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THE GRADUATE UNIVERSITY FOR ADVANCED STUDIES [SOKENDAI]

宇宙線直接観測の成果と展望

宇宙線観測と素粒子物理学

Cosmic-ray observations and particle physics

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Contents

- Dark Matter (WIMP)との関係　メインに話します

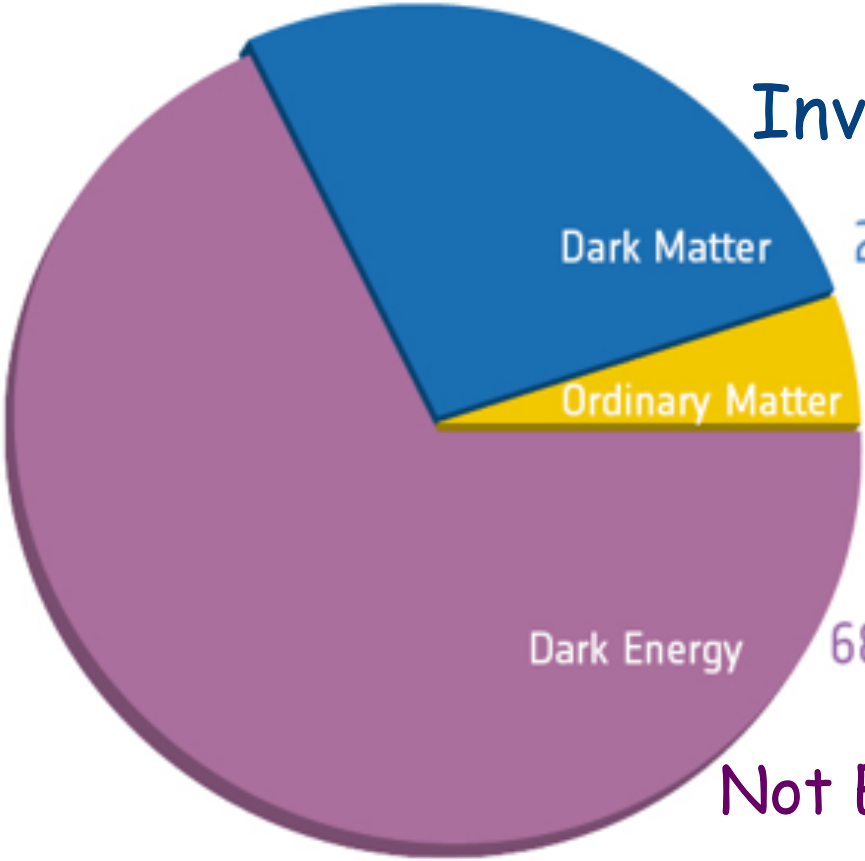
    1) ガンマ線観測から (Fermi, CTA)
    2) 電子陽電子、反陽子観測から (AMS-02, CALET)

- Axion Like Particles との関係 ほとんど話さない

- Primordial Black Holesとの関係 ほとんど話さない

Planck Satellite

$$\Omega_i \equiv \left.\frac{\rho_i}{\rho_c}\right|_0$$



Einstein's Cosmological Constant

Or unknown scalar field?

Weakly-interacting massive particle (WIMP)

- σ_{ann} is close to that of Weak Interaction

- Ω_{WIMP} coincides $\Omega_{DM,obs}$ (if $\langle\sigma v\rangle \sim 3 \times 10^{-26}\ cm^3/s$)

- Lightest SUSY Particle (LSP) can be WIMP

$$\chi = c_1 \tilde{B} + c_2 \tilde{W} + c_3 \tilde{H}_1 + c_4 \tilde{H}_2 \quad \Leftrightarrow \text{ photon, Z-boson, Higgs}$$

Thermal freeze out of WIMP

Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle[(n_\chi)^2 - (n_\chi^{eq})^2]$$

$$x_F \equiv \frac{m}{T_F} \sim 24 + \ln\left(\frac{m}{\text{TeV}}\right) + \ln\left(\frac{\langle\sigma|v|\rangle}{\text{TeV}^{-2}}\right)$$

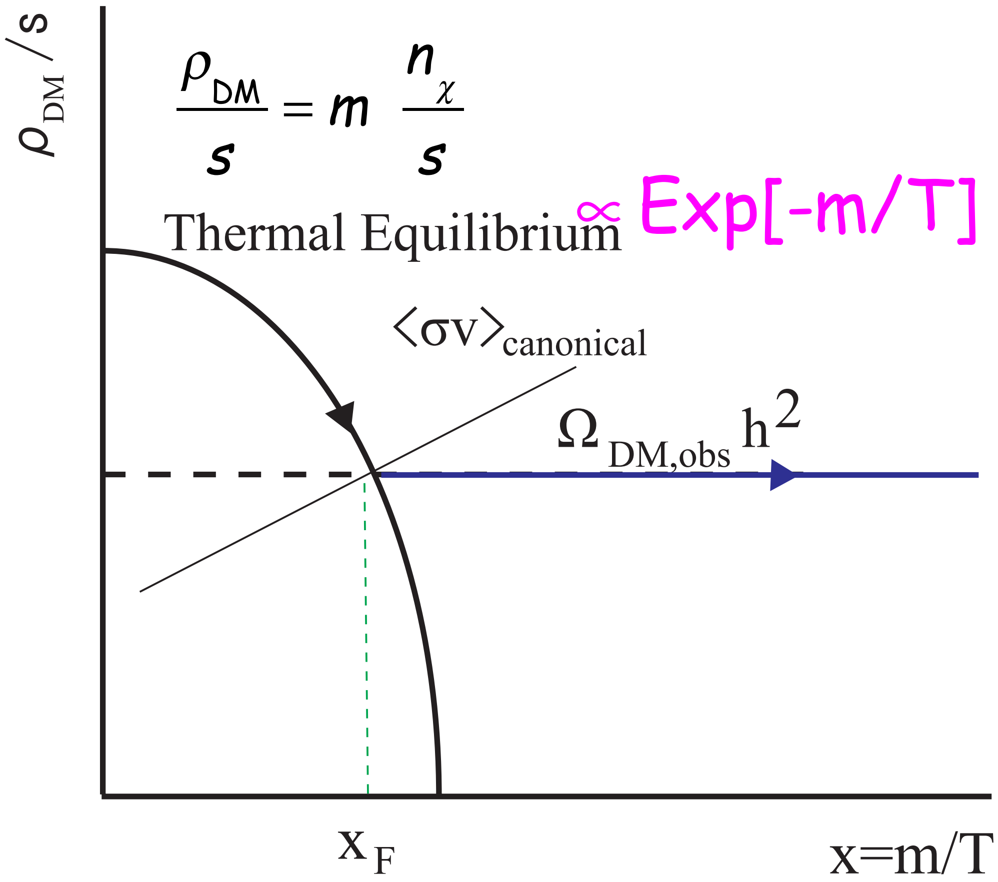
Freeze-out

$$\left.\frac{n_\chi}{s}\right|_F \sim \left.\frac{3H}{\langle\sigma v\rangle s}\right|_F$$

$$\Omega_\chi \sim 0.25\left(\frac{\langle\sigma v\rangle}{\left(0.1/\text{TeV}\right)^2}\right)^{-1}$$

Ω_χ does not depend on m

$$\langle\sigma|v|\rangle_{\text{canonical}} = 3\times10^{-26}\frac{cm^3}{sec} \sim \frac{0.3^4}{(\text{TeV})^2}$$

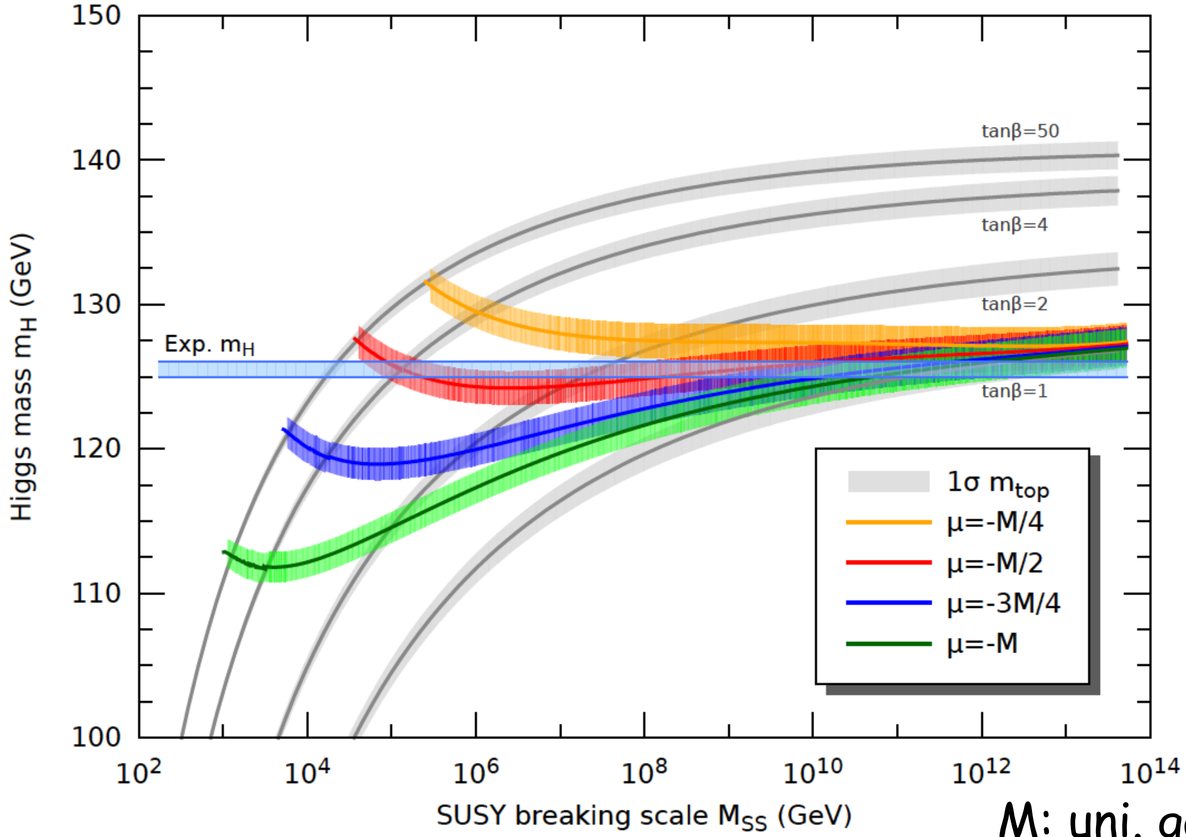


Suggesting TeV -scale Physics, e.g., SUSY

$$m_{\text{SUSY particles}} \sim \Delta m_{\text{Higgs}} \sim O(1)\text{TeV}$$

Higgs mass and SUSY breaking

$$m_{\rm Higgs}^2 \approx m_Z^2 \left[1 + \frac{3m_t^2}{2\pi^2 m_Z^2} \log(m_{\rm stop}/m_{\rm top}) \right]$$



M: uni. gaugino mass

We need a higher SUSY breaking with >>10 TeV

Ibanez et al, arXiv:1301.5167

SUSY breaking scales

- Gravitino mass represents the scale of SUSY breaking

$\tilde{W}$ tends to be the LSP

$$m_{3/2} \sim \frac{F}{M_p} \sim \begin{cases} \gg O(1)\text{TeV} & \text{anomaly mediation} \\ \gtrsim O(10^2)\text{GeV-}O(1)\text{TeV} & \text{gravity med.} \\ < O(10^2)\text{GeV-}O(1)\text{TeV} & \text{gauge med.} \end{cases}$$

gravitino tends to be the LSP

Mass matrix of neutralinos

- Mass matrix

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

in the basis $(-i\tilde{B}, -i\tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$

- Mass parameters, e.g., in anomaly-mediated SUSY breaking

$$M_i = -b_i g_i^2 M_{\rm SUSY}$$

Giudice, Luty, Murayama, Rattazzi, 1998
Randall and Sundram, 1998

g_i are gauge coupling constants

b_i are the 1-loop β-function coefficients

$$M_1 \; : \; M_2 \; : \; M_3 = 3.3 \; : \; 1 \; : \; -10$$

Should we stick to canonical one?

$\sigma < \sigma_{canonical}$

- Such a larger relic density can be diluted by entropy production e.g, by massive-decaying particles (moduli, gravitino, ...)

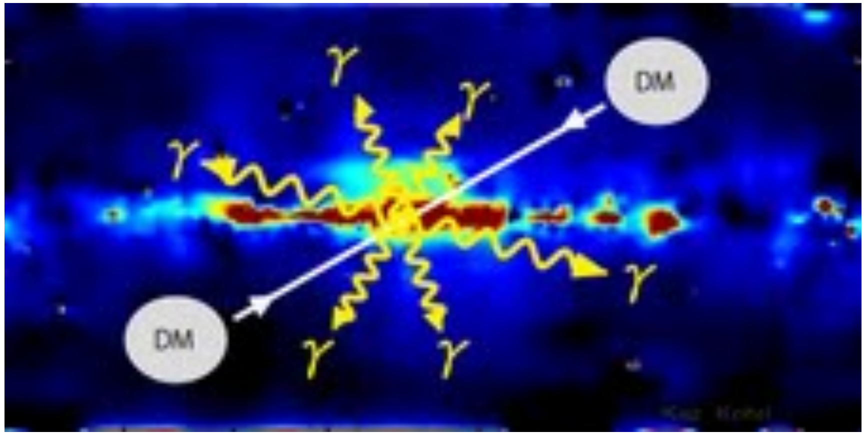
$\sigma > \sigma_{canonical}$

- Such a smaller relic density can be replaced by non-thermally-produced DM e.g, by massive-decaying particles (moduli, gravitino, ...)

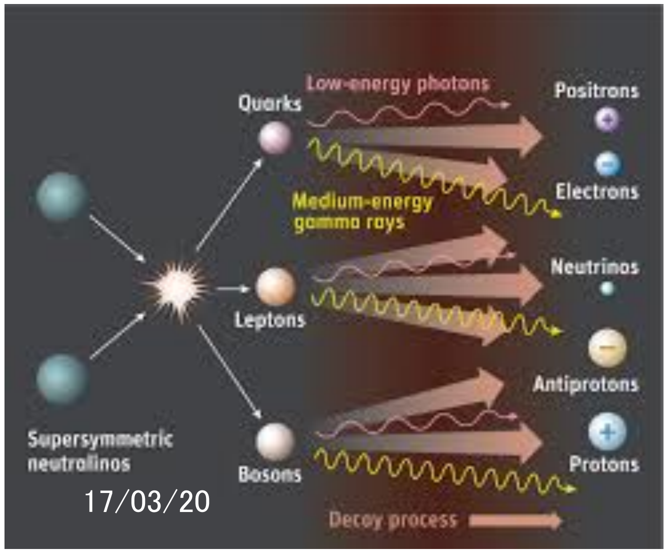
We may allow even a decaying DM with lifetime of > 10^{26} sec through another interactions or a parity violation (e.g., R-parity violation in SUSY)

Indirect detection of DM

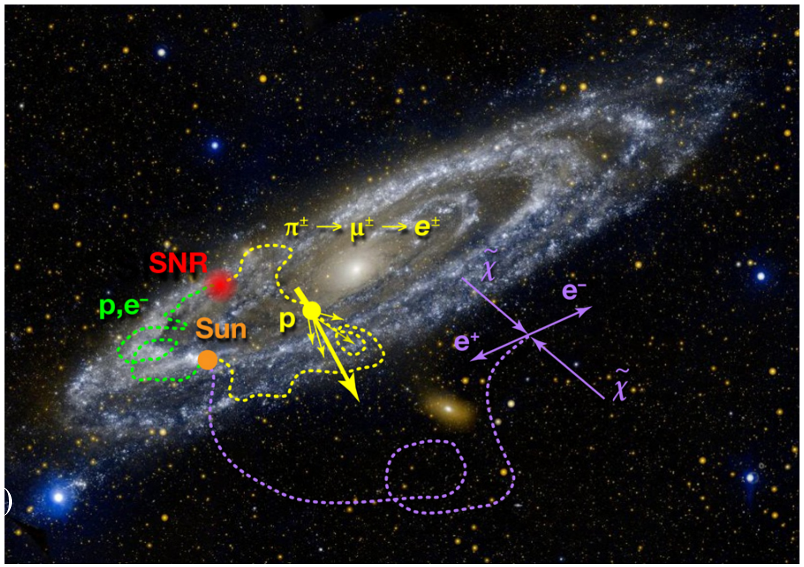
Annihilation or Decay?



Daughter particles



Propagations of charged particles



Products from DM annihilation/decay

- DM → WW (Wino neutralino LSP or ...)

$$\begin{cases} \to q+\bar{q} \to p+\bar{p}+n+\bar{n}+\pi^{+}+\pi^{-}+\pi^{0}+\ldots \\ \qquad\qquad \to p+\bar{p}+e^{-}+\nu+\gamma+\ldots \\ \to \ell^{\pm}+\nu \to e^{-}+\nu+\gamma+\ldots \end{cases}$$

- DM → b bbar (neutralino LSP, or ...)

$$\to p+\bar{p}+n+\bar{n}+\pi^{+}+\pi^{-}+\pi^{0}+\ldots$$

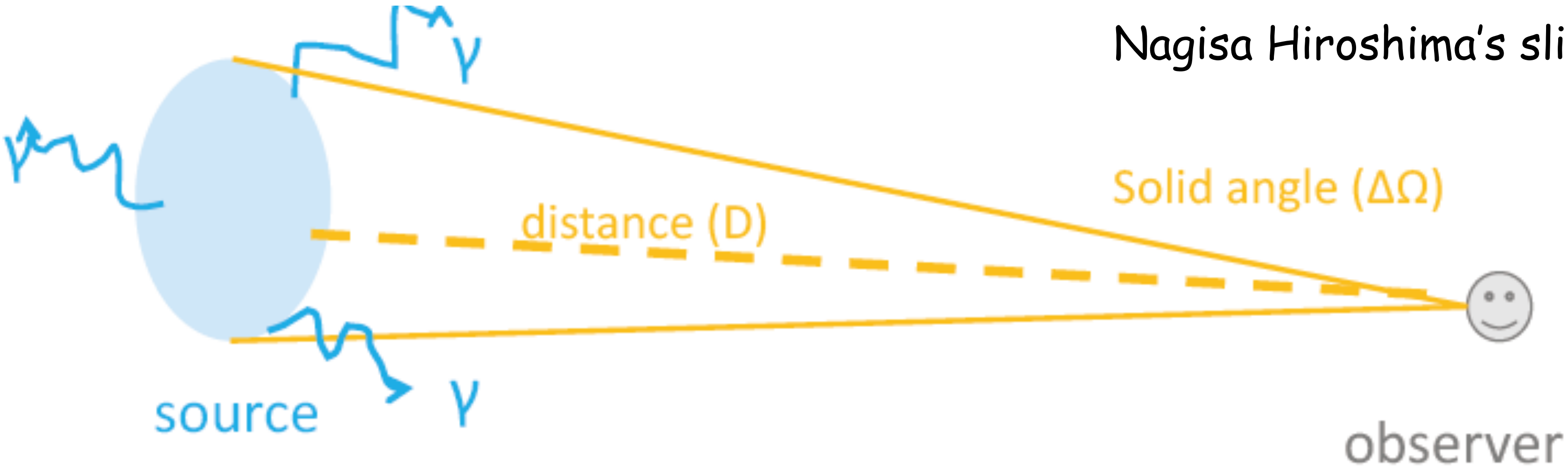
$$\to p+\bar{p}+e^{-}+\nu+\gamma+\ldots$$

- DM → leptons (slepton LSP, $\nu_{R,}$, scalar $\nu_{R,}$, or ...)

$$\to \ell^{\pm}+\nu \to e^{-}+\nu+\gamma+\ldots$$

Gamma-ray observations

How can we obtain the flux from a source?



$$\sim \frac{dN_\gamma}{dE_\gamma} n_{DM}^2 \langle\sigma v\rangle = \frac{dN_\gamma}{dE_\gamma} \frac{\rho_{DM}^2}{m_{DM}^2} \langle\sigma v\rangle$$

$$\phi(\Delta\Omega) = \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{2m_{DM}^2} \int_{E_{min}}^{E_{max}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \times \int_{\Delta\Omega} \int_{LoS} \rho_{DM}^2 \, dl \, d\Omega'$$

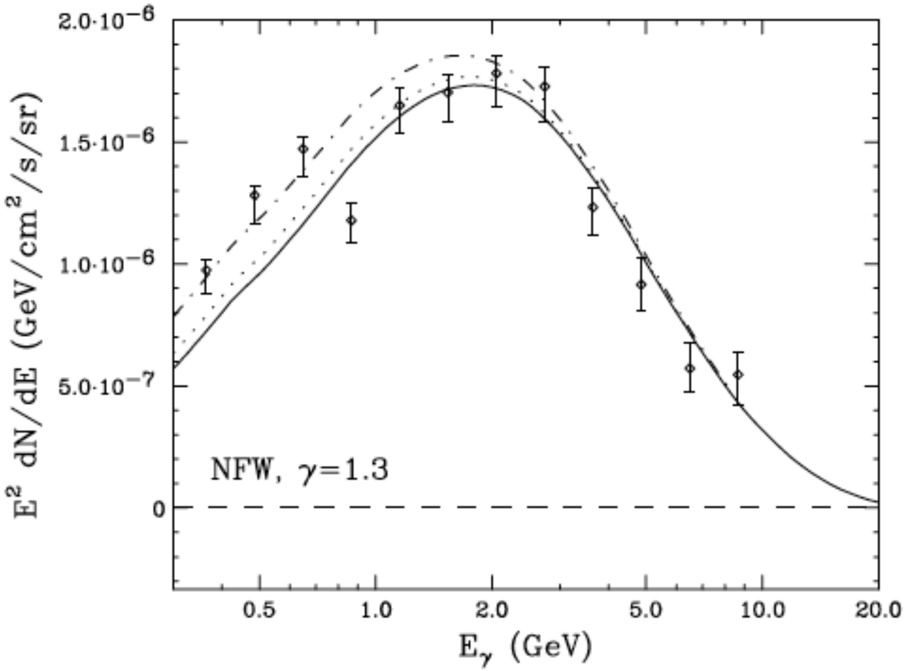
particle physics part

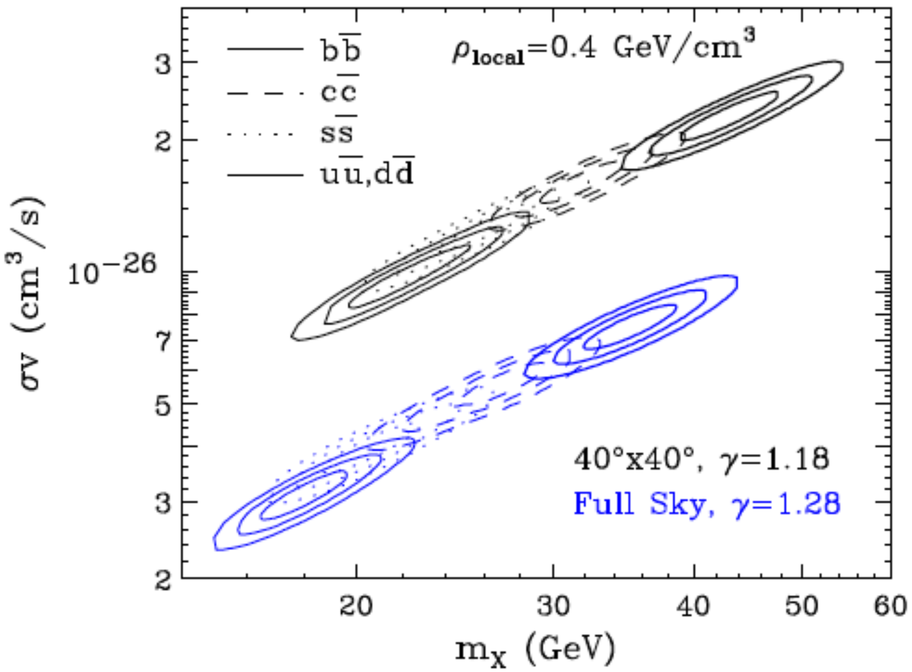
astrophysical part (J-factor)

J-factor $\sim 10^{16} - 10^{20}$

Galactic-center gamma-ray excesses and dark matter annihilation

Daylan et al, 2014

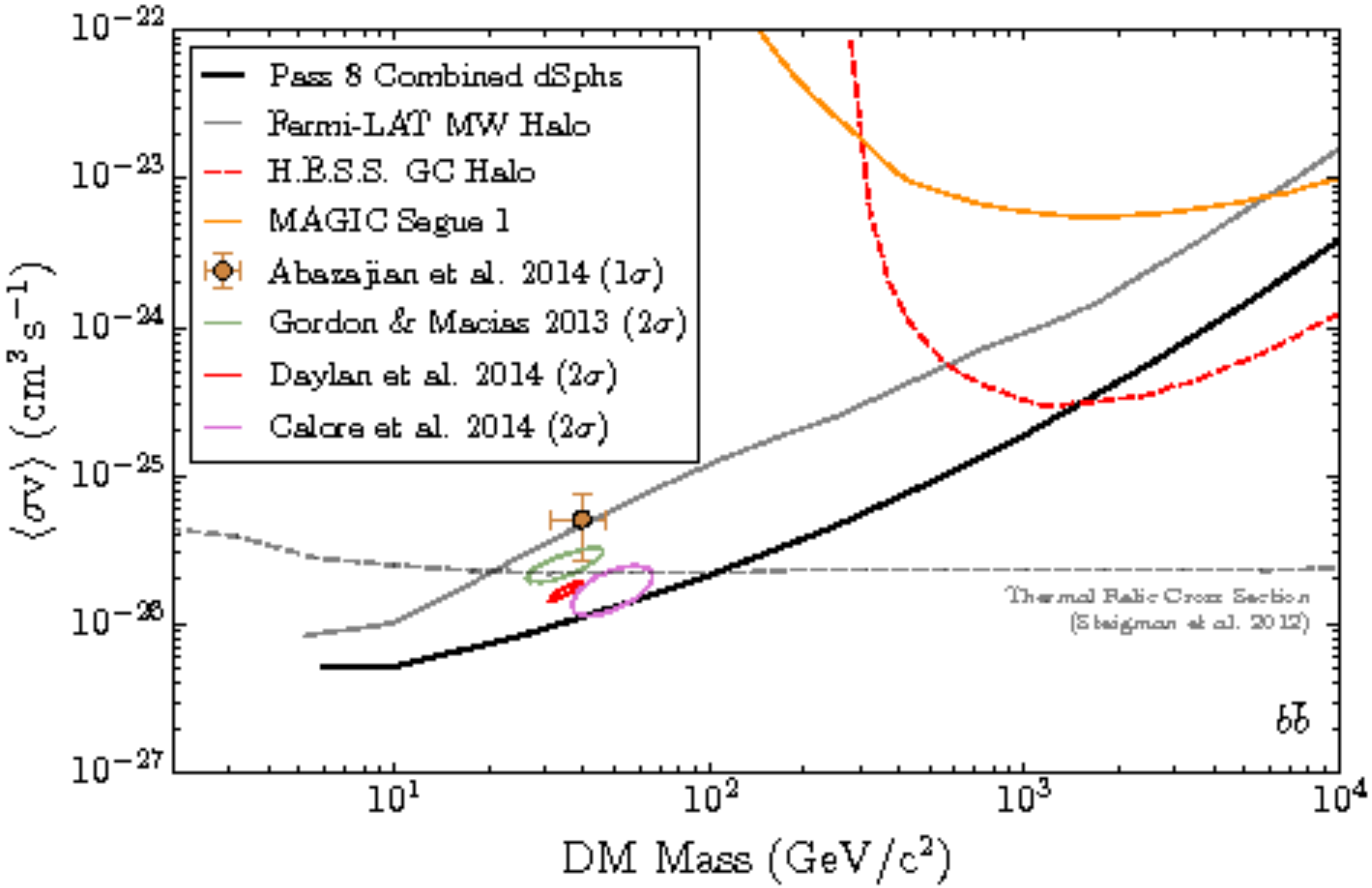




Constraints by Fermi gamma-ray sattelite

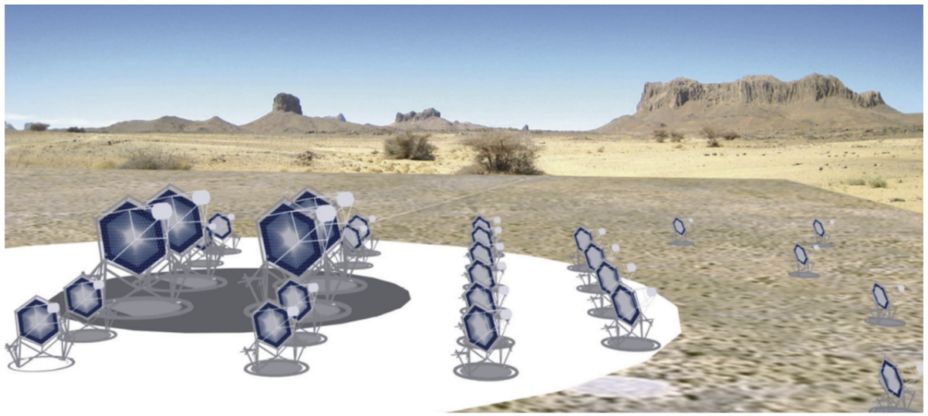
Fermi-LAT Collaboration (Ackermann, M. et al.) Phys.Rev.Lett. 115 (2015)

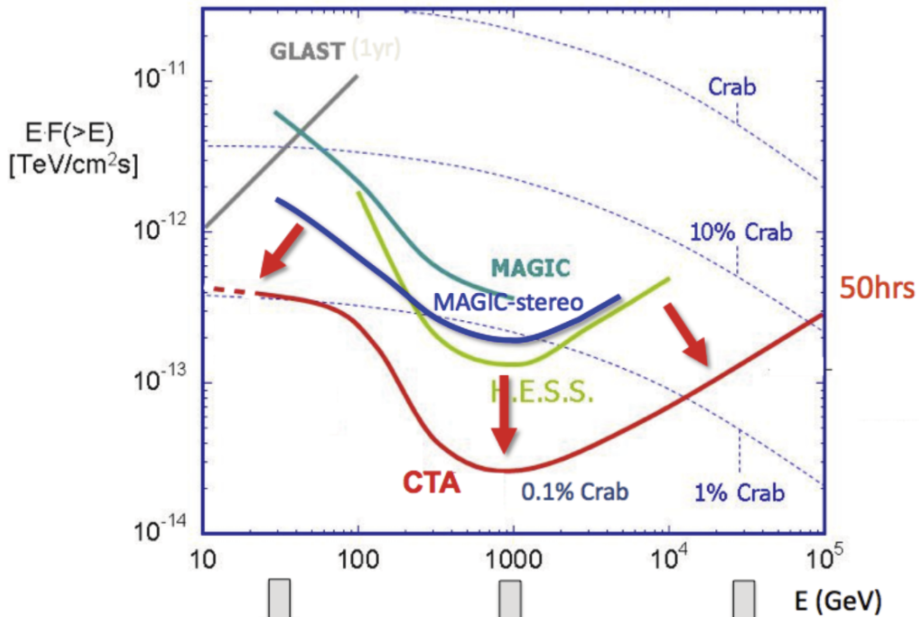
See also, FermiLAT-Magic combined, Ahnen et al., arXiv:1601.06590



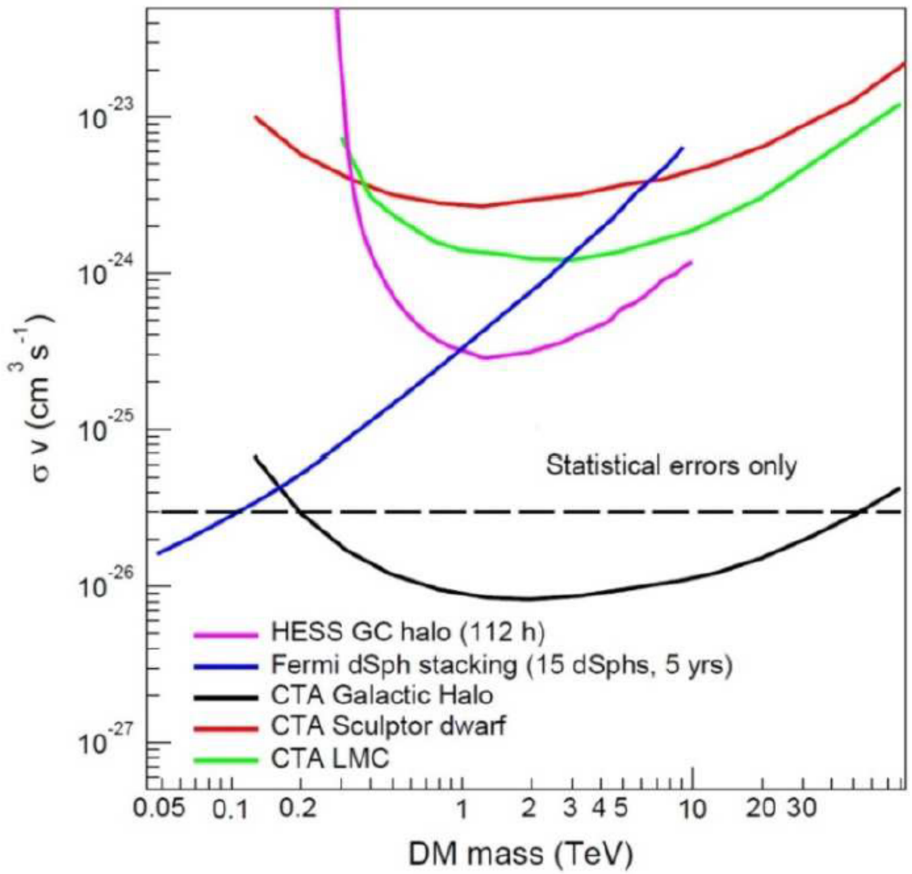
Future TeV-gamma observation
Cherenkov Telescope Array (CTA)

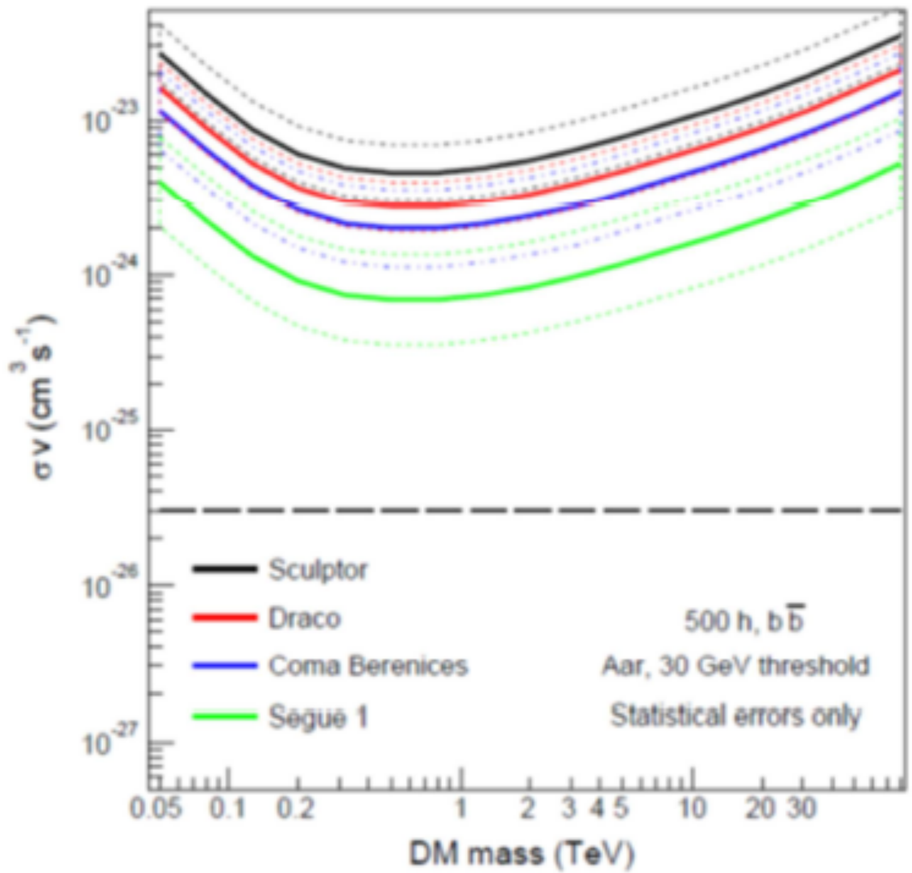
One order of magnitude better sensitivity at TeV





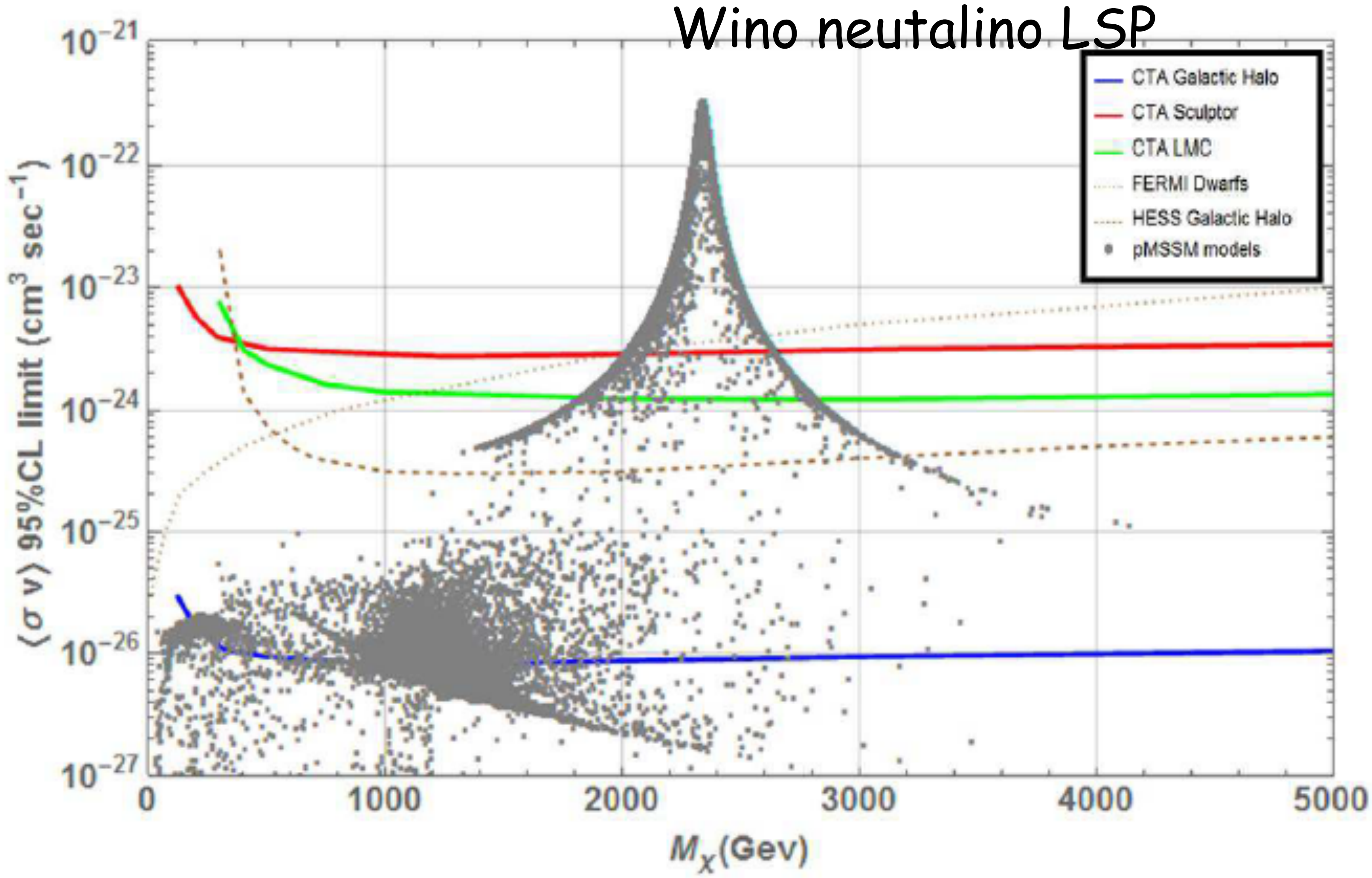
CTA sensitivity





CTA collaboration, John Carr et al, arXiv:1508.06128 [astro-ph.HE]

CTA sensitivity



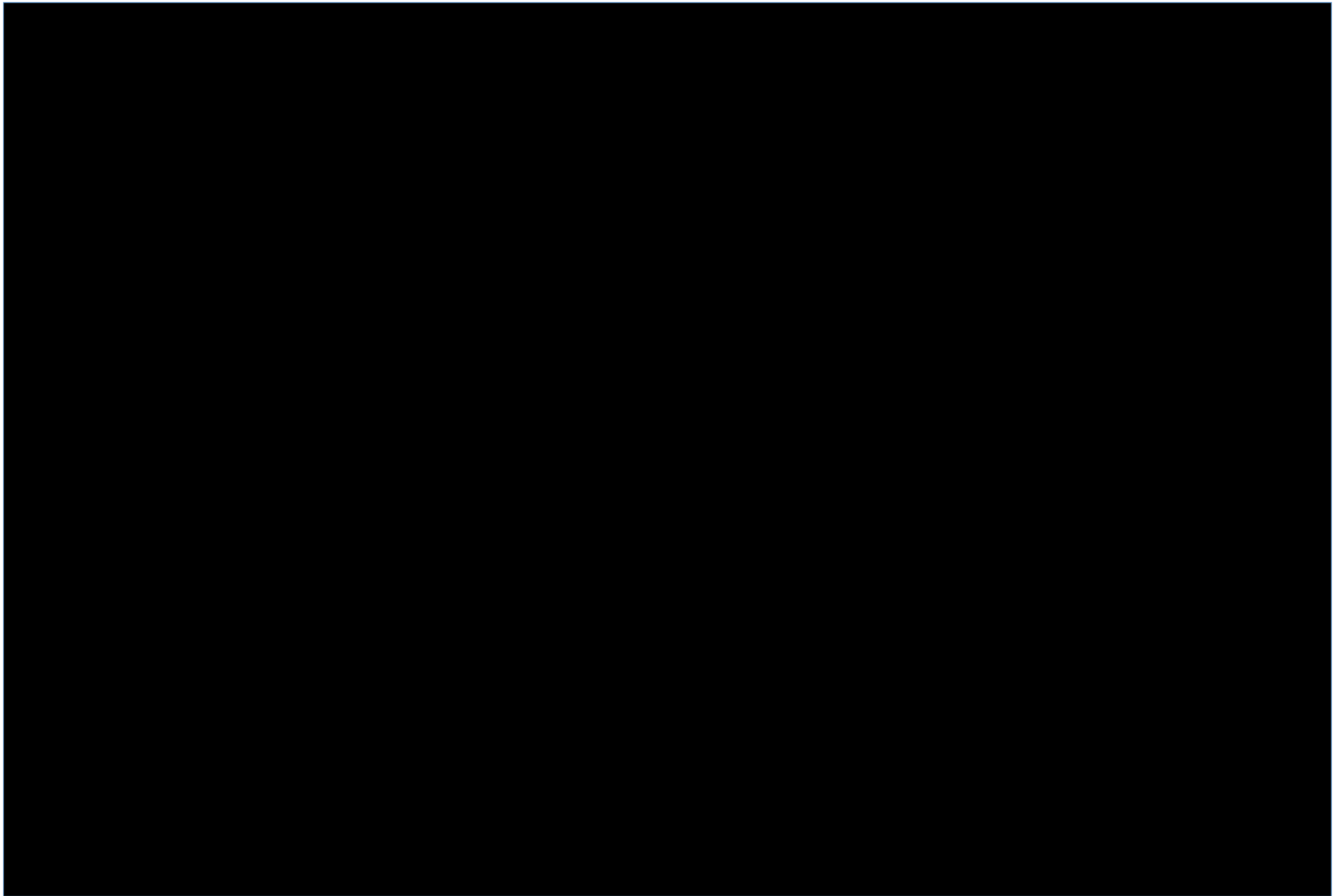
CTA collaboration, John Carr et al, arXiv:1508.06128 [astro-ph.HE]

CTAに特化した宇宙物理の専門家による解析が必要

Hiroshima, M. Hayashida, KK (2017) in preparation

- 空間分布を考慮した解析
- Backgroundとsignalの区別
- Calibrationの難しさ(何をもってoffとするか)
- …

Nagisa Hiroshima's slide



Nagisa Hiroshima's slide

Detectability

Hiroshima, M. Hayashida, KK, 2017 in preparation

Charged particles from DM annihilation/decay

positron e^+

antiproton $\bar{p}$

Diffusion of charged particles

Diffusion model

$$\frac{\partial}{\partial t} f(E,\vec{x}) = K(E)\nabla^2 f(E,\vec{x}) + \frac{\partial}{\partial E}[b(E) f(E,\vec{x})] + Q(E,\vec{x})$$

Source term by decaying /annihilating DM

Flux

$$\Phi_{e+}^{(\mathrm{DM})}(E,\vec{x}_\odot) = (c/4\pi) f(E,\vec{x}_\odot)$$

Steady-state solution

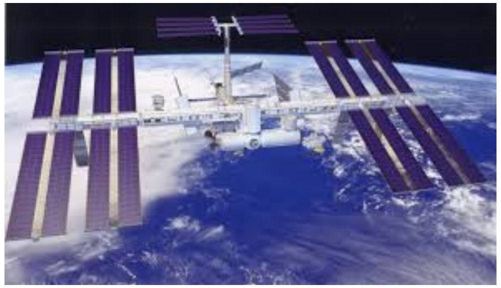
$K(E) \propto E^{-\delta}$: diffusion coefficient ($\delta \sim 1/3$ by AMS-02, 2016)

$b(E)$: energy-loss rate

Propagating within a few kpc, normalized to fit B/C

$$r_{\mathrm{propagation}} \sim \sqrt{EK(E)/b(E)} \sim \mathrm{kpc}(E/\mathrm{TeV})^{-(1-\delta)/2}$$

Positron and antiproton by AMS-02 or CALET



KK and Sahu et al 2017

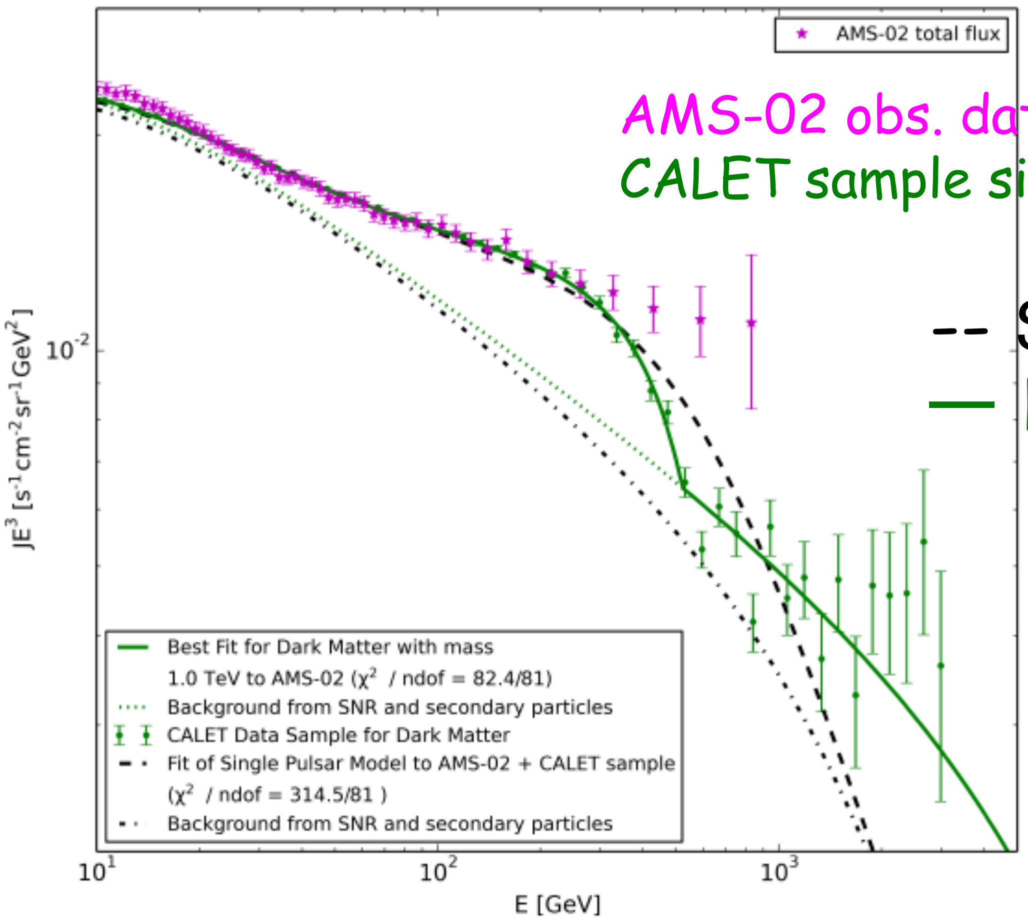
[redacted]

But still large uncertainties, e.g., in p-N cross sections, propagation models and so on

Discriminate Pulsar from DM by CALET?

S. Bhattacharyya, H.Motz, S.Torii, Y.Asaoka, arXiv:1702.02546 [astro-ph.HE]

$e^- + e^+$ flux



-- Single Pulsar

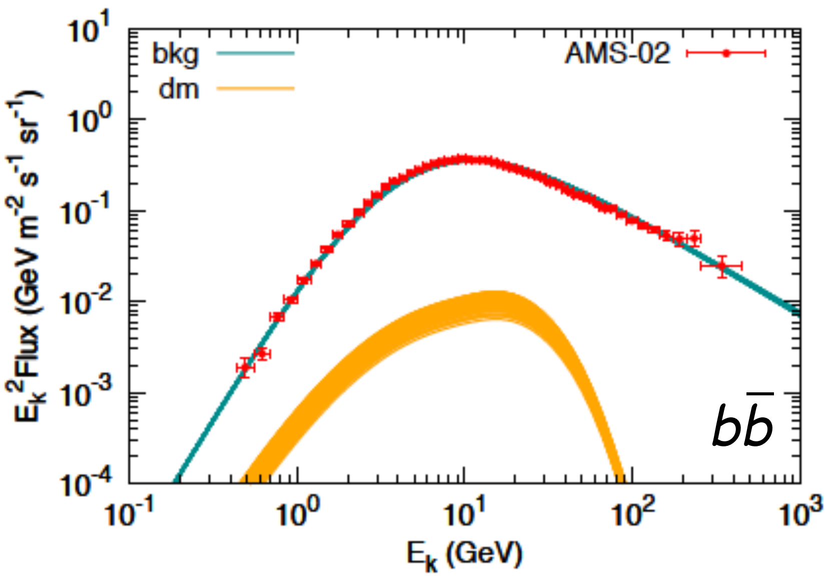
— DM

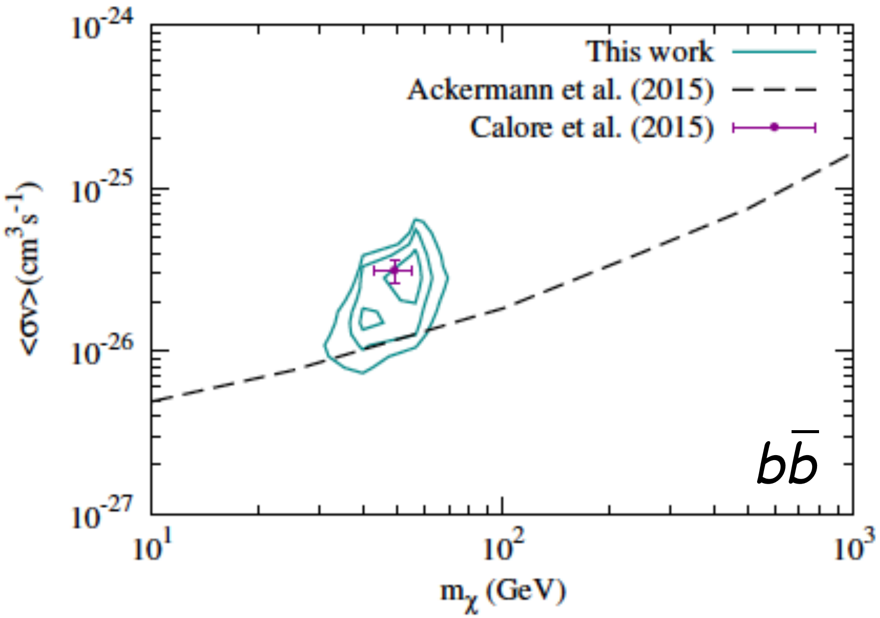
Decaying DM→μμν: 73% and eeν: 27% with m_{DM} = 2TeV

Antiprotons from annihilating/decaying dark matter and the galactic center anomaly

Qui et al, arXiv:1610.03840
Cuocco et al, arXiv: 1610.03071

See also Hamaguchi, Nakayama, Moroi, arXiv:1504.05937
Ibe, Matsumoto, Shirai, Yanagida, arXiv:1504.05554



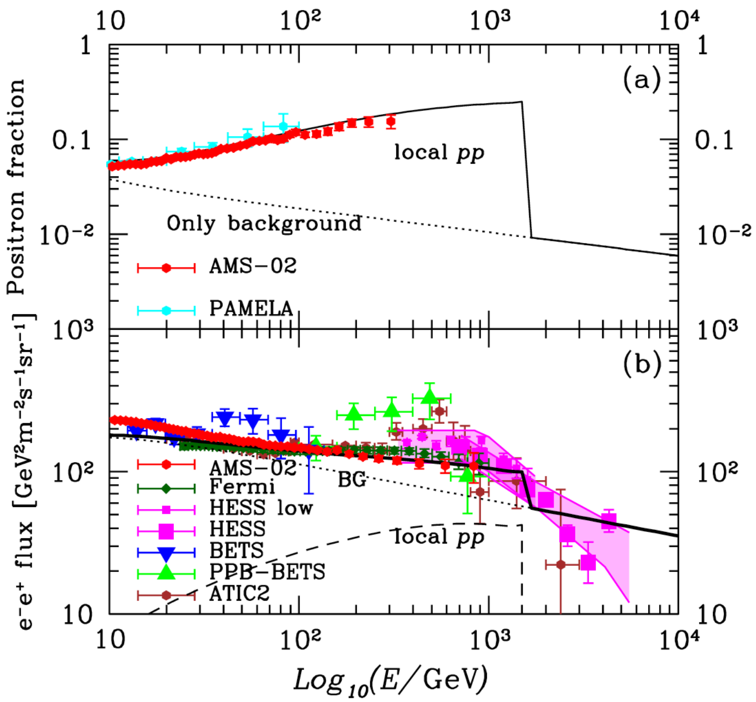


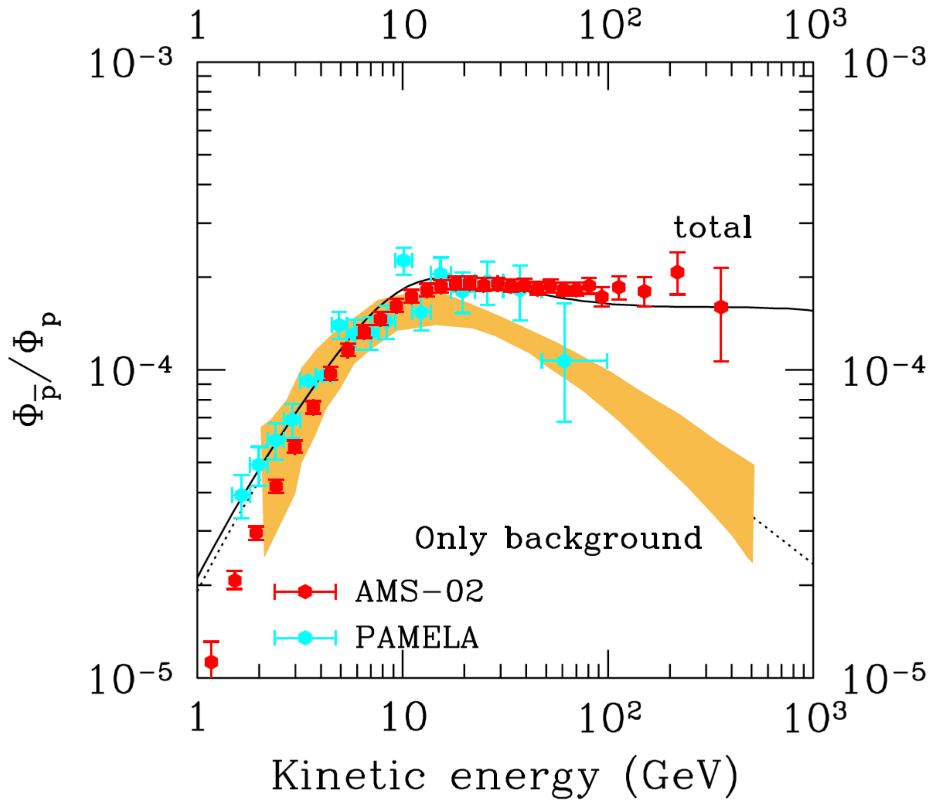
A simultaneous fitting to positron anomaly is a big challenge

Astrophysics models
Fitted to a data by local SNR model

Fujita, KK, Yamazaki, Ioka, arXiv:0903.5298

KK, Ioka, Fujita, Yamazaki, arXiv:1505.01236



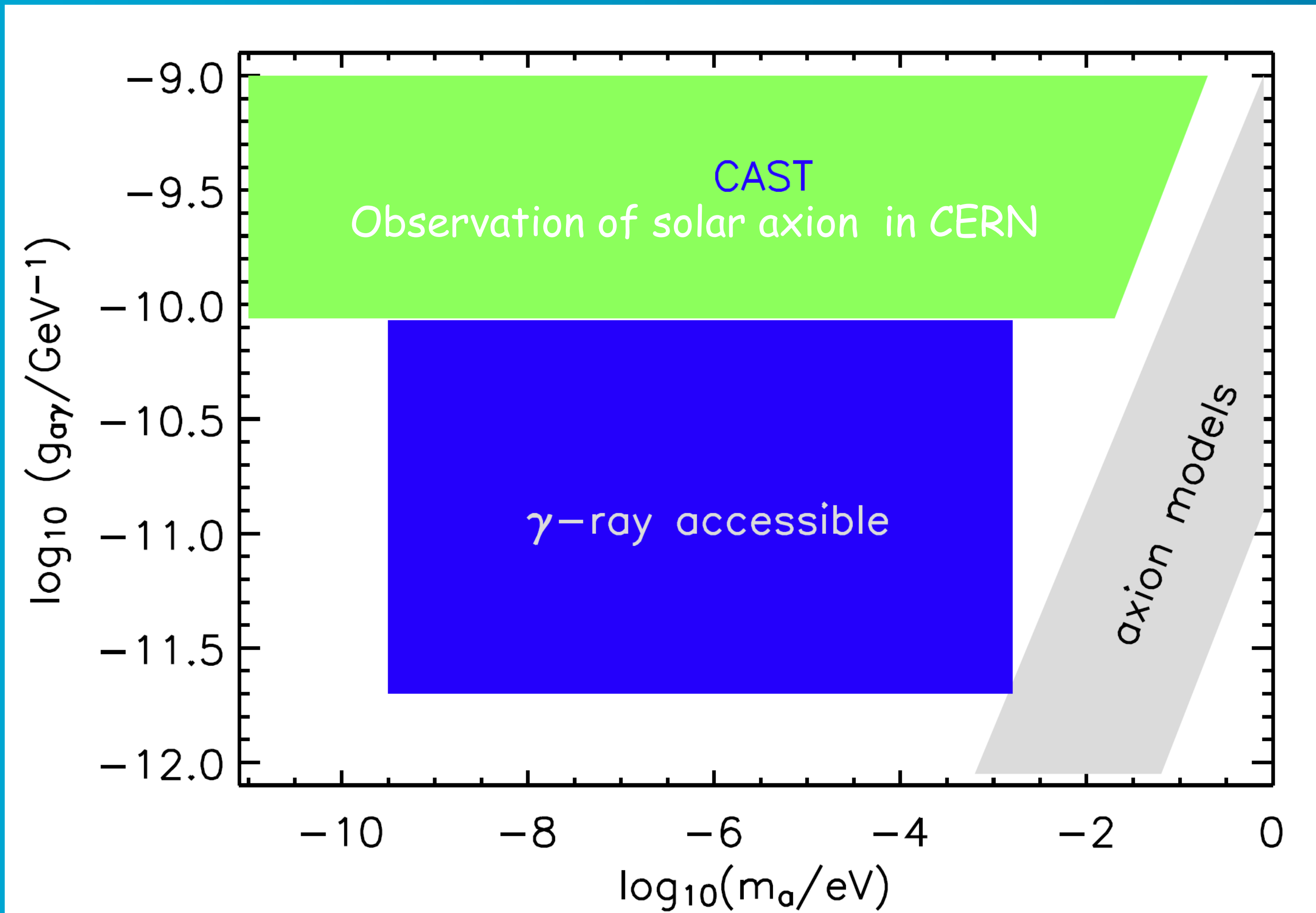


Can DM models be more attractive?

Summary

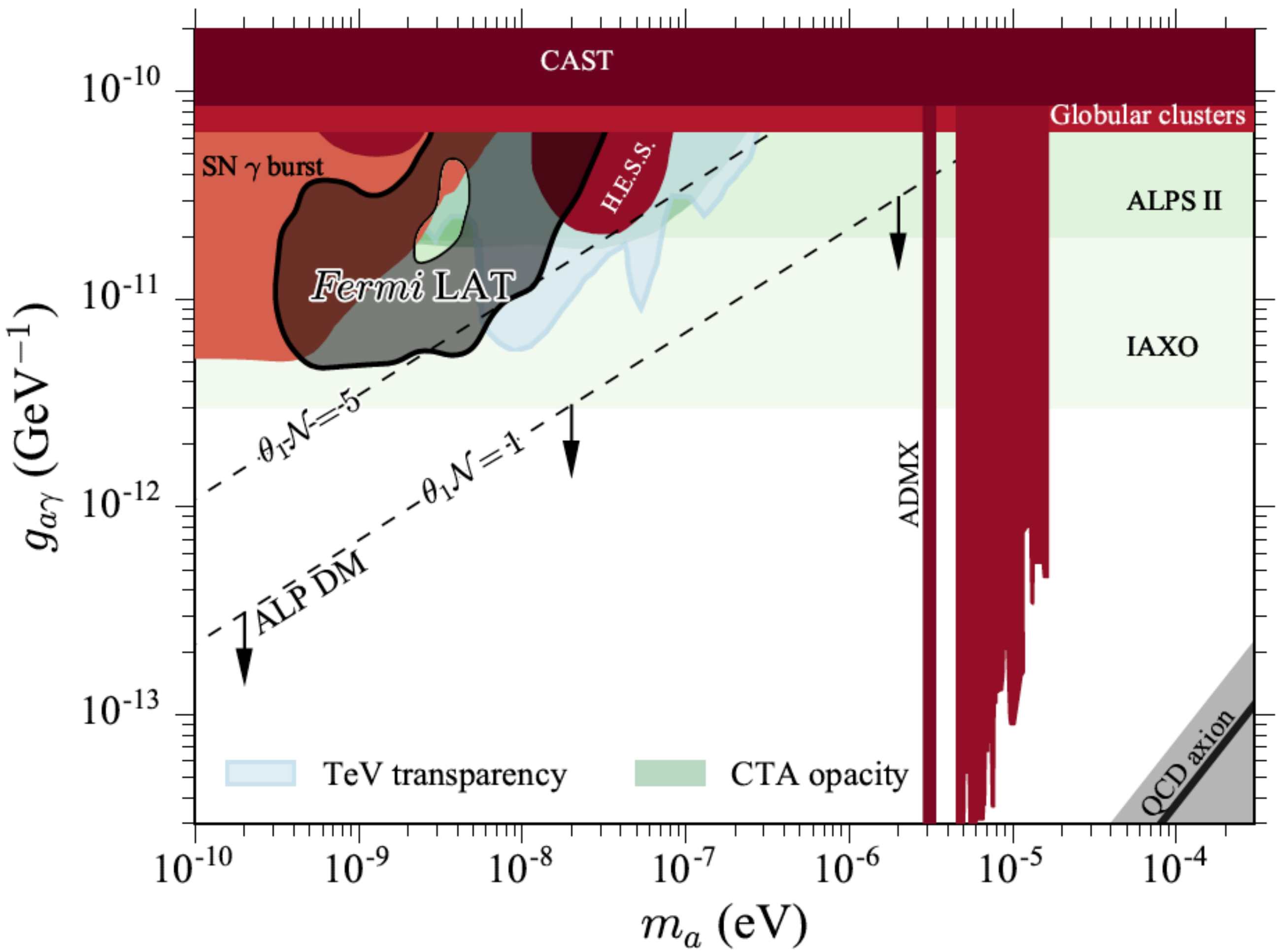
- WIMP DM is a good target searched by cosmic-ray physics
- Future experiments such as CALET and CTA will reveal the nature of WIMP dark matter
- SUSY models with Wino dark matter will be tested in near future
- A simultaneous fitting to both positron and antiproton with satisfying gamma-rays obs. is a big challenge

Gamma-ray accessible parameters



Hooper-Serpico (07)

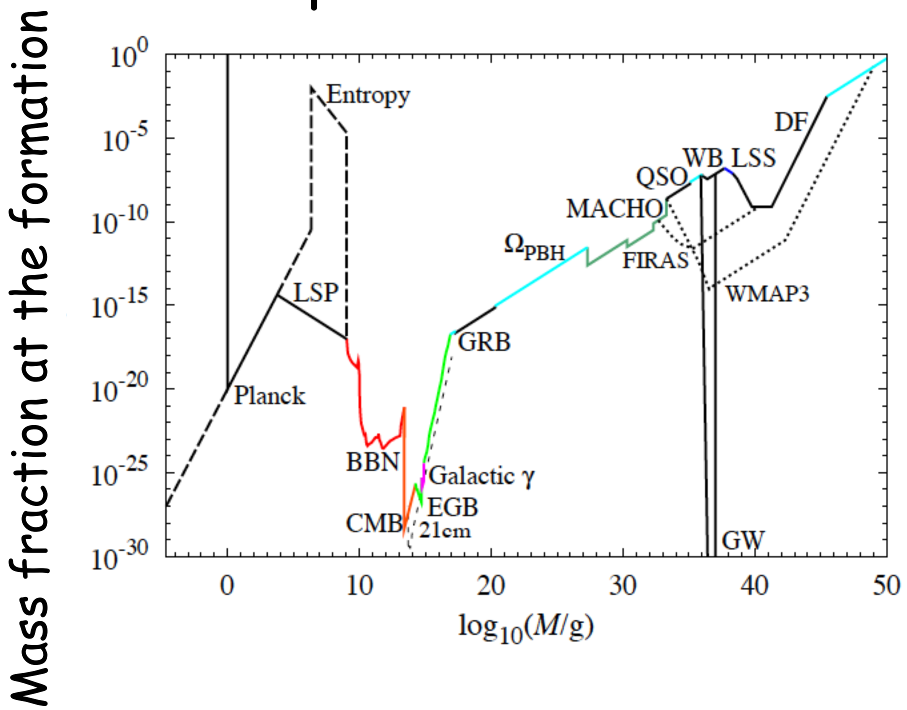
Excluded regions, which highly depends on magnetic field configulations

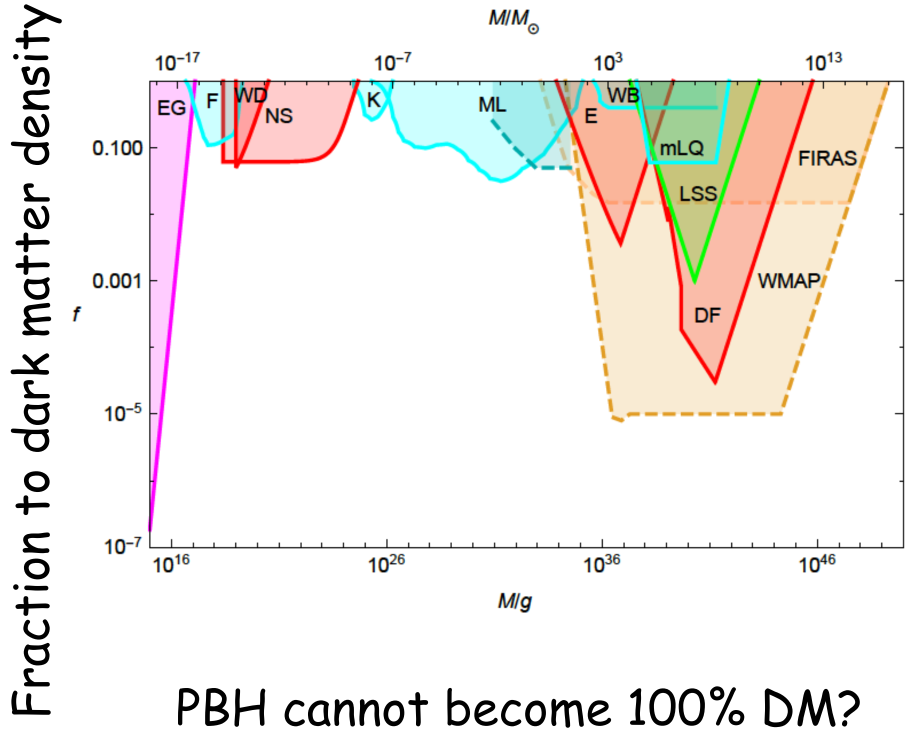


The Fermi-LAT Collaboration, arXiv:1603.06978

Primordial Black Hole dark matter

Horizon mass with the density fluctuation of the order O(1) can collapse to a PBH





PBH cannot become 100% DM?

Carr, Kohri, Sendouda, Yokoyama (2009)

Carr, Kunel, Sandstad (2016)