Constrained analytic model of Galactic dark matter subhalos

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Based on works with ***Gaétan Facchinetti***, ***Thomas Lacroix***, ***Martin Stref***, ***et al.***
(1610.02233, 1805.02402, 1904.10935, 1905.02008 + work in prep)

Dark Side of the Universe

UBA, Buenos Aires – July 18, 2019

Outline

* **Motivations**

* **Roadmap for a consistent model + some results**

* **Perspectives**

CDM issues on small (subgalactic) scales

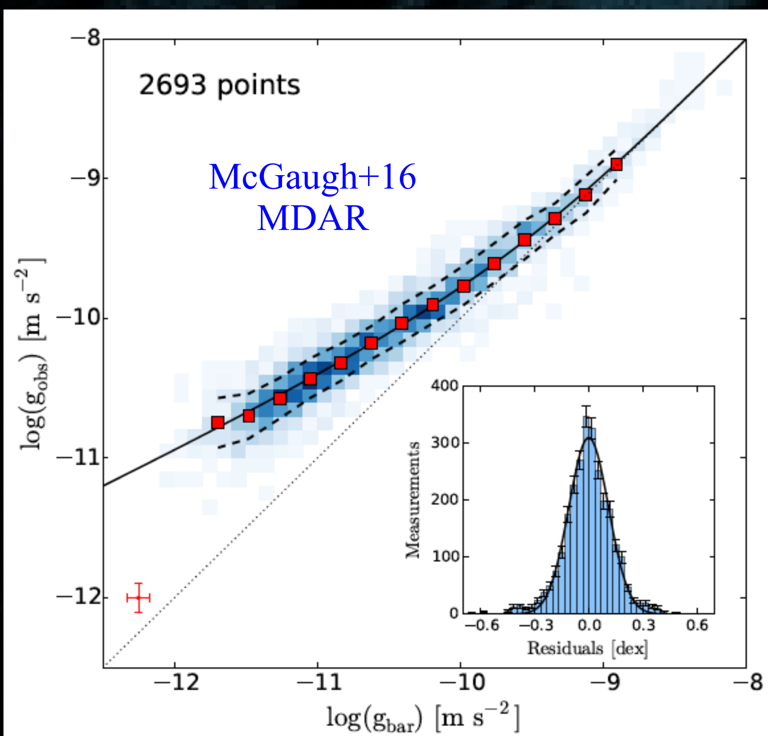
Small-Scale Challenges to the ΛCDM Paradigm

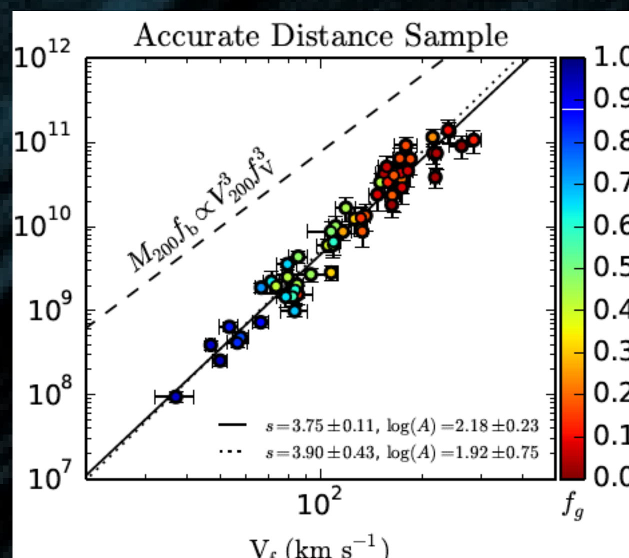
arXiv:1707.04256

James S. Bullock[1] and Michael Boylan-Kolchin[2]

[1]Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA; email: bullock@uci.edu
[2]Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712, USA; email: mbk@astro.as.utexas.edu

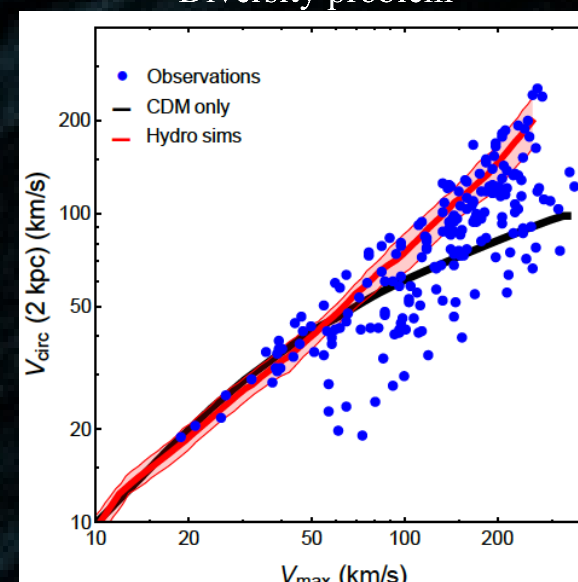
See also NFW's talks





Lelli+15, BTFR

Tulin+18 after Oman+15
Diversity problem



Core/cusp problem ↔ regularity vs. diversity problems.
Maybe baryonic effects. Important to clarify.

CDM issues on small (subgalactic) scales

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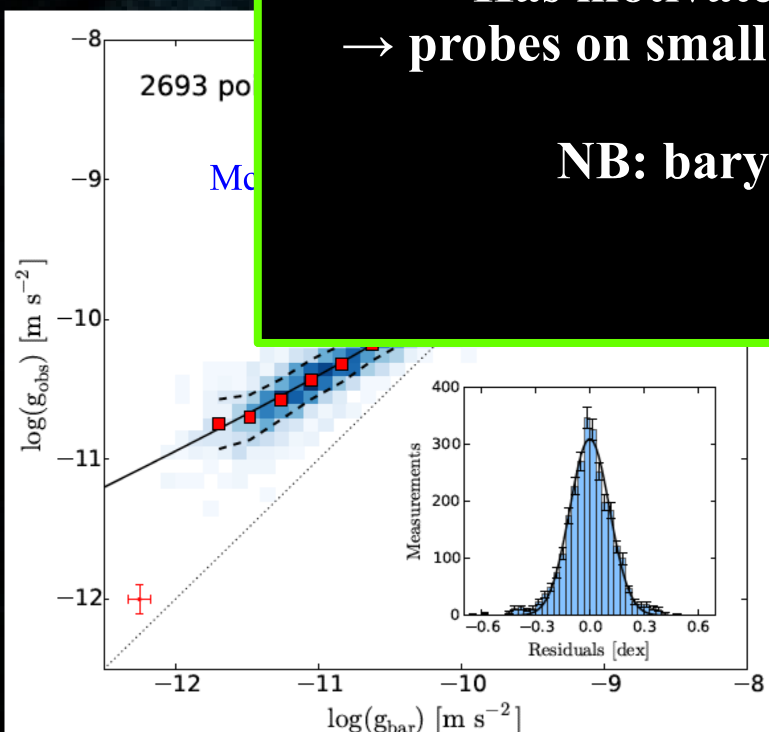
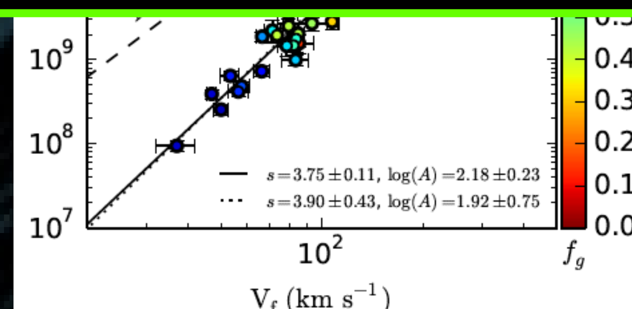
Has motivated pure DM solutions: eg ULA, SIDM
→ probes on small scales important tests for all DM scenarios

NB: baryonic physics does matter anyway!





Lelli+15, BTFR

Oman+15
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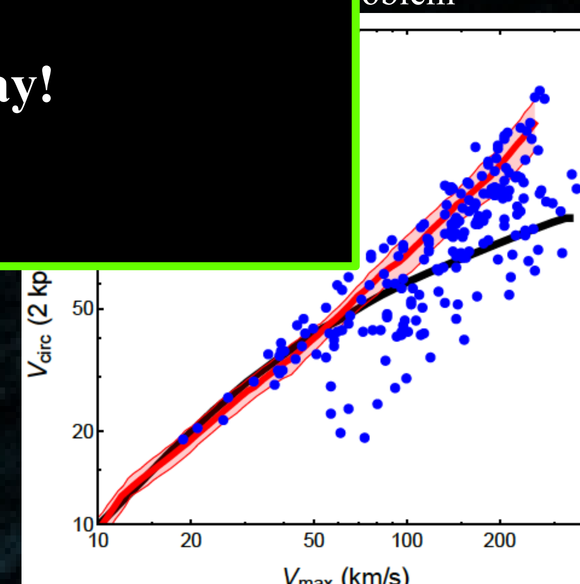

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A test of dark matter-only structuring properties: Dark subhalos

Proving/excluding the existence of dark matter subhalos?

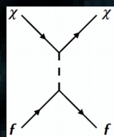
*** deep implication for dark matter scenarios + cosmology**
*** access to both DM candidate properties and primordial power spectrum**

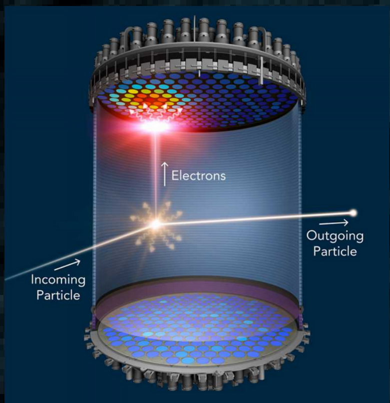
*** independent test of "dark matter solutions" to the current small-scale issues**

Looking for CDM subhalos in the Milky Way?

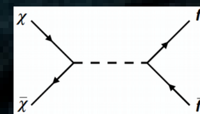
=> need for an accurate and dynamically consistent population model (MW=strongly constrained system)

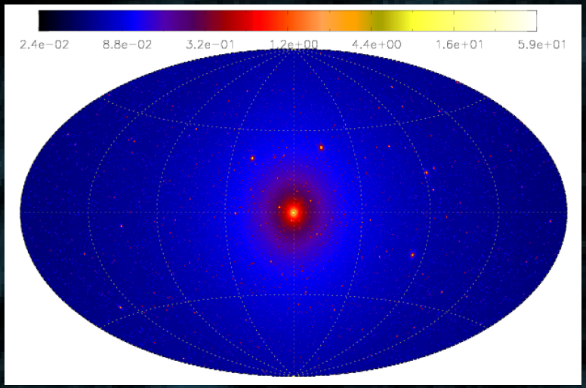
Looking for / impact of dark matter subhalos
1. Particle dark matter searches



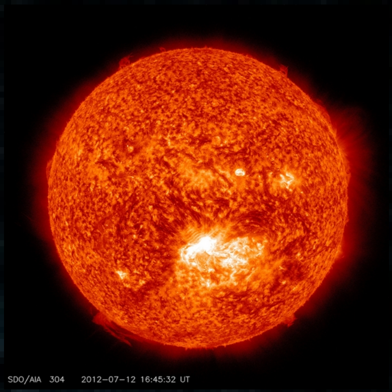


@KIPAC

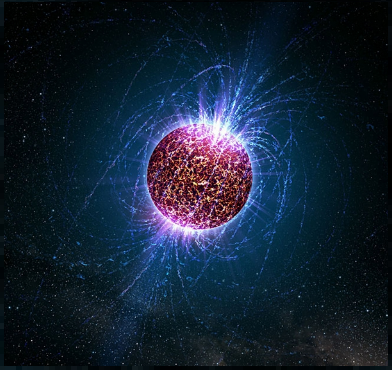




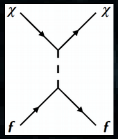
Pieri, JL+'11



@SDO/NASA



@Casey Reed/Penn State University



Direct searches (WIMPs or axions) + solar neutrinos:
→ (large) fluctuations in local density (A. Ibarra's talk)
→ streams in local velocity distribution (S. White's talk)

Indirect searches:
→ boost in the annihilation rate (S. White's talk)
→ impact on v-dependent signatures
→ individual sources e.g. in gamma-rays

Interaction with stars:
→ DM capture enhanced (A. Ibarra's talk)

Looking for / impact of dark matter subhalos
2. Gravitational searches

Gaia satellite @ ESA

++ astrometry + lensing (micro/weak/strong) + pulsar timing + others

→ features in stellar streams, wakes in stellar density, lensing, etc.
[e.g. Calberg+, Erkal+, Belokurov+, Bushmann+, Ezaveh+, Penarrubia+, Feldmann+, Sandford+, Van Tilburg+, Dror+, etc.]

[NB1: DM clustering also impacts microlensing limits on PBHs]
[NB2: different DM scenarios imply different clustering properties]

Modeling Galactic subhalos

Theoretical framework well defined:

* Inflation model → **primordial power spectrum** (model dependent)
* DM-baryons coupling properties (model dependent)
* **Matter power spectrum** (model-dependent cutoff)
* Press-Schechter and extensions → **sub/halo mass function** (z)
…

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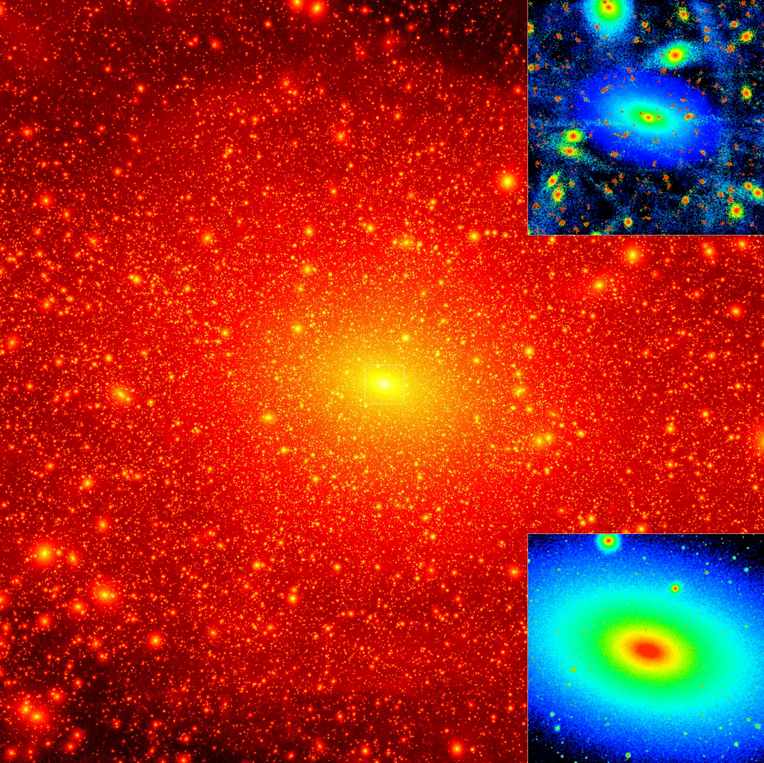
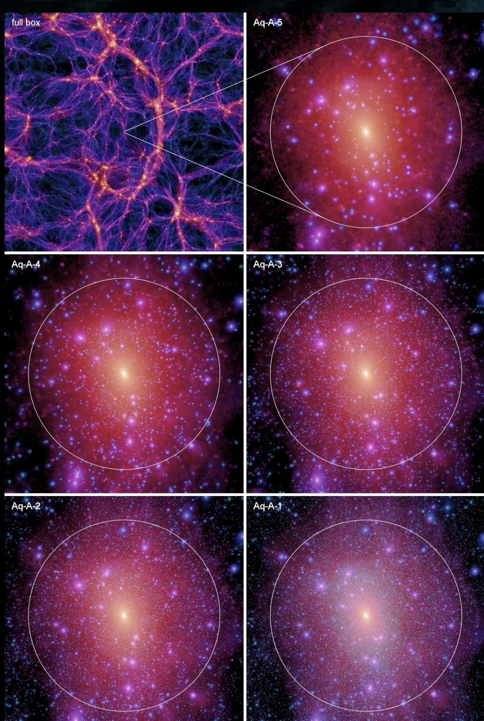

Via Lactea II, Diemand+08



Aquarius, Springel+08

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=> Statistical properties of sub/halos + links with cosmology
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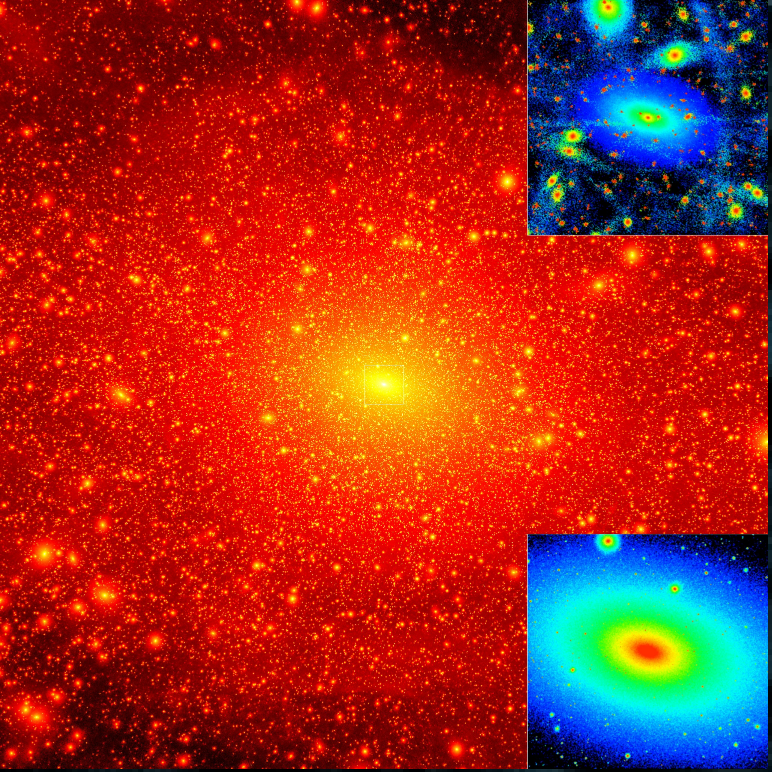

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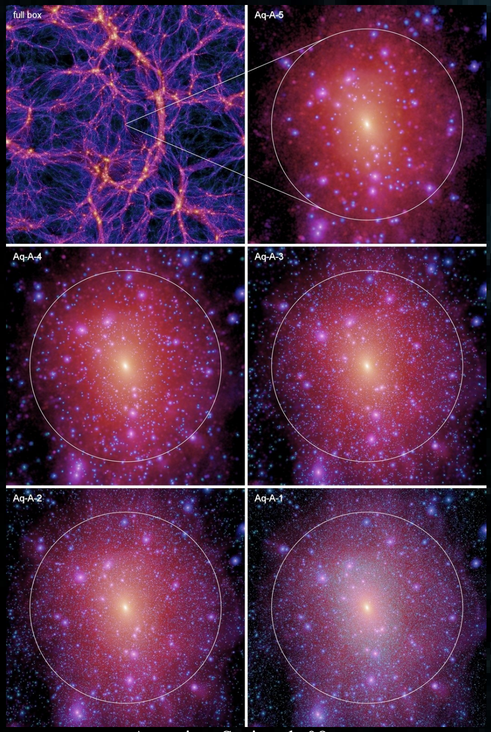
* Impact of baryons from hydro-runs / adiabatic growth of disks



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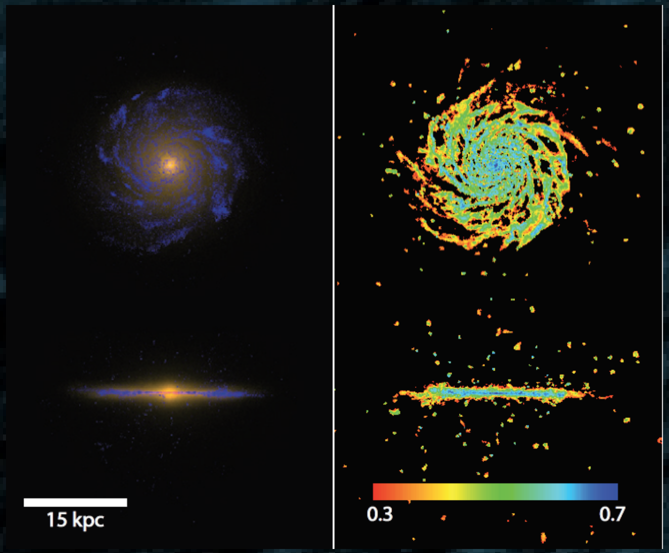
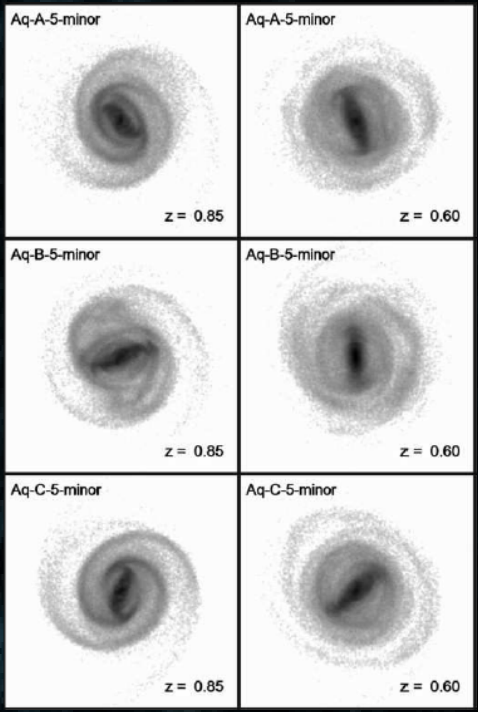
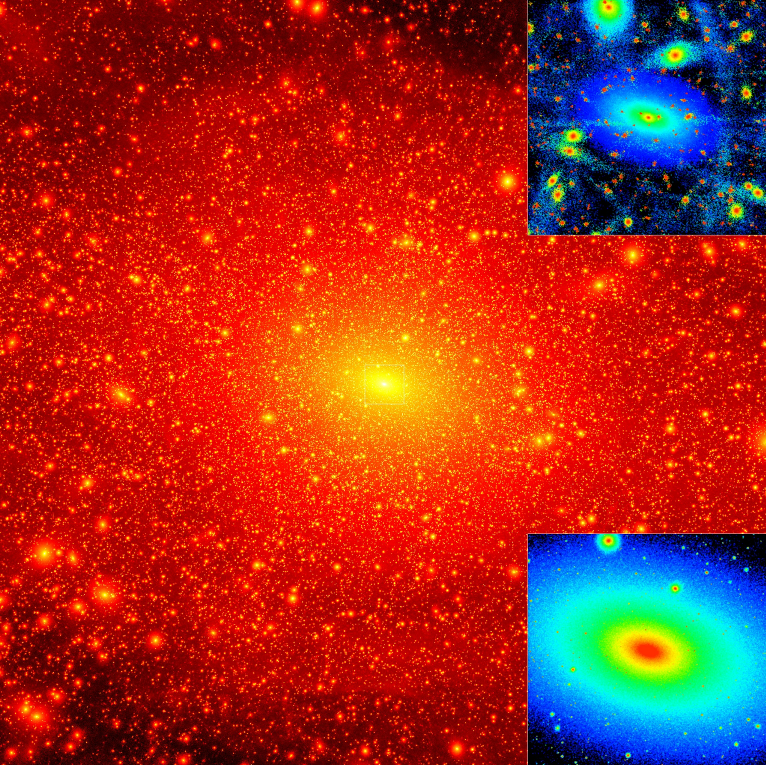


Eris, Guedes+11
[see also Molitor+'15]



Aquarius + baryons, Yurin+15



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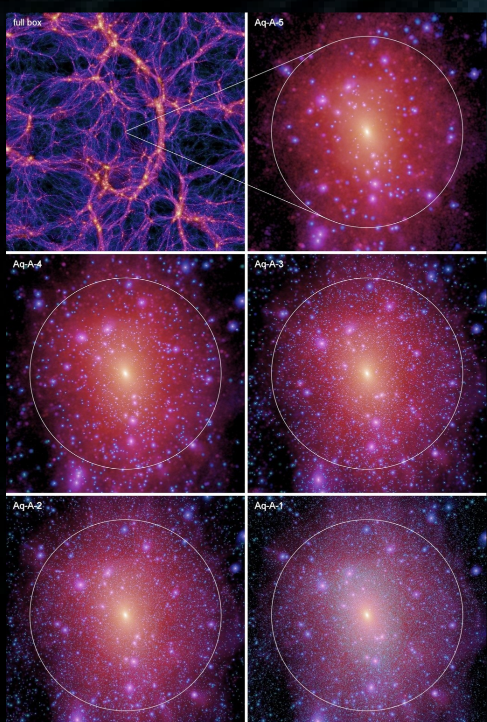

Aquarius, Springel+08

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PROBLEMS ARE

* **Resolution limit**: compare $10^5 M_{sun}$ with $10^{-10} M_{sun}$ (in DM-only)
* … getting worst in hydro-runs

…

* (Large uncertainties in baryonic physics)

…

* Modifications in cosmological inputs very expensive

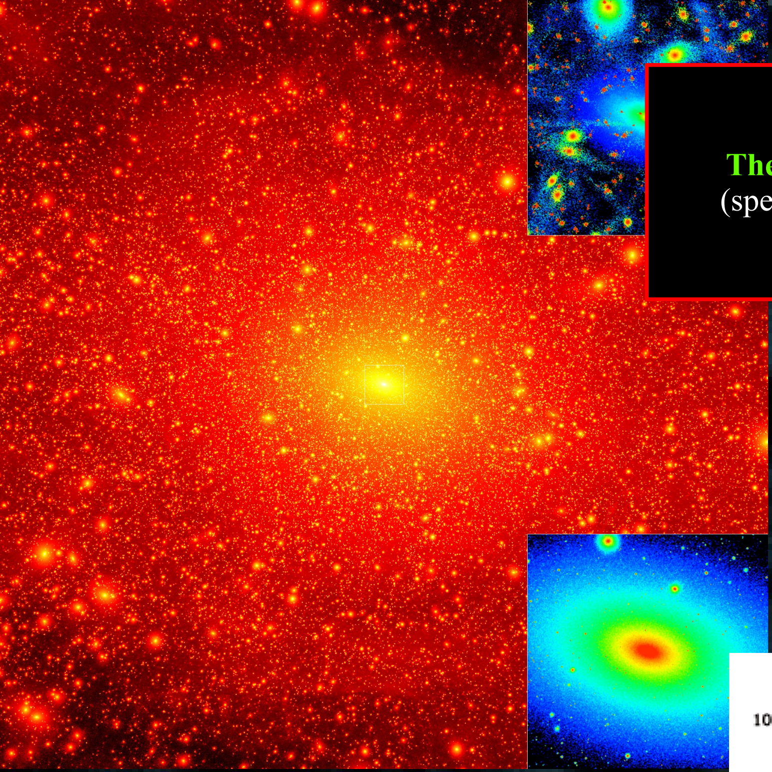
…

* How is "Milky Way-like" defined?
* What's special with "8 kpc" in a cosmological simulation? …. etc.

Making predictions for DM searches?

The Milky Way a strongly constrained system!
(specific history + properties + observational data)

[F. Iocco's talk]



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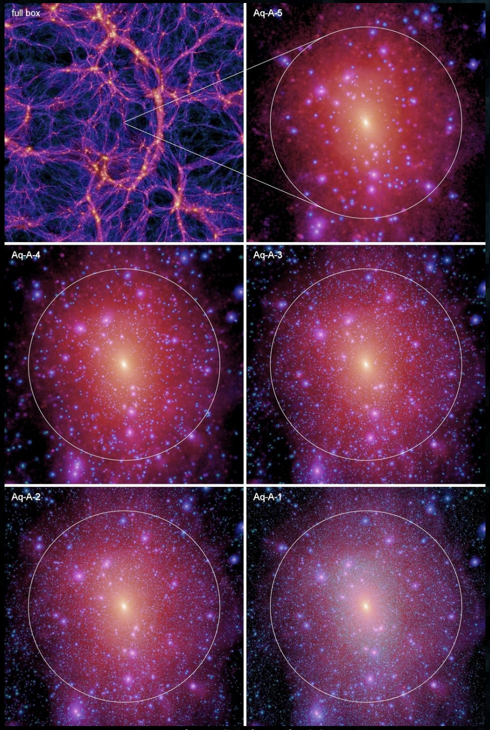
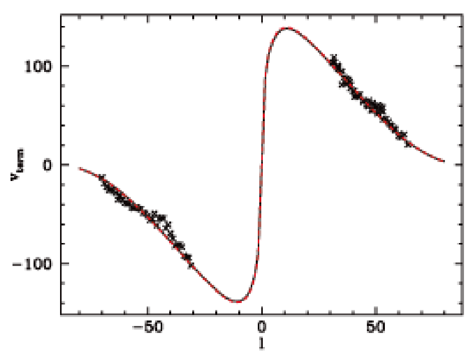
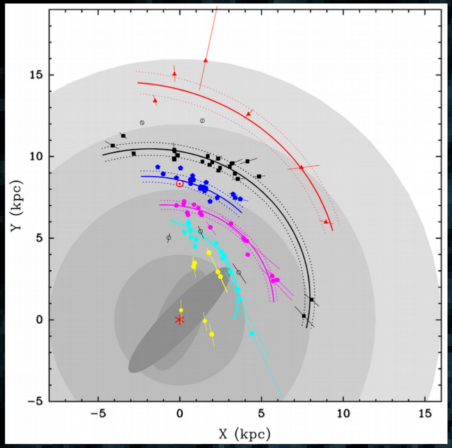


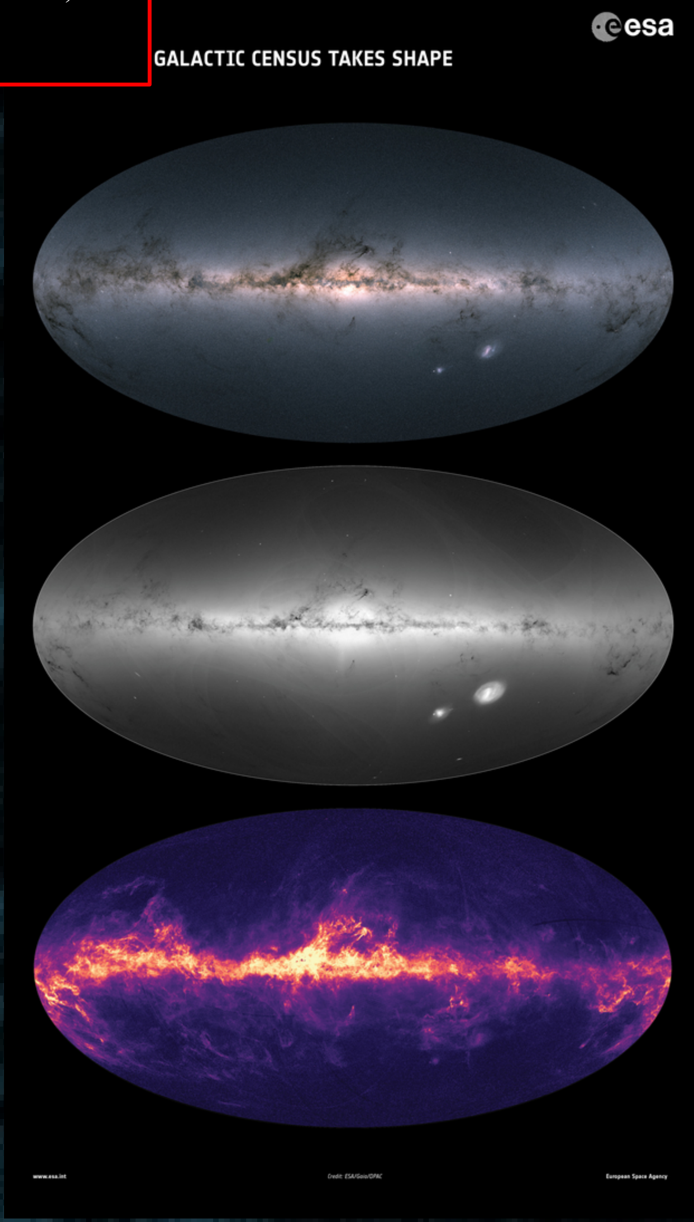
Aquarius, Springel+08



MW terminal velocities, McMillan '11



MW masers, Reid+14



Gaia: Data Release 2 (DR2) @ESA

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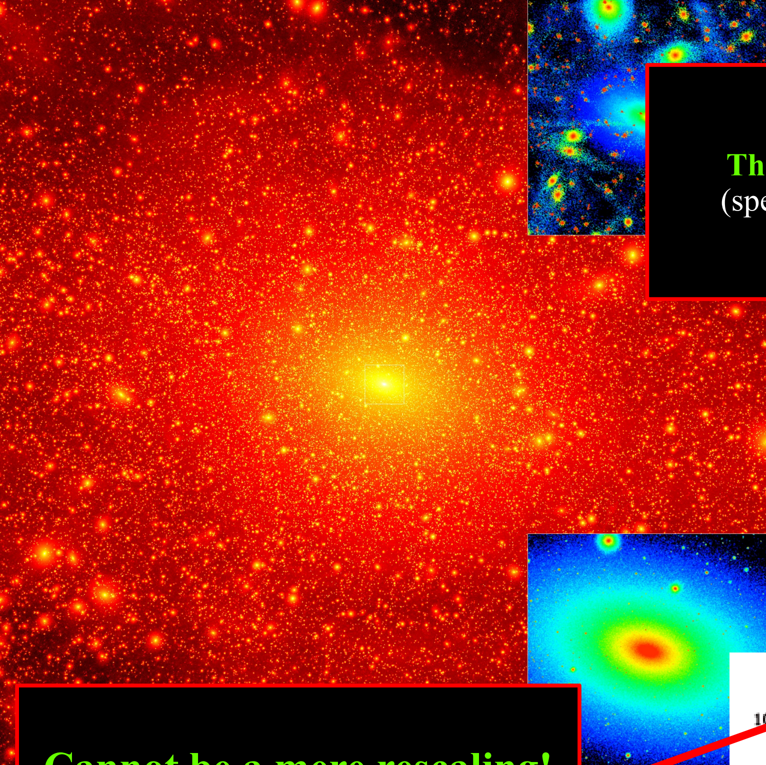
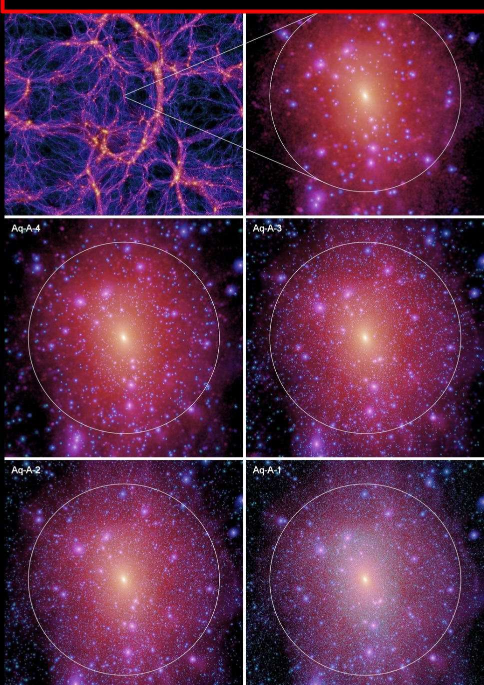
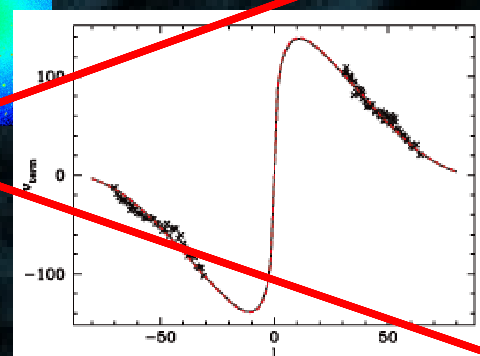


Cannot be a mere rescaling!



Aquarius, Springel+08
[see also Molitor+’15]



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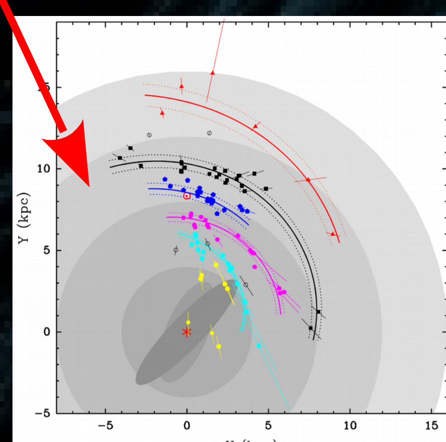

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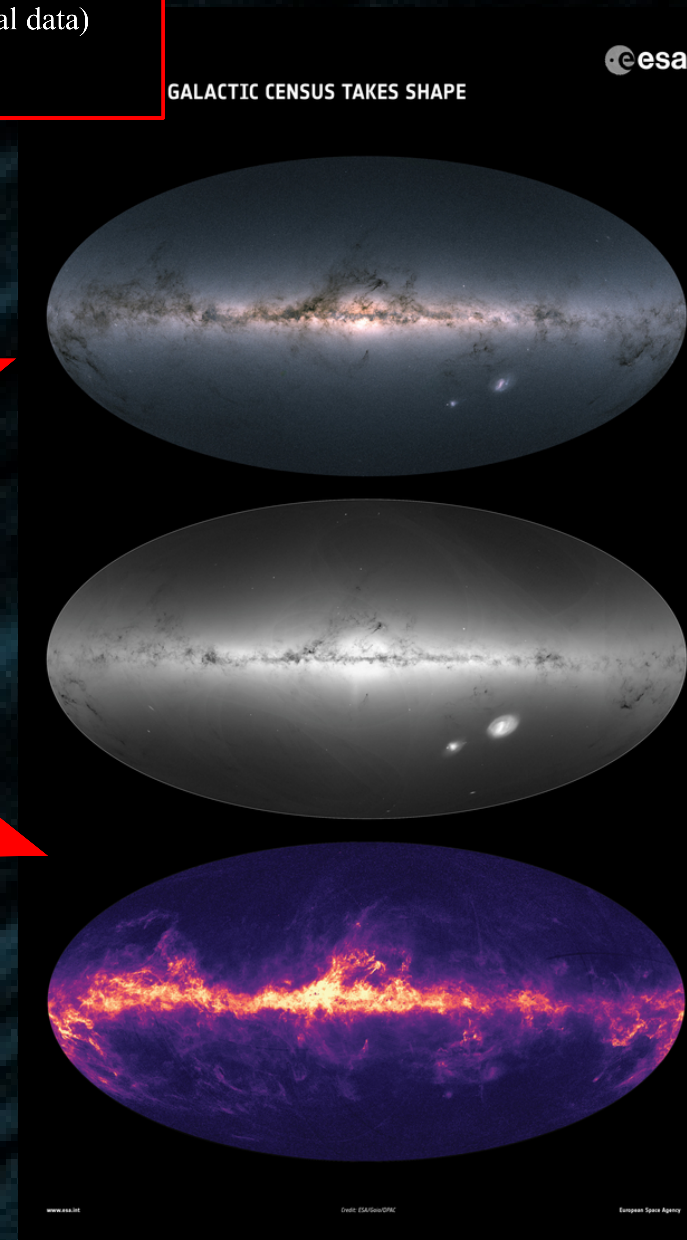

Gaia: Data Release 2 (DR2) @ESA

Analytical model: defining the whole subhalo "phase space"

At MW formation, all (cosmological) properties factorize out

$$\frac{d^n N^0}{d\omega^n} = N_0 \, \frac{d\mathcal{P}_V^0(\vec{x})}{dV} \times \frac{d\mathcal{P}_m^0(m)}{dm} \times \frac{d\mathcal{P}_c^0(c,m)}{dc}$$

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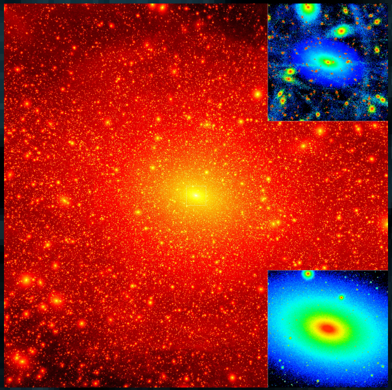

Step 1: compute tides induced by final MW halo
=> parameter space becomes intricate!

=> generic enough to be calibrated from simulations
=> subhalo mass fraction ~10% in range $(10^{-5},10^{-2})$ M_h
(eg Diemand+08) fixes N_0

$$\frac{d^n \bar{N}}{d\omega^n} = \frac{\bar{N}_{\rm tot}}{\bar{K}_w} \frac{d\bar{\mathcal{P}}_V(\vec{x})}{dV} \times \frac{d\bar{\mathcal{P}}_m(m,\vec{x})}{dm} \times \frac{d\bar{\mathcal{P}}_c(c,m,\vec{x})}{dc}$$

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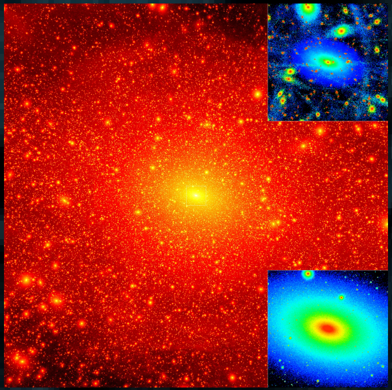

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Step 2: compute tides induced by MW baryons
=> parameter space even more intricate

=> CANNOT be calibrated from simulations

$$\frac{d^nN}{d\omega^n} = \frac{N_{\rm tot}}{K_w}\,\frac{d\mathcal{P}_V(\vec{x})}{dV}\times\frac{d\mathcal{P}_m(m,\vec{x})}{dm}\times\frac{d\mathcal{P}_c(c,m,\vec{x})}{dc}$$

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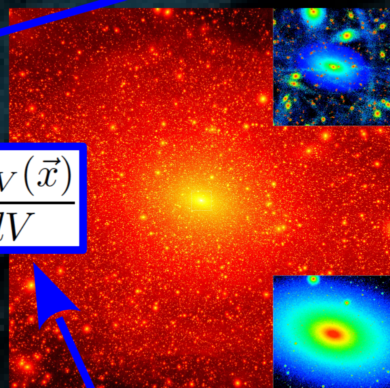
$$\frac{d\mathcal{P}^0_V(\vec{x})}{dV} = \frac{\rho_{\rm tot}(\vec{x})}{M_{\rm h}} = \frac{d\mathcal{P}_V(\vec{x})}{dV}$$



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Hard sphere argument:

Subhalos track the evolving DM distribution, even after disruption.

=> redistribution of DM from subhalos to the smooth component.

=> only the final mass function knows about tidal stripping and disruption

Step 2: compute tides induced by MW baryons
=> parameter space even more intricate

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$$\frac{d^n N}{d\omega^n} = \frac{N_{\rm tot}}{K_w} \frac{d\mathcal{P}_V(\vec{x})}{dV} \times \frac{d\mathcal{P}_m(m,\vec{x})}{dm} \times \frac{d\mathcal{P}_c(c,m,\vec{x})}{dc}$$

Input parameters (m_{200}, r_{200}, c_{200}) are not physical observables!

(m_{200}, r_{200}, c_{200}) + inner profile
→ set initial properties (flat background)
→ help fix scale parameters r_s and ρ_s

↓

Physical parameters are
→ scale parameters r_s and ρ_s
→ tidal mass m_t and extension r_t + position
(m_t, r_t < m_{200}, r_{200})

$$\rho_{\rm tot}(R) = \rho_{\rm sm}(R) + \rho_{\rm sub}(R)$$

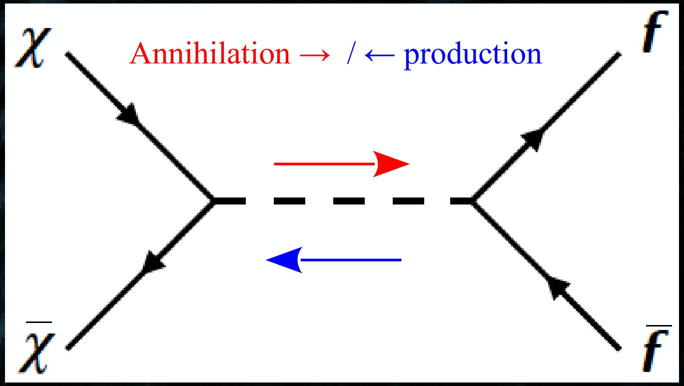
Kinematic constraints
[use McMillan'18 here]

Predicted
[our model]

Setting the subhalo cutoff mass scale (thermal DM)

More details in Gaétan Facchinetti's poster

Production/annihilation => chemical+thermal equilibrium
→ Chemical decoupling => freeze out ($x_f = m/T_f \sim 20$)
→ Relic abundance fixed
NB: links with indirect searches



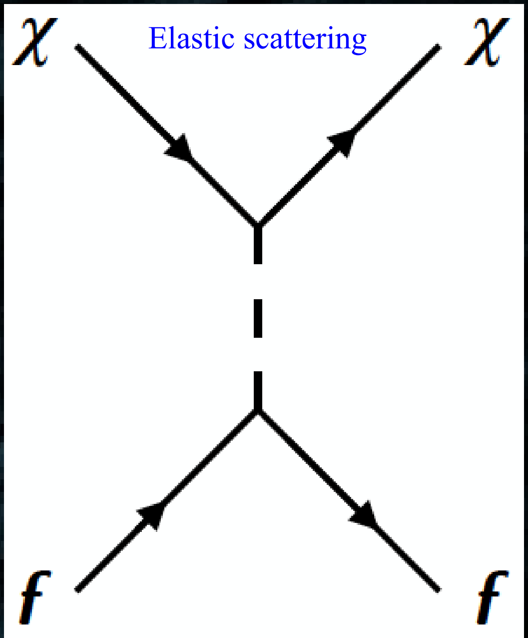
$$\Gamma_{\rm ann} = n_\chi \langle \sigma_{\rm ann} v \rangle$$

Elastic collisions => thermal contact with relativistic plasma after freeze out

Thermal contact ceases
→ kinetic decoupling => free streaming ($x_k = m/T_k \sim 10^2$-10^4)

Matter-radiation eq. → DM grows density fluctuations larger than free streaming scale

=> Sets the minimal scale of DM halo
NB: links with direct searches / interaction with stars



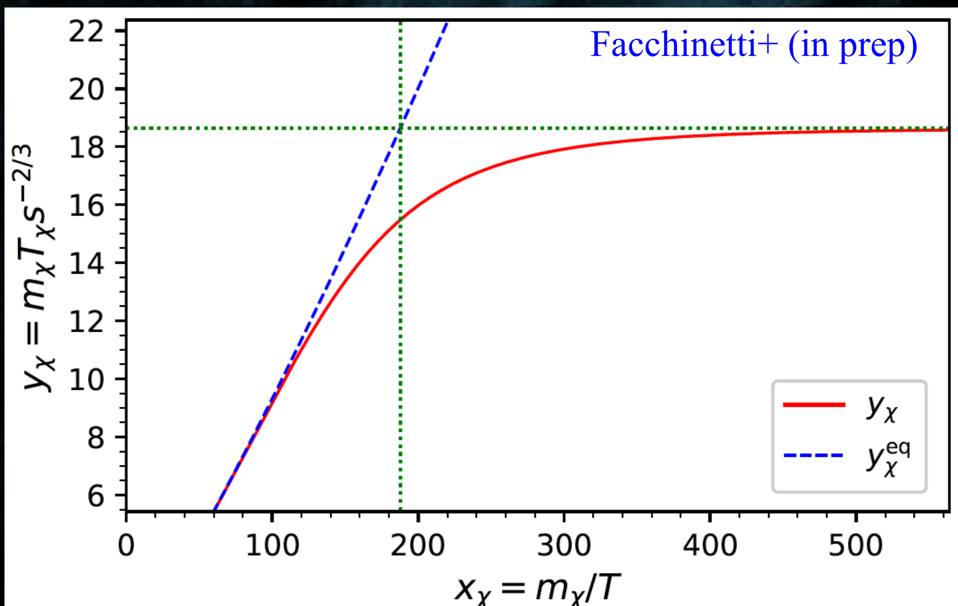
$$\Gamma_{\rm scatt.} = n_{\rm f} \langle \sigma_{\rm scatt} v \rangle$$

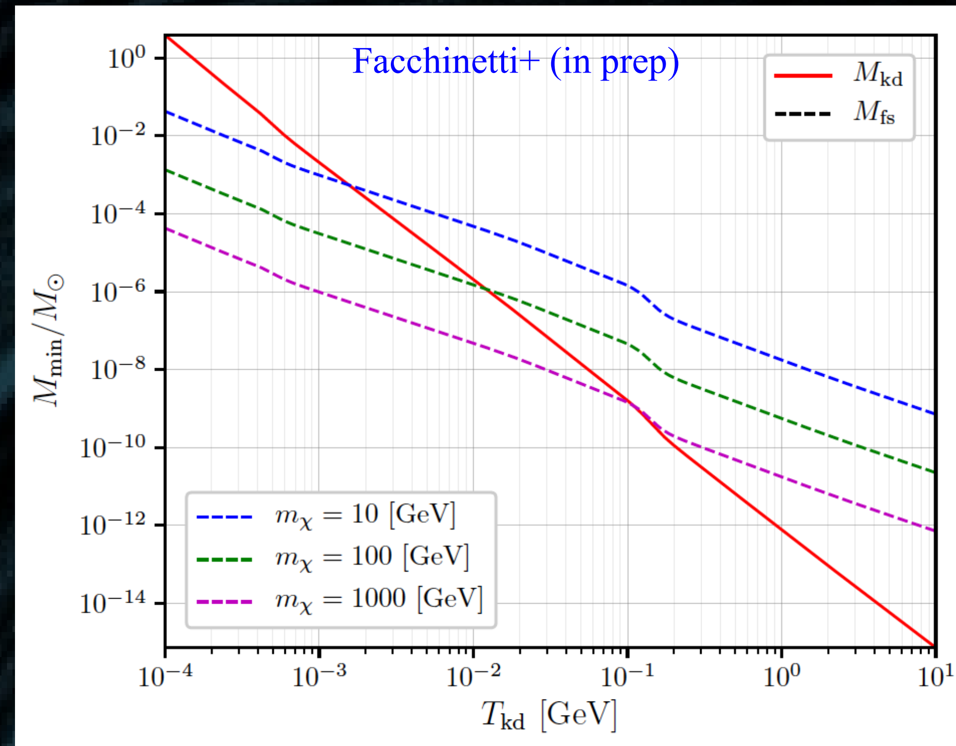
Solve moments of Liouville-Boltzmann equation for coupled species

$$\frac{d\, f(x^\mu, p^\mu)}{d\lambda} = \hat{C}[f]$$

Setting the subhalo cutoff mass scale (thermal DM)

More details in Gaétan Facchinetti's poster





$$\frac{\mathrm{d}\ln(y_\chi)}{\mathrm{d}\ln(x_\chi)} = -\left(1 + \frac{\mathrm{d}\ln\left(h_{\rm eff}(T)\right)}{3\,\mathrm{d}\ln\left(T\right)}\right)\frac{\gamma(T)}{H}\left(1 - \frac{y_\chi^{\rm eq}}{y_\chi}\right)$$

$$\lambda_{\rm fs}(t) = a(t)\int_{t_{\rm kd}}^{t}\frac{v(t')}{a(t')}\mathrm{d}t'$$

Minimal halo mass from ~$10^{-12} M_{sun}$ (>1 TeV WIMPs) to ~$10^{-3} M_{sun}$ (<10 GeV WIMPs)

Like relic abundance, fixed by interaction properties of DM particles!

[see also Schwartz+, Hofmann+, Green+, Bringmann+, Boehm+, Gondolo+, etc.]

Entangling the subhalo "phase space": step 1

At MW formation, all (cosmological) properties factorize out

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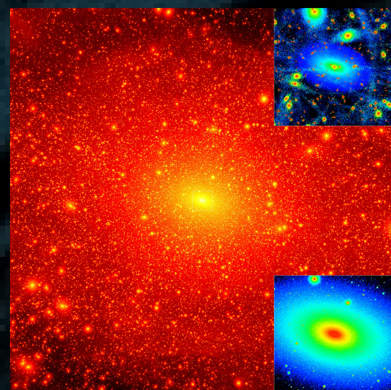

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$$\frac{d^n \bar{N}}{d\omega^n} = \frac{\bar{N}_{\rm tot}}{\bar{K}_w} \frac{d\bar{\mathcal{P}}_V(\vec{x})}{dV} \times \frac{d\bar{\mathcal{P}}_m(m,\vec{x})}{dm} \times \frac{d\bar{\mathcal{P}}_c(c,m,\vec{x})}{dc}$$

Step 2: compute tides induced by MW baryons

$$\frac{d^n N}{d\omega^n} = \frac{N_{\rm tot}}{K_w} \frac{d\mathcal{P}_V(\vec{x})}{dV} \times \frac{d\mathcal{P}_m(m,\vec{x})}{dm} \times \frac{d\mathcal{P}_c(c,m,\vec{x})}{dc}$$

Global tidal effects

Competition between global MW potential and internal subhalo potential → tidal radius

Solve EoM for test particle orbiting objects m and M (m<<M) in co-rotating frame of frequency ω (King '62, Spitzer '87).
+ Demand force to vanish (Lagrange points L2, L3)

$$\ddot{x} = \frac{G\,m}{x^2} - \frac{G\,M}{(R-x)^2} - \omega^2 \left\{ (\mu/m) R - x \right\} = 0$$

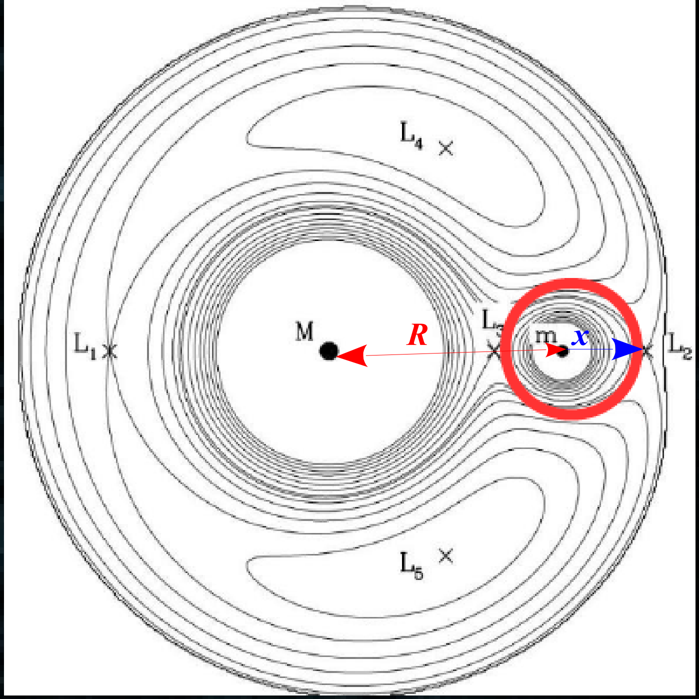
Point-like Jacobi tidal radius

$$r_{t\bullet} = r_{t\bullet}(R, m, M) = \left\{ \frac{m_t}{3\,M} \right\}^{1/3} R$$

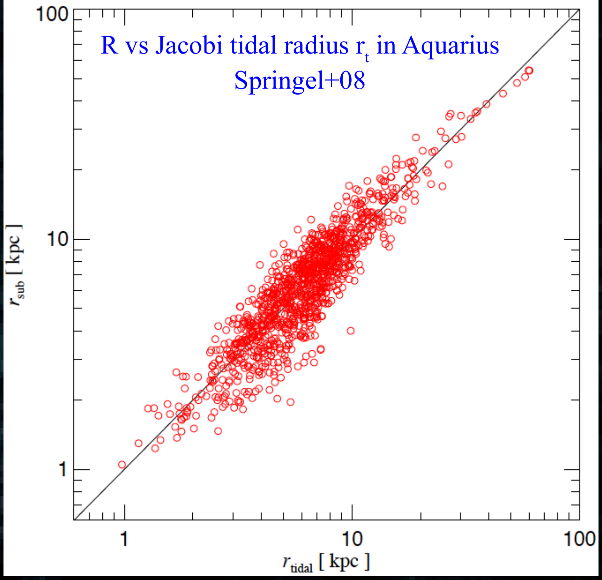
Extension to smooth systems

$$r_t = \left\{ \frac{m(r_t)}{3\,M(R)\left(1 - \frac{1}{3}\frac{d\ln M(R)}{d\ln R}\right)} \right\}^{1/3} R$$

Smooth Jacobi tidal radius



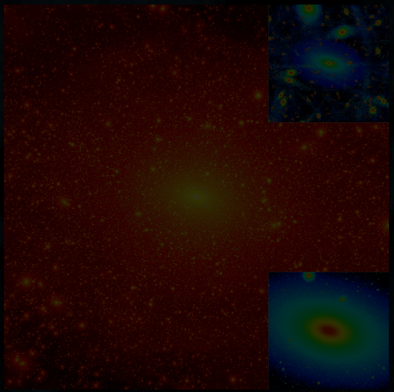
Binney&Tremaine '87, '08



Entangling the subhalo "phase space": step 2

At MW formation, all (cosmological) properties factorize out

$$\frac{d^n N^0}{d\omega^n} = N_0 \, \frac{d\mathcal{P}^0_V(\vec{x})}{dV} \times \frac{d\mathcal{P}^0_m(m)}{dm} \times \frac{d\mathcal{P}^0_c(c,m)}{dc}$$



Step 1: compute tides induced by final MW halo

$$\frac{d^n \bar{N}}{d\omega^n} = \frac{\bar{N}_{\rm tot}}{\bar{K}_w} \, \frac{d\bar{\mathcal{P}}_V(\vec{x})}{dV} \times \frac{d\bar{\mathcal{P}}_m(m,\vec{x})}{dm} \times \frac{d\bar{\mathcal{P}}_c(c,m,\vec{x})}{dc}$$

Step 2: compute tides induced by MW baryons

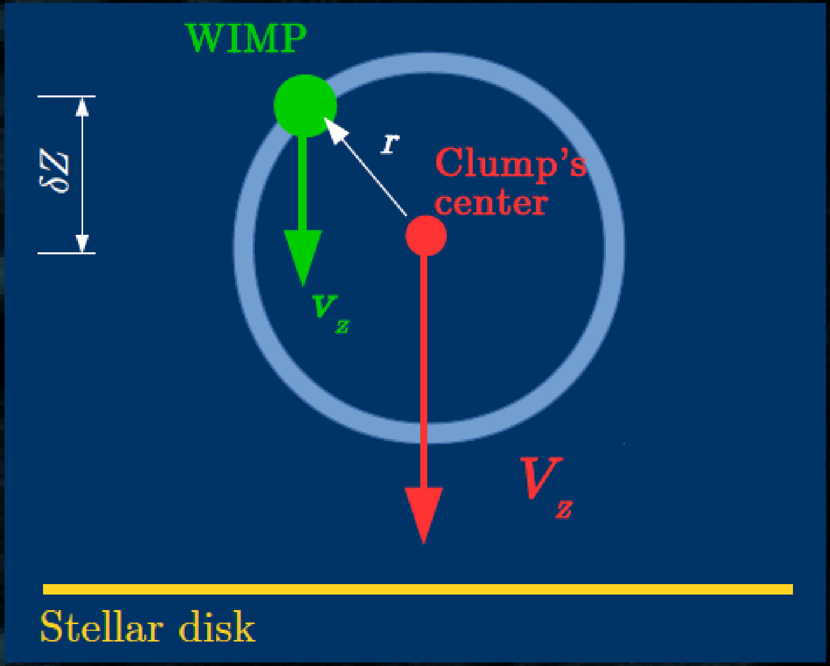
$$\frac{d^n N}{d\omega^n} = \frac{N_{\rm tot}}{K_w} \, \frac{d\mathcal{P}_V(\vec{x})}{dV} \times \frac{d\mathcal{P}_m(m,\vec{x})}{dm} \times \frac{d\mathcal{P}_c(c,m,\vec{x})}{dc}$$

Tides from stellar encounters and disk shocking

Encounters with stars:
[Spitzer+,Gerhard+, Carr+, Zhao+, Green+, Gnedin+, Berezinsky+, etc.]
* impulse approximation during fly-by
=> strong in the very inner parts of MW

$$\Delta E = \frac{1}{2}\int d^3\vec{r}\,\rho_{\rm int}(r)(\delta v_x - \delta\tilde{v}_x)^2$$

$$\Delta E = \frac{2\pi}{3}\left(\frac{2G_{\rm N}M_*}{v_{\rm rel}l^2}\right)^2\int_0^R dr\,r^4\,\rho_{\rm int}(r)$$



Disk shocking:
[Ostriker+,Weinberg+, Gnedin+, Berezinsky+, etc.]
* impulse approximation during crossing
* adiabatic invariance correction
=> always strong

$$\frac{dv_z}{dt} = g_{\rm d}(R,z_{\rm p}) - g_{\rm d}(R,z_{\rm c}) \simeq \Delta z\,\frac{\partial g_{\rm d}}{\partial z}(z_{\rm c})\ ,$$

$$\Delta v_z = \int dt\,\Delta z(t)\,\frac{\partial g_{\rm d}}{\partial z}\left[z_{\rm c}(t)\right]$$

$$\epsilon_k(z) \equiv \frac{2\,g^2_{z,\rm disk}(z=0)\,z^2}{V_z^2}\,A(\eta)$$

Tidal radius definition
[demand E(r)<0 after N crossings]

$$r_{t,i} \text{ such that } \langle\epsilon_k\rangle(r_{t,i}) = -\tilde{\phi}(r_{t,i},r_{t,i-1})$$

Tidal disruption criterion (criteria?)

Subhalo tidal mass

$$m_t = m(r_t) = 4\,\pi\,r_s^3 \int_0^{x_t} dx\,x^2\,\rho(x\,r_s)\,\zeta(x_t)$$

$dm = m_{200} - m_t$ given back to the smooth component

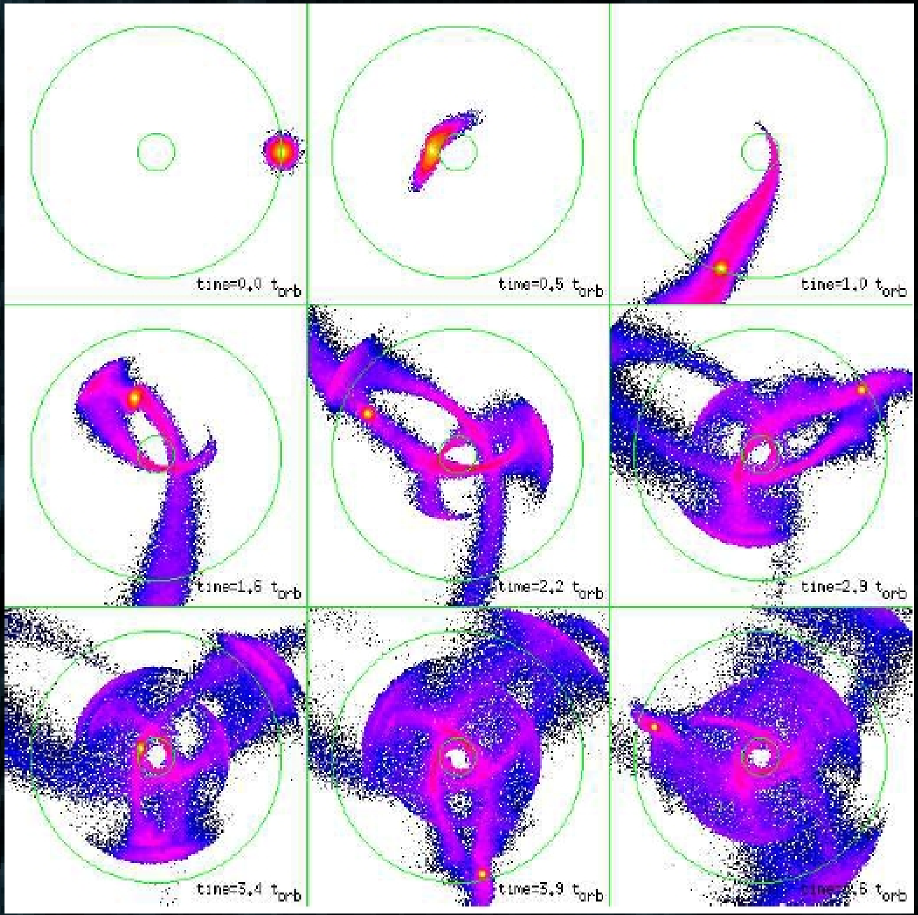
Disruption function

$$\zeta\left(x_t \equiv \frac{r_t}{r_s}\right) \equiv \theta\left(x_t - \varepsilon_t\right)$$

Disruption parameter ε_t

$$x_t = \frac{r_t}{r_s} \geq \varepsilon_t \Longleftrightarrow c_{200} \geq c_{\min}(R)$$

If circular orbit assumed,
Minimal concentration independent from mass!



Hayashi+03

From past numerical studies
$\varepsilon_t \sim 1$

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$$x_t = \frac{r_t}{r_s} \geq \varepsilon_t \iff c_{200} \geq c_{\min}(R)$$

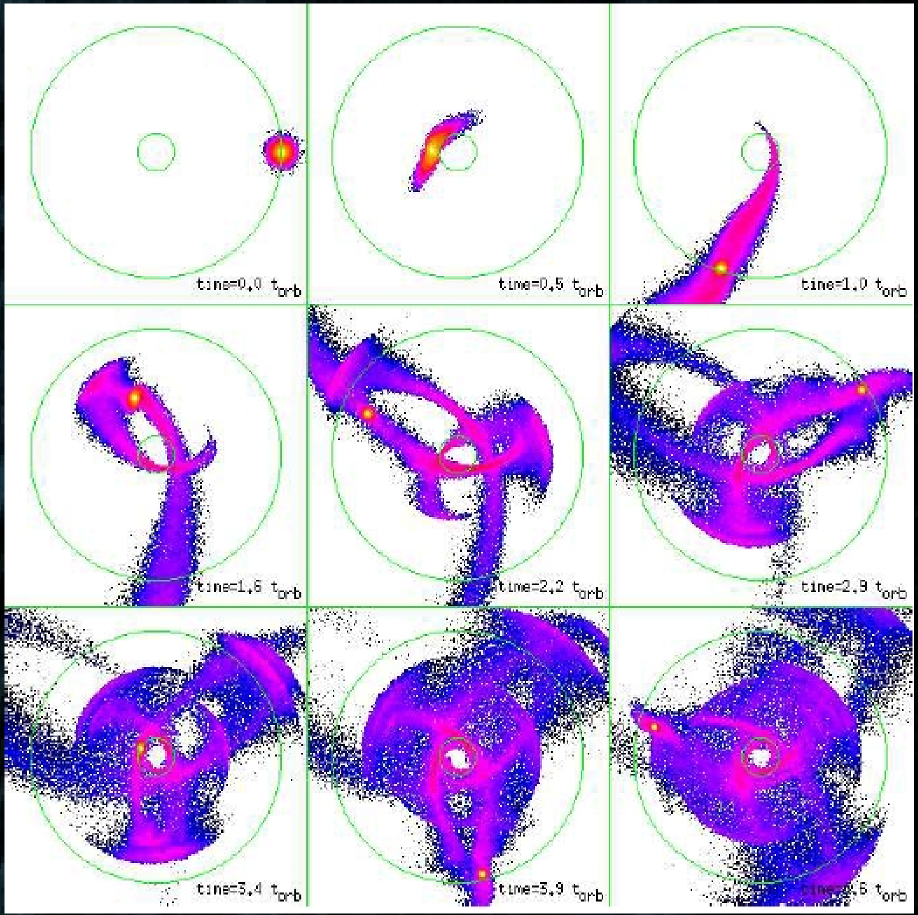
If circular orbit assumed,
Minimal concentration independent from mass!

BUT …

If mini-cores dense enough, fast orbits should be resilient down to x_t<<1 … (adiabatic invariance)

van den Bosh+’17’18 => tidal disruption strongly overestimated in simulations (resolution + softening issue). Also Errani+17.

=> ε_t<<1 most likely

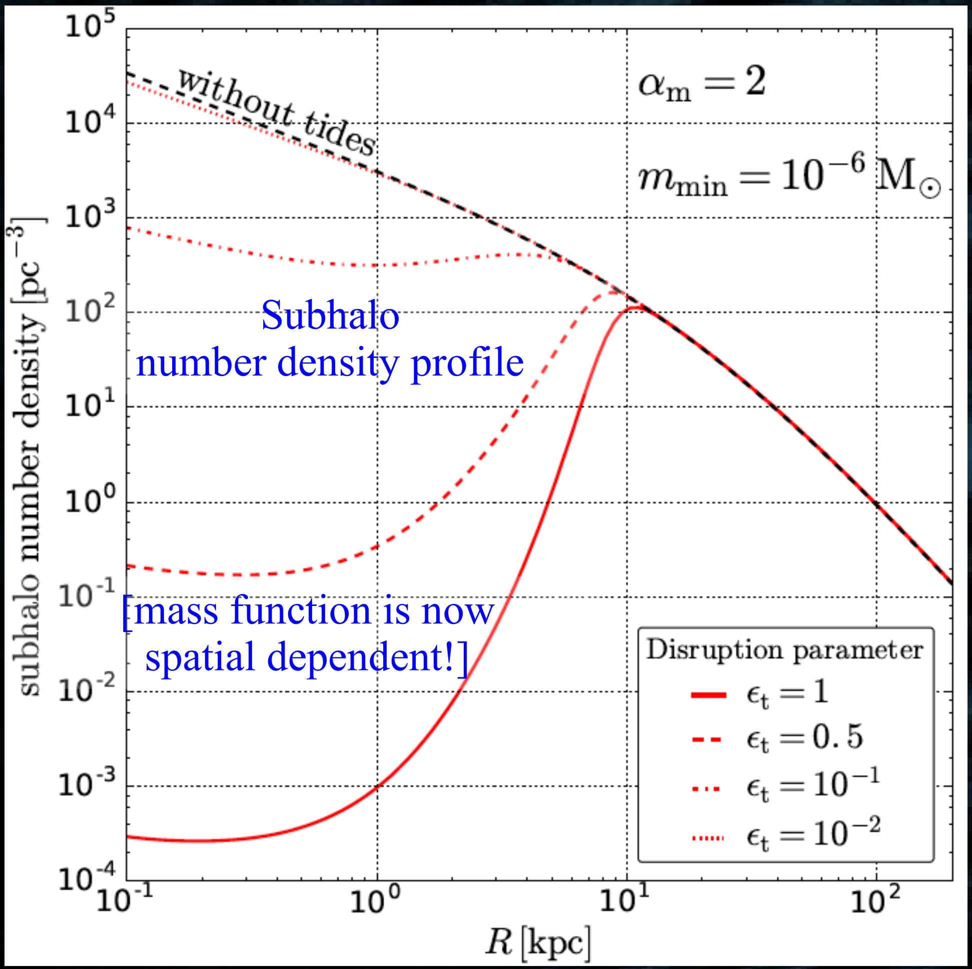


Hayashi+03

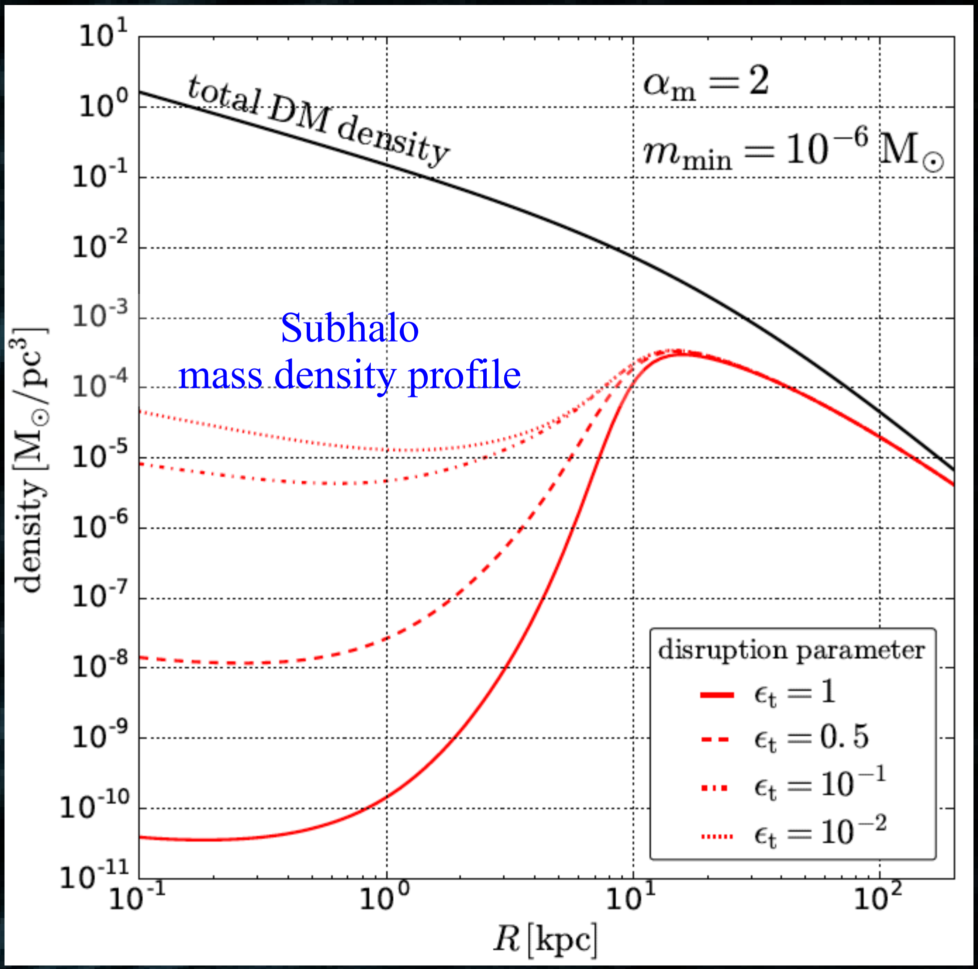
From past numerical studies
$\varepsilon_t \sim 1$

Impact of tidal disruption on number/mass density profiles

Constrained Galactic mass model from McMillan'18 assumed [NFW+bulge+gas/stellar thin/thick disks]



Subhalo number density profile, Stref PhD th. '18

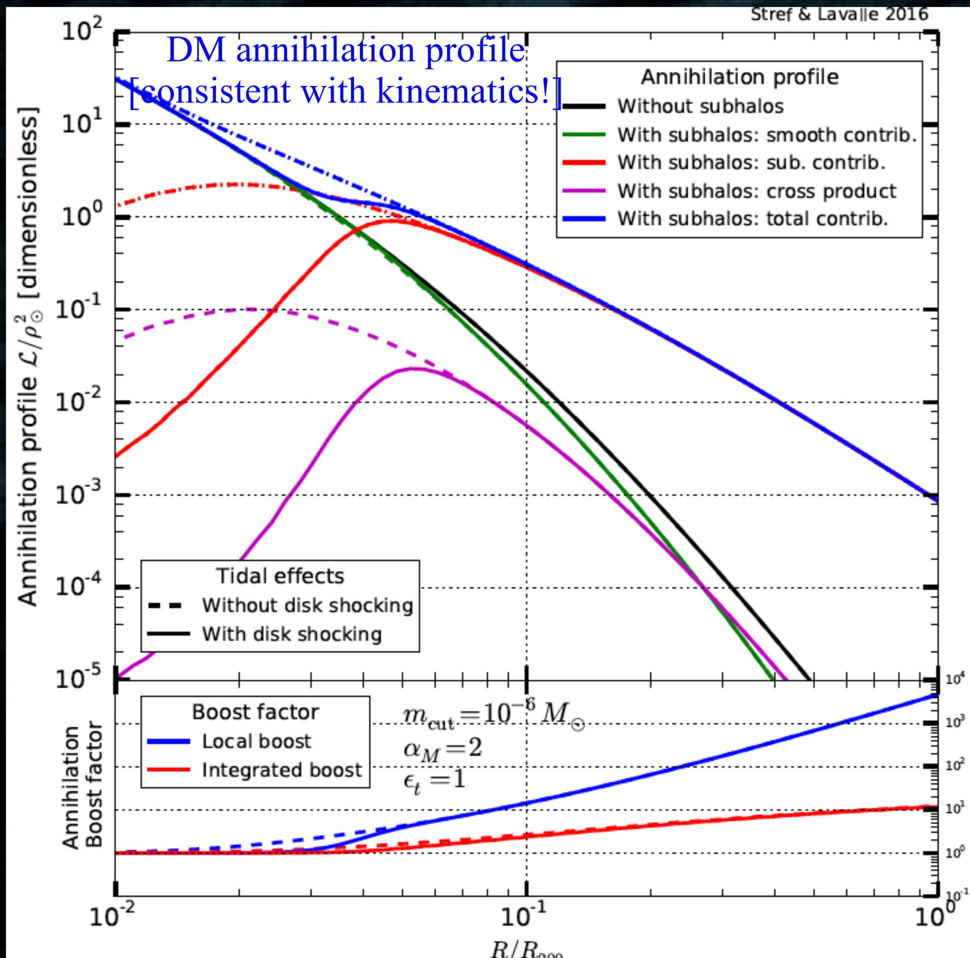


Global subhalo mass density profile, Stref PhD th. '18

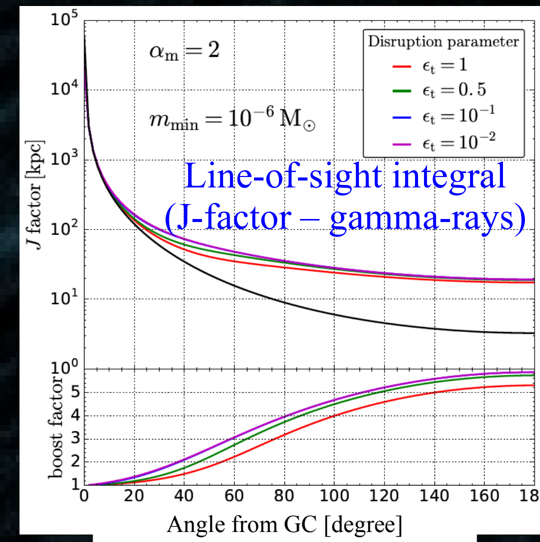
Sizable number density of tiny clumps expected locally! (~µpc size)
But on average, contribute a tiny fraction of the local density (~1 %)

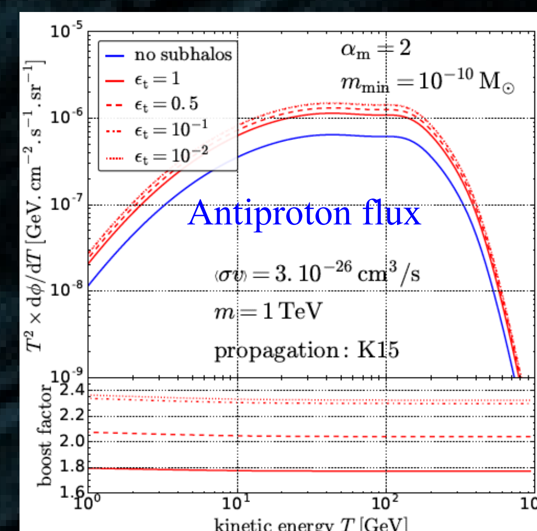
Hidden above but important:
mass + concentration pdfs have become spatial-dependent!

Amplification of annihilation rate in the Milky Way



Annihilation profile + local/integrated boost, Stref+17





Stref PhD. th '18

Minimal subhalo mass matters for α >1.9
(always in the central regions due to effective mass index => local fluctuations suppressed)
[see also Silk&Stebbins'93, Bergström+'98, JL+07, etc.]

Summary

* Analytical models of subhalos complementary to cosmological simulations
  + no resolution limit and fast
  + can easily probe different cosmologies
  + can be made consistent with dynamical constraints (e.g. the MW)
  + can apply to any DM candidate
  - have to rely on simplifying assumptions (e.g. spherical symmetry)

* Other analytical models on the market:
  - Berezinsky+: fully analytical (even density profiles), include baryons – qualitative estimates
  - van den Bosch+, Ando+, Hiroshima+: accretion+stripping, mass function (z), no baryons – EG gamma-rays
  - etc.

* Milky Way a perfect place to probe DM properties on small scales!
  → a strongly constrained system (global potential + baryons)
  → theoretical + dynamical self-consistence of DM distribution very important (smooth+subhalo components)

* Montpellier model (Facchinetti, Lavalle, Stref et al.) predicts properties of MW subhalo population
  - includes tidal stripping from both DM + baryons
  - consistent with MW kinematic constraints
  - qualitatively consistent with simulations results in relevant mass range
  - predictions for a series of observables: gamma-rays, antimatter cosmic rays, etc.

* Perspectives
  - full evolution from dark ages
  - detailed investigation of subhalo interactions with stars (DM capture)
  - application to PBHs

Backup

The dark halo: smooth vs subhalo component

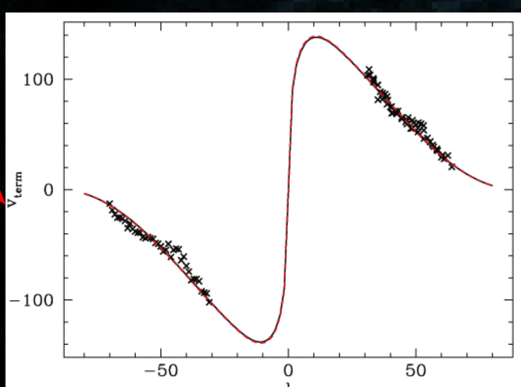
$$\rho_{\rm tot}(R) = \rho_{\rm sm}(R) + \rho_{\rm sub}(R)$$

Overall profile constrained by non-linear theory: NFW, Einasto +/- cores

++++

****** Strongly constrained by MW kinematic data ******

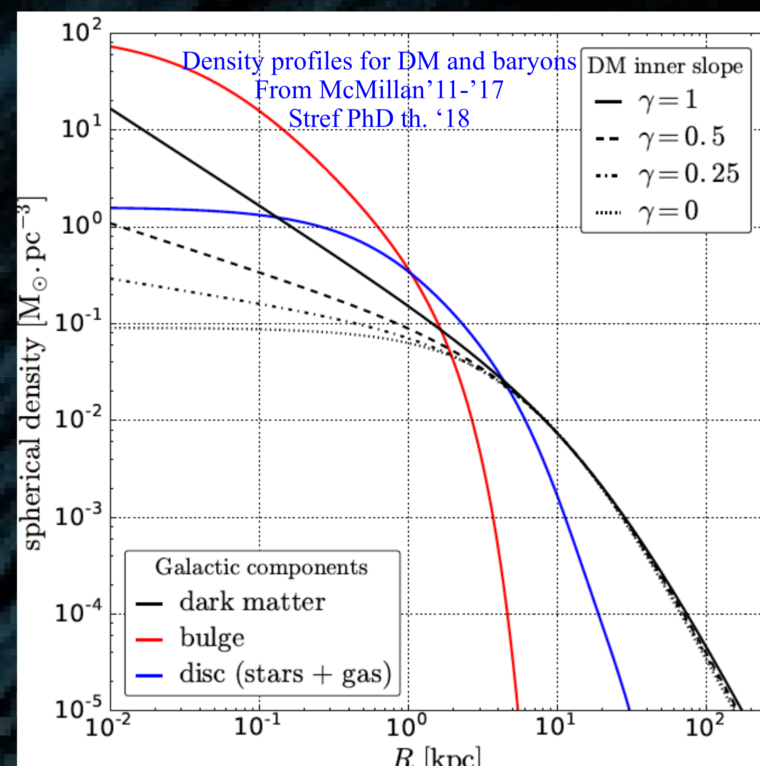
$$\rho_{\rm sub}(R) = \frac{N_{\rm sub}}{K_w}\frac{d\mathcal{P}_V(R)}{dV}\int_{m_{\rm min}}^{m_{\rm max}} dm \int_{c_{\rm min}(R)}^{c_{\rm max}} dc\, m_t(r_t(c,m,R),m,c)\,\frac{d\mathcal{P}_m}{dm}\frac{d\mathcal{P}_c}{dc}$$



McMillan'11

Series of kinematic constraints on baryons+DM mass models

++ will improve with Gaia ++



Tidal disruption criterion (criteria?)

Subhalo tidal mass

$$m_t = m(r_t) = 4\,\pi\,r_s^3 \int_0^{x_t} dx\,x^2\,\rho(x\,r_s)\,\zeta(x_t)$$

$dm = m_{200}\text{-}m_t$ given back to the smooth component

Disruption function

$$\zeta\left(x_t \equiv \frac{r_t}{r_s}\right) \equiv \theta\,(x_t - \varepsilon_t)$$

Disruption free parameter ε_t

$$x_t = \frac{r_t}{r_s} \geq \varepsilon_t \iff c_{200} \geq c_{\rm min}(R)$$

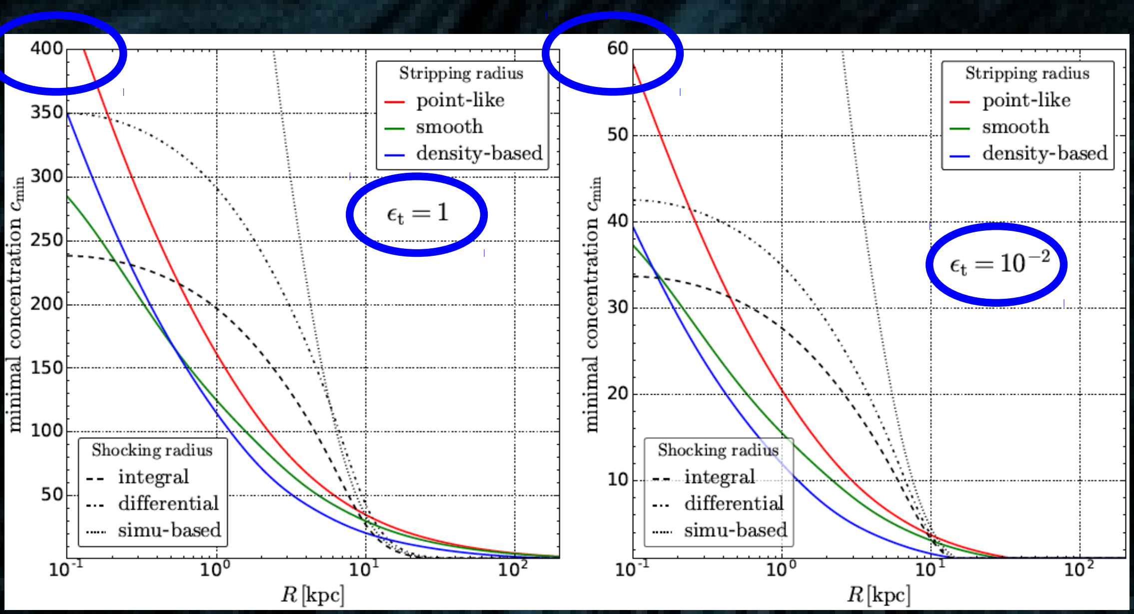
Minimal concentration independent from mass!

But …

What about adiabatic invariants?
→ If mini-cores dense enough, fast orbits should be resilient down to x_t<<1 …

Recent work by van den Bosh+'17'18 suggests tidal disruption strongly overestimated in simulations. See also Errani+17.

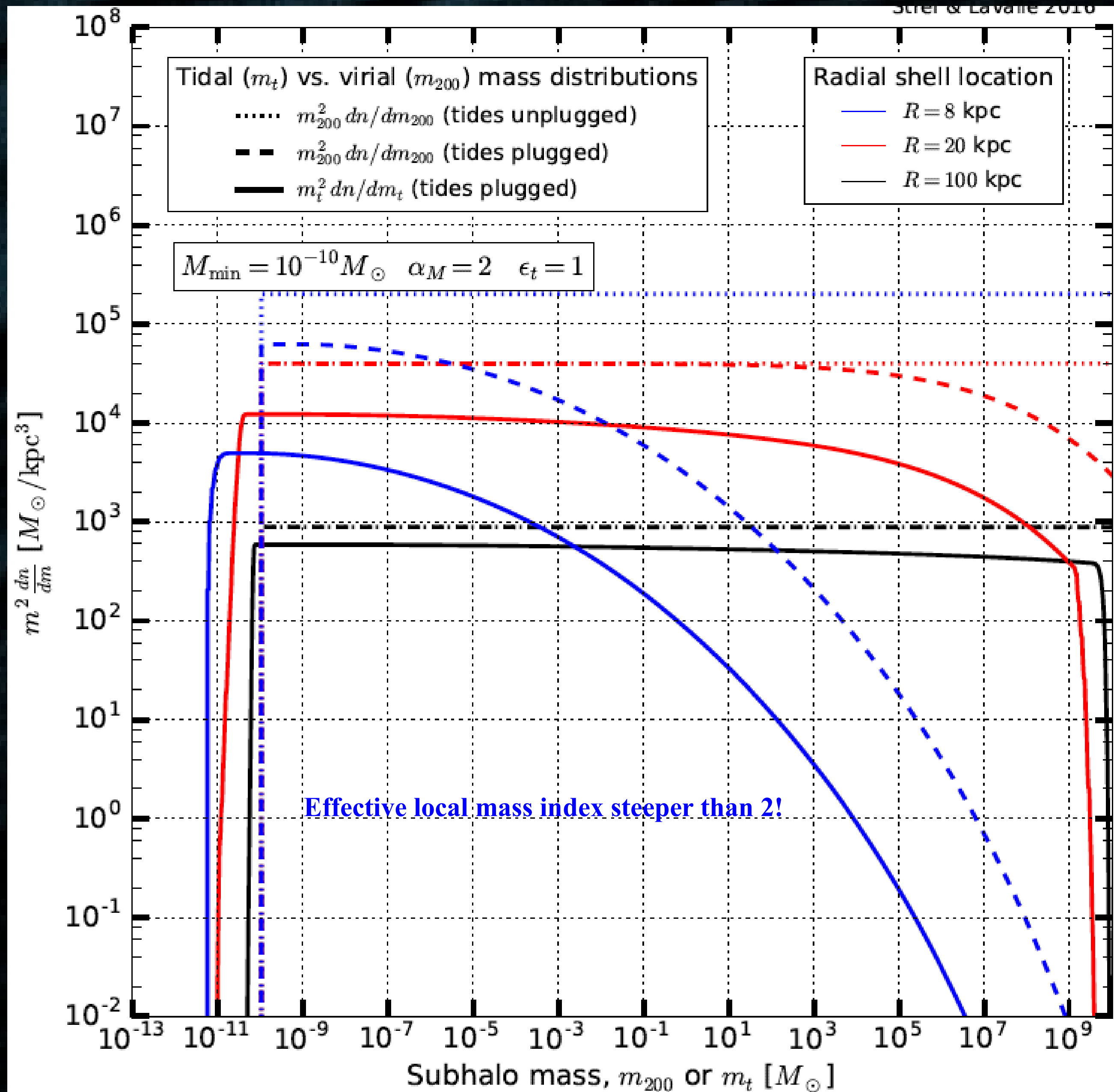
NB: again a resolution issue → analytical arguments may catch on.



Minimal concentration vs position, Stref PhD th. '18 => mean concentration gets spatial-dependent
(see also Pieri+11, Moline+15)

Post-tides properties

Concentration function cut from the left => spatial-dependent mass index!



Modified local mass function, Stref+17

Evolution of species in the Early Universe

$$\frac{d\, f(x^\mu, p^\mu)}{d\lambda} = \widehat{C}[f]$$

$$\frac{dY_\chi}{dx} \propto -\frac{g_\star^{1/2}(x)}{x^2} \langle \sigma v \rangle \left\{Y_\chi^2 - Y_{\rm eq}^2\right\}$$

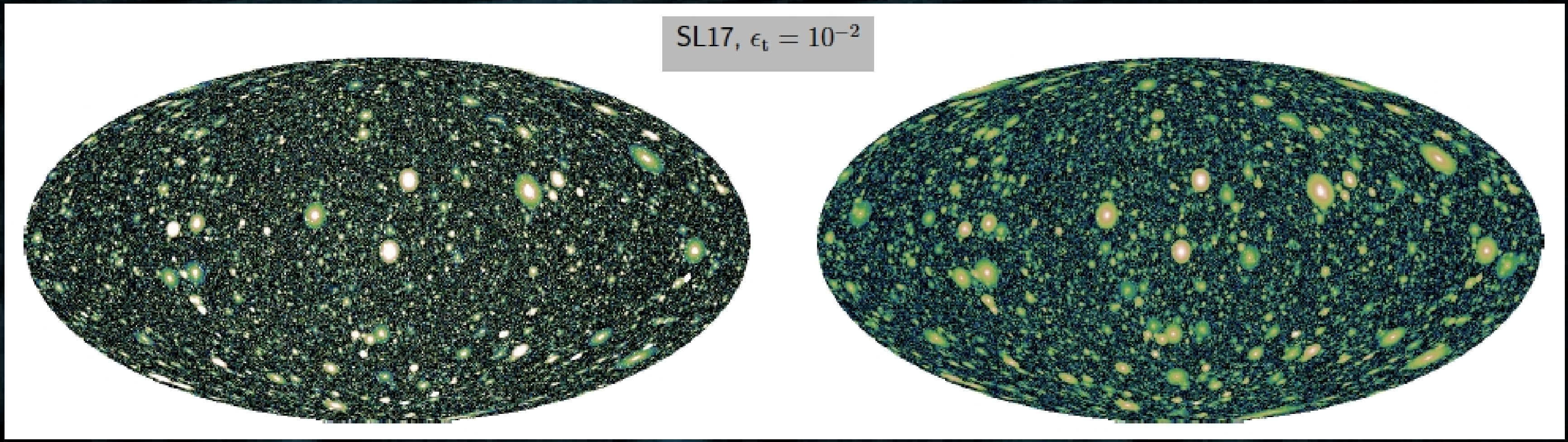
$$T_\chi \equiv \left\langle \frac{p^2}{3m_\chi} \right\rangle = \frac{g_\chi}{3m_\chi n_\chi} \int p^2 f_\chi(p,t) \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3}.$$

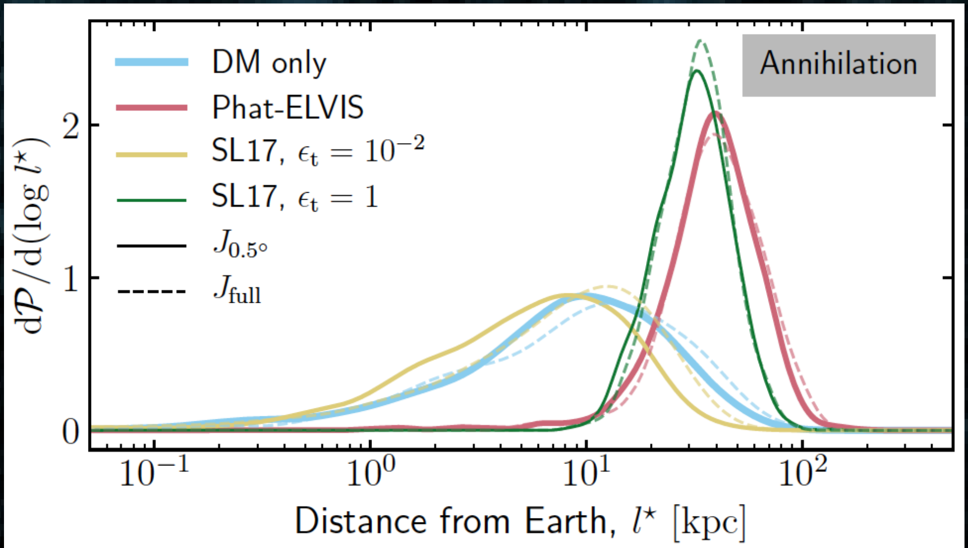
$$\frac{\partial T_\chi}{\partial t} + 2HT_\chi = \gamma(T)(T - T_\chi)$$

$$\gamma(T) = \frac{1}{48 g_\chi m_\chi^3 \pi^3} \sum_{\text{species}\, i} \int_{m_i}^{\infty} \mathrm{d}\omega\, f_i^{\rm eq}(\omega, t) \frac{\partial}{\partial \omega} \left(\int_{-4p_{\rm cm}^2}^{0} (-t) \widetilde{|\mathcal{M}_i|^2} \mathrm{d}t \right)$$

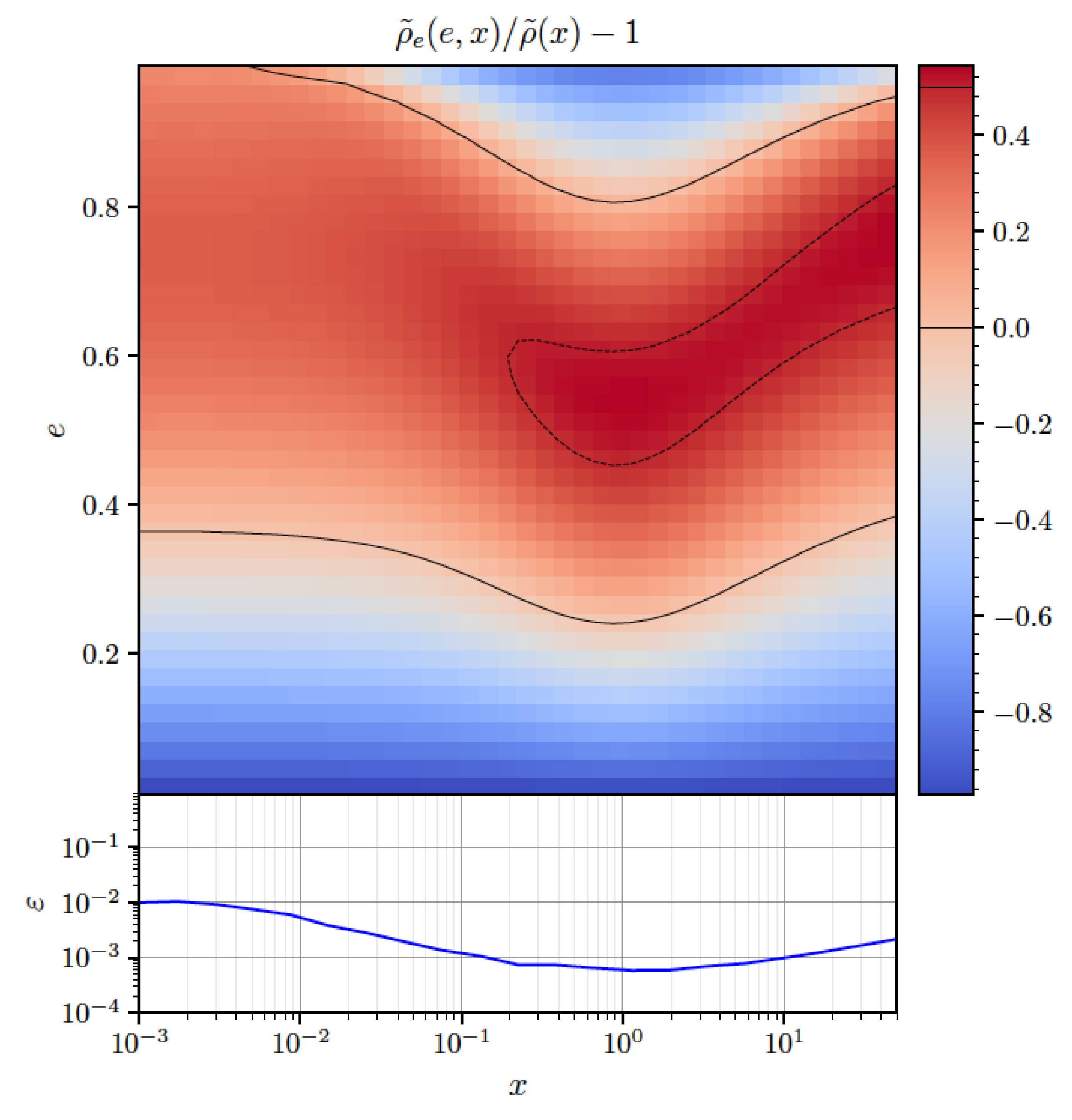
$$\frac{\mathrm{d}\ln(y_\chi)}{\mathrm{d}\ln(x_\chi)} = -\left(1 + \frac{\mathrm{d}\ln\left(h_{\rm eff}(T)\right)}{3\,\mathrm{d}\ln(T)}\right) \frac{\gamma(T)}{H} \left(1 - \frac{y_\chi^{\rm eq}}{y_\chi}\right)$$

Closest visible object



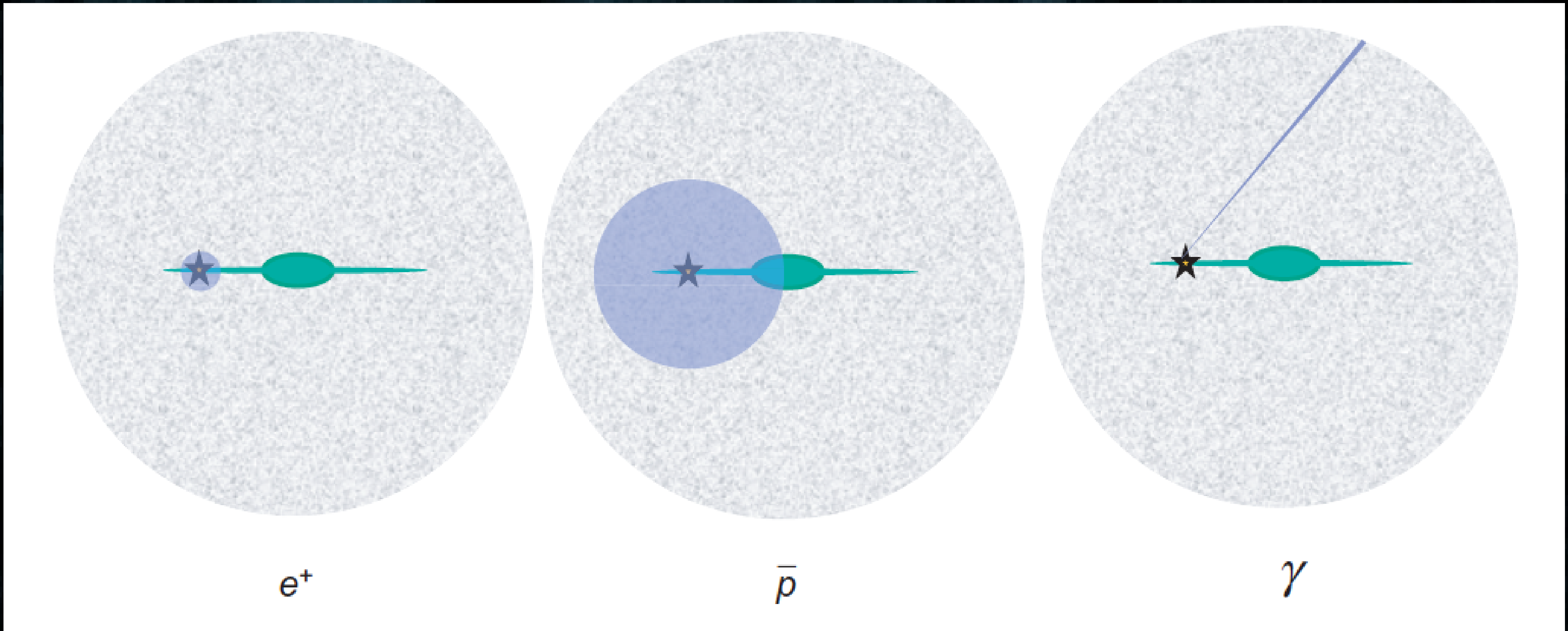


Subhalo eccentricity distribution



Facchinetti+, in prep

Boost factors in context

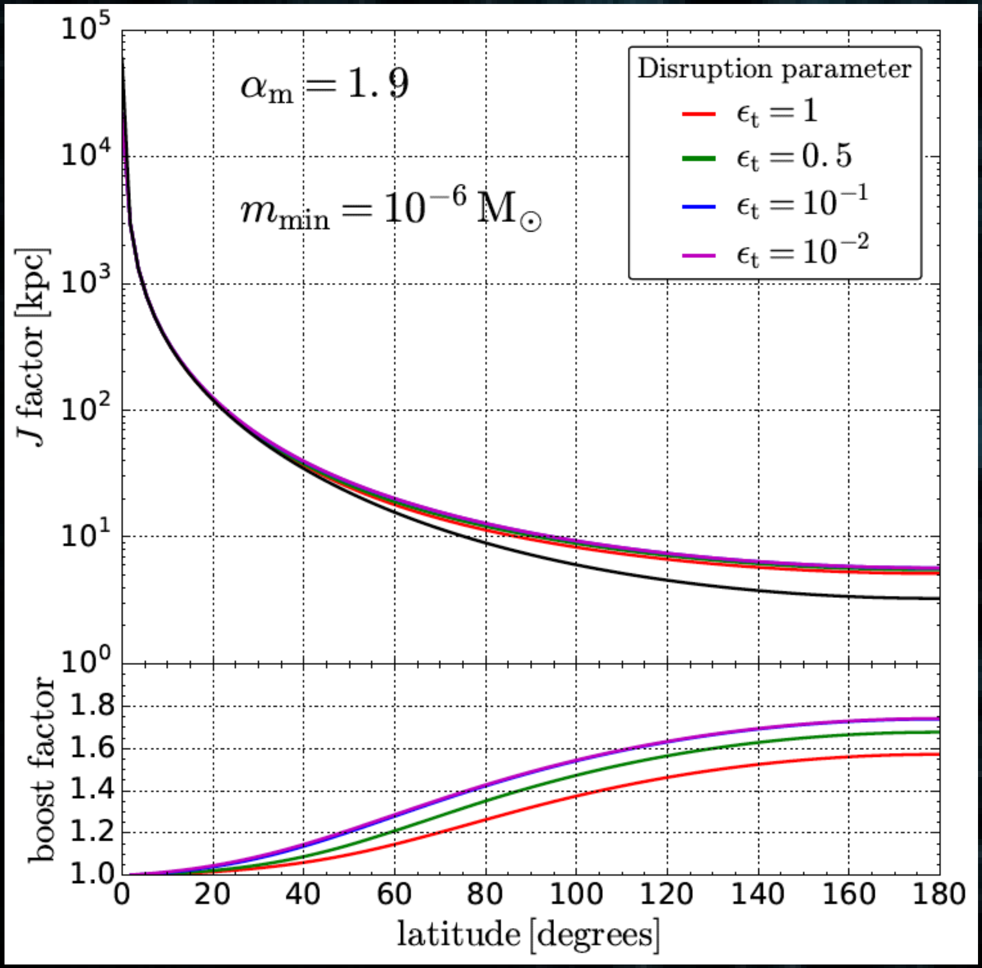


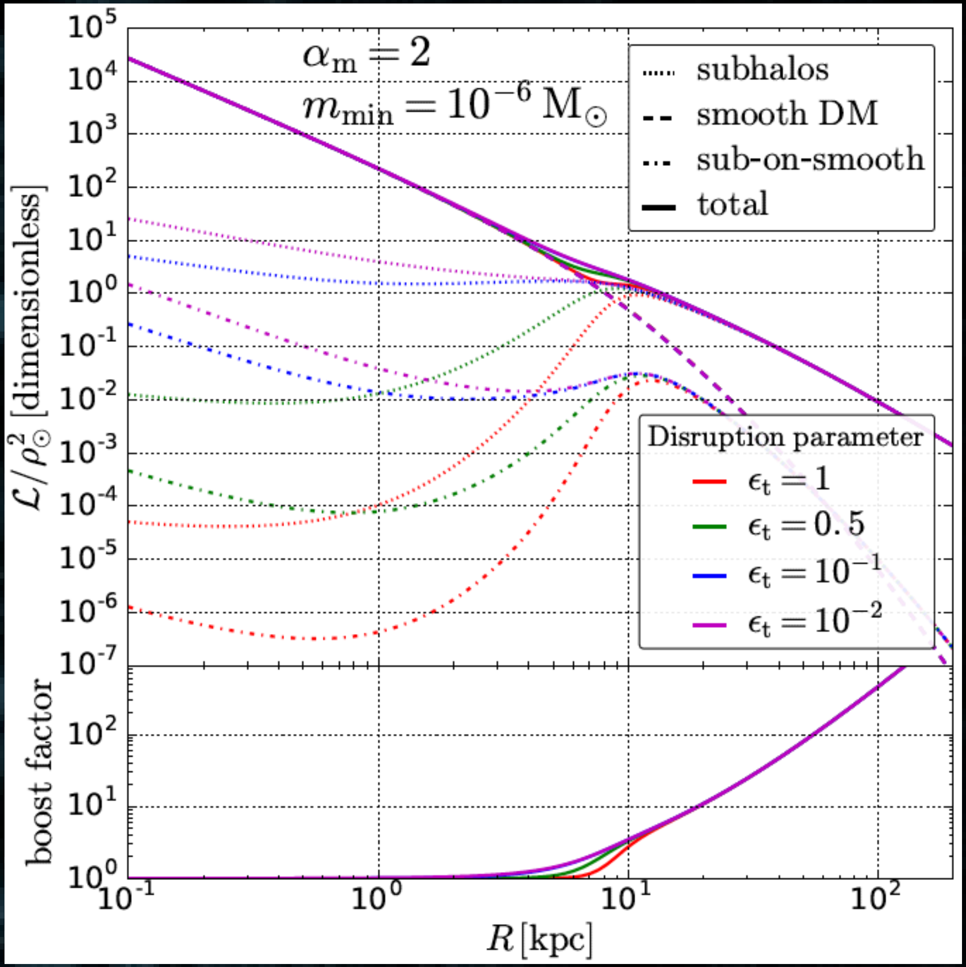
Bergström'09

Boost factor depends on integration volume!

See also Silk & Stebbins'93, Begström+99, Lavalle+07-08

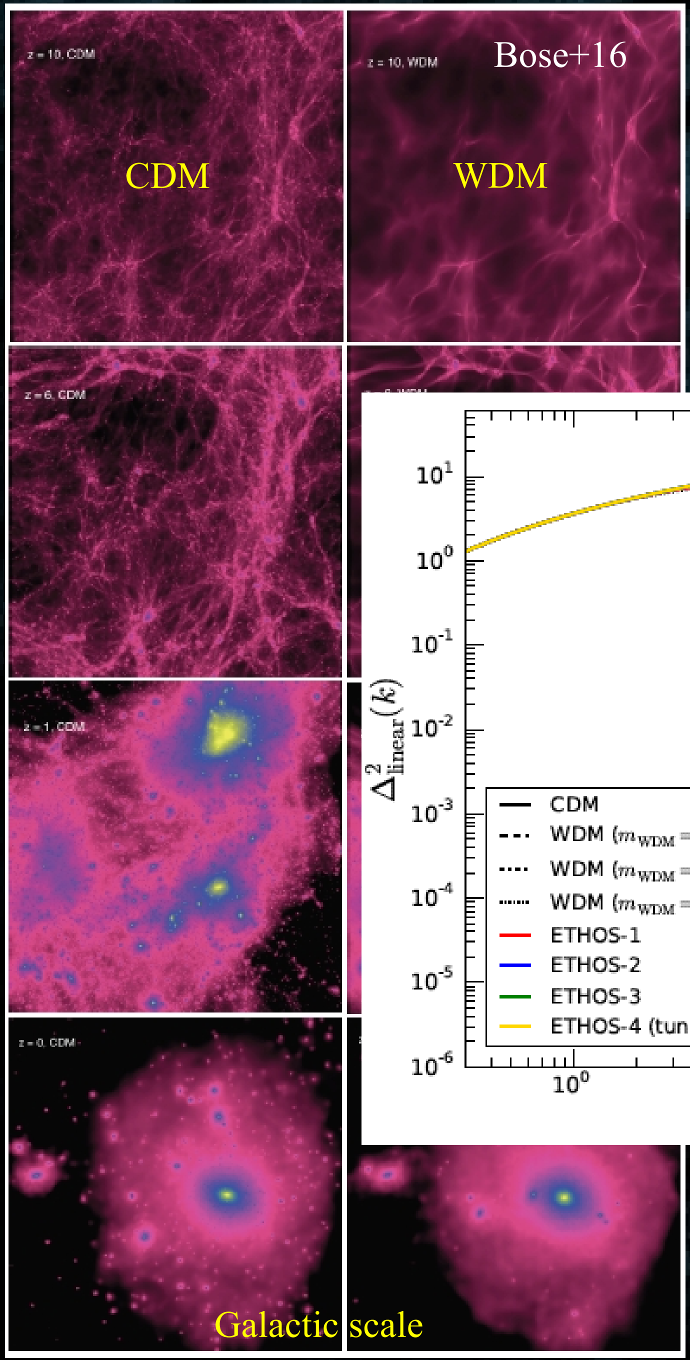
J factors! (at last)



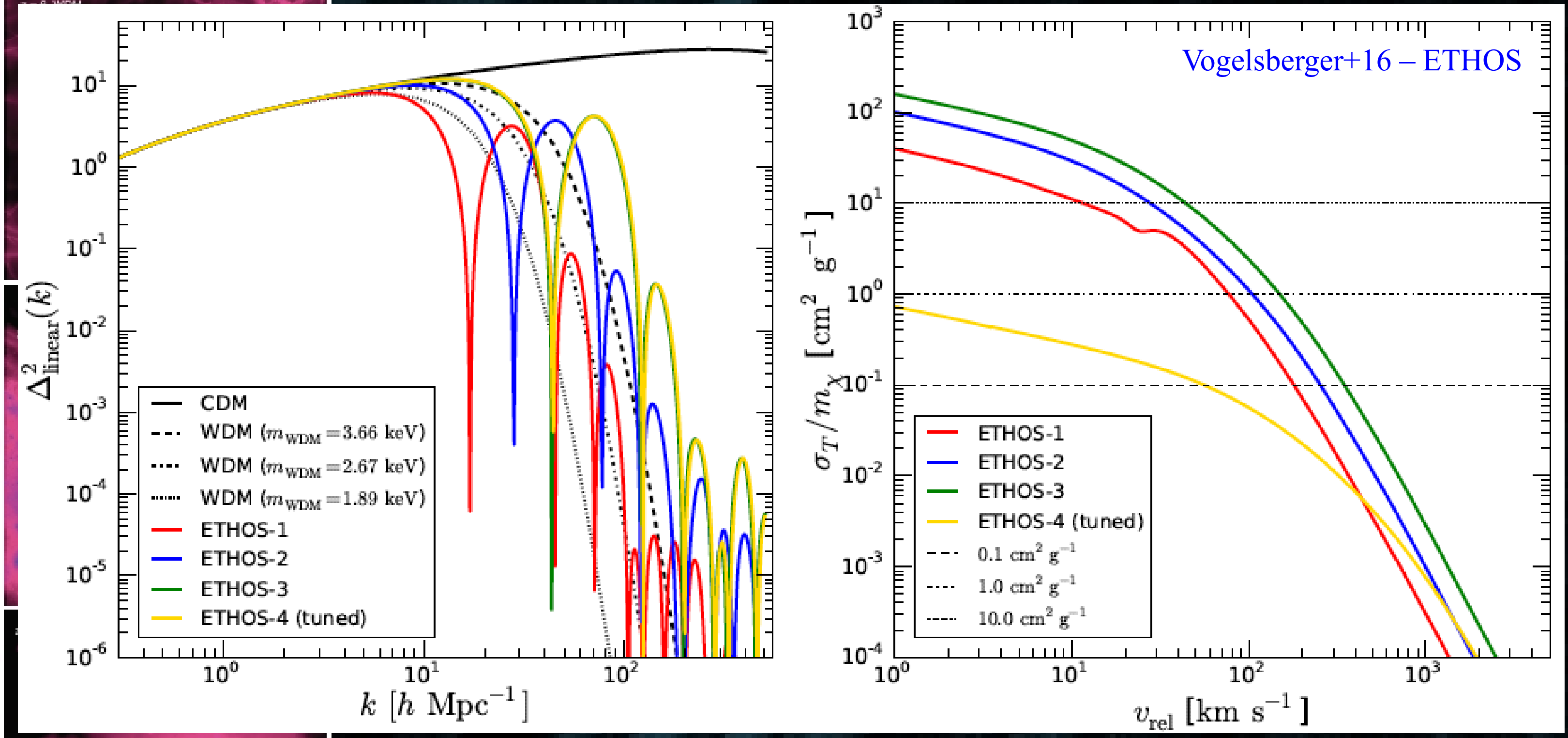


Stref PhD th '18

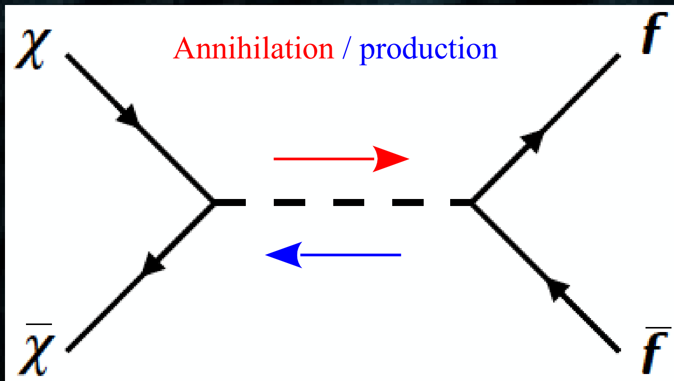
Kinetic decoupling, free streaming scale, and small-scale structures



$$\lambda_{\rm fs} = a_{\rm eq}\int_{t_{\rm kd}}^{t_{\rm eq}} dt\,\frac{v(t)}{a(t)} \approx v_{\rm kd}(a_{\rm kd}/a_{\rm eq})/H_{\rm eq}$$



Searches for thermal dark matter

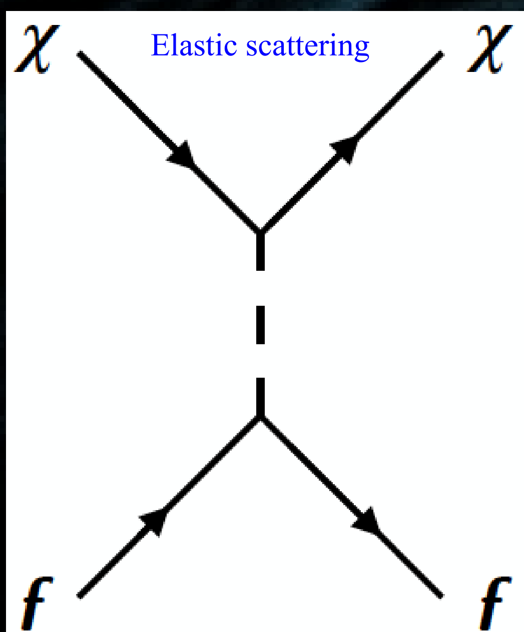


$$\Gamma_{\rm ann} = n_\chi \langle \sigma_{\rm ann} v \rangle$$

* Production at colliders (model dependent)
=> collider searches

* Annihilation/decay rate potentially large in dense DM regions: centers of halos + CMB
=> indirect searches

* Beware velocity dependence
(scalar exchange between fermions v-suppressed; pseudo-scalar exchange is not)



$$\Gamma_{\rm scatt.} = n_{\rm f} \langle \sigma_{\rm scatt} v \rangle$$

* elastic or inelastic scattering
→ nuclear recoils at underground experiments
=> direct searches

→ scattering with astrophysical objects
=> stellar physics
=> neutrinos from capture+annihilation in stars
=> indirect searches

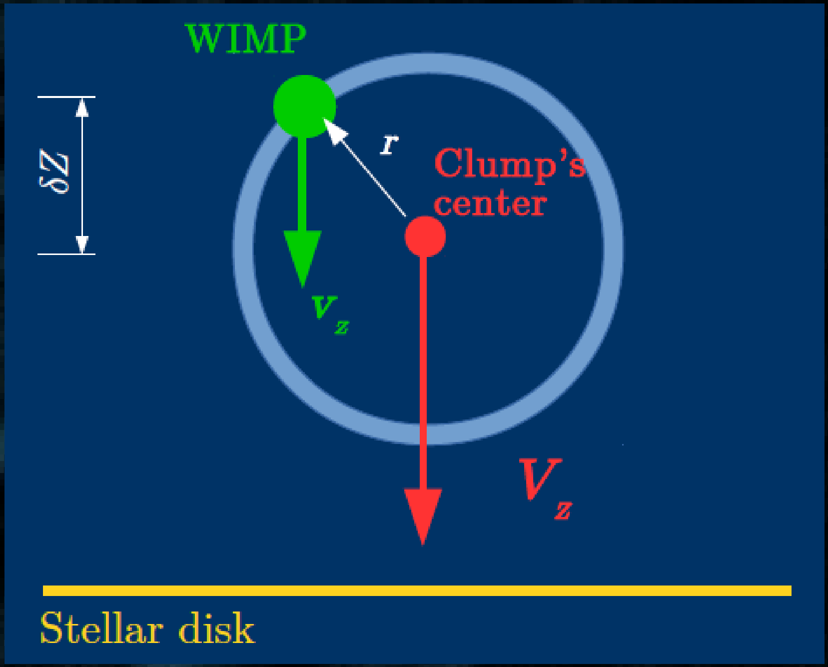
* Beware velocity dependence
(pseudo-scalar exchange v-suppressed;
scalar exchange is not)

Tides from stellar encounters and disk shocking

Encounters with stars:
(Ostriker+,Weinberg+, Gnedin+,80-00, Berezinsky+03)
*** impulse approximation during fly-by**
=> strong in the very inner parts of MW

$$\Delta E = \frac{1}{2}\int \mathrm{d}^3\vec{r}\,\rho_{\rm int}(r)(\delta v_x - \delta\tilde{v}_x)^2$$

$$\Delta E = \frac{2\pi}{3}\left(\frac{2G_{\rm N}M_*}{v_{\rm rel}l^2}\right)^2\int_0^R \mathrm{d}r\,r^4\,\rho_{\rm int}(r)$$



Disk shocking:
*** impulse approximation during crossing**
*** adiabatic invariance correction**
=> always strong

$$\frac{\mathrm{d}v_z}{\mathrm{d}t} = g_{\rm d}(R,z_{\rm p}) - g_{\rm d}(R,z_{\rm c}) \simeq \Delta z\,\frac{\partial g_{\rm d}}{\partial z}(z_{\rm c})\;,$$

$$\Delta v_z = \int \mathrm{d}t\,\Delta z(t)\,\frac{\partial g_{\rm d}}{\partial z}\,[z_{\rm c}(t)]$$

$$\epsilon_k(z) \equiv \frac{2\,g^2_{z,{\rm disk}}(z=0)\,z^2}{V_z^2}\,A(\eta)$$

Tidal radius definition
[demand E(r)<0]

Differential definition (default)

$r_{t,i}$ such that $\langle\epsilon_k\rangle(r_{t,i}) = -\tilde{\phi}(r_{t,i}, r_{t,i-1})$

Integrated definition

r_t such that $N_{\rm cross}\,E_k(r_t,R) = E_b(r_t)$

Fit from D'Onghia+10

$$\frac{\tilde{E}_k(r_t,R)}{E_b(r_t)} = \frac{(1.84\,r_{1/2})^2\,g^2_{z,{\rm disk}}}{3\,\tilde{\sigma}_v^2\,V_z^2}$$