The Dark Side of the Milky Way and other nearby galaxies

(Why bother?)

Subha Majumdar

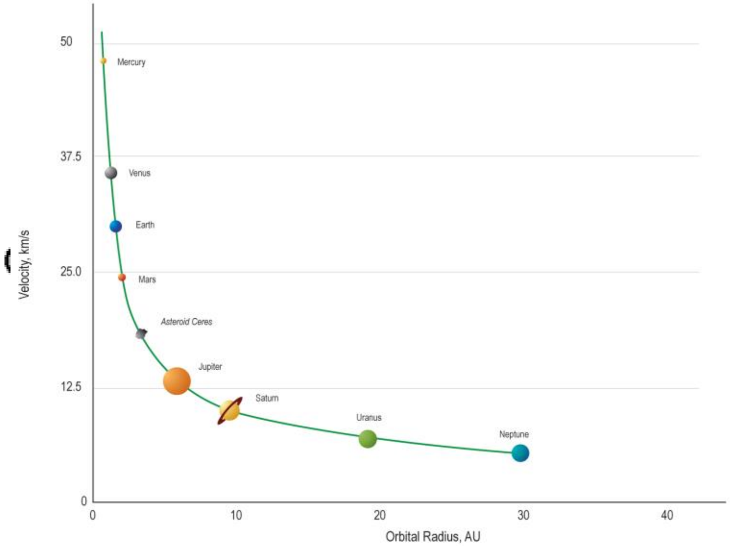
TIFR - Mumbai

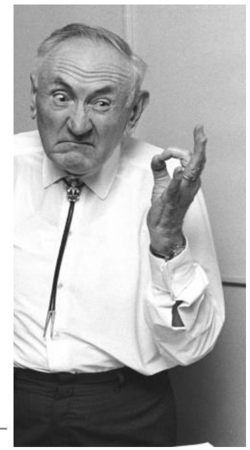
Sutirtha Mukherjee (IISERM)
Sravya Kalachaveedu (IISERM)
Amogh Srivastava (IITB)
Manush Manju (NYU)
Aakash Pandey (MPE)
Aditya Singh (LMU)
Viraj Karambelkar (Caltech)

Ritoban Basu Thakur (JPL)
Vikram Rentala (IITB)
Piushpani Bhattacharjee

Dark Matter is Ubiqutous…

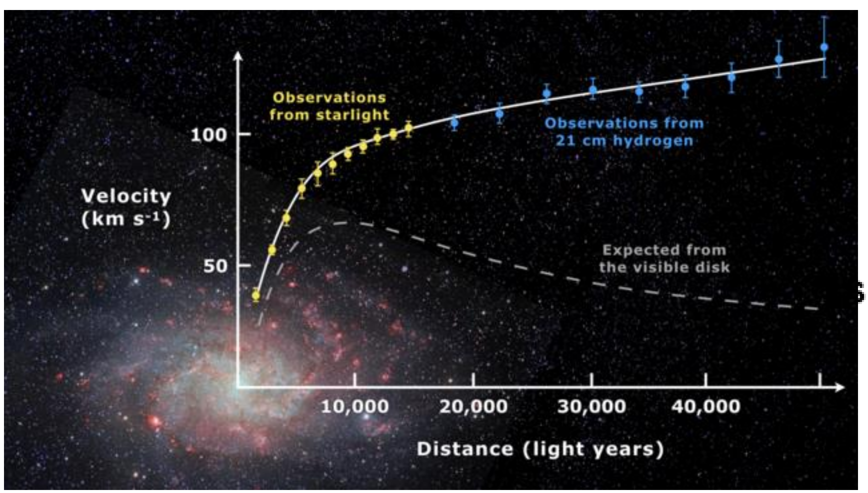
It connects Astrophysics , Cosmology and Particle Physics





"On the masses of nebulae and of clusters of nebulae", *Astrophysical Journal*, **86**: 217, (1937)
- Zwicky, F.

Currently – The Zwicky Transient Factory



"Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions", *Astrophysical Journal*, **159**: 379, (1970)
-Rubin, V & Ford, Kent Jr.

Currently – The Rubin Observatory (LSST)

And why do we care?

What is Dark Matter?

That's the 9 million+ Kroner question !!!

Many many efforts (i.e 100's – billion of $$ of expt)

A) Direct Detection - scattering in lab expts
B) Indirect detection – gamma ray sky etc

BOTH depends crucially on own knowledge of the Milky Way Halo (especially with increasing precision)

C) Collider searches

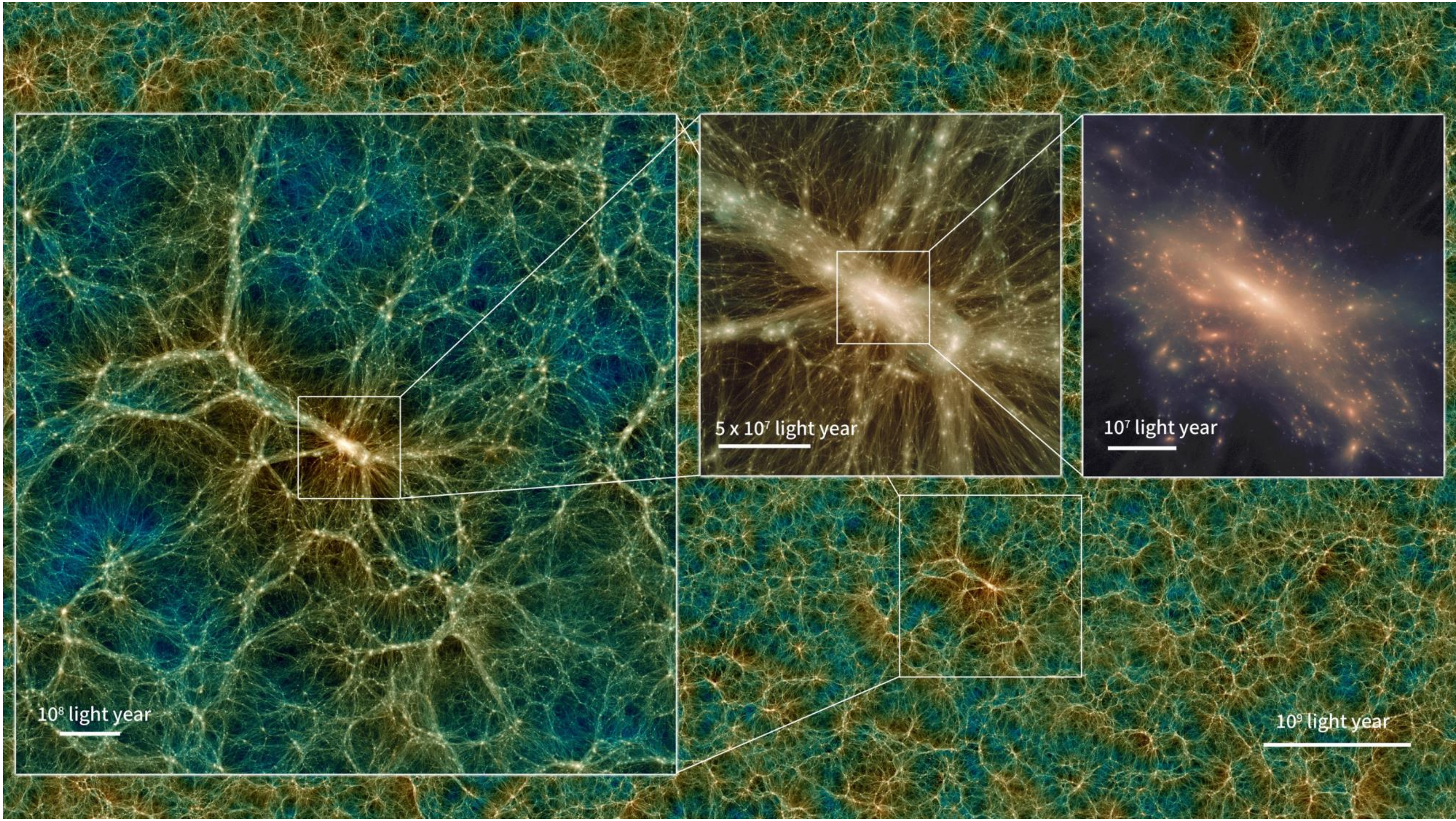
There are billions of galaxies in the observable Universe.

Every galaxy has a DM halo.

Milky Way happens to be our galaxy.

It is our own DM laboratory

Billions of galaxies and their DM halos…



Uchuu simulations

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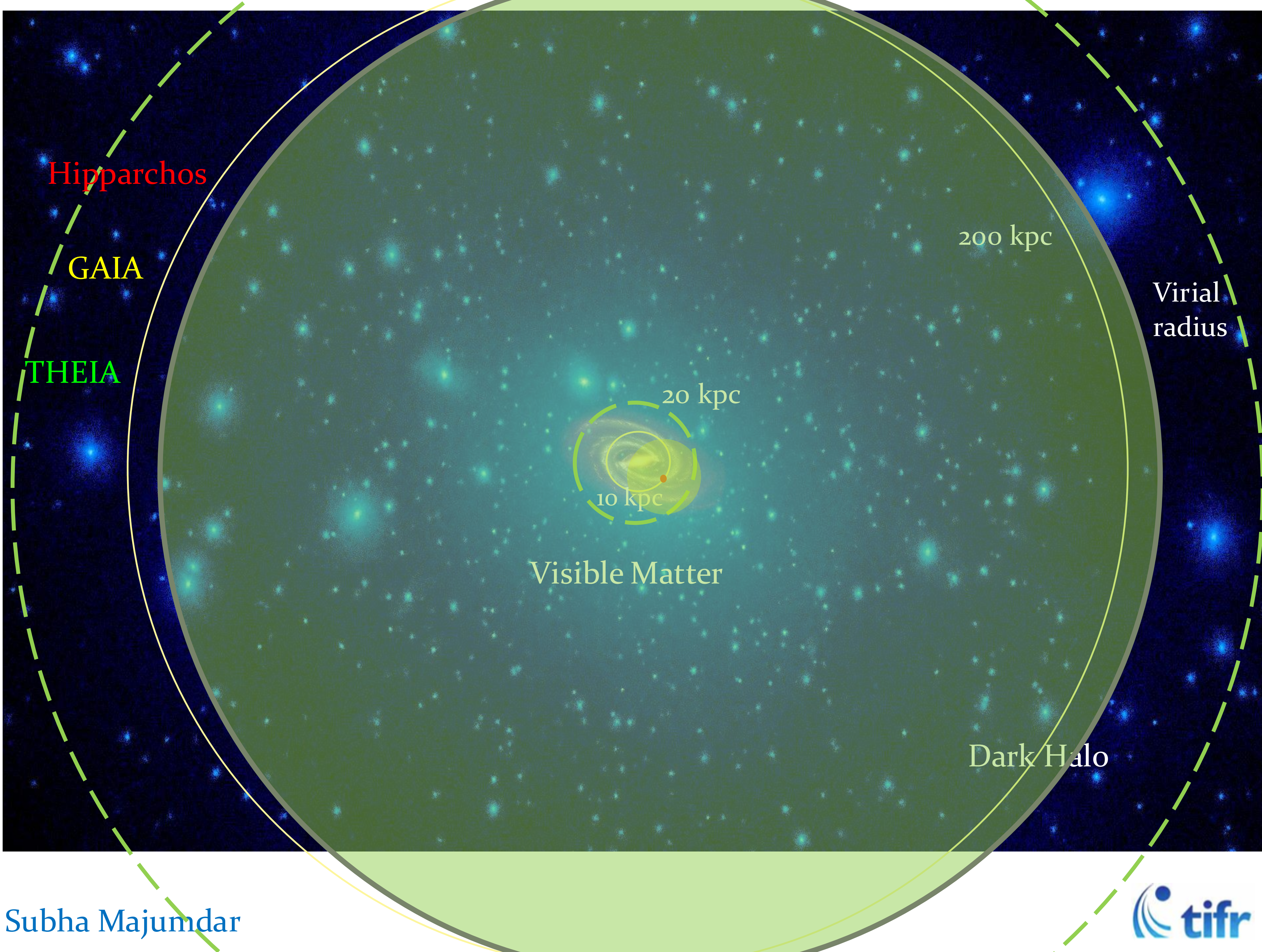

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DM - A true melting pot of ideas in physics…

Cosmology
Particle Physics/Nuclear Physics
Astrophysics

Dark Matter Direct Detection –
The true melting pot of physics

One of the most amazing equations in Physics.
Assuming isotropic scattering in the center-of-mass frame of the DM-nucleus system, the rate of direct detection signal events per unit recoil energy (ER), per unit detector mass is

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \mathcal{I}(E_R) F^2(E_R) \epsilon(E_R)$$

$$R_0 = \frac{320}{m_D m_T} \left(\frac{\sigma_0}{1\text{ pb}}\right) \left(\frac{\rho_{DM,\odot}}{0.3\text{ GeV}/c^2}\right) \left(\frac{v_0}{220\text{ km/s}}\right) \text{tru}$$

1 tru is 1 count/kg/day

$$E_0 = \frac{1}{2} m_D v_0^2$$

$$r = 4 m_D m_T / (m_D + m_T)^2$$

$$\sigma_0 = \left(\frac{\mu_{D,N}}{\mu_{D,n}}\right)^2 A^2 \sigma_n$$

μ = reduced mass

Particle Physics Nuclear Physics Detector Physics Astrophysics

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Dark Matter Indirect Detection – Another case of Synergy

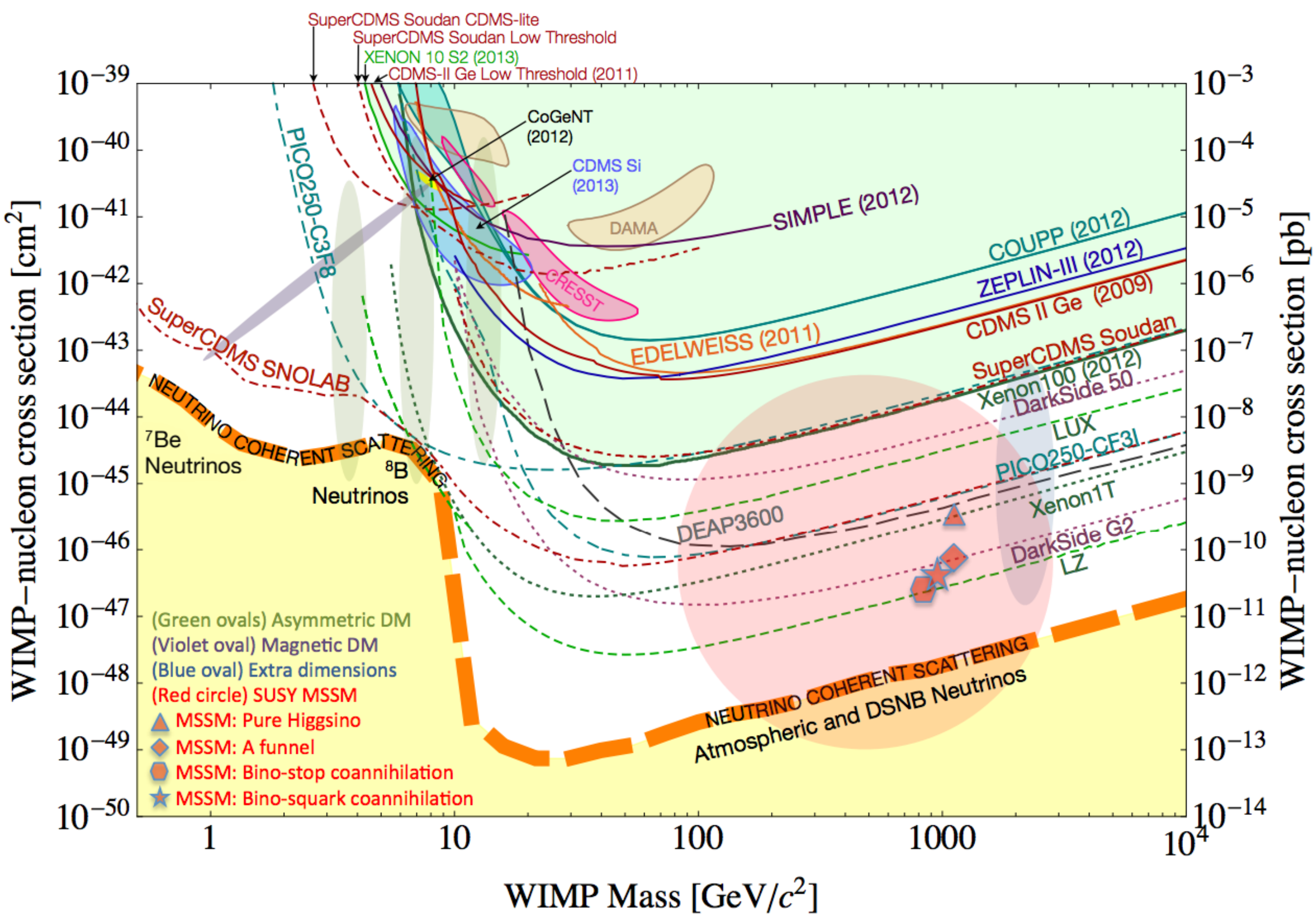
Particle Physics

$$\frac{d\phi}{dE} = \frac{1}{4\pi}\frac{< \sigma v_{rel} >}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int_{\triangle\Omega} d\Omega \int_{l.o.s.} dl\,\rho^2(r)$$

$$J = \int_{\triangle\Omega} d\Omega \int_{l.o.s.} d\mu \int d\vec{v_1}\, f_{DM}(\vec{x},\vec{v_1}) \int d\vec{v_2}\, f_{DM}(\vec{x},\vec{v_2})\, S(|\vec{v_{rel}}|)$$

Astrophysics

Direct Detection DM: Progress & Prospects



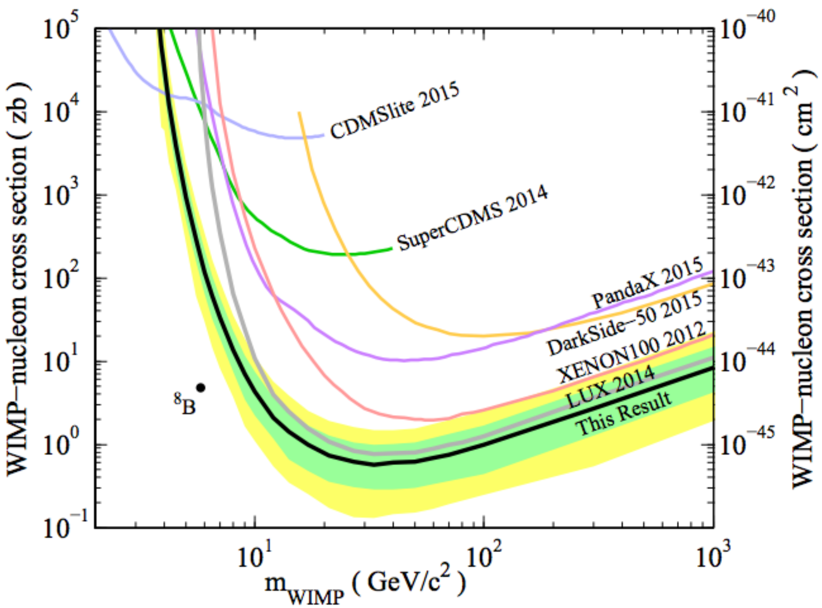
Precision of direct detection experiments and what is missing?

Improved Limits on Scattering of Weakly Interacting Massive Particles from Reanalysis of 2013 LUX Data

D. S. Akerib *et al.* (LUX Collaboration)
Phys. Rev. Lett. **116**, 161301 – Published 20 April 2016

An random expt
As an example

Systematic uncertainties in background rates are treated via nuisance parameters in the likelihood: their constraints are listed with other fit parameters in Table I. *S1*, *S2*, z, and r are each useful discriminants against backgrounds and cross sections are tested via the likeli-



tic [35] is employed to test signal hypotheses. For each WIMP mass we scan over cross section to construct a 90% confidence interval, with test statistic distributions evaluated by MC using the RooStats package [36]. At all masses, the maximum-likelihood value of σ_n is found to be zero. The background-only model gives a good fit

respectively. Upper limits on cross section for WIMP masses from 4 to 1000 GeV c^{-2} are shown in Fig. 3; above, the limit increases in proportion to mass until $\gtrsim 10^8$ GeV c^{-2}, 10^6 zb, where the Earth begins to attenuate the WIMP flux. The raw PLR result lies between one and two Gaussian σ below the expected limit from background trials. We apply a power constraint [37] at the median so as not to exclude cross sections for which sensitivity is low through chance background fluctuation. We include systematic uncertainties in the nuclear recoil response in the PLR, which has a modest effect on the limit with respect to assuming the best-fit model exactly: less than 20% at all masses. Limits calculated with the alternate, Bezrukov parametrization would be 0.48, 1.02, and 1.05 times the reported ones at 4, 33, and 1000 GeV c^{-2}, respectively. Uncertainties in the assumed dark matter halo are beyond the scope of this Letter but are reviewed in, e.g., [38]. Limits on spin-dependent cross sections are presented elsewhere [39].

In conclusion, reanalysis of the 2013 LUX data has excluded new WIMP parameter space. The added fiducial mass and live time, and better resolution of light and charge yield a 23% improvement in sensitivity at high WIMP masses over the first LUX result. The reduced, 1.1 keV cutoff in the signal model improves sensitivity by 2% at high masses but is the dominant effect below 20 GeV c^{-2}, and the range 5.2 to 3.3 GeV c^{-2} is newly demonstrated to be detectable in xenon. These techniques further enhance the prospects for discovery in

The Standard Halo Model

Density - a single-component **isothermal sphere**
(local density - 0.3 Gev/cc) [Bahcall 1984]

Velocity - VDF is assumed to be isotropic and of **Maxwell-Boltzmann**

$$f(\mathbf{v}) \propto \exp(-|\mathbf{v}|^2 / v_0{}^2) \qquad v_0 = v_{c,\odot}$$

→ truncation at an assumed value of the local escape speed (~ 544 km/s)

Neither of these two assumptions are right!
Multiple efforts (from theory mainly) to go beyond SHM to see how that affects results.

WE TAKE ANOTHER WAY →

So, what has been our aim?

Observations all the way to particle phy expts

Do full "end-to-end", as self-consistently as possible

starting with observational tracers --constructing rotation curve upto ~ 200 kpc. And then add local kinematical tracers

*1) **The best MW Rotation Curve that's possible circa 2025***

[SM, Mukherjee, Kalachaveedu, Srivastava, Manju]

*2) **The DM density (local and upto edge of MW)***

[Karambelkar, Singh, Mukherjee, Kalachaveedu, Srivastava, Manju & SM]

3) First estimation of MW DM phase-space of the entire MW

[SM e tal]

4) Impact of local DM phase-space on DM exclusions

[Mandal, SM, Rentala, BasuThakur]

5) The most comprehensive J-factor for Milky Way and Indirect detection

[Pandey, Majumdar, Rentala, etal]

5) Other than MW - SPARCs galaxies – a series of papers

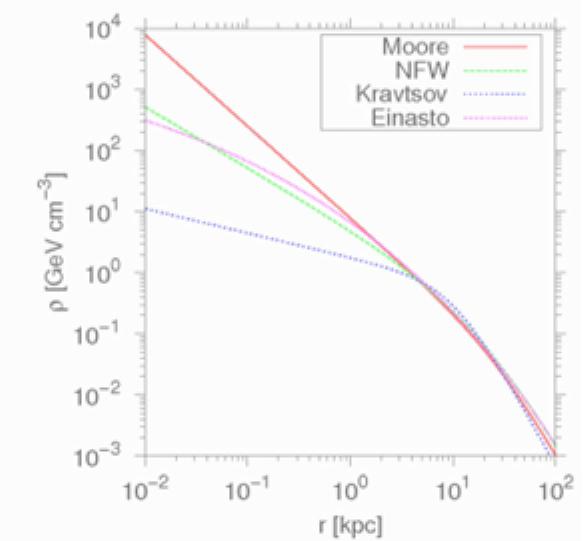
6) New galaxy – halo connection

[Manju & SM]

Connecting observations to densities

Rotation curve as function of galacto-centric distance is given by:

$$v_c^2(R) = R\frac{\partial}{\partial R}\left[\Phi_{\rm DM}(R, z=0) + \Phi_{\rm VM}(R, z=0)\right]$$



Φ(r) and ρ(r) are connected by the Poisson eqn.

MCMC analysis to constrain the component densities (modulo assumption of functional forms)

[We have also looked beyond DM profiles suggested by N-body simulations]

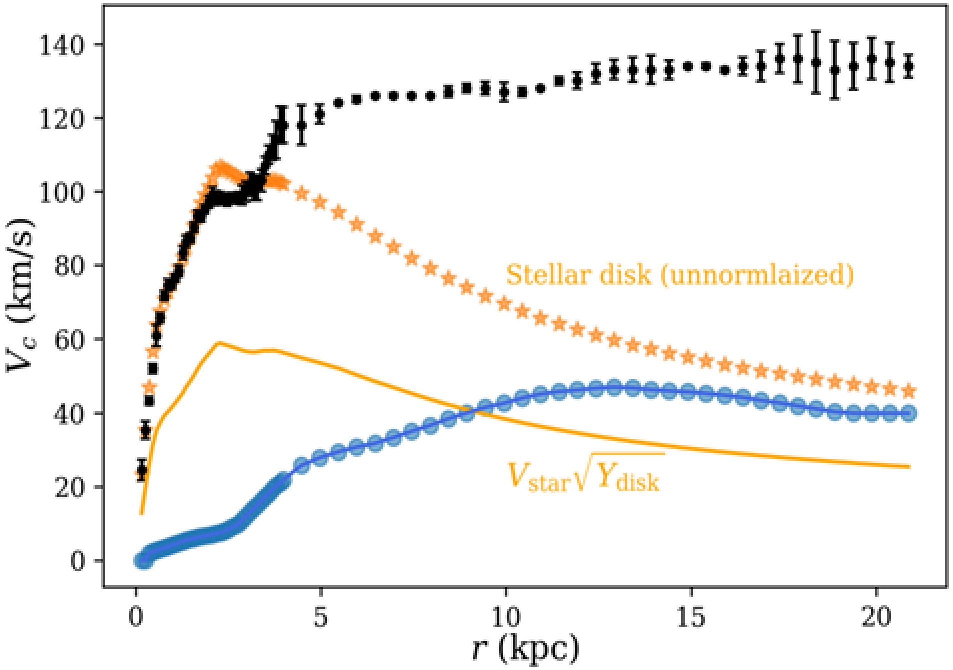
Another method is look at vertical kinematics of stars

The observations aka The Rotation Curves

SPARC: Spitzer Photometry & Accurate RCs

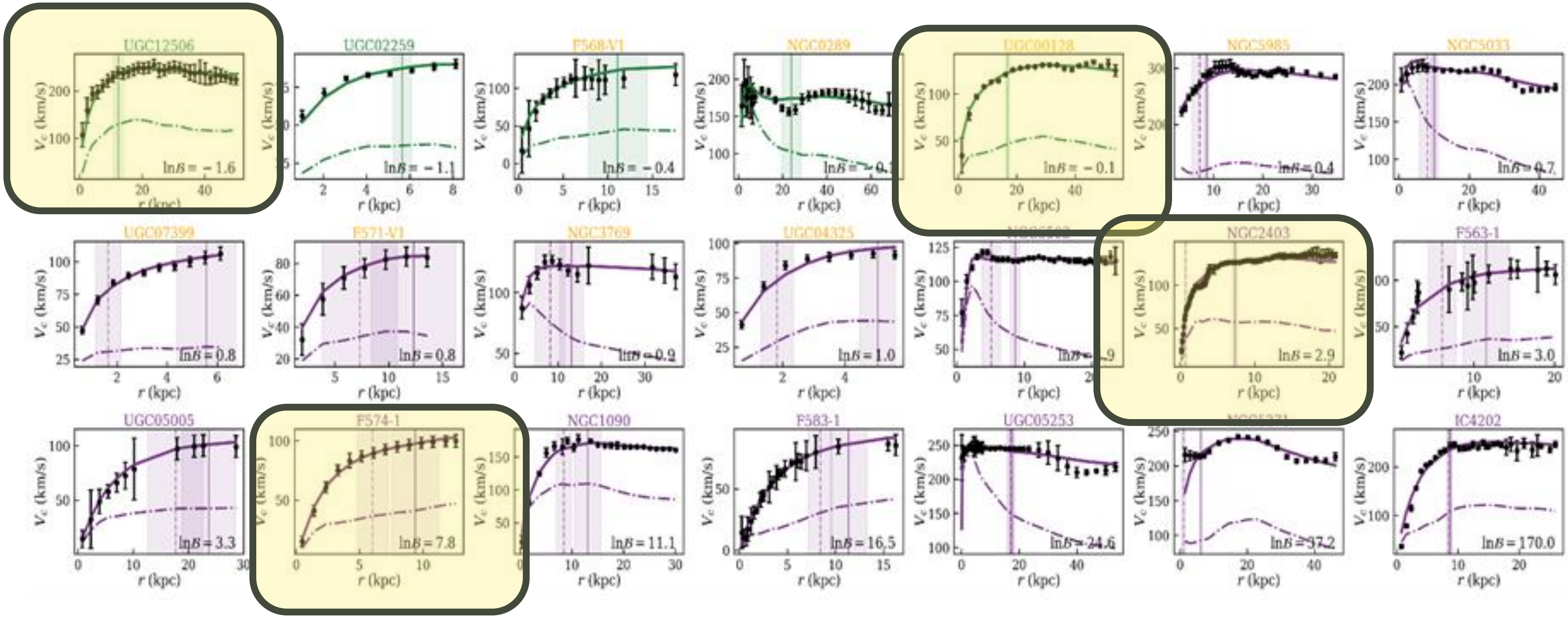
High quality H I/Hα RCs

Surface photometry at 3.6μm



$$V_c^2(r) = V_{\rm DM}^2(r) + V_{\rm gas}^2(r) + [Y_{\rm disk}/(M_\odot L_\odot^{-1})]\, V_{\rm disk}^2(r)$$

More Reliable Rotation Curves…



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Local DM density (last decade)-

A) HI rotation curve + global model for MW:

Catena & Ullio 2010
Weber & deBoer 2010
McMillan 2011
Piffl etal 2014

(0.2 – 0.6) Gev/cc
Most popular **0.4-0.44 Gev/cc**
consistent at 1-sgma

B) Independent of rotation curve from grav potn upto height 1-1.5 kpc with local stars

(0 – 0.9 GeV/cc)

Garbari etal 2012, K stars,	-- 0.88 +/- 0.56 Gev/cc
Zhang etal (2013), K dwarfs	-- 0.26 +/1 0.1. Gev/cc
Bovy & Rix (2013), G dwarfs	-- 0.32 +/- 0.1 Gev/cc
Bieneyme etal (2014), red stars, 2kpc	-- 0.57 +/- 0.05 Gev/cc
Moni Bidin etal (2010, 2012), upto 4kpc–	~ 0.0 +/- 0.08 Gev/cc

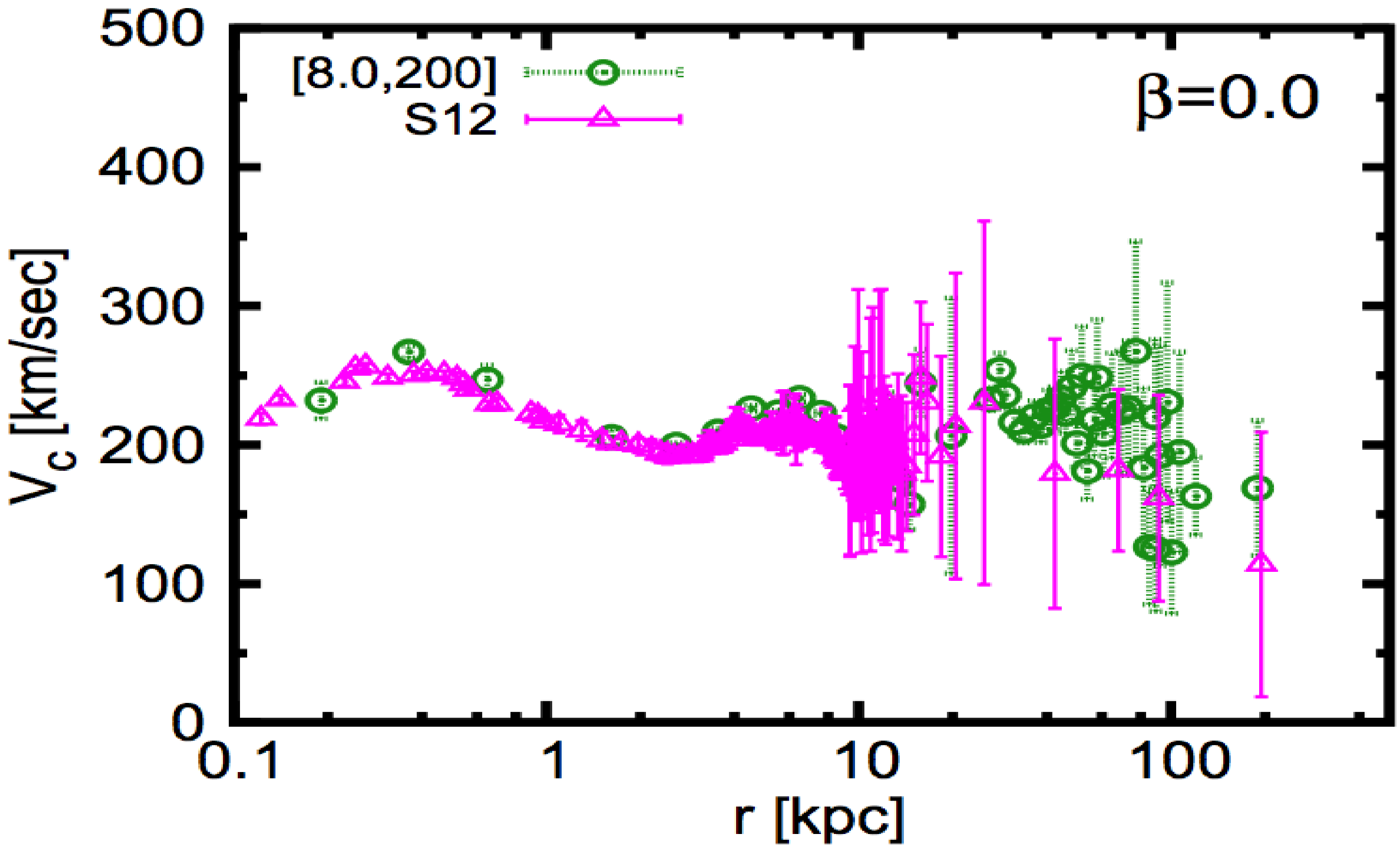
Bovy & Tremaine (2012), same

Local DM density (last decade)-

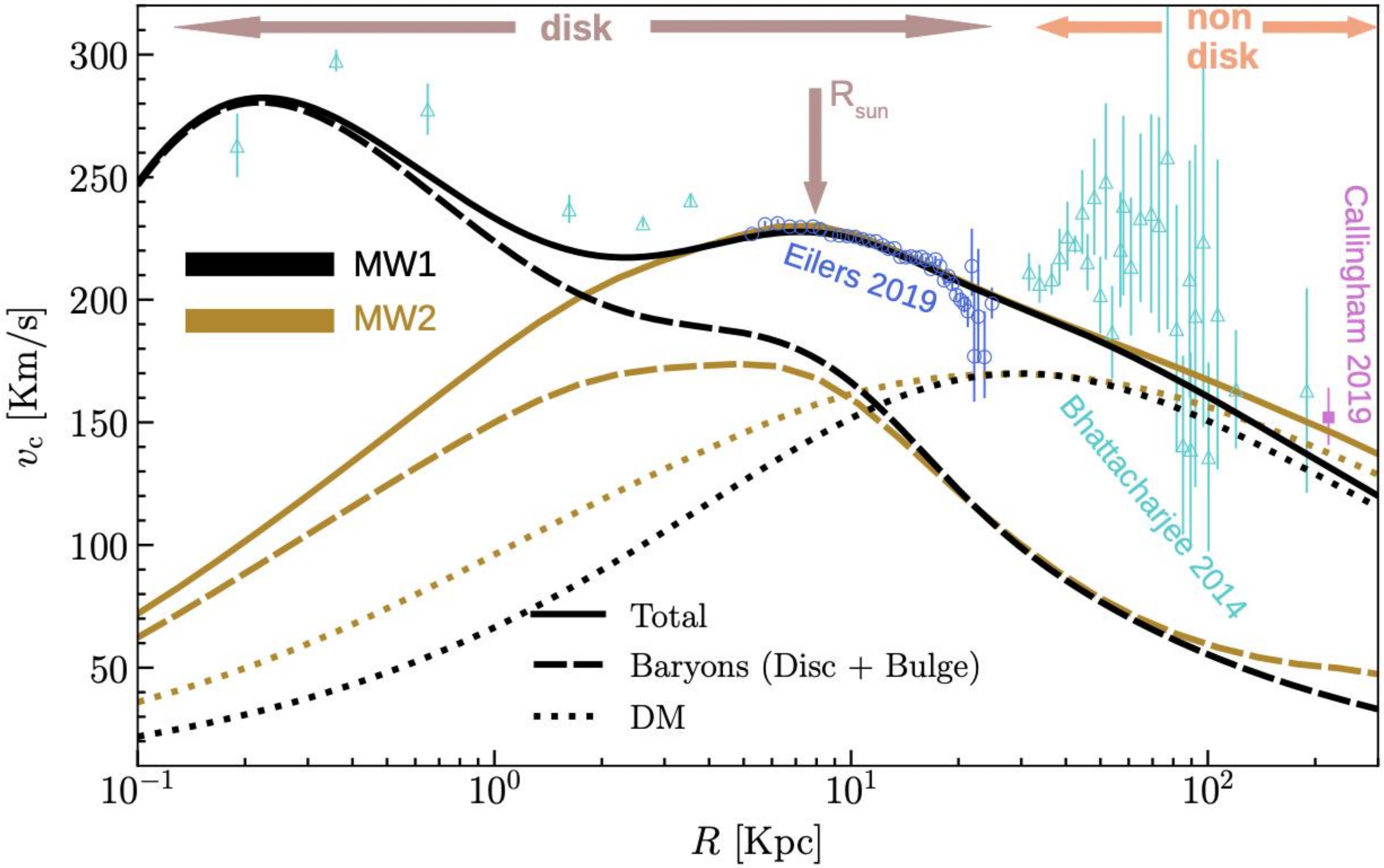
Method and assumptions dependent
Varies from ~ 0 – 1 GeV/cc (i.e one order of mag)
1-sigma error ~ 0.1+ GeV

And of course the issue of data quality

Combining to get the current 'best' RC (pre GAIA)



Post GAIA DR1 best RC → Mass modeling



LSR – The Local Standard of Rest

The **local standard of rest** or **LSR** is a reference frame which follows the mean motion of material in the Milky Way in the **neighborhood of the Sun** (stars in radius 100 pc from the Sun),[1] on average sharing the same velocity around the Milky Way as the Sun
The LSR velocity is anywhere from ~ 200–250 km/s.
The solar dist is anywhere between 8 -8.5 Kpc from GC.

LSR1 : 8 Kpc, 200 km/s
LSR2: 8.5 Kpc, 220 km/s
LSR3: 8.3 Kpc, 244 km/s

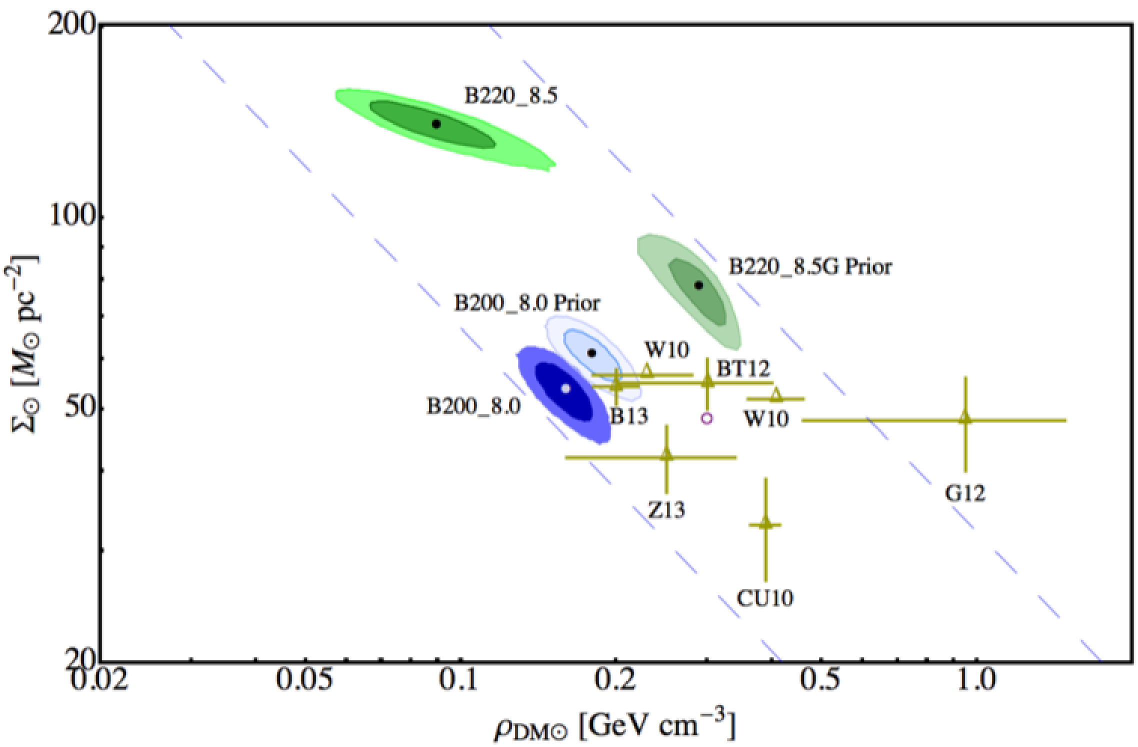
Visible matter – how well do we know?

Not that well, actually.

Local surface density: 34 – 74 M_{o}/pc^{2}

What is local DM density?

Range from 0.1 – 1 GeV/cc.
But scatter due to implicit, VM priors and LSR



The most common approach- Local kinematics dispersion velocity of local stars

Mean velocities of stars given by 3 components wrt solar peculiar velocity

The vertical Jeans equation

$$\frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz}) + \frac{1}{R\nu}\frac{\partial}{\partial \phi}(\nu\sigma_{\phi z}) + \frac{1}{\nu}\frac{d}{dz}(\nu\sigma_z^2) = -\frac{d\Phi}{dz}$$

Φ is the grav potn, ν stellar density

Assuming axial symmetry

$$\frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz}) + \frac{1}{\nu}\frac{d}{dz}(\nu\sigma_z^2) = -\frac{d\Phi}{dz} = F_Z(R,Z)$$

Poisson eqn in cyndrical co-ordinates

$$\Sigma(R,z) = -\frac{1}{2\pi G}[\int_0^z dz\frac{1}{R}\frac{\partial(RF_R)}{\partial R} + F_Z(R,Z)]$$

The velocity dispersion (observed) is given by

$$\sigma_z^2(z) = \frac{1}{\nu(z)}\int_0^z \nu(z')[F_z(z') - \frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz})]dz' + \frac{C}{\nu(z)}$$

Solved under assumption of separability and exponential distribution

$$\nu(R,z) = \nu(z)exp(-\frac{R}{h_R}) = \nu(R_\odot)exp(-\frac{z}{h_z})exp(-\frac{R}{h_R})$$

$$\sigma_{Rz}(R,z) = \sigma_{Rz}(z)exp(-R/h_\sigma)$$

$$\sigma_{Rz}(R_\odot,z) = A + B(z-2.5)$$

$h_R = h_\sigma = 3.8$ kpc

$h_z = 0.9$kpc.

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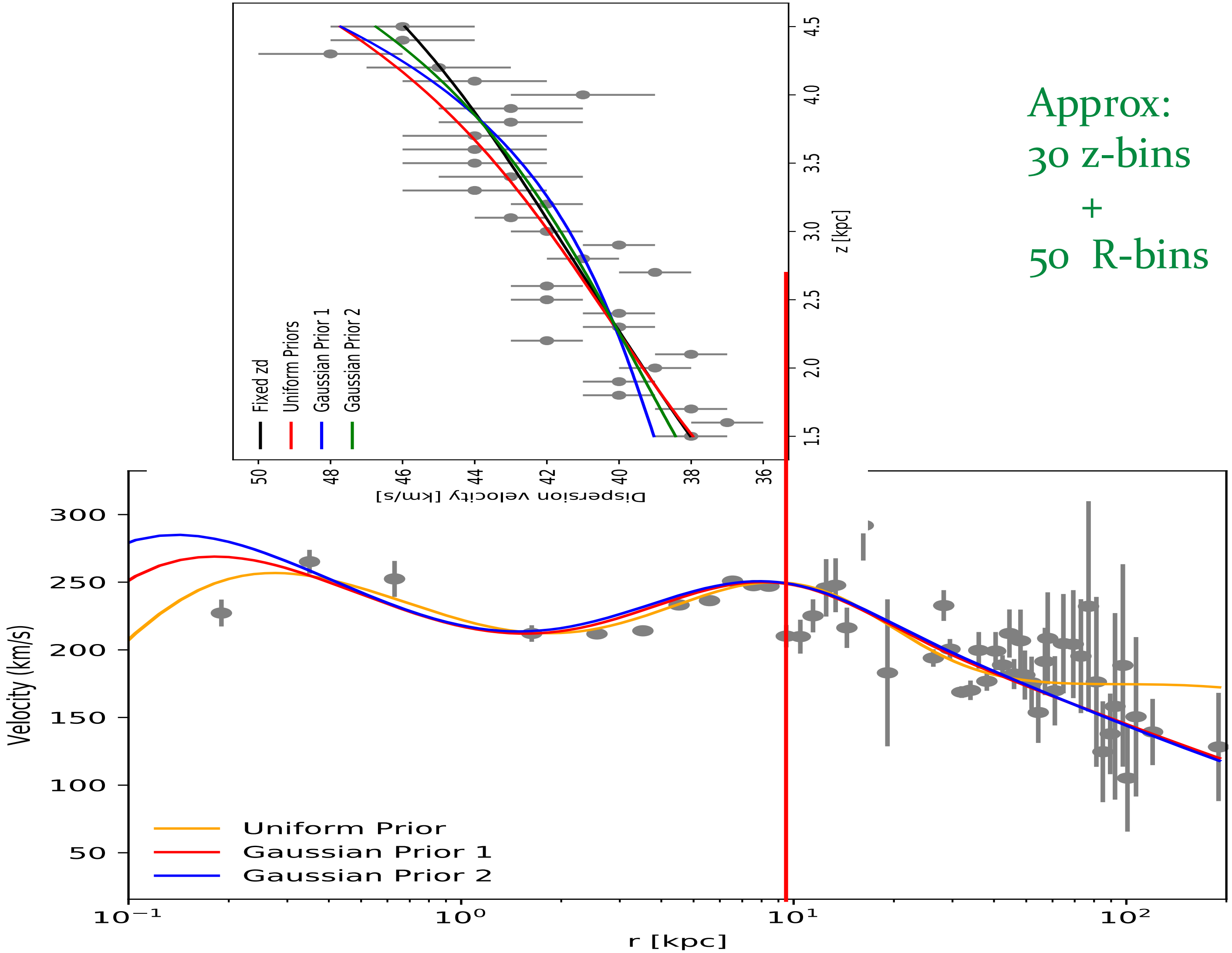
Joint Radial and Vertical probe



Approx:
30 z-bins
+
50 R-bins

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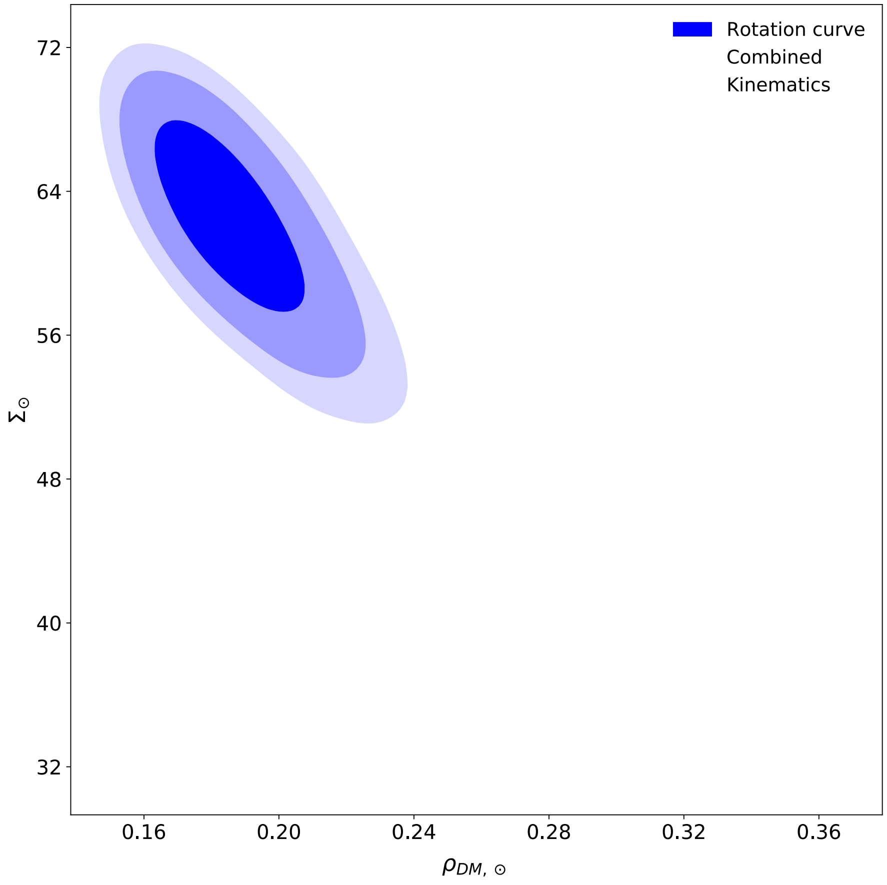
DM vs Visible: Local vs Global vs Joint
(partially eliminated unknown bias from priors)



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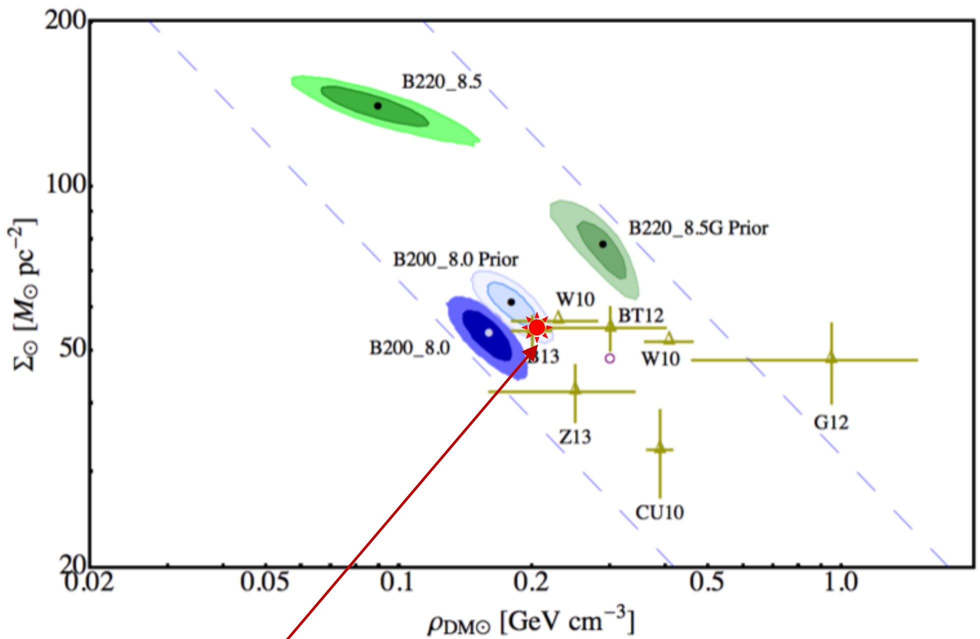
So, what is local DM density?



This is the tightest constraint yet

Local DM density ~ $0.210^{+0.015}_{-0.018}$ Gev/cc

Compared to fiducial 0.03 +/- 0.1
(Also recently by Bovy&Tremaine 2012)

$0.284^{+0.034}_{-0.026}$ 0.327 ± 0.045

Or 0.43 by Salucci (2010) or 0.4 by Catena & Ullio

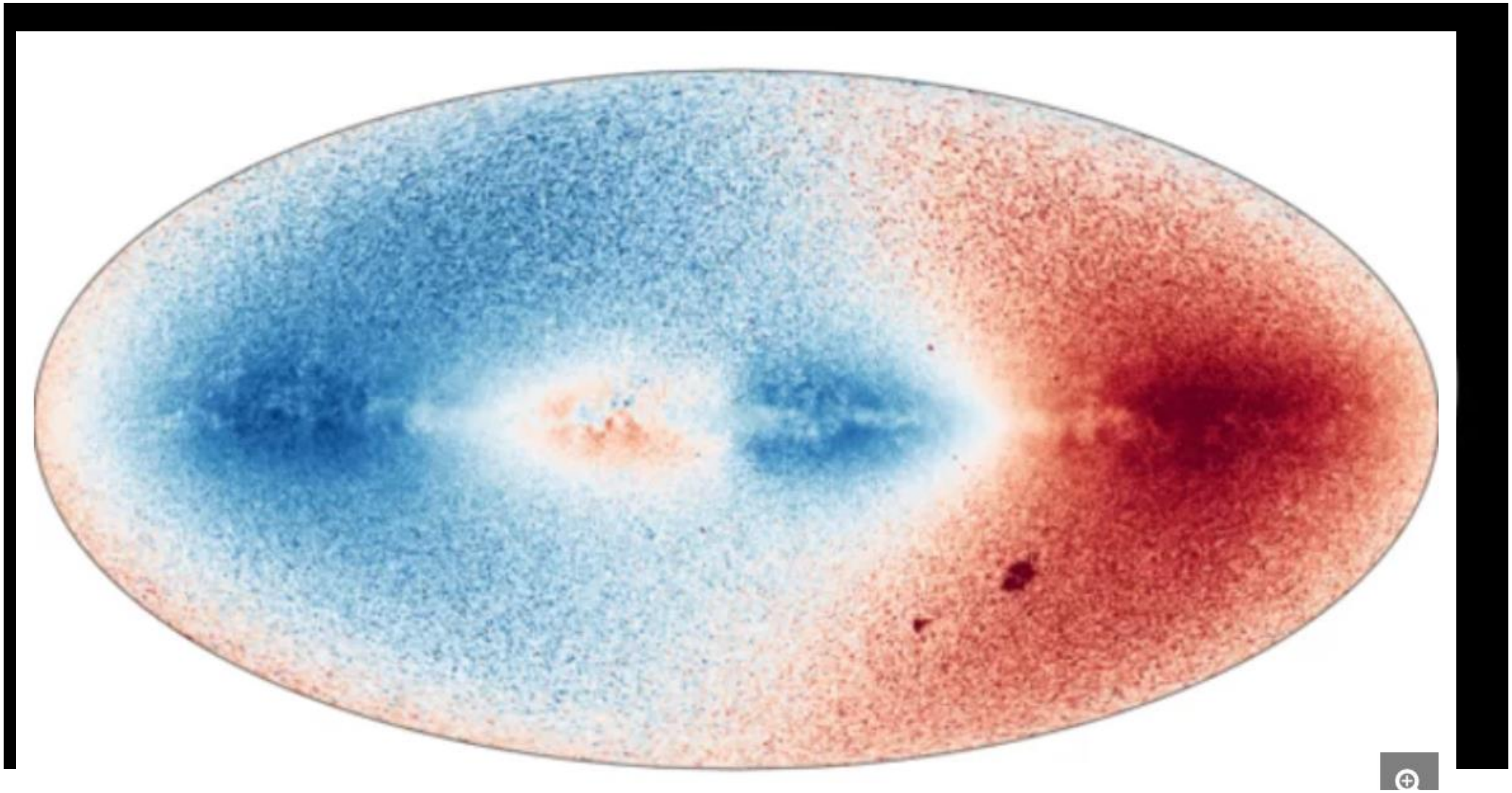
This is where I talk about GAIA DR3!

GAIA is revolutionizing our knowledge of Milky Way

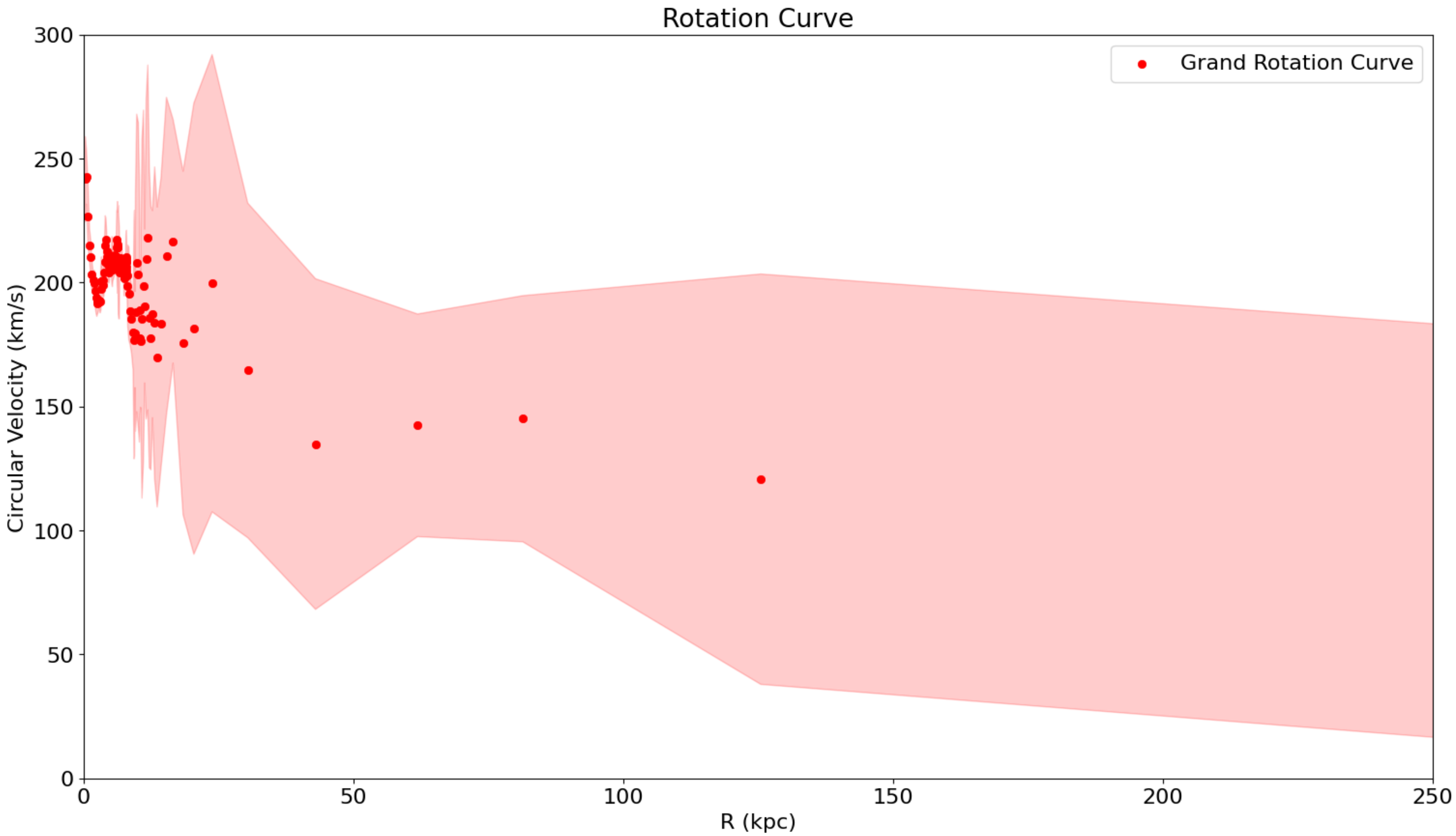
Gaia: Complete, Faint, Accurate

	Hipparcos	Gaia
Magnitude limit	12	20 mag
Completeness	7.3 – 9.0	20 mag
Bright limit	0	6 mag
Number of objects	120 000	26 million to V = 15 250 million to V = 18 1000 million to V = 20
Effective distance limit	1 kpc	50 kpc
Quasars	None	5×10^5
Galaxies	None	$10^6 – 10^7$
Accuracy	1 milliarcsec	7 μarcsec at V = 10 10-25 μarcsec at V = 15 300 μarcsec at V = 20
Photometry photometry	2-colour (B and V)	Low-res. spectra to V = 20
Radial Velocity	None	15 km/s to V = 16 -17
Observing programme	Pre-selected	Complete and unbiased

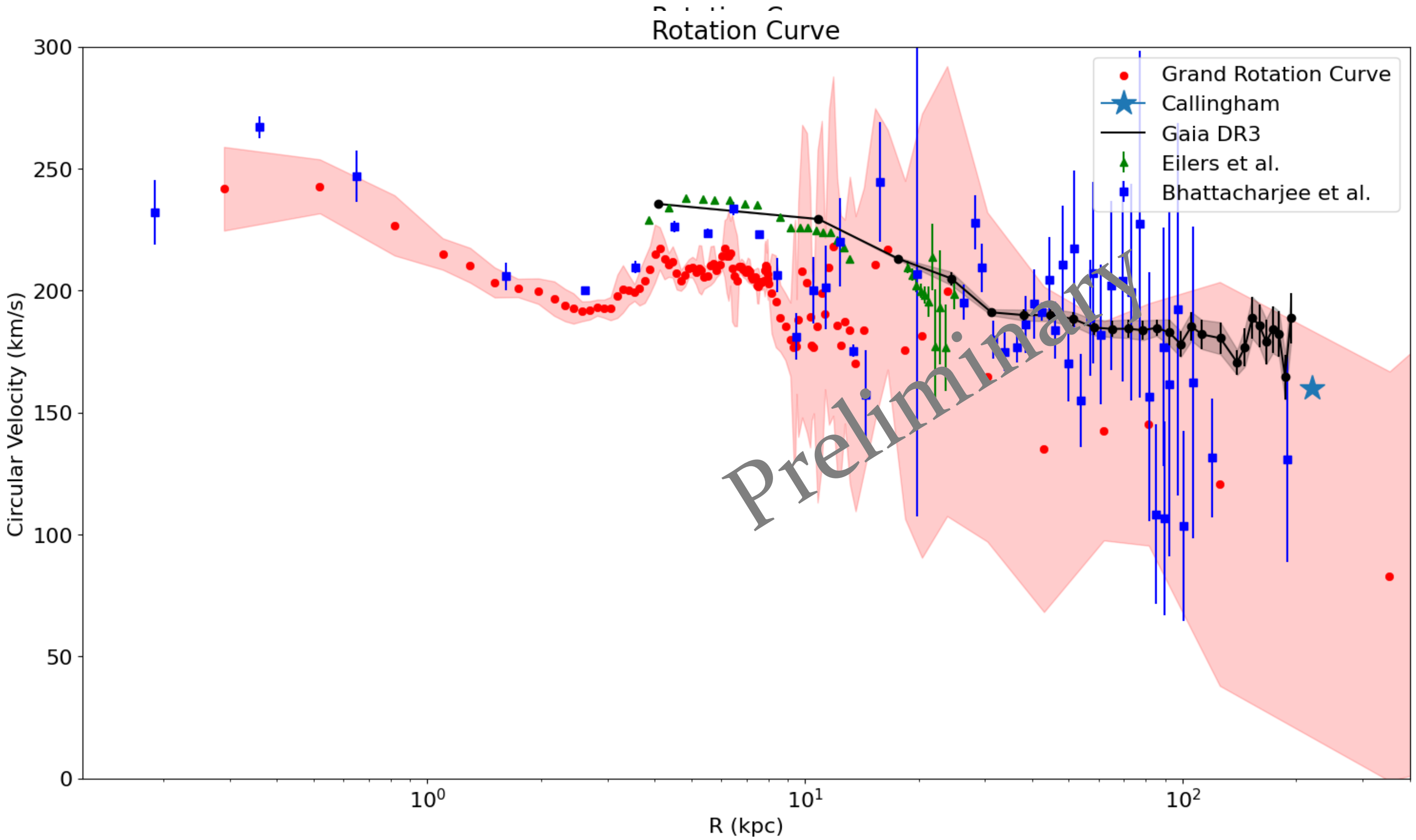
GAIA view of Milky Way



Pre-GAIA vs Post-GAIA DR1



Pre-GAIA vs Post-GAIA DR1



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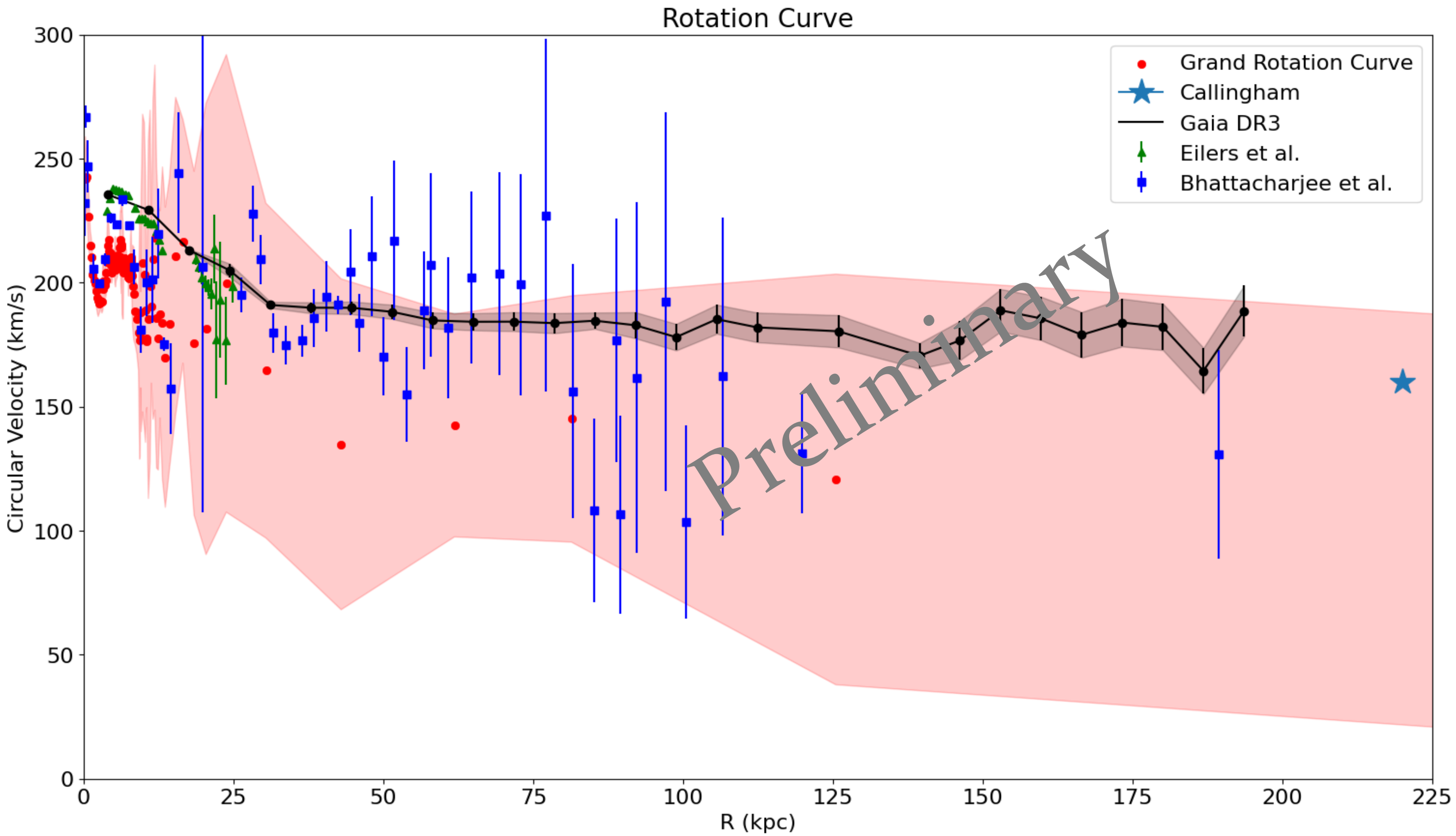
Pre-GAIA vs Post-GAIA DR3



A thin band, but after a very very long effort

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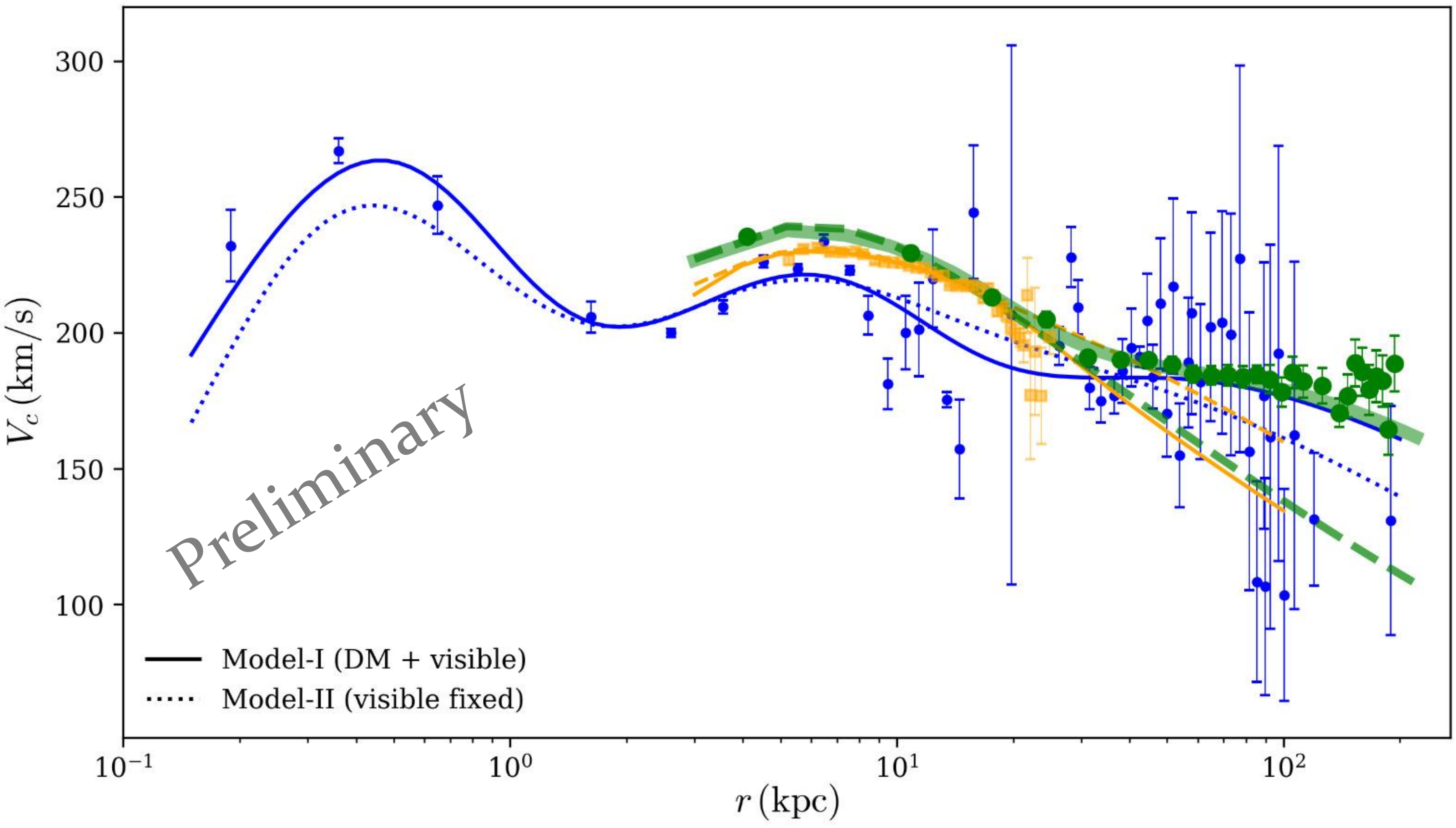
Pre-GAIA vs Post-GAIA



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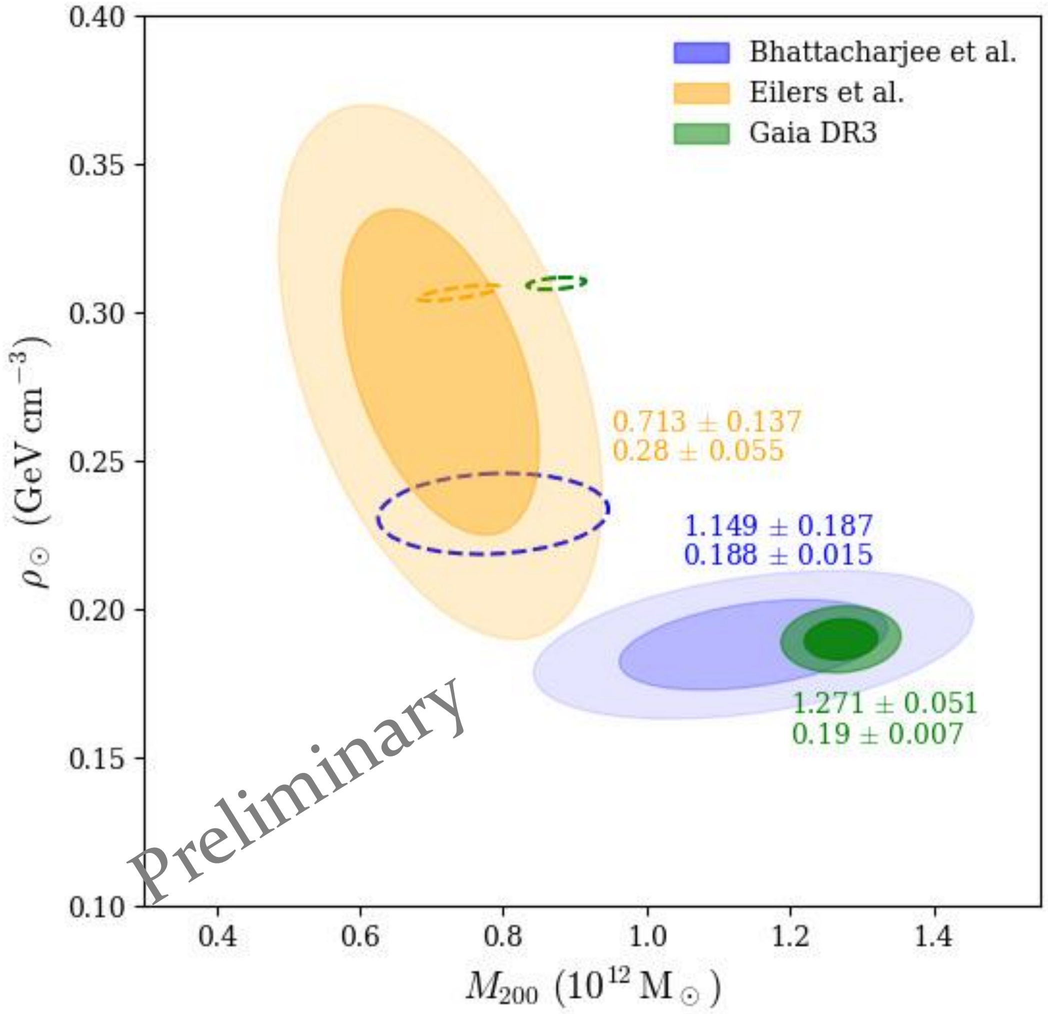
Finally, the GAIA MW DM halo

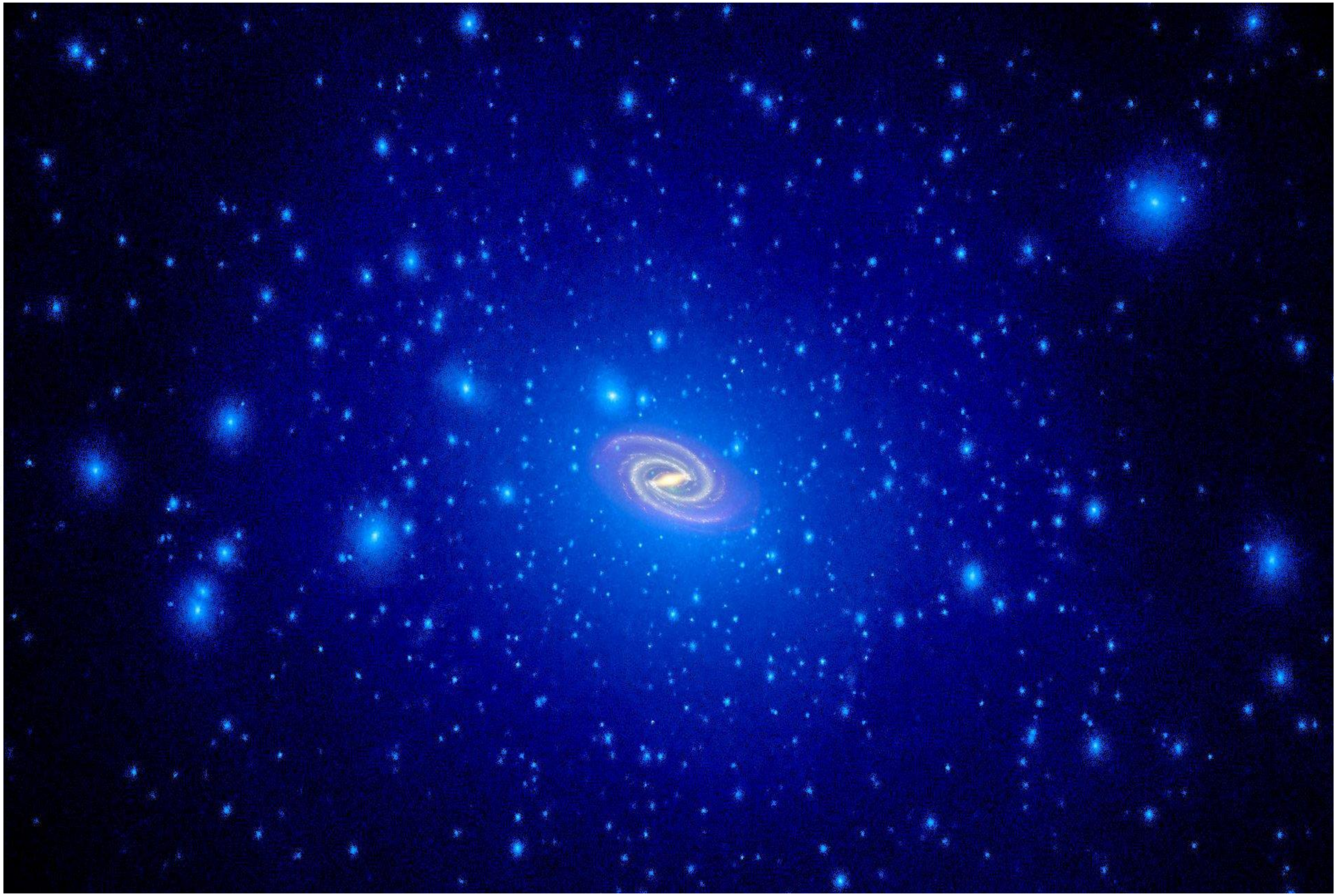


Local DM density $0.210^{+0.015}_{-0.018}$
Gev/cc

Local DM density ~ 0.19 ± 0.007
Gev/cc

Also:
Is Andromeda still the big brother to MW??

The DM density has more up its sleeve



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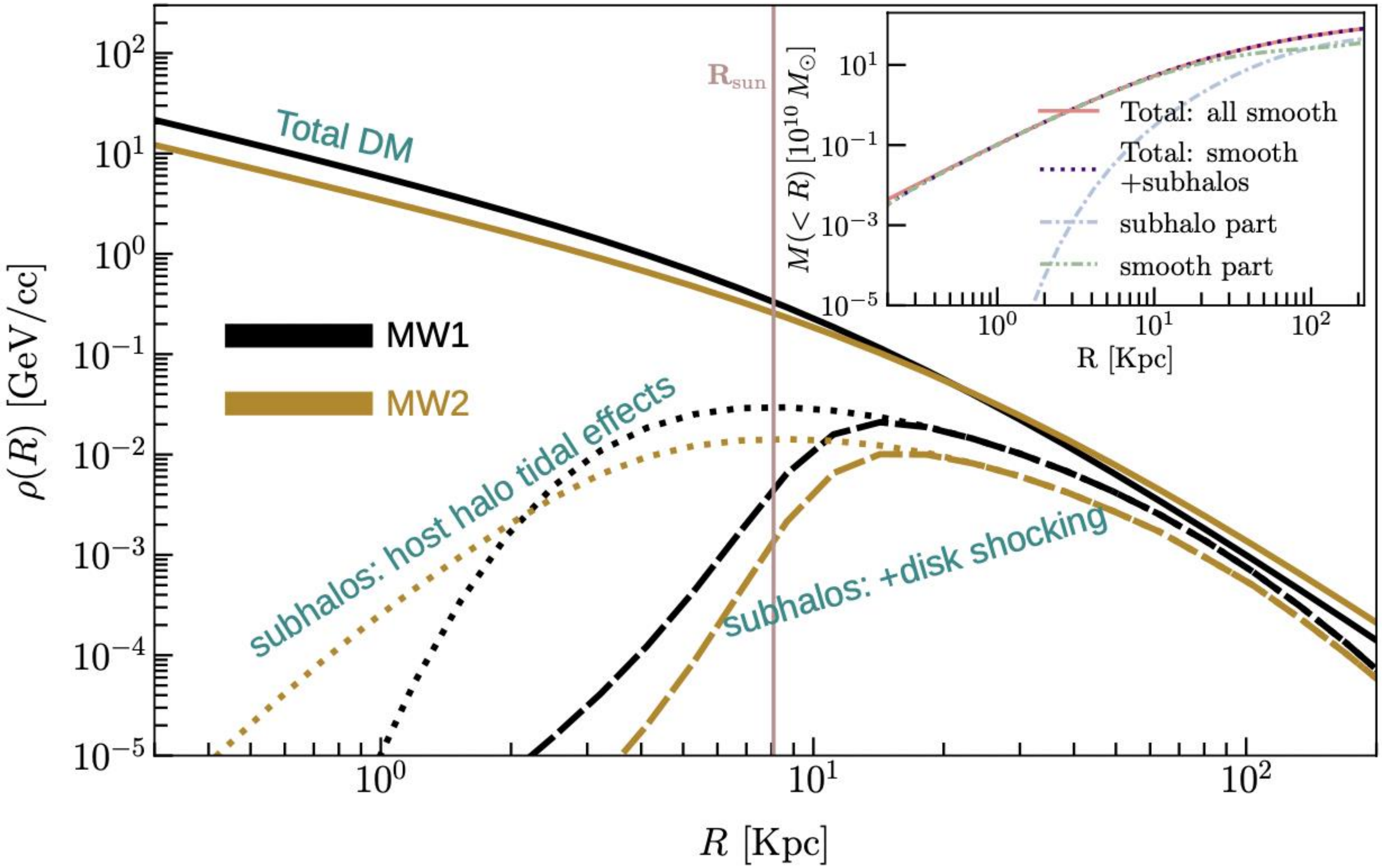
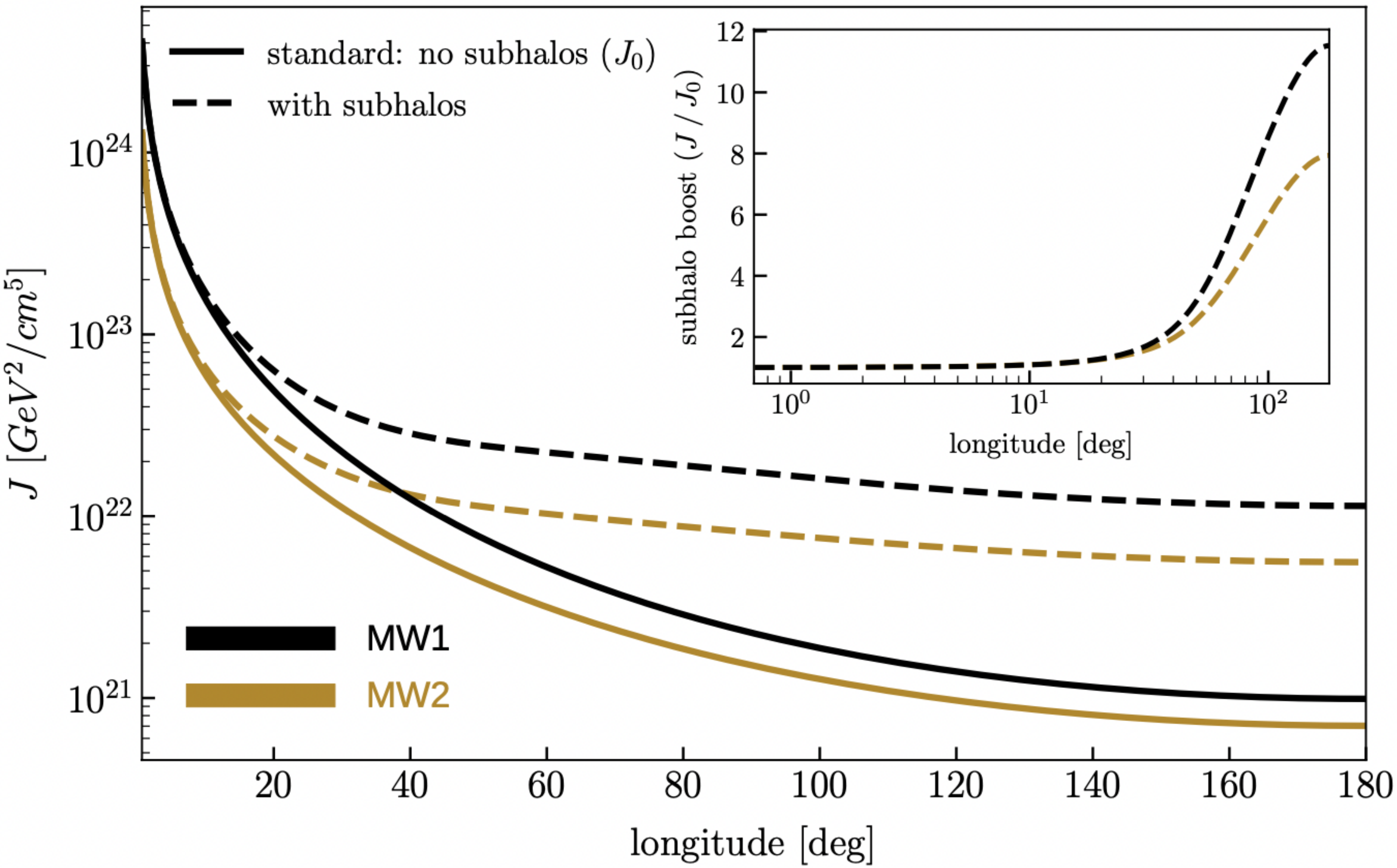
The DM density has more up its sleeve



The sub-structure boost



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From density to velocity –
The full dark matter phase-space

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DM Phase-Space in halos…

Density: Despite hierarchical formation, N-body simulations have shown that haloes exhibit a degree of universality → NFW profile.

Velocity: Extend the universality of density prof to the velocity distribution functions (VDFs) of dark matter particles.

The SIMPLICITY of such a violent process is AMAZING

Two points –

1. Hierarchical nature of structure formation could result in haloes having different VDFs due to the variations in the merger history and other factors such as tidal stripping & heating.

2. Process of violent relaxation (Lynden-Bell, 1967) → near-equilibrium distributions.
   → the Standard Halo Model (SHM), King model, the double power-law model, and the Tsallis model, are all variants of the Maxwell–Boltzmann distribution.

More motivations for studying DM VDFs …

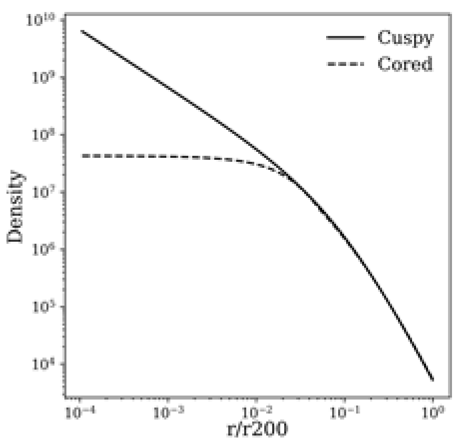
1. DM phase-space distribution in dark matter halos motivate a study of the VDF.
Just for a theoretical understanding of the phase-space distribution in dark matter halos

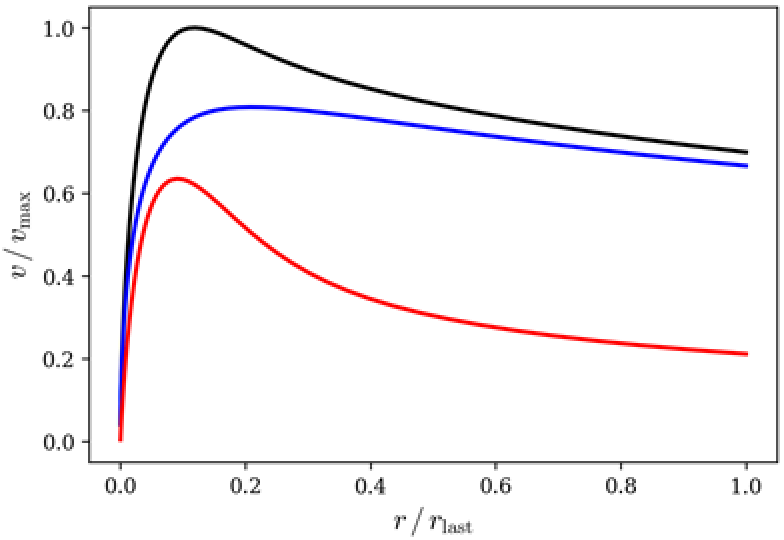
2. DM VDF affects DM detection :
Implications for direct (and indirect) DM detection limits

3. A well parameterized VDF :
Understand relations between the VDF and other physical quantities of the halos, such as mass, density profile, shape, and formation history.

An example - SIDM and cusp-vs-core DM profiles

$$v(r) = \sqrt{v^2_{\rm bary}(r) + v^2_{\rm dark}(r)}$$





$$v_{\rm dark}(r) = \sqrt{\frac{G\,M_{\rm dark}(r)}{r}}, \text{ where}$$
$$M_{\rm dark}(r) = \int_0^r \rho_{\rm dark}(r')4\,\pi\,r'^2\,dr'$$

$$\Sigma(r) = \Sigma_0 e^{-\frac{r}{r_d}}; \quad \Sigma_0 = \frac{M_{\rm bary}}{2\pi r_d^2}$$
$$\Sigma_0 = \Upsilon(M_\odot/L_\odot) \times \Sigma_0'$$

$$\rho_{\rm dark}(r \to 0) \sim 1/r \equiv \text{cuspy}$$
$$\implies v_{\rm dark} \sim \sqrt{r}$$

$$\rho_{\rm dark}(r \to 0) \sim r^0 \equiv \text{cored}$$
$$\implies v_{\rm dark} \sim r$$

Particle nature of dark matter

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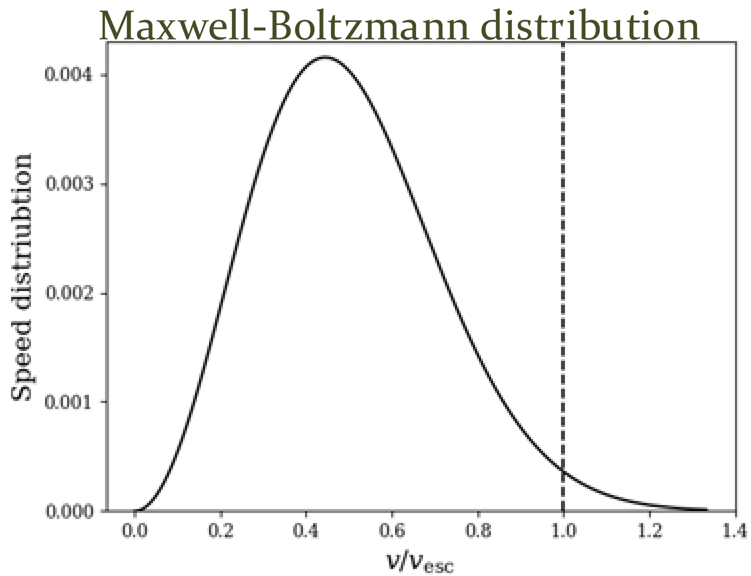
Velocity Distribution Function (VDF) of self-gravitating collisionless particles:

When the velocities are determined by many small independent causes acting in random directions, we should expect the velocities to follow **Maxwellian law**, and the only possible steady state is the **isothermal law**:



$$f \sim e^{\phi - \frac{v^2}{2}}; \qquad \rho \sim e^{\phi}$$

Different from what is actually found, N-body simulations: NFW (1996)

$$\rho = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

Densities to Velocities –

Based on classic work by Jeans, Eddington, Chandrasekhar, Lynden-Bell, Osipkov, Merritt

Jeans Theorem – Any steady state soln. of the Collisionless Boltzman Equation depends on the phase-space co-ords only through functions of integrals of motion.

Spherical system - any orbit in a spherical potential has for isolating integrals of motion (E, L_x, L_y, L_z)

Strong Jeans Theorem :
The DF of a steady state spherical system can be expressed as $f = f(E,\vec{L})$

Now, if the system is spherically symmetric in all its properties, then. $f = f(E, L^2)$
(so no directional dependence) .

Now, if you assume further that the system is isotropic, we have $f = f(E)$

Isotropic, spherically symmetric is not a bad assumption for a dark matter halo

The Eddington Method for VDF

Assuming the density distribution is such that it can be maintained in a **steady state** by a suitable distribution of velocities and the velocity distribution is **isotropic**,

$$\rho = 4\pi \int_0^{v_{esc}} \mathrm{d}v v^2 f(\phi - \frac{v^2}{2}) = 4\pi \int_0^{\phi} \mathrm{d}\mathcal{E} f(\mathcal{E}) \sqrt{\phi - \mathcal{E}}$$

Regarding ρ as a function of ϕ instead of r,

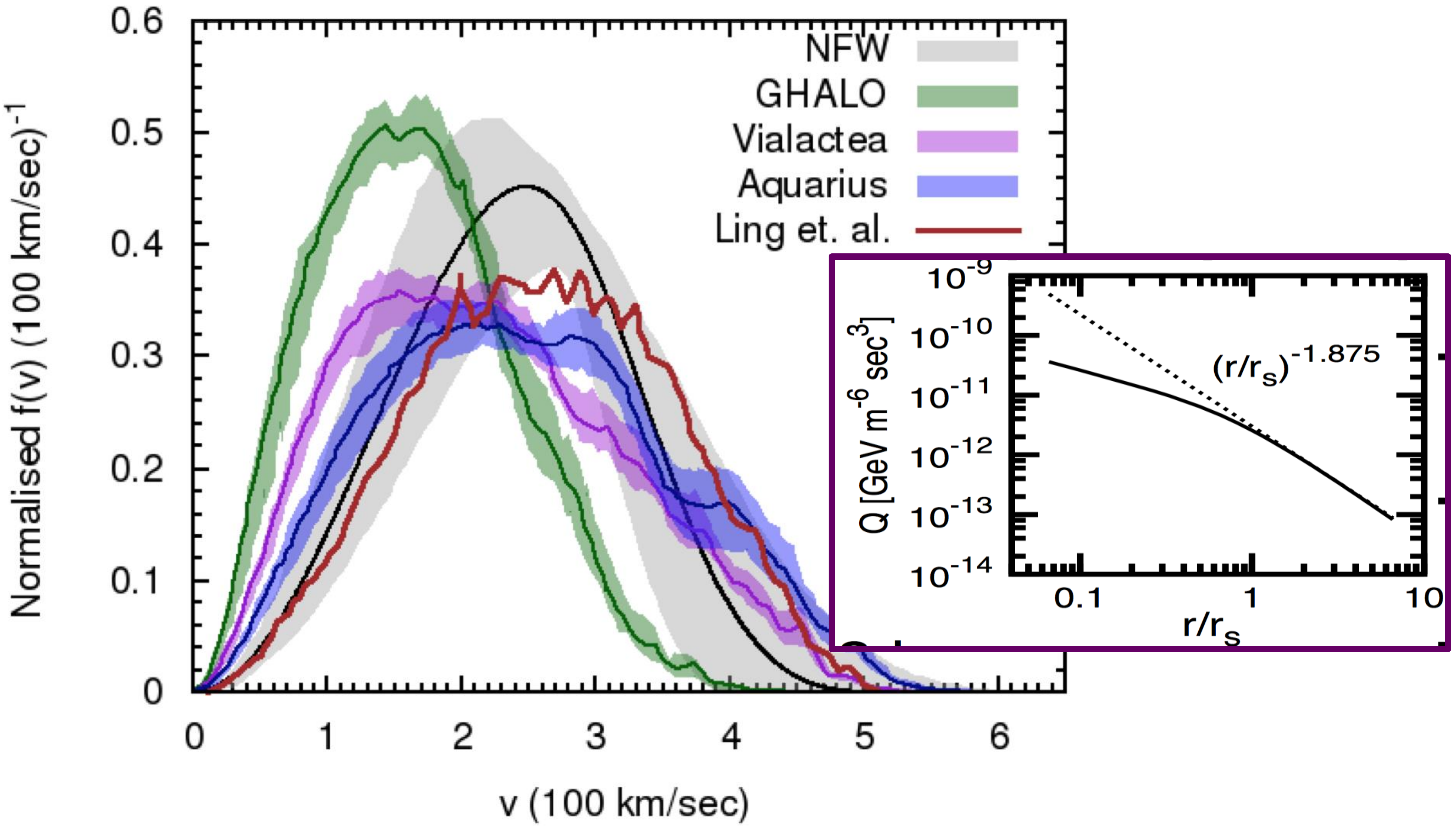
$$\frac{1}{\sqrt{8}\pi} \frac{\mathrm{d}\rho}{\mathrm{d}\phi} = \int_0^{\phi} \mathrm{d}\mathcal{E} \frac{f(\mathcal{E})}{\sqrt{\phi - \mathcal{E}}}$$

This is a case of Abel's integral equation, and the solution is,

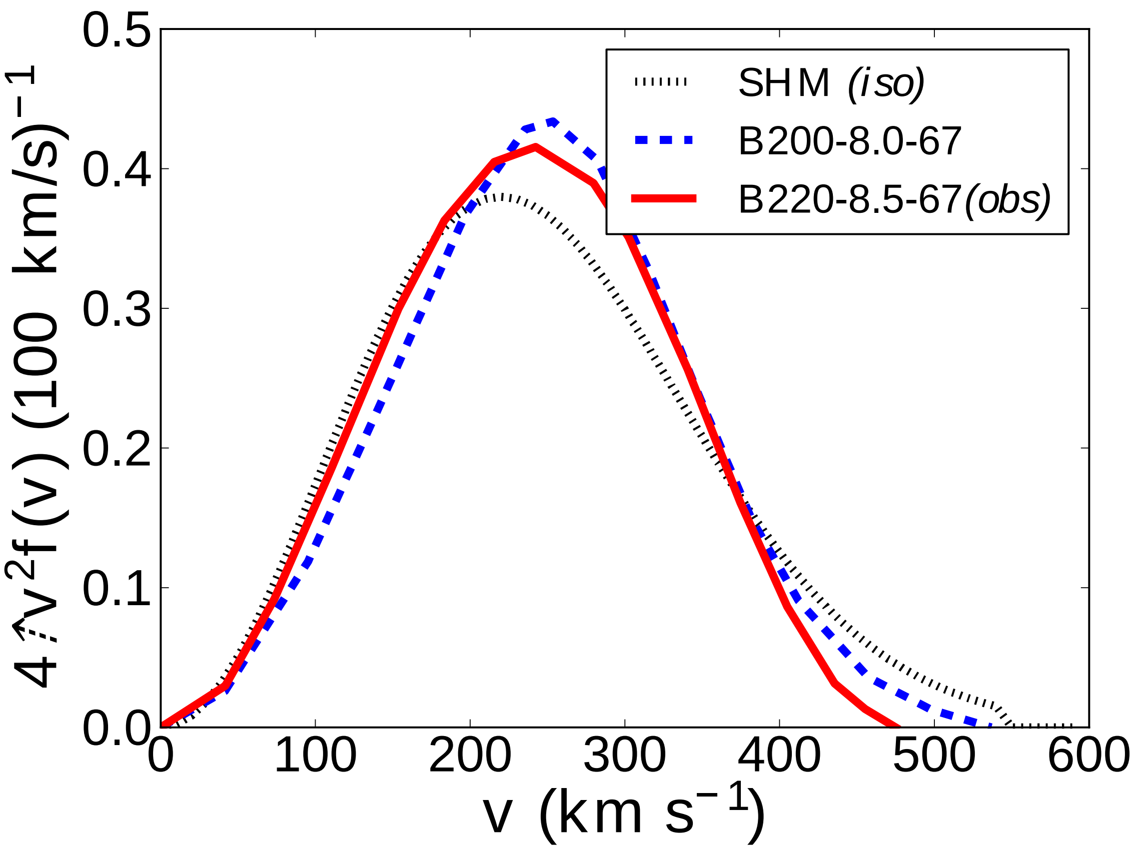
$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2} \frac{\mathrm{d}}{\mathrm{d}\mathcal{E}} \int_0^{\mathcal{E}} \frac{\mathrm{d}\phi}{\sqrt{\mathcal{E} - \phi}} \frac{\mathrm{d}\rho}{\mathrm{d}\phi}$$

At any location r, the VDF, $f_r(v) = f(\varepsilon)/\rho$. *Also* , $\rho = \int f(\varepsilon) d^3\vec{v}$

Observational reconstruction –vs- simulations
Our first estimate of the local DM VDF



An improved DM density - VDF (Pre GAIA)



SHM

$\rho_{DM,\odot}$ = 0.3 GeV/cc.

Escape vel = 544.0 km/s.

B200-8.0-67

LSR - R_o = 8 kpc

v_{co} = 200 km/s,

$\rho_{DM,\odot}$ = 0.18 ± 0.02 GeV/cc.

Escape vel = 536.8 km/s.

B220-8.5-67 (OBS)

LSR - R_o = 8.5 kpc

v_{co} = 220 km/s,

$\rho_{DM,\odot}$ = 0.29 ± 0.02 GeV/cc.

Escape vel = 475.0 km/s.

Note, how density and velocities both change !!

Milky Way DM

Direct Detection Experiments
(the DM around us)

Back to Astrophysics for DM detection

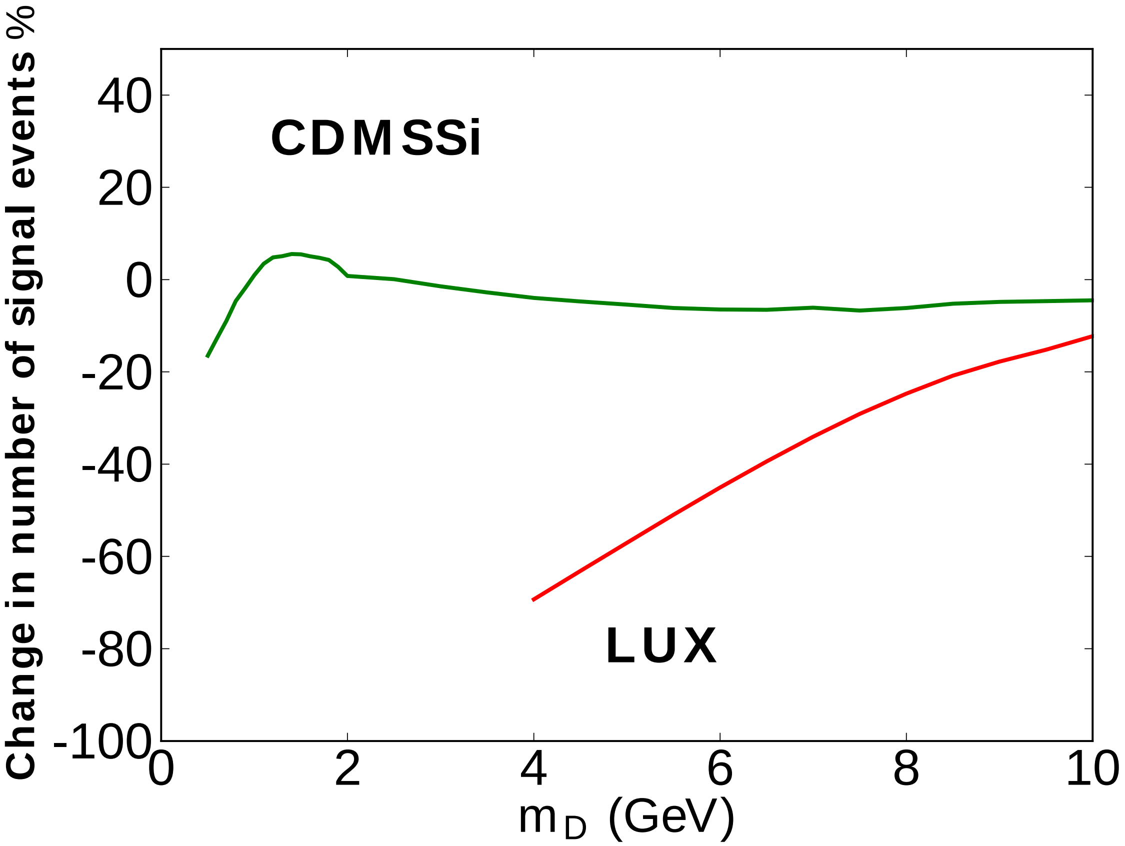
$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \mathcal{I}(E_R) F^2(E_R) \epsilon(E_R)$$

$$R_0 = \frac{320}{m_D m_T} \left(\frac{\sigma_0}{1\ \text{pb}}\right) \left(\frac{\rho_{DM,\odot}}{0.3\ \text{GeV}/c^2}\right) \left(\frac{v_0}{220\ \text{km/s}}\right) \text{tru}$$

$$\mathcal{I}(E_R) = \int_{v_r > v_{\min}} \frac{v_0}{v_r} f(\mathbf{v_r} + \mathbf{v_e}) d^3\mathbf{v_r}.$$

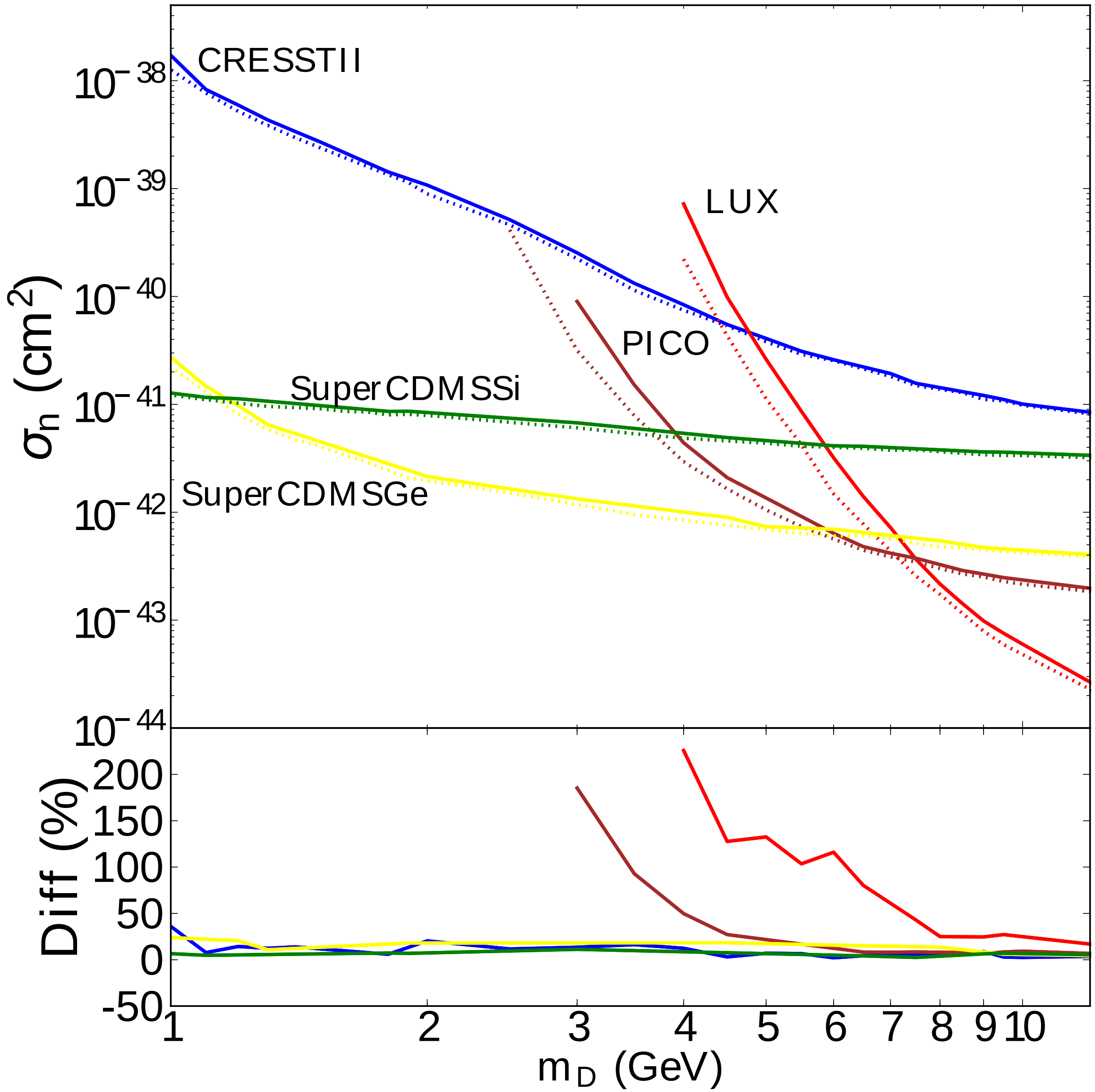
We can put in the and re-calculate

The change in fully integrated signal counts



…And the re-calculated exclusion plots

Using
Self-consistent
density & full VDF



tifr

Astrophyics vs Other Sytematics

There are four main sources of systematic errors :

(i) astrophysical uncertain-ties on the local DM density and the VDF

(ii) detector response uncertainty,

(iii) uncertainty of the nuclear form factors and

(iv) uncertainty on the detector background.

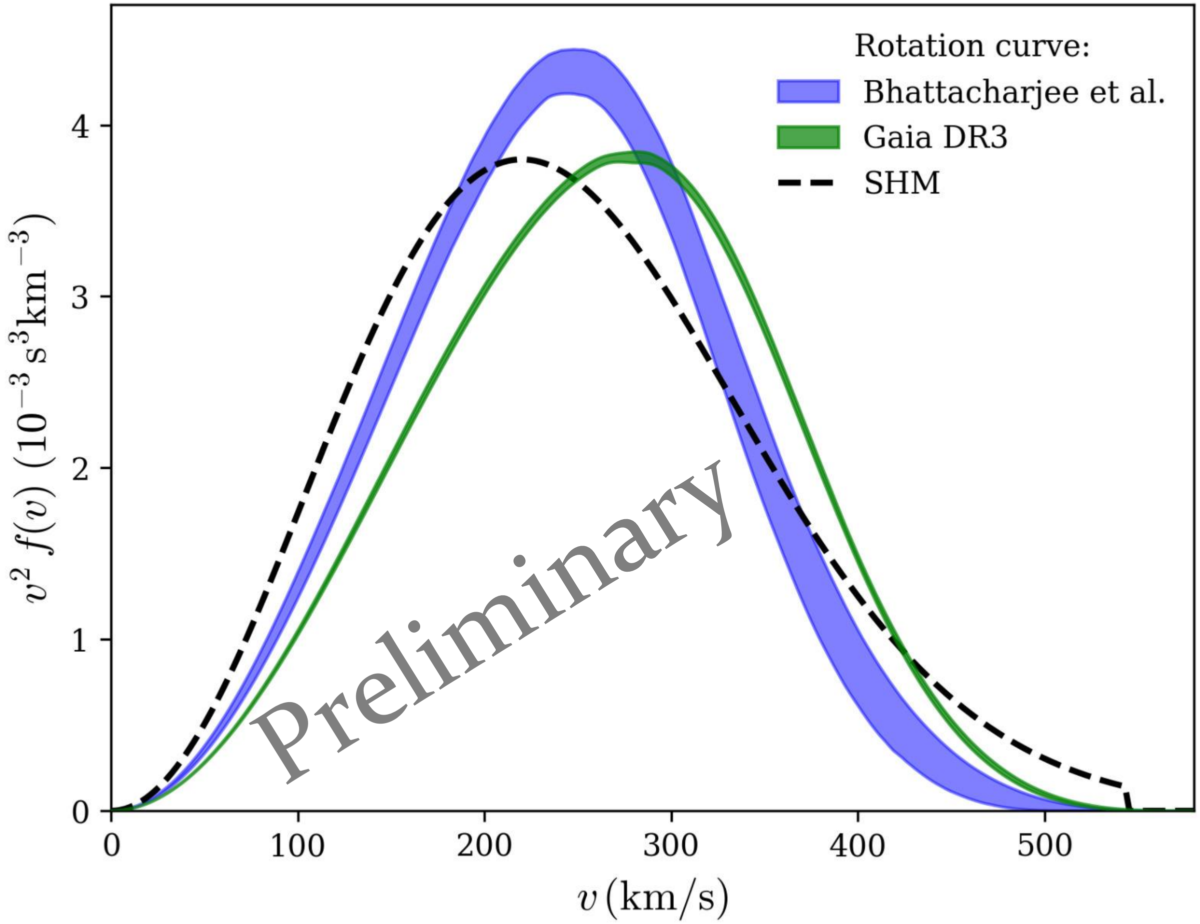
Using LUX as benchmark - their bounds indicate ~ 50% detector related uncertainties, at all candidate DM masses.

Expected uncertainties in the mean DM exclusion from future errors on the obs VDFs are ~ 30%

Combined uncertainty ~ 60% but mean deviation to Obs VDF ~ 200%

It is clearly important to use the best available observationally determined VDF when presenting the results of DM direct detection experiments.

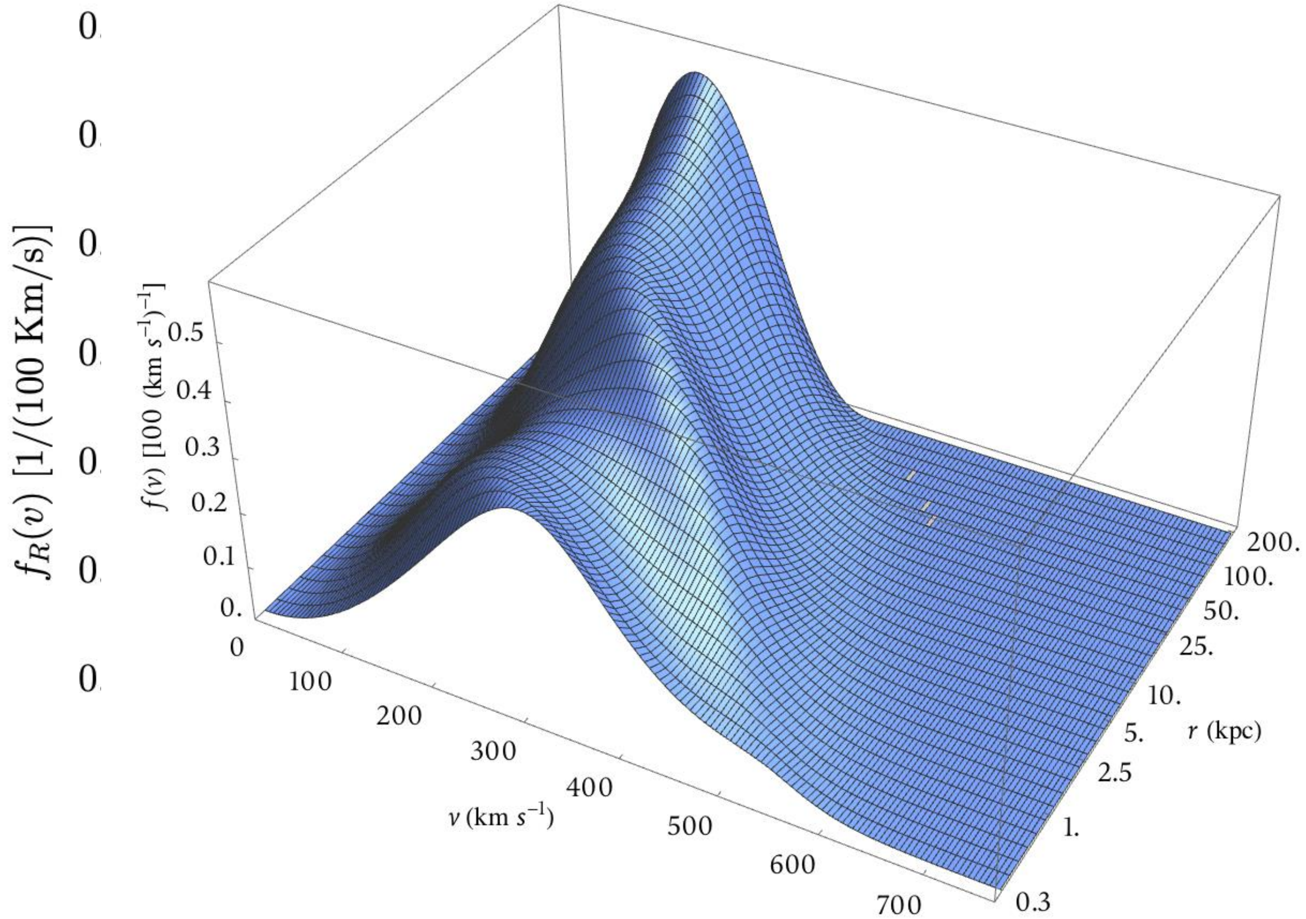
...the impact of GAIA DR3 in the VDF



Milky Way DM

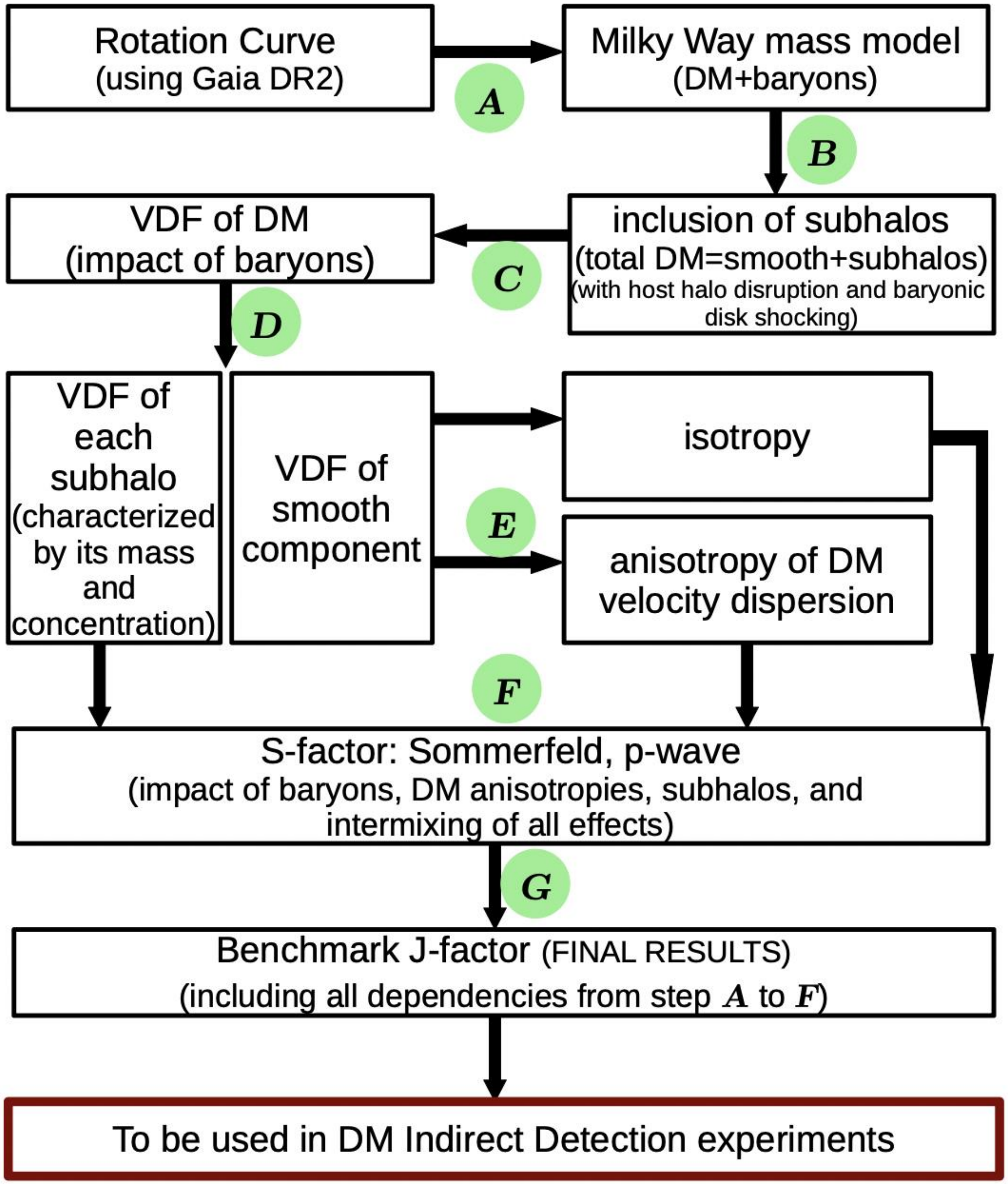
Indirect Detection Experiments
(the DM all over Milky Way)

The entire MW DM phase-space (pre GAIA)



Subha Majumdar

The most accurate template for estimating `fluxes' in Indirect DM detection experiments



Subha Majumdar

Why restrict to Milky Way only?

1. Connection to
Direct Detection Experiments

2. The galaxy-halo connection and
nature of DM halos

An ensemble of real Milky Way lookalikes ...

1. We employ criteria for choosing MW-like galaxies similar to simulations (Bozorgnia 2017)

   Milky Way mass range of $7\times10^{11} < M_{200}/M_\odot < 3\times10^{12}$

→ **32 galaxies**

2. **Stellar mass: $4.5 \times 10^{10} < M_{star}/M_\odot < 8.3 \times 10^{10}$** within 3σ observed value of MW,

3. Define the angular circular velocity ($\omega = V_c(r)/r$)

$$\chi^2 = \sum_{r_i < 2\text{kpc}}^{<30kpc} \frac{[\omega_{\rm MW}(r_i) - \omega_{\rm RC}(r_i)]^2}{[\Delta\omega_{\rm MW}(r_i)]^2}$$

We implement a cut-off condition of $\mathrm{sqrt}[\chi^2/(N-1)] < 90$ to choose MW-like RCs.

Note: Bozorgnia (2017) chose this < 300.

Our results very mildly depend on this choice

→ **8 Milky Way galaxies**

An ensemble of Milky Ways …

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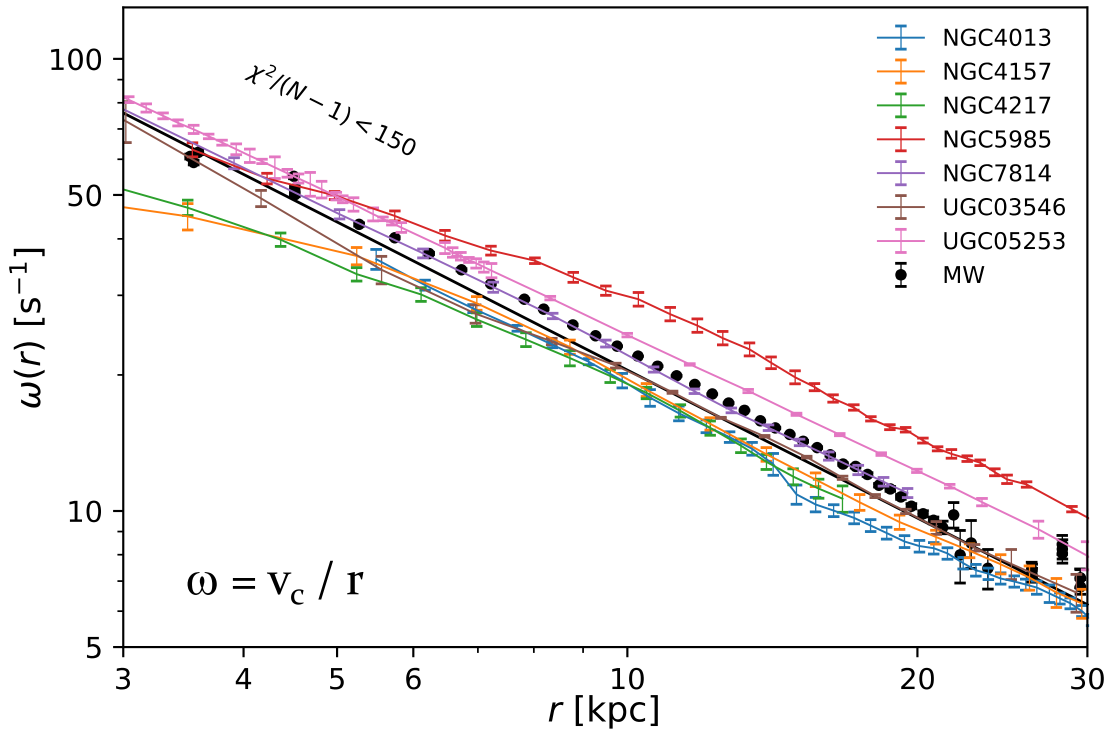
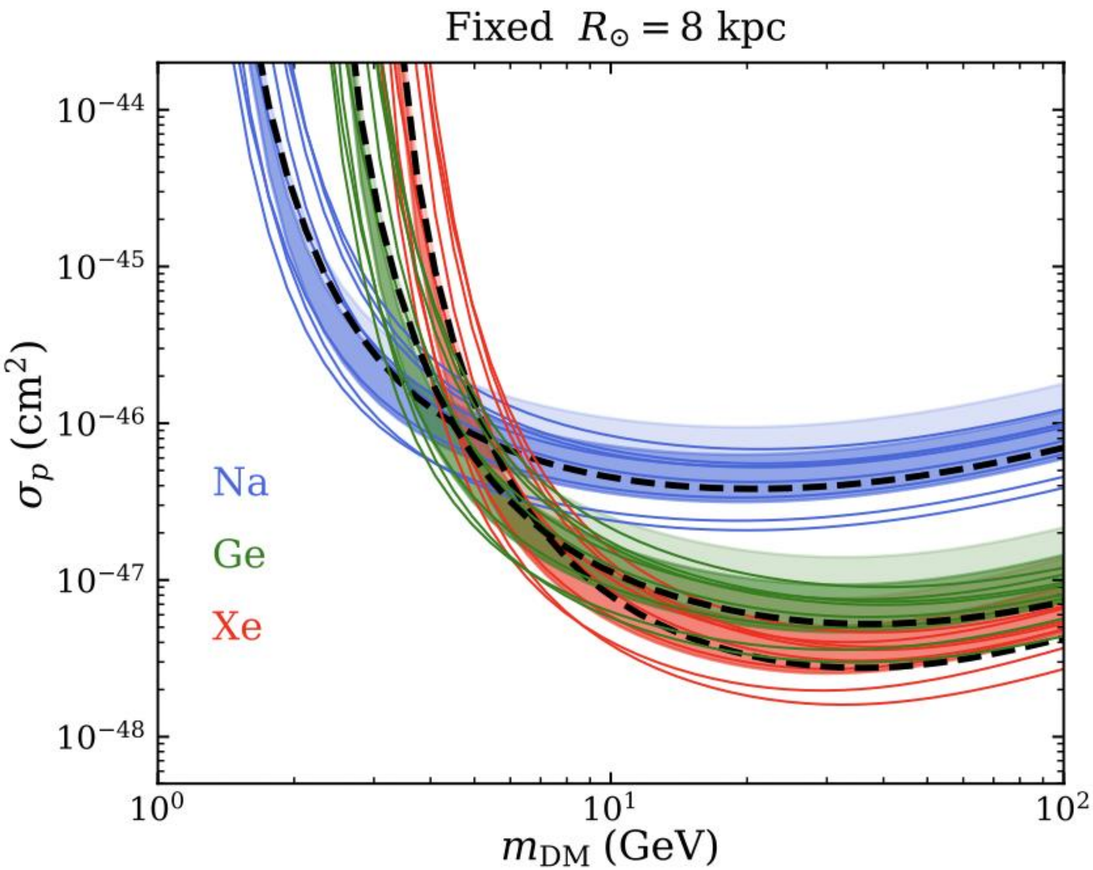
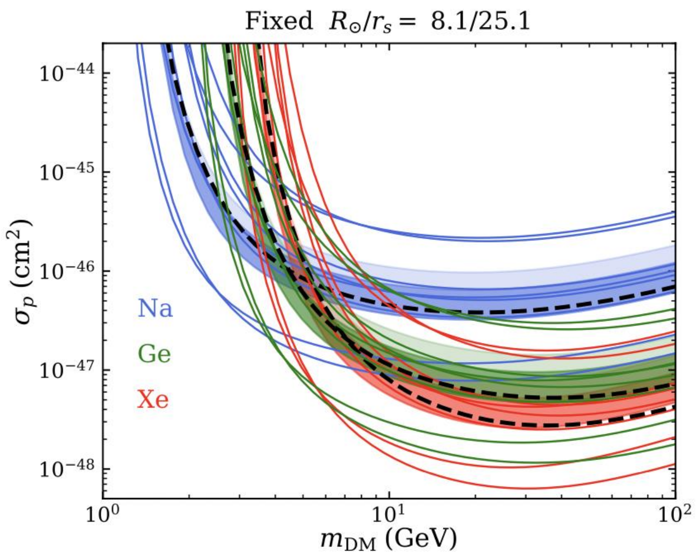


1. MW c_{200} = 4 - 16 in literature: not well constrained.
2. circular velocity $V_c(R_\odot) \sim$ 200 km/s at solar radius also uncertain -> determines the DM VDF peak velocity → significant impact on the direct detection results.
3. Baryon dominated central region of all the 8 MW-like galaxies. [exception UGC05253]
4. The MW local DM $\rho_\odot = 0.2 - 0.8$ GeV/cc. All MW-like galaxies falls in this range.

The cosmological sample variance in DM exclusion limits …





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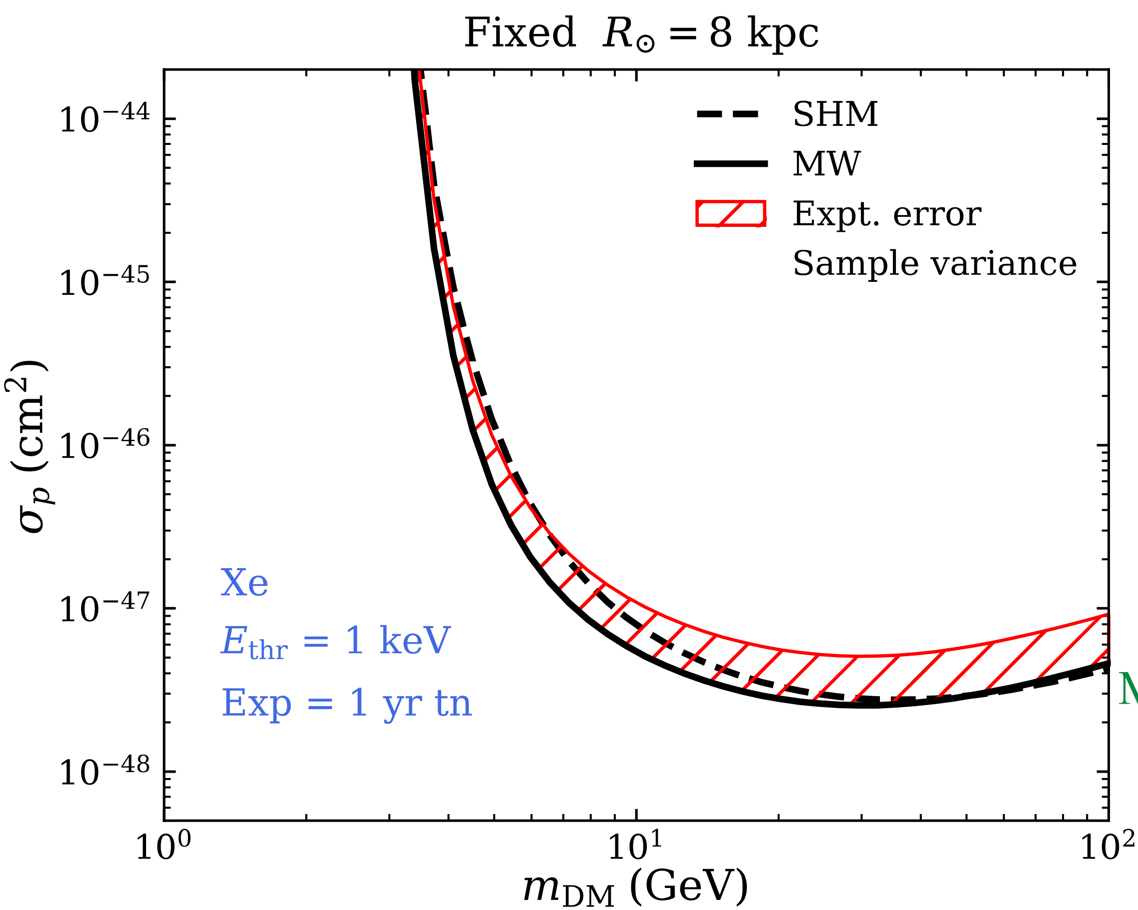
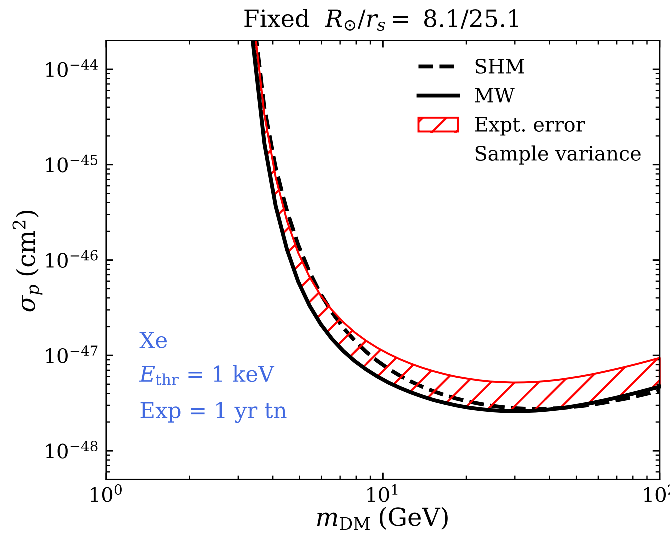
The irreducible error (shown for Xe)...





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Better density, better VDF, and better expts will reduce error bars on limits

But you cannot do better than the sample variance

THANK YOU