THE SEARCH OF DARK SATELLITES WITH GAMMA RAYS

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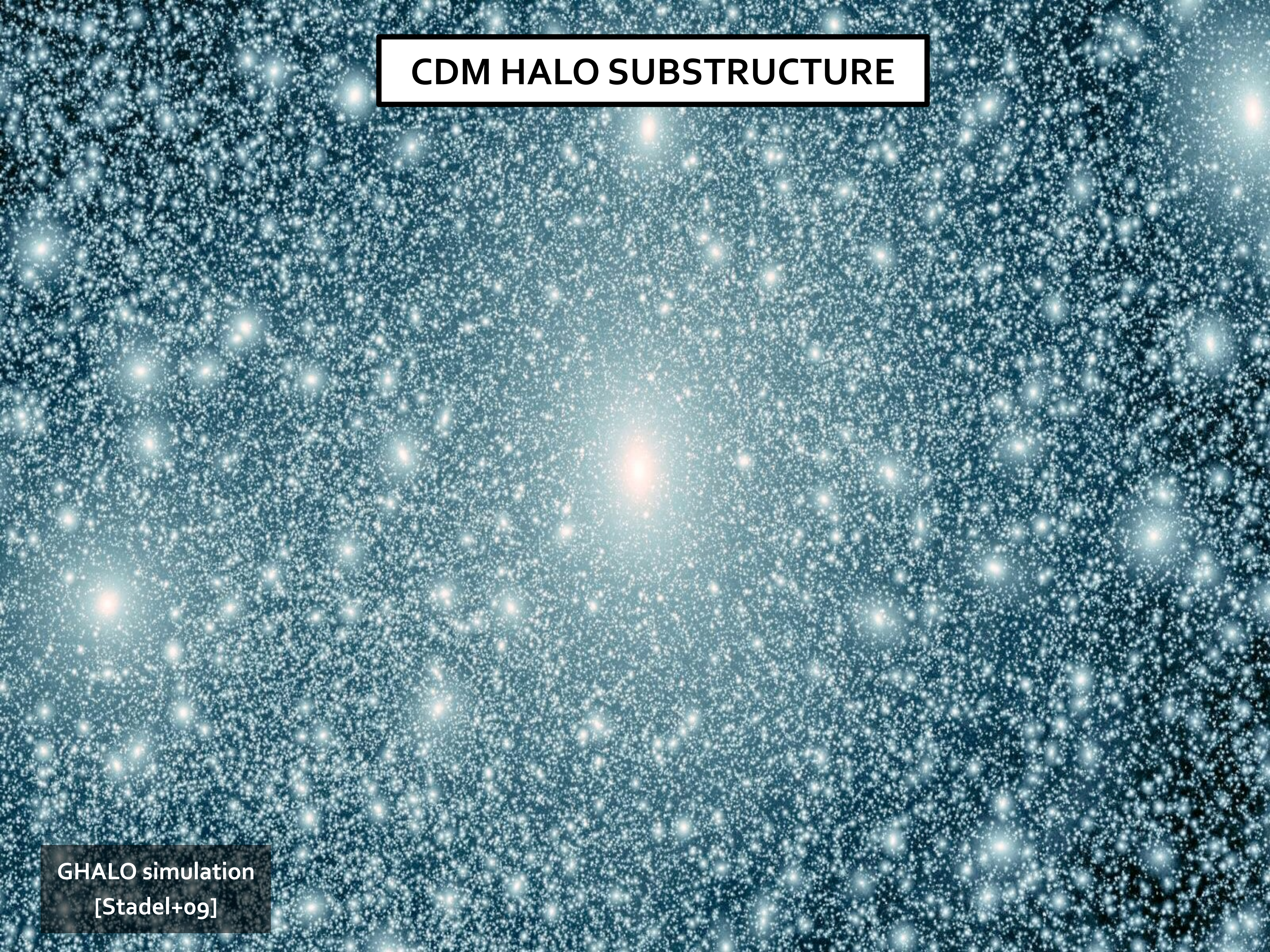
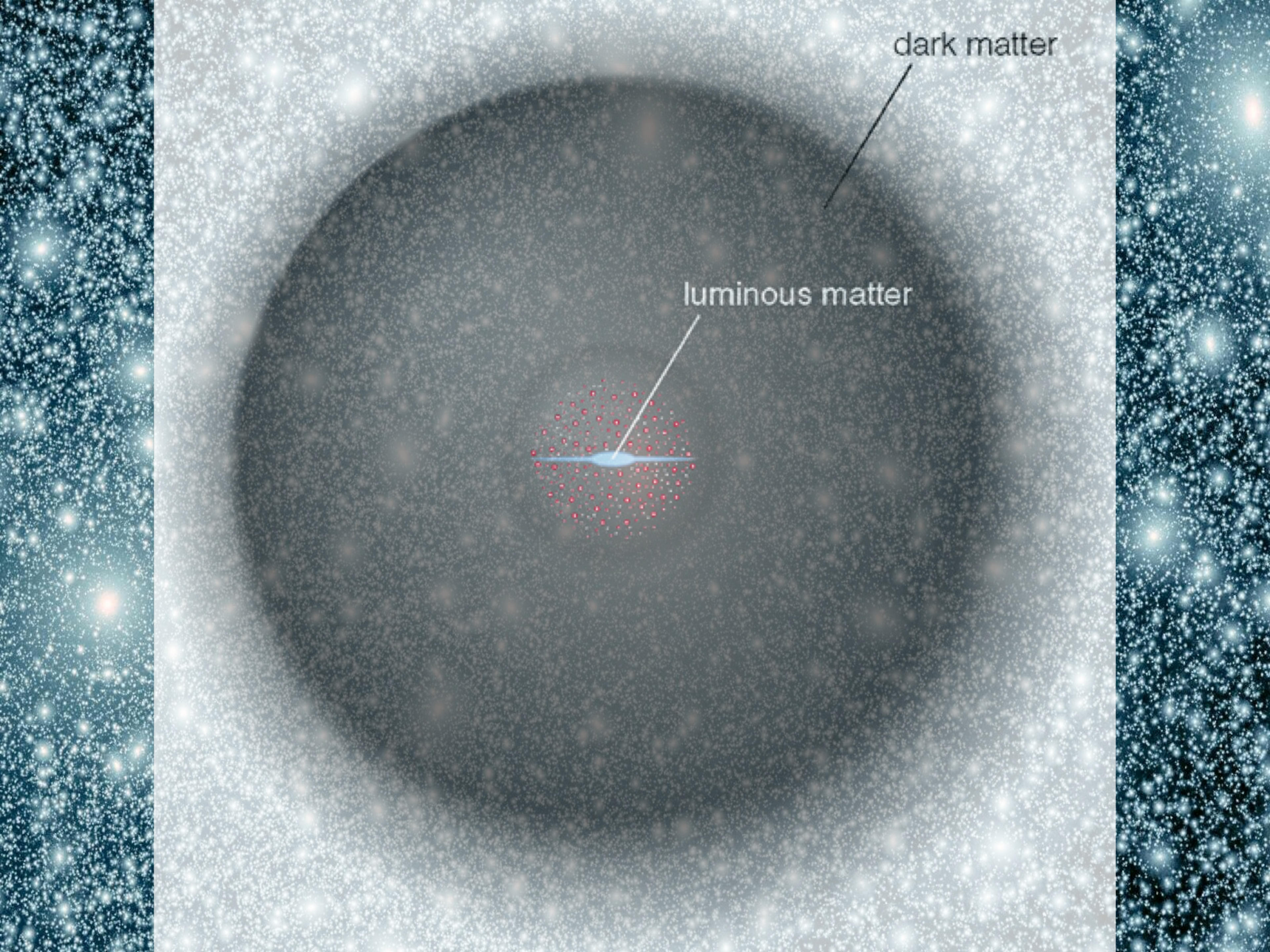
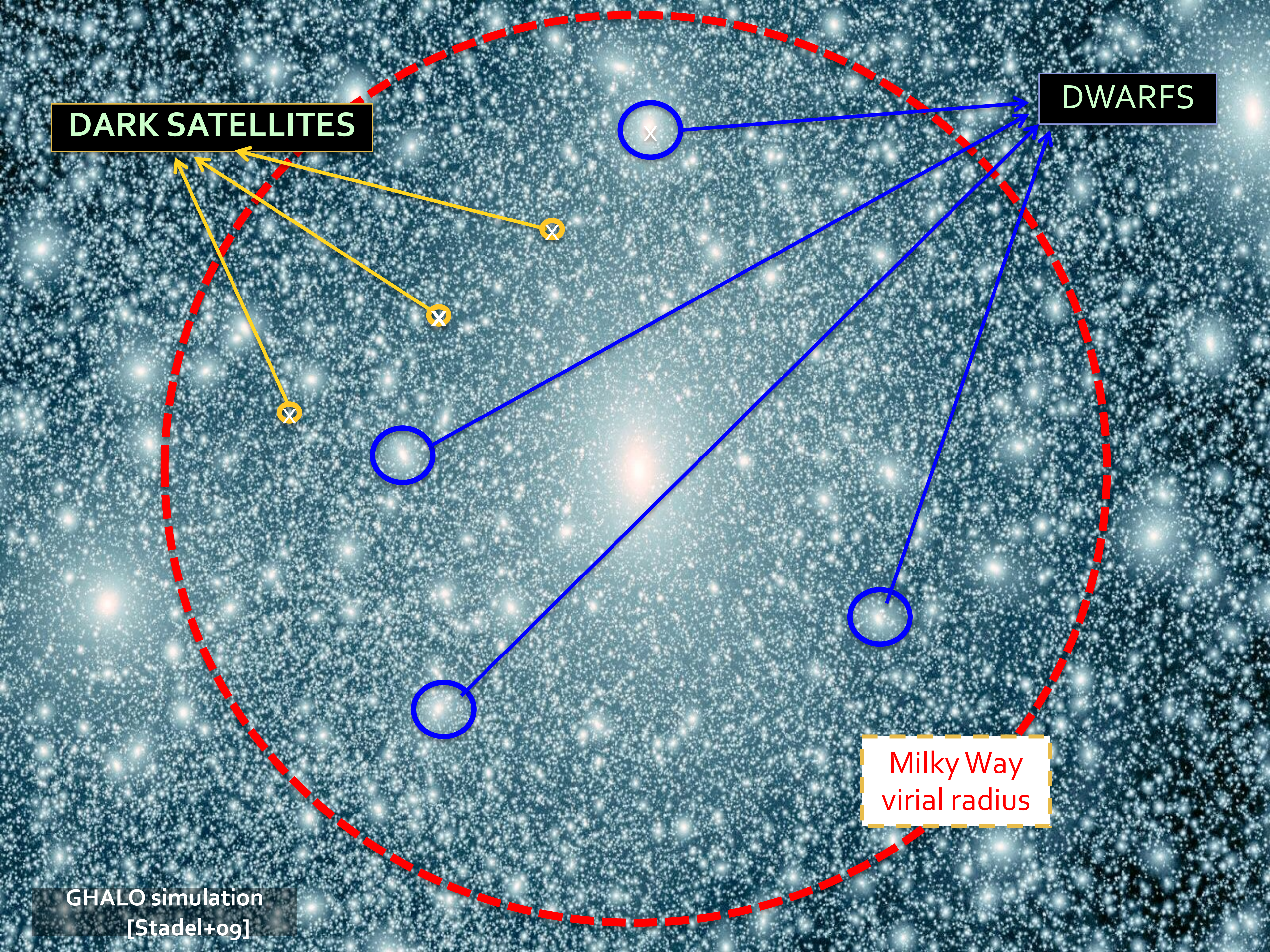
Credit: Lovell+12

CDM HALO SUBSTRUCTURE



GHALO simulation
[Stadel+09]


dark matter
luminous matter

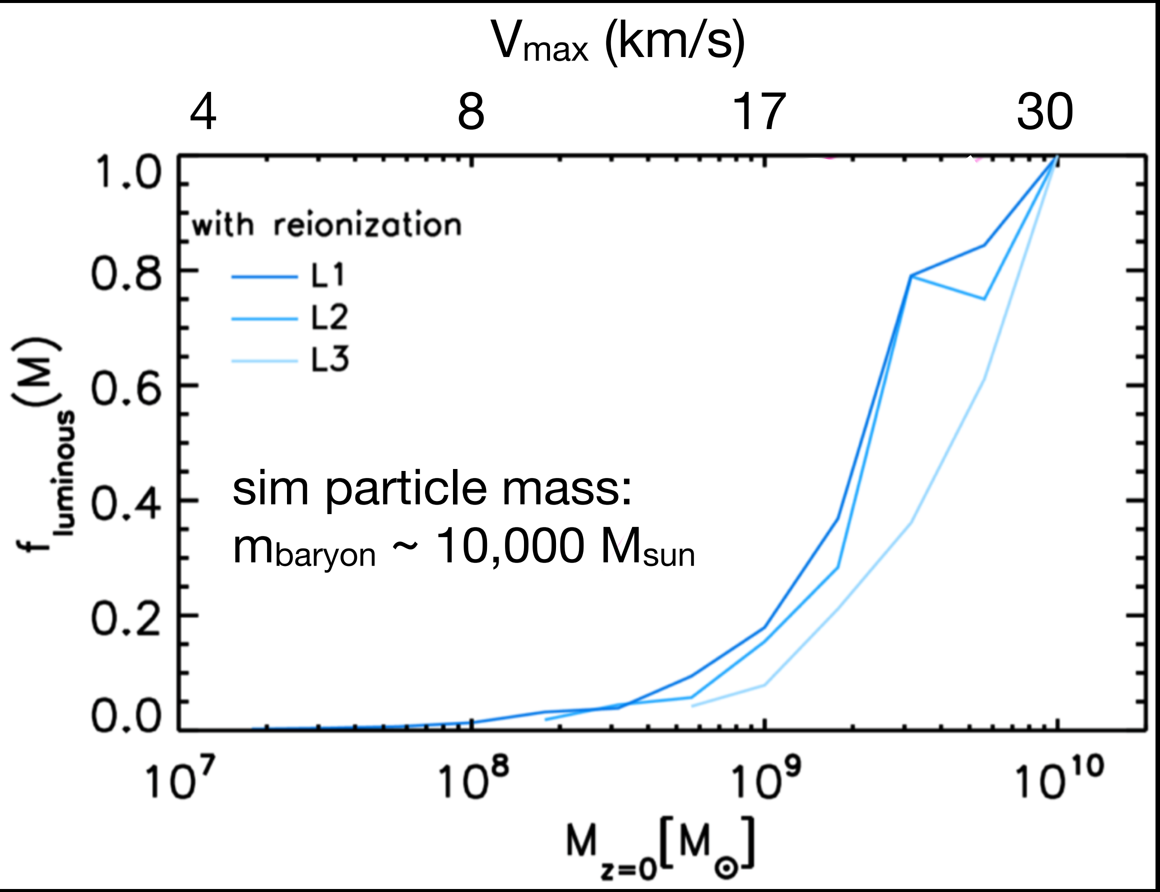


DARK SATELLITES
DWARFS
Milky Way virial radius
GHALO simulation [Stadel+09]

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

The most massive subhalos will host visible satellite galaxies

Light subhalos expected to remain completely dark.



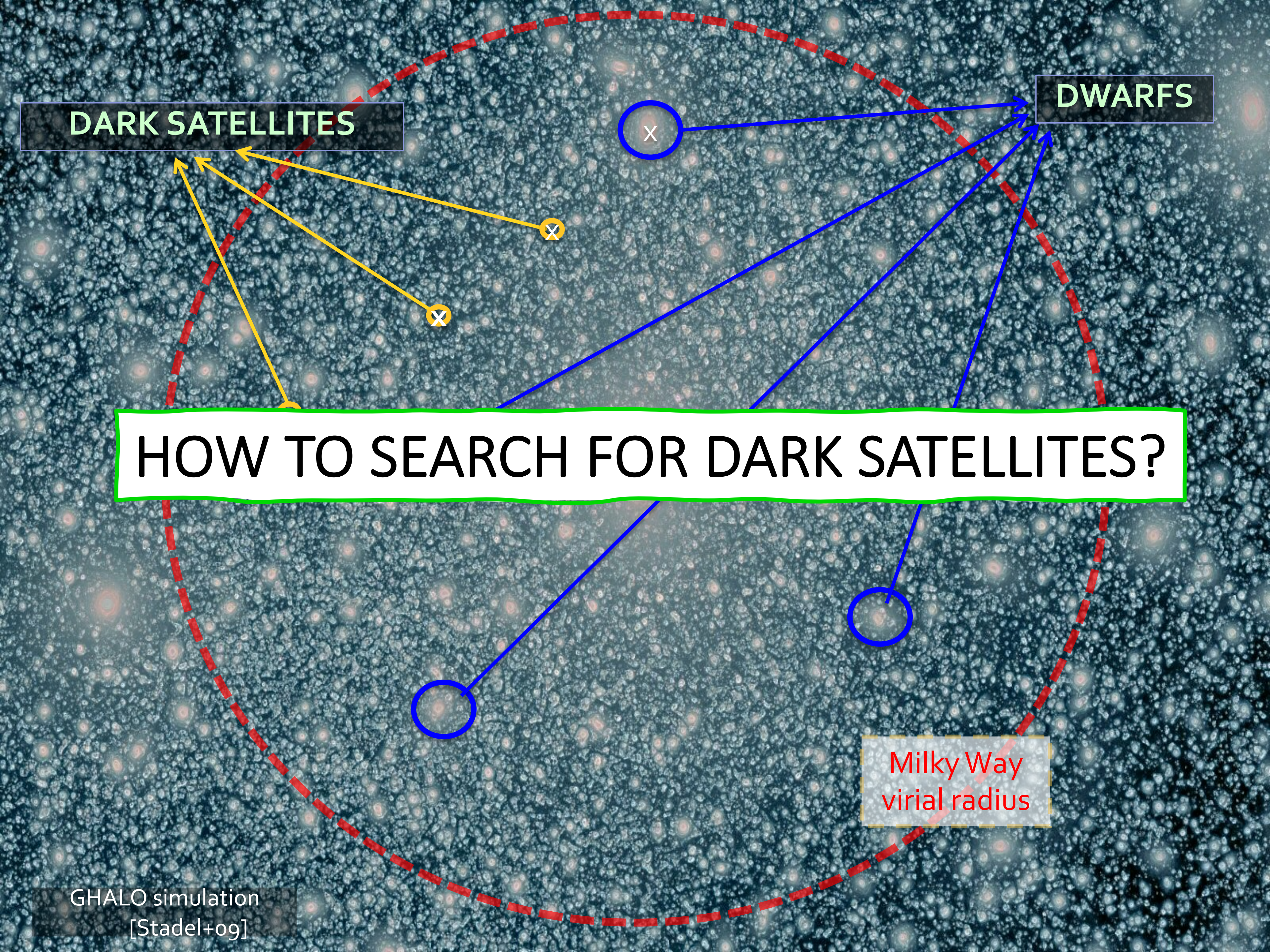
[Sawala+15]

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

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

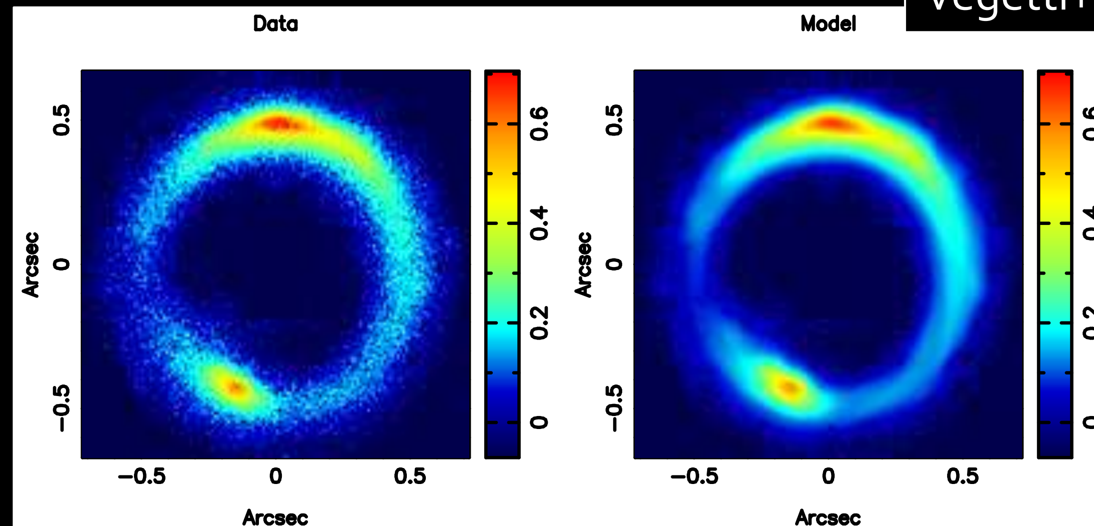
→ dark subhalos < 10^7 M_{sun}

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


DARK SATELLITES
DWARFS
HOW TO SEARCH FOR DARK SATELLITES?
Milky Way
virial radius
GHALO simulation
[Stadel+09]

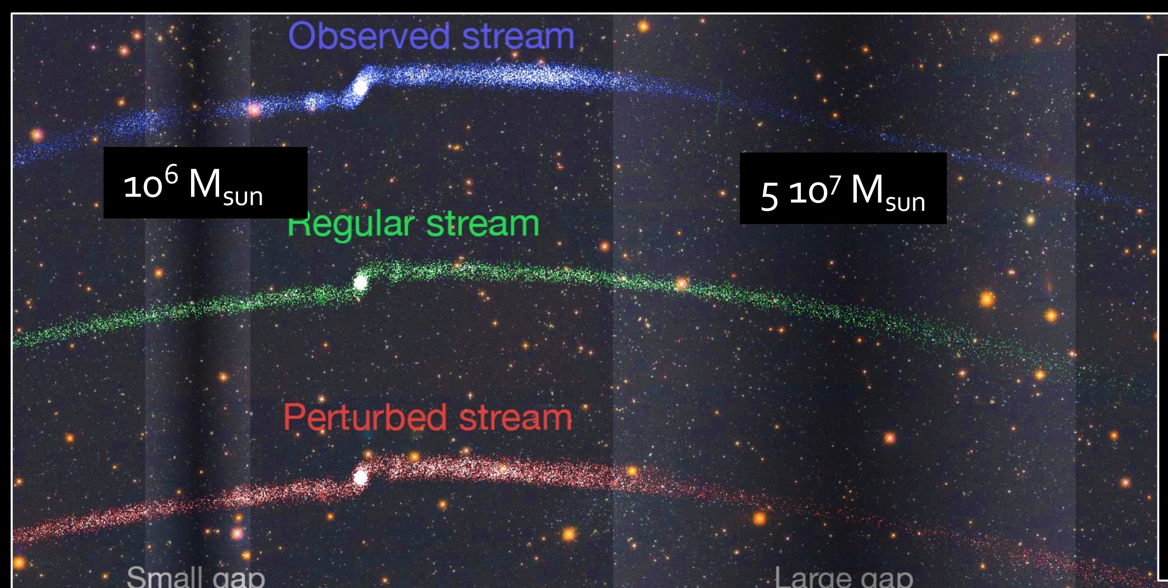
Dark satellite searches

Vegetti+12



I. (Strong) LENSING

[Vegetti+10,12,18;
Hezaveh+16;
Nierenberg+14,17;
Birrer+17;
Alexander+19; Varma+20;
Meneghetti+20]



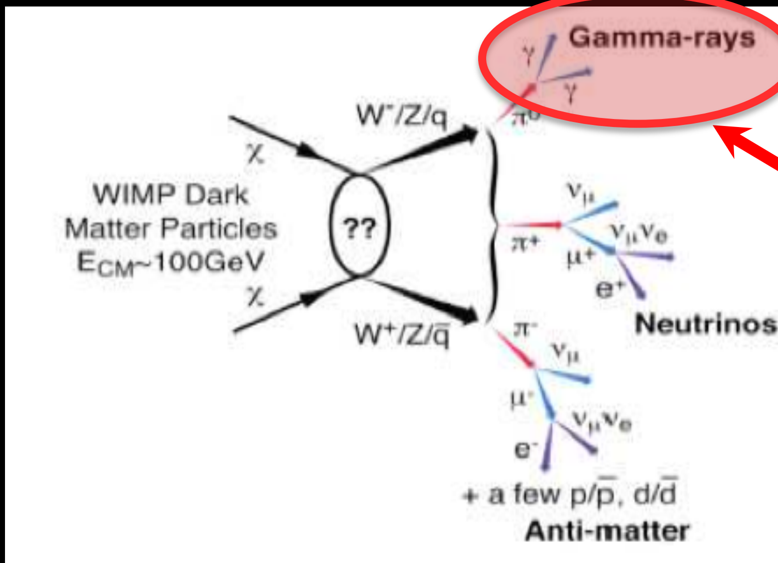
V. Belokurov, D. Erkal, S.E. Koposov

II. STELLAR GAPS

[Carlberg 12,15;
Erkal+15, 16, 17;
Price-Whelan+18
Boer+18; Banik+19;
Bonaca+19; Malhan+19]

DARK SATELLITE SEARCHES:
III. GAMMA RAYS

If dark matter (DM) is made of WIMPs → subhalo annihilates → gamma rays



GAMMA RAYS the 'golden' channel

Fermi LAT
[>2008]

MAGIC
[>2003]

HESS
[>2002]

VERITAS
[>2006]

HAWC
[>2015]

DARK SATELLITE SEARCHES:
III. GAMMA RAYS

- If DM is made of WIMPs → subhalo annihilates → gamma rays
- Some dark satellites could be bright enough in gamma rays to be detected.
- Maybe the only way to probe subhalo masses below ~10^7 solar masses

  → critical to differentiate CDM from e.g. WDM cosmology.
- The only subhalo search that provides info on the nature of the DM particle.

Dark satellite search with gammas: general methodology

Around 1/3 of sources in gamma-ray catalogs are unidentified (unIDs)
(e.g., ~1700 unIDs in the latest '4FGL-DR2' Fermi-LAT catalog)

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

Search for potential DM subhalo candidates by identifying those unIDs compatible with DM subhalo annihilation.

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

Possible results:

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

DM constraints from gamma-ray unID sources?

VS.

dark subhalo J-factors, number density, spatial extension…

instrument sensitivity to DM annihilation, pool of unID sources

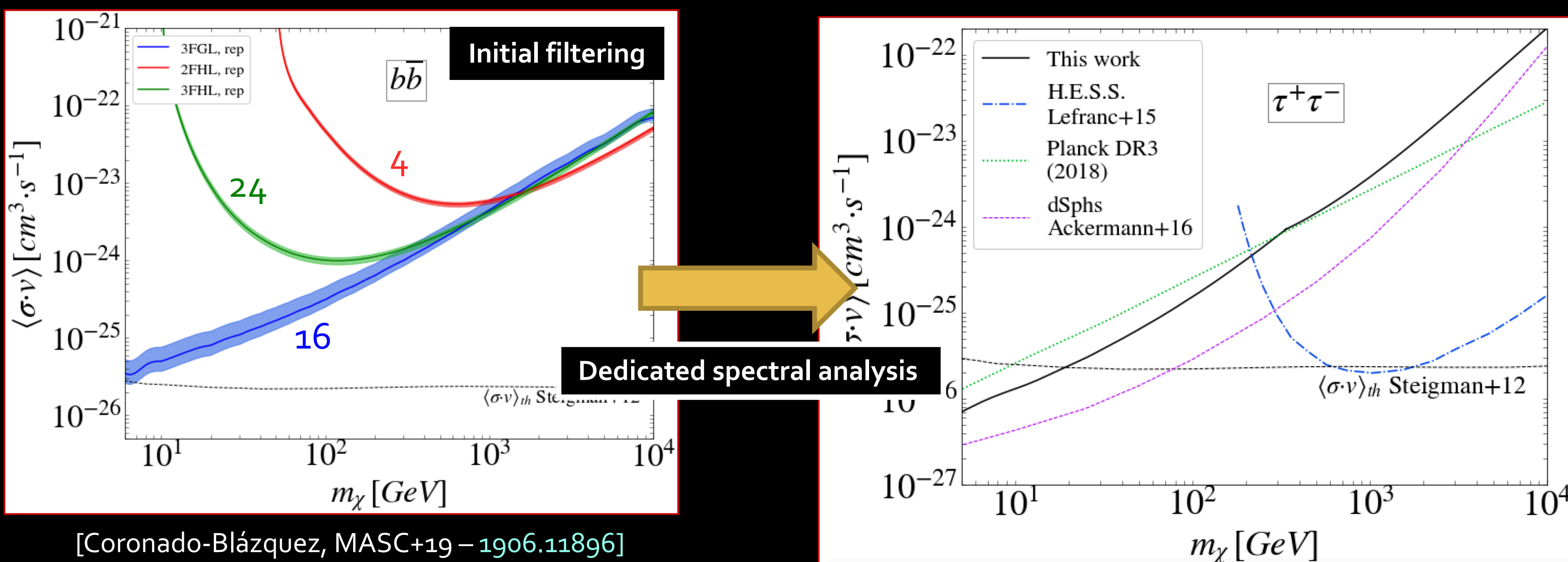
Number of predicted detectable subhalos VS. number of unIDs compatible with DM

DM CONSTRAINTS

[The less DM candidates among unIDs the better the constraints]

Latest search in Fermi-LAT catalogs (I)

- List of O(10) VIP candidates in the 2FGL+2FHL+ 3FGL Fermi LAT catalogs.
- Dedicated **spectral analysis** of best DM subhalo candidates → improved constraints
- DM limits competitive with other targets, reach thermal cross section.
- 4FGL search ongoing (MASC+, in prep.)



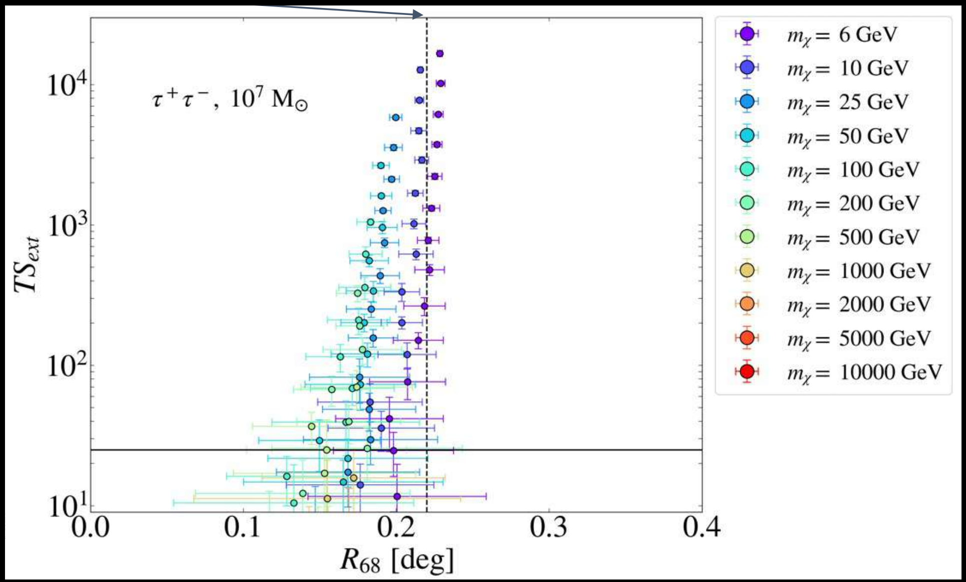
[Coronado-Blázquez, MASC+19 – 1906.11896]

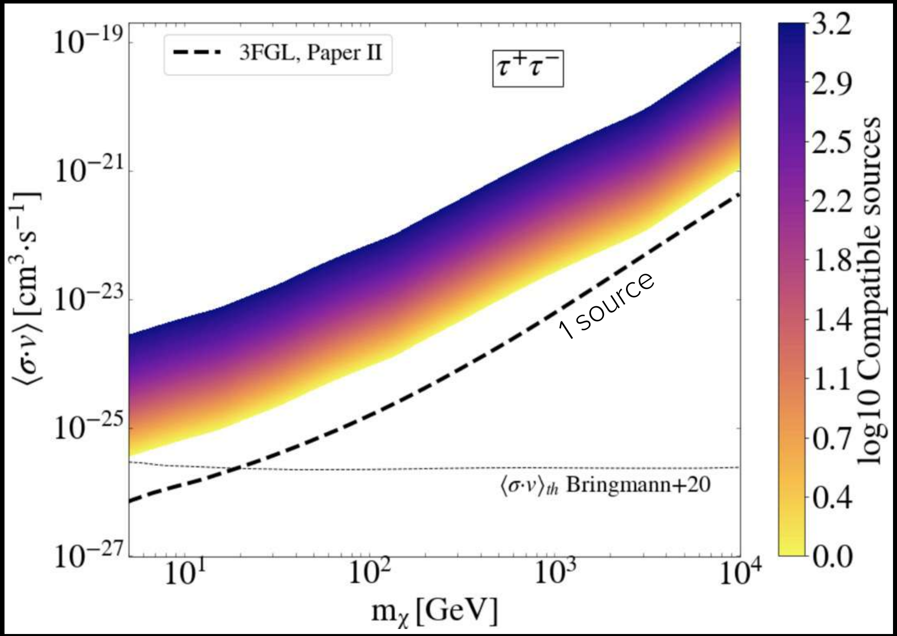
[Coronado-Blázquez, MASC+19b – 1910.14429]

Also: Tasitsiomi&Olinto 02; Pieri+05; Kuhlen+07; Springel+08; Anderson+10; Brun+11; Belikov+12; Ackermann+12; Zechlin+12;+13; Berlin&Hooper 13; Mirabal+16; Hooper+16; Bertoni+16; Schoonenberg+16; Calore+17; Abeysekara+19

Latest search in Fermi-LAT catalogs (II)

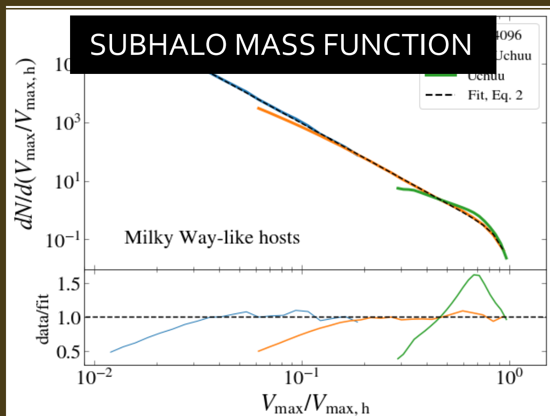
- Study of the **spatial properties** of the expected DM-induced gamma-ray emission and of the implications for Fermi-LAT detectability and DM constraints.
  - Realistic LAT simulations of ‘typical’ (extended) subhalos
  - Careful spatial analysis of O(100) VIP candidates.
- Fermi should tipically detect a subhalo extension **O(0.2 - 0.3 degrees)**
- More robust/realistic DM constraints, but weaker than previous ones by a factor 2-3.

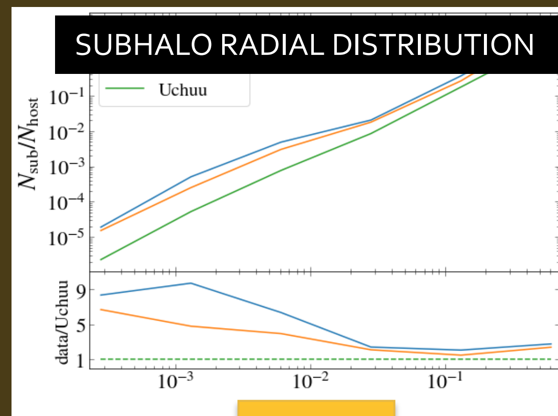


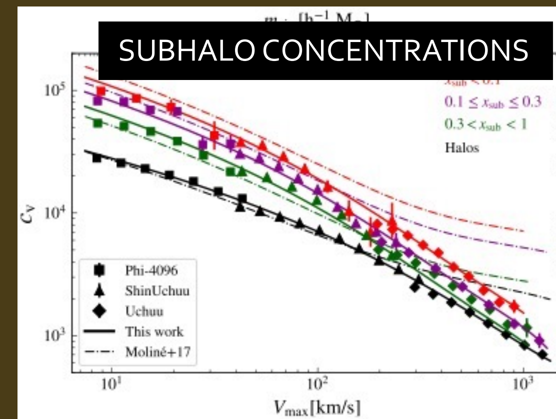


[J. Coronado-Blázquez, MASC, A. Aguirre-Santaella, J. Pérez-Romero; 2204.00267]

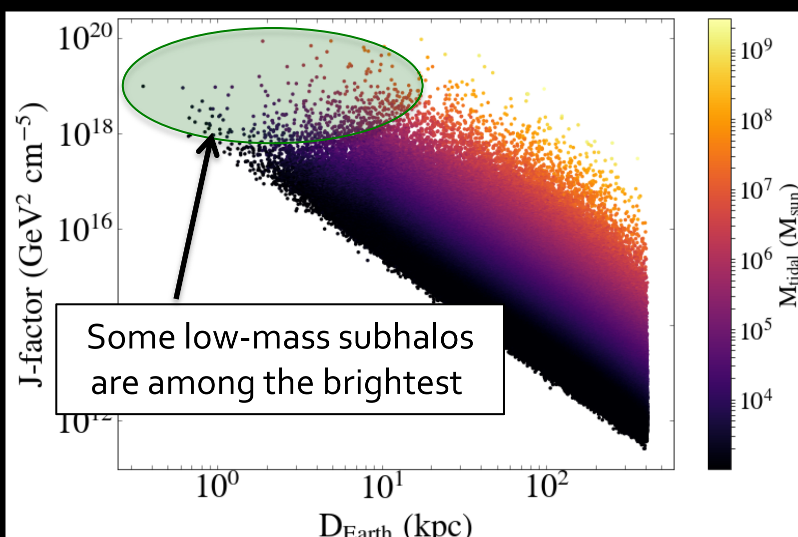
Numerical simulation work is critical

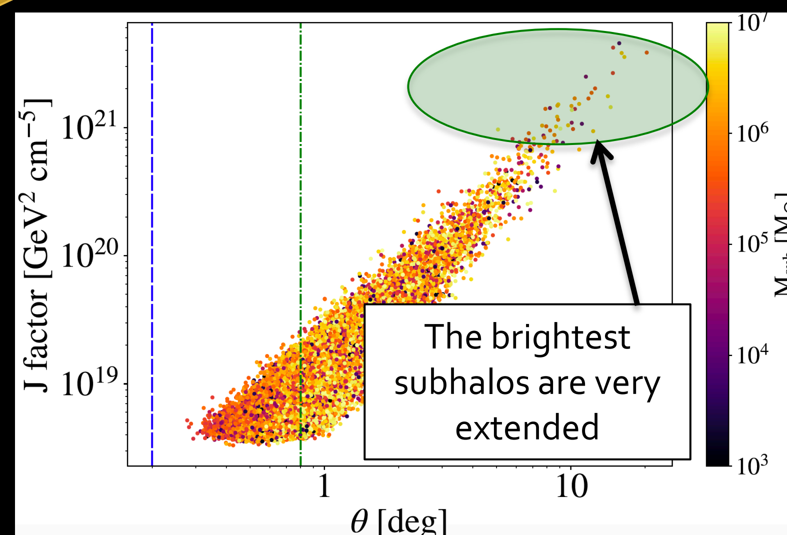






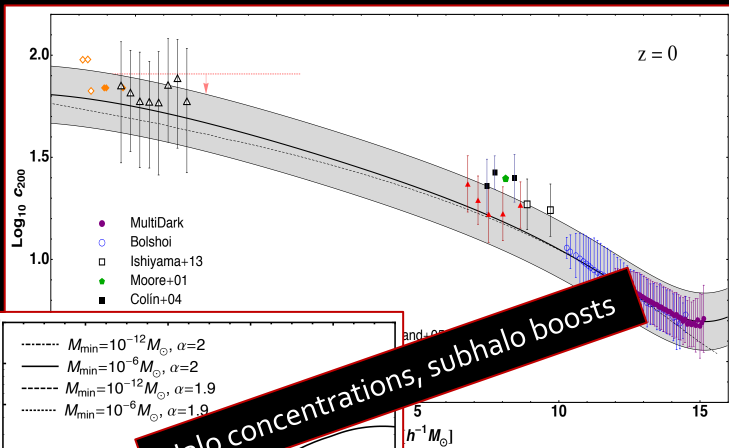
[Moliné, MASC, Aguirre-Santaella et al., 2110.02097]

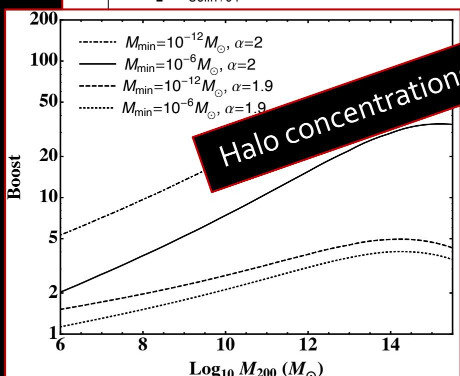




[Coronado-Blázquez, MASC+19] – [Aguirre-Santaella, MASC+, in prep.]

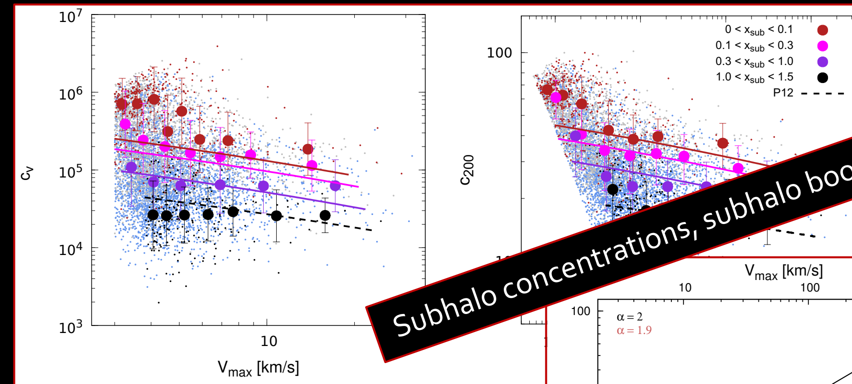
A lot of work done so far…





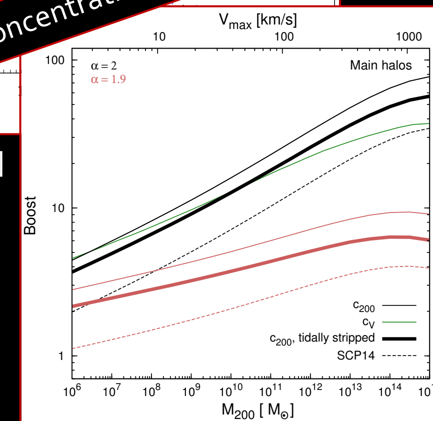
Halo concentrations, subhalo boosts

[MASC & Prada 2014]

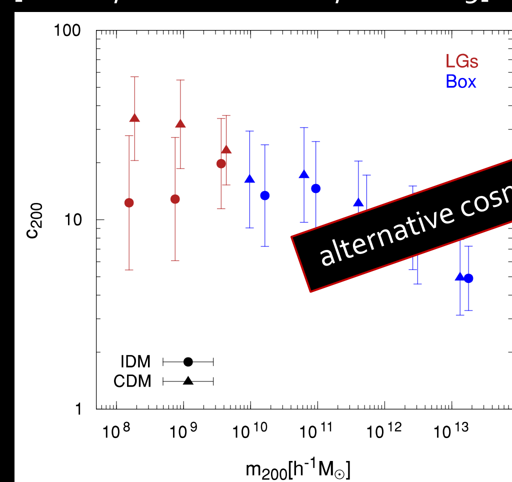


Subhalo concentrations, subhalo boosts

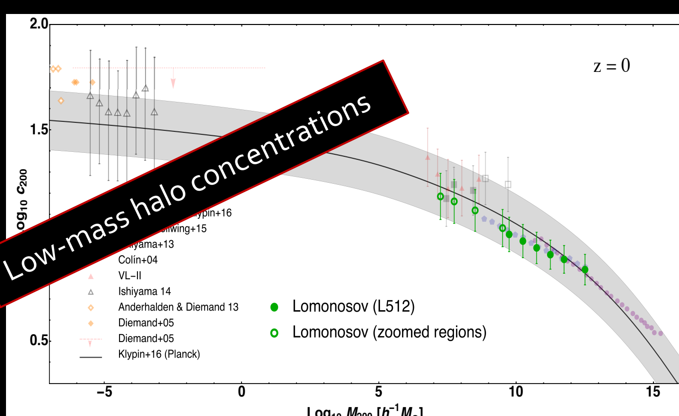
[Moliné, MASC+17]



[Moliné, Schetwschenko, MASC+19]



alternative cosmologies



Low-mass halo concentrations

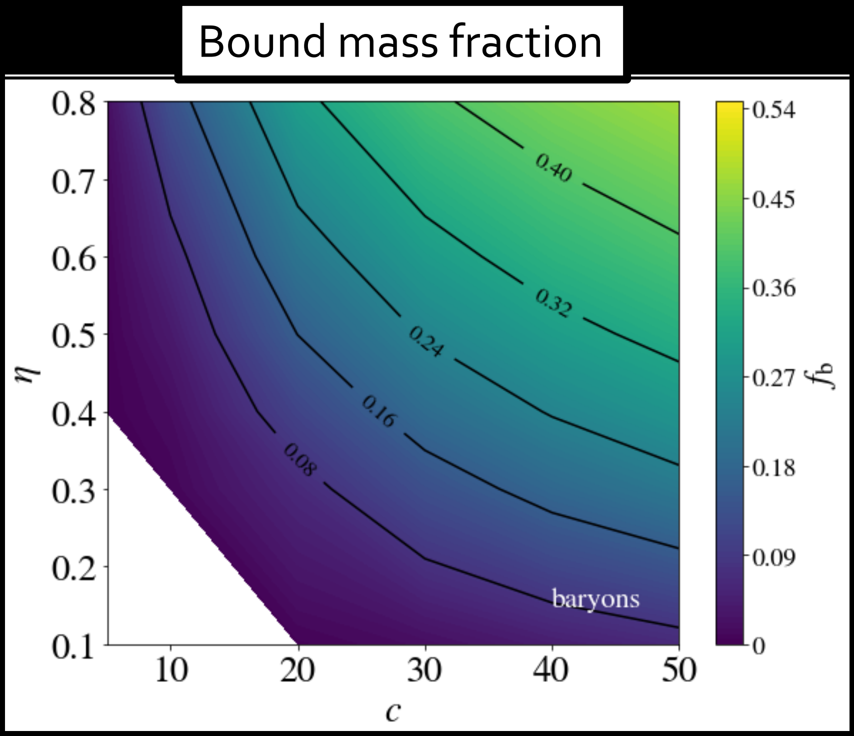
[Pilipenko, MASC+17]

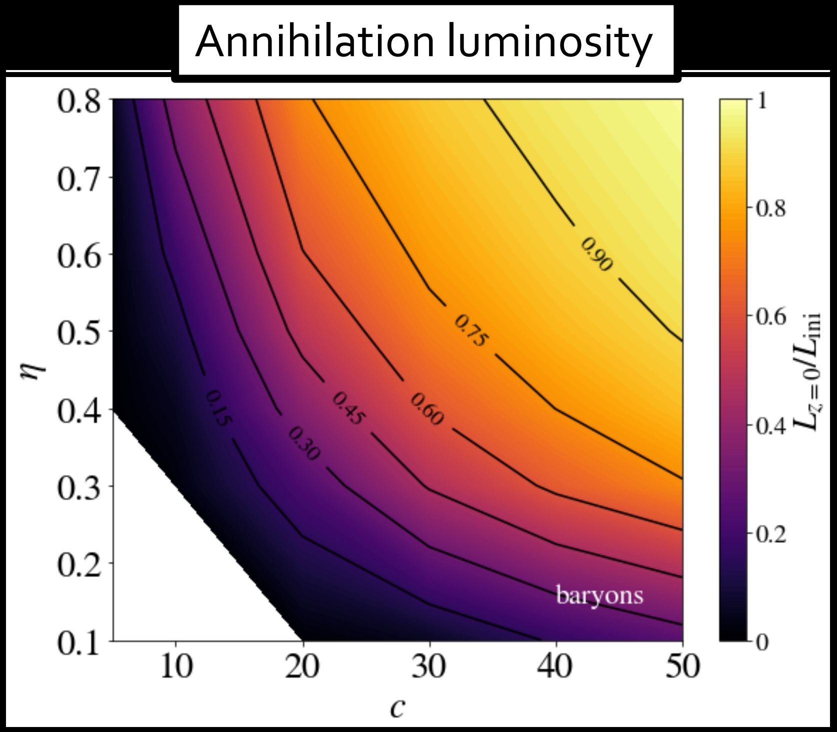
… but further work needed and ongoing

Recent insight into subhalo survival

[Aguirre-Santaella, MASC, Angulo, Ogiya, Stücker, astro-ph/2207.08652]

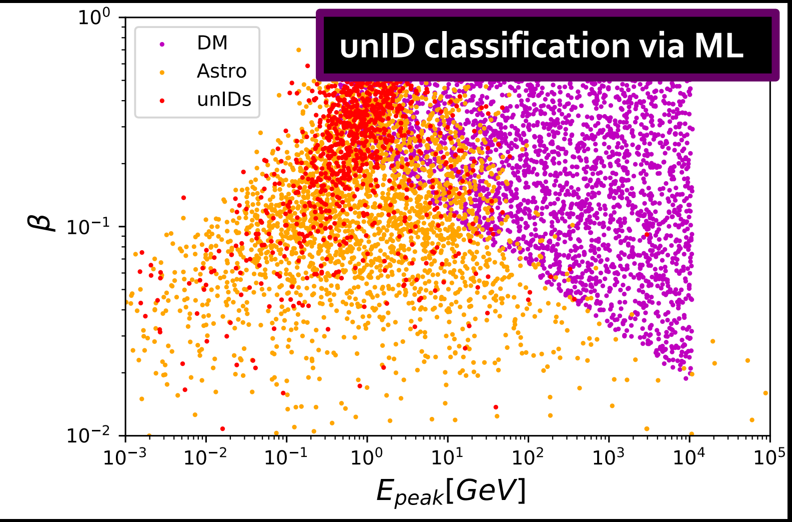
- High-res numerical simulations of subhalos falling into a Milky-Way-size halo analytical potential.
- Improved version of the DASH code (Ogiya+19).
- Galactic potential includes baryonic components (gas, stars, bulge).
- Goal is to understand subhalo mass loss and implications for dark satellites' search.



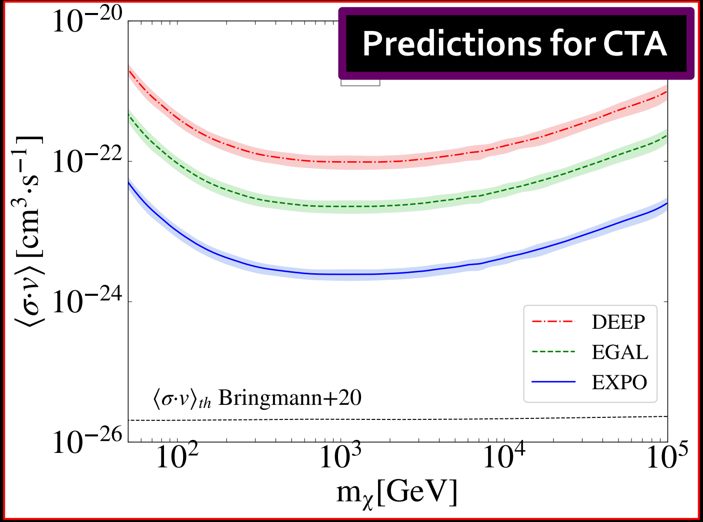


Future of dark satellite search in γ rays

- Dedicated observing proposals at other wavelengths for VIP candidates.
- More refined spectral/spatial unID ‘filters’ and data analyses.
- Search in upcoming gamma-ray catalogs.
- Further numerical work to refine predictions and constraints.
- Use of new techniques (e.g., Machine Learning) to disentangle true source type.
- Use of future gamma-ray facilities (CTA, AMEGO, e-ASTROGRAM...)



Gammaldi et al. [2207.09307]



Coronado-Blázquez et al. [2101.10003]

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Thanks!

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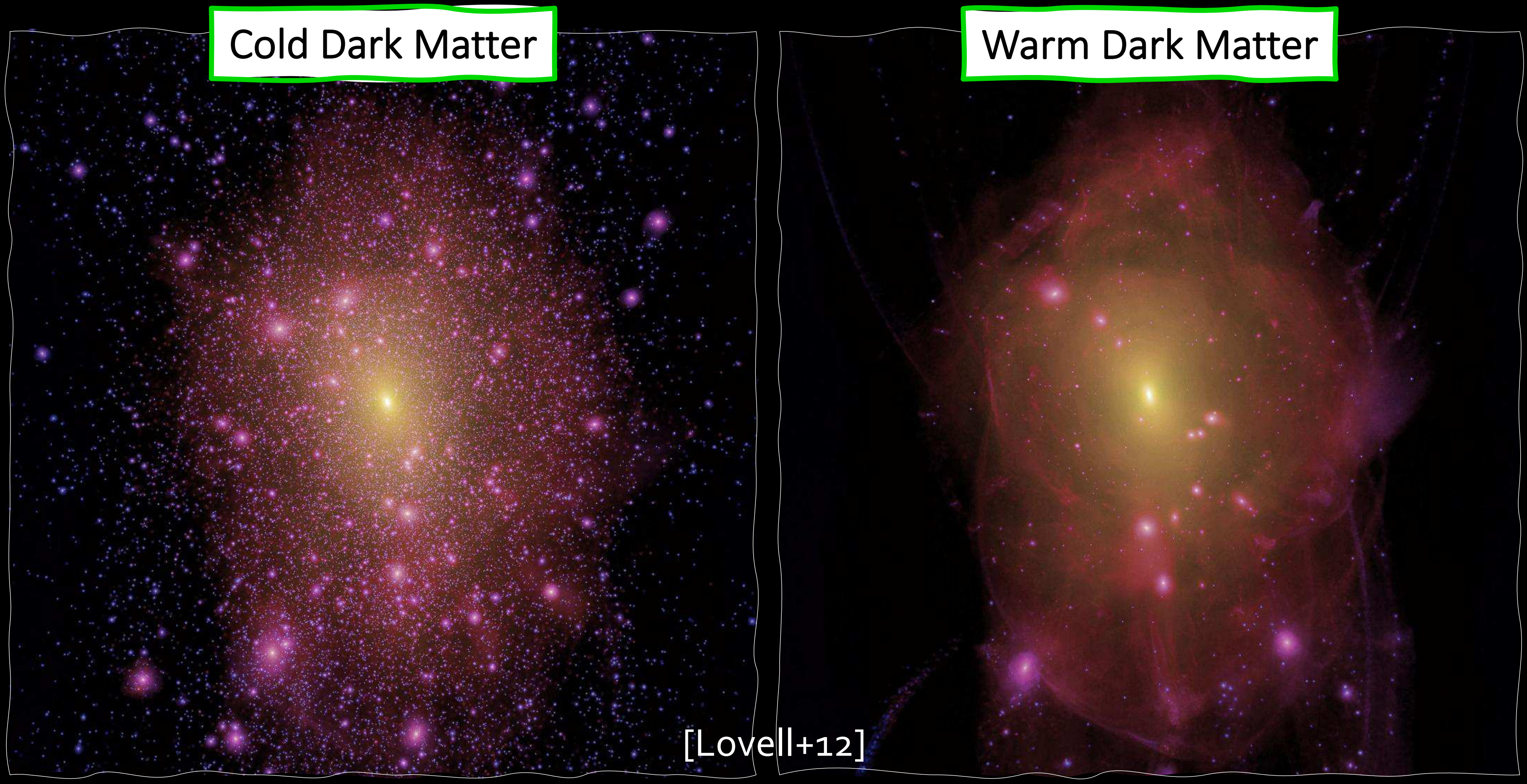
https://projects.ift.uam-csic.es/damasco/

Daniel López / IAC

ADDITIONAL MATERIAL

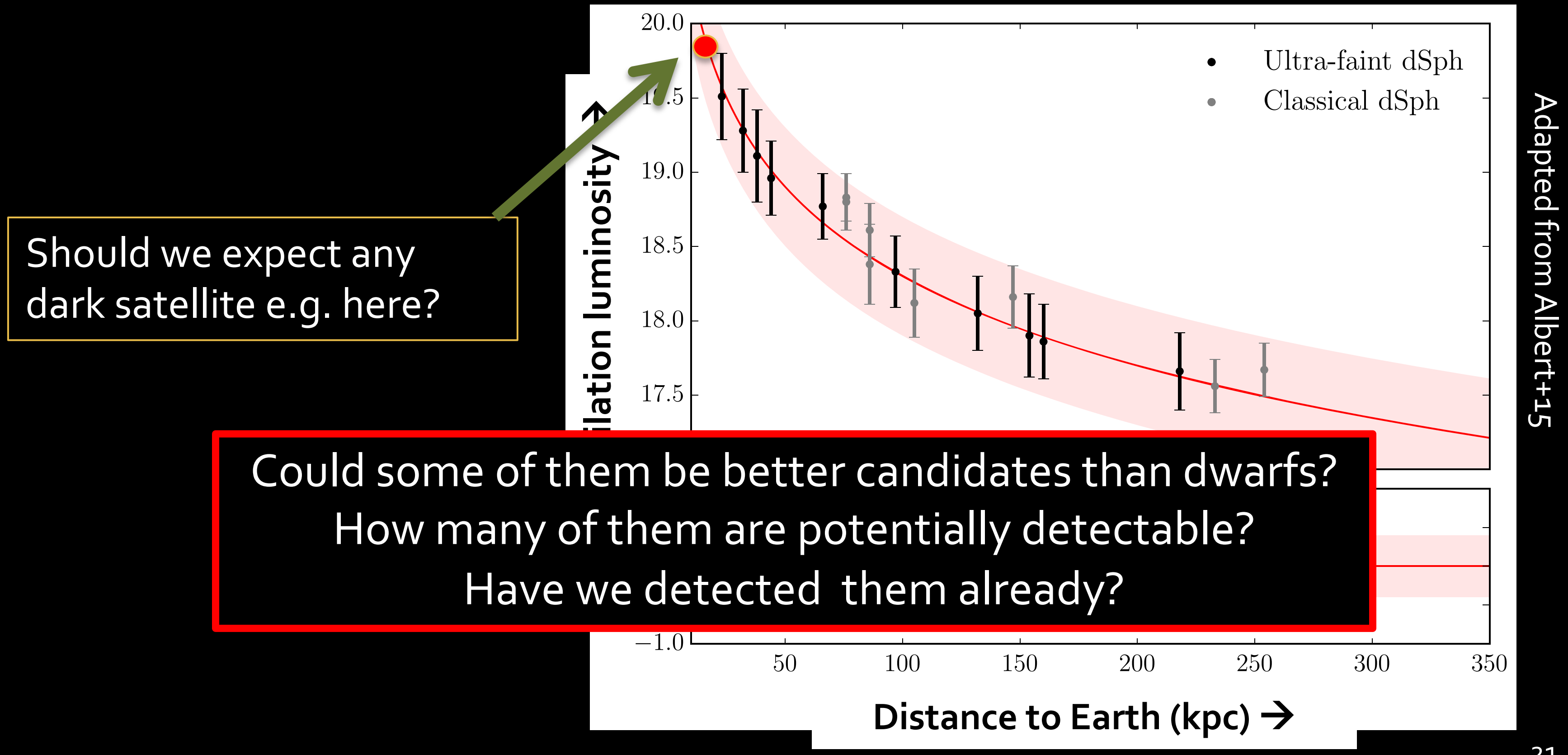
Subhalos as a test of the cosmological model



Substructure abundance very similar in both cases above ~10^8 M_{sun}
Below, differences should be significant → **cosmological test**

DARK SATELLITE SEARCHES:
III. GAMMA RAYS

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



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.

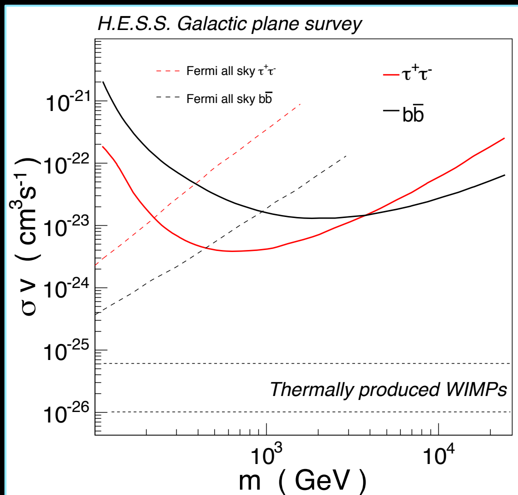
Number of predicted detectable subhalos VS. number of remaining unIDs in catalogs.

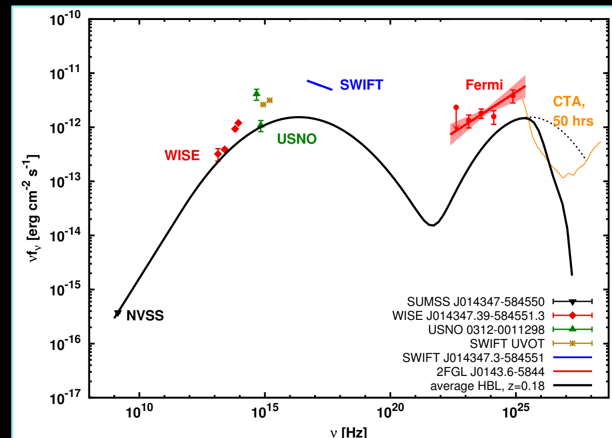
DM CONSTRAINTS

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

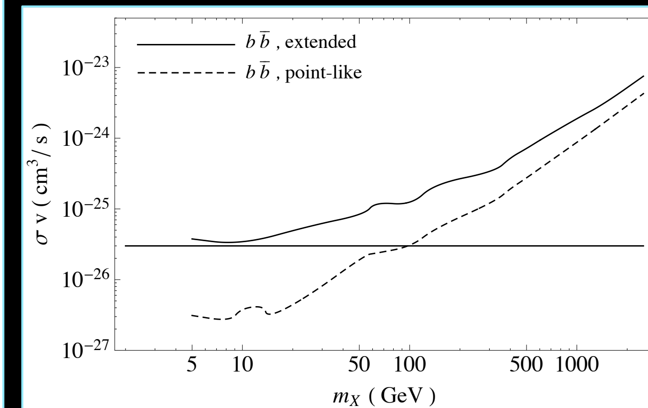
(Some) past work

Brun+11

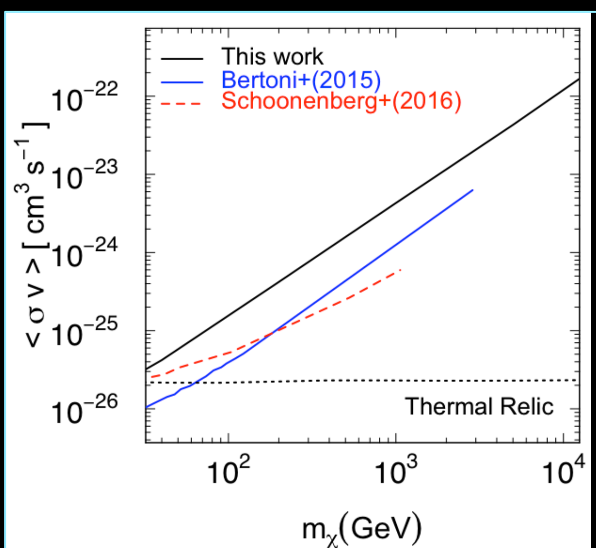




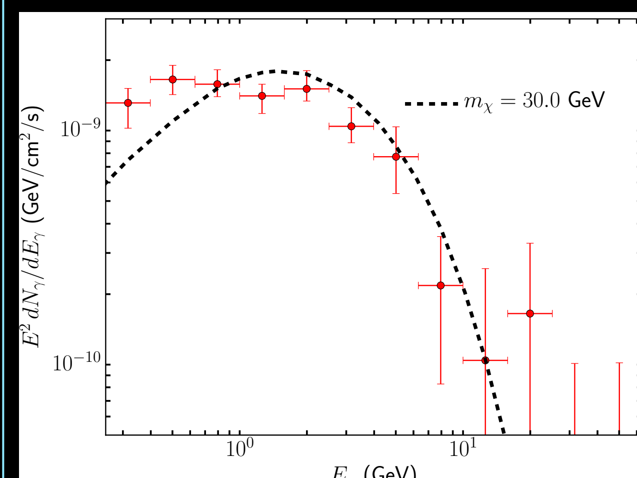
Zechlin+12;+13



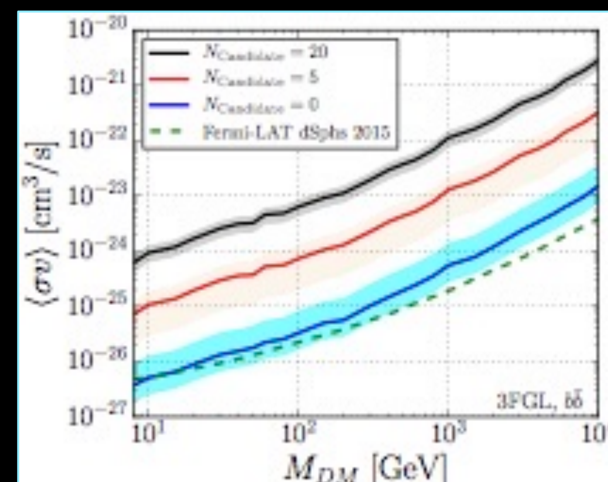
Berlin&Hooper 13



Mirabal+16



Bertoni+16



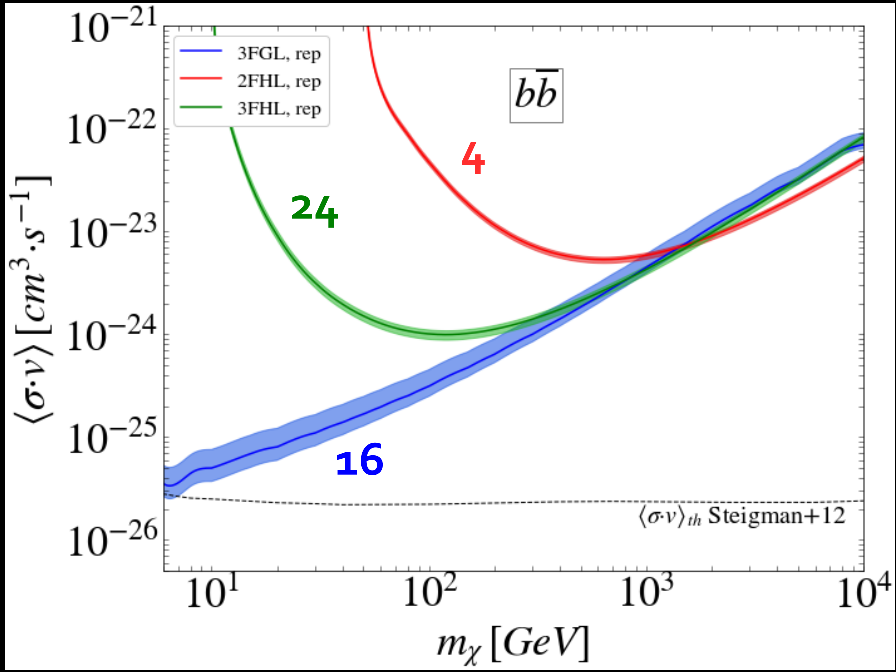
Calore+17

Also: Tasitsiomi&Olinto 02; Pieri+05; Kuhlen+07; Springel+08; Anderson+10; Belikov+12; Ackermann+12; Hooper+16; Schoonenberg+16; Abeysekara+19

Latest search in Fermi-LAT catalogs (I)

[J. Coronado-Blázquez, MASC et al., JCAP 07 (2019) 020]

- Search in the 3FGL, 2FHL and 3FHL Fermi-LAT catalogs.
- 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 with low-mass subhalos below resolution limit.



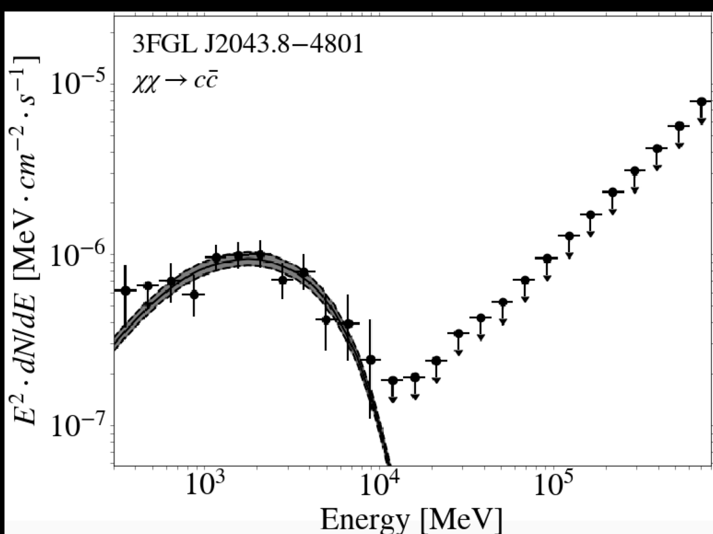
Latest search in Fermi-LAT catalogs (II)

[J. Coronado-Blázquez, MASC et al. (2019)]

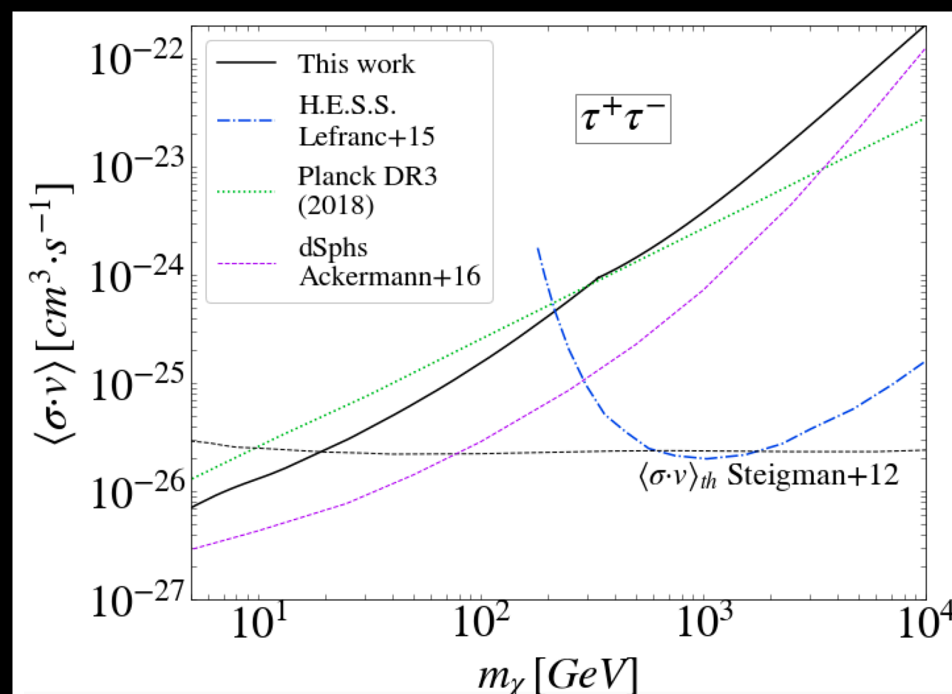
- Remaining 44 DM subhalo candidates scrutinized in further detail:
  → Dedicated LAT **spectral and spatial analysis** using 10 years of data.

- DM spectral models are compared to astrophysical models via a likelihood ratio test.
  → Only 7 sources marginally compatible with DM (not statistically significant).

- New (shorter) DM subhalo candidate list → Updated, more stringent DM constraints.

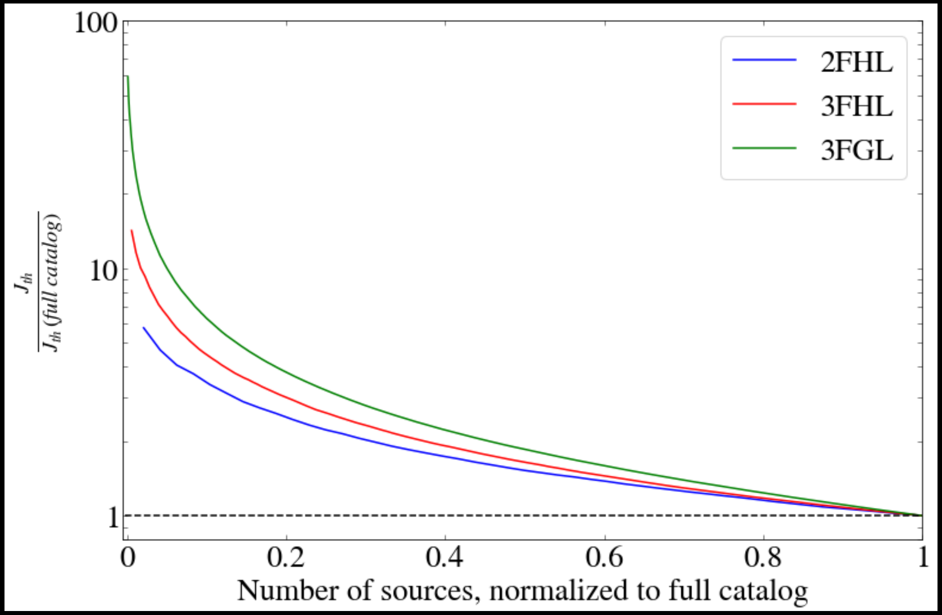


[Best DM subhalo candidate]



Importance of unIDs "filtering"

[J. Coronado-Blázquez, MASC et al., JCAP 07 (2019) 020]



- <σv> proportional to J-factor
  → less unIDs means better constraints
- Exponential rise in constraining power below ~20% of sources in every catalog
- **20% = 202 sources in 3FGL, 10 in 2FHL and 35 in 3FHL**
- From these numbers down, every source we remove has a large impact

Some OPEN ISSUES on subhalo population

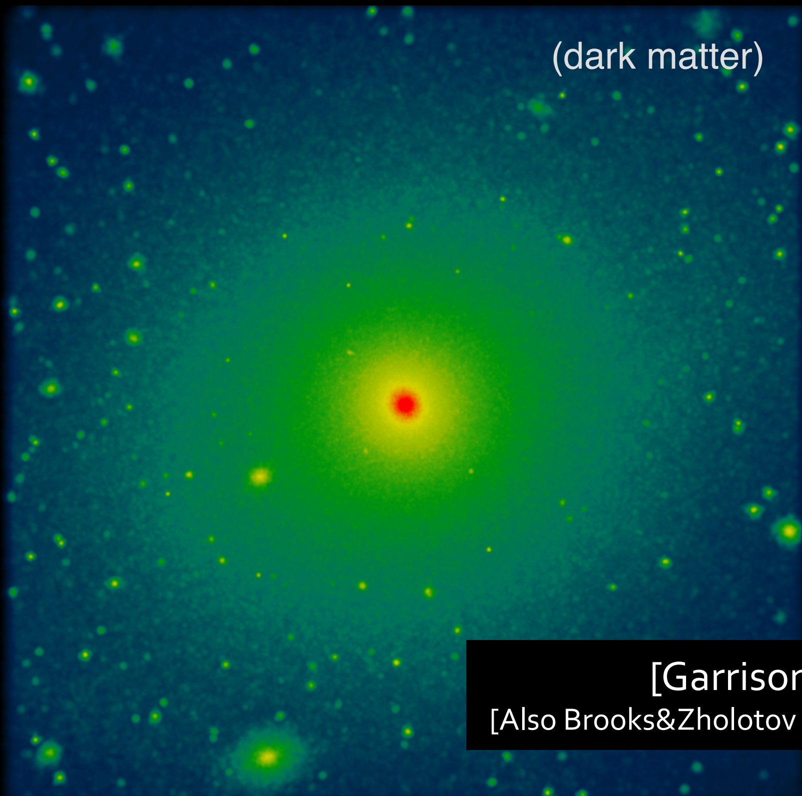
(most relevant for gamma-ray searches)

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

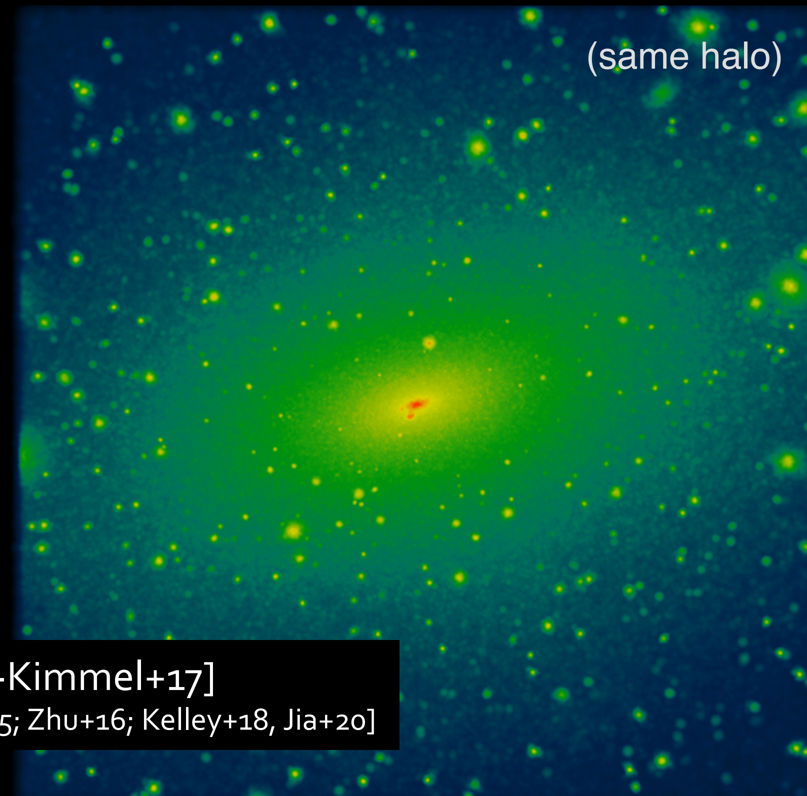
[In particular at Solar Galactocentric radius and for < 10 million solar masses]

OPEN ISSUES (I): Role of baryons

FIRE Hydrodynamics



Pure N-Body



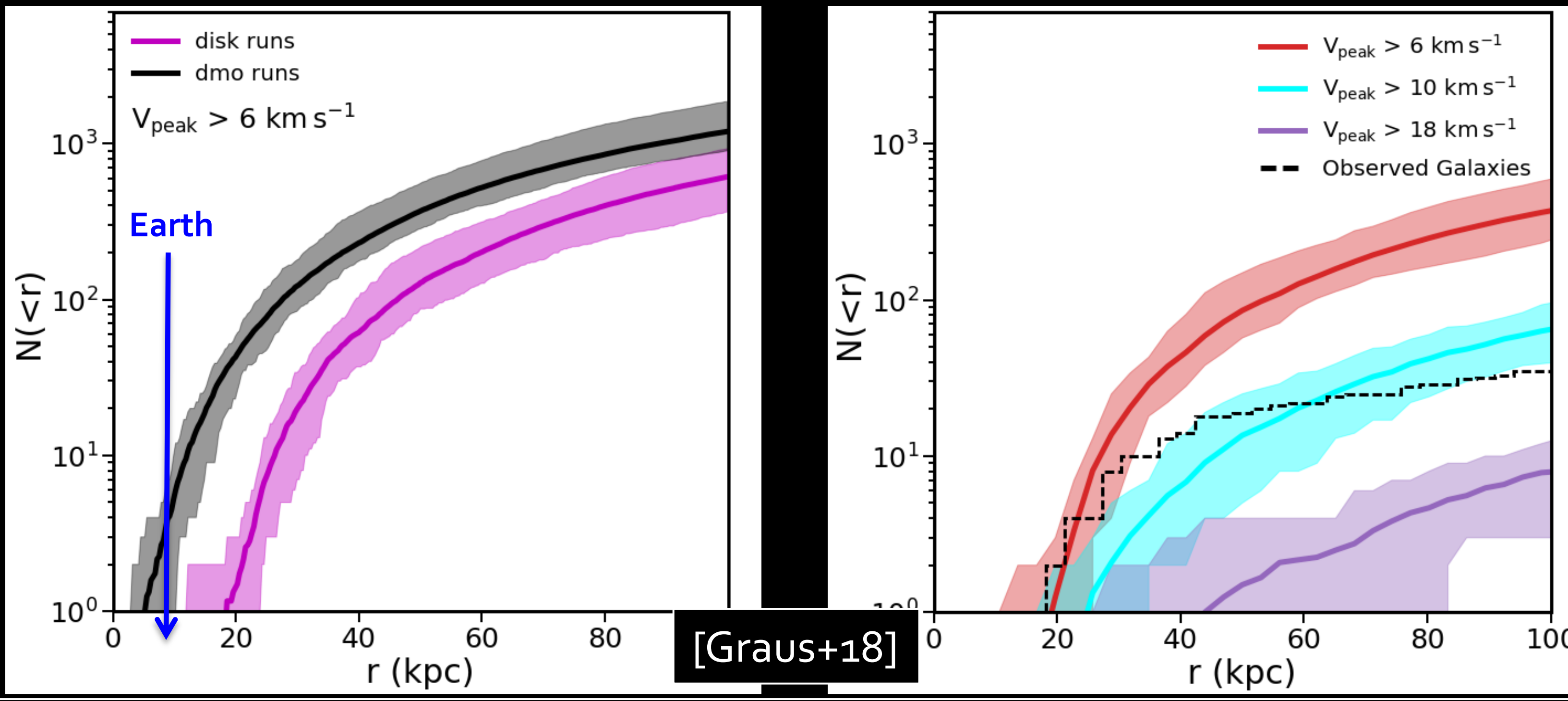
[Garrison-Kimmel+17]
[Also Brooks&Zholotov 15; Zhu+16; Kelley+18, Jia+20]

100 kpc

100 kpc

Up to a factor ~2 reduction in substructure within ~100 kpc
A factor ~10 within ~25 kpc.

OPEN ISSUES (II): Subhalo survival



[Graus+18]

No substructure within ~20 kpc with $V_{max} > 5$ km/s.
Yet, radial distribution in hydro simulations do not match observations.

Van den Bosch+18; van den Bosch&Ogiya 18:

- Subhalo disruption is numerical in origin
- Bound remnant survives provided it is well resolved in the simulation

→ What is the actual subhalo radial distribution?

[Also Diemand+07; Peñarrubia+10; Errani&Navarro 20, Webb & Bovy 20]