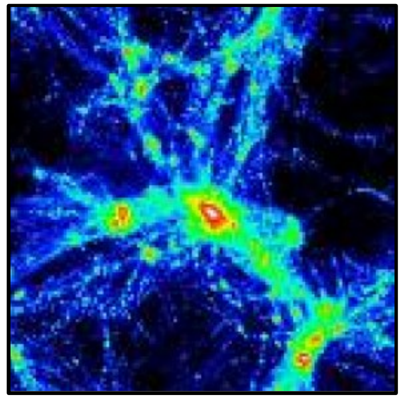
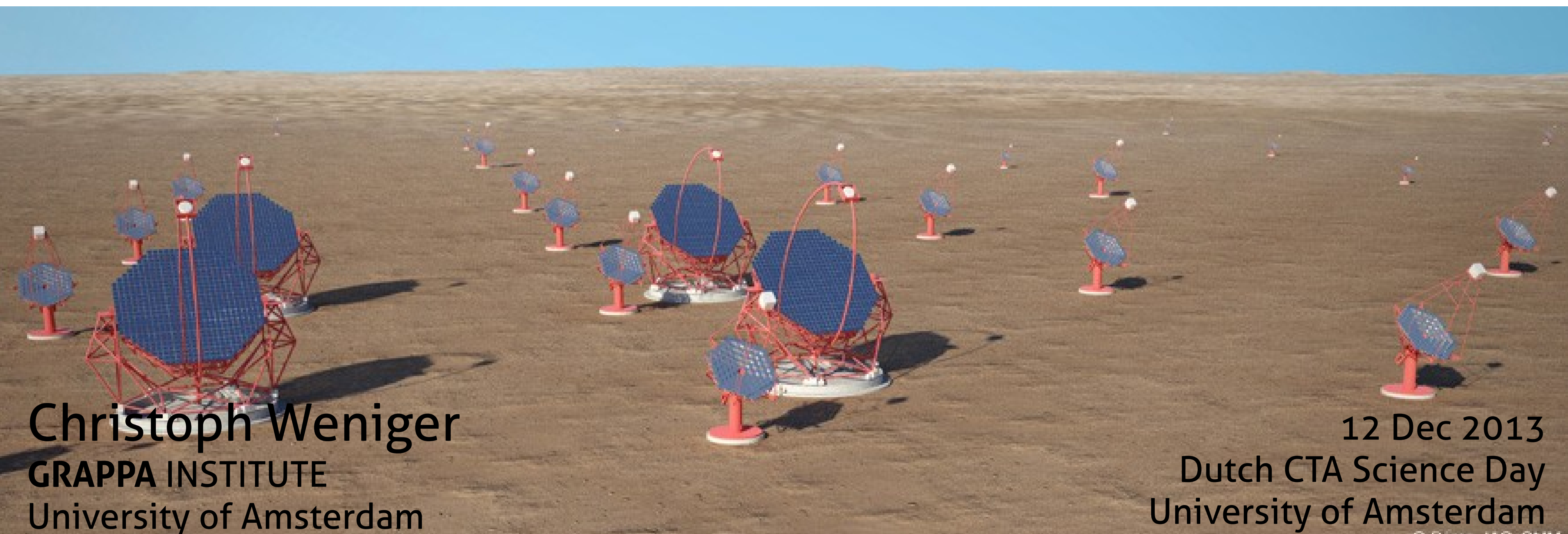
Dark Matter Searches with the Cherenkov Telescope Array





Christoph Weniger
GRAPPA INSTITUTE
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12 Dec 2013
Dutch CTA Science Day
University of Amsterdam

Disclaimer

A) I am a theoretical particle physicist.

My research interest is to determine the *Lagrangian* that describes *dark matter*.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

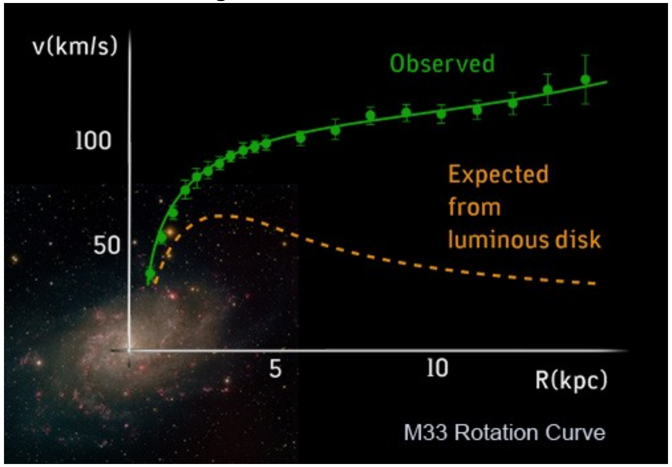
+ DM

B) I am not member of the CTA collaboration right now.

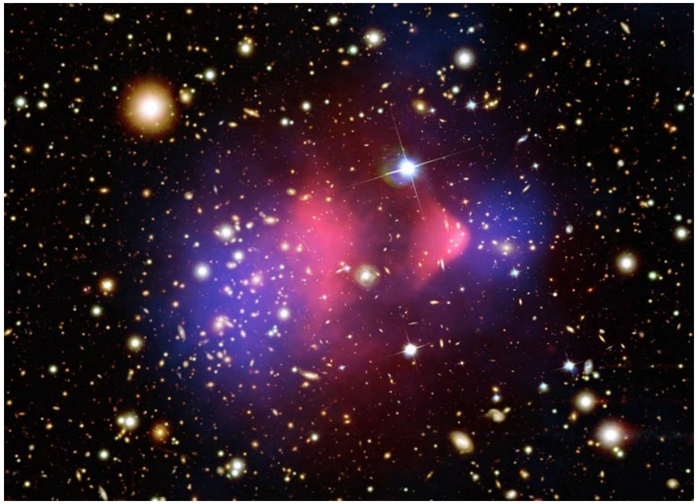
Evidence for dark matter

Evidence for the existence of an invisible “dark” matter component in the Universe comes from different observations at different length scales (from galaxies to cosmology, kpc to Gpc).

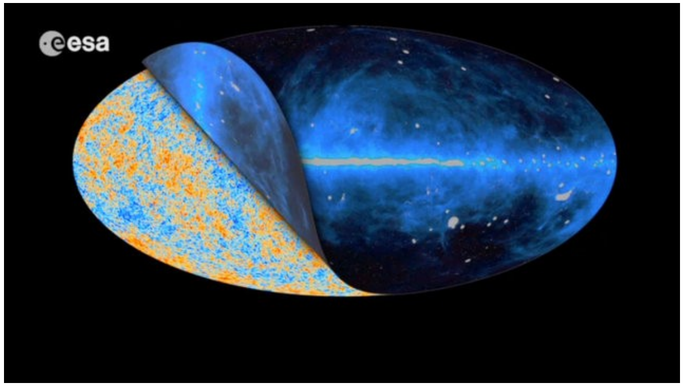
Galaxy rotation curves



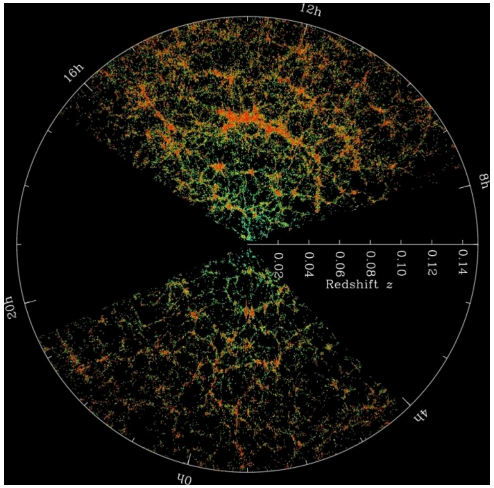
Galaxy clusters



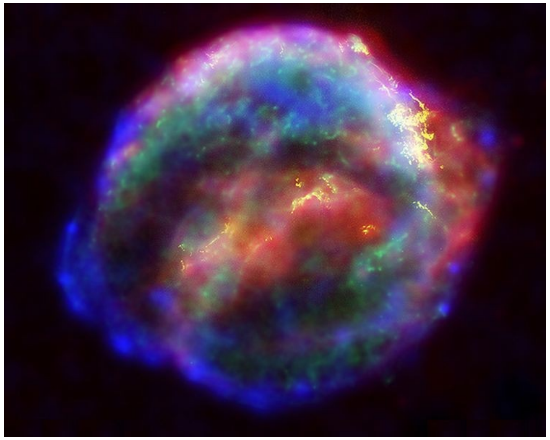
Cosmic microwave background

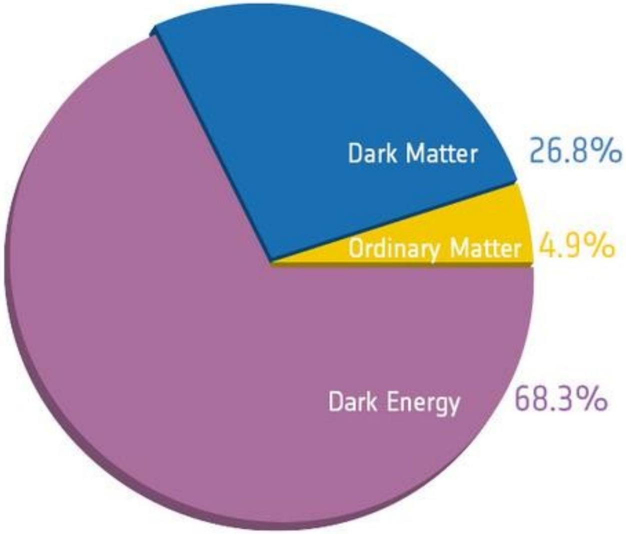


Large scale structures



Supernova Type 1A





Planck 2013

What we know about dark matter

We can bracket the mass of dark matter "particles"
to **within 80 orders of magnitude**

Uncertainty principle

Hu+ 2000

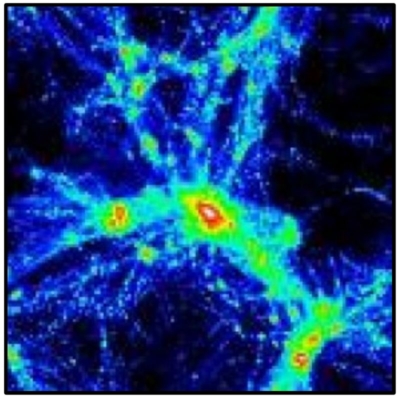
MACHO searches

Tisserand+ 2007

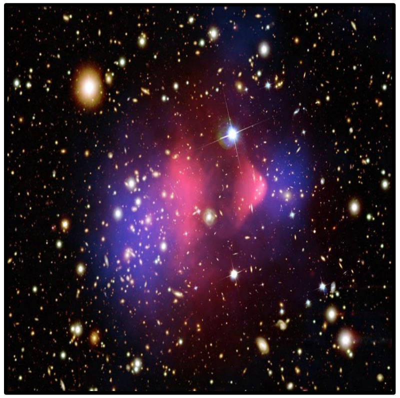
$$10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{50}\mathrm{GeV}$$

Further DM properties

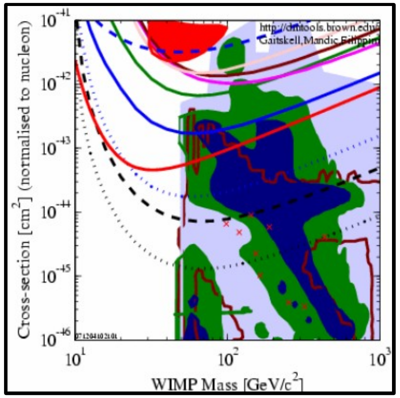
cold:
negligible velocity dispersion

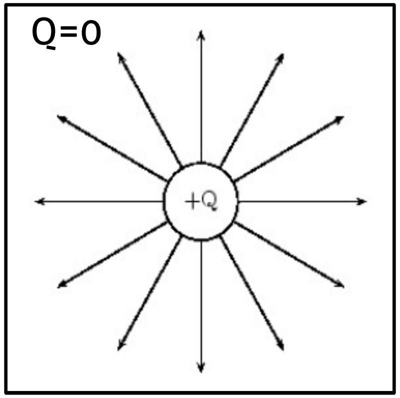


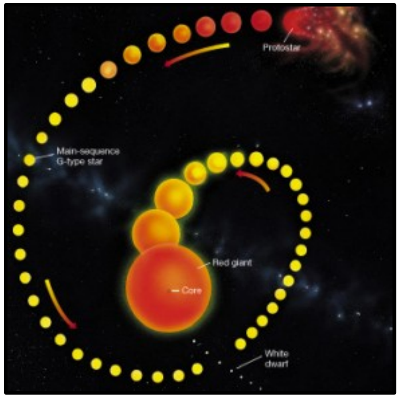
collisionless:
negligible self-interaction



weakly coupled:
negligible interaction with the rest of the world







Dark matter might not be completely dark

Dark matter is stable + cold.

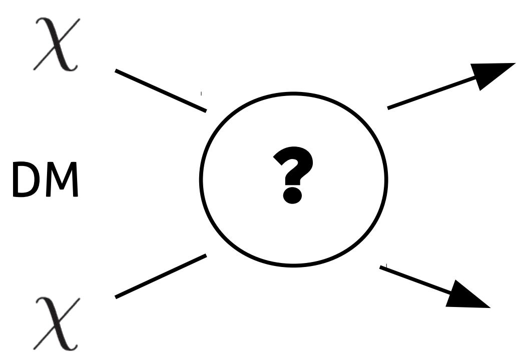
This suggests

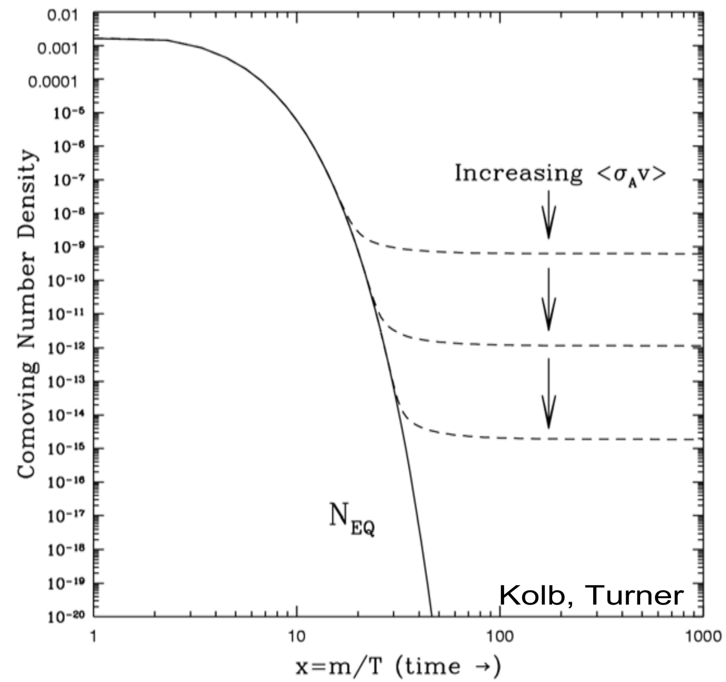
number density of order of other stable relics (photons, neutrinos).

DM particles being heavy.

Problem: We would have way too much DM around today.
Solution for electrons + protons: they self-annihilate with positrons + anti-protons.

Possible solution in case of DM: DM can self-annihilate.





Relic density:

$$\Omega_{\rm dm} h^2 \approx \frac{3\times 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma v\rangle} \simeq 0.1$$

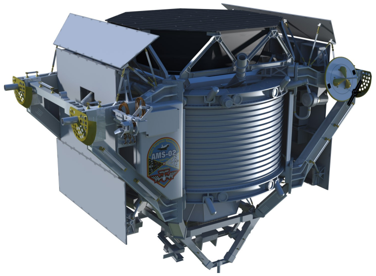
$\langle \sigma v\rangle$ Annihilation cross-section

This self-annihilation would also happen today! Predicted by many theoretical models (supersymmetric scenarios, scenarios with extra dimensions)

Search strategies for WIMP dark matter

(Weakly Interacting Massive Particles)

Indirect searches:
Search for exotic energy sources in the Universe



Direct searches:
Search for recoil off atomic nuclei

χ χ

DM

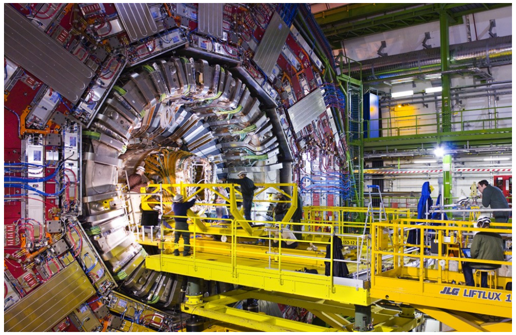
?

$W^+, Z^0, g, q^+, l^+, \gamma$

Standard model

$W^-, Z^0, g, q^-, l^-, \gamma$

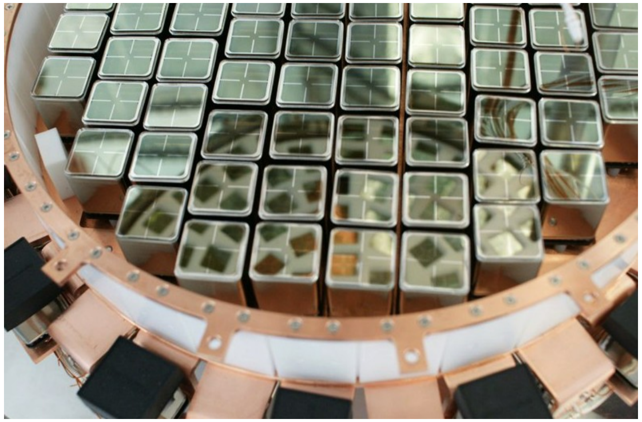
Collider searches:
Searches at particle colliders

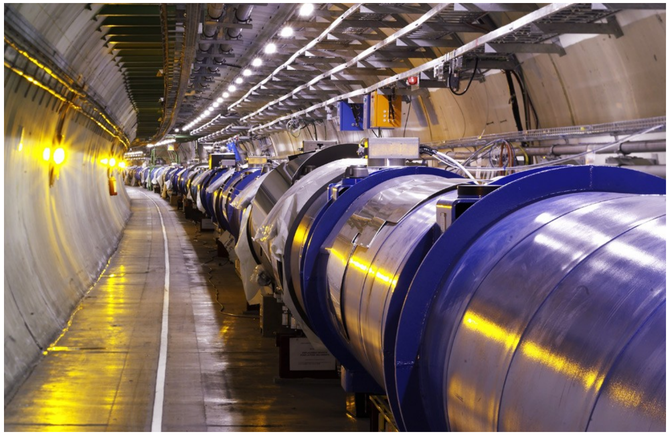


The decade of WIMP discovery/refutation

Indirect searches
- Only way to directly test *freeze-out mechanism!*
- Gamma rays are "golden channel", more data, new strategies, tentative signals
- New anti-matter results just got released (AMS-02), more to come soon (later GAPS)
- Neutrinos are probed at decreasingly low energies (IceCube)
- Further constraints from Planck polarization data and others

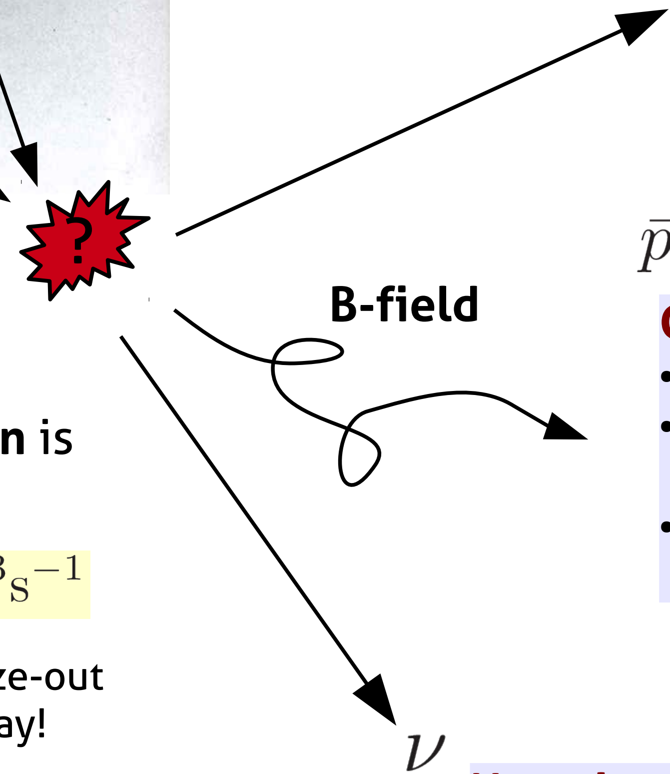
Direct searches
- Only way to directly measure local properties of DM
- Tentative signals(?) in DAMA/LIBRA, CoGeNT, CDMS-Si, CRESST
- Strong results expected from LUX, XENON 1T, later DARWIN, …
- 2 orders of magnitude sensitivity improvement expected during this decade





Collider searches
- Only way to make our own DM particles
- Generic searches (mono-jets, mono-photons, …) put strong constraints on dark matter models
- Even stronger limits on specific scenarios like MSSM
- No signs for new physics found yet
- Hope: restart in 2015 with higher energy and much higher sensitivity

Indirect Searches for Dark Matter



Gamma rays
- Very simple propagation (geodesics)
- Absorption negligible on Galactic scales
- Point towards their sources

Charged cosmic rays
- Electrons/positrons, nuclei
- Propagation distorted by galactic magnetic fields
- Sizable energy losses & interactions

Neutrinos
- Simple propagation
- But: very hard to measure

Today's dark matter **annihilation cross-section** is roughly given by

$$\langle \sigma v \rangle_{\rm tot} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Caveat: conditions during freeze-out are very different from today!

Local annihilation rate: $\frac{dR}{dE} = \frac{\rho_0^2}{m_{\rm DM}^2} \frac{\langle \sigma v \rangle}{2} \frac{dN}{dE}$

Indirect searches are the most convincing probe for the "freeze-out" mechanism of WIMPs

Current gamma-ray experiments

GeV to TeV energy range

Space based:
(Pair conversion detector)

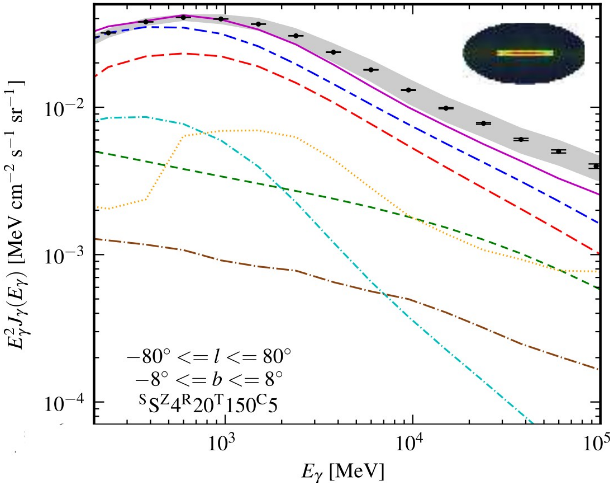
A_{eff}~$1m^2$
T~<10yr
20 MeV – 300 GeV

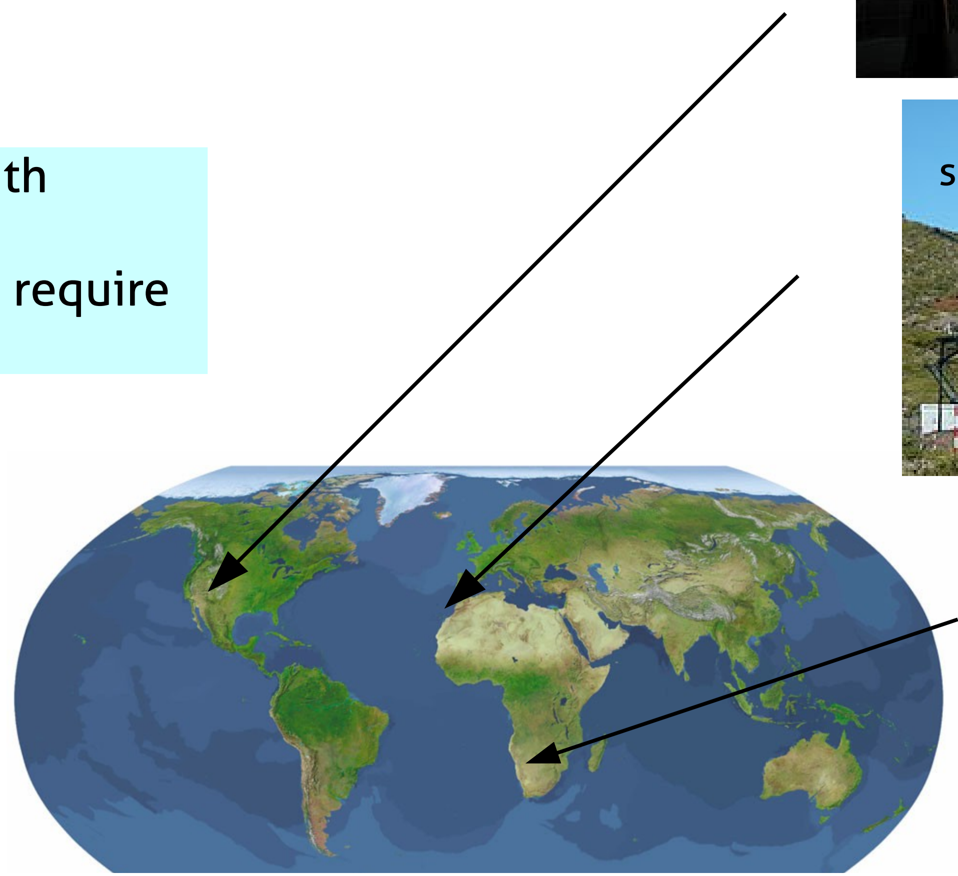
Fermi LAT
since 2008

Ground based:
(Atmospheric Cherenkov Telescopes)

A_{eff}~$1km^2$
T~<100h
>10 GeV

Fluxes are falling <u>rapidly</u> with increasing energy
High energy measurements require huge collection areas





Dark Matter Signal Flux

Velocity averaged annihilation cross-section

Signal intensity:
[photon flux per steradian per energy]

Photon energy spectrum per annihilation

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$

Dark matter mass density

Dark matter mass

Line-of-sight integral

Particle Physics

Astrophysics

Characteristic **Energy Spectrum**

Characteristic **Morphology**
(point-like, extended or diffuse)

[review DM searches with gamma rays: Bringmann & Weniger (2012)]

It is convenient to define a "J-value":

$$J_{\Delta\Omega} \equiv \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho(r[s, \vec{\Omega}])^2$$

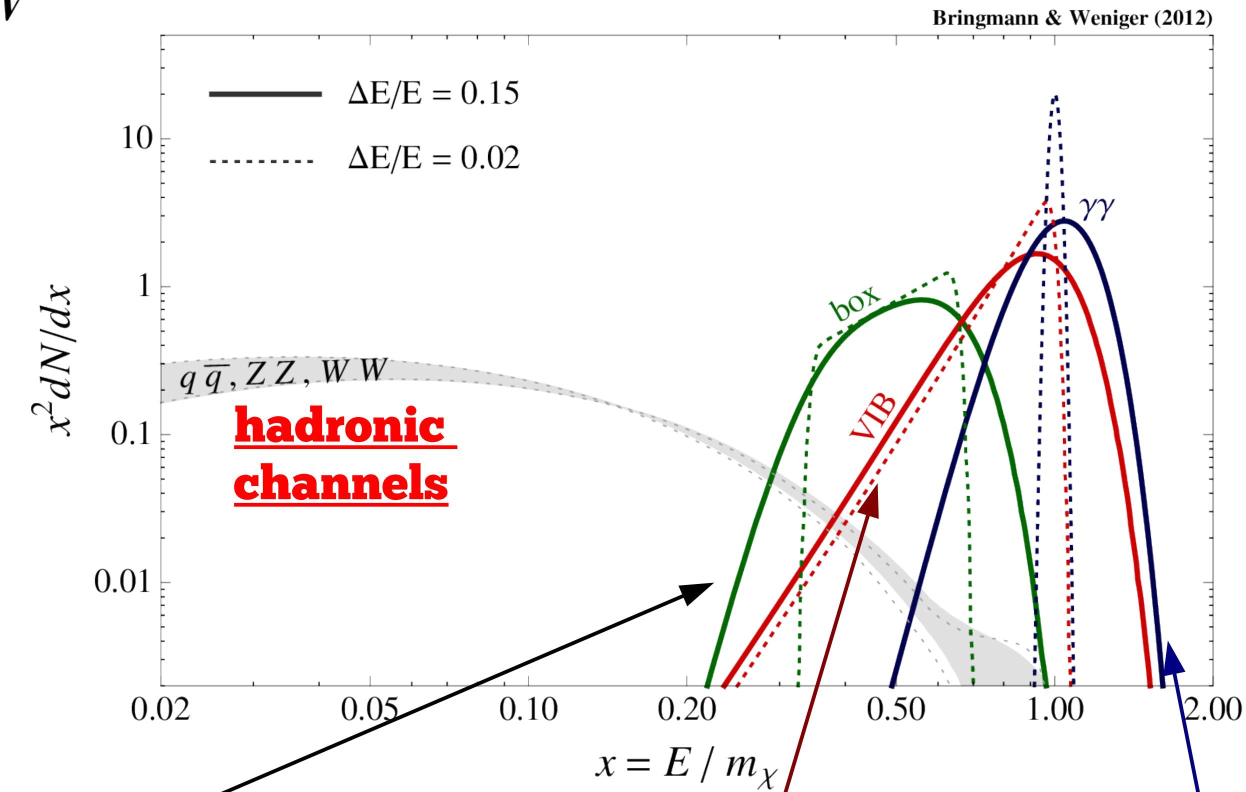
$\chi\chi \to \bar{q}q$

$\chi\chi \to W^+W^-$

$\chi\chi \to \gamma\gamma$

$\chi\chi \to \dots$

Annihilation spectra



Box-like spectra
- Cascade-decay into monochromatic photons
- already at tree level

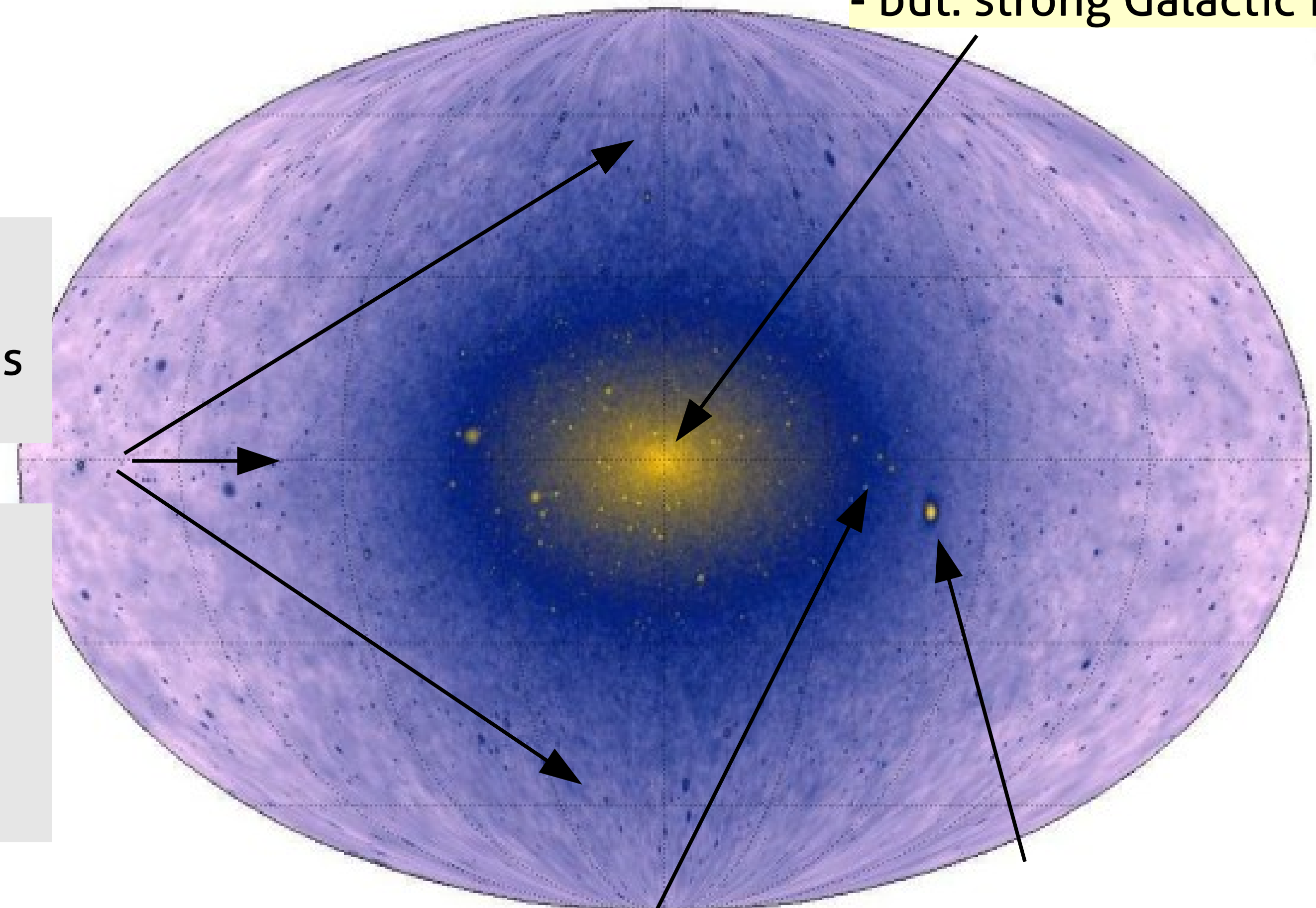
Internal Bremsstrahlung (IB)
- radiative correction to processes with charged final states
- Generically suppressed by O(α) $\chi\chi \to \bar{f}f\gamma$

Gamma-ray lines
- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²) $\chi\chi \to \gamma\gamma$

Two primary targets for dark matter searches

Dark matter signal predicted by N-body simulations:

Kuhlen+ 2007



Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

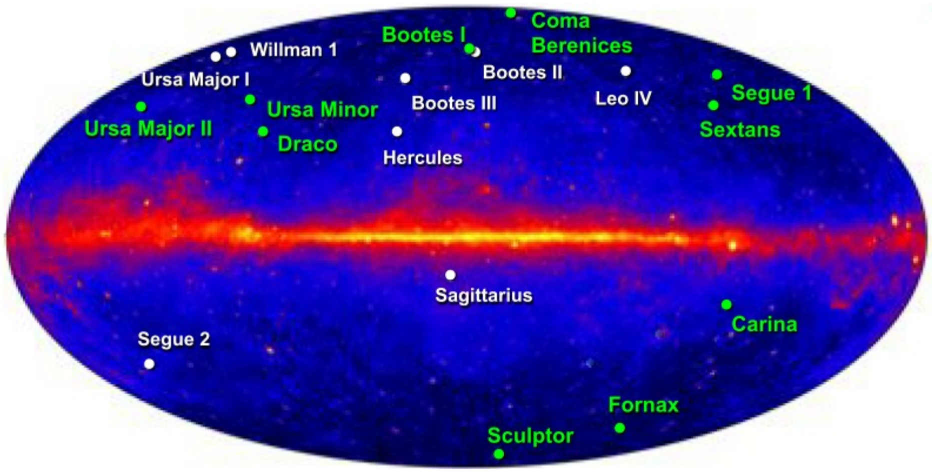
Extragalactic signal
- nearly isotropic
- only visible close to Galactic poles
- angular information
- **Galaxy clusters!**

Galactic center
- brightest DM source in sky
- but: strong Galactic foregrounds

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

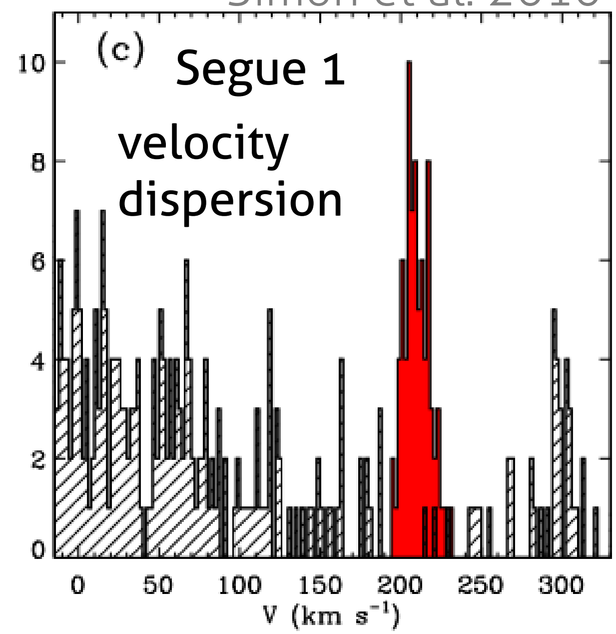
Dwarf Spheroidal Galaxies
- contain small number of stars
- dark in gamma rays

Dwarf Spheroidal Galaxies

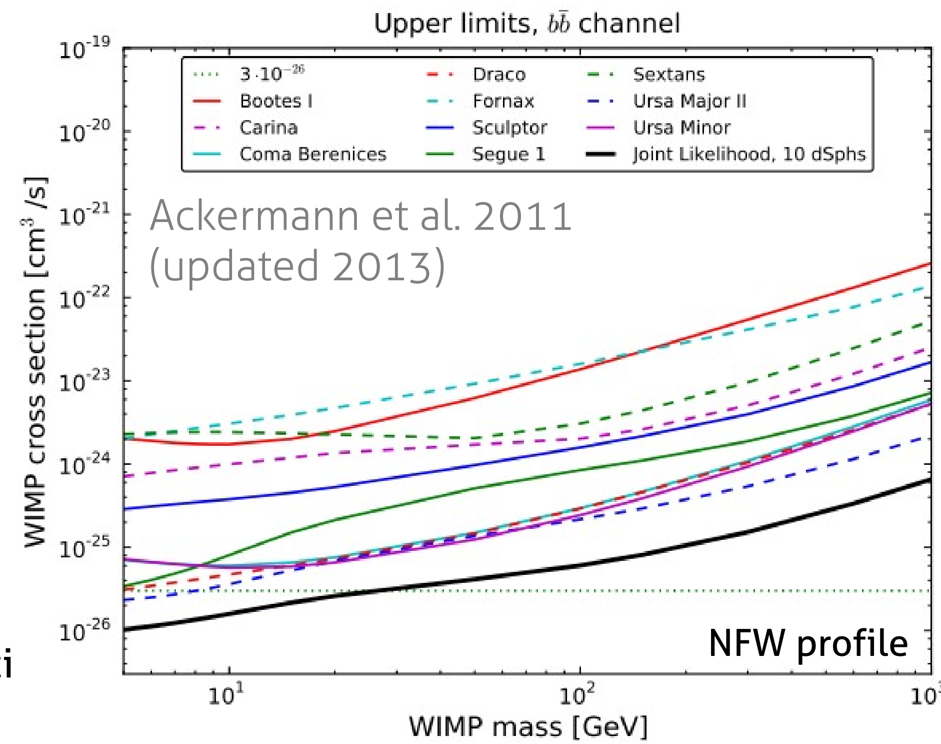


[from Drlica-Wagner, Fermi Symp. 2012]

Simon et al. 2010

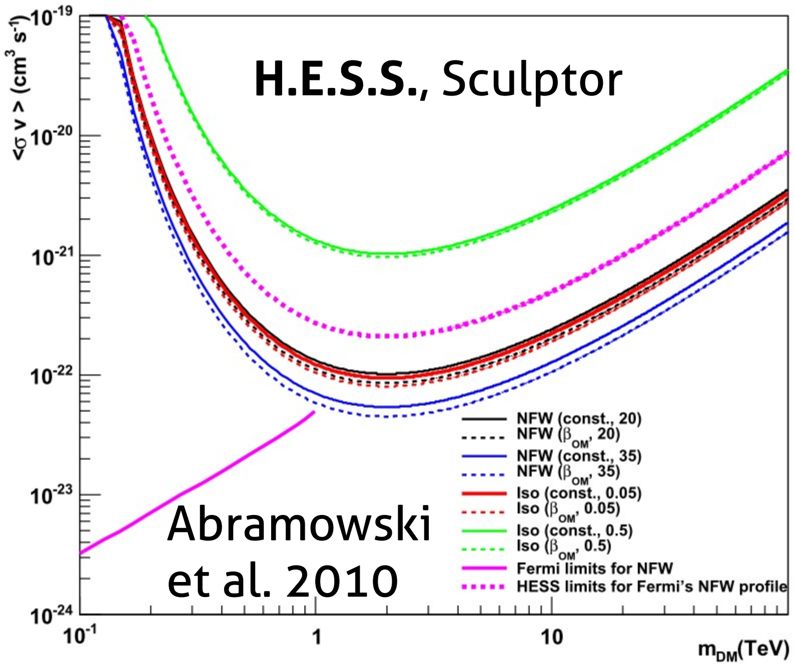


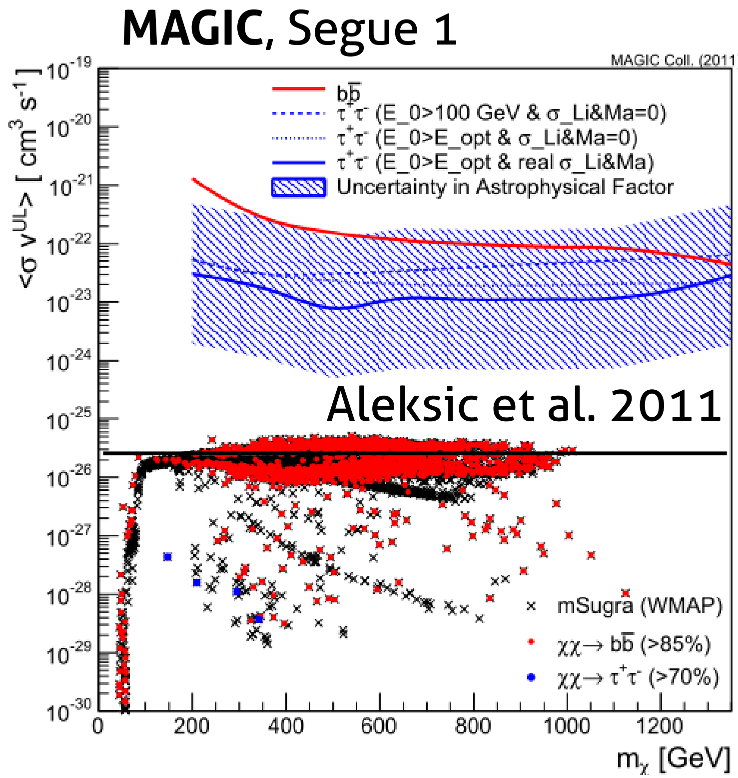
- Large M/L ratios ($\sim 1000 M_\odot / L_\odot$ and more)
- Combined likelihood analysis (not stacking) of many dwarfs
  → reduces J-value uncertainties
  → improves limits
- Current Fermi LAT limits exclude thermal annihilation cross-sections below ~30 GeV (bb final states)

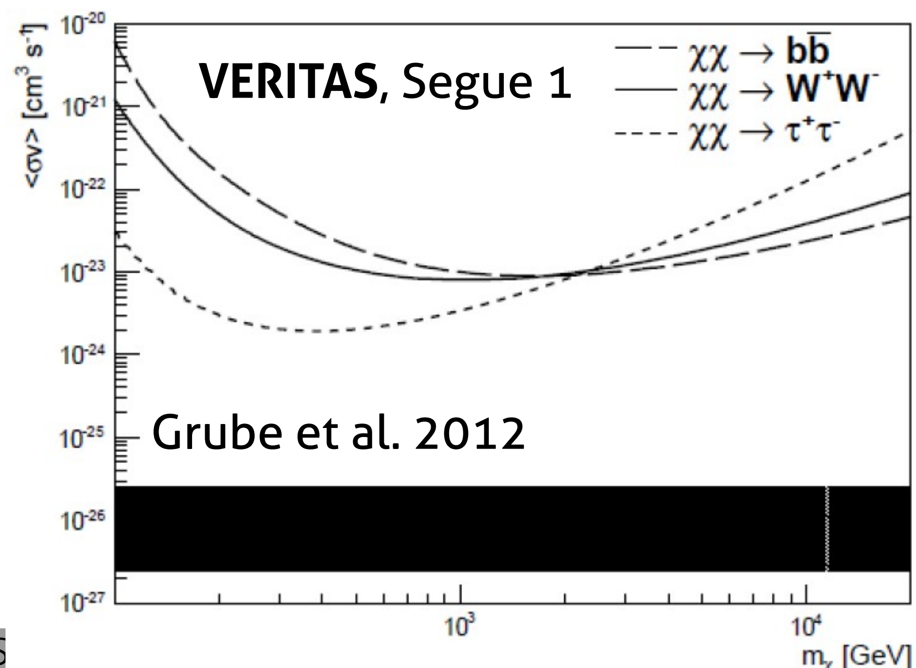


See also: Scott et al. 2010; Geringer-Sameth & Koushiappas 2011; Mazziotta et al. 2012; Cholis & Salucci 2012; Salucci et al. 2011; Charbonnier et al. 2011

DM limits from Dwarf Spheroidals





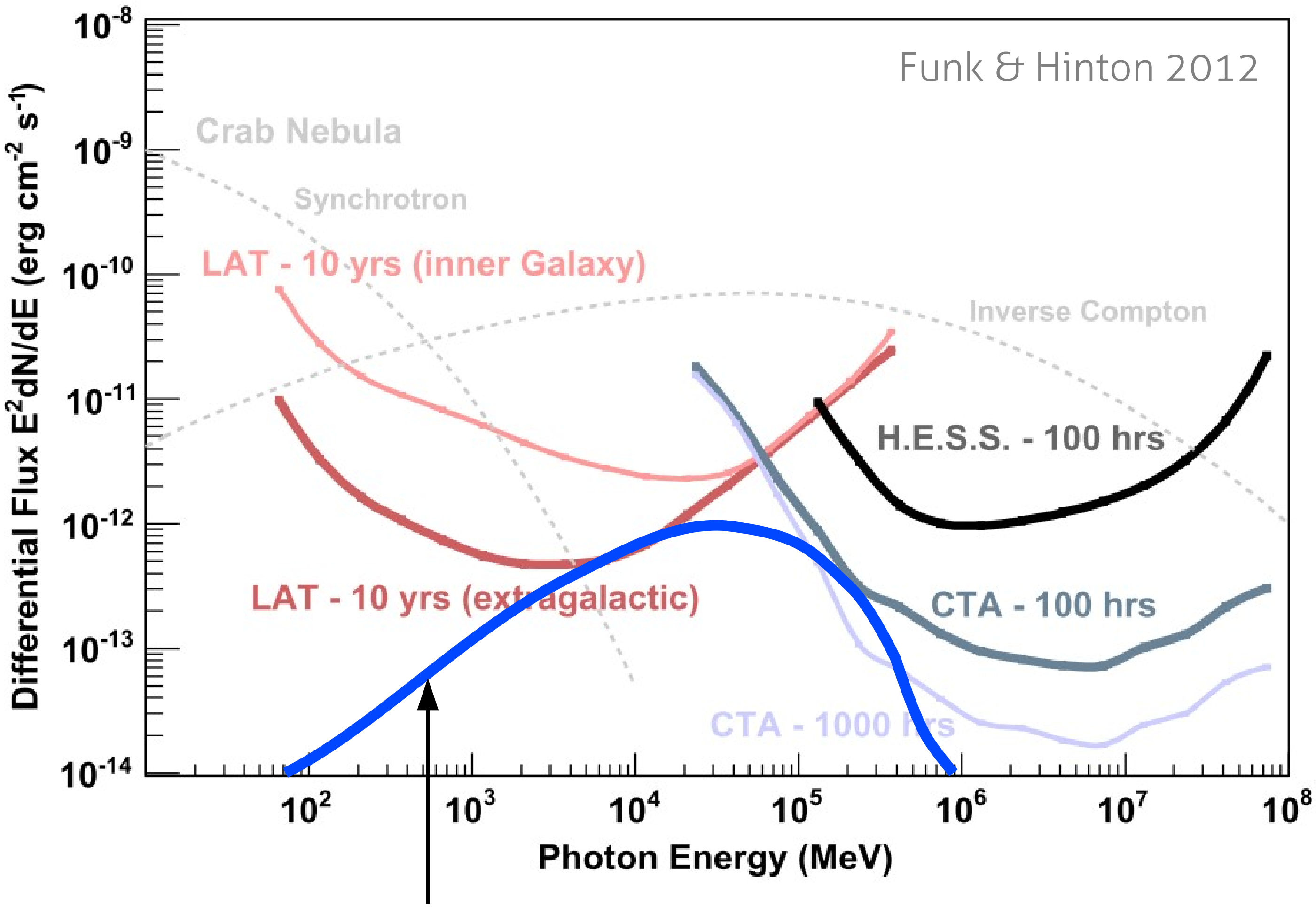


DM limits from Dwarf Spheroidals

- But: limits still ~100 away from thermal cross-section
- Main challenges w.r.t. space-based telescopes:
  - large cosmic-ray background at low energies (at least 10^3 larger than IGRB)
  - energy threshold ~100 GeV

- IACT observation times are relatively short, which makes them excellent for quick follow-up observations if LAT finds signal from multi TeV DM

Differential sensitivity of CTA and DM spectra

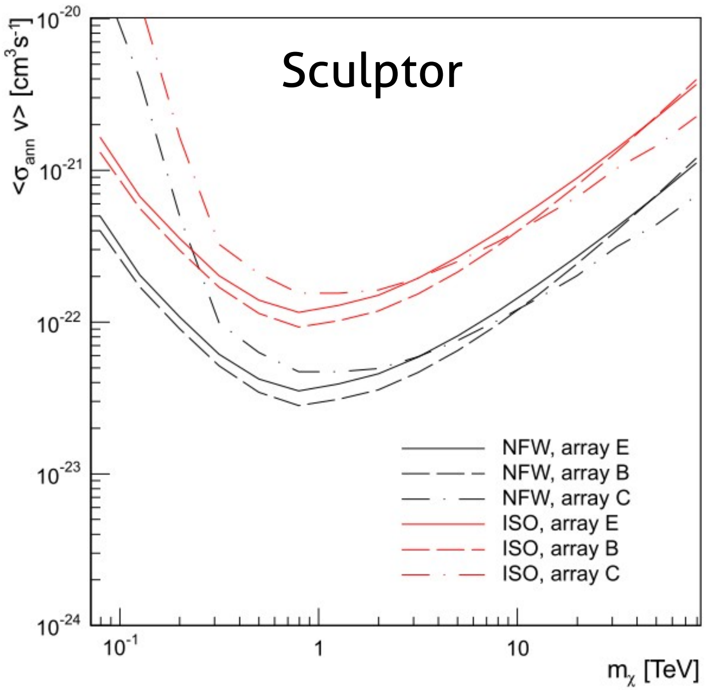


Annihilation into quark/anti-quark pairs
DM mass is 1 TeV.

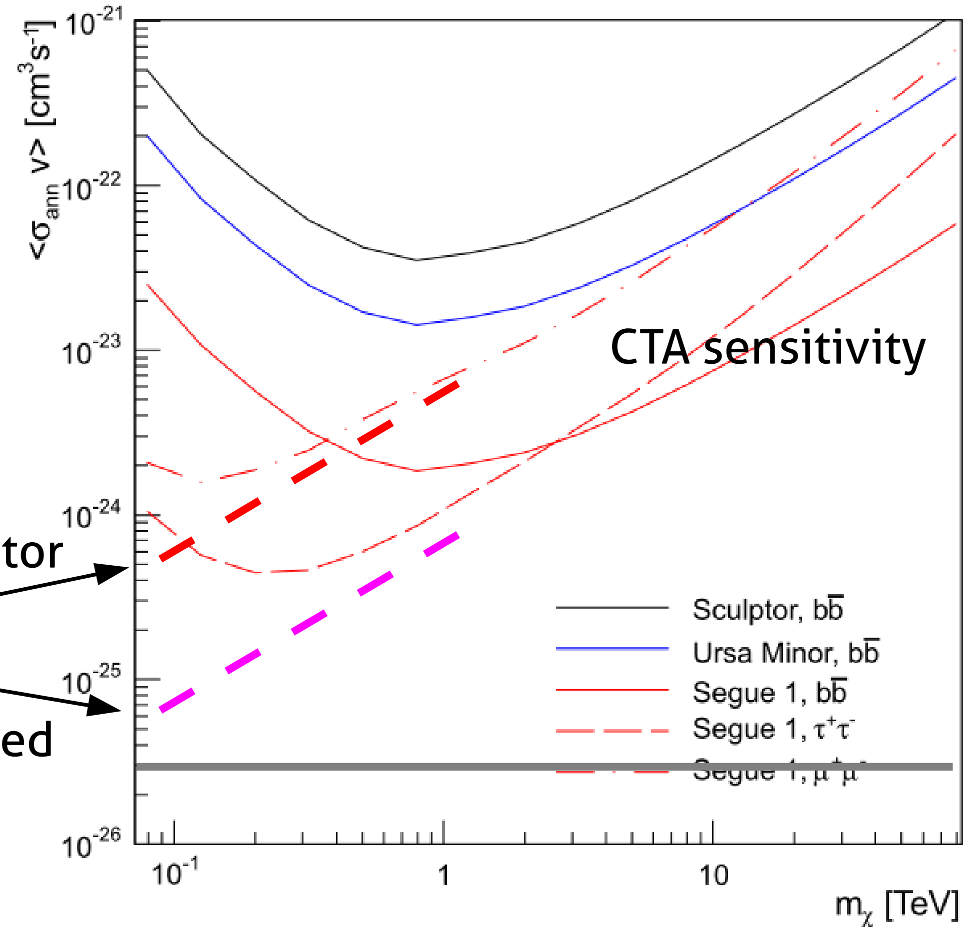
→ CTA dwarf limits will in general dominate above ~1 TeV DM mass

Prospects for CTA dwarf searches

Doro+ 2013



Weak (within factor 2) dependence on array configuration (E,B,C); larger dependence on DM profile.



Sculptor

Fermi LAT limits

stacked

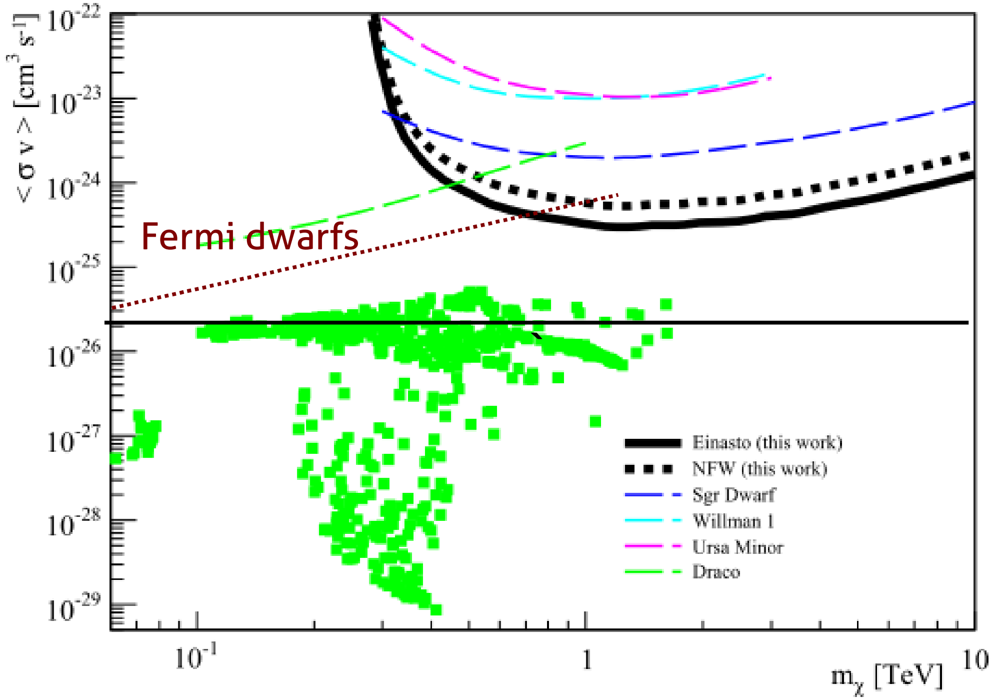
CTA will improve limits from dwarf spheroidals above ~1 TeV DM mass, but it will be extremely hard to reach the thermal cross-section.

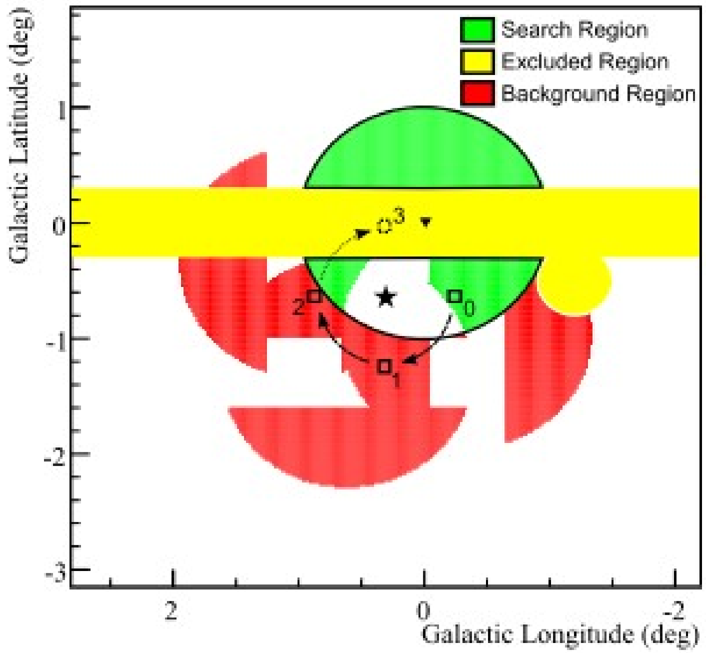
H.E.S.S. observation of the Galactic center

Galactic center is arguably the most promising target for DM searches with IACTs

- Large signal flux (which more easily overcomes CR BG)
- Target interesting for other purposes (long observation times)

Abramowski+ 2011

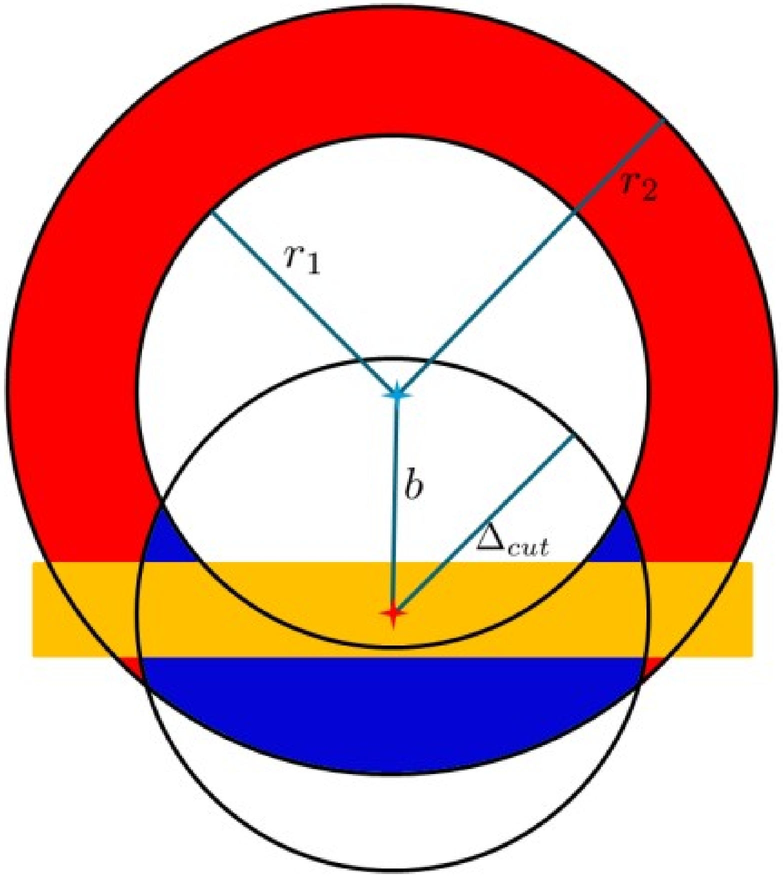




Non-observation of excess in signal region w.r.t. Background region implies constraints on DM signals.

Prospects for CTA: GC obs. with Ring-method

"Ring-method" from Doro+ 2013



Array	b	r_1	r_2	Δ_{cut}
E	1.42°	0.55°	2.88°	1.36°
B	1.40°	0.44°	2.50°	1.29°

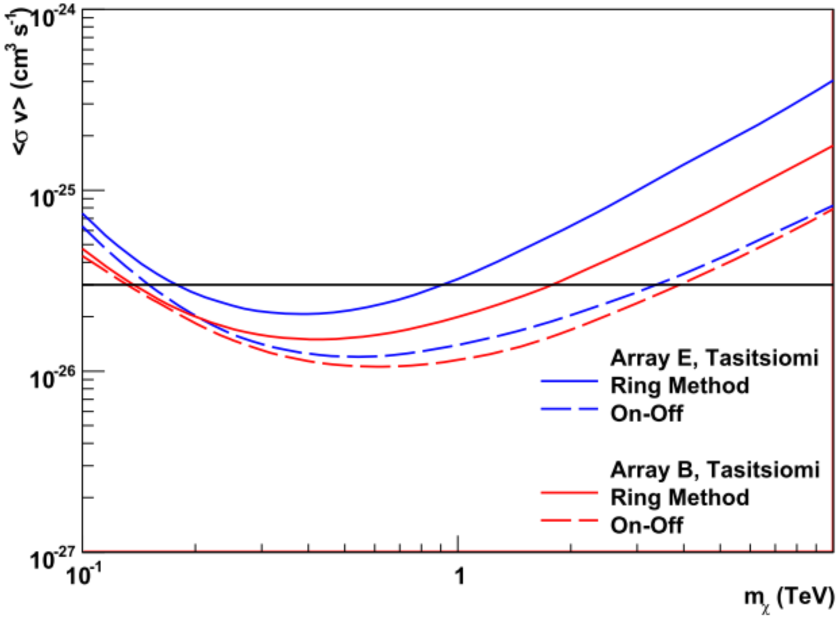
Problem: Minimize systematic differences between signal and background region.

Region-of-interest definitions:
- ON-region (blue)
- OFF-region (red)
- Exclude bright sources observed by HESS
- Exclude galactic ridge, |b|>0.3 deg

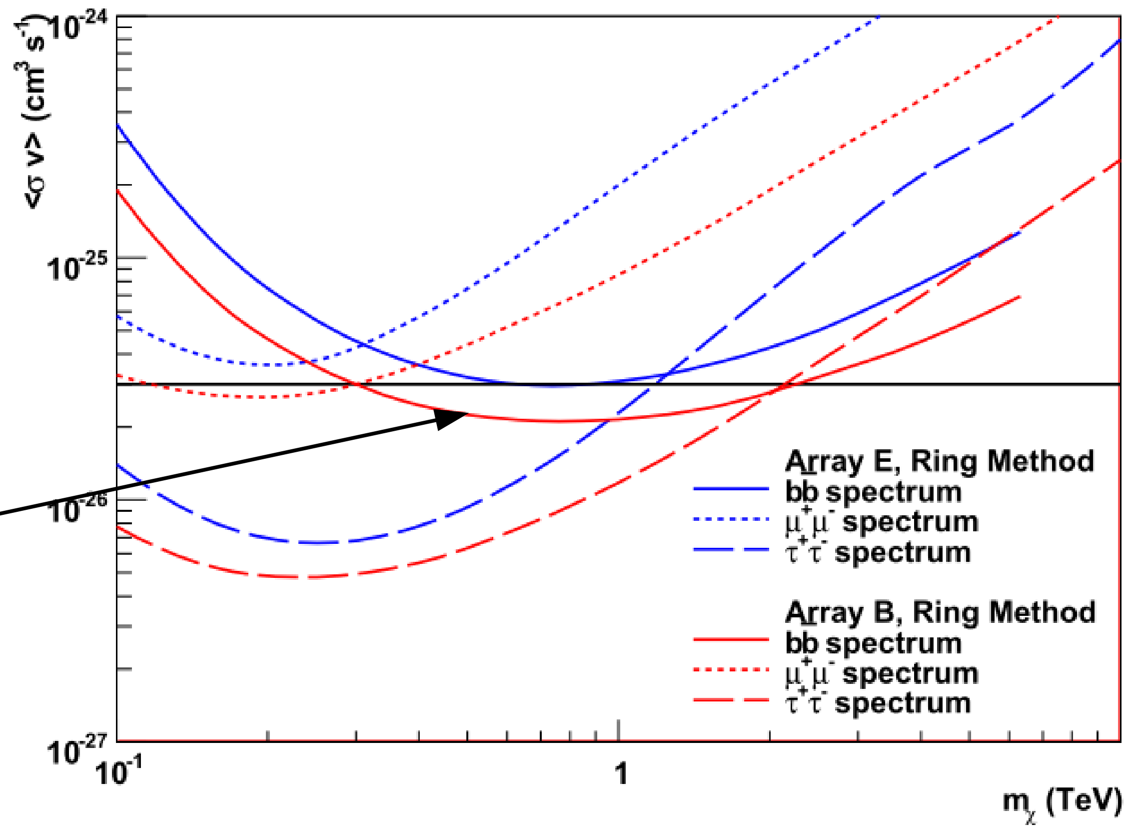
- Search for DM signal in difference between gamma-ray flux in ON and OFF regions

Projected limits on annihilation cross-section

"Ring-method" from Doro+ 2013



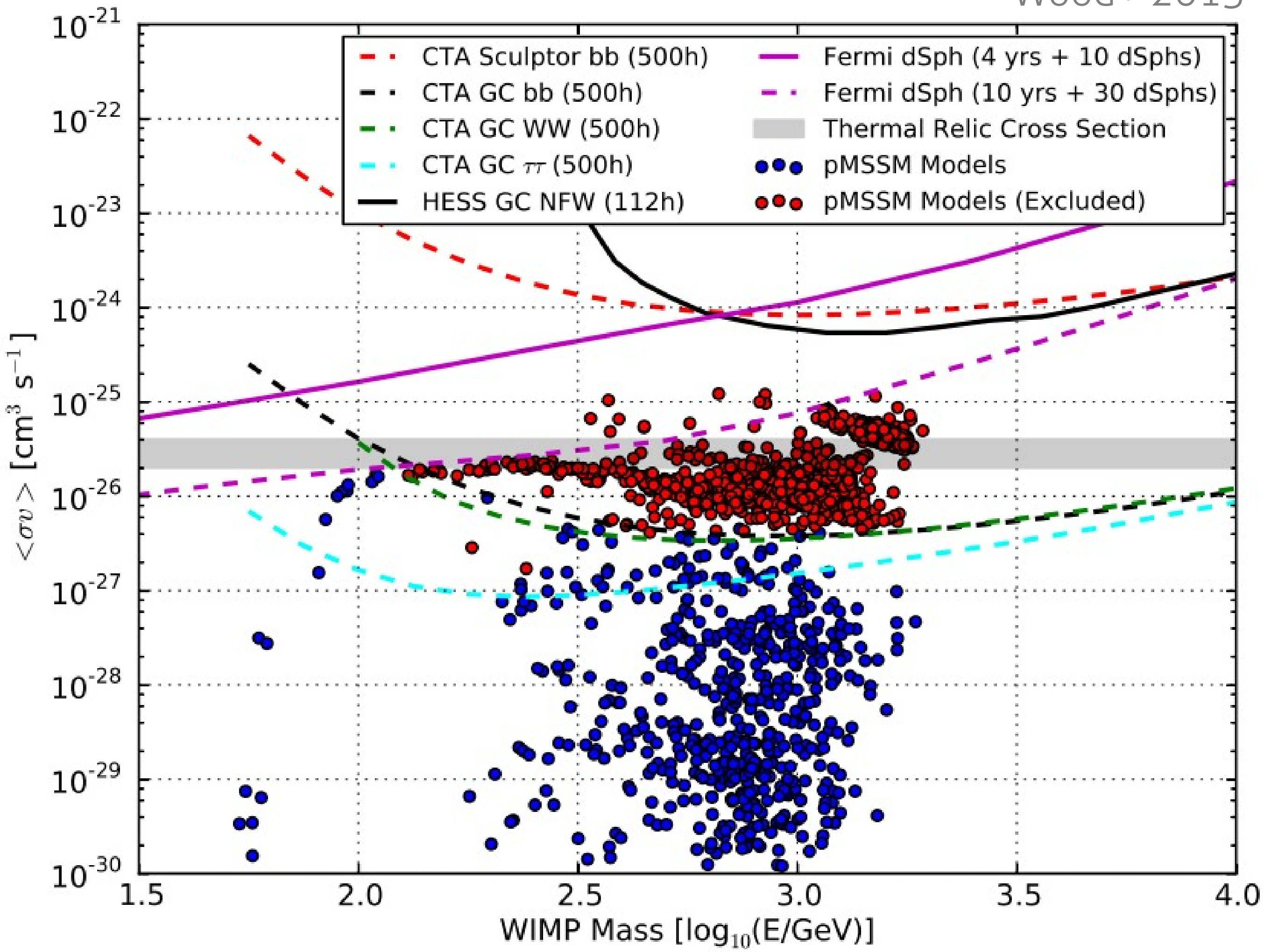
Different array configurations (E and B) change sensitivity by less than factor 2.



Using the ring-method, limits on annihilation into quark/anti-quark pairs could reach the thermal cross-section.

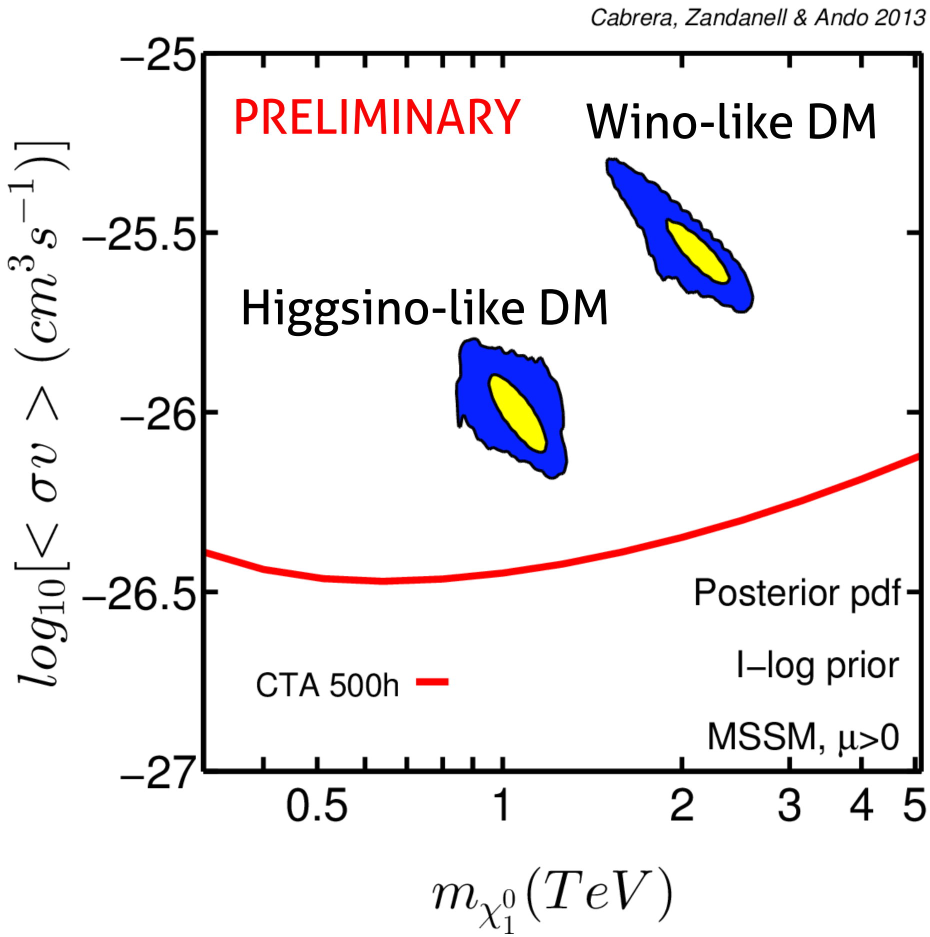
CTA reach and MSSM predictions

Wood+ 2013

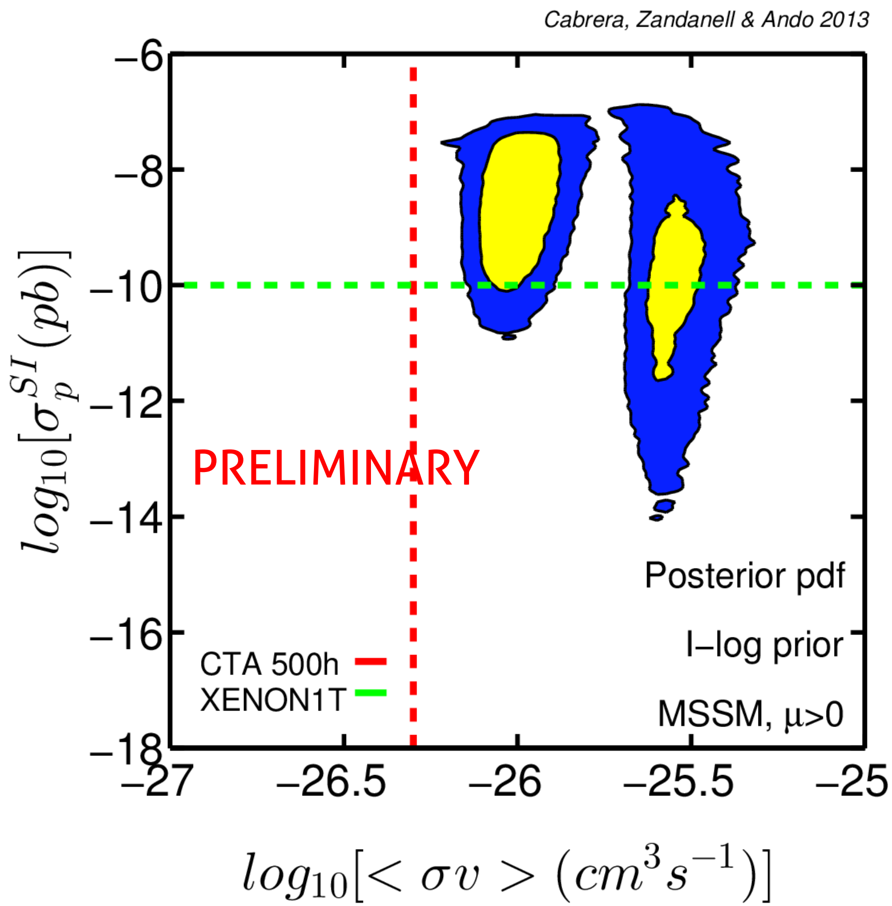


With 500h of Galactic center observations with **61 MSTs**, and having systematics perfectly under control (following Wood+ 2013), one can probe a significant fraction of allowed pMSSM models, with limits down to 5x10^-27 cm^3/s.

CTA reach and MSSM predictions



Complementarity with other searches!



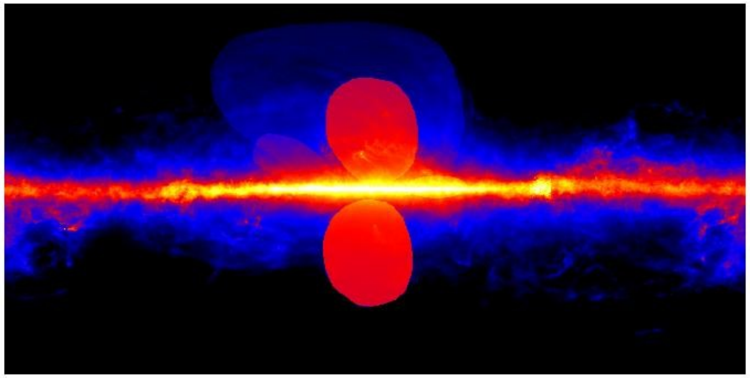
Predictions for 9-parameter MSSM:
(non-universal Gaugino and Higgsino masses)
- Direct detection limits (XENON-100)
- Electroweak constraints
- Dark matter relic density
- Higgs mass

CTA and future XENON-1T are complementary in probing the WIMP parameter space.

Cabrera, Zandanell & Ando 2013
In preparation

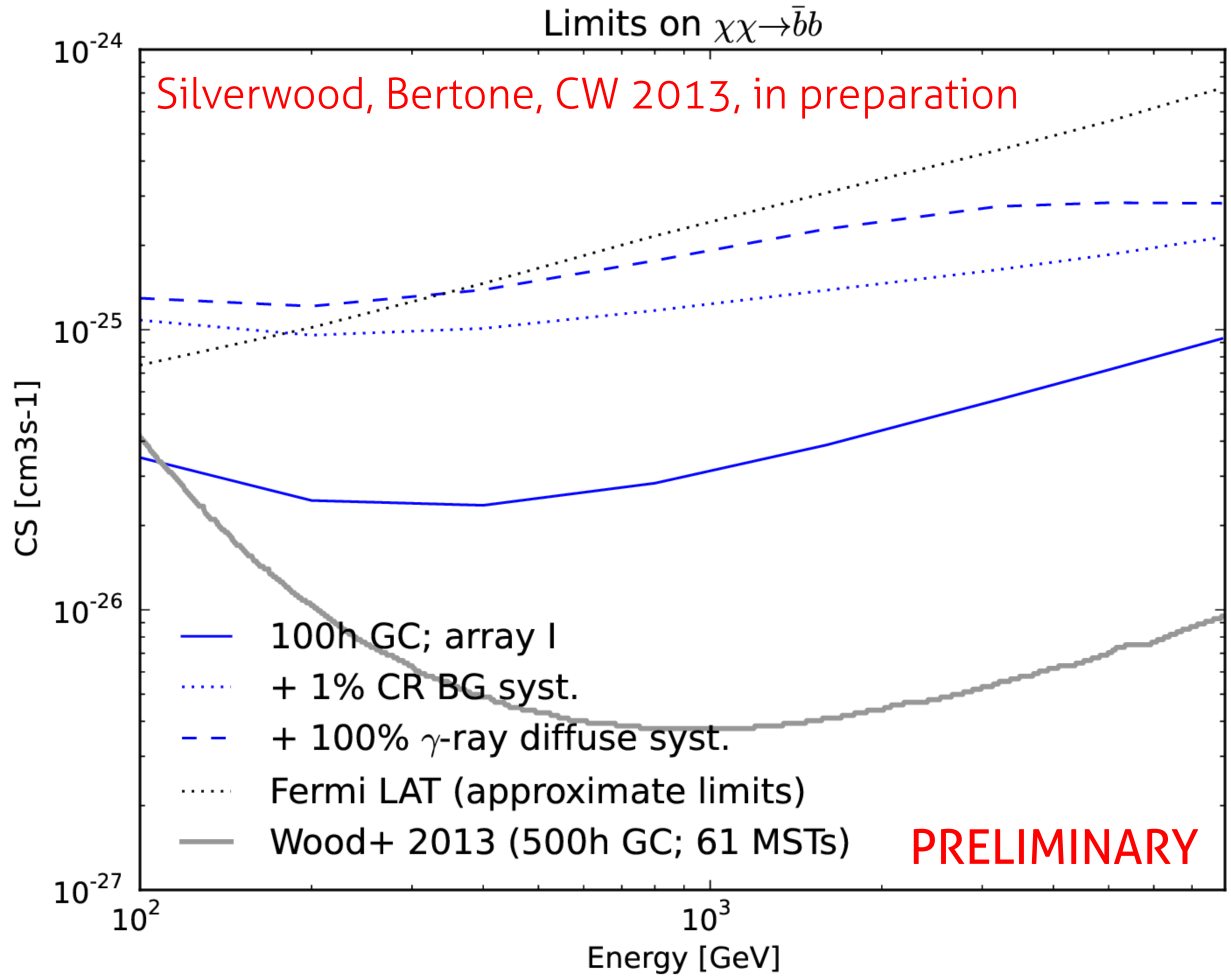
Impact of diffuse gamma-ray bkg. on Ring-method

- Einasto dark matter profile (Cline+ 2013)
- Array I configuration
- 100h observation of GC
- Ring method
- Including diffuse gamma-ray emission by Fermi in ON/OFF regions (using latest model for diffuse bkg up to ~600 GeV)



Successful measurement requires:

- Ability to clearly identify diffuse emission at >~100 GeV energies, ~1 deg away from Galactic disc
- Discrimination of this diffuse emission from a DM signal → morphology, spectrum



Bernlohr+ 2012: Array I residual CR bkg, effective area, PSF

Gamma-ray line searches

Gamma-ray lines

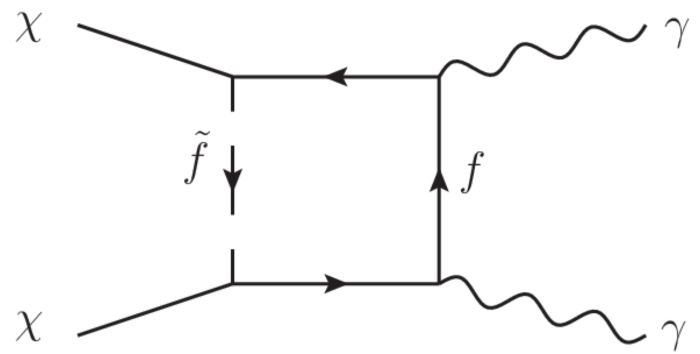
- are produced via two-body annihilation

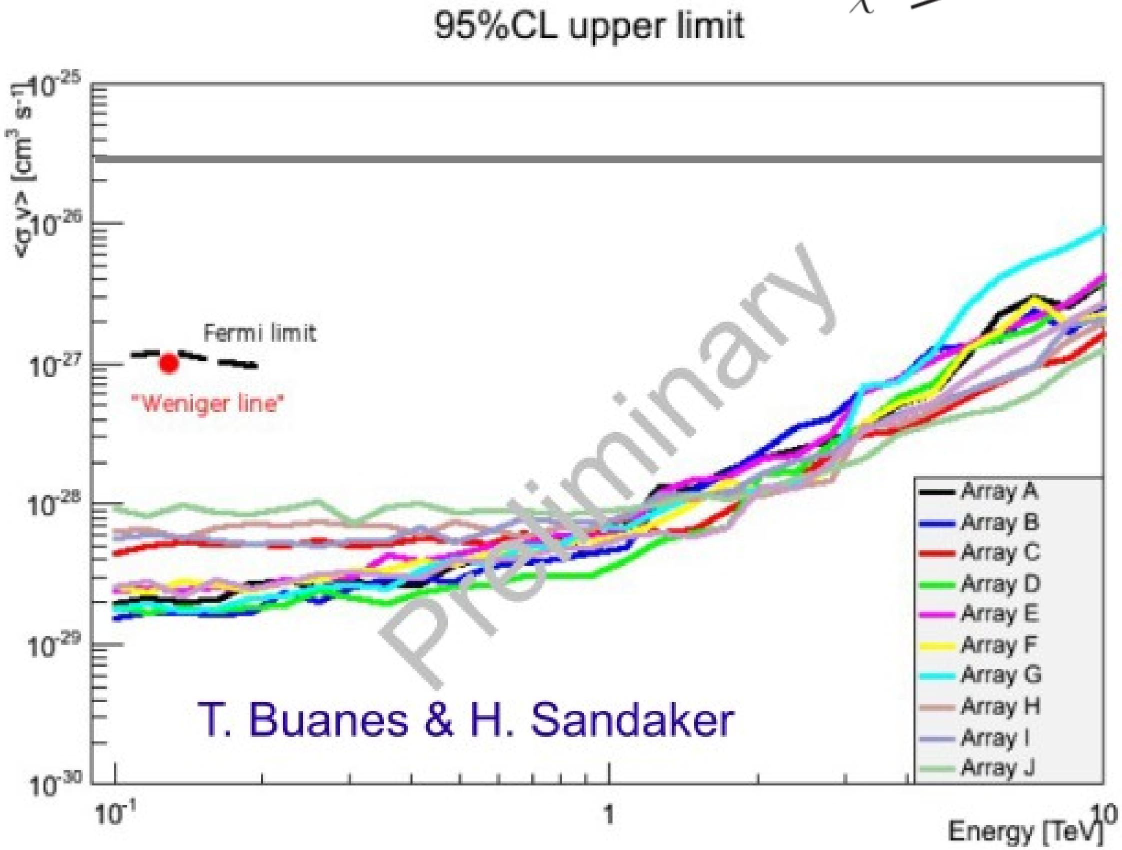
$$\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$$

- have a trivial energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \qquad E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

Direct annihilation into photons is loop-suppressed:





Thermal cross--section

From G. Pedaletti; Talk in Trieste Sep 2013

Dark Matter Searches with CTA in the Netherlands

Search strategies and challenges

- Best observation strategy for diffuse measurements (Ring vs On-off method)
- Reduction/modeling of proton/electron backgrounds
- Interpretation of diffuse gamma-ray backgrounds, possibly in combination with Fermi LAT data at lower eneriges (GRAPPA Institute)

Combination with other search strategies for WIMP DM

- Direct searches (XENON-100/1T at UvA and NIKHEF)
- Collider searches (UvA, NIKHEF, Nijmegen, ...)
- Global analyses of multiple experiments (GRAPPA Institute)

Conclusions

- The self-annihilation of dark matter particles could show up in gamma-ray and cosmic-ray measurements at Earth.
- Ongoing experiments like Fermi LAT and HESS/VERITAS/MAGIC start to probe the interesting parameter space.
- CTA is beats Fermi LAT for dark matter masses above 1 TeV. Challenges:

  → In case of IACTs, we need for the first time to discriminate Galactic diffuse and dark matter emission to make significant progress (HESS obtained upper limits in their ROIs up to now)
- Gamma-ray line searches are extremely efficient and will improve Fermi LAT searches by x10 or more, down to ~100 GeV DM masses.
- CTA searches for dark matter will nicely complement other search strategies (direct and collider searches).

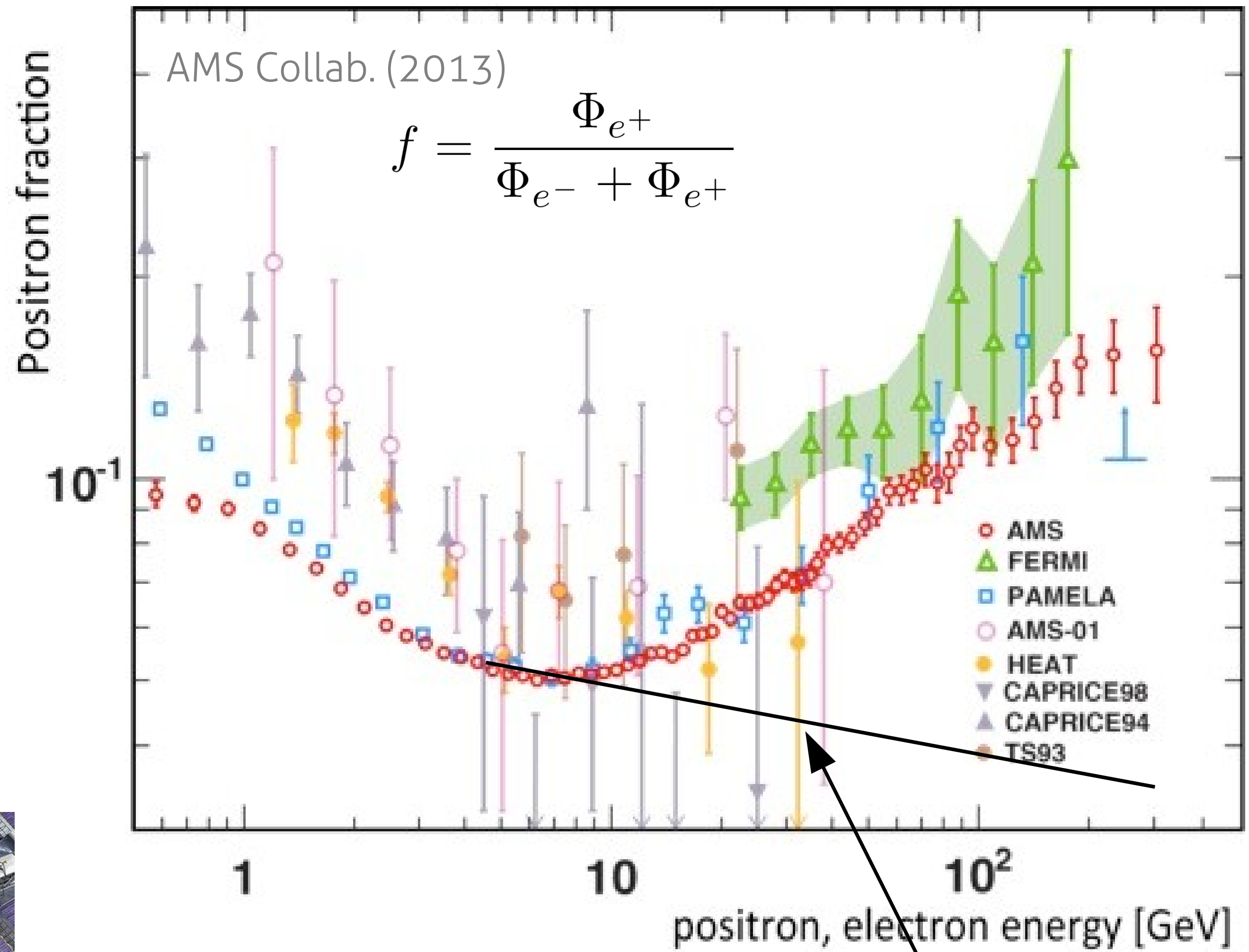
Thank you.

Backup slides.

Rise in the positron fraction above 10 GeV

First observed by PAMELA in 2008.

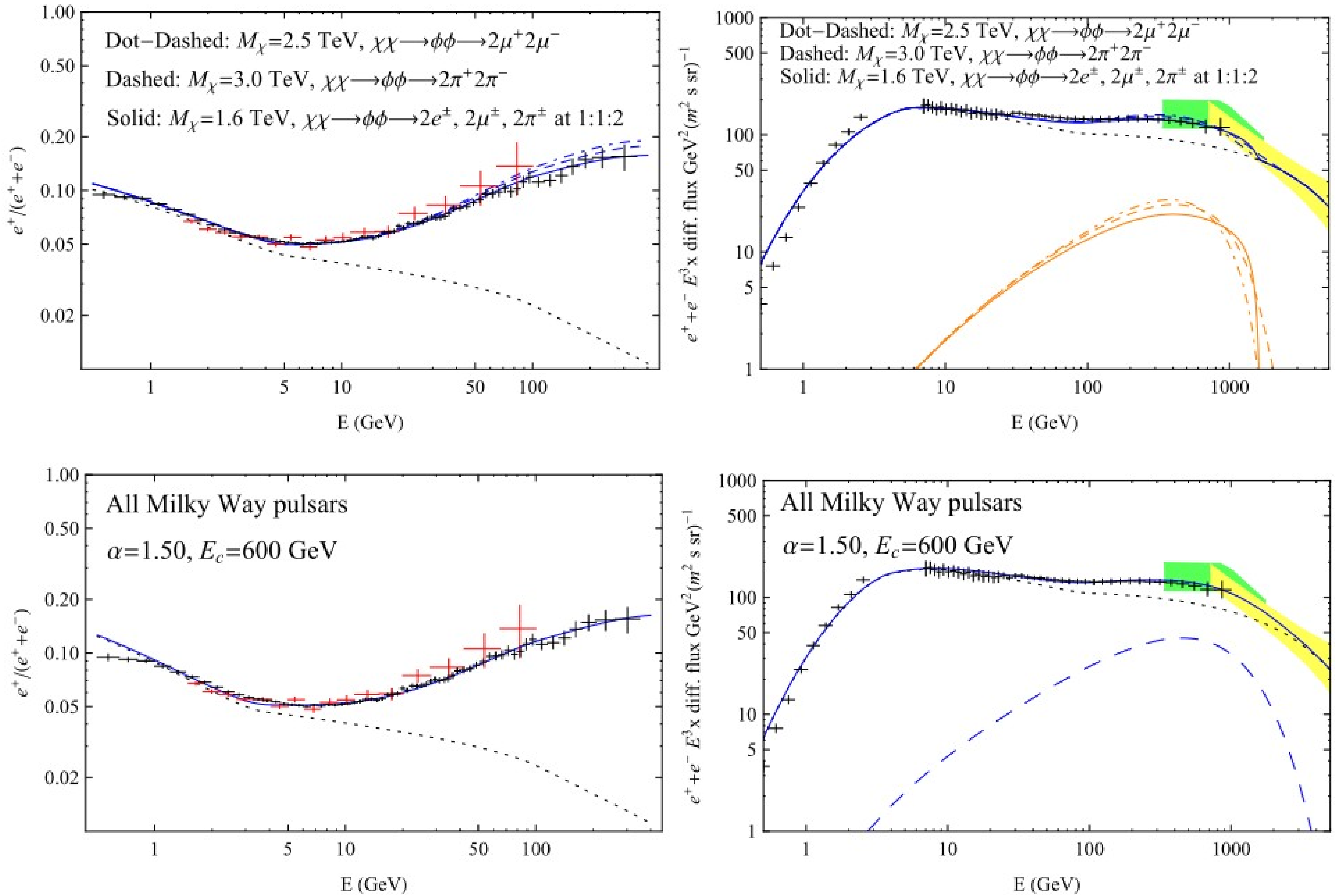
Confirmed by Fermi LAT, and recently by AMS-02.



Positron fraction from secondary production should <u>decrease</u>

AMS-02 on board the ISS

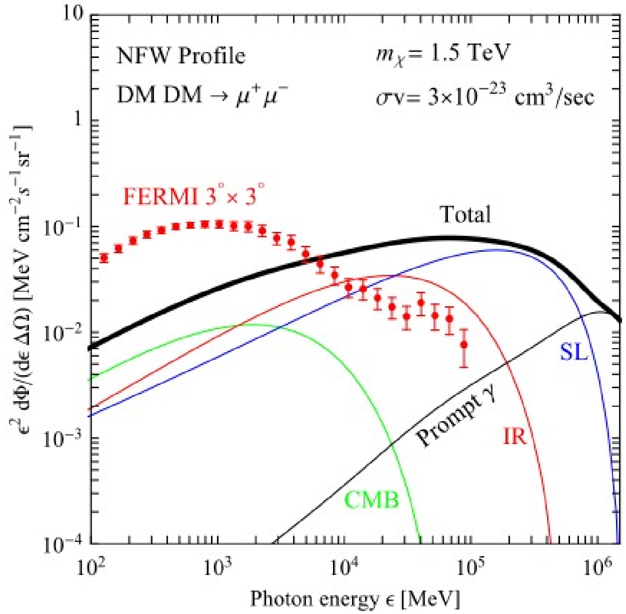
DM and nearby PWNs can explain rise



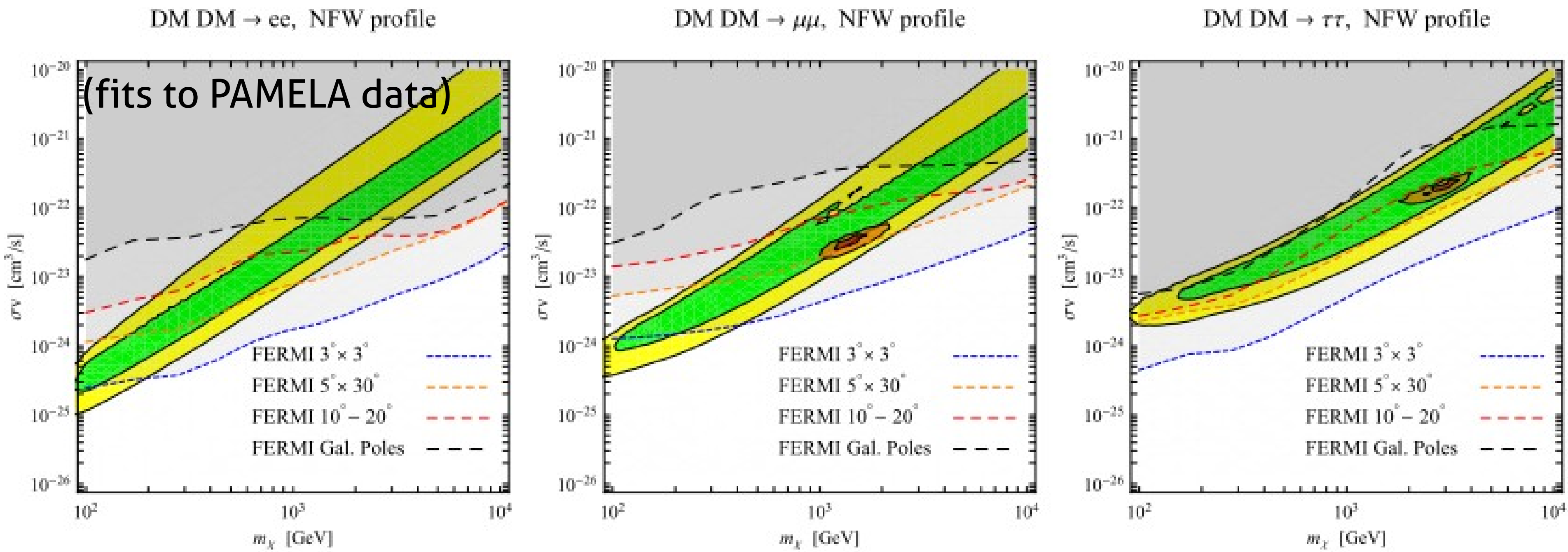
[Cholis & Hooper (2013)]

Associated gamma-ray signals

Annihilation into leptons produces always an Inverse Compton Emission component, that is not seen in gamma rays



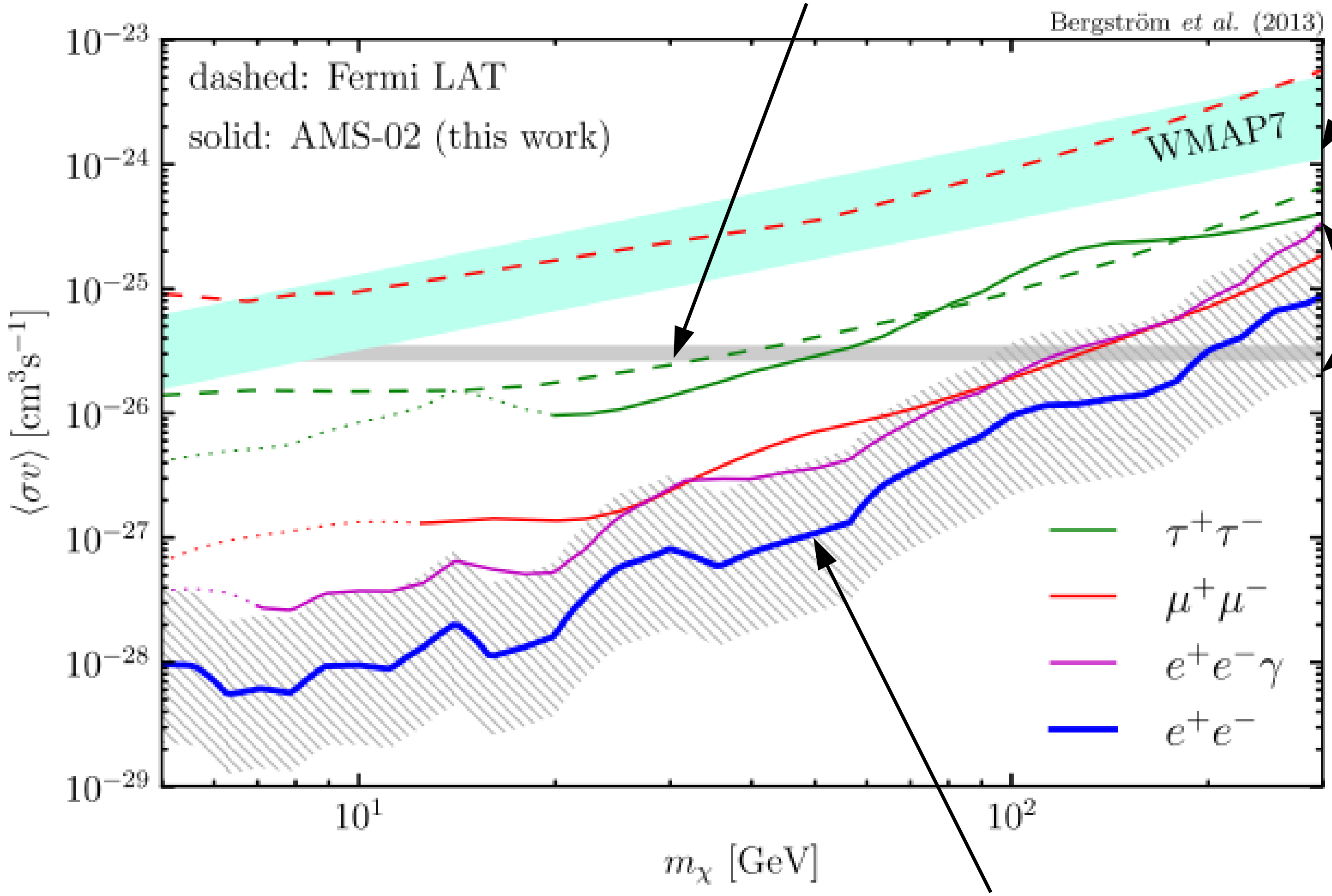
[Cirelli, Panci & Serpico (2009)]



Searches for step-like features are extremely efficient

Gamma-ray observations of dwarf spheroidals

Limits from polarization measurements of the CMB



Uncertainties from local DM density and energy losses

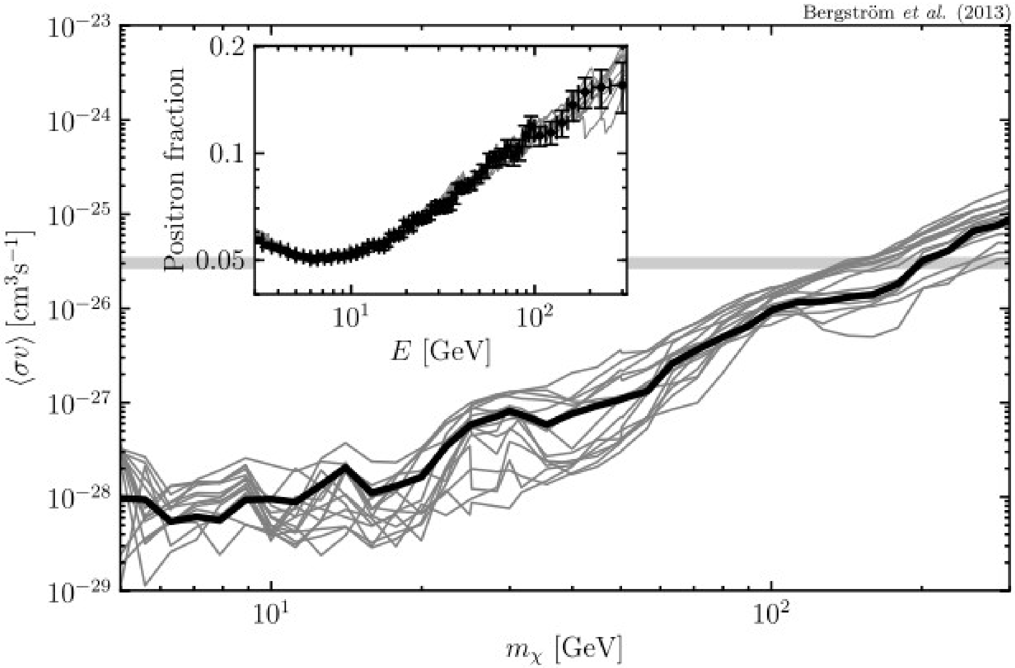
Non-observations of spectral features in positron fraction

Why this is not just terribly wrong

Effect of solar modulation
- Force-field approximation: affects fluxes down to 5 GeV by less then 20 – 40%.

Physical background models
- still have to fit data → no big change expected
- we find O(3) variations for different physical background models (that fit the positron fraction slightly worse than the simple model above)

DM signal could hide between pulsar bumps
- We simulated multi-pulsar backgrounds
  - taking pulsar distances, P & Pdot from ATNF catalog (w/o MSPs, <4kpc)
  - random variation of fraction that goes into e+/e- pairs (~O(5%))



<u>Outlook</u>: marginalize over background realizations + propagation models → make limits as robust as Fermi LAT dwarf spheroidal limits