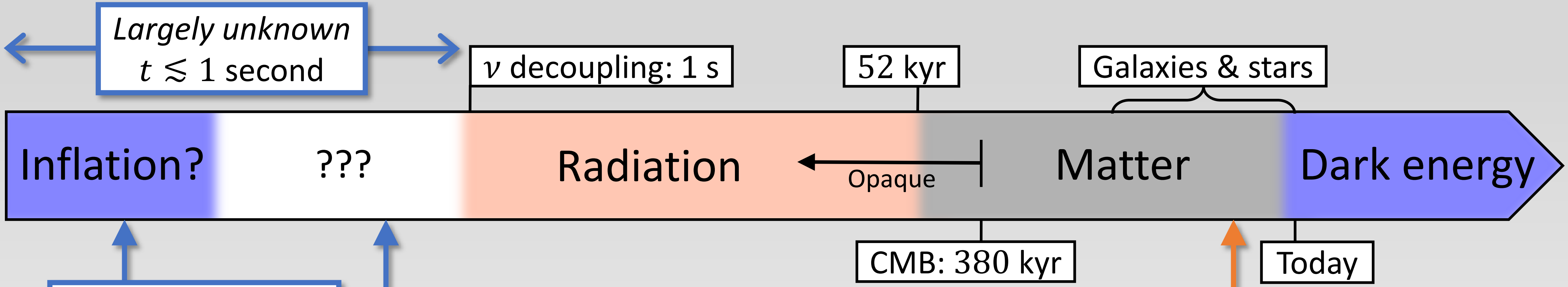
Probing cosmology using dark matter microhalos

M. Sten Delos
University of North Carolina at Chapel Hill

Talk prepared for the Perimeter Institute
February 6, 2020

Three questions in cosmology



Inflation is invoked to solve horizon & flatness problems and seed density variations. But…

What drove inflation?

(Or alternative process)

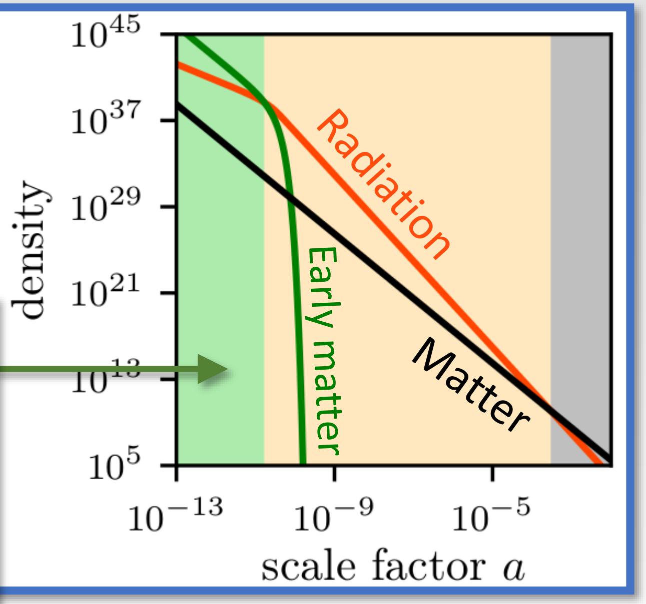
What happened after inflation?

Observations only require radiation domination by ∼1s.

Early matter domination?

- Moduli fields
- Hidden-sector mediator
- Inflaton

[Must decay into radiation by 1s]



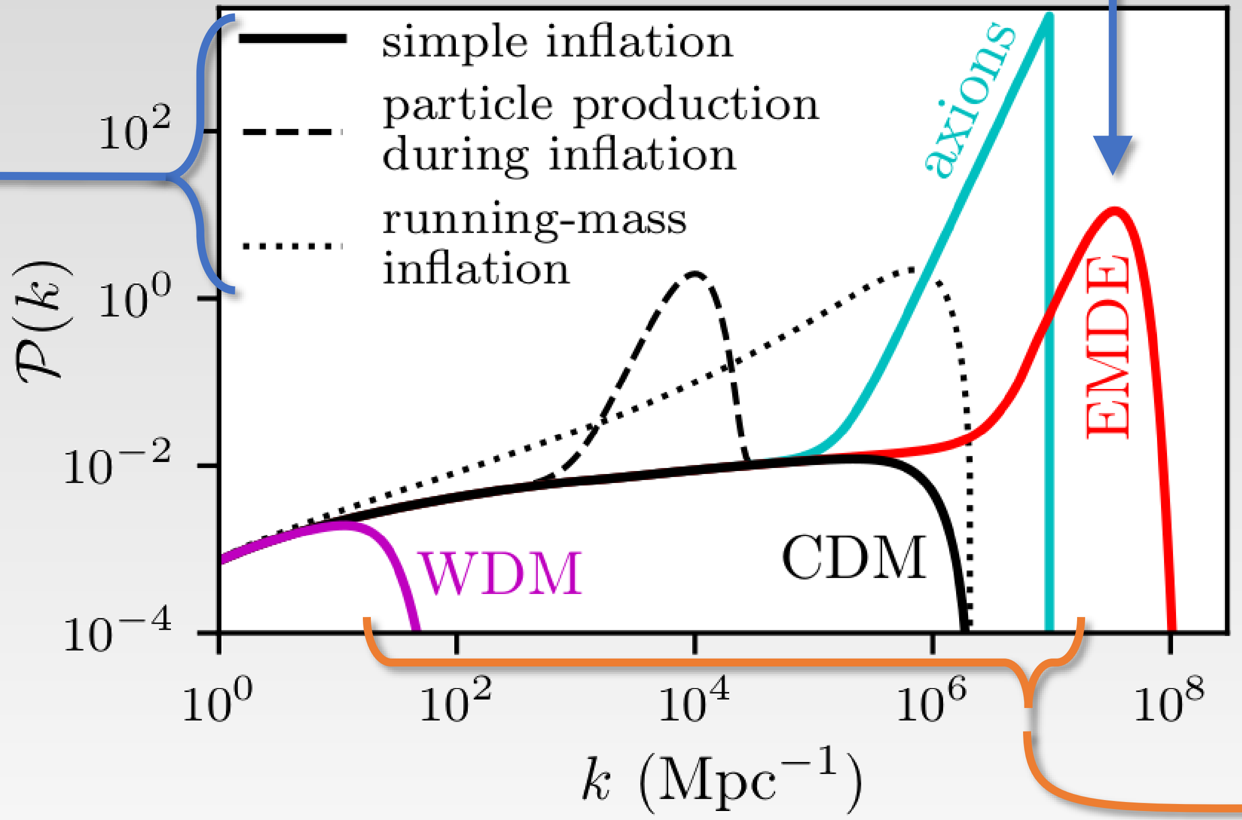
Most matter is nonbaryonic *dark matter*.

What is dark matter?

Signatures in the (linear) matter power spectrum

What happened after inflation?
Early matter domination boosts density variations.
[Early matter species clusters, carrying DM with it]

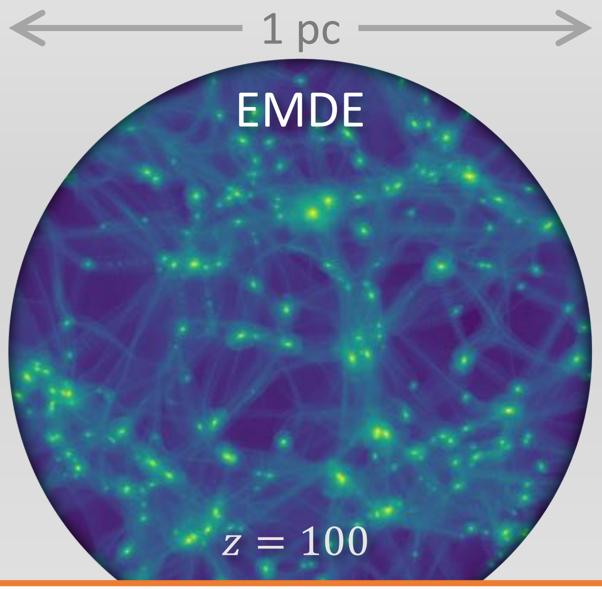
What drove inflation?
Dynamics of the inflaton field imprint on the primordial power spectrum.



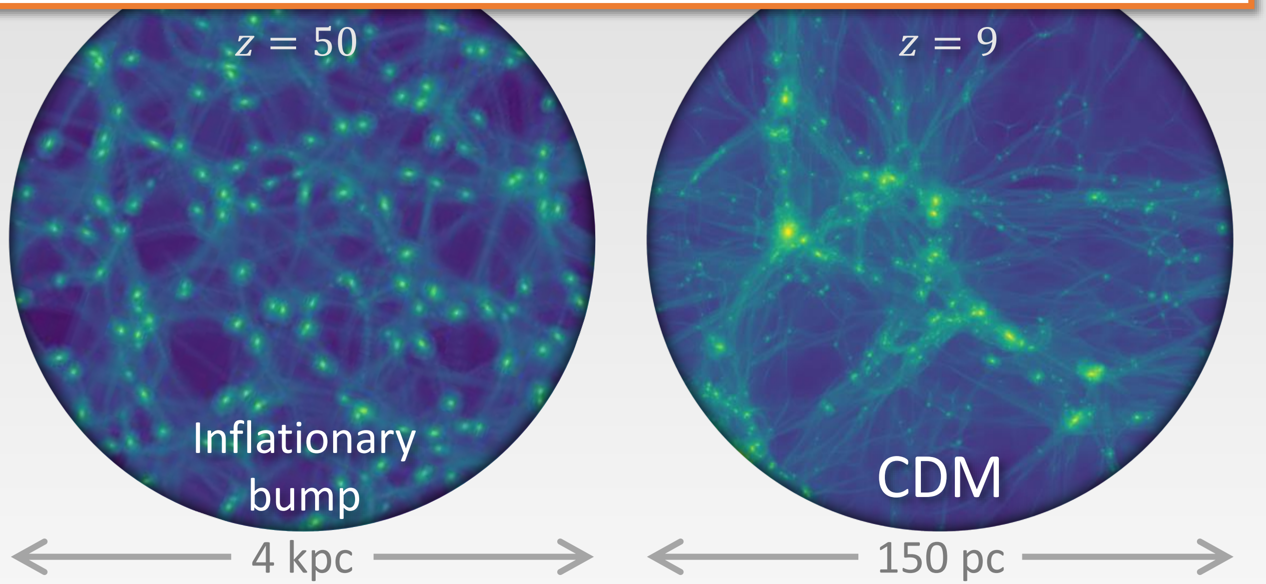
What is dark matter?
- Free-streaming (CDM vs WDM)
- Poisson noise (axion, PBH)

Dark matter microhalos

The first dark matter halos are a powerful probe of subkiloparsec-scale density variations.



Goal: Connect microhalo population to (linear theory) $\mathcal{P}(k)$



The theoretical challenge:

- Nonperturbative dynamics: must use simulations
- Microhalos are too small and dense to simulate in full context

We require (semi)analytic modeling.

Modeling dark matter structure

An ideal model:

- Includes substructure — ~~Standard Press-Schechter~~
- Is valid for arbitrary $\mathcal{P}(k)$ — ~~Concentration-mass relations~~
- Accounts for nonuniversal density profile:*

$\rho \propto r^{-3/2}$ [direct collapse]

The first halos

NFW/Einasto [hierarchical assembly]

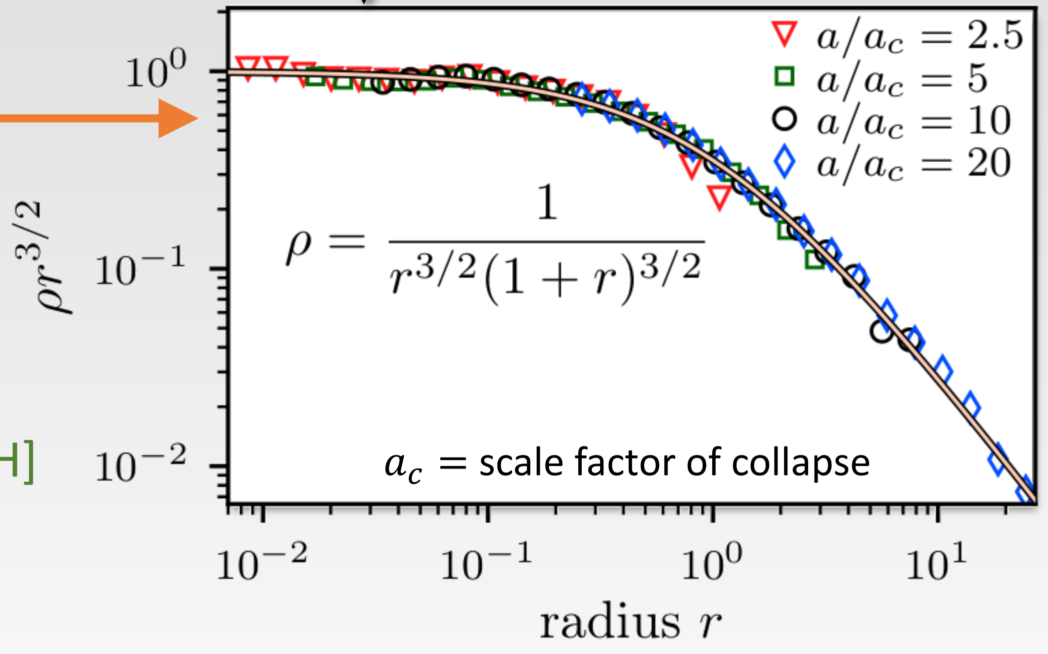
Later-generation halos

~~$\rho \propto r^{-9/4}$~~ [uncompensated overdensity, e.g., PBH]

Does not arise from Gaussian random field

<u>Simulating the density profiles of the first halos</u>

Ishiyama, Makino, Ebisuzaki 2010 [arXiv:1006.3392]
Anderhalden & Diemand 2013 [arXiv:1302.0003]
Ishiyama 2014 [arXiv:1404.1650]
Polisensky & Ricotti 2015 [arXiv:1504.02126]
Ogiya, Nagai, Ishiyama 2016 [arXiv:1604.02866]
Angulo, Hahn, Ludlow, Bonoli 2017 [arXiv:1604.03131]
Ogiya & Hahn 2018 [arXiv:1707.07693]
Gosenca, Adamek, Byrnes, Hotchkiss 2017 [arXiv:1710.02055]
Delos, Erickcek, Bailey, Alvarez 2018a [arXiv:1712.05421]
Delos, Erickcek, Bailey, Alvarez 2018b [arXiv:1806.07389]
Delos, Bruff, Erickcek 2019 [arXiv:1905.05766]
Ishiyama & Ando 2020 [arXiv:1907.03642]

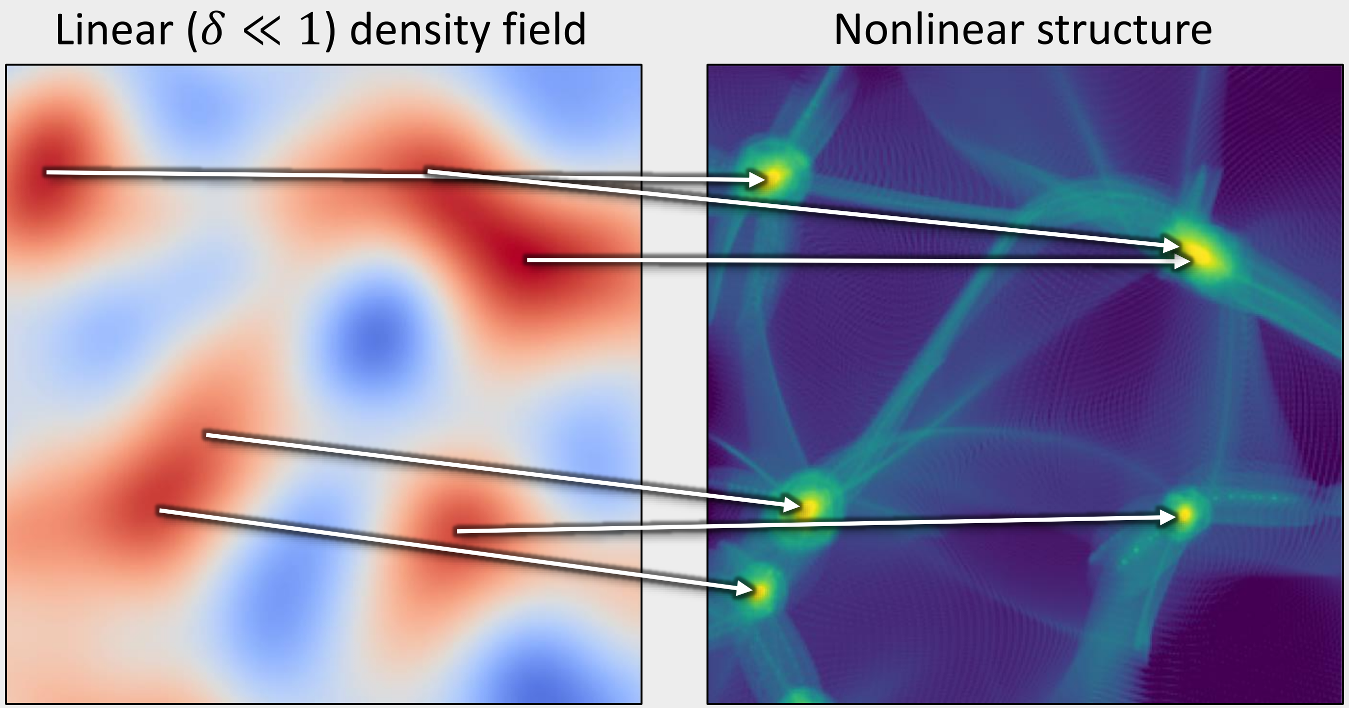


(Micro)halos from density peaks

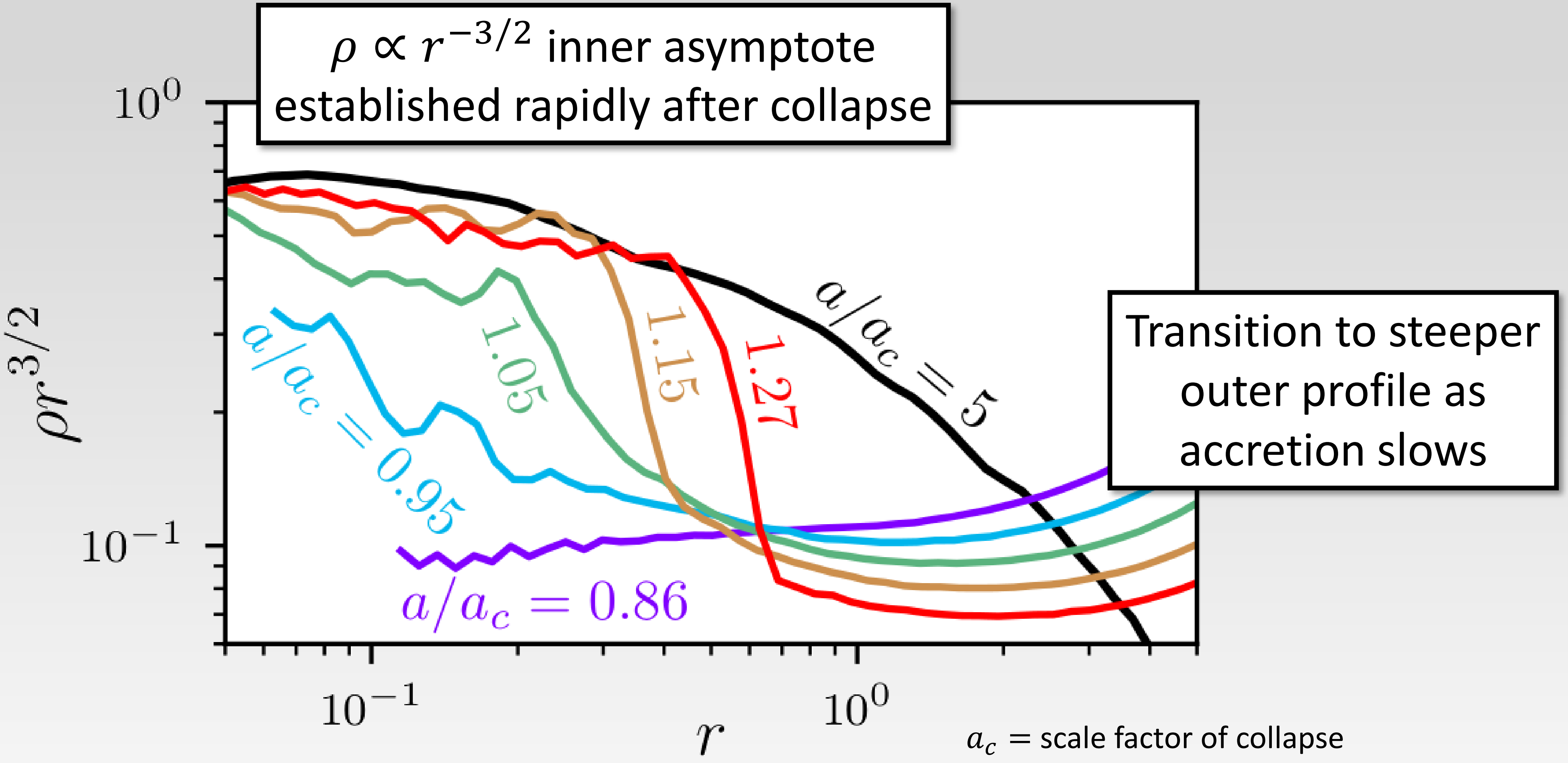
When studying the first (and smallest) halos, it is natural to consider the unfiltered density field.

[Contrast with Press-Schechter. Free-streaming cutoff tames divergence in σ.]

Associate each peak in the density field with a collapsed halo:



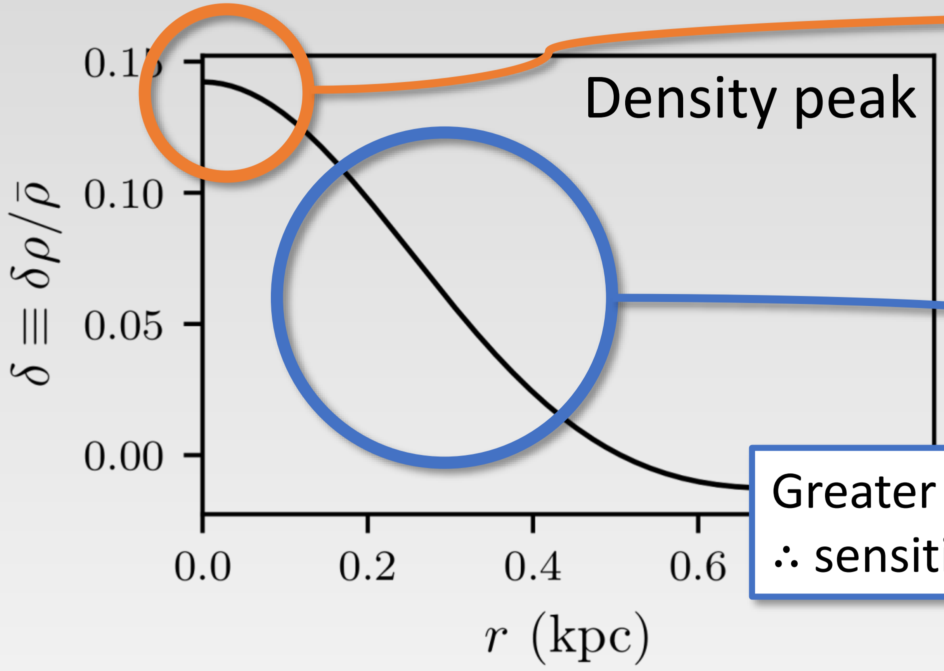
Formation and growth of the first halos

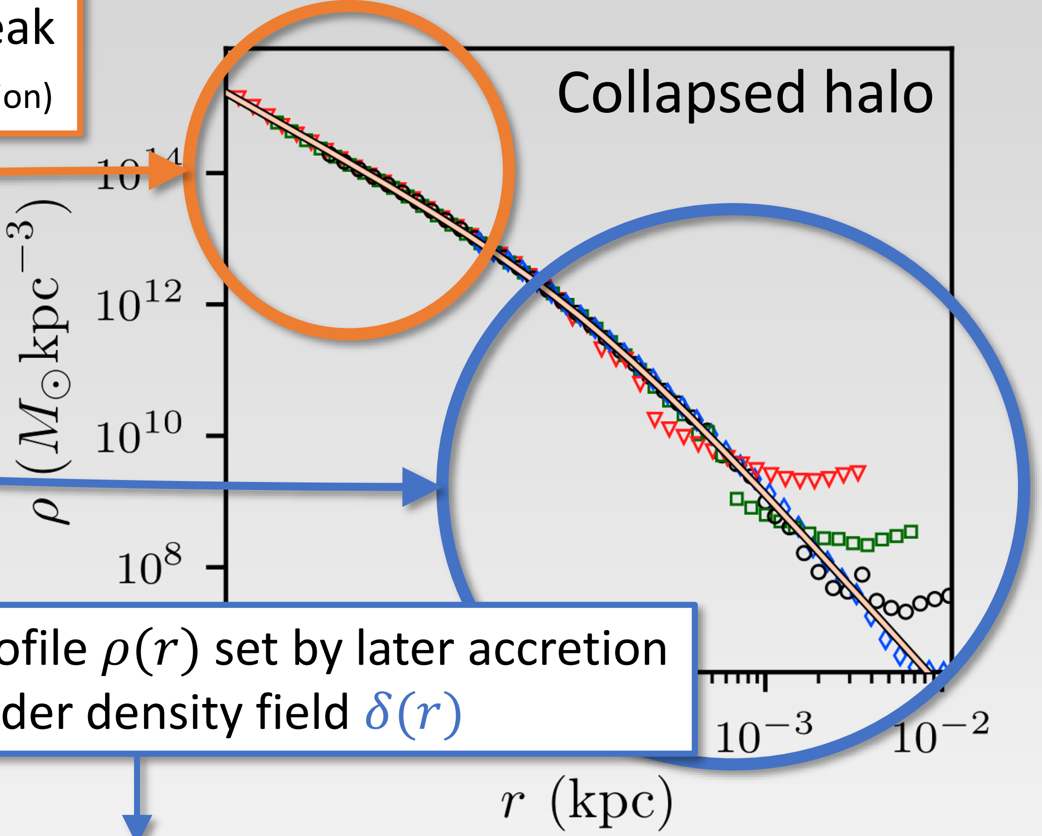


a_c = scale factor of collapse

Halo structure from peak structure

Inner asymptote set at formation time
∴ only sensitive to neighborhood of density peak
i.e., $\delta \equiv \delta\rho/\bar{\rho}$ and $\nabla^2\delta$ at peak (+ ellipsoidal correction)





Greater density profile $\rho(r)$ set by later accretion
∴ sensitive to broader density field $\delta(r)$

Slow accretion → use a secondary infall model

Gunn & Gott 1972; Gott 1975; Gunn 1977; Fillmore & Goldreich 1984; Bertschinger 1985; Hoffman & Shaham 1985; Ryden & Gunn 1987; White & Zaritsky 1992; Zaroubi & Hoffman 1993; Lokas & Hoffman 2000; Nusser 2001; Ascasibar, Yepes, Gottlöber, Müller 2004; Lu, Mo, Katz, Weinberg 2006; Ascasibar, Hoffman, Gottlöber 2007; Zukin & Bertschinger 2010a,b; Dalal, Lithwick, Kuhlen 2010

Inner asymptote from peak structure

Peak has local properties
- Height δ
- Derivatives $\partial_i \partial_j \delta$ [w.r.t. comoving coordinates]

Halo has: $\rho = A r^{-3/2}$

The connection: $A \propto \delta^3 \left[\delta^{-1} \left(\frac{\delta}{|\nabla^2 \delta|} \right)^{1/2} \right]^{3/2} \left[\frac{\delta_{ec}(e,p)}{\delta_{sc}} \right]^{-3/2}$

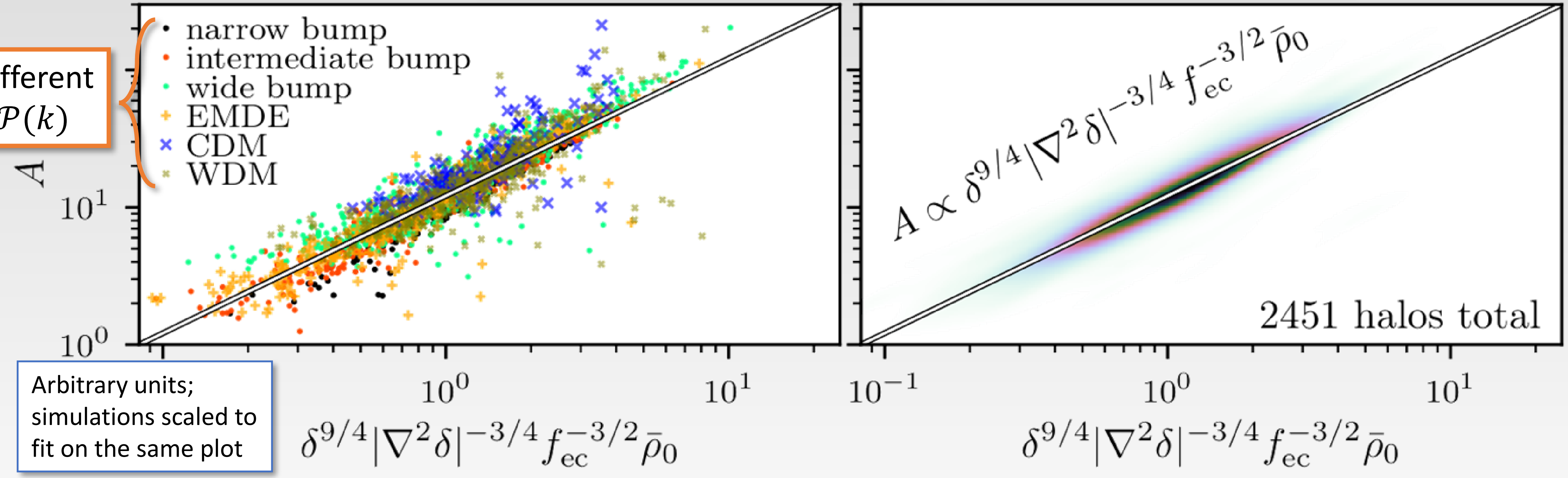
Physical length scale at collapse $\propto a_c q \propto \delta^{-1} q$

Ellipsoidal correction f_{ec}

Density at collapse $\propto a_c^{-3} \propto \delta^3$

Comoving length scale q

Different $\mathcal{P}(k)$



Arbitrary units; simulations scaled to fit on the same plot

More detail: Delos, Bruff, Erickcek 2019 [arXiv:1905.05766]

Halo formation prior to matter domination

Early-universe scenarios that boost $\mathcal{P}(k)$ could induce collapse before matter dominates [$t < 52$ kyr].

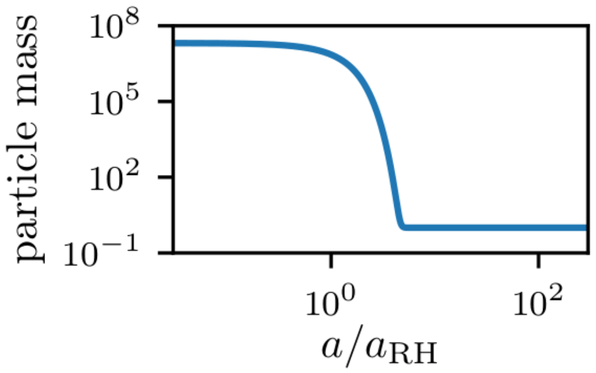
Can halos form (or persist) during radiation domination? No net forces $\implies$ no bound structures.

But δ still grows during RD.

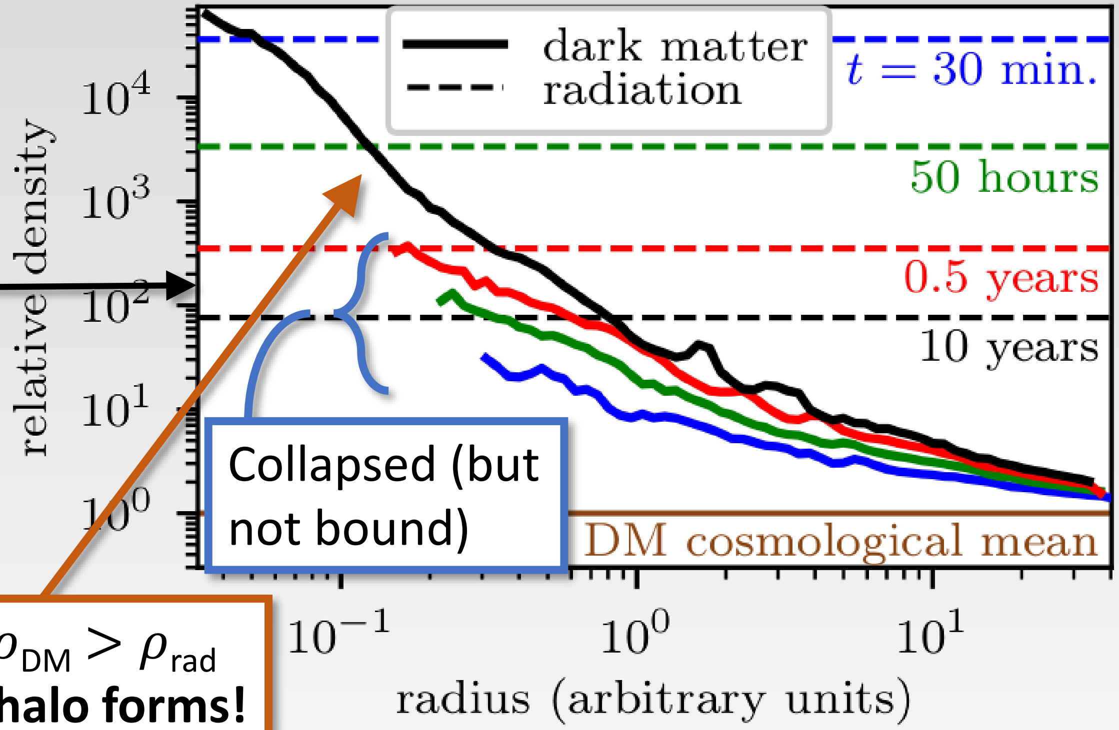
[Convergent DM drift sourced during horizon entry or EMDE]

I modified GADGET-2 to represent an early matter-dominated era.

- Concept: time-dependent particle mass
  [includes both DM & decaying early matter]



- Technical: scale $\mathrm{d}t_{\text{kick}}$ instead
  [interpolates better between time steps]



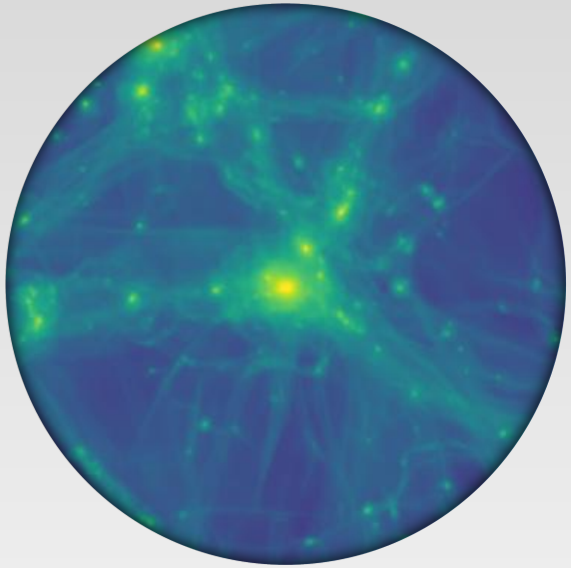
Local $\rho_{\text{DM}} > \rho_{\text{rad}}$
Bound halo forms!

More detail: Blanco, Delos, Erickcek, Hooper 2019 [arXiv:1906.00010]

Halo evolution

Isolated halos maintain static $\rho(r)$…

but most microhalos do not remain isolated.



Can we understand how microhalos structurally evolve as they merge to produce larger objects?

Microhalo-microhalo mergers:
a topic of future research.

Approximately, $\sum_{\text{halos } i} A_i^2 \simeq \text{constant}$

Mass additive in mergers (approx.)

Conceptually: $A^2 \sim \rho^2 r^3 \sim \rho\, M$

Characteristic density preserved (approx.)
[e.g., Drakos et al. 2019]

(Recall $\rho = A r^{-3/2}$ at small r)

Useful because DM annihilation rate $\propto A^2$

Accretion onto larger (e.g., galactic) halos:
Subhalo evolution.

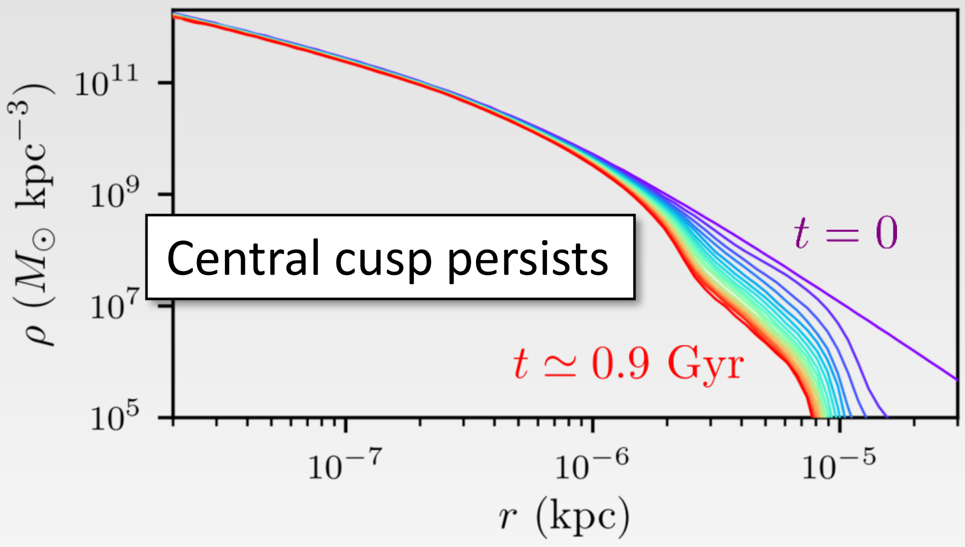
- Tidal forces
- Encounters with other objects

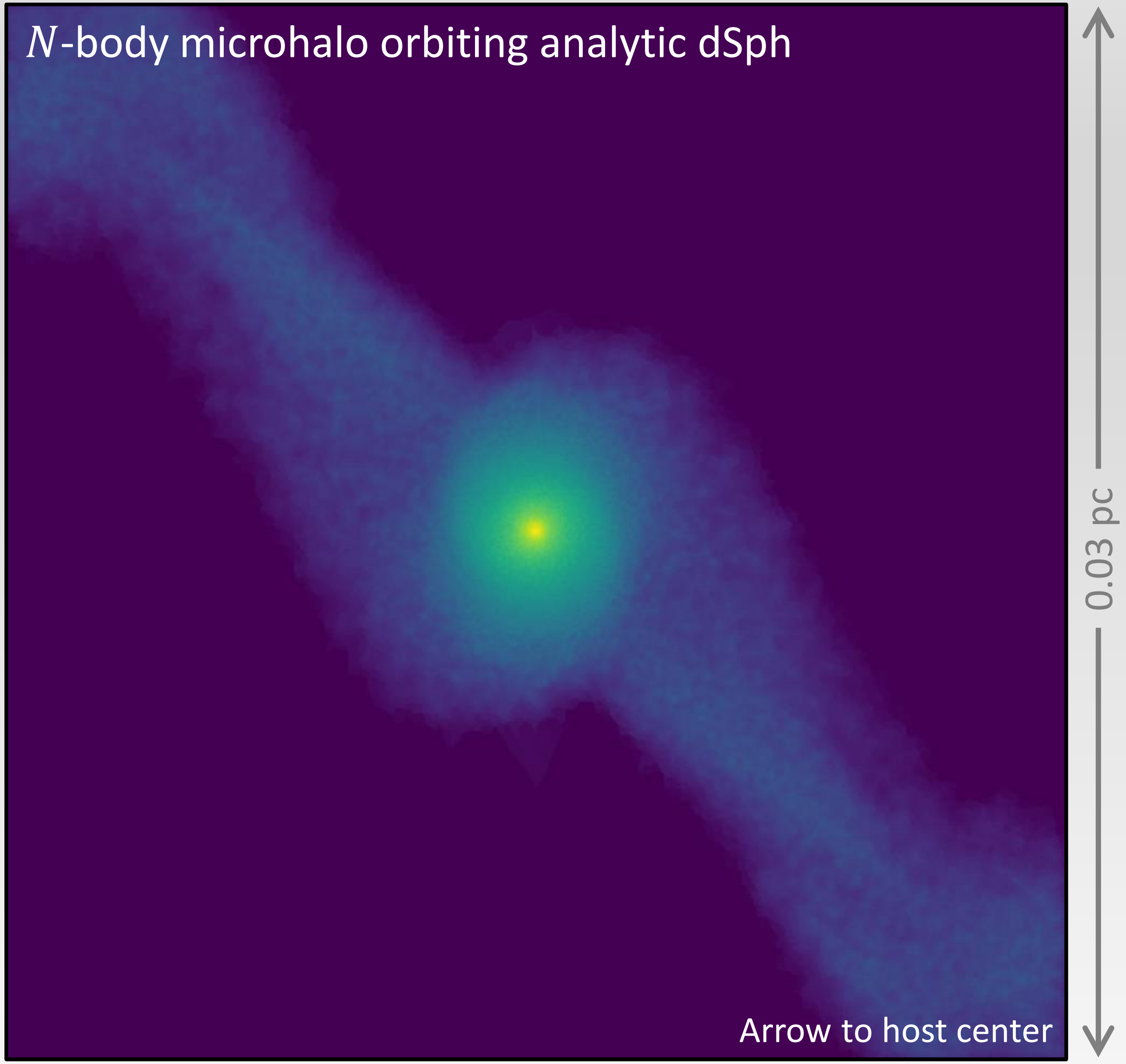
Tidal evolution

Given a subhalo orbit $\boldsymbol{R}(t)$,
I modified GADGET-2 to apply the time-dependent tidal force directly:

$$\boldsymbol{F}_{\mathrm{tidal}}(\boldsymbol{r}) = -\frac{\mathrm{d}F}{\mathrm{d}R}(\boldsymbol{r}\cdot\hat{\boldsymbol{R}})\hat{\boldsymbol{R}} - F(R)\frac{\boldsymbol{r}-(\boldsymbol{r}\cdot\hat{\boldsymbol{R}})\hat{\boldsymbol{R}}}{R}$$

[Evades numerical artifacts associated with scale disparity between orbital and internal dynamics.]





More detail: Delos 2019a [arXiv:1906.10690]

Host-subhalo system

Parameters:
- Subhalo size r_s
- Subhalo density ρ_s
- Host size R_s
- Host density P_s
- Orbit radius R_c
- Orbit shape η
- Time t

Minimal:

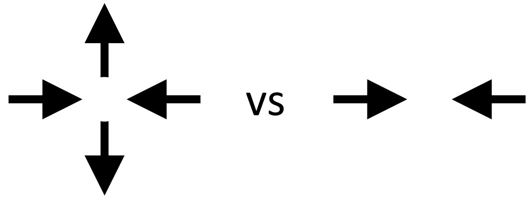
ρ_s/P_s

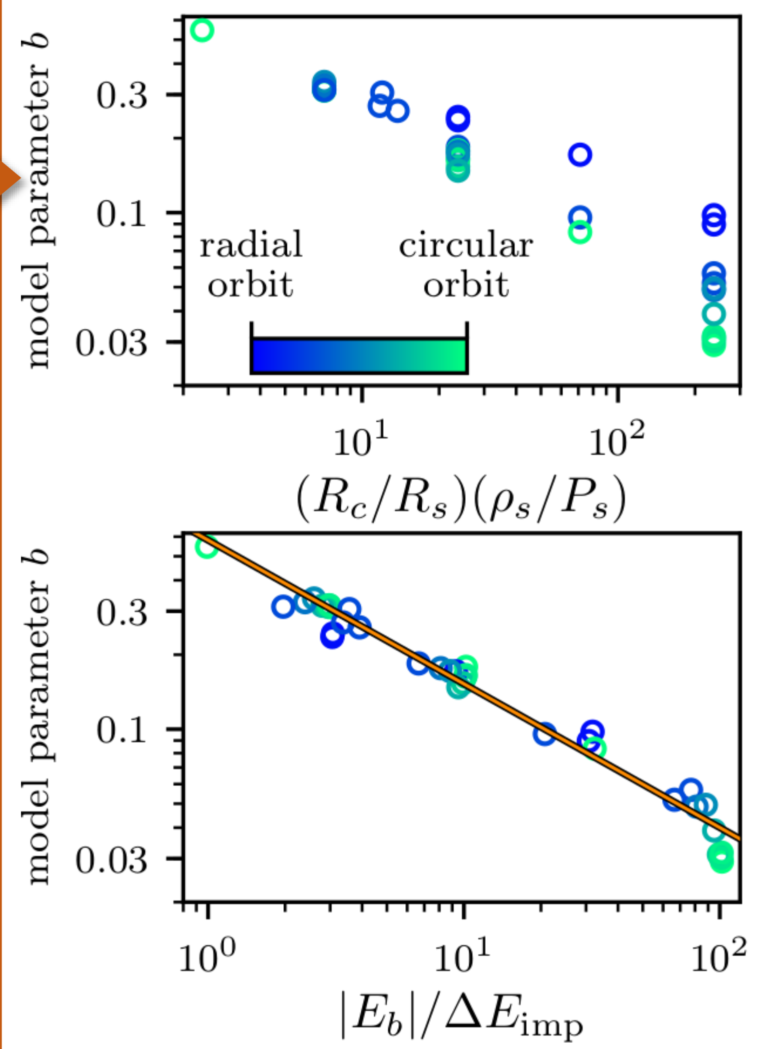
R_c/R_s

η

$t/\sqrt{R_c/F(R_c)}$

Better parametrization:

$\frac{\Delta E_{imp}}{\lvert E_b \rvert}$	Relative energy injection per orbit [impulse approx.]
$\bar{R}/R_s$	Sets direction of tidal forces  vs ; $\bar{R} \gtrsim R_s$; $\bar{R} \ll R_s$
tidal → r_a/r_t ← adiabatic shielding	Orbit shape ⟹ timescale for tidal forces ⟹ tidal heating distribution ⟹ subhalo density profile
t/T	Orbit count



More detail: Delos 2019a [arXiv:1906.10690]

Modeling tidal evolution

Focus on the dark matter annihilation rate ∝ $J \equiv \int \rho^2 \mathrm{d}V$.

[Story is similar for other subhalo properties]

Evolution satisfies:

$$\frac{1}{J}\frac{\mathrm{d}J}{\mathrm{d}n} = -bn^{-c}, \quad n = \frac{t}{T}$$

Coefficient b depends on

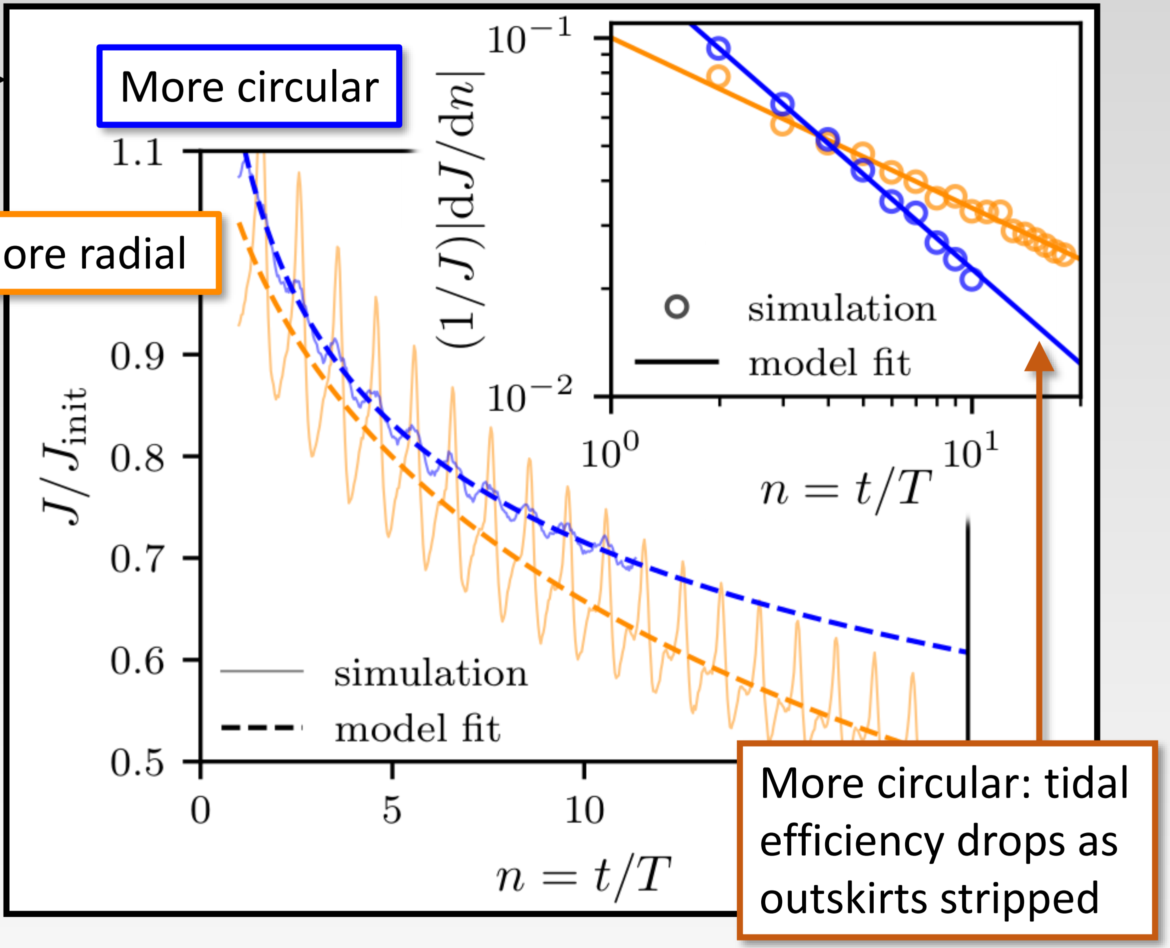
- $\Delta E_{imp}/|E_b|$ [*energy injection per orbit*]
- $\bar{R}/R_s$ [*direction of tidal forces*]

Factor related to change in density profile shape; index c depends on r_a/r_t [*tidal heating distribution*]

Fixed by overall scale:

$$J|_{t/T=1} = AJ_{\mathrm{init}}$$

Compression/stretching; depends on $\bar{R}/R_s$ and $\Delta E_{imp}/|E_b|$ [*tidal force direction and strength*]

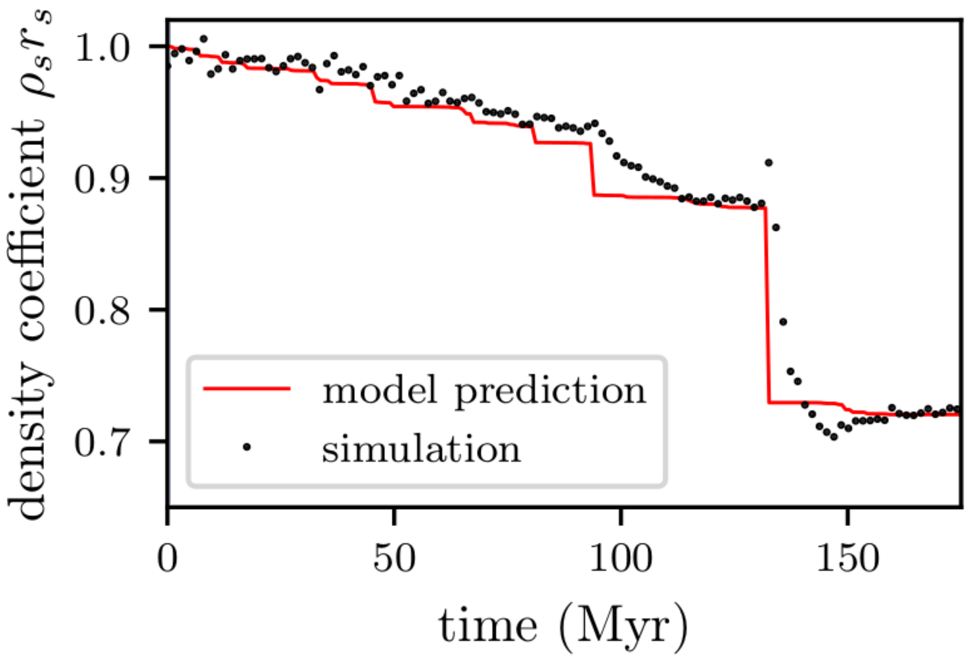


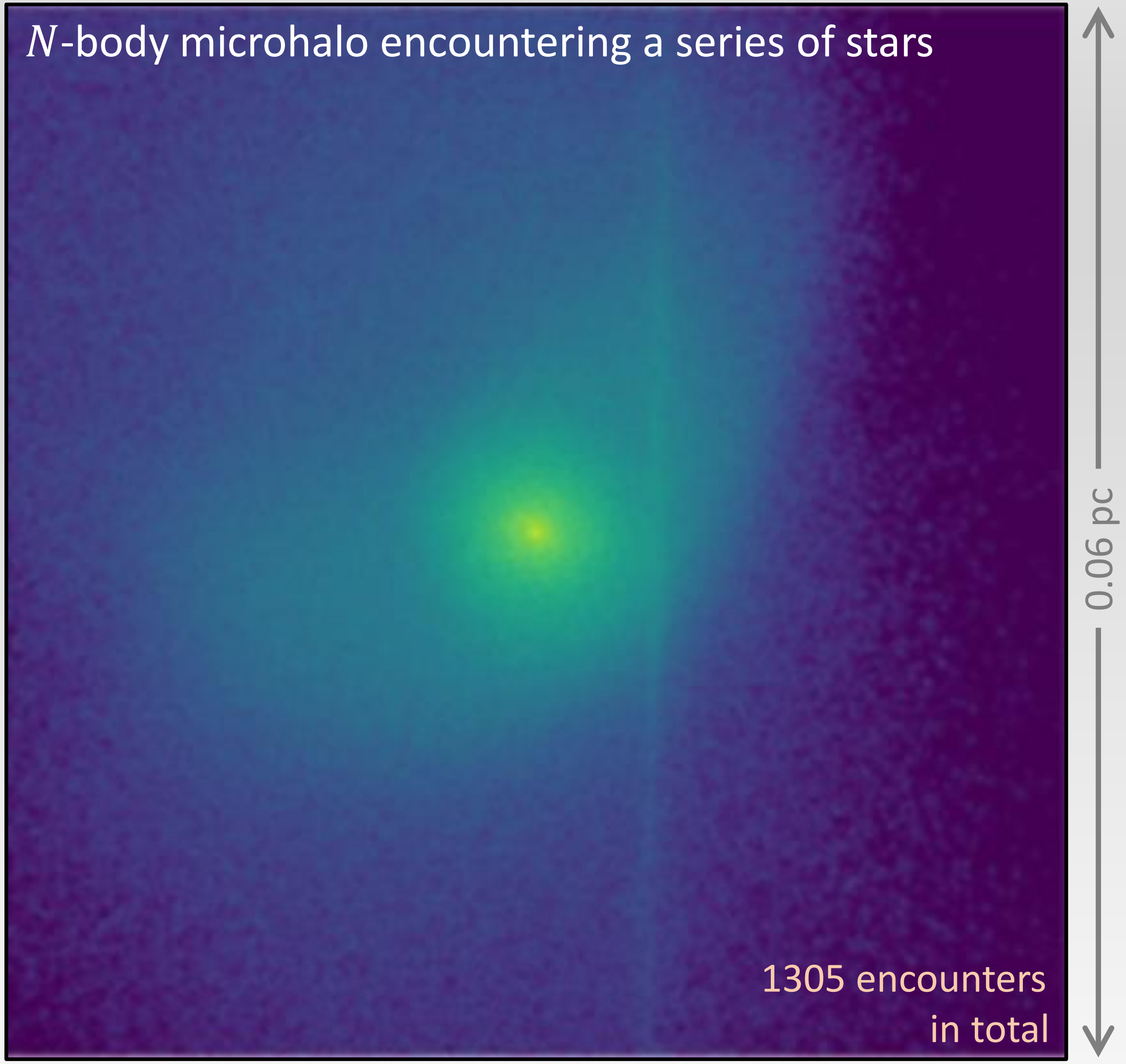
More detail: Delos 2019a [arXiv:1906.10690]

Stellar encounters

I modified GADGET-2 to apply $\Delta\vec{v}$ induced by a series of stellar encounters…

…and developed an accurate predictive model:

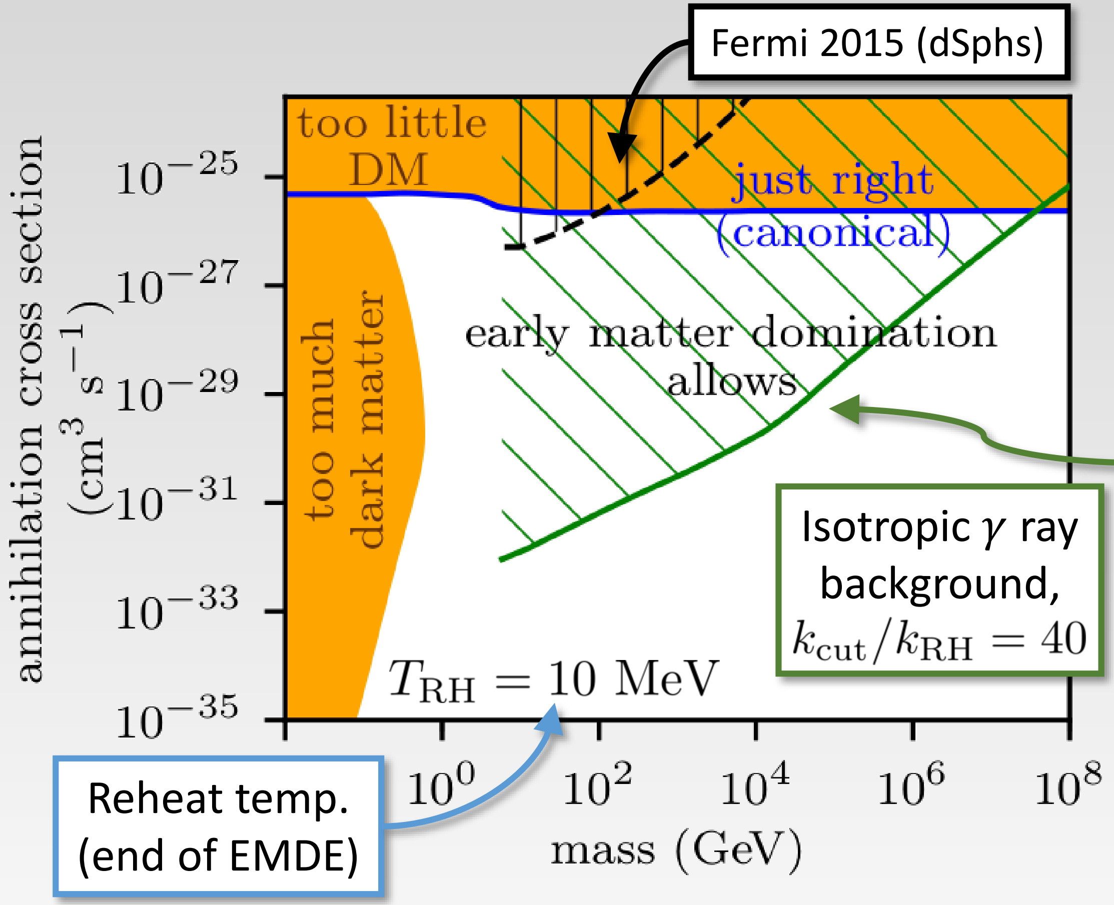




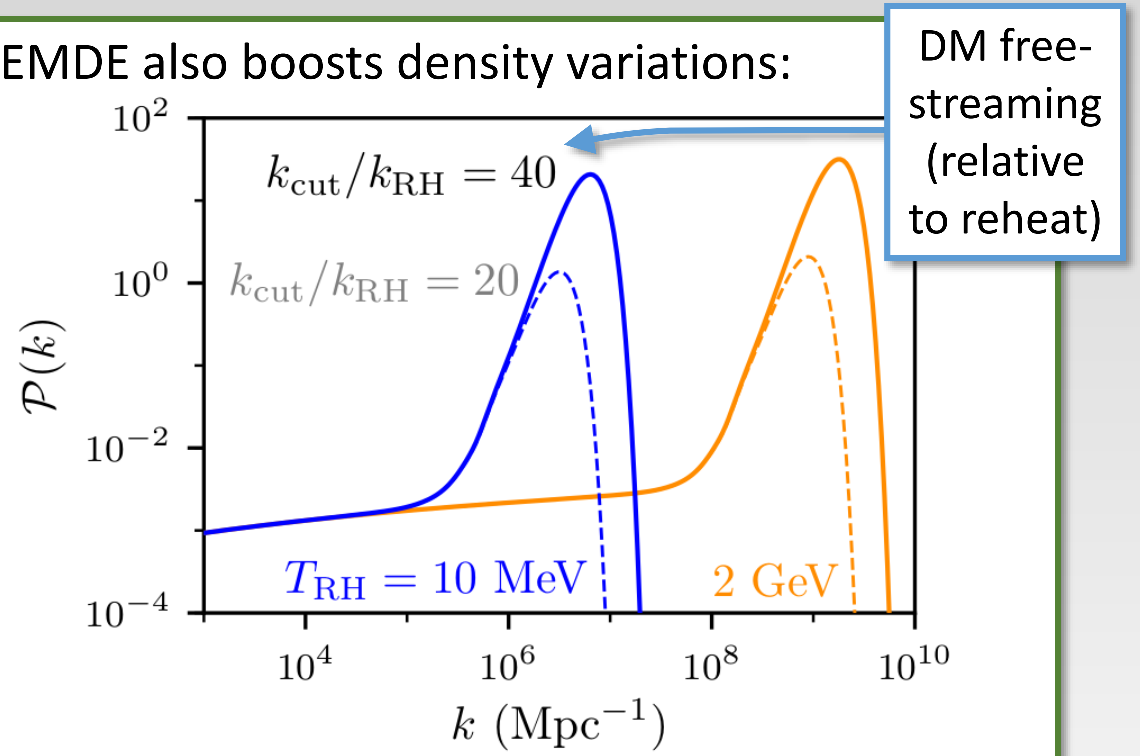
More detail: Delos 2019b [arXiv:1907.13133]

Application: Breaking a dark degeneracy

An early matter-dominated era (EMDE) broadens the range of viable parameters for thermal-relic dark matter. [Decay sources radiation that dilutes DM → need more DM → smaller $\langle\sigma v\rangle$.]



EMDE also boosts density variations:



$\Longrightarrow$ Early, highly dense microhalos

$\Longrightarrow$ Improved indirect-detection bounds

More detail: Delos, Linden, Erickcek 2019 [arXiv:1910.08553]

Application: Breaking a dark degeneracy

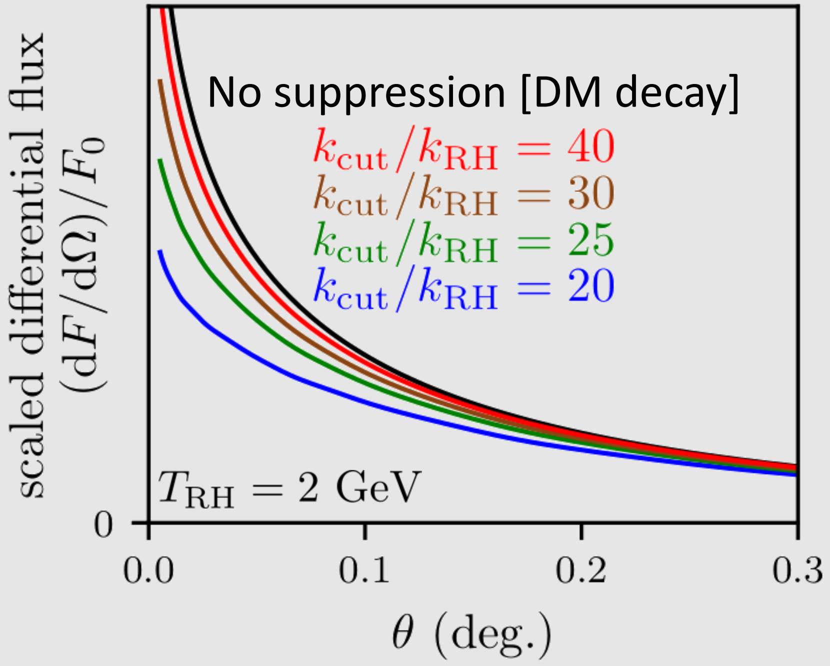
Annihilation signal from microhalos resembles DM decay.

Microhalo distribution ~ DM distribution

Galactic systems can discriminate.

Disruption of microhalos by
tidal forces & stellar encounters
$\Longrightarrow$ Differential microhalo suppression
$\Longrightarrow$ Unique annihilation signal morphology:

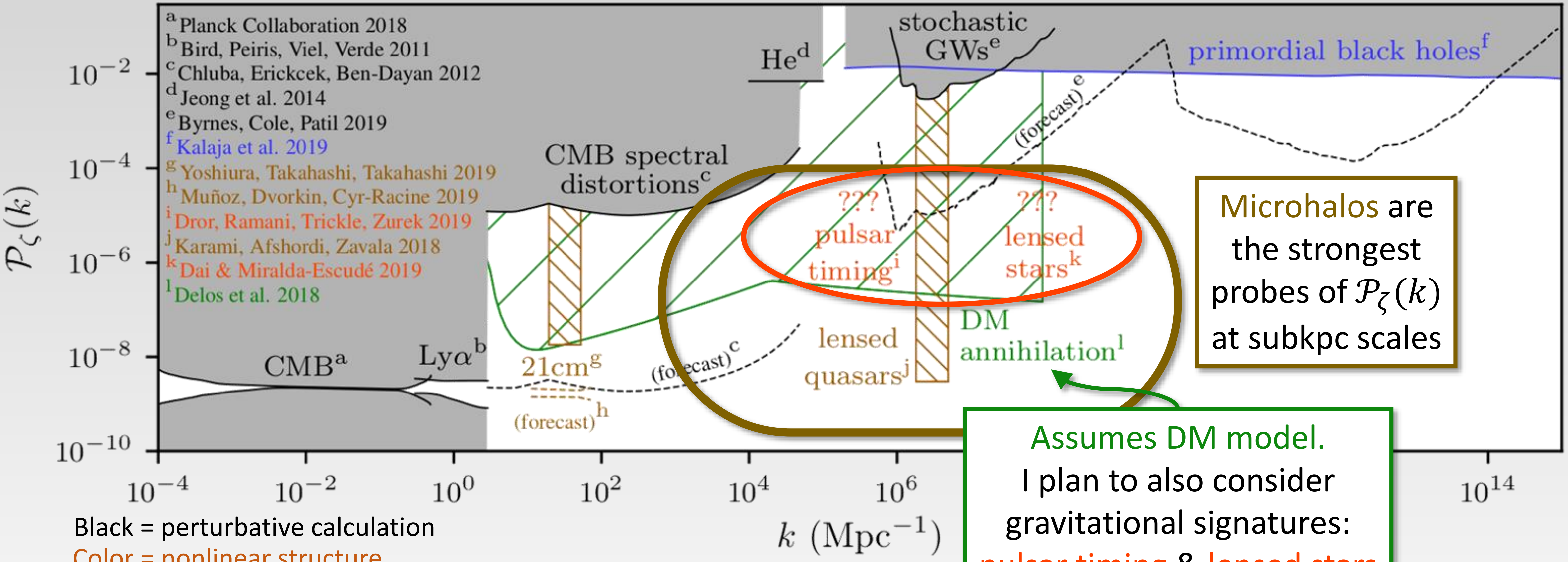
- DM decay vs microhalo annihilation
- Different DM & EMDE parameters



More detail: Delos, Linden, Erickcek 2019 [arXiv:1910.08553]

Application: The primordial power spectrum

Constraints on superhorizon curvature fluctuations (sourced by inflation):



Microhalos are the strongest probes of $\mathcal{P}_\zeta(k)$ at subkpc scales

Assumes DM model.
I plan to also consider gravitational signatures:
pulsar timing & lensed stars

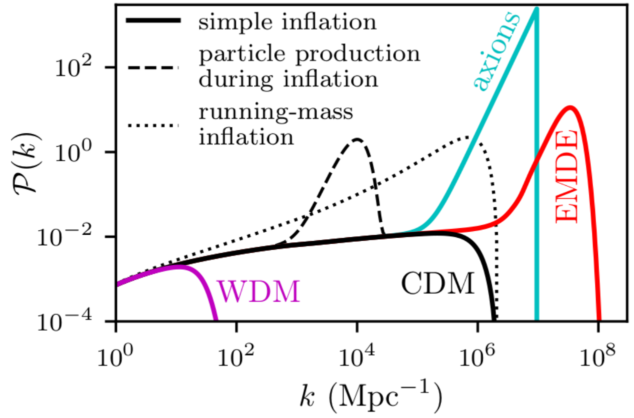
Black = perturbative calculation
Color = nonlinear structure

More detail: Delos, Erickcek, Bailey, Alvarez 2018b [arXiv:1806.07389]

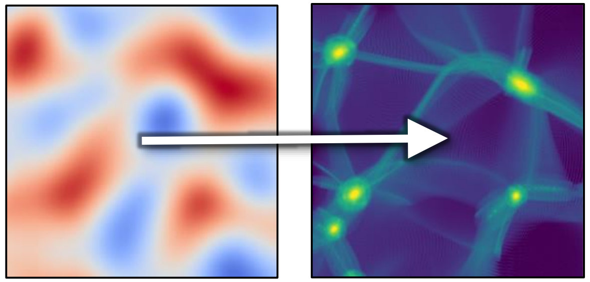
Summary: Microhalos as cosmological probes

Key cosmological questions
- What drove inflation?
- What happened after inflation?
- What is dark matter?

are connected to the small-scale (linear) matter power spectrum.

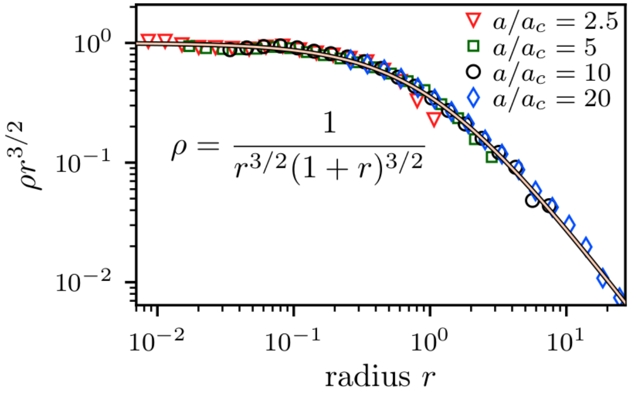


My research connects $\mathcal{P}(k)$ to microhalos today, looking toward observational signatures



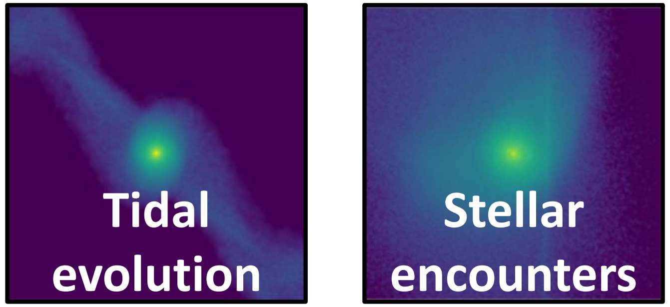
Peak-to-halo model

Predicts the density profiles of the first (micro)halos



Accurate for arbitrary $\mathcal{P}(k)$

Subhalo evolution models



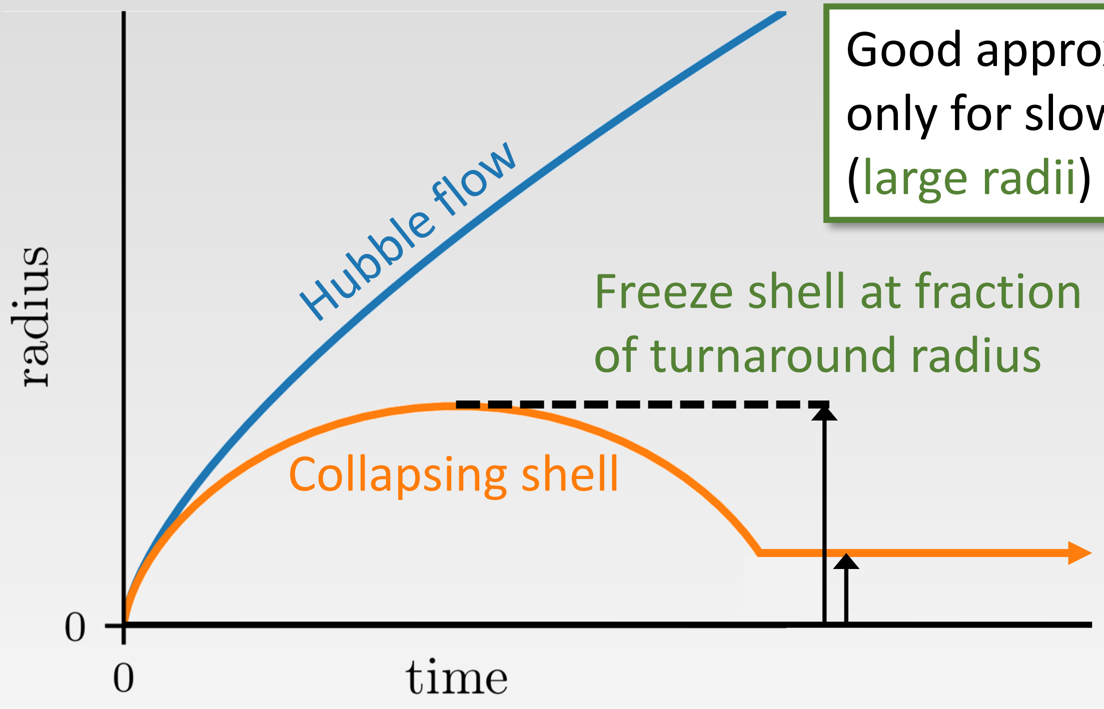
Predict microhalo evolution after accretion onto larger systems

Applications I have explored:
- Constraints on thermal-relic dark matter that account for our ignorance of the early cosmic history
- Constraining the small-scale primordial power spectrum

Supplemental

Greater density profile from peak structure

Connect halo's mass profile $M(r)$ to peak's mass-contrast profile $\Delta(q)$ using a spherical infall model:



Good approximation only for slow accretion (large radii)

Simplest model:

$$r \propto q/\Delta(q)$$

$$M \propto (4\pi/3)q^3\bar{\rho}_0$$

Refinements, e.g., adiabatic contraction:

$$r \propto \frac{q}{\Delta(q)}\frac{1}{X(q)}$$

$$M \propto (4\pi/3)q^3\bar{\rho}_0 X(q)$$

$$\frac{\mathrm{d}\ln X}{\mathrm{d}\ln q} = -\frac{3-[3(3-s)\epsilon(q)-s](X-1)}{1+(4-s)(X-1)}$$

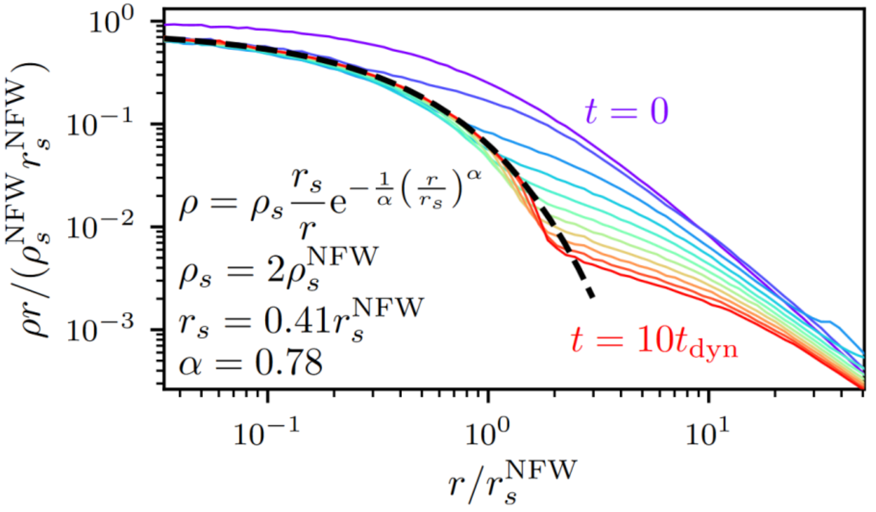
$$\epsilon(q) = 1-\delta(q)/\Delta(q)$$

Models not new, but application is.

More detail: Delos, Bruff, Erickcek 2019 [arXiv:1905.05766]

Supplemental
Modeling stellar encounters

Universal postencounter density profile



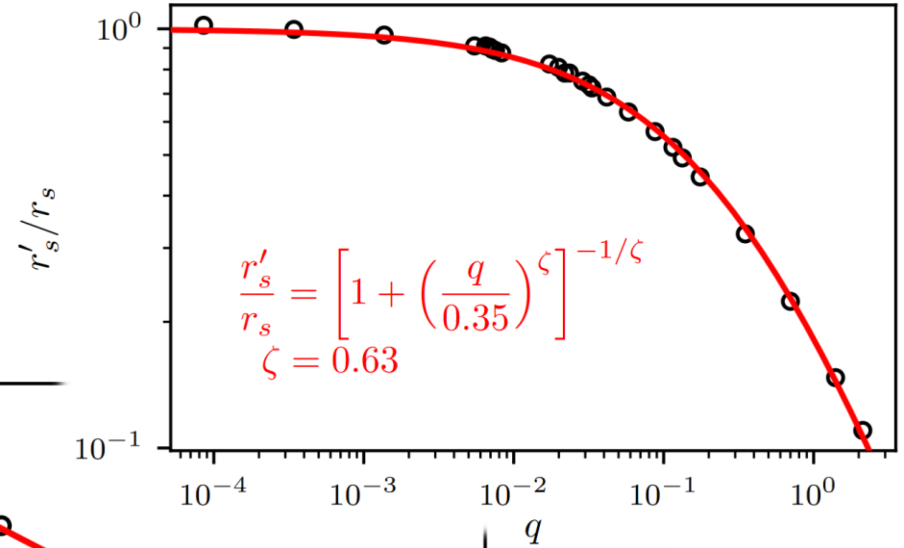
Encounter with

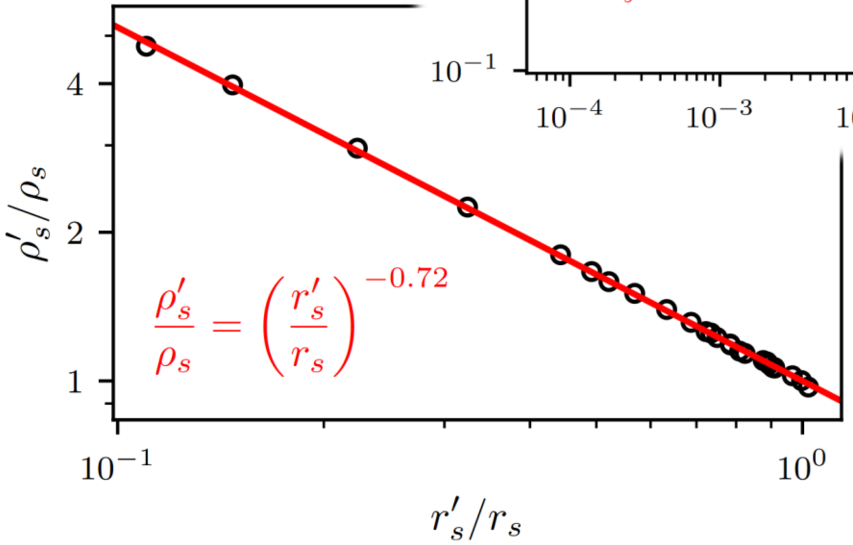
$q \equiv \Delta E/|E_b|$

causes:

$r_s \to r_s'$

$\rho_s \to \rho_s'$





Other variables

- b/r_s (relative impact parameter)
- $t_{dyn}/(b/V)$ ("impulsiveness")

typically $\gg 1 \implies$ irrelevant

More detail: Delos 2019b [arXiv:1907.13133]

Supplemental
Note on universality

An ideal model:

- Includes substructure — ~~Standard Press-Schechter~~
- Is valid for arbitrary $\mathcal{P}(k)$ — ~~Concentration-mass relations~~
- Accounts for nonuniversal density profile:*

$\rho \propto r^{-3/2}$ [direct collapse]

The first halos

NFW/Einasto [hierarchical assembly]

Later-generation halos

~~$\rho \propto r^{-9/4}$~~ [uncompensated overdensity, e.g., PBH]

Does not arise from Gaussian random field

Simulating the density profiles of the first halos

Ishiyama, Makino, Ebisuzaki 2010 [arXiv:1006.3392]
Anderhalden & Diemand 2013 [arXiv:1302.0003]
Ishiyama 2014 [arXiv:1404.1650]
Polisensky & Ricotti 2015 [arXiv:1504.02126]
Ogiya, Nagai, Ishiyama 2016 [arXiv:1604.02866]
Angulo, Hahn, Ludlow, Bonoli 2017 [arXiv:1604.03131]
Ogiya & Hahn 2018 [arXiv:1707.07693]
Gosenca, Adamek, Byrnes, Hotchkiss 2017 [arXiv:1710.02055]
Delos, Erickcek, Bailey, Alvarez 2018a [arXiv:1712.05421]
Delos, Erickcek, Bailey, Alvarez 2018b [arXiv:1806.07389]
Delos, Bruff, Erickcek 2019 [arXiv:1905.05766]
Ishiyama & Ando 2020 [arXiv:1907.03642]

*Consistent with:

Universality in the structure of dark matter haloes over twenty orders of magnitude in halo mass

Wang, J.[1], Bose, S.[2], Frenk, C. S.[3], Gao, L.[1], Jenkins, A.[3], Springel, V.[4] & White, S. D. M.[4]