Indirect dark matter searches with H.E.S.S.

Emmanuel Moulin
CEA Saclay

ILP Thematic Day on Dark Matter
June 19, 2014

Weakly interacting Massive Particles (WIMPs)

- Weakly interaction mass scale and standard gauge couplings give the right relic dark matter density
- Masses of O(GeV) to O(TeV) make them cold dark matter

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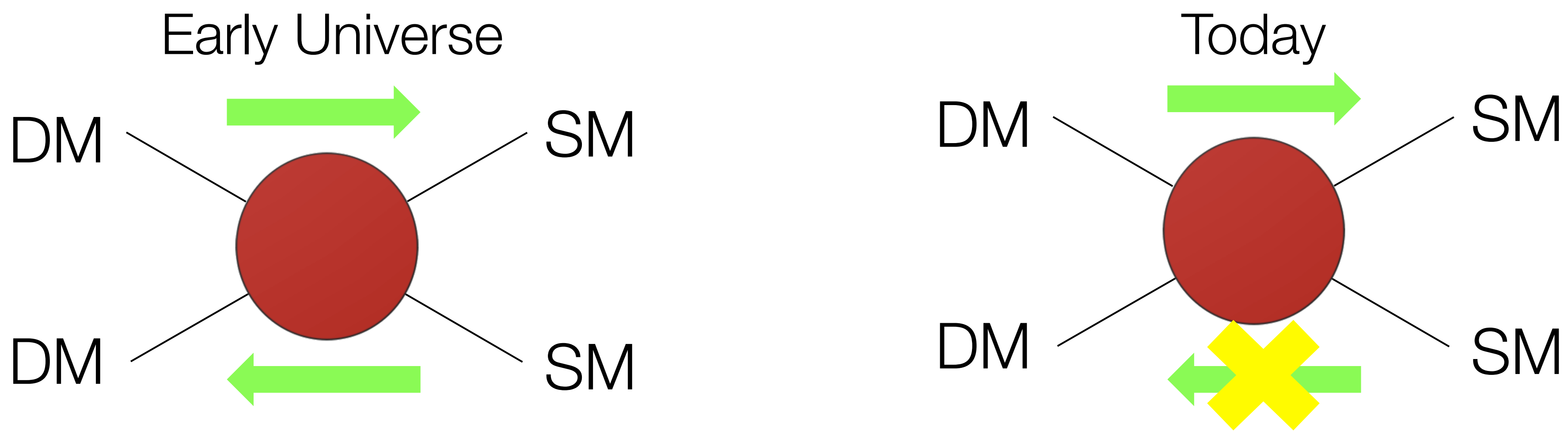

$$\Omega_{\mathrm{W}} \approx \frac{10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle_{\mathrm{W}} \sim \frac{\alpha^2}{m_{\mathrm{W}}^2} \sim 10^{-25}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

Provide a benchmark annihilation cross section for indirect detection!

Dark matter annihilation flux

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

Particle Physics :
- Cross sections
- Differential photon yield
- DM particle mass

Astrophysics

→ modelling required for the DM distribution in the object

Dark matter annihilation flux

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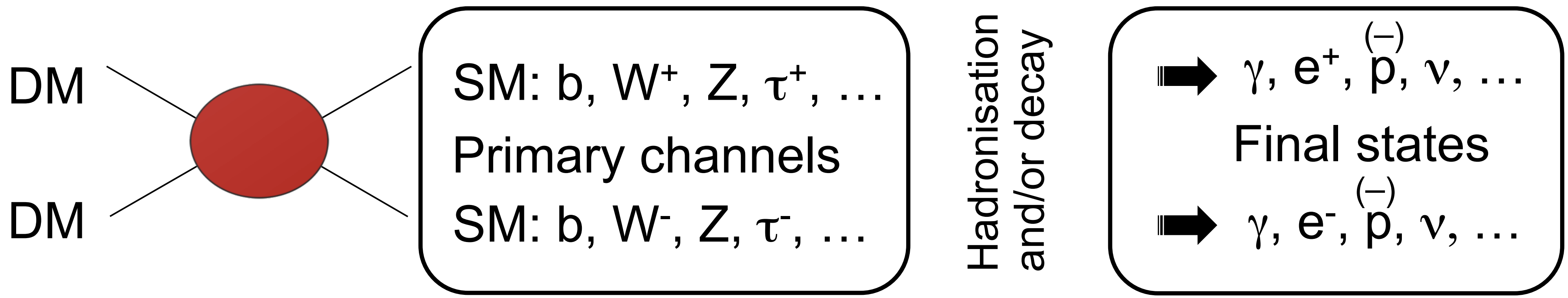
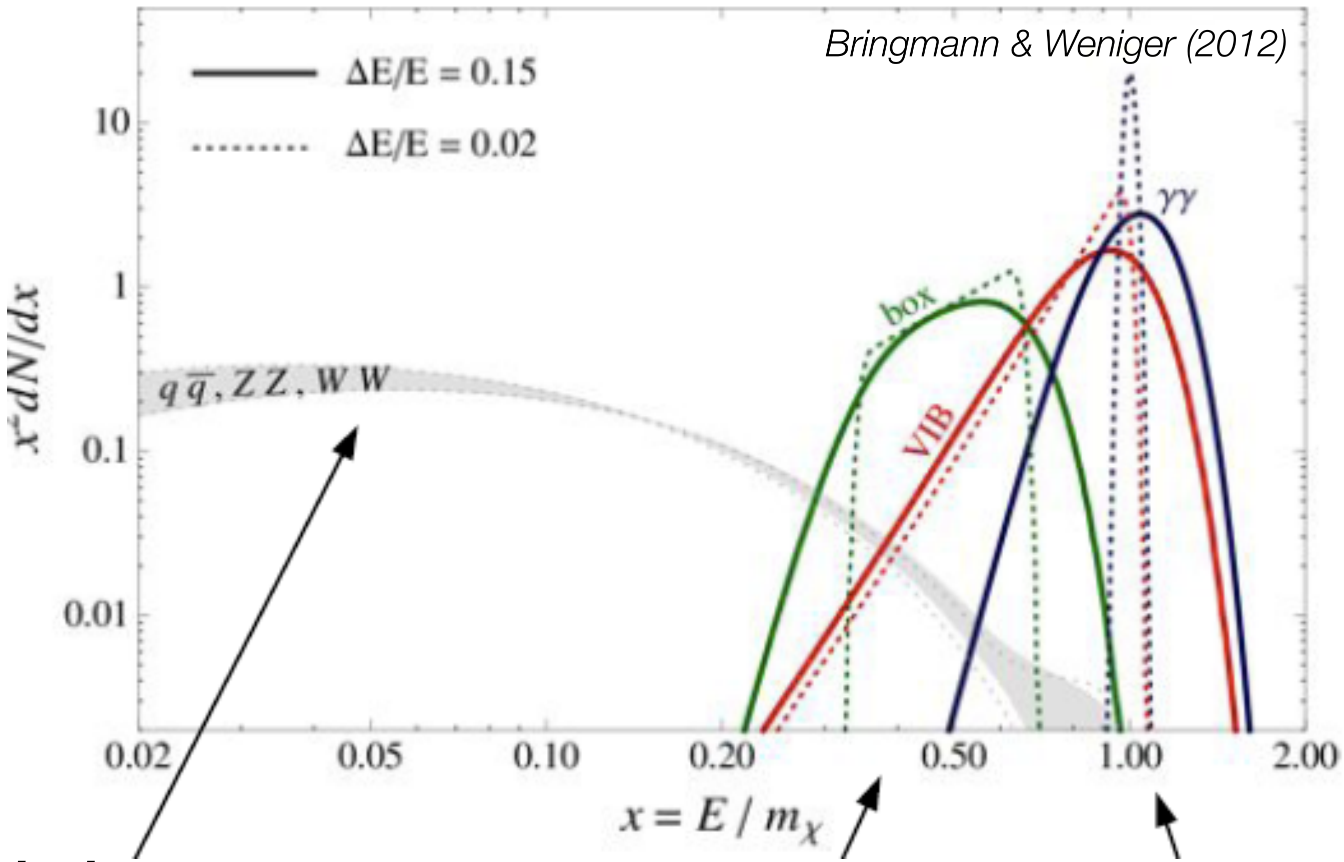


Spectral signatures



Continuum emission
("Secondary photons")
→ from fragmentation of quarks/massive gauge bosons (via π_0 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)

Dark matter signals : additional contributions

- Particle physics enhancements
- Sommerfeld effect (1931)

→ particularly effective in the low-velocity regime

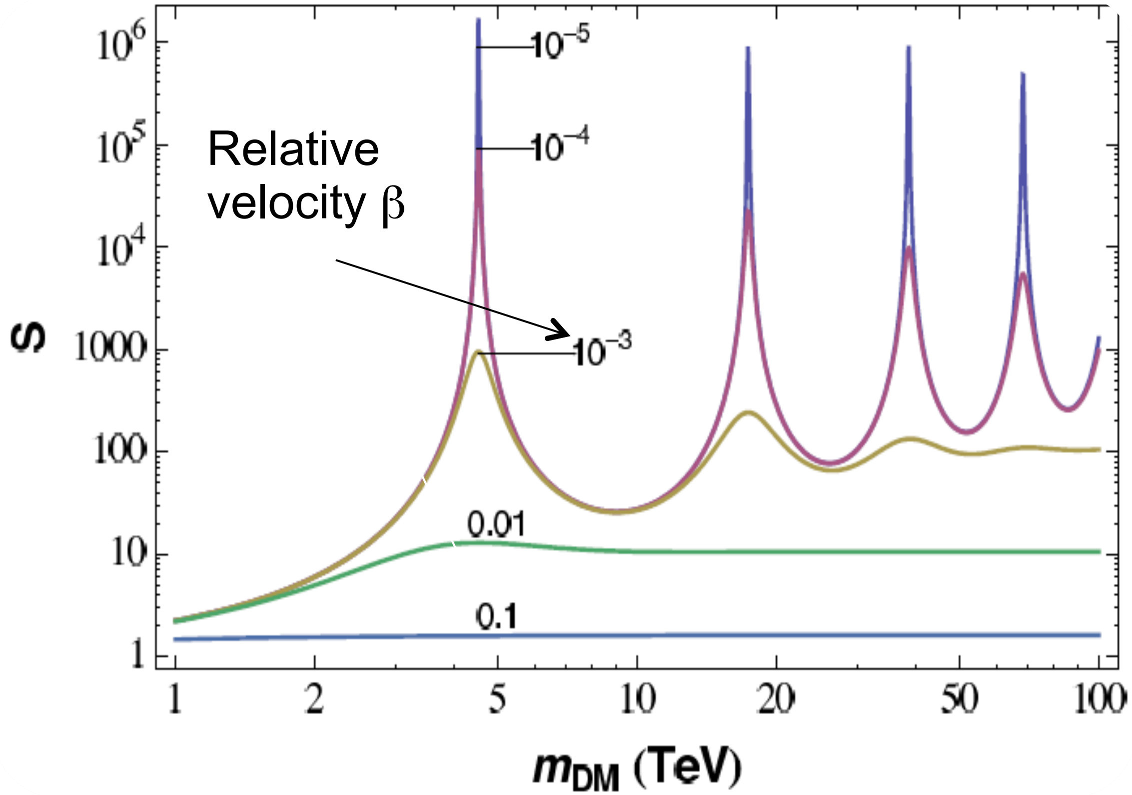
$$\beta \ll \alpha_2 \approx 1/30$$

→ resonant effect at

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

→ expected to be important for winos

Lattanzi & Silk PRD79, 083523 (2009)

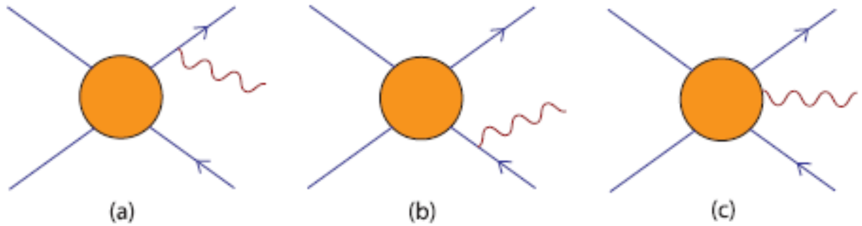


Huge enhancement, TeV DM masses required

Dark matter signals : additional contributions

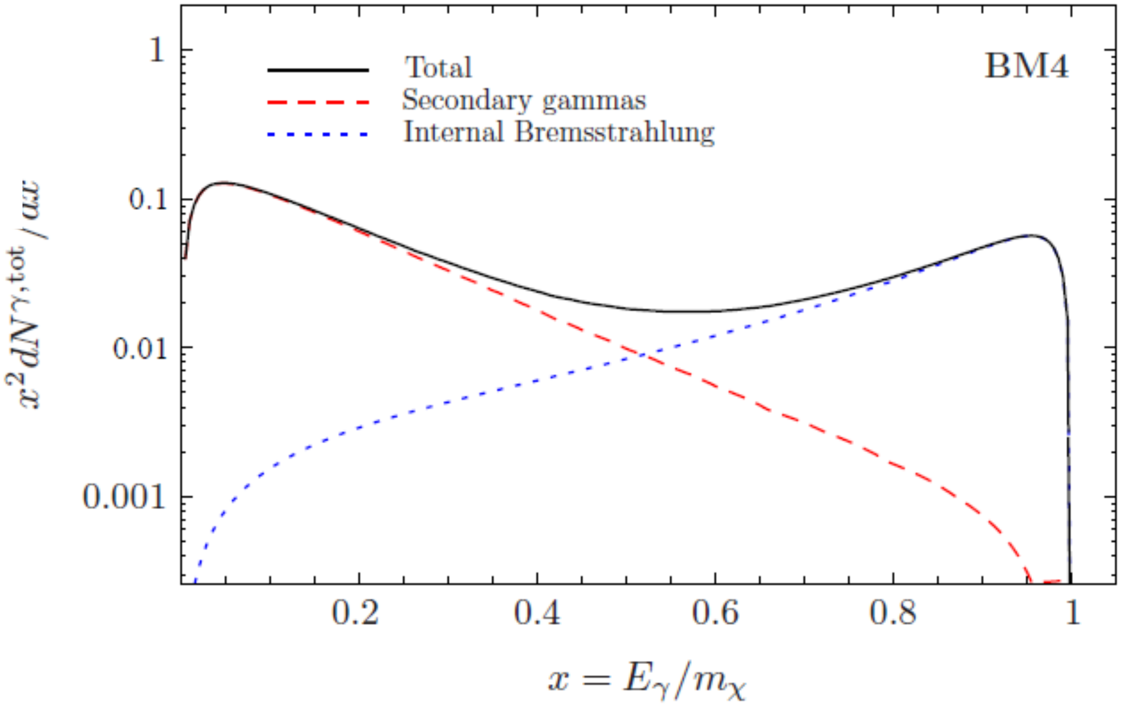
- Particle physics enhancements
- – Sommerfeld effect (1931)

- – 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

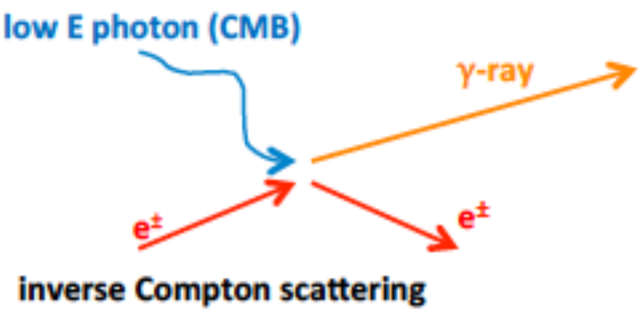
Bringmann et al, JHEP, 01, 049 (2008)

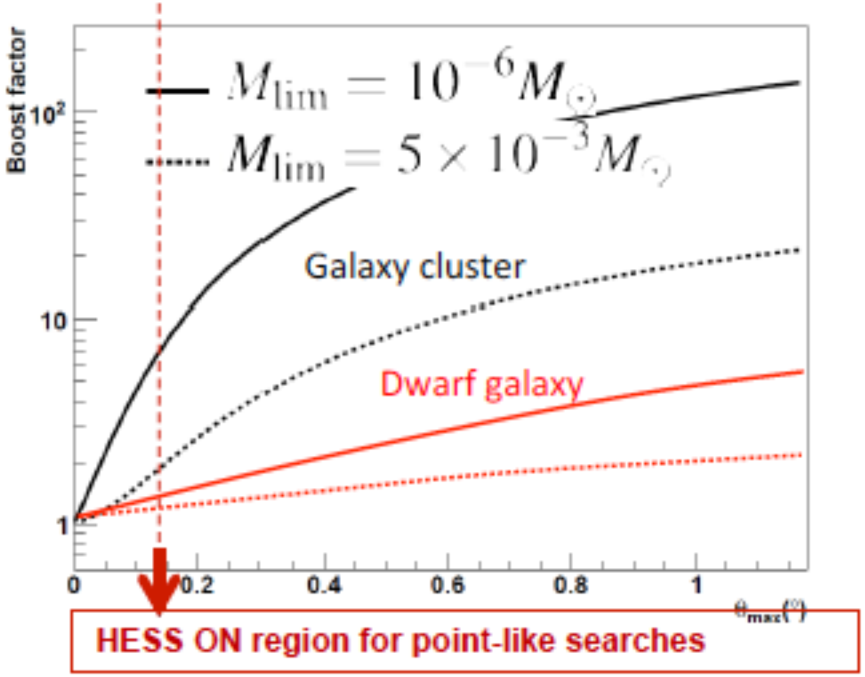


Dark matter signals : additional contributions

- Particle physics enhancements
  - Sommerfeld effect (1931)
  - Internal bremsstrahlung *Bergström et al. PRL 95, 241301 (2005)*

- Astrophysics enhancements
  - Substructures (suhhalos) in the host halo as predicted by N-body simulations of CDM
  - Inverse Compton scattering on CMB





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

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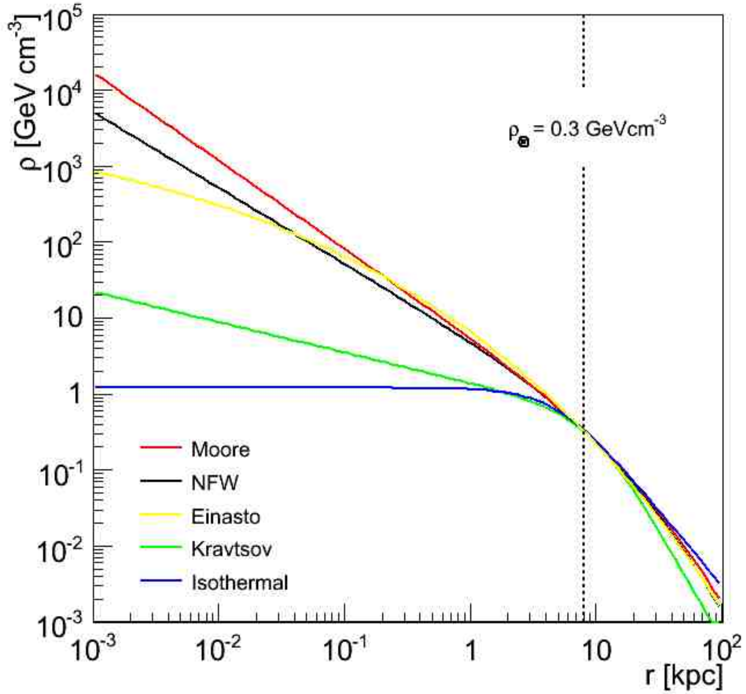
✓ Aquarius predicts a shallower than r^{-1} in the innermost profile

- Situation a bit unclear: effects of baryons?

- The DM density at small scale is poorly known → need to take into account both class of models



High Energy Stereoscopic System (H.E.S.S.) Phase 1 : 2003 -2012

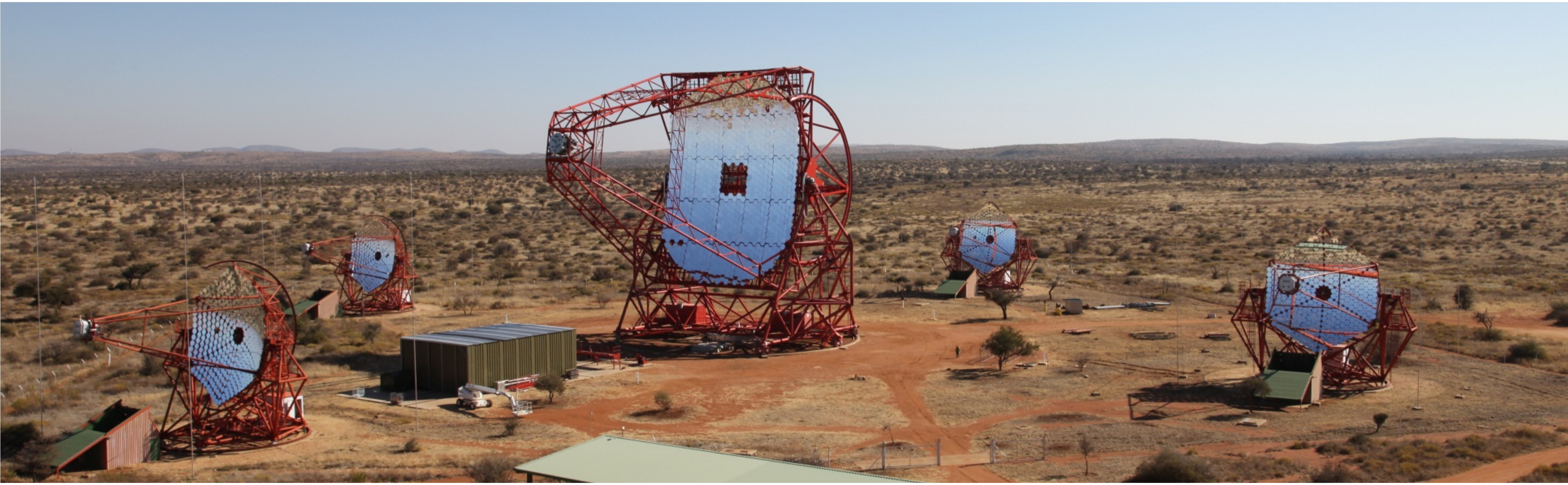
Array of four Imaging Atmospheric Cherenkov Telescopes located in Namibia (1800 m a.s.l.)

- 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

High Energy Stereoscopic System (H.E.S.S.) Phase 2 : first light on July 2012

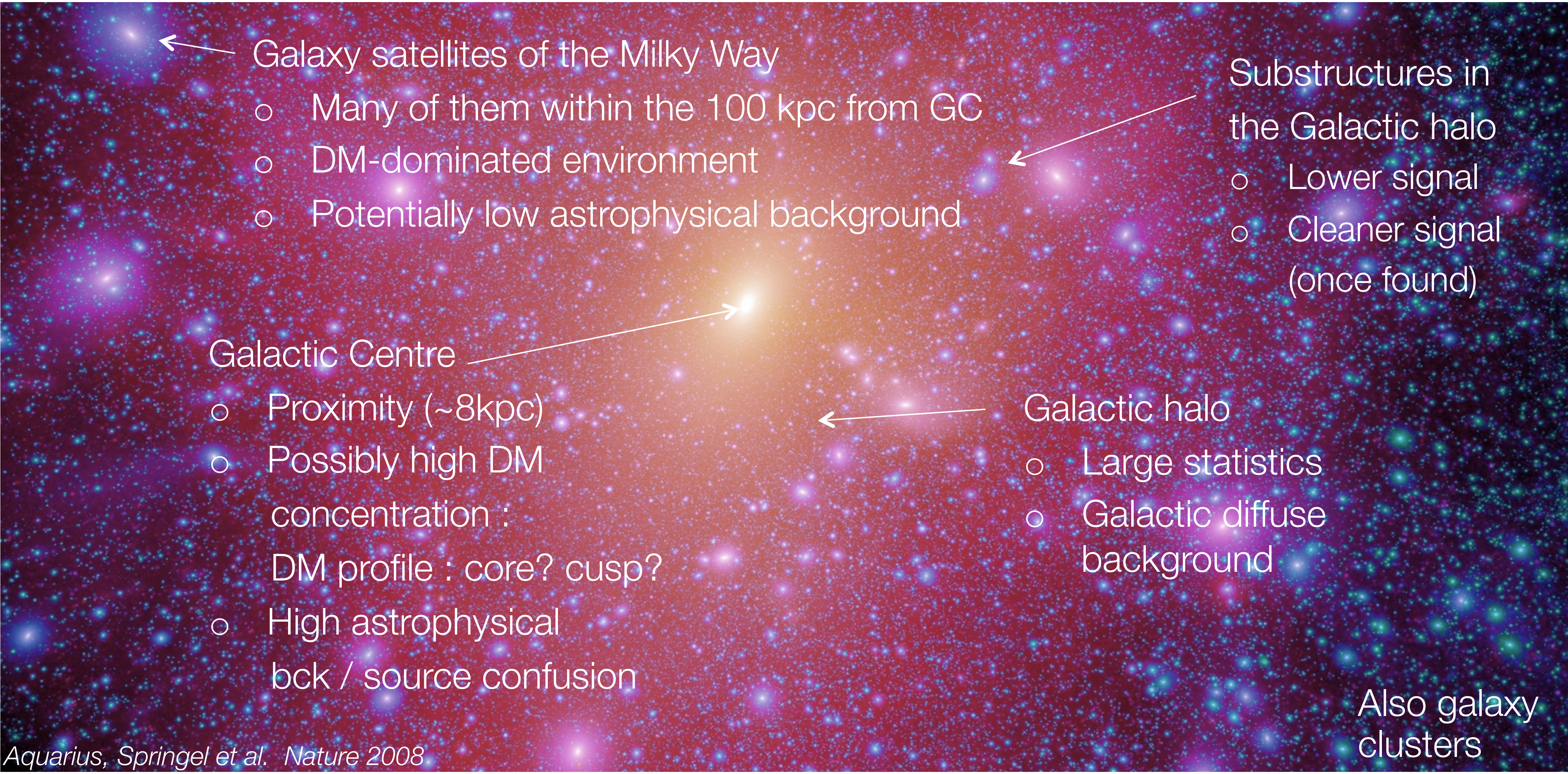
Array of FIVE Imaging Atmospheric Cherenkov Telescopes
Located in Namibia (1800 m a.s.l.)



- 5th telescope:
  - Ø 28 m, 600 m^2
  - 2048 PMTs
- Field of view : 3.5°

→ Energy threshold (zenith) :~ 30 GeV
→ Sensitivity x 2 in the TeV range

Dark matter targets



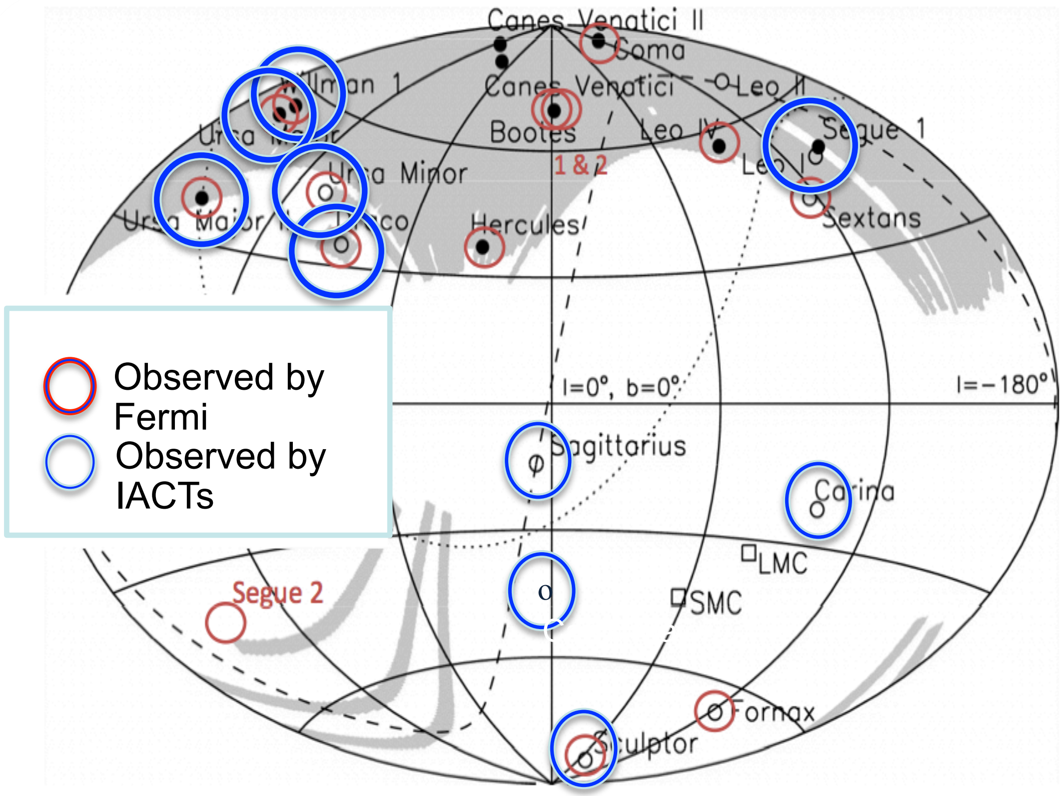
Aquarius, Springel et al. Nature 2008

DM density profile matters …

astrophysical background matters as well

Dwarf galaxies of the Milky Way

Name	Distance (kpc)	Obs. Time (hours)
Sagittarius	24	11 (90)
Canis Major	8	10
Sculptor	79	11.8
Carina	101	14.8
Coma Be.	44	8.6
Fornax	140	6.1



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

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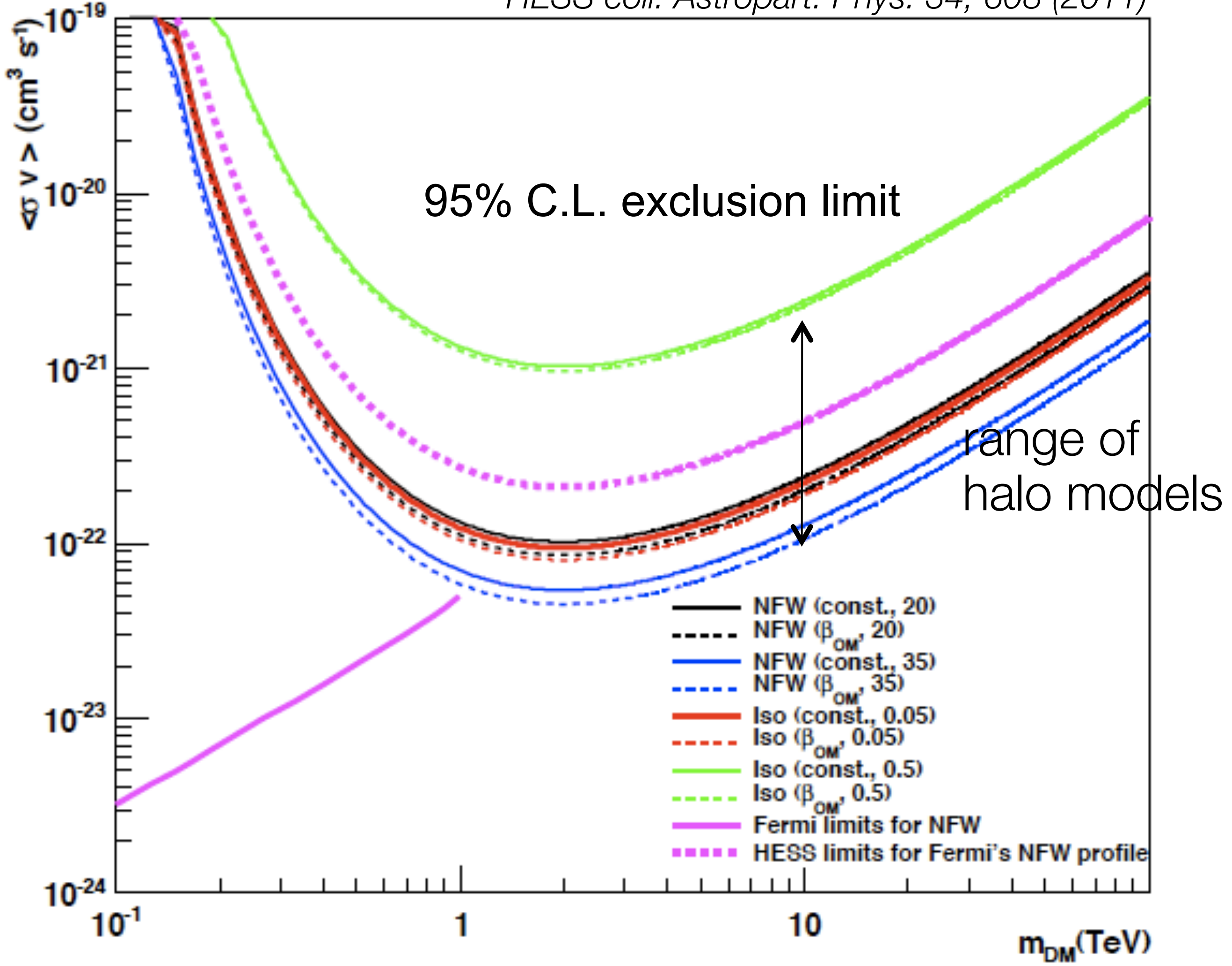
New article about to be published with stacking analysis including 90 hours of observation towards Sagittarius dwarf

The example of Sculptor: halo dependence

- 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))

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



- Various DM halo profile studied

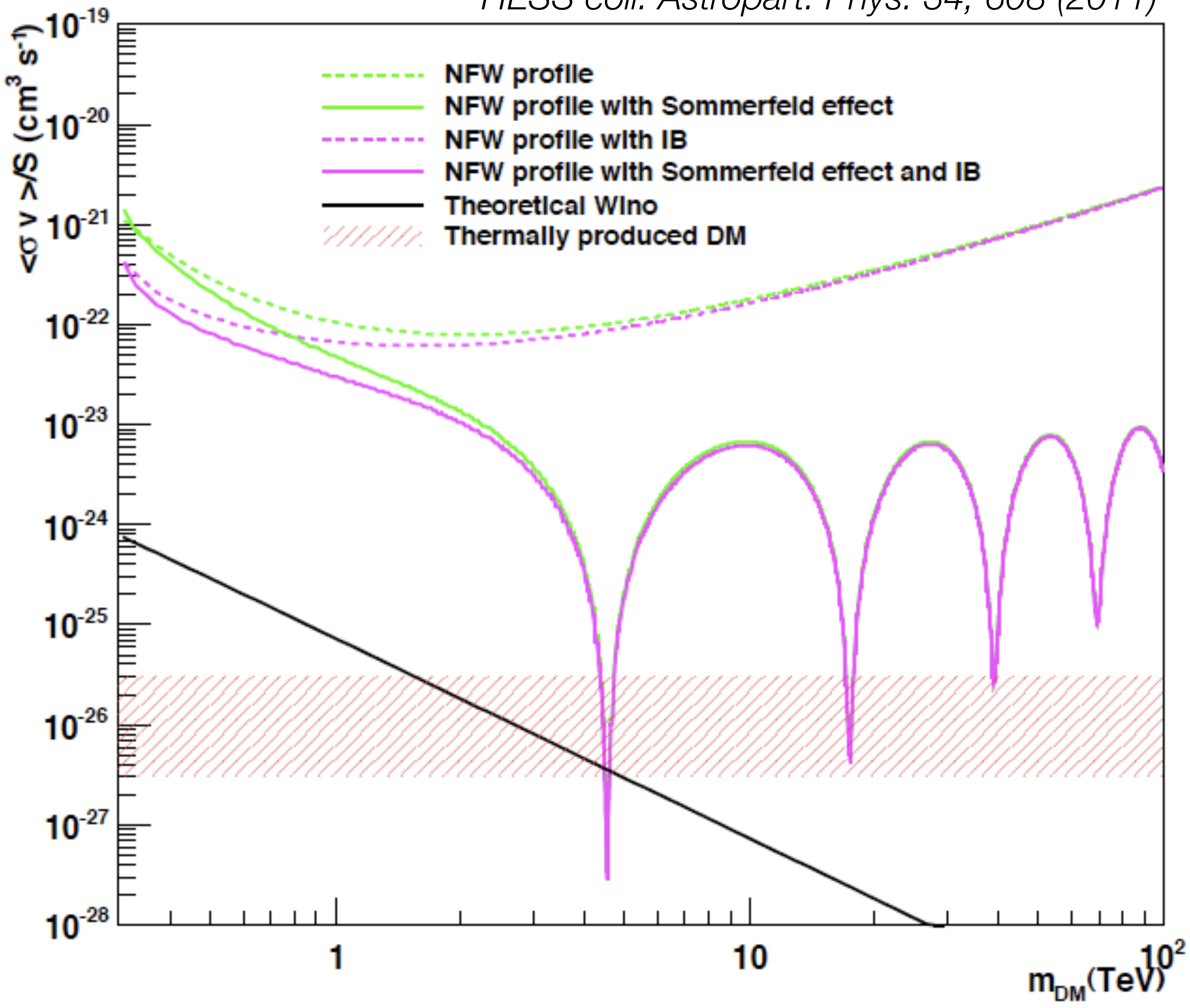
→ helps to estimate the uncertainties due to the halo modeling

- Complementary limits to Fermi

The example of Sculptor: additional contributions

- Resonant exclusion limits with Sommerfeld effect
- More than one order of magnitude effect outside resonances above 1 TeV
- Internal Bremmstrahlung only significant in the low mass region

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

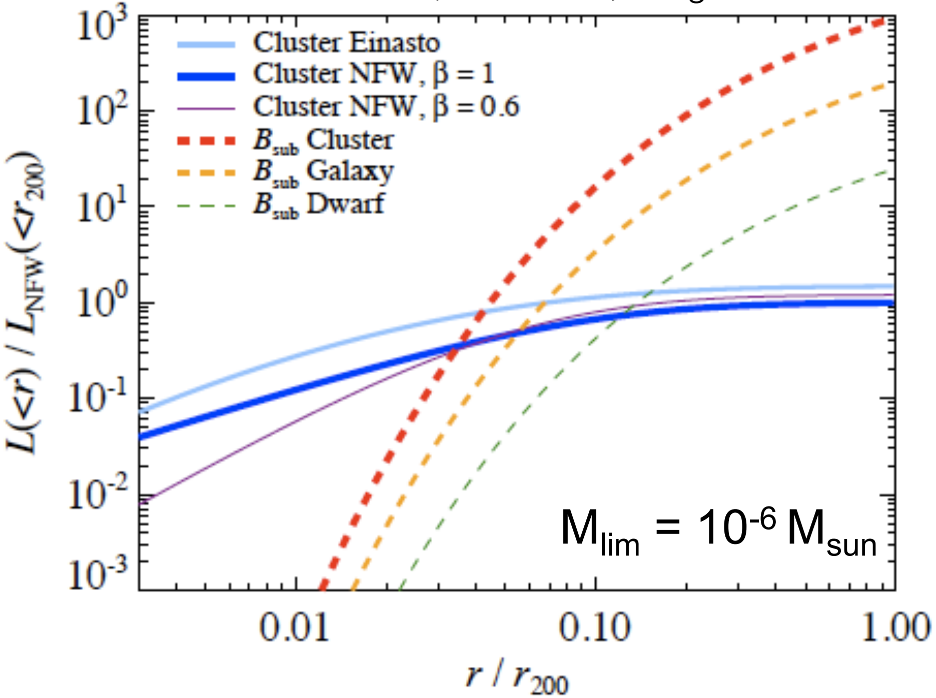


Galaxy clusters

Largest gravitationally bound objects $10^{14} – 10^{15}$ M_{sun}

- Most recent structures to form
- N-body simulations predict unmerged substructures in the DM host halo → may potentially boost the expected gamma-ray flux

Pinzke, Pfrommer, Bergström 2011



- dependence on the assumed smooth halo profile
- dependence on the limiting substructure mass

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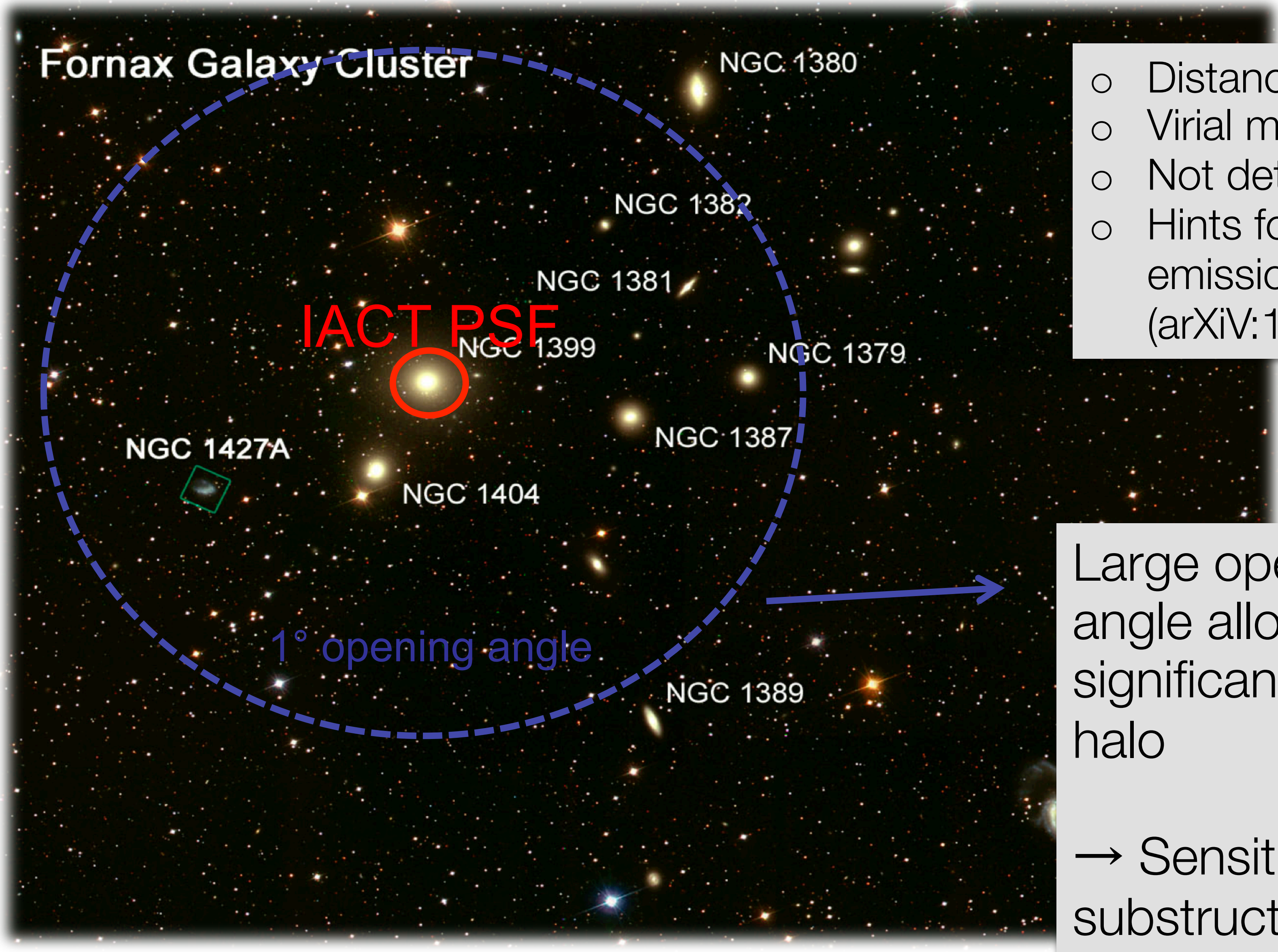
Largest gravitationally bound objects $10^{14} - 10^{15}$ M_{sun}

- Most recent structures to form
- N-body simulations predict unmerged substructures in the DM host halo
  → may potentially boost the expected gamma-ray flux

- Further distances w.r.t. dwarf galaxies but higher annihilation luminosities

Galaxy clusters: the case for Fornax



- Distance = 19 Mpc
- Virial mass = 10^{14} M_{sun}
- Not detection so far in VHE
- Hints for an extended emission with Fermi data (arXiV:1201.1003)

Large opening integration angle allows to probe a significant fraction of the DM halo

→ Sensitivity to DM substructure contribution

The Fornax galaxy cluster

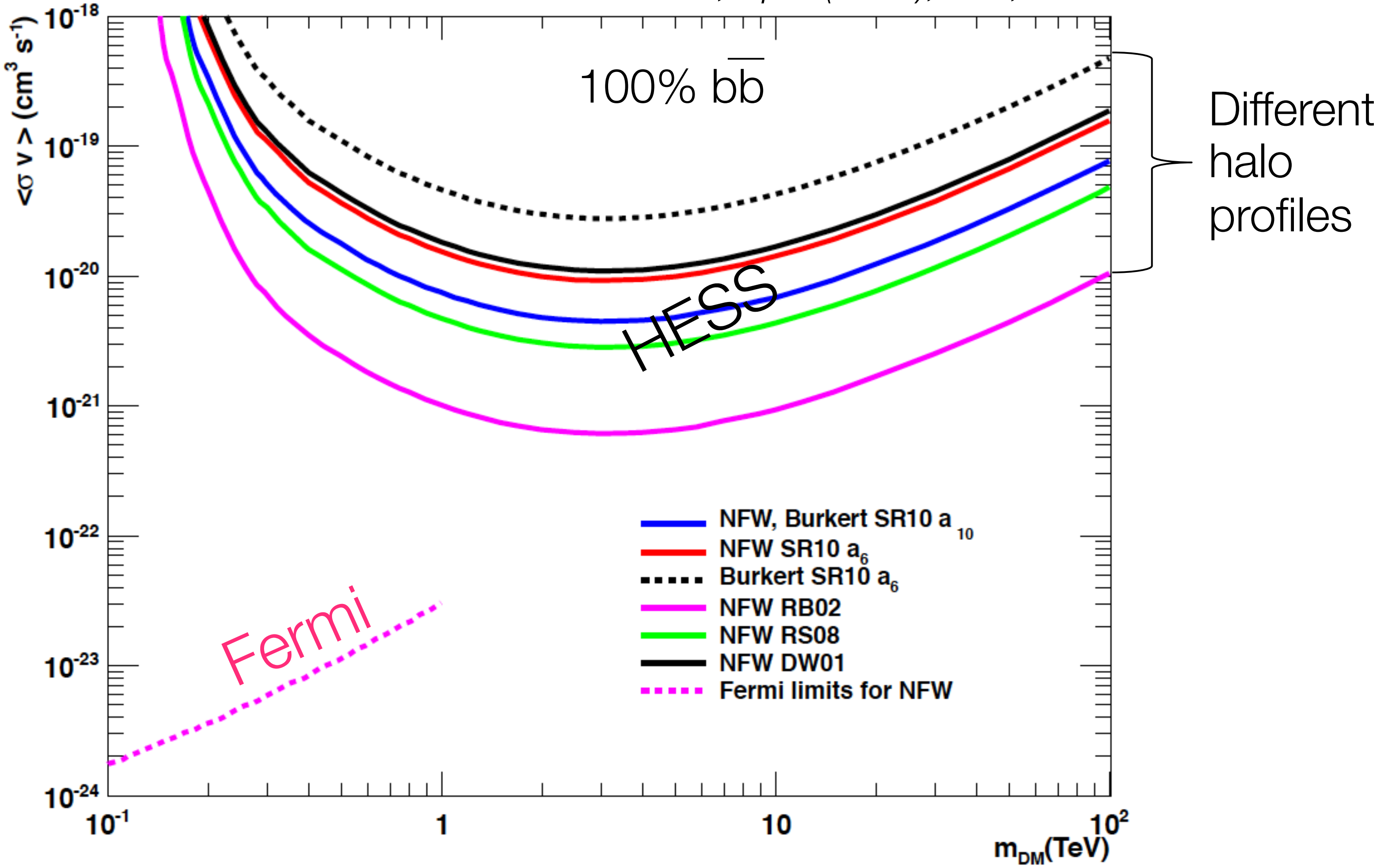
Several tracers used for The halo modeling

- Hydrogen gas (X-rays)
- Satellite galaxies
- Globular clusters
- Stars

Two hypotheses of halo profile

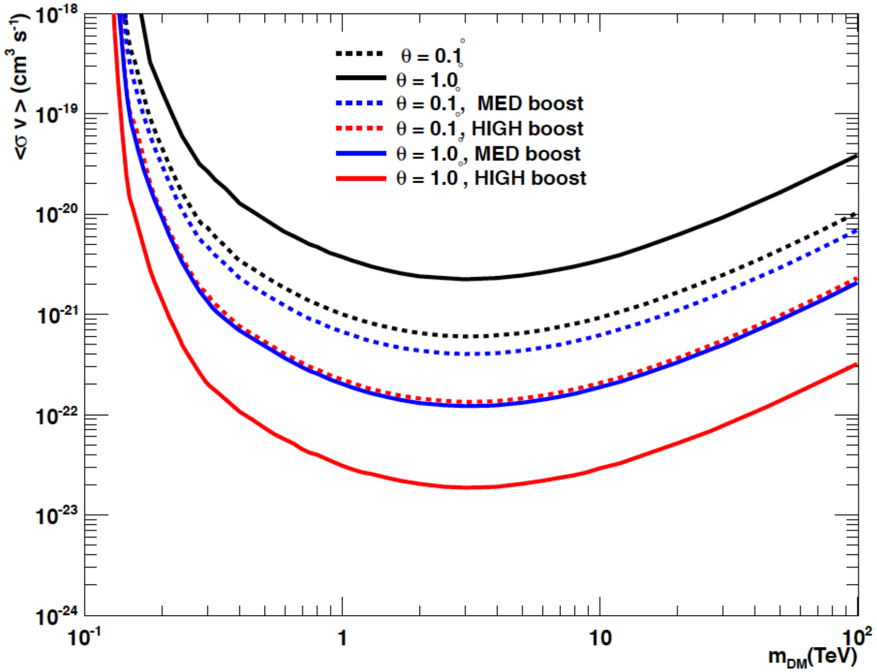
- Cuspy: NFW profile
- Cored: Burkert profile

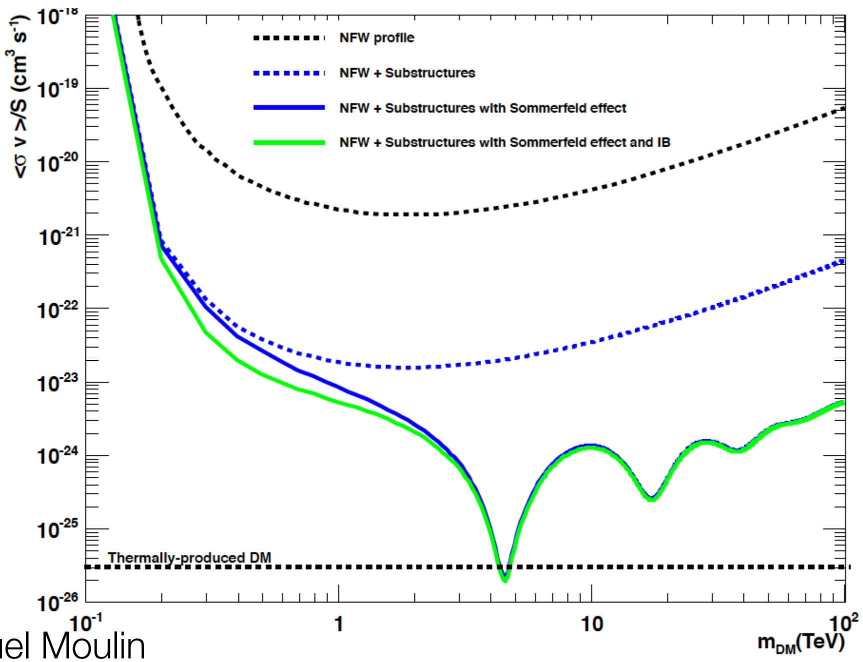
HESS coll., ApJ (2012), 750, 123

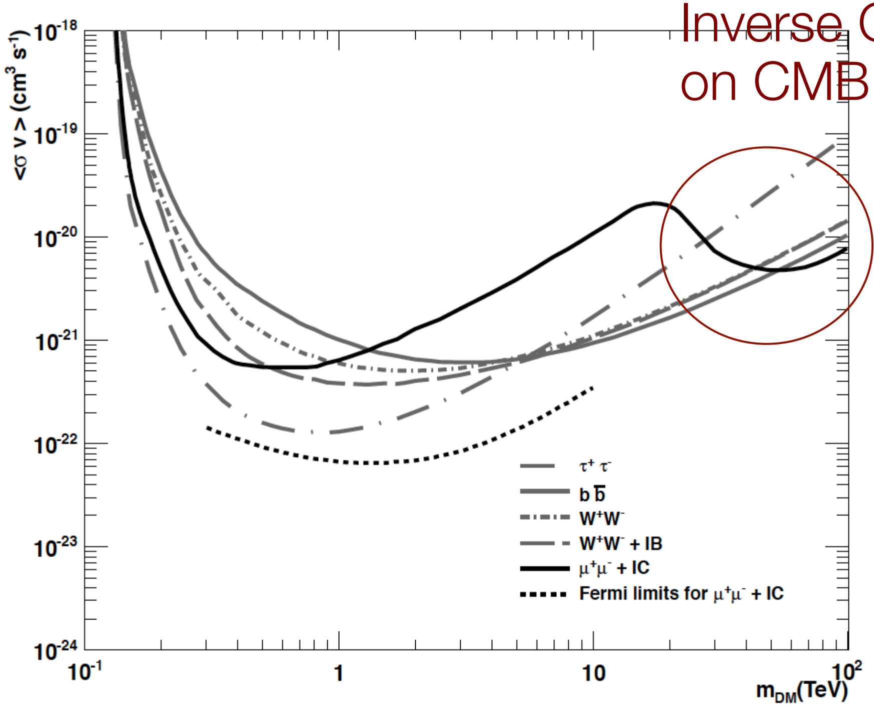


- o Choice of the tracer samples induces uncertainties up to one order of magnitude
- o Complementary to Fermi limits

The Fornax galaxy cluster







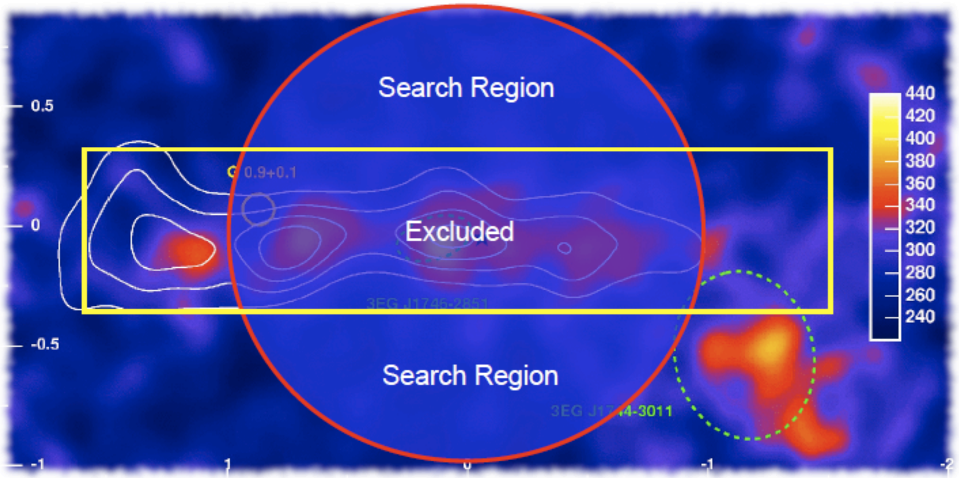
HESS coll., ApJ (2012), 750, 123

- Extended analysis allows
→ significant improvement on the limits
- Thermally produced DM can be probed for some specific masses
- Competitive limits to dwarf galaxies limits

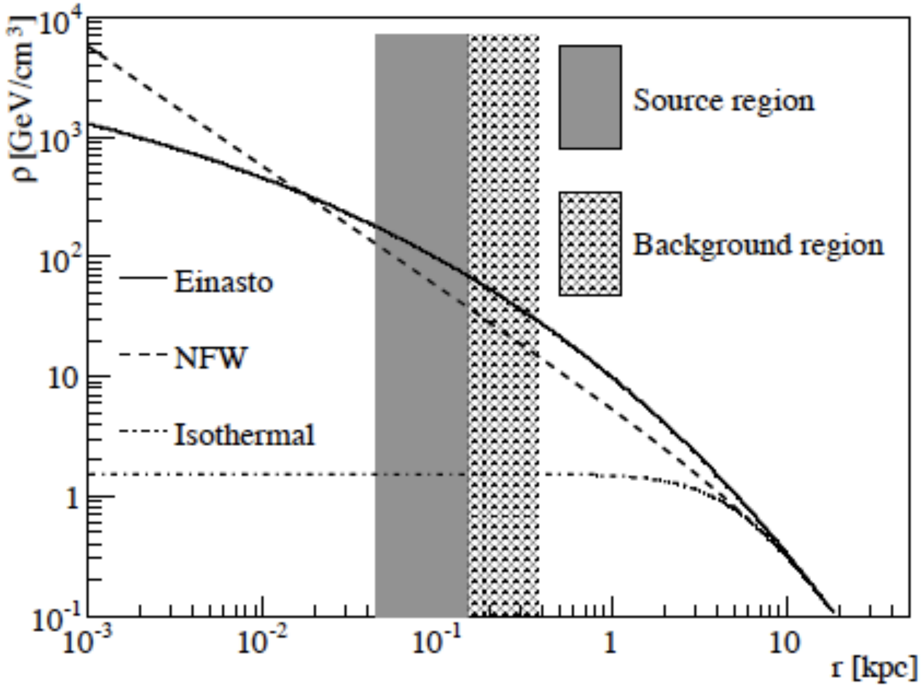
Galactic halo

Galactic center obvious target for DM searches, but crowded region

- Galactic halo at relatively short distance from GC is well-defined



HESS Coll. PRL 106 (2011)



→ 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

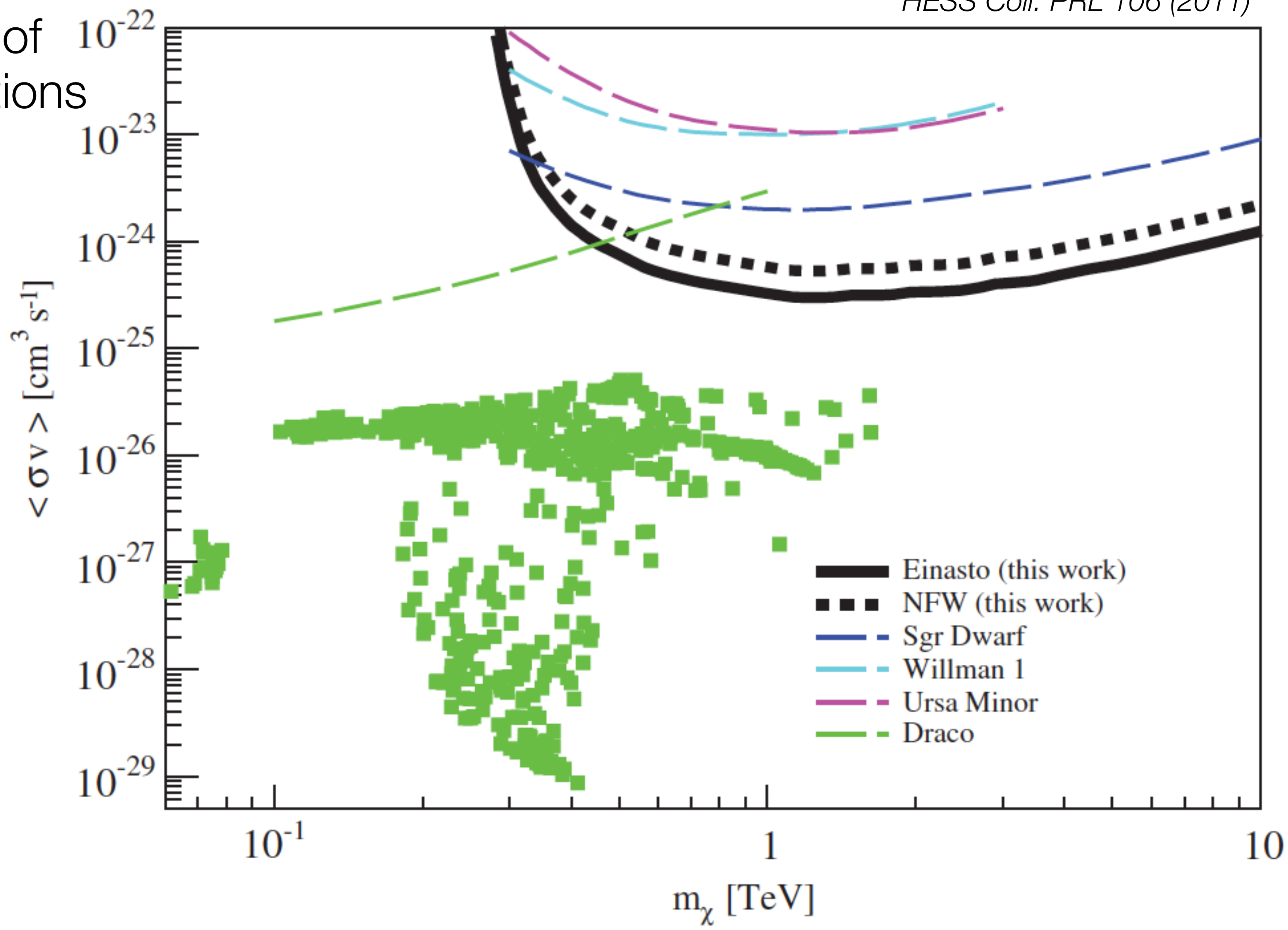
Galactic halo: continuum signal

- 112 h live time of HESS observations (2004-2008)

→ Best limits so far in the TeV mass range for NFW/Einasto Profiles

→ ~1 order of magnitude above thermal relic cross section at ~1TeV

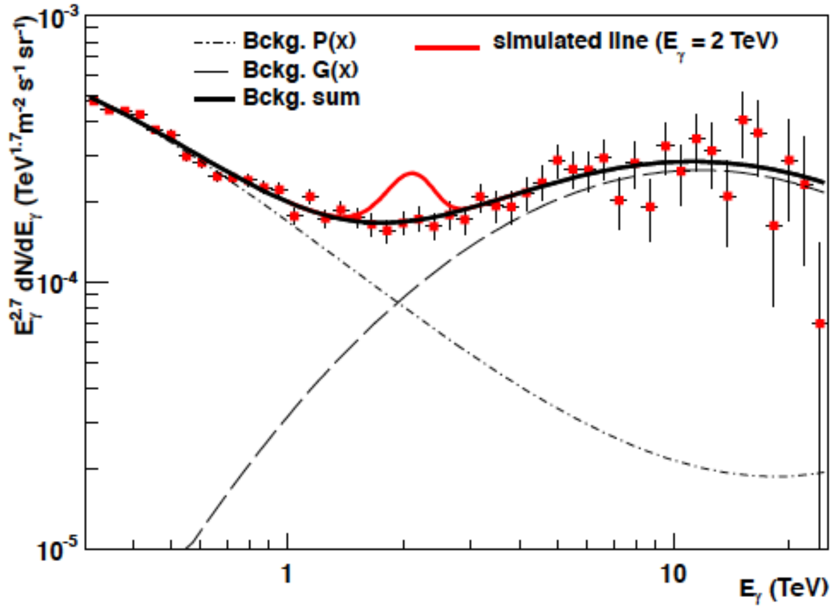
HESS Coll. PRL 106 (2011)



Galactic halo: line-like signal

Search for line signatures in the Galactic halo and extragalactic field

→ Gaussian fit on top of background



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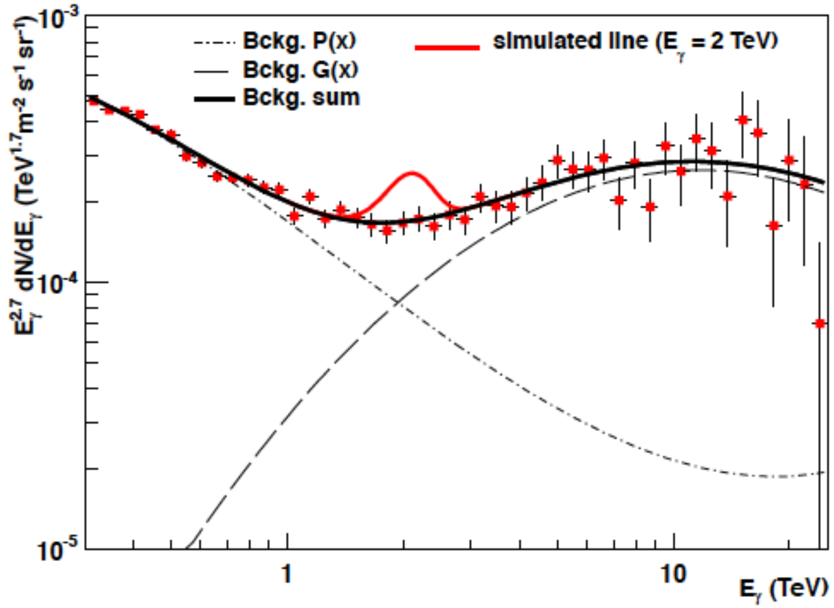
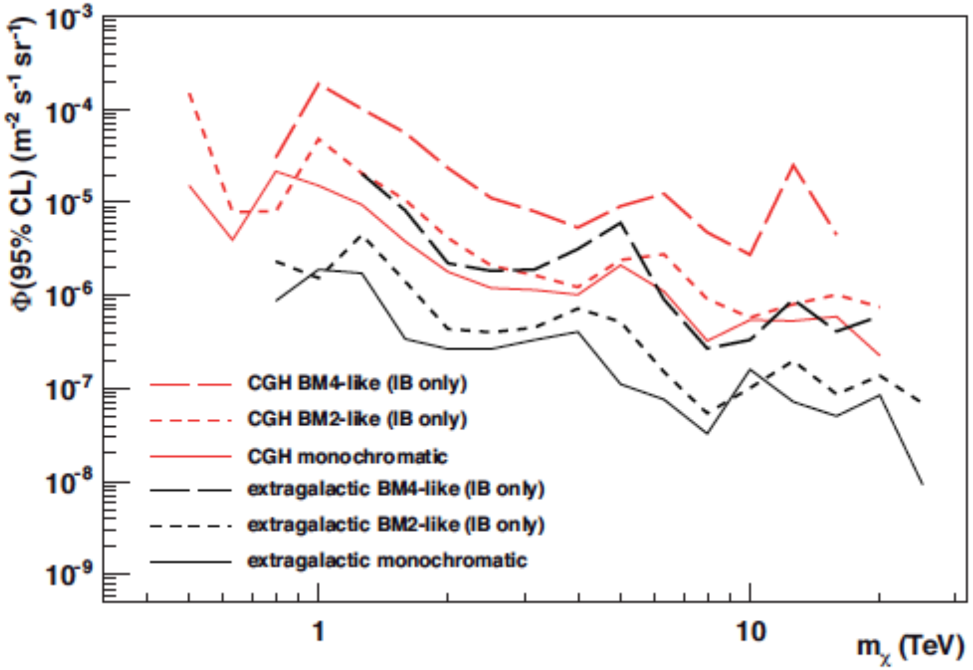
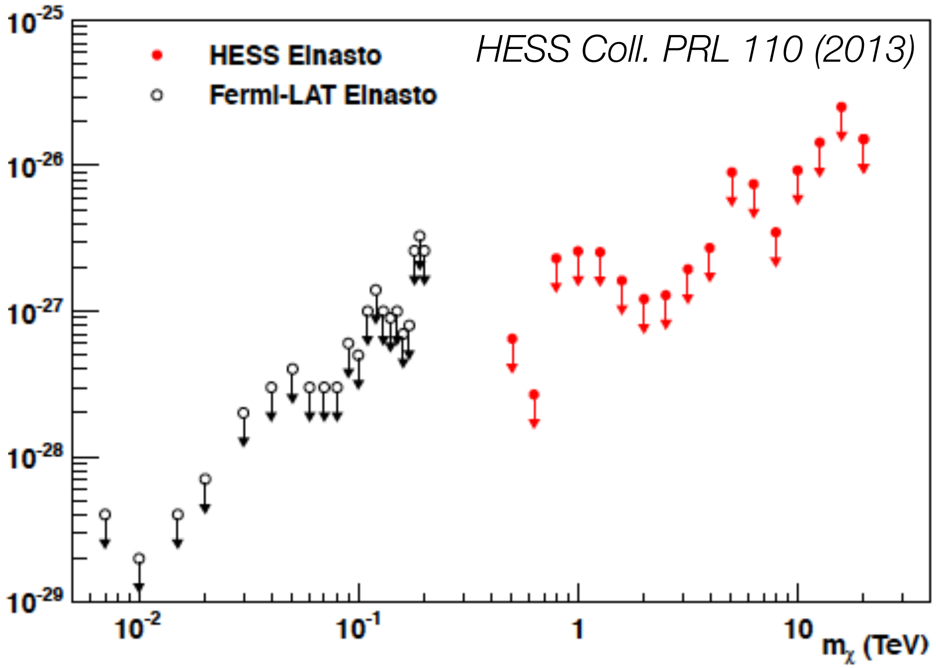
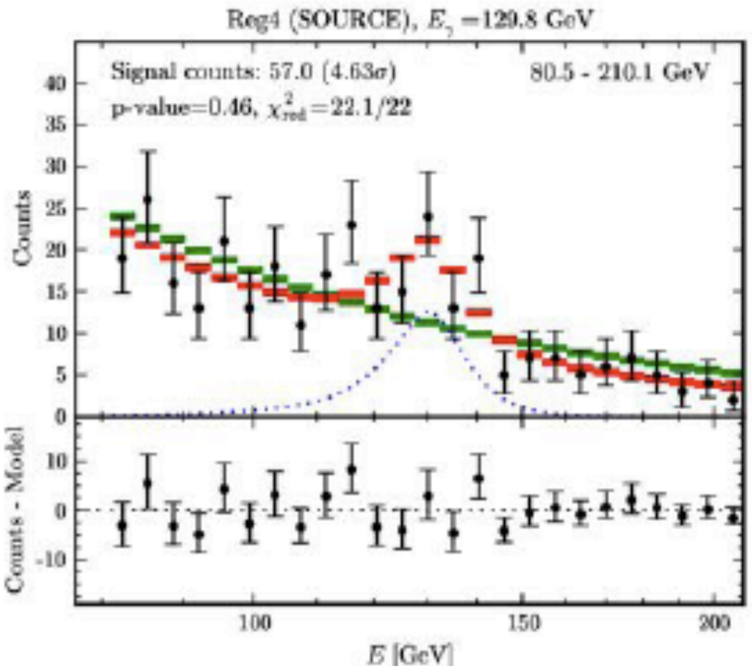






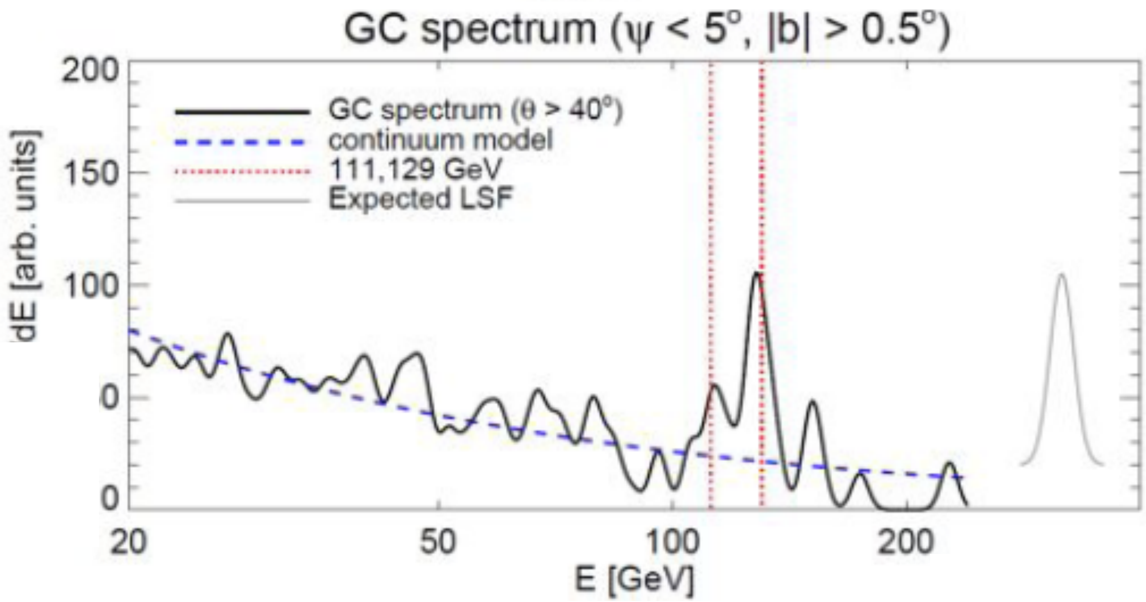
Best limits so far
for DM masses > 500 GeV

A 135 GeV gamma-ray line in Fermi-LAT data ?



Global significance: 3.2σ
(Weniger 2012)
annihilation cross-section
$\langle\sigma v\rangle_{\chi\chi\rightarrow\gamma\gamma} \sim 1.3 \times 10^{-27}\ cm^3s^{-1}$

Two lines ?
Global significance: ~4σ
(Su&Finkbeiner 2012)



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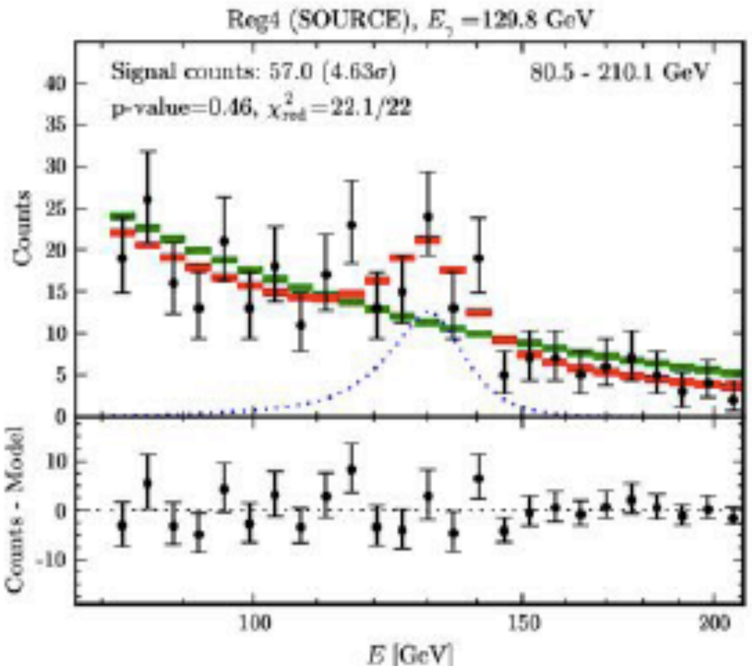
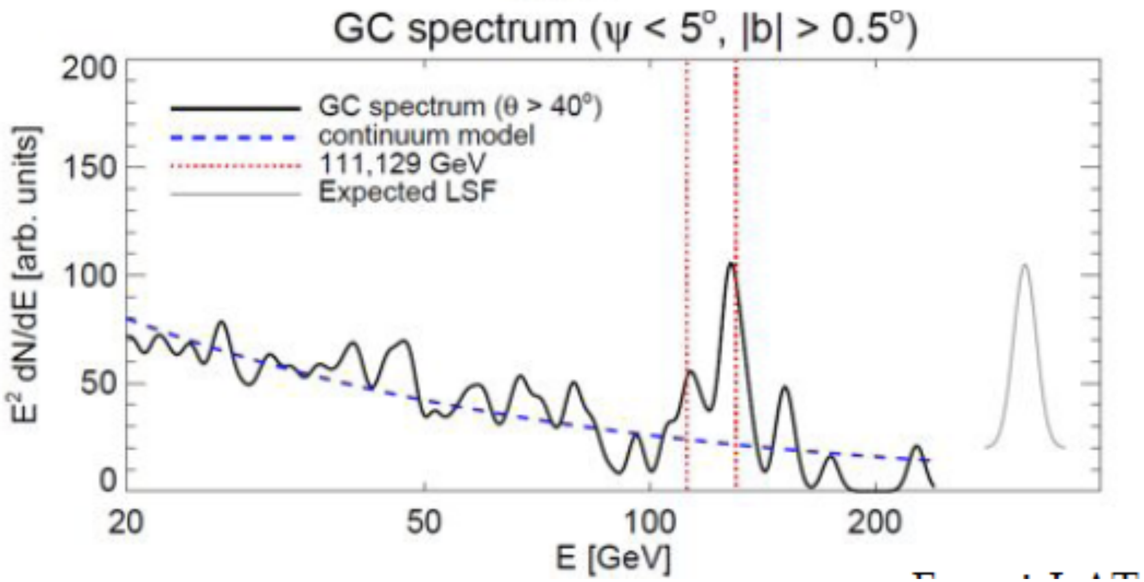
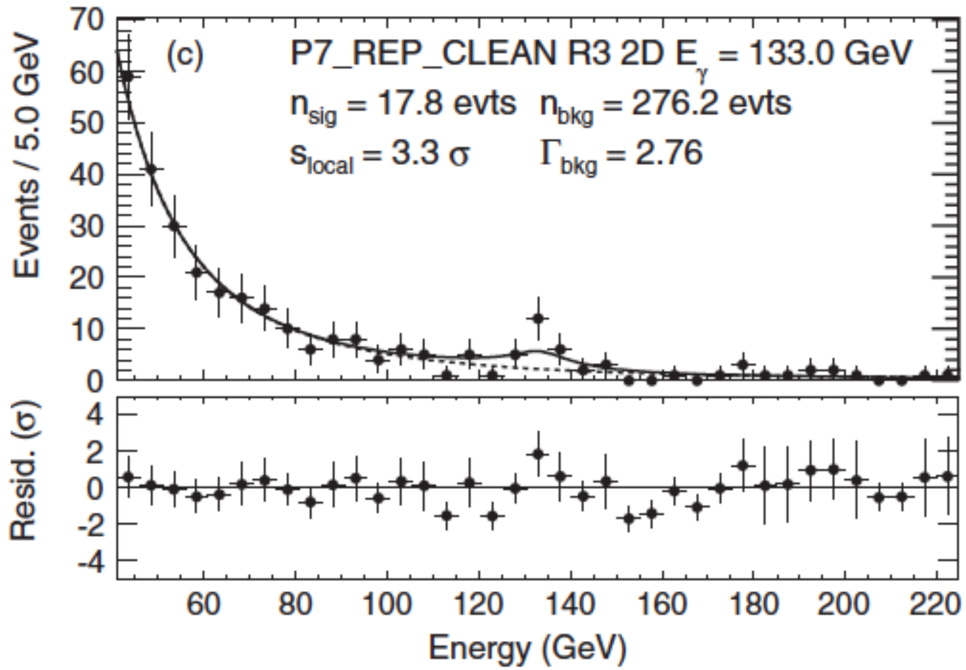




Fermi Coll. (Ackerman 2013)

- Global significance: 2σ after trial factor

- Signal also in the Earth limb control sample



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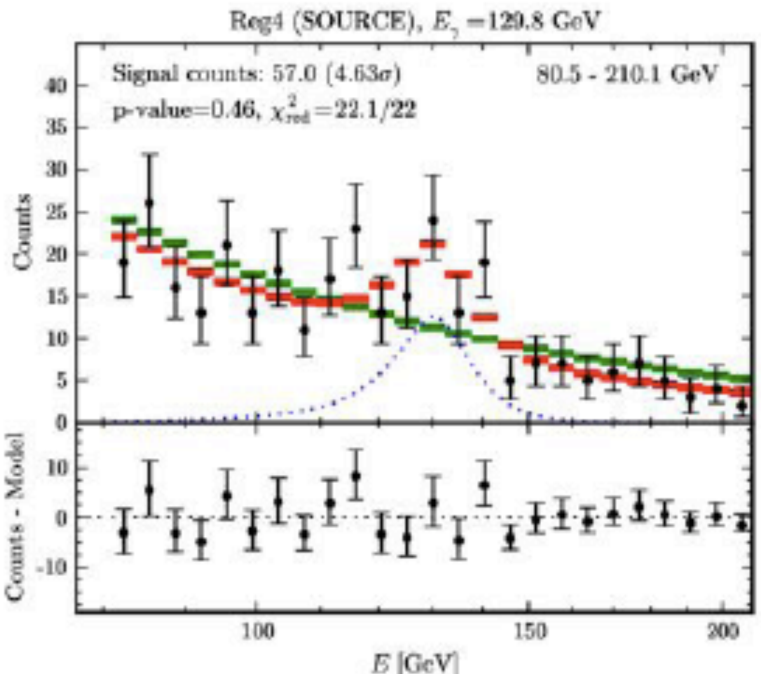
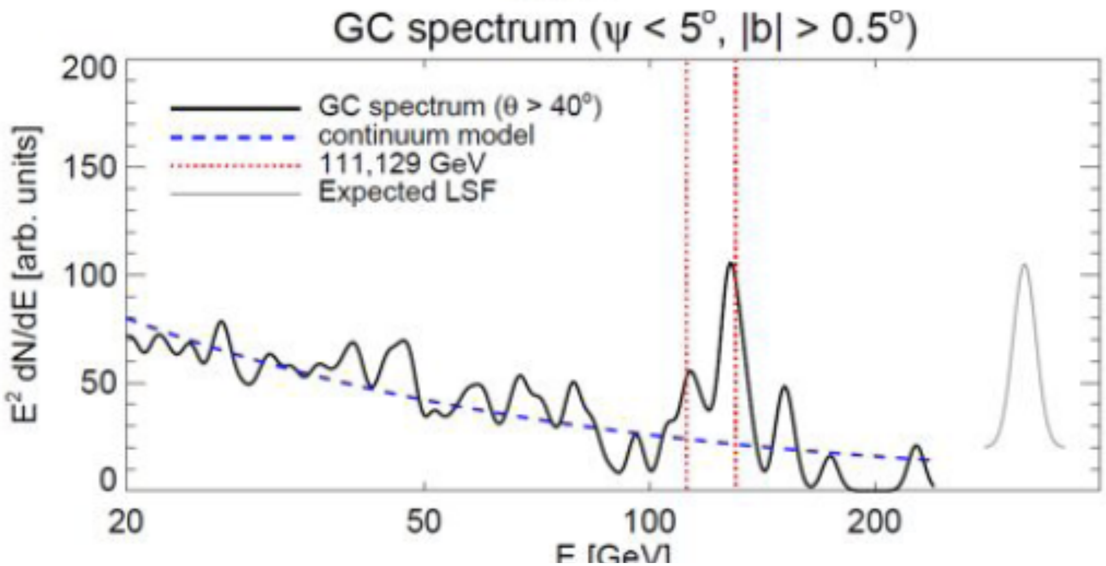
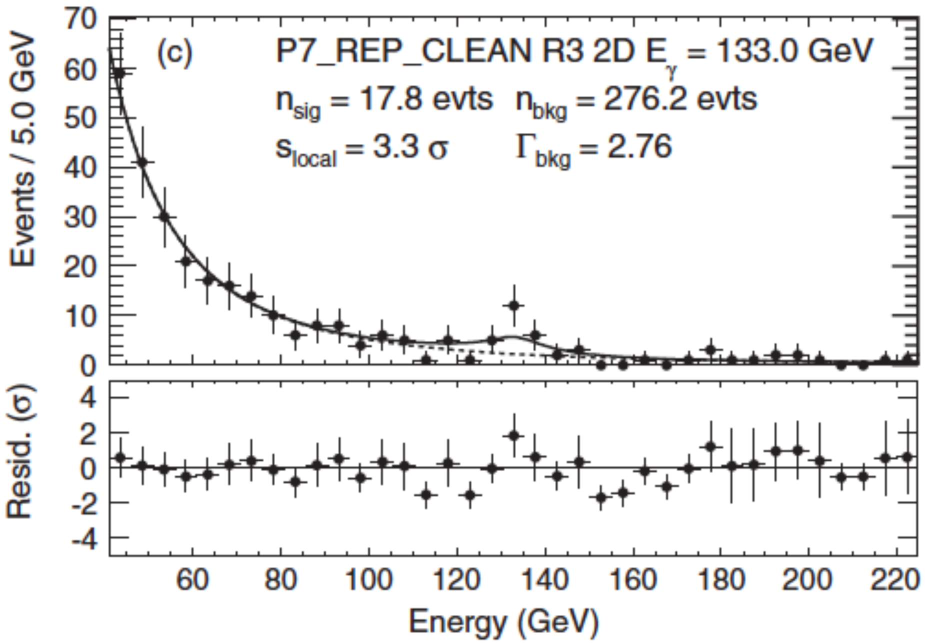
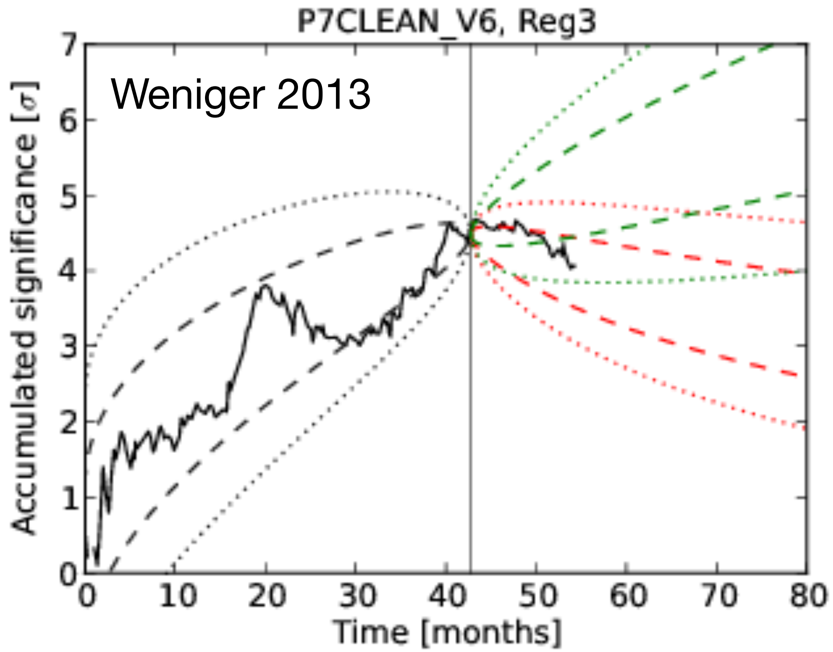




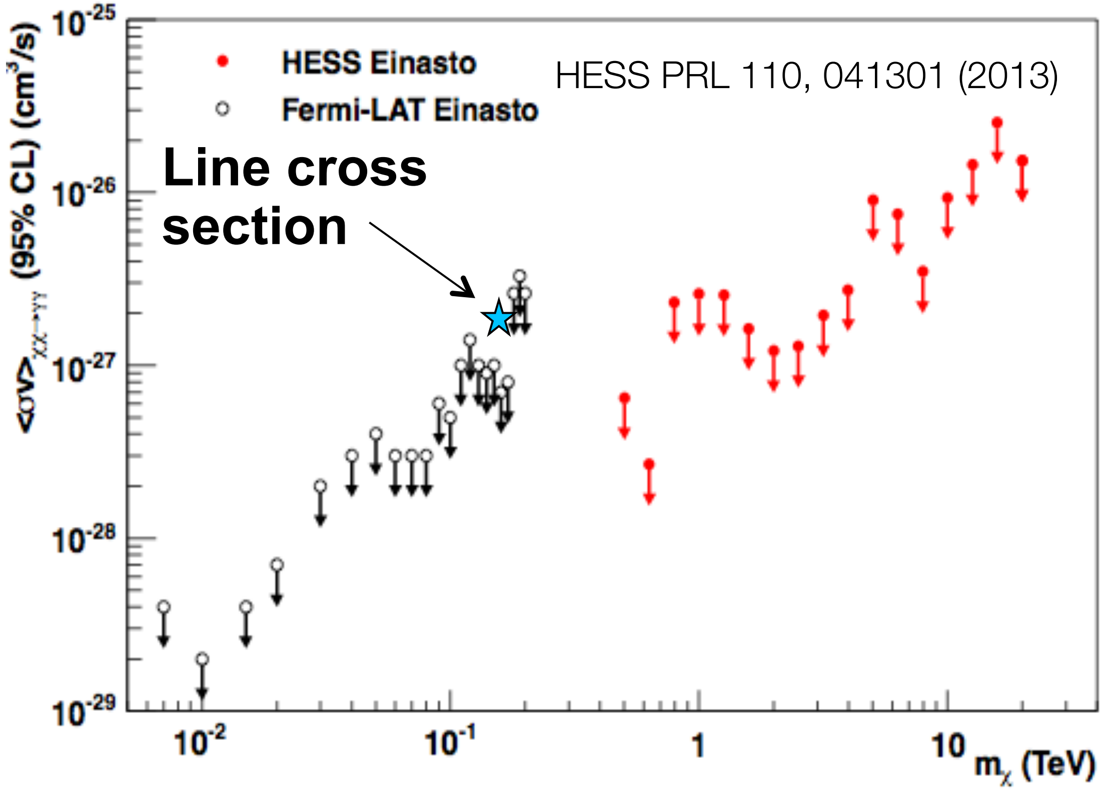




Significance is decreasing with time and improved analysis

A 135 GeV gamma-ray line in Fermi-LAT data ?

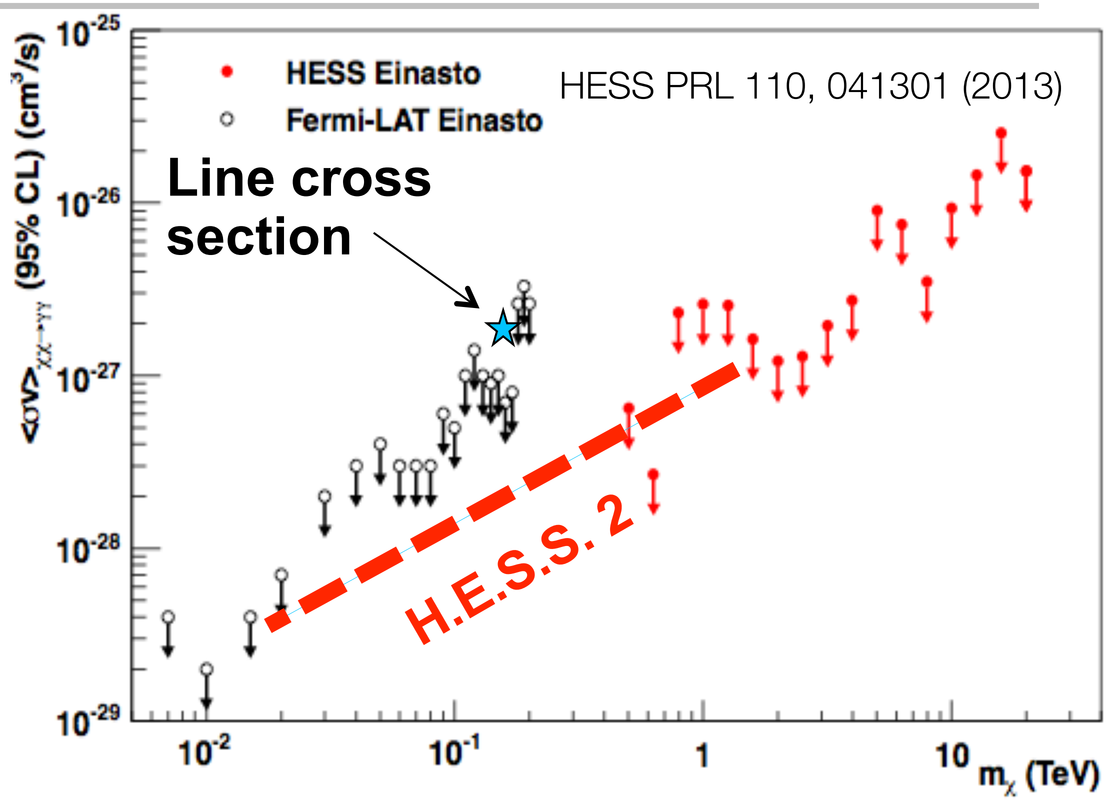
- Fermi-LAT will collect more data optimized for viewing the GC

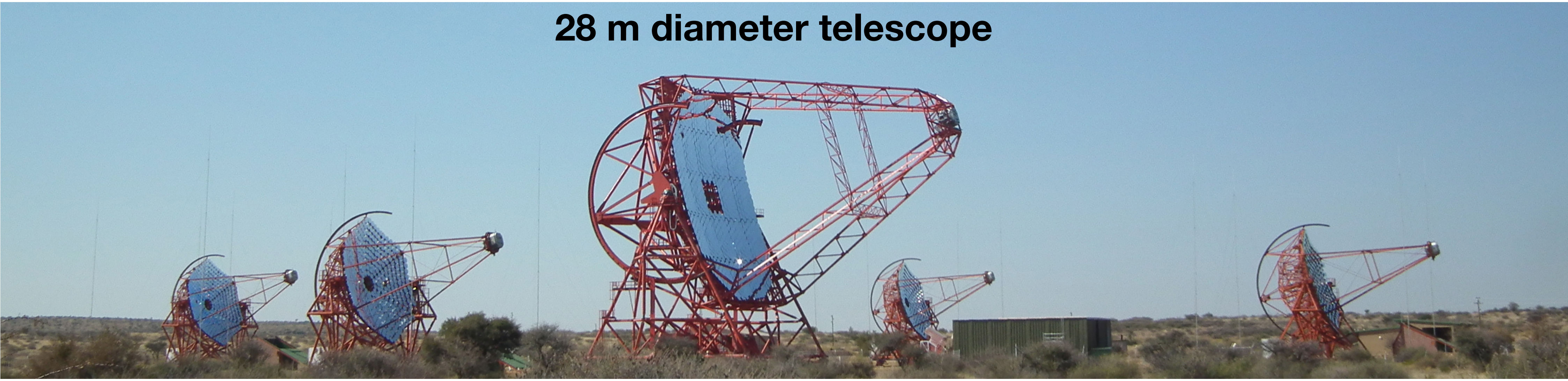


A 135 GeV gamma-ray line in Fermi-LAT data ?

- Fermi-LAT will collect more data optimized for viewing the GC → Fermi Symp.2014

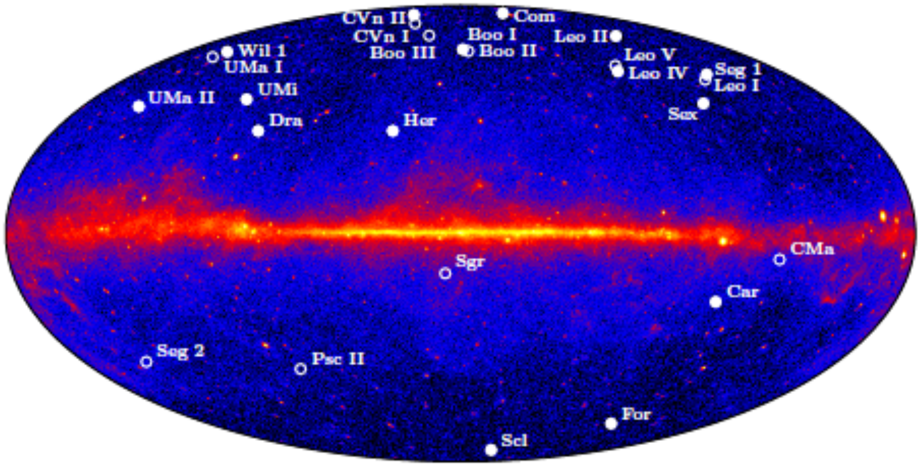
- H.E.S.S. 2 has a golden opportunity to either conclusively make a statement or rule out the effect: first results by end of the year, stay tuned !

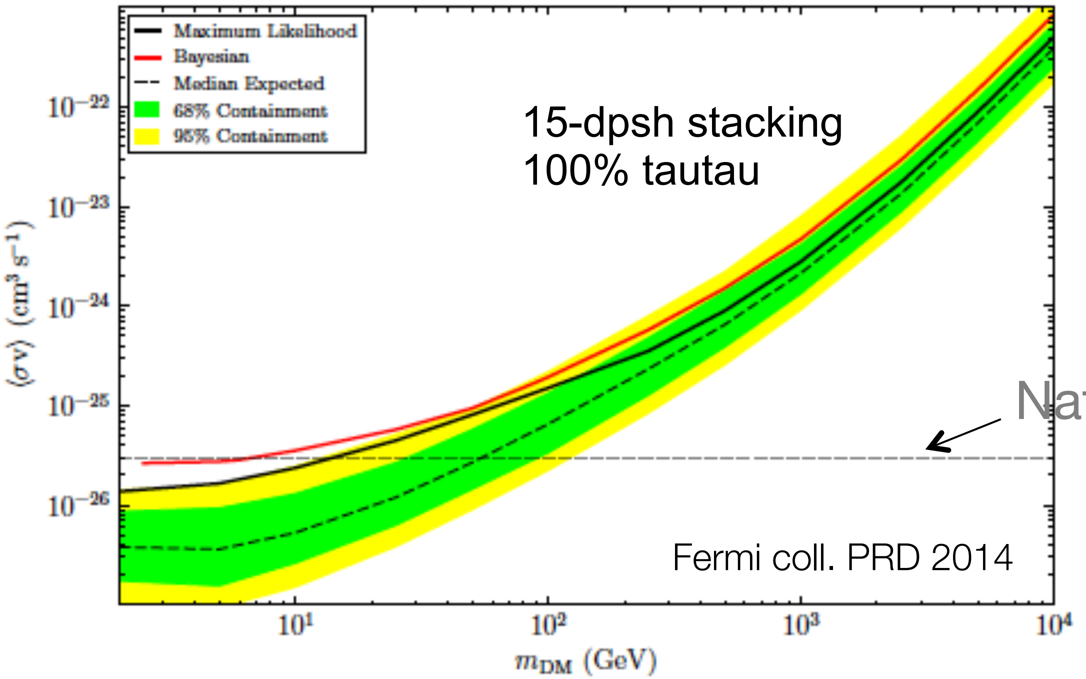




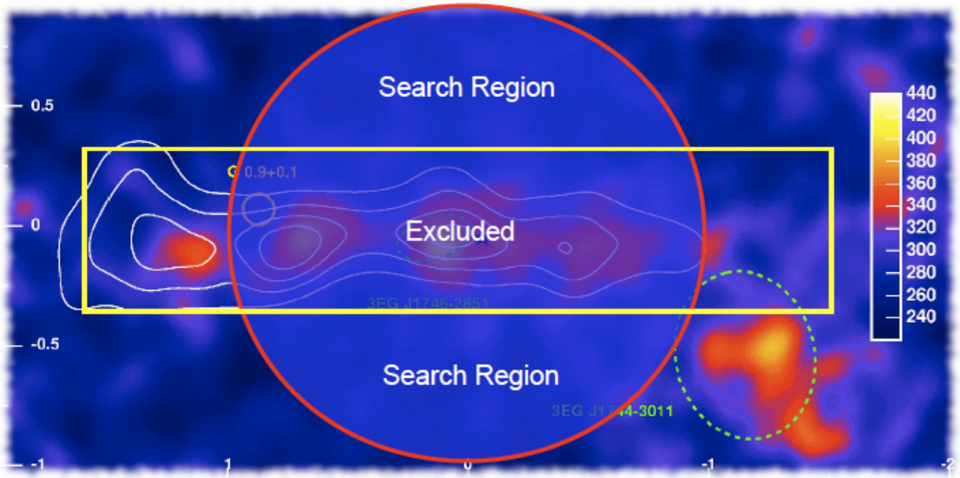
Strongest gamma-ray constraints to date

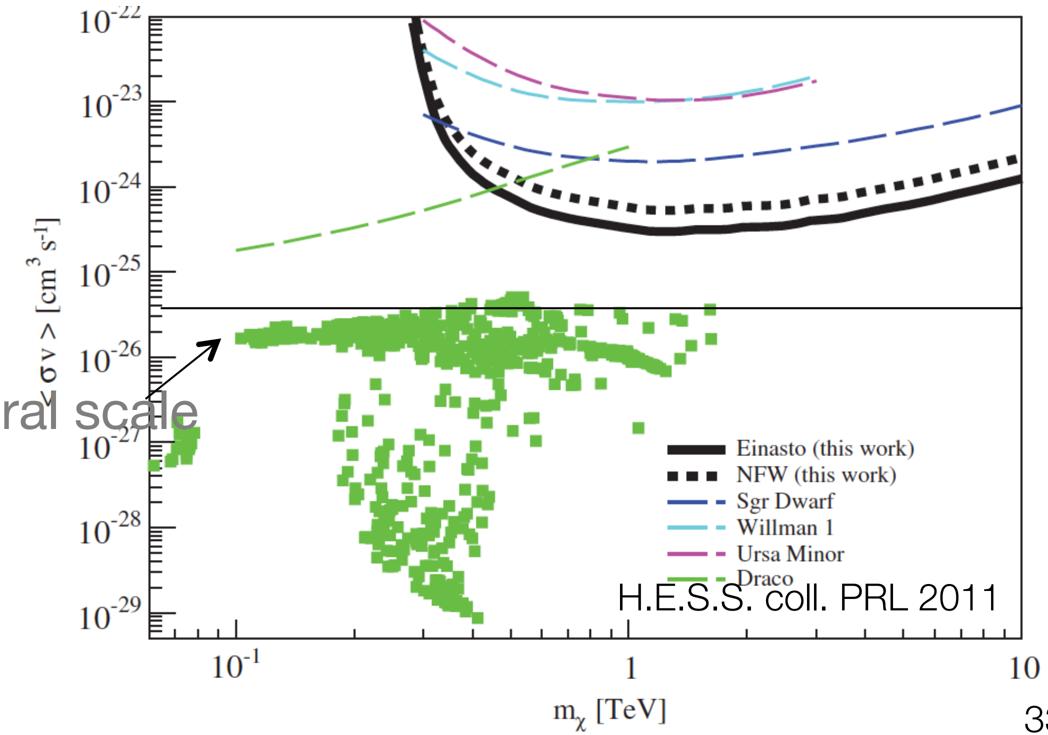
Nearby (~100kpc) dwarf galaxies





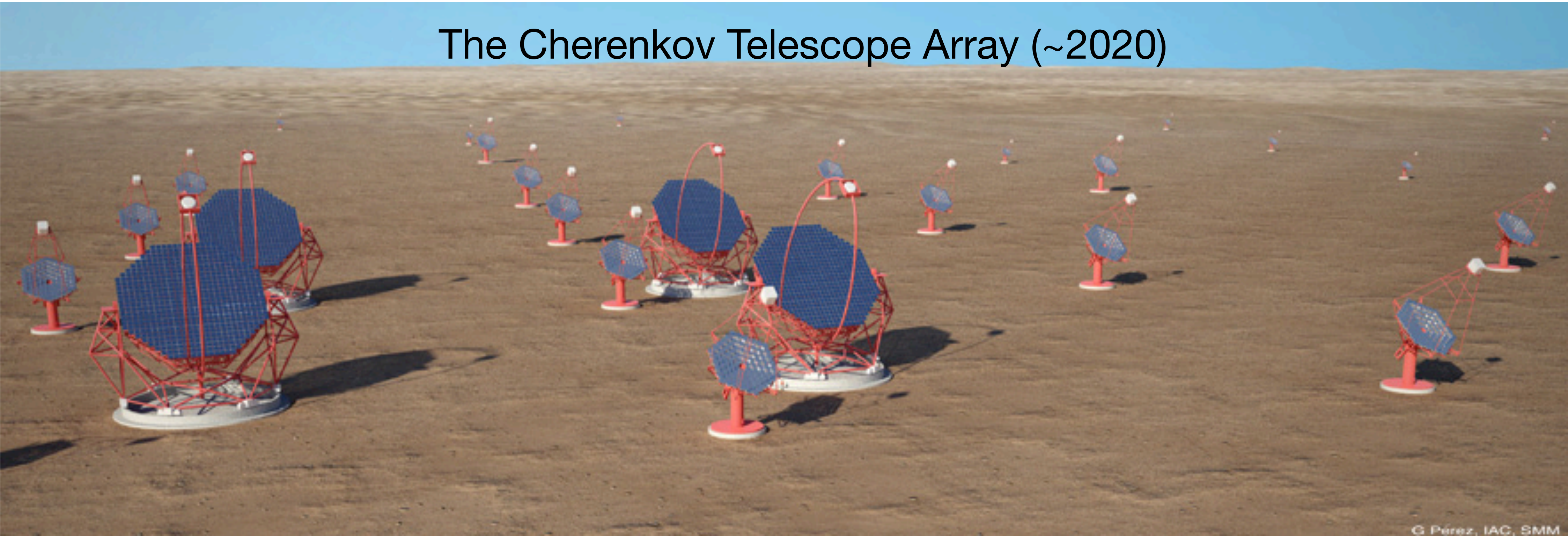
Inner Galactic halo





Gamma-ray status and outlook

- The most stringent constraints are obtained from dwarf galaxies (Fermi) and the inner region of the Galactic Center (H.E.S.S.)



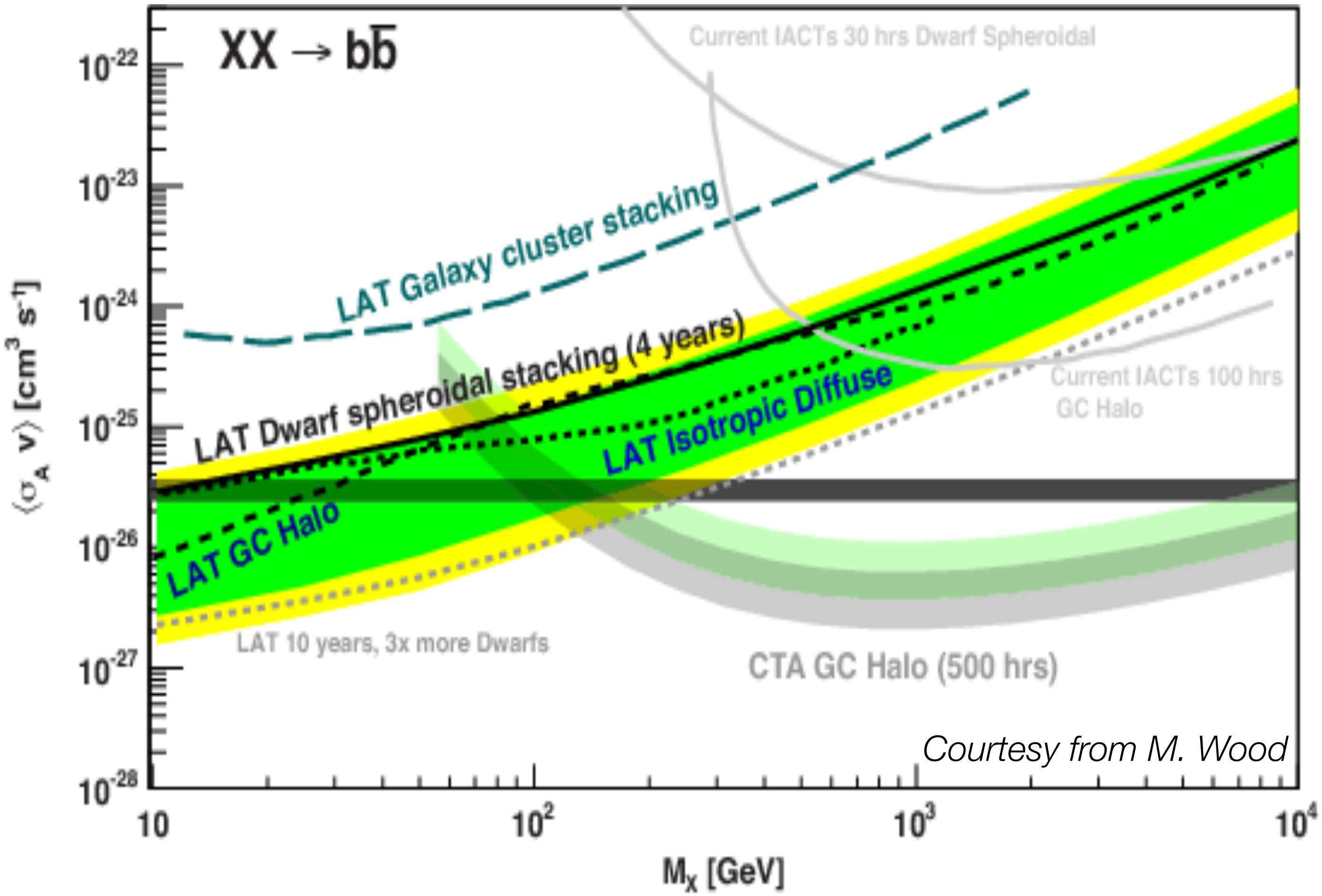
The Cherenkov Telescope Array (~2020)

- A factor 10 better in sensitivity than current instruments
- Wider energy range coverage, wider field of view, substantially better angular and energy resolution

Gamma-ray status and outlook

- The most stringent constraints are obtained from dwarf galaxies (Fermi) and the inner region of the Galactic Center (H.E.S.S.)

Fermi/CTA will be able to exclude thermal WIMPs from a few GeV up to a few tens of TeV (~2020)



Summary

- Gamma-rays are the golden channel for indirect detection of dark matter
  → most stringent constraints to date from the dwarf galaxies (Fermi) and Galactic halo (HESS)

- H.E.S.S.-1 dark matter program :
  - Dwarf galaxies: Sagittarius (2008), Canis Major (2009), Sculptor (2010), Carina (2010), Fornax, Coma Berenices
  - DM substructures: IMBH (2008), Galactic subhalos (2012)
  - Galaxy clusters: Fornax (2012)
  - Globular clusters: M 15 (2012), NGC 6388 (2012)
  - Galactic halo : continuum (2011), line (2013) signals

- Dwarf galaxies / Galaxy clusters: among the best and robust constraints so far with IACTs

- Galactic Centre region: best constraints so far for DM masses above 500 GeV

Outlook

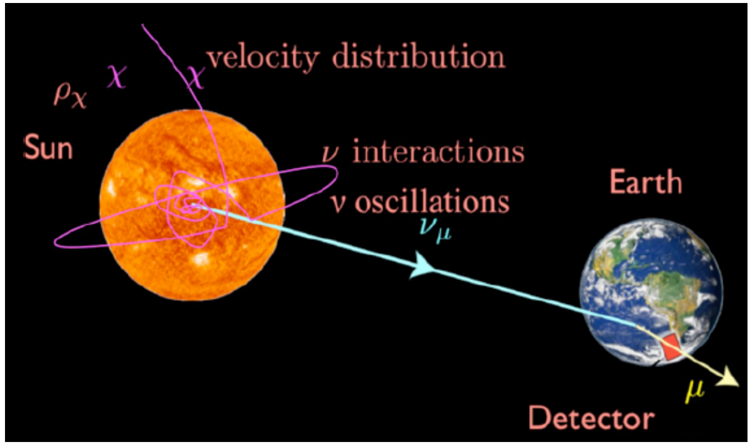
- H.E.S.S. 2 prospects in Astroparticle Physics:
  - Galactic halo
  - Line search
  - (Cosmic ray electrons: anisotropy studies)
  - (Opacity of the universe and axion-like particle searches)

- The 130 GeV gamma-ray line : excess still exists but significance is decreasing with time
  → Fermi with optimized GC observations and H.E.S.S. 2 by the end of the year

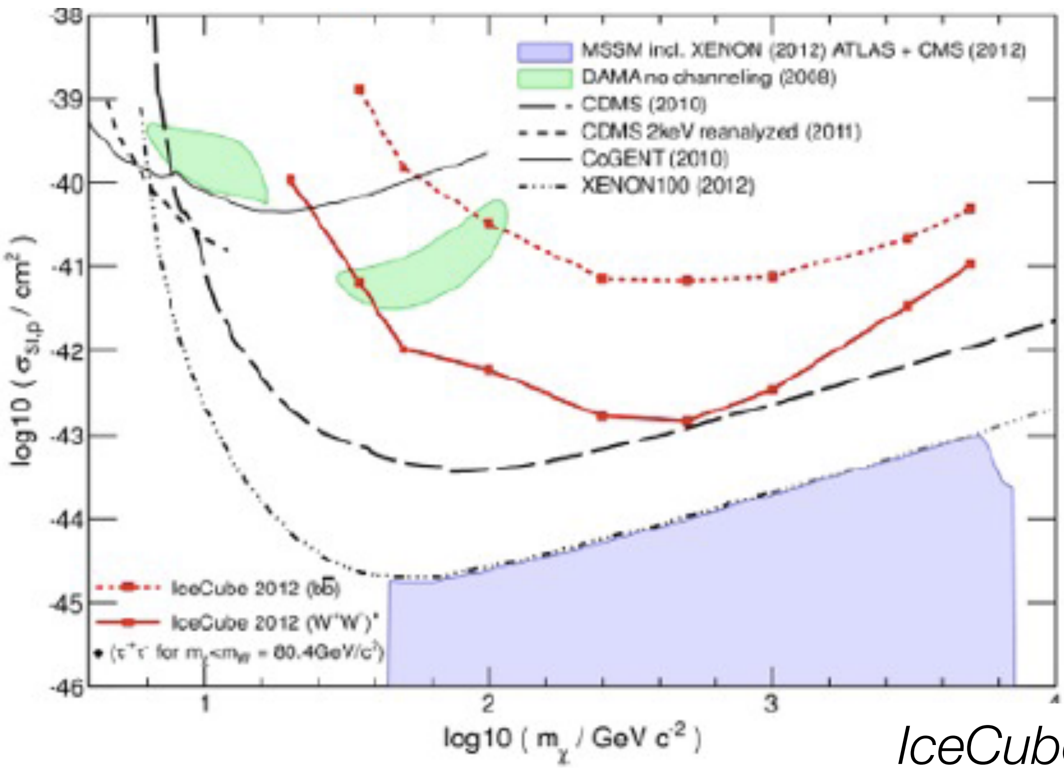
- The Galactic center: 90h taken with H.E.S.S. 2 in 2013, observations continue in Spring/Summer 2014

High energy neutrinos: WIMPs from the Sun

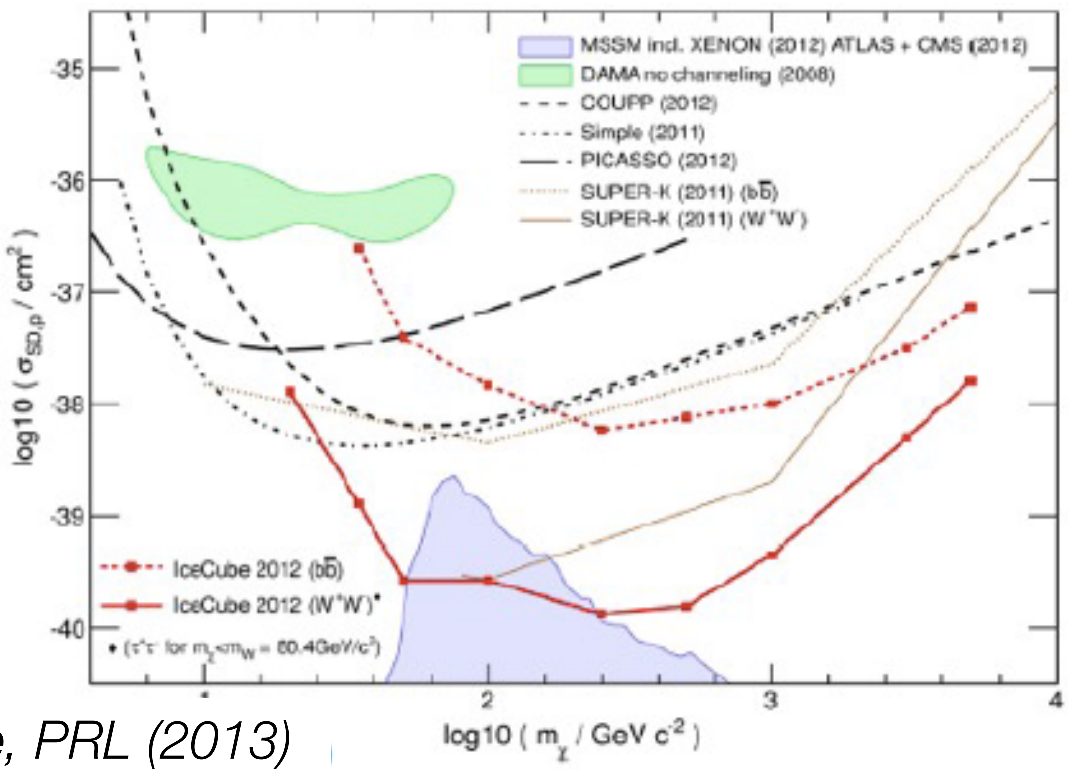
- WIMPs gravitationany captured by the Sun
- Accumulate in the core and annihilate
- Hydrogen-dominated target
  → Excellent sensitivity to SD cross section



Spin-Independent interaction

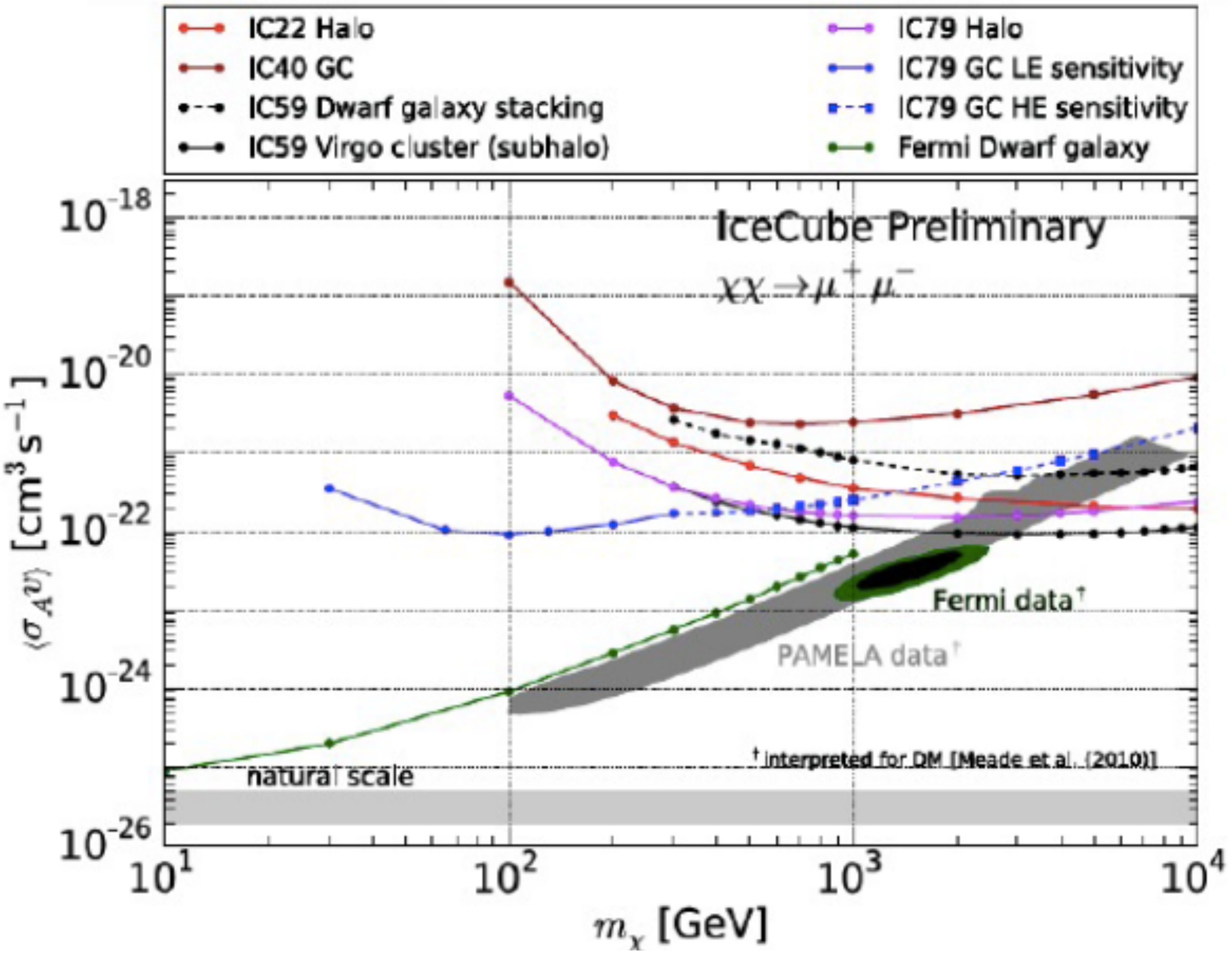


Spin-Dependent interaction



IceCube, PRL (2013)

High energy neutrinos: other targets



- Hard to compete with IACTs
- Maybe at O(10) TeV DM masses

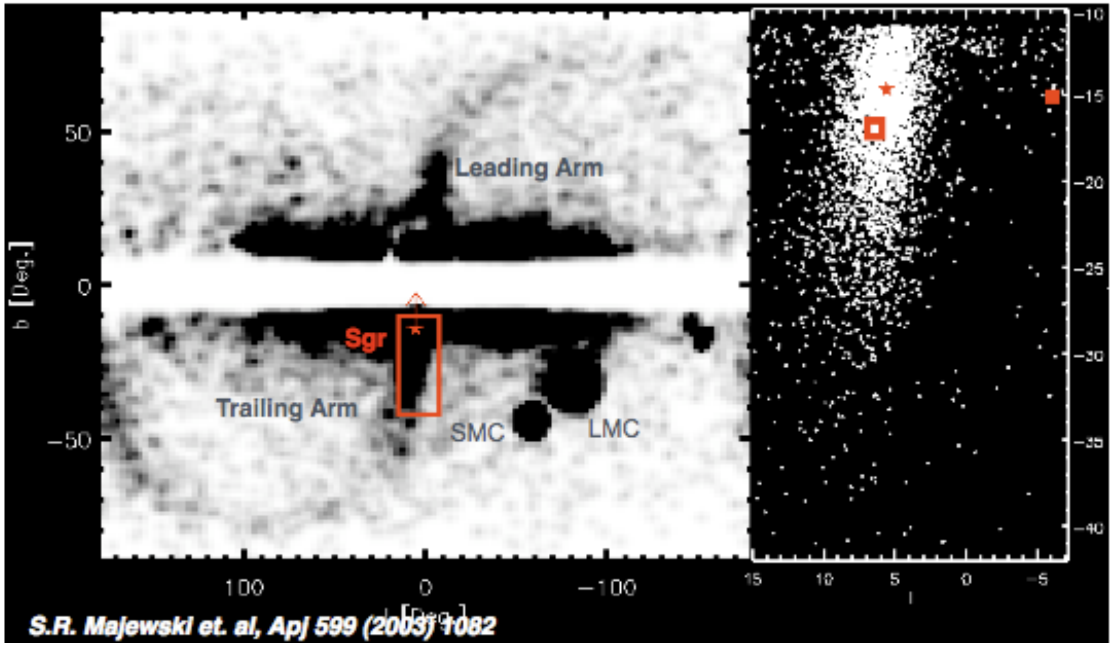
Status: ANTARES and Icecube running well

Outlook: go further down in energy

→ PINGU (IceCube) energy threshold at about 10 GeV

The case for Sagittarius dwarf

- Discovered by Ibata, Gilmore, Irwin (1994)
- Distance 24 kpc
- Closest dwarf for the Southern hemisphere observatories
- Has been claimed to be among the best target



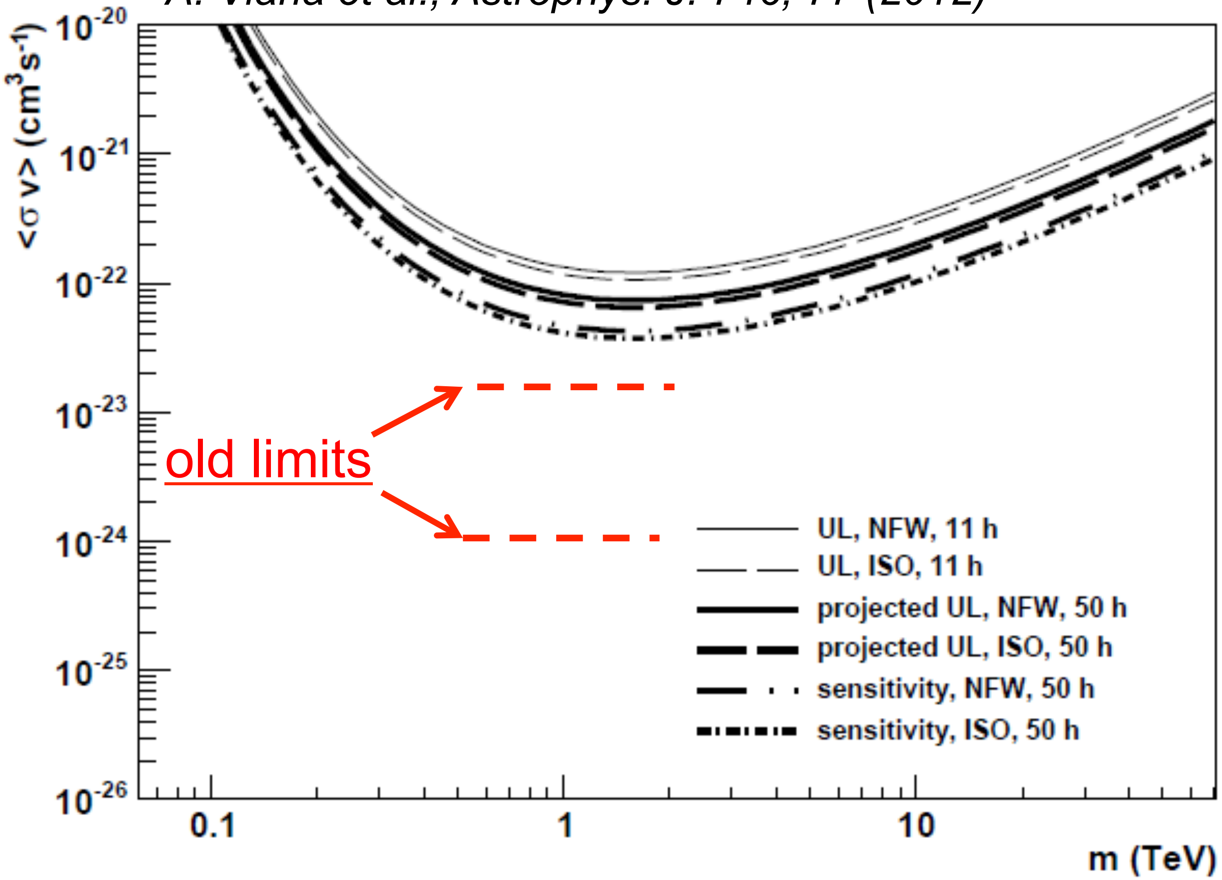
Clear tidal streams
→ Difficult halo modeling

Dark matter halo modelling:

- NFW profile :
  - Thightly bound dark matter cusp is more resilient to tidal disruption
  - The kinematics of stars that locate the central regions of the dwarf are not influenced by external tidal field
- Cored isothermal profile : J. Peñarrubia, et al. (2010). MNRAS, 408, L26
  - Fitting the visible streams to simulations allows to recover the actual DM halo profile

The case for Sagittarius dwarf : updated limits

A. Viana et al., Astrophys. J. 746, 77 (2012)



- Update of former HESS limits (2008) with more realistic halos models
- Old limits (2008) overestimate the DM gamma-ray flux, due to lack of accurate modelling of SgrDw at that time
- Projected upper limits and sensitivity for 50h with H.E.S.S.

Are globular clusters better targets than dwarfs?

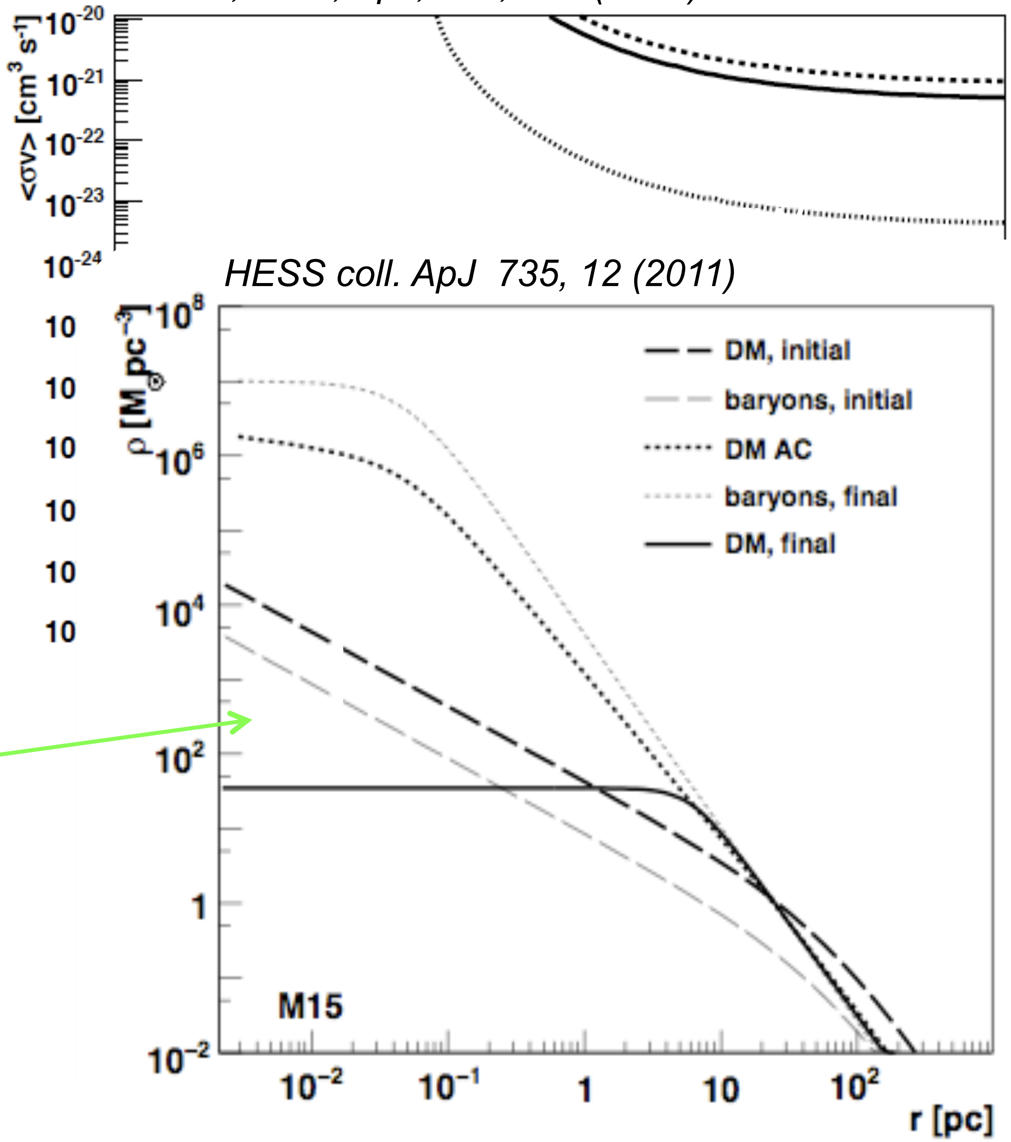
- Whipple sinlge dish ø 10m, 1.2 hr

- 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 735, 12 (2011)

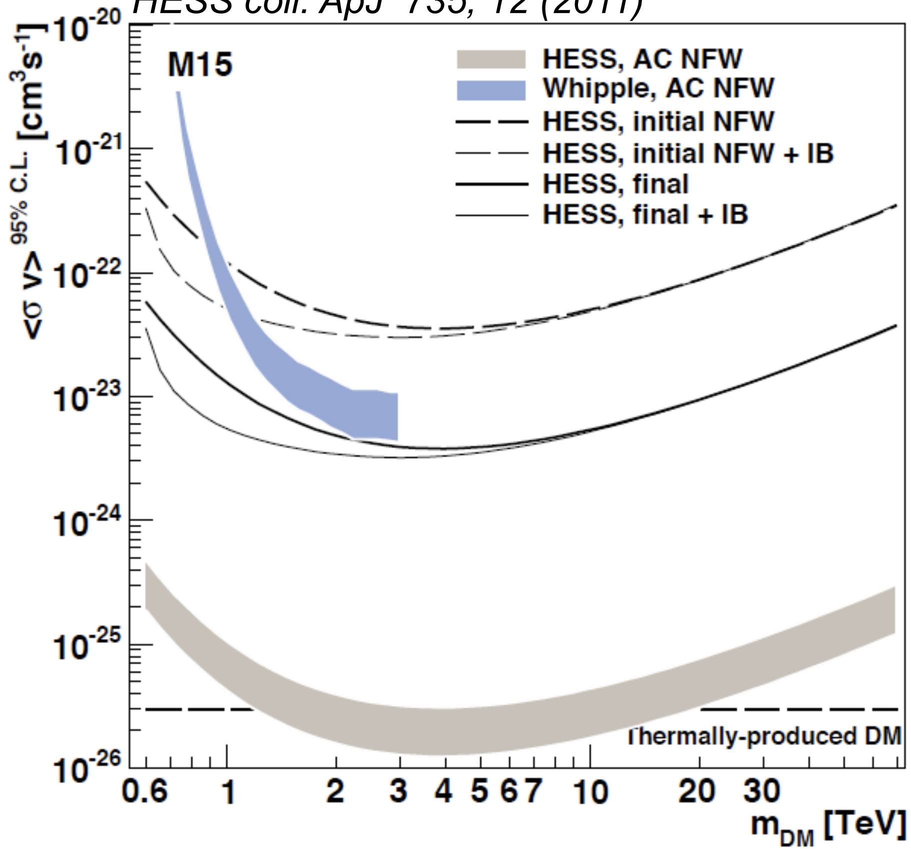


Are globular clusters better targets than dwarfs?

- 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}

HESS coll. ApJ 735, 12 (2011)



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