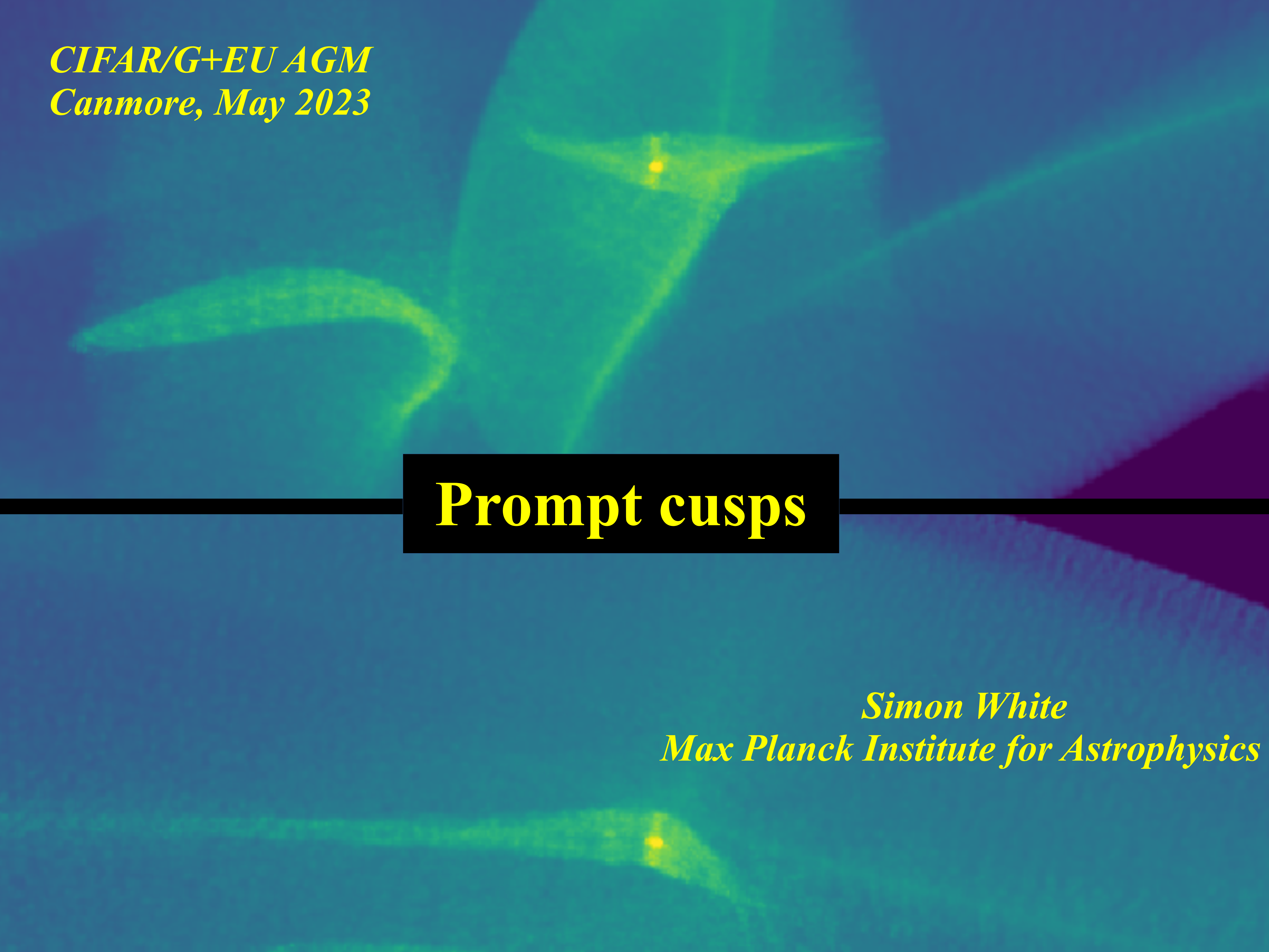

CIFAR/G+EU AGM
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Prompt cusps

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Springel et al 2008

Forming a Milky Way mass dark matter halo in ΛCDM

The formation of normal ΛCDM halos

Assume an otherwise uniform EdS universe with a power-law, ellipsoidal initial linear density perturbation

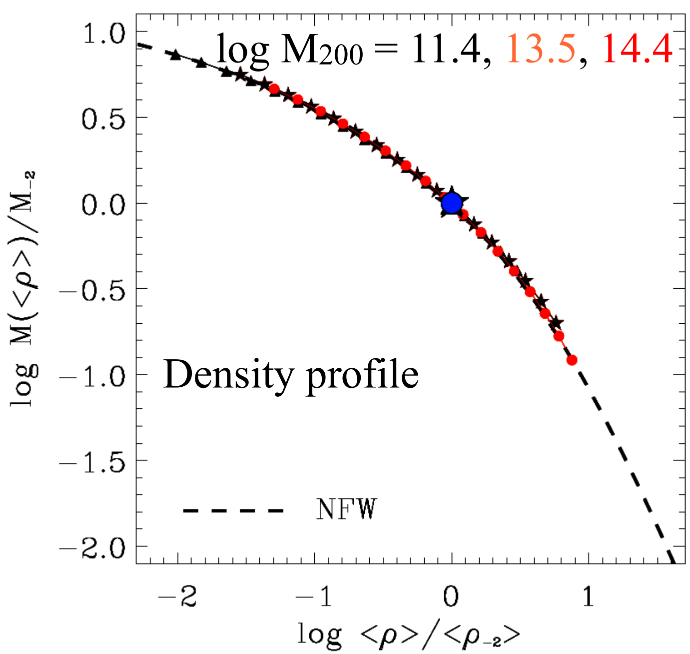
$$\delta(\mathbf{x}, t) \; = \; \delta_o \, (t / t_o)^{2/3} \, (\mathbf{x} \,.\, A \,.\, \mathbf{x})^{-\alpha/2} , \qquad |A| = 1,$$

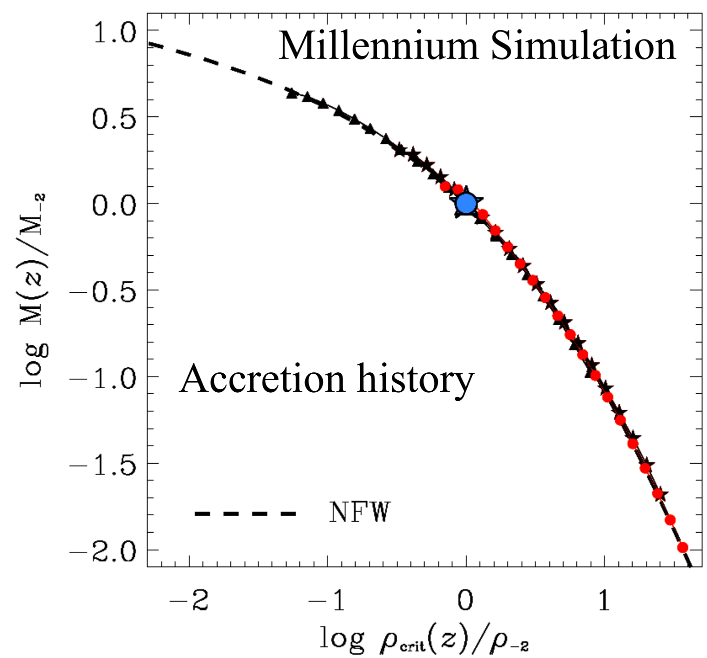
$$\propto \; \bar{\rho}(t)^{-1/3} \, M(\mathbf{x})^{-\alpha/3}$$

At t_{coll}, when the shell containing M collapses, $\delta(\mathbf{x}, t_{coll}) \simeq \; \delta_{crit} \sim 1.69$

→ $\bar{\rho}(t_{coll}) \propto M^{-\alpha}$, hence a halo profile $\rho(r) \propto \; r^{-\gamma} \quad \text{with } \gamma = 3\alpha/(1 + \alpha),$

assuming each mass shell stays at a mean density proportional to $\bar{\rho}(t_{coll})$





ΛCDM halos
Ludlow et al 2014

The formation of prompt cusps

Close to a peak of the (unsmoothed) density field with collapse time t_o

$$\delta(\mathbf{x}, t) = \delta_{crit} (t / t_o)^{2/3} (1 - \mathbf{x} \,.\, A \,.\, \mathbf{x}), \qquad \mathbf{x} \,.\, A \,.\, \mathbf{x} \ll 1,$$

so

$$\delta(\mathbf{x}, t_o+\Delta t) = \delta_{crit} (1 + 2\Delta t/3t_o - (M/M_o)^{2/3}).$$

Hence at collapse of the shell containing mass M, $\Delta t \propto M^{2/3}$.

Assuming that $\Delta t \propto \bar{\rho}(M)^{-1/2}$ in the resulting quasi-equilibrium structure,

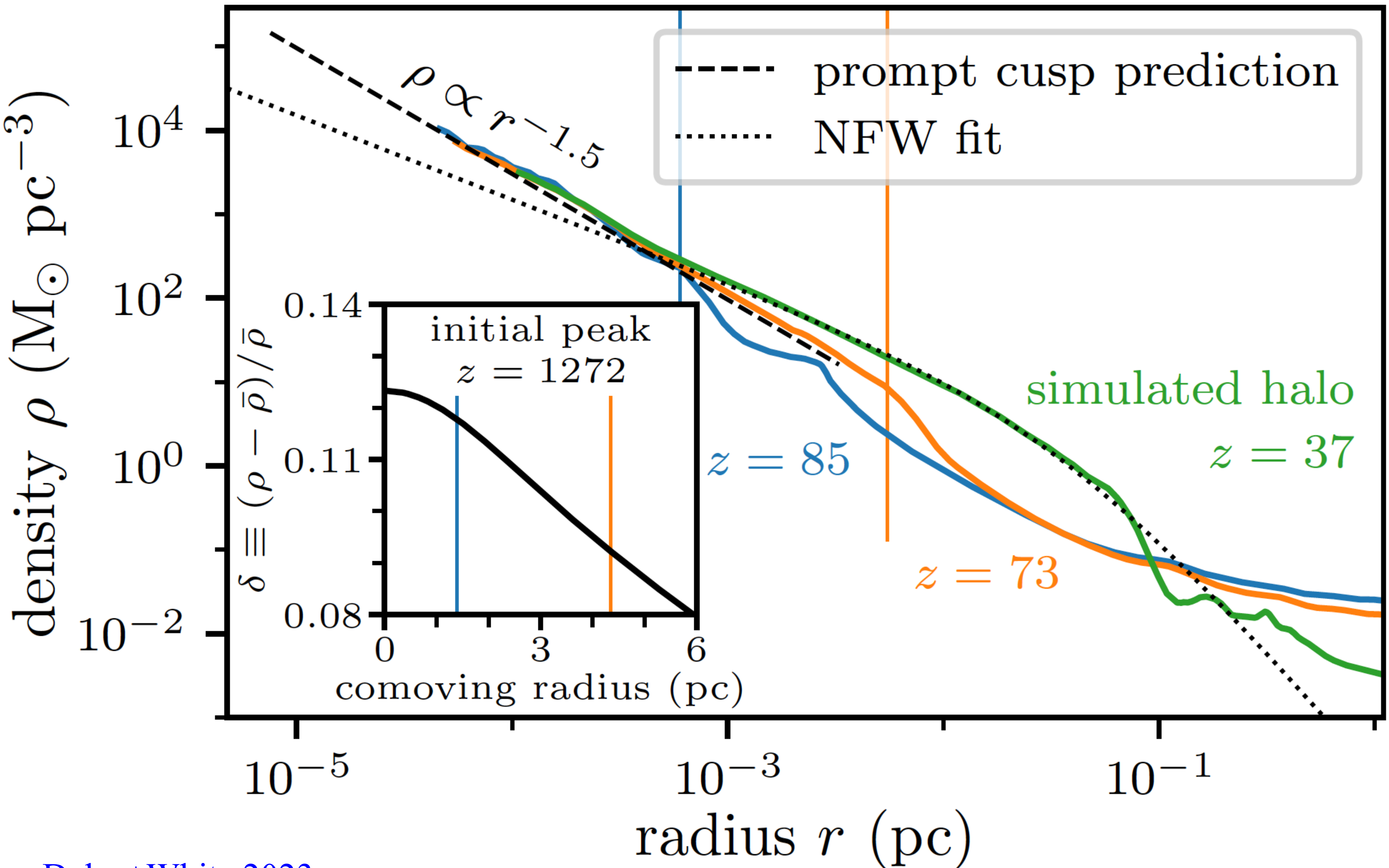
$\longrightarrow$ $\rho(M)^{-1/2} \propto M^{2/3}$, implying $\boxed{\rho(r) \propto r^{-12/7}}$

Prompt cusps approximate similarity solutions, but the relevant time is the time since peak collapse, NOT the cosmic time,

Prompt Cusps

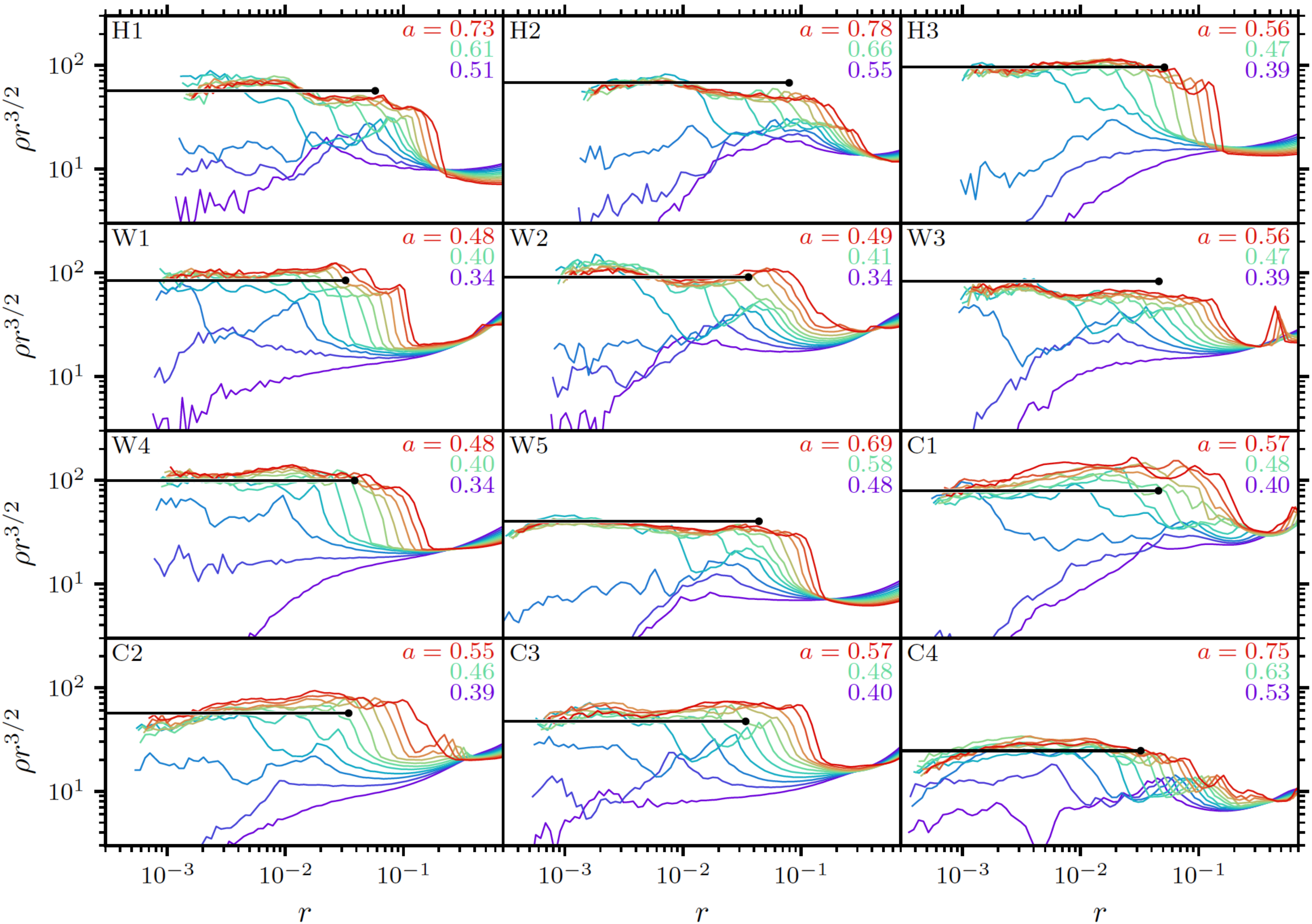
- ...are relevant whenever $P(k)$ is sharply truncated at high k
- ...form promptly as each initial density peak collapses
- ...have density profiles, $\rho(r) \approx 24\,\bar{\rho}\,(r / R)^{-1.5}$, where $\bar{\rho}$ is the mean cosmic DM density and $R = a_c(\delta / \nabla^2\delta)^{1/2}$ is the size of the linear overdensity peak (both measured at t_c, the time of peak collapse)
- ...have, by $1.2\ t_c$, mass, $M_{cusp} \sim 7\,R^3\,\bar{\rho}$, and size, $r_{cusp} \sim 0.1\ R$
- ...have an inner core radius set by phase-space constraints, thus dependent on the nature and cosmological origin of the DM
- ...suffer late-time tidal disruption only in star-dominated regions of galaxies (through encounters with individual stars)
- ...dominate the dark matter annihilation signal in all but the very densest regions of galaxies

Prompt cusp and subsequent halo growth for a peak with $z_{coll} = 87$

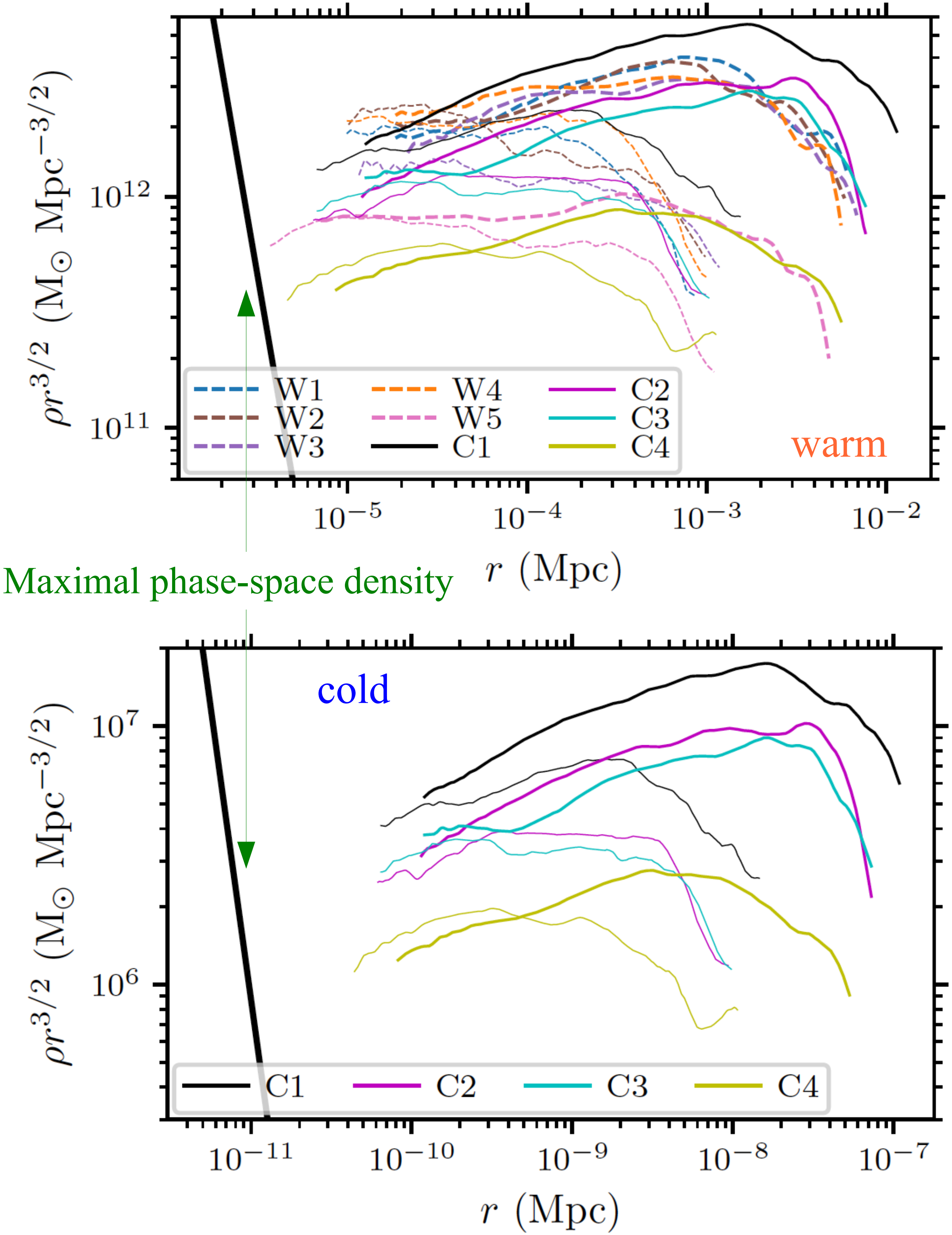


Delos+White 2023

Delos+White 2022



Delos+White 2022

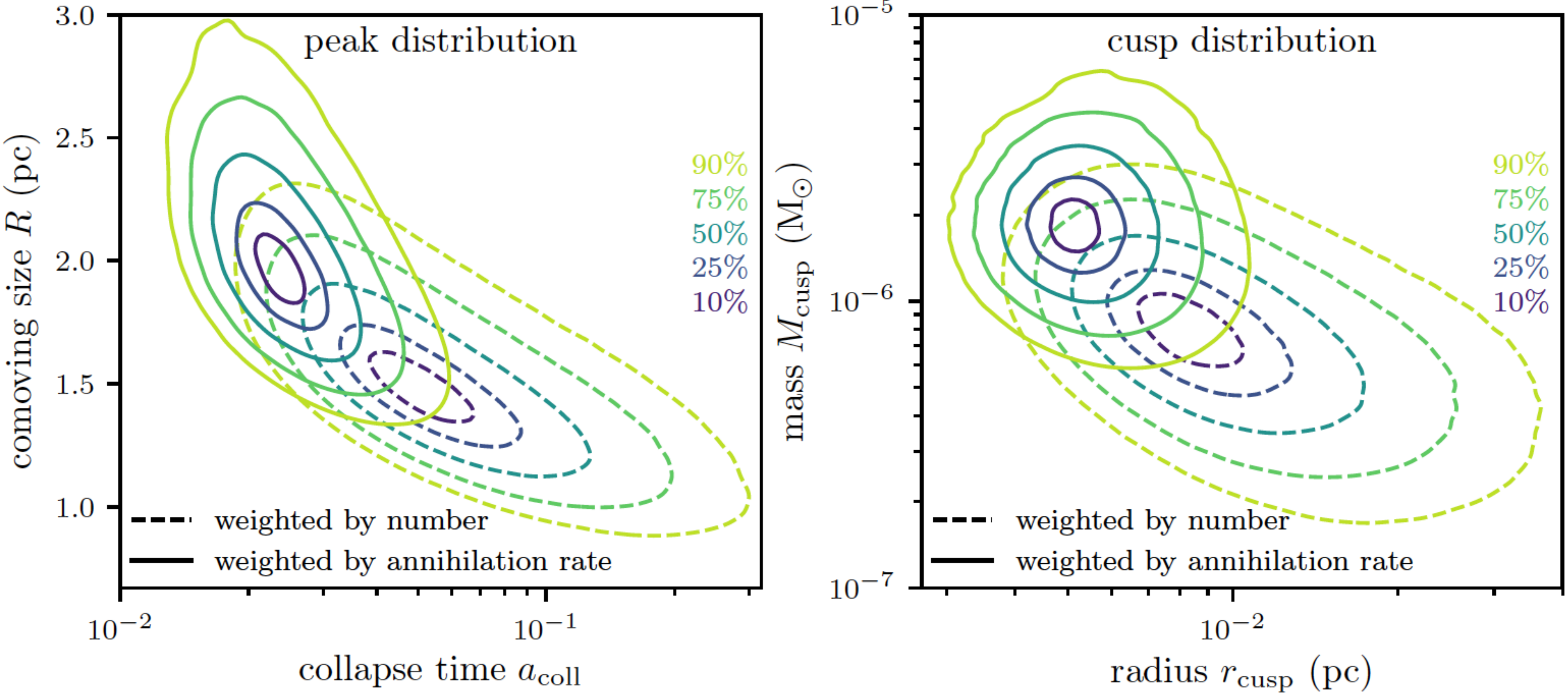


The core radii of prompt cusps are set by the phase-space density at thermal decoupling.

They are factors of 2 – 5 or 5 – 20 smaller than the simulation resolution limit in the warm (3.5 keV WDM) and cold (100 GeV CDM) cases, respectively.

BBKS-predicted peak and cusp distributions in ΛCDM

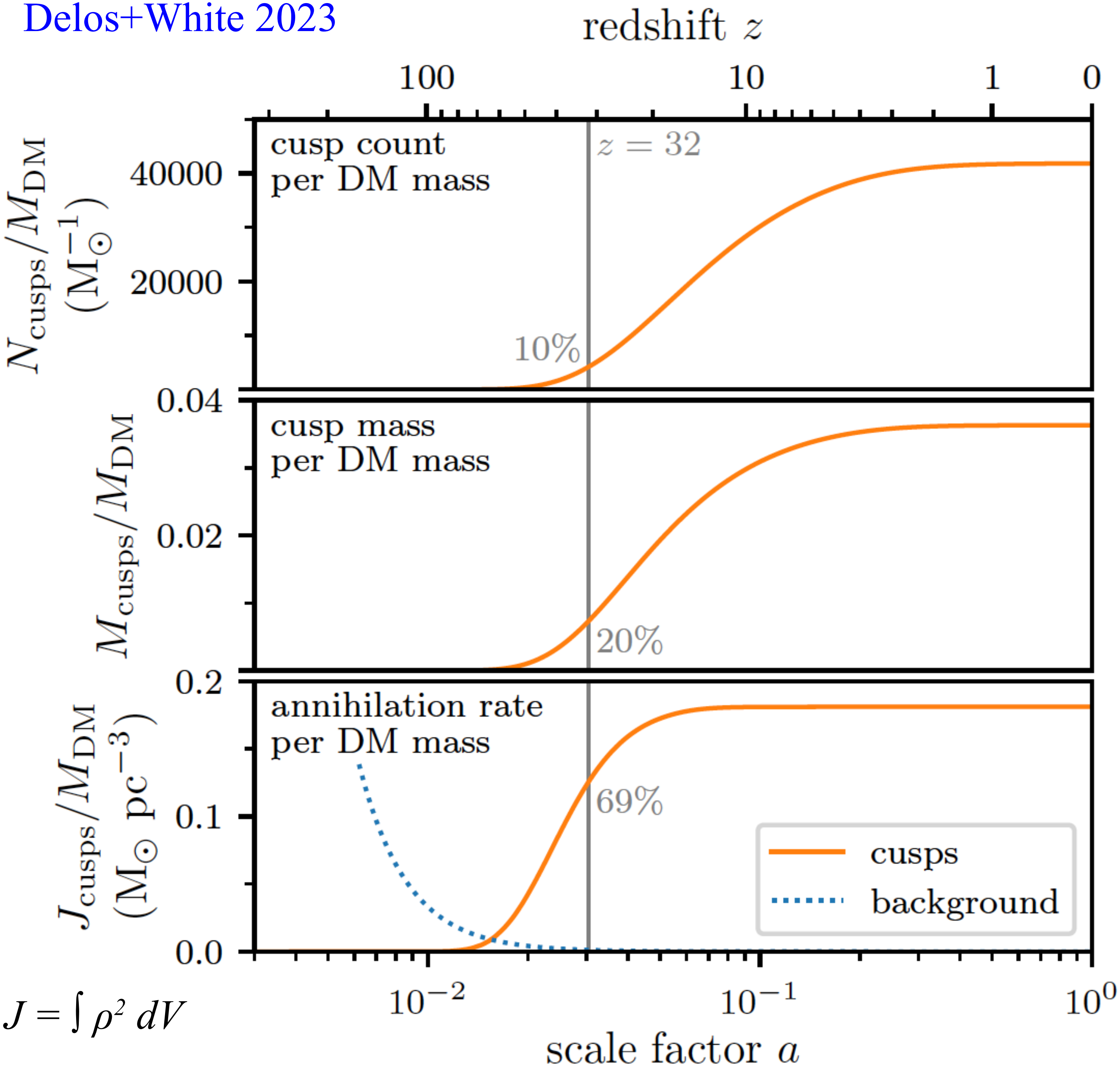
Delos+White 2023



$m_\chi = 100$ GeV, $T_{kd} = 30$ GeV

$J = \int \rho^2 \, dV$

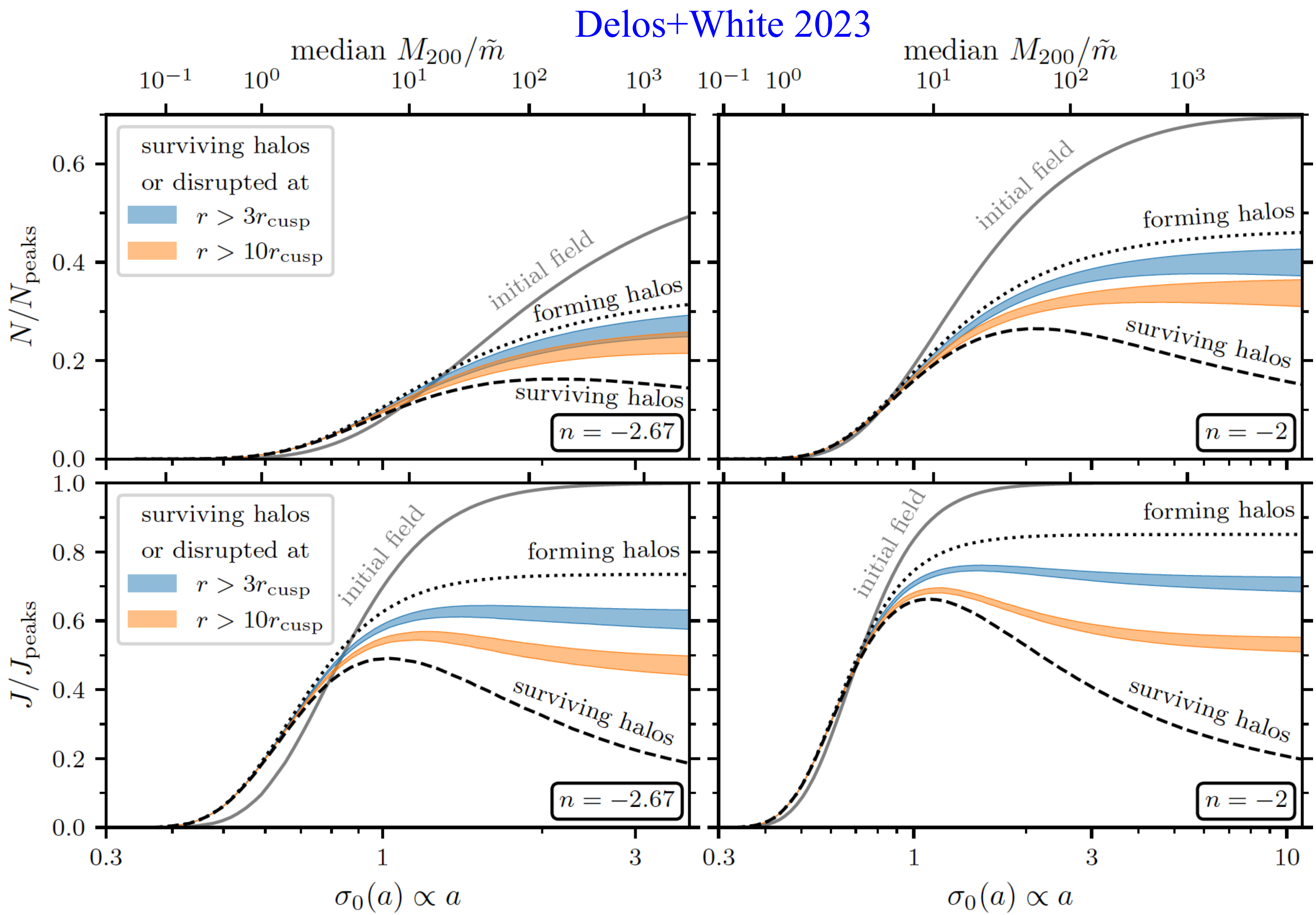
Delos+White 2023



$J = \int \rho^2 \, dV$

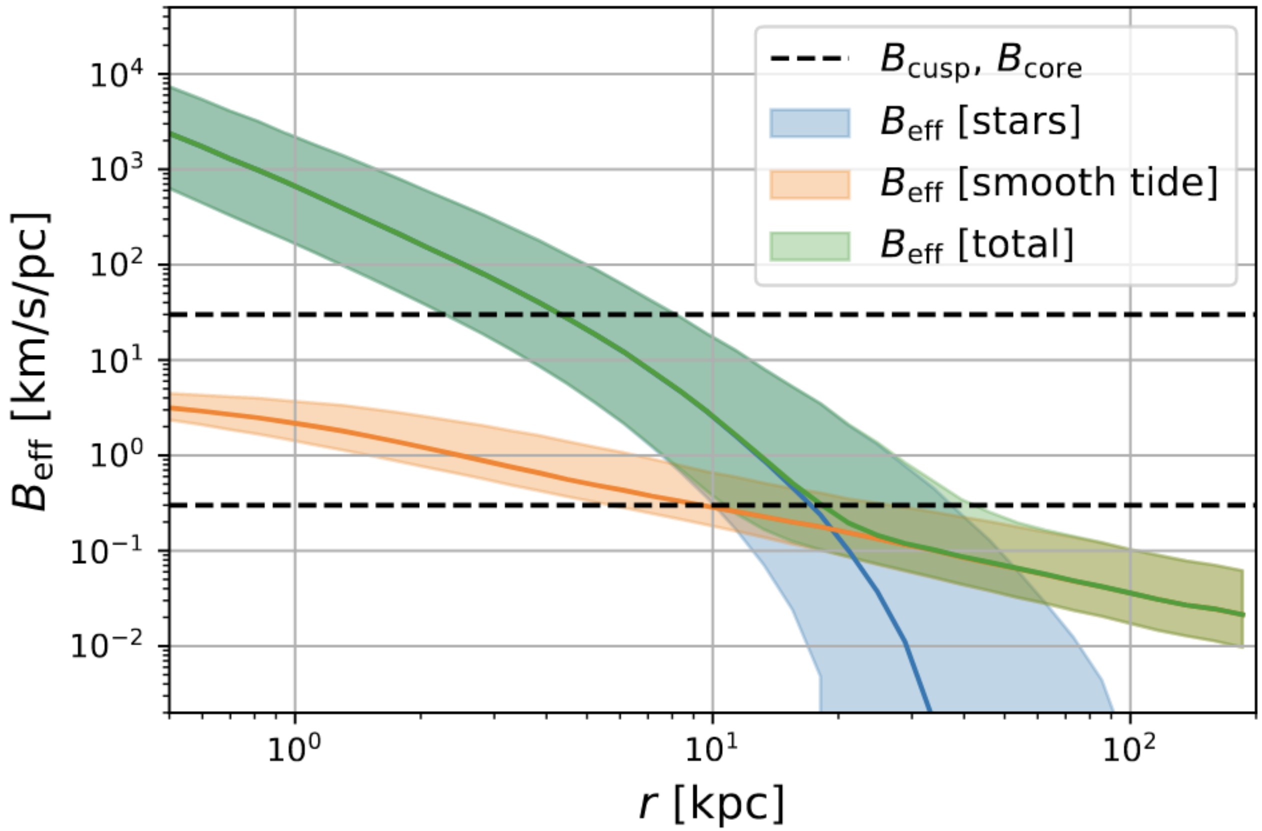
Growth with time of the prompt cusp population and its annihilation signal

About half the linearly predicted cusps survive the initial phase of hierarchical growth



Tidal effects on prompt cusps in the Milky Way

Stücker et al 2023



Cusp cores disrupted

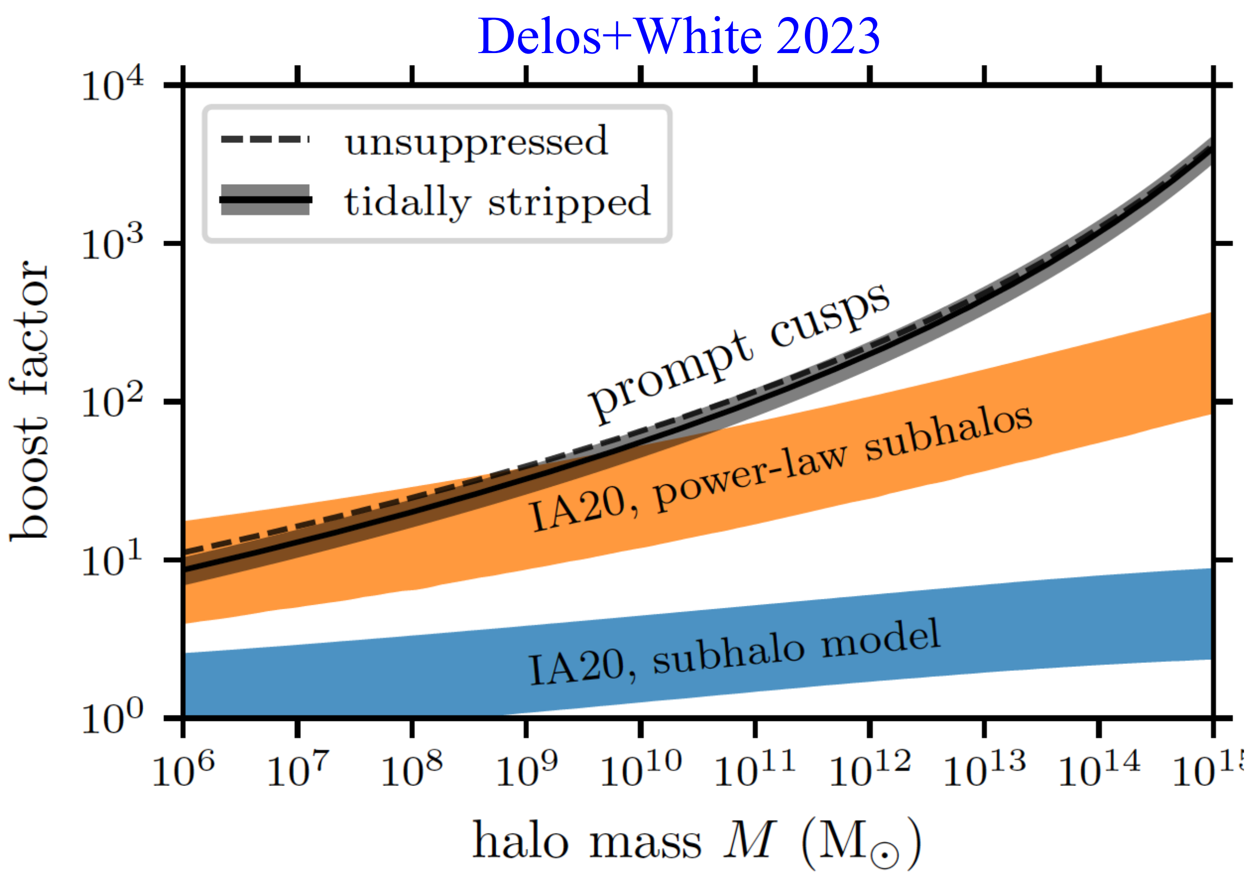
Cusp outskirts disrupted

A impulsive stellar encounter is characterised by strength, $B = 2GM_*/Vb^2$

For a given cusp, $d\bar{N}/dB = 2\pi G B^{-2} \int \rho_*(\mathbf{x}(t))\, dt$; $B_{eff} = (\Sigma\, B_i^{1.2})^{1/1.2}$

Mean field truncation is approximated by $B_{mean} = (42.2\, |r^{-2}\, \partial_r\, r^2\, \partial_r\, \Phi|_{peri})^{1/2}$

Annihilation radiation boosts in field halos...

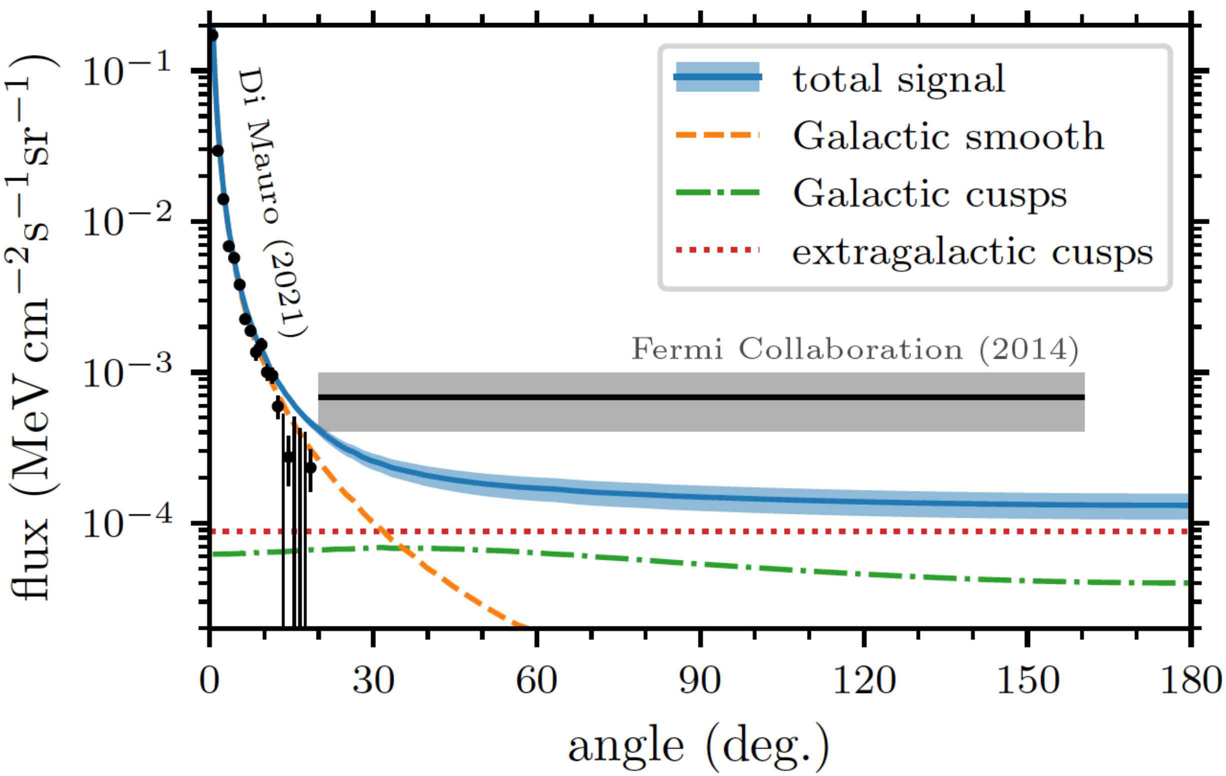


Prompt cusps boost the emission from distant halos by factors ~20 (small dwarfs) ~200 (MW-like galaxies) and ~2000 (rich clusters)

These are much larger than recent estimates of the boost due to substructure made by extrapolating results of high-resolution halo simulations .

….and in the Milky Way

Delos+White 2023



The profile due to cusps is much shallower than that due to the smoothly distributed dark matter

Cusp emission dominates at >20° from the Galactic Centre.

The mean surface brightness coming from the MW's halo is comparable to that from the halos of external galaxies

Prompt cusps do not affect the Fermi Galactic Centre Excess, but if this is due to annihilation then they contribute much of the 1 – 10 GeV background

Prompt cusps

- The formation mechanism and structure of prompt cusps differ from those of "normal" halos
- For a $m = 100$ GeV, $T_{kd} = 30$ GeV WIMP, prompt cusps have Earth mass and are a million times more abundant than Earth-mass planets in the Milky Way, accounting for a percent or two of all dark matter
- In the Milky Way they are significantly disrupted both by tides and (particularly) by stellar encounters within ~20 kpc
- They have no observable dynamical or gravitational lensing effects
- They dominate the dark matter annihilation signal from the outer halo of the Milky Way and from all extragalactic objects, leading to a local luminosity density that is proportional to $\bar{\rho}_{dm}$ rather than $\bar{\rho}_{dm}^2$