THE SEARCH FOR DARK MATTER HALO SUBSTRUCTURE WITH GAMMA RAYS

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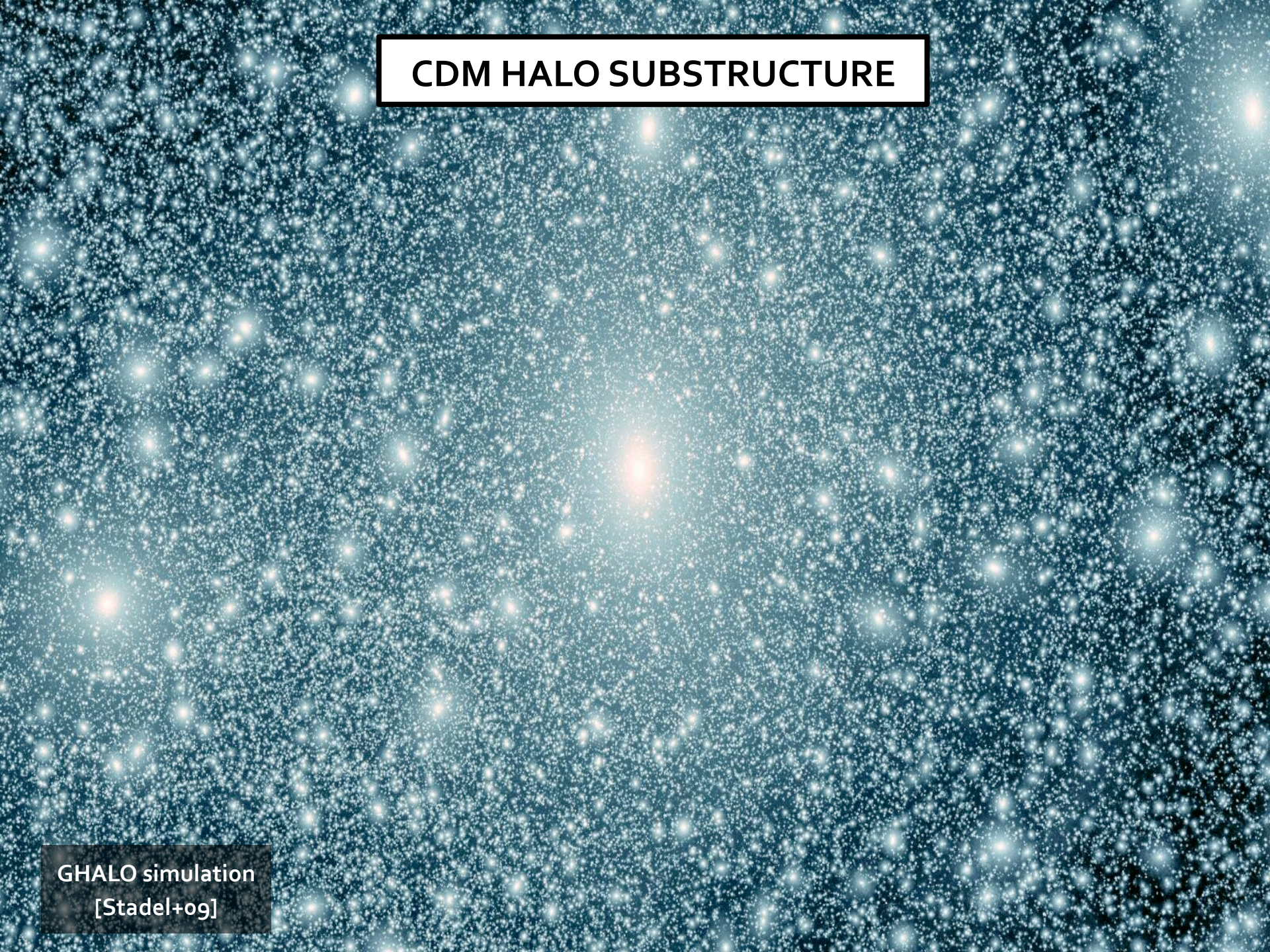
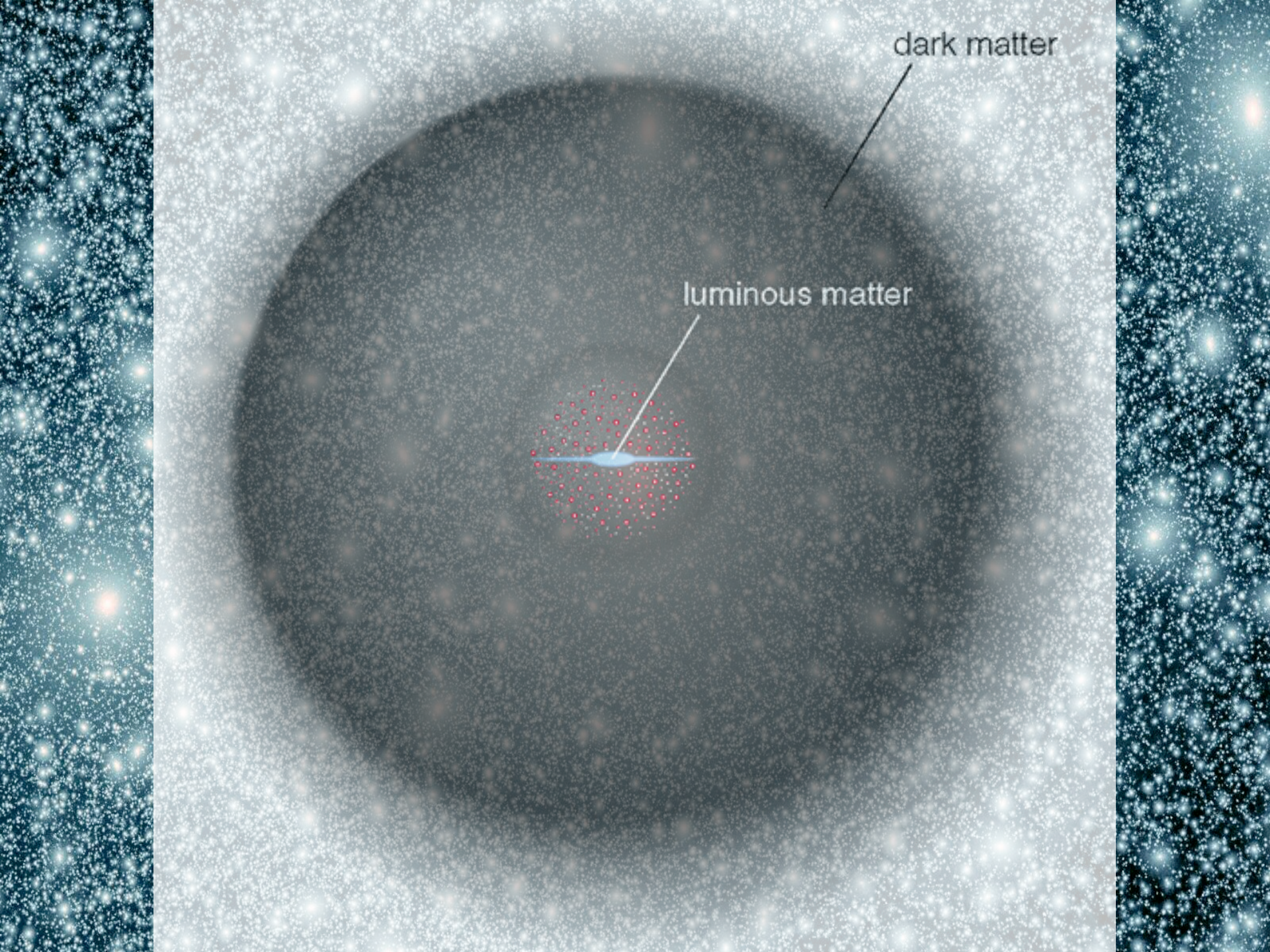
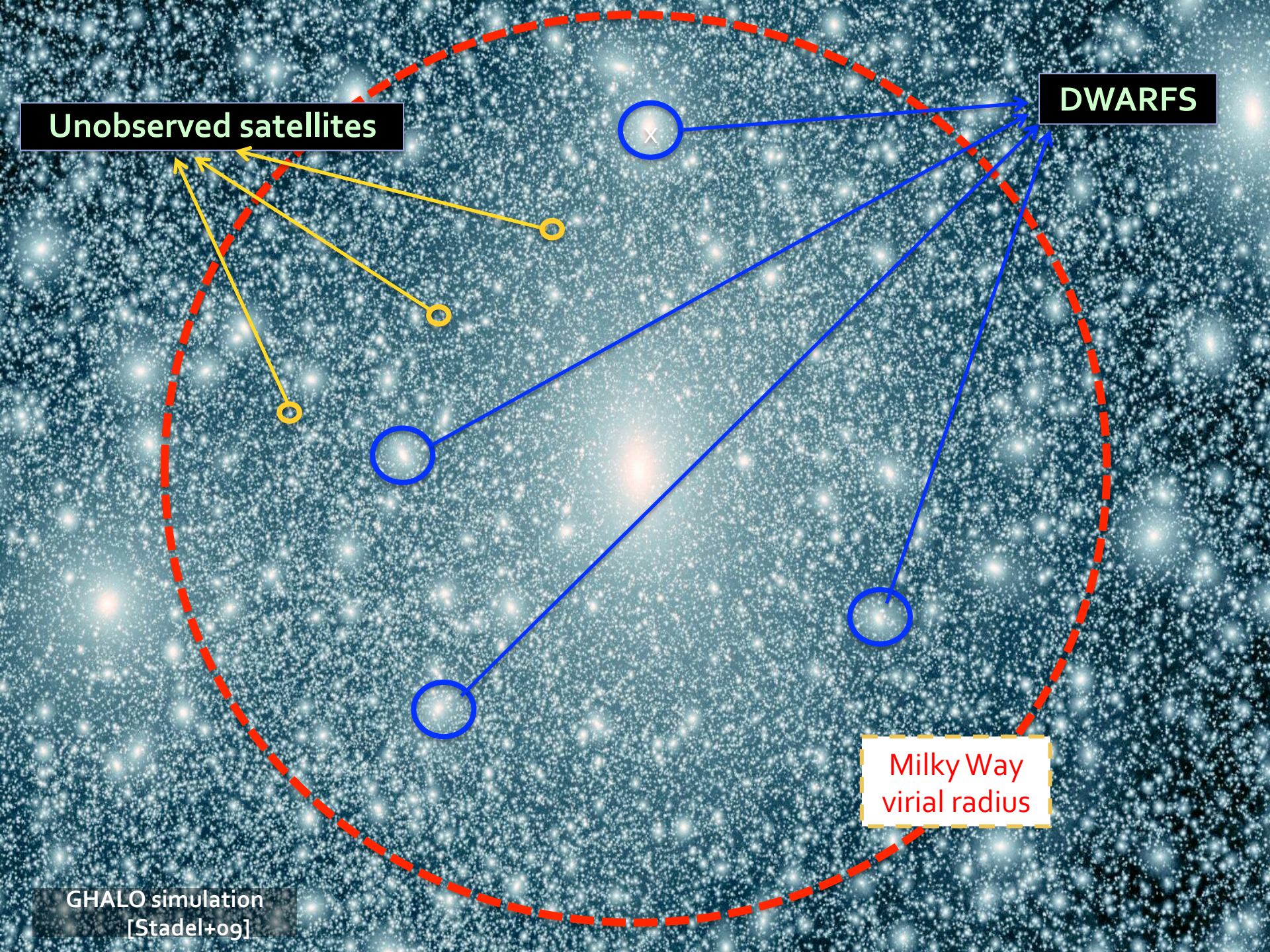
CDM HALO SUBSTRUCTURE



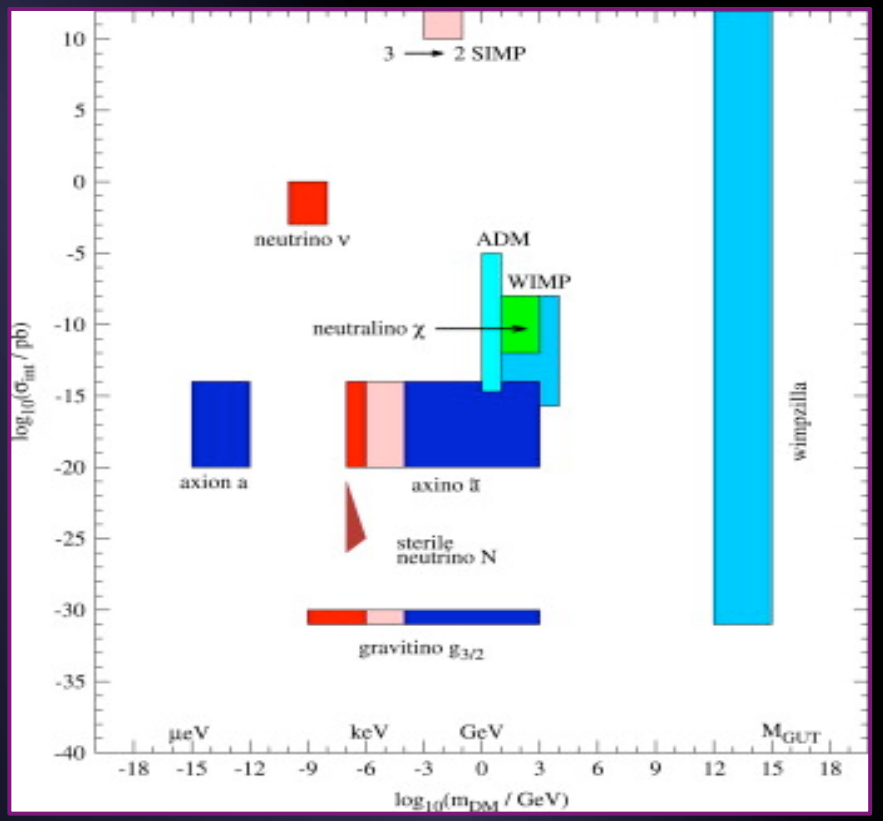
GHALO simulation
[Stadel+09]


dark matter
luminous matter


Unobserved satellites
DWARFS
Milky Way
virial radius
GHALO simulation
[Stadel+09]

What is the DM made of?
WIMP model

- ✓ No viable dark matter (DM) candidate within the Standard Model.
- ✓ Many DM particle candidates beyond the Standard Model.
- ✓ Weakly interacting massive particles (WIMPs) among the preferred ones.



Baer+14

WIMP searches:

A. Direct detection: scattering of DM particles on target nuclei.

B. Direct production of DM particles at the lab.

C. Indirect detection: DM annihilation products (neutrinos, antimatter, gammas)

The DM-induced gamma-ray flux

$$F(E_\gamma > E_{th}, \Psi_0) = J(\Psi_0) \times f_{PP}\left(E_\gamma > E_{th}\right)$$

photons cm^{-2} s^{-1}

Astrophysics

Integration of the squared DM density

$$J(\Psi_0) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2_{DM}[r(\lambda)]\, d\lambda$$

SMOOTH + SUBSTRUCTURE

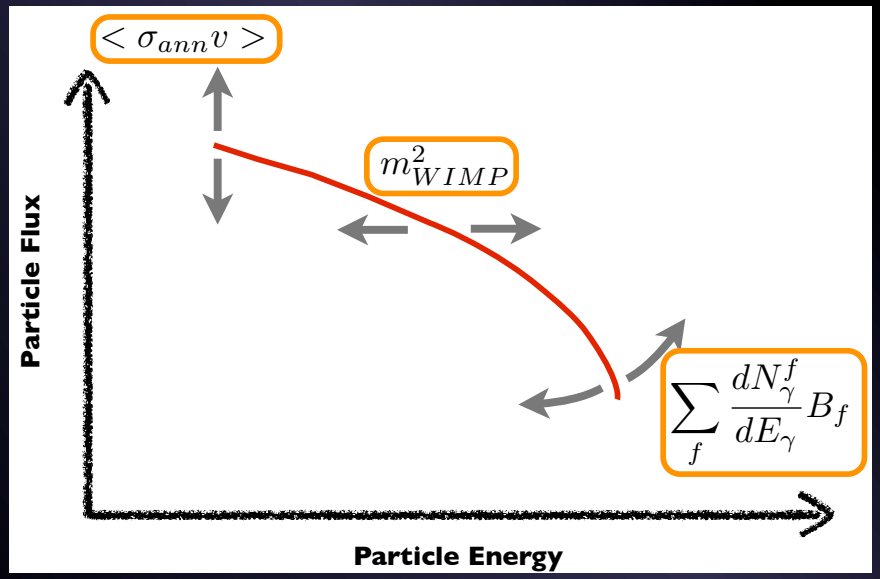
Where to search?

- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...

Particle physics

$$f_{PP} \propto \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f \frac{\langle \sigma \cdot v \rangle}{m_\chi{}^2}$$

- N_g : number of photons per annihilation above E_{th}
- $\langle \sigma v \rangle$: cross section
- m_χ: neutralino mass



The role of DM halo substructure in (indirect) DM searches

Both *dwarfs* and *dark satellites* are highly DM-dominated systems

→ **GOOD TARGETS**

The *clumpy distribution* of subhalos inside larger halos may boost the annihilation signal importantly.

→ **"SUBSTRUCTURE BOOSTS"**

The role of DM halo substructure in (indirect) DM searches

Both *dwarfs* and *dark satellites* are highly DM-dominated systems

→ **GOOD TARGETS**

THIS TALK

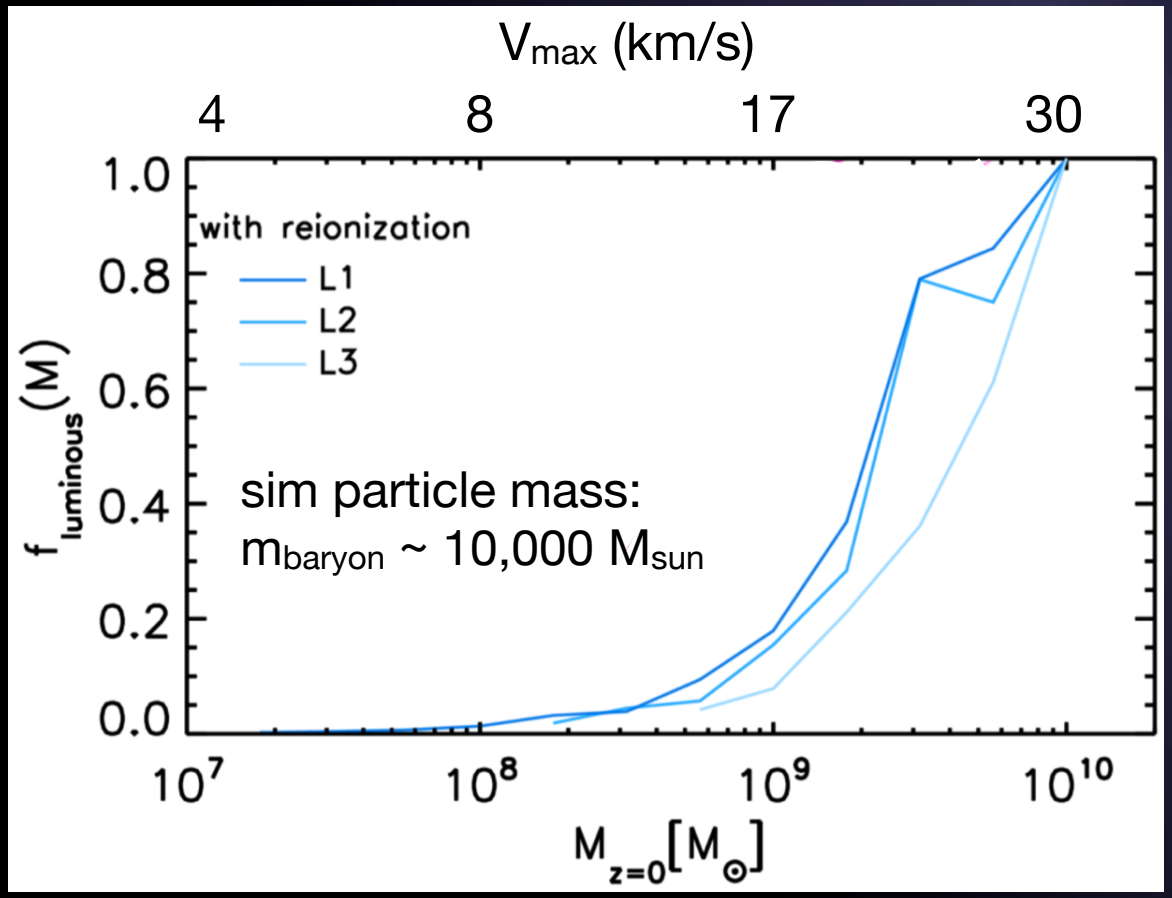
The *clumpy distribution* of subhalos inside larger halos may boost the annihilation signal importantly.

→ **"SUBSTRUCTURE BOOSTS"**

DM subhalos (a.k.a. 'dark satellites')

The most massive subhalos will host visible satellite galaxies

Light subhalos expected to remain completely dark.



[Sawala+15]

Every **halo** is dark below ~8 km/s ~ 10^8 M_{sun}

Subhalos can lose >90% of its mass due to tidal forces

→ dark subhalos < 10^7 M_{sun}

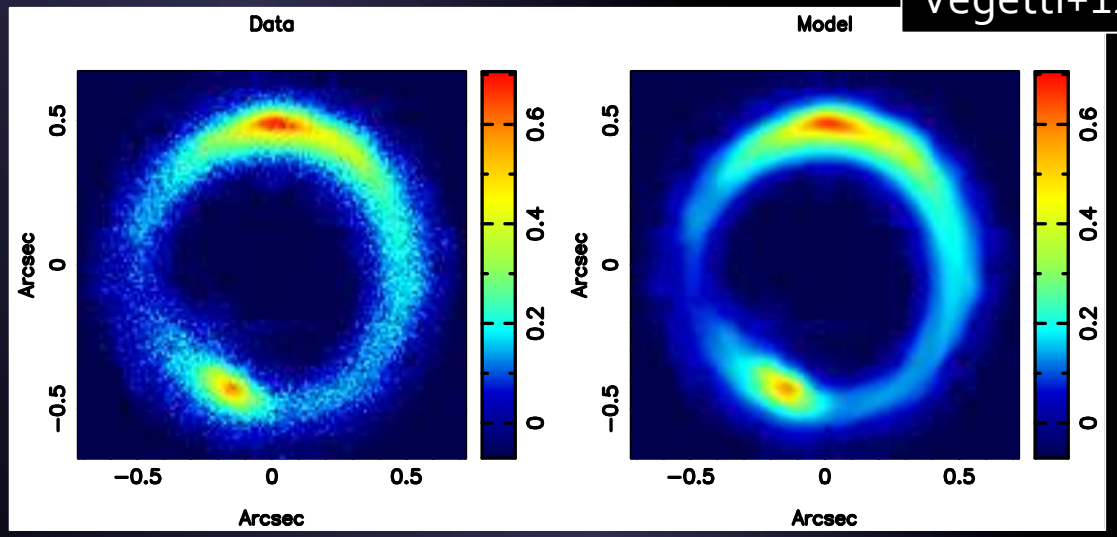
Similar results by Gnedin'00; Hoeft+06; Okamoto+08; Ocvirk+16; Fitts+17; etc

DM subhalo searches

I. (Strong) LENSING

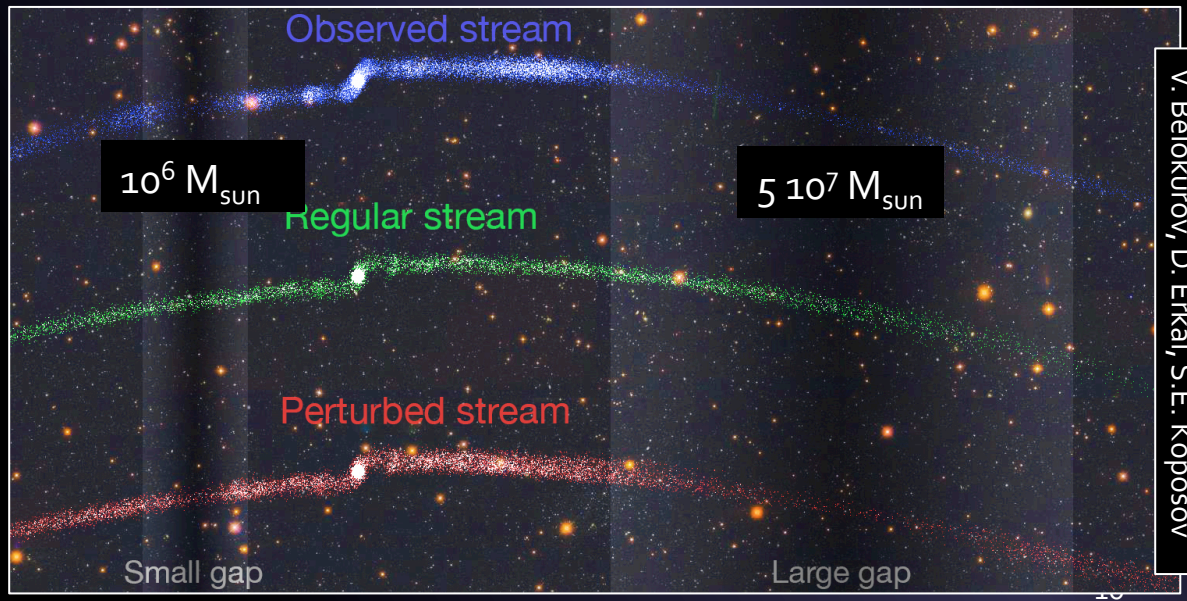
[Vegetti+10,12,18;
Hezaveh+16;
Nierenberg+14,17;
Birrer+17]

Vegetti+12



II. STELLAR GAPS

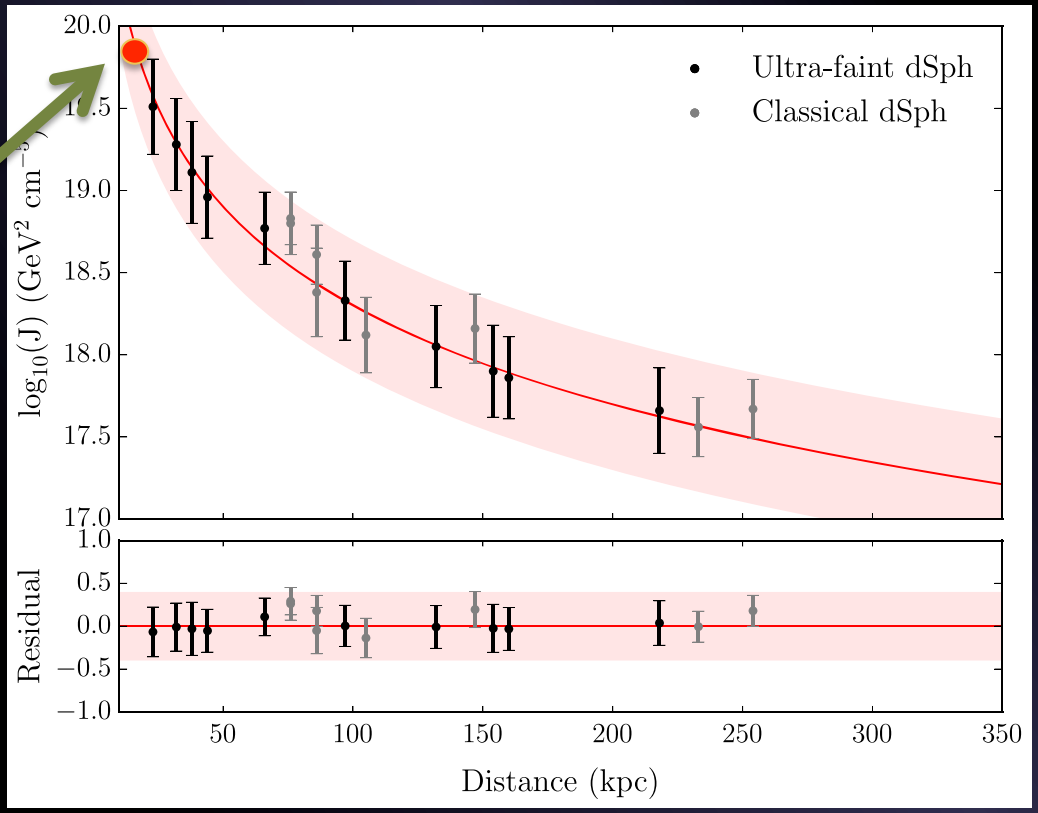
[Carlberg 12,15;
Erkal+15, 16, 17]



DM SUBHALO SEARCHES:
III. GAMMA RAYS

- If DM is made of WIMPs and annihilates → gamma rays
- Maybe the only way to probe subhalo masses below ~10^7 solar masses
- The only subhalo search that provides info on the nature of the DM particle.

Should we expect any dark satellite e.g. here?



Adapted from Albert+15

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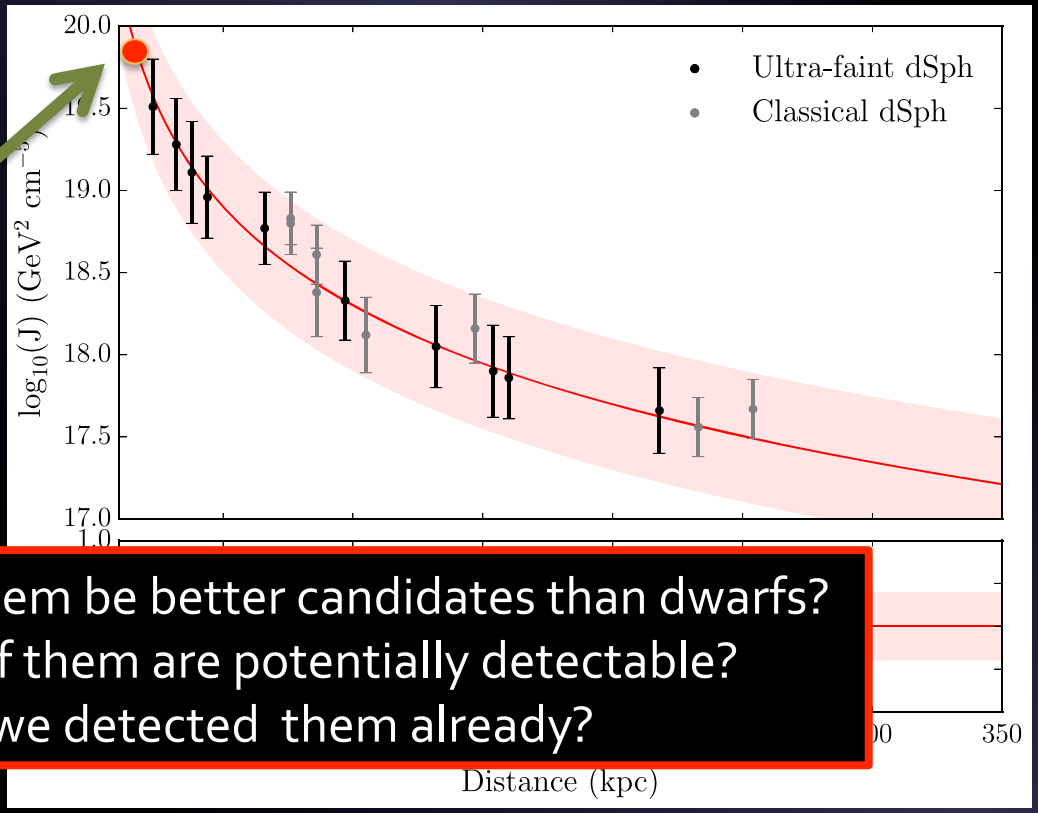

Adapted from Albert+15

Could some of them be better candidates than dwarfs?
How many of them are potentially detectable?
Have we detected them already?

Dark satellites' search in Fermi-LAT catalogs

Around 1/3 of sources in LAT catalogs are unidentified (~1000 unIDs in the 3FGL)

Exciting possibility: some of them may be subhalos annihilating to gammas!

Objective: to build a list of potential DM subhalo candidates by identifying those unIDs compatible with DM subhalo annihilation.

Method:

Apply a series of '*filters*' based on expected DM signal properties.

Most common filters used:

1. Associations
2. Variability
3. Latitude
4. Multiwavelength emission
5. Spectrum
6. Extension

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Results:

1. A few VIP candidates → dedicated LAT analyses, IACT follow-ups…
2. A few more subhalo candidates (yet uncertain) → set DM constraints
3. No unIDs compatible with DM? → best achievable constraints

DM constraints from LAT unIDs?

$$F(E > E_{th}) = J_{factor} * f_{pp}(E > E_{th})$$

Astrophysics (Density profile, distance…)

Particle Physics (channel, annihilation spectra…)

$$\langle \sigma v \rangle \propto \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot \int_{E_{th}}^{E} \left(\frac{dN}{dE}\right) dE} = \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot N_\gamma}$$

Instrument

Theory

Simulations

N-body simulations → dark satellites' J-factors, typical angular sizes, etc.

↓

LAT sensitivity to DM annihilation → number of detectable subhalos.

↓

Number of predicted detectable subhalos VS. number of remaining unIDs in catalogs.

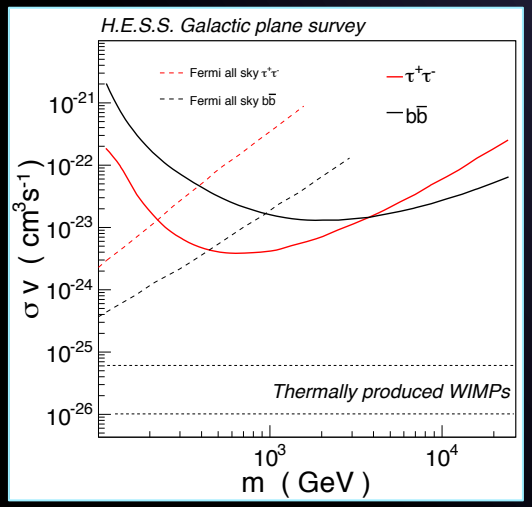
↓

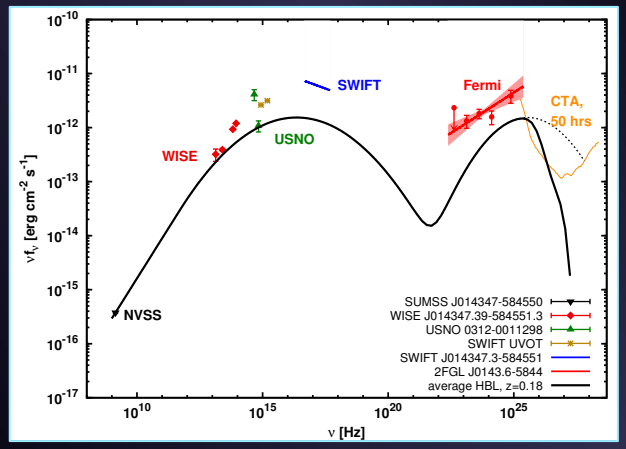
DM CONSTRAINTS

The less DM candidates left in catalogs the better the DM constraints.

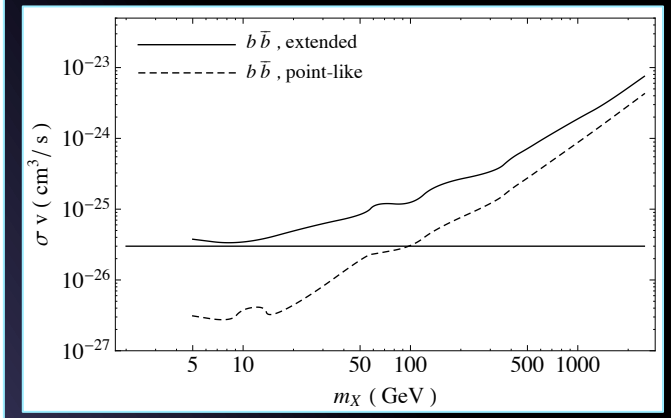
(Some) past work

Brun+11

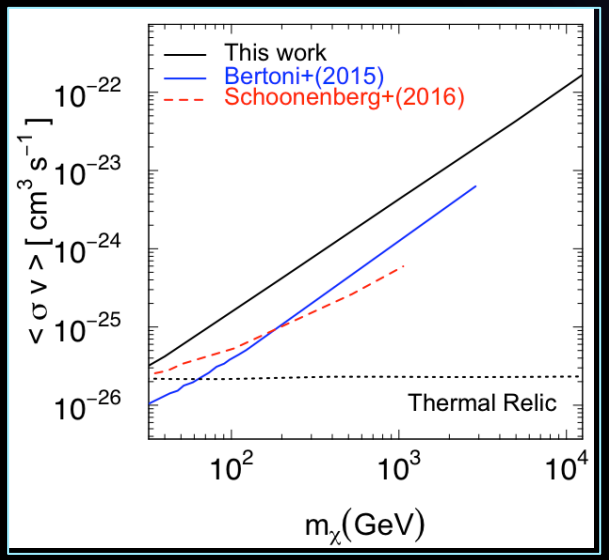




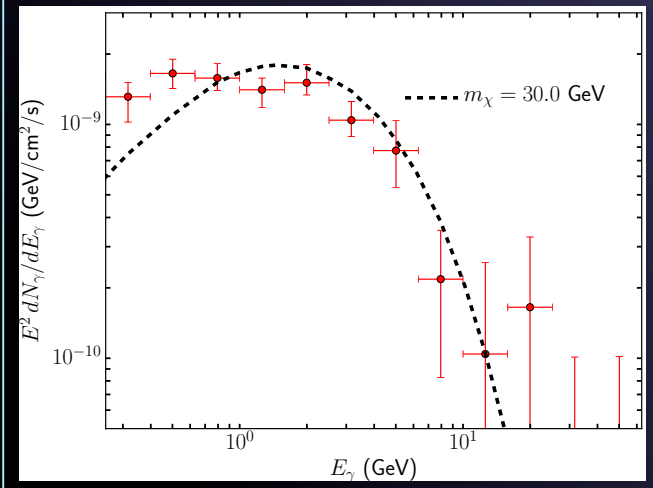
Zechlin+12;+13



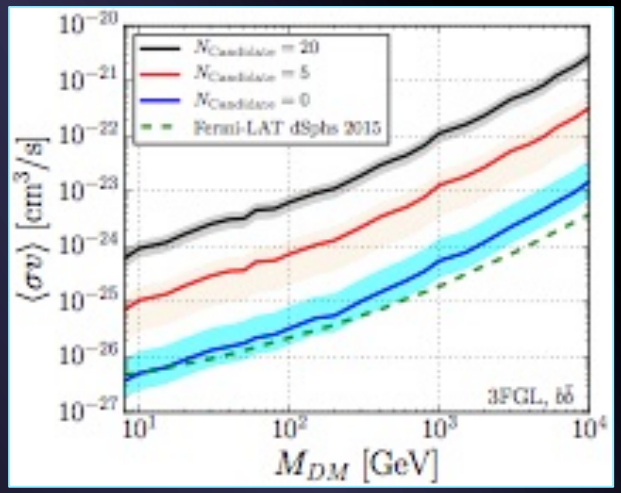
Berlin&Hooper 13



Mirabal+16



Bertoni+16



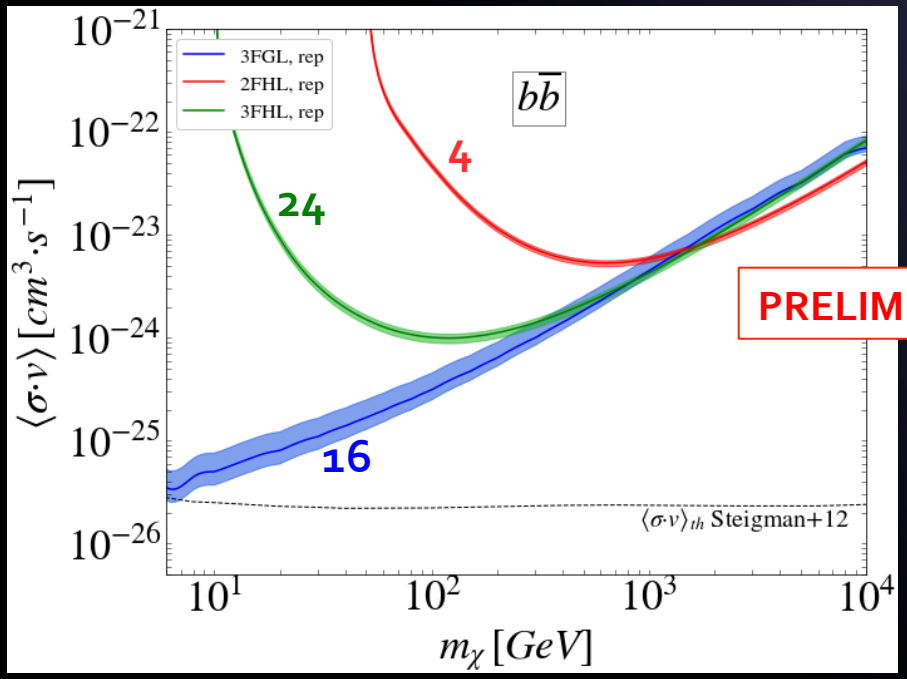
Calore+17

Also: Tasitsiomi&Olinto 02; Pieri+05; Kuhlen+07; Springel+08; Anderson+10; Belikov+12; Ackermann+12; Berlin&Hooper+13; Hooper+16; Schoonenberg+16

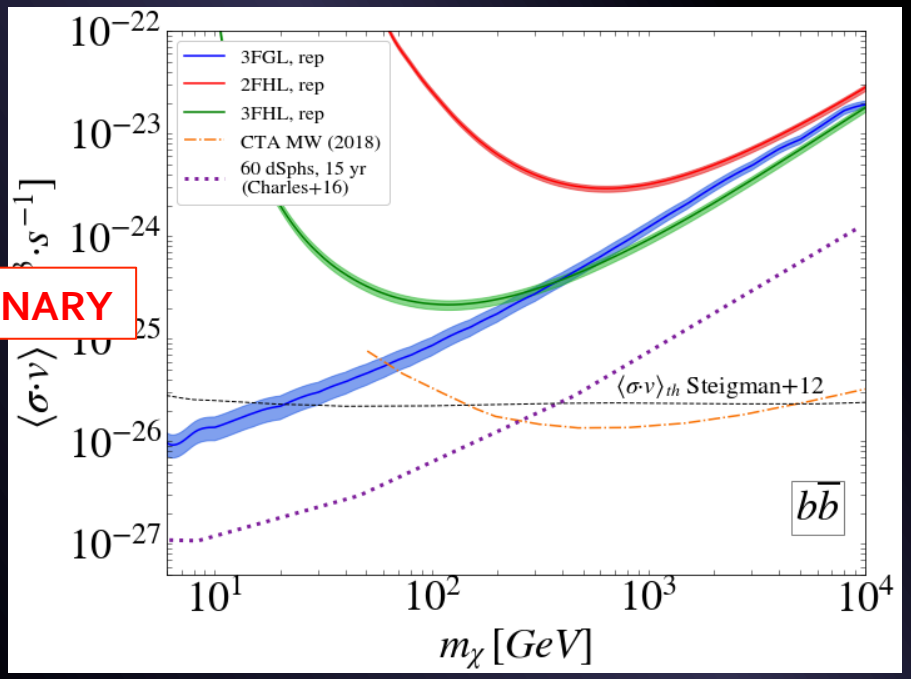
Fermi-LAT work ongoing

[J. Coronado-Blázquez, MASC et al., submitted]

- Search in the most recent LAT catalogs (3FGL, 2FHL, 3FHL)
- Careful unIDs 'filtering' work.
- Precise characterization of LAT sensitivity to DM annihilation.
- Best knowledge of subhalos' structural properties (MASC&Prada14, Moliné+17)
- Repopulation of VL-II N-body simulation below its resolution limit.



PRELIMINARY



Most realistic constraints

Maximum potential (1 subhalo)

(Another) Fermi-LAT work ongoing

[J. Coronado-Blázquez, MASC et al., in prep.]

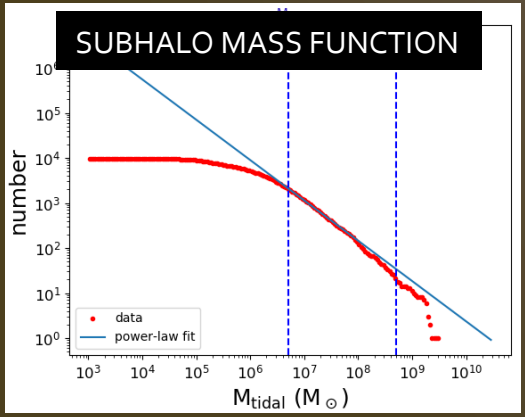
- Remaining DM subhalo candidates scrutinized in further detail:
  - Dedicated LAT **spectral** analysis
  - Dedicated LAT **spatial** analysis
- New (shorter) DM subhalo candidate list.

  → Updated, more stringent DM constraints.
- Currently under LAT internal refereeing; public results soon…

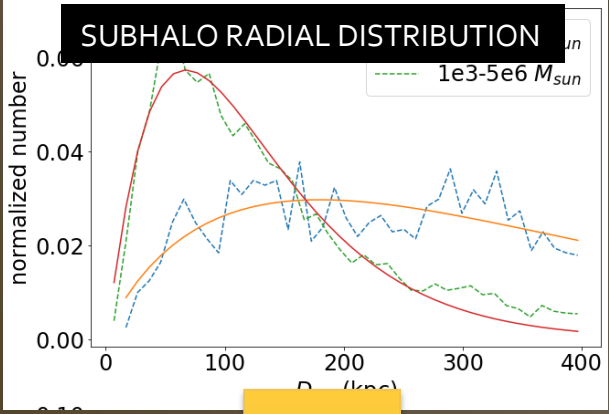
Ongoing N-body simulation work

[A. Aguirre-Santaella, MASC, et al., in prep.]

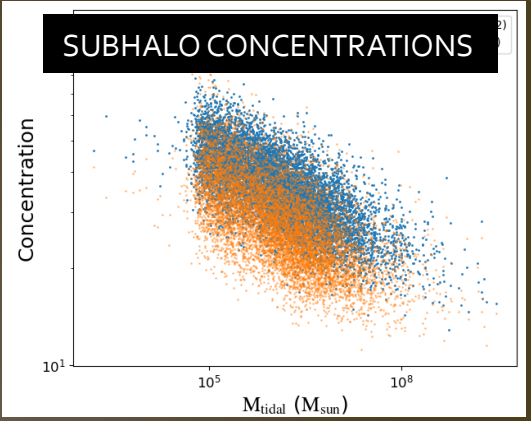
SUBHALO MASS FUNCTION

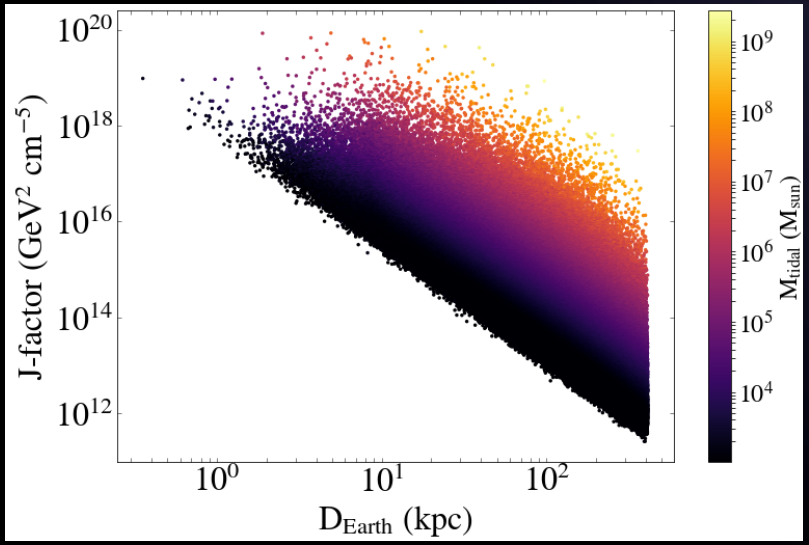


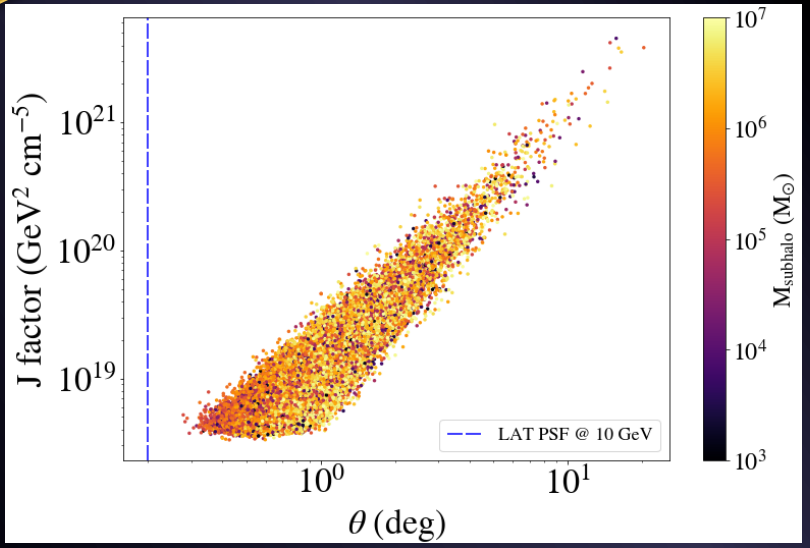
SUBHALO RADIAL DISTRIBUTION



SUBHALO CONCENTRATIONS







Some OPEN ISSUES on subhalo population

(most relevant for gamma-ray searches)

- Precise subhalo structural properties.
- Subhalo survival (to tidal stripping; baryons; dynamical friction).
- Role of baryons on:
  - Subhalo abundance.
  - Subhalo structure.
- Dependence of all the above on distance to host halo center and mass.

ONGOING WORK @ IFT

Remarks

- Halo substructure very relevant for dark matter searches.
  - Most massive subhalos (dwarf galaxies) the best targets for indirect DM detection.
  - Less massive subhalos, with no optical counterparts, can be used to set very competitive constraints.
  - Subhalos can significantly *boost* the annihilation signal from halos and alter the DM signal spatial properties.
- 'Dark satellites' gamma-ray searches:
  - Current constraints close to the ones from dwarfs.
  - Sensitivity reach can rule out thermal cross section up to few tens of GeV WIMP masses.
- New N-body simulation work needed to address current issues.

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