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Indirect search of DM from multiple aspects

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1. DM in the Universe

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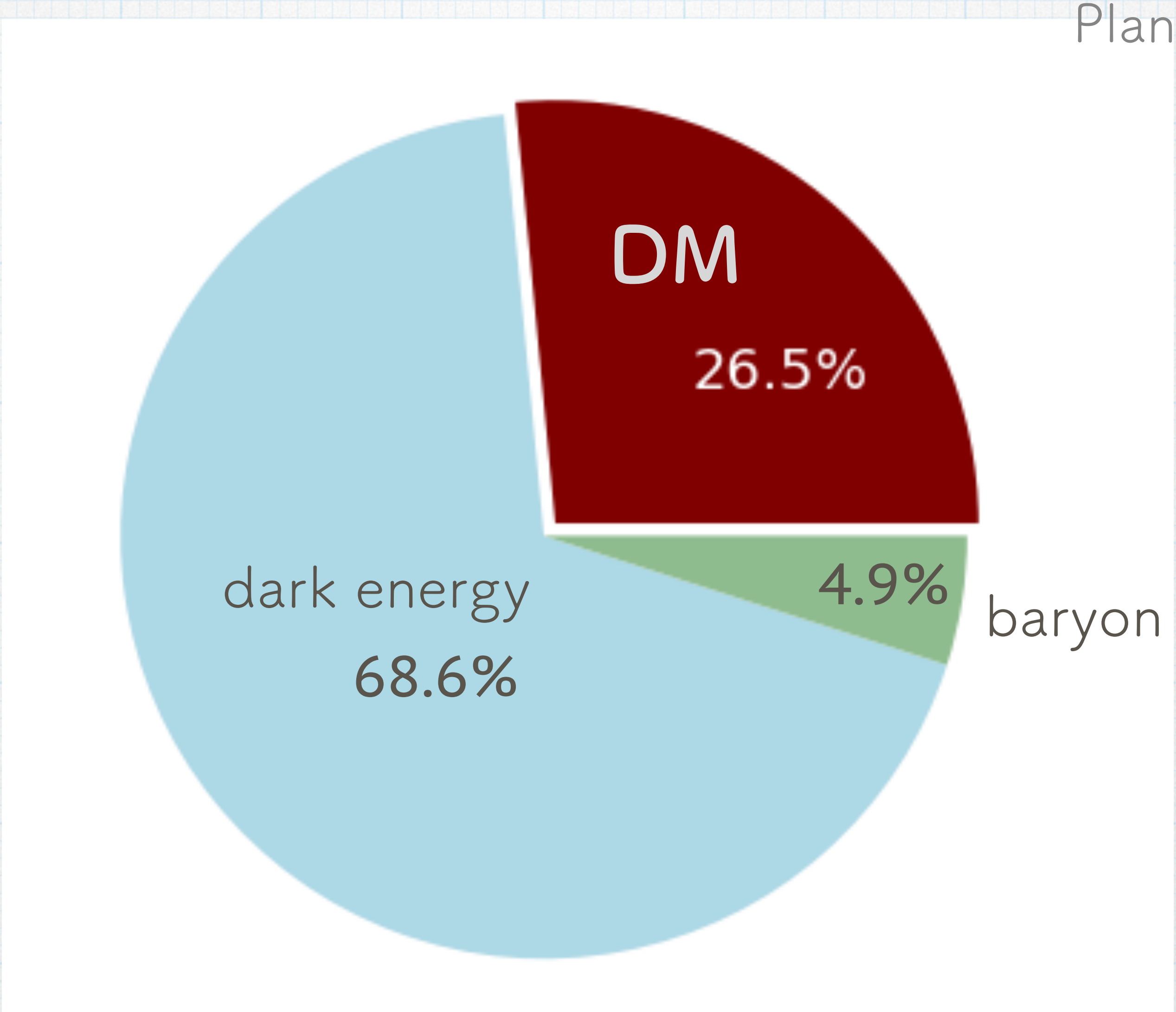
4. Conclusion

1. DM in the Universe

What is dark matter (DM)?

Planck 2018



The 1st evidence: Galaxy cluster

THE ASTROPHYSICAL JOURNAL

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ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

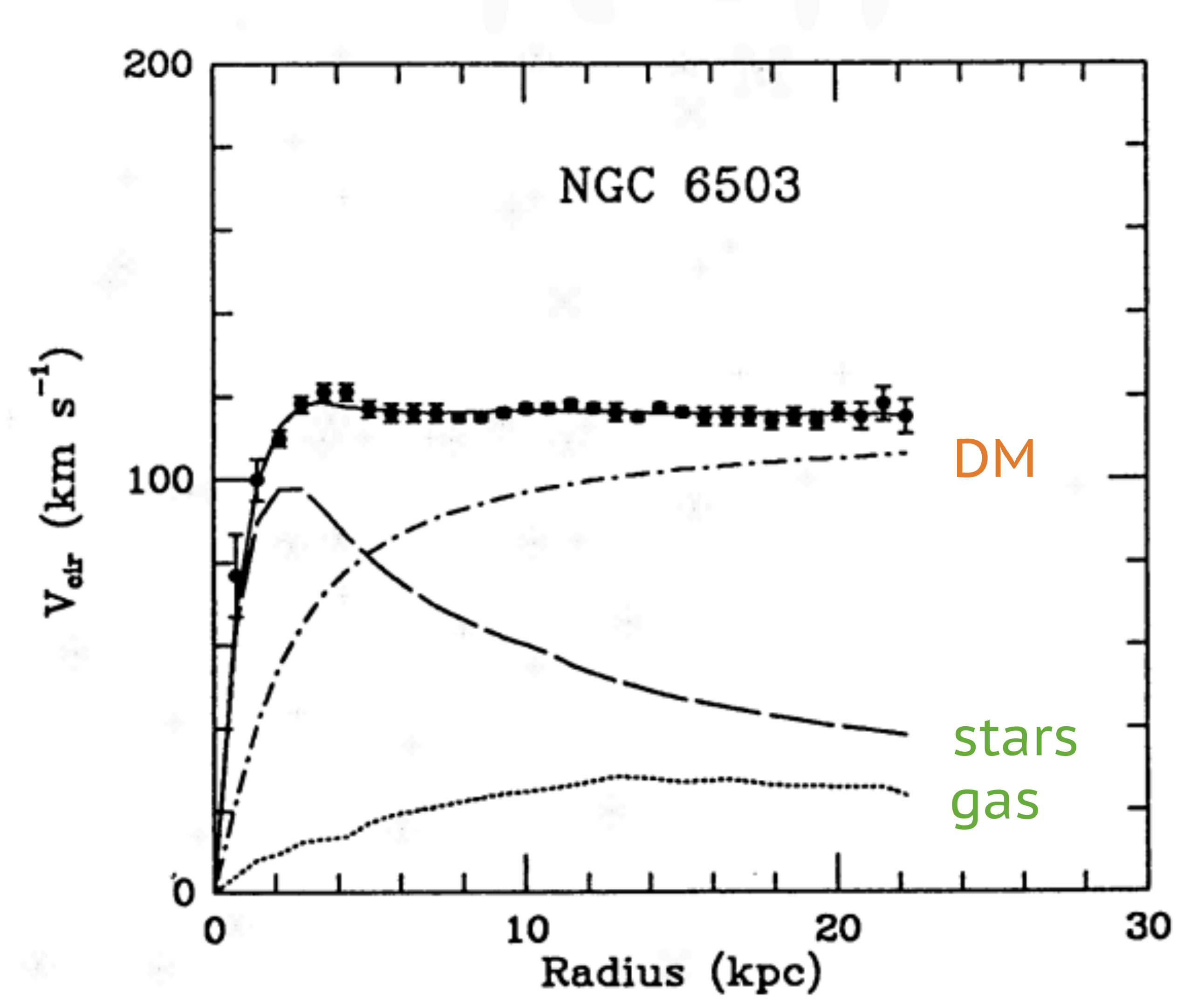
ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal

result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

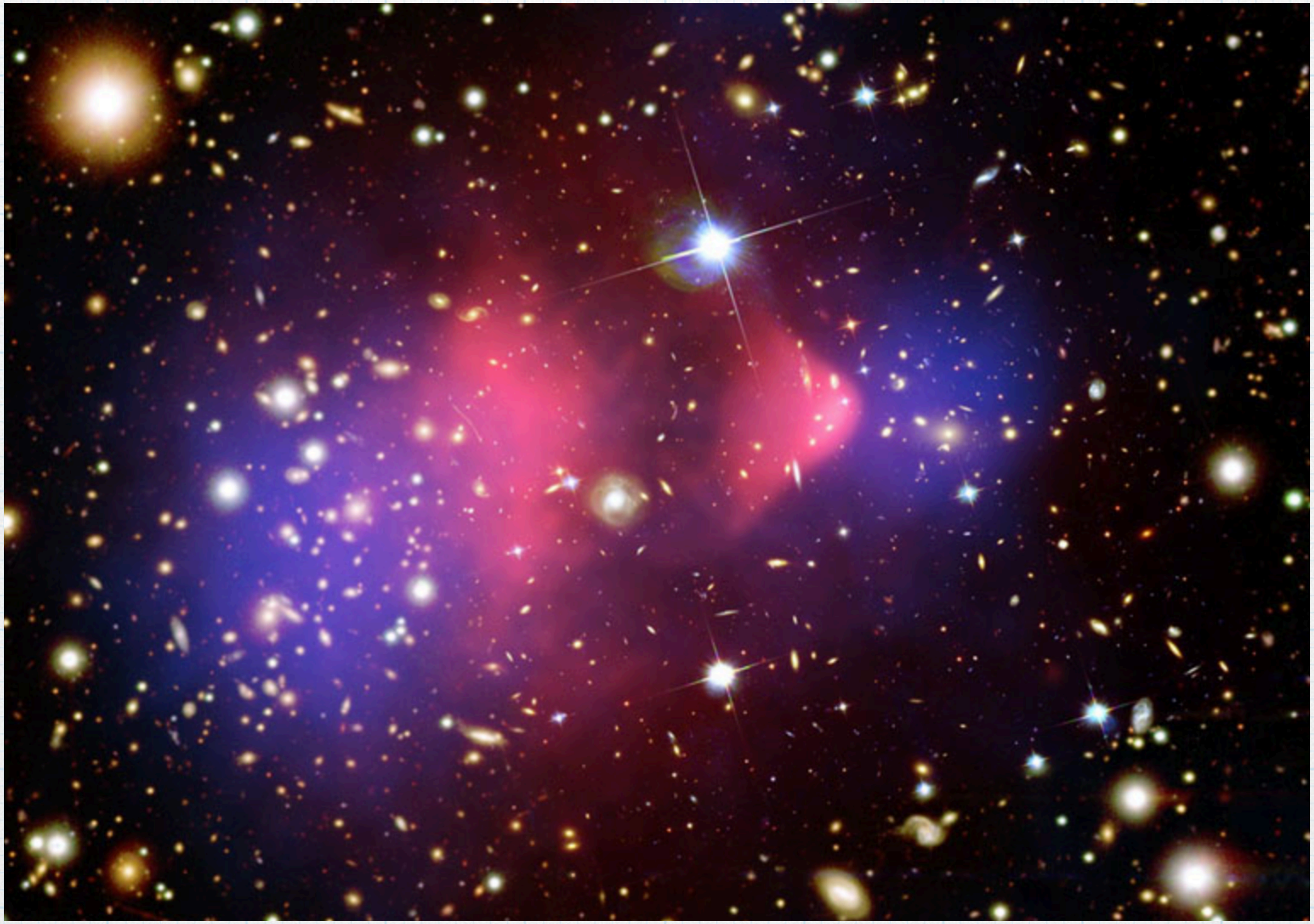
Rotation Curves

Begeman et al., 1991



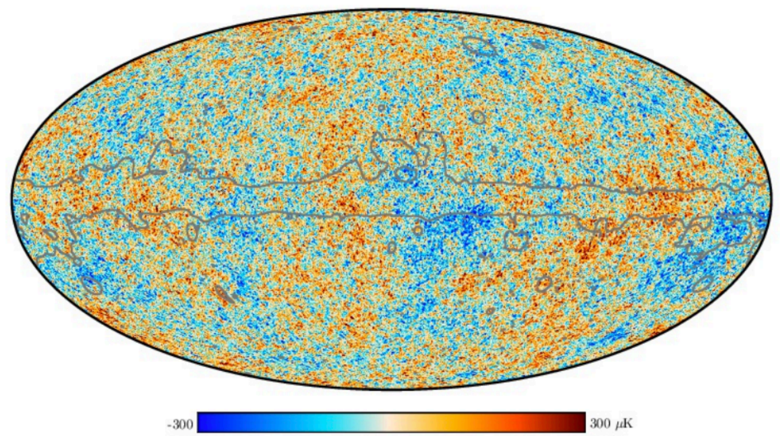
Bullet Clusters

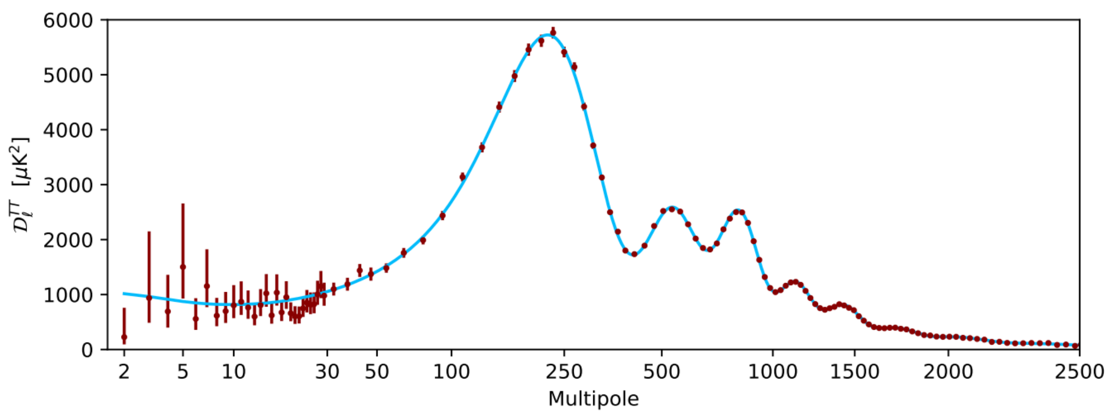
Clowe et al., 2006



Galaxy cluster 1E0657-558

Cosmological Requirement





Planck 2018

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Brief cosmological history

Inflation

↓

radiation dominated era

↓ **DM structure formation starts**

matter dominated era $T \sim \mathcal{O}(10^4)$ K (z=3500)

CMB $T \sim \mathcal{O}(10^3)$ K (z=1100)

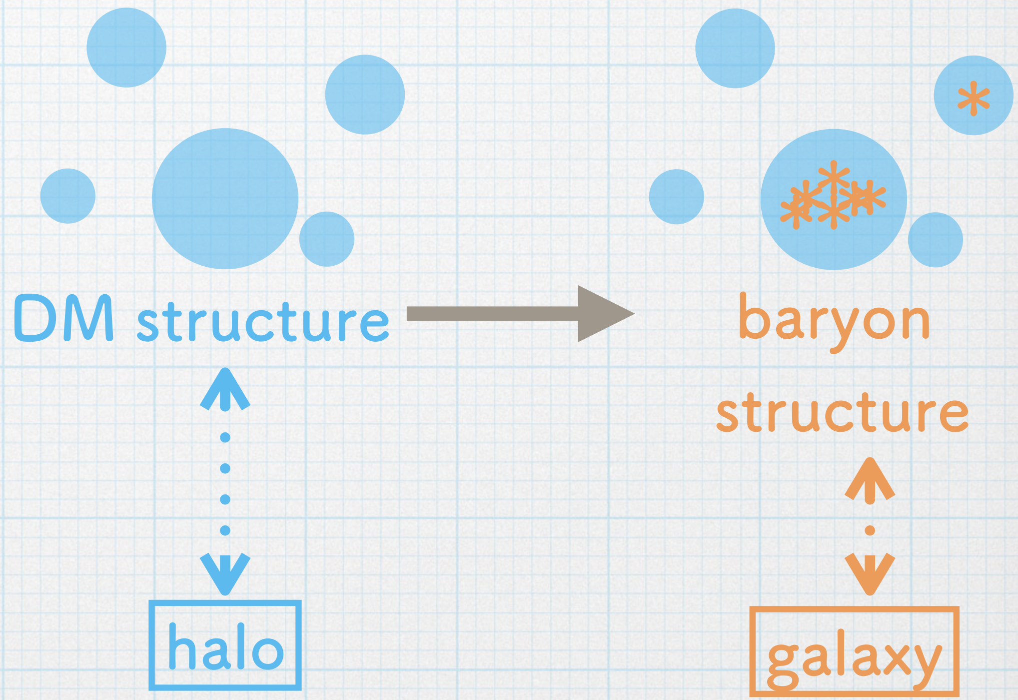
↓ baryon structure formation starts

current Universe $T \sim 2.7$K (z=0)

Motivation for DM

DM=non-baryonic matter in the Universe of $\Omega_{\rm DM}h^2 \sim 0.12$

- **motivation**
  - structure formation
  - rotation curves
  - bullet cluster
  - …
- **properties**
  - non-relativistic
  - cold (warm, hot)
  - almost invisible
  - feel gravity



Candidates

- Weakly Interacting Massive Particle (WIMP)
- Strongly/self- interacting massive particle (SIMP)
- sterile neutrinos
- axion and/or axion-like particle (ALP)
- primordial black hole (PBH)···

We focus on WIMP today.

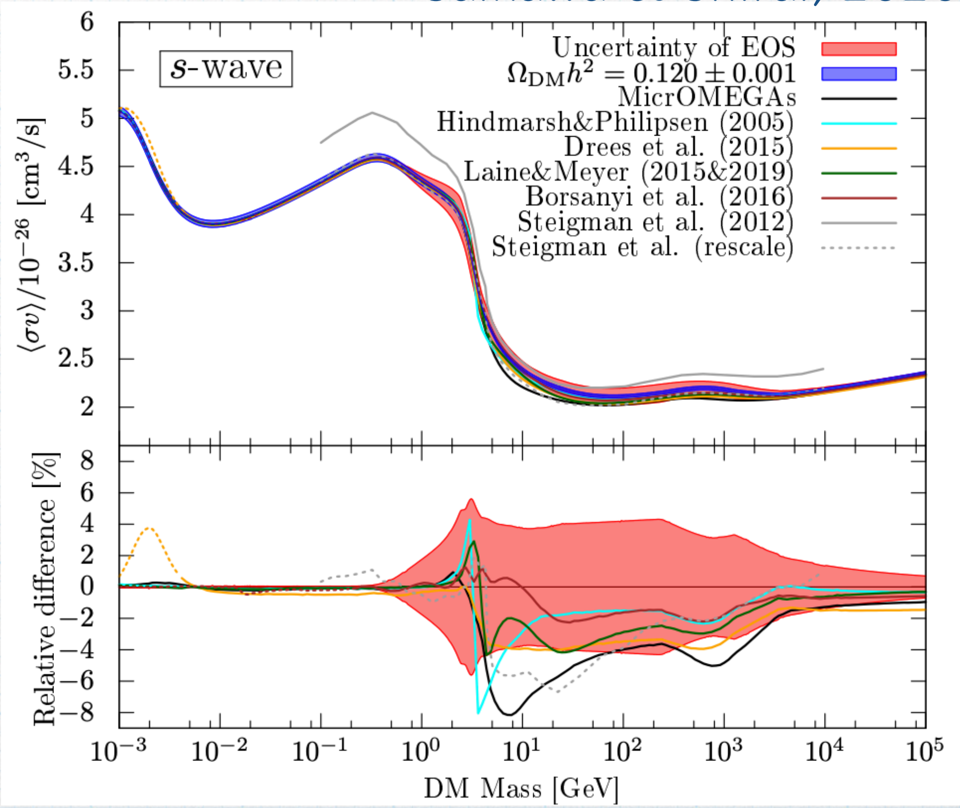
WIMP

- the mass $m_{\rm DM} \sim \mathcal{O}(\rm GeV) - \mathcal{O}(\rm TeV)$
- freeze-out scenario to achieve the relic abundance $\Omega_{\rm DM}h^2 \sim 0.12$
- the annihilation cross-section

$\langle \sigma v \rangle \sim \mathcal{O}(10^{-26}{\rm cm}^3 s^{-1})$

DM + DM → SM + SM

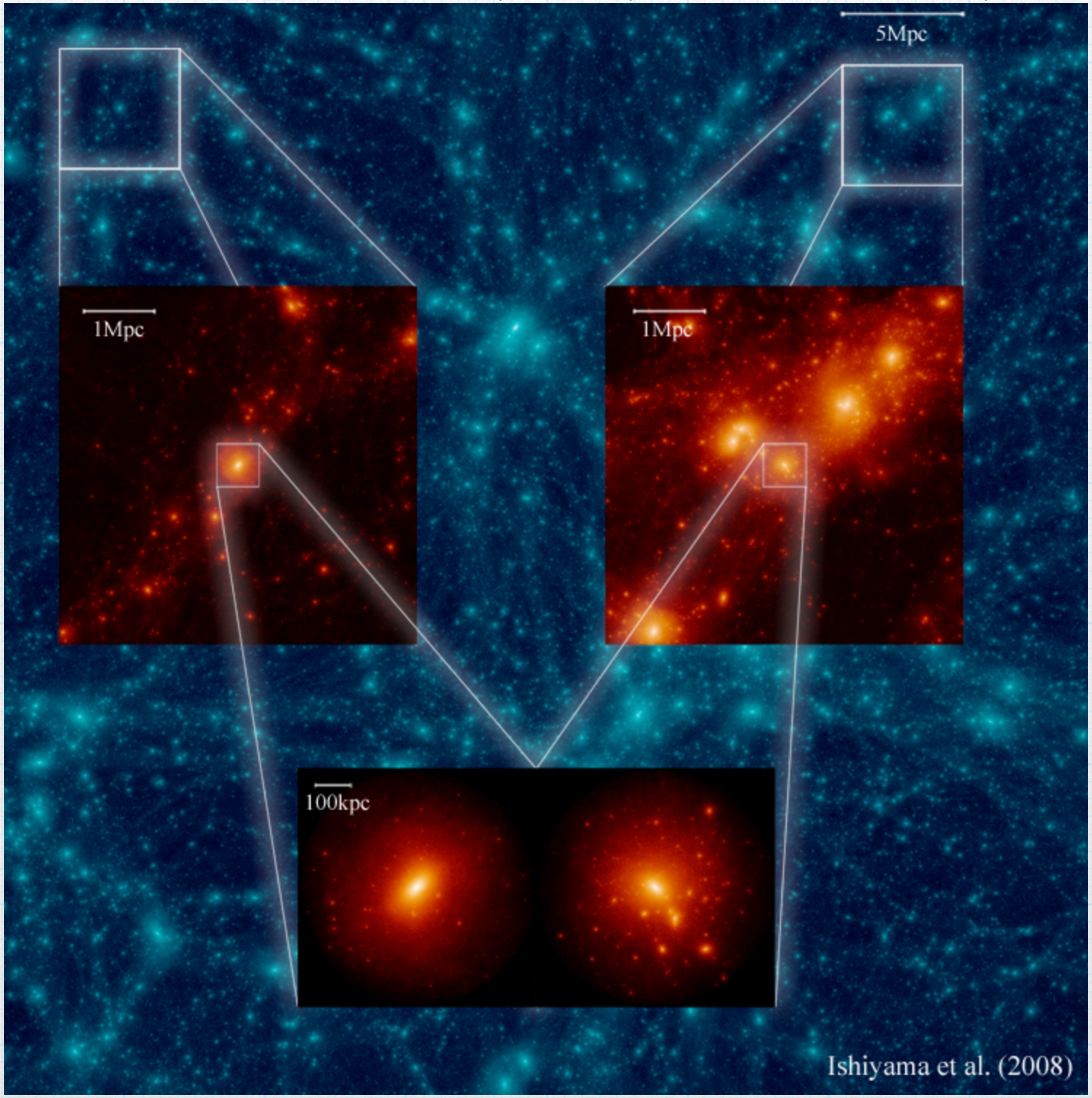
Saikawa & Shirai, 2020



Behave as cold dark matter (CDM)

CDM structure

https://hpc.imit.chiba-u.jp/~ishiymtm/gallery.html



2. Indirect search

Indirect detections

DM + DM → **something in the SM**

somewhere

in the Universe

- photons
- weak bosons
- quarks
- leptons
- …

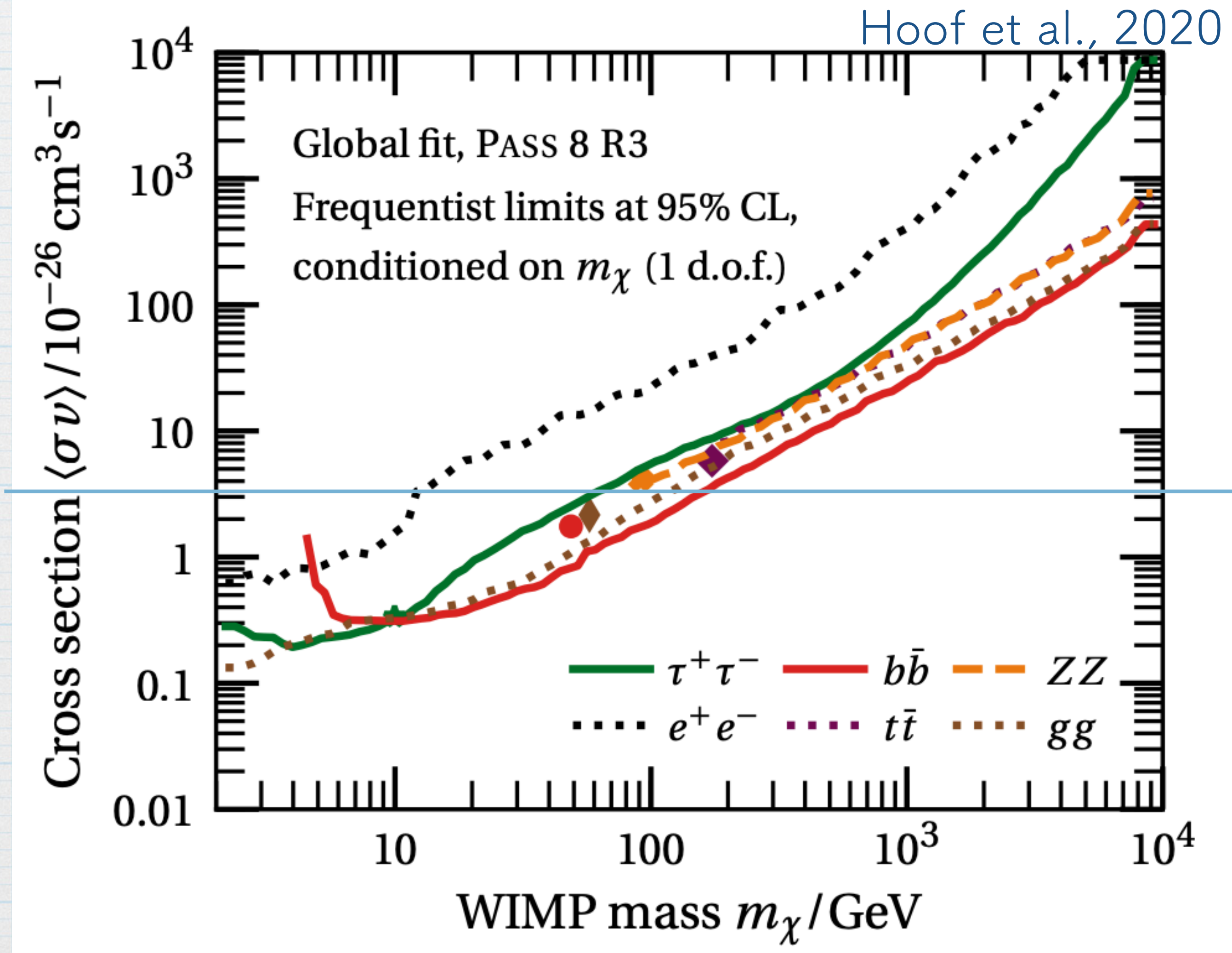
on/around the Earth

$\gamma, e^{\pm}, p, \bar{p}, \nu, \ldots$

probe:
stable species

Current limits for WIMP

Fermi-LAT, 11y, 27 dwarf spheroidal galaxies (dSphs)



canonical

$\sim 3\times10^{-26}\mathrm{cm}^3/s$

Indirect detections

γ-ray search

- straight path from the source to the Earth
- absorption is negligible at $z \lesssim 0.1$ for $E_\gamma \lesssim$ 1PeV
- all the SM particle associates photons at the production

flux $$\phi_\gamma = \frac{1}{8\pi} \int_{E_{\rm th}}^{m_{\rm DM}} dE_\gamma \int_{\Delta\Omega} d\Omega \int_{l.o.s} ds \frac{dN_\gamma}{dE_\gamma} \langle \sigma v \rangle n_{\rm DM}^2$$

$$= \boxed{\frac{1}{8\pi} \frac{\langle \sigma v \rangle}{m_{\rm DM}^2} \int_{E_{\rm th}}^{m_{\rm DM}} dE_\gamma \frac{dN_\gamma}{dE_\gamma}} \cdot \boxed{\int_{\Delta\Omega} d\Omega \int_{l.o.s} ds \rho_{\rm DM}^2}$$

particle model

J-factor (astrophysics)

Input & Output

$$\phi = \frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\int dE\frac{dN}{dE}\int d\Omega\int_{los} ds\ \rho_{\rm DM}^2$$

observable

Input: γ – ray flux ϕ

knowns and/or assumptions

- properties of DM halo
- annihilation spectrum

↔ particle nature

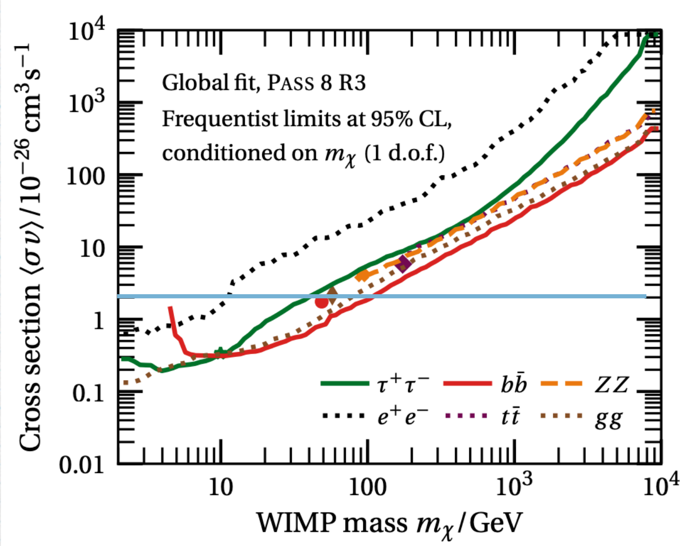
Output: model parameter $m_{\rm DM}$ & $\langle\sigma v\rangle$

3. Particle side

&

Halo side

Particle Side:



Current limit:

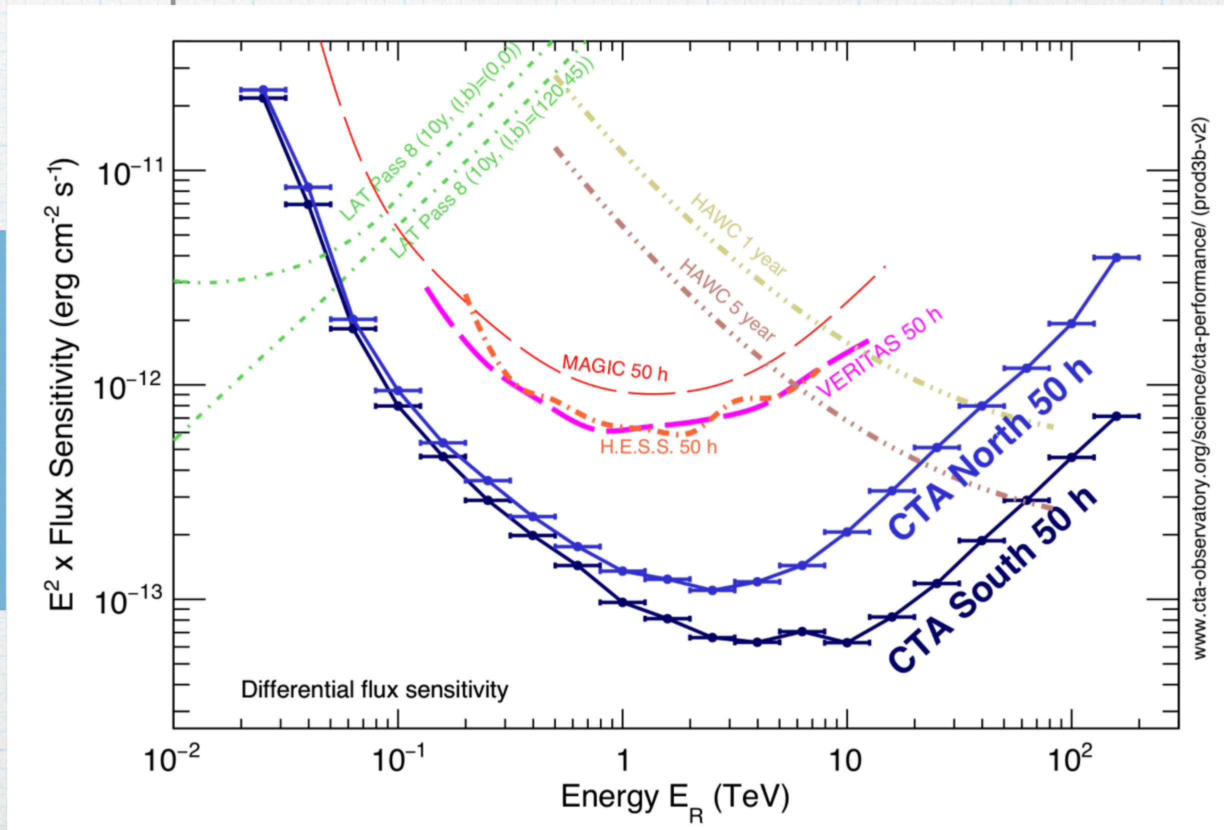
WIMP mass $m_{\rm DM} \lesssim \mathcal{O}(100)$GeV

- Fermi-LAT
- dSph

future:

probe the

heavier with CTA

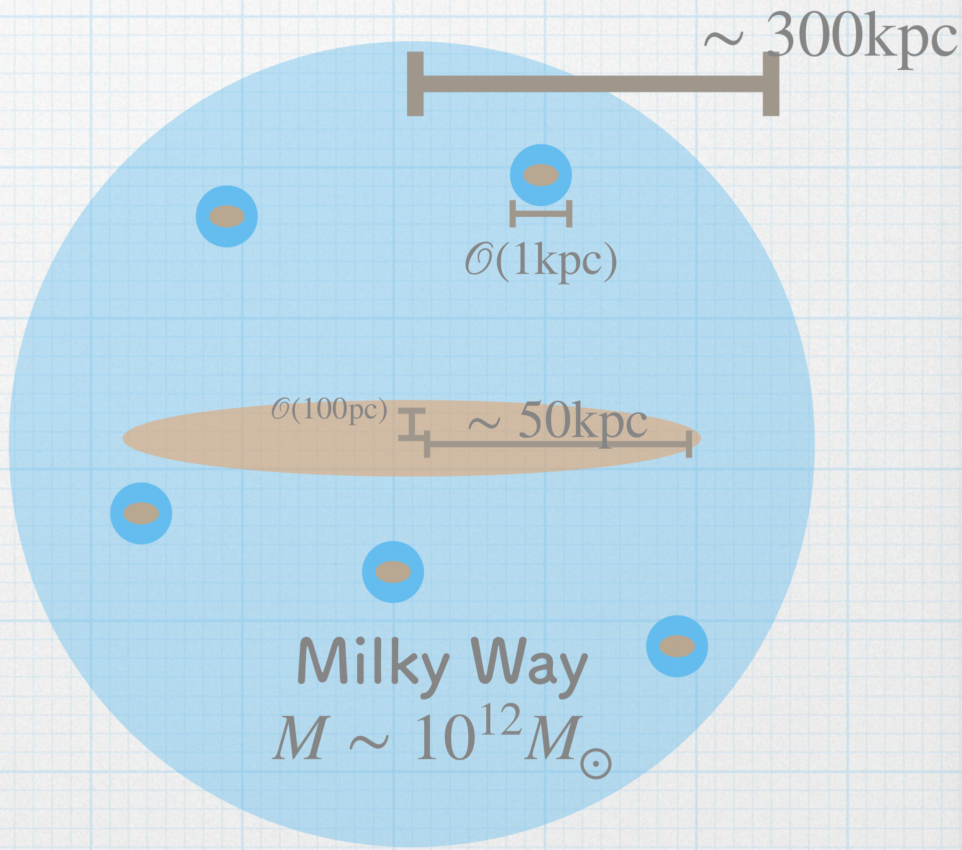


Facilities

	Fermi	CTA
type	satellite	IACT
observation	survey	pointing
energy coverage	20MeV-300GeV	30GeV-100TeV
energy resolution	<8%	~10%
flux sensitivity	10^{-12} erg cm^{-2} s^{-1} (100GeV, 10year)	10^{-13} erg cm^{-2} s^{-1} (1TeV, 50h)
angular resolution	3.5-0.15deg	0.2-0.03deg

Properties of dSphs

- satellites of the Milky Way
- ~40 are confirmed
- do not show star formation activities
- $M/L \lesssim 10^3 M_\odot/L_\odot$
- $M \sim 10^{8-9} M_\odot$
- $\Delta\theta \lesssim \mathcal{O}(1\mathrm{deg})$
- dist $(d) \sim \mathcal{O}(100)$ kpc

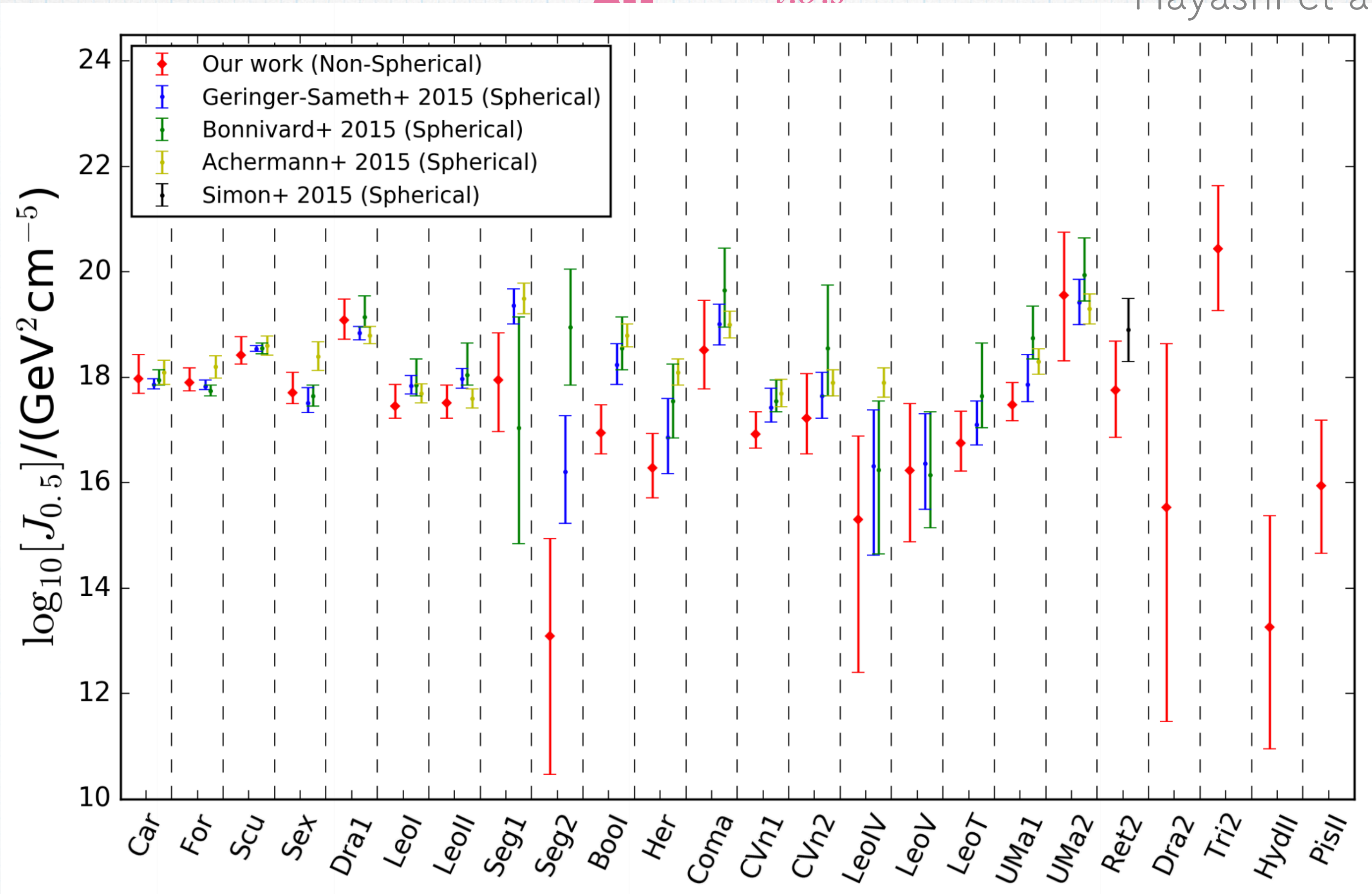


CTA should resolve them as extended sources

difficulties: dSph's J-factor

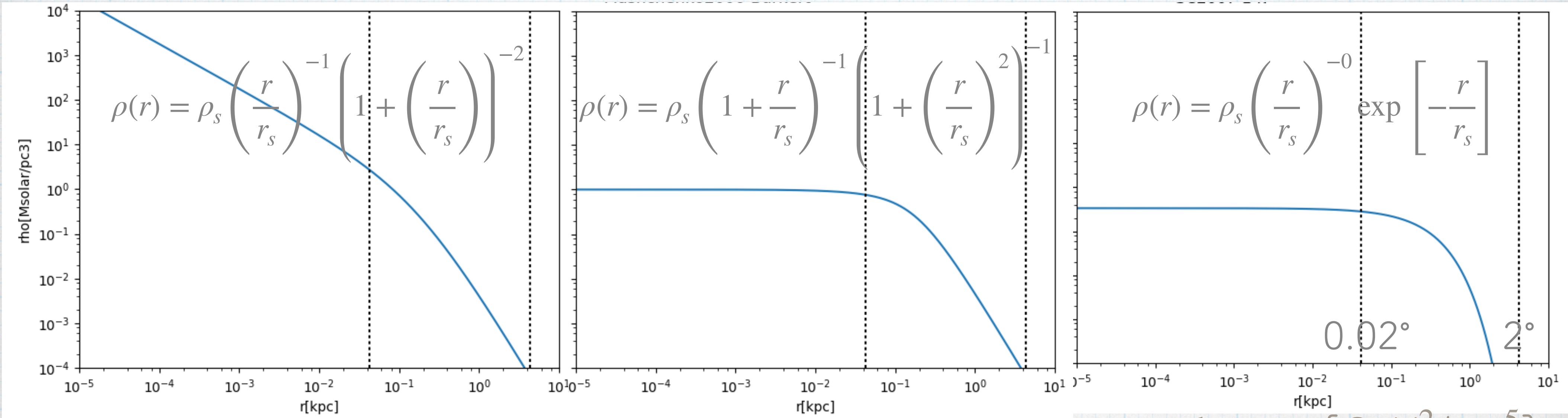
$$\phi_\gamma \propto J = \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho_{\rm DM}^2(r) ds$$

Hayashi et al., 2016

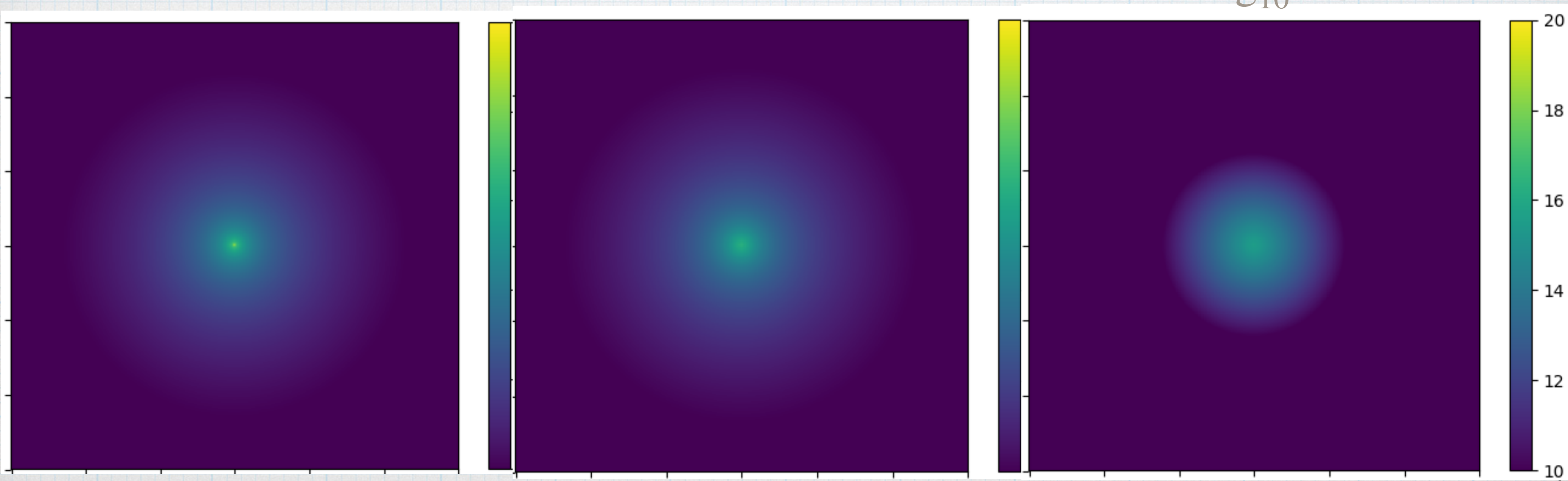


Case of Draco:

$\ln r$ vs $\ln \rho_{\rm DM}(r)$

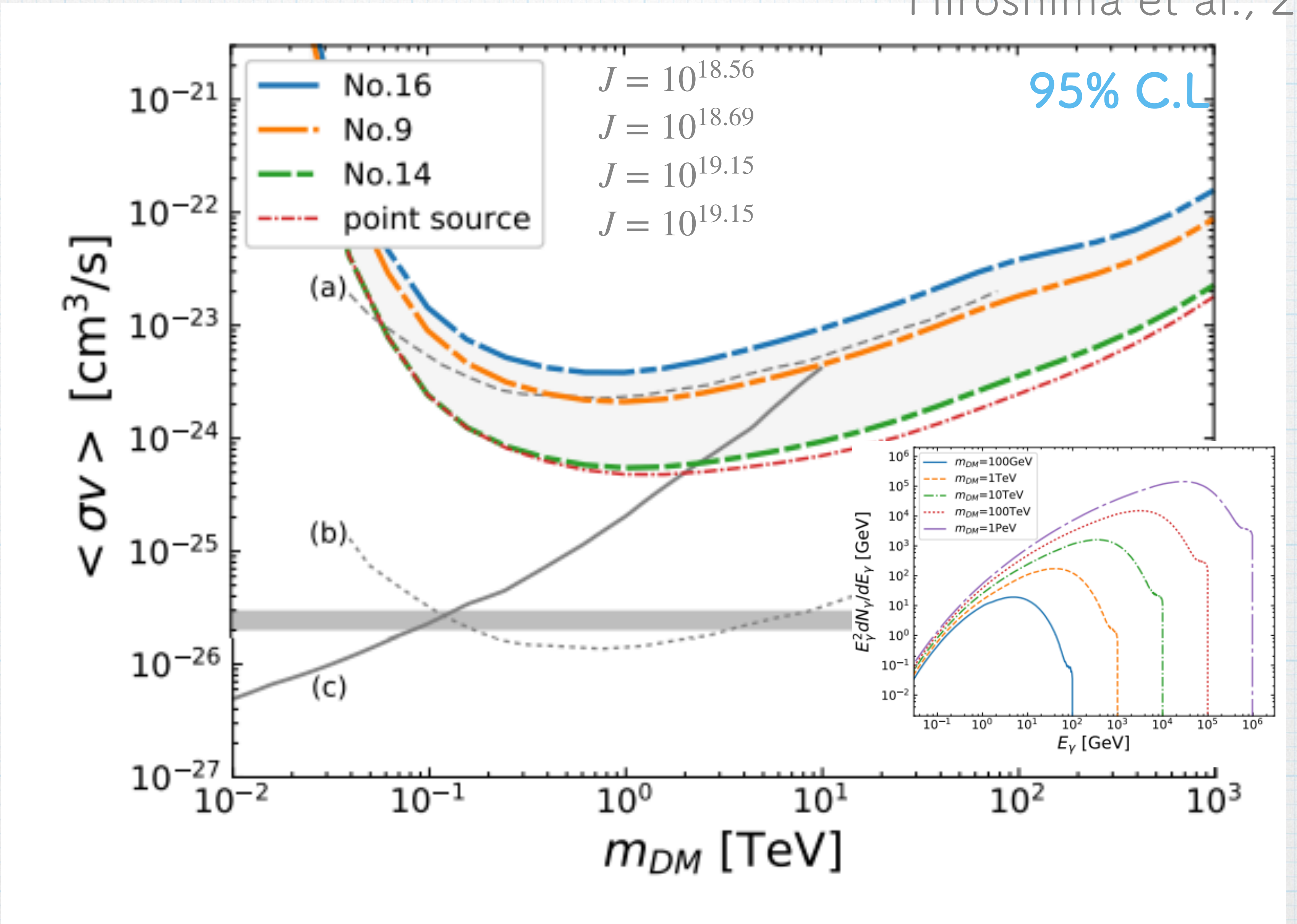


$\log_{10} J$ [GeV^2/cm^5]



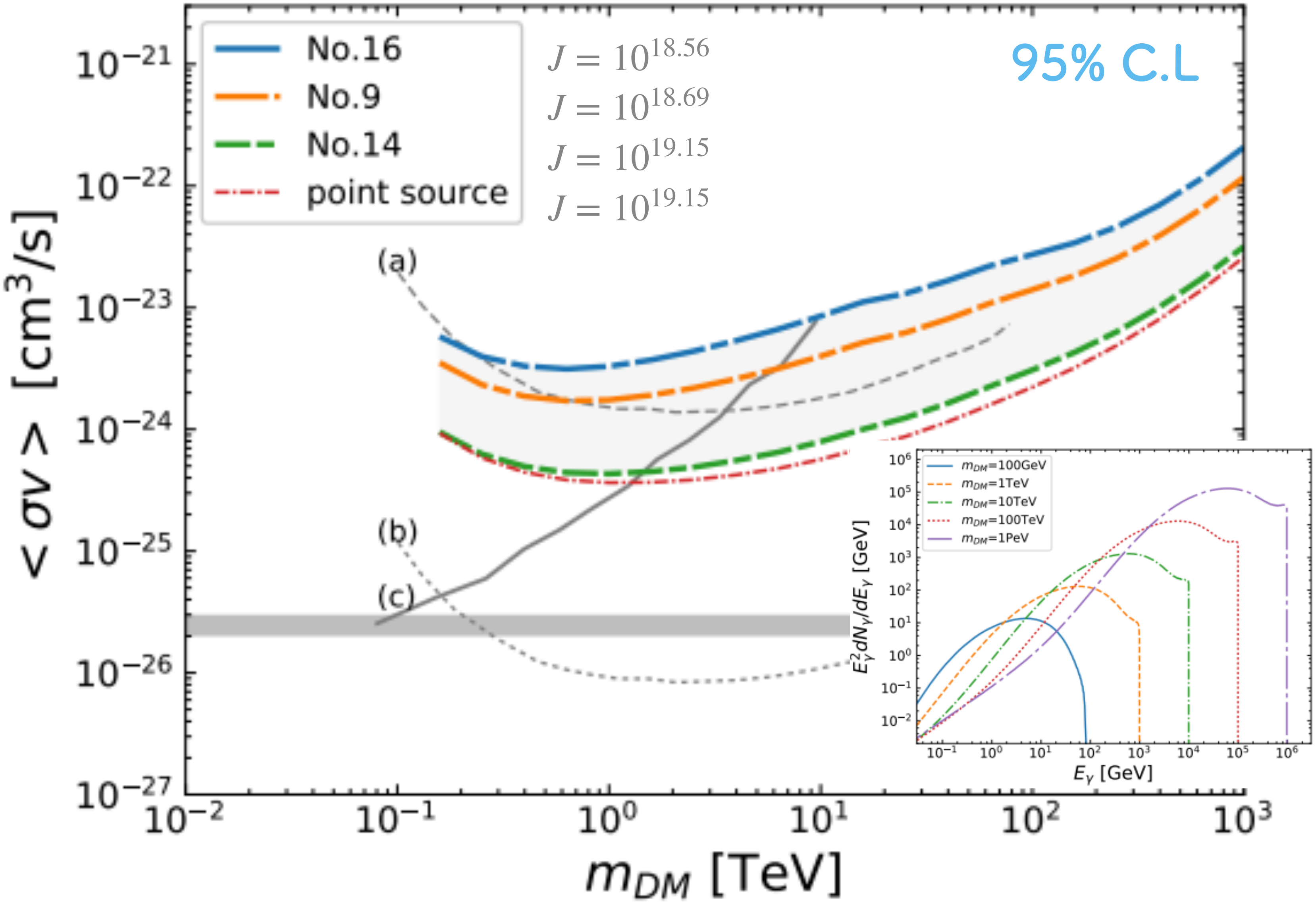
Prospects with CTA: $\bar{b}b$

Hiroshima et al., 2019



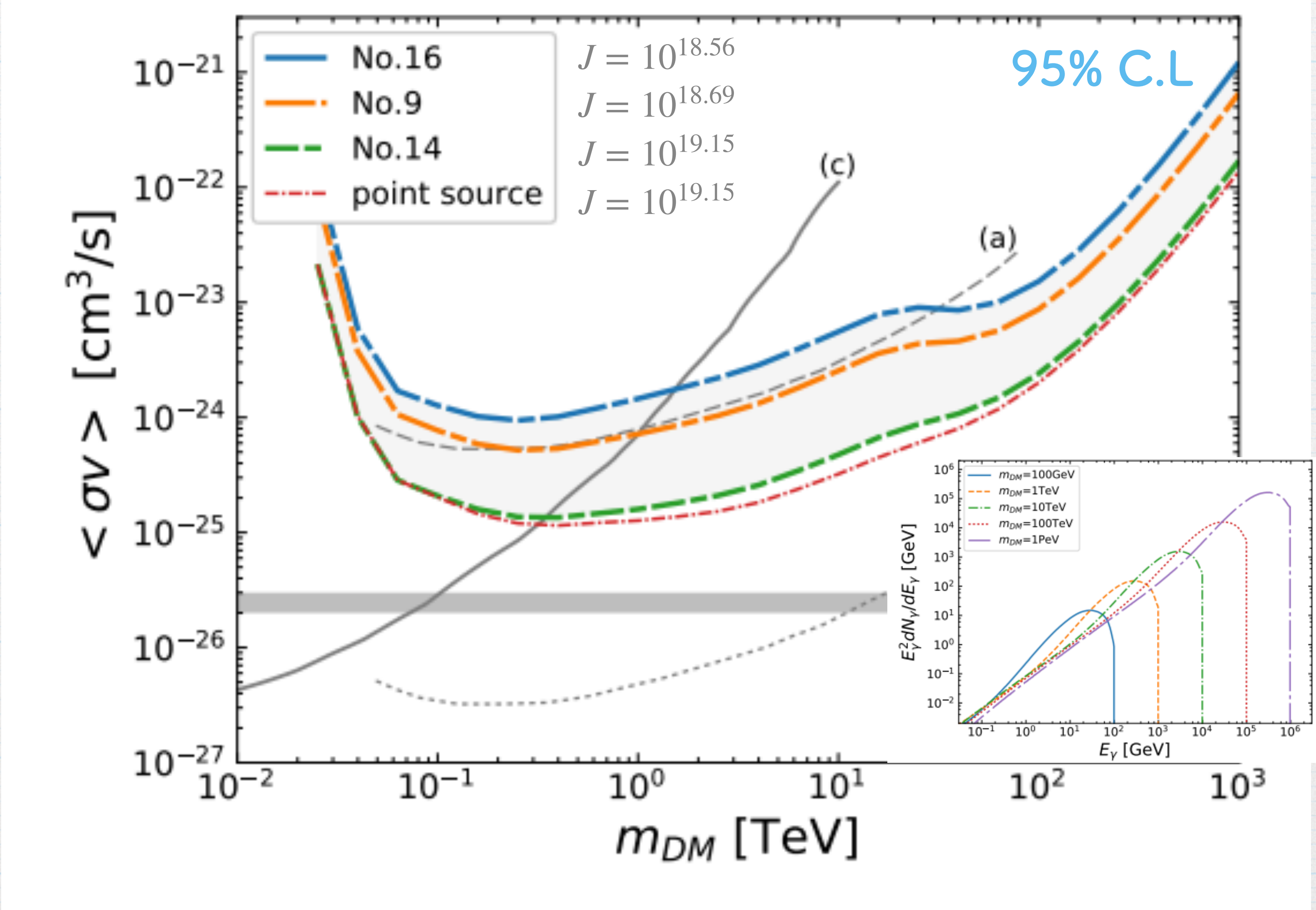
Prospects with CTA: W^+W^-

Hiroshima et al., 2019



Prospects with CTA: $\tau^+\tau^-$

Hiroshima et al., 2019



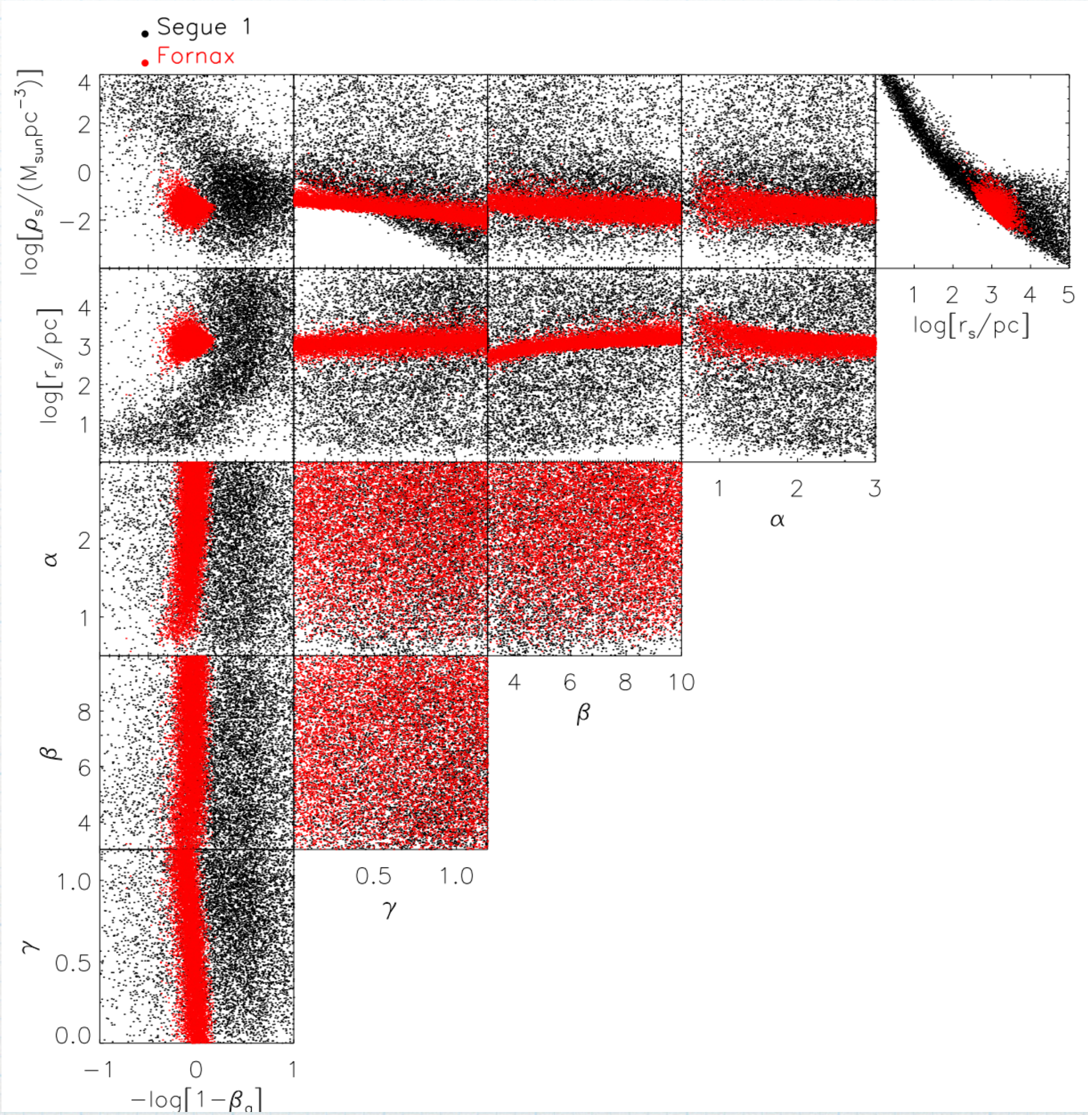
To do:

Improve the understanding of dSph halo

To obtain $\rho_{\rm DM}$:

- observe stellar motions
- reconstruct the gravitational potential: e.g.) analyzing O(10)-O(1000) stars for determining ~ 5 profile parameters

<u>fitting with flat priors do not converge</u>



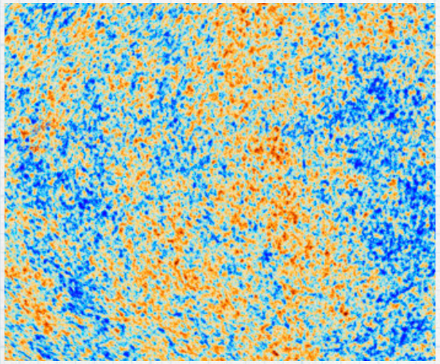
Physical prior construction

- dSphs are good targets for WIMP search
- WIMP has CDM properties
- subhalos are described within CDM picture
- dSph= satellite galaxy of the Milky Way
- structure formation picture should be applicable for each target dSph

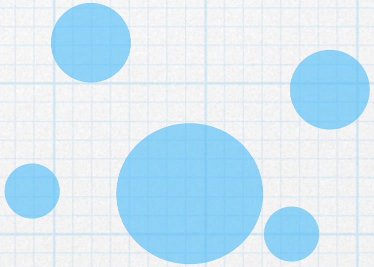
Physical prior for <u>each</u> dSph: analytical method

Halo side

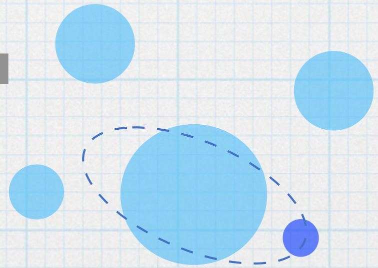
1, initial density fluctuation



2, gravitational collapse
(halo formation)

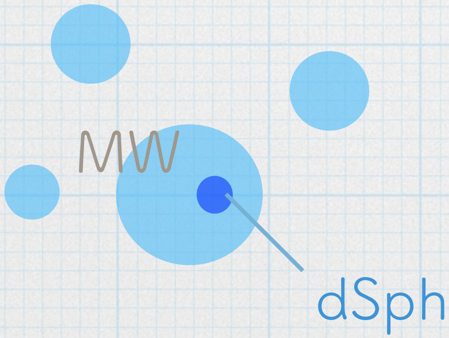


3, halo evolution



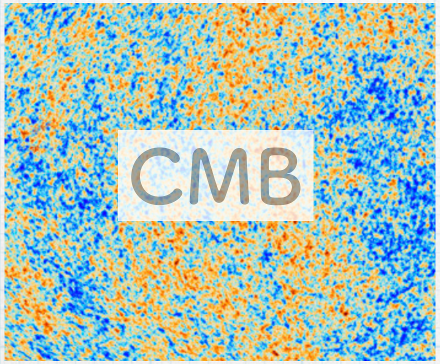
- merger
- accretion
- stripping

4, hierarchal halo structures

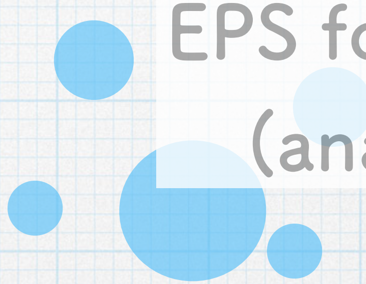


Halo side

1, initial density fluctuation



2, gravitational collapse (halo formation)



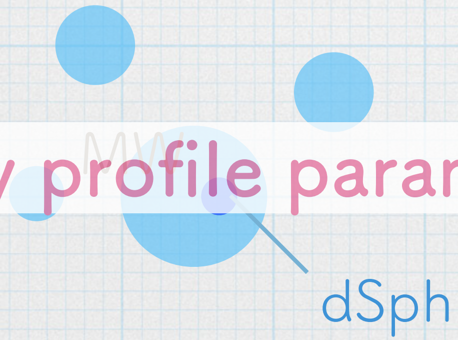
EPS formalism (analytic)

3, halo evolution

- merger
- accretion
- stripping

analytical modeling

4, hierarchal halo structures



density profile parameters

Assumptions

- The DM density distribution of the host and accreting subhalo follow the NFW profiles

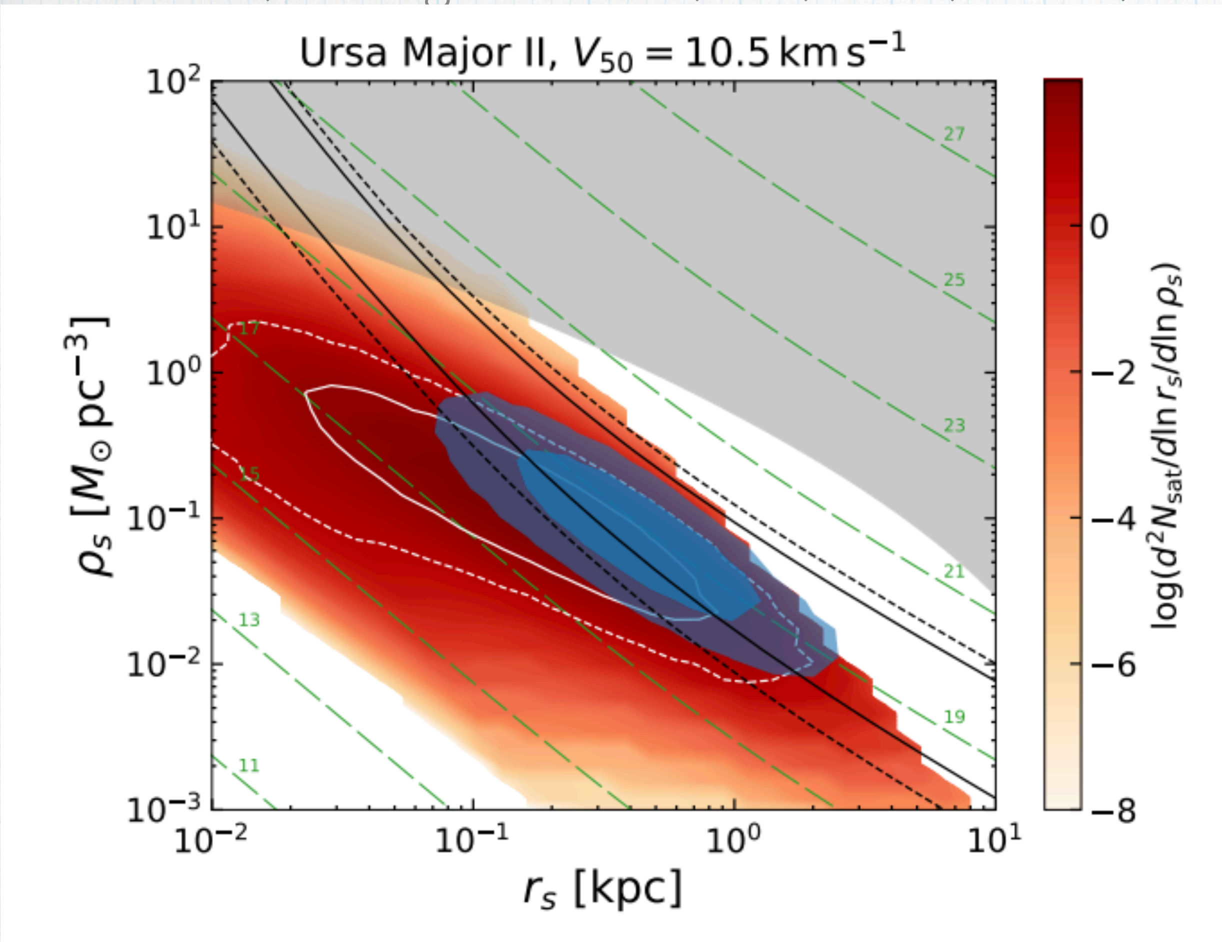
$$\rho(r) = \rho_s \left(\frac{r}{r_s} \right)^{-1} \left(1 + \frac{r}{r_s} \right)^{-2}$$

- Tidal stripping rate is determined at the pericenter of the accreting orbit

- The DM distribution of subhalos after the tidal stripping are NFW profile with truncation

dSph in subhalo of Milky Way

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020

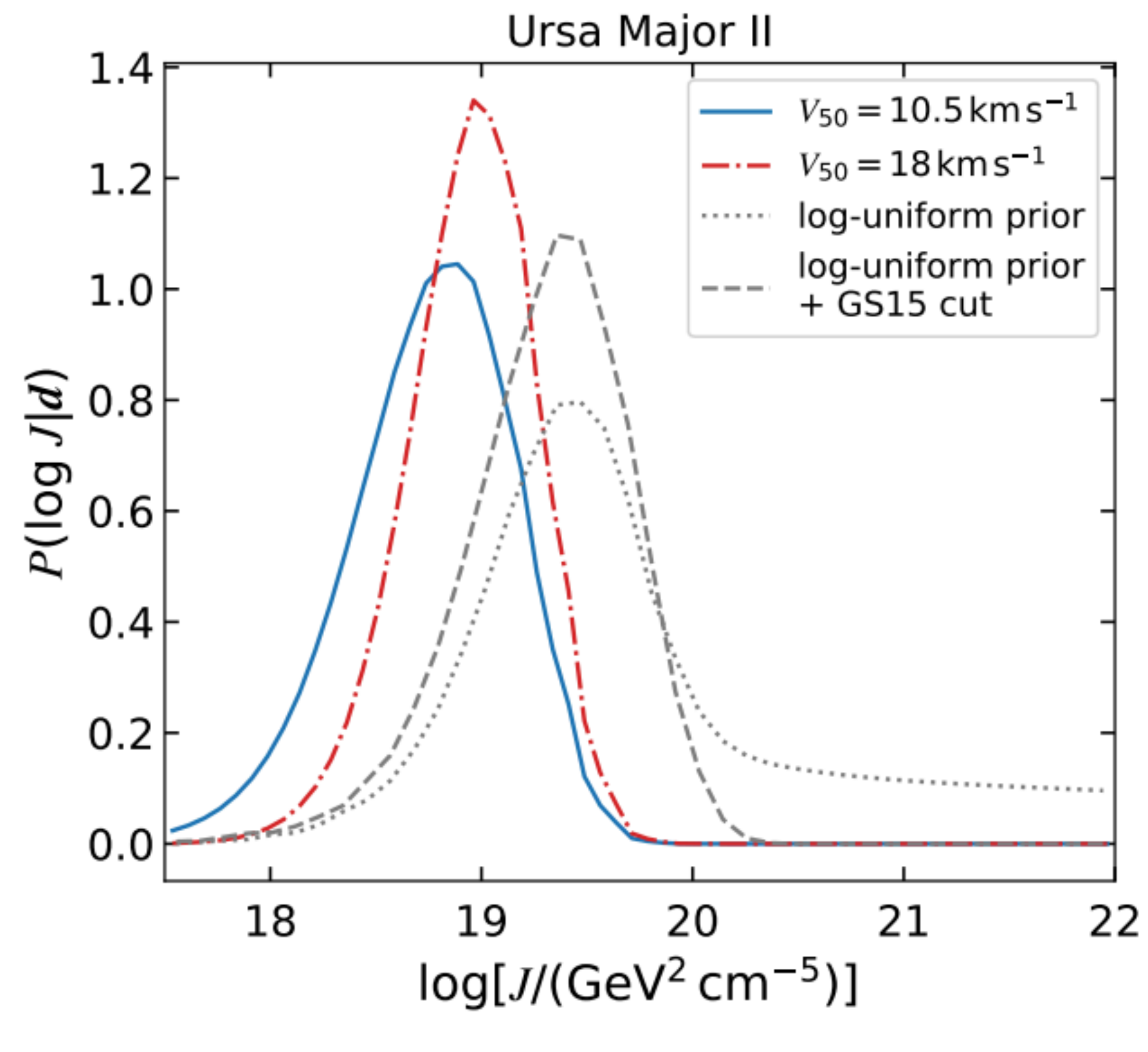


- red: number of the satellite in Via Lactae II simulation
- **white: "informative" prior distribution**
- black: likelihood
- blue: posterior distribution

making use of the evolution history of DM halos to obtain good priors for the Milky Way's satellites

J-factor

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020

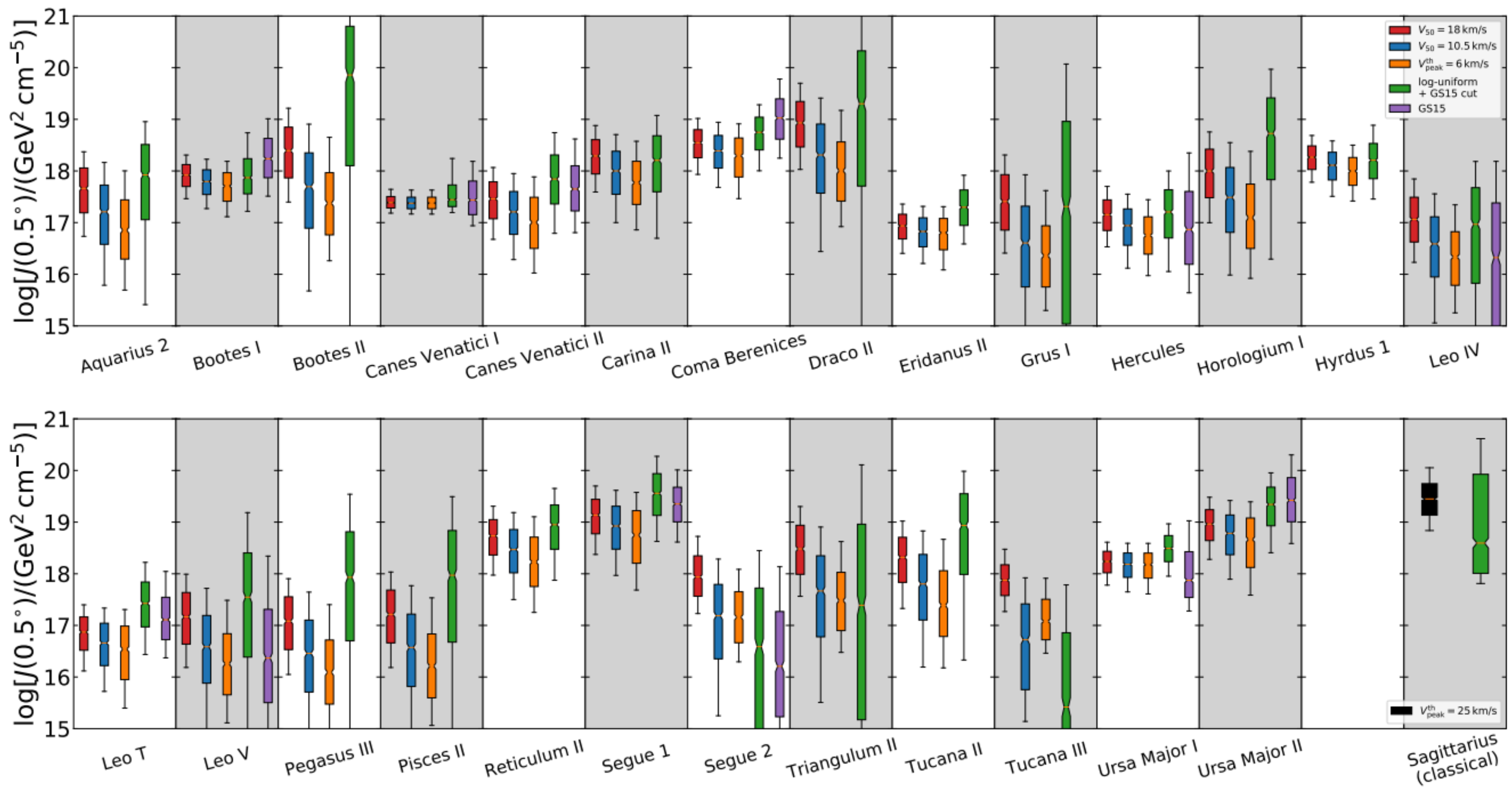


$$J = \int_{\Delta\Omega=0.5^\circ} d\Omega \int_{l.o.s} \rho^2_{\mathrm{DM}}(r)ds$$

- The J-factor shifts to a lower value.
- The probability distribution of the J-factor gets sharper.

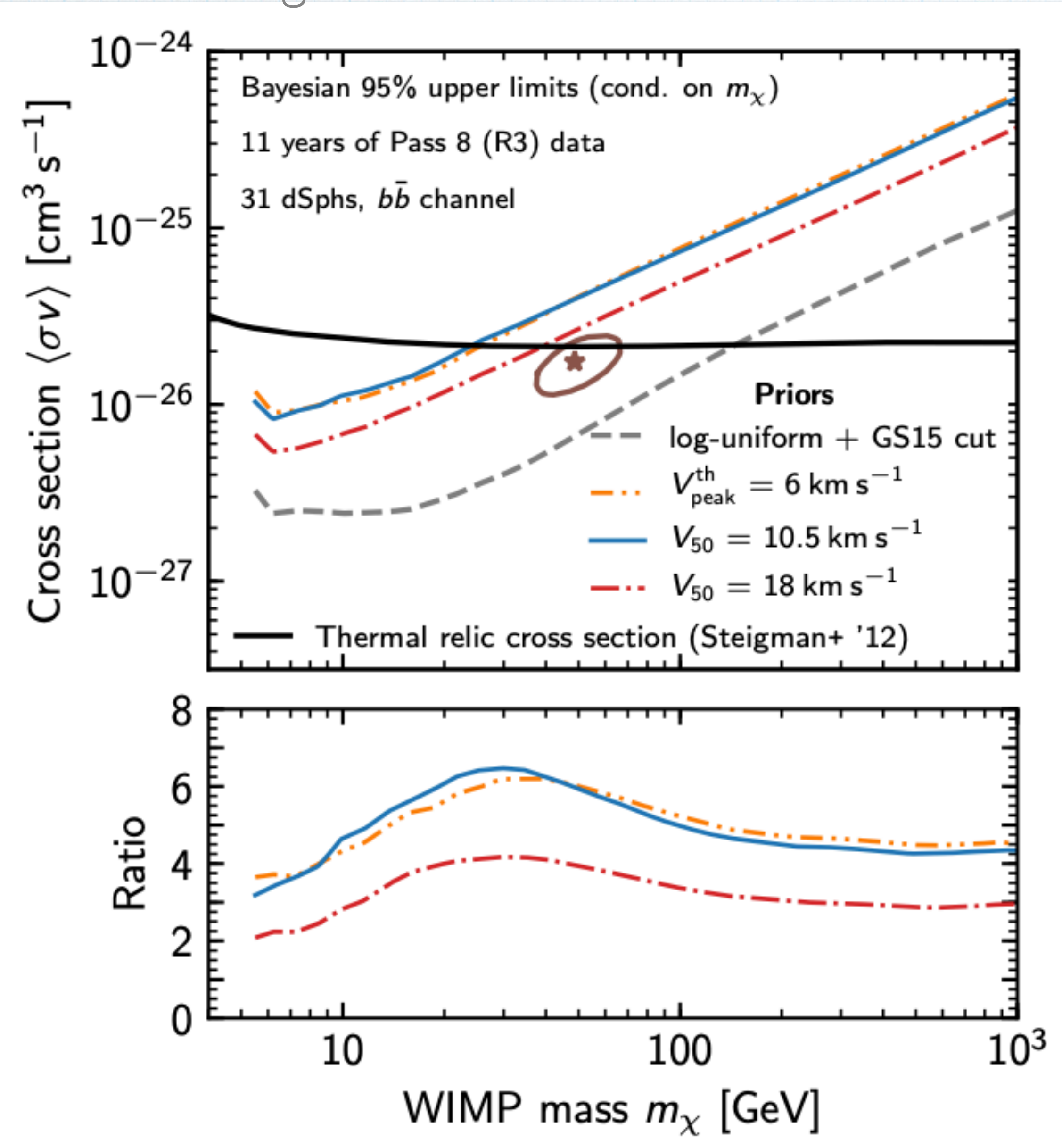
J-factor: summary

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020



Constraints on the $< \sigma v >$

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020



$$\phi_\gamma = \frac{1}{8\pi} \frac{\langle \sigma v \rangle}{m_{\rm DM}^2} \left(\int \frac{dN}{dE} dE \right) \cdot J$$

- Bayesian analysis is conducted combining 31 dSph's data
- The constraints gets milder by a factor of 2-6 due to the shifts in the J-factors.

4. Conclusion

Conclusion:

- WIMP is a well-motivated DM candidate.

- Property of DM halo directly affects the observables in indirect searches.
- It also contain information about particle DM nature.

- Halo formation history is a key to study DM from multiple aspects.

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