Irfu
cea
saclay

23rd Rencontres de Blois
Particle Physics and Cosmology
May 29-June 3, 2011

Astroparticle physics with HESS:

dark matter and LIV studies

Emmanuel Moulin for the HESS collaboration
Irfu - CEA Saclay

HESS : High Energy Stereoscopic System

Khomas Highlands, Namibia (1800m a.s.l.)

- 4 telescopes: Ø 12 m ,107 m^2 each
- Stereoscopic reconstruction
- 960 PMTs/camera
- Field of view : 5°
- Observations : ~1000h/year
- Source position : ~ 10''

- Angular resolution < 0.1°/γ
- Energy threshold (zenith) :~100 GeV
- Energy resolution ~ 15%
- Sensitivity (5σ): 1% Crab in 25 h

HESS 2 coming soon: an additional telescope Ø 28 m …expected July 2012!

Gamma-ray flux from dark matter annihilations

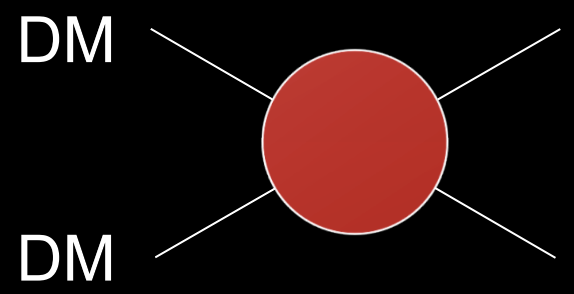
$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\frac{dN_\gamma}{dE_\gamma}}_{\text{Particle Physics}} \times \underbrace{\int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r[s])ds}_{\text{Astrophysics}}$$

<u>Particle Physics :</u>

- Cross sections
- Branching ratios
- Differential photon yield
- DM particle mass

<u>Astrophysics</u>

→ modelling required for the DM distribution in the object



SM: b, W^+, Z, τ^+, …

Primary channels

SM: $\bar{b}$, W^-, Z, τ^-, …

Hadronisation and/or decay

➡ γ, e^+, $\overset{(-)}{p}$, ν, …

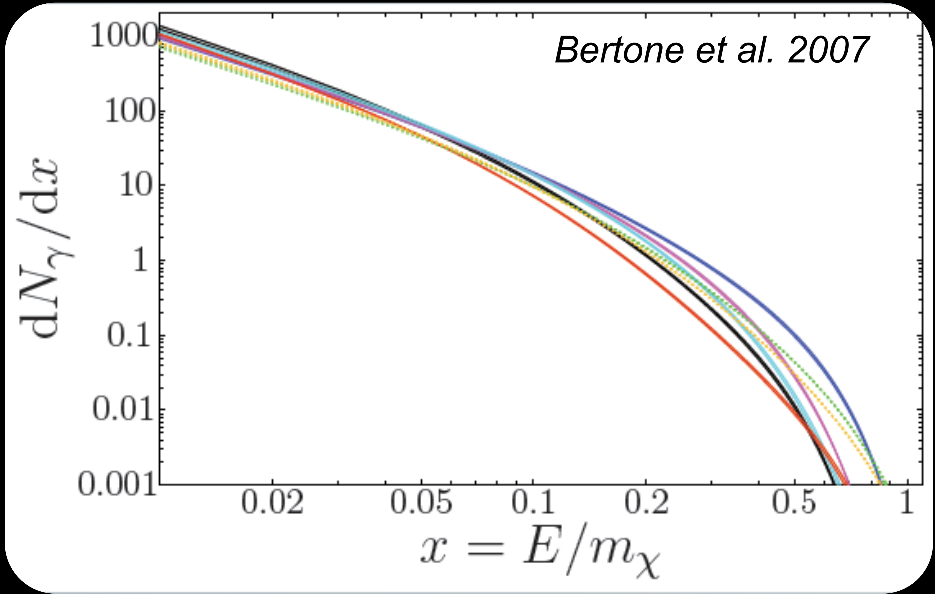
Final states

➡ γ, e^-, $\overset{(-)}{p}$, ν, …

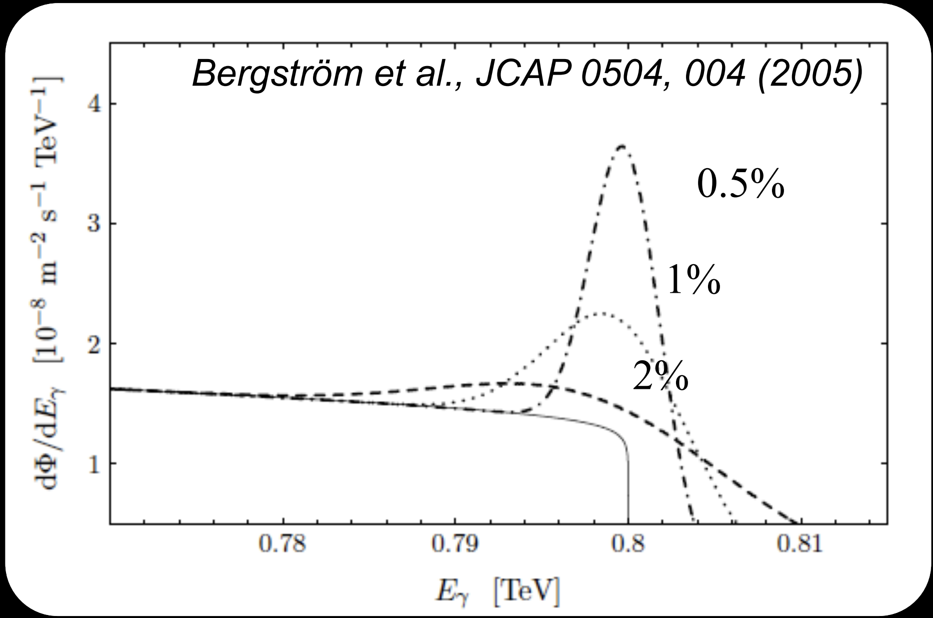
Dark matter annihilation signal

Types of signals

- Continuum spectrum with a cut-off at the DM mass
  → model-independent spectrum



- Mono-energetic line signal: necessarily loop-suppressed
  → smoking-gun signature



Dark matter annihilation signal

Boost factors

- Particle physics enhancement:

– Sommerfeld effect (1931)

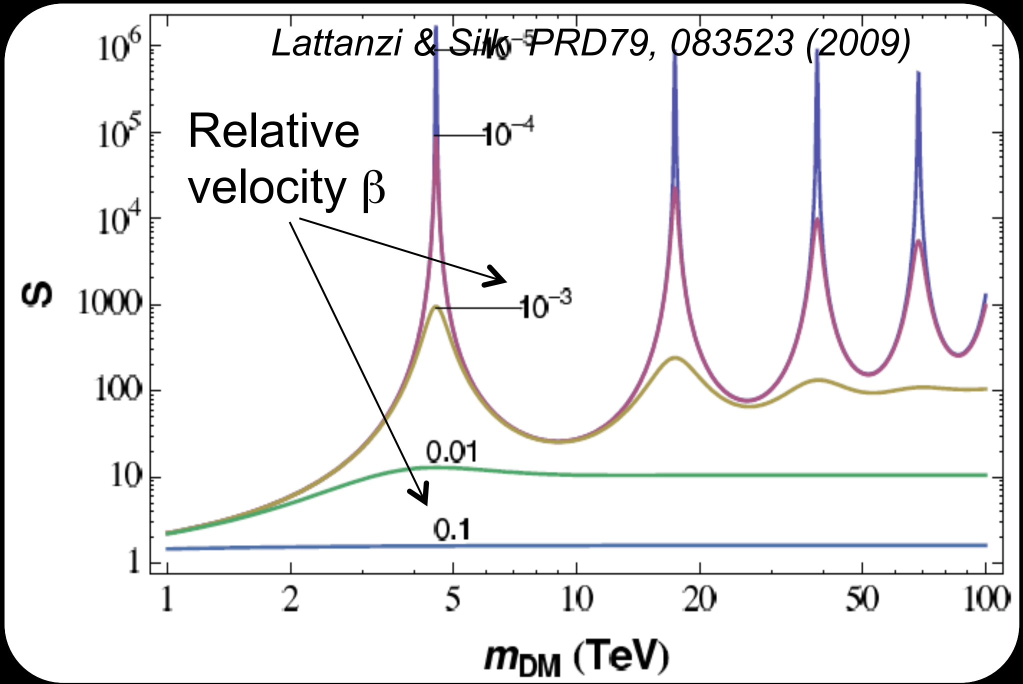
→ particularly effective in the low-velocity regime

$$\beta \ll \alpha_2 \approx 1/30$$

→ resonant effect at

$$m_{\rm DM} = \frac{M_{\rm Z}}{\alpha_2} n^2$$

→ expected to be important for winos

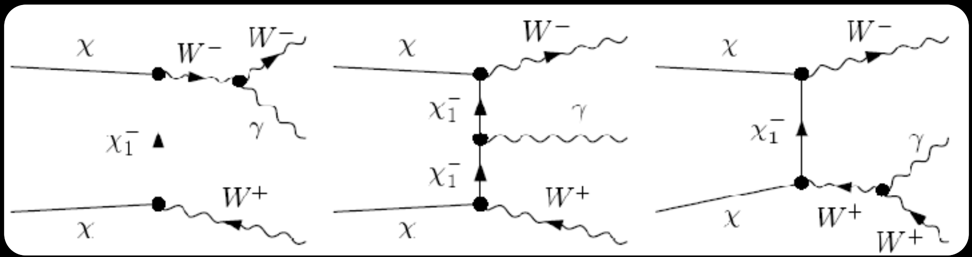


Dark matter annihilation signal

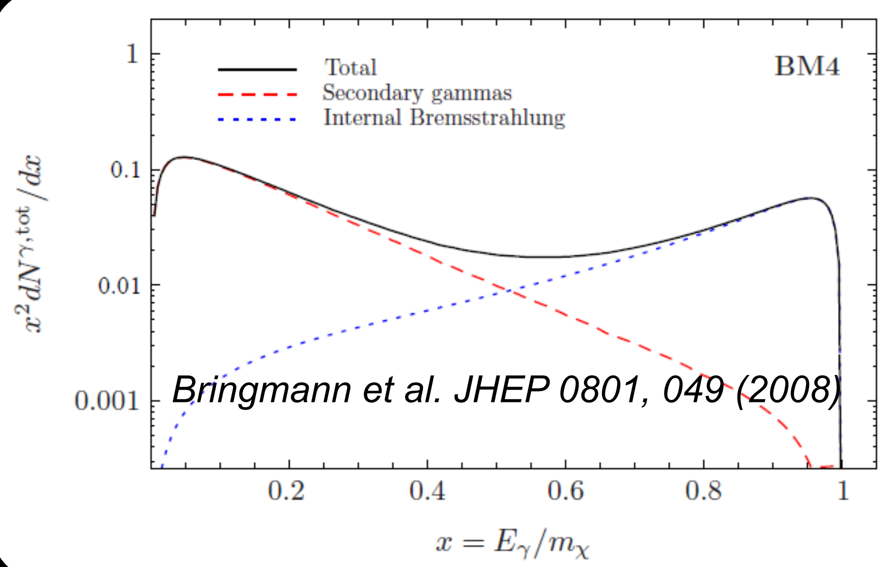
Boost factors

- Particle physics enhancement:
  - Sommerfeld effect (1931)

  - Internal bremsstrahlung when charged particles are present (W^+W^-, $f\bar{f}$, …)



→ may enhance the gamma-ray flux in some specific region of the MSSM parameter space



Bringmann et al. JHEP 0801, 049 (2008)

Dark matter annihilation signal

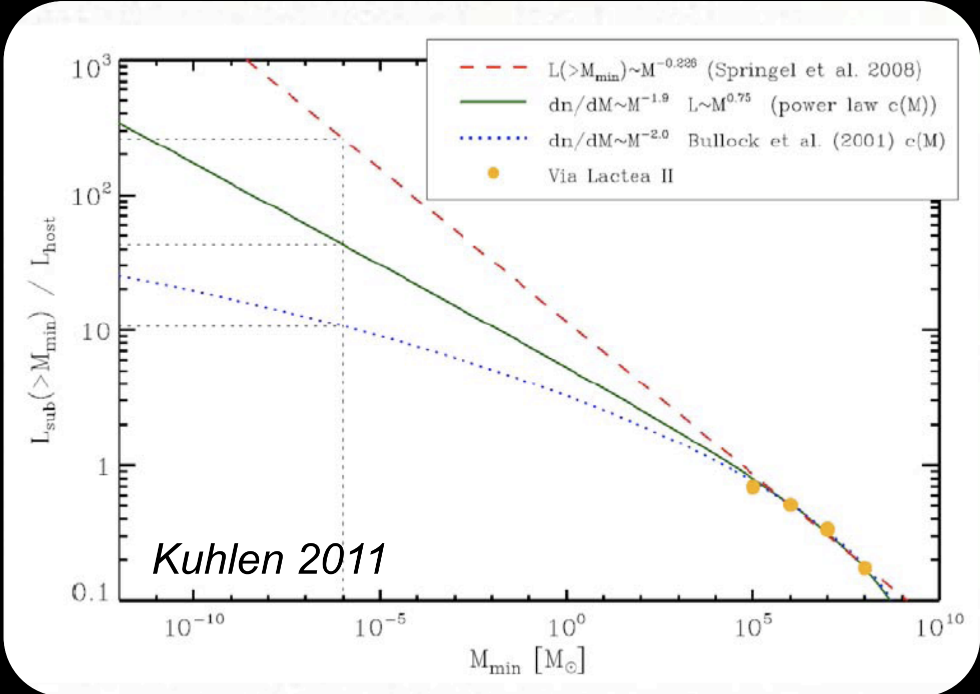
Boost factors

- Particle physics enhancement
  - Sommerfeld effect (1931)
  - Internal bremsstrahlung *Bergström et al. PRL 95, 241301 (2005), Bringmann et al, JHEP*, 01, 049 (2008)

- Astrophysics enhancements

  i.e. substructures in the host halo as predicted by N-body simulations of CDM

Caveat: depends critically on what one assumes for the concentration-mass relation for subhalos below the simulation resolution limit



Dark matter halo profile

- From ΛCDM N-body simulations

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)}$$

$$\rho_{\rm Einasto}(r) = \rho_s e^{-\frac{2}{\alpha}\left((r/a)^\alpha - 1\right)}$$

- From rotation curves

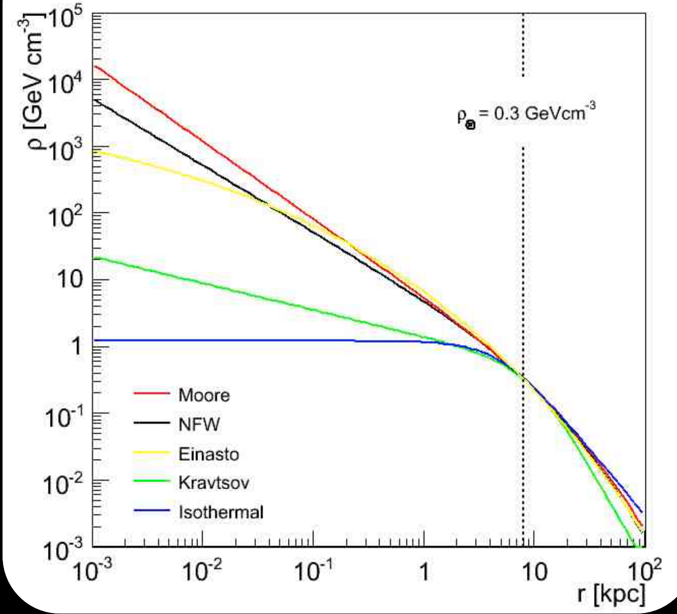
$$\rho_{\rm Buckert}(r) = \frac{\rho_c}{(1+r/r_c)(1+(r/r_c)^2)}$$

$$\rho_{\rm CIS}(r) = \frac{\rho_c}{1+(r/r_c)^2}$$

✓ Via Lactea predicts a cuspier profile: $r^{-1.2}$

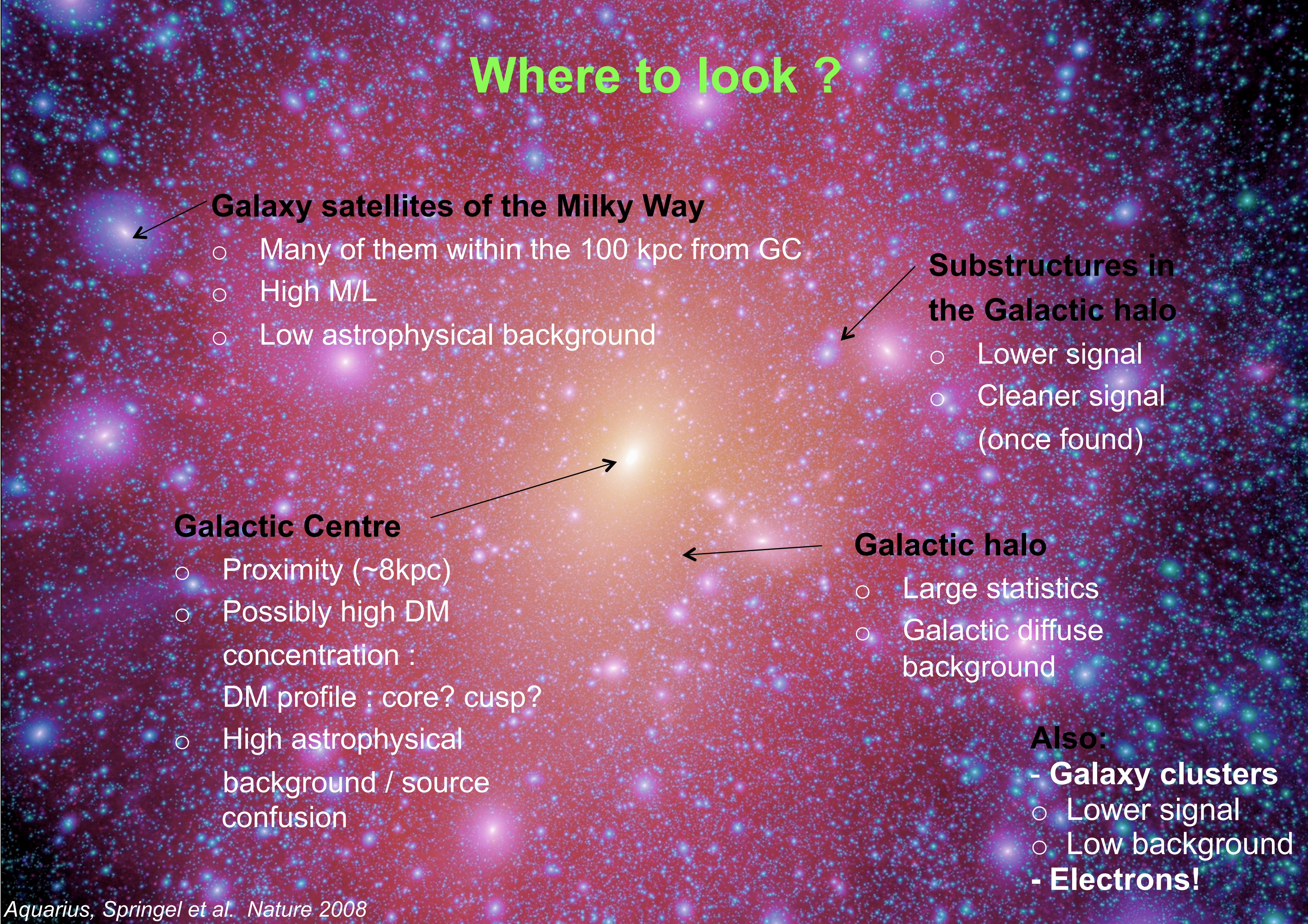
✓ Aquarius predicts a shallower than r^{-1} in the innermost profile

- Situation a bit unclear: effects of baryons?
- The DM density at small scale is poorly known
  → major uncertainty for indirect detection



Caveat: the flux towards the Galactic Center may vary by a factor 10^3 or more…
→ situation much better for dwarf galaxies

Where to look ?



Galaxy satellites of the Milky Way
- Many of them within the 100 kpc from GC
- High M/L
- Low astrophysical background

Substructures in the Galactic halo
- Lower signal
- Cleaner signal (once found)

Galactic Centre
- Proximity (~8kpc)
- Possibly high DM concentration :
  DM profile : core? cusp?
- High astrophysical background / source confusion

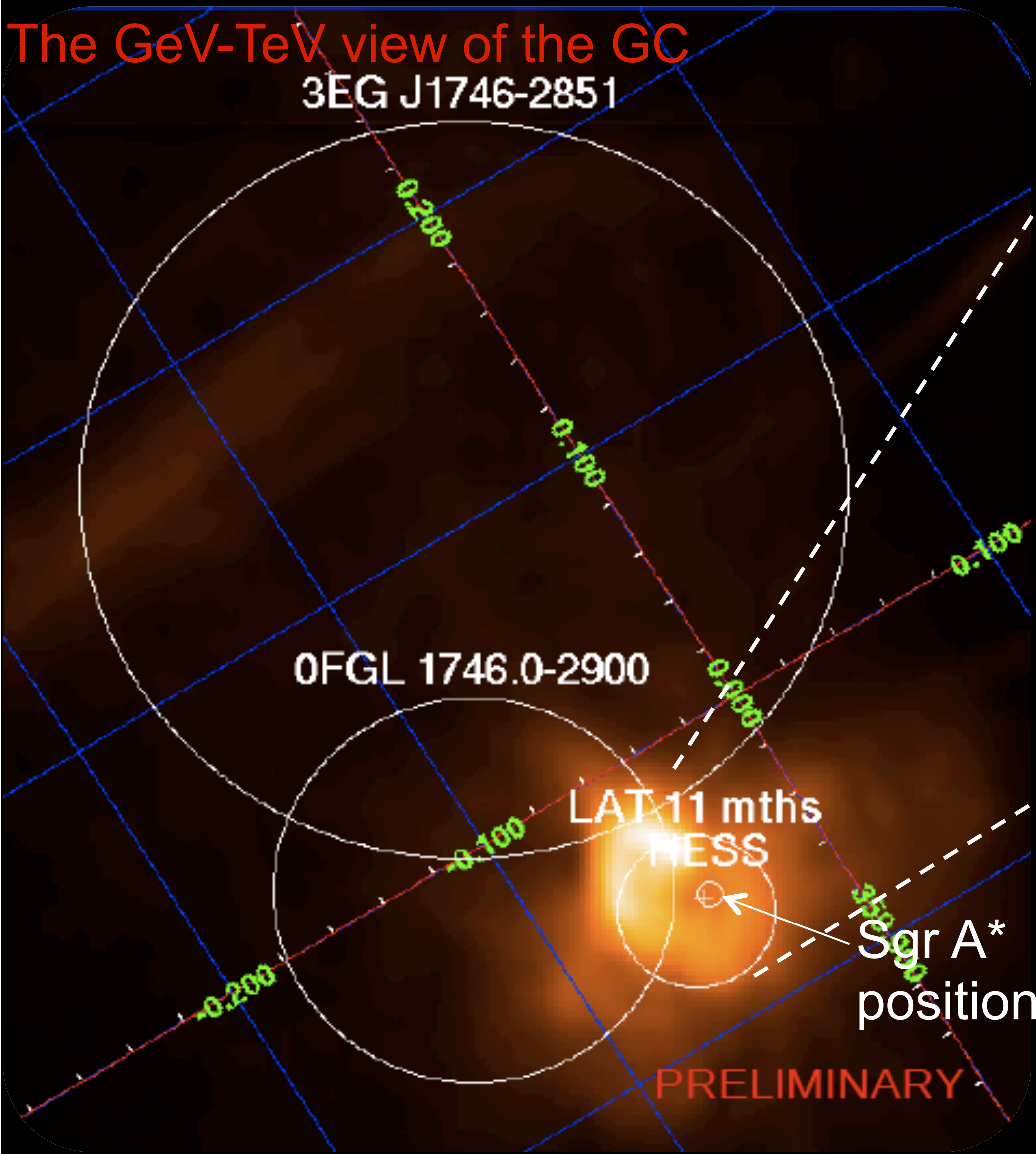
Galactic halo
- Large statistics
- Galactic diffuse background

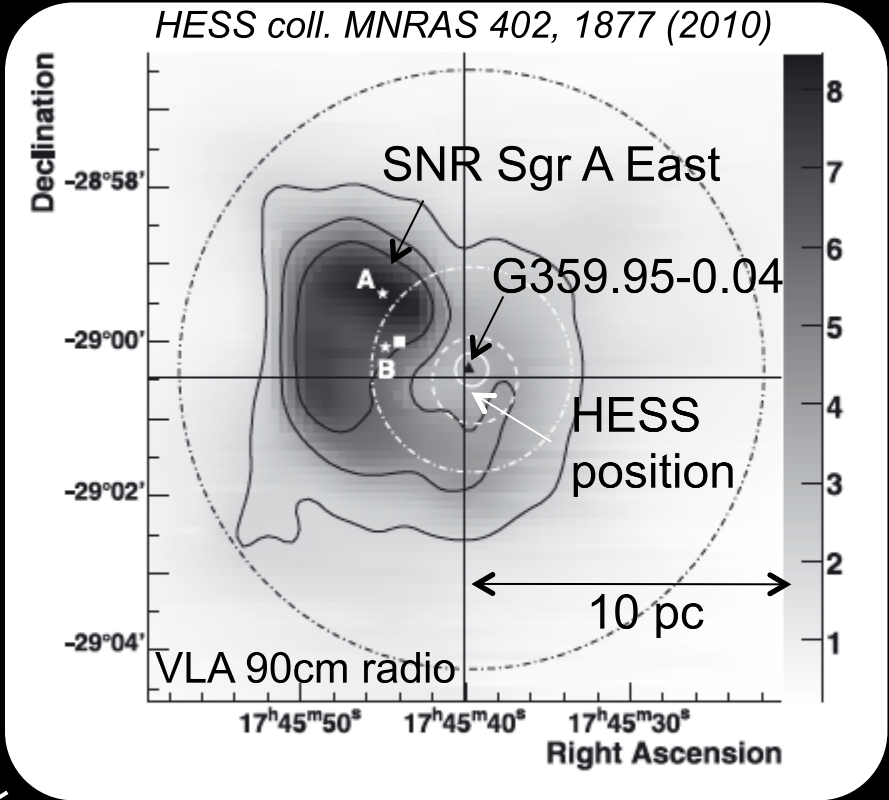
Also:
- Galaxy clusters
- Lower signal
- Low background

- Electrons!

Aquarius, Springel et al. Nature 2008

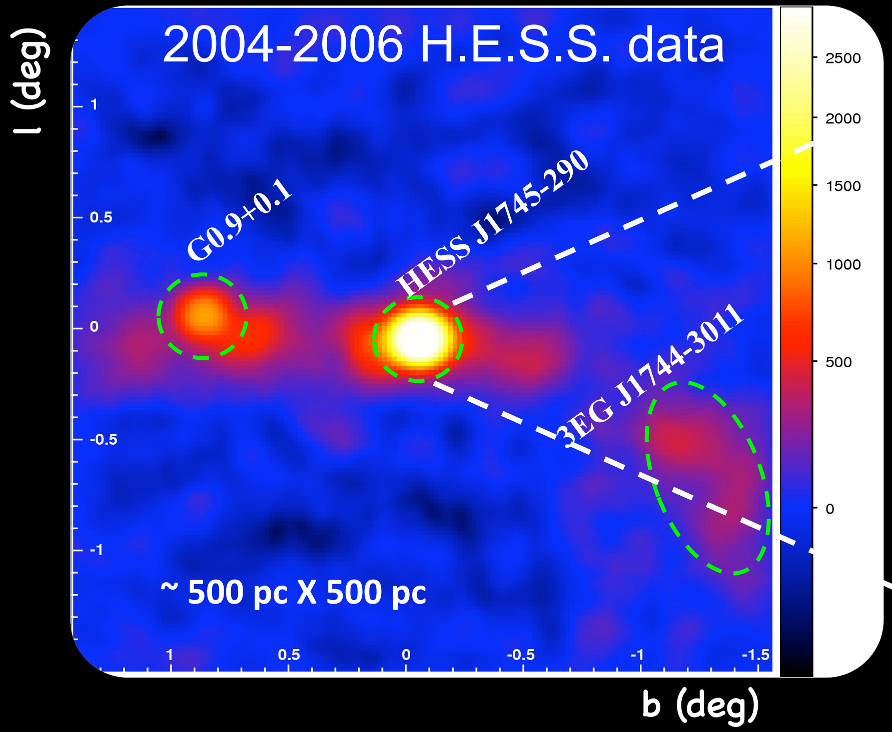
The Galactic Center source: what did we learn?

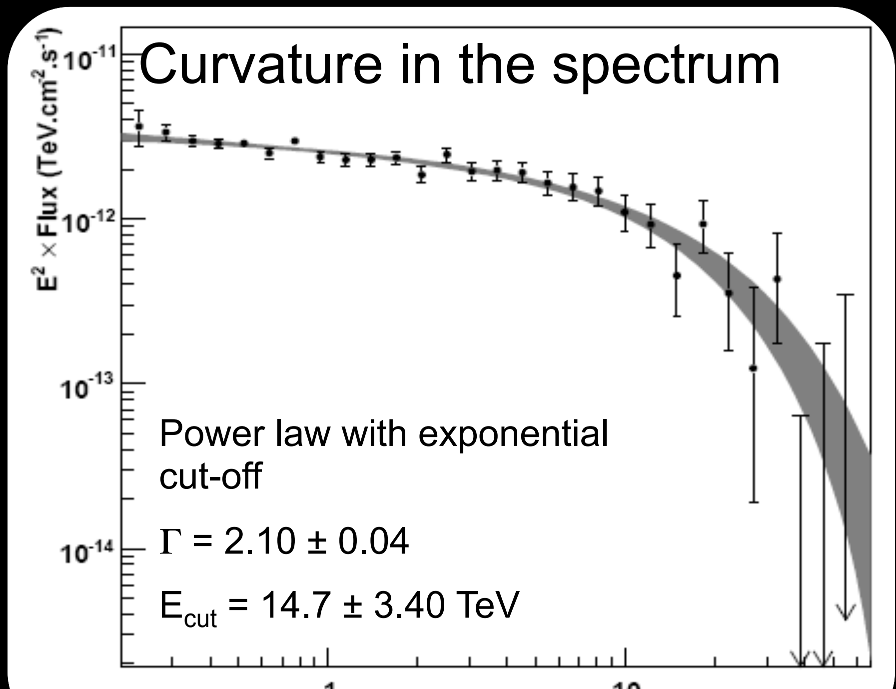




- Bulk of the VHE emission not from Sgr A East
- Both SMBH and PWN are good candidates

The TeV signal from the Galactic Center





HESS coll. A&A 503, 817 (2009)

- strong emission (>10% of Crab >1 TeV)
- point like source
- constant flux: 1 γ/min

A DM contribution is not excluded: estimated to be < 10%

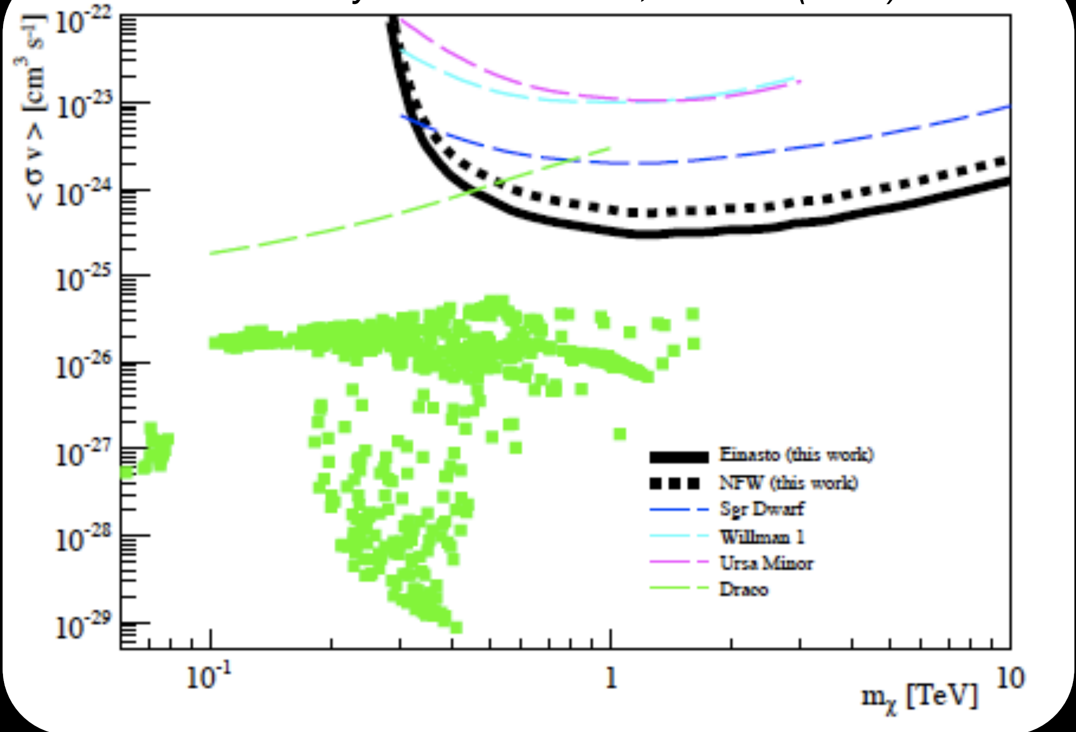
- Most probably, if DM signal exists is overcome by other astrophysical emitters
- Interpretation of DM signal embedded in astrophysical emission is hard

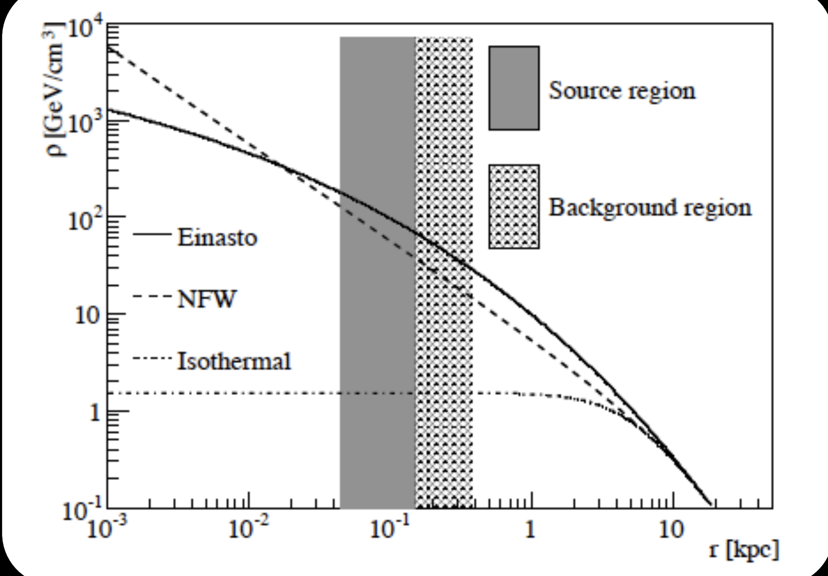
Constraints from the Galactic halo in the TeV range

- Avoid sky regions with strong astrophysical gamma ray signals
- Focus at the same time on regions with an expectedly large DM density

→ Search region : 45-150 pc around GC, Galactic plane excluded

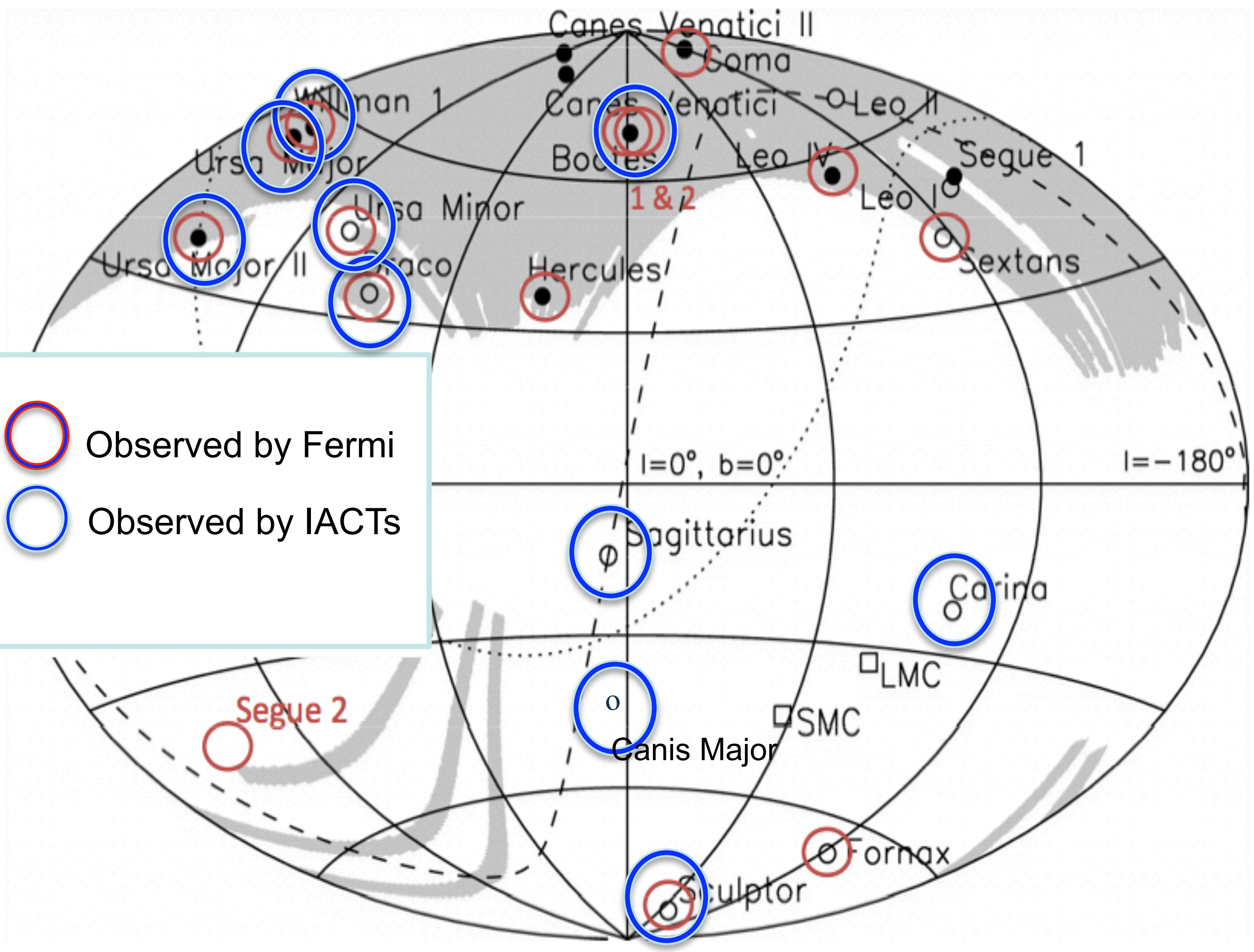
HESS coll. Phys. Rev. Lett. 106, 161301 (2011)





- Among the most sensitive so far at VHE: 3×10^{-25} cm^3 s^{-1} @1 TeV for Einasto profile
- Upper limits are still one order of magnitude too weak

Dwarf galaxy satellites of the Milky Way



Belokurov, V., et al. 2007, ApJ, 654, 897

- Most DM-dominated systems in the Universe
- Very high M/L ratios
- Many of them within 100 kpc from GC
- Expected to be free from astrophysical background

✓ Several dwarf galaxies already observed by IACTs

✓ Fermi observations of high latitude objects

Constraints towards dwarf galaxies

Sagittarius
+ closeby : 24 kpc
- halo modeling uncertain: tidal interaction with MW

Astropart. Phys. 29, 55 (2008)

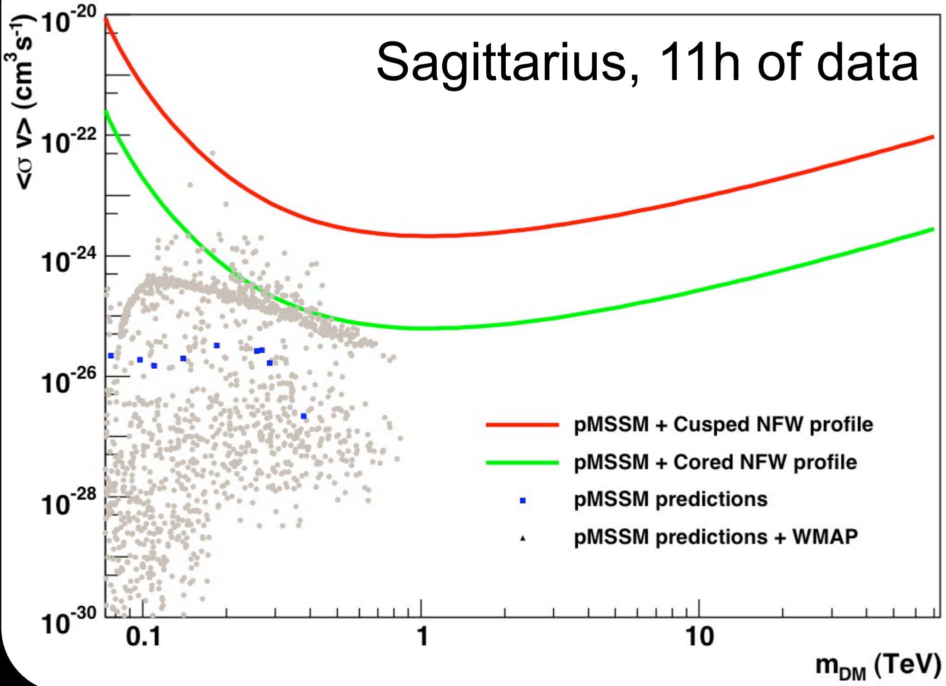
Canis Major
+ closeby : 8 kpc
+ ovedensity environment
- astrophysical nature under debate strong disruption by MW

ApJ 691, 175 (2009)

Sculptor/Carina
+ far from the disk
+ no significant disruption (at least fro Sculptor)
+ large DM halo profile uncertainty coverage
- large distance from the Sun

Astropart. Phys. 34, 608 (2011)

HESS coll. Astropart. Phys. 29, 55 (2008)



- No signal so far only upper limits

  … but start to be very competitive
- Also upper limits from MAGIC and VERITAS on Draco, Ursa Minor, Willman 1, Bootes 1, Segue 1, …
- Complementary limits between Fermi and IACTs

The case for Sculptor

- **Halo modelling** : NFW and core profiles

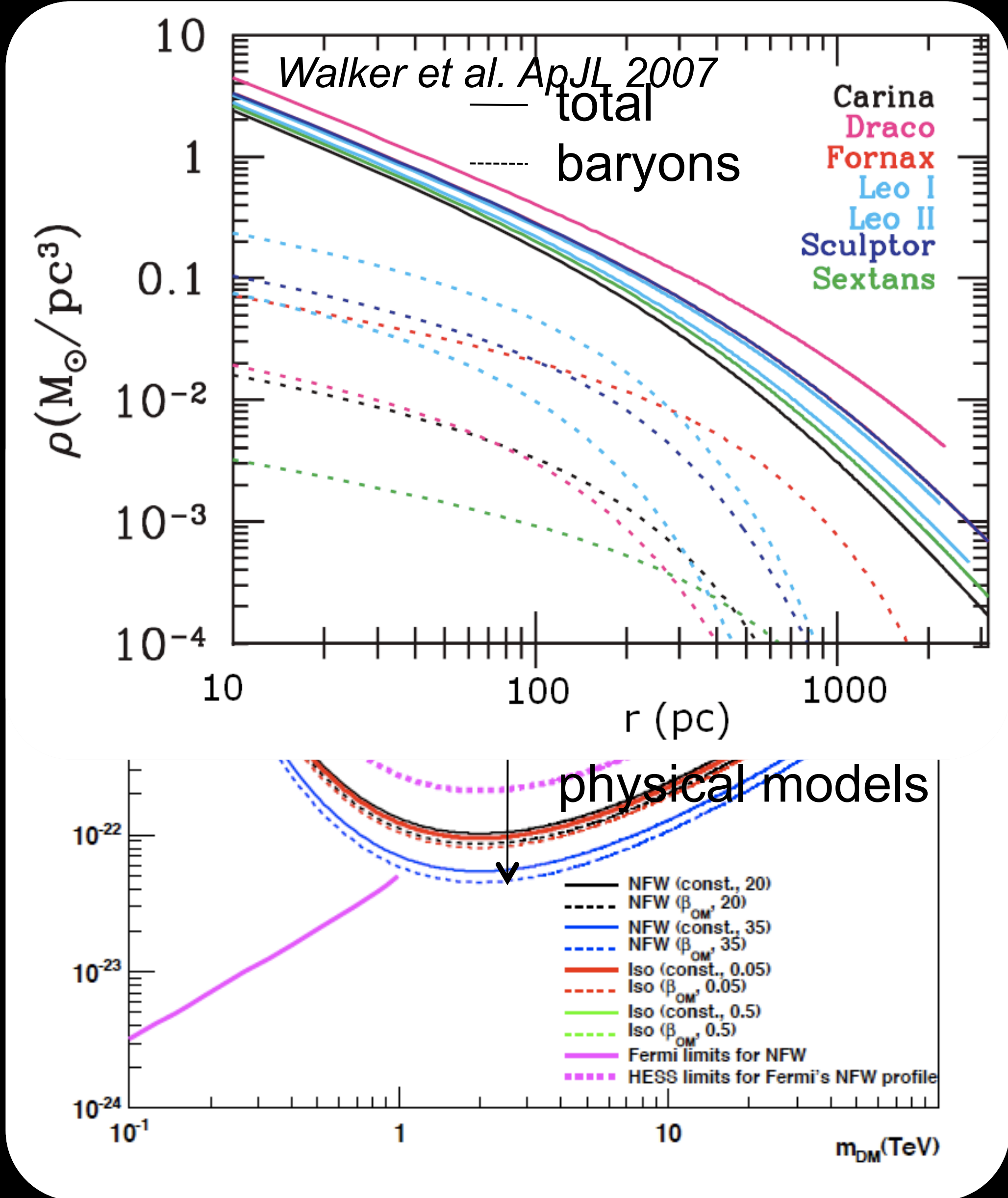
→ models fitted from luminosity profile and velocity dispersion data

Battaglia's thesis, Battaglia et al. ApJ 681, 13 (2008)

- **Exclusion limits**

→ constraints of about 5x10^{-22} cm^{3}s^{-1}

→ about 1 order of magnitude astrophysical uncertainty



The case for Sculptor

- Halo modelling : NFW and core profiles

→ models fitted from luminosity profile and velocity dispersion data

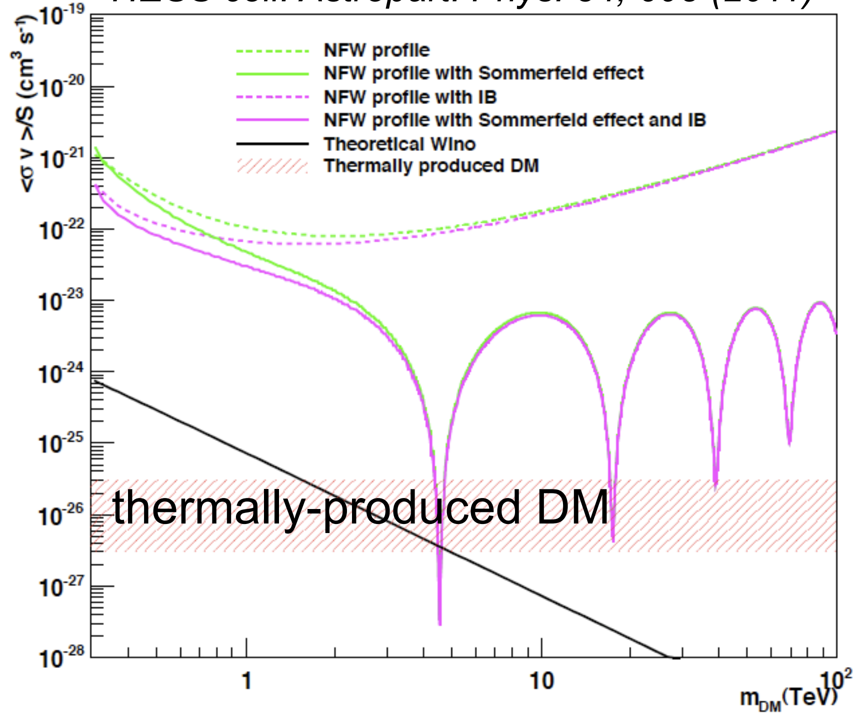
- Exclusion limits: constraints of about 5×10^{-22} $cm^3 s^{-1}$

- Effects of boost factors

  - Sommerfeld effect
    dispersion velocity : 10 kms^{-1}
    → $\beta \sim 2 \times 10^{-5}$

✓ some models can be excluded due the resonant effect
✓ outside resonances, a factor 10 to 100 improvement in the TeV range

HESS coll. Astropart. Phys. 34, 608 (2011)



The case for Sculptor

- Halo modelling : NFW and core profiles

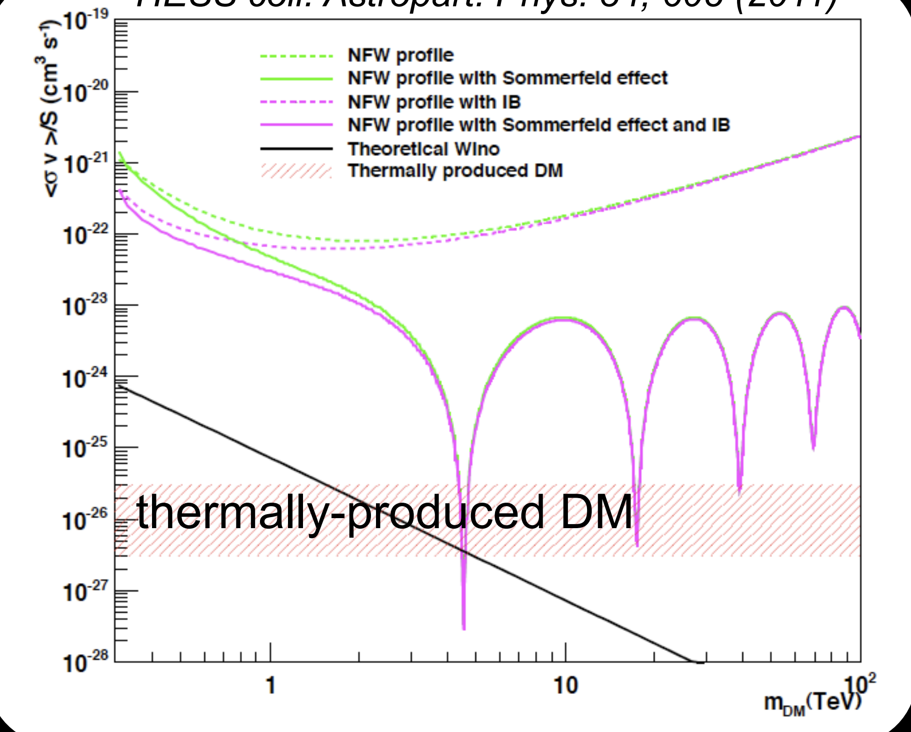
→ models fitted from luminosity profile and velocity dispersion data

- Exclusion limits: constraints of about 5×10^{-22} cm^3s^{-1}

- Effects of boost factors
  - Sommerfeld effect
  - Substructures enhancement:

  → a few percent for pointlike searches

HESS coll. Astropart. Phys. 34, 608 (2011)



Are globular clusters better targets than dwarfs?

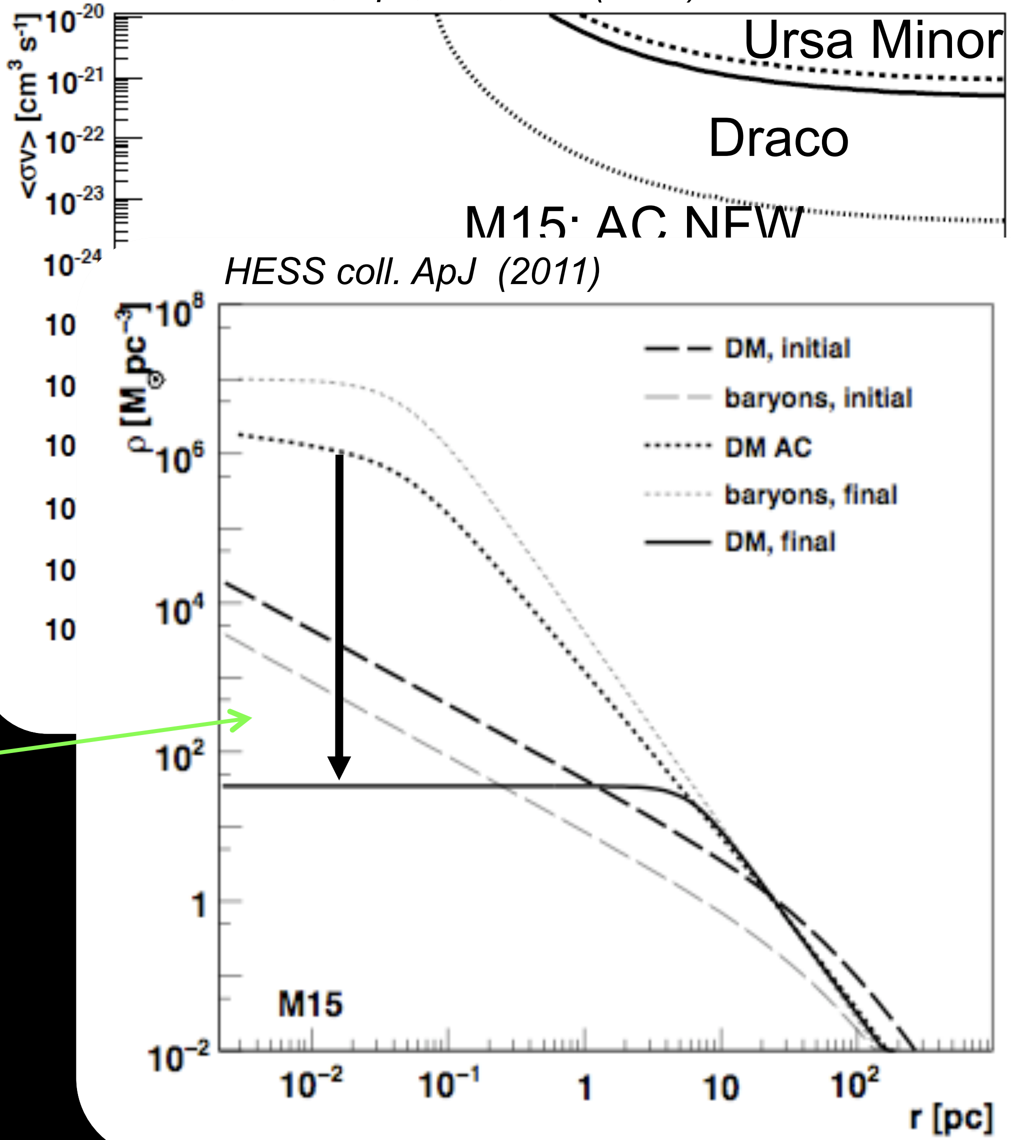
- Whipple sinlge dish ø 10m, 1.2 hr
  → limits quite constraining on M15

- HESS observations: 15 hr
  - ✓ halo modelling:
    - initial NFW profile
    - adiabatic contraction by baryons
    - heating of DM by stars in the core

    → depletion of DM in a few relation times

Wood, et al., ApJ, 678, 594 (2008)

HESS coll. ApJ (2011)

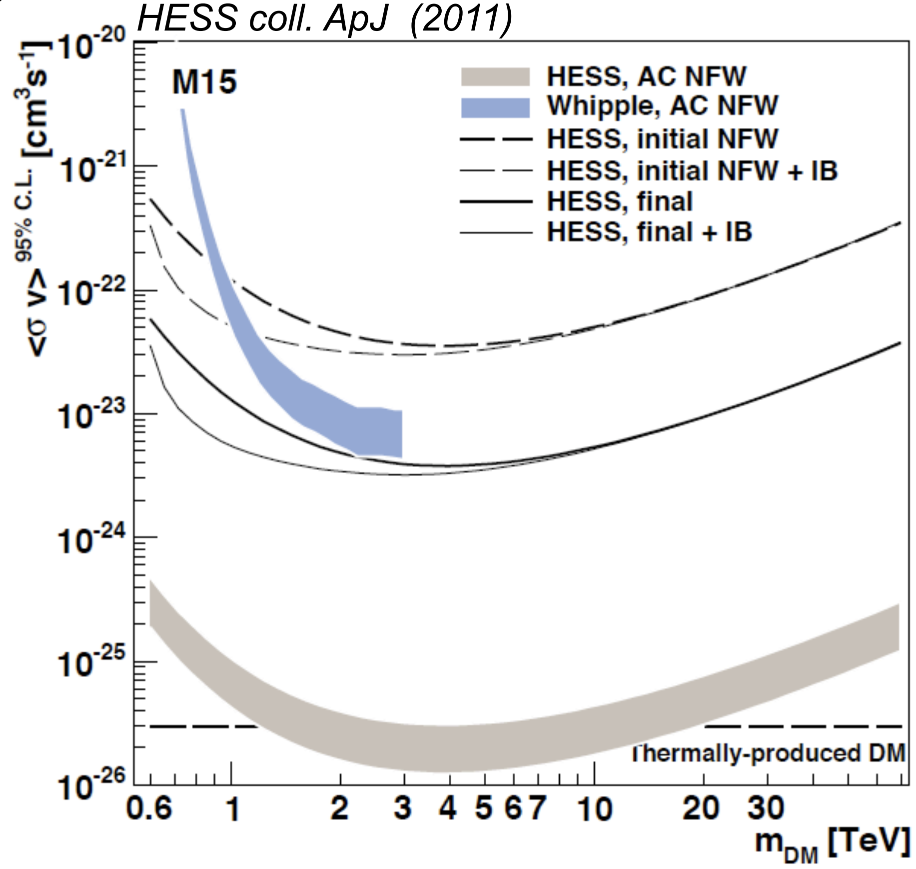


Are globular clusters better targets than dwarfs?

- Whipple, single dish ø 10m, 1.2 hr
  → limits quite constraining on M15… optimistic halo from DM adiabatic contraction

- HESS observations: 15 hr
  - ✓ halo modelling
  - ✓ exclusion limits
    at the level of 10^{-23} cm^3s^{-1}

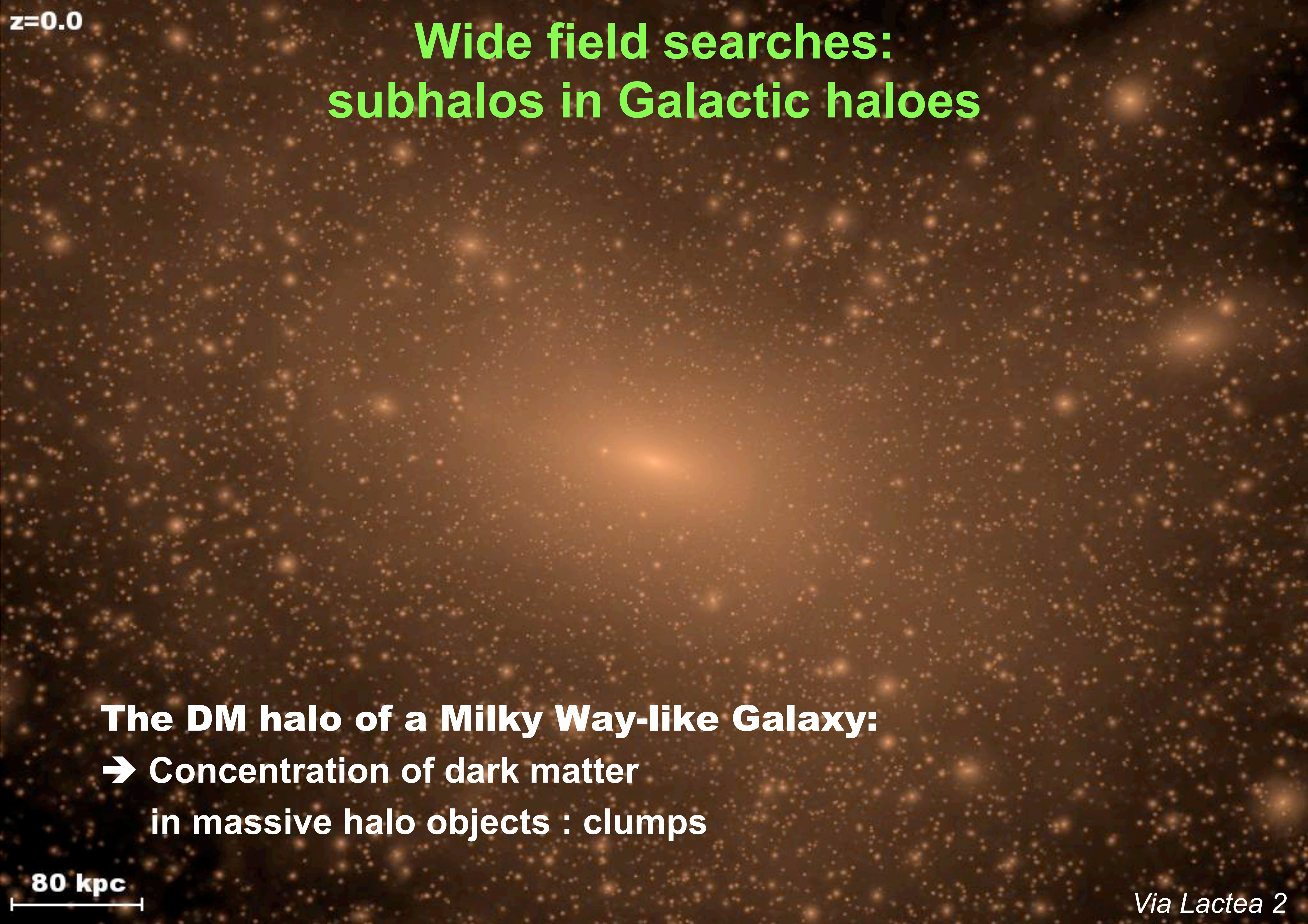
Caveat: limits assume GC to be formed in DM minihalos
→ no consensus on the GC formation scenario yet



Wide field searches: subhalos in Galactic haloes

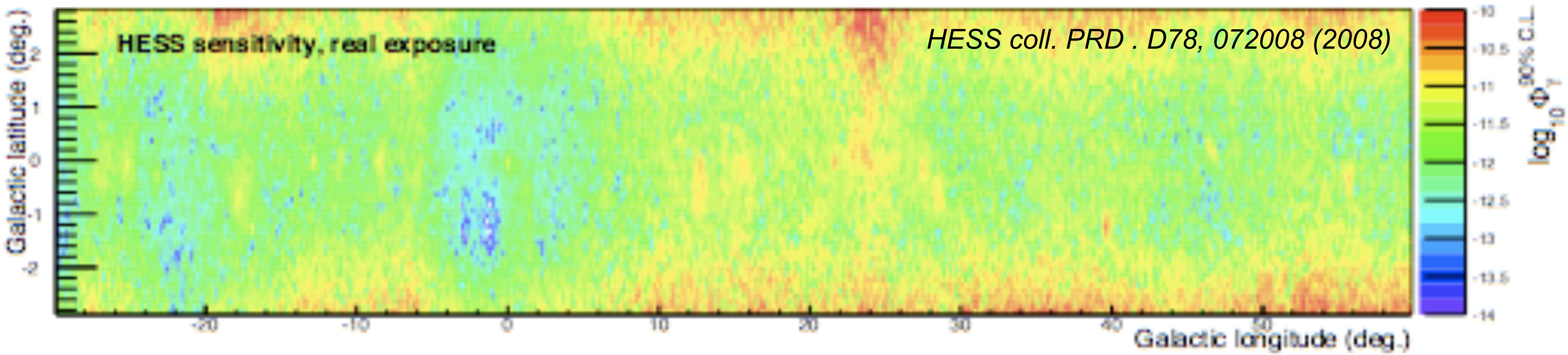
The DM halo of a Milky Way-like Galaxy:

➔ Concentration of dark matter
in massive halo objects : clumps



Search for DM clumps in the Galactic halo

- Requires large field of view since the position is not known *a priori*
  …not well suited for IACTs
- However make use of the HESS Galactic plane survey data!
  largest field of view for IACTs



- No DM clump so far in HESS data!

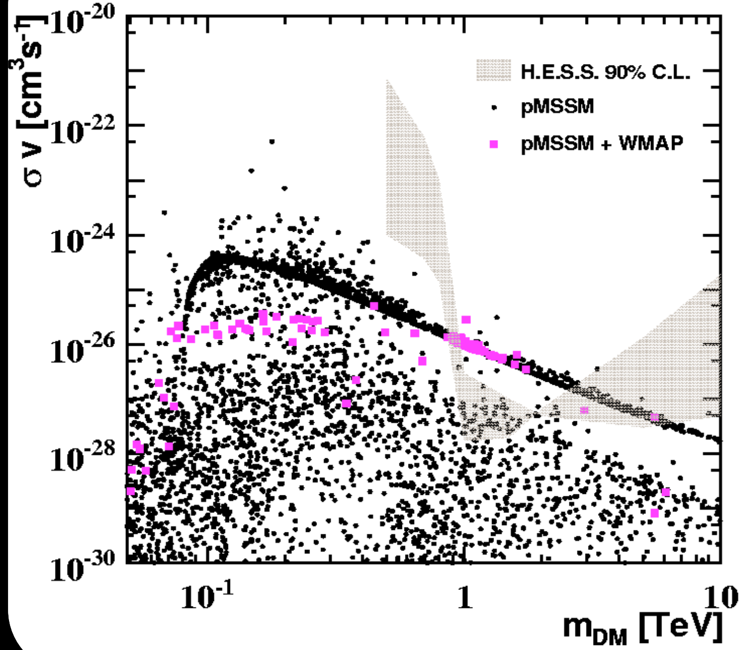
Search for DM clumps in the Galactic halo

- Requires large field of view since the position is not known *a priori*
  …not well suited for IACTs
  However make use of the HESS Galactic plane survey data!
- No clump candidate within HESS data so far

- Constraints on the IMBH scenario
  - ~100 IMBHs de ~10^5 $M_\odot$ in the Galactic halo *Koushiappas, 2004*
  - accumulation of DM around these objects
  Bertone, Zentner, Silk PRD 72, 103517 (2005)

→ contraints on the entire gamma-ray production scenario around IMBHs

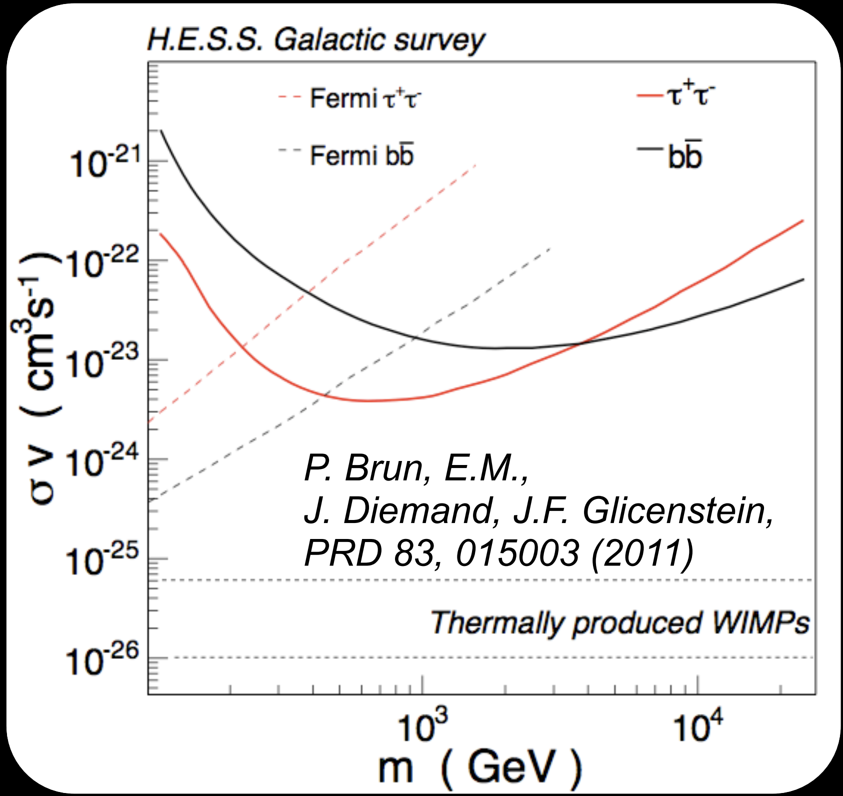
HESS coll. PRD78, 072008 (2008)



Search for DM clumps in the Galactic halo

- Requires large field of view since the position is not known *a priori*
  …not well suited for IACTs
  however make use of the HESS Galactic plane survey data!
- No clump candidate within HESS data so far
- Strong constraints on IMBH scenario
- Constraints on subhalos from
  Via Lactea II simulation

→ Widely accepted formation scenario
→ Competitive limits wrt dSph limits
→ Results complementary to Fermi ones



Search for Lorentz invariance violation

- Lorentz invariance : fundamental symmetry at high energy

- Strong theoretical interest for possible high energy violation of LI:
absence of LIV $\rightarrow$ discard models which predict LIV phenomena

- Energy dependence of the dispersion relation of photons
$\rightarrow$ Search for photon energy dependent time lag

Modified dispersion relation for unpolarized photons of energy E and momentum p:

$$c^2p^2 = E^2\left(1 + \xi\frac{E}{E_p} + \zeta\left(\frac{E}{E_p}\right)^2 + ...\right)$$

Detect LIV is a measure of ξ, ζ

Search for Lorentz invariance violation

- Astrophysical experiments with photons
  - space mission: SWIFT, Fermi from GRBs, AGNs
  - ground-based: IACTs from AGN flares

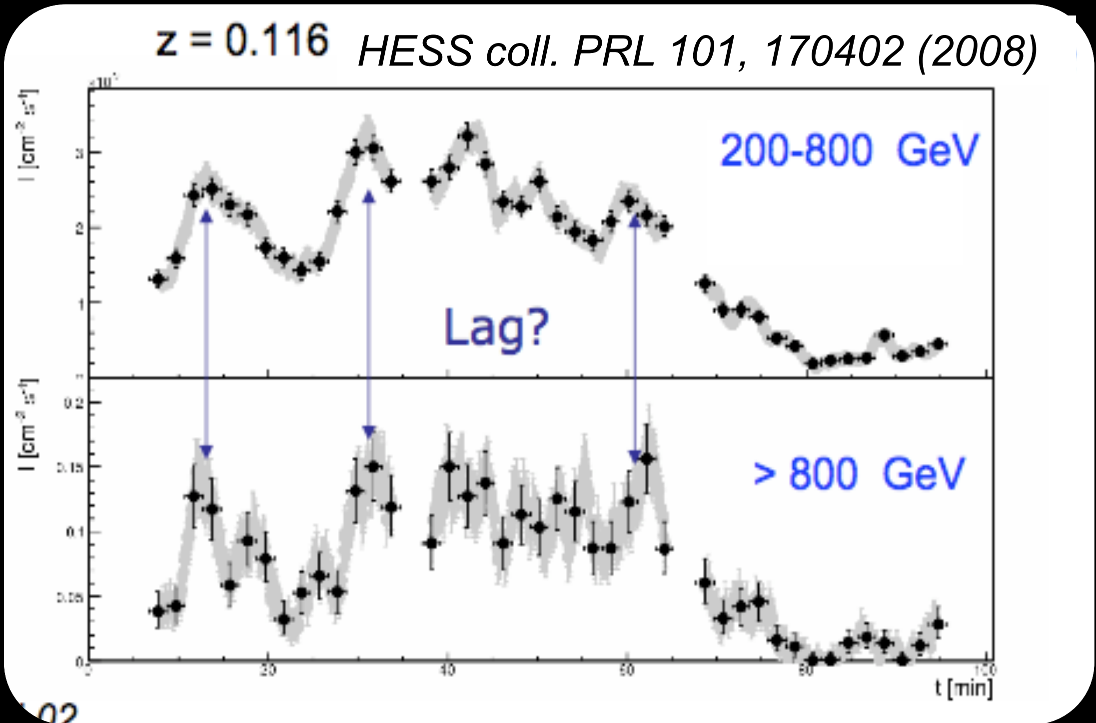
- Which targets for dispersion measurements with IACTs?

  → AGN are well suited *(Amelino-Camelia et al., Nature 395, 1998)*

    - transient sources
    - bright
    - at cosmological distances
    - wide energy range emission (0.1 MeV–TeV)

HESS - PKS2155-304 big flare

- Exceptional flare in 2006: 7 x CRAB flux *HESS Coll., ApJ 664, L71 (2007)*
  - statistics after cuts ~ 10000 photons in 1.5 hrs
  - light curve presents several well resolved bursts described by fast rise and slow decay
  - energy spectrum: broken power-law : no strong indication of spectral variability

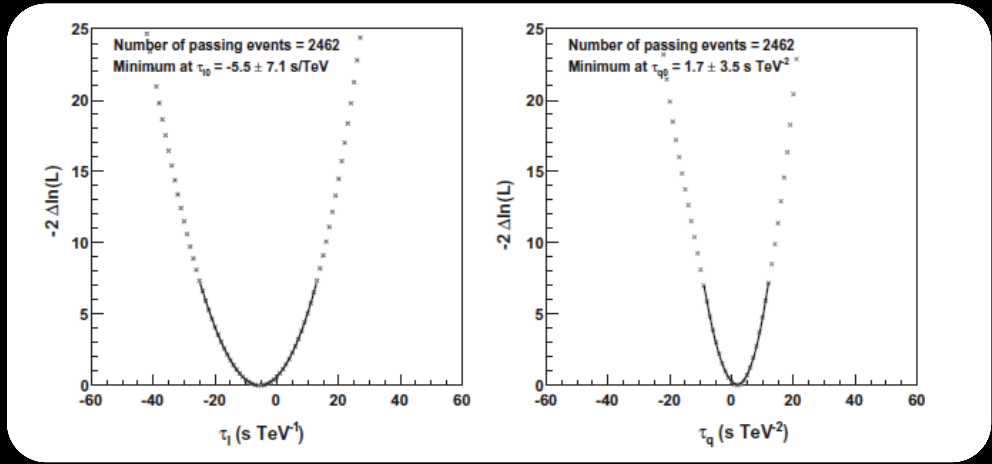


→ Find a time-lag with light curves in 2 different energy ranges

→ $\xi^{-1}E_p > 0.7 \times 10^{18}$ GeV at 95% CL

HESS constraints with likelihood method

- Event-by-event Likelihood fit with a template (model) light curve
- Maximization of likelihood for the linear and quadratic cases



No significant time-lag detected in PKS2155-304 big flare data > 2σ in Δt

- Linear term: $E > 2.1 \times 10^{18}$ GeV (95% CL)
- Quadratic term: $E > 0.6 \times 10^{11}$ GeV (95% CL)

HESS coll. Astropart. Phys. 34, 738 (2011)

- Best constraints with AGNs
- Need a factor of ~5 to probe the Planck energy scale
- Fermi GBM + LAT from GRB 090510 with the detection of a 31 GeV photon

  → $E >$ several E_p (95% CL)

Summary

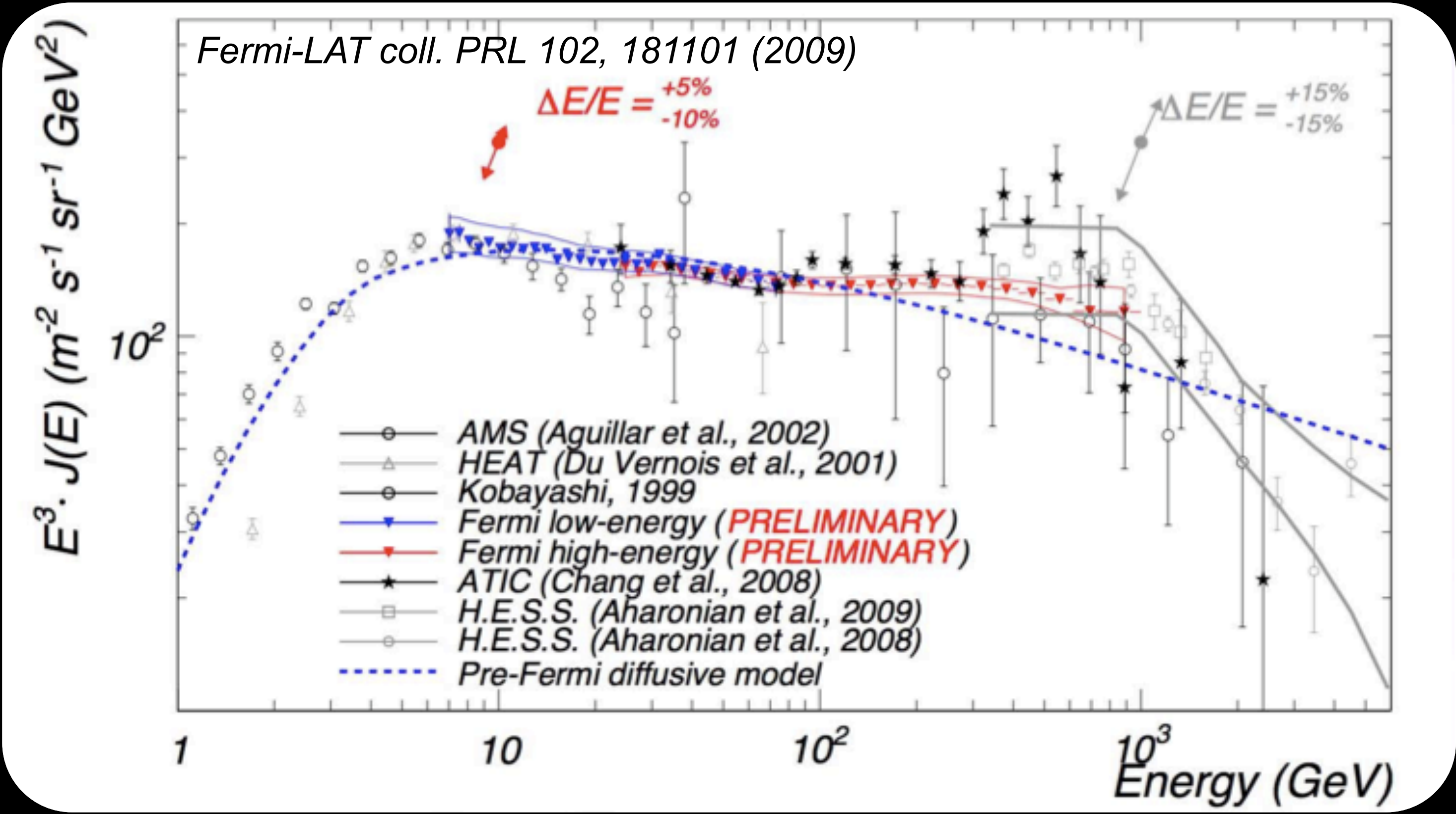
Dark Matter searches :

- Galactic Center : signal dominated by standard astrophysical emitters
- Most promising DM targets are likely to be :
  - Galactic halo
  - dwarf satellite galaxies
  - substructures in Galactic halo
- DM detection may be just “around the corner”
  - no signal so far
  - indirect detection experiments start to probe realistic parameter space of WIMP models

Lorentz Invariance Violation studies:

- Most promising targets with IACTs are flaring AGN
- Strongest constraints from time-of-flight measurements on PKS2155-304 flare

Cosmic ray electron spectrum



- Prominent peak seen by ATIC (Nature, 2008) excluded by Fermi/HESS
- Fermi-LAT sees an excess
- Fermi and Pamela excess can be simultaneously fitted

→ DM annihilation interpretation plausible :
- requires DM annihilating preferentially into *leptons* to avoid an overproduction of antiprotons
- large boost factor required $O(10^3)$

[Bergstrom et al. PRL 103, 031103 (2009)]

→ More prosaic explanation is local e^+e^- sources : nearby pulsars, SNRs

Bushing et al 2008, Hooper et al. 2008, Profumo 2008, Blasi PRL 103, 051104 (2009), …
[Not a new idea : Boulares ApJ 342, 807 (1989), Atoyan et al. PRD 52, 3265 (1995)]