大学共同利用機関法人
高エネルギー加速器研究機構 KEK

国立大学法人
総合研究大学院大学
THE GRADUATE UNIVERSITY FOR ADVANCED STUDIES [SOKENDAI]

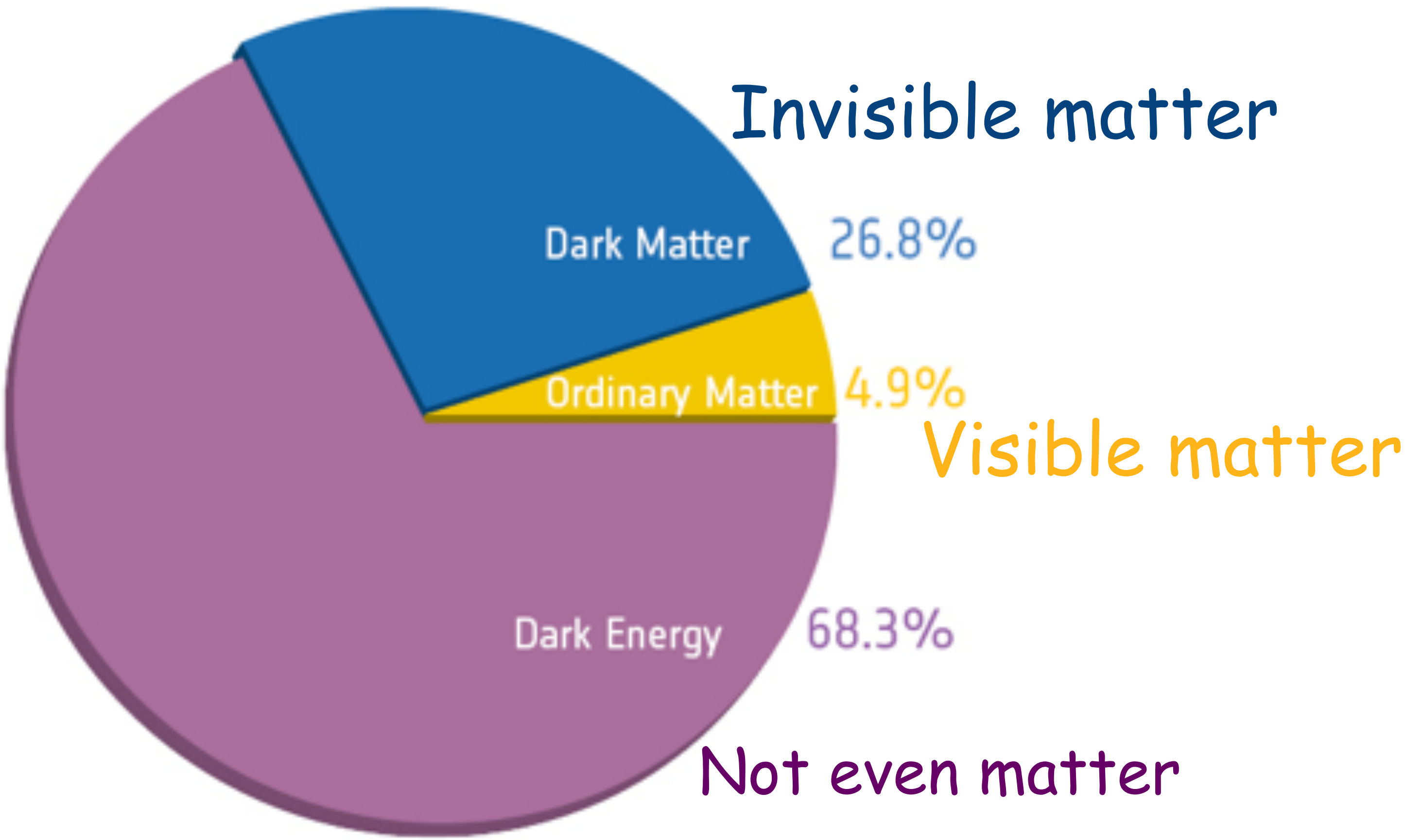
Search for Dark Matter with CTA

Kaz Kohri
郡 和範

Theory Center, KEK and SOKENDAI, Tsukuba

Planck Satellite

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



After Planck

Candidate of Dark Matter
My favorite DM (推しダークマター)

- WIMP

- Axion

- Primordial Black Hole

- …

WIMP

Weakly-Interacting Massive Particle (WIMP)

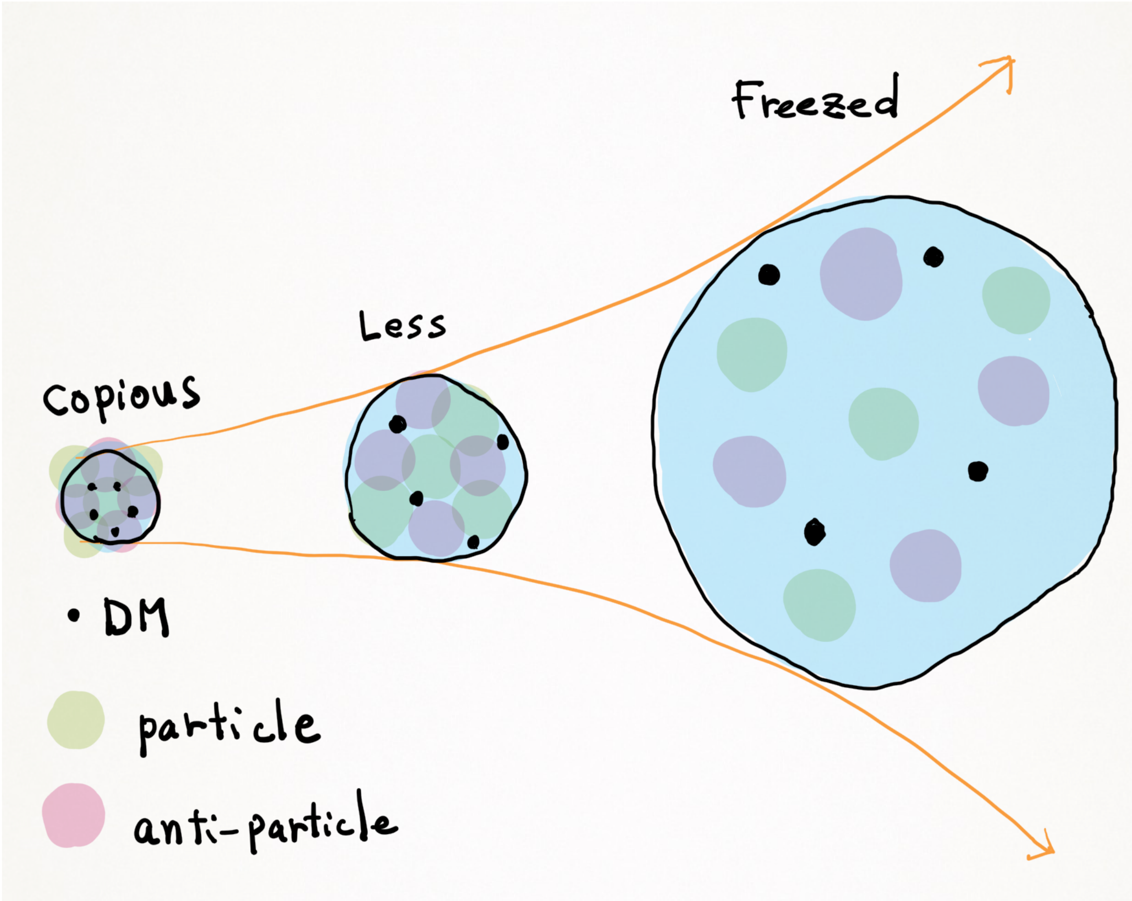
- σ_{ann} is close to that of Weak Interaction [~(TeV)$^{-2}$]
- Ω_{WIMP} coincides $\Omega_{DM,obs}$ (if $<\sigma v>\sim 3\times10^{-26}$ cm^3/s)
- The Lightest SUSY Particle (LSP) can be WIMP

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

Bino, Wino, Higgsino 1, Higgsino 2

1) Production of WIMP in the early Universe

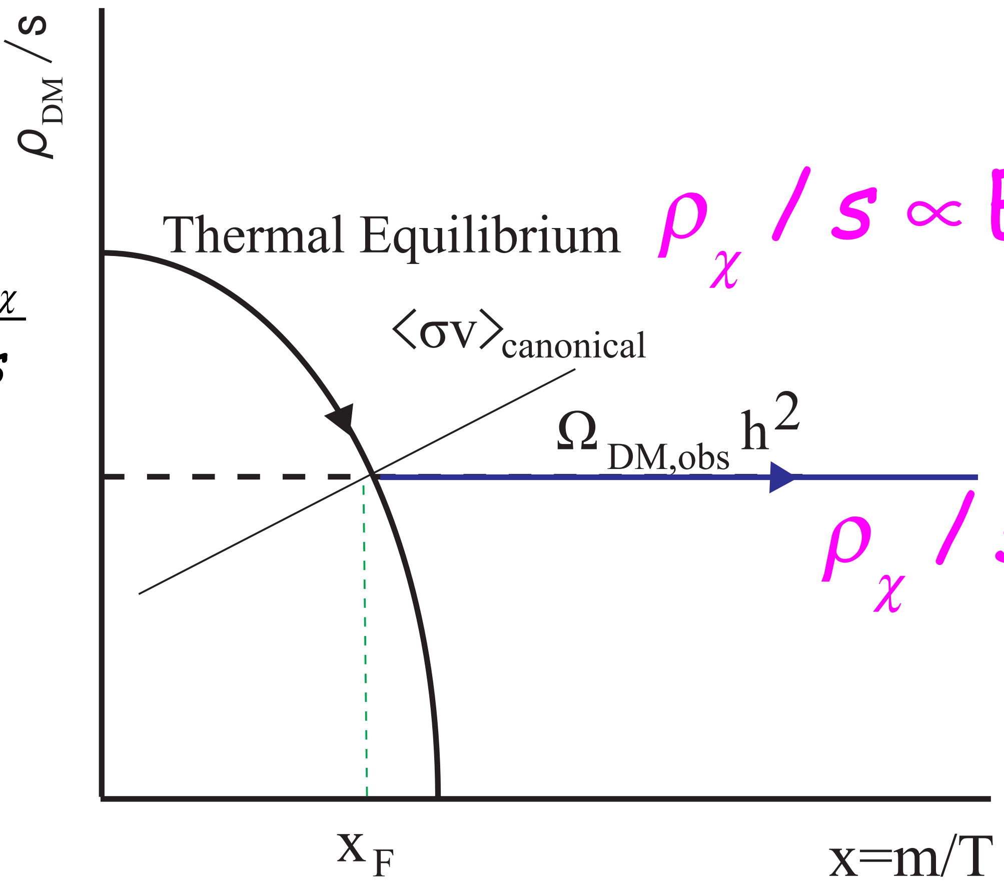
- Left from the cosmic expansion (freeze-out)



Thermal freeze out of WIMP

$$\frac{\rho_{DM}}{s} = m \frac{n_\chi}{s}$$

($\rho_{DM} \propto a^3$, $s \propto a^3$)



$$\rho_\chi / s \propto \text{Exp}[-m/T]$$

$$\rho_\chi / s \to \text{const.}$$

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

Only weakly-dependent on mass and cross section

Canonical Cross section $\langle \sigma |v| \rangle_{\text{canonical}}$

Boltzmann equation

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

Freezeout (expansion rate $\gtrsim$ annihilation rate)

$$\left.\frac{\rho_\chi}{s}\right|_F = m\left.\frac{n_\chi}{s}\right|_F \sim m\left.\frac{3H}{\langle \sigma v \rangle s}\right|_F \sim \frac{1}{\langle \sigma v \rangle m_{\text{Planck}}} \times \left.\frac{m}{T}\right|_F$$

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

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

Ω_χ does not depend on m

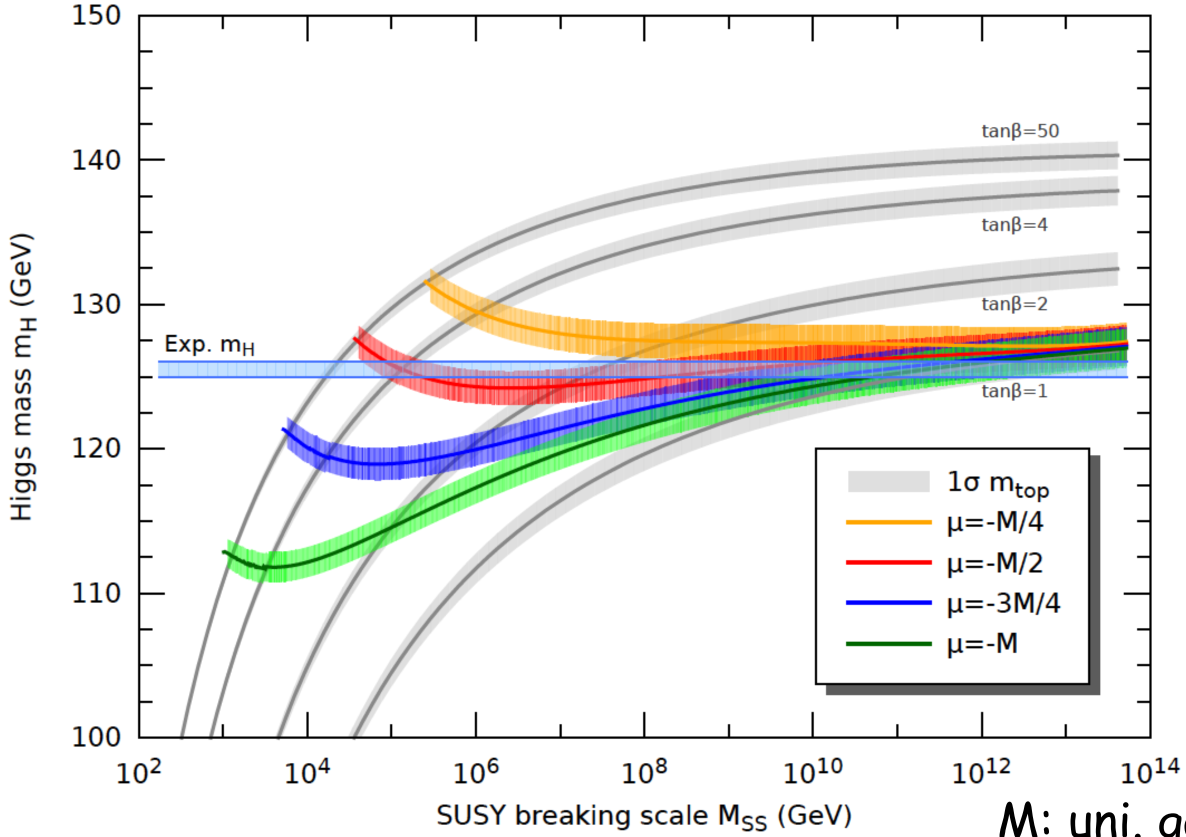
Suggesting TeV -scale Physics, e.g., SUSY

$$\langle \sigma |v| \rangle_{\text{canonical}} = 3 \times 10^{-26} \frac{cm^3}{sec} \sim \frac{0.3^4}{(\text{TeV})^2}$$

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

Higgs mass and SUSY breaking

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



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

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

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 σ?

$\sigma < \sigma_{canonical}$

- 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)

Products from DM annihilation/decay

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

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

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

$$\rightarrow p+\bar{p}+n+\bar{n}+\pi^{+}+\pi^{-}+\pi^{0}+\dots$$

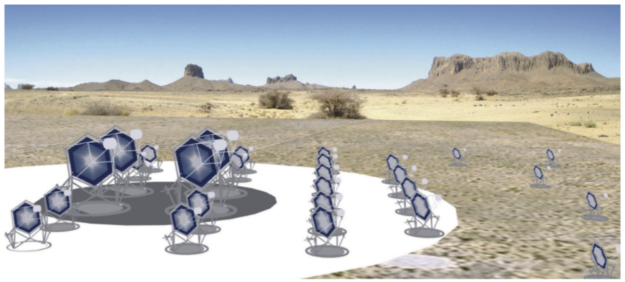
$$\rightarrow p+\bar{p}+e^{-}+\nu+\gamma+\dots$$

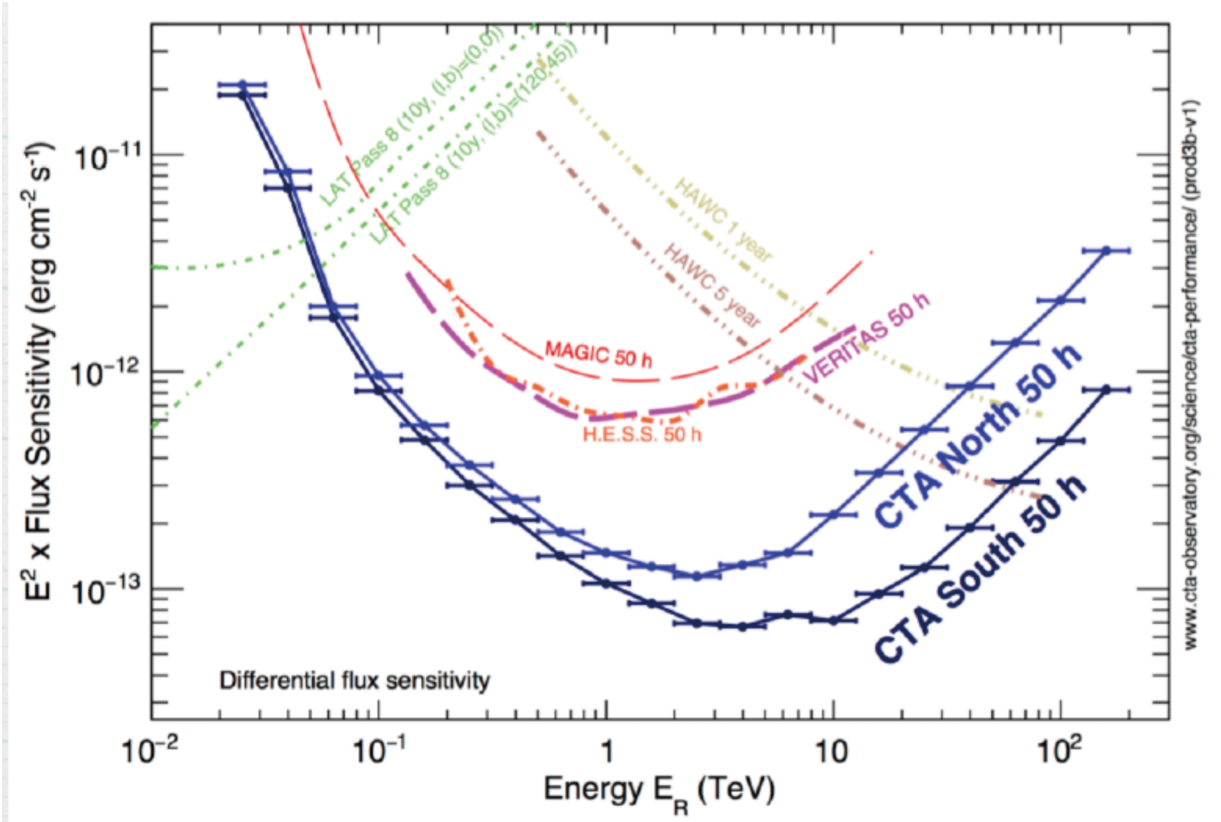
- DM → leptons (slepton LSP, $\nu_{R,}$, scalar $\nu_{R,}$, or ...)

$$\rightarrow \ell^{\pm}+\nu \rightarrow e^{-}+\nu+\gamma+\dots$$

Future TeV-gamma observation Cherenkov Telescope Array (CTA)

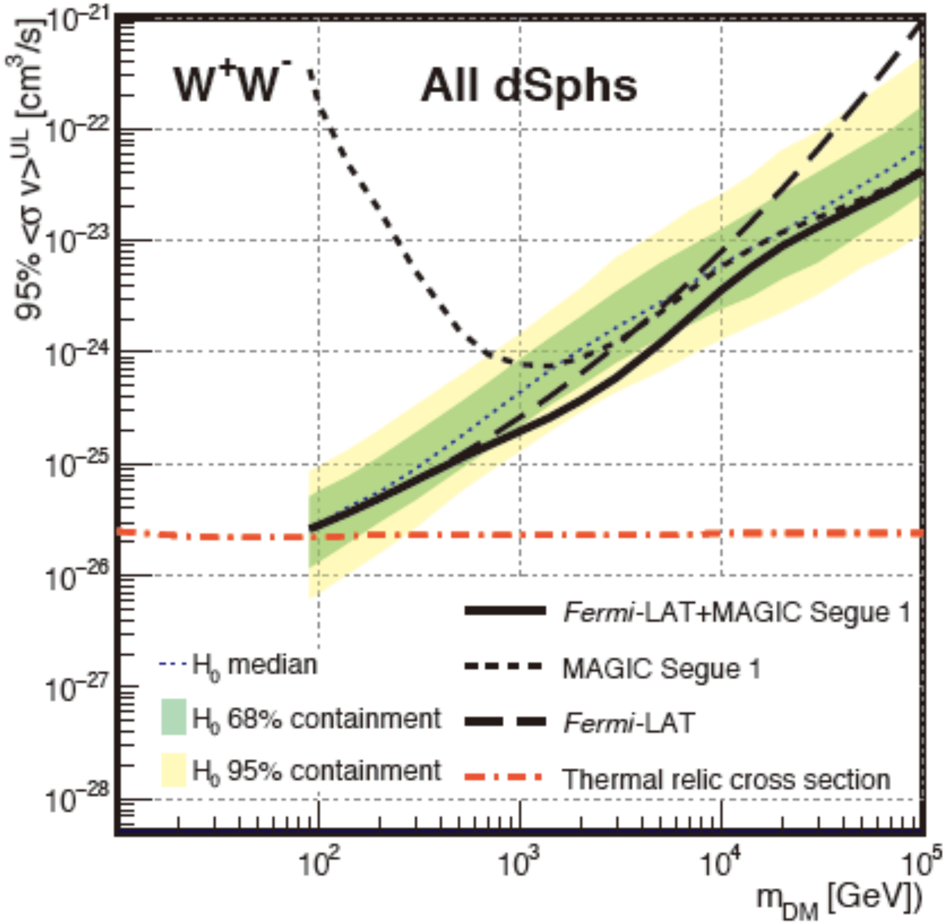
One order of magnitude better sensitivity at TeV





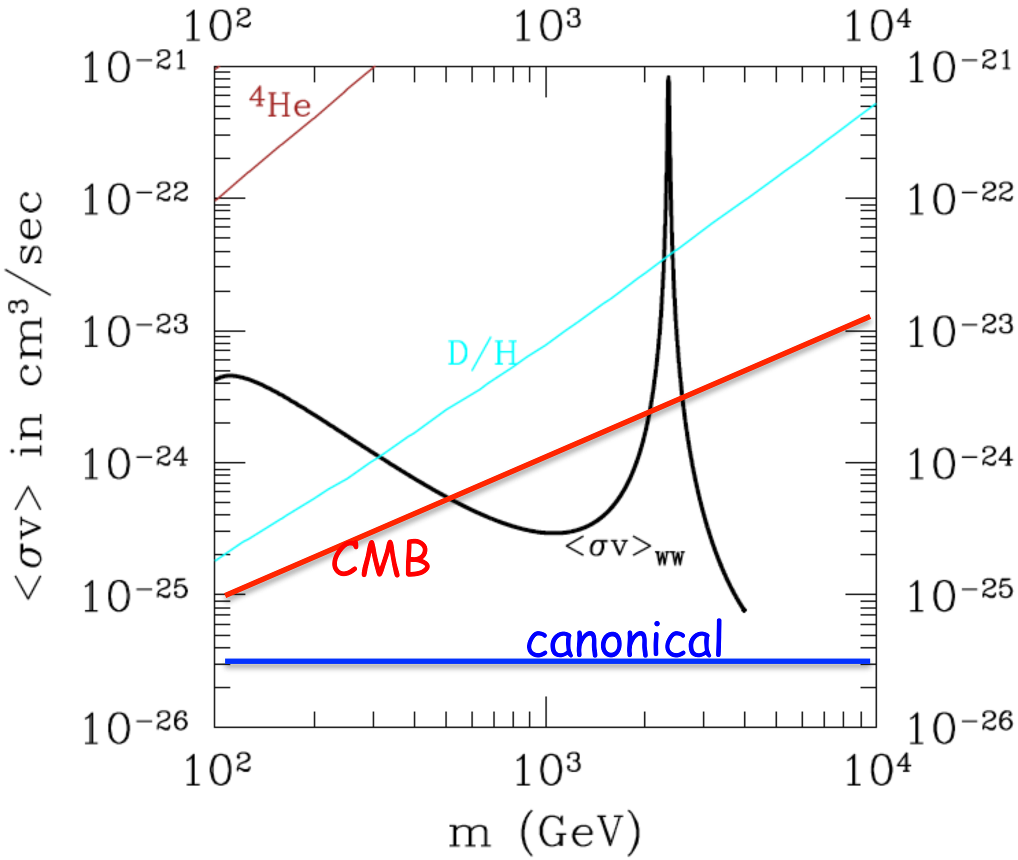
Fermi bounds on annihilation into WW

M. L. Ahnen et al., MAGIC and Fermi-LAT Collaborations, arXiv:1601.06590 [astro-ph.HE]



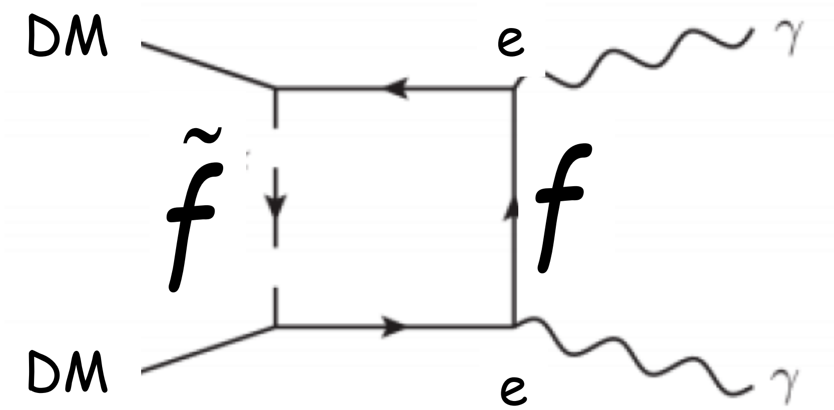
BBN and CMB constraints on wino annihilations

Hisano, Kawasaki, Kohri, Moroi, Nakayama, 2008; 2009
Kawasaki, Kohri, Moroi, Takaesu, 2015



See also, Hisano, S.Matsumoto, M.M.Nojiri, O.Saito, 2004

Line search

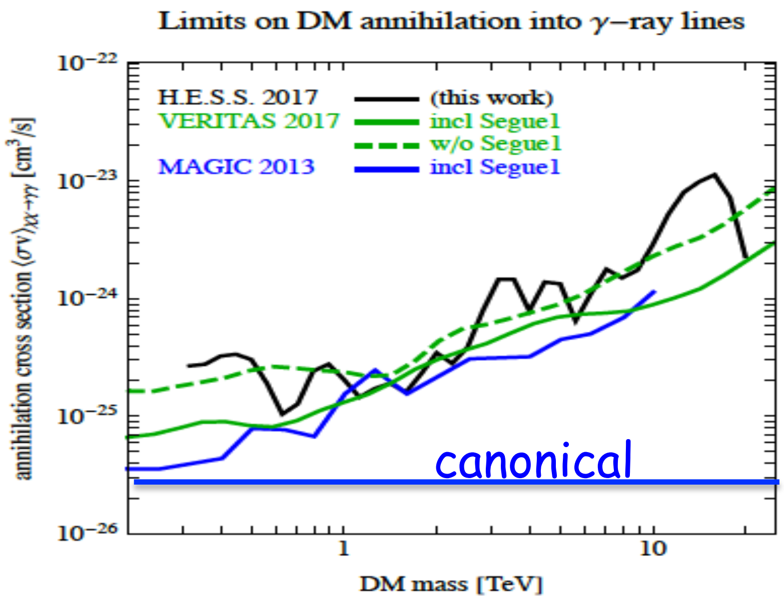


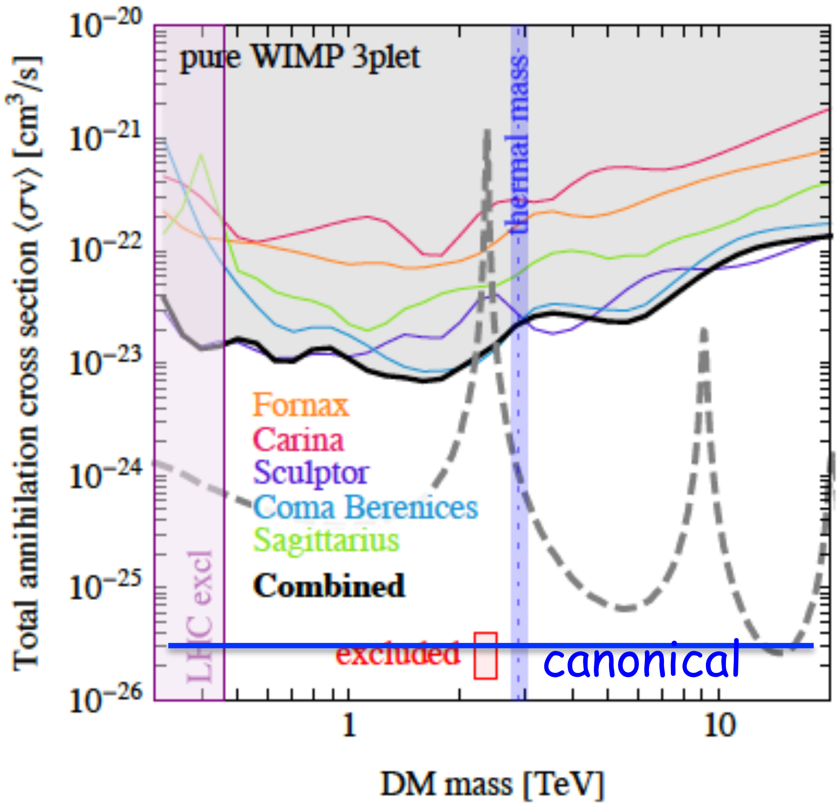
$$Br(DM+DM \to \gamma+\gamma) \equiv \frac{\sigma(DM+DM \to \gamma+\gamma)}{\sigma_{total}} \sim \alpha^2 \sim 10^{-4}$$

Note that Br to line gammas can be 0.01 – 0.1 for wino LSP because wino couples to gauge boson

HESS constraints on line-emission by annihilating DM for both general and Wino cases

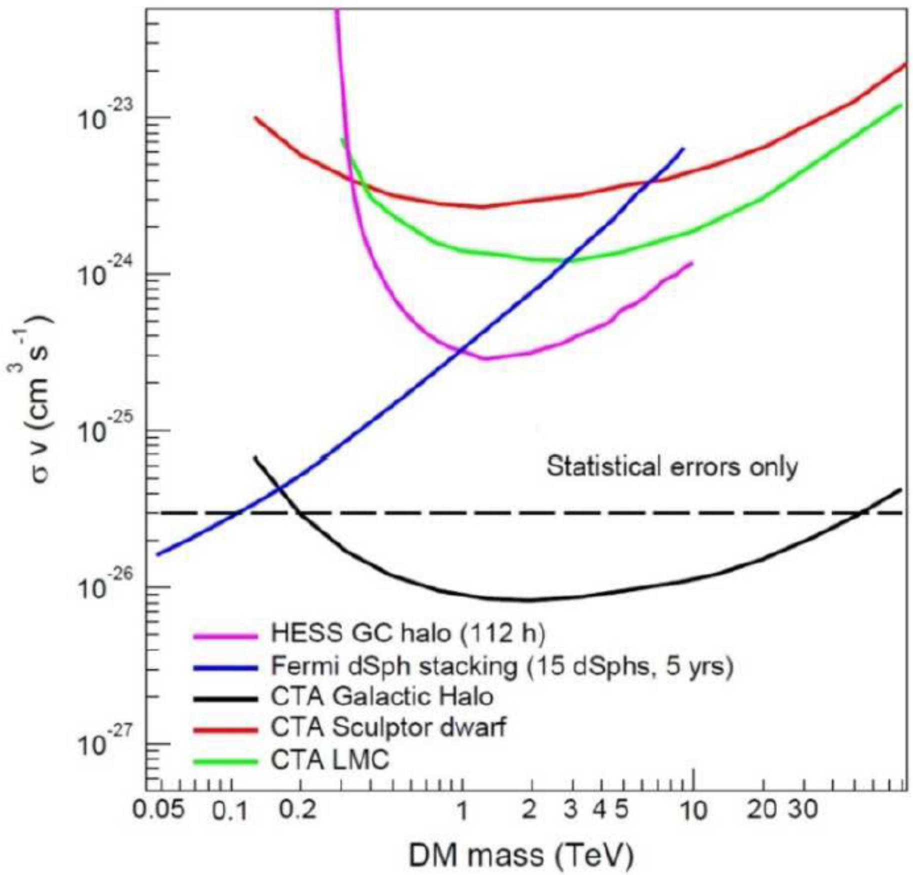
H.E.S.S. Collaboration: H. Abdalla, F. Aharonian et al, arXiv:1810.00995 [astro-ph.HE]





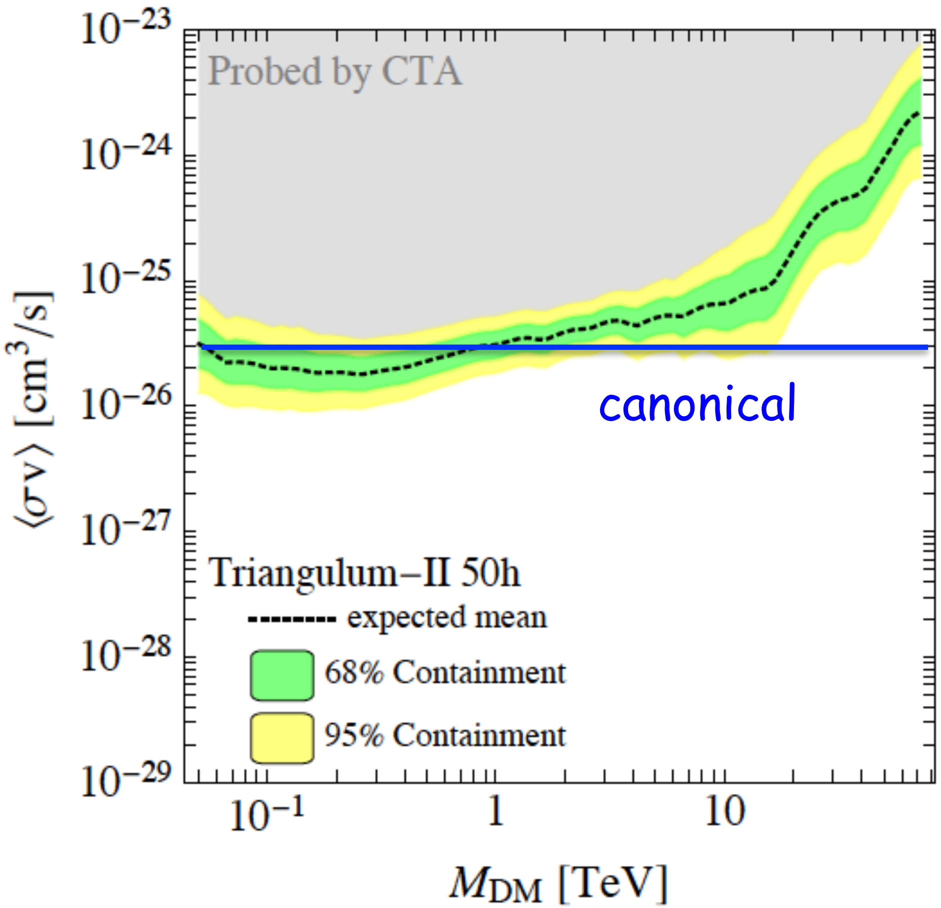
Sensitivity of CTA

General cases



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

Line gamma case



Lefranc et al, arXiv:1608.00786 [astro-ph.HE]

Point source or Diffusive source?

- However, Fermi observed each dwarf Spheroidal galaxy to be a point source in O(0.1°) x O(0.1°)

- CTA can resolve the spatial structure much better in future, e.g., in 0.03° x 0.03°

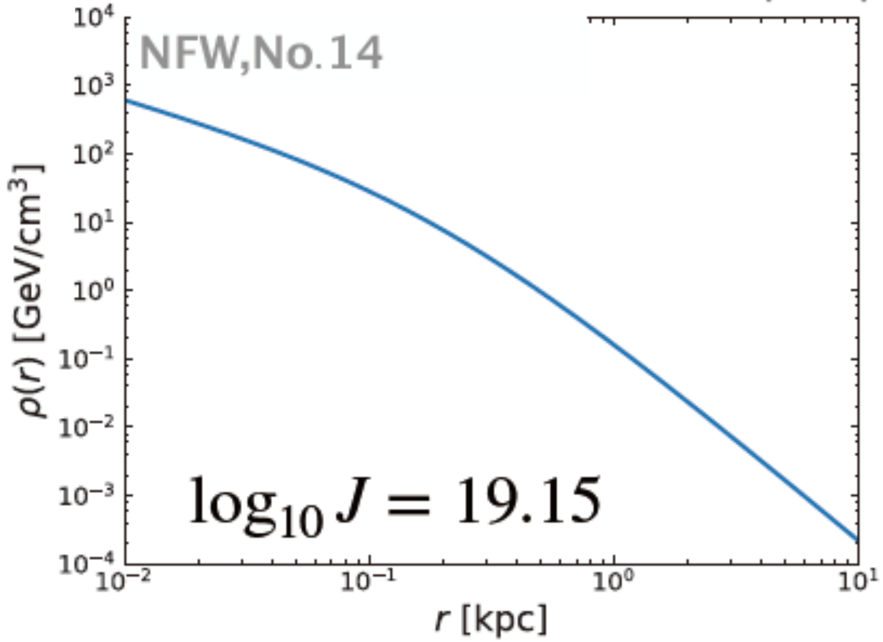
- The limit should have been stronger by measuring it to be a point source

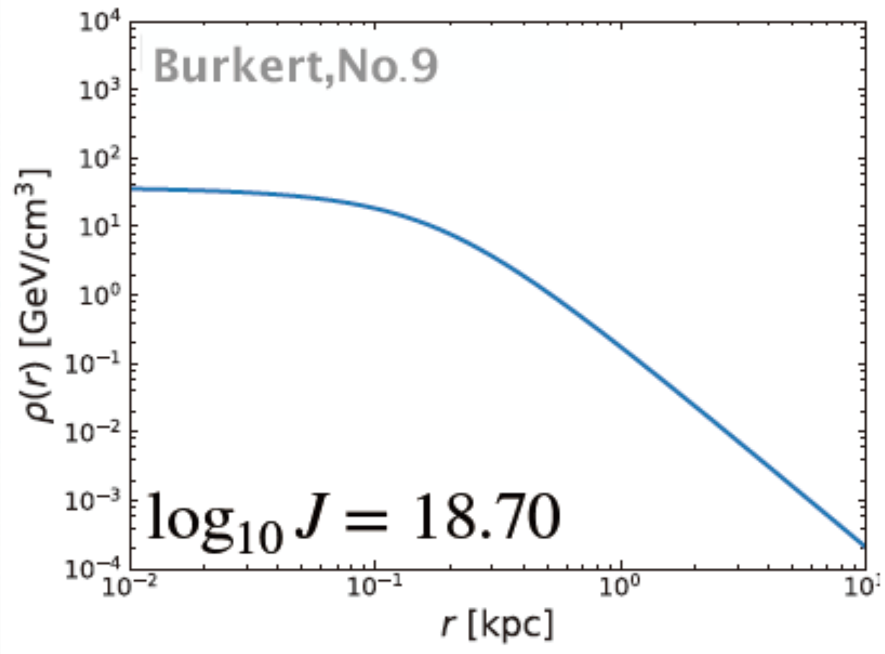
profiles

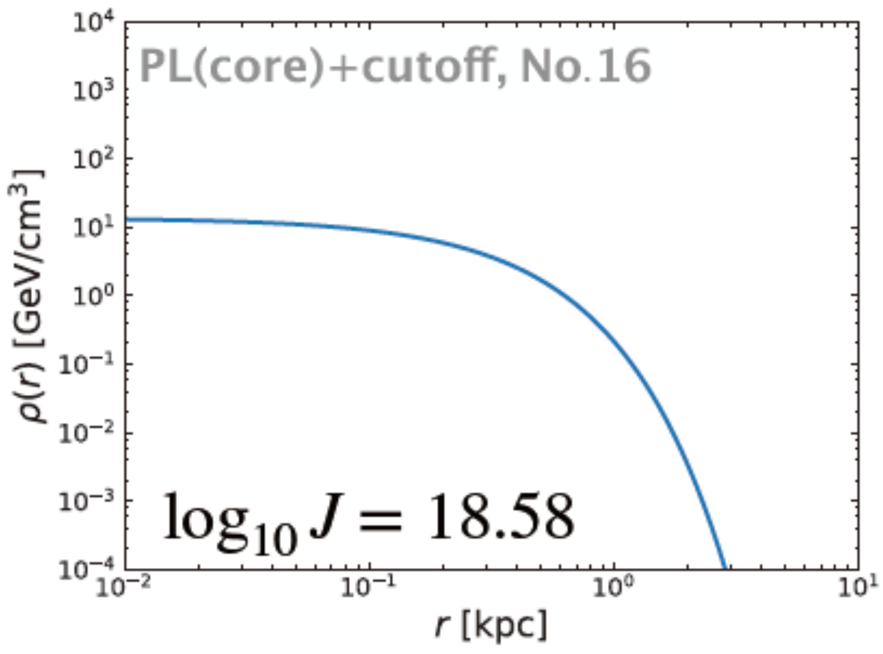
Nagisa Hiroshima's talk slide

Hiroshima et al., in prep

- 16 spherical profiles for Draco in the literature
- fitted or compared to stellar data



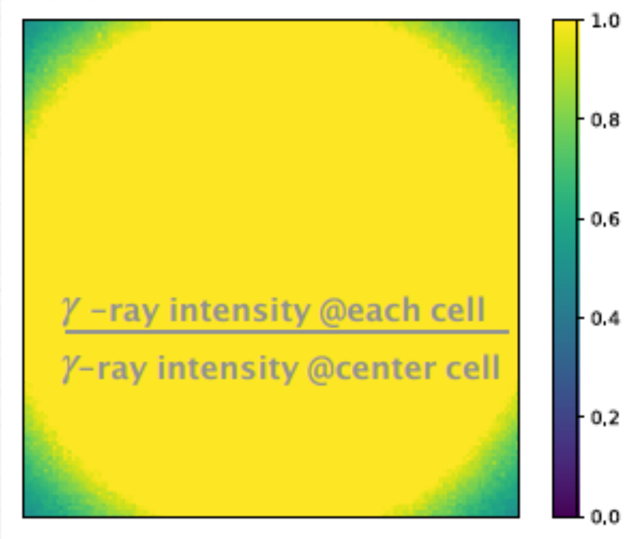




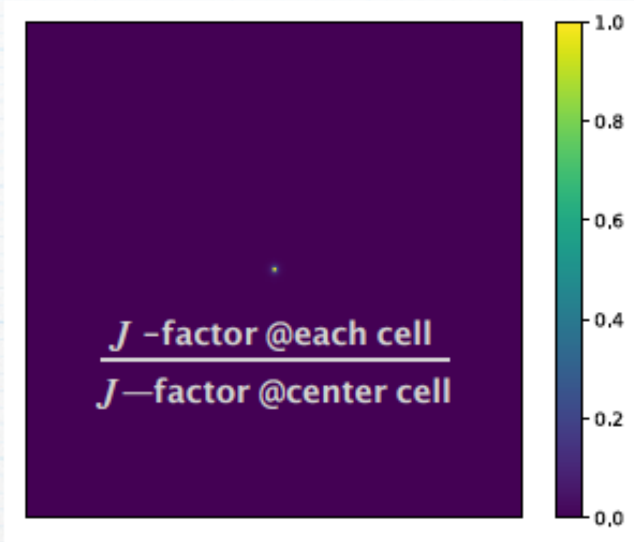
How differ they are?

Nagisa Hiroshima's talk slide

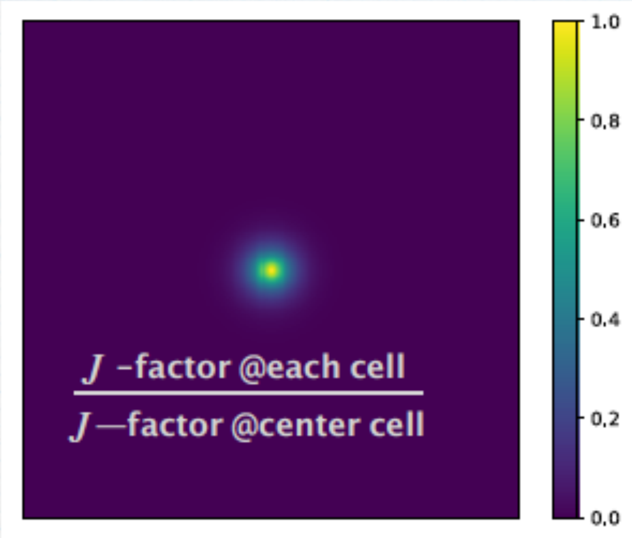
Hiroshima's thesis



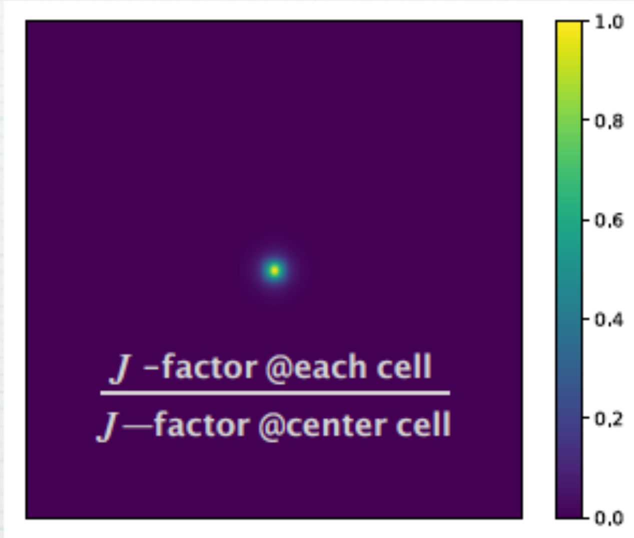
background



NFW
No.14



Burkert,
No.7



PL+cutoff
No.16

Summary

- CTA improves the sensitivity at 100 GeV – 100 TeV approximately by a factor of more than one order of magnitude

- CTA can resolve the spatial structure of dwarf spheroidal to constrain WIMP dark matter for the first time. Then, we definitely need information for density profiles of dSphs

- By using CTA, we will be able to discriminate a true dark matter model from the others among WIMP, PBHs, ALPs and so on in near future