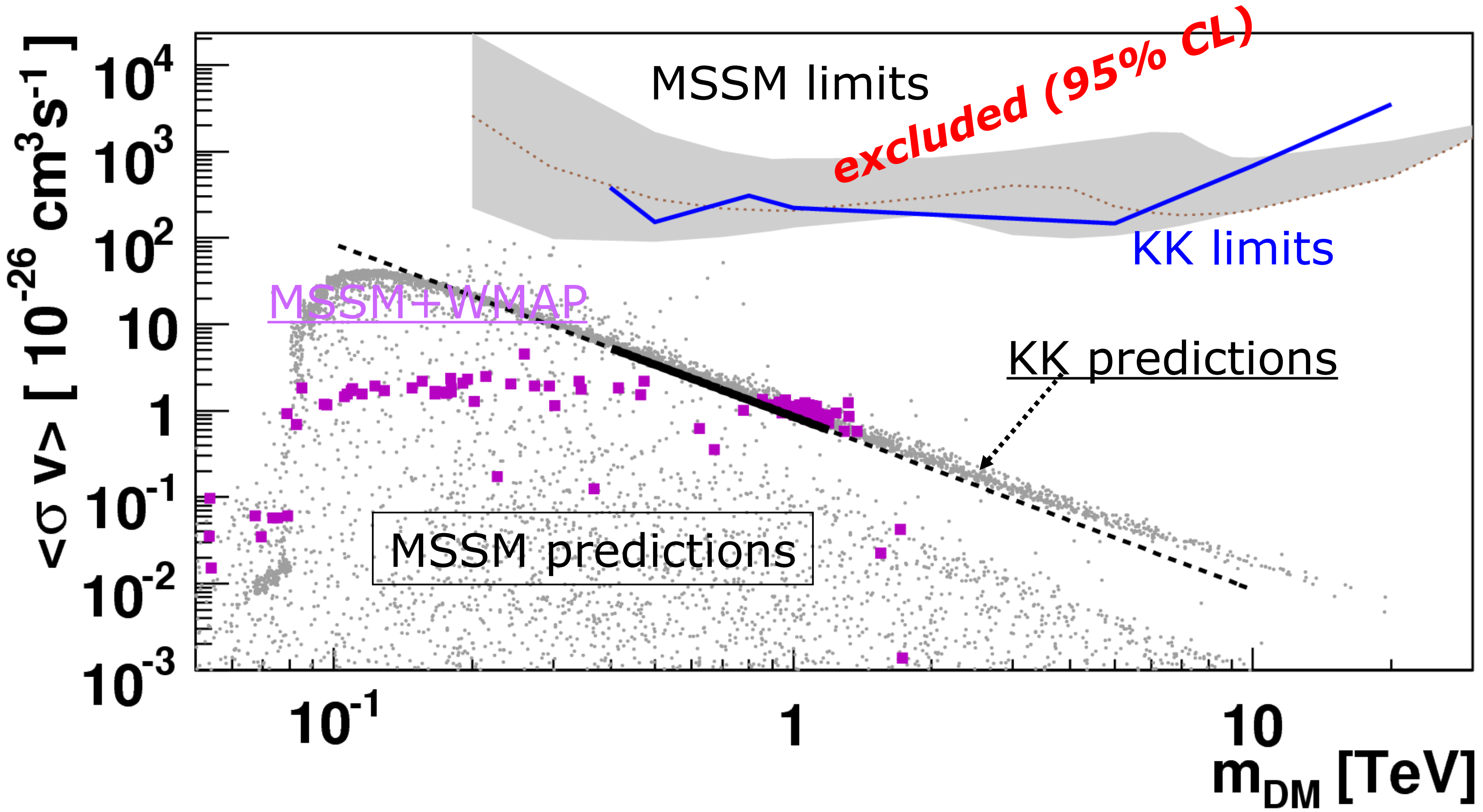


- blazar at z=0.116 (L=580Mpc)
- > 5 outbursts (up to 15 Crab Units) observed on 28/07/2006
- flux-doubling time = 330±40 s
- shortest rise time =173±28s ~($R_{Schwarzschild}$/c)/100

$\Rightarrow$ large boost factor

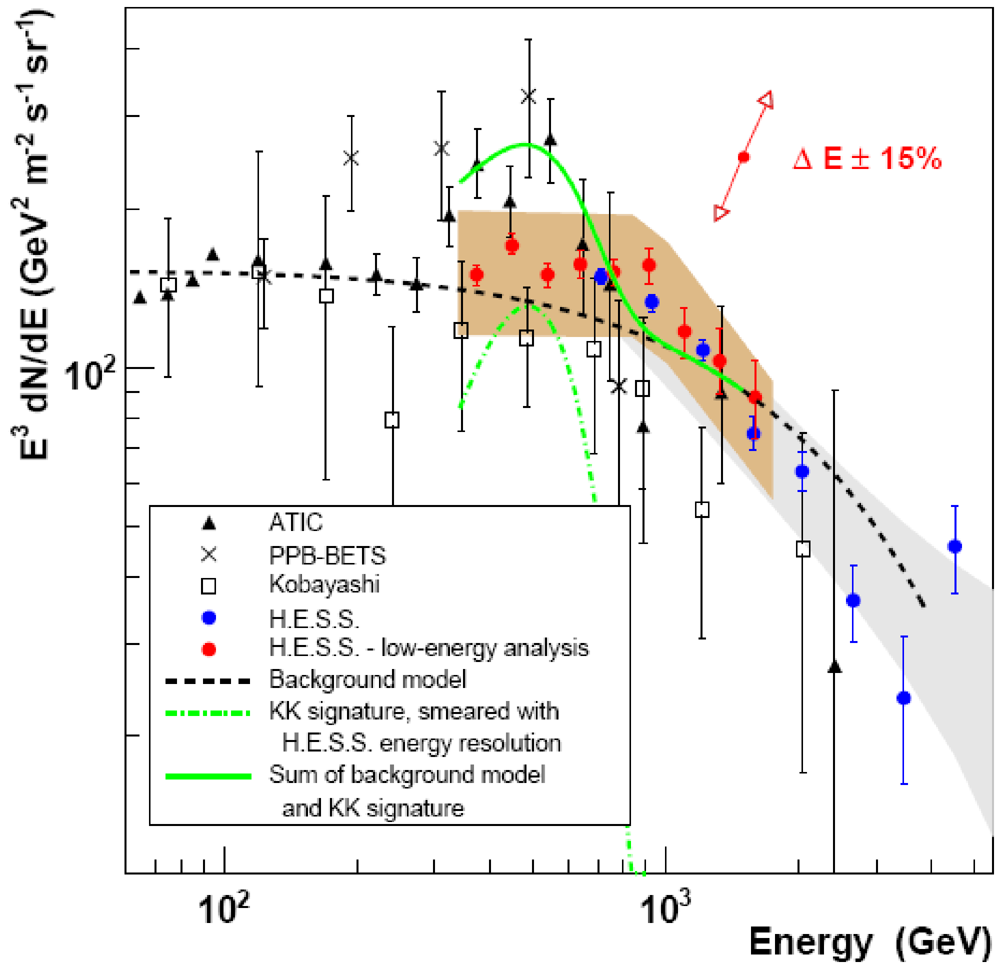
F.Aharonian et al. (HESS), ApJ 664,L71 (2007)

GC: exclusion plot

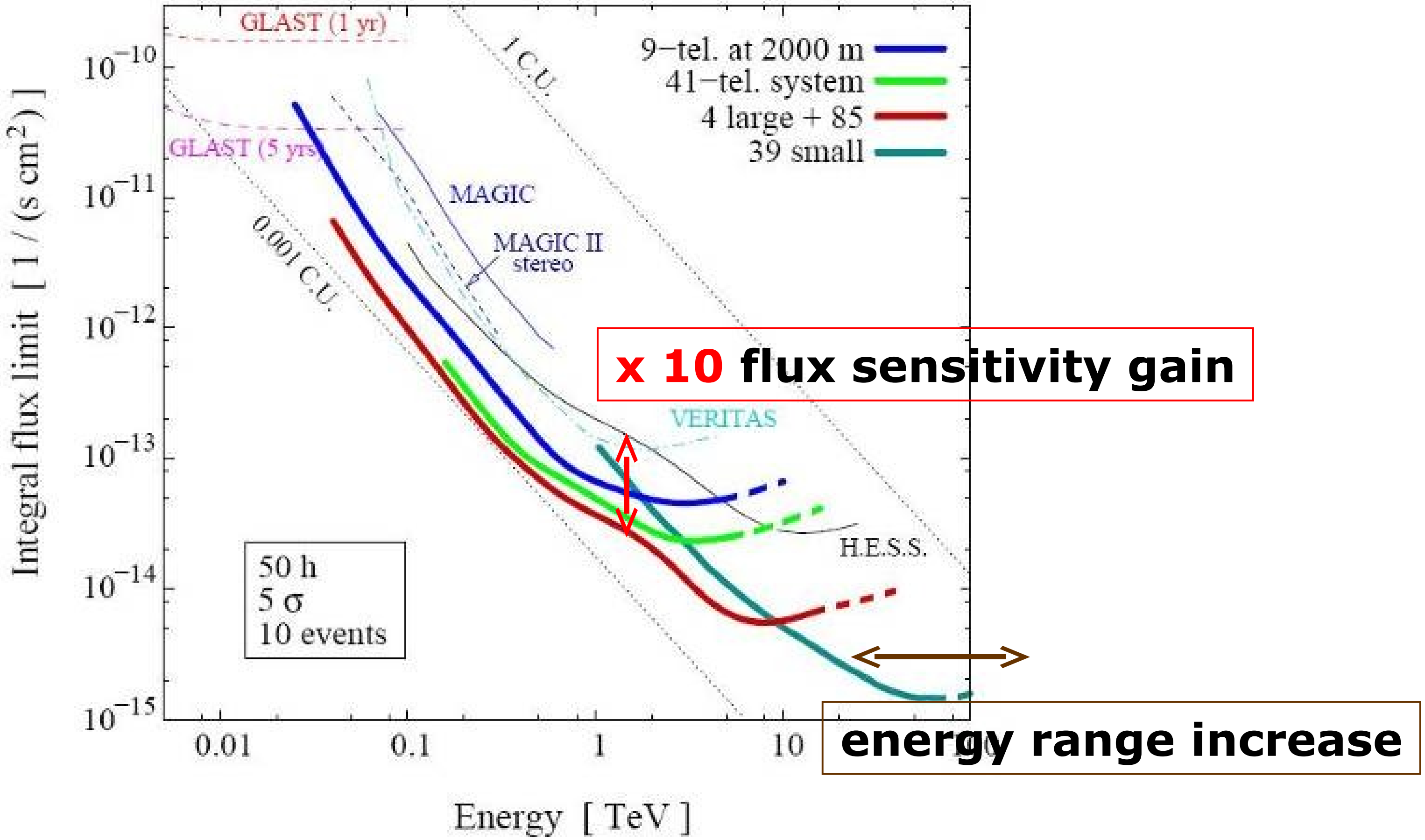


(p)MSSM predictions: DarkSusy 4.1

HESS high energy electron signal



Performances: array sensitivity

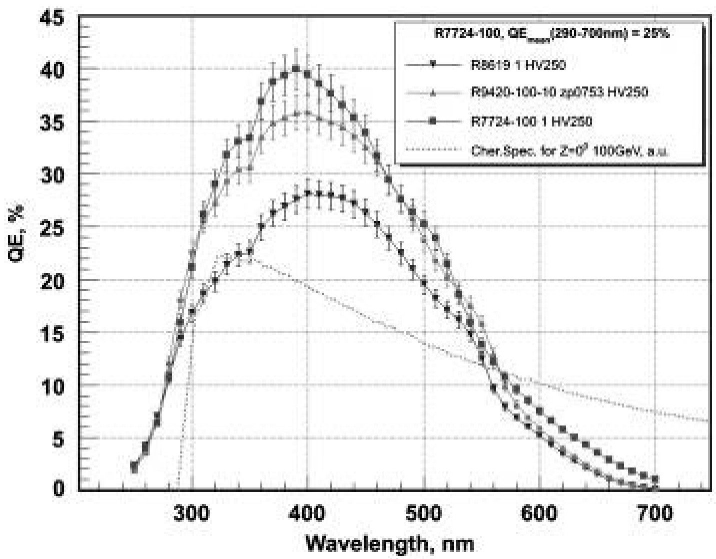


K. Bernloehr, arXiV0801.5722

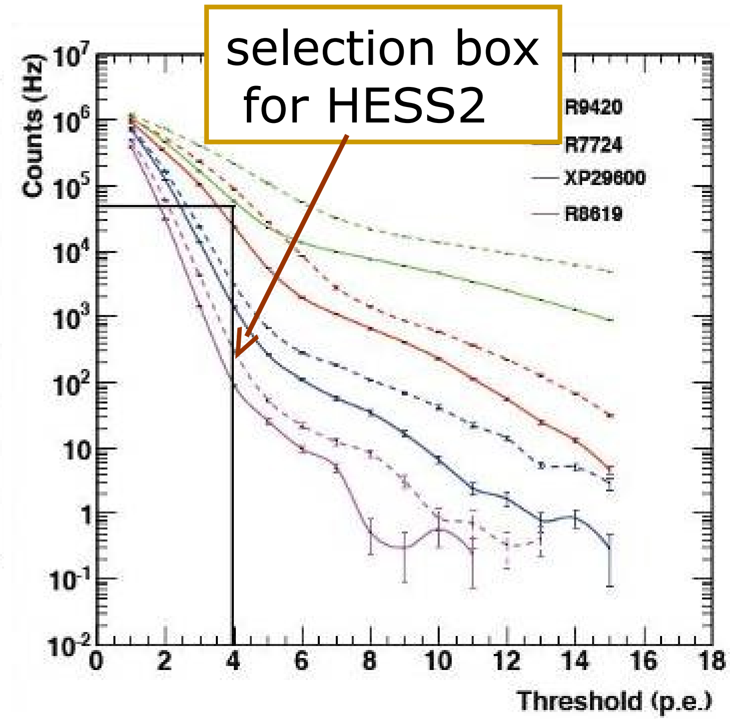
Focal plane instrumentation (1)

- Baseline option: PMTs (Hamamatsu, Electron Tubes)
- look for compromise between QE, afterpulsing, pulse width, cost..

R8619
R9420-100



Quantum efficiencies
M.Shayduk et al, NIM A (2010)



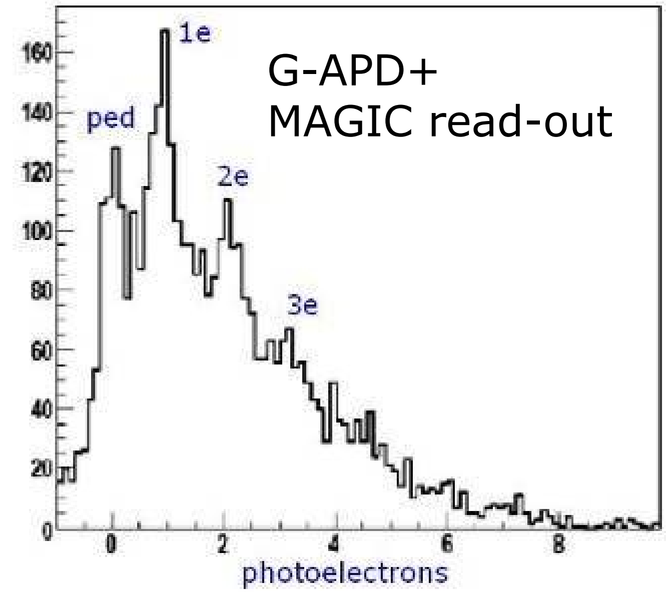
Afterpulsing rates
J.Bolmont

Focal plane instrumentation (2)

- other options: MCPPMT,G-APD
- useful for 2-mirror telescopes designs
- test: 4 MPPC in MAGIC camera
  A.Biland et al, NIM A (2008)
- FACT camera *(see talk by T.Krahenbuhl)*

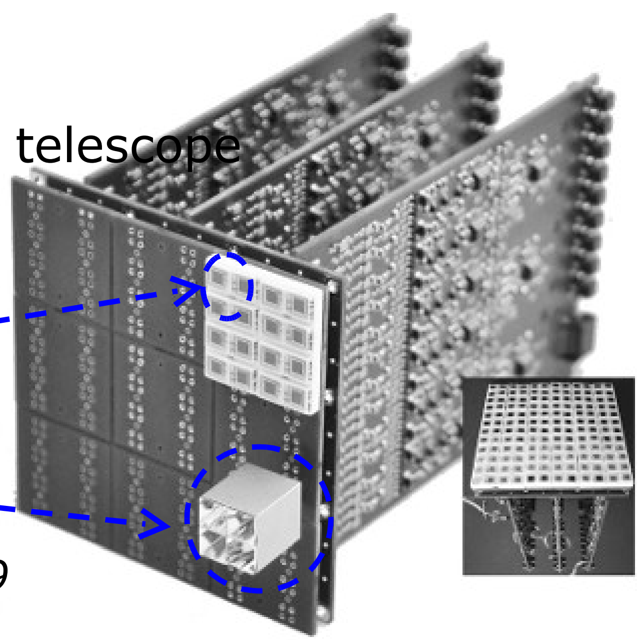
I.Braun et al, NIM A (2009)

  - full camera
  - 1440 pixels
  - on HEGRA CT3 telescope

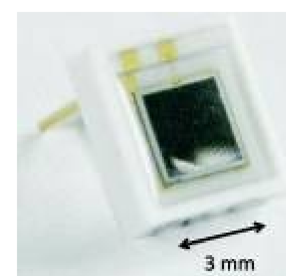


1 pixel=4 G-APD

Winston cone



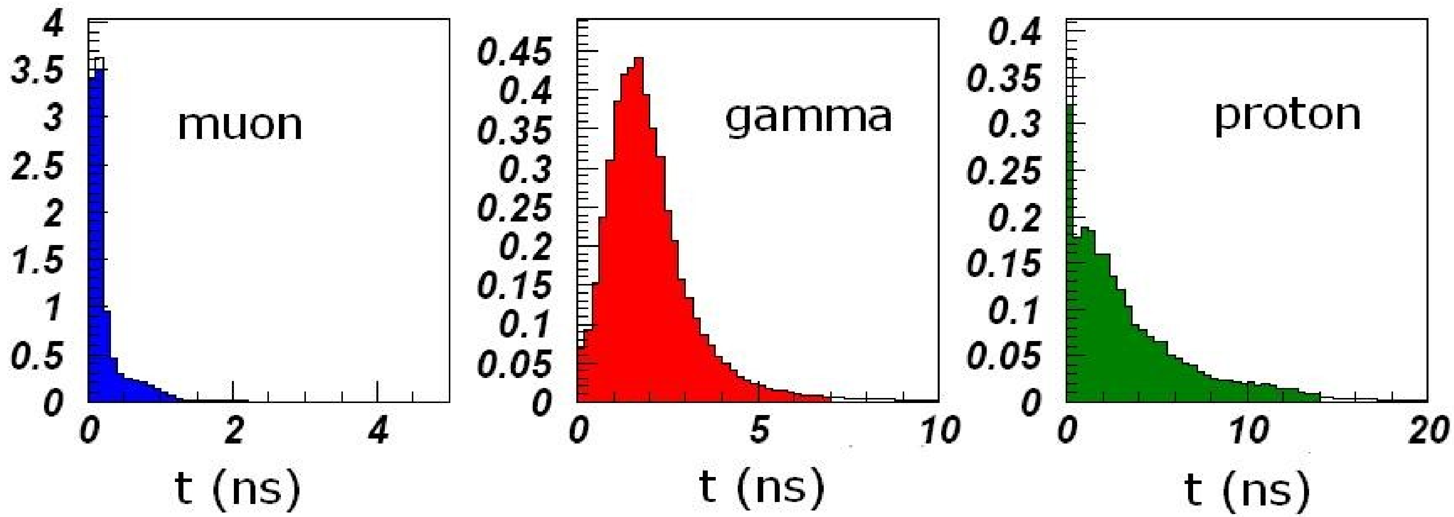
Weitzel et al, ICRC 2009



Hamamatsu MPPC
S10362-33-50C
50 μ x 50 μ cell size

Front end electronics

- Main backgrounds in ground based VHE astronomy:
  - parasitic, diffuse light
  - charged cosmic rays: protons, helium, electrons showering in atmosphere
- Cherenkov signal from particle showers very fast (~2 ns for γ rays)



- Typical trigger rate ~1 kHz/telescope (Crab nebula rate ~0.1 Hz) ⇒ **dominated by background**
- Fast electronics improves the rejection of parasitic light

Signal readout and telescope trigger

- Options for camera:
  - compact camera with electronics on board (HESS, VERITAS) or
  - signal sent to ground (MAGIC)
  - ⇒ compact option was retained (except maybe LST…)
- Options for read-out:
  - Sampling at ~ 300 MHz with FADC (fully digital camera)

    MPIK Heidelberg, ETH Zurich, Leeds, Uni. Zurich, AGH
  - analogue memories (1 GHz sampling)+ADC

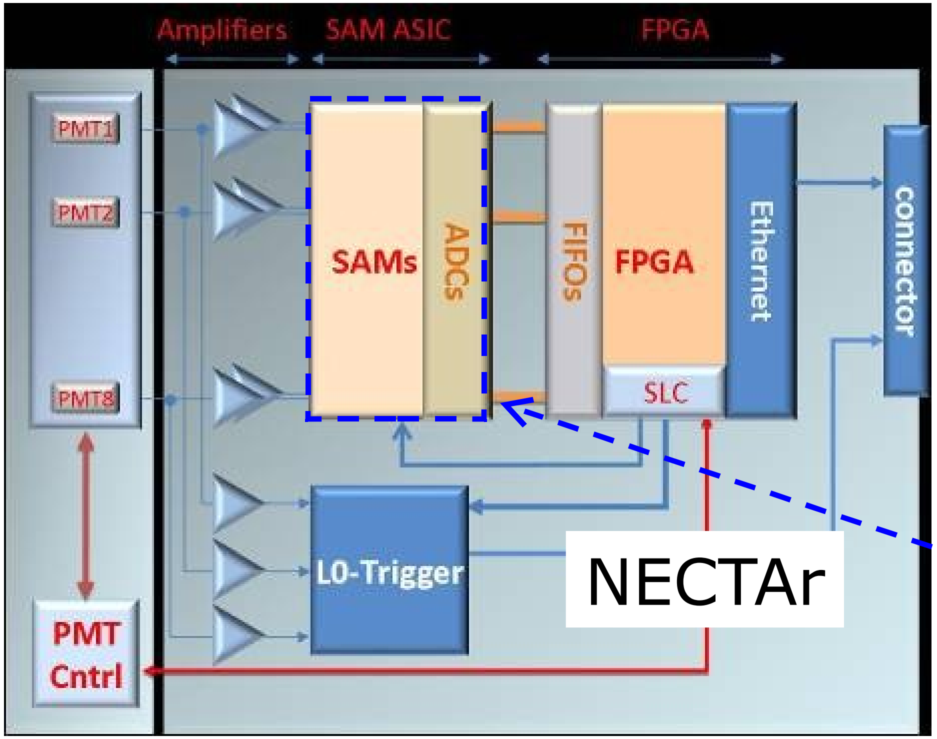
    Pisa, IRFU Saclay, LPNHE, LPTA, Uni. Barcelona
- Local trigger of telescope:
  - analog or digital (analogue memories based read-out)

    spanish groups (IFAE..), DESY
  - digital (FADC)

Analogue memories-based FE boards

- NECTAr: *IRFU/LPNHE/LPTA/Univ. Barcelona*
  - see poster by S.Vorobiov
  - based on **SAM chip** (HESS2)
  - new developpment to reduce power consumption and integrate the ADC
- Dragon: *Pisa*
  - based on commercially available **DRS-4 chip**

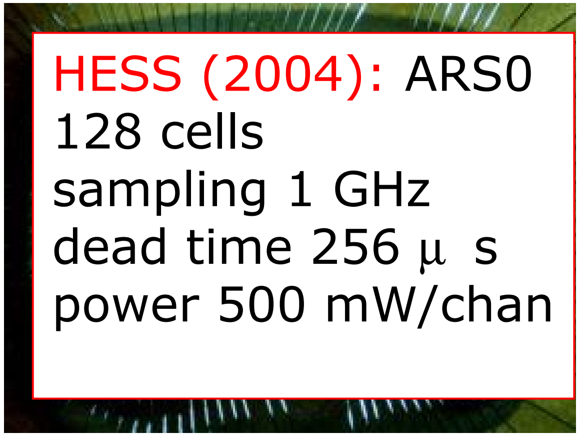
photons



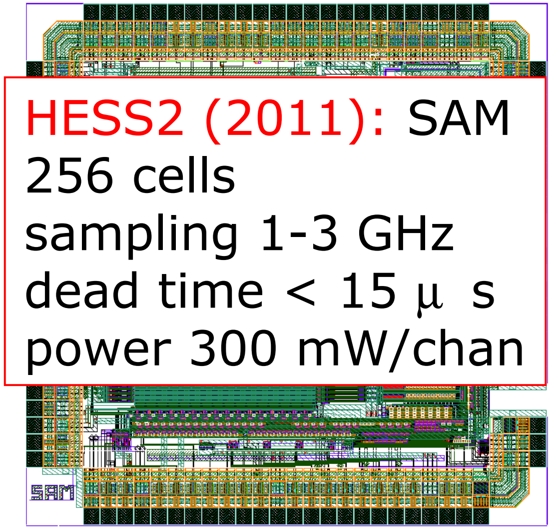
digital output to acq. farm

integrated analogue memories+ ADC conversion

analogue memories design @ IRFU

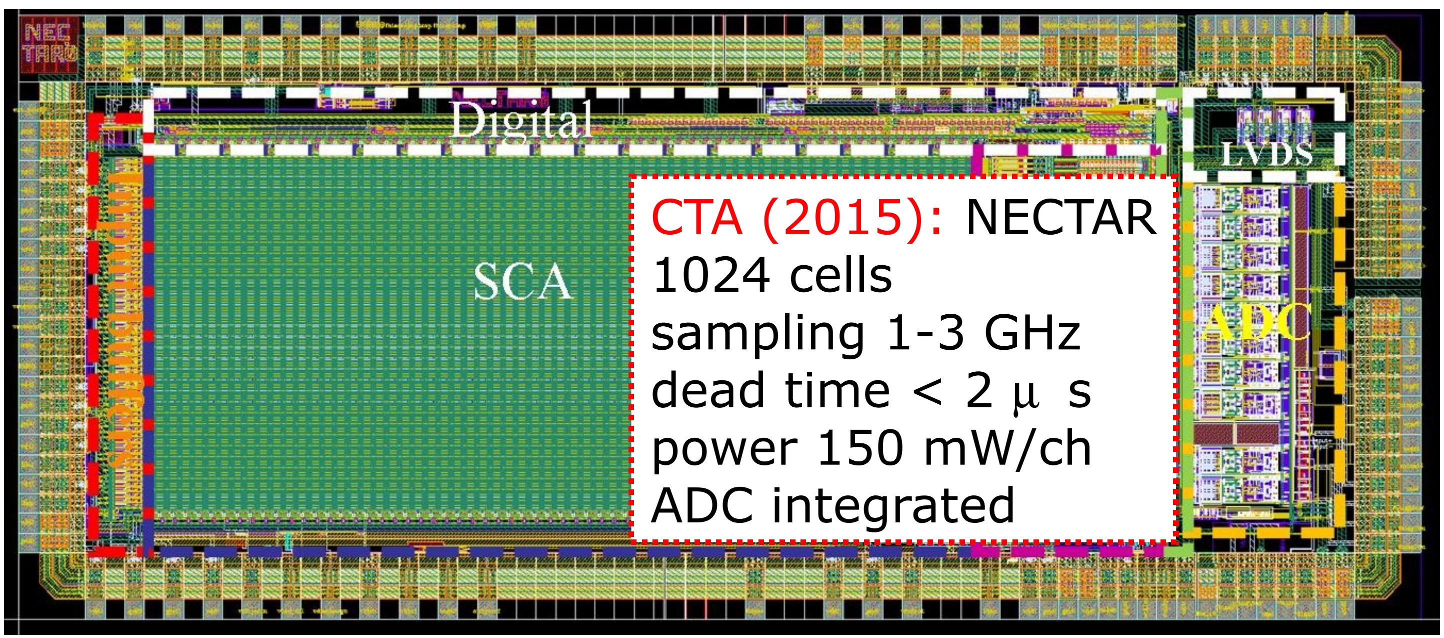


HESS (2004): ARS0
128 cells
sampling 1 GHz
dead time 256 μ s
power 500 mW/chan



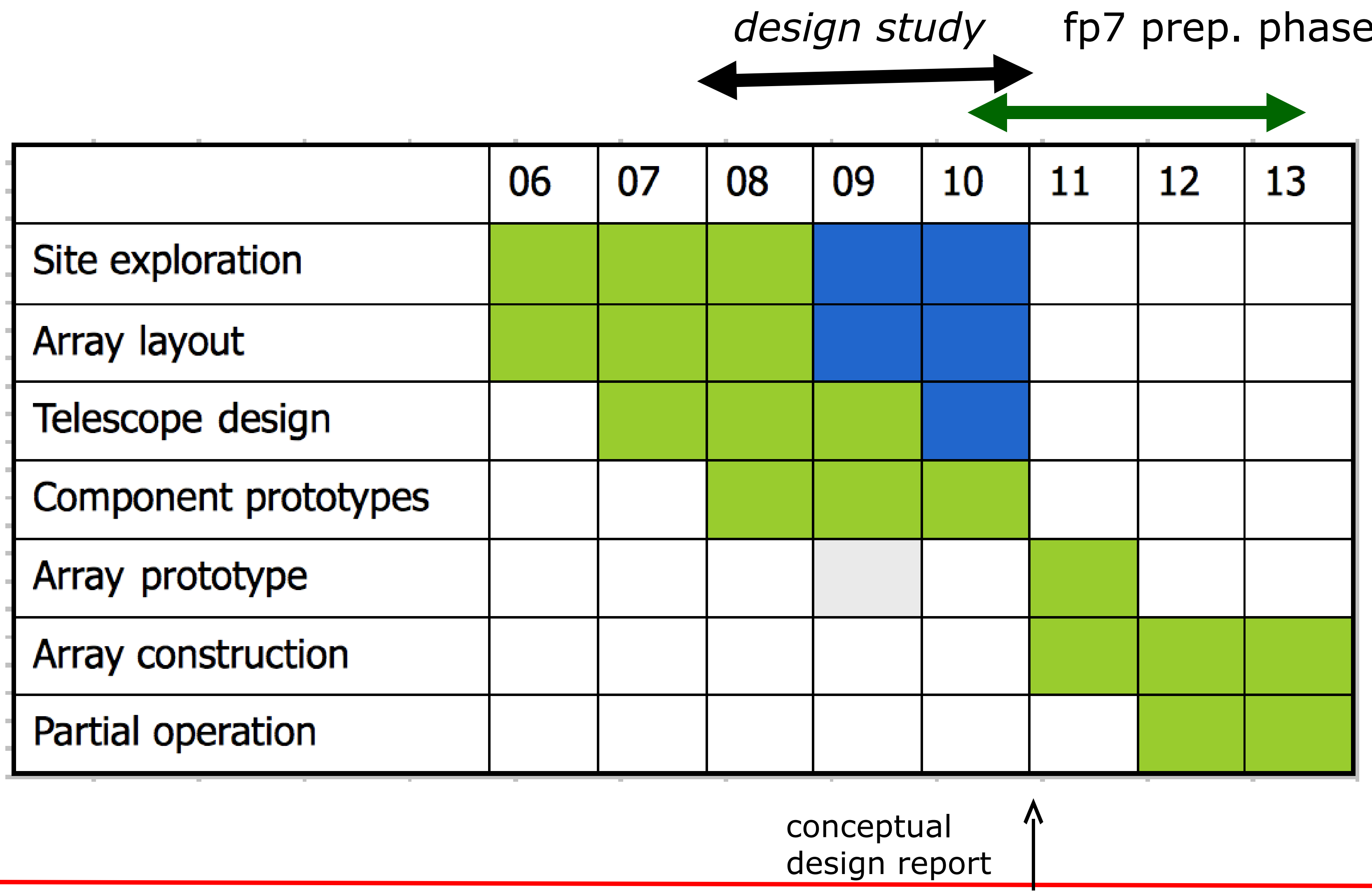
HESS2 (2011): SAM
256 cells
sampling 1-3 GHz
dead time < 15 μ s
power 300 mW/chan

E. Delagnes (IRFU)



CTA (2015): NECTAR
1024 cells
sampling 1-3 GHz
dead time < 2 μ s
power 150 mW/ch
ADC integrated

Timeline for CTA



CTA in context of HE/VHE gamma rays facilities