From neutrino to multimessenger astronomy : status and perspectives
April 2011, Marseille

Indirect dark matter search

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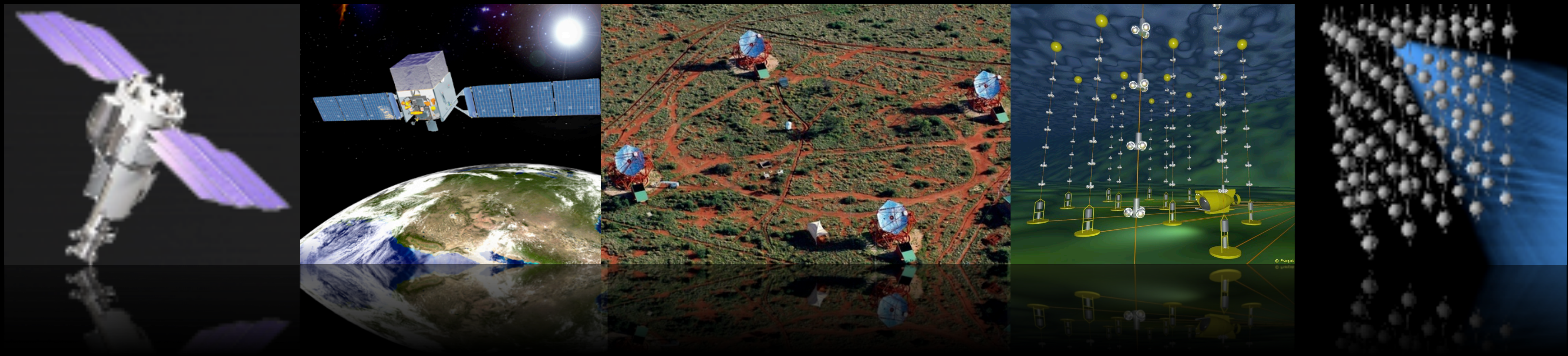
Irfu - CEA Saclay

Indirect detection technique



Neutrino telescopes

- *AMANDA, ICECUBE*
- *ANTARES*

Anti-matter telescopes

- *PAMELA*
- *ATIC, PPB-BETS*

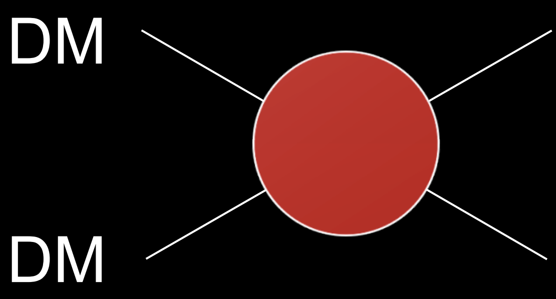
Gamma-ray telescopes

- Ground based: *CANGAROO, HESS, MAGIC, MILAGRO, VERITAS*
- Satellite: *Fermi*

Other

- Radio to microwave emission from synchrotron
- Gammas from ICS and SSC
- …

Indirect detection technique



SM: $b, W^+, Z, \tau^+, \ldots$

Primary channels

SM: $\bar{b}, W^-, Z, \tau^-, \ldots$

Hadronisation and/or decay

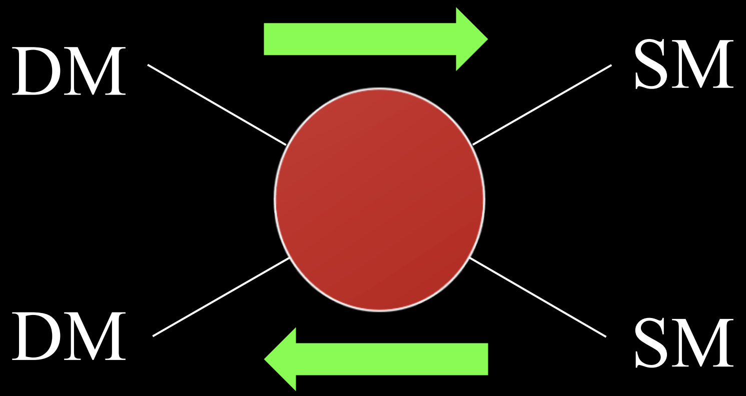
$\Rightarrow \gamma, e^+, \overset{(-)}{p}, \nu, \ldots$

Final states

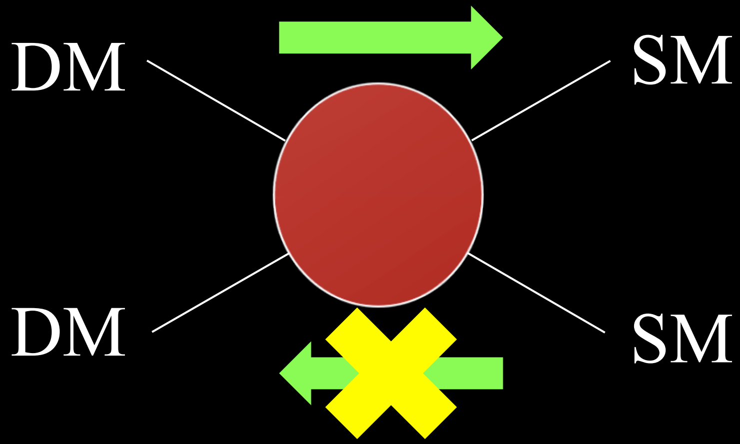
$\Rightarrow \gamma, e^-, \overset{(-)}{p}, \nu, \ldots$

Why annihilations?

Early Universe



Today



Estimate of the relic density:

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\sigma v}$$

Electroweak scale cross section can reproduce the correct relic density

- **Natural scale for $\sigma v \sim 10^{-26}$ cm^{3}s^{-1}**
- Neutralino LSP in SUSY and KK in UED are good candidates!

Flux from DM annihilations:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E}(E, \Delta\Omega) = \frac{1}{4\pi} \frac{\sigma v}{m^2} \frac{\mathrm{d}N}{\mathrm{d}E} \bar{J} \Delta\Omega$$

- Input from extensions of the Standard Model of particle physics on the DM particle
- Distribution of DM along the line of sight : halo modelling required

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

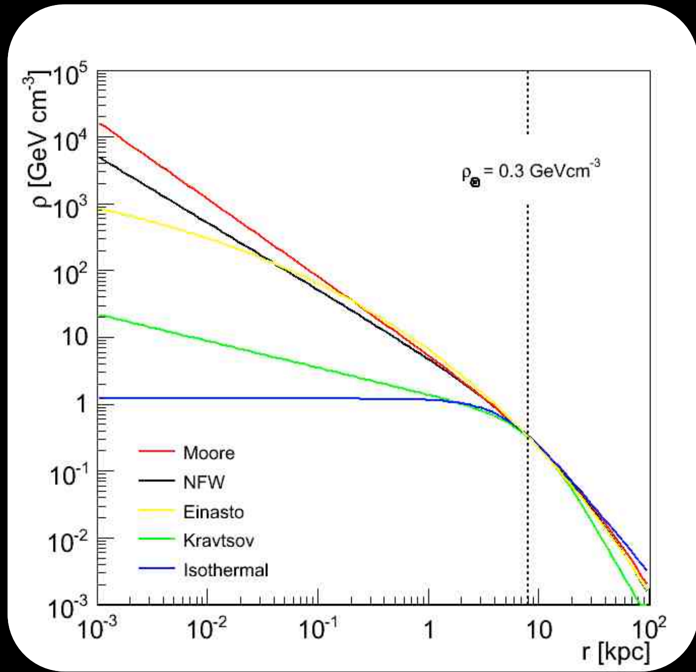
$$\rho_{\rm Buckert}(r) = \frac{\rho_c}{(1+r/r_c)(1+(r/r_c)^2)}$$

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

✓ 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



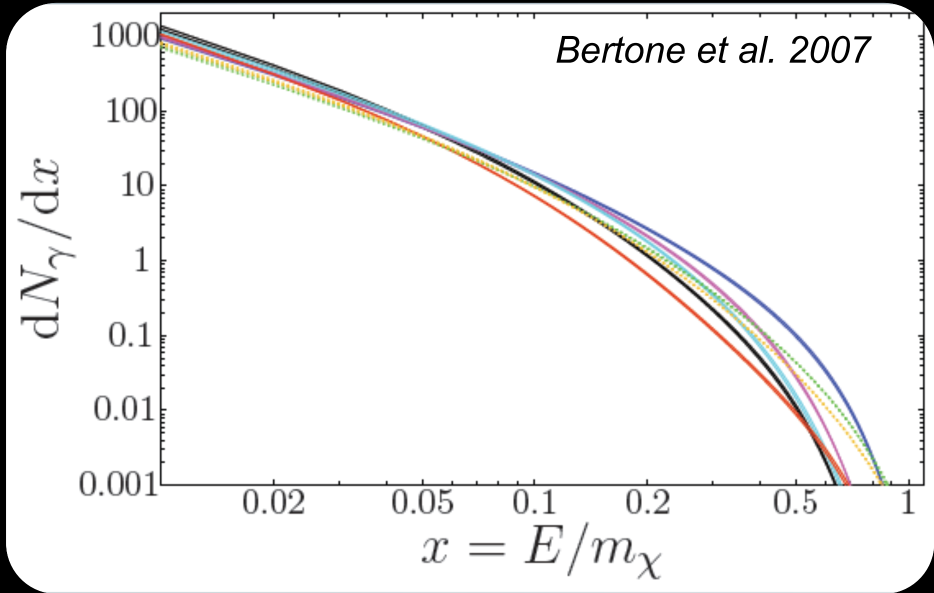
Caveat: the flux towards the Galactic Center may vary by a factor 10^3 or more…

→ situation much better for dwarf galaxies

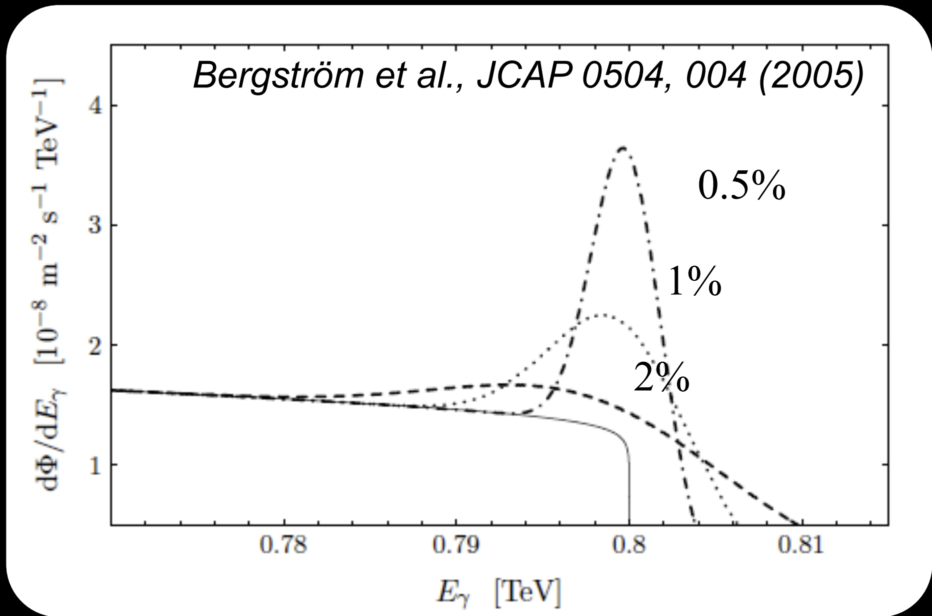
Dark matter annihilation signal

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

Types of signals

- Continuum spectrum with a cut-off at the DM mass: model-independent spectrum
- Mono-energetic line signal: smoking-gun signature

Boost factors

○ Particle physics enhancement:

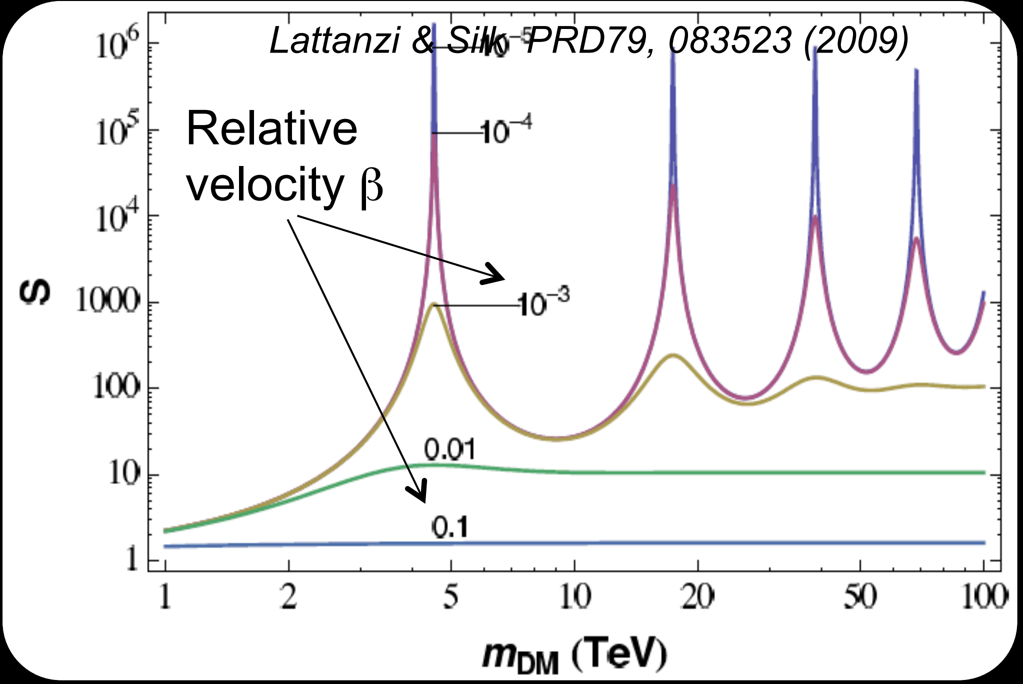
– Sommerfeld effect (1931)

→ particularly effective in the low-velocity regime

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

→ resonant effect at

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



→ expected to be important for winos

Dark matter annihilation signal

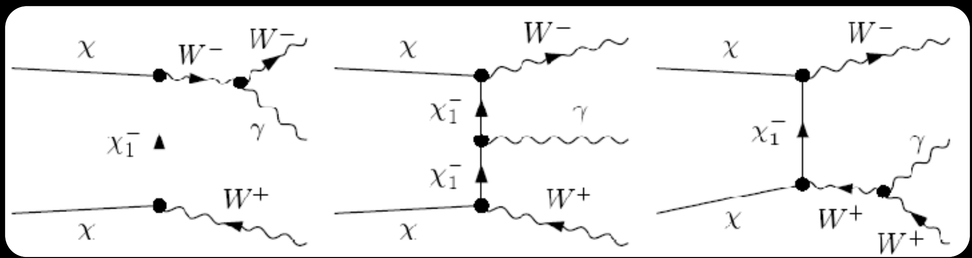
Types of signals

- Continuum spectrum with a cut-off at the DM mass
- Mono-energetic line signal

Boost factors

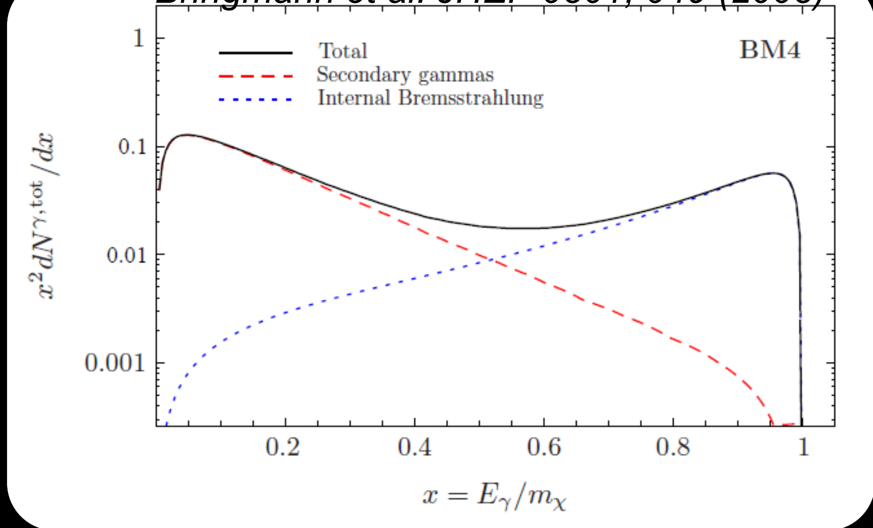
○ Particle physics enhancement:

- Sommerfeld effect (1931)
- Internal bremsstrahlung when charged final states 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

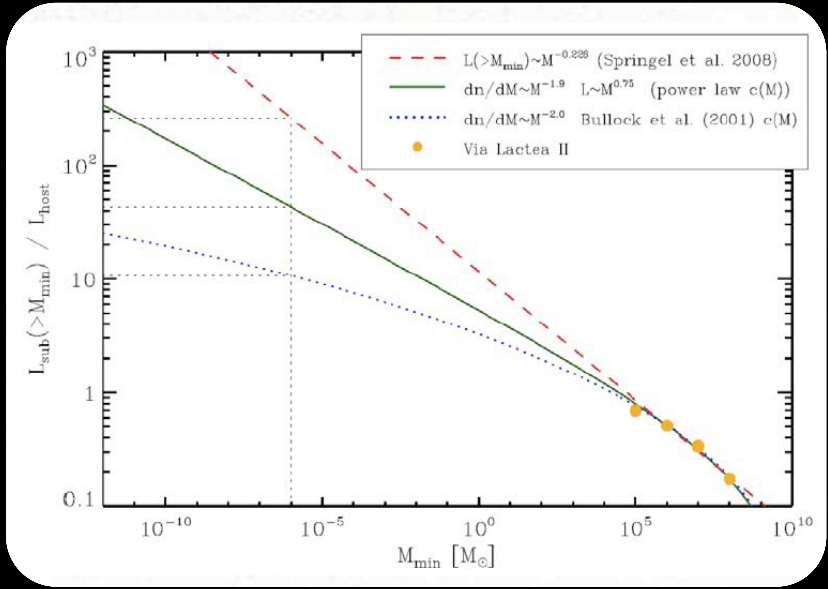
Types of signals

- Continuum spectrum with a cut-off at the DM mass
- Mono-energetic line 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



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

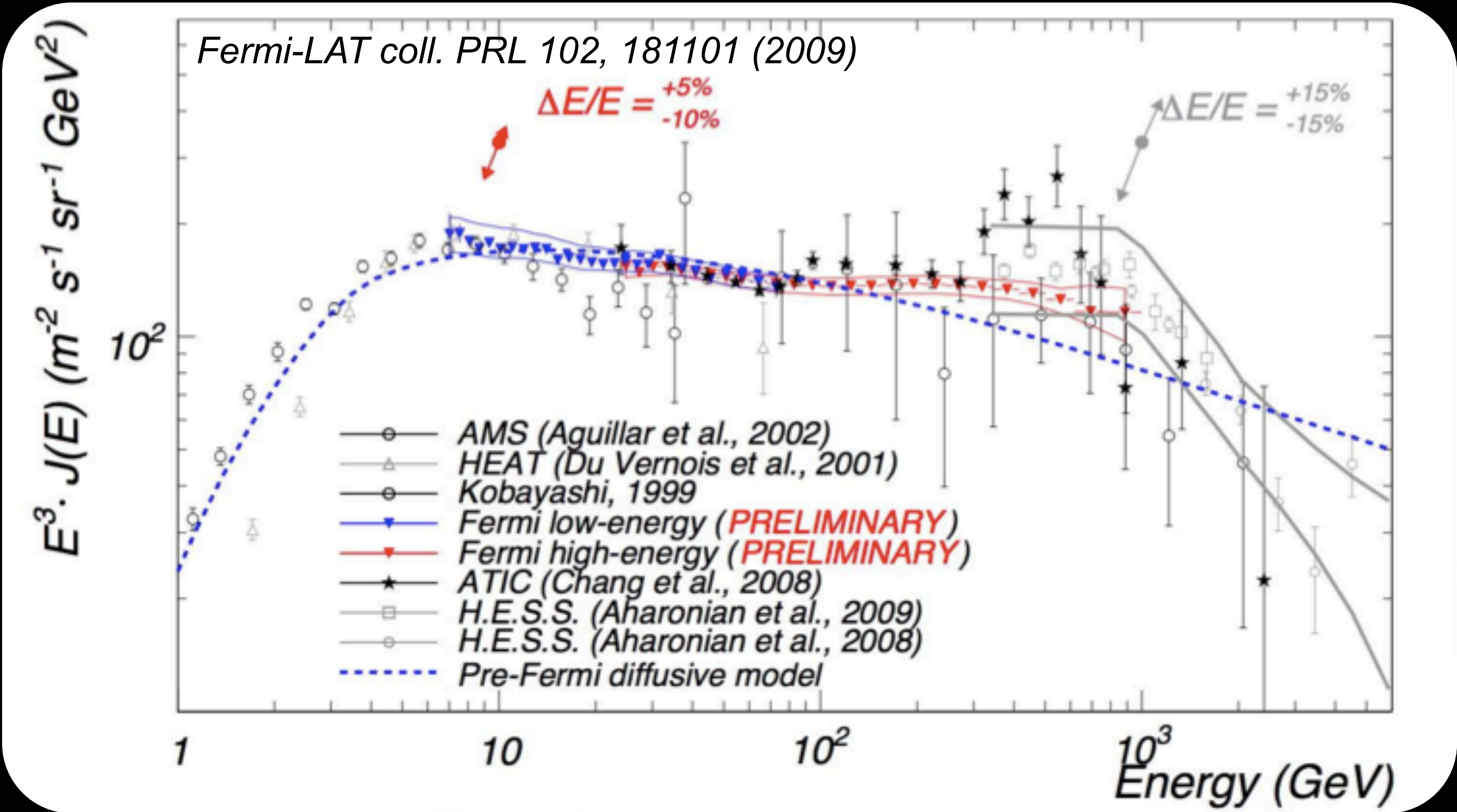
Galactic halo
- Large statistics
- Galactic diffuse background

Also:
- Galaxy clusters
- Lower signal
- Low background

- Electrons!

Aquarius, Springel et al. Nature 2008

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

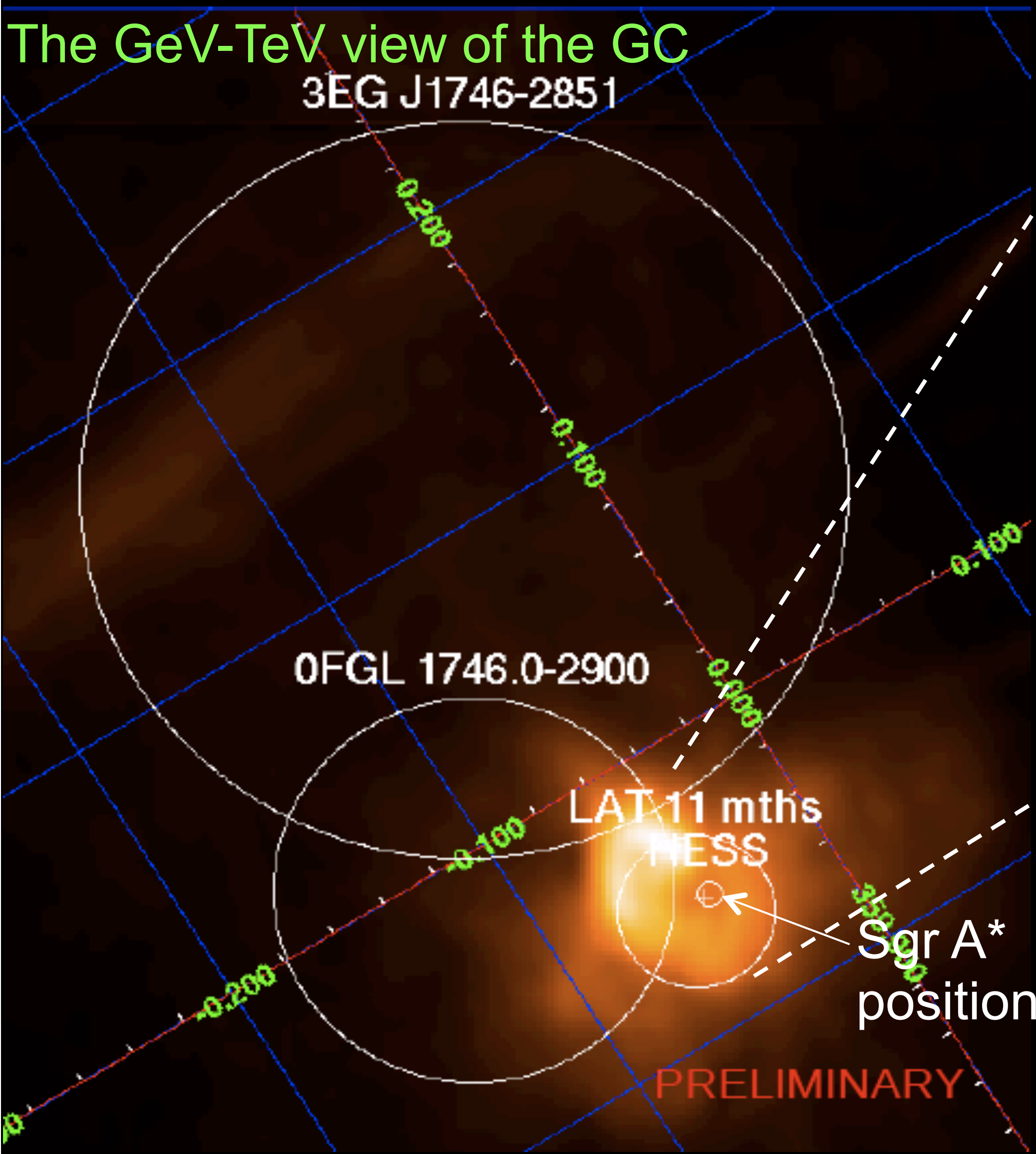
→ DM annihilation interpretation plausible :
- requires DM annihilating preferentially into *leptons* to avoid an over-production of antiprotons
- large boost factor required O(10^3)

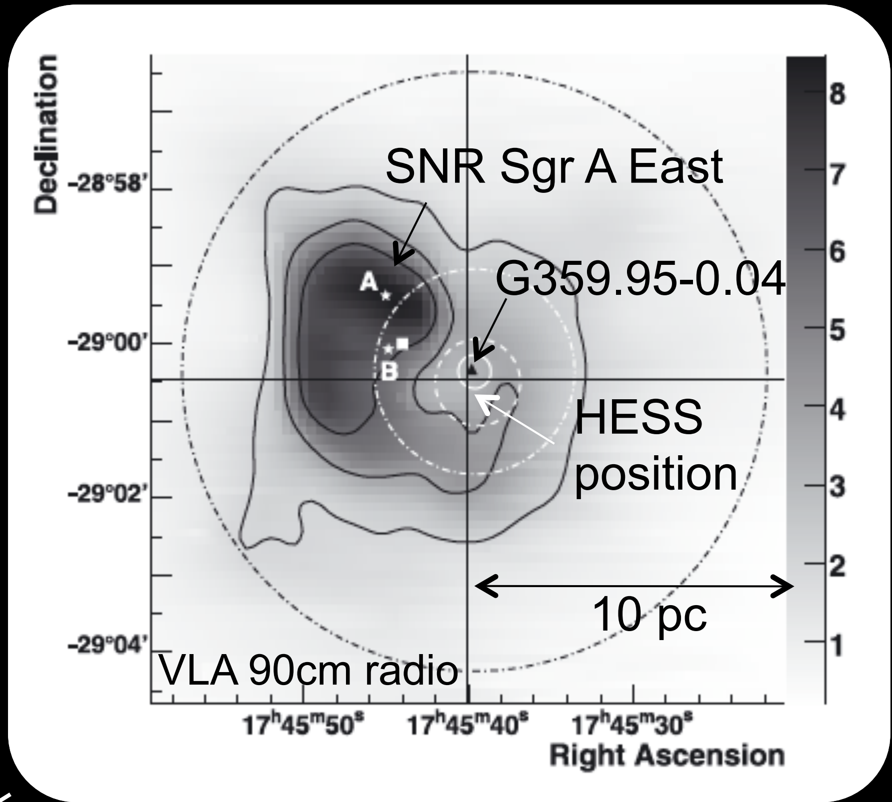
[Bergstrom et al. PRL 103, 031103 (2009)]

→ 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)]

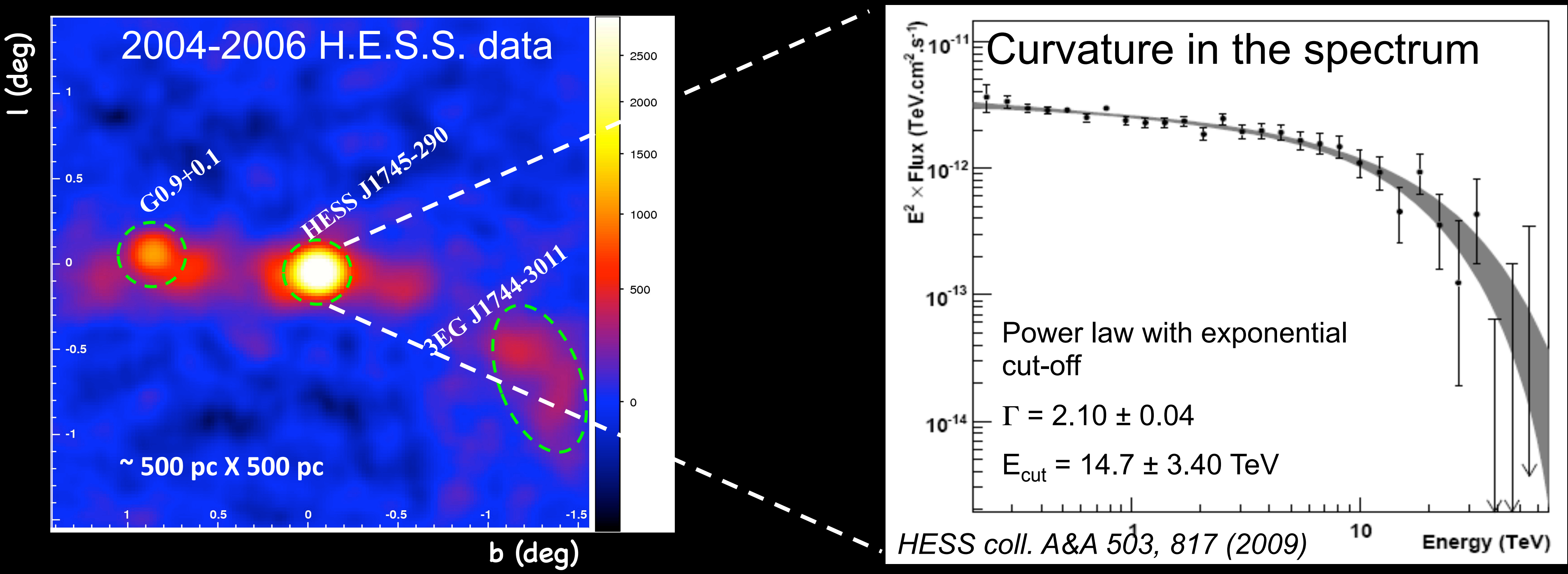
The Galactic Center source: what did we learn?





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

The TeV signal from the Galactic Center



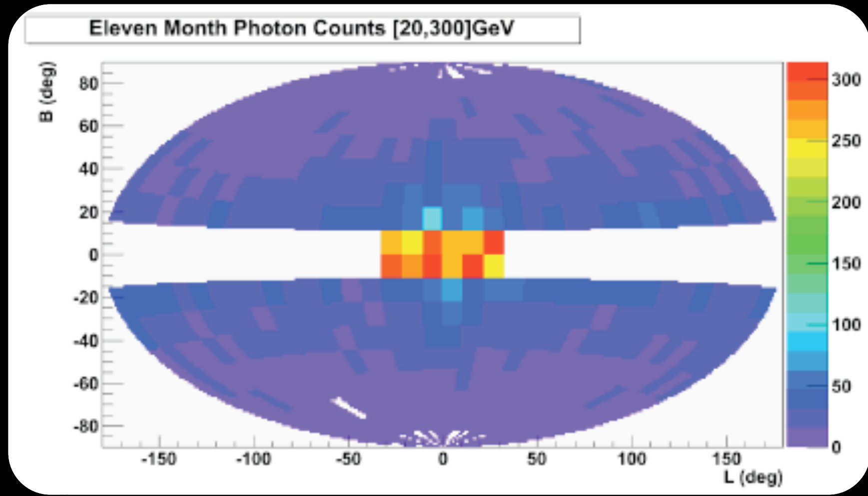
- ○ strong emission (>10% of Crab >1 TeV)
- ○ point like source
- ○ constant flux: 1 γ/min

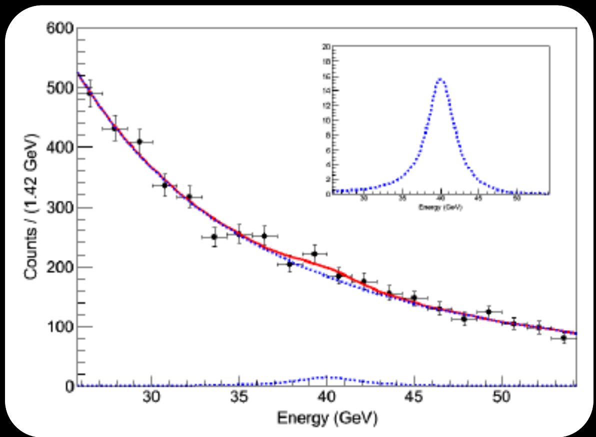
A DM contribution is not excluded: estimated to be < 10%

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

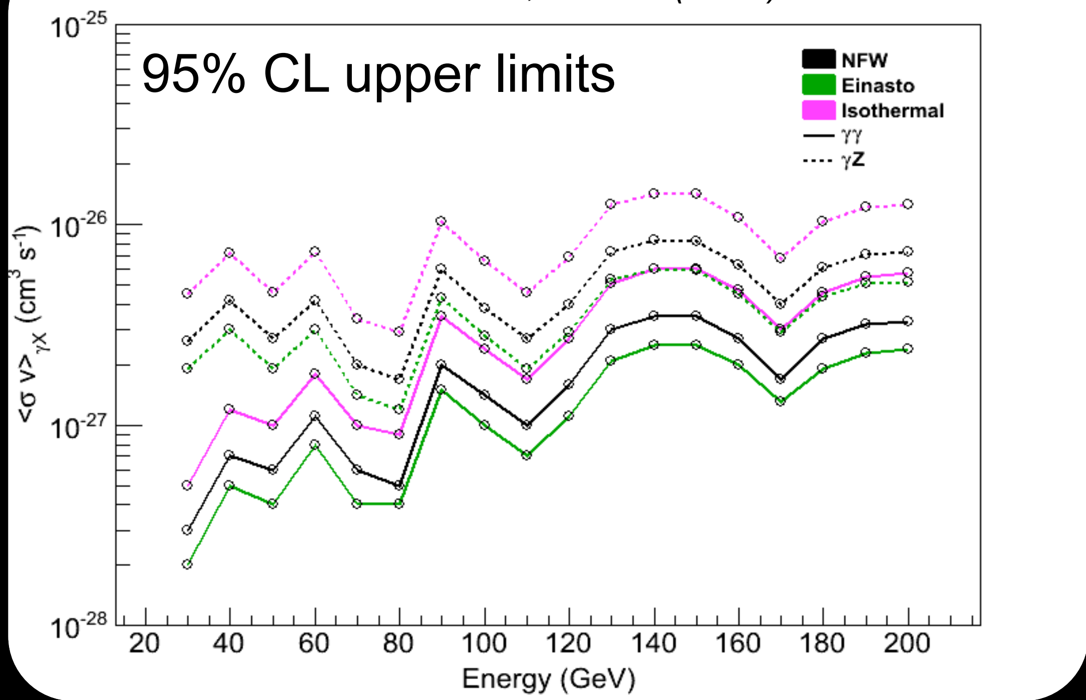
Line searches in the halo with Fermi

- ROI: b>10 and 20x20 around GC
- Galactic plane and point sources excluded
- Sources removed for b > 10





Fermi-LAT coll. PRL104,091302 (2010)

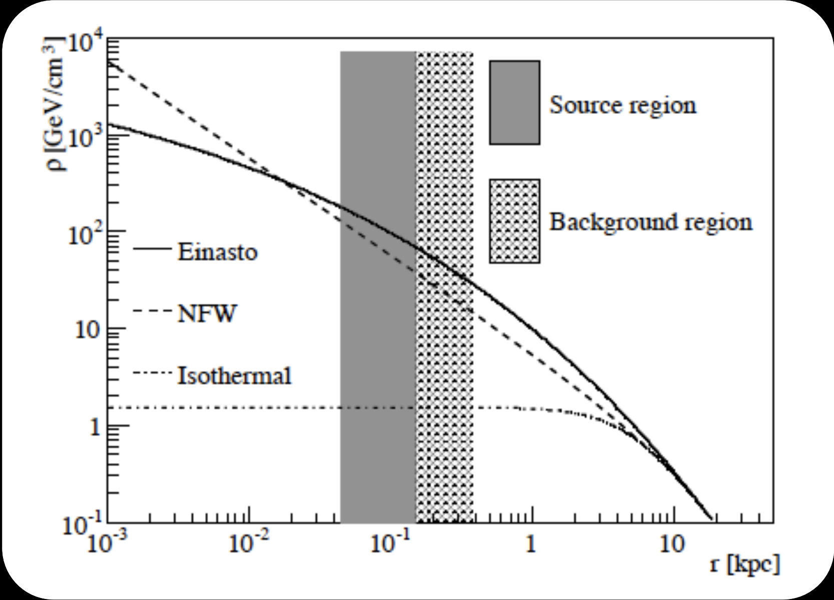


Constraints at least one order of magnitude weaker
to probe thermally-produced DM

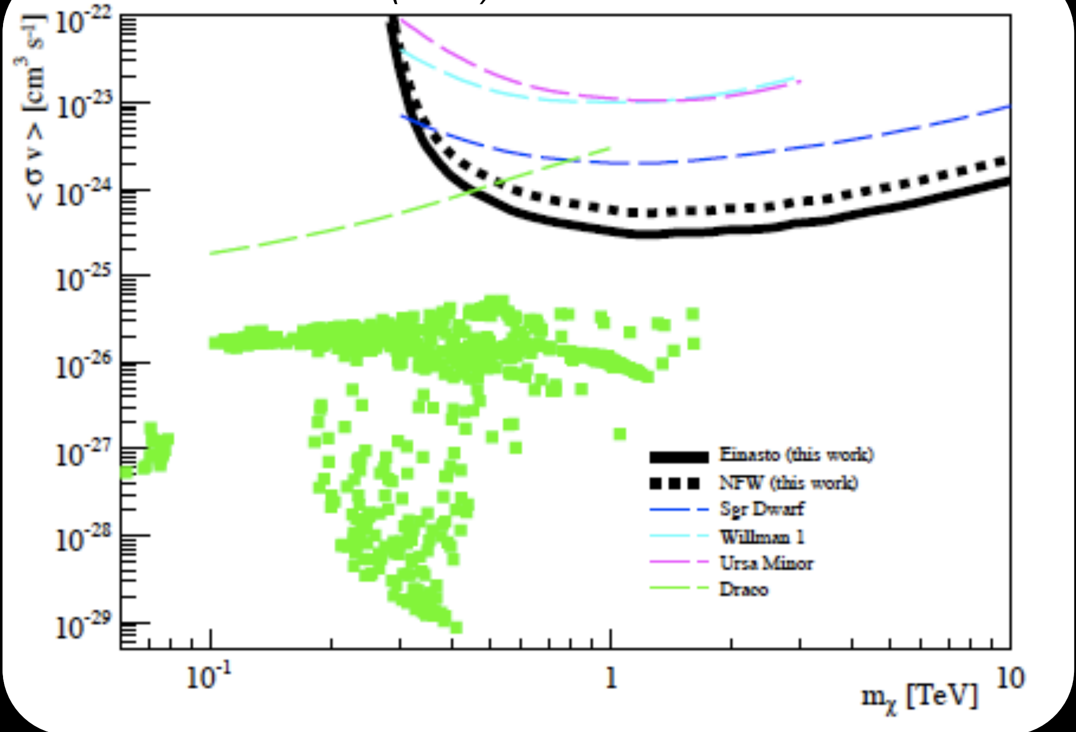
Constraints from the Galactic halo in the TeV range

- 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, Galactic plane excluded



HESS coll. PRL (2011)

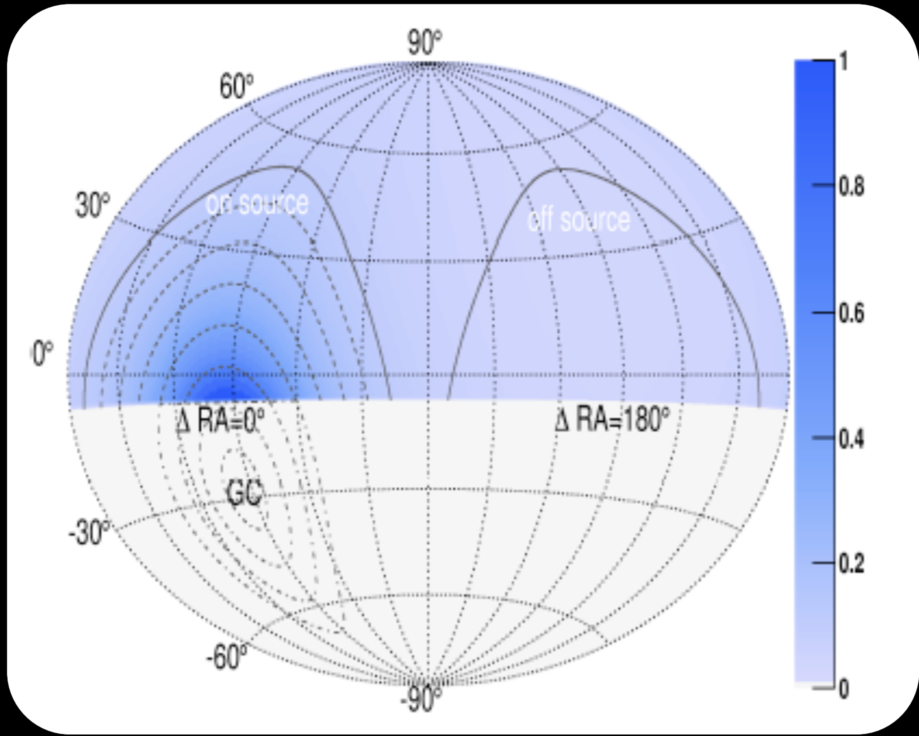


- Among the most sensitive so far at VHE: 3×10^{-25} cm^3 s^{-1} @1 TeV for Einasto profile
- Upper limits are still one order of magnitude too weak

Constraints from the Galactic halo with neutrinos

- IceCube : 276 days of data (2007-2008) from the 22-string onfiguration detector

→ Look for spatially-extended excess neutrino using the point source sky map

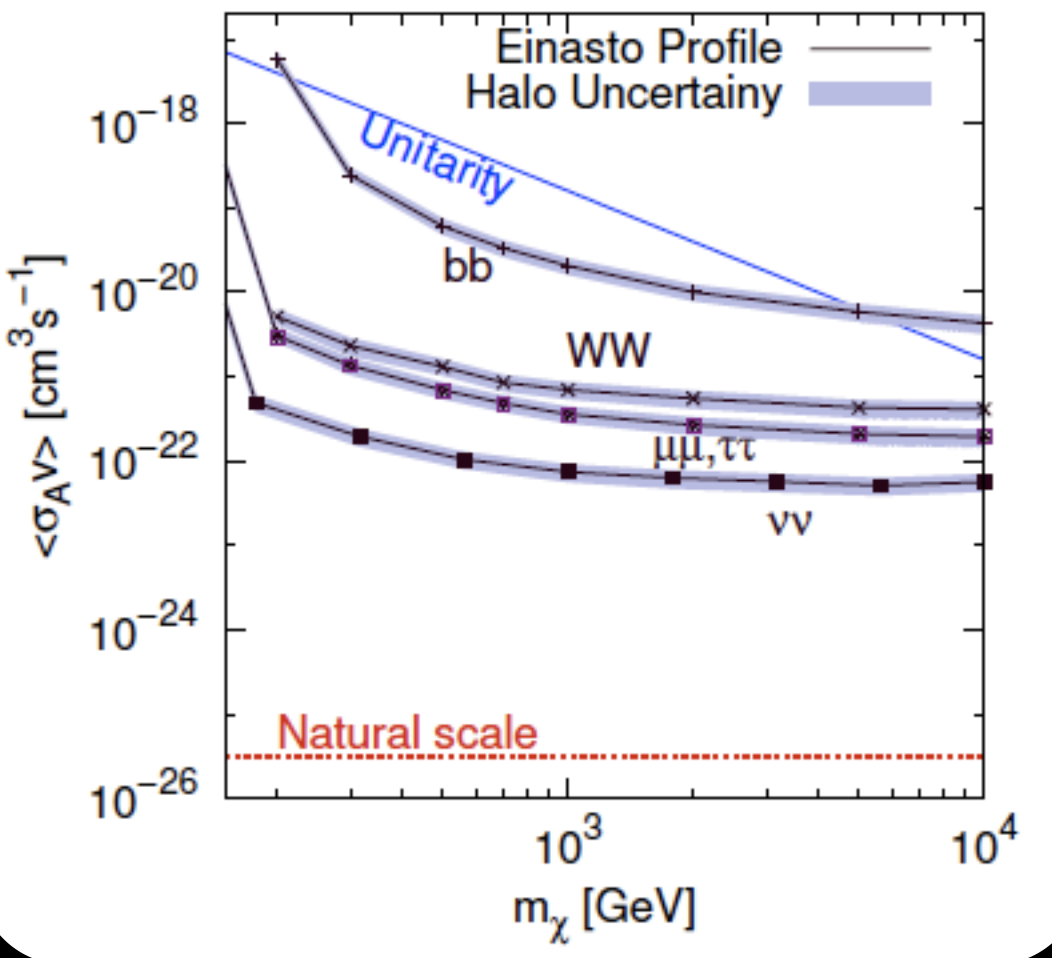


Constraints from the Galactic halo with neutrinos

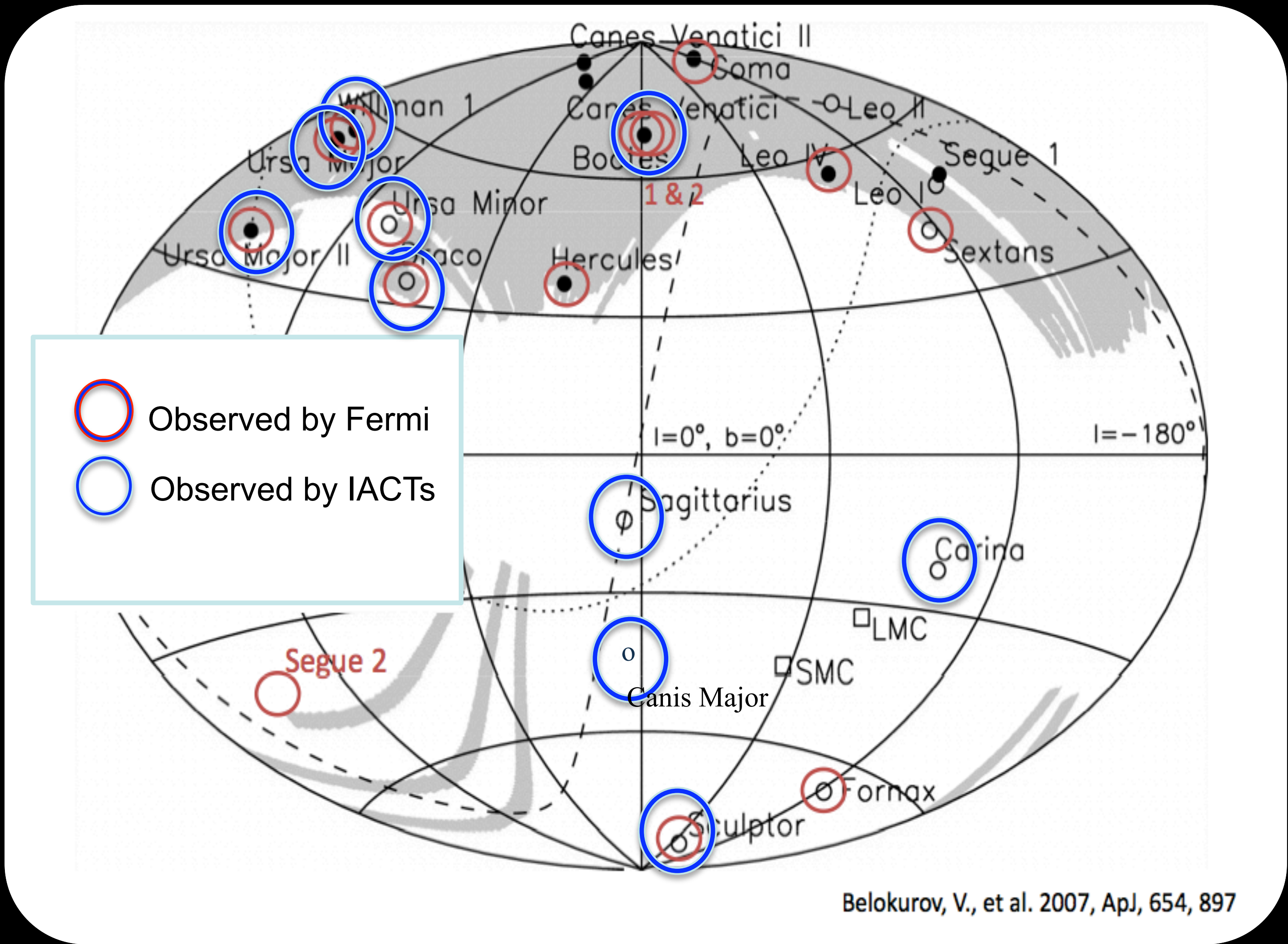
- IceCube : 276 days of data (2007-2008) from the 22-string configuration detector
- Exclusion limits:
  10^{-22} cm^3s^{-1} for 1 TeV neutrino lines
- Cleaner analysis than for the solar DM

Constraints 3 to 4 orders of magnitude weaker to probe natural values

IceCube coll. arXiv:1101.3349



Dwarf satellite galaxies of the Milky Way



- 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

✓ Fermi observations of high latitude objects

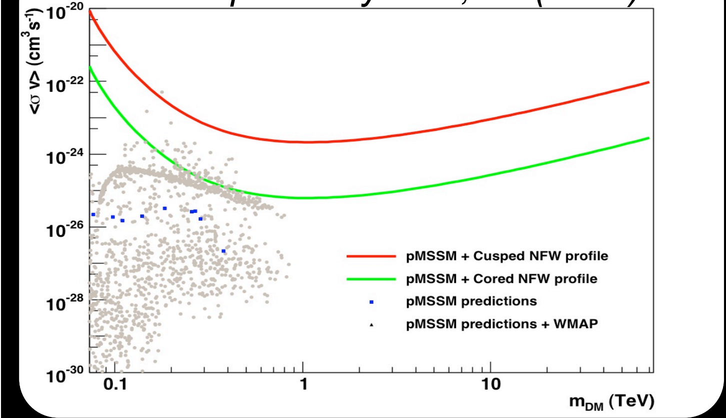
✓ Several dwarf galaxies already observed by IACTs

Constraints towards dwarf galaxies

❑ HESS:

- 2006 Sagittarius: 11 h

Astropart. Phys. 29, 55 (2008)



- 2007 Canis Major: 9 h

ApJ 691, 175 (2009)

- 2008/2009 Sculptor, Carina

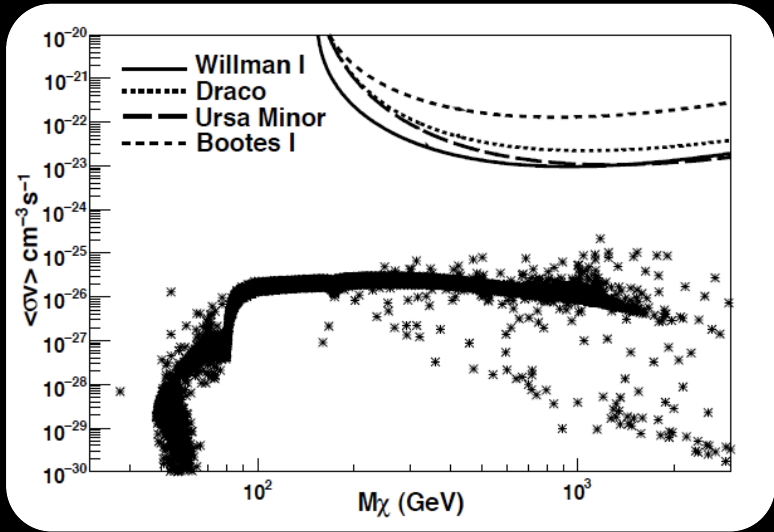
Astropart. Phys. 34, 608 (2011)

❑ VERITAS:

Draco (20h), Ursa Minor (20 h)

Willman 1: 15h

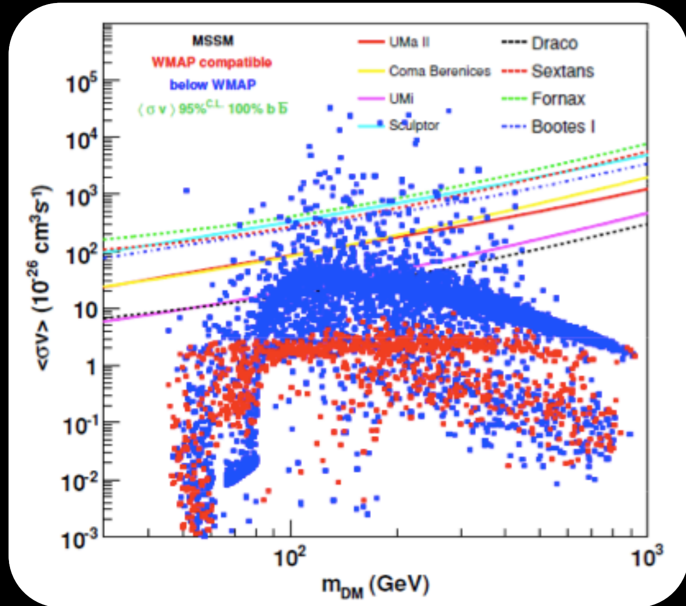
ApJ 720, 1174 (2010)



❑ Fermi:

High latitude (|b|>30°) 11 months

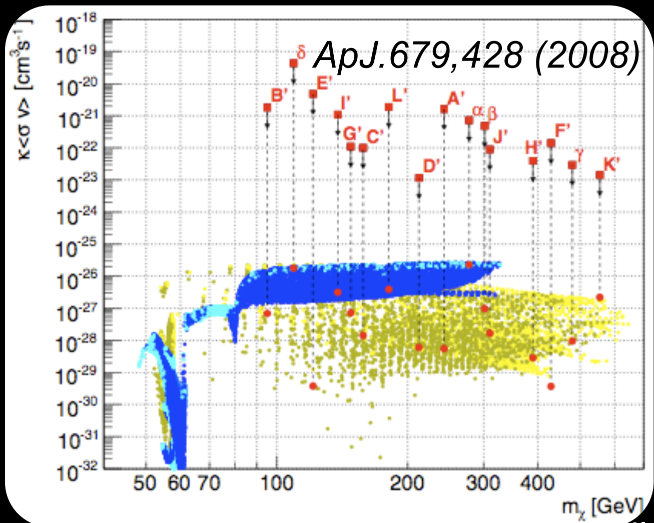
ApJ 712, 147 (2010)



❑ MAGIC:

- 2008 Draco: 8 h
- 2009 Willman 1: 15 h

ApJ 697, 1299 (2009)



- ○ Only upper limits ...
- ○ … but start to be very competitive
- ○ Complementary limits between Fermi and IACTs

The case for Sculptor dwarf

- Halo modelling : NFW and core profiles

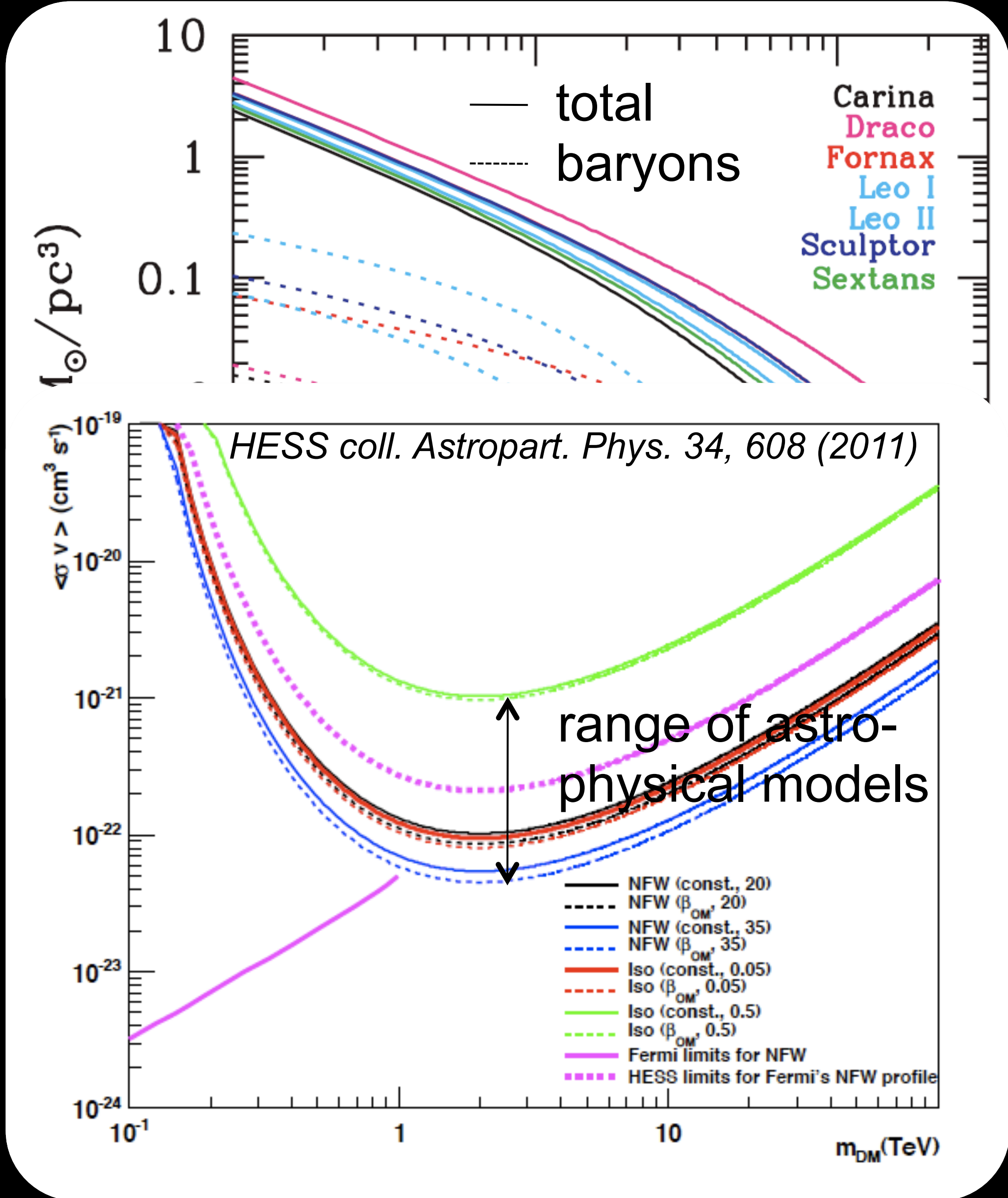
→ models fitted from luminosity profile and velocity dispersion data

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

- Exclusion limits

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

→ about 1 order of magnitude astrophysical uncertainty



The case for Sculptor dwarf

- Halo modelling : NFW and core profiles

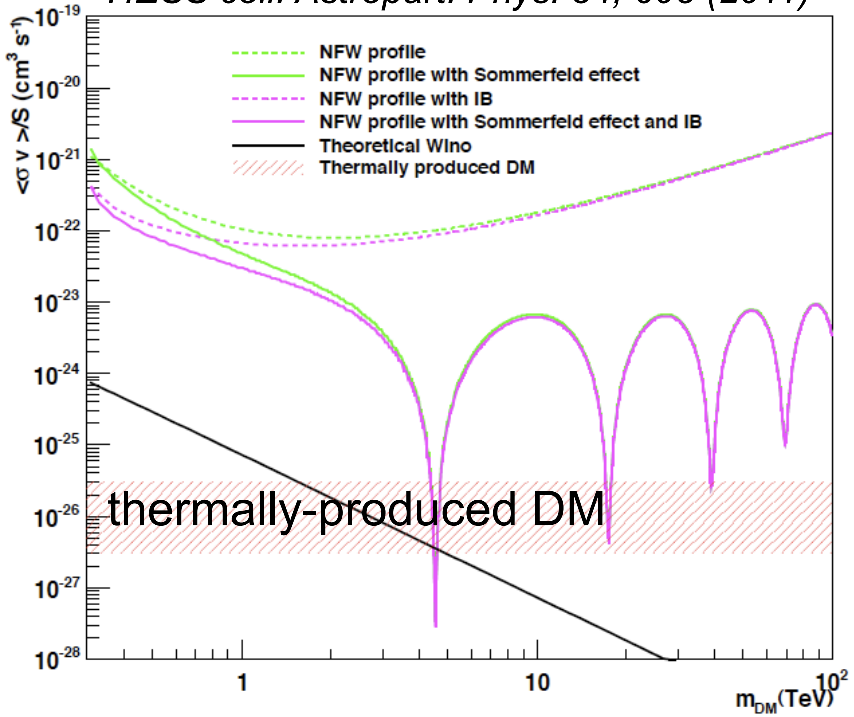
→ models fitted from luminosity profile and velocity dispersion data

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

- Effects of boost factors
  - Sommerfeld effect
    dispersion velocity : 10 kms^{-1}
    → $\beta \sim 2\times10^{-5}$

✓ 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 dwarf

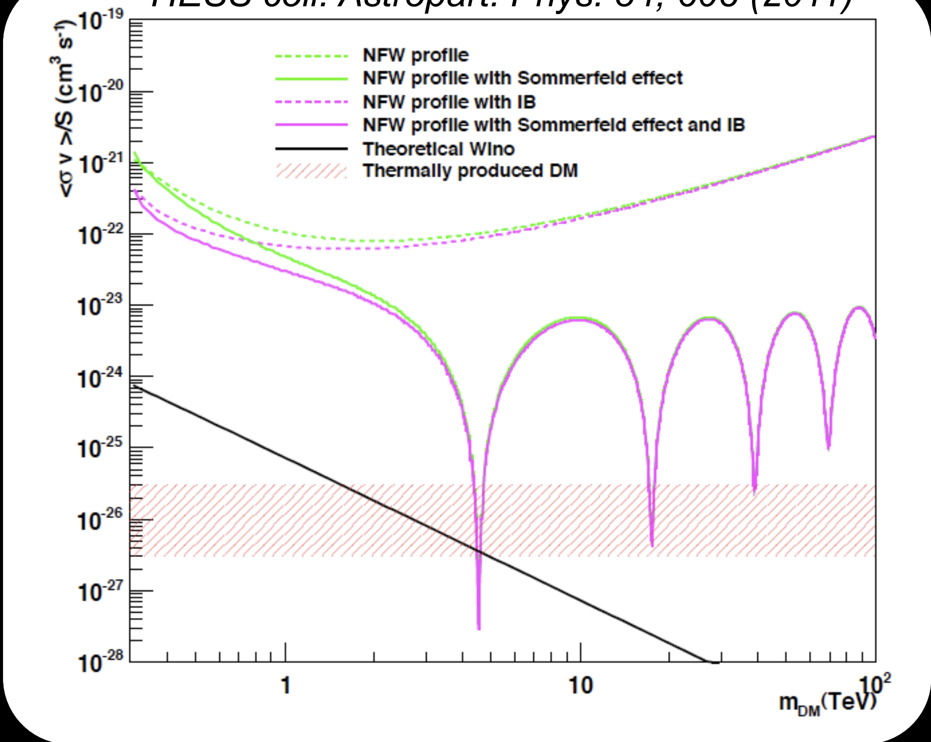
- Halo modelling : NFW and core profiles

→ models fitted from luminosity profile
and velocity dispersion data

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

- Effects of boost factors
  - Sommerfeld effect
  - Substructures enhancement:
  → a few percent for pointlike searches

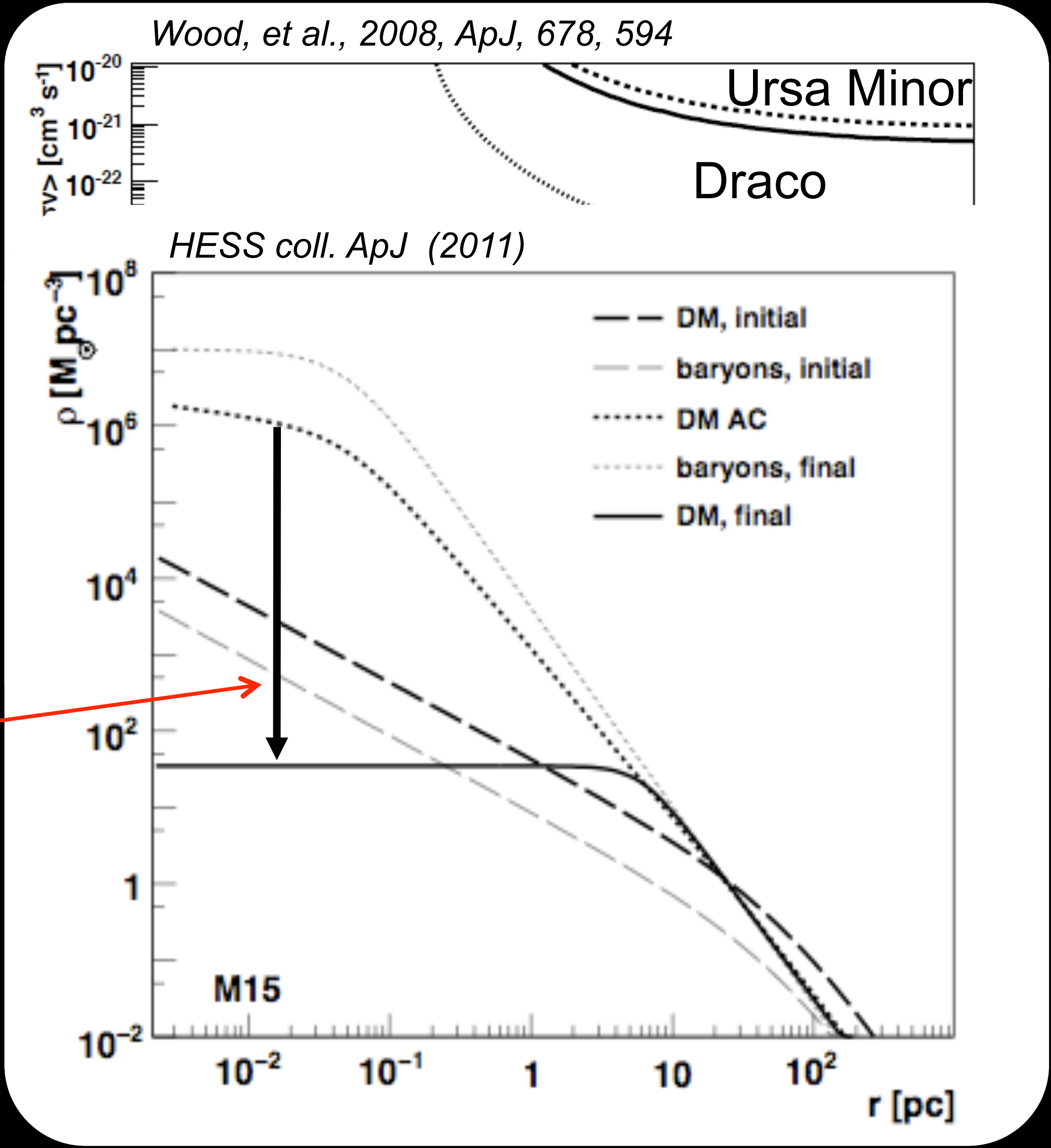
HESS coll. Astropart. Phys. 34, 608 (2011)



Are globular clusters better targets than dwarfs?

- Whipple 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

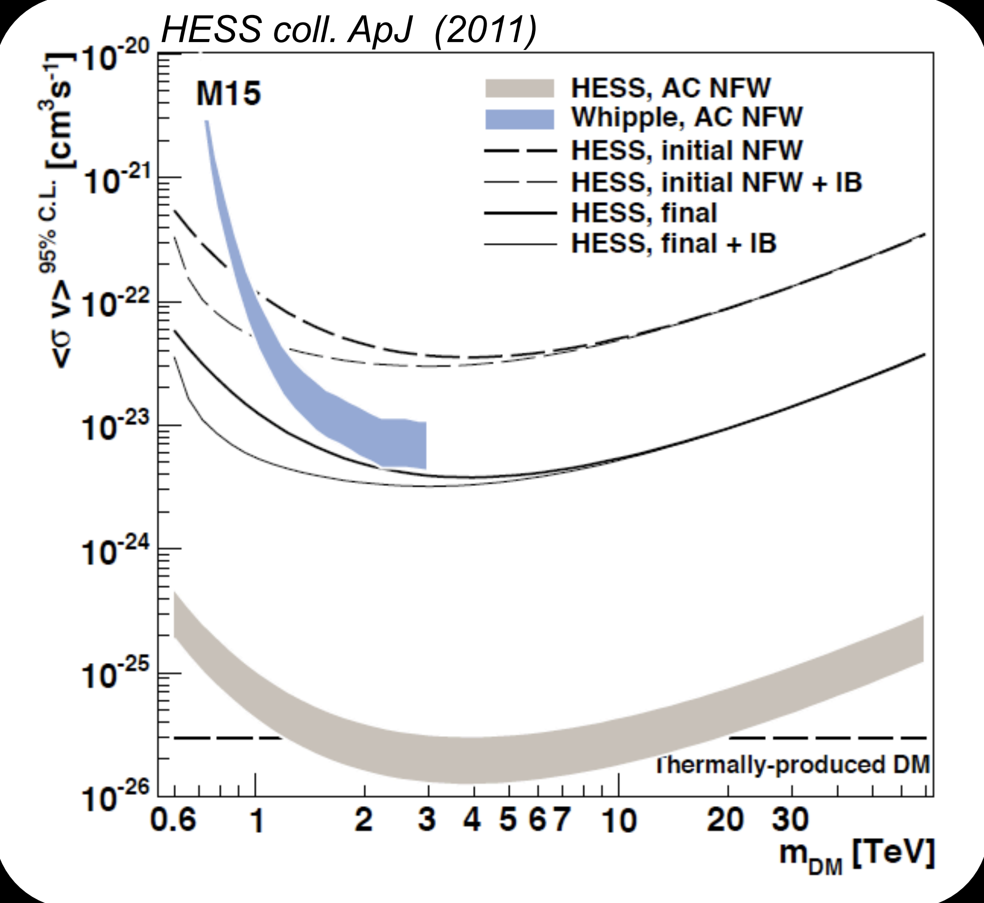
    → depletion of DM in a few relation times



Are globular clusters better targets than dwarfs?

- Whipple 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 of the GC formation scenario yet

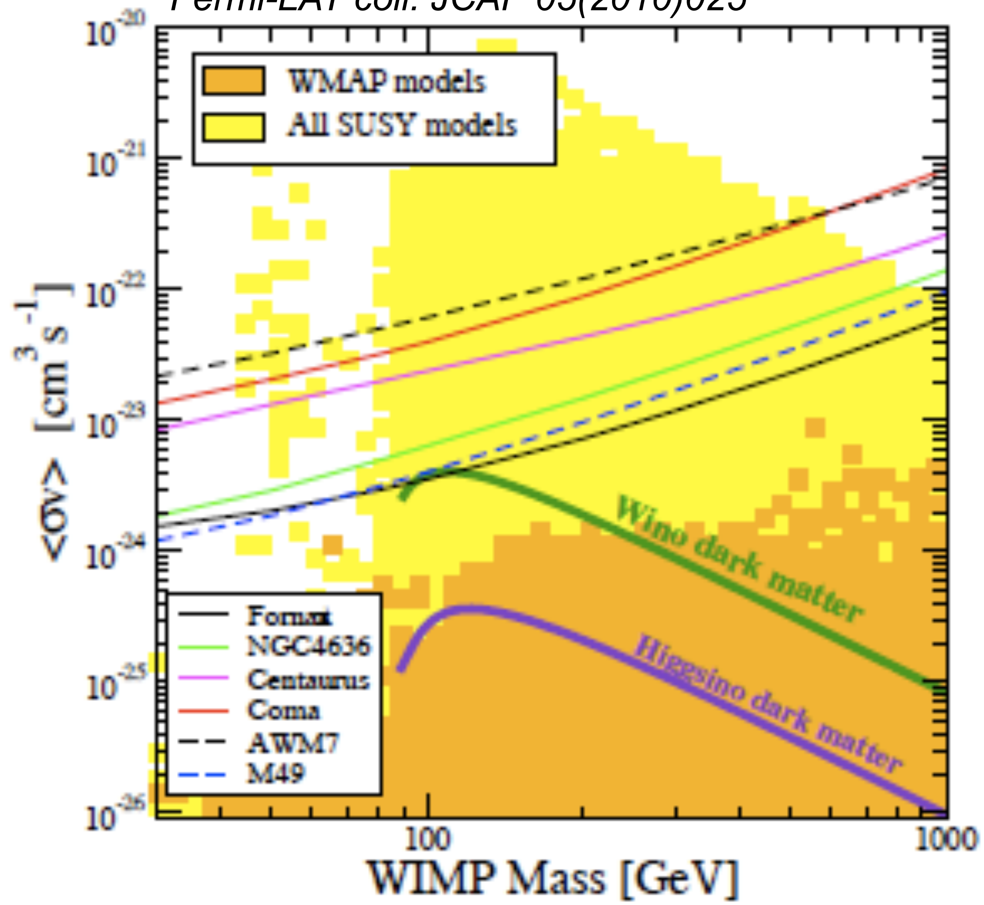


Clusters of galaxies observed by Fermi

- Most massive DM dominated objects
- Halo modelling: NFW

- Exclusion limits
  from 10^{-24} to 10^{-23} cm^3s^{-1}
  → constraints typically weaker
  than dwarfs

Fermi-LAT coll. JCAP 05(2010)025



Clusters of galaxies observed by Fermi

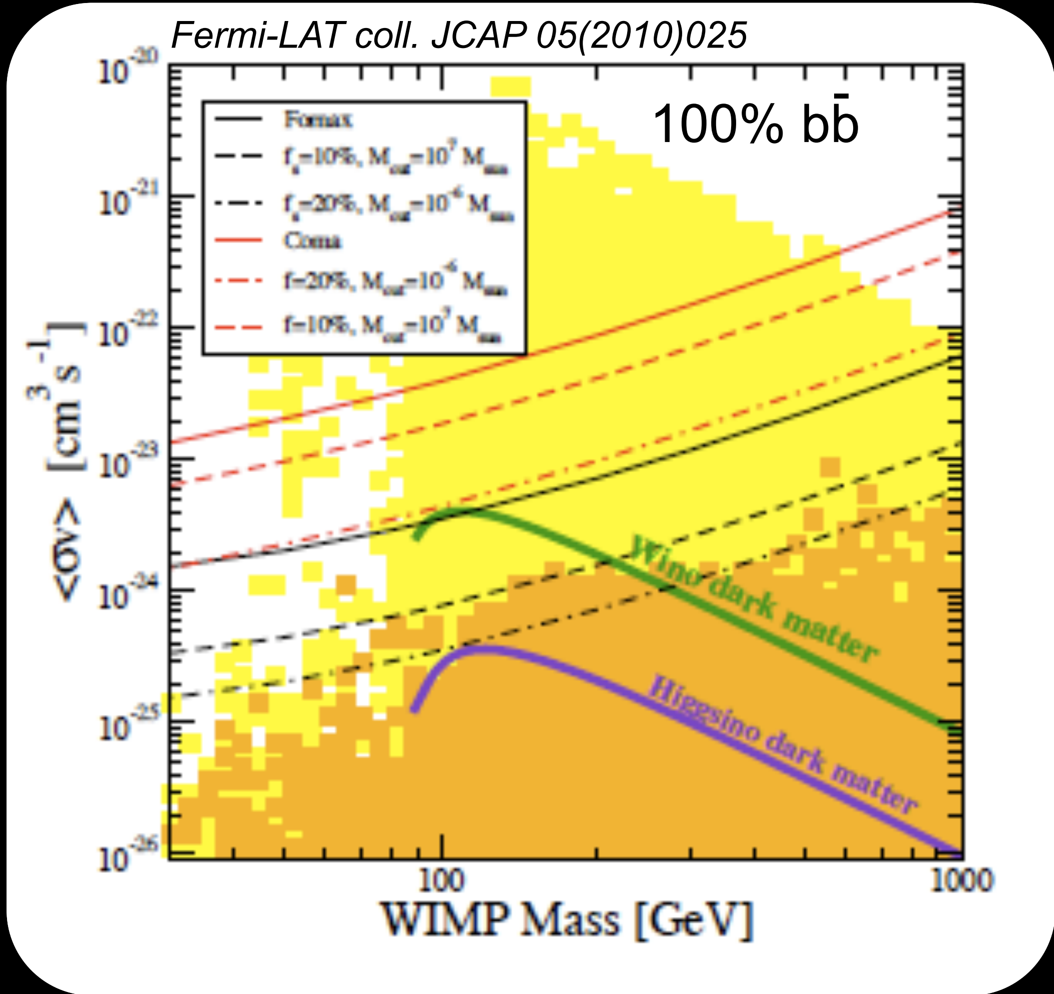
- Most massive DM dominated objects
- Halo modelling: NFW

- Exclusion limits
  from 10^{-24} to 10^{-23} cm^3s^{-1}
  - ✓ effects of substructures

Only smooth halo

Galaxies only

Substructures with
M $>10^{-6}$ M_{sun}



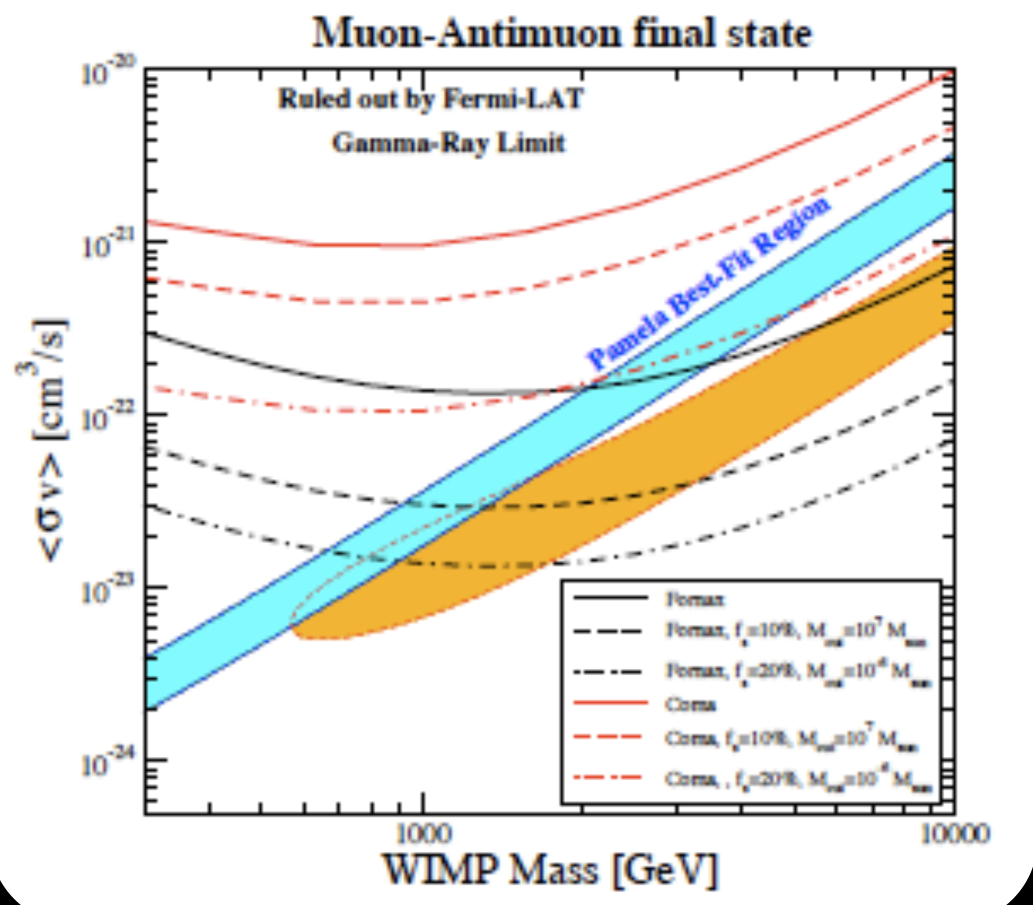
Clusters of galaxies observed by Fermi

- Most massive DM dominated objects
- Halo modelling: NFW

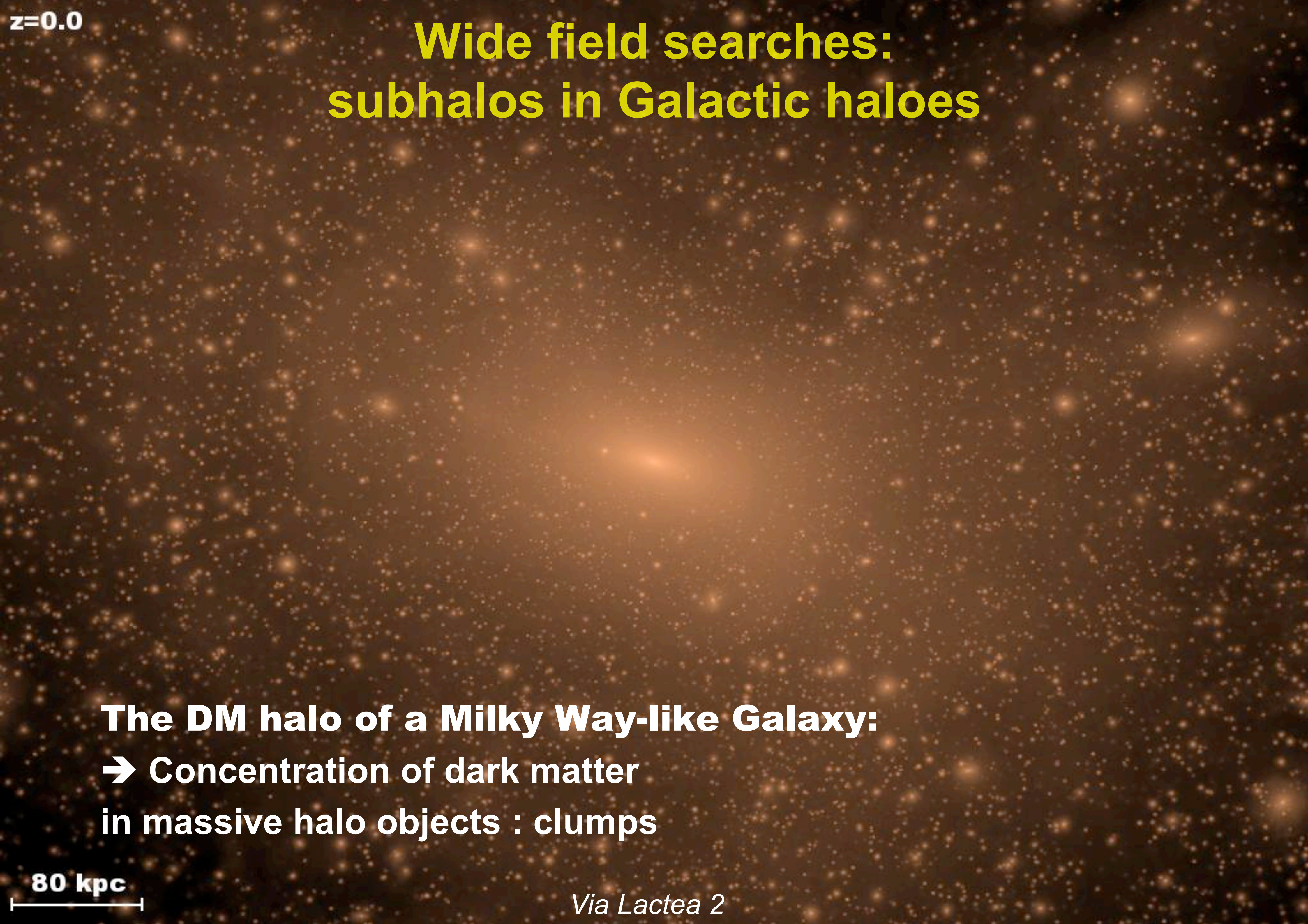
- Exclusion limits
  from 10^{-24} to 10^{-23} $cm^3 s^{-1}$
  - ✓ effects of substructures
  - ✓ leptophilic models :
    $\mu^+\mu^-$ final states FSR and
    IC on CMB

    → models fitting PAMELA data
    above ~2 TeV are excluded

Fermi-LAT coll. JCAP 05(2010)025



Wide field searches:
subhalos in Galactic haloes



The DM halo of a Milky Way-like Galaxy:

➔ Concentration of dark matter

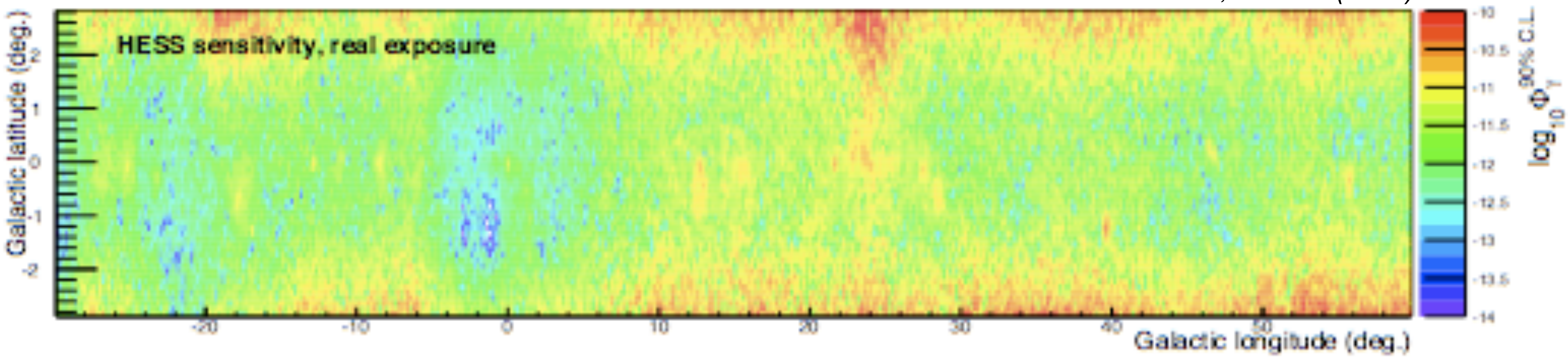
in massive halo objects : clumps

Via Lactea 2

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!

HESS coll. PRD . D78, 072008 (2008)



- No DM clump so far in HESS data!

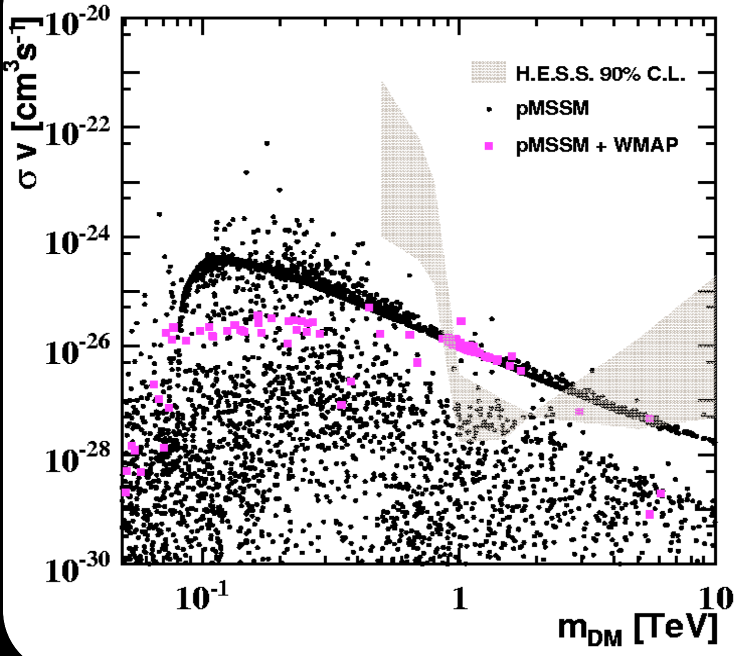
Search for DM subhalos in the Galactic halo

- Require 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, 2005)

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

HESS coll. PRD78, 072008 (2008)

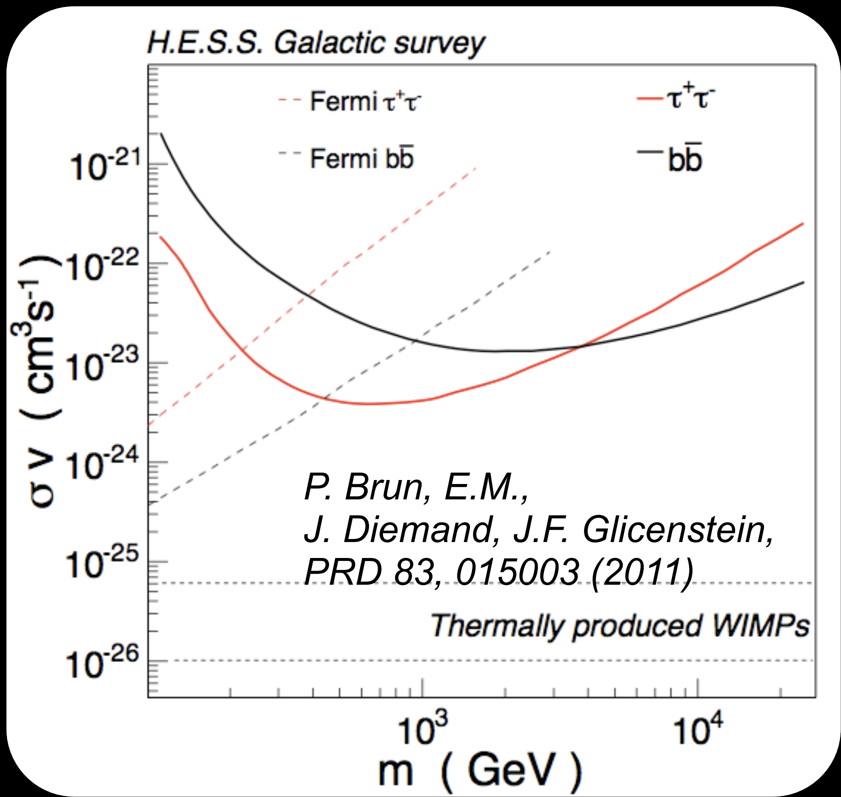


Search for DM subhalos in the Galactic halo

- Require 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

→ Competitive limits wrt dSph limits
→ Results complementary to Fermi ones



Summary

- Galactic Center
  - Bulk of the gamma-ray signal unlikely to be of dark matter origin
  - Standard astrophysical emitters

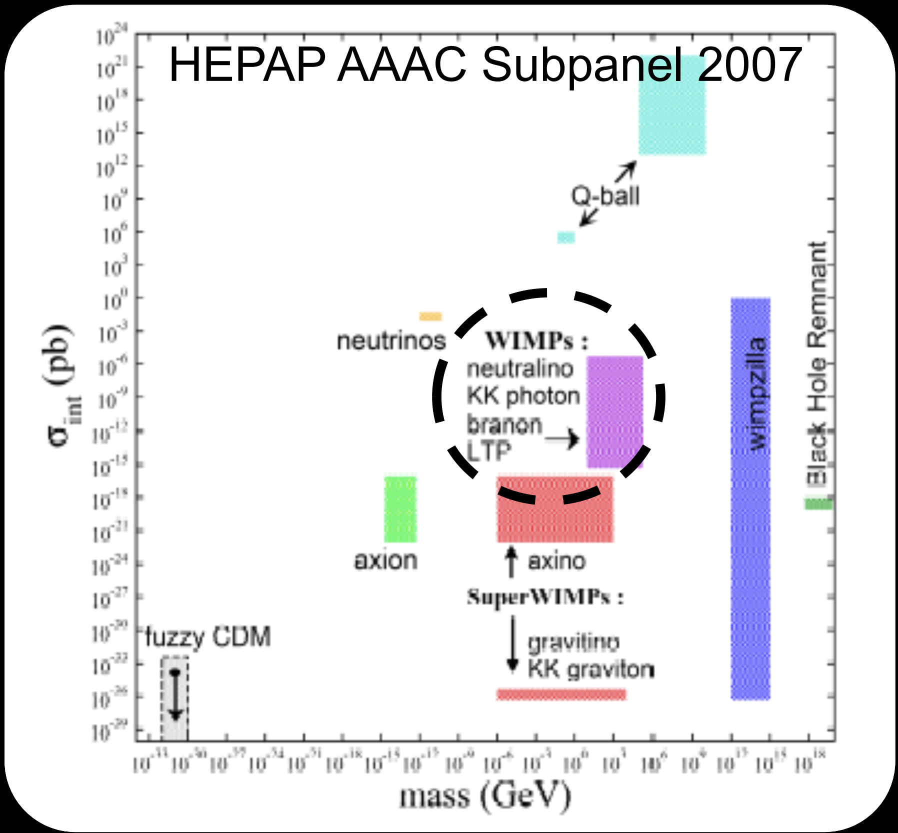
- Most promising DM targets are likely to be :
  - Galactic halo
  - dwarf satellite galaxies
  - substructures in Galactic halo

- DM detection may be just “around the corner”
  - no unambiguous signal so far
  - indirect detection experiments start to probe realistic parameter space of WIMP models

BACK-UP SLIDES

Dark matter candidates

- Numerous extensions of the Standard Model of particle physics predict the existence of a new particle that is a good to account for the dark matter

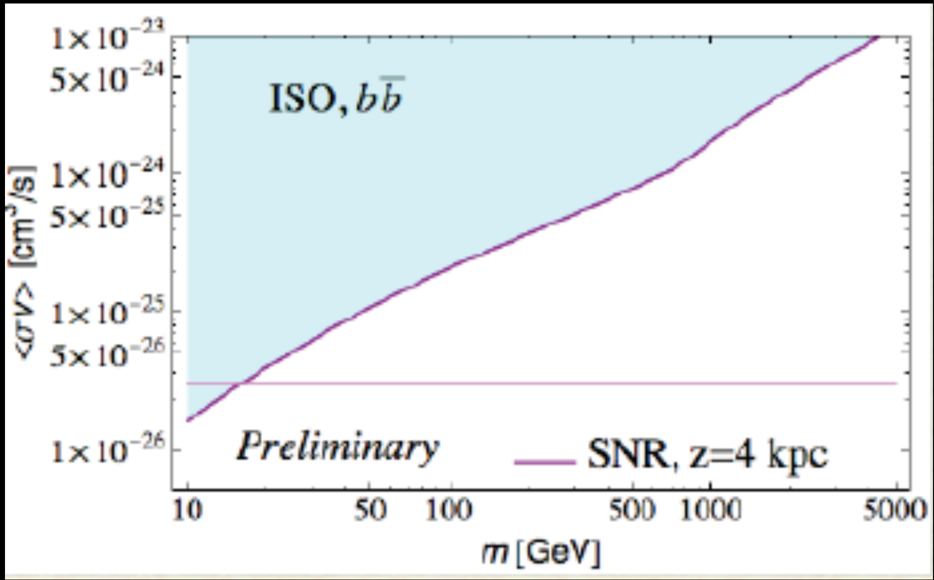


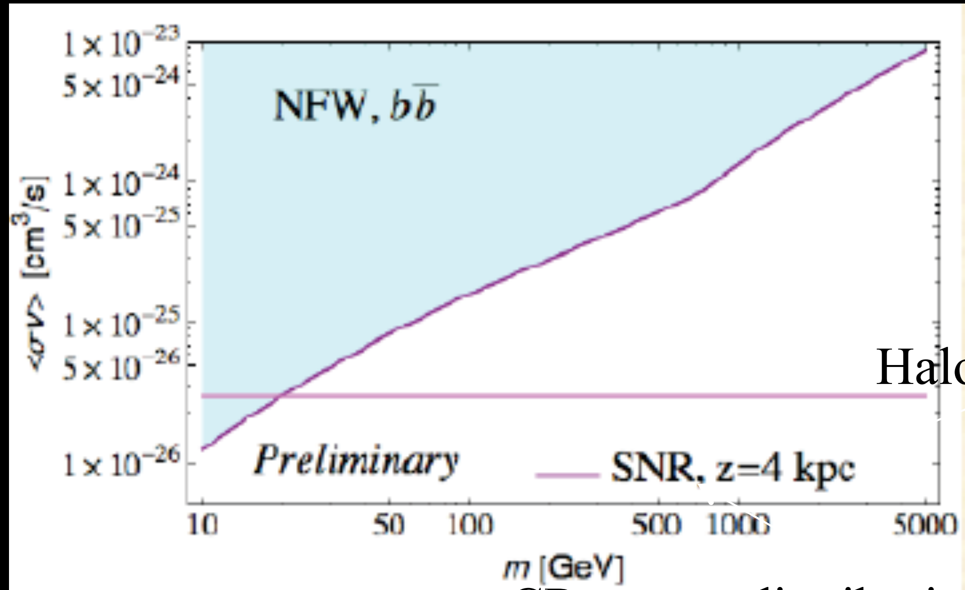
Masses near the electroweak scale are especially motivated

Here, we focus on WIMPs, Weakly Interacting Massive Particles

Galactic Halo Dark Matter Limits (|b|>10°) from Fermi

PRELIMINARY

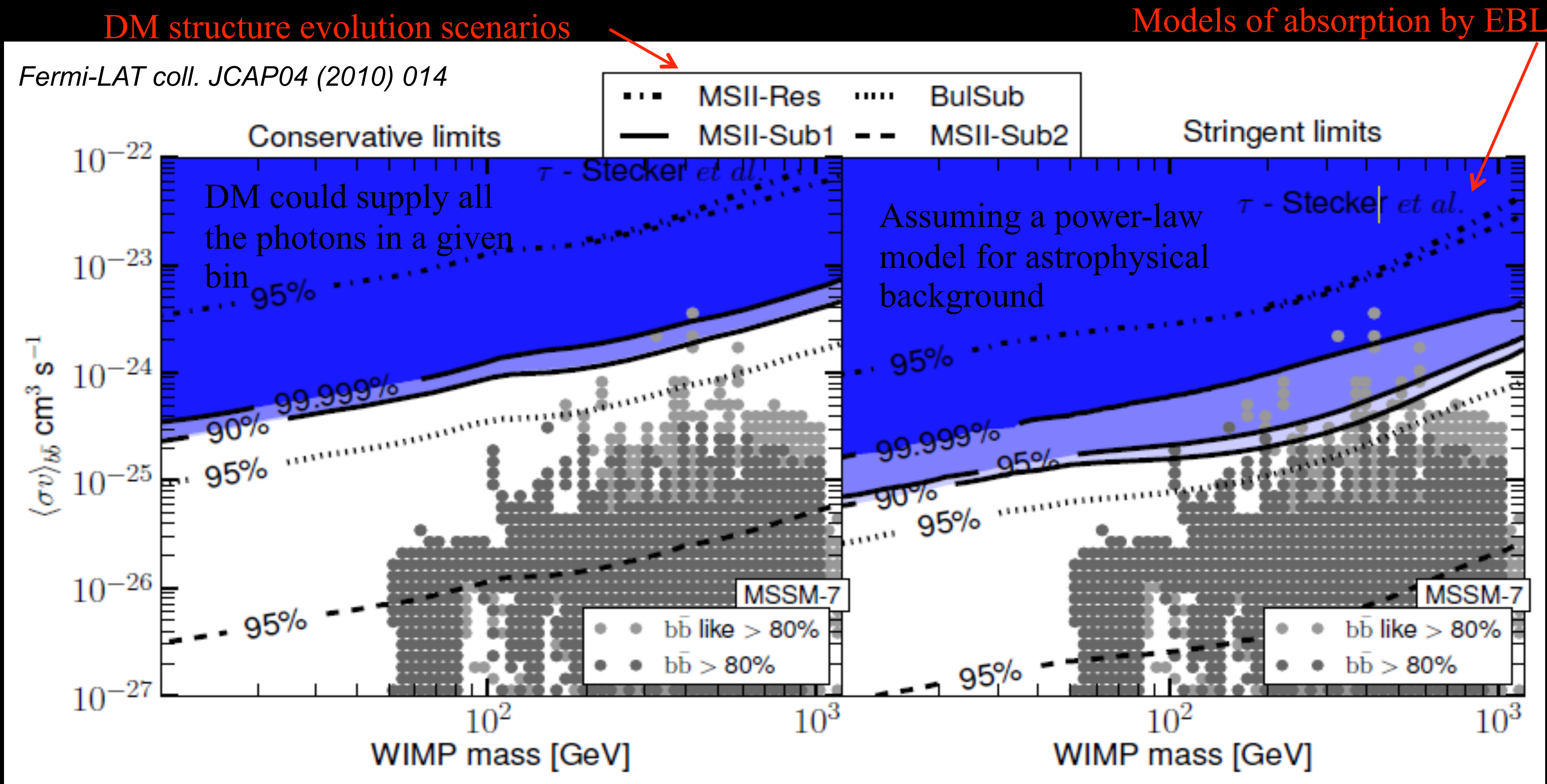




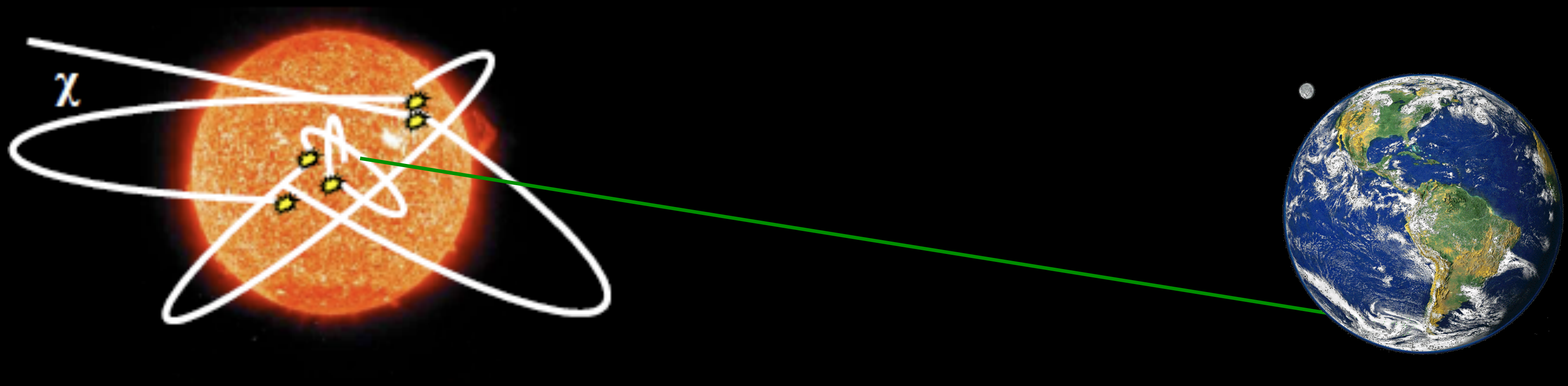
- The diffuse flux from the Galactic halo can be used to set limits on dark matter annihilation.
  - Relies on differences in the angular and spectral distributions of the diffuse production from cosmic rays versus dark matter.
  - Still very preliminary. The constraints are very sensitive to the choice of the Galactic diffuse model. Investigations are still in progress of the dependence of the result on our astrophysical models of the Galaxy (e.g the CR source distribution, halo height, diffusion coef. etc.).

Fermi : Cosmological Dark Matter

The isotropic extragalactic contribution have be interpreted in terms of limits on cosmological dark matter [***Dark matter annihilation*** *in all halos at all red-shifts should contribute]*



Constraints on solar WIMPs with neutrinos



Caveat: some modelling required

- neutrino energy losses after WIMP annihilation
- dependence on DM-nucleon scattering assumptions

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Constraints are very competitive wrt to direct detection