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DM search in dSphs combined with structure formation models of halo

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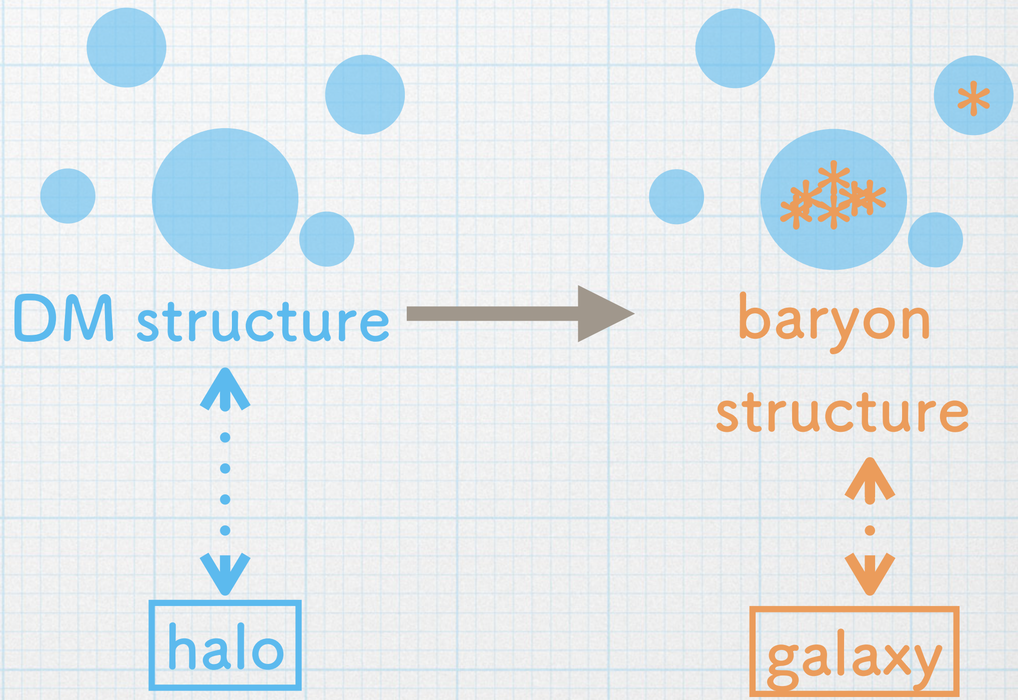
1. DM in the Universe

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

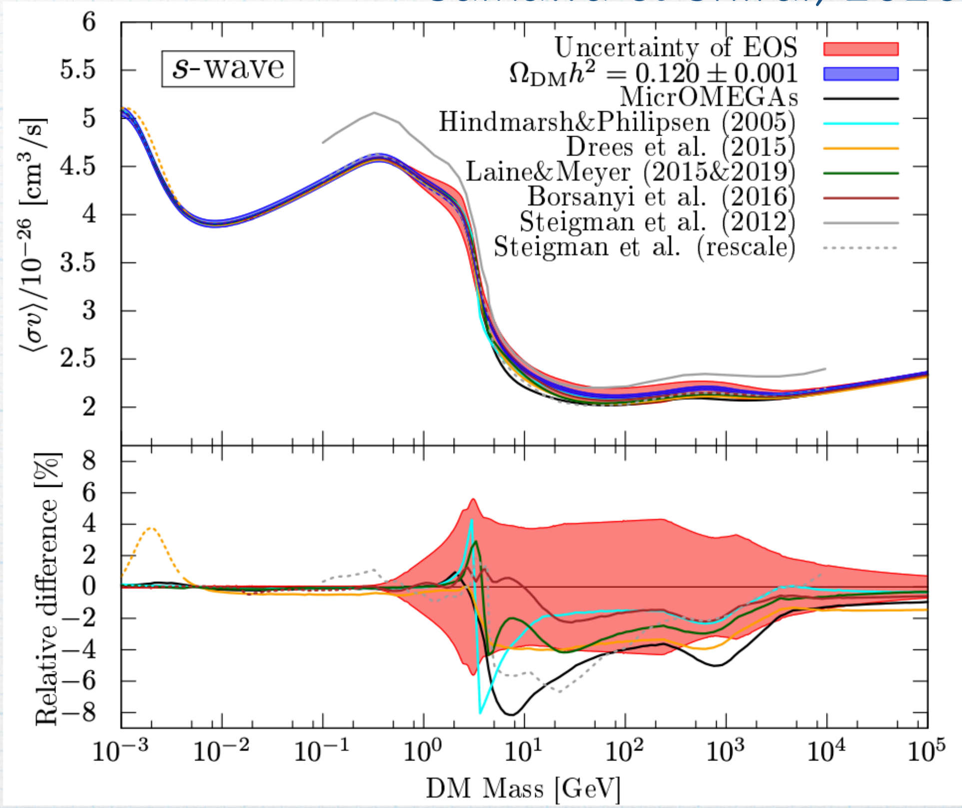
- Weakly Interacting Massive Particle (WIMP)
- Strongly/self- interacting massive particle (SIMP)
- sterile neutrinos
- axion and/or axion-like particle (ALP)
- primordial black hole (PBH)···

We focus on WIMP today.

WIMP

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

Saikawa & Shirai, 2020

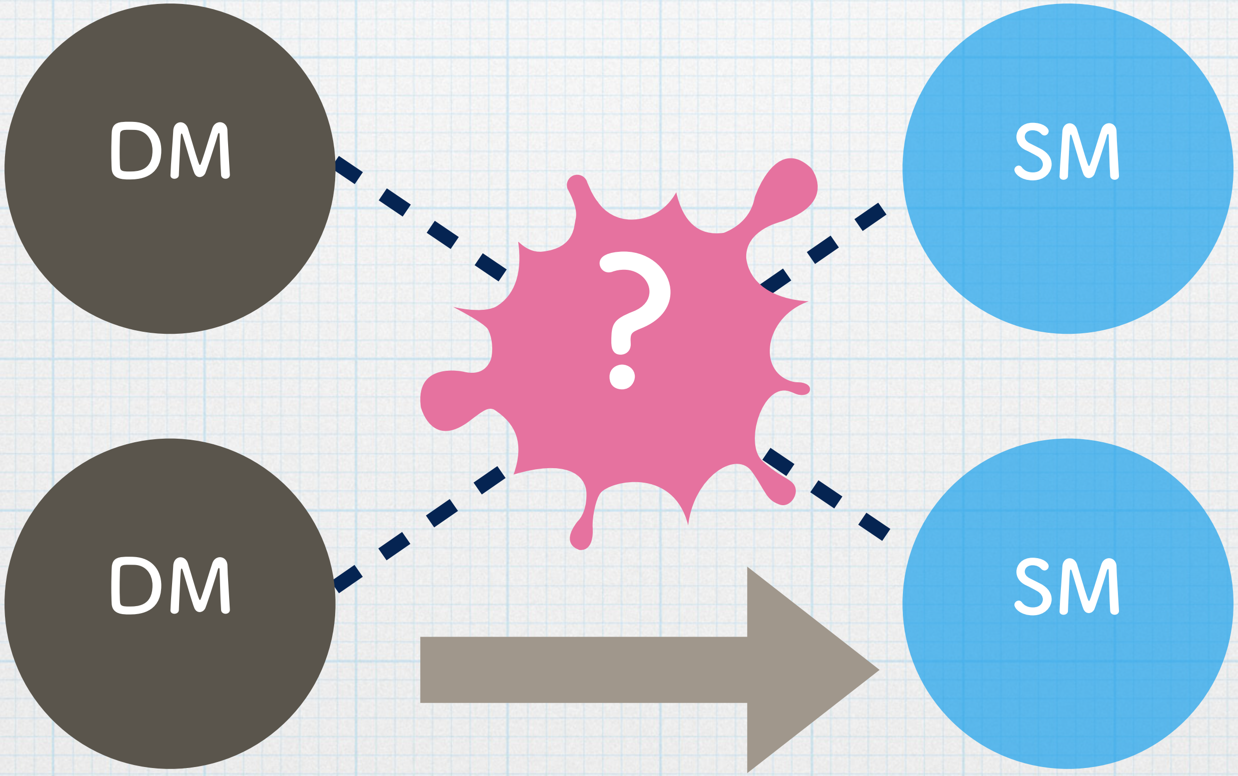


We do not see the annihilation signature yet.

WIMP annihilation @z=0

Before $z = z_{\text{freeze out}}$, WIMP annihilates into SM particles.

The same process also occurs in somewhere/anywhere in the Universe after the freeze-out



Indirect detection experiments

Indirect detections

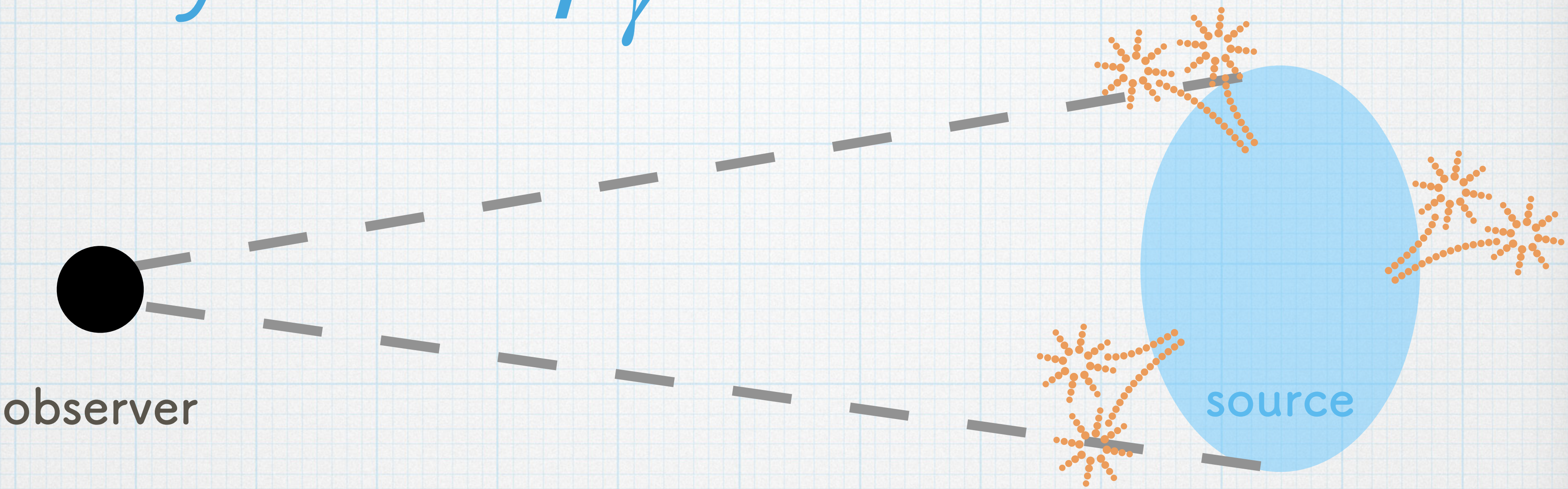
DM + DM somewhere in the Universe → **something in the SM** on/around the Earth

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

- **γ-ray search**

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

γ-ray flux ϕ_γ



$$\phi_\gamma = \frac{1}{2}\frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{l.o.s} \int dE\ \langle\sigma v\rangle n_{\rm DM}^2 \frac{dN}{dE}$$

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

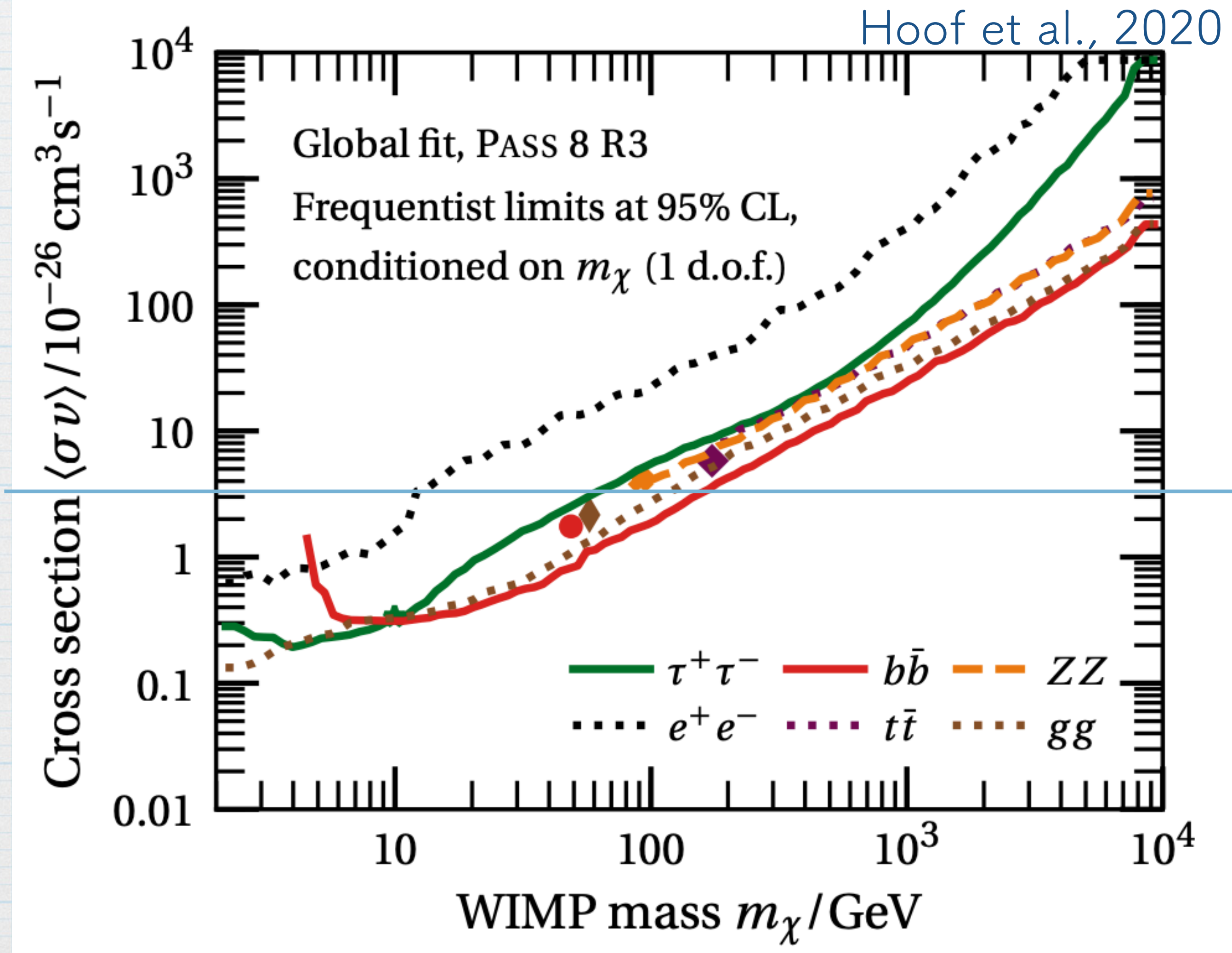
(astrophysical) J-factor

We should select high J-factor (i.e., $\rho_{\rm DM}$) targets.

Current limits for WIMP

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

Hoof et al., 2020

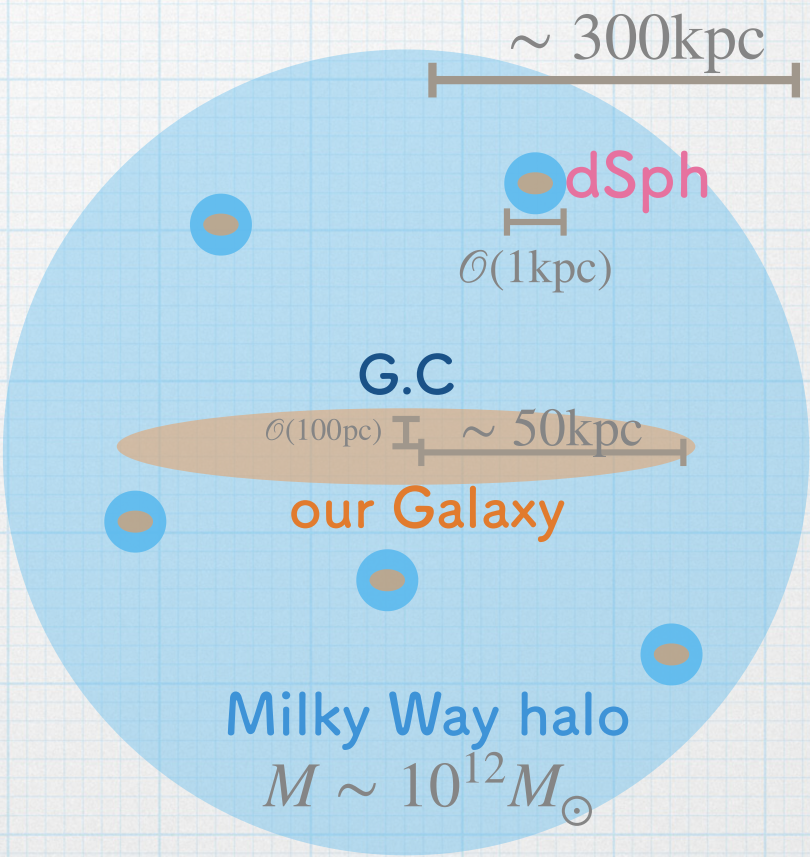


canonical

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

dSphs: Fermi's targets

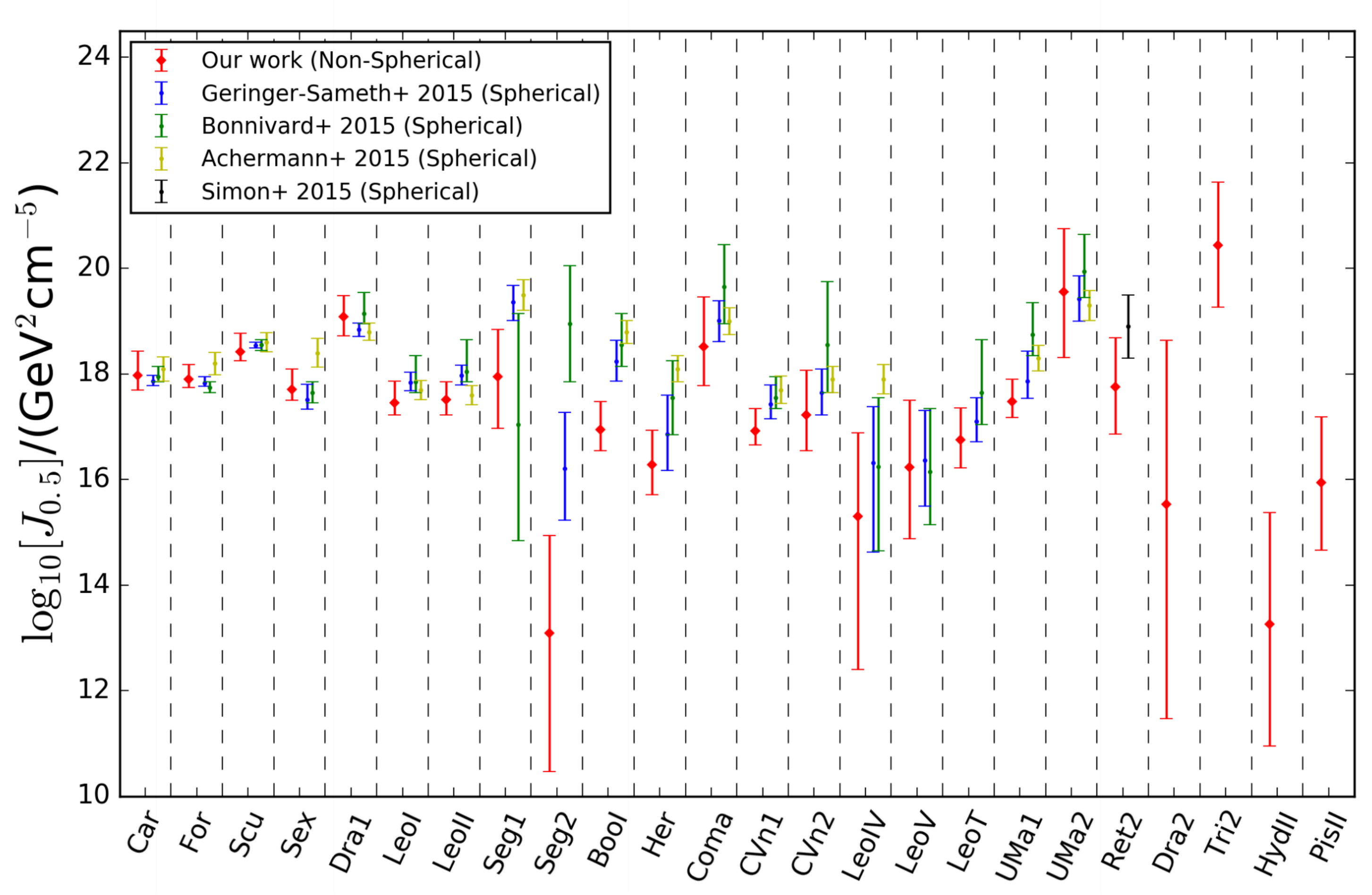
- **satellite galaxies of the Milky Way**
- ~40 are confirmed
- $M \sim 10^{8-9} M_\odot$, $M/L \sim \mathcal{O}(10^3) M_\odot / L_\odot$
- do not show star formation activities
- dist $d \sim \mathcal{O}(100)$ kpc
- $\Delta\theta \lesssim \mathcal{O}(1\mathrm{deg})$



difficulties: dSph's J-factor

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

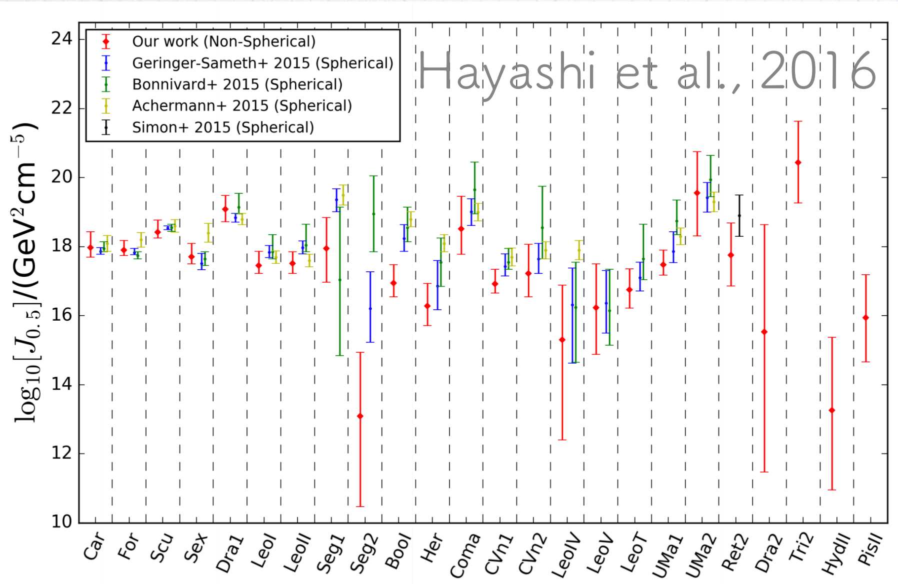
Hayashi et al., 2016



2. DM in dSphs

Evolution of the DM subhalo in host's potential

ρ_{DM}: the source of the J-factor



$$\frac{dJ}{d\Omega} = \int_{l.o.s} \rho_{\mathrm{DM}}^2(r)\,ds$$

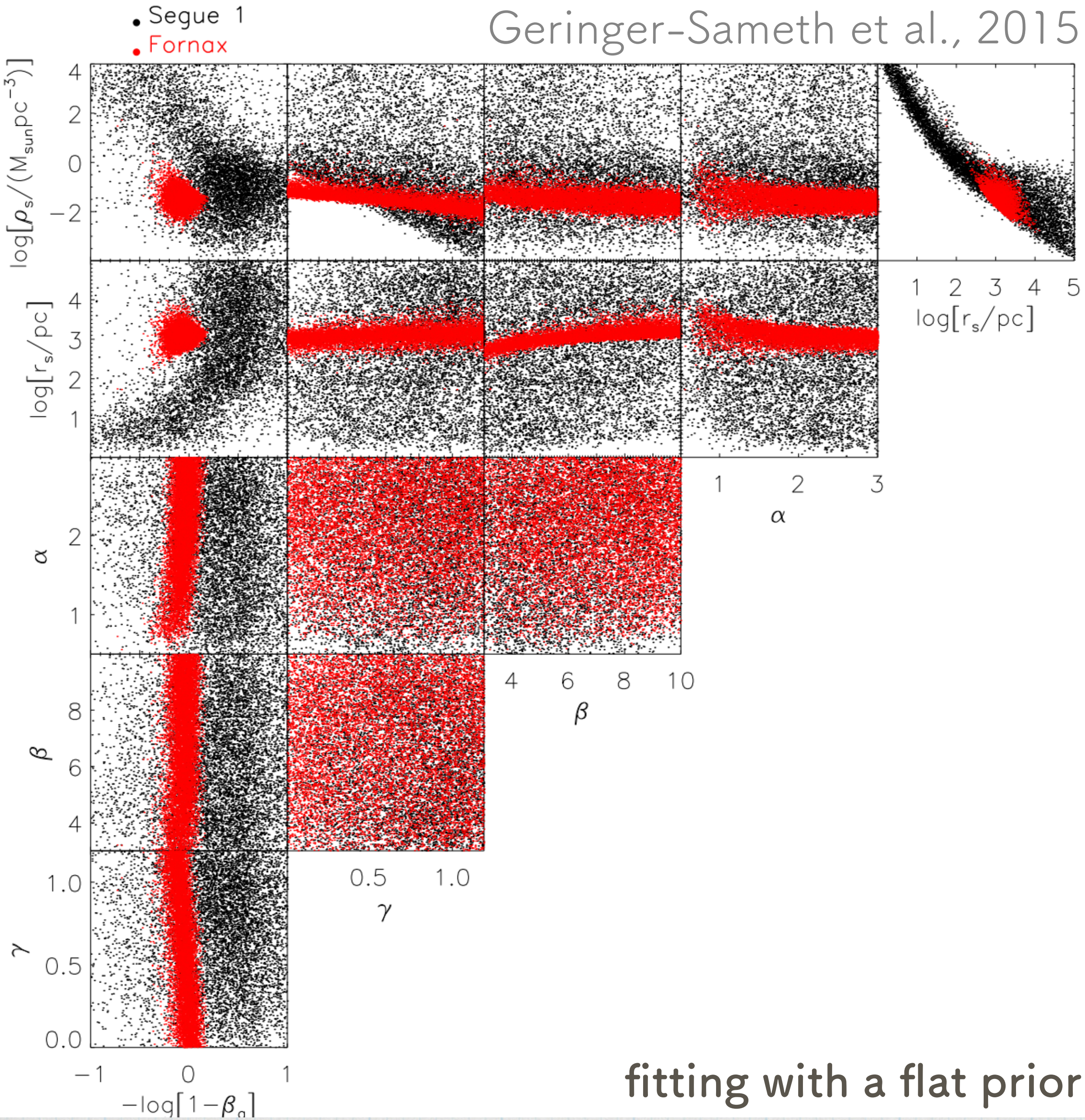
$$\rho_{\mathrm{DM}} = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{-\alpha}\right]^{-\frac{\beta-\gamma}{\alpha}}$$

1. measure the proper motion of stars in dSphs
2. derive the gravitational potential
3. reconstruct the density profile $\rho_{\mathrm{DM}}(r)$

dSph is dark, and the number of the tracer is limited

Problem around the prior

Geringer-Sameth et al., 2015



fitting with a flat prior

1. We need to fit ~5 parameters using O(10)-O(1000) stars
2. (The fraction of the foreground star in the data is unknown)
3. The error of the best-fit value of each parameter becomes large

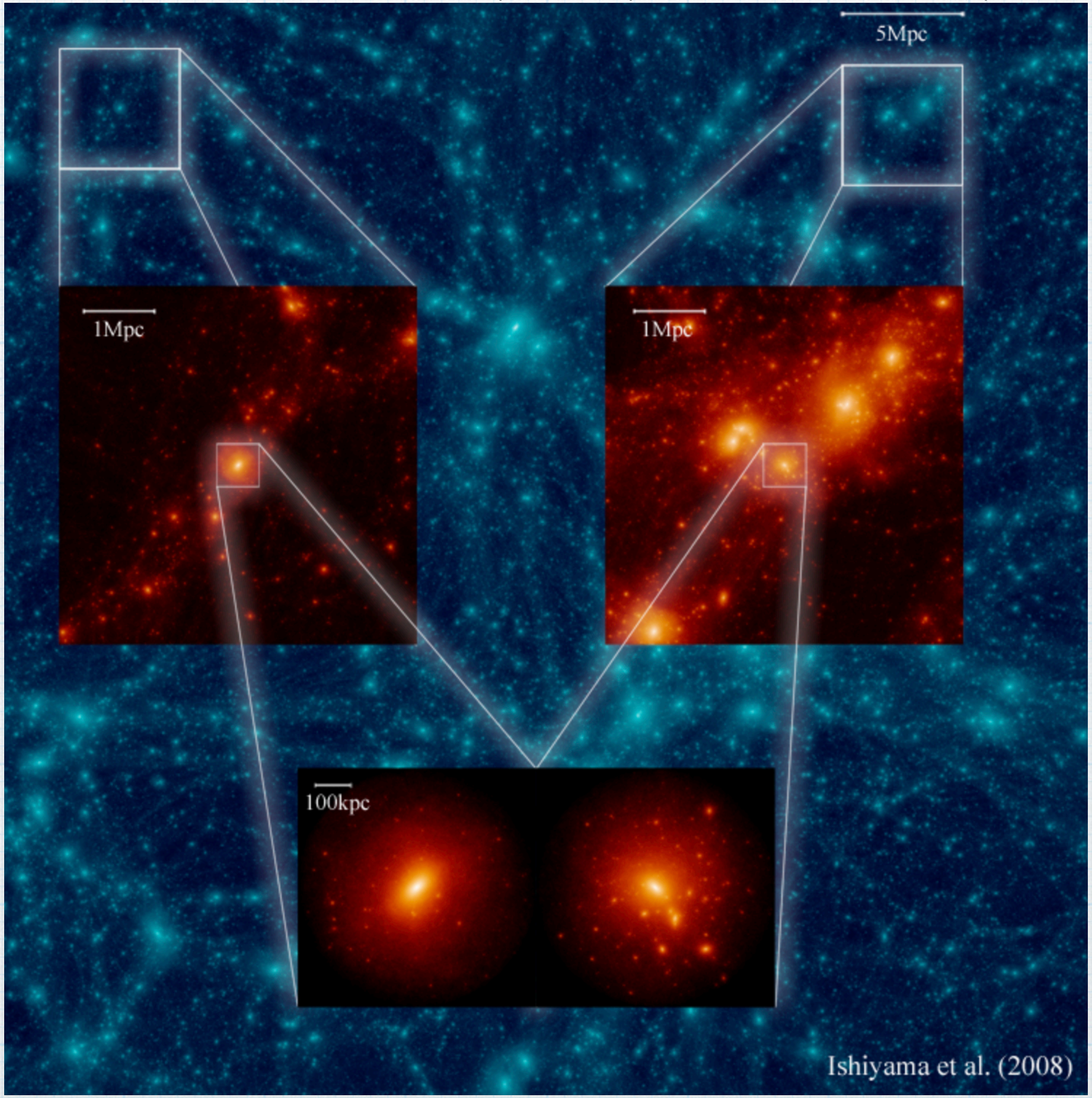
Situation:

1. dSphs are good targets to search WIMP annihilation signal.
2. They are DM rich **satellite of our Galaxy**.
3. Density profile parameters of dSphs are difficult to determine.
4. **If we have a good prior of the density parameter, the precision of the J-factor could improve**

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

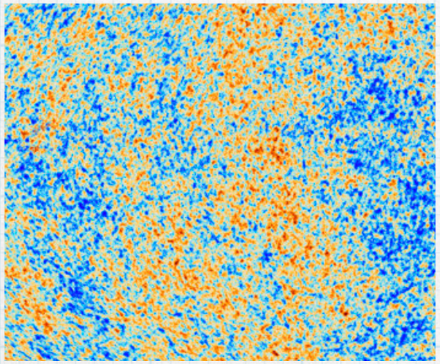
hierarchical DM structure

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

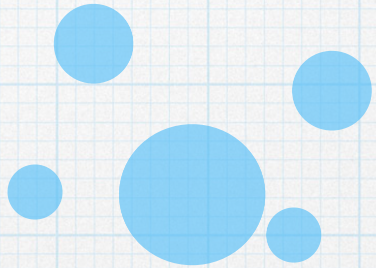


Story of DM halo

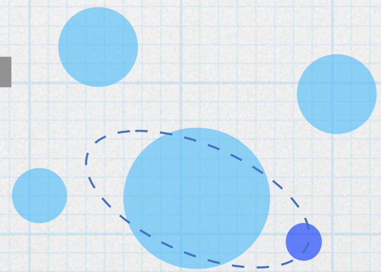
1, initial density fluctuation



2, gravitational collapse
(halo formation)

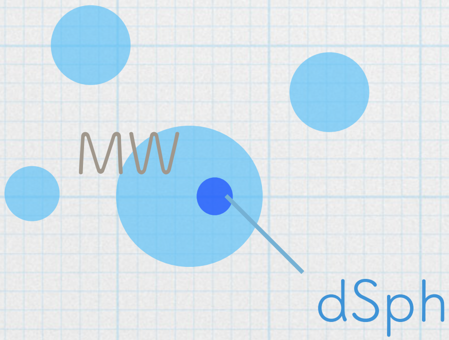


3, halo evolution



- merger
- accretion
- stripping

4, hierarchal halo structures



Story of DM halo

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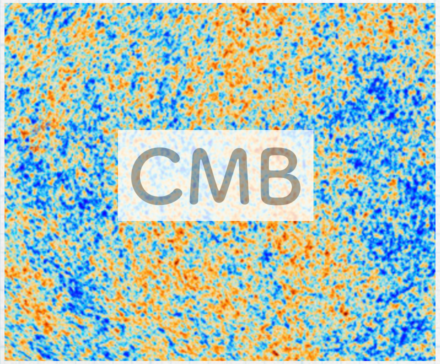

2, gravitational collapse

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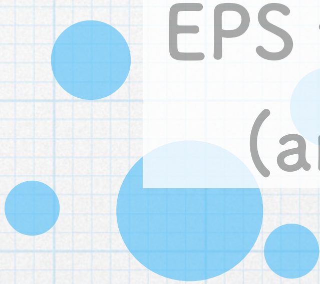
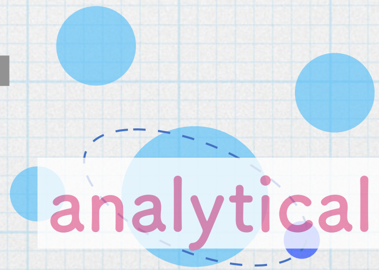


EPS formalism

(analytic)

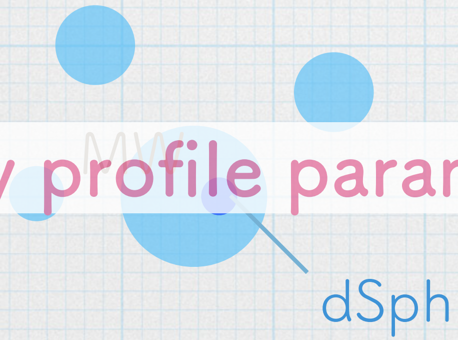
3, halo evolution



- 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

Evolution

1. initial (ρ_s, r_s): from $c = r/r_s$ in simulation and m

$$m = 4\pi\rho_s r_s^3 \left[\ln(1+c) - \frac{c}{1+c}\right]$$

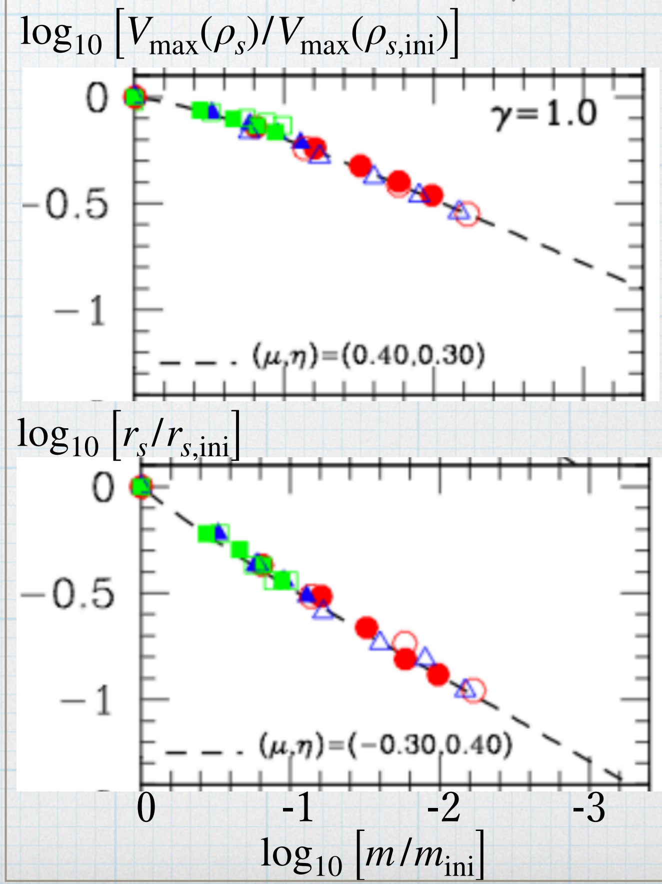
2. tidal mass loss from z=7 to z=0

$$\dot{m} = \frac{m - m(<r_t)}{T}$$

3. m, r_t, (ρ_s, r_s) at z=0

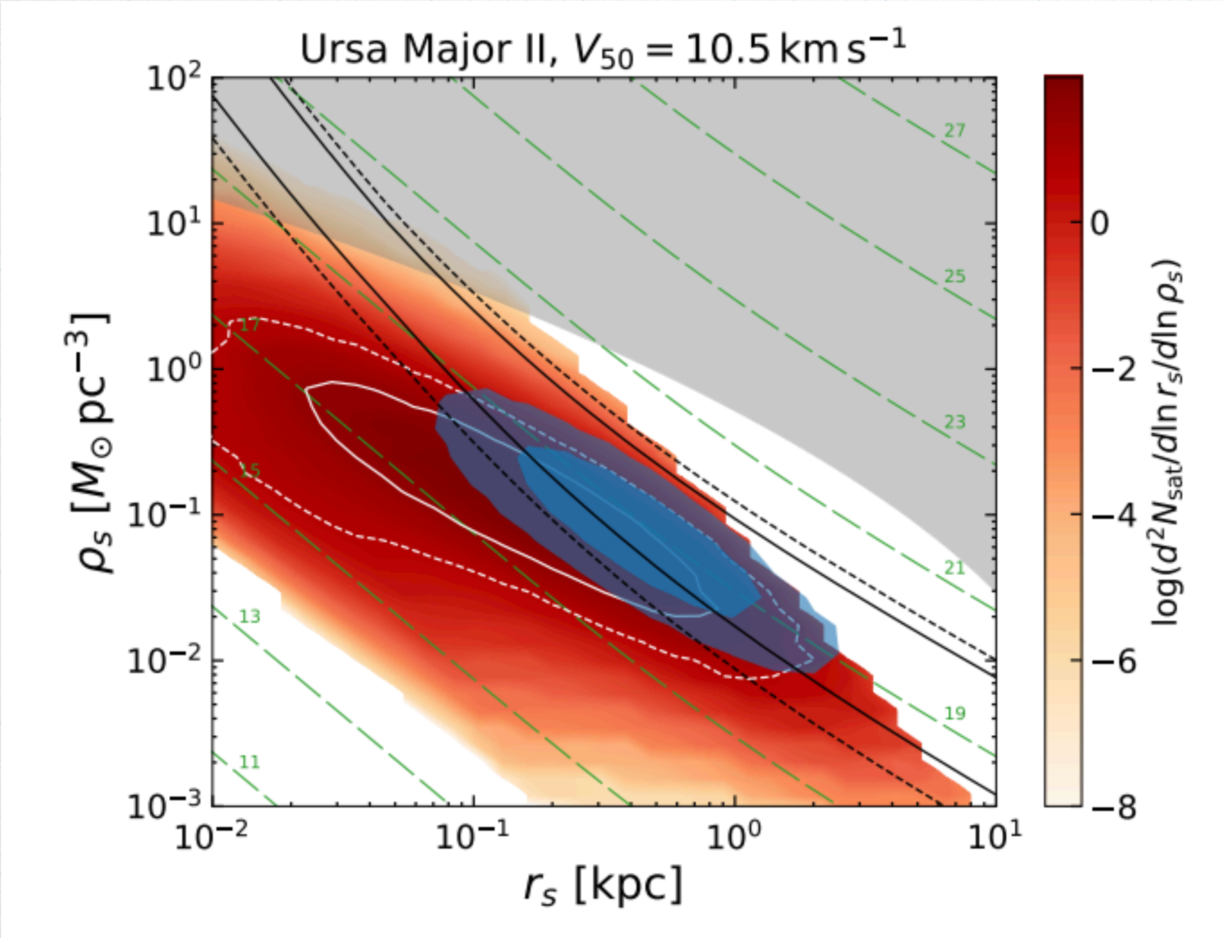
$$m_0 = 4\pi\rho_{s,0} r_{s,0}^3 \left[\ln(1+c_t) - \frac{c_t}{1+c_t}\right]$$

Penarrubia et al., 2010



The $\rho_s - r_s$ plain @z=0

Ando et al., 2020



red: number of the satellite in Via Lactae II simulation

white: "analytical" prior distribution

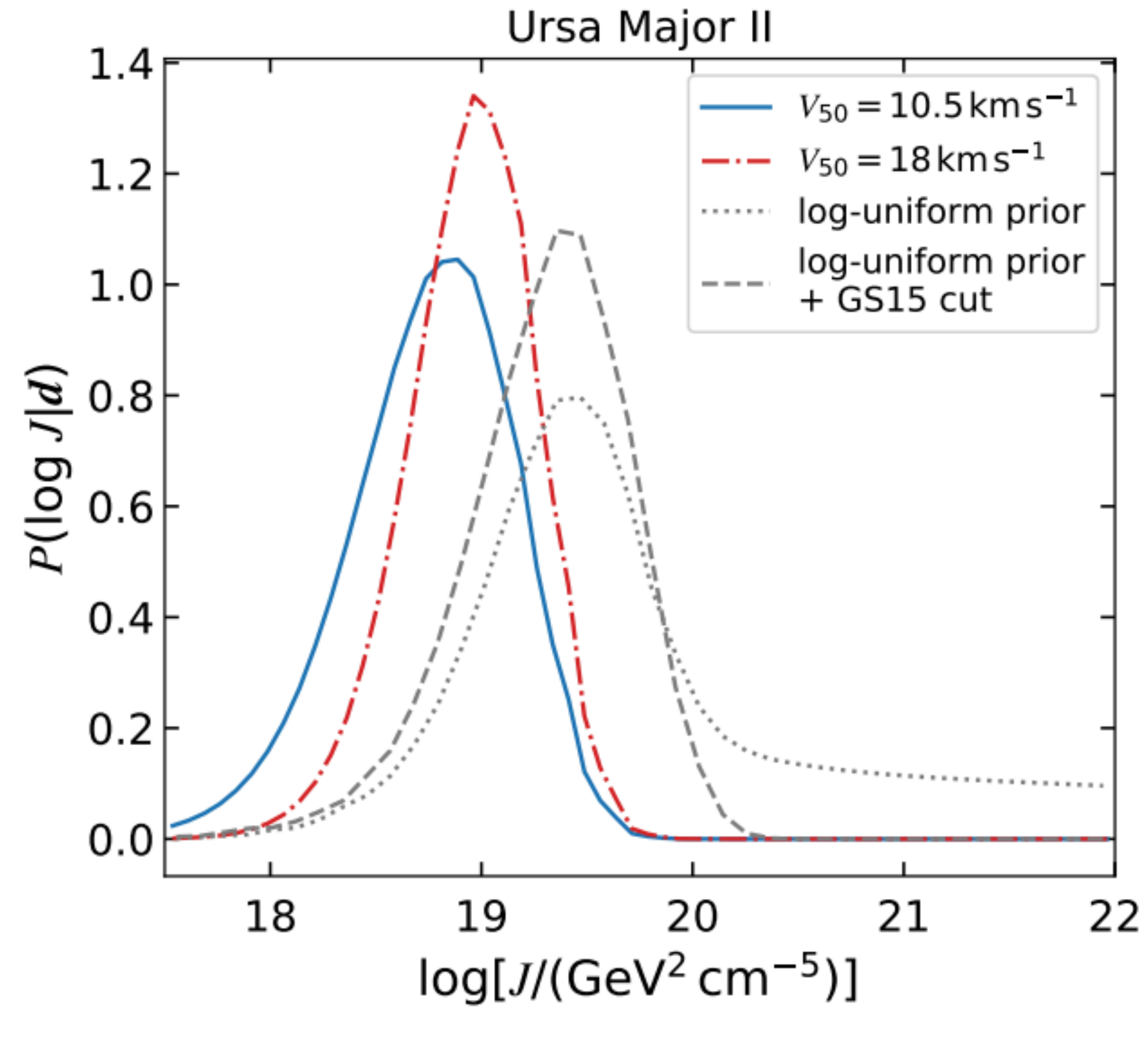
black: likelihood

blue: posterior

3. DM signal in dSphs

J-factor

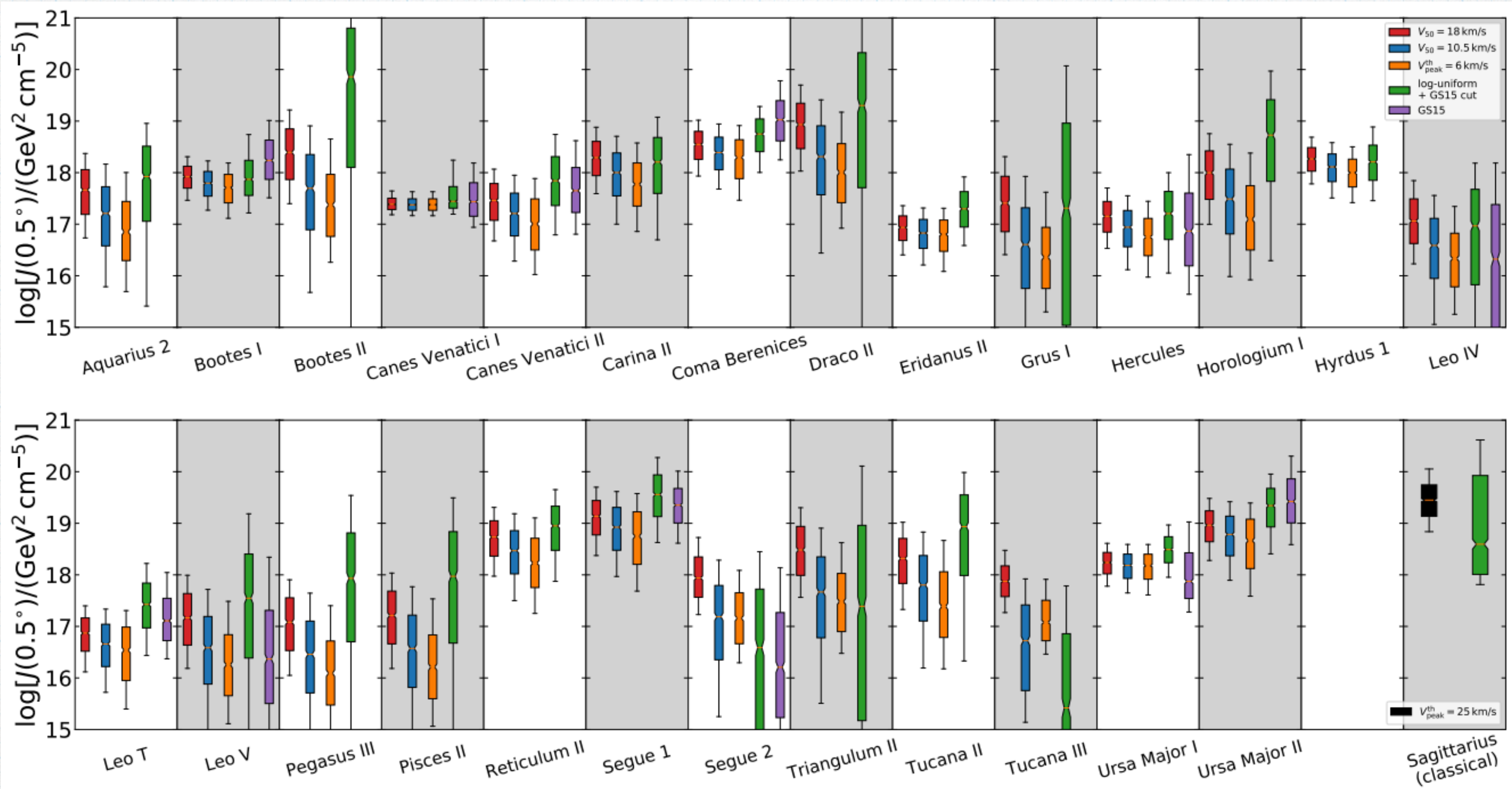
Ando et al., 2020



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

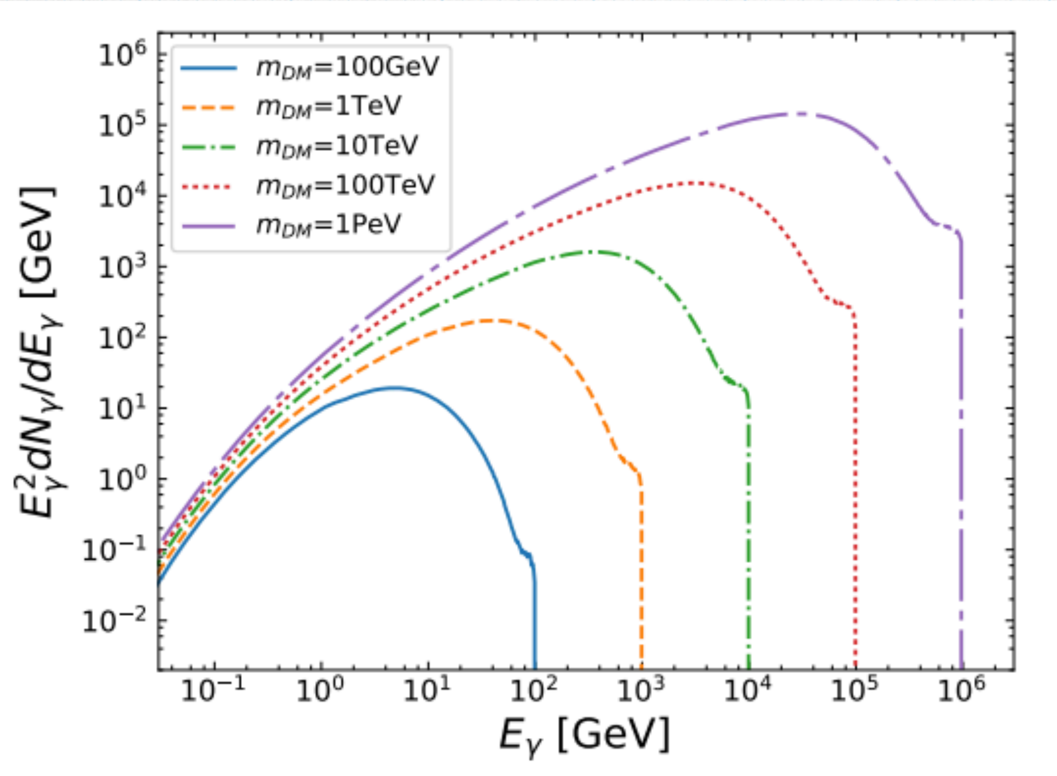
- The J-factor shifts to a lower value.
- The probability distribution of the J-factor gets sharper.

J-factor: summary



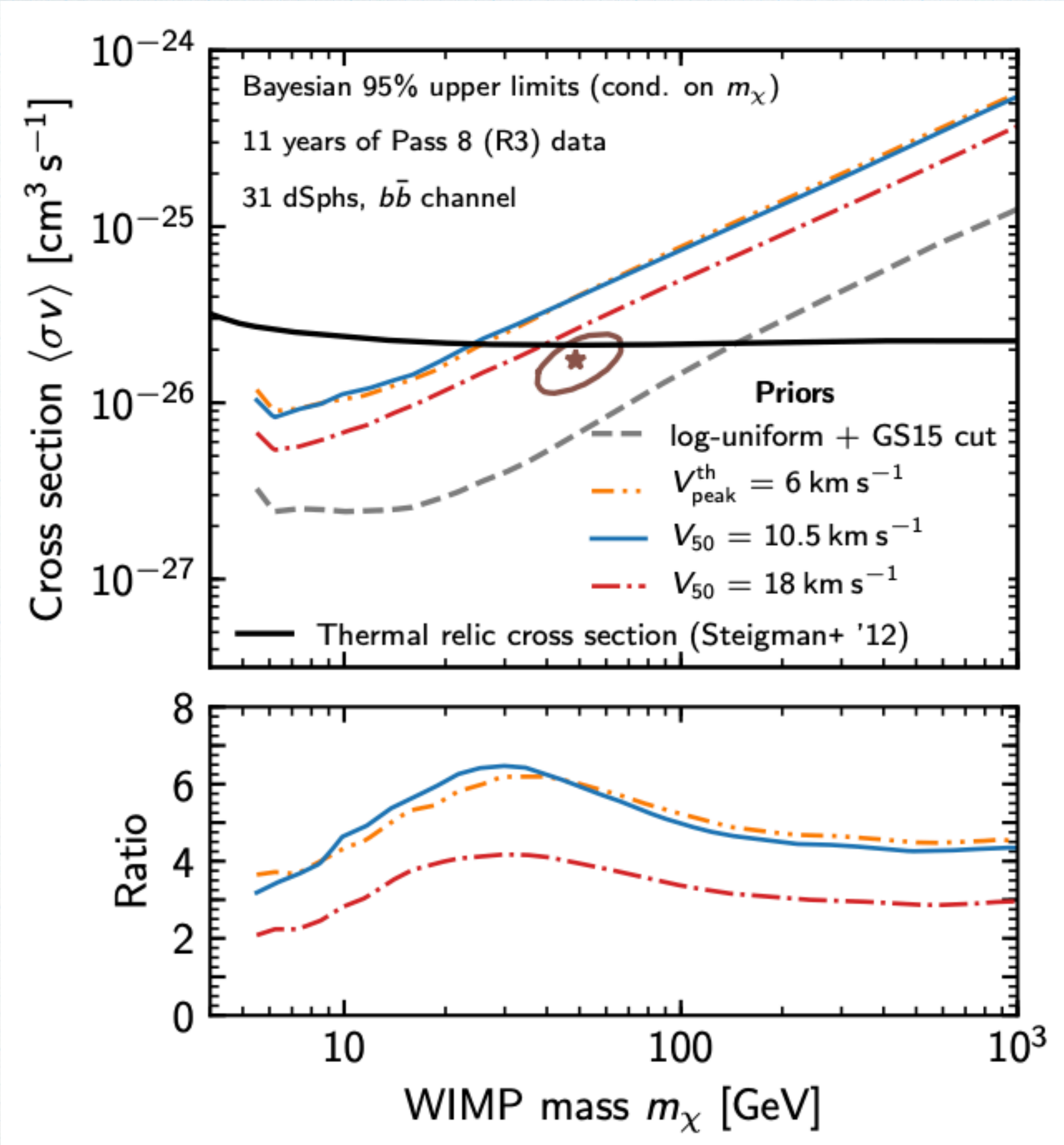
γ-ray from WIMP annihilation

$$\phi_\gamma = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\int_{E_{\rm th}}^{m_{\rm DM}}\frac{dN}{dE}dE\cdot\int_{0.5^\circ}d\Omega\int_{l.o.s}ds\rho_{\rm DM}^2$$



$$\chi + \chi \to \bar{b} + b$$
$$\to \pi^0 + \ldots$$
$$\to 2\gamma + \ldots$$

Constraints on the $< \sigma v >$



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

- 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.

Conclusion

Conclusion:

- dSphs are good targets for WIMP search
- The main difficulty in the WIMP search in dSphs is the estimate of the J-factor (i.e., DM distribution in the target dSphs)
- We can obtain a good prior for DM distribution by combining the information from the structure evolution theory
- Using the theoretically motivated prior, the constraint on the WIMP annihilation cross-section is relaxed by a factor of 2-6.

References:

- Ando et al., 2020, Phys. Rev. D102, 061302 arXiv 2020.11956
- Hiroshima et al., 2018, Phys. Rev. D97, 123002 arXiv 1803.07691
- Geringer-Sameth et al., 2015, ApJ, 801, 74 arXiv 1408.0002
- Hoof et al., 2020, JCAP 02 (2020) 012 arXiv 1812.06986
- Penarrubia et al., 2010, MNRAS 406, 1290 arXiv 1002.3376
- Jiang & van den Bosch, 2014, arXiv 1403.6827