THE SEARCH FOR DARK MATTER HALO SUBSTRUCTURE WITH GAMMA RAYS

Miguel A. Sánchez-Conde

Instituto de Física Teórica IFT UAM/CSIC & Departamento de Física Teórica
Universidad Autónoma de Madrid

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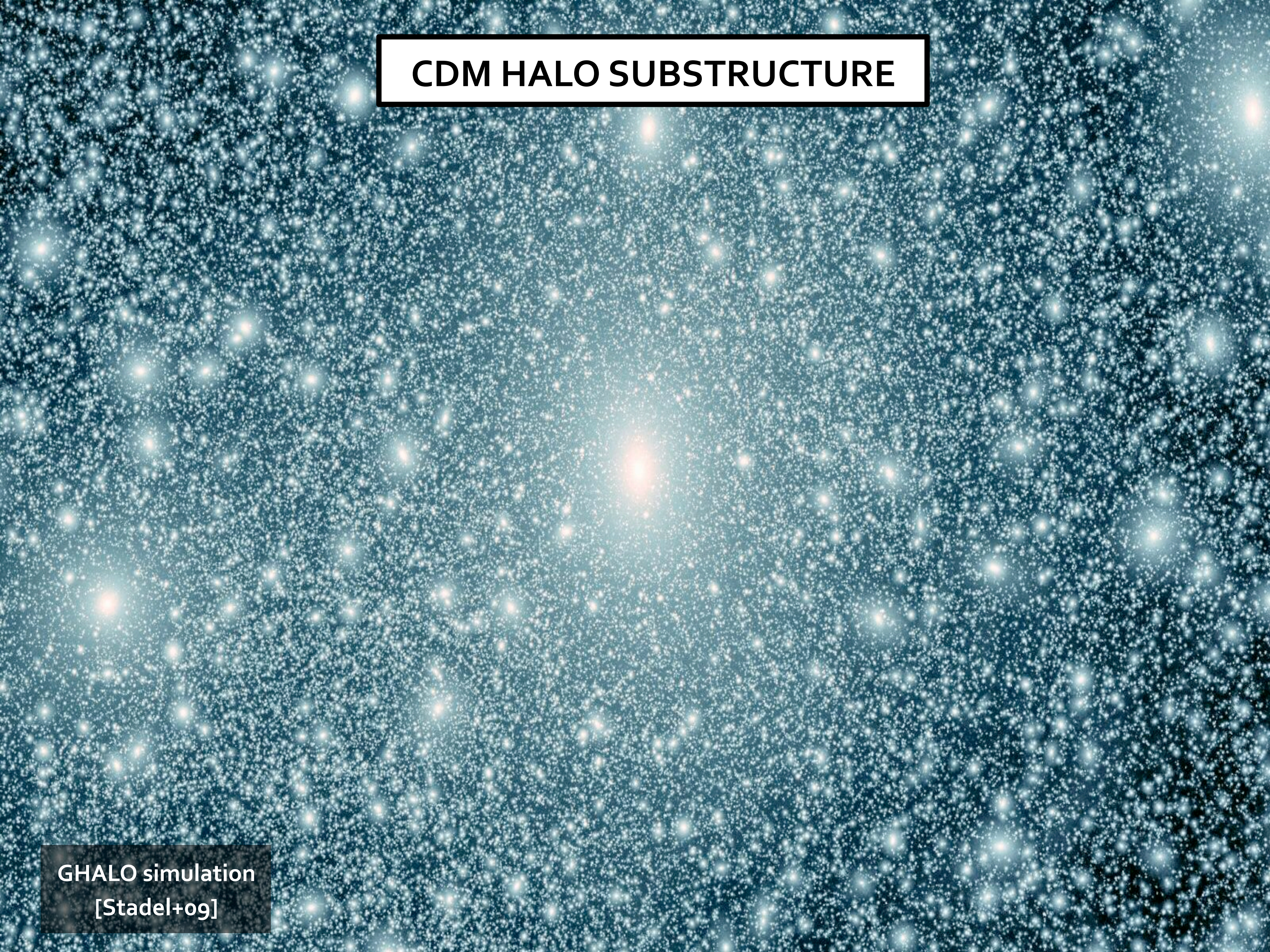
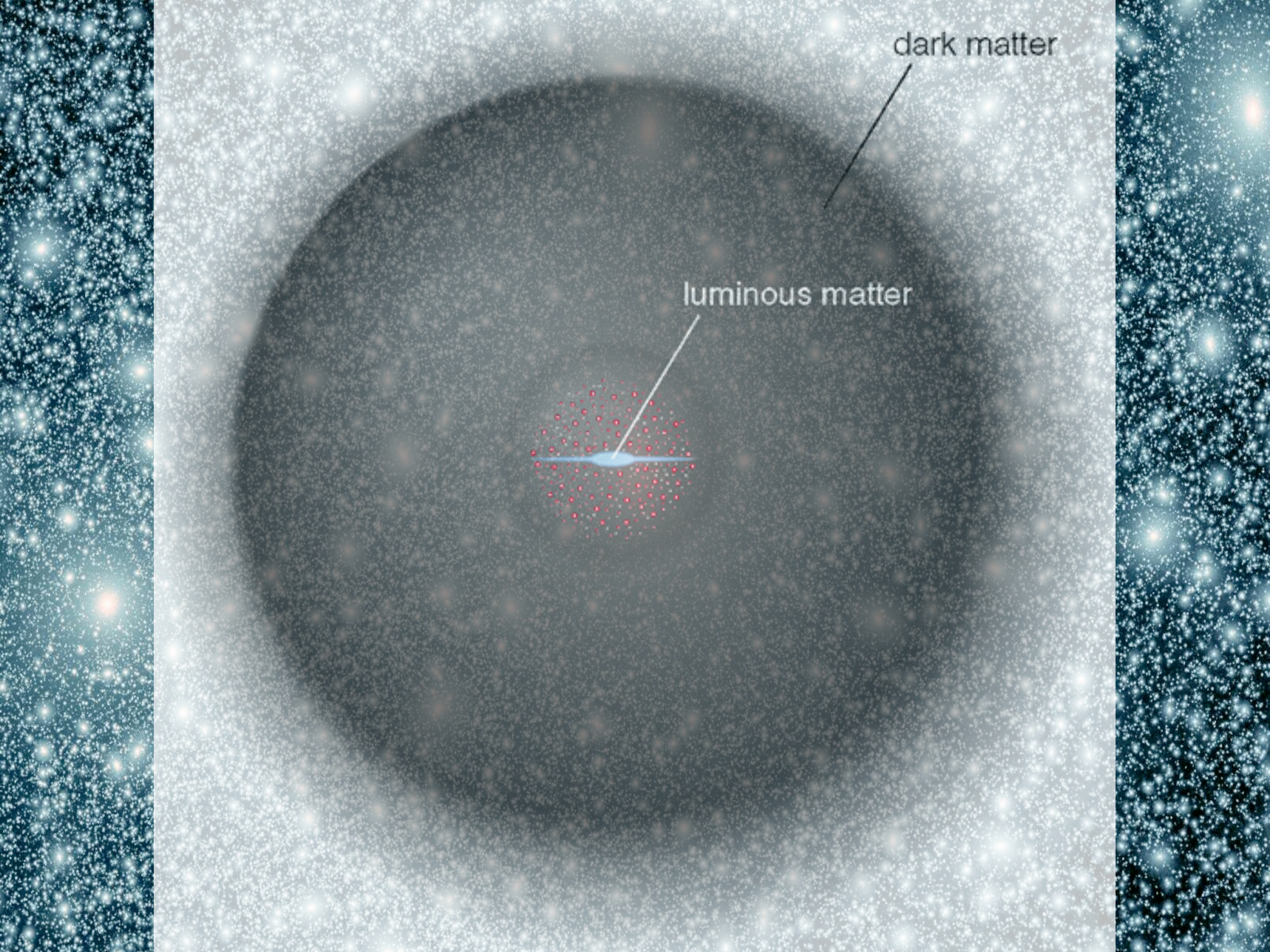
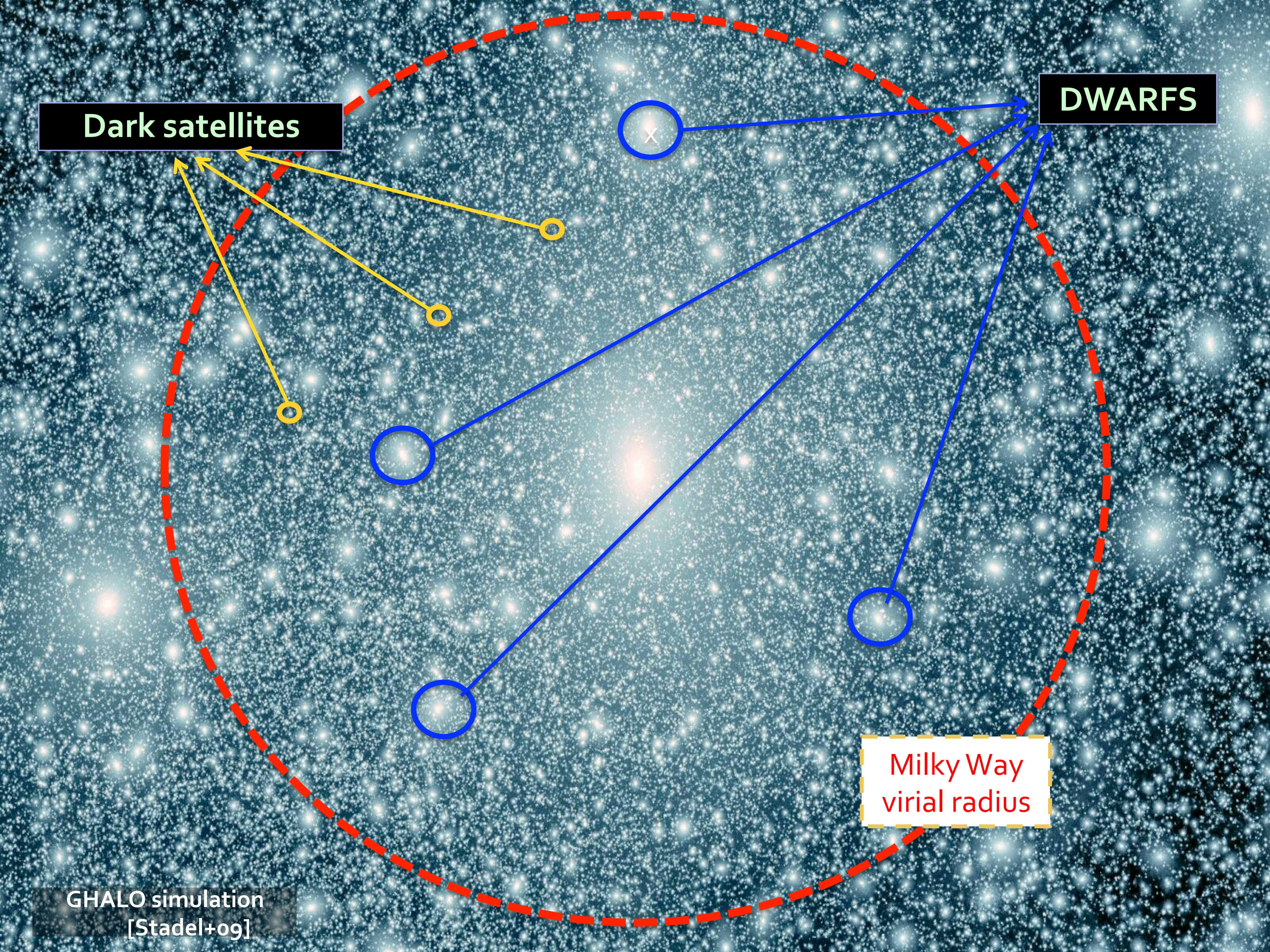
CDM HALO SUBSTRUCTURE



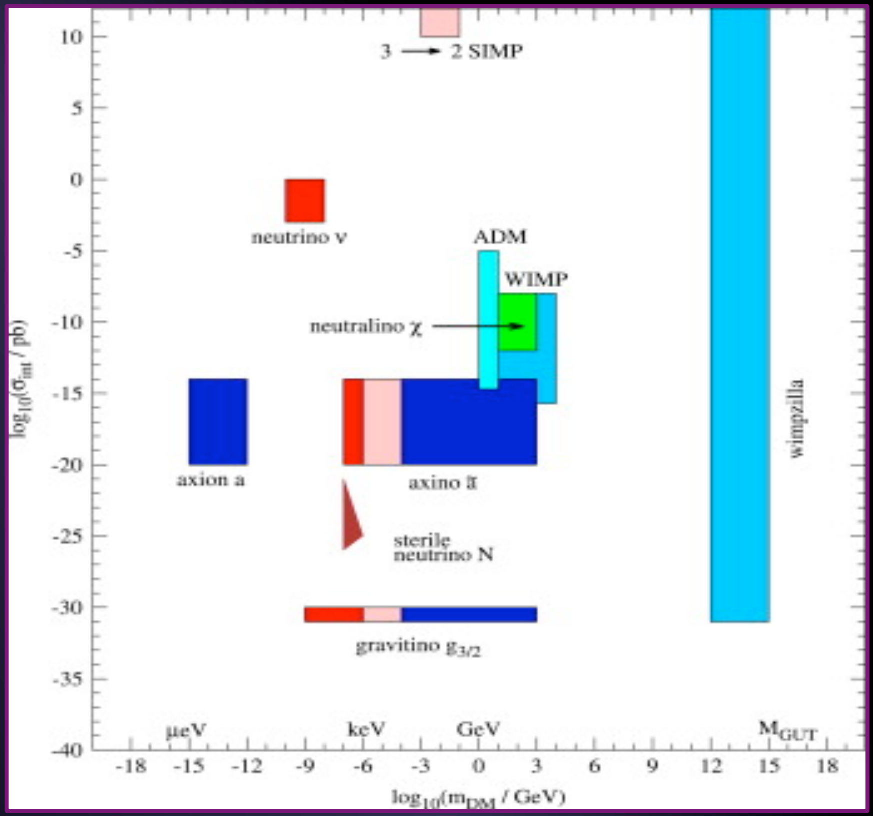
GHALO simulation
[Stadel+09]


dark matter
luminous matter


Dark 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

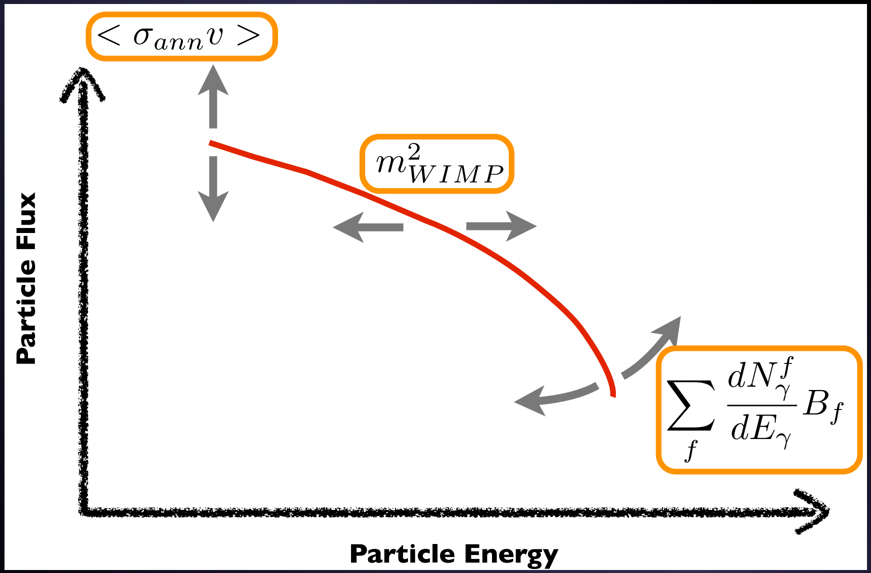
Where to search?

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

Particle physics

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

- N_g : number of photons per annihilation above E_{th}
- $<\sigma\, v>$: 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

THIS TALK

→ **GOOD TARGETS**

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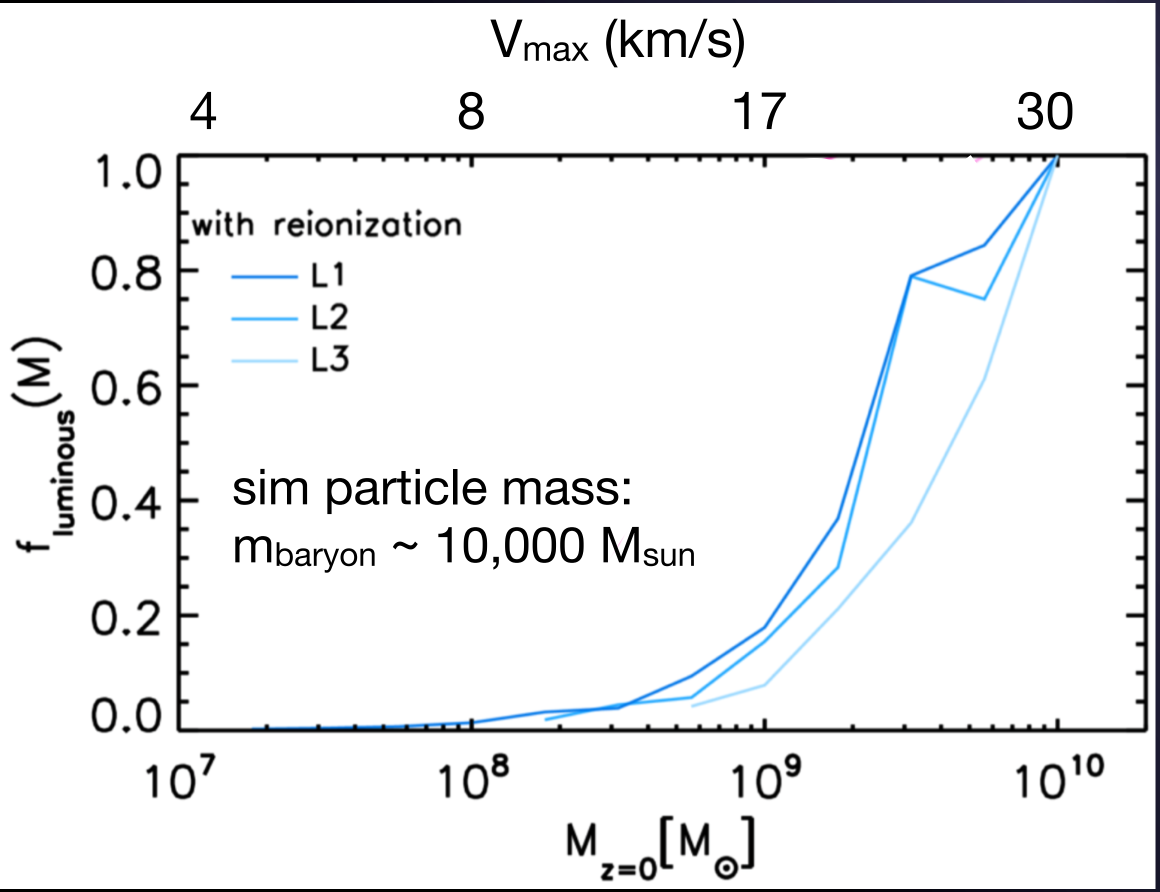
→ **"SUBSTRUCTURE BOOSTS"**

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}

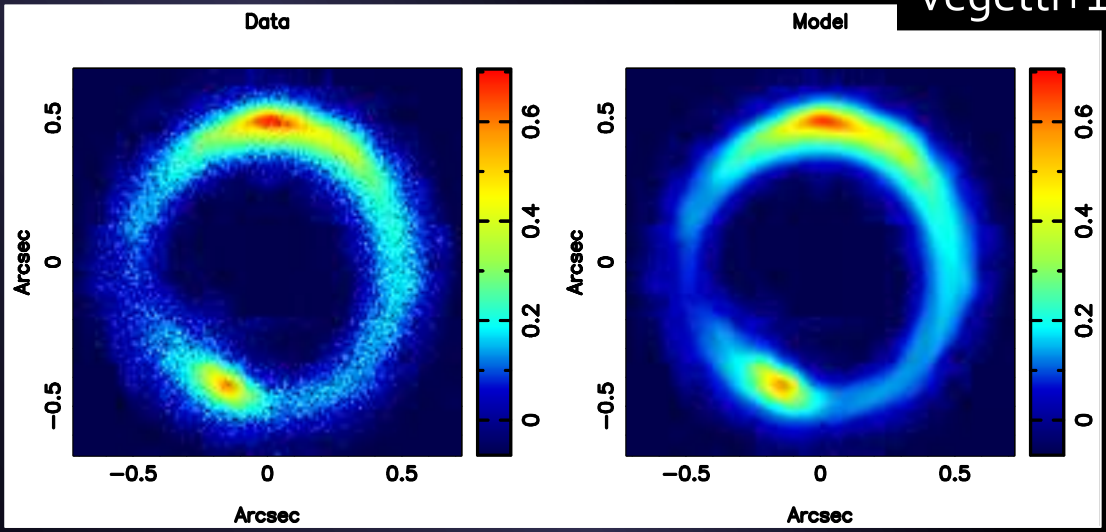
Similar results by Gnedin'00; Hoeft+06; Okamoto+08; Ocvirk+16; Fitts+17; etc

DM subhalo searches

I. (Strong) LENSING

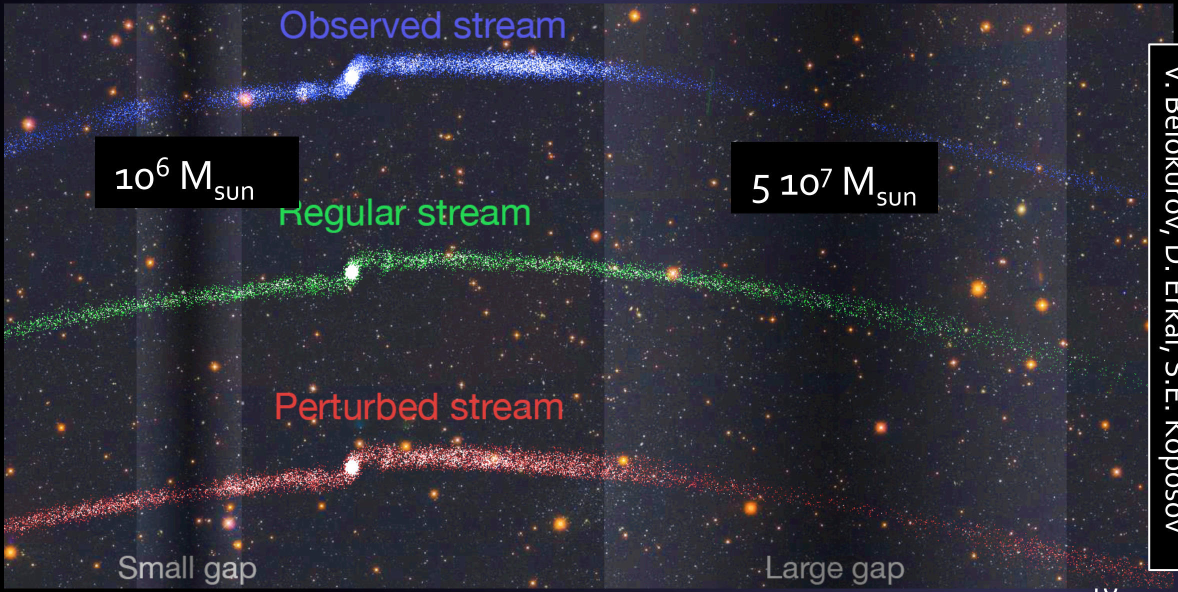
[Vegetti+10,12,18;
Hezaveh+16;
Nierenberg+14,17;
Birrer+17]

Vegetti+12



II. STELLAR GAPS

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

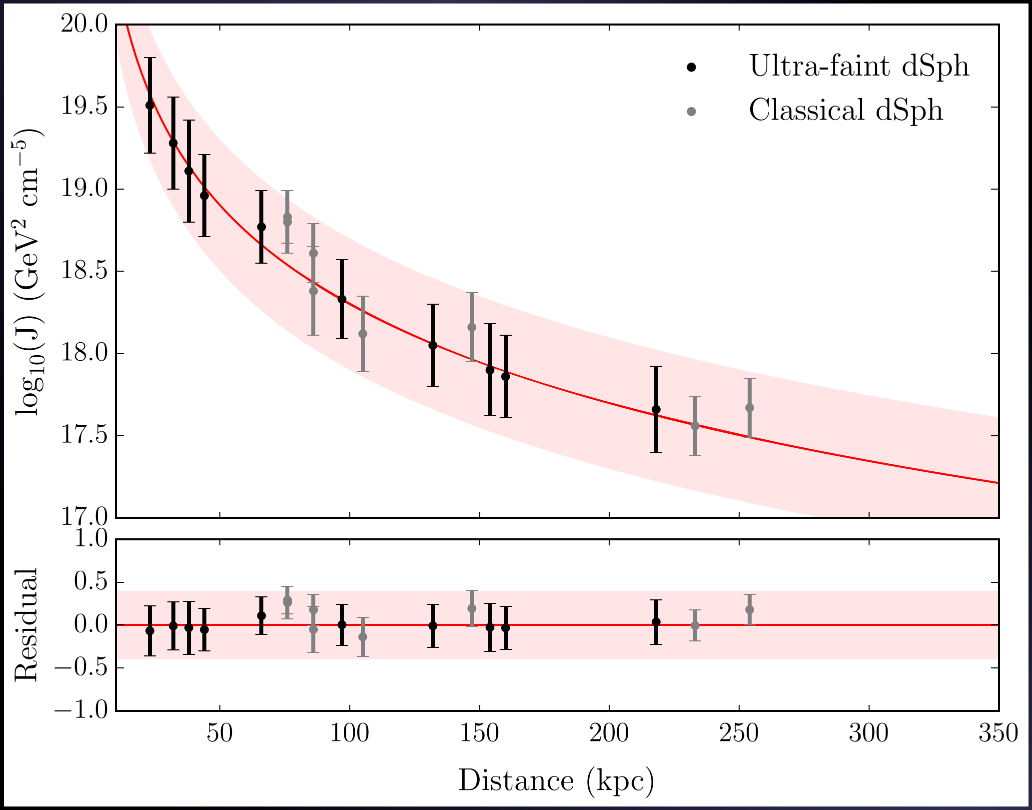


V. Belokurov, D. Erkal, S.E. Koposov

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.



Adapted from Albert+15

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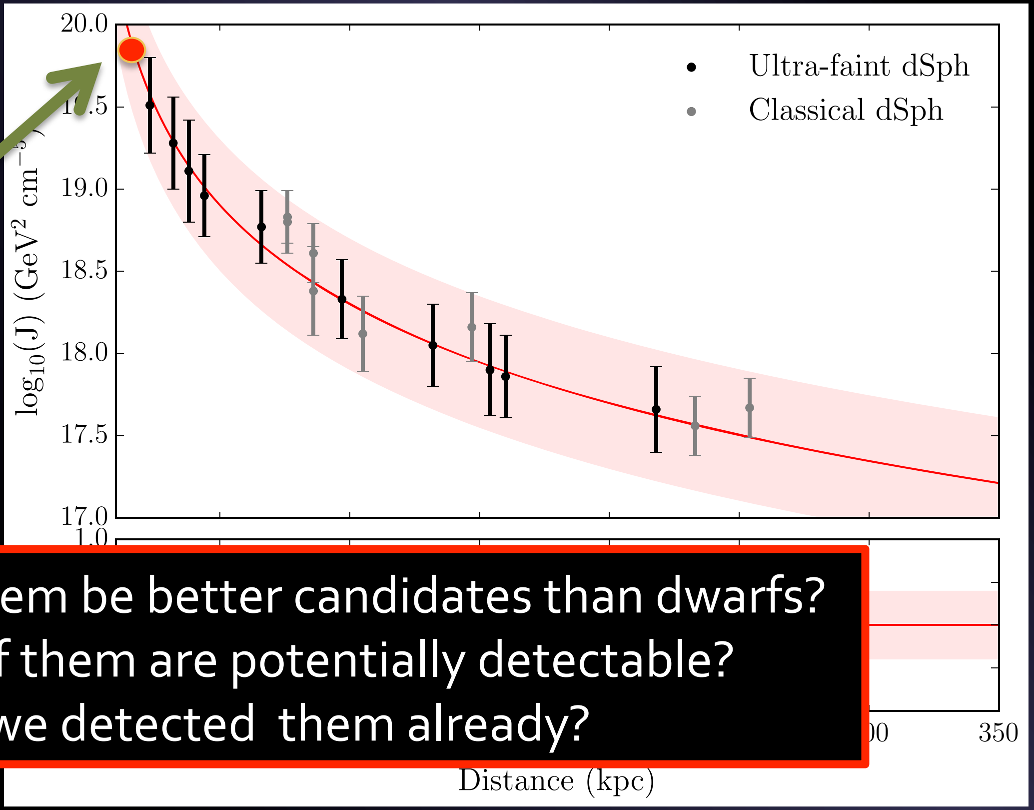

Adapted from Albert+15

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

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.

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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 (F_{min}), Theory (N_γ), Simulations (J_{factor})

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.

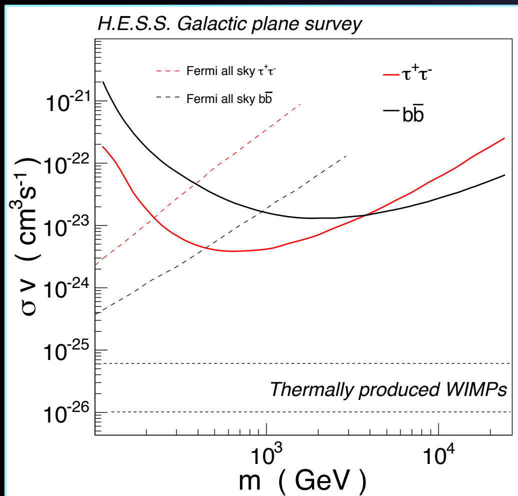
↓

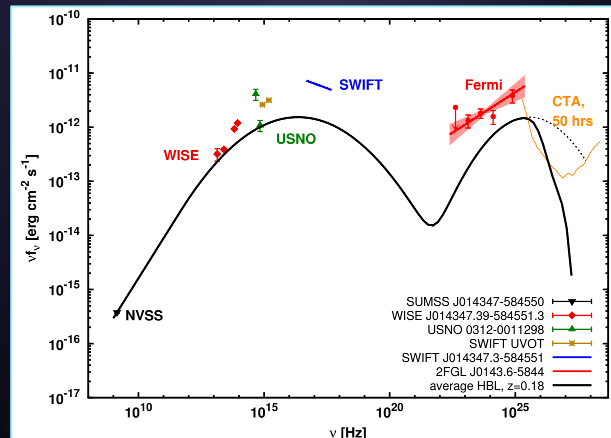
DM CONSTRAINTS

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

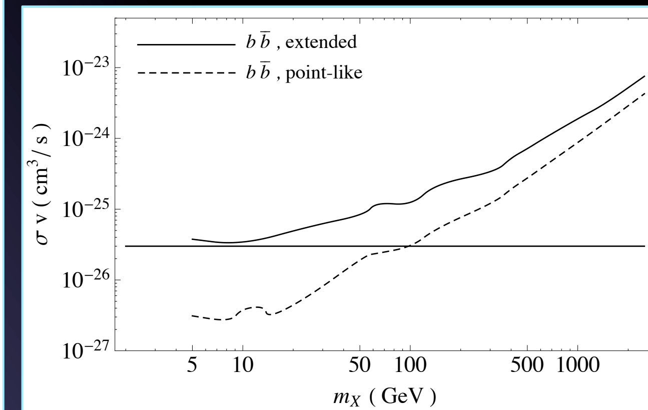
(Some) past work

Brun+11

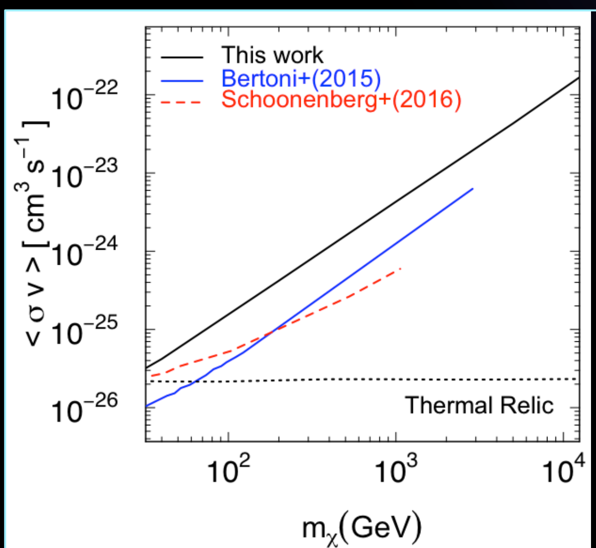




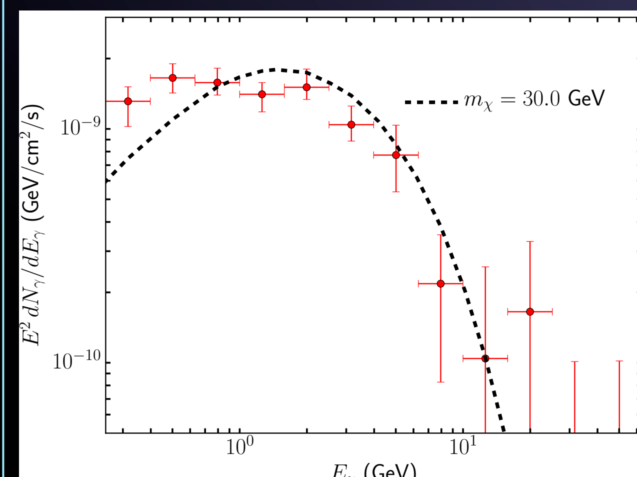
Zechlin+12;+13



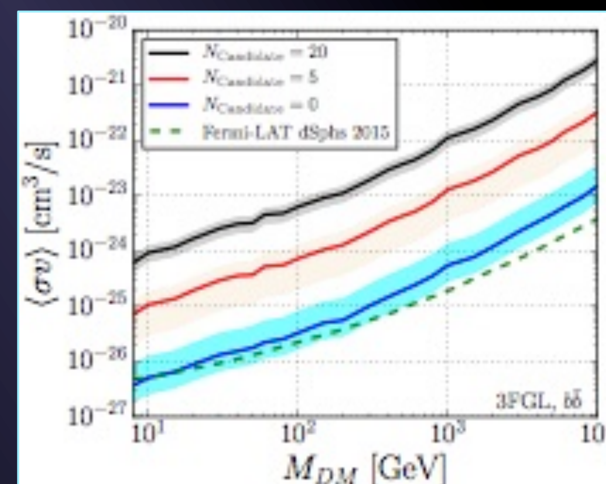
Berlin&Hooper 13



Mirabal+16



Bertoni+16



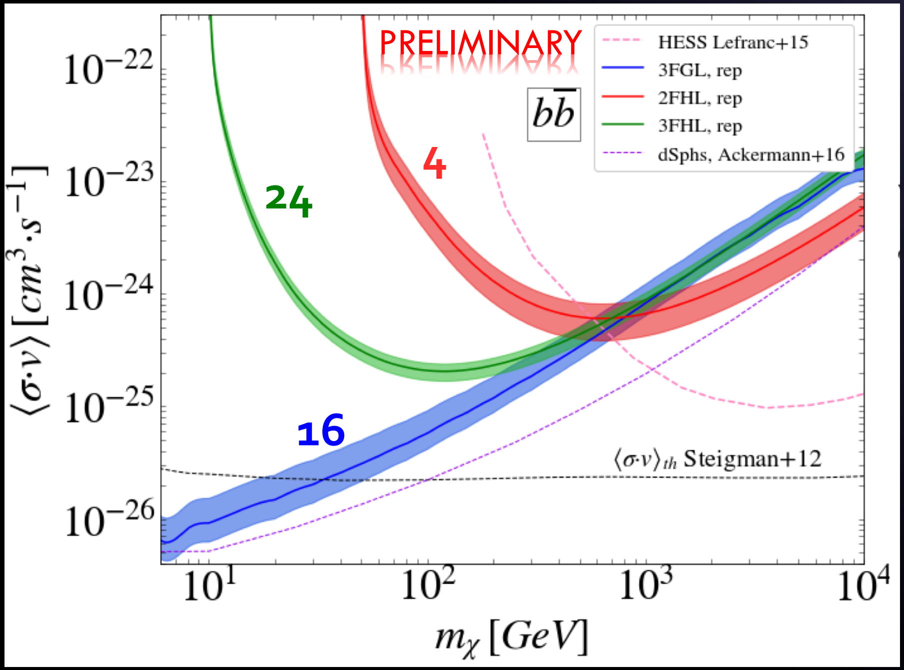
Calore+17

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

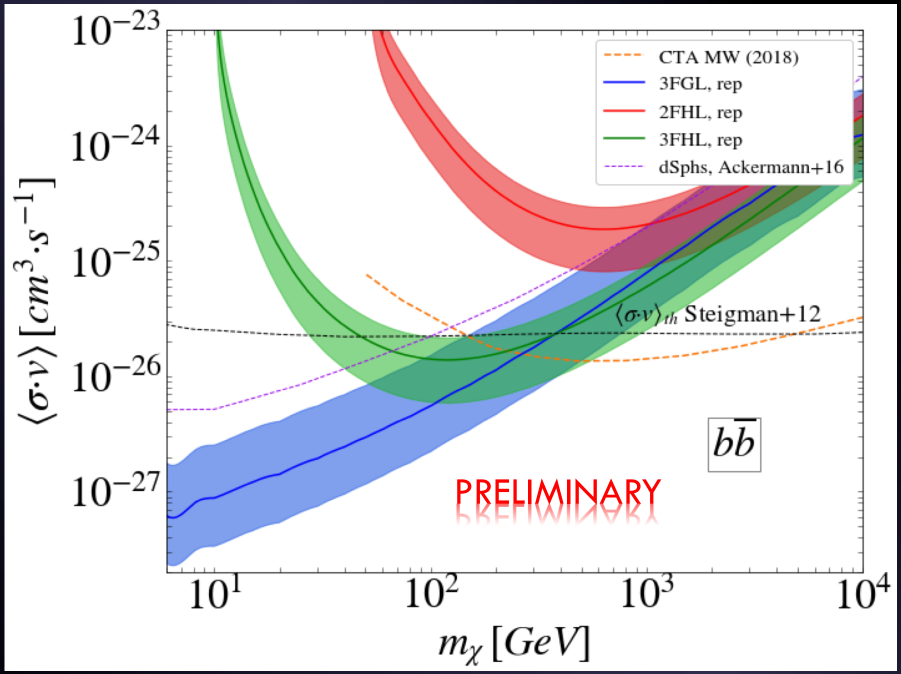
New LAT work ongoing

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

- 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.



Most realistic constraints



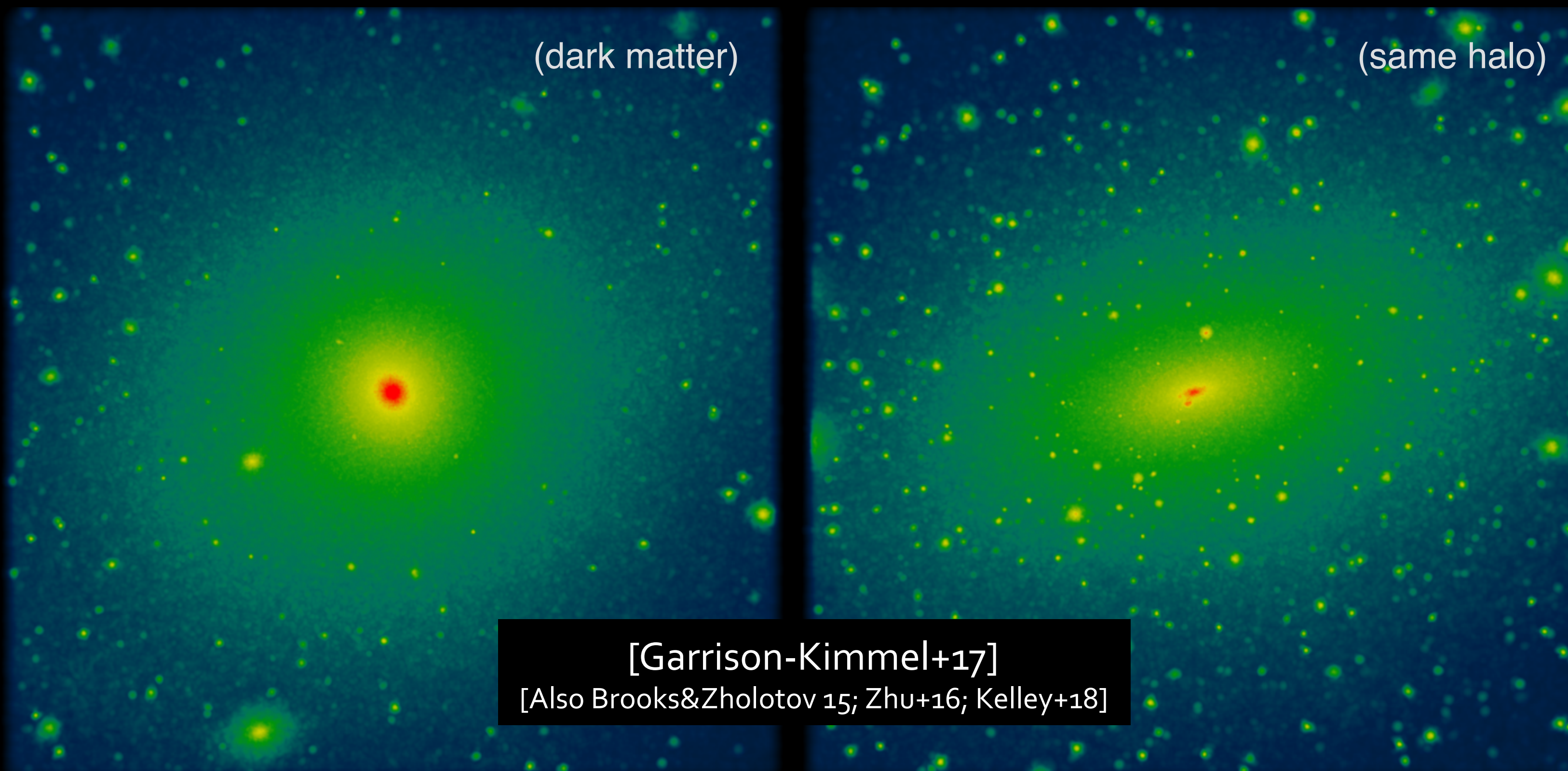
Maximum potential (no subhalos)

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.

OPEN ISSUES (I): Role of baryons

FIRE Hydrodynamics | Pure N-Body

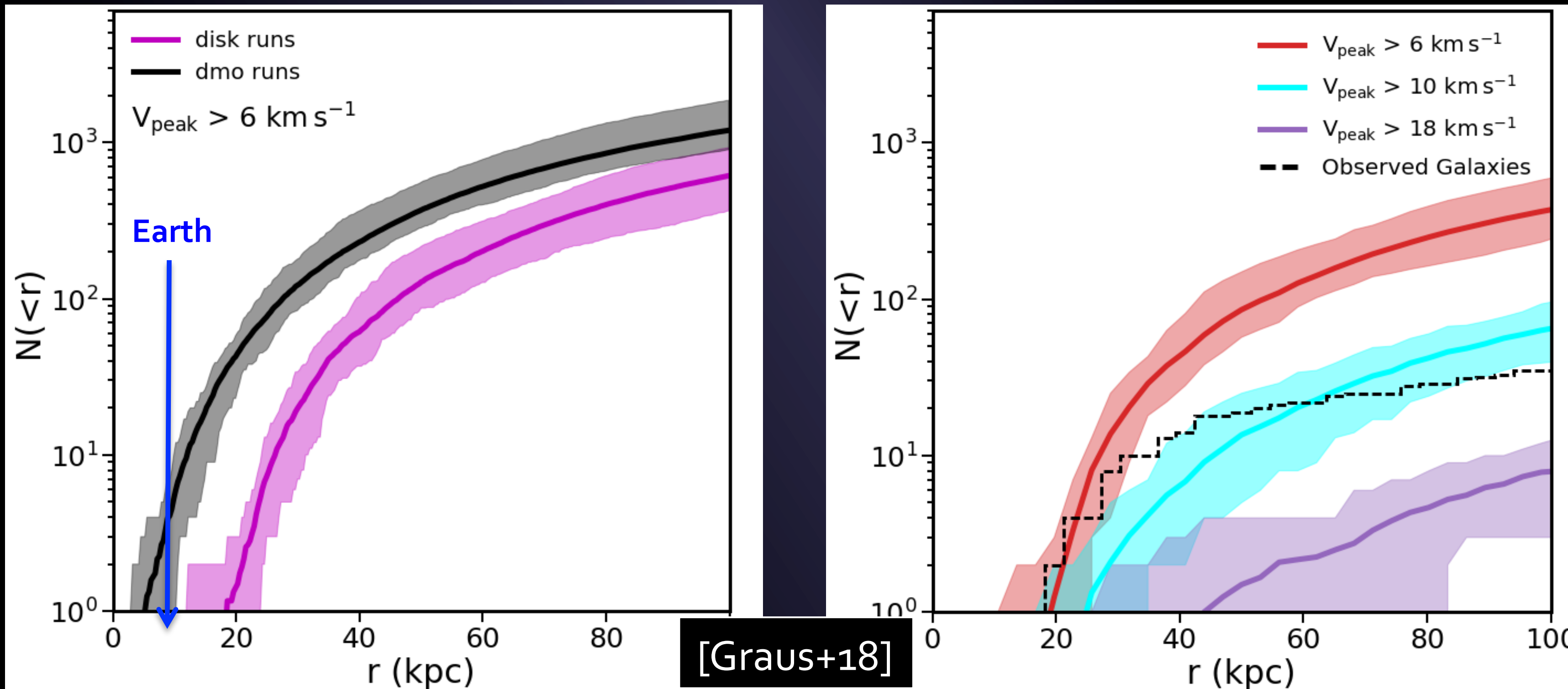


[Garrison-Kimmel+17]
[Also Brooks&Zholotov 15; Zhu+16; Kelley+18]

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



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 [Also: Kazantzidis+04; Diemand+07; Peñarrubia+10]:

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

→ What is the actual subhalo radial distribution?

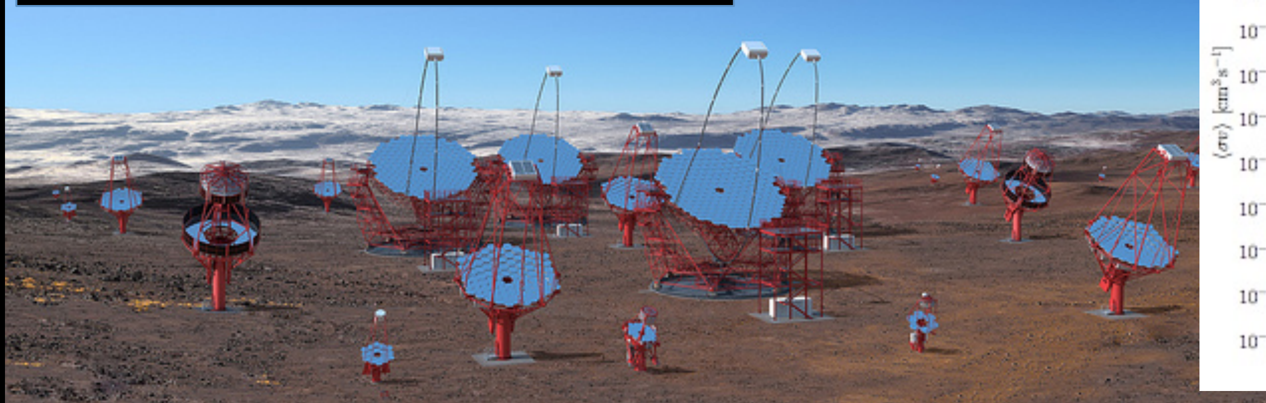
Remarks

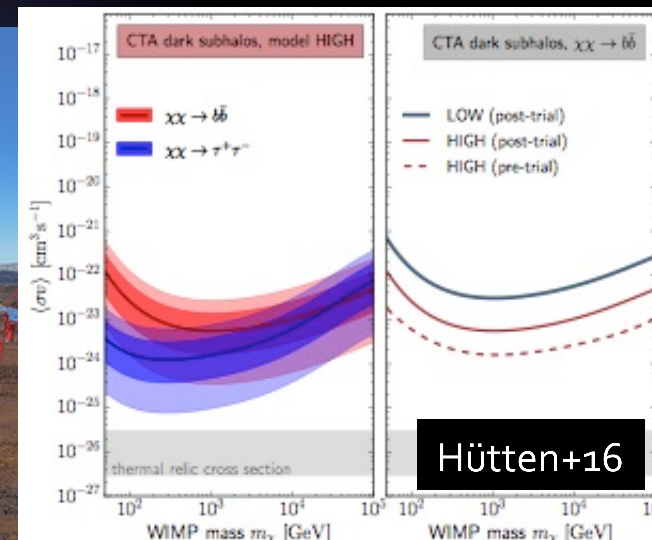
- Halo substructure very relevant for dark matter searches.
  - Most massive subhalos (dwarf galaxies) the best targets for indirect DM detection.
  - Less massive subhalos, with no optical counterparts, can be used to set very competitive constraints.
  - Subhalos can significantly *boost* the annihilation signal from halos and alter the DM signal spatial properties.

- ‘Dark satellites’ searches:
  - Current constraints close to the ones from dwarfs.
  - Sensitivity reach can rule out thermal cross section up to few hundred GeV WIMP masses.
  - Up to O(10) intrinsic (ΛCDM) uncertainty difficult to mitigate.

Future of dark satellites' searches with gamma rays

Cherenkov telescope array (CTA)
to go further in the TeV range

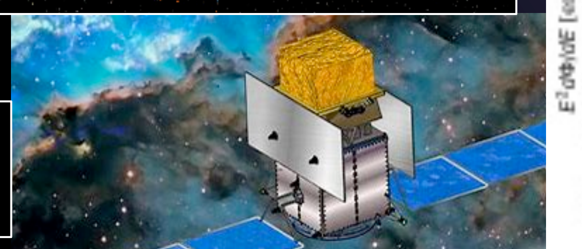




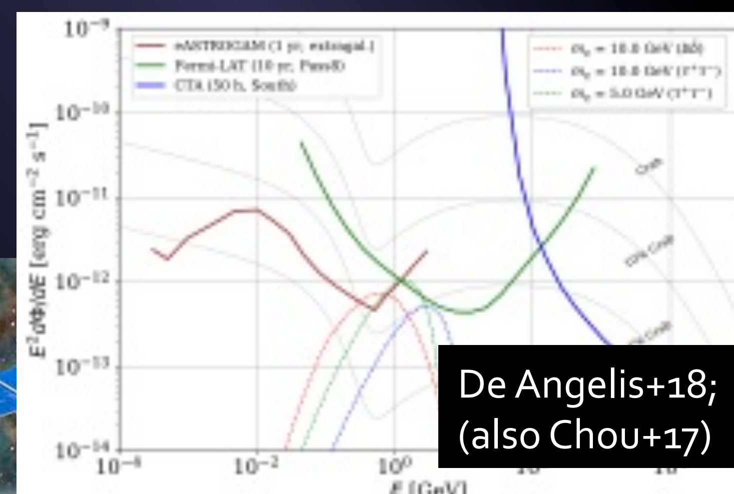
Hütten+16

AMEGO
ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY

Future MeV/sub-GeV missions



E-ASTROGAM



De Angelis+18; (also Chou+17)

Future of dark satellites' searches with gamma rays

- Higher resolution DM-only and/or hydro simulations to shed further light on subhalo survival, structural properties, etc.
- New gamma-ray catalogs (e.g., upcoming 4FGL)
- More refined spectral and spatial unID 'filters'
- Possible follow up of VIP candidates with IACTs

DM halo substructure CRITICAL for current and future gamma-ray DM search strategies.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ift Instituto de Física Teórica UAM-CSIC
MULTIDARK
Multimessenger Approach for Dark Matter Detection
Thanks!
Miguel A. Sánchez-Conde
miguel.sanchezconde@uam.es
www.miguelsanchezconde.com
Daniel López / IAC