DARK MATTER SUBHALOS
[and gamma-ray DM searches]

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MAGIC DM school

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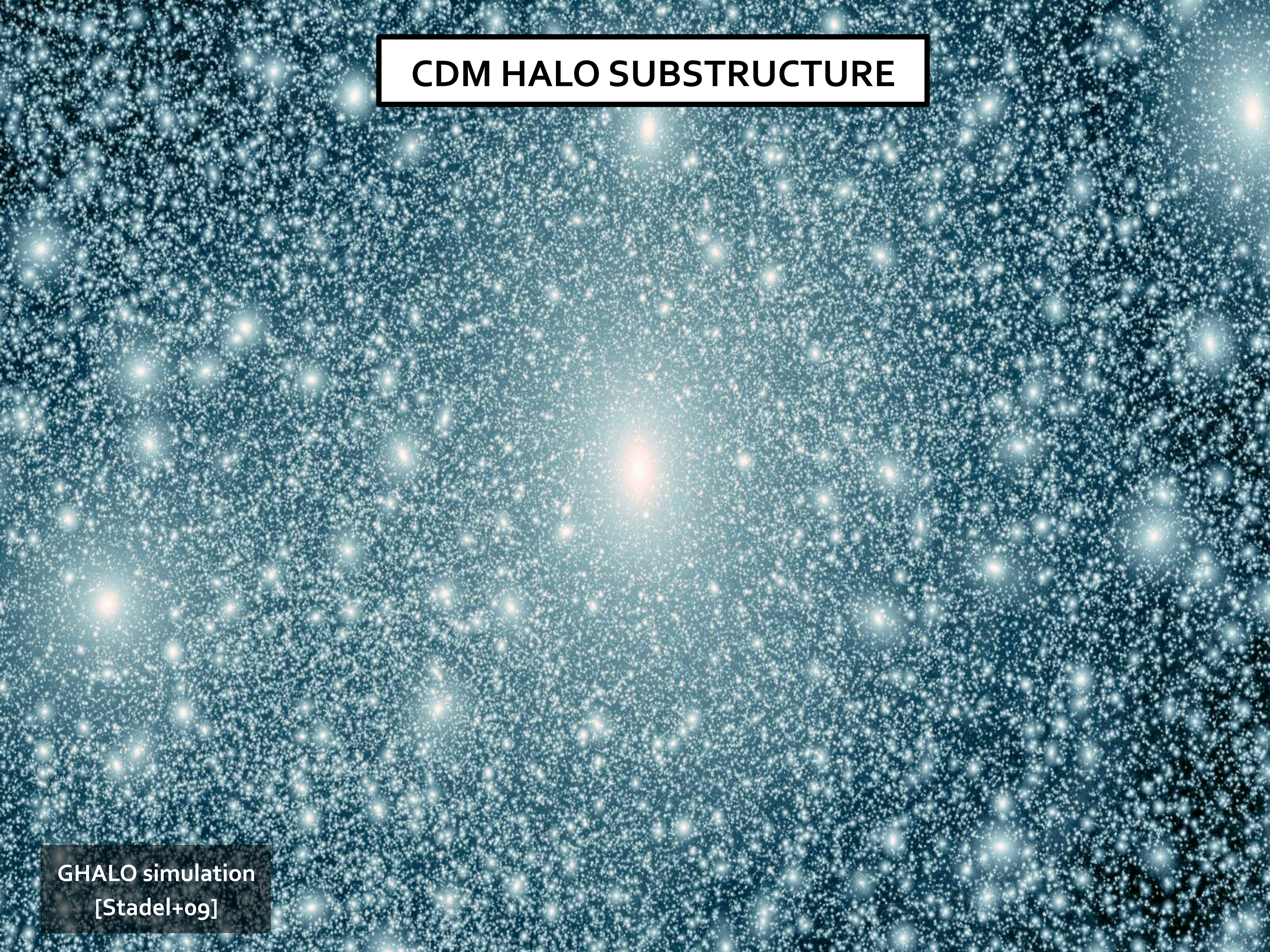
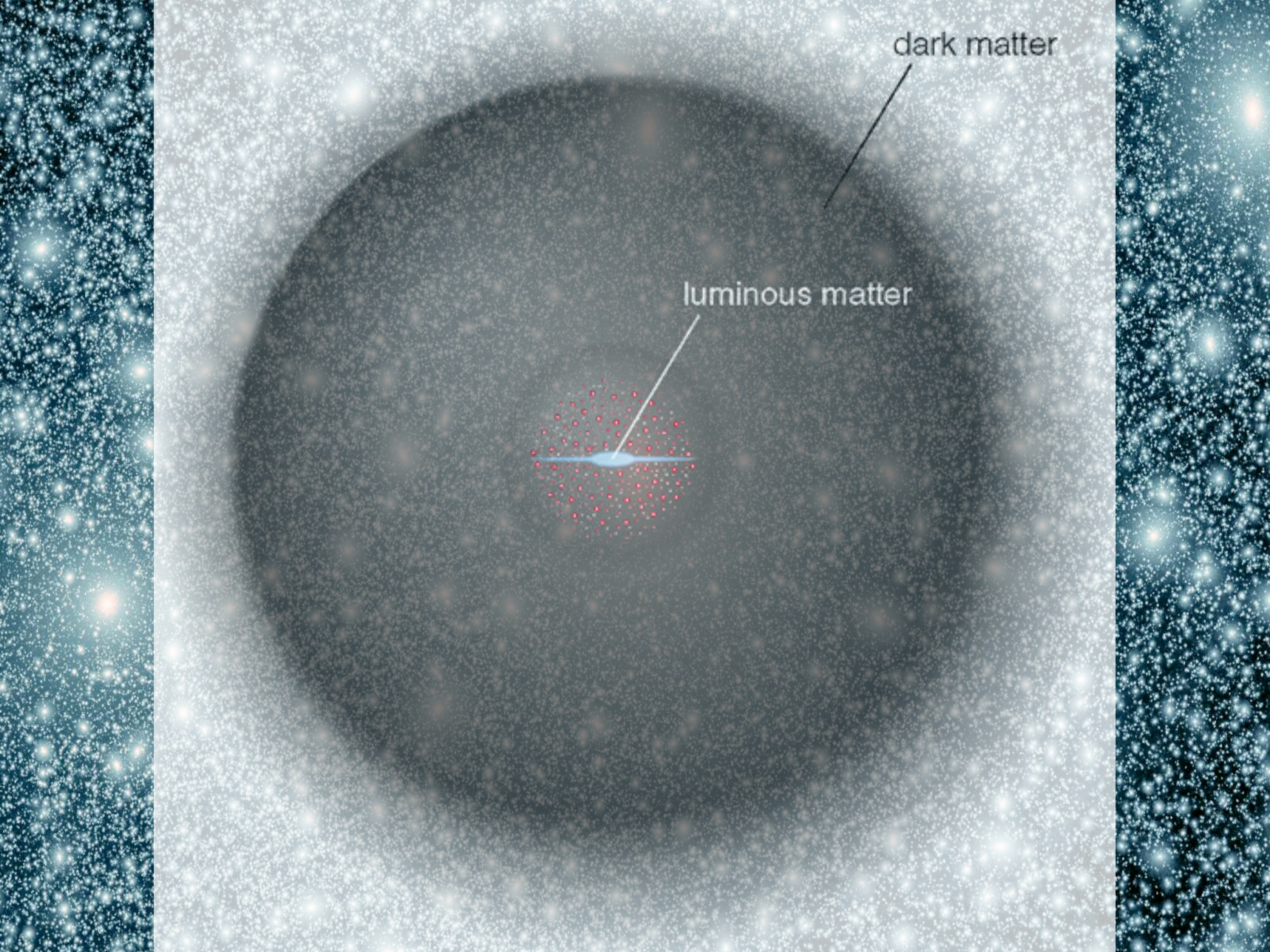
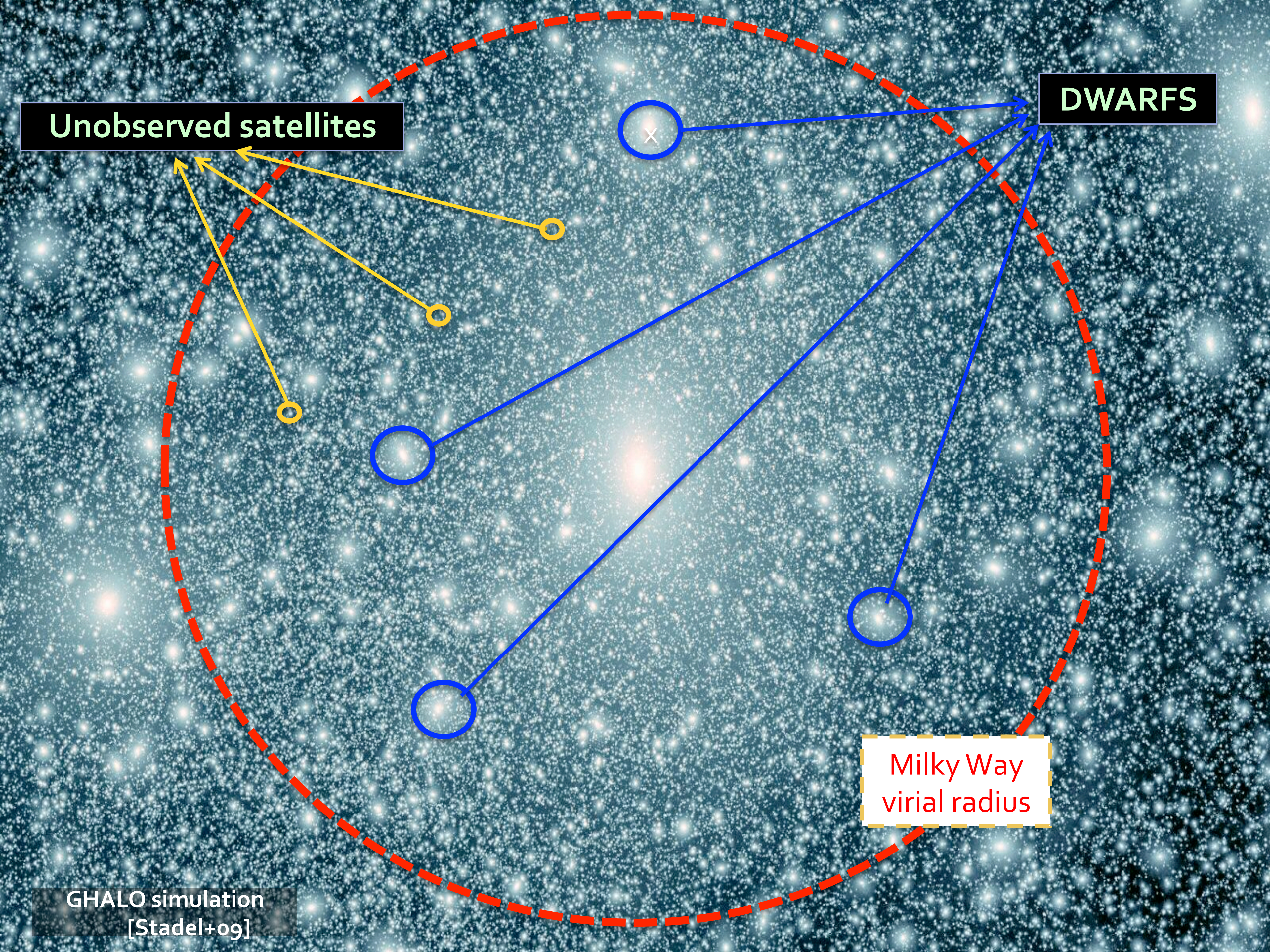
CDM HALO SUBSTRUCTURE



GHALO simulation
[Stadel+09]


dark matter
luminous matter


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

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"**

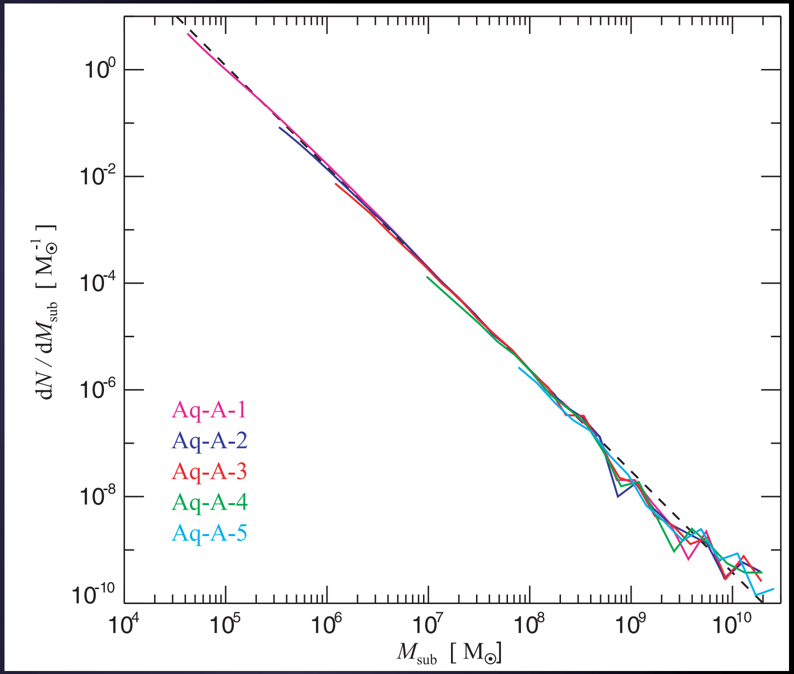
Important to characterize in detail the DM subhalo population

Subhalo mass function

$$\frac{\mathrm{d}N}{\mathrm{d}M} = a_0 \left(\frac{M}{m_0} \right)^n$$

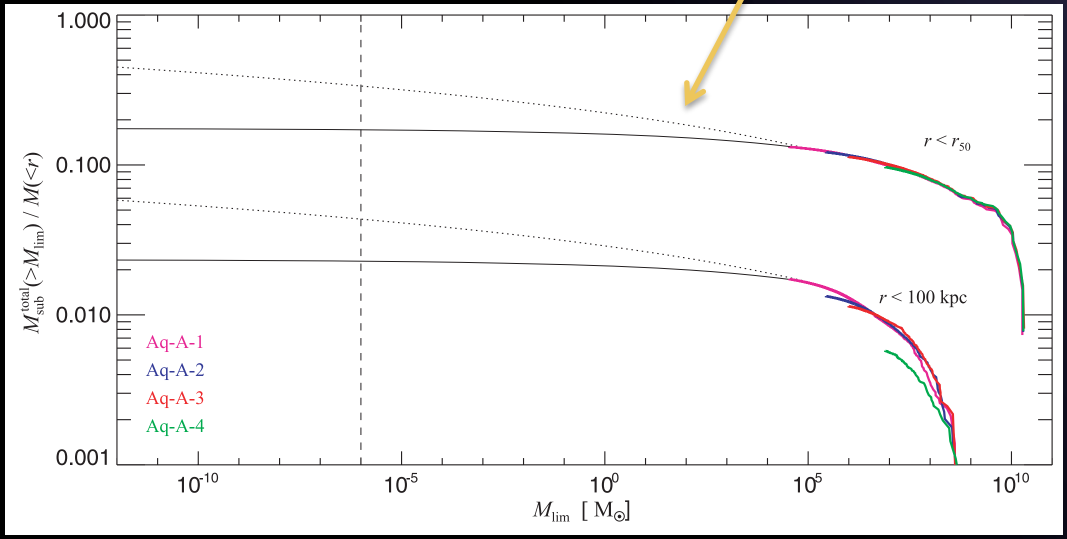
(m_o = minimum subhalo mass)

Simulations: 1.9 < n < 2
LCDM predictions (PS theory): 1.8 < n < 2



Aquarius. Springel+08

A small variation makes a BIG difference!



Caveat: below ~10^7 solar masses the subhalo survival is uncertain

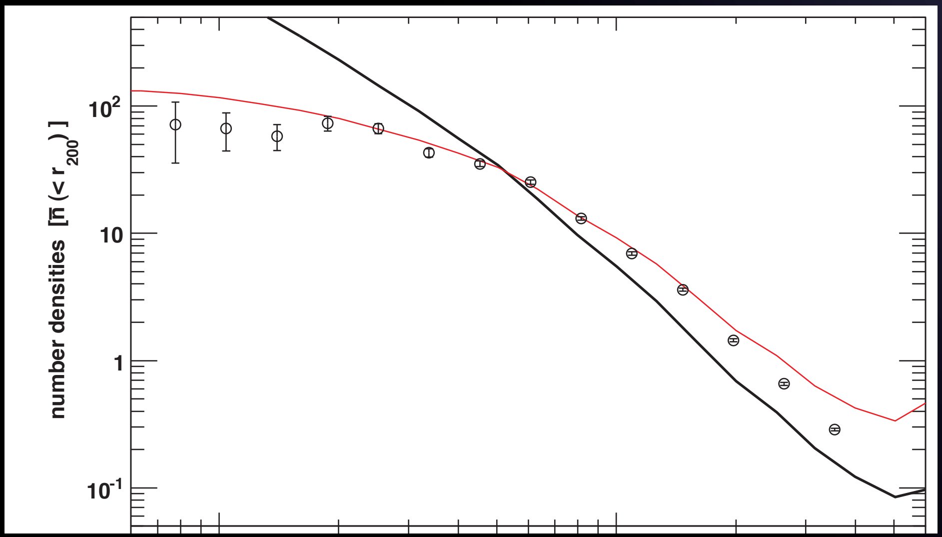
Subhalo radial distribution

In VL-II, subhalos follow the so-called antibiased distribution.

Biased in Aquarius.

$$n(r) \propto r\,\rho_{\rm host}(r)$$

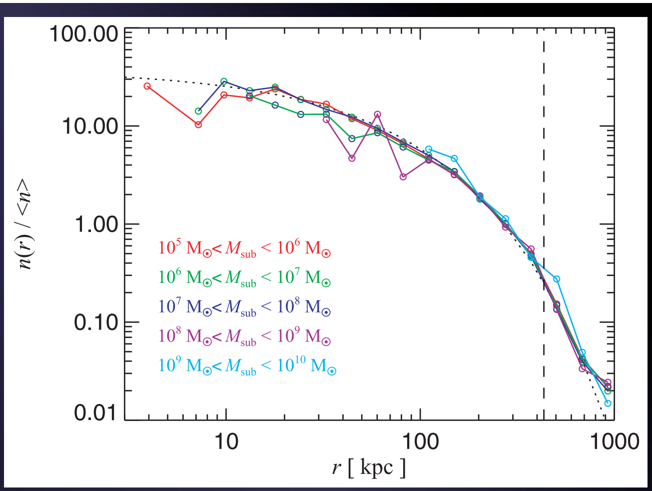
$$\rho_{\rm sub}^{VLII}(R) = \frac{\rho_{\rm tot}^{VLII}(R)\,(R/R_a)}{\left(1+\frac{R}{R_a}\right)}$$

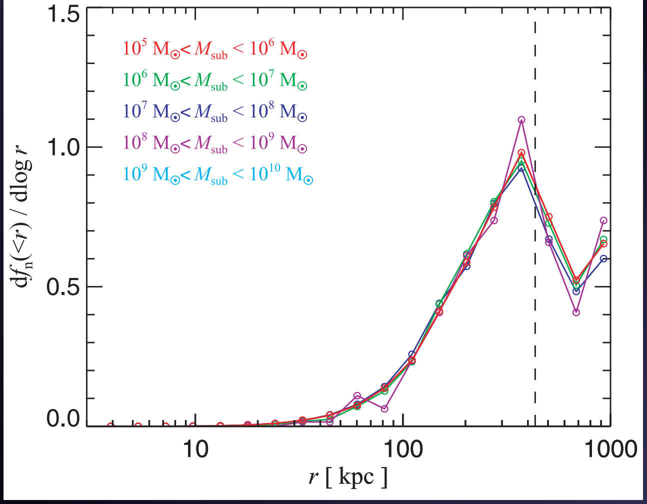


VL-II, Diemand+08

$$n_{\rm sh}(r) \propto \rho_{\rm Ein}(r)$$

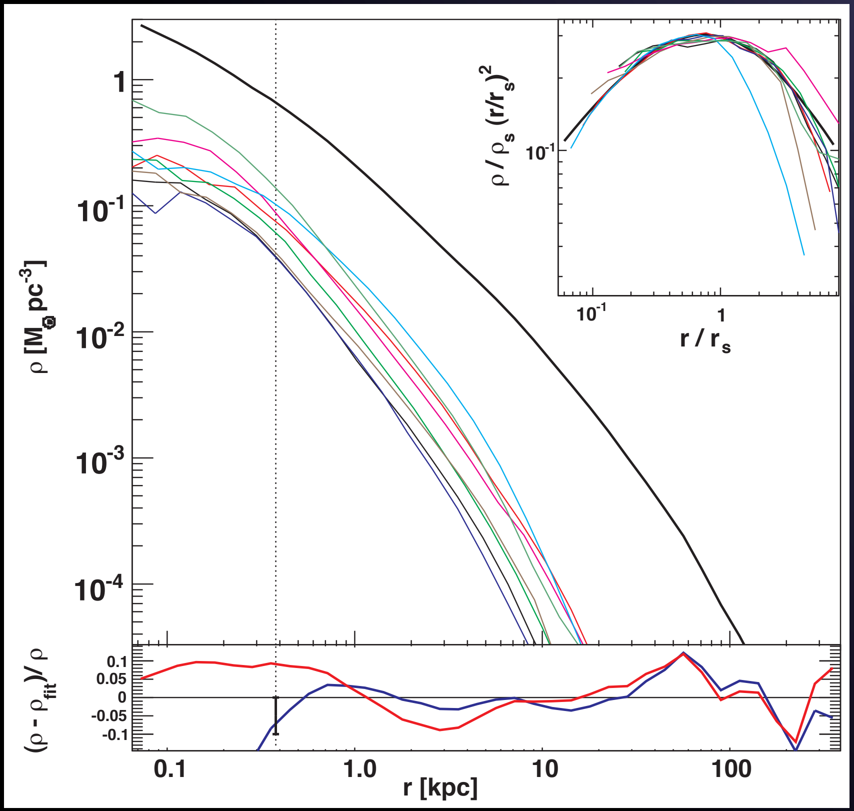
$$\rho_{\rm sub}^{Aq}(R) = \rho_a \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{R}{R_a}\right)^{\alpha} - 1\right]\right\}$$

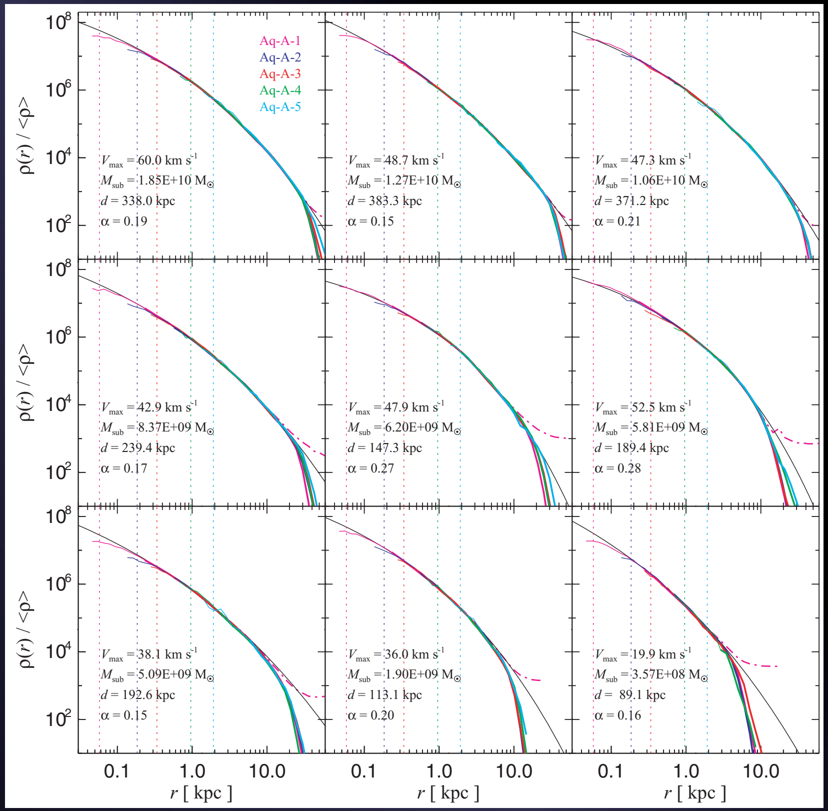




Aquarius. Springel+08

Subhalo DM density profiles





Springel+08

Similar to those of main halos but in the outermost regions, where they exhibit a exponential cut-off (tidal stripping)

→ 'standard' virial radius definition not valid

Subhalo 'concentrations'

- Difficulty in defining them:
  - More complex evolution compared to field halos.
  - Tidal forces modify the DM density profile (e.g. Kazantzidis+04)
  - Reduced R_{max}, i.e. the radius at which the maximum circular velocity V_{max} is reached (e.g. Bullock+01).

- Solution: choose a definition independent of the profile

$$c_{\rm V} = \frac{\bar{\rho}(R_{\rm max})}{\rho_c} = 2\left(\frac{V_{\rm max}}{H_0\, R_{\rm max}}\right)^2$$

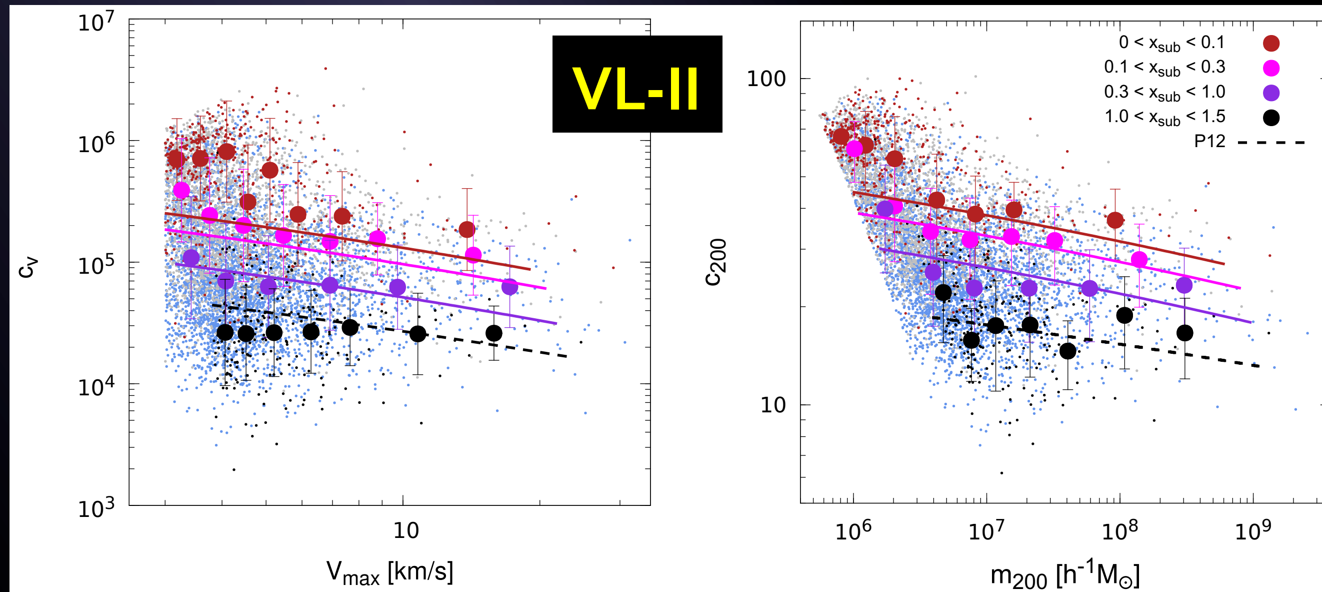
See also Diemand+08

- Still useful to compare to the standard c_{200}:

For NFW:

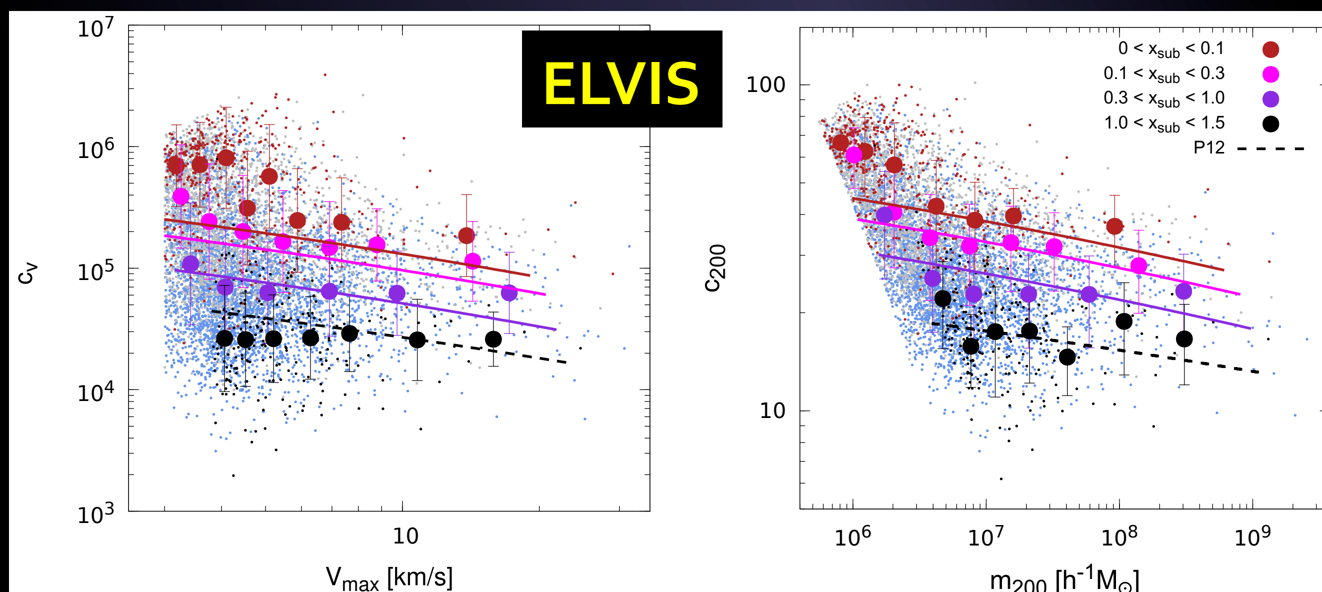
$$c_{\rm V} = \left(\frac{c_\Delta}{2.163}\right)^3 \frac{f(R_{\rm max}/r_s)}{f(c_\Delta)}\,\Delta$$

c_v results from VL-II and ELVIS



Clear **increase** of subhalo concentration as we approach the host halo center

Important implications for e.g. indirect detection of DM



Moline+17

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

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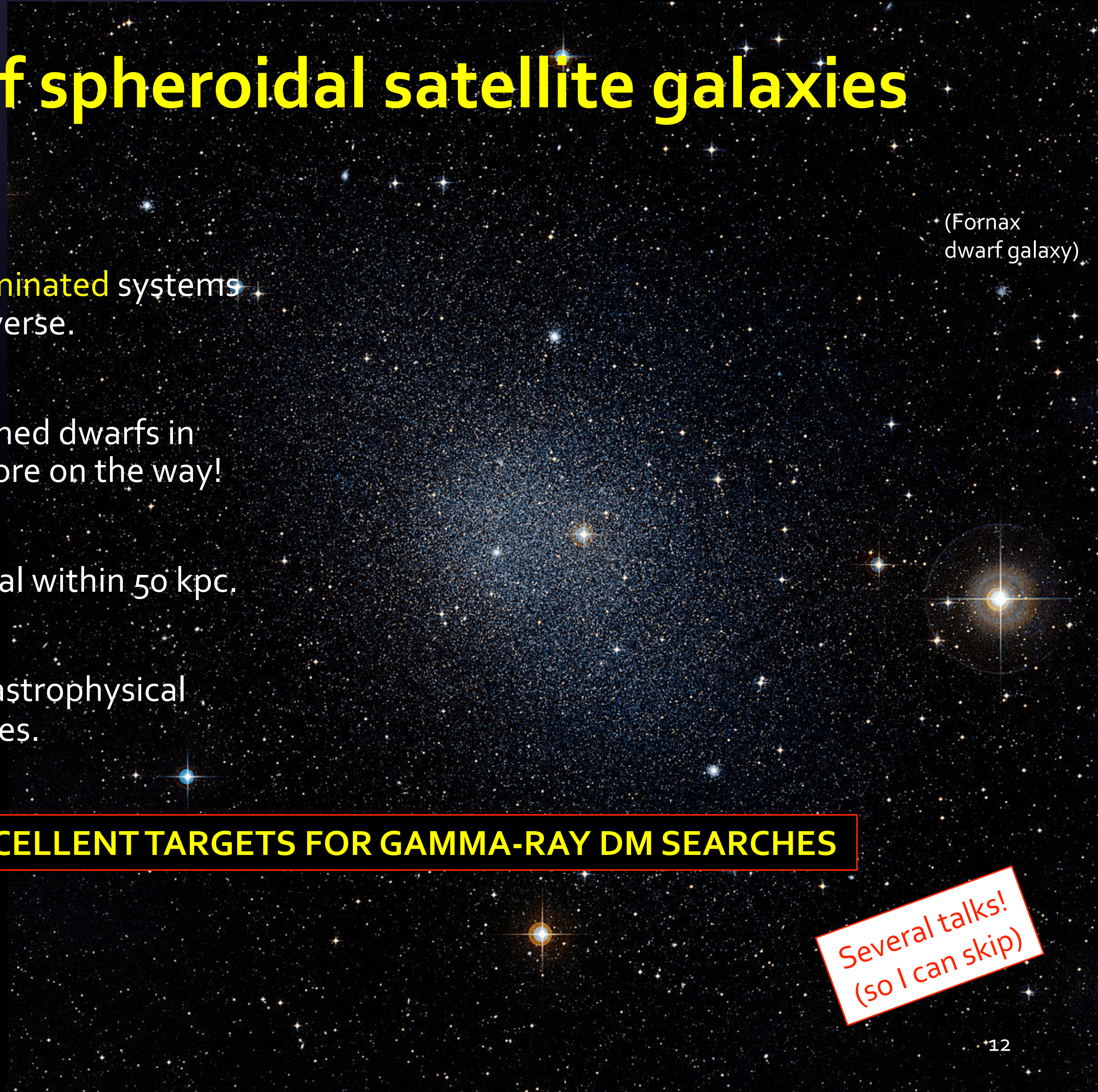
Dwarf spheroidal satellite galaxies



(Fornax dwarf galaxy)

- The most DM dominated systems known in the Universe.
- Around 30 confirmed dwarfs in the Milky Way. More on the way!
- Close to us. Several within 50 kpc.
- Free from bright astrophysical gamma-ray sources.

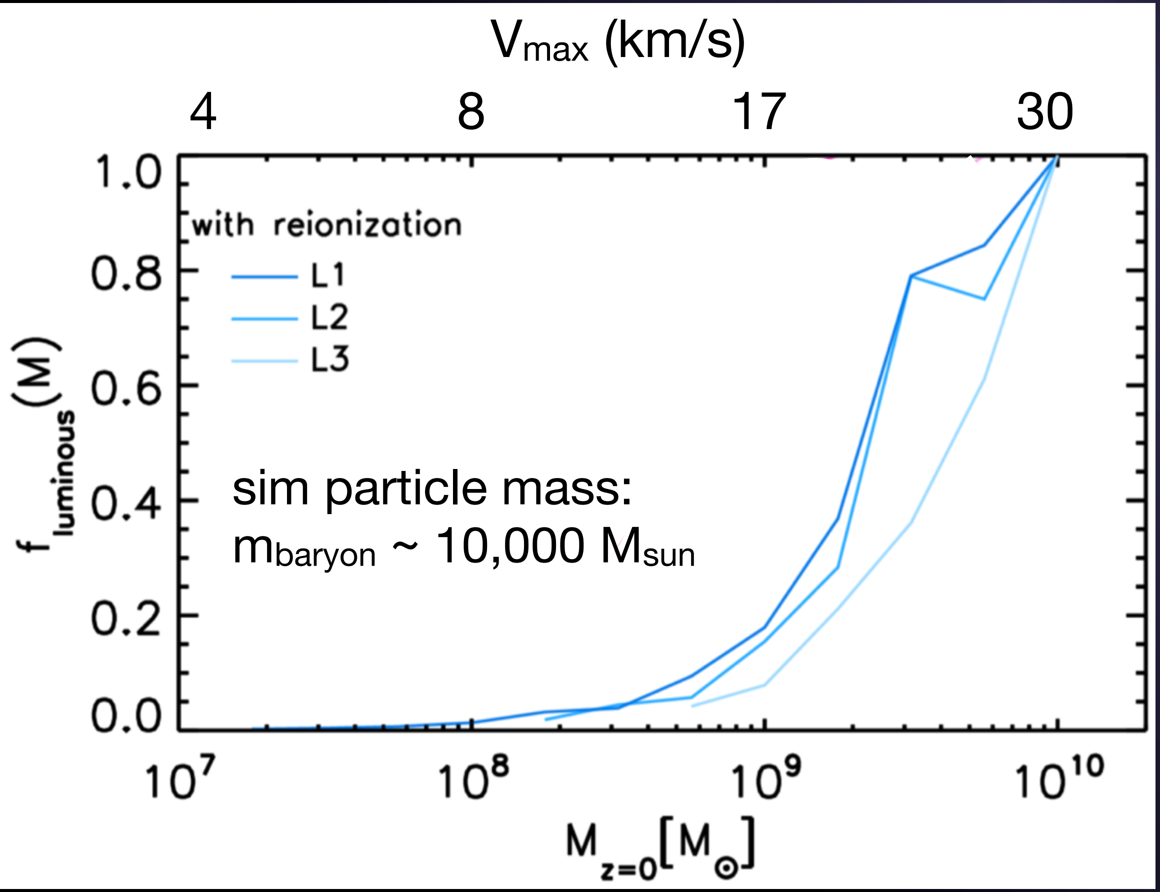
EXCELLENT TARGETS FOR GAMMA-RAY DM SEARCHES

Several talks!
(so I can skip)

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 ~ $10^8\, M_{sun}$

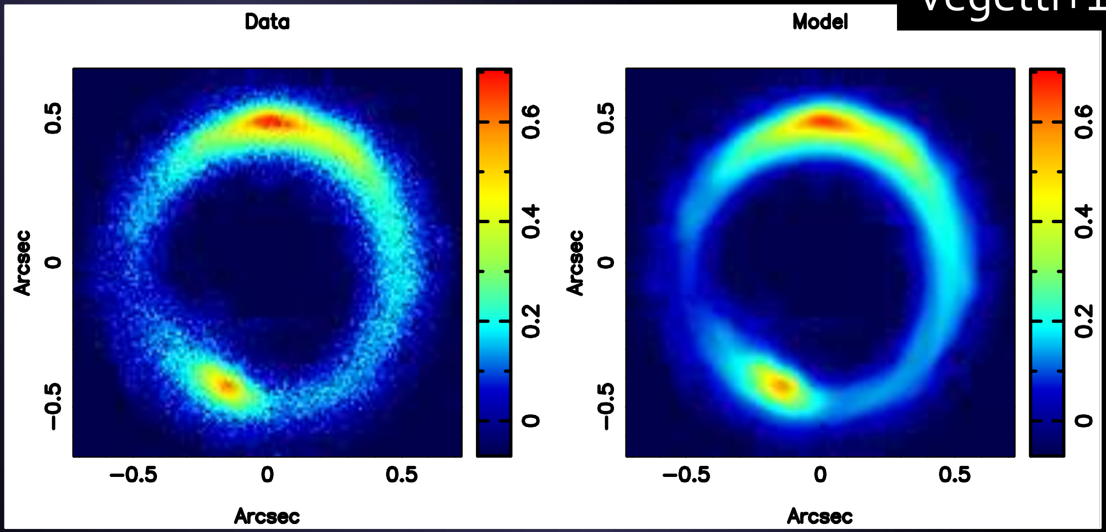
Subhalos can lose >90% of its mass due to tidal forces

→ dark subhalos < $10^7\, M_{sun}$

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

DM subhalo searches

Vegetti+12

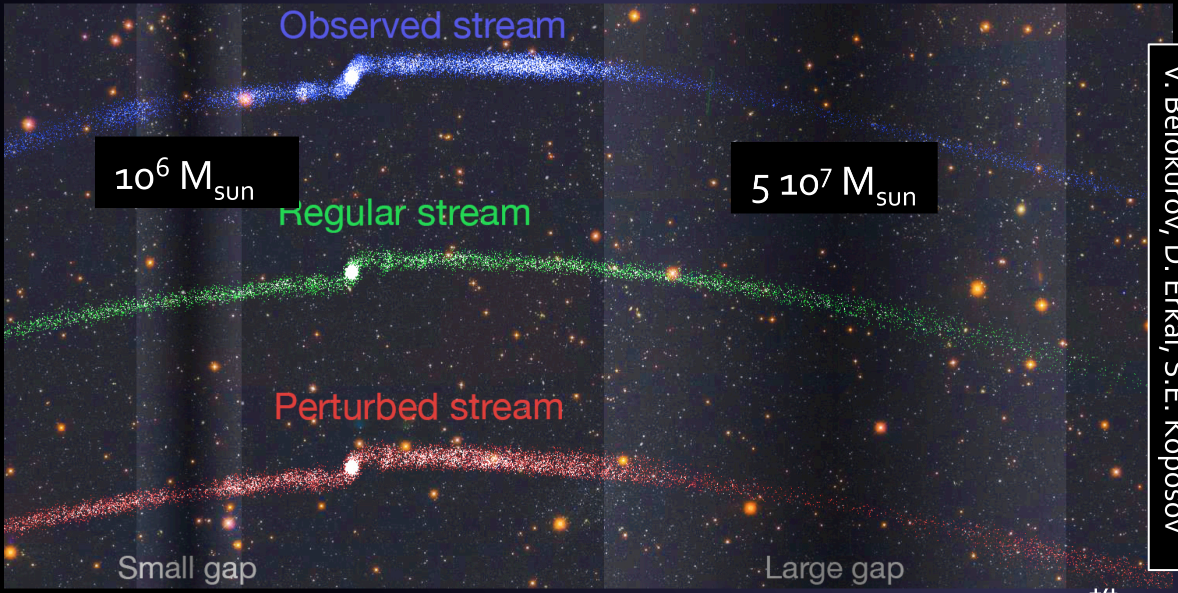


I. (Strong) LENSING

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

II. STELLAR GAPS

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



$10^6\ M_{sun}$

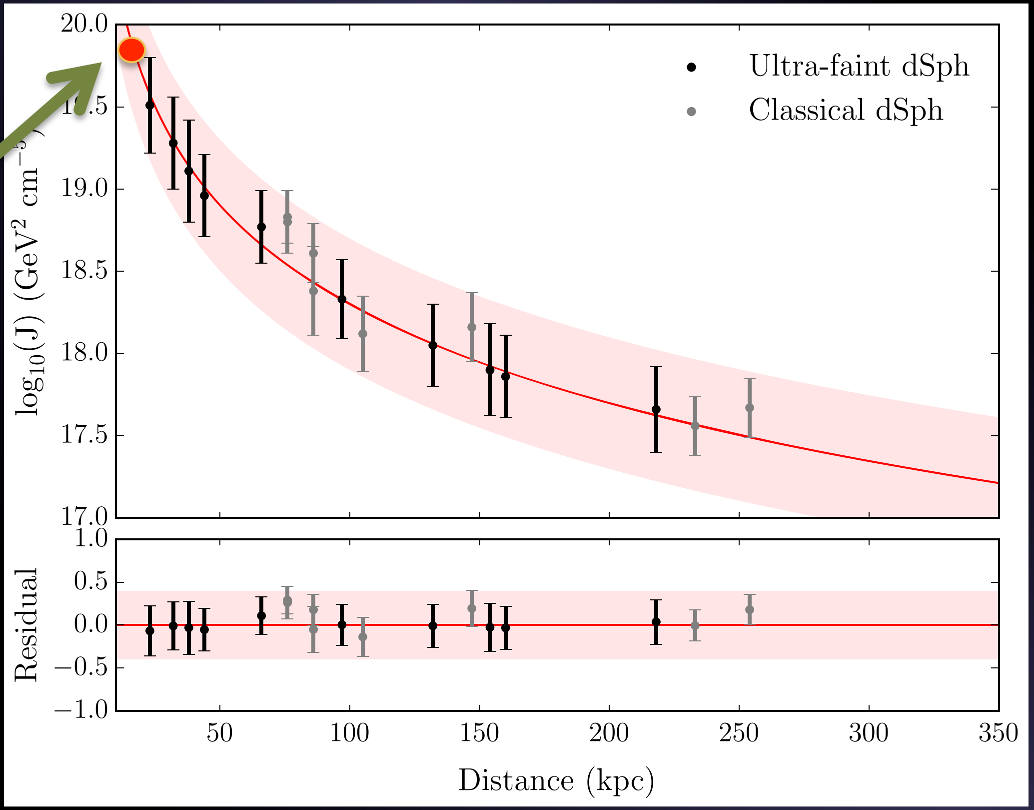
$5\ 10^7\ M_{sun}$

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.

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



Adapted from Albert+15

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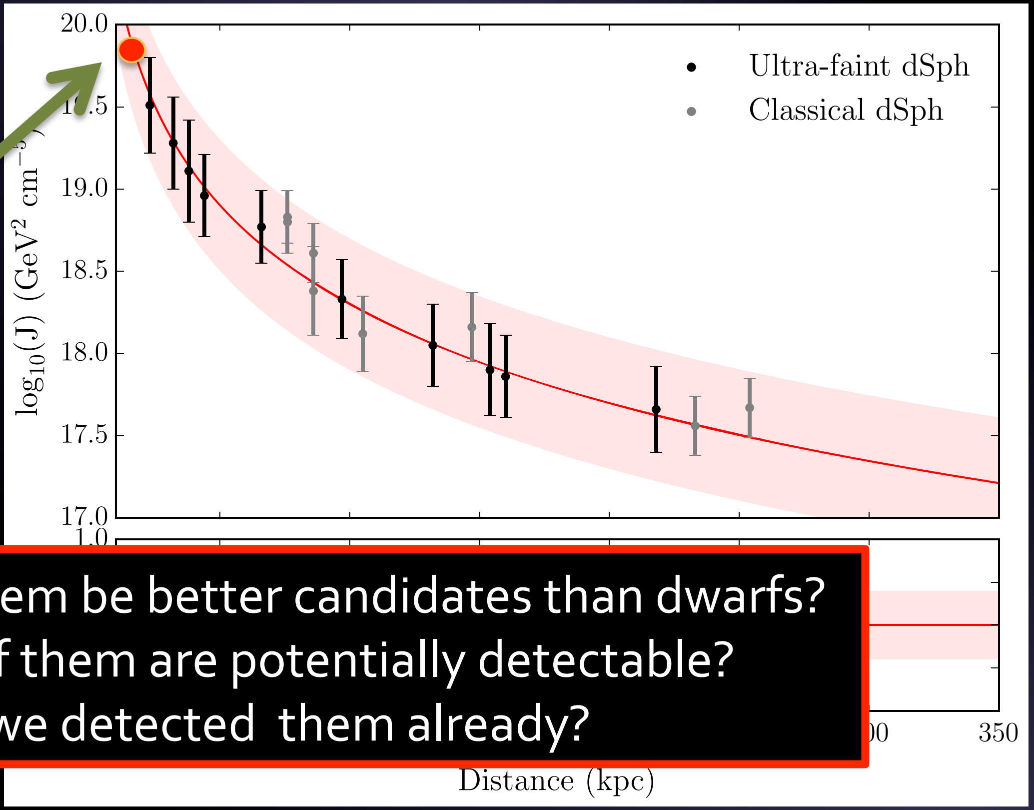

Adapted from Albert+15

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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Method:

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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 and spatial properties.

LAT sensitivity to DM annihilation → number of detectable subhalos.

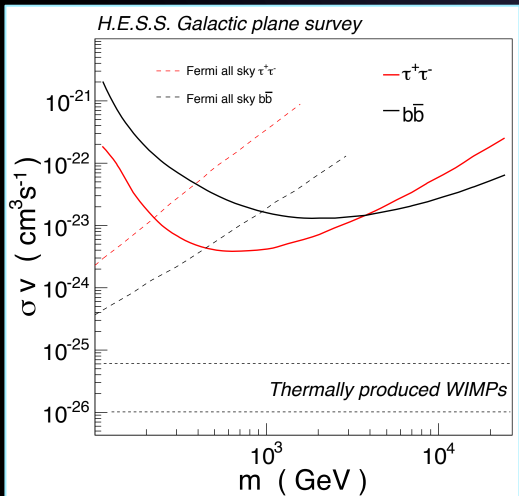
Number of predicted detectable subhalos VS. number of remaining unIDs in catalogs.

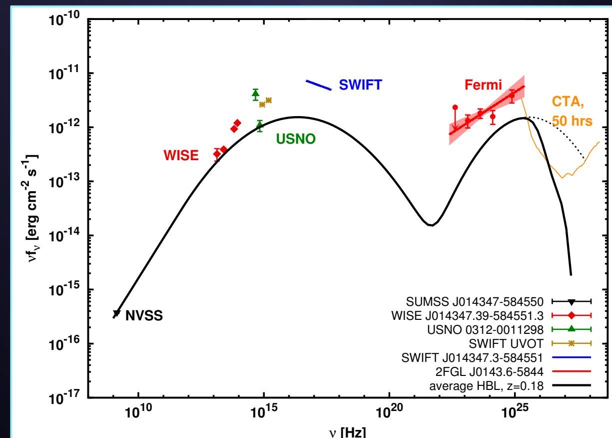
DM CONSTRAINTS

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

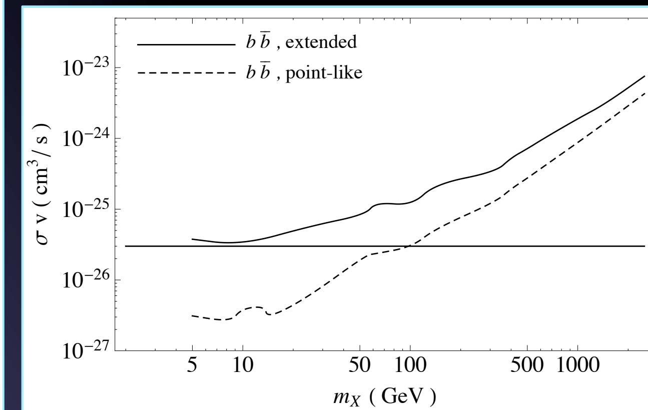
(Some) past work

Brun+11

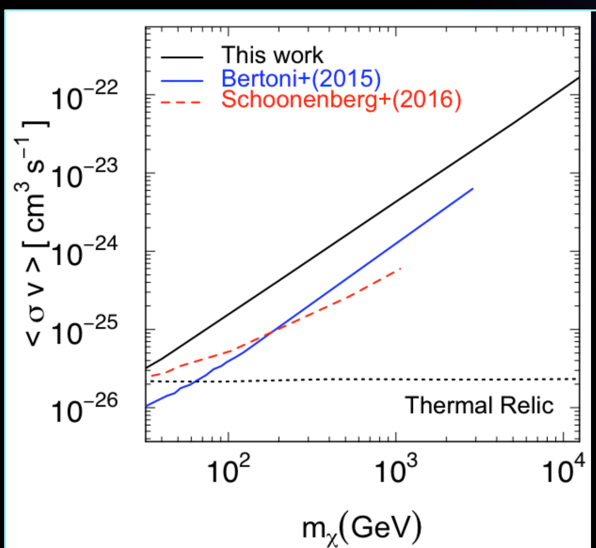




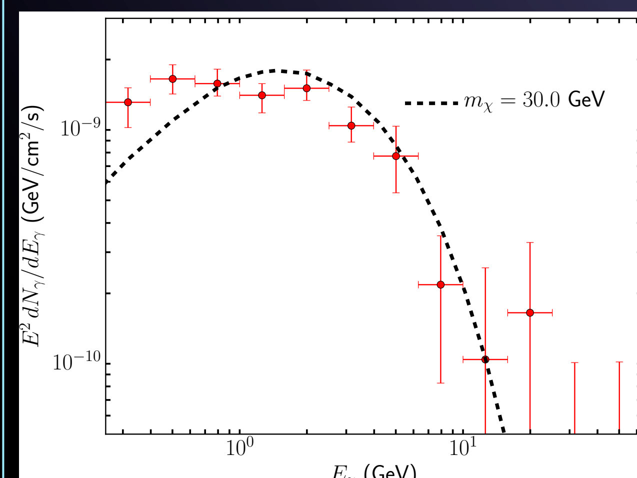
Zechlin+12;+13



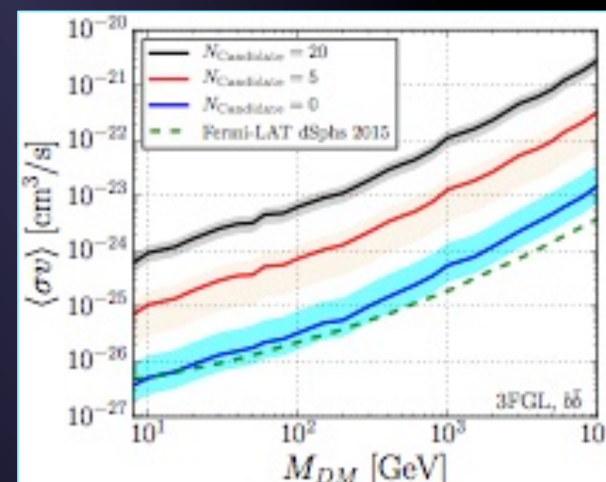
Berlin&Hooper 13



Mirabal+16



Bertoni+16



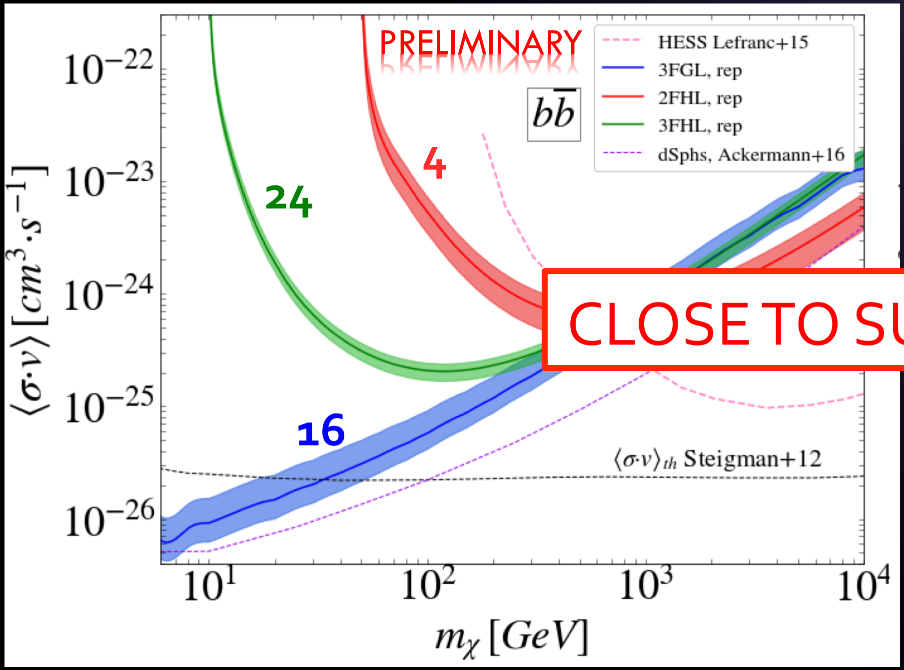
Calore+17

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

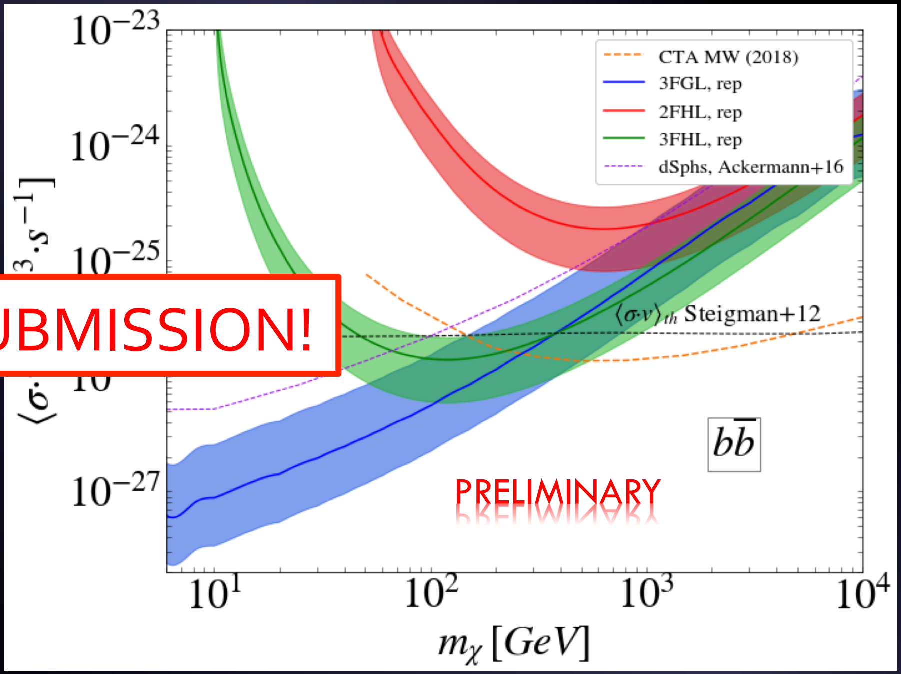
New LAT work ongoing

[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 (1 subhalo)

Some OPEN ISSUES

- Subhalo mass function.
- 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.

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DM annihilation boost factor from substructure

DM annihilation signal is proportional to the DM density squared
→ *Enhancement of the DM annihilation signal expected due to subhalos.*

Substructure **BOOST FACTOR**: $L = L_{host} * [1+B]$, so B=0 → no boost
B=1 → L_{host} x 2 due to subhalos

$$B(M) = \frac{1}{L(M)} \int_{M_{min}}^{M} (dN/dm)\ [1 + B(m)]\ L(m)\ dm$$

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Subhalo mass function

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(dN/dm): Subhalo mass function

$L(m)$: Subhalo luminosity

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Minimum halo mass

Subhalo mass function

Subhalo luminosity

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- M_{min}: Minimum halo mass
- (dN/dm): Subhalo mass function
- $[1 + B(m)]$: Other levels of sub-substructure
- $L(m)$: Subhalo luminosity

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$$B(M) = \frac{1}{L(M)} \int_{M_{min}}^{M} (dN/dm)\,[1+B(m)]\,L(m)\,dm$$

- $L(M)$: Host halo luminosity
- M_{min}: Minimum halo mass
- (dN/dm): Subhalo mass function
- $[1+B(m)]$: Other levels of sub-substructure
- $L(m)$: Subhalo luminosity

B(M) depends on the internal structure of the subhalos and their abundance

→ N-body cosmological simulations

- Integration down to the minimum predicted halo mass ~10^{-6} Msun.
- Current Milky Way-size simulations "only" resolve subhalos down to ~10^5 Msun.

→ ***Extrapolations below the mass resolution*** *needed.*

Subhalo mass function

$$dN/dm = A/M(m/M)^{-\alpha}$$

α = -1.9 in Aquarius
α = -2 in VL-II

Subhalo annihilation luminosity

J-factor $\propto \rho_s^2 r_s^3 \propto M \frac{c^3}{f(c)^2}$ with

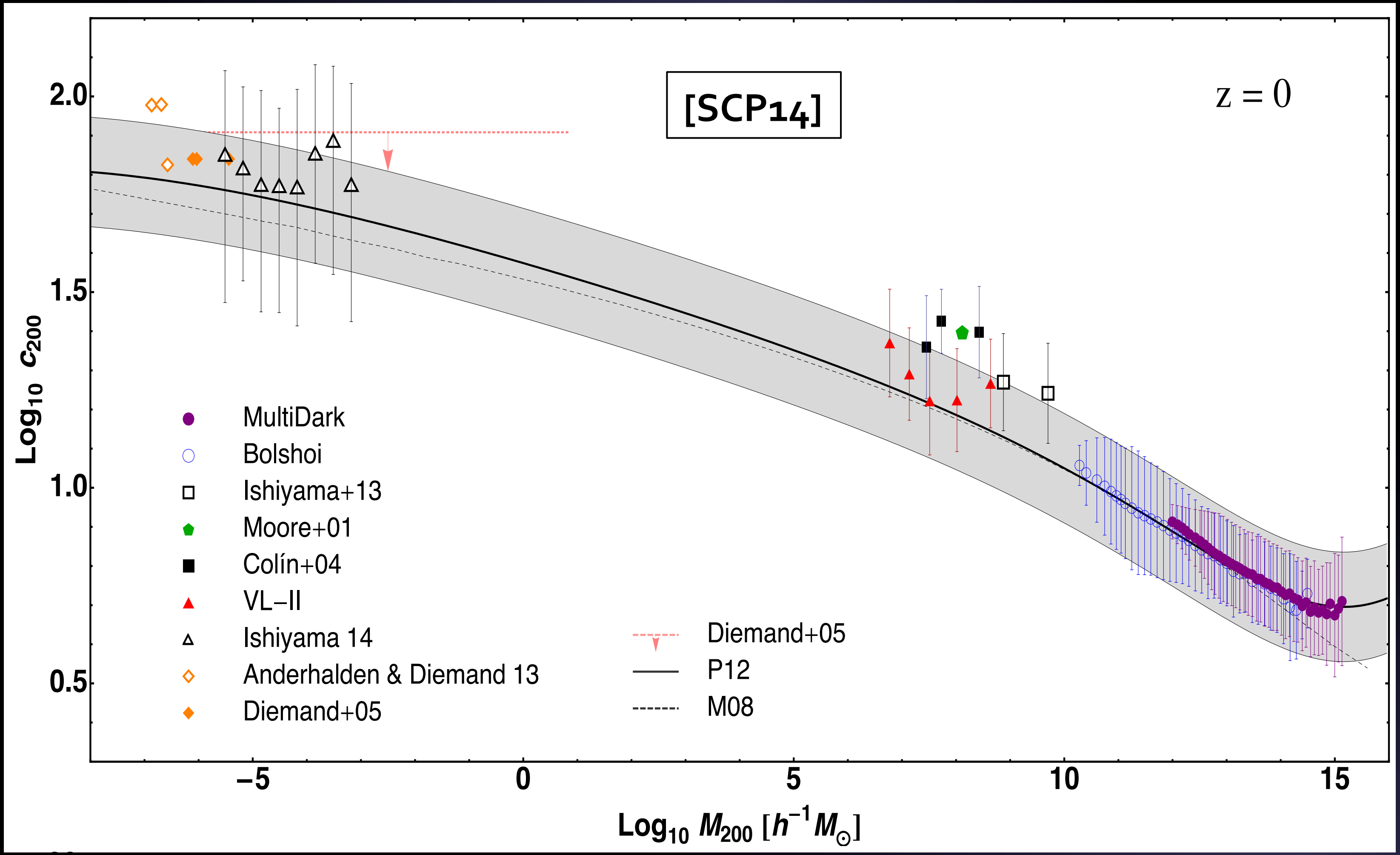
Concentration c = R_{vir} / r_s

$$f(c) = ln(1+c) - c/(1+c)$$

→ Results very sensitive to the c(M) extrapolations down to M_{min}

Current knowledge of the c(M) relation at z=0

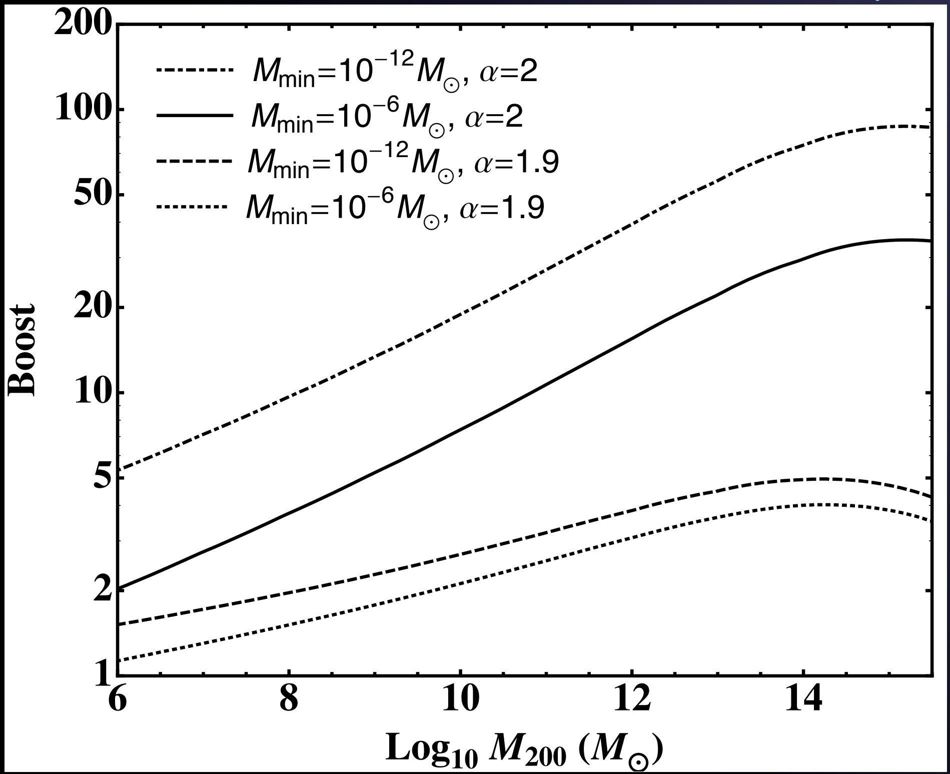
Concentration $c = R_{vir} / r_s$

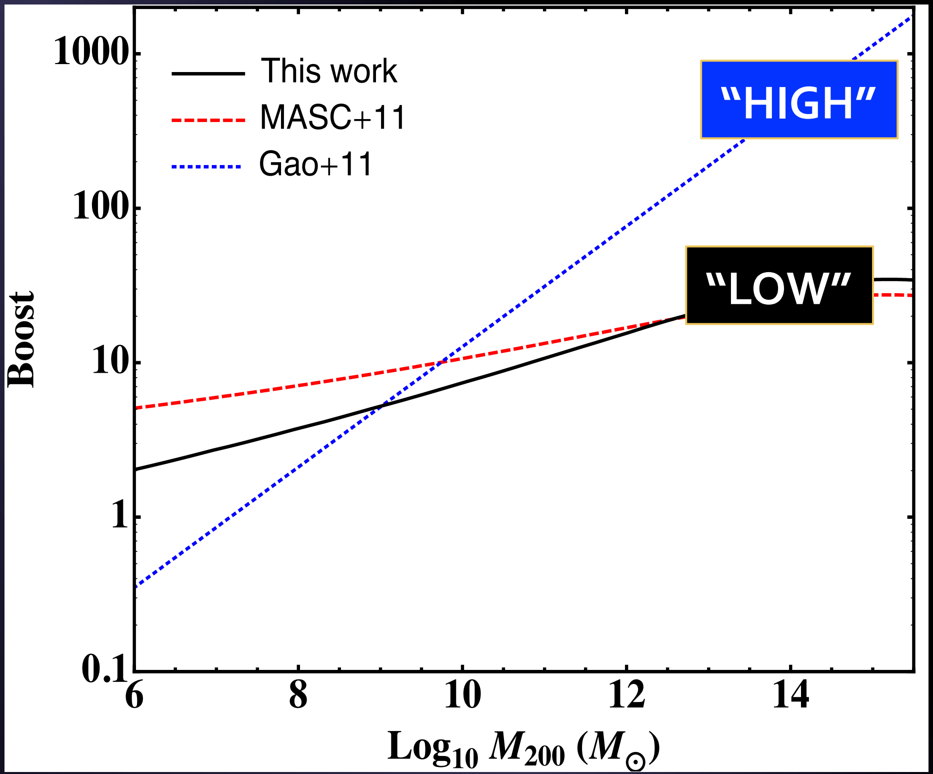


MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]

SCP14 substructure boosts

MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]





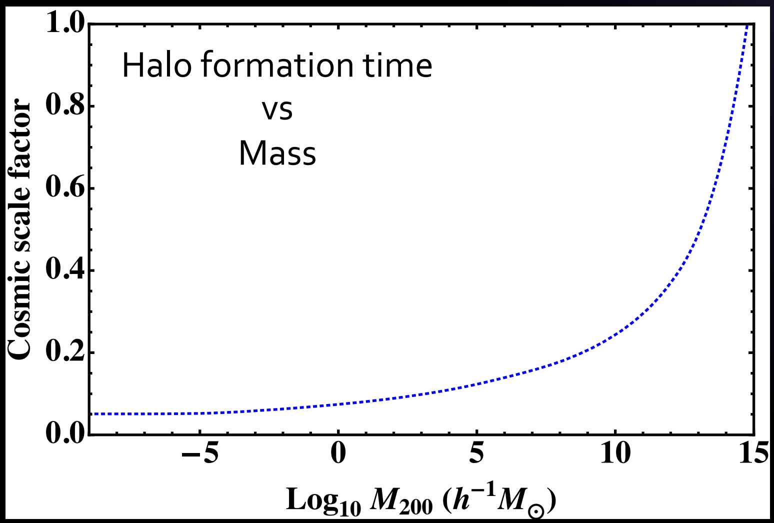
Variation with M_{min} and α
[only first two substructure levels included]

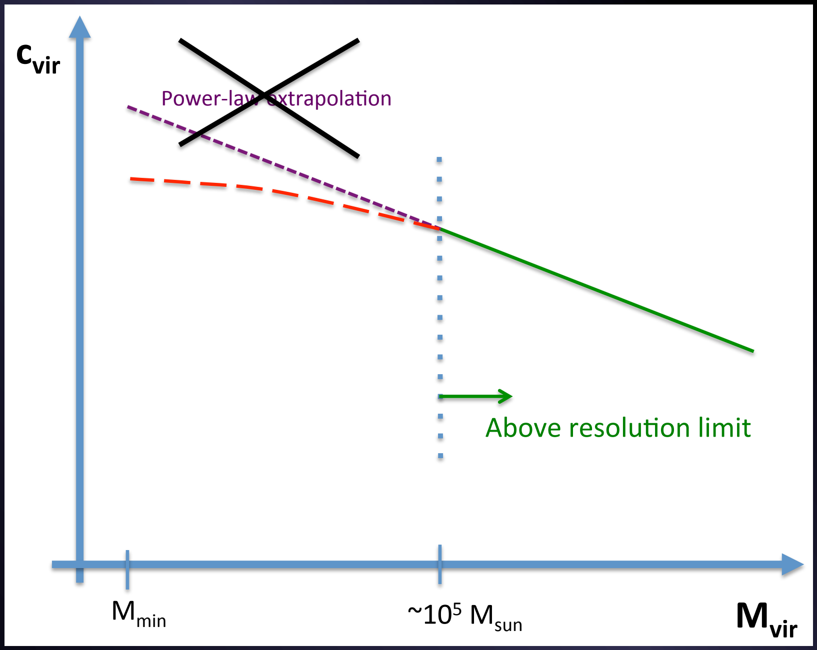
Comparison with previous boost models

Warning: they all assume that both main halos and subhalos possess similar structural properties…

What does ΛCDM tell us about c(M) at the smallest scales?

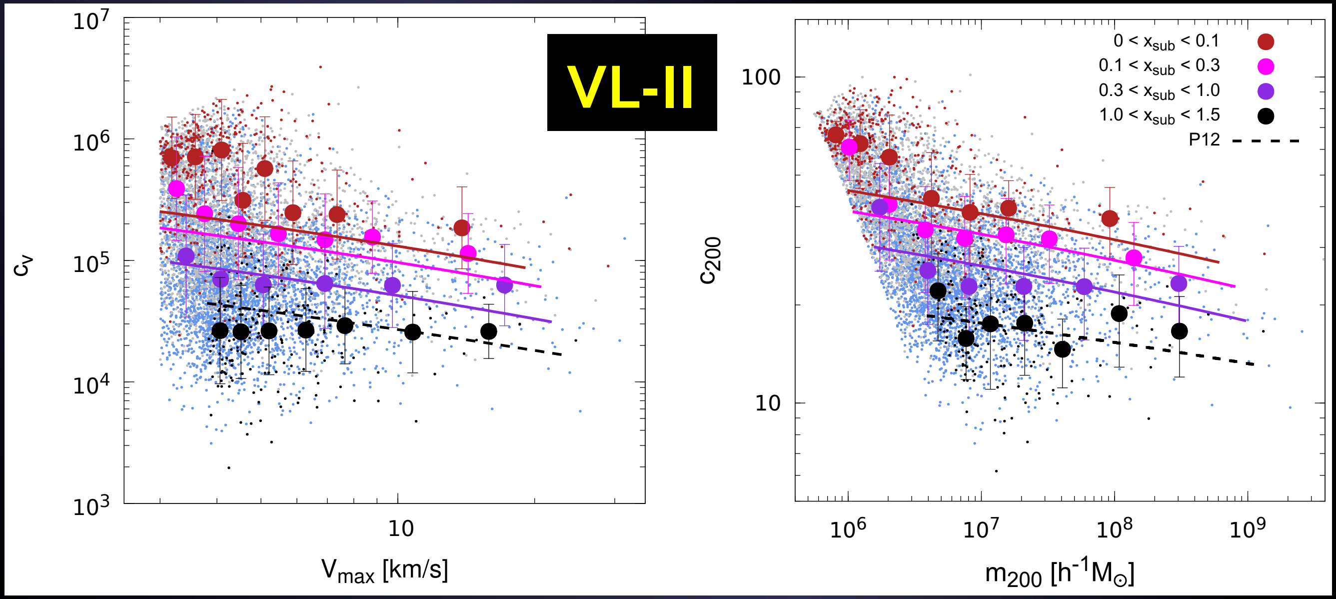
- Natal concentrations are mainly set by the halo formation time.
- Given the CDM power spectrum , the smallest halos typically collapse *nearly* at the same time:
  - → Concentration is nearly the same for the smallest halos over a wide range of masses.
  - → power-law c(M) extrapolations not correct!

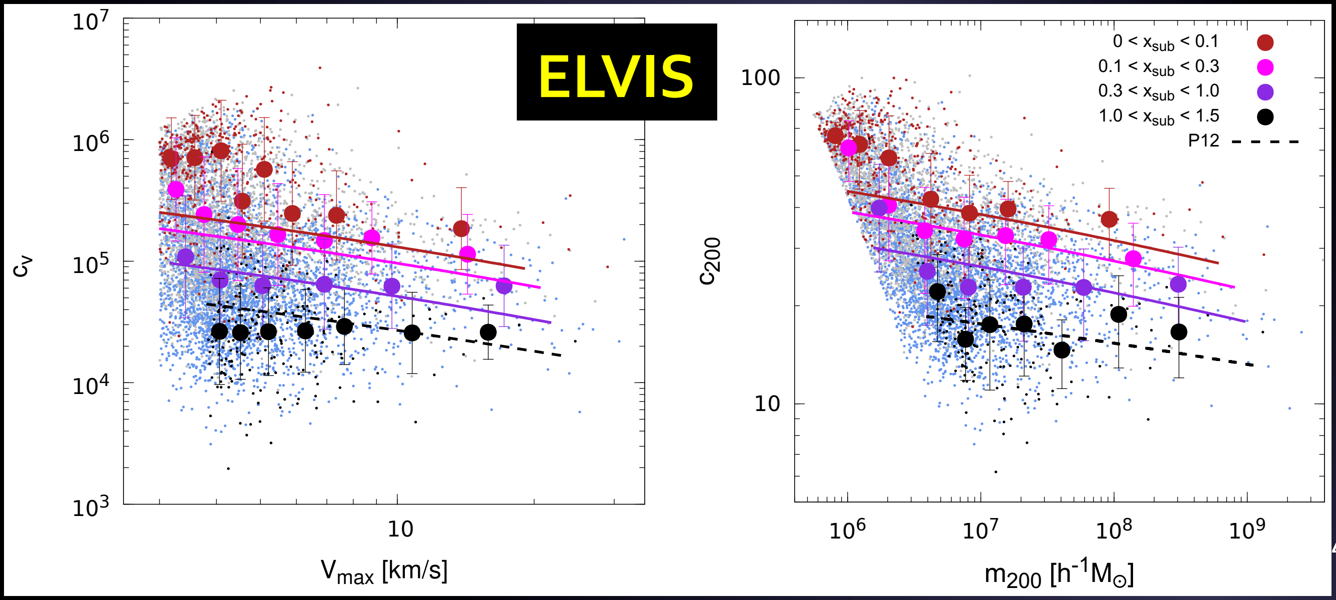




Subhalo concentrations from VL-II and ELVIS

Clear **increase** of subhalo concentration as we approach the host halo center!



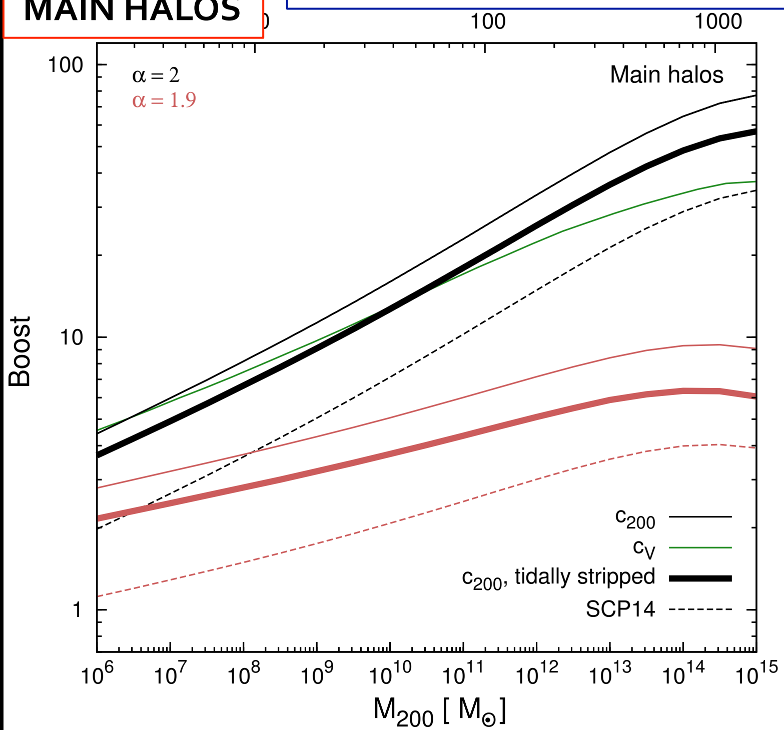


(Improved) subhalo boost model

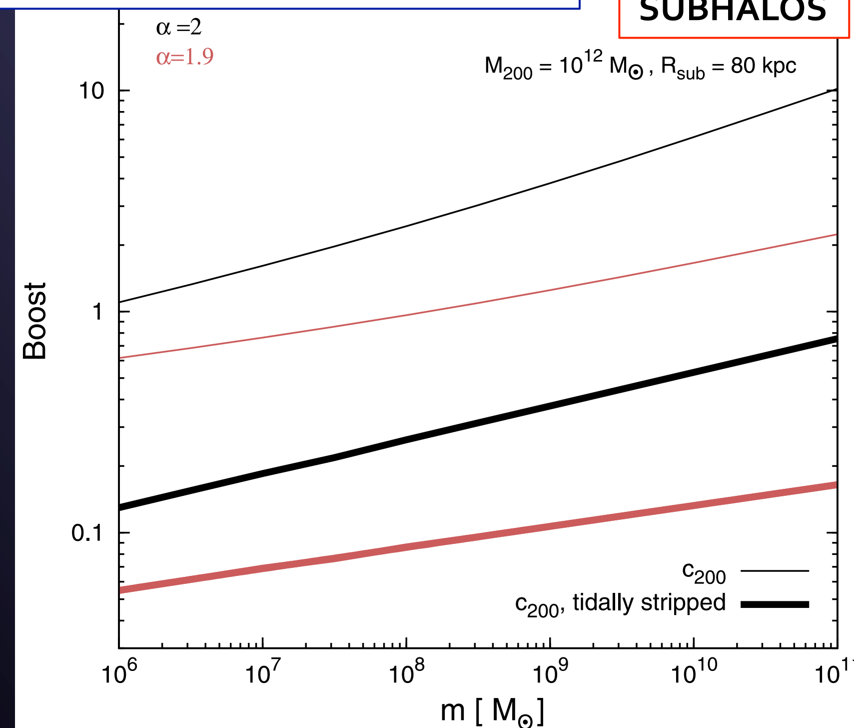
1. Make use of our better knowledge on subhalo concentrations.
2. Tidal stripping included (Roche criterium).

[Moliné, MASC, Palomares and Prada (2017) MNRAS, 466, 4974]

MAIN HALOS



SUBHALOS



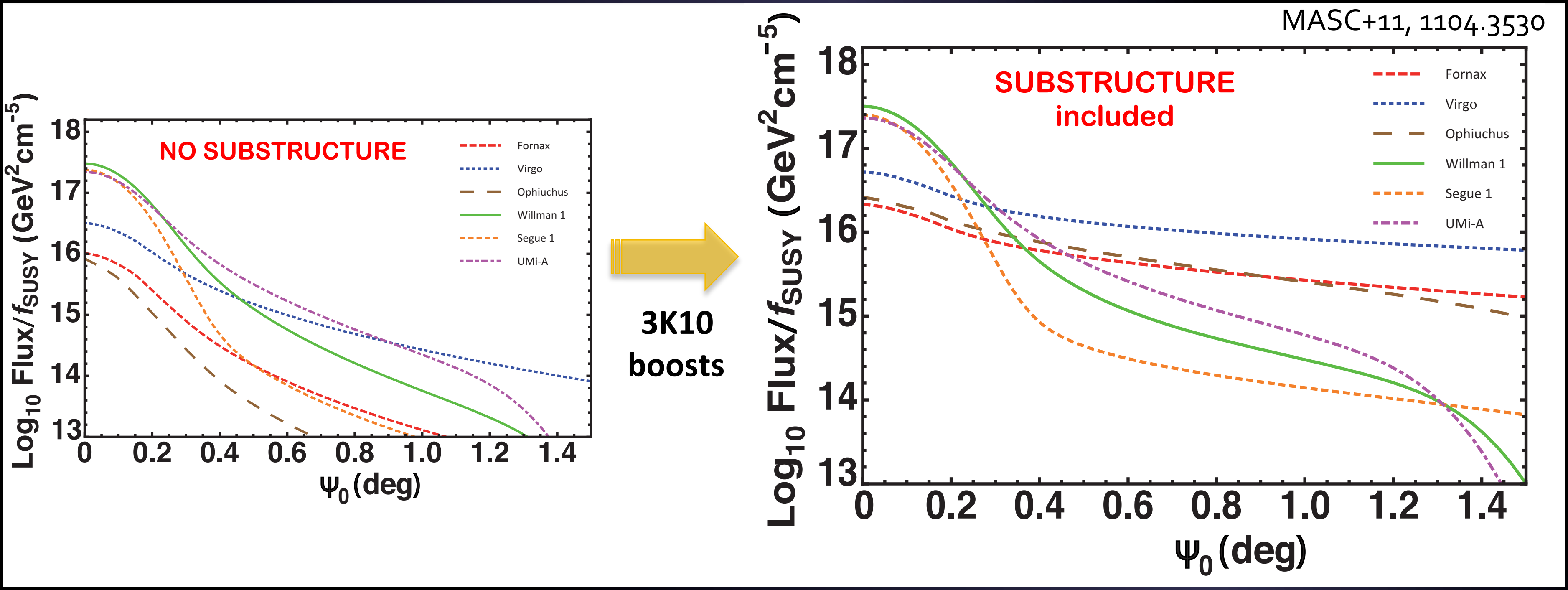
O(30) boost for MW-size halos
(factor ~2 higher than SCP14)

Very small boost for subhalos, e.g. **dwarfs**

[Agrees also with Bartels & Ando (2015) and Zavala & Afshordi (2015)]

Substructure modifies the annihilation flux profile

[MASC, Cannoni, Zandanel et al., JCAP 12 (2011) 011]



Annihilation signal becomes *more spatially extended*.

Some remarks

- Halo substructure is an unavoidable prediction of ΛCDM.
  - 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 signal spatial properties.

DM halo substructure CRITICAL for current and future gamma-ray DM search strategies.

Thanks!

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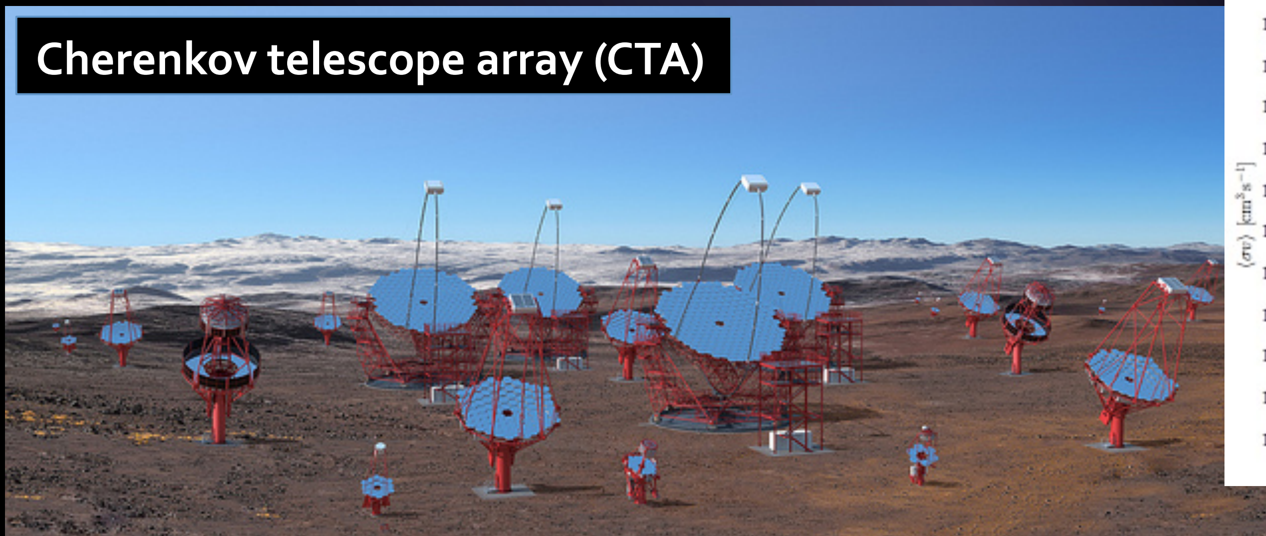
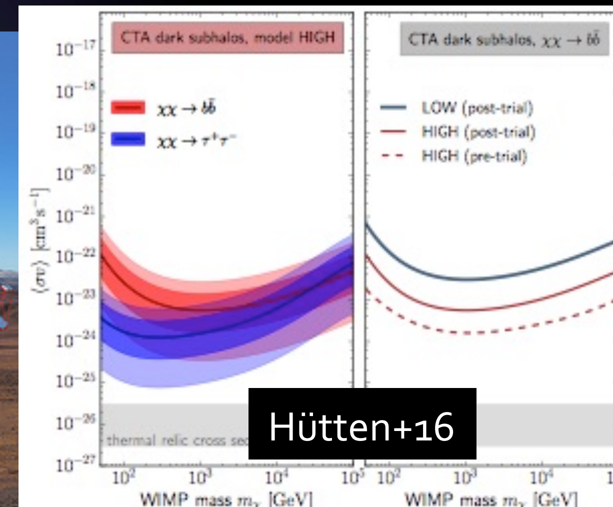
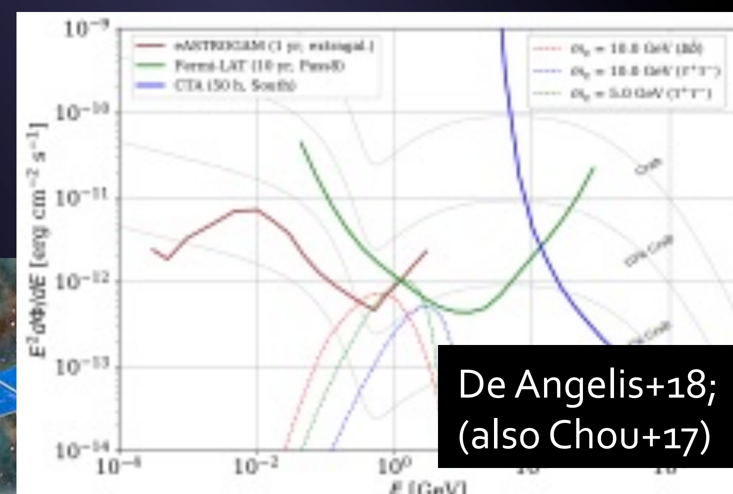
ADDITIONAL MATERIAL

Future of dark satellites' searches with gamma rays





Future
MeV/sub-GeV missions

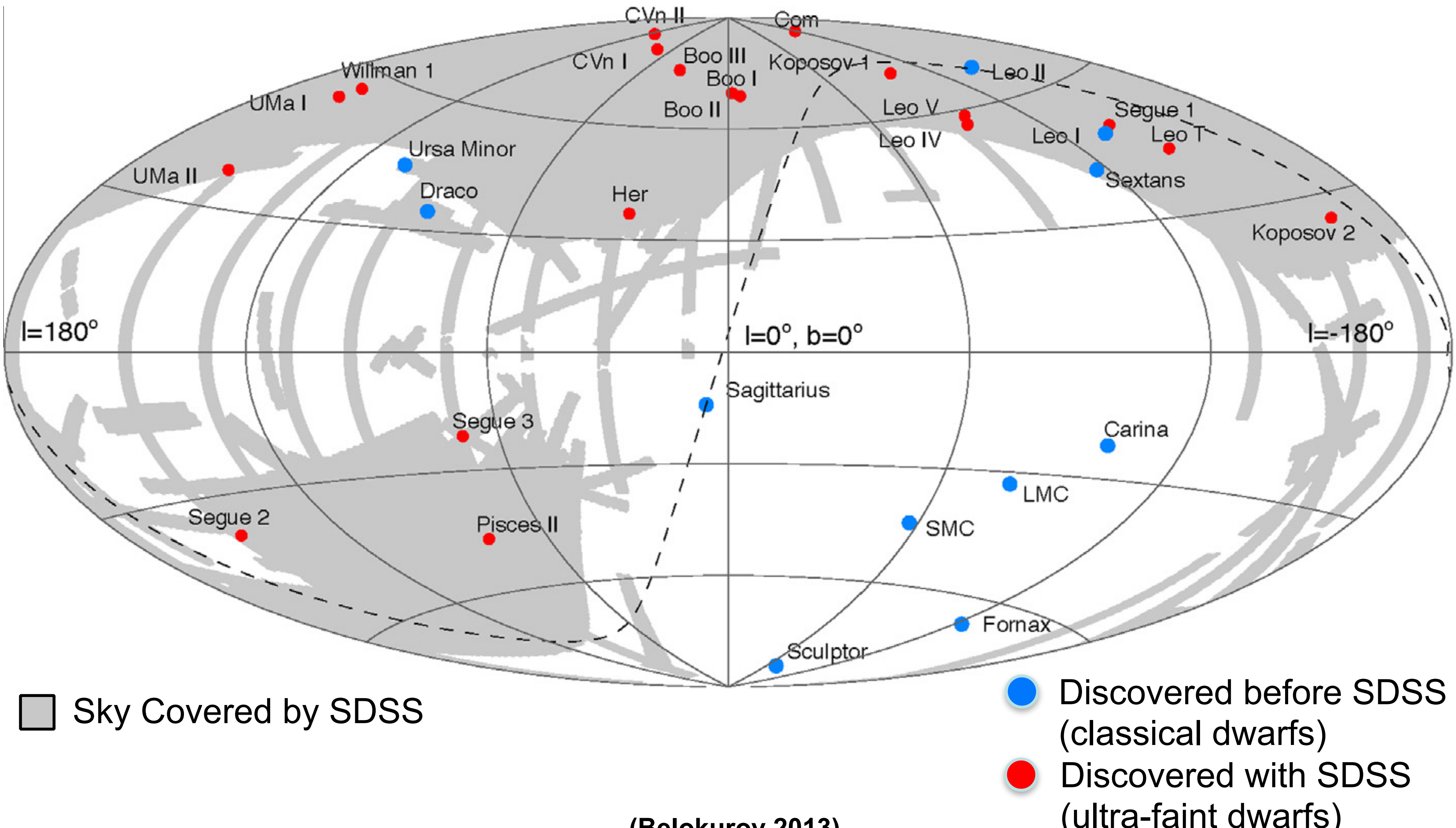


Future of dark satellites' searches with gamma rays

- Higher resolution DM-only and hydro simulations to shed 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.

Census of dwarfs (circa 2014)

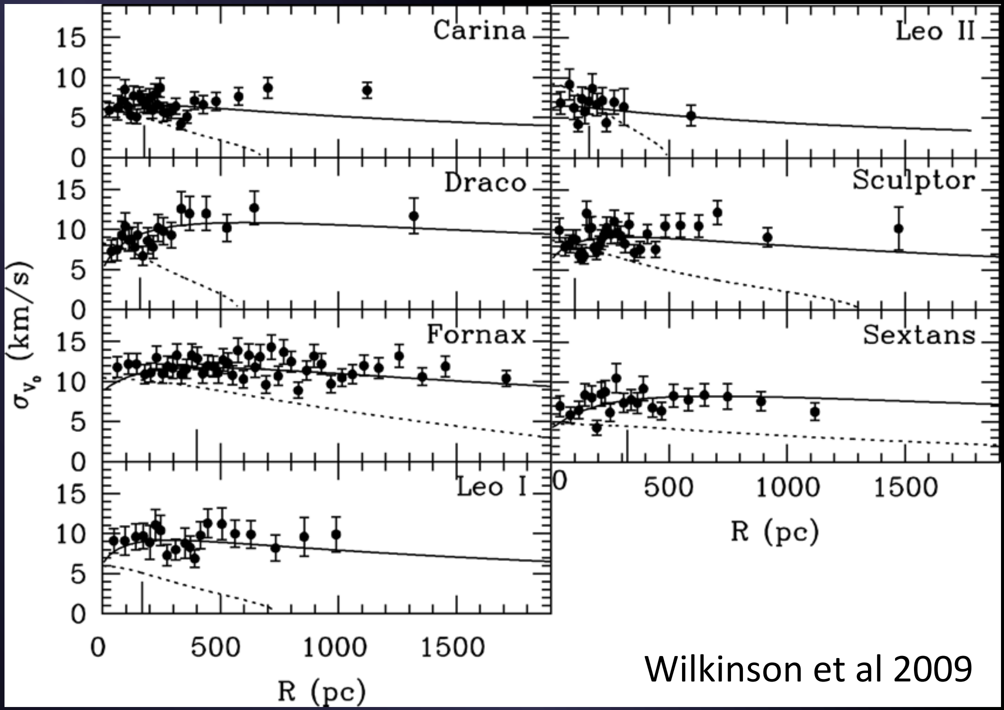


(Belokurov 2013)

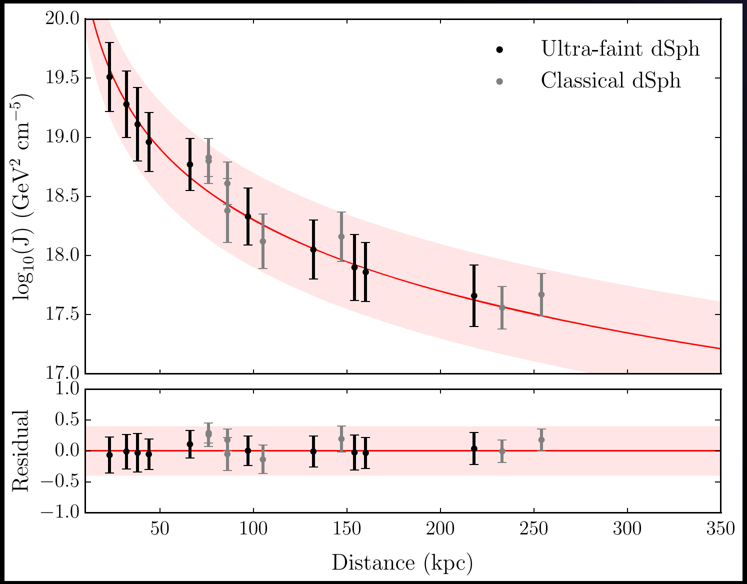
[A. Drlica-Wagner, Berolo, Sep 17]

Measuring the DM content in dwarfs

- Determined spectroscopically from **stellar velocity dispersions**:
  - O(100) in classical dwarfs.
  - O(10) in ultra-faint dwarfs.
- Dispersion profiles generally remain flat up to large radii
  → **highly DM dominated**



Wilkinson et al 2009



Albert+15

"J-factor" of MW dwarf satellite galaxies inferred from:

- l.o.s. velocity dispersion profiles
- DM density profile (e.g. NFW)

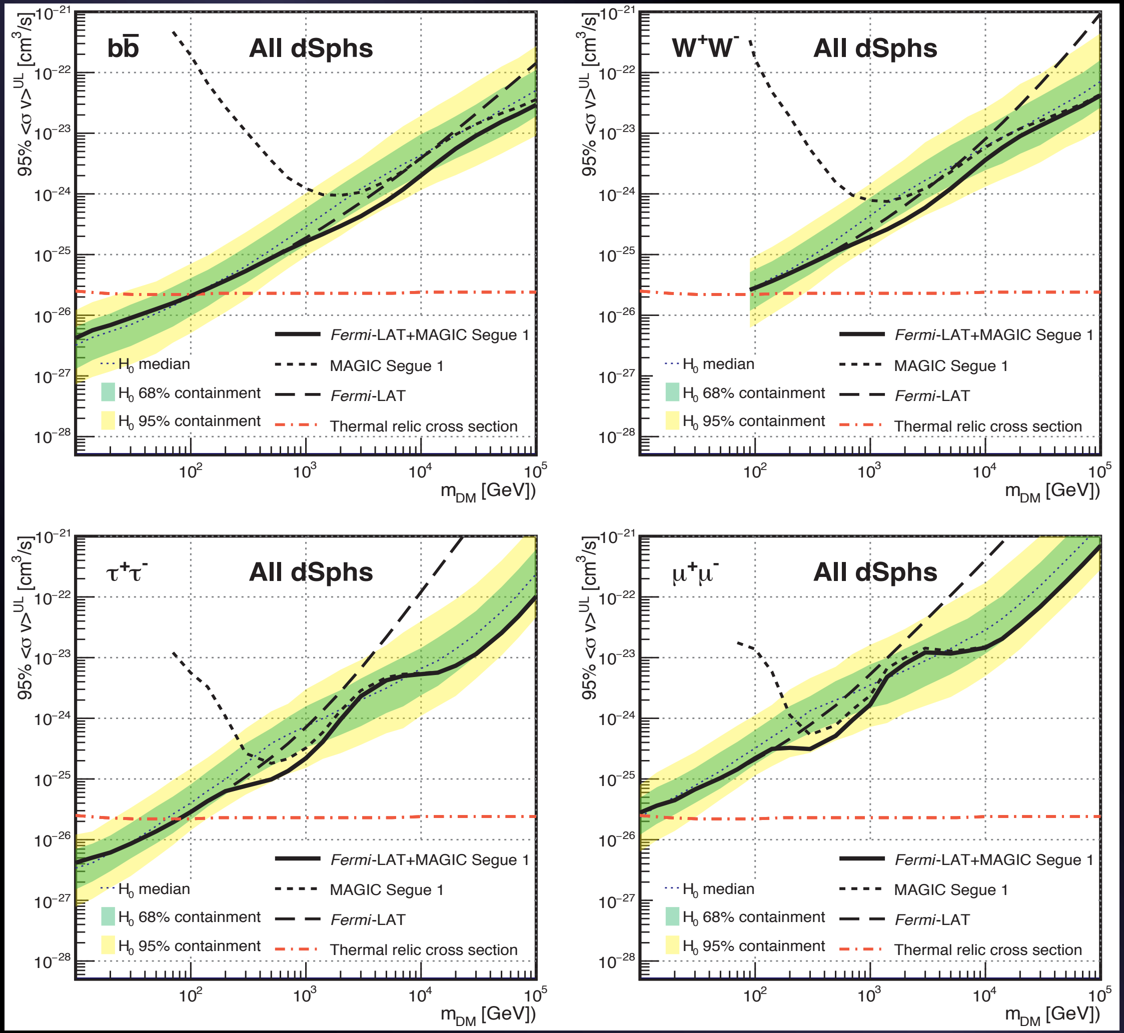
MAGIC + Fermi-LAT combined limits

MAGIC: Segue 1, 158 h
Fermi-LAT: 15 dwarfs, 6 yr

Combined likelihood, global analysis

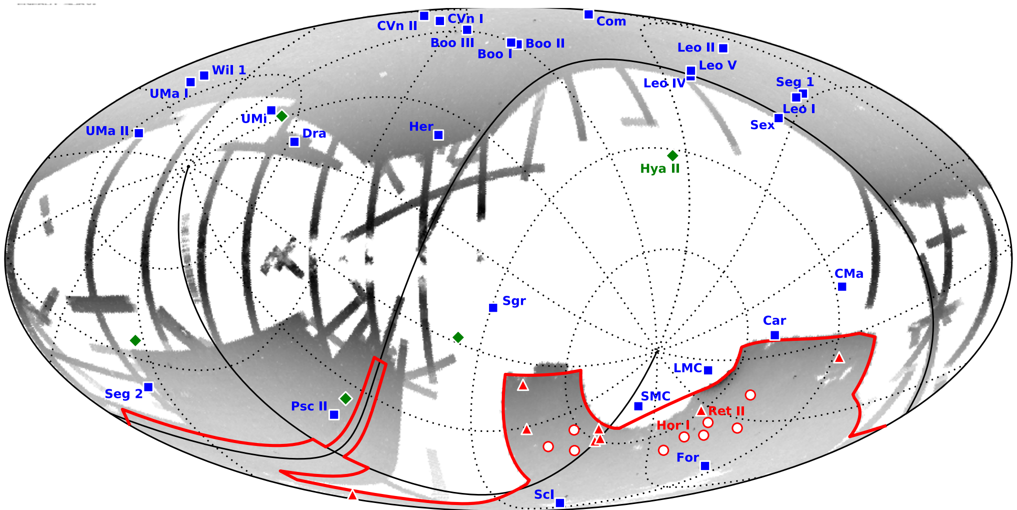
Most constraining results between **10 GeV to 100 TeV**

Same method can be easily used to **combine** results from other experiments, targets, messengers



Ahnen+16, The MAGiC and Fermi-LAT collaborations; [1601.06590]

Recent discovery of new satellites



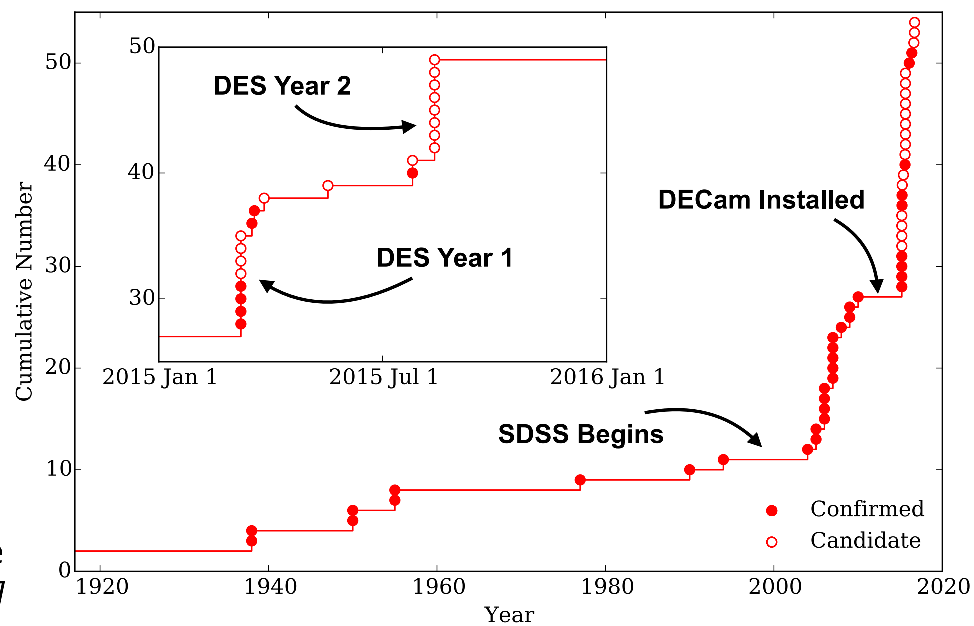
Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS/SDSS

Red outline - DES footprint
Red circles - DES Y1 satellites
Red triangles - DES Y2 satellites

>20 NEW DWARF CANDIDATES in 2015 alone!

[these dwarfs will help to improve the DM limits]

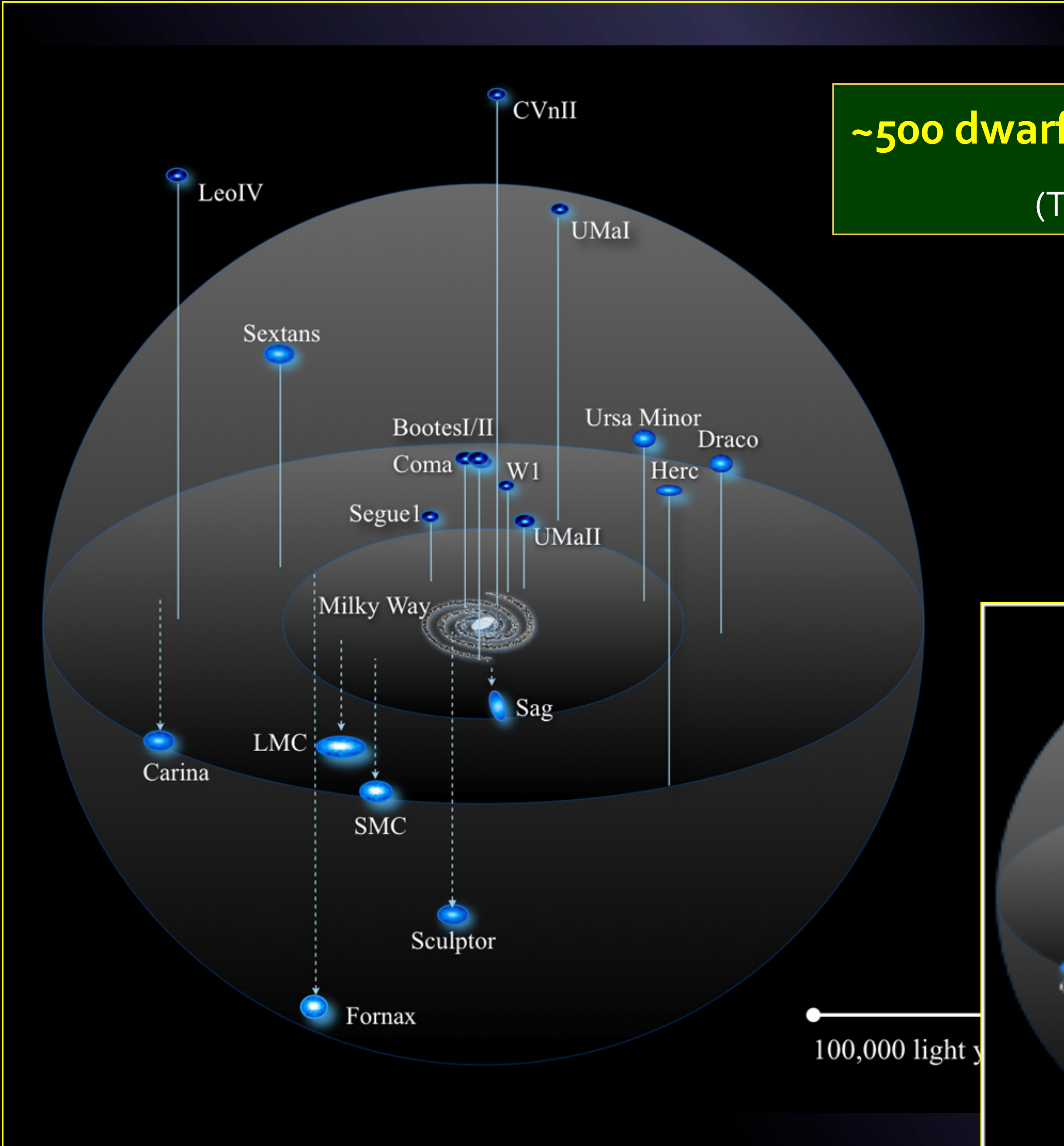
Bechtol+15
Drlica-Wagner+15
Leavens+15
Koposov+15
Kim&Jerjen15
Kim+15
Martin+15

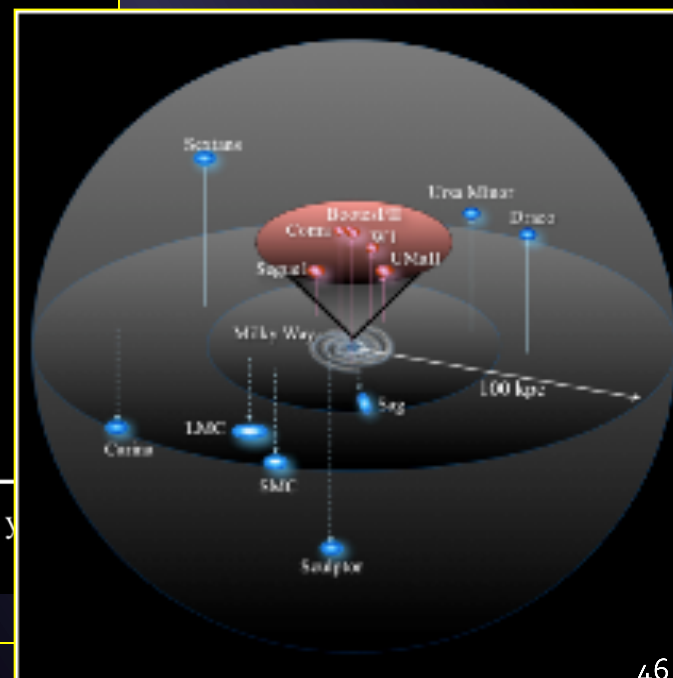


A. Drlica-Wagne
[Barolo, Sep 2017]

~500 dwarfs inside the virial radius?

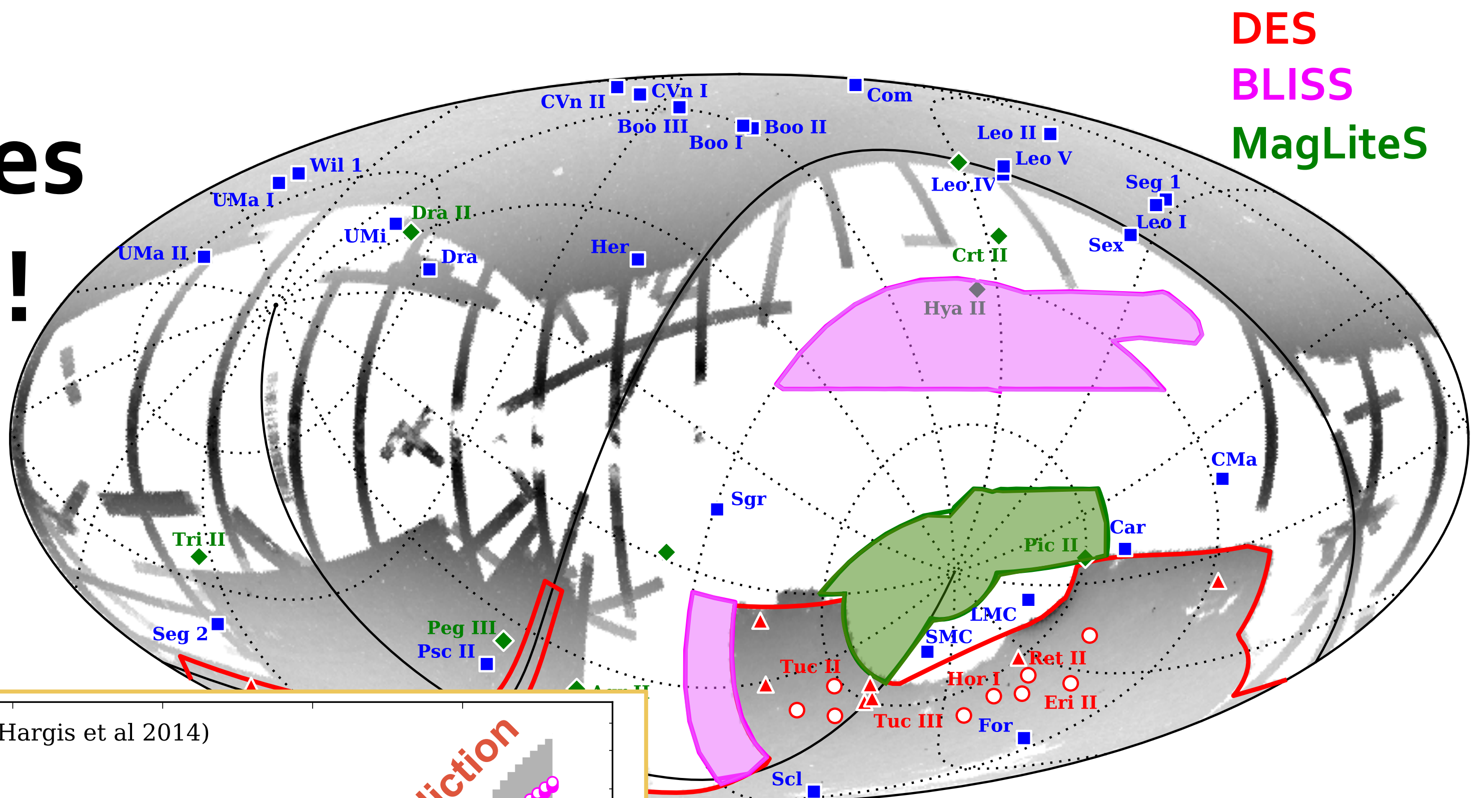
(Tollerud+08; Walsh+09; Hargis+14)

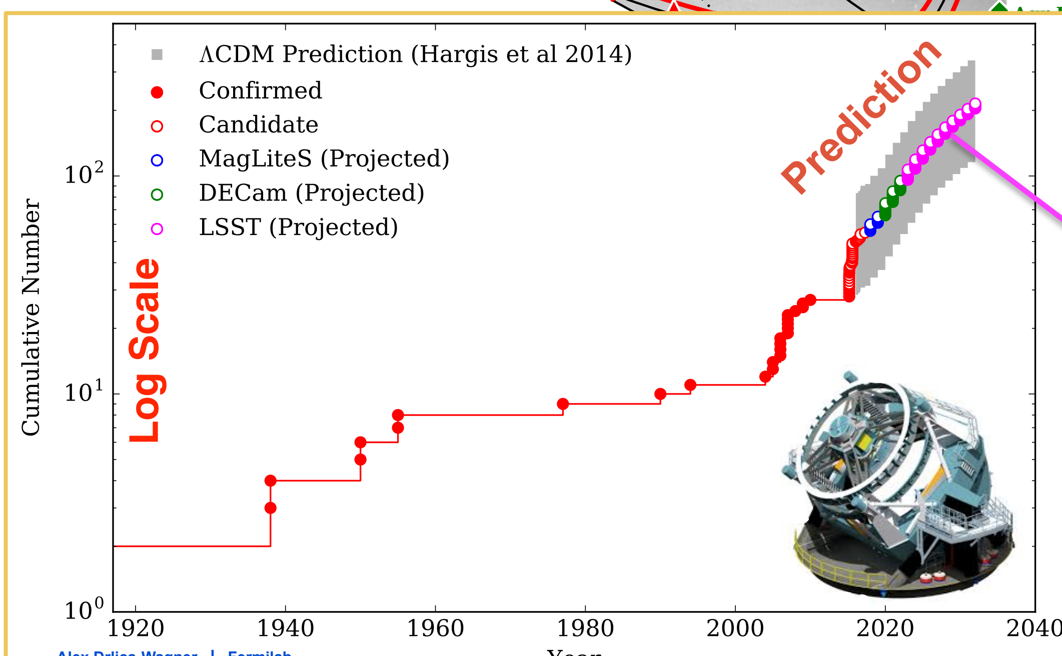




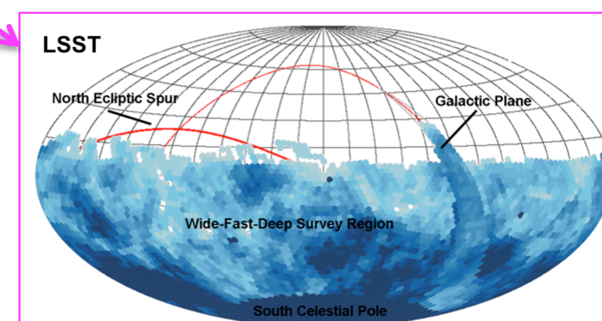
(Bullock et al. 2009)

More discoveries to come!





+ LSST coming!



New (LAT) work ongoing

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

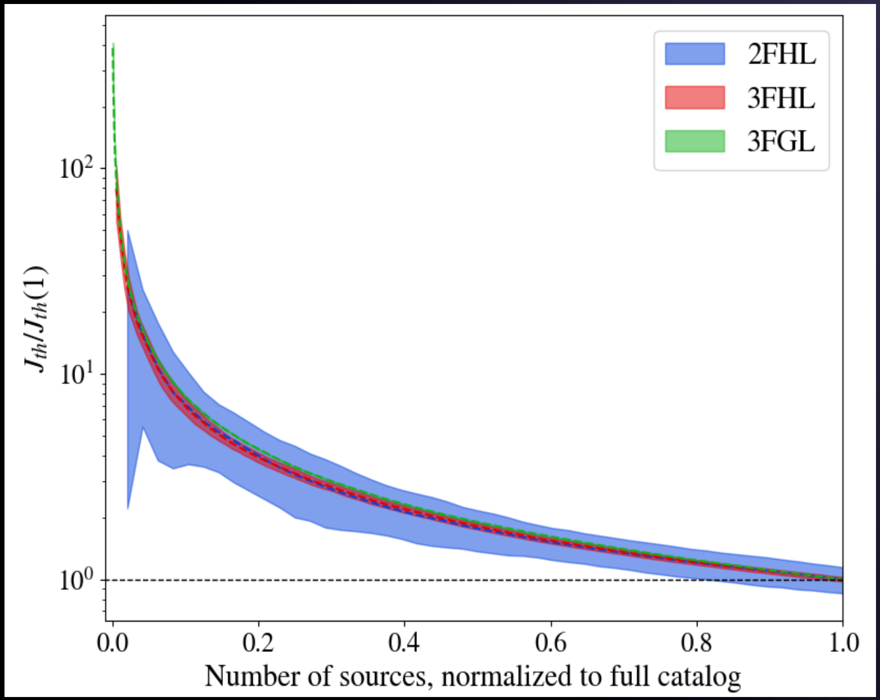
- Search in the most recent LAT catalogs (3FGL, 2FHL, 3FHL)
- Careful unID 'filtering' work.

DM subhalo search 'filters':

1. Associations
2. Variability
3. Latitude
4. Machine learning
5. Multiwavelength emission
6. Complex regions

(No spectral information used for the moment.)

Importance of unIDs “filtering”



- <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

Preliminary results:

	Original	Result
2FHL	48	4
3FHL	177	24
3FGL	1010	16

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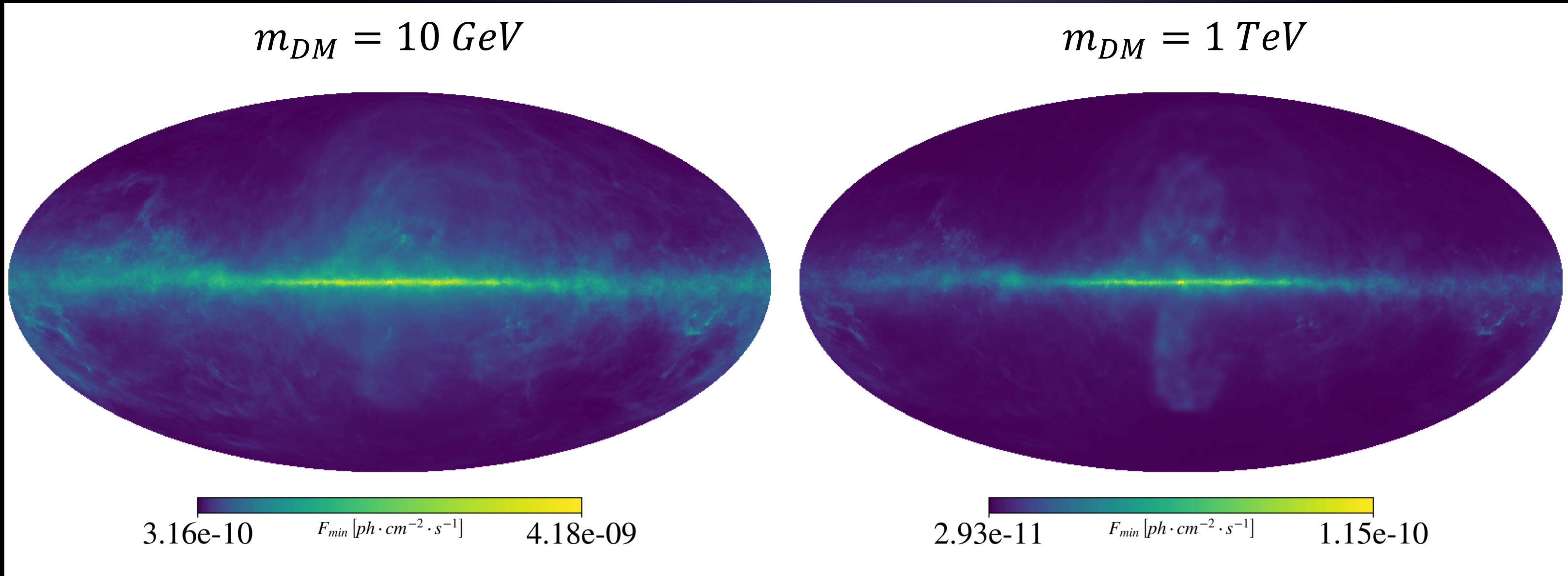
- Careful unID 'filtering' work.
- Careful characterization of LAT sensitivity to DM annihilation.



3FGL setup, $\tau^+\tau^-$ channel

Dependence on WIMP mass, annihilation channel and latitude

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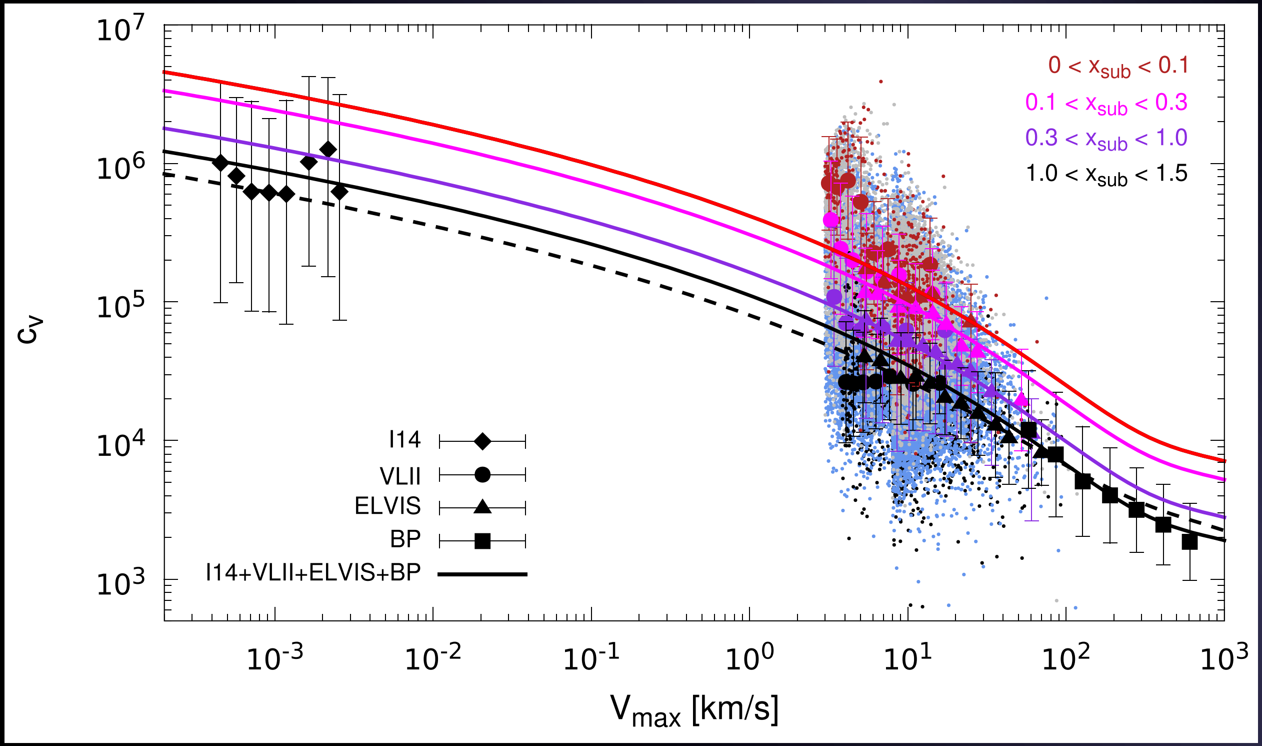
- Careful unID 'filtering' work.
- Careful characterization of LAT sensitivity to DM annihilation.
- Best knowledge of subhalos' structural properties (MASC&Prada14, Moline,MASC+17)

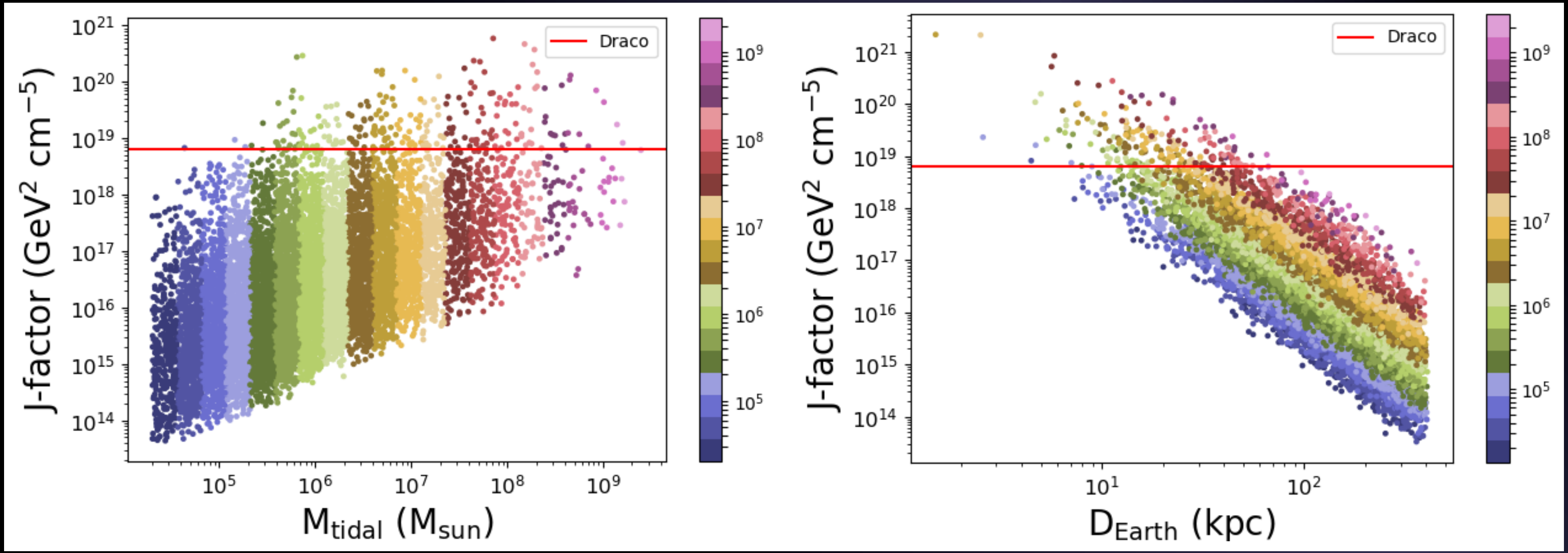


Moline+17

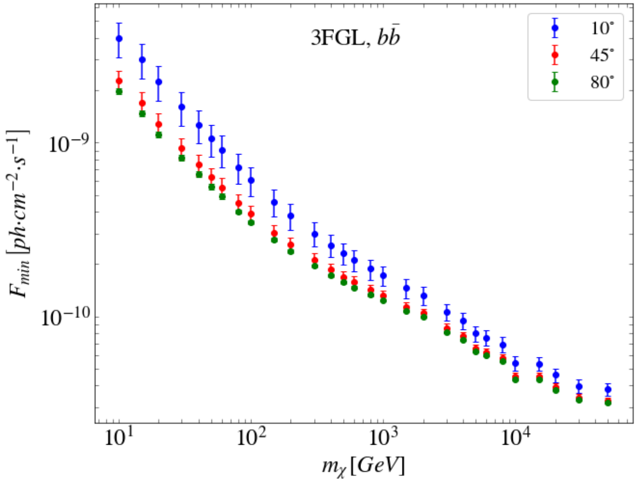
New (LAT) work ongoing

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

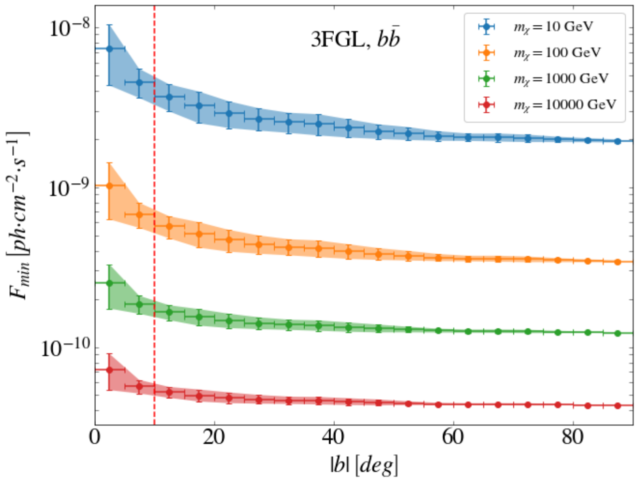
- Search in the most recent LAT catalogs (3FGL, 2FHL, 3FHL)
- Careful unID 'filtering' work.
- Careful characterization of LAT sensitivity to DM annihilation.
- Best knowledge of subhalos' structural properties (MASC&Prada14, Moline,MASC+17)
- Repopulation of current N-body simulations to reach lower subhalo masses.



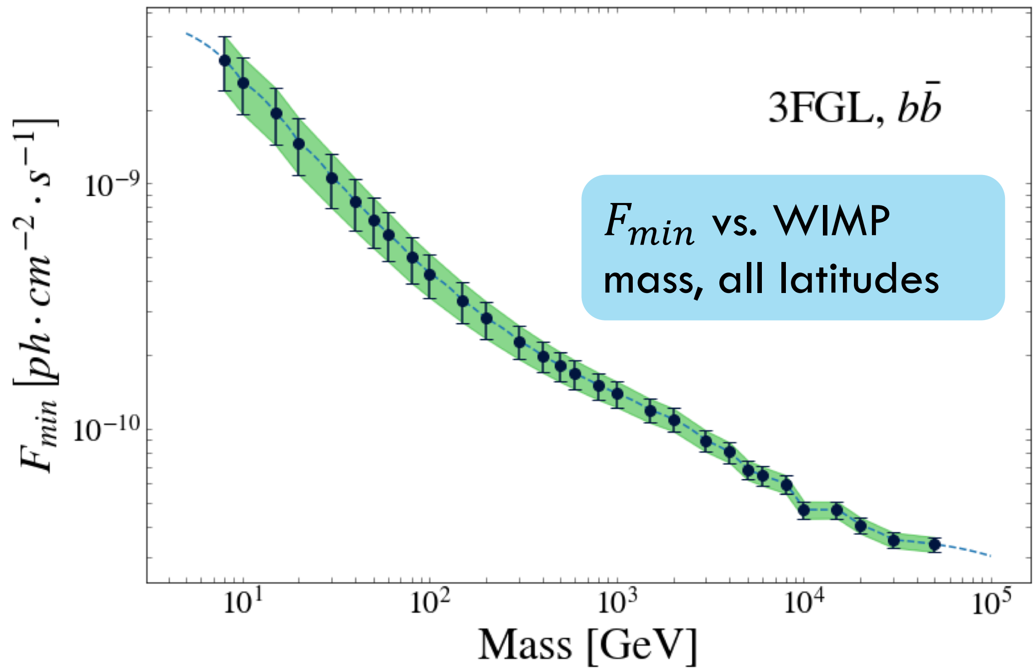
Aguirre-Santaella, MASC, et al., in prep.



F_{min} vs. WIMP mass



F_{min} vs. Gal. latitude



F_{min} vs. WIMP mass, all latitudes

30

Credit: J. Coronado-Blázquez

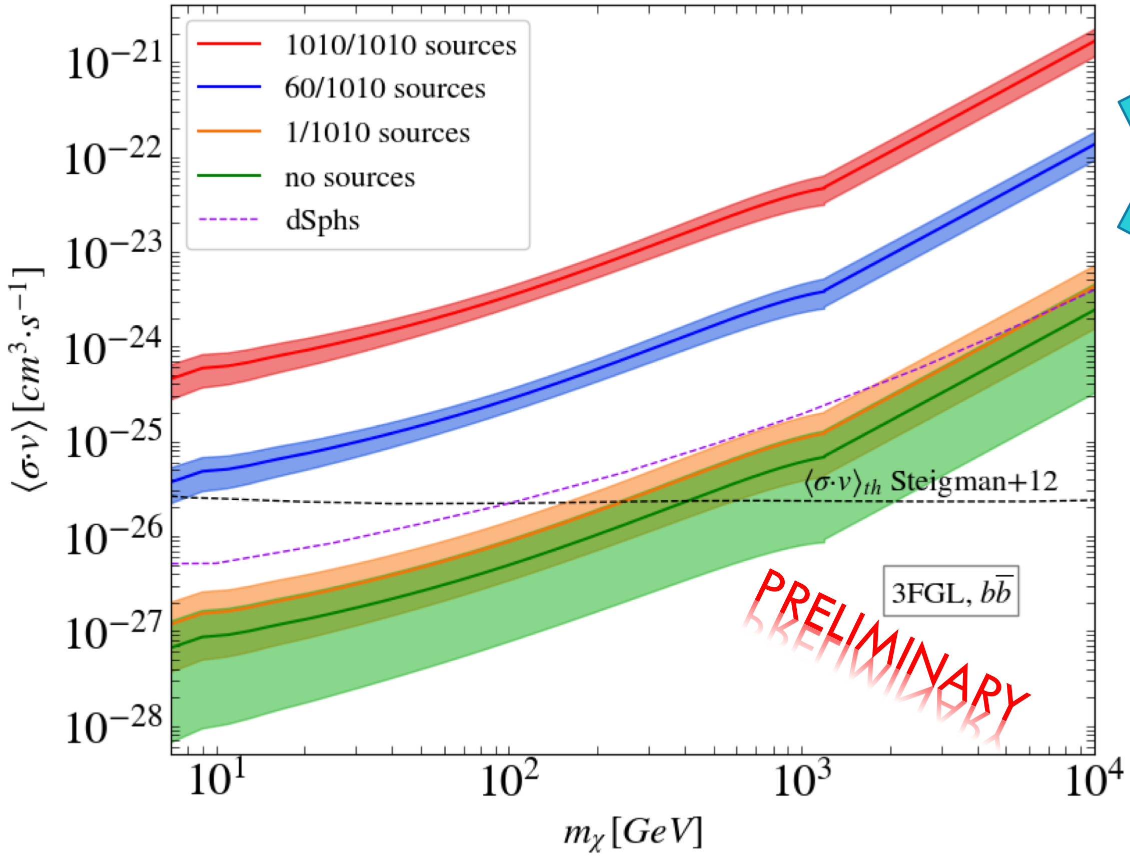
FAMOUS (EX-)CANDIDATES

- 3FGL J2212.5+0703 (Bertoni+16) – actually 2 sources
- 3FGL J1924.8-1034 (Xia+17) – classified as AGN by machine learning
- 3FGL J1119.9-2204 (Hooper+17) – seen with SWIFT
- 3FGL J0318.1+0252 (Hooper+17) – seen with SWIFT

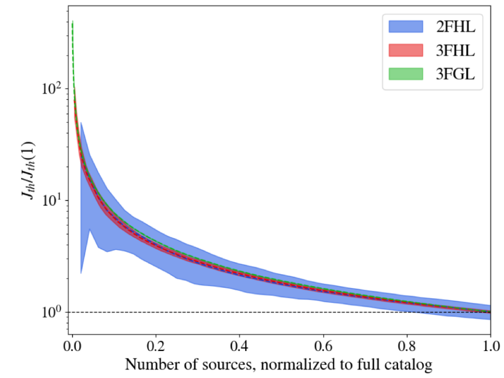
All 3FGL (low energy) sources

Credit: J. Coronado-Blázquez

CONSTRAINTS DEPENDING ON THE NUMBER OF UNIDs



More improvement removing the last 60 sources than the first 950!

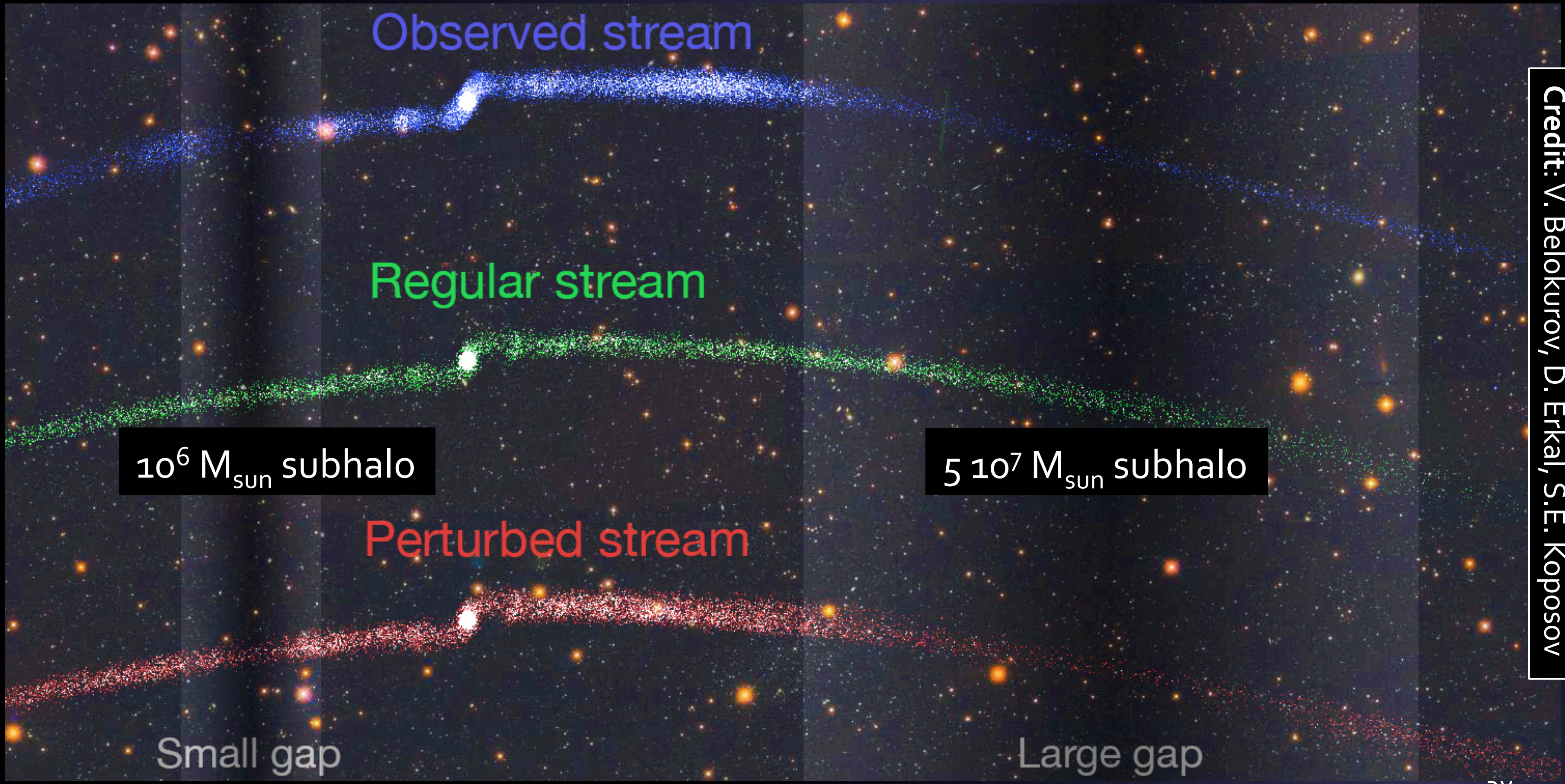


Credit: J. Coronado-Blázquez

SUBHALO SEARCHES:

II. STELLAR GAPS

- Subhalos may induce 'gaps' in stellar streams (Carlberg 12,15; Erkal+15, 16, 17)
- Statistical analysis of the distribution of stars can be used to 'detect' subhalos
- Probably not possible below ~one million solar masses.



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

Simulating Milky Way size halos

VIA LACTEA I – II - GHALO

Three MW-size halos with different cosmological parameters.

VLII (GHALO) over one (two) billion particles

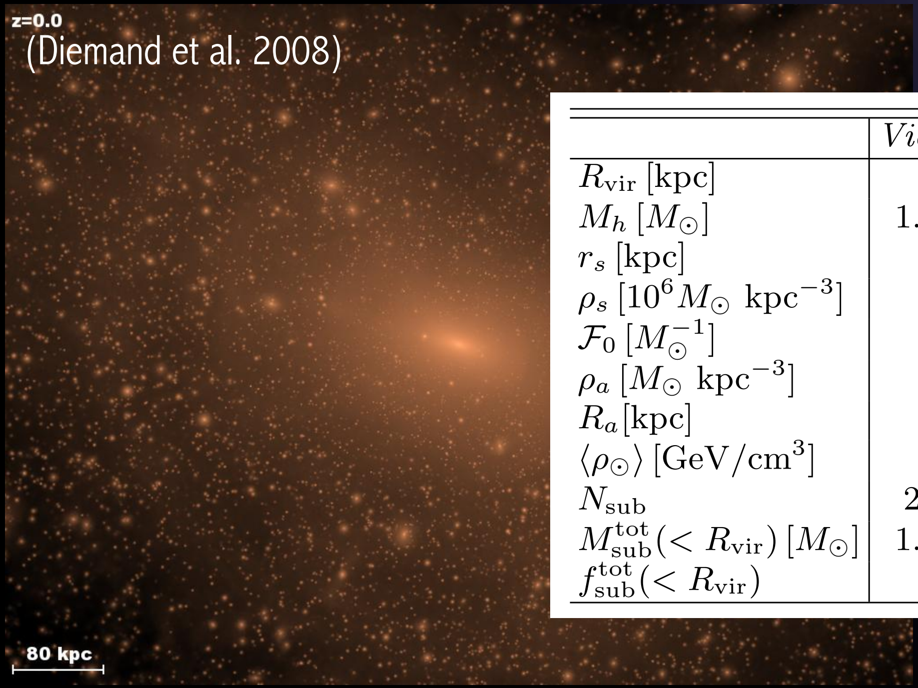
Cusp profiles compatible with NFW.

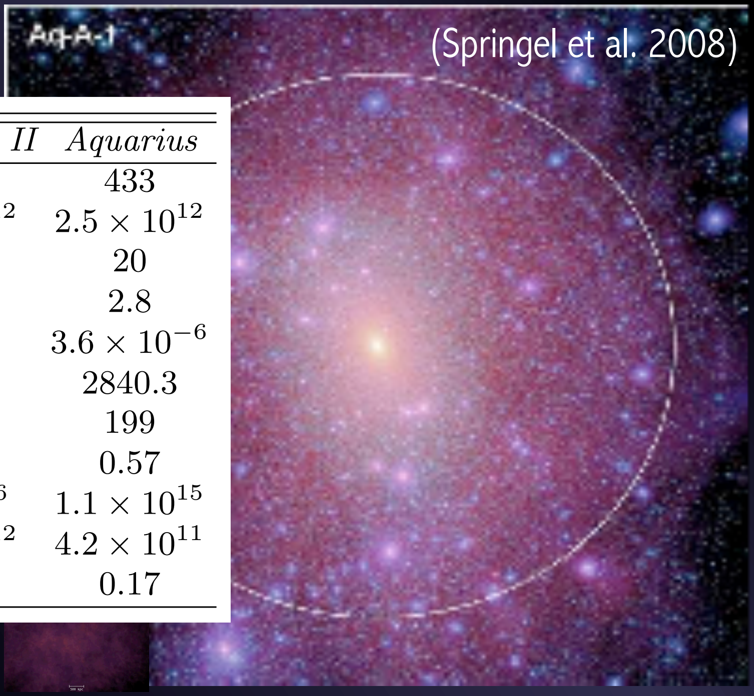
AQUARIUS

Six MW halos with different resolutions.

AQ-A1 has over four billions particles.

Cusp profiles, but better modeled by Einasto.

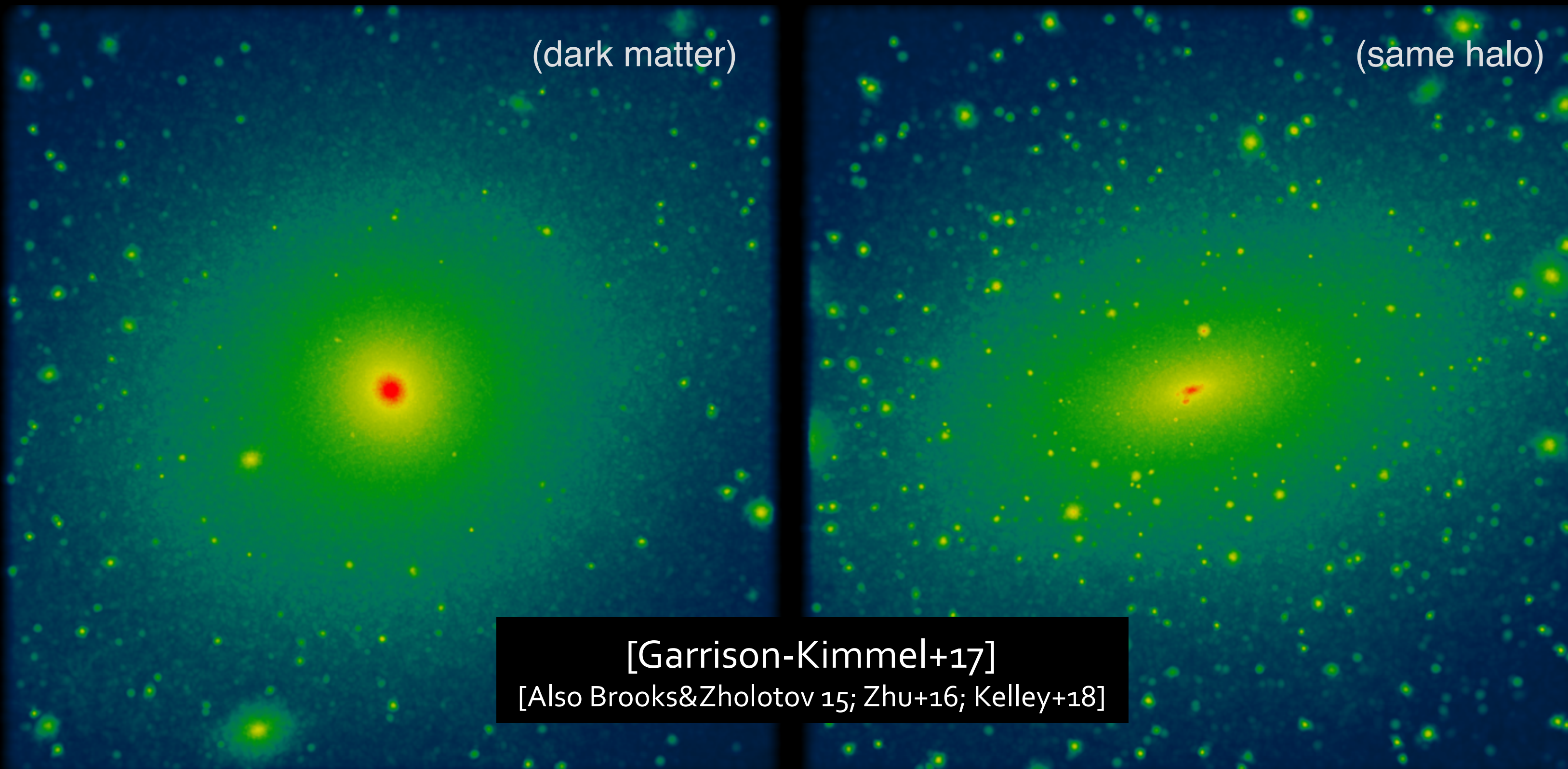




	Via Lactea II	*Aquarius*
$R_{\rm vir}$ [kpc]	402	433
M_h [$M_\odot$]	1.93×10^{12}	2.5×10^{12}
r_s [kpc]	21	20
ρ_s [$10^6 M_\odot$ kpc^{-3}]	8.1	2.8
$\mathcal{F}_0$ [$M_\odot^{-1}$]	10^{-6}	3.6×10^{-6}
ρ_a [$M_\odot$ kpc^{-3}]	-	2840.3
R_a[kpc]	85.5	199
$\langle\rho_\odot\rangle$ [GeV/cm^3]	0.42	0.57
$N_{\rm sub}$	2.8×10^{16}	1.1×10^{15}
$M_{\rm sub}^{\rm tot}(< R_{\rm vir})$ [$M_\odot$]	1.05×10^{12}	4.2×10^{11}
$f_{\rm sub}^{\rm tot}(< R_{\rm vir})$	0.53	0.17

OPEN ISSUES (I): Role of baryons

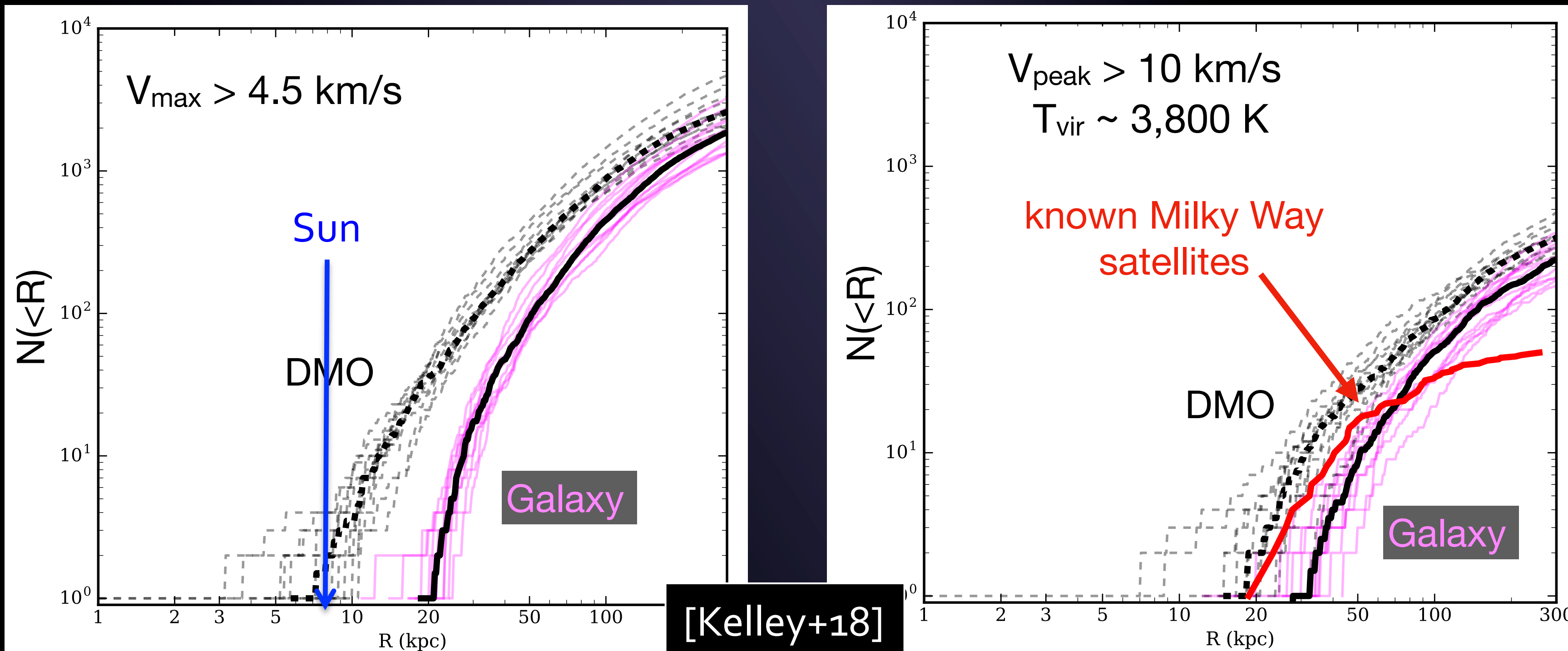
FIRE Hydrodynamics | Pure N-Body



100 kpc | 100 kpc

Up to factor ~10 reduction in substructure within ~25 kpc
No substructure within ~20 kpc with $V_{max} > 5$ km/s

OPEN ISSUES (II): Subhalo survival



[Kelley+18]

Credit: J. Bullock

Radial distribution of massive subhalos 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?