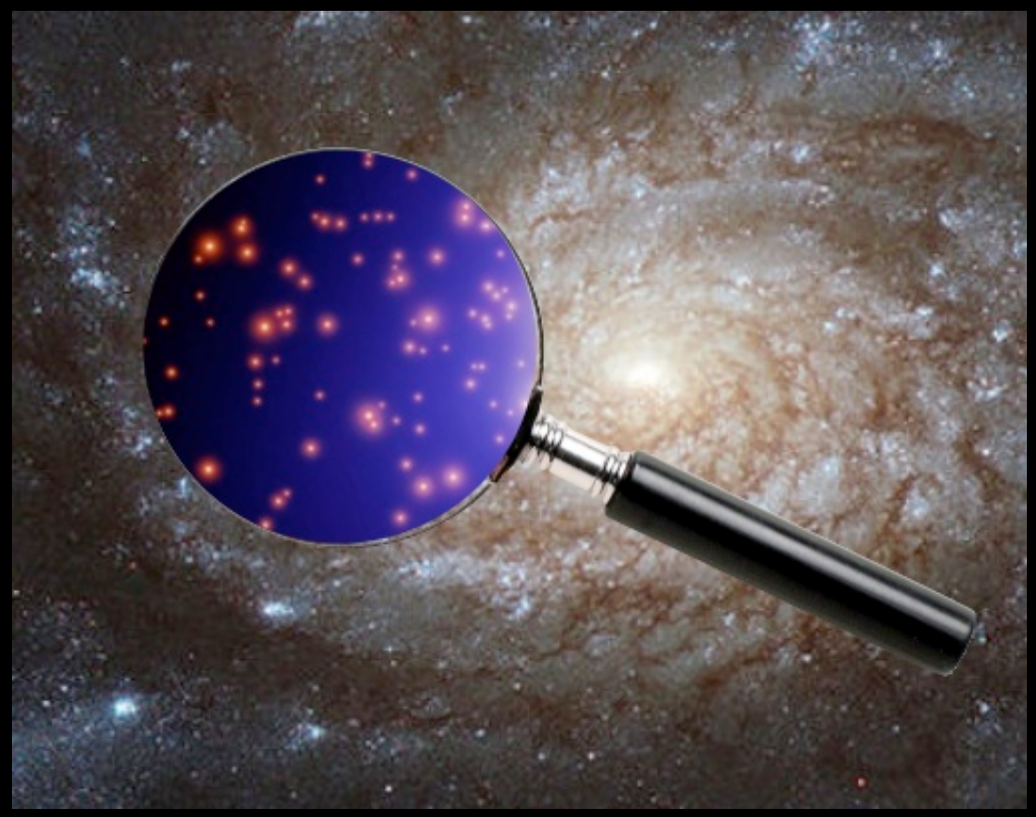
Probing the Early Universe with Dark Matter



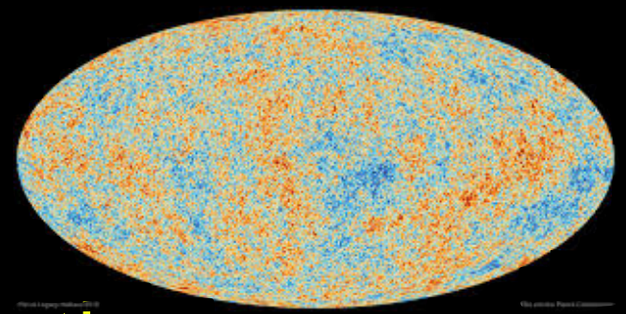
Adrienne Erickcek
UNC Chapel Hill

LSST Dark Matter Workshop
KICP, Chicago
August 6, 2019

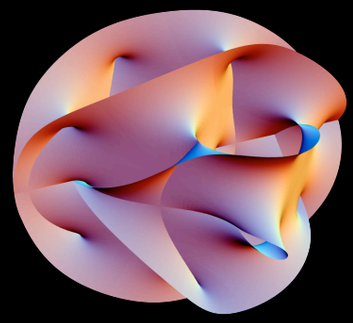
What happened before BBN?

The (mostly) successful predictions of the primordial abundances of light elements tell us that the Universe was radiation dominated during BBN.

But we have good reasons to think that the Universe was not radiation dominated before BBN.



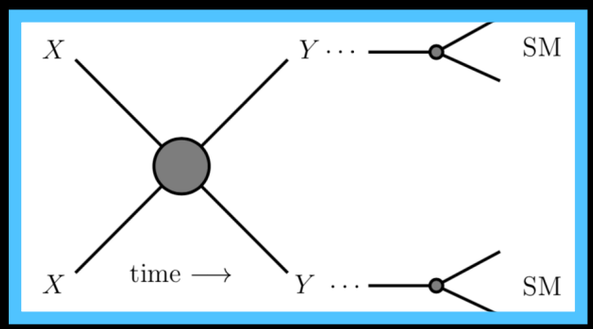
- Primordial density fluctuations point to inflation.
- Other scalar fields or massive particles may dominate the Universe after the inflaton decays.



- The string moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.

Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008
Summary: Kane, Sinha, Watson 1502.07746

- Hidden-sector dark matter: massive gauge bosons dominate the Universe *Zhang 2015; Berlin, Hooper, Krnjaic 2016; Dror, Kuflik, Melcher, Watson 2018*

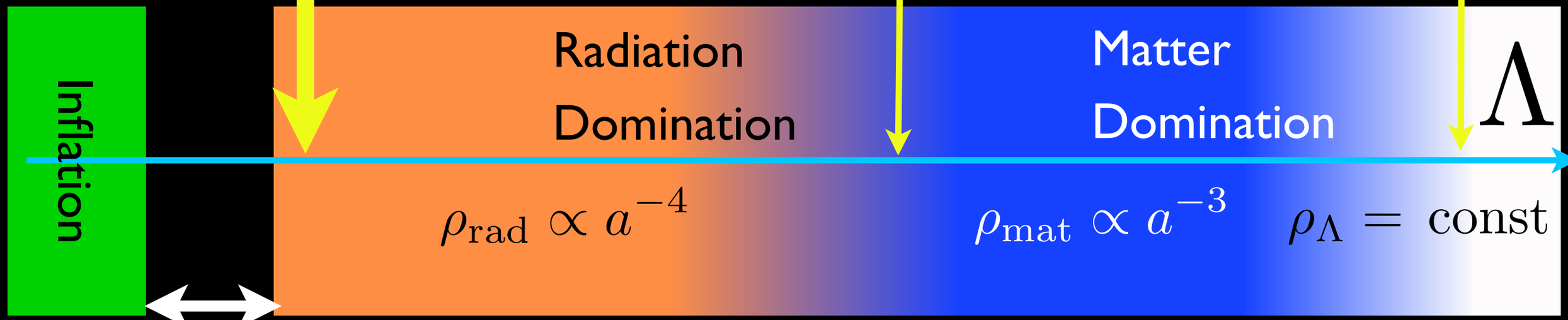


Cosmic Timeline

Big Bang Nucleosynthesis $0.07\,\mathrm{MeV} \lesssim T \lesssim 3\,\mathrm{MeV}$ $0.08\,\mathrm{sec} \lesssim t \lesssim 4\,\mathrm{min}$

CMB $T = 0.25\,\mathrm{eV}$ $t = 380,000\,\mathrm{yr}$

Now $T = 2.3 \times 10^{-4}\,\mathrm{eV}$ $t = 13.8\,\mathrm{Gyr}$



The gap: $10^{16}\,\mathrm{GeV} \gtrsim T \gtrsim 0.003\,\mathrm{GeV}$

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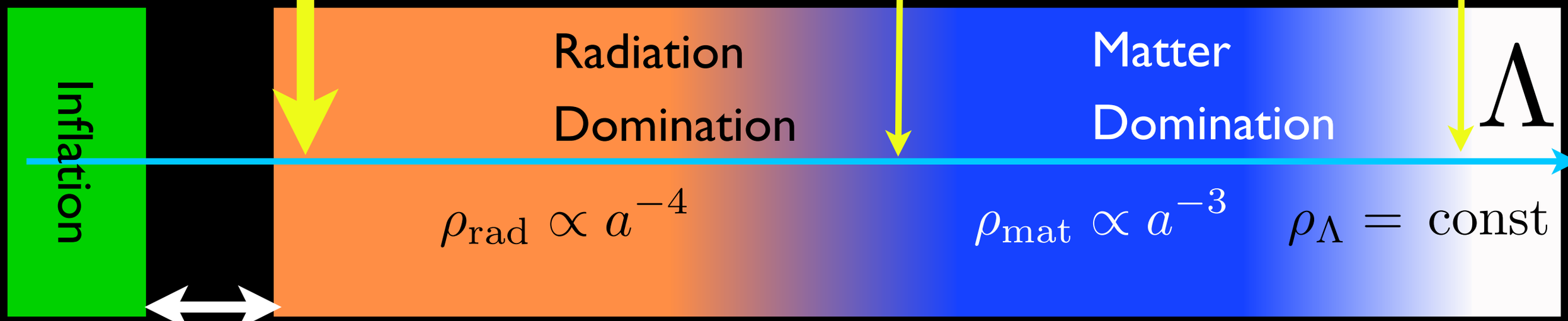
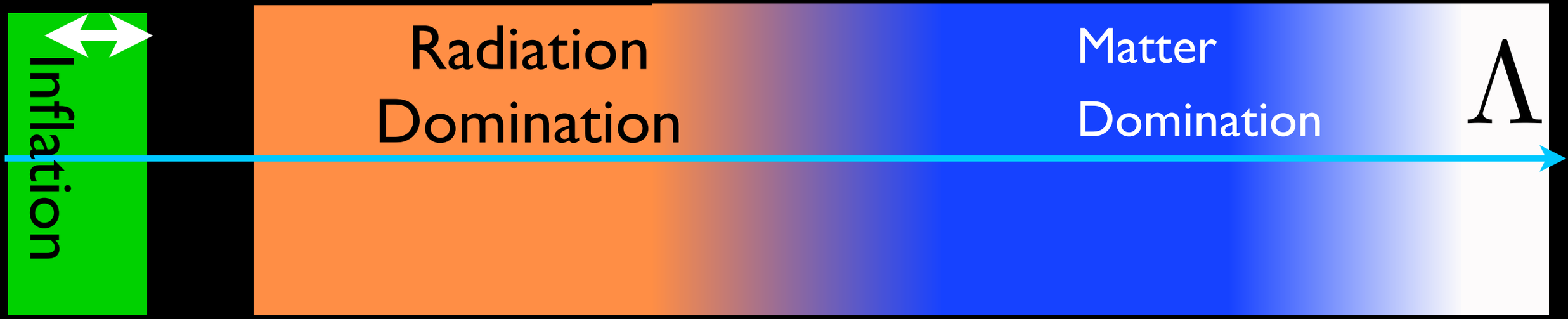


The gap: $10^{16}\,\mathrm{GeV} \gtrsim T \gtrsim 0.003\,\mathrm{GeV}$

Why should the DM community care about this gap?

- sets the abundance of dark matter: there are thermal relics with $m_\chi > 100\,\mathrm{TeV}$!
- sets the size and abundance of the smallest dark matter halos
- changes dark matter annihilation morphology, mimicking decaying dark matter
- dark matter is the best probe we have of the later stages of inflation and the gap

Part I
Probing Inflation with Minihalos



Li, ALE, Law PRD 86, 048519 (1202.1284)

***M. Sten Delos**, ALE, Avery Bailey, Marcelo Alvarez*

PRD Rapid Communications 97, 041303 (1712.05421)

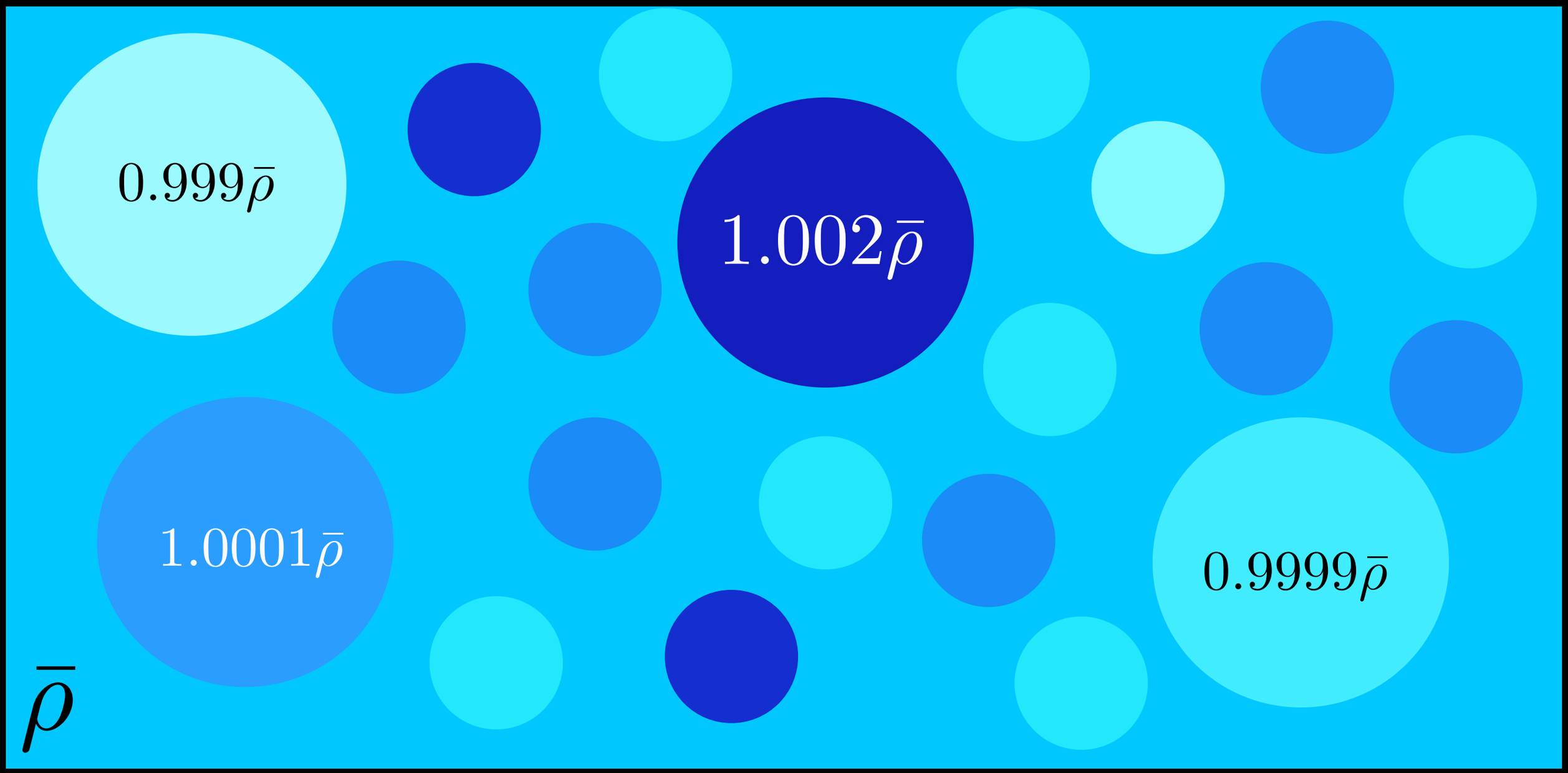
PRD 98, 063527 (1806.07389)

***M. Sten Delos**, Margie Bruff, ALE*

PRD 100, 023523 (1905.05766)

UCMH Formation

If a region has an initial density $\rho > 1.001\bar{\rho}$, then all the dark matter in that region collapses at early times ($z \gtrsim 1000$) and forms an Ultra-Compact Minihalo. *Ricotti & Gould 2009*



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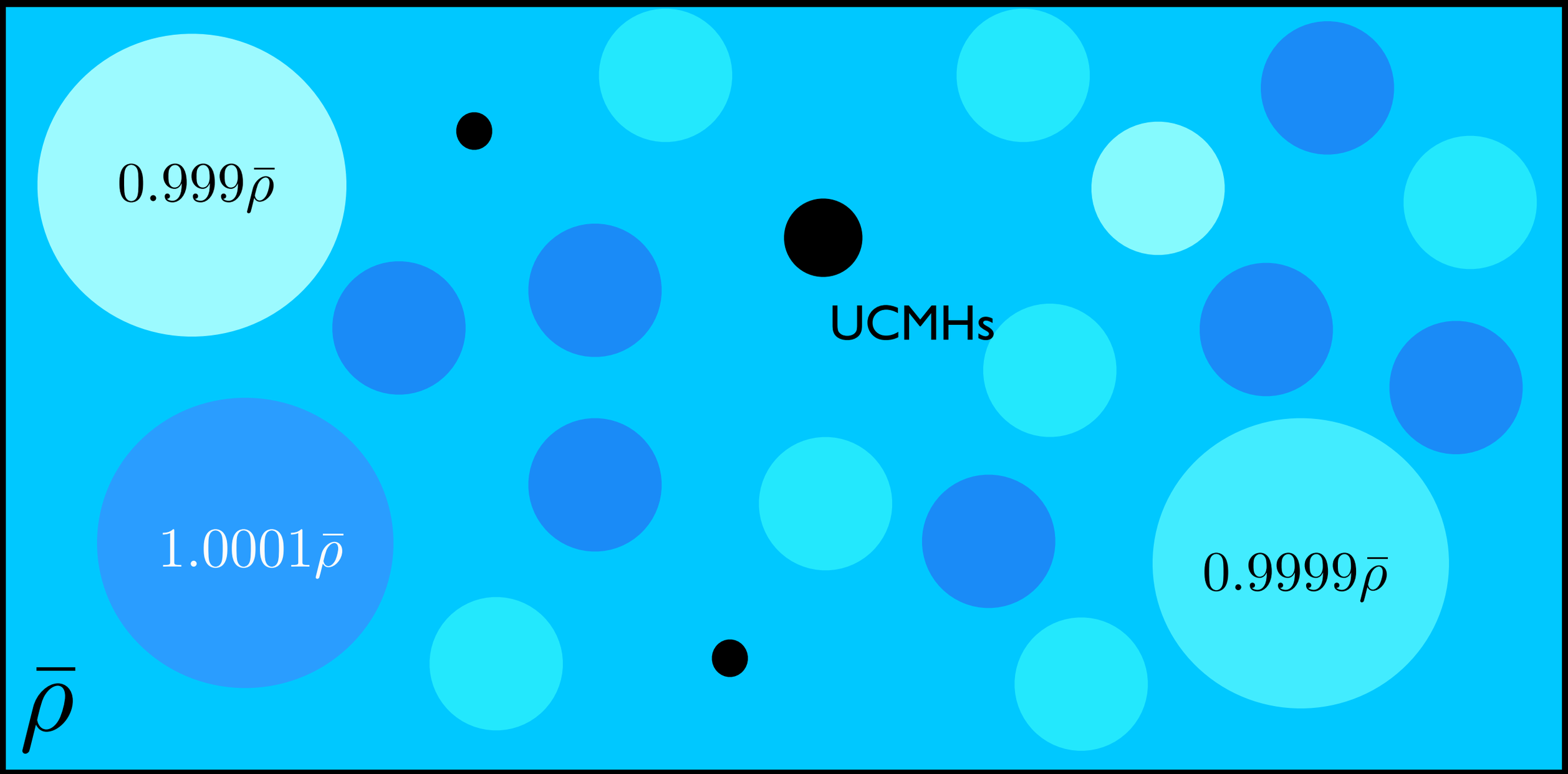


Astrometric Microlensing by UCMHs

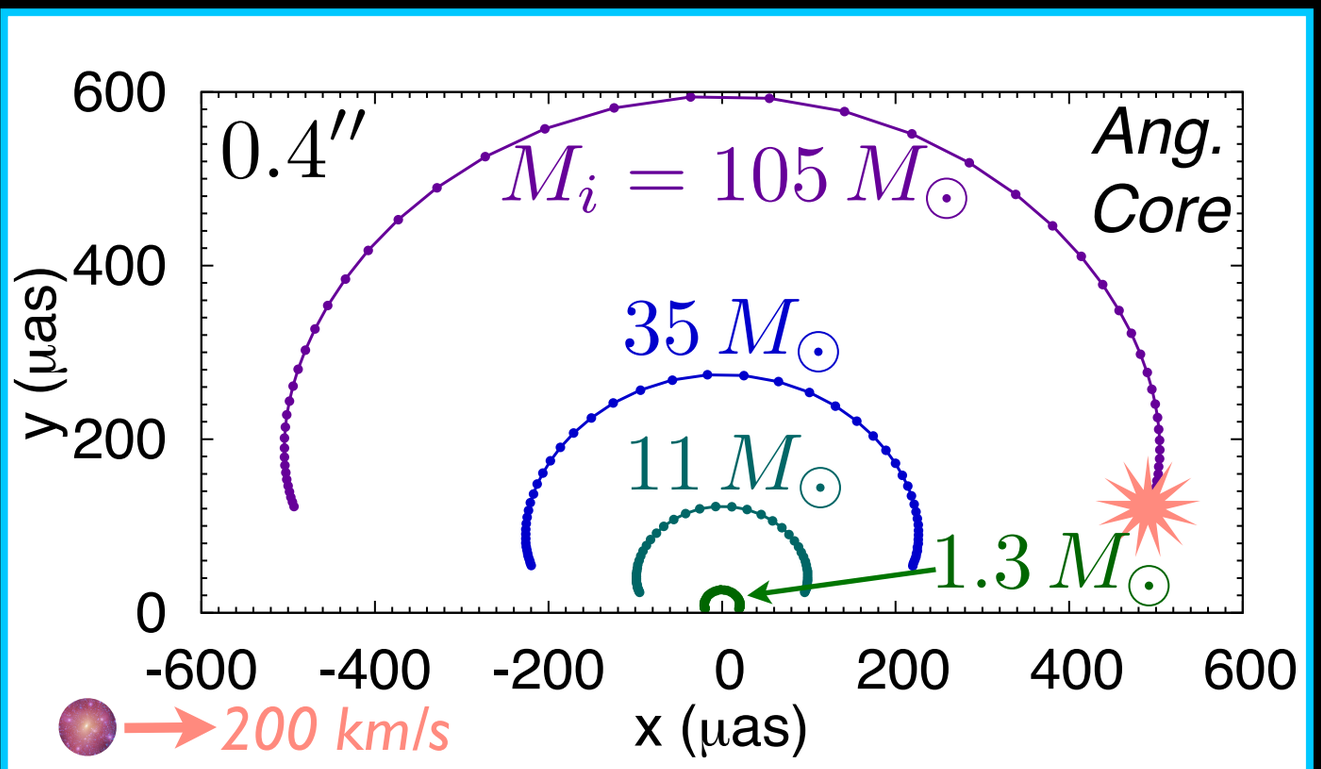
As UCMH passes in front of a star, the star moves!

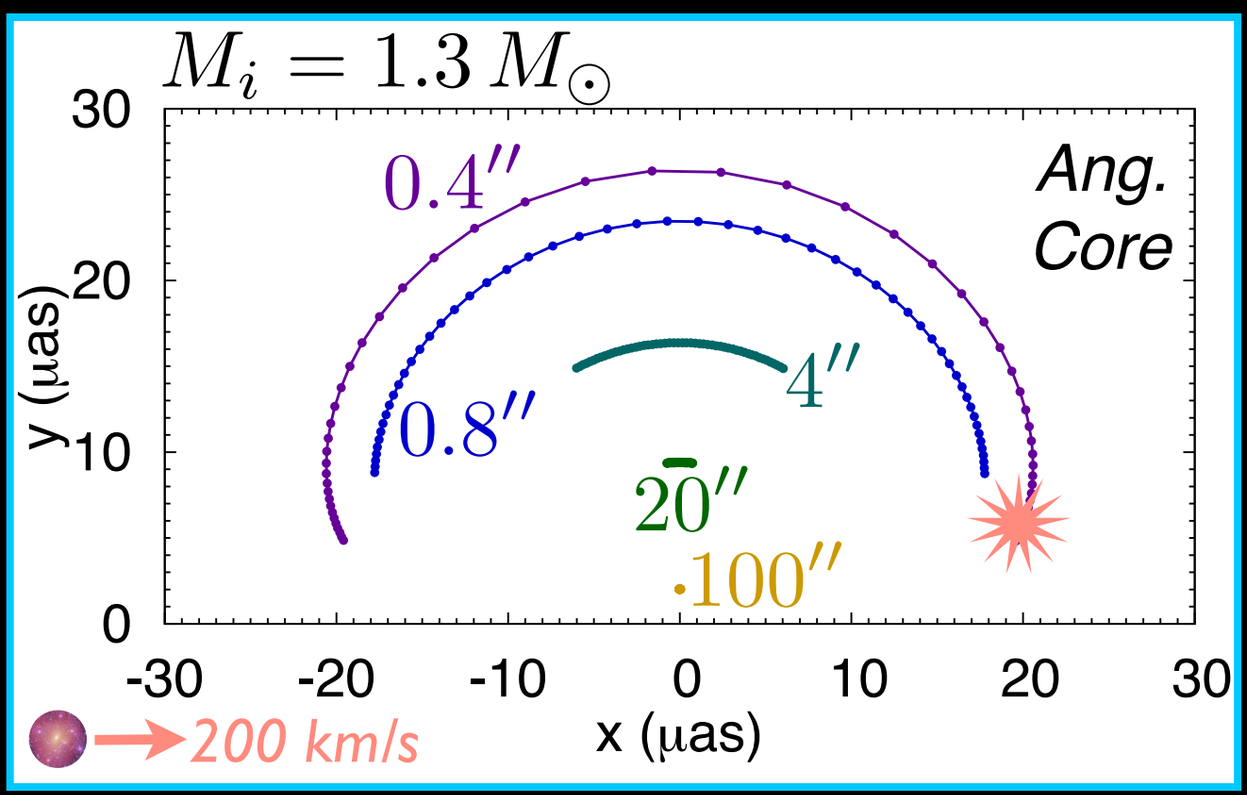
Li, ALE, Law 2012

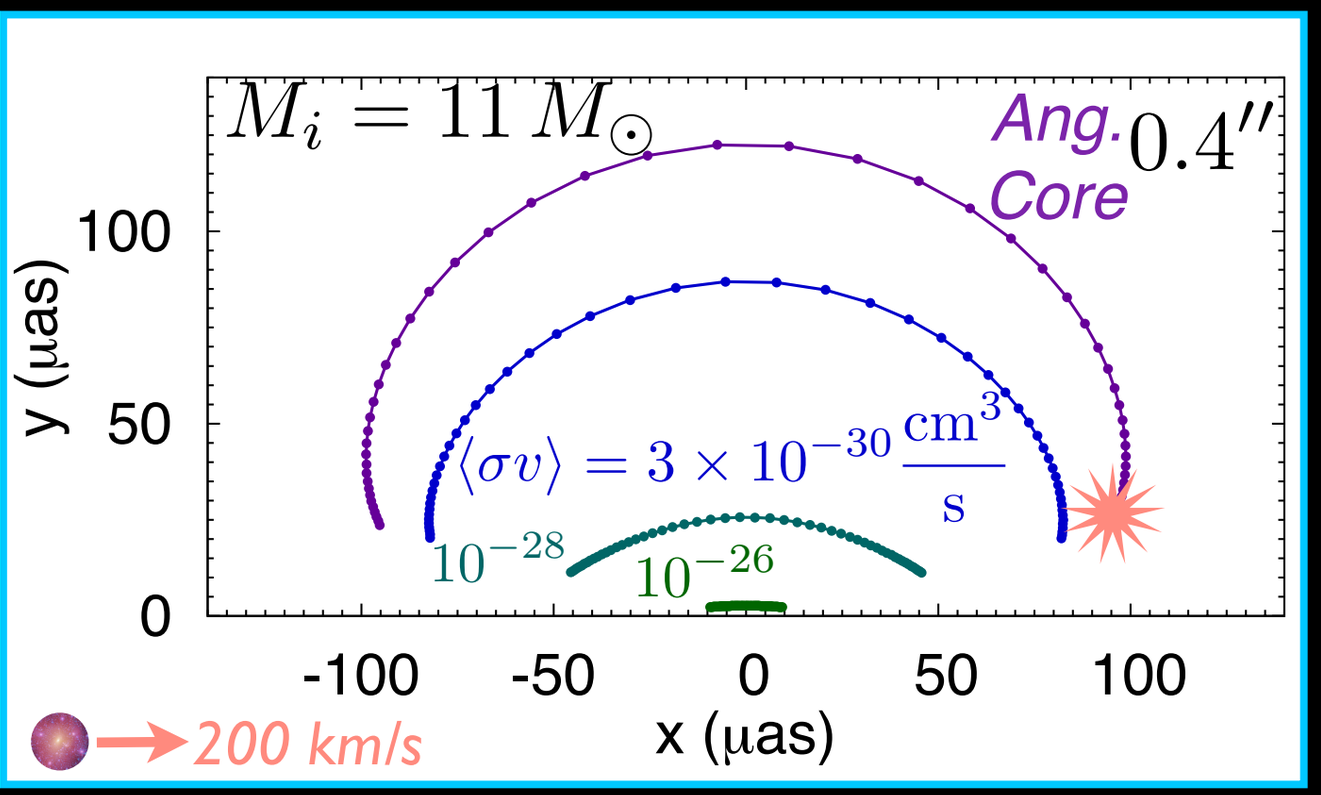
Trajectory depends on

- initial microhalo mass
- impact parameter
- core radius

4 yrs, monthly obs;
Lens distance: 50 pc;
Source Distance: 2 kpc



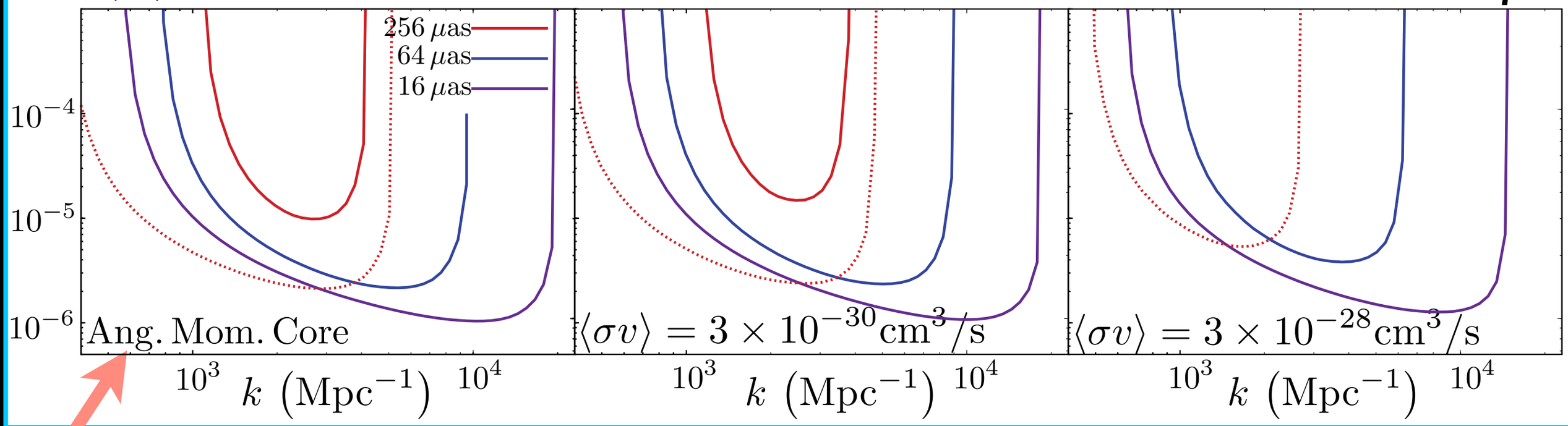




Probing the Primordial Perturbations

An upper bound on the UCMH number density leads to an upper bound on the primordial power spectrum.

If Gaia doesn't detect microlensing by UCMHs,



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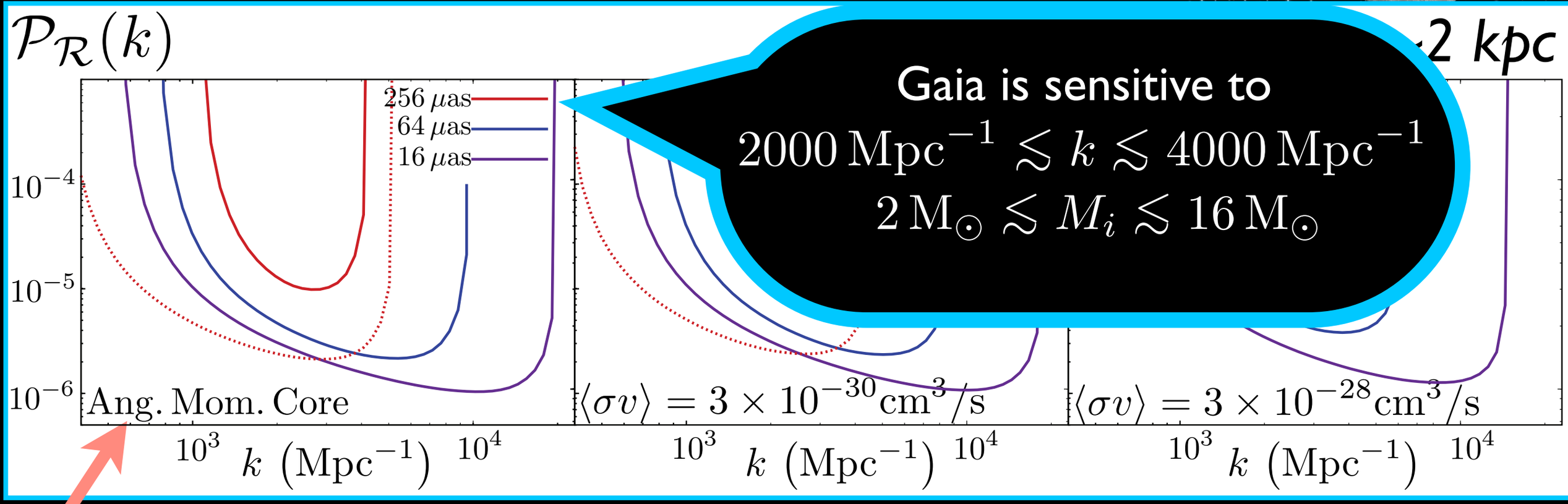

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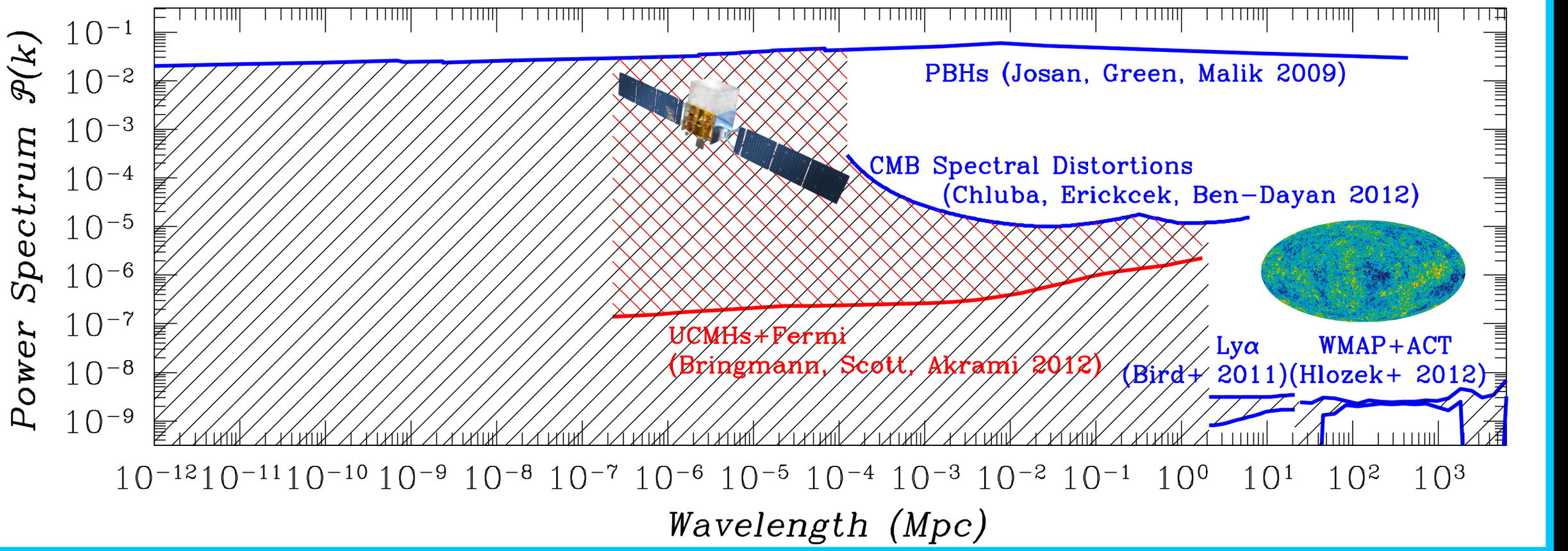
UCMHs Probe Power Spectrum

If dark matter is a thermal relic, the fact that Fermi-LAT has not found any UCMHs gives a powerful bound on *P(k)*.

Josan & Green 2010; Bringmann, Scott, Akrami 2012



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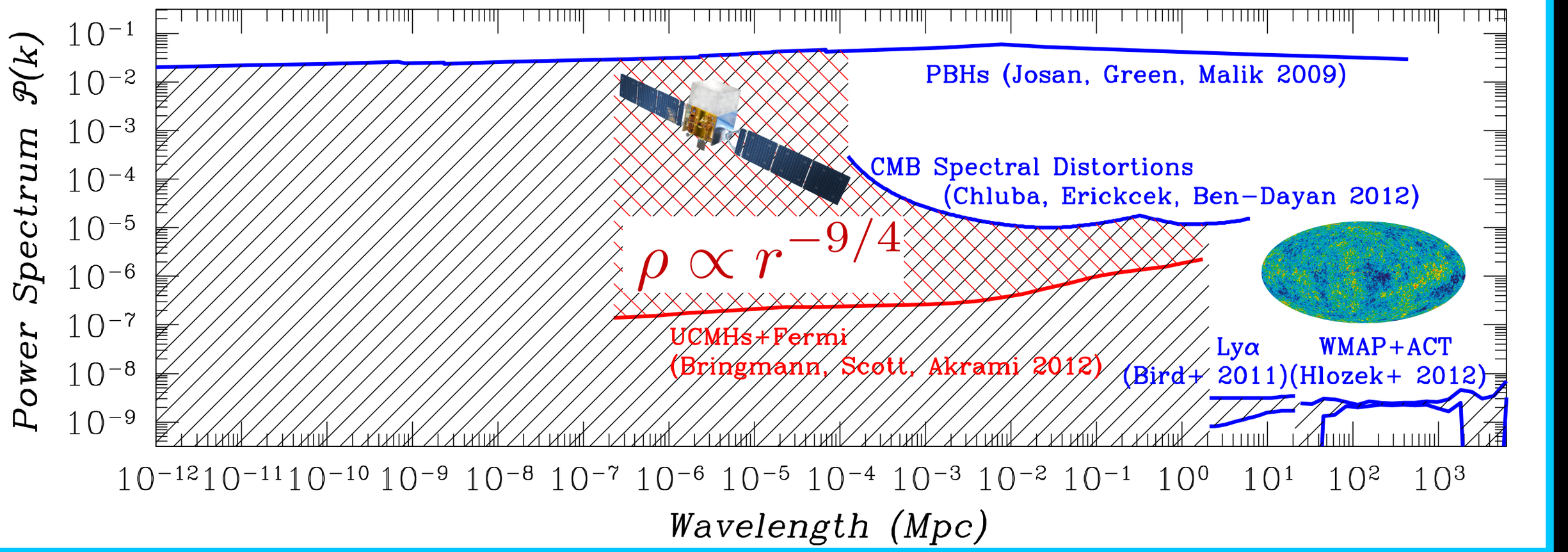

These bounds (and our Gaia projections) assume that UCMHs have a radial-infall density profile.

Simulations of UCMHs

***M. Sten Delos**, ALE, Bailey, Alvarez*
PRD(R) 2018,1712.05421
See also Gosenca+ 2017

1. Modify GadgetV2 to include smooth radiation component.

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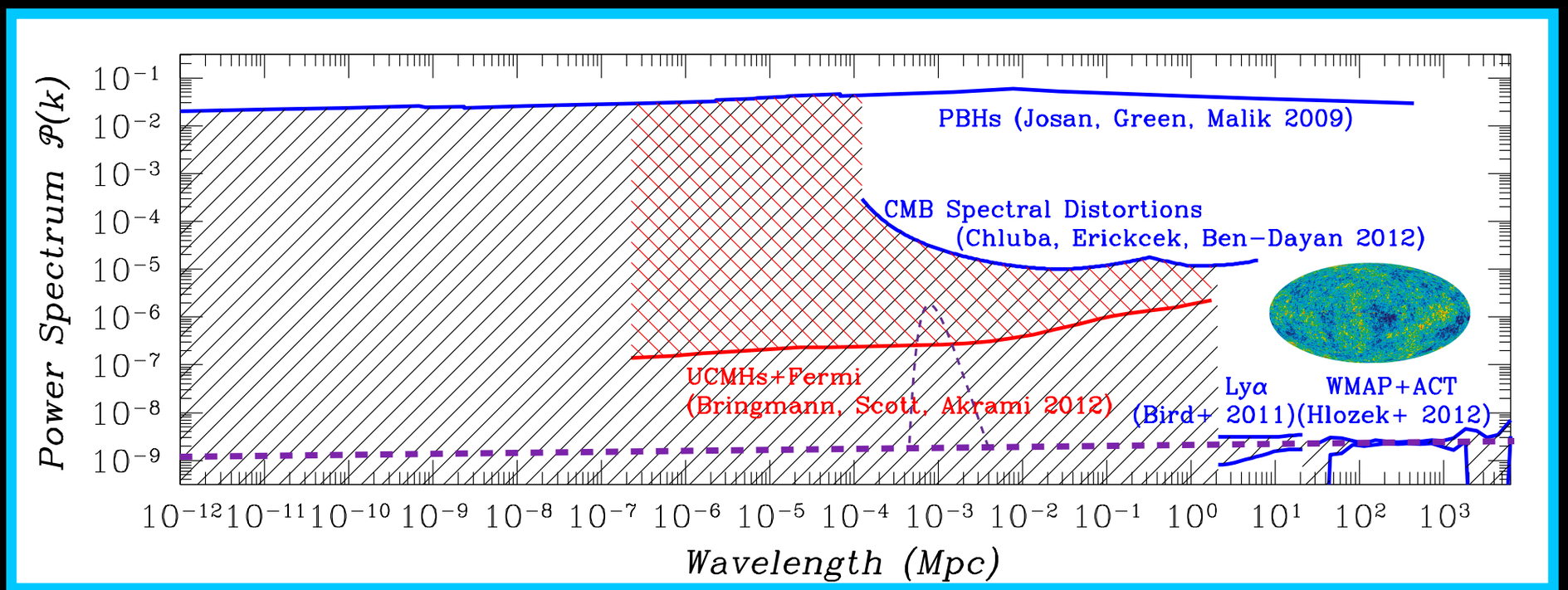

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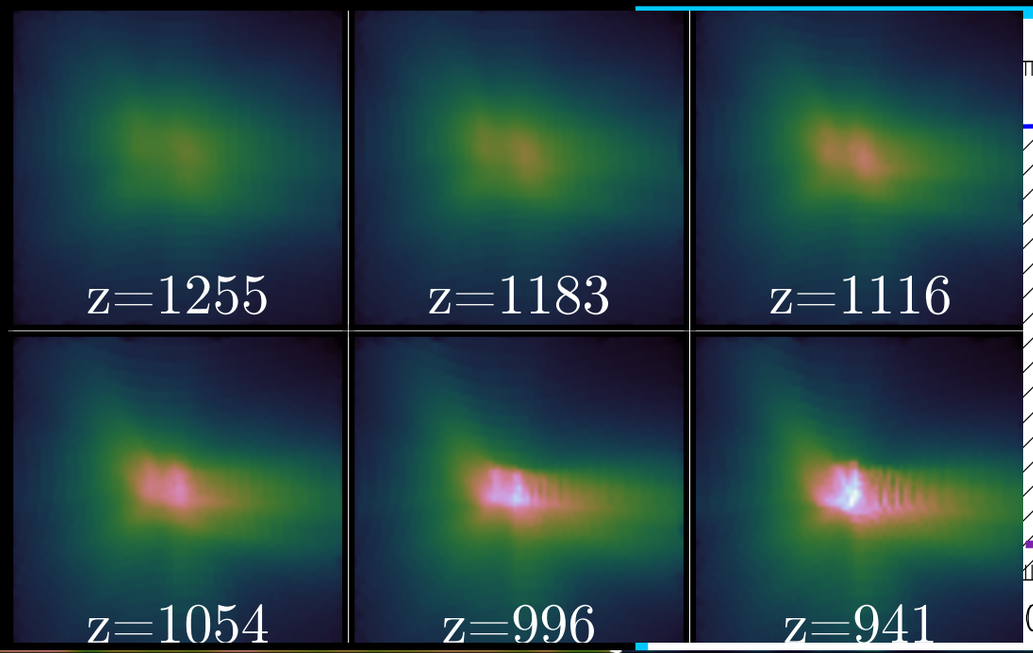
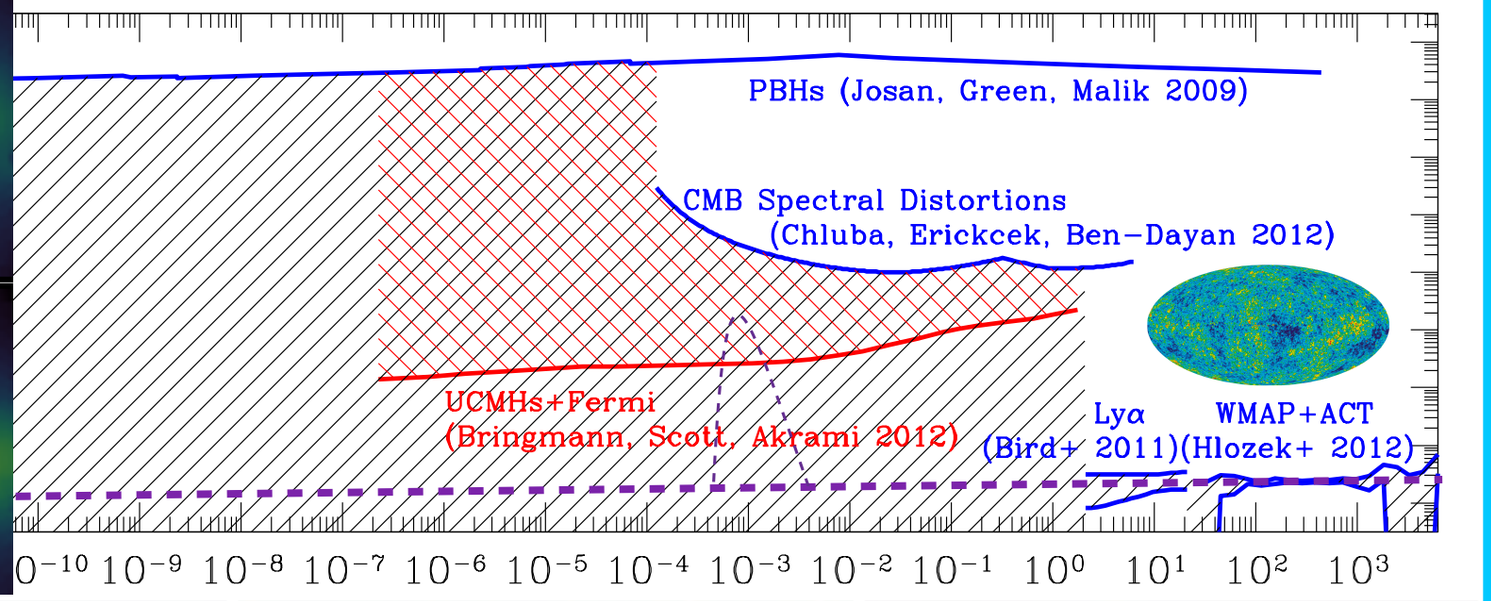
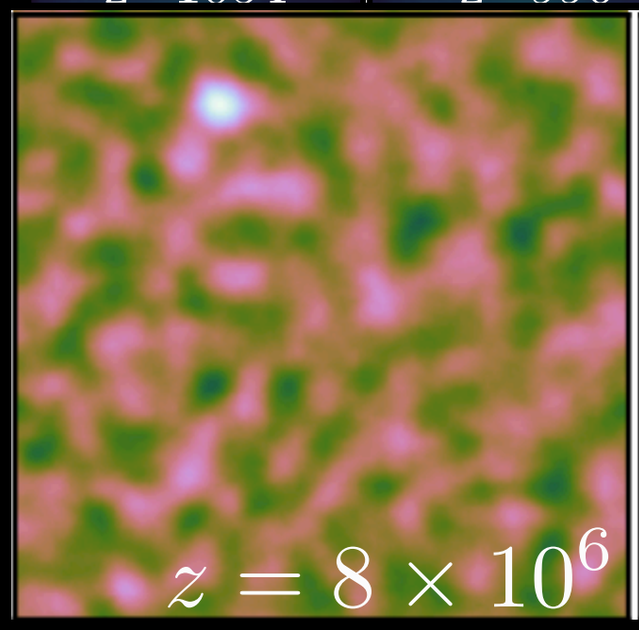
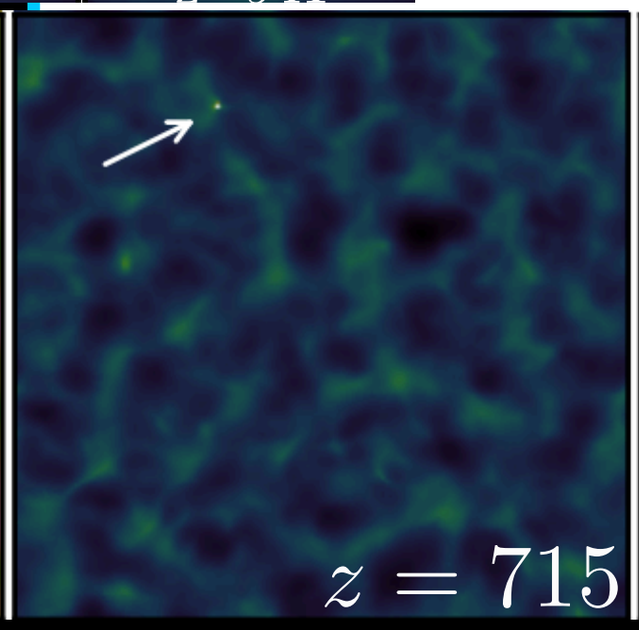
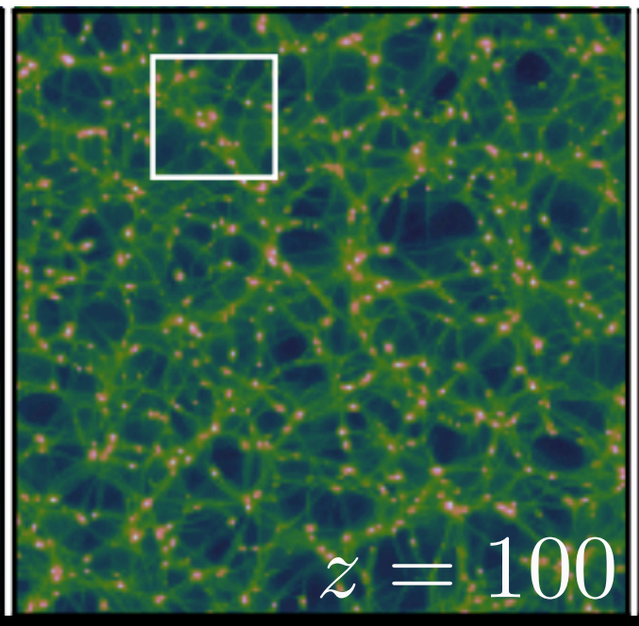
3. Make an UCMH!

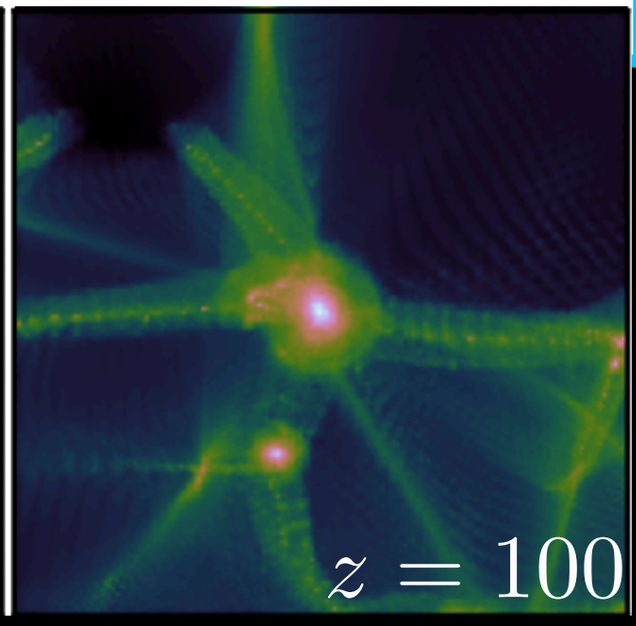




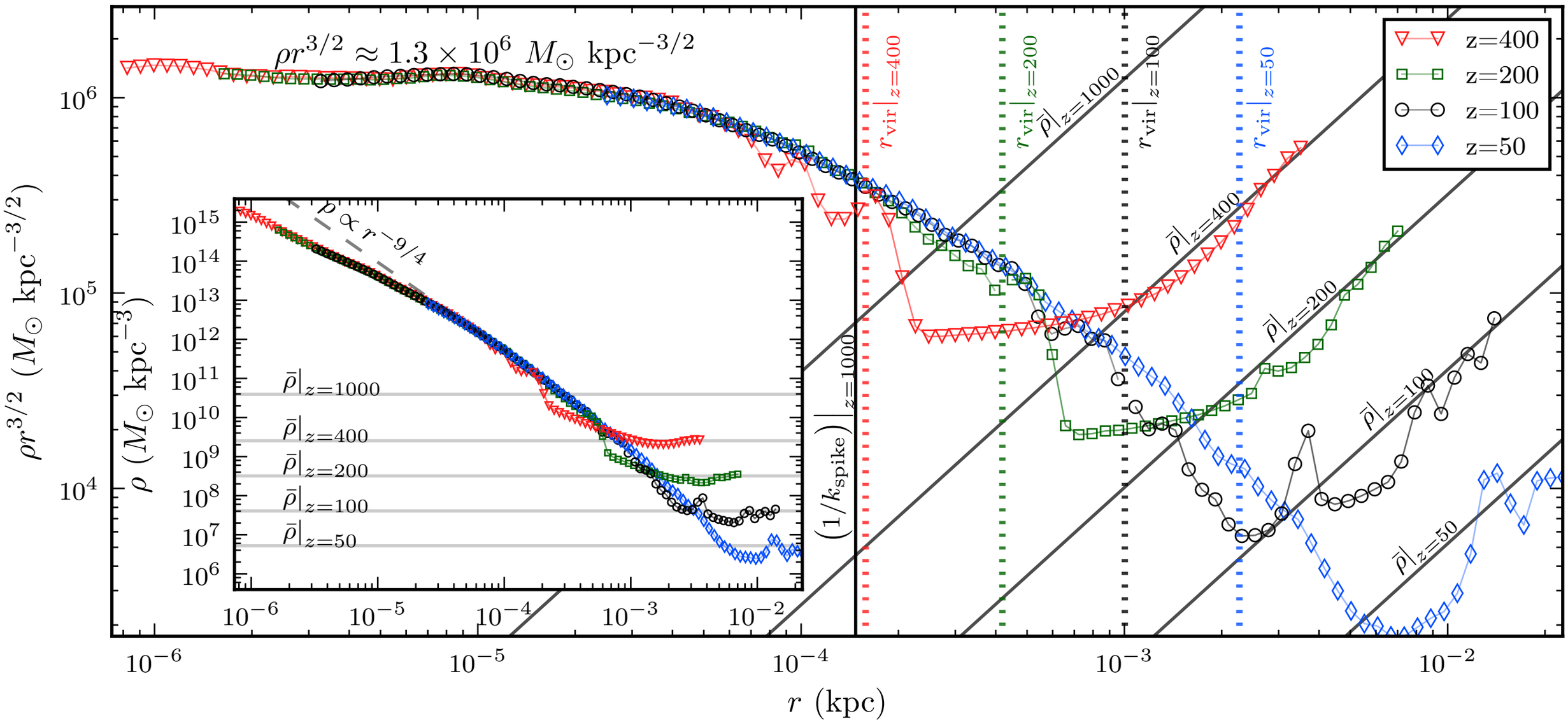








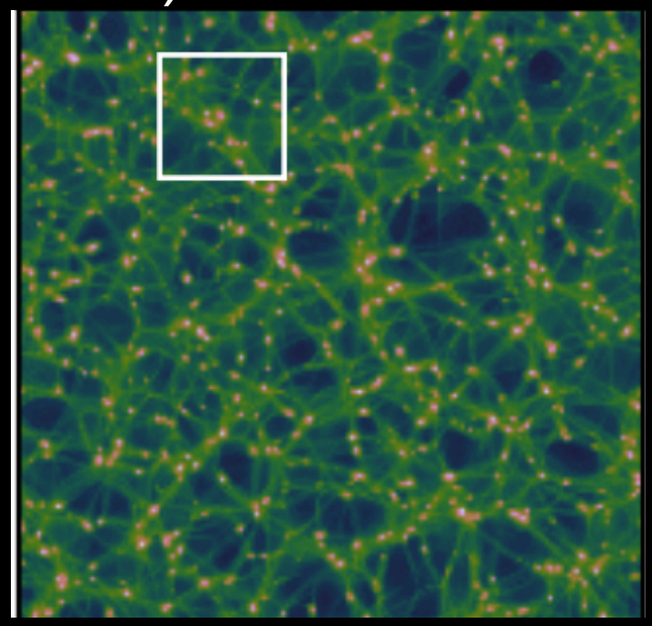
UCMH Density Profiles: Spike



- Nine simulated UCMHs
- All have similar density profiles: $\rho = \dfrac{\rho_s}{(r/r_s)^{1.5}(1+r/r_s)^{1.5}}$
- Stable with redshift, unless there's a merger....

Implications for *P(k)* bounds

- UCMHs that form from spikes in the primordial power spectrum have Moore profiles ($\rho \propto r^{-1.5}$), while plateaus in the primordial power spectrum generate UCMHs with NFW profiles ($\rho \propto r^{-1}$).
- The dark matter annihilation rate within the UCMHs is reduced by a factor of 200, which reduces upper bound on UCMH abundance by a factor of 3000.
- But we have so many more halos to consider...



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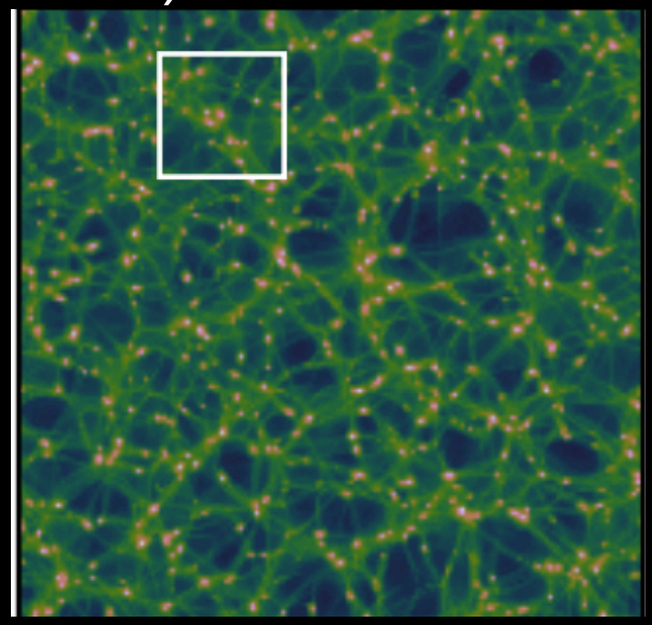

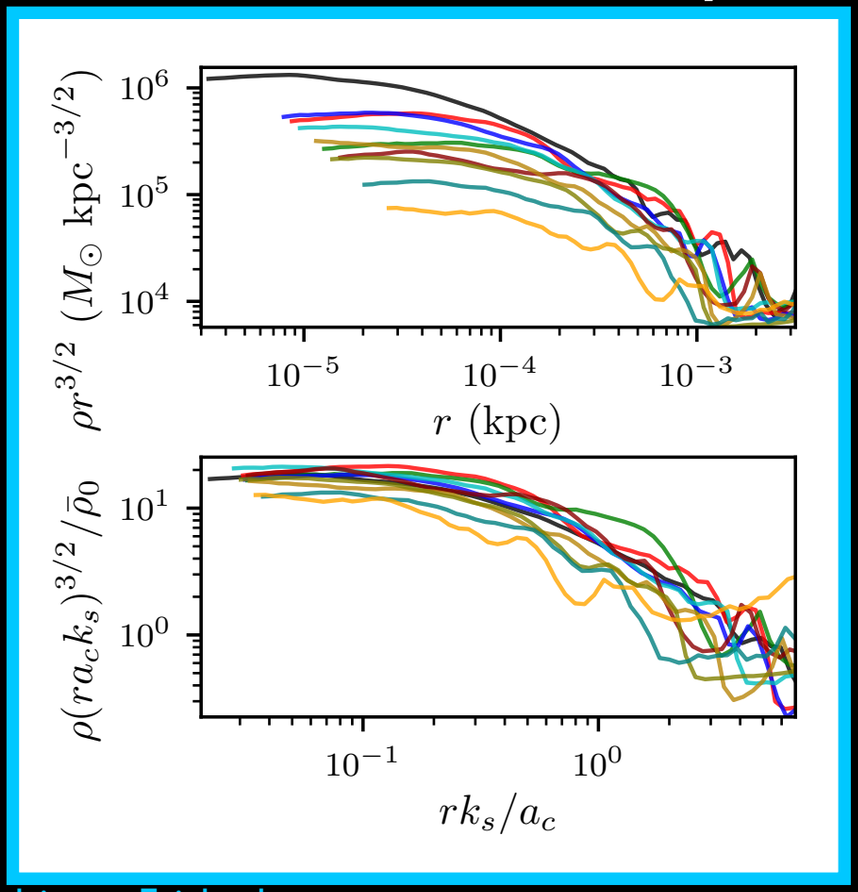

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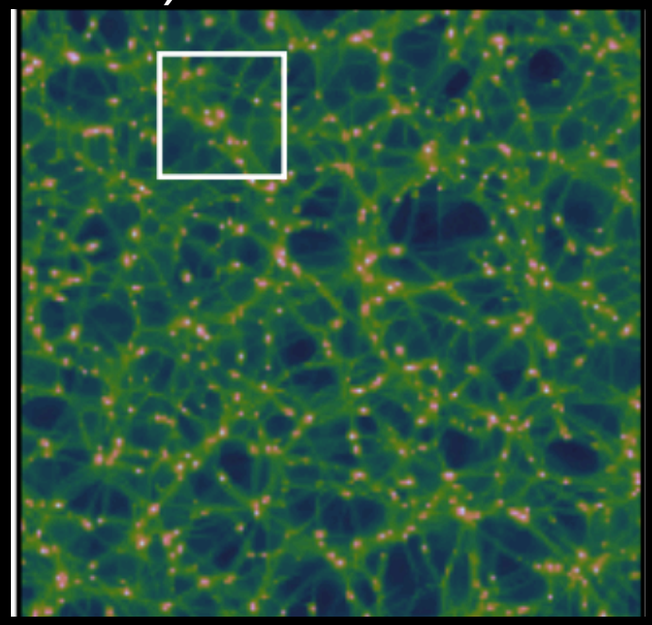
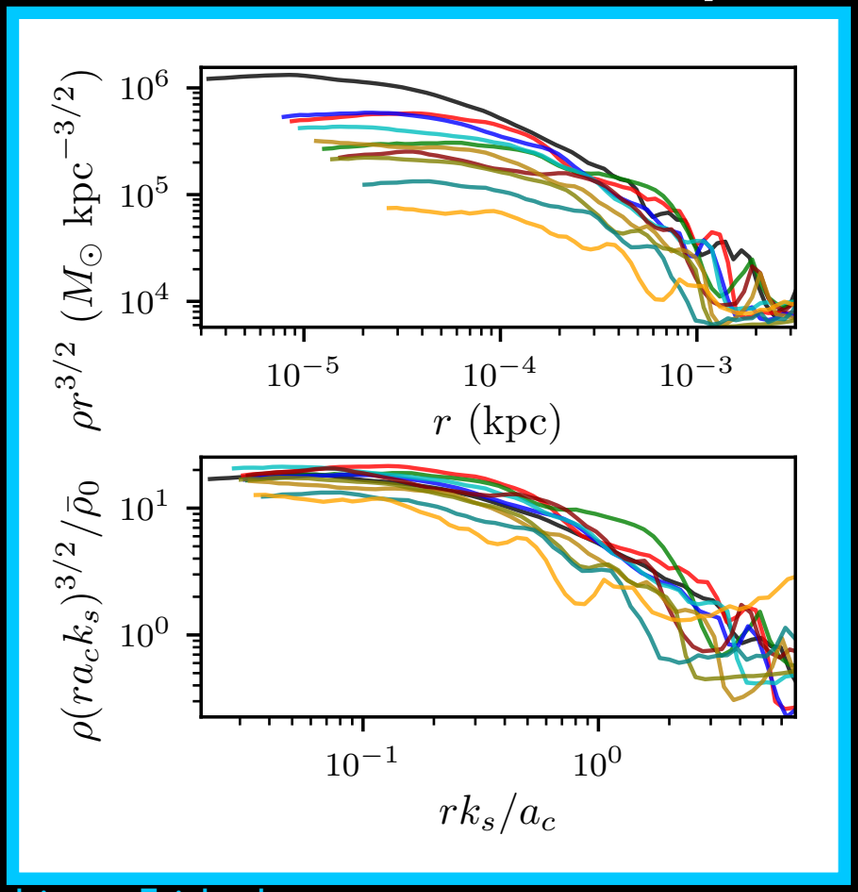




- To use these later-forming halos, we need a model to link halo density to formation time.

$$r_s \propto a_c/k_s \qquad \rho_s \propto \bar{\rho}_0 a_c^{-3}$$

See Delos, Bruff, ALE (2019) for improved model.

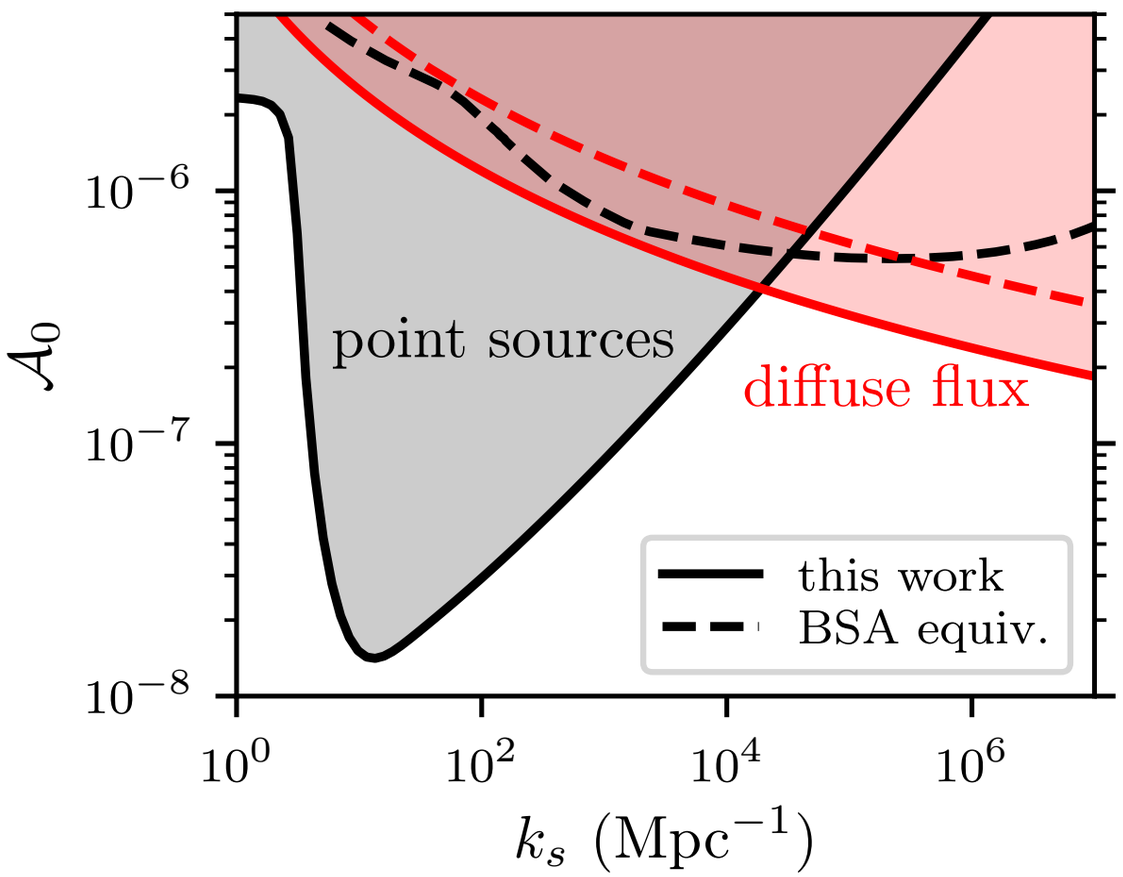
- We then use statistics of peaks to get the number density of halos as a function of formation time.

New Constraints on *P(k)*

Delos, ALE, Bailey, Alvarez
PRD (2018) 1806.07389

As a proof of concept, we apply this method to a delta-function spike in the primordial curvature power spectrum:

$$\mathcal{P}_\zeta(k) = \mathcal{A}_0 k_s \delta(k - k_s)$$



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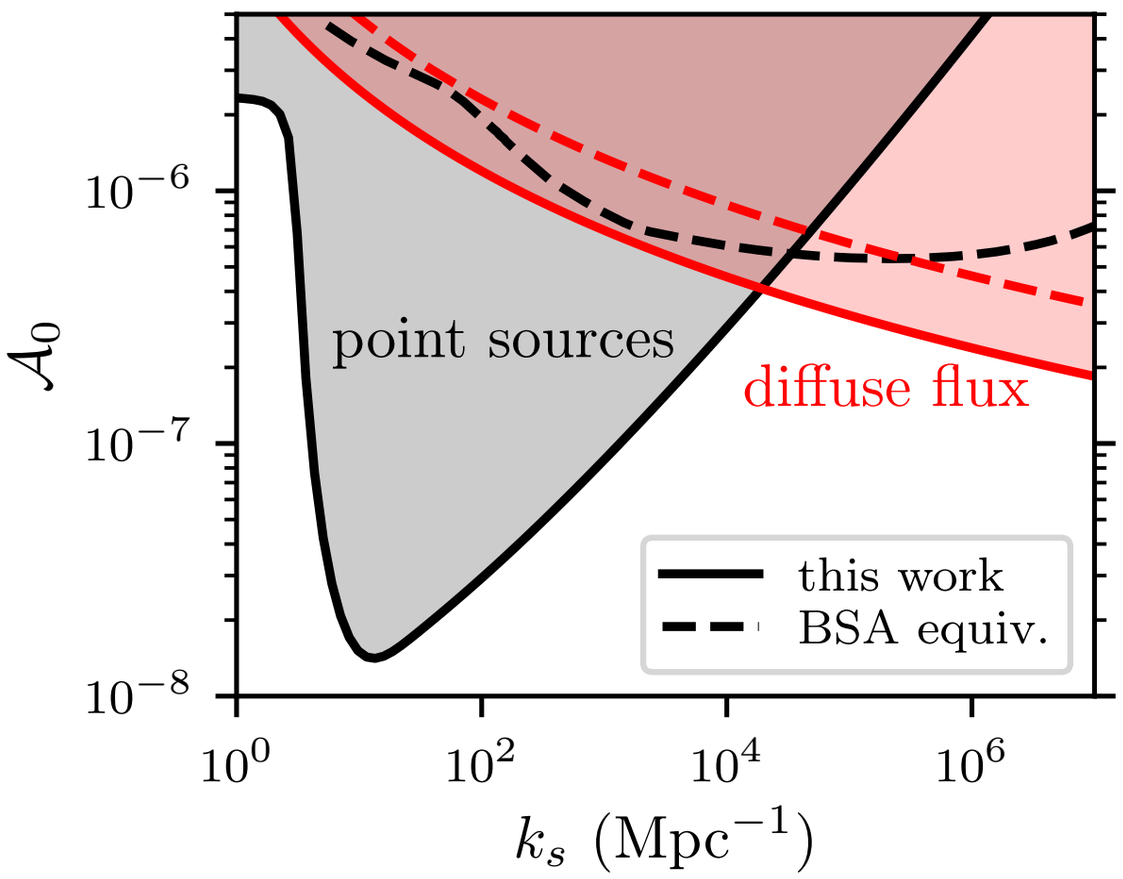

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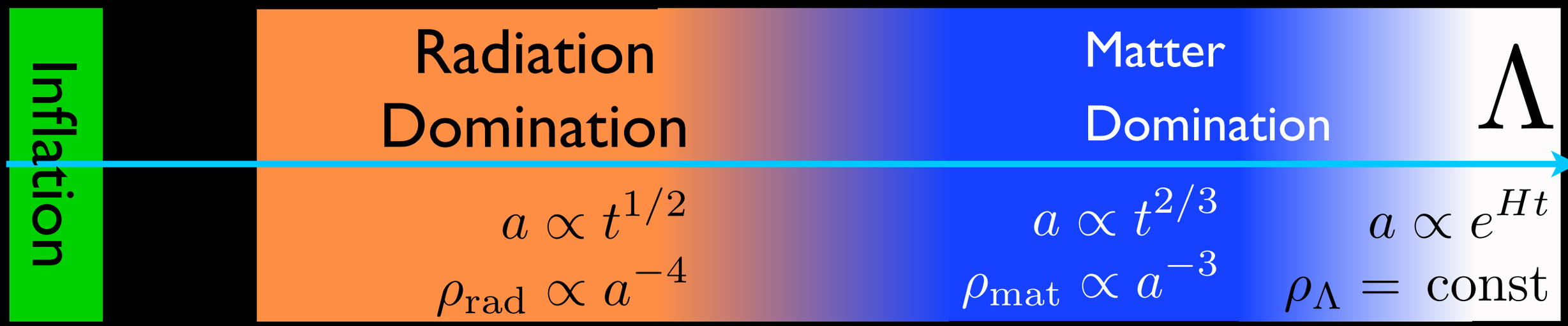
What about lensing?

Part 2:
Probing the pre-BBN universe with small-scale and micro-scale structure



ALE & Kris Sigurdson, PRD 84, 083503 (2011)
ALE PRD 92, 103505 (2015)
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Work in progress with **Carisa Miller**, **M. Sten Delos**, Tim Linden, and **Sheridan Green**

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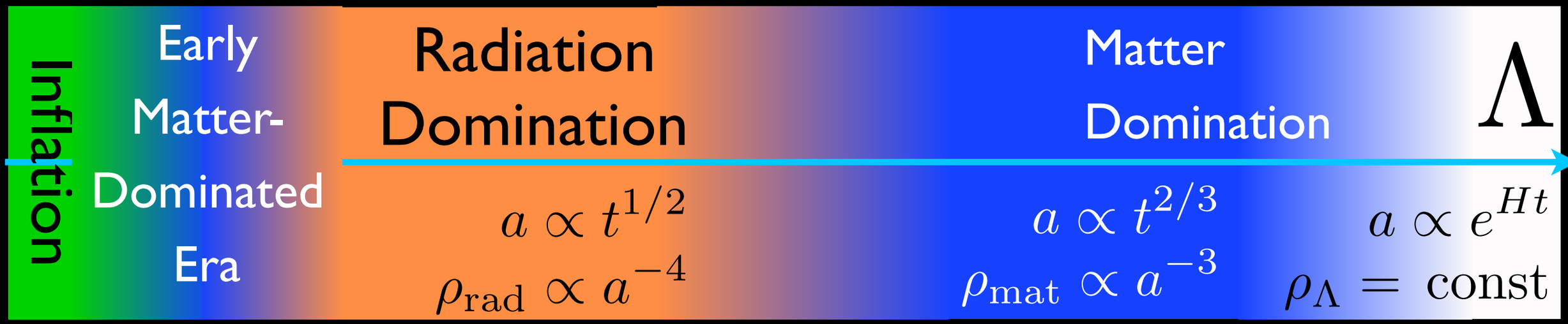

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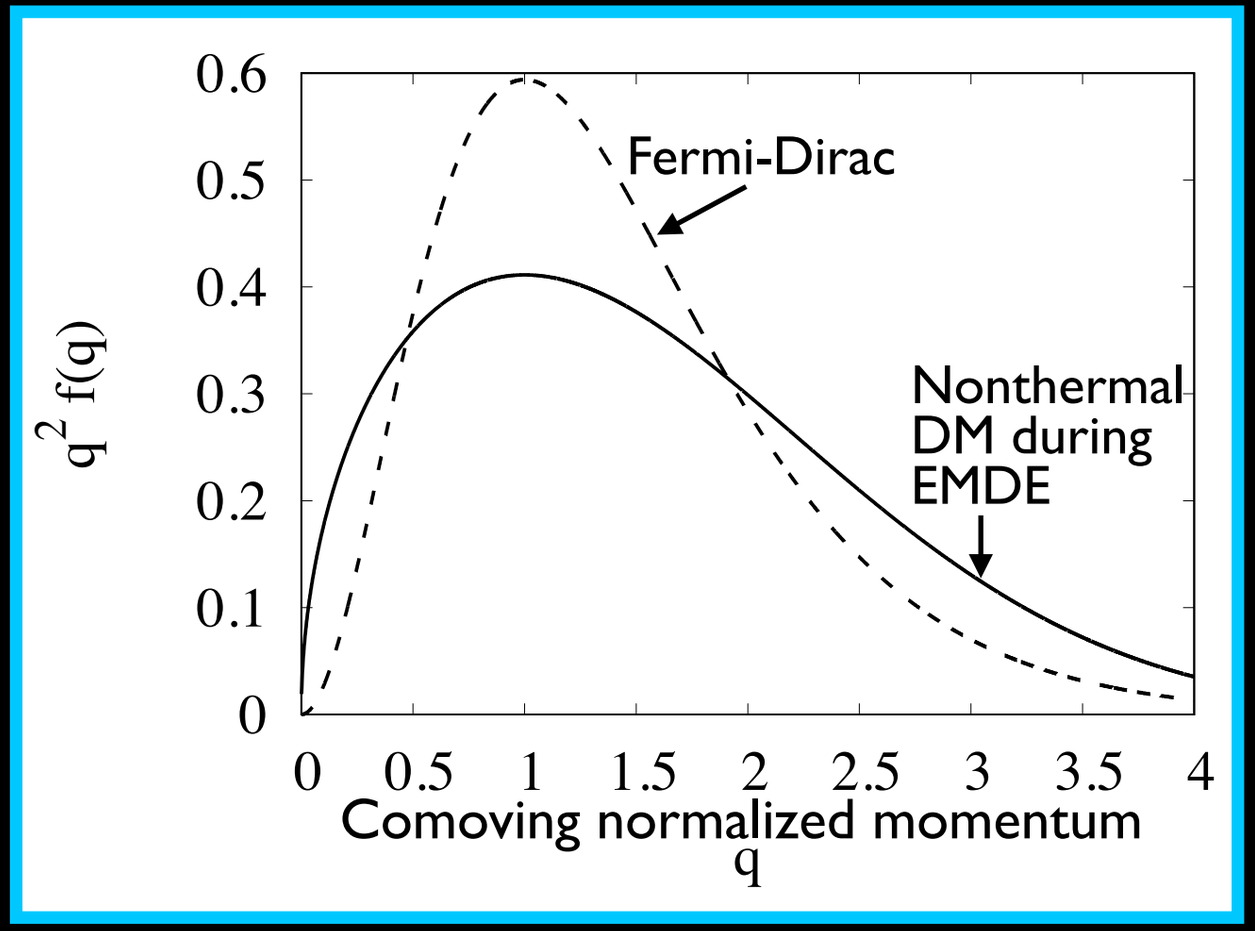
Nonthermal dark matter

Dark matter may have been created directly from the decay of the heavier particle that dominated the Universe during the EMDE.

***Carisa Miller**, ALE*
coming soon

- Without fine-tuning, DM will be relativistic when produced.
- Assume decay into two DM particles; unique distribution function from the timing of decays.



Probing nonthermal DM production

We can use probes of small-scale structure to constrain the nonthermal production of dark matter.

- Use CLASS to determine matter power spectrum.
- Free-streaming length predicts suppression scale.
- Bounds from Lyman-Alpha forest. *Murgia et al. 2018*

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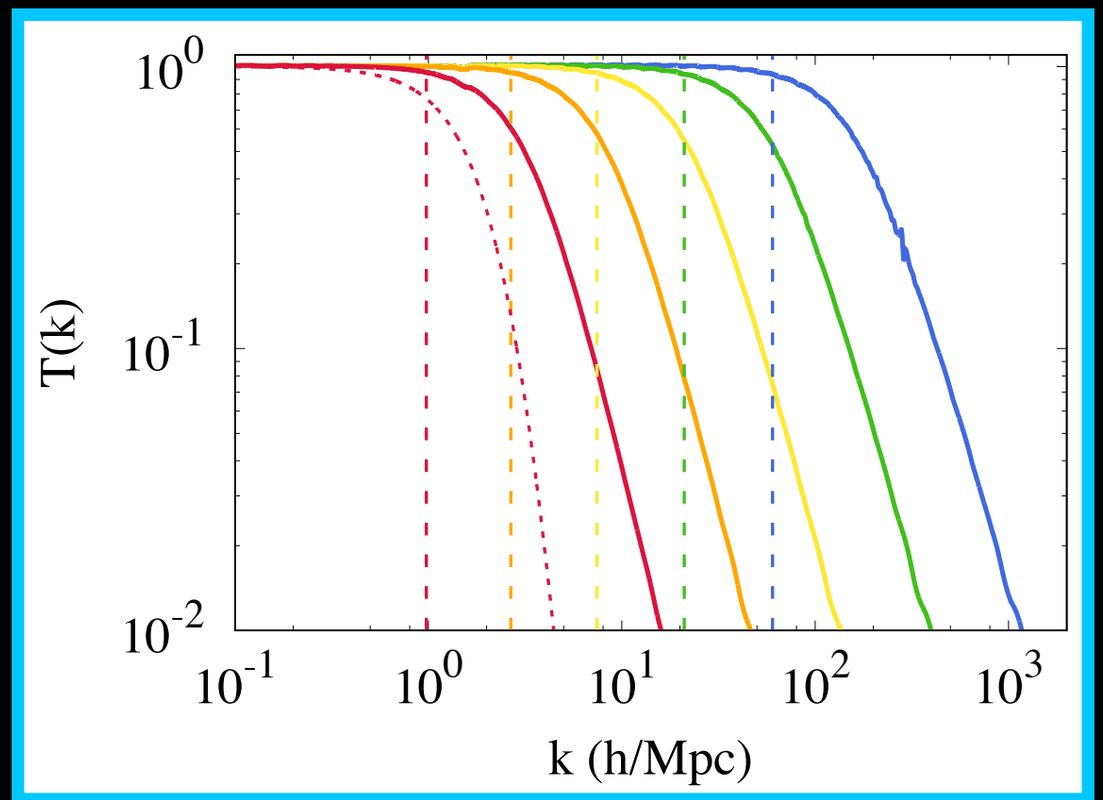

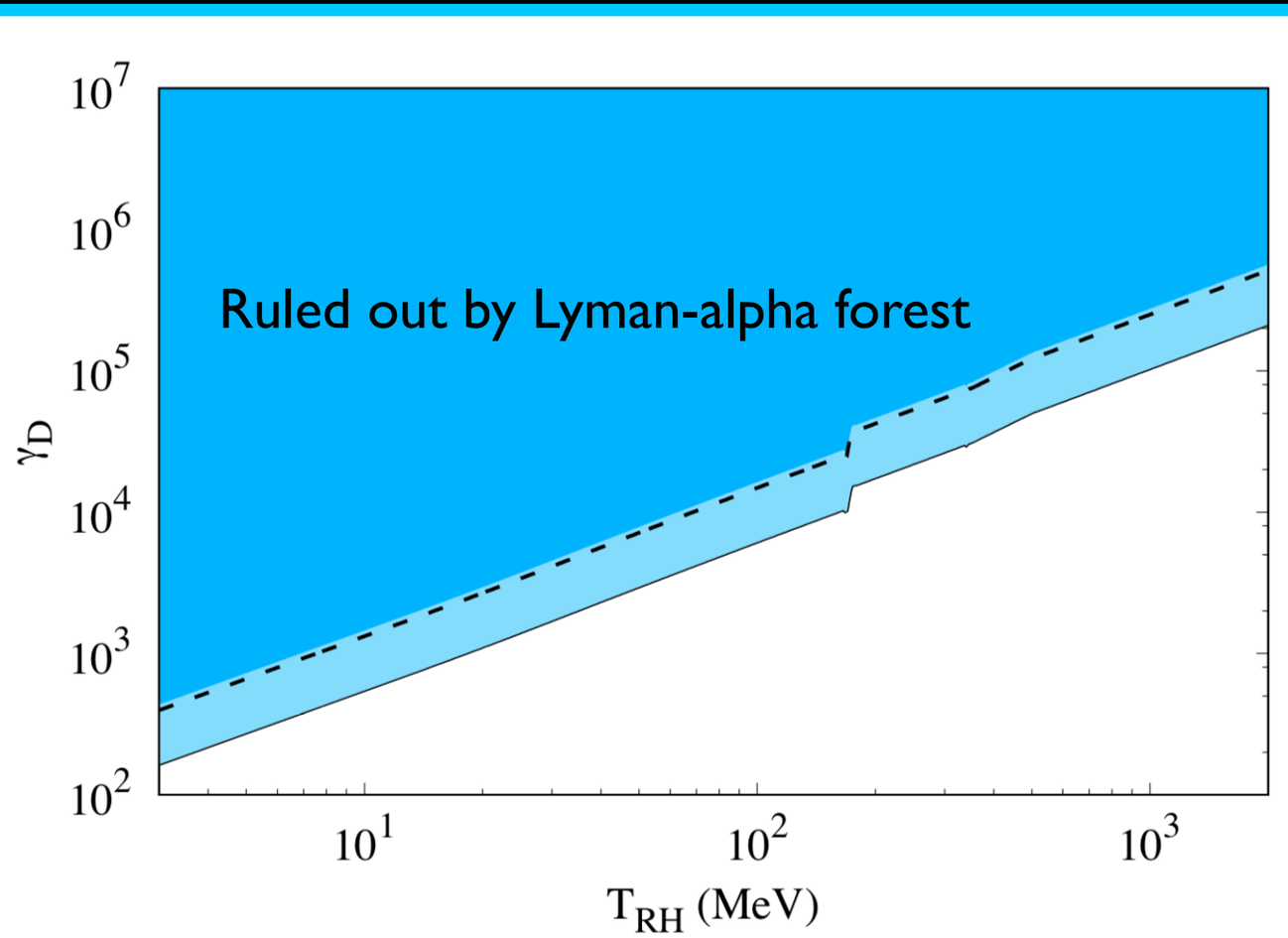

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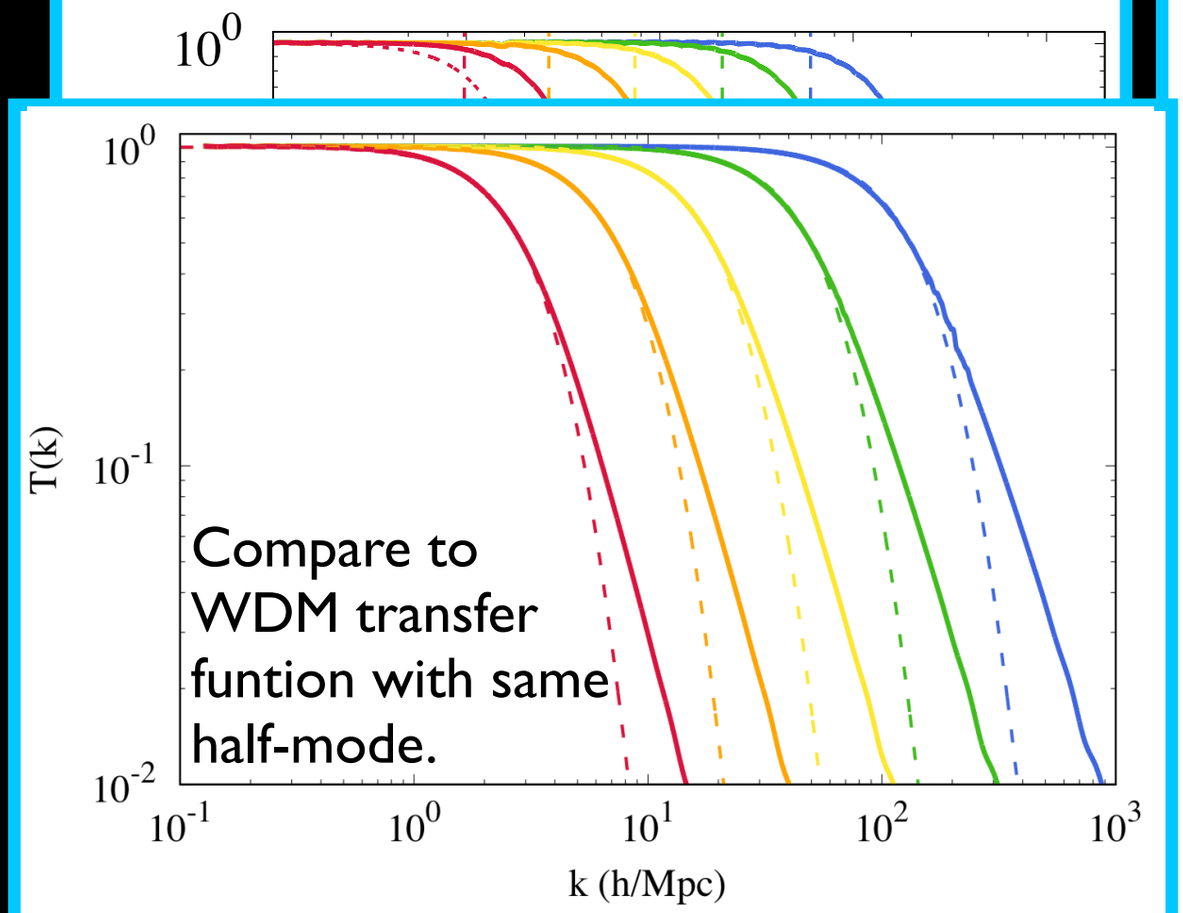

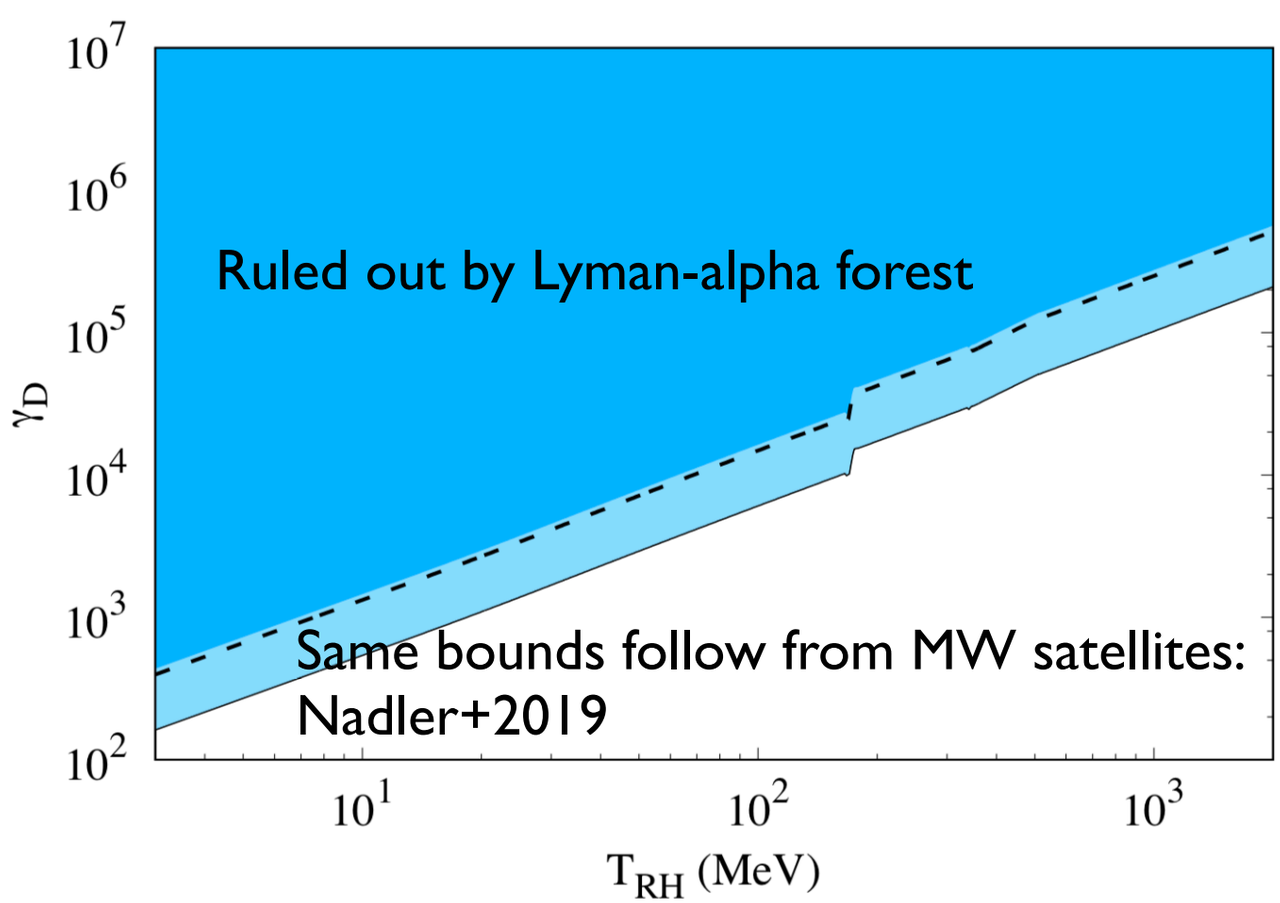

Probing thermal DM production

Thermal DM production during an early matter-dominated era requires smaller annihilation cross sections!

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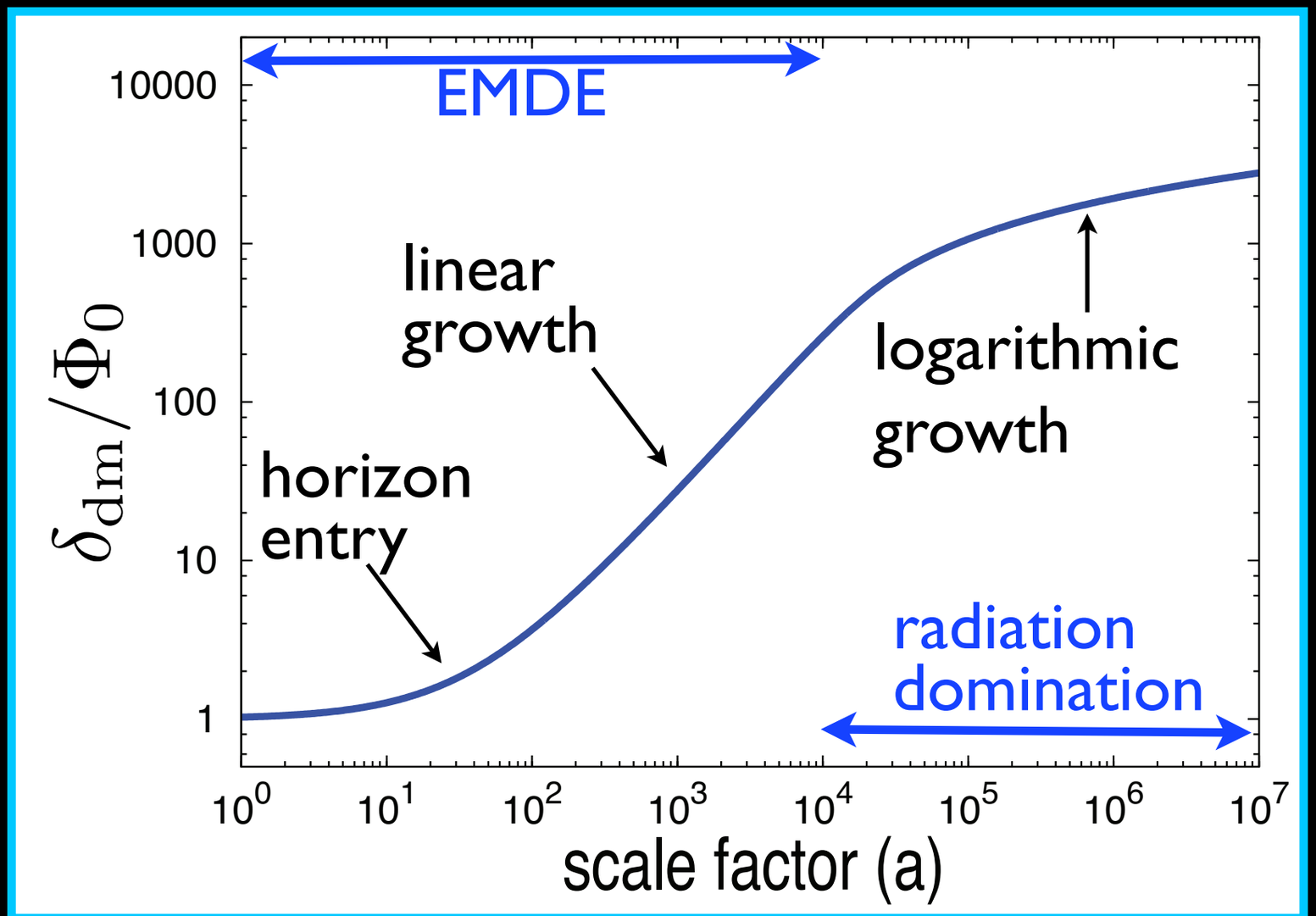
The Evolution of Perturbations



ALE & Sigurdson 2011; Fan, Ozsoy, Watson 2014; ALE 2015

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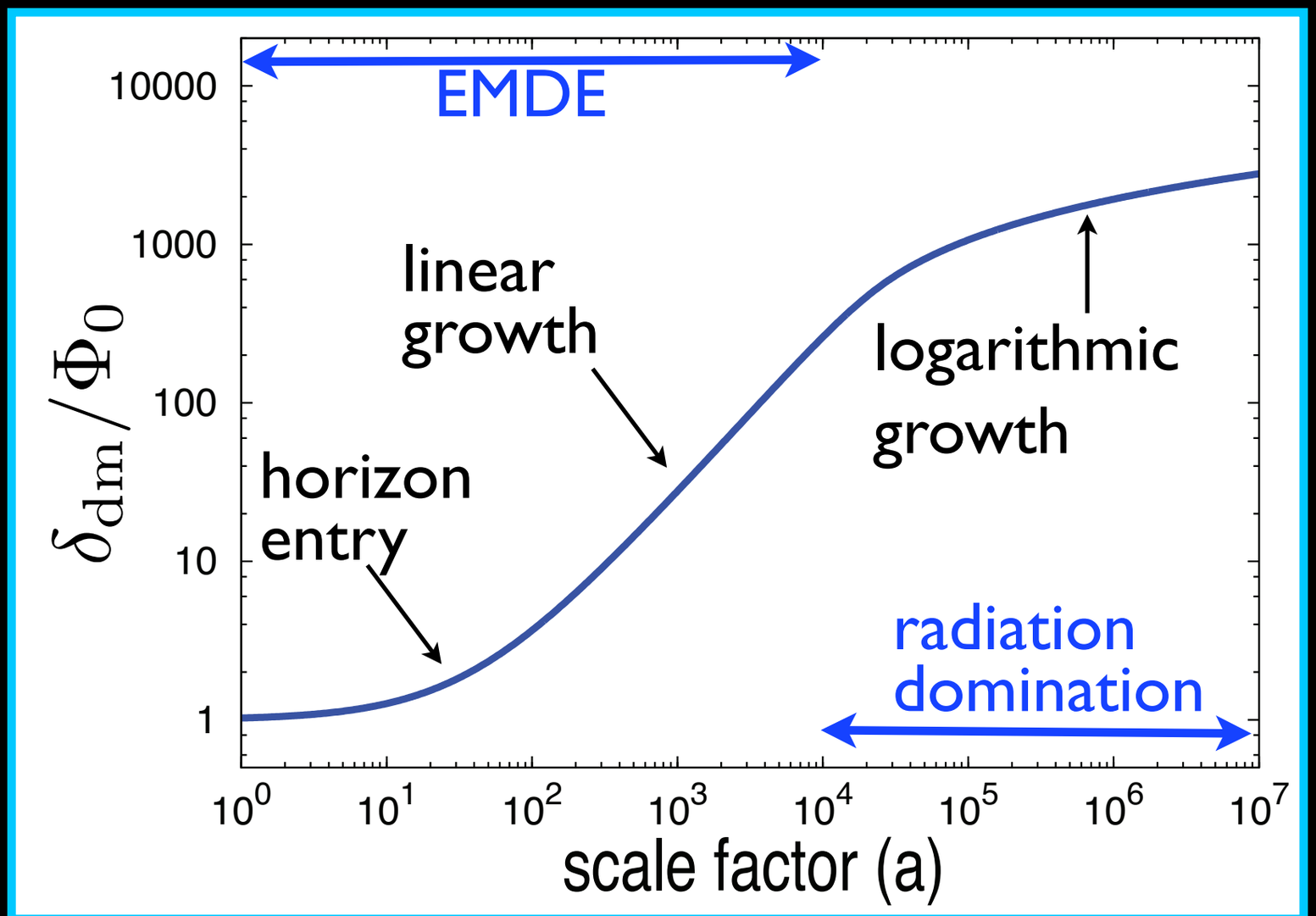


- Enhanced perturbation growth affects subhorizon scales: $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be mass within this comoving radius.

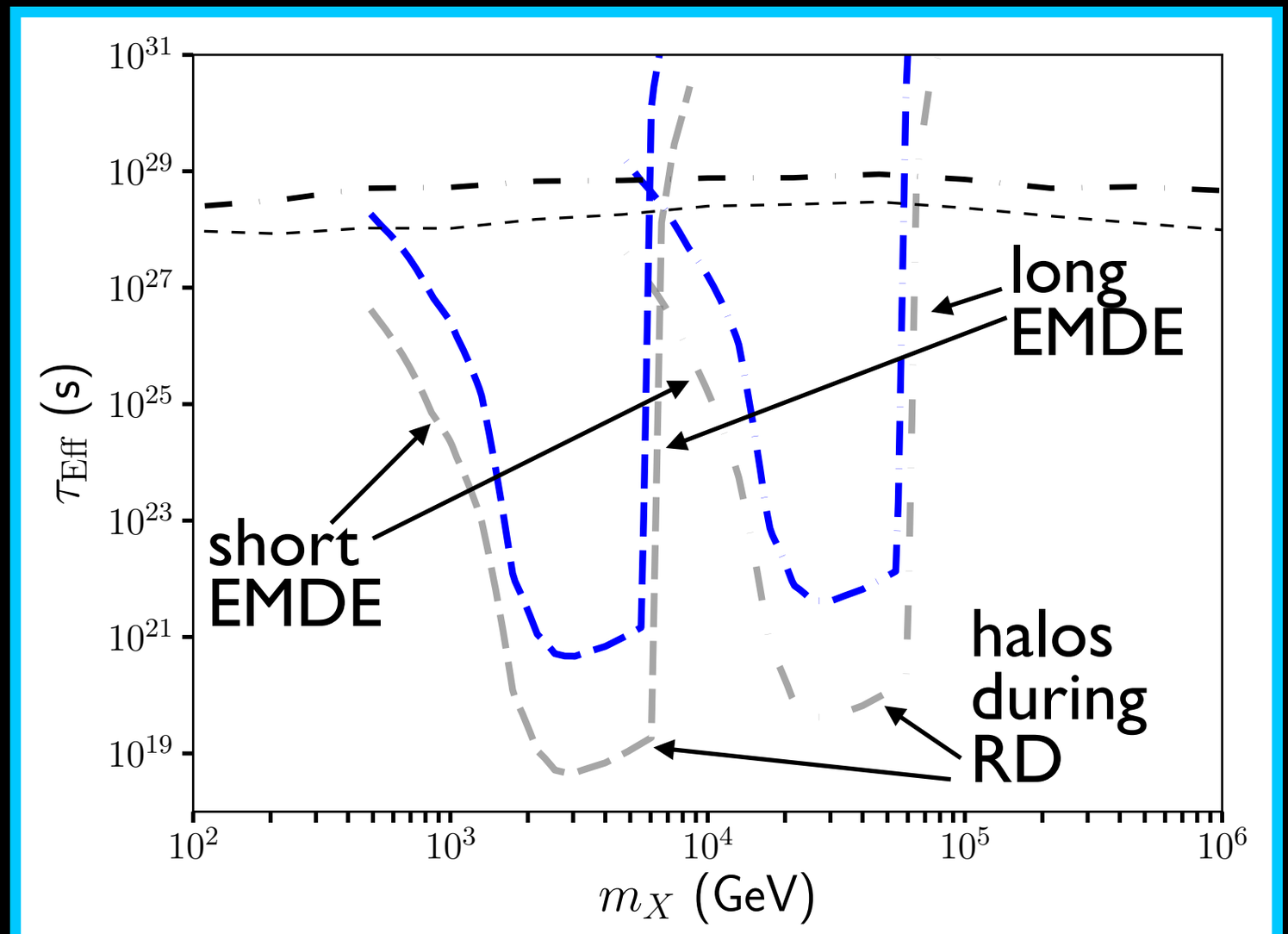
$$M_{\rm RH} \simeq 10^{-5}\, M_\oplus \left(\frac{1\,{\rm GeV}}{T_{\rm RH}}\right)^3$$

ALE & Sigurdson 2011; Fan, Ozsoy, Watson 2014; ALE 2015

DM Annihilation within Microhalos

Dark matter annihilation within early-forming microhalos dominates all other emission, mimicking the signal of decaying dark matter.

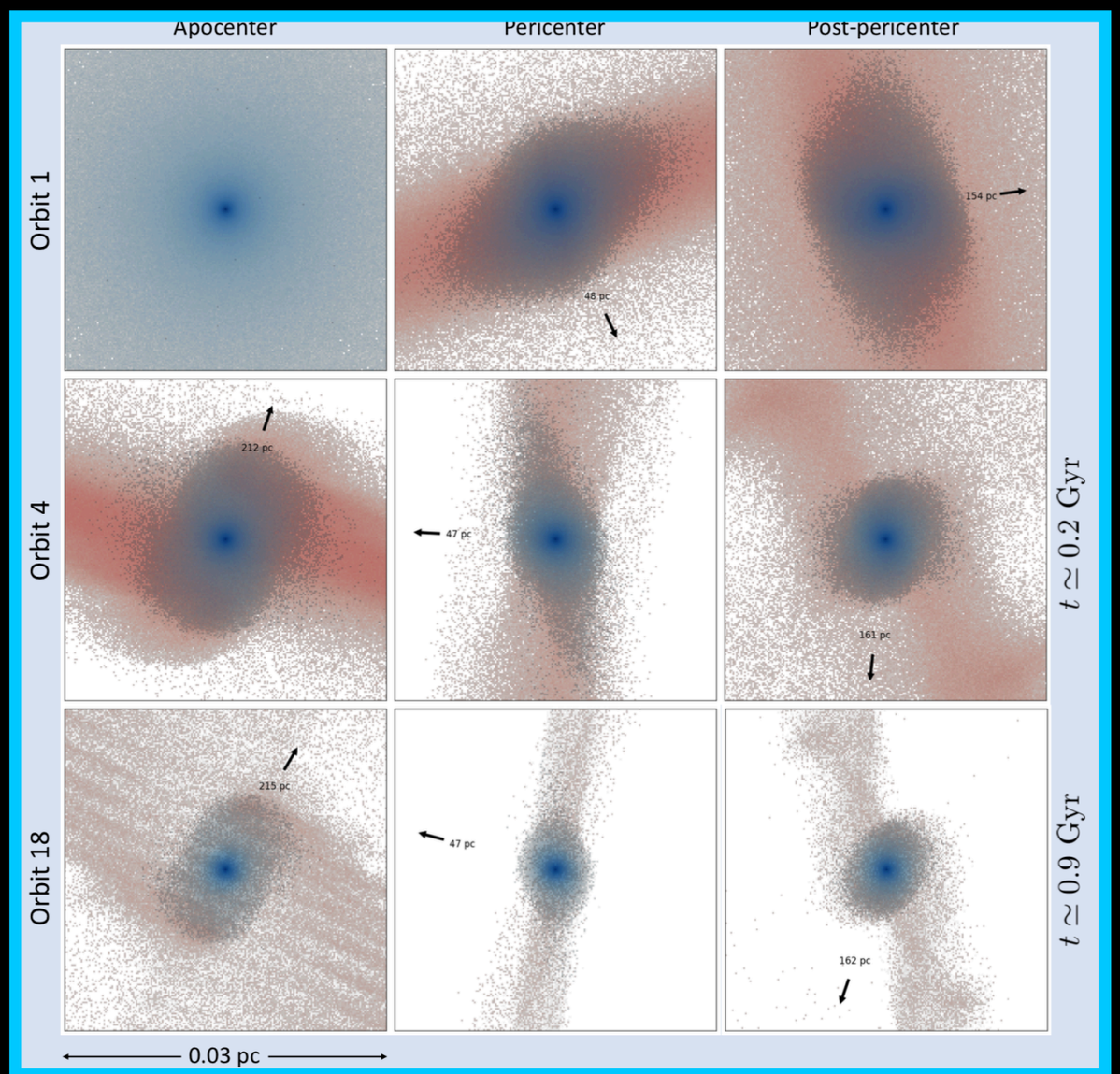
- Annihilation rate per DM mass is set by the density within the first halos and is constant in time and space.
- Can translate into an effective decay rate and compare to observational bounds on decaying dark matter (with twice the mass).
- For hidden sector dark matter, the isotropic gamma-ray background provides powerful constraints.

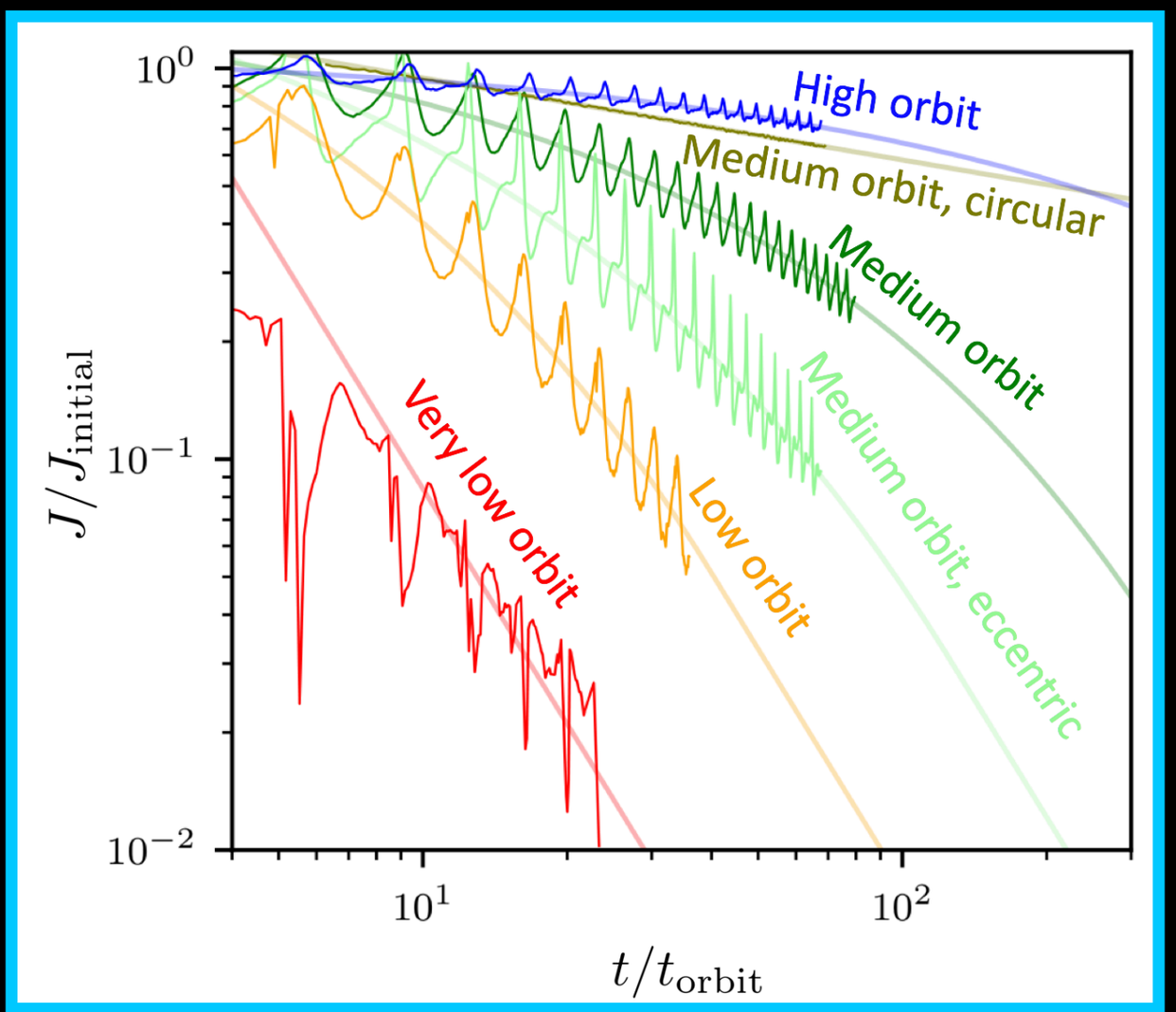


Blanco, Delos, ALE, Hooper 2019

Microhalos within Galaxies

Dwarf spheroidal galaxies also provide constraints (and a potential unique signature). Microhalos within these systems will be stripped by tidal forces and stellar encounters, reducing their J-factor.





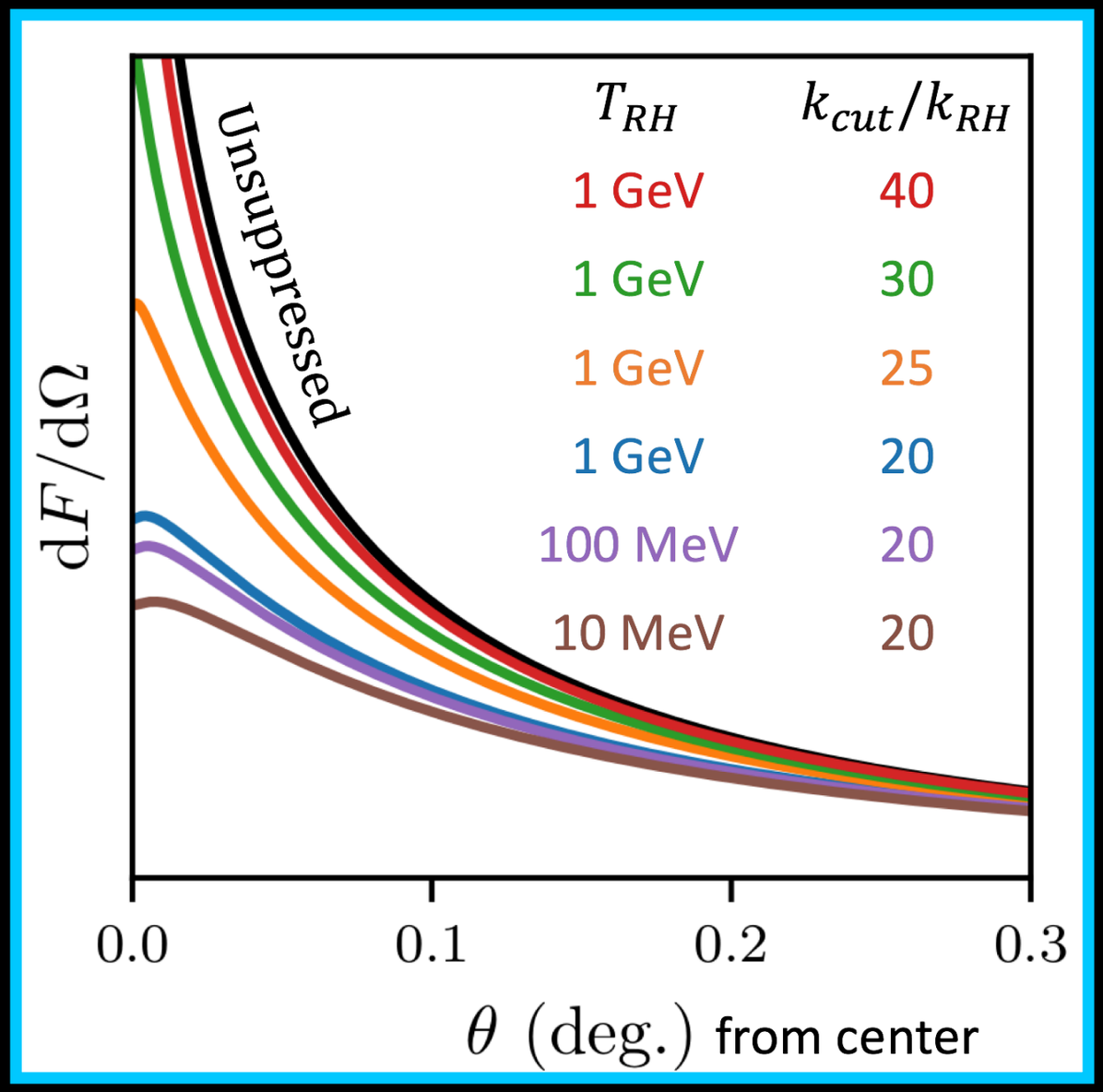
M. Sten Delos 1906.10690 and 1907.13133

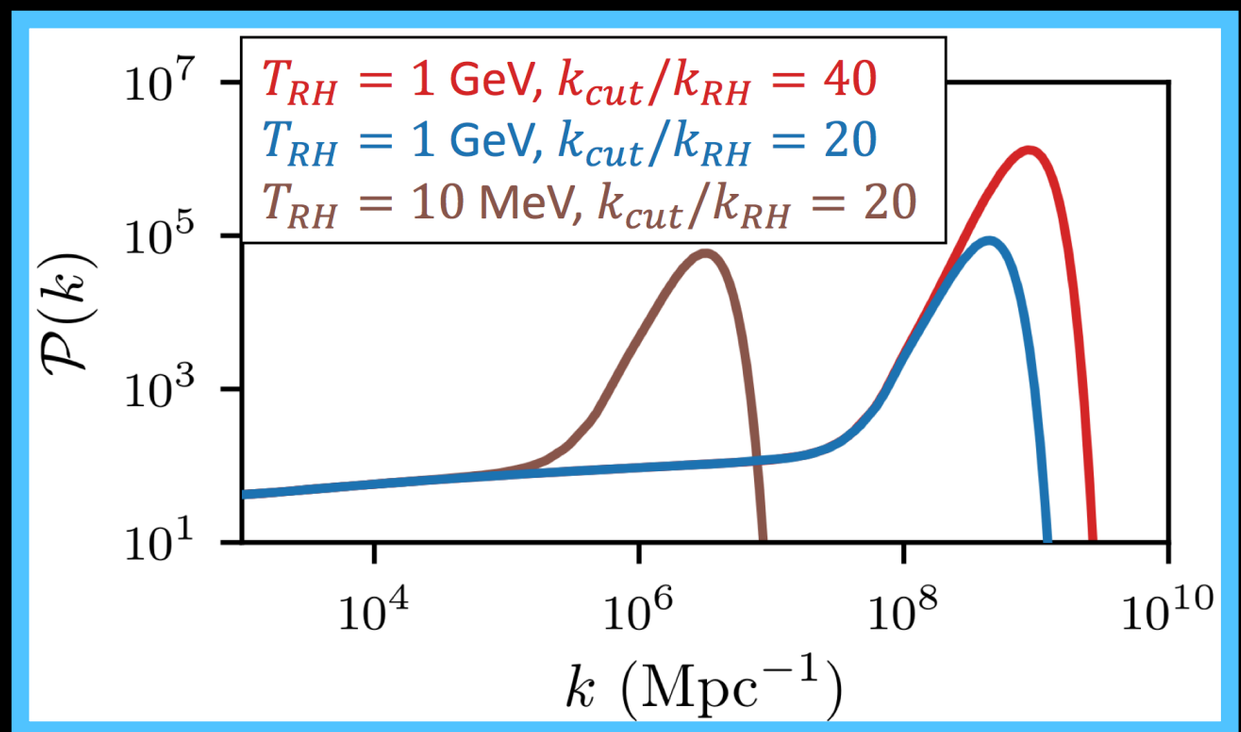
Observational Signatures and Constraints

Case study: Draco

Microhalos in the central region are disrupted, reducing the annihilation signature.

***Sten Delos**, ALE, Tim Linden, coming soon*





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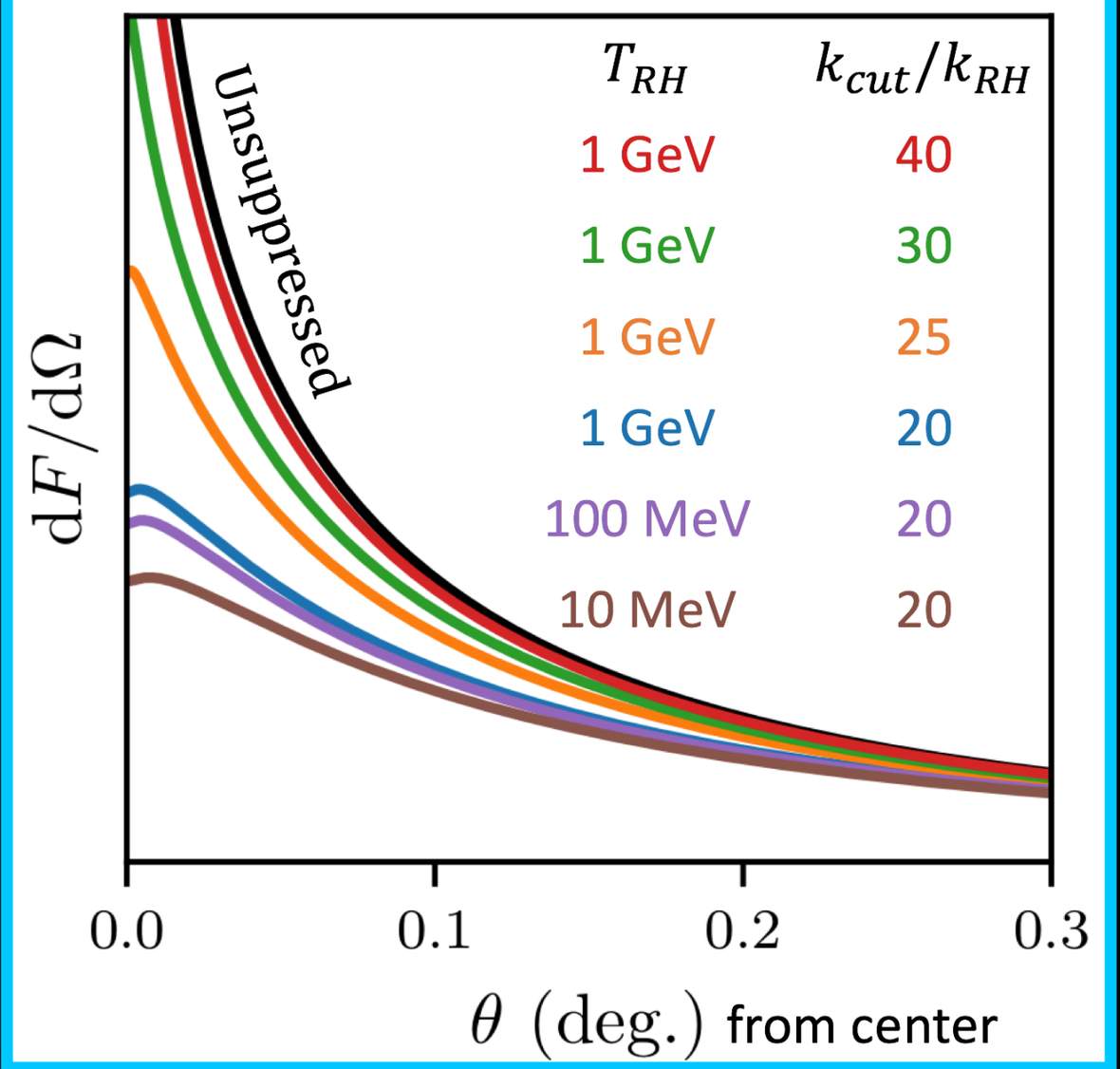
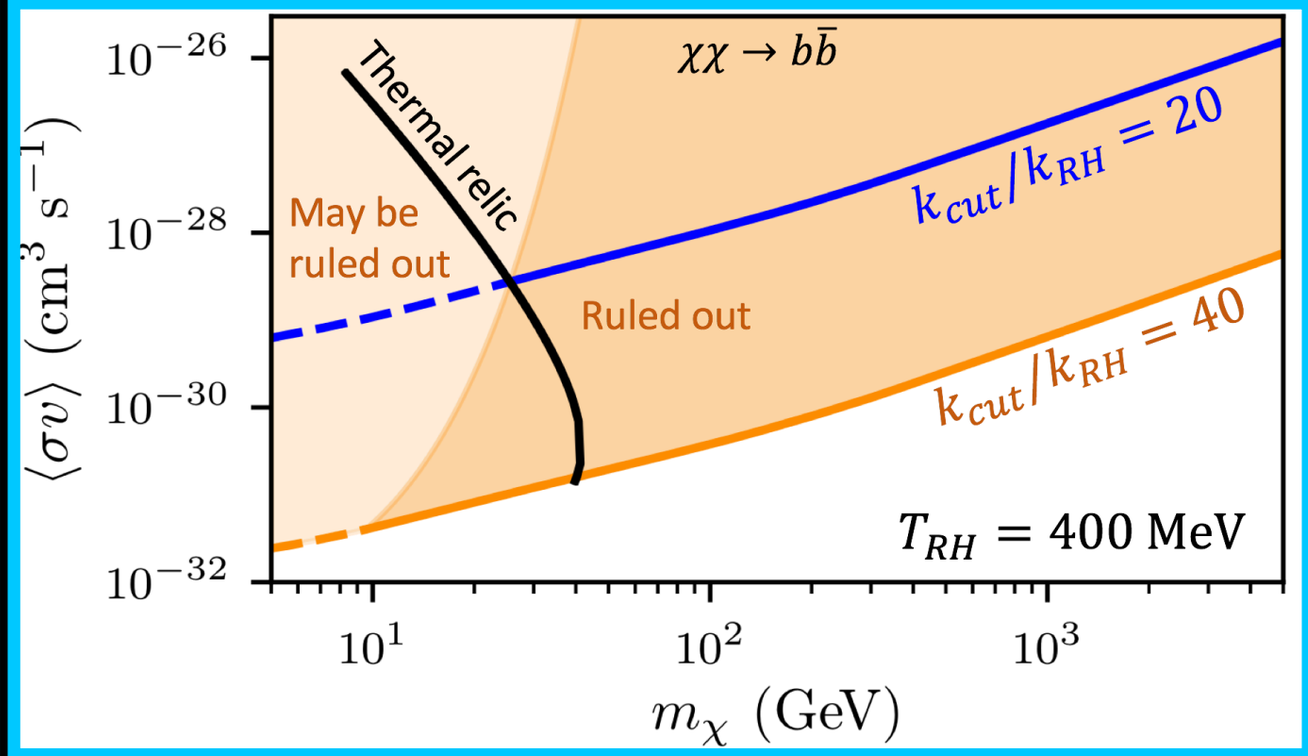
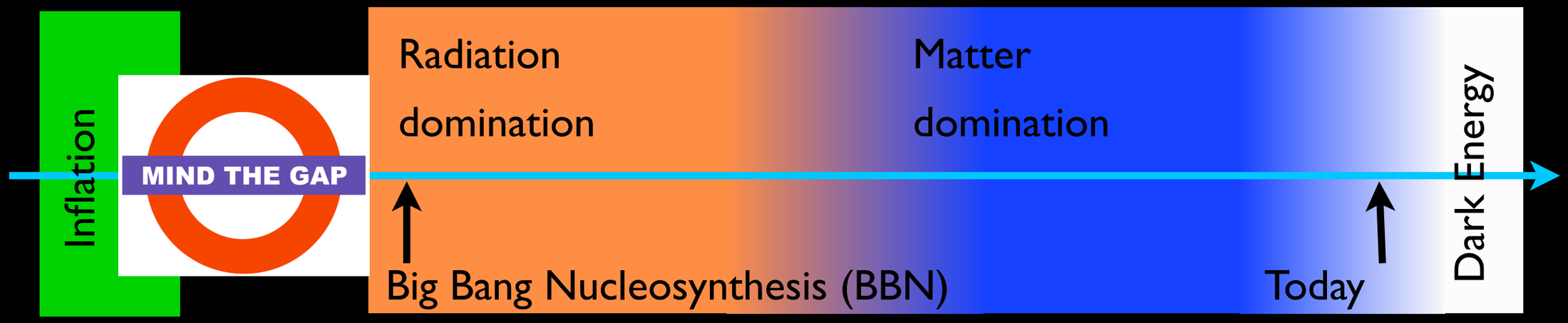




Fermi-LAT observations of Draco limit this emission profile, leading to constraints on EMDE cosmologies.

Summary: Mind the Gap after Inflation

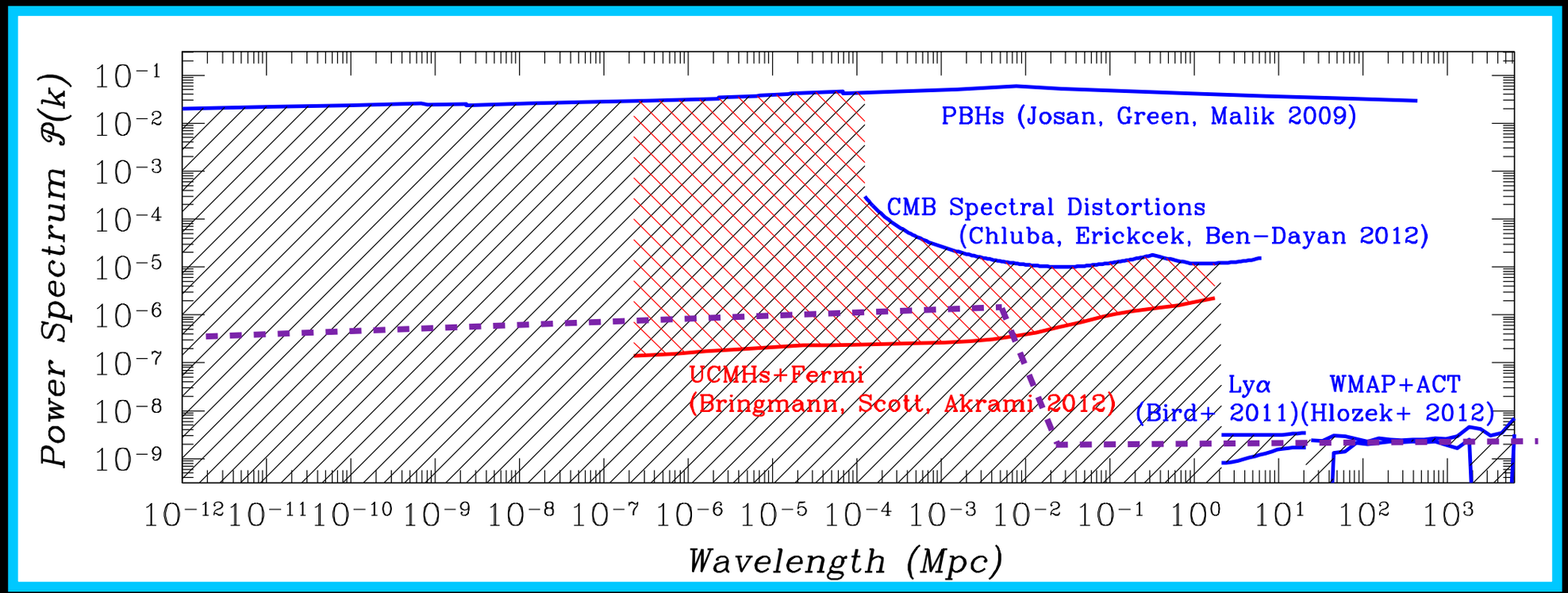


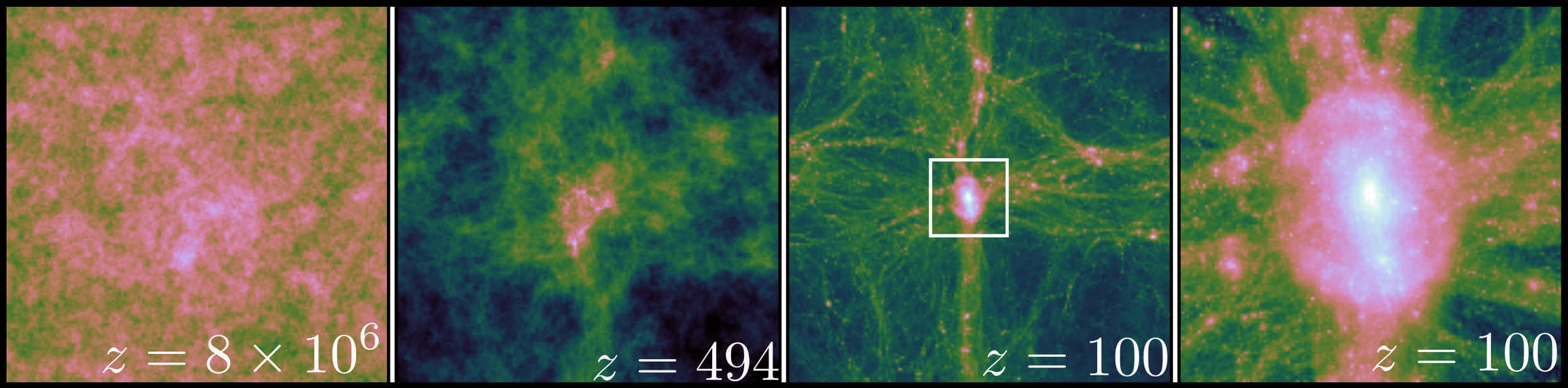
- There is a gap in the cosmological record between inflation and the onset of Big Bang nucleosynthesis: $10^{16}\,\mathrm{GeV} \gtrsim T \gtrsim 0.003\,\mathrm{GeV}$
- Dark matter microhalos offer hope of probing the gap.
- An early matter-dominated era (EMDE) enhances the growth of sub-horizon density perturbations, boosting the DM annihilation rate.
- We can use gamma-ray observations, the Ly-A forest, and the smallest observed halos to probe the evolution of the early Universe and the origins of dark matter.
- Nonthermal DM production can be constrained by LSST.
- Minihalos also probe inflation, but we need to use the right density profile.

Extra Slides

UCMH Density Profiles: Plateau

We also formed UCMHs using a plateau feature





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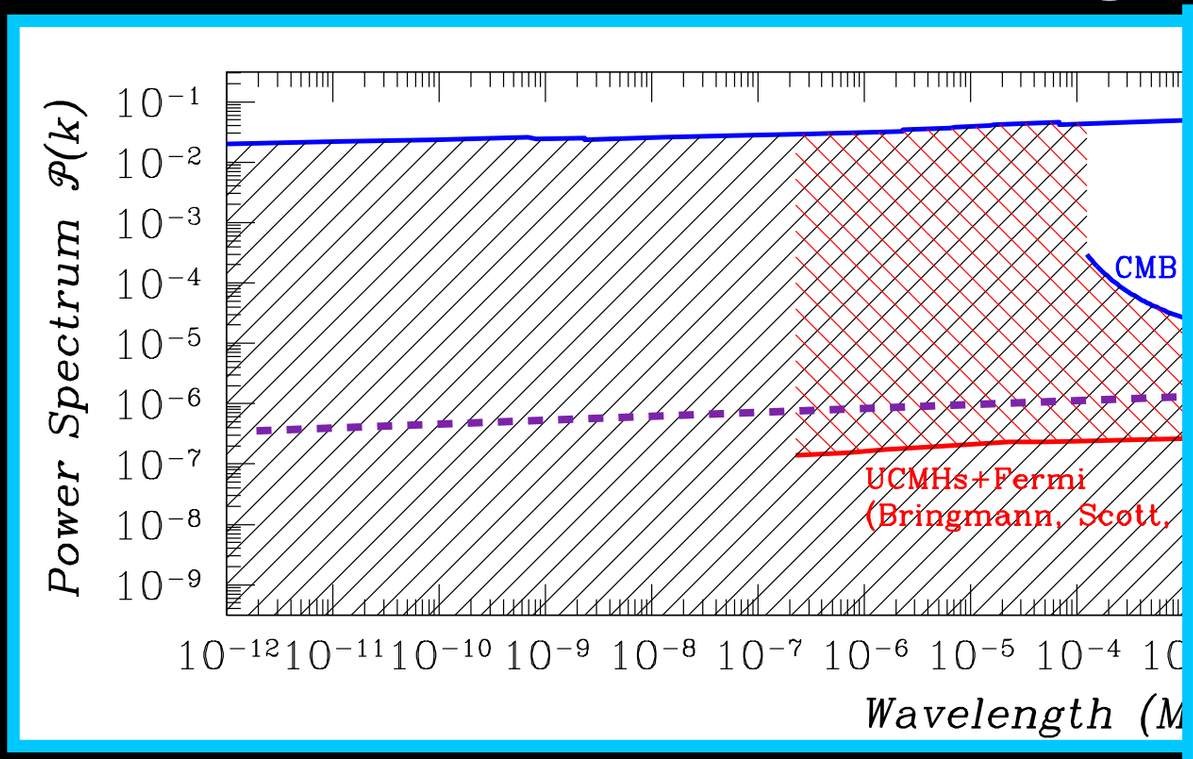
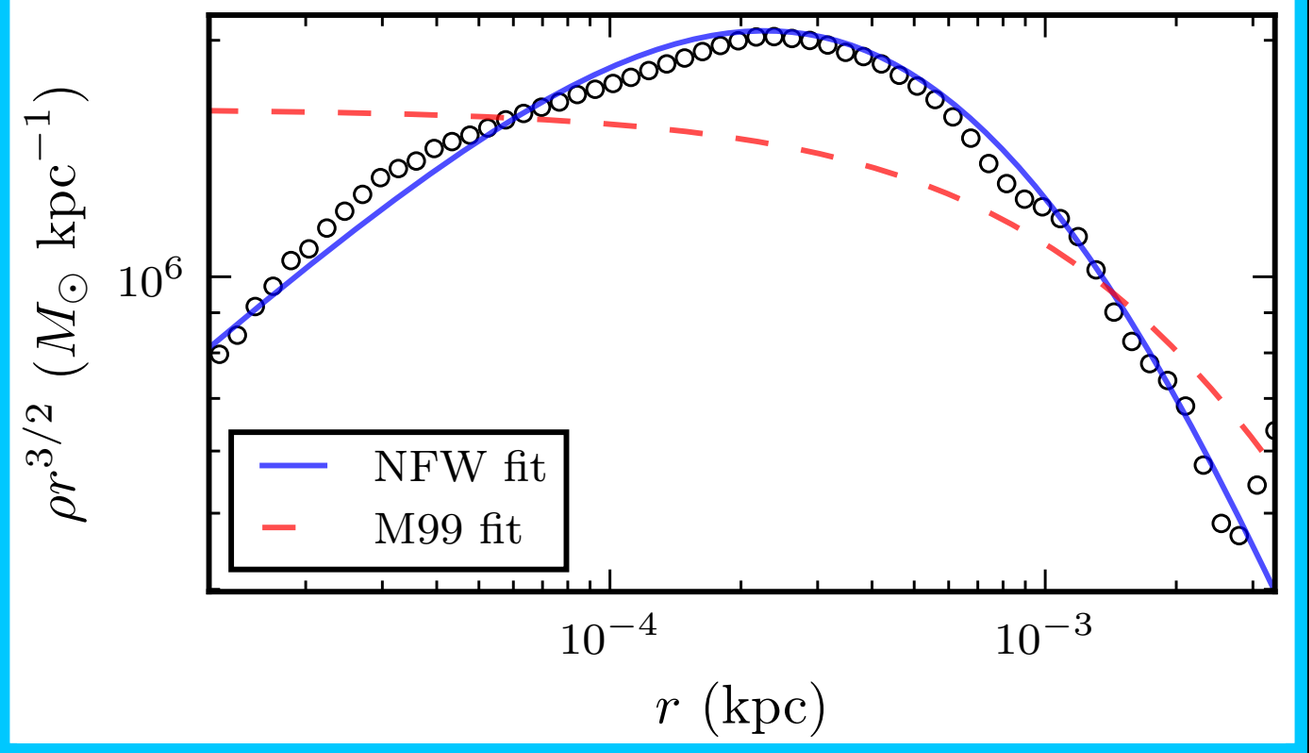
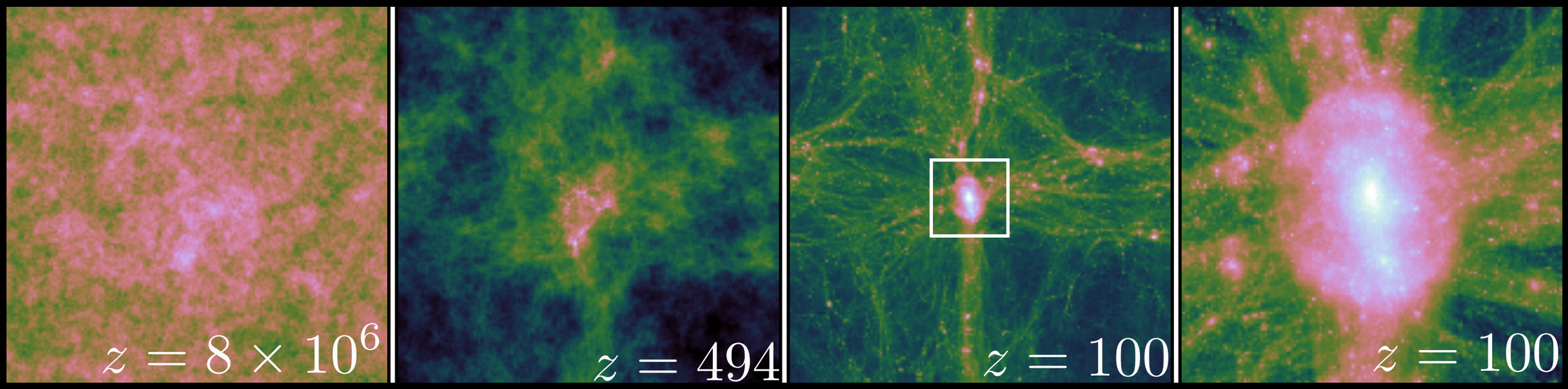


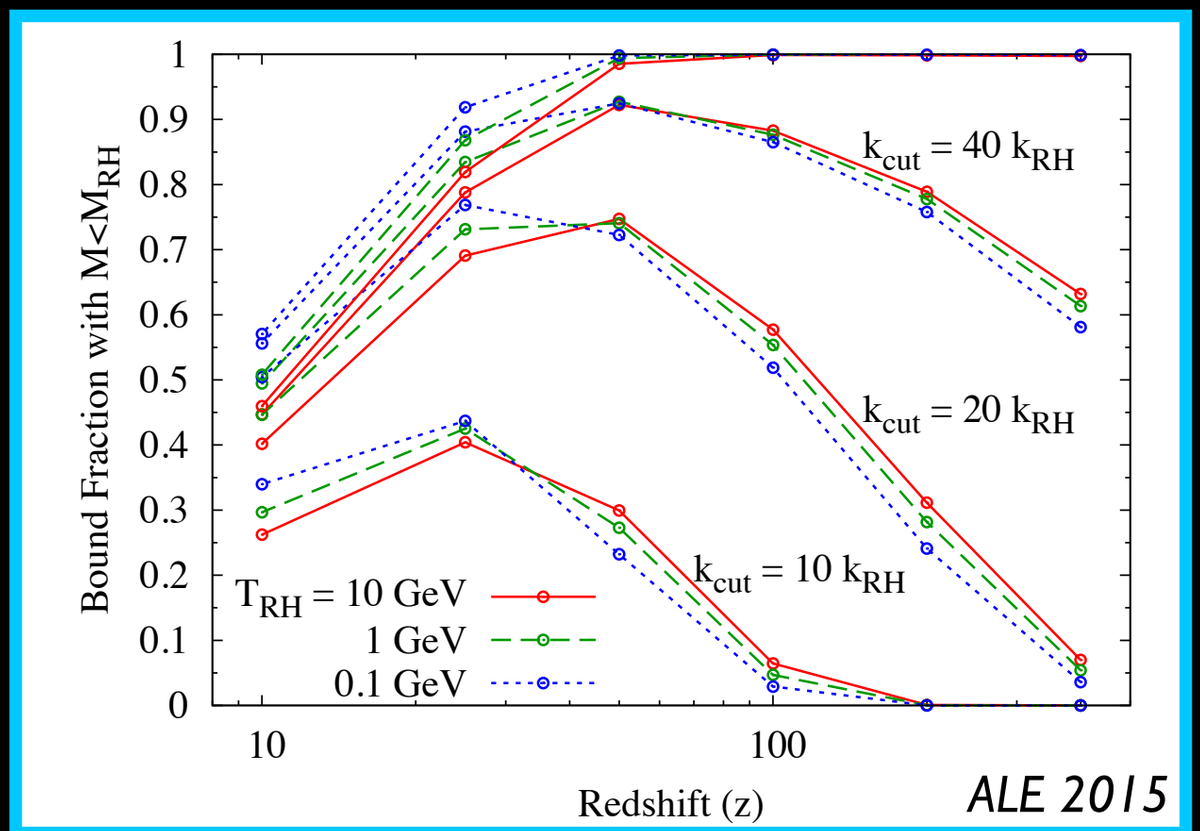


and these UCMHs have NFW proflies!

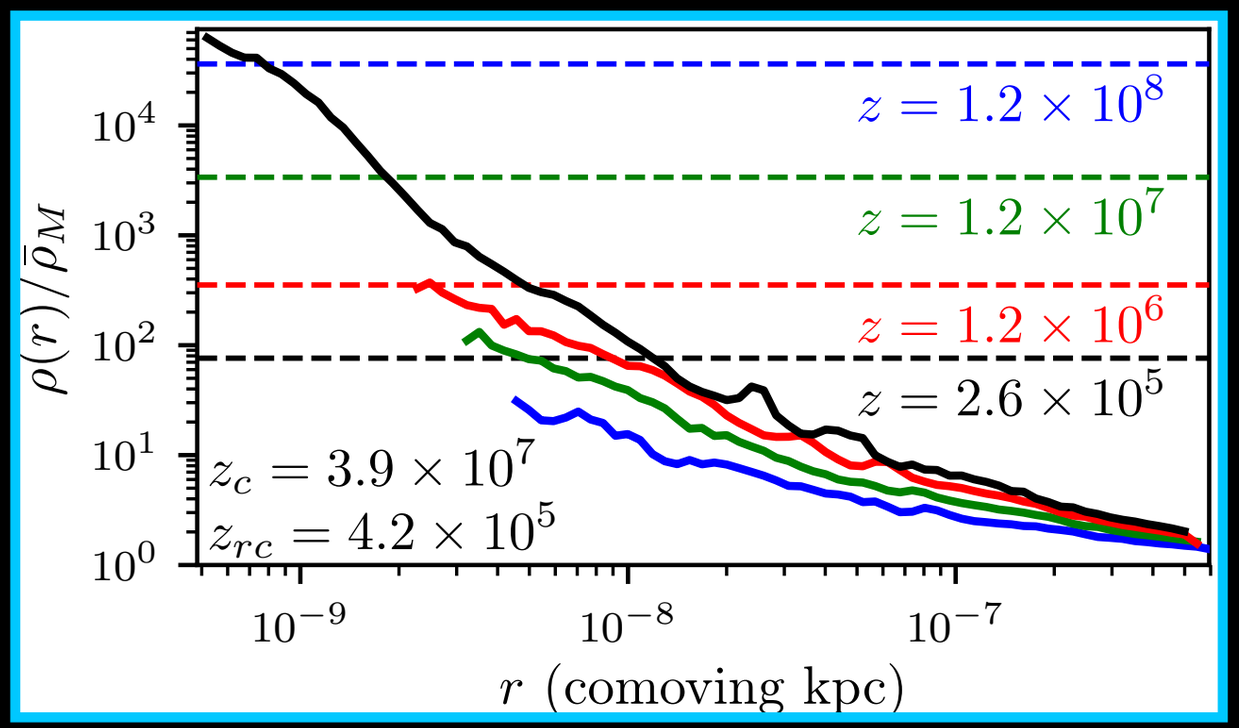


The Microhalo Abundance

To estimate the abundance of halos, we use the Press-Schechter mass function to calculate the fraction of dark matter contained in halos of mass M.



- For WIMP dark matter thermally produced during an EMDE, microhalos form during matter domination.
- With HS dark matter, we can form halos earlier, during radiation domination! *Blanco, Delos, ALE, Hooper 2019*



- Beware halo formation during the EMDE; it heats your dark matter!

Estimating the Boost Factor

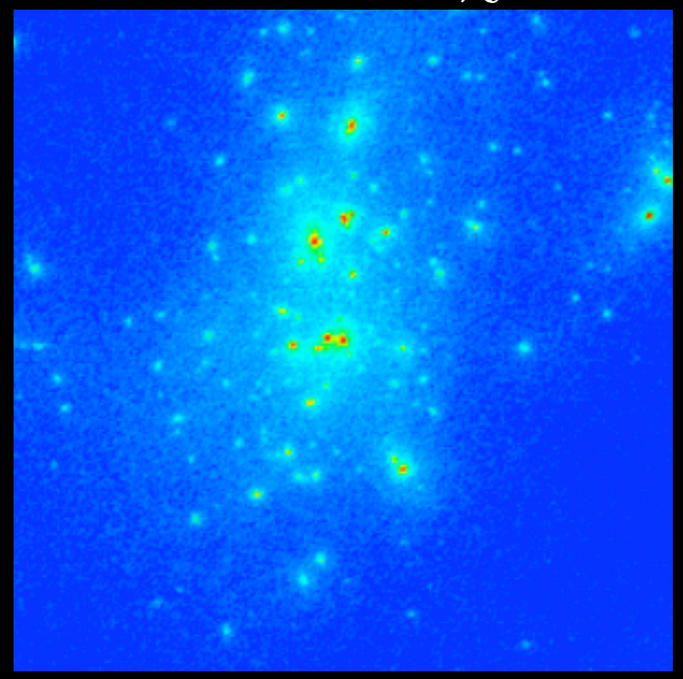
Dark matter annihilation rate: $\Gamma = \dfrac{\langle \sigma v \rangle}{2m_\chi^2} \int \rho^2(r) d^3r \equiv \dfrac{\langle \sigma v \rangle}{2m_\chi^2} J$

Halo filled with microhalos:

$$J = N J_{\rm micro} + 4\pi \int_0^R (1 - f_0)^2 \rho^2_{\rm halo}(r)\, dr$$

Number of microhalos:

$$N = \int (\text{survival prob.}) \frac{M_{\rm halo}}{M} \frac{df}{d\ln M}\, d\ln M$$



Assume microhalo NFW profile with c = 2 at formation redshift.

Anderhalden & Diemand 2013

Ishiyama 2014

- early forming microhalos: $z_f \gtrsim 50$
- dense cores: $\bar{\rho}_{\rm micro}(r_s) > 2\bar{\rho}_{\rm halo}(r)$ for $r > 1\,{\rm kpc}$
- assume that microhalo centers survive outside of inner kpc: reduces number of microhalos by 1%.
- assume that microhalos are stripped to $r = r_s$: reduces $J_{\rm micro}$ by <20%

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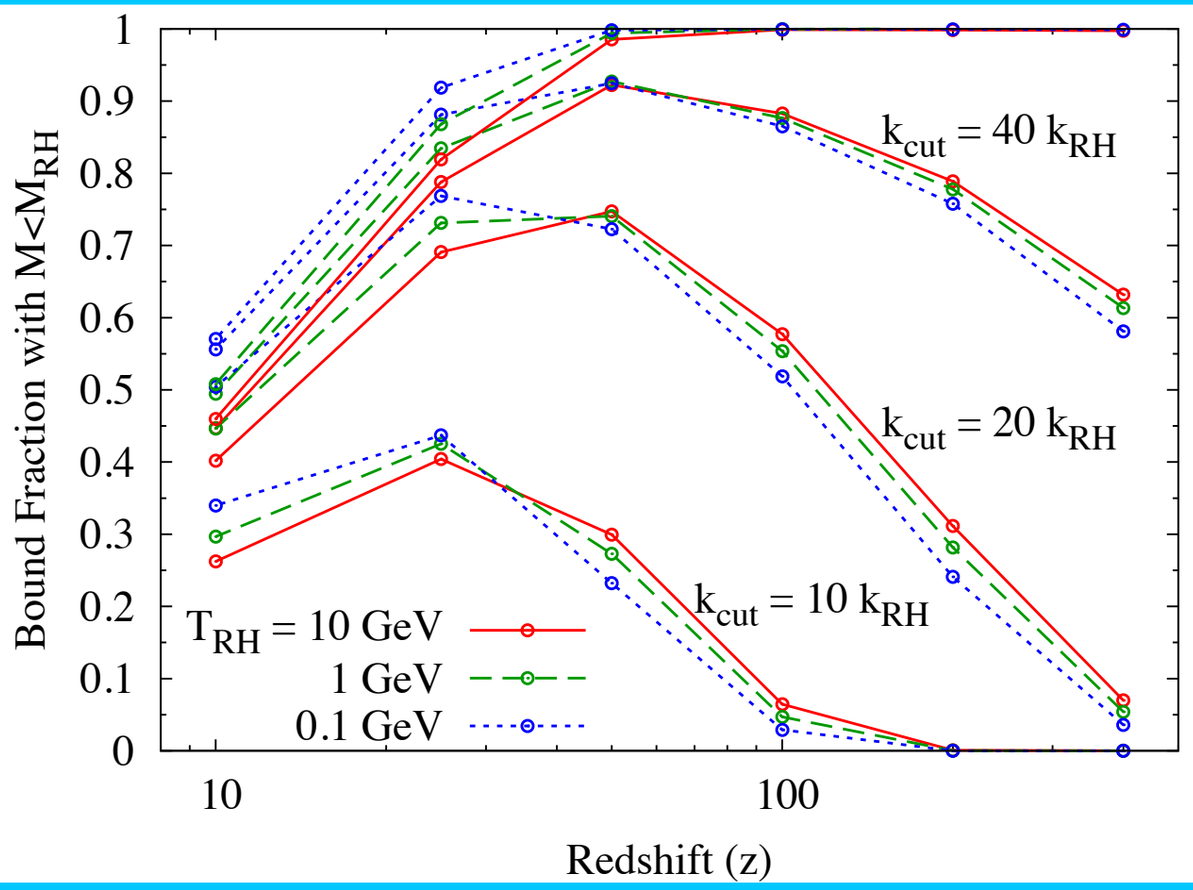
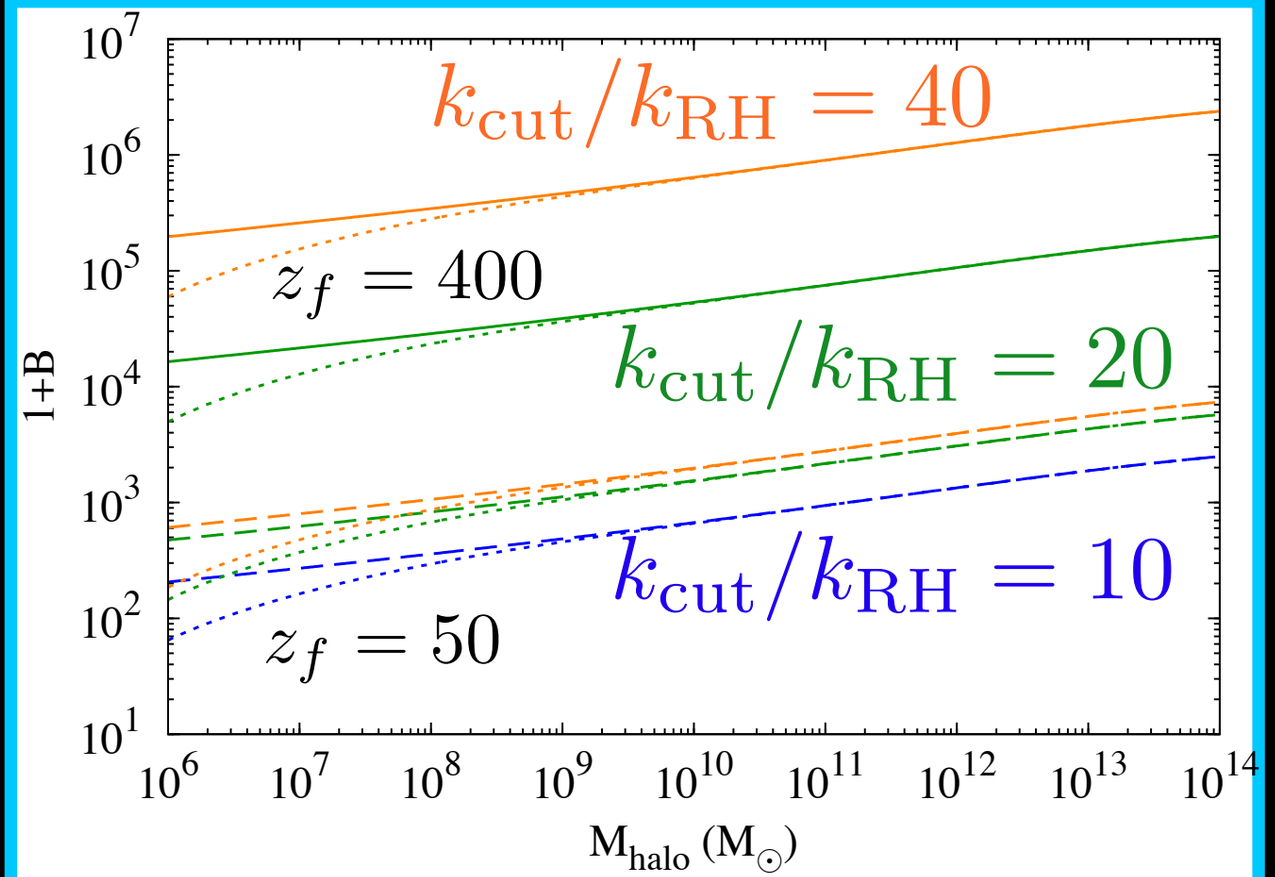
Boost Factor assuming that microhalos forming at z_f survive:

$$1 + B(M) \equiv \frac{J}{\int \bar{\rho}_\chi^2(r)\, 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c_h^3} f_{\rm tot}(M < M_{\rm RH}, z_f)$$





ALE 2015

Boost from Microhalos