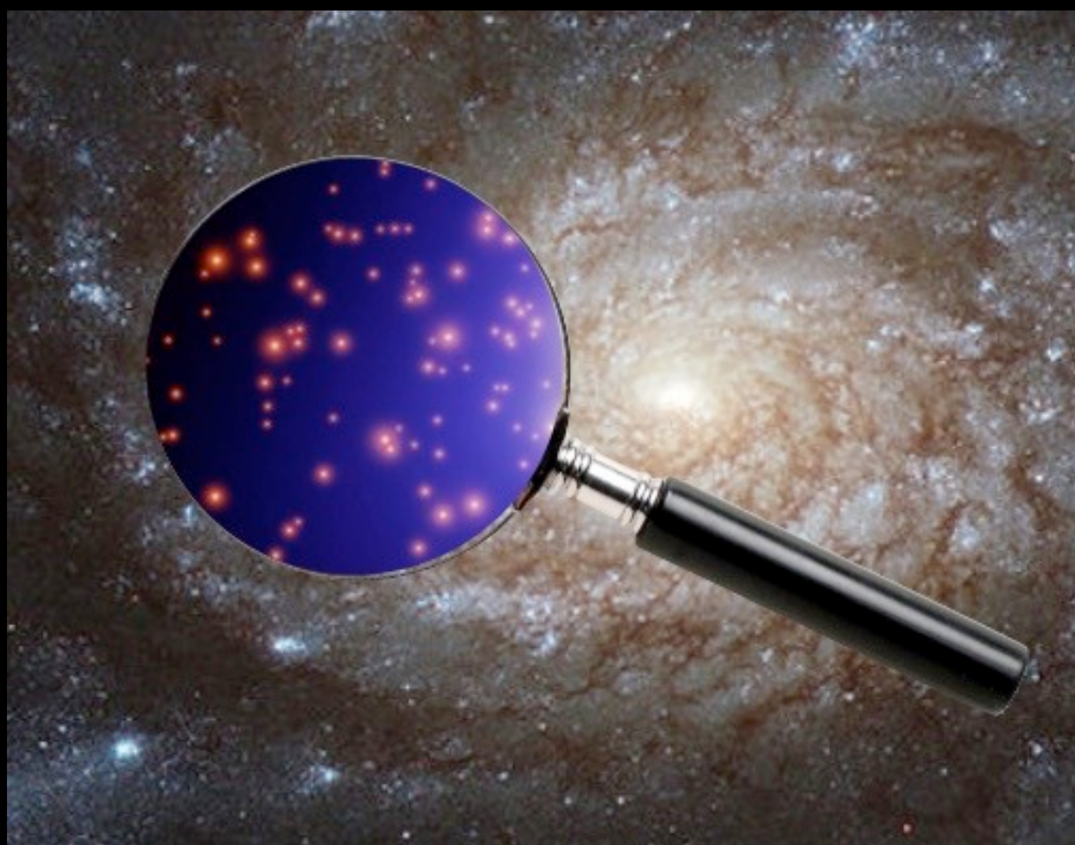
The Early Universe's Imprint on Dark Matter



Adrienne Erickcek
UNC Chapel Hill

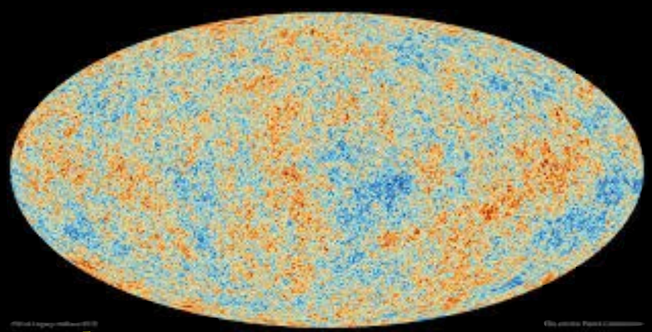
Inflationary Reheating Meets Particle Physics Frontier
KITP, UCSB
February 5, 2020

What happened before BBN?

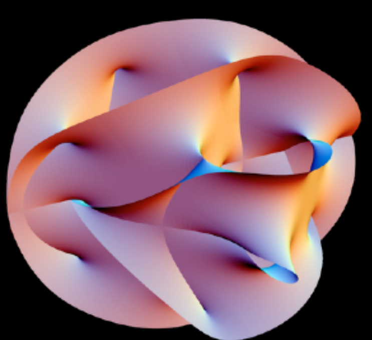
The (mostly) successful predictions of the primordial abundances of light elements tell us that the the Universe was radiation dominated when neutrinos decoupled prior to BBN.

Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008

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.

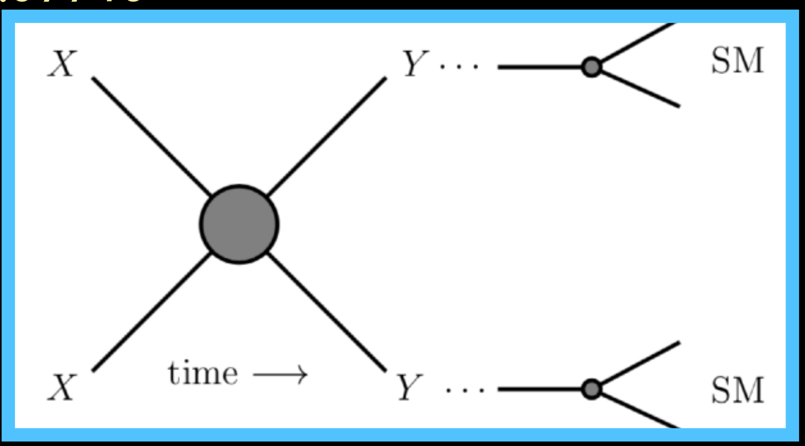


- The string moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.

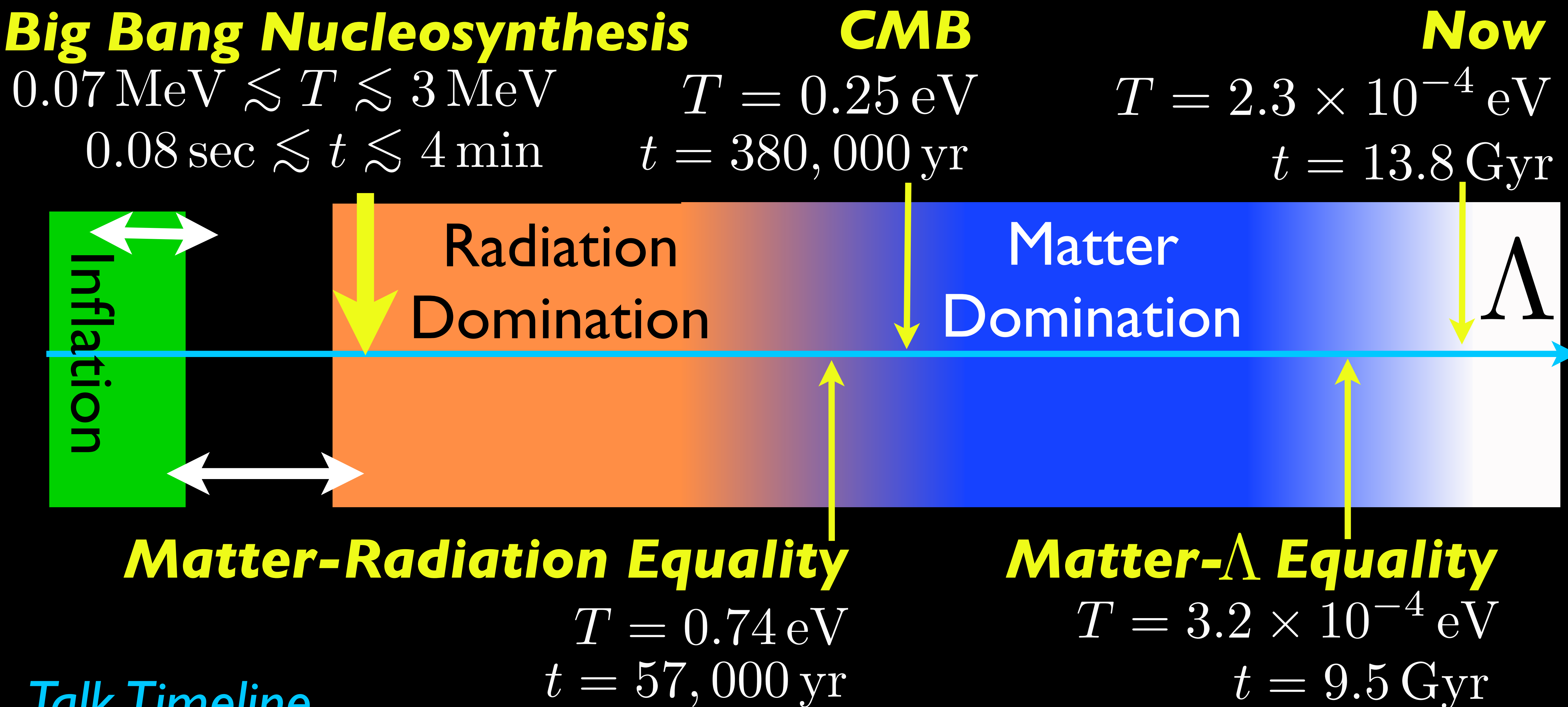
Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008
Summary: Kane, Sinha, Watson 1502.07746

- Dark matter in a hidden sector: massive mediators dominate the Universe before BBN

Zhang 2015
Berlin, Hooper, Krnjaic 2016
ALE, Ralegankar, Shelton (coming soon)
Dror, Kuflik, Ng 2016
Dror, Kuflik, Melcher, Watson 2018



Cosmic Timeline

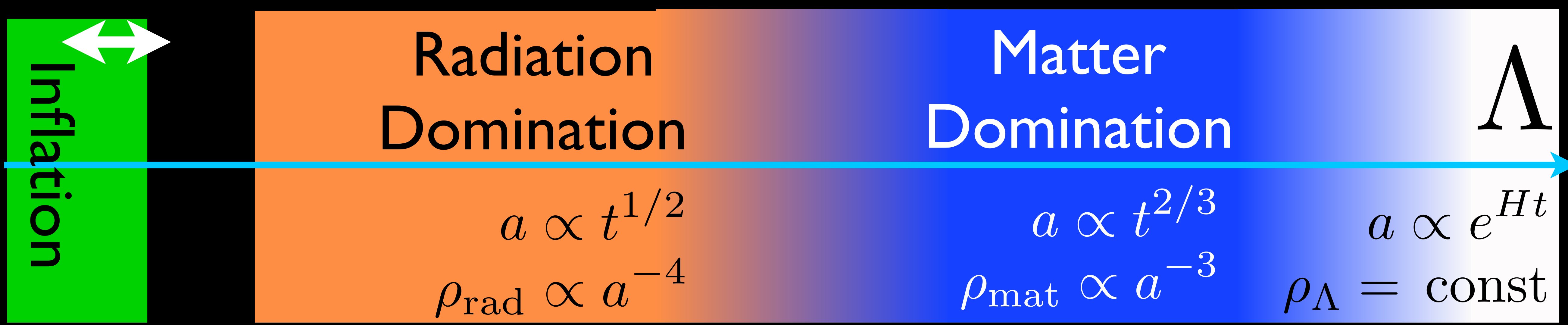


Talk Timeline

Part 1: Probing inflation with dark matter minihalos

Part 2: Probing the pre-BBN thermal history and the origins of dark matter with small-scale and micro-scale structure

Part I
Probing Inflation with Minihalos



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

PRD Rapid Communications 97, 041303 (1712.05421)

PRD 98, 063527 (1806.07389)

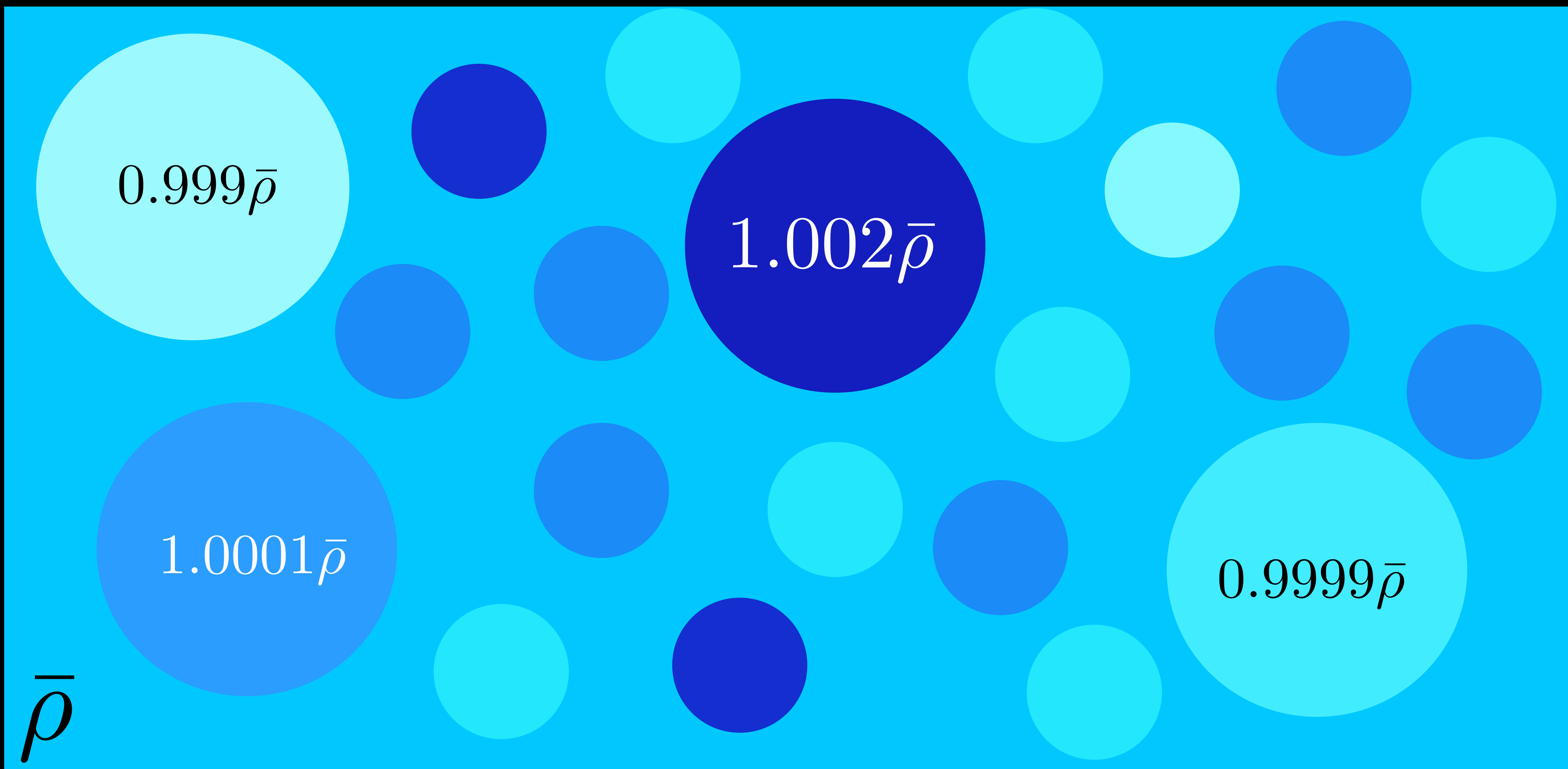
M. Sten Delos, *Margie Bruff, ALE*

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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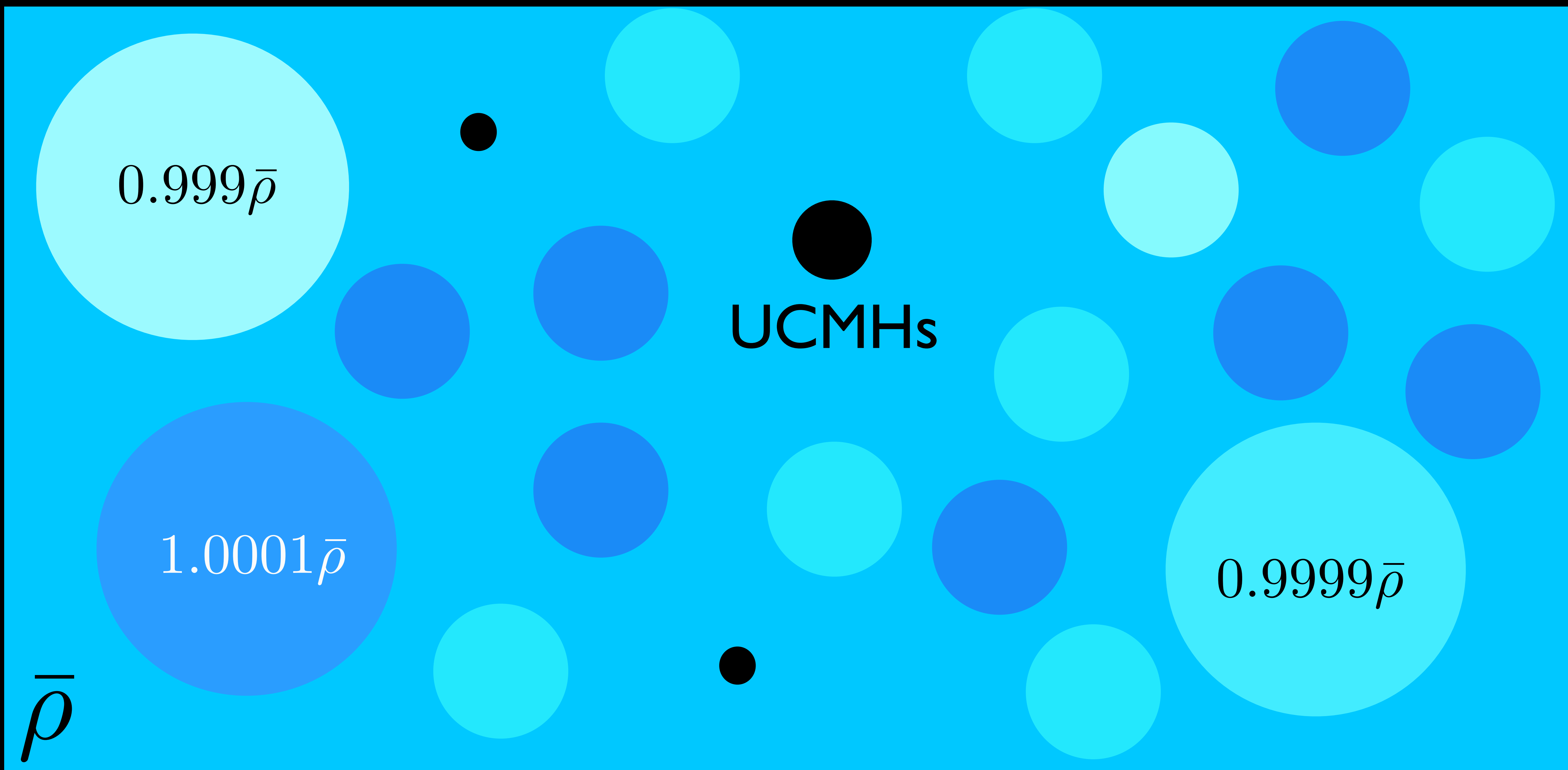
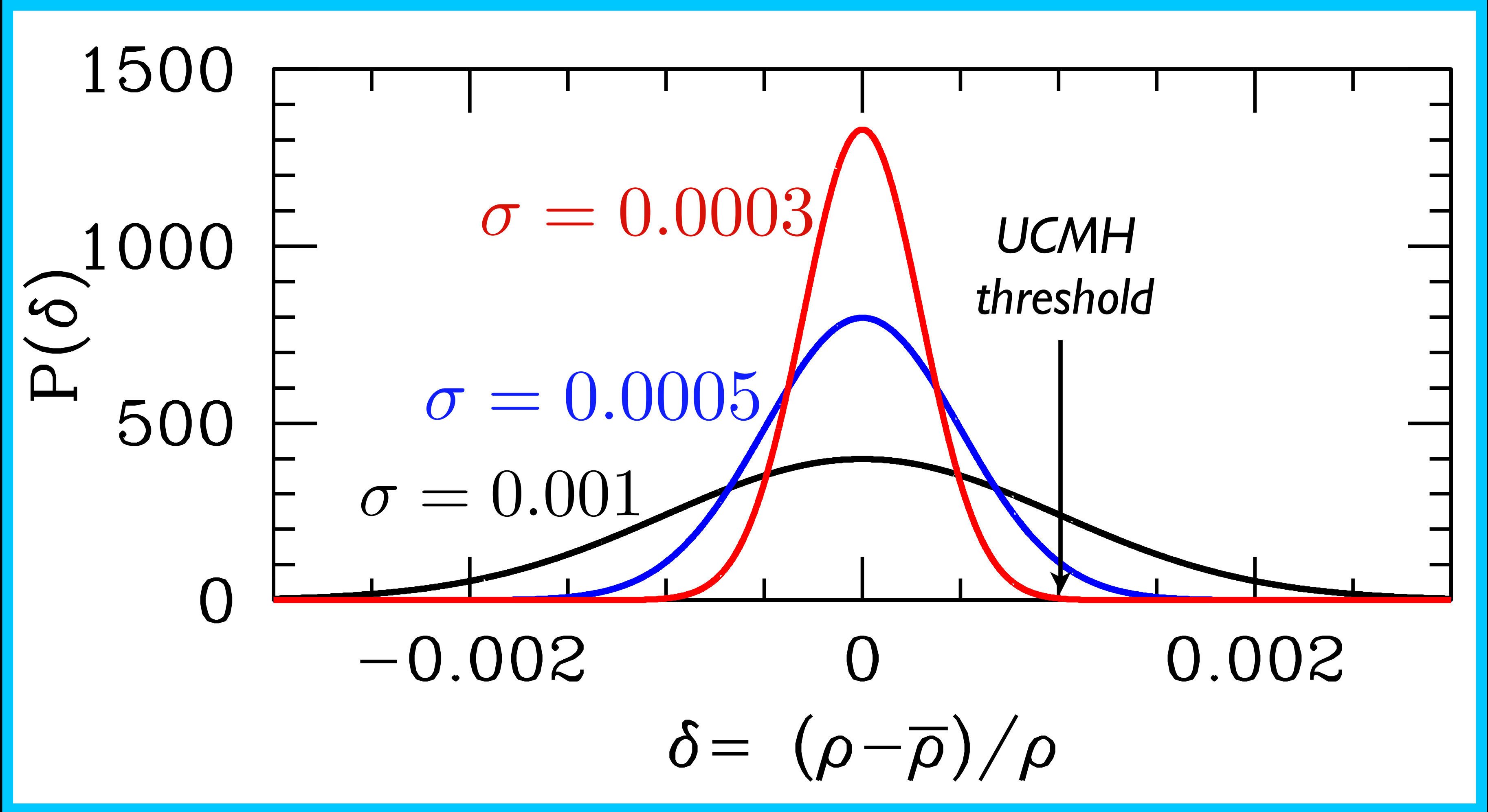


UCMHs Probe Power Spectrum

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



$$\sigma^2(R) = \text{variance of } \delta(R)$$

directly related to primordial power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = 1.1\sigma^2_{\text{hor}}(R = k^{-1})$$

Josan & Green 2010; Bringmann, Scott, Akrami 2012

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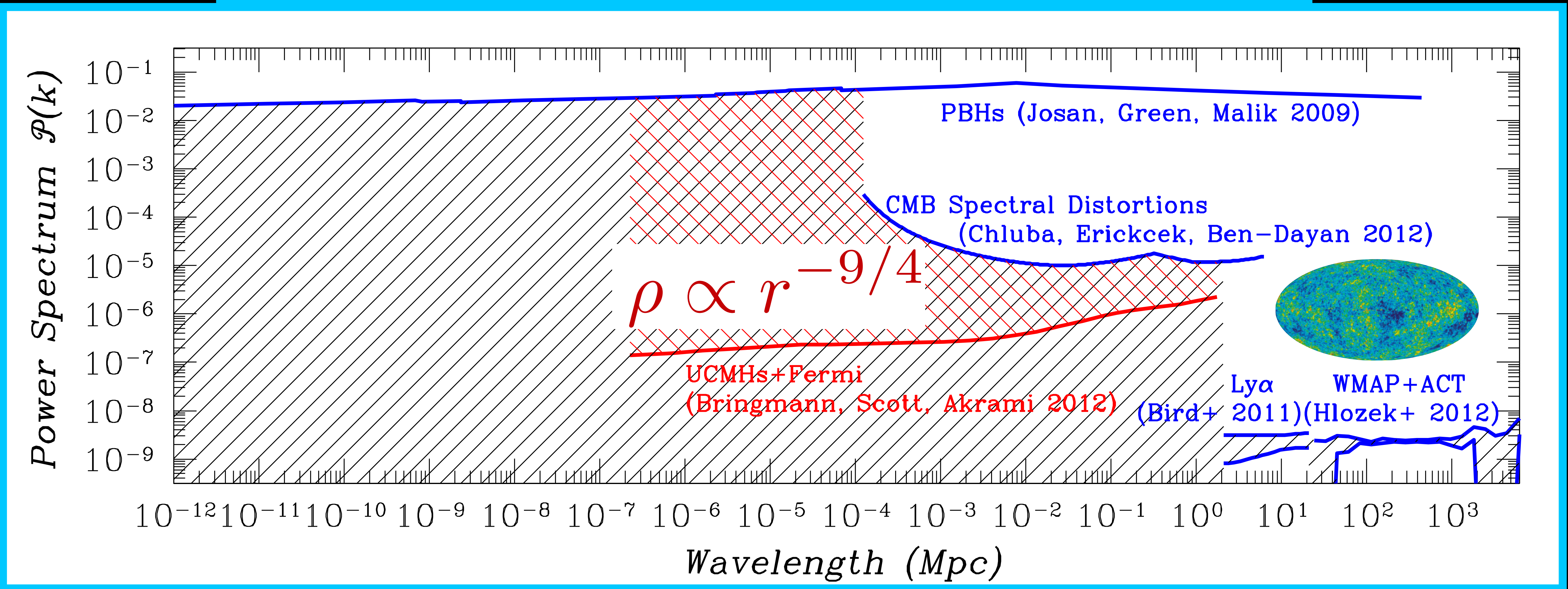

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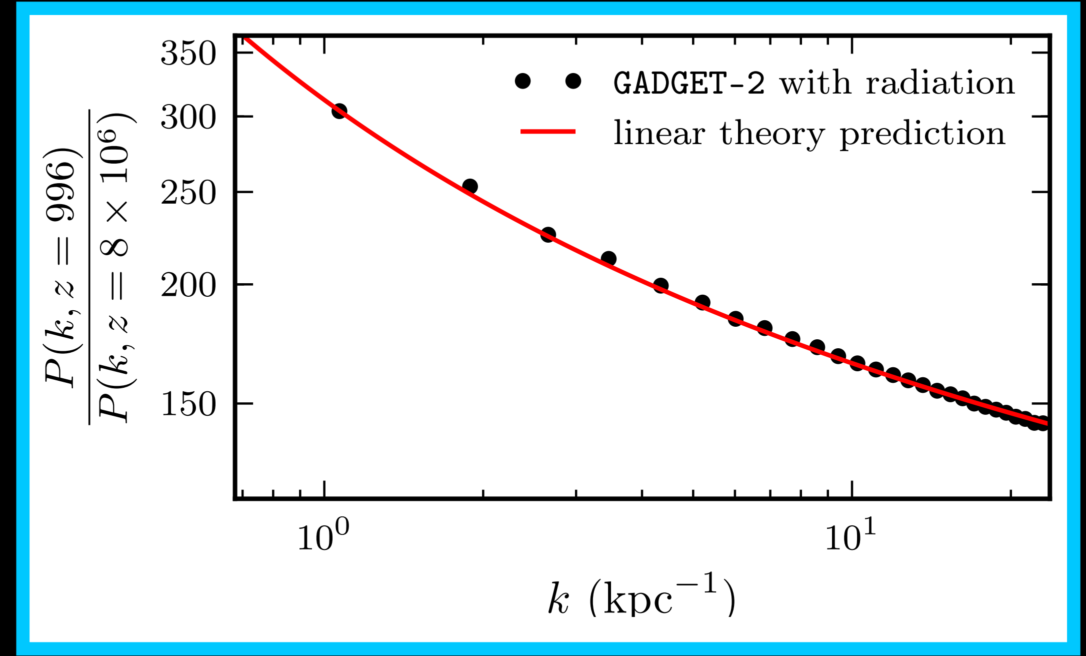
Simulations of UCMHs

Delos, ALE, Bailey, Alvarez
1712.05421
See also Gosenca+ 2017

1. Modify GadgetV2 to include smooth radiation component.



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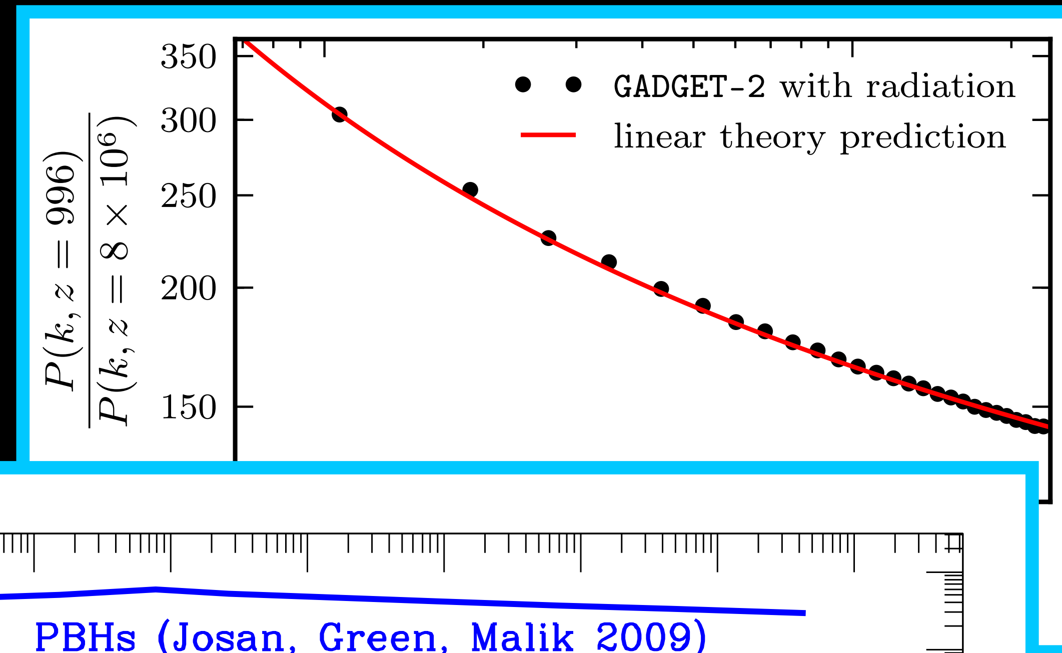

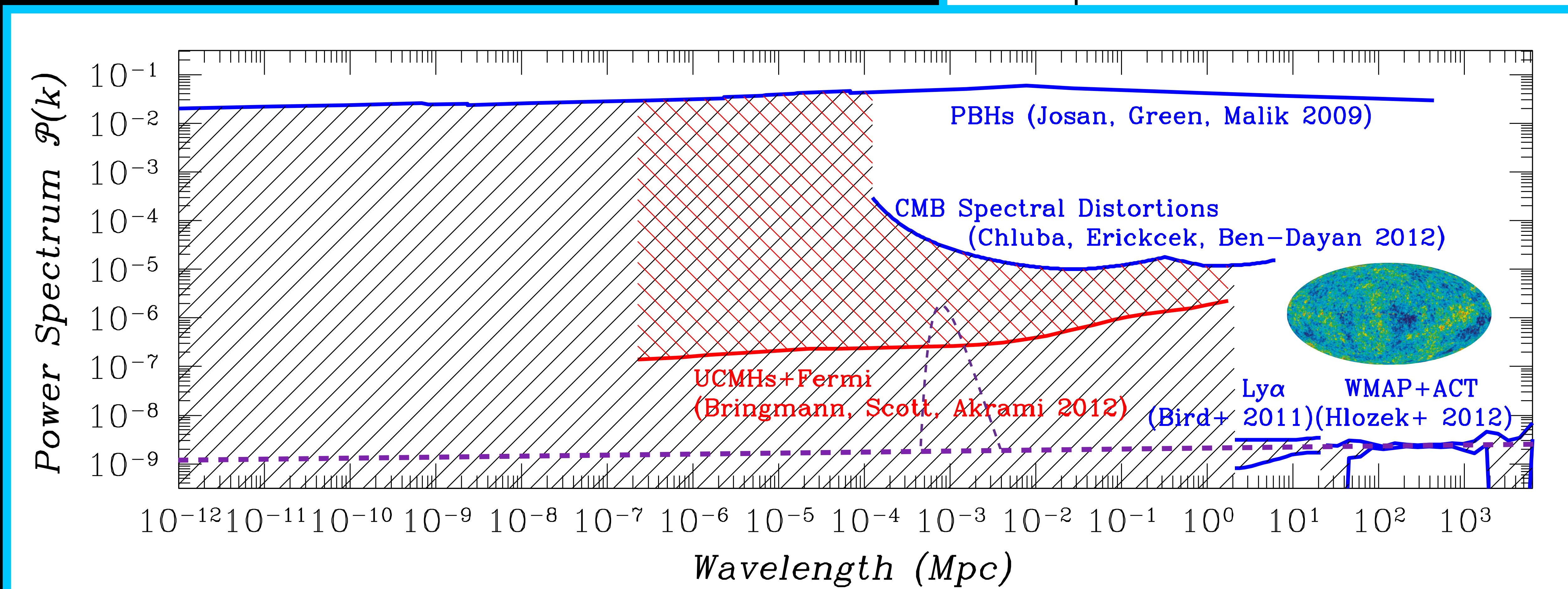

Simulations of UCMHs

Delos, ALE, Bailey, Alvarez
1712.05421
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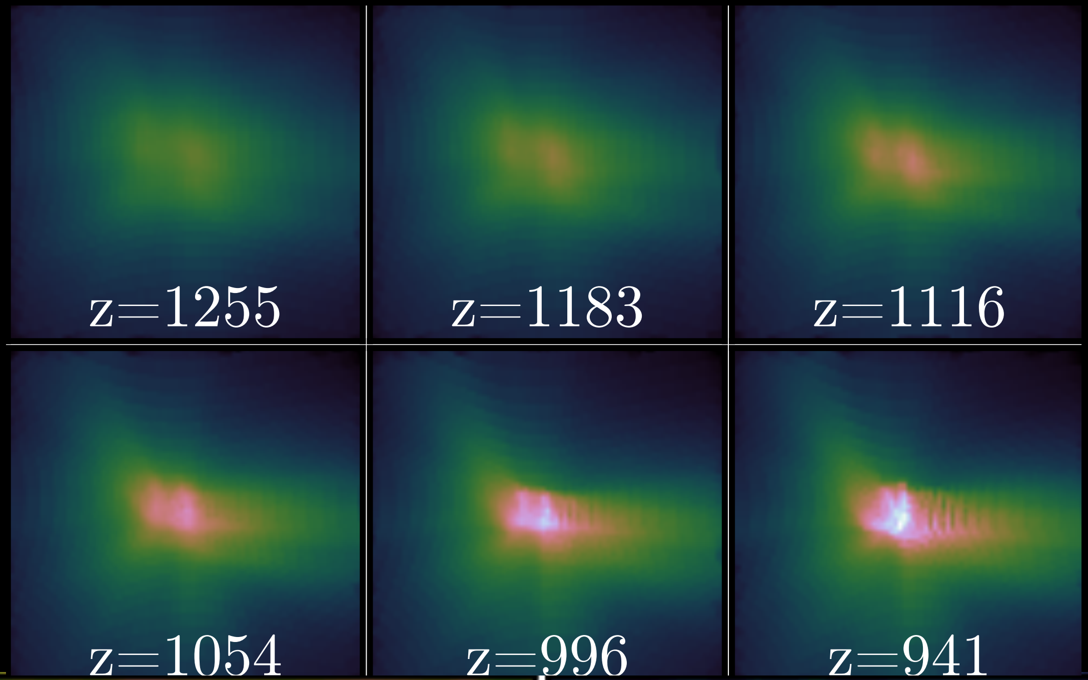
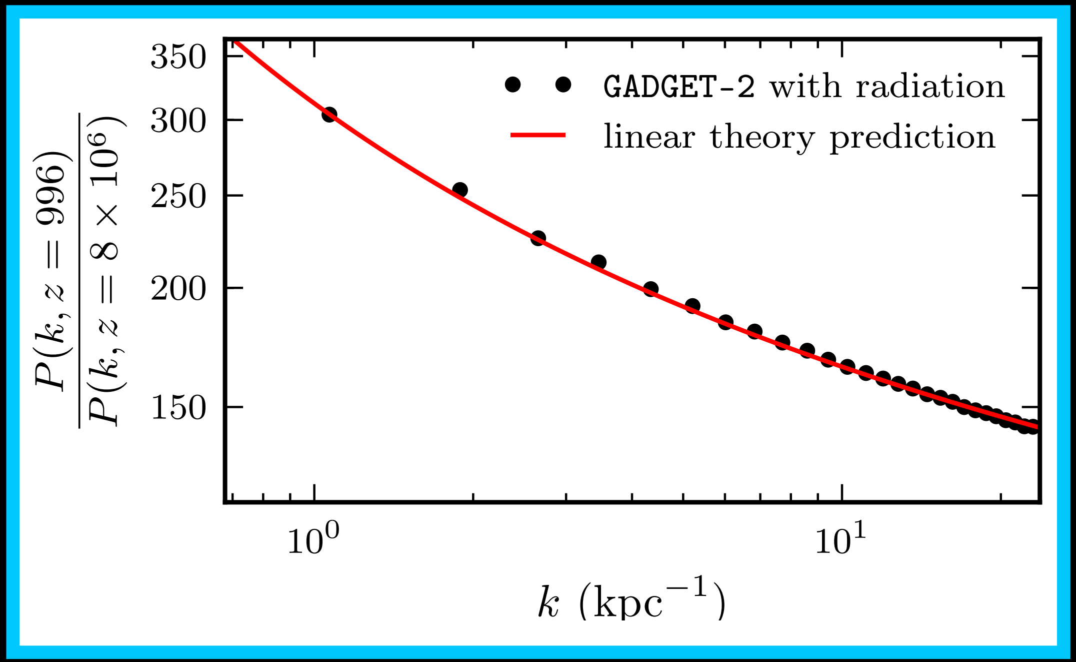
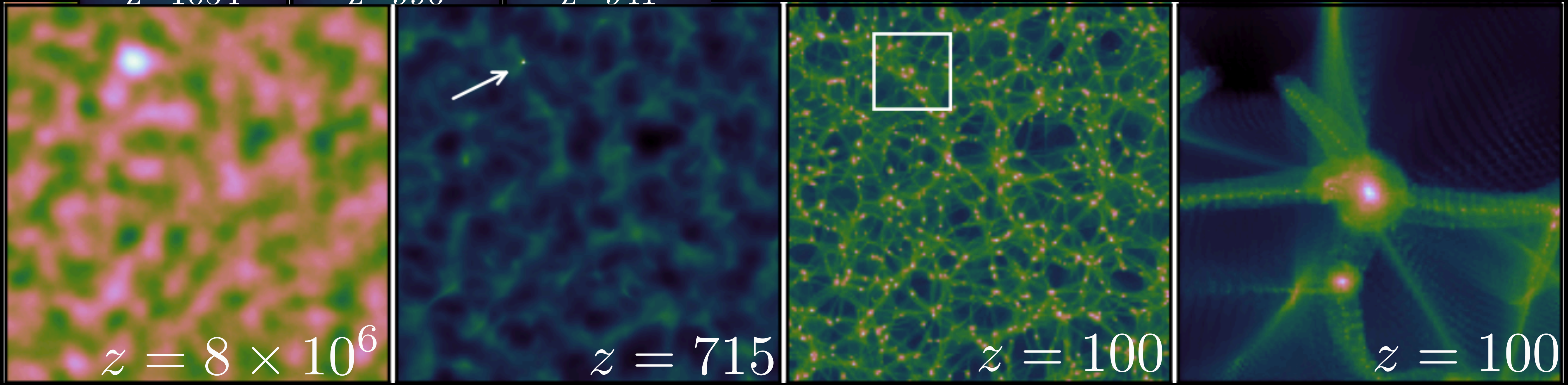
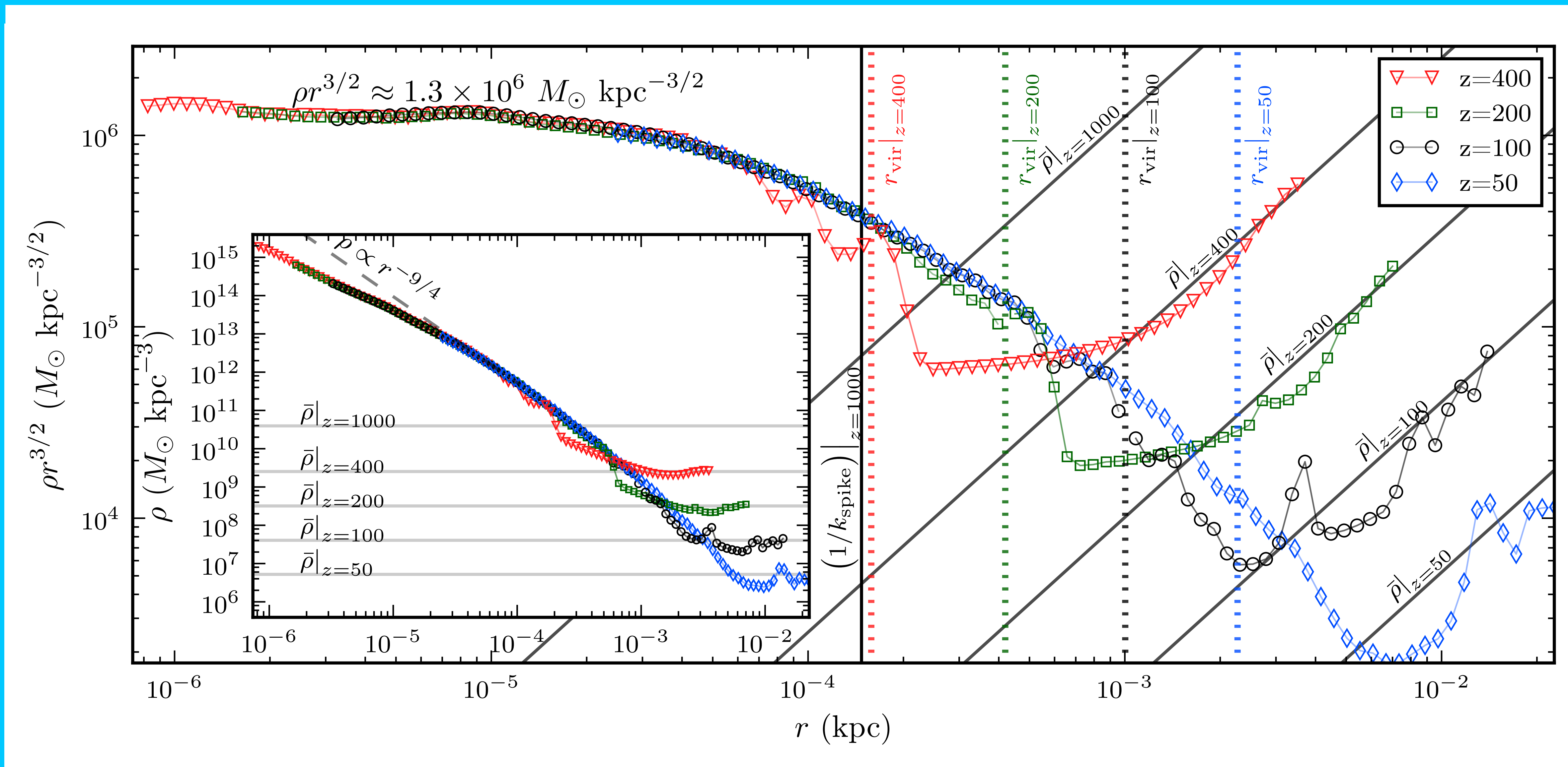
1. Modify GadgetV2 to include smooth radiation component.
2. Generate initial conditions from a power spectrum with a spike.
3. Make an UCMH!





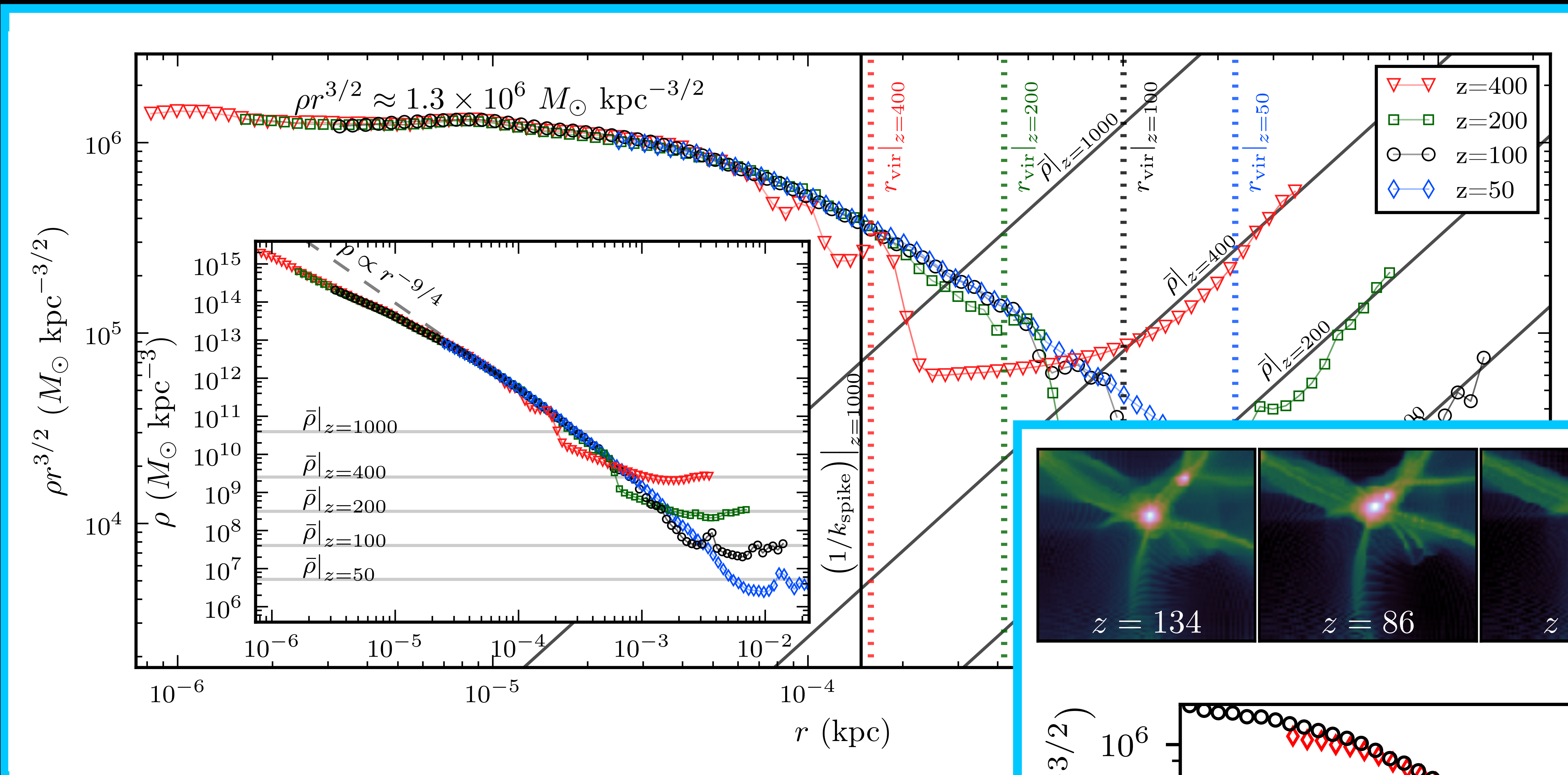


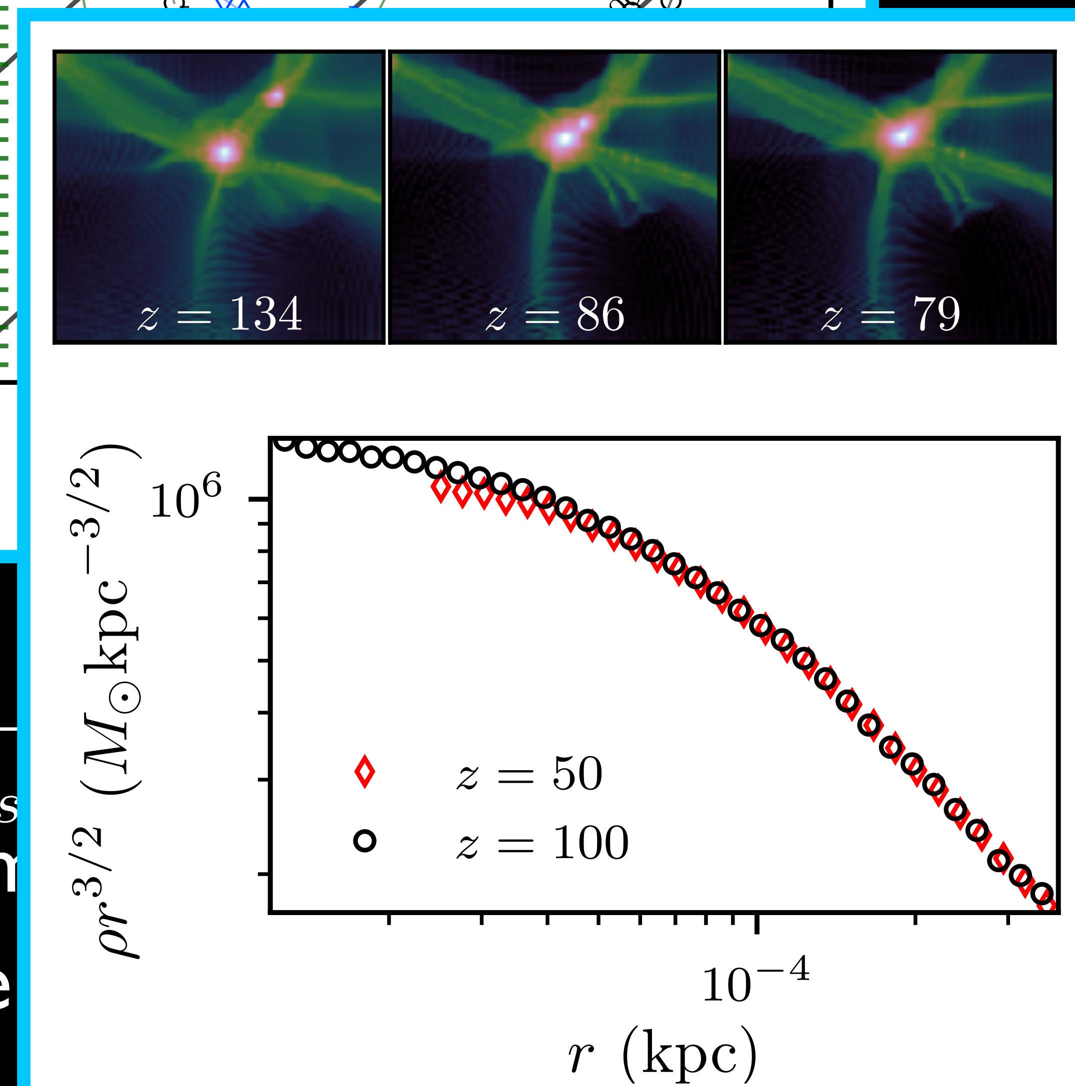
UCMH Density Profiles: Spike



- Nine simulated UCMHs
- All have similar density profiles: $\rho = \dfrac{\rho_s}{(r/r_s)^{1.5}(1+r/r_s)^{1.5}}$
- This profile is shared by the first halos in many different scenarios
- Stable with redshift, unless there's a merger....

UCMH Density Profiles: Spike





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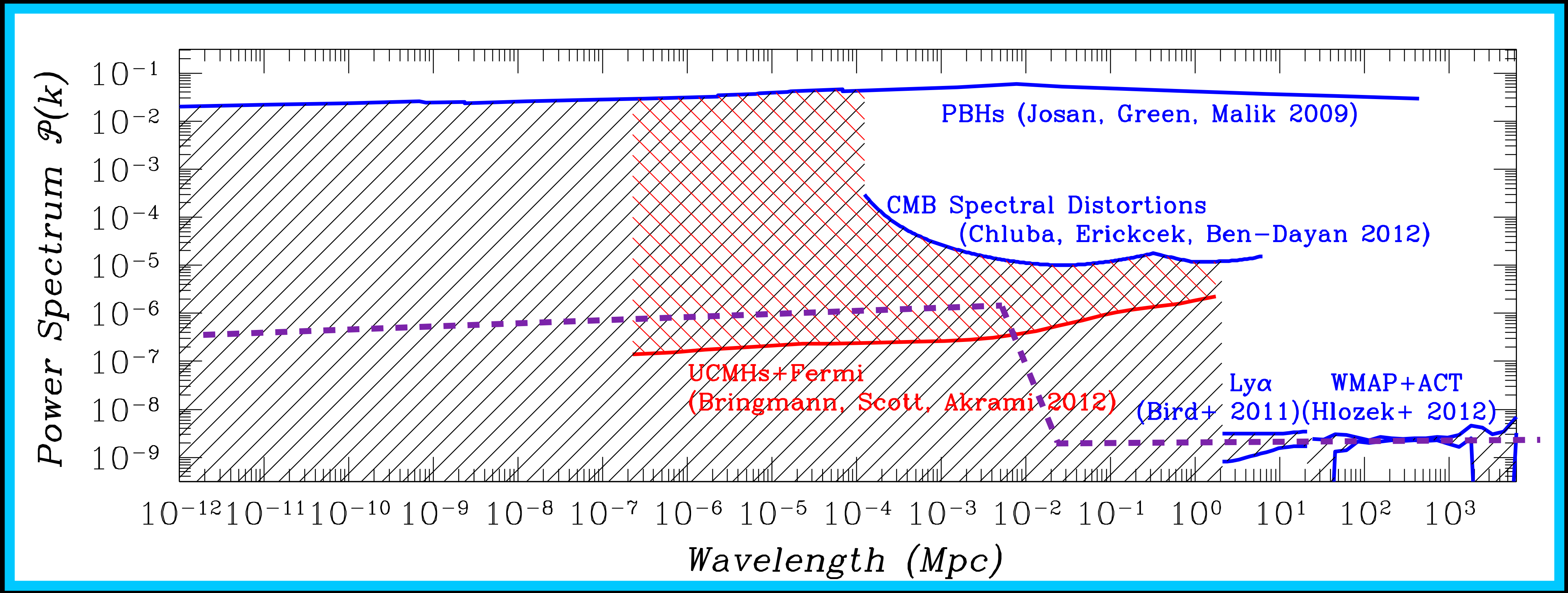
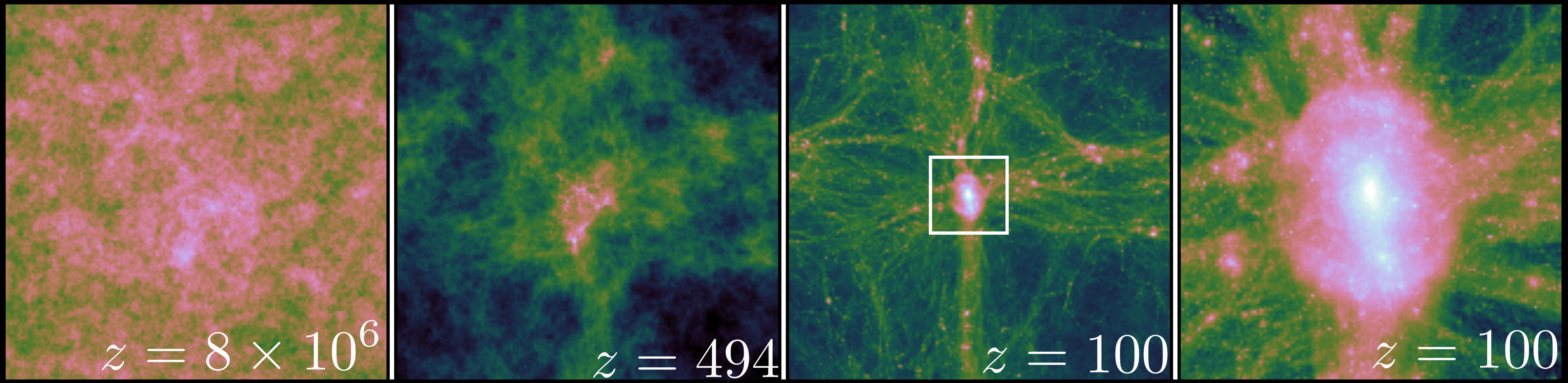
UCMH Density Profiles: Plateau

We also formed UCMHs using a plateau feature





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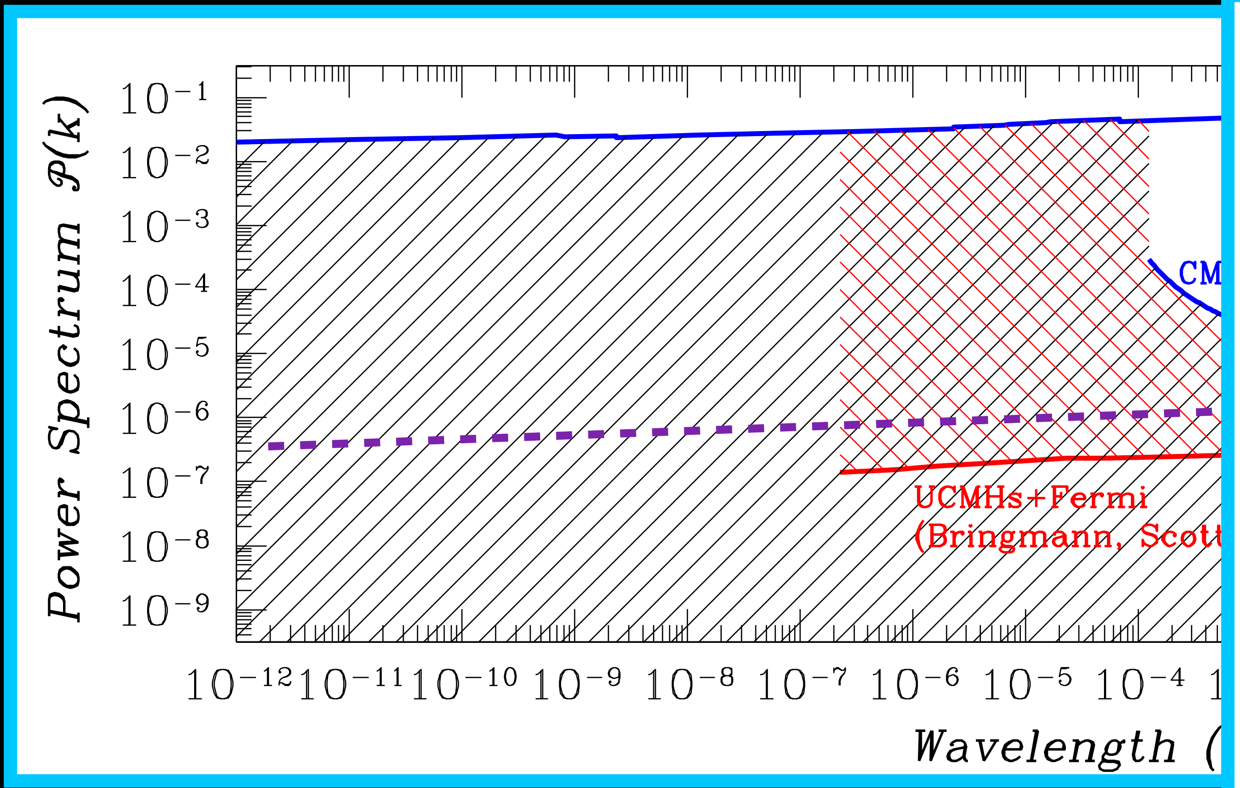
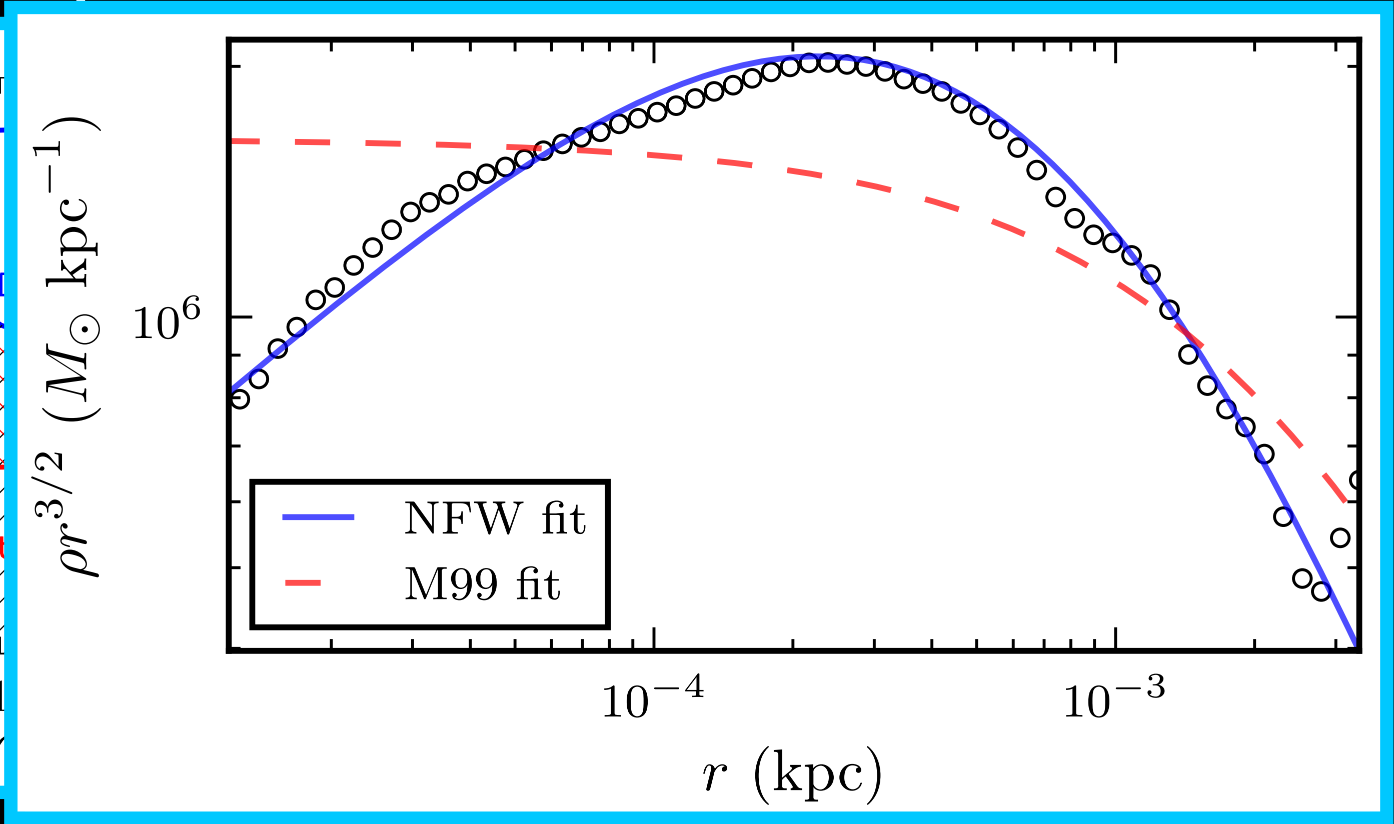
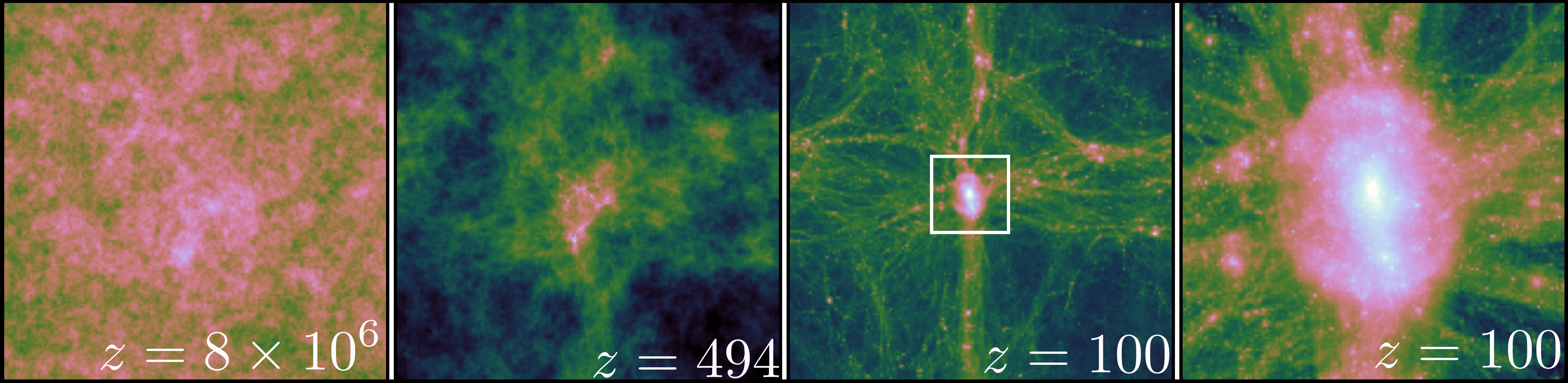


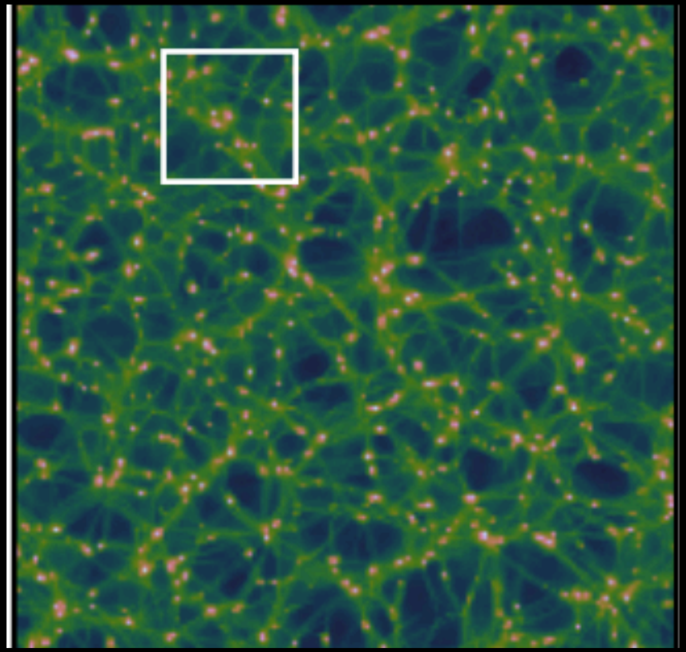


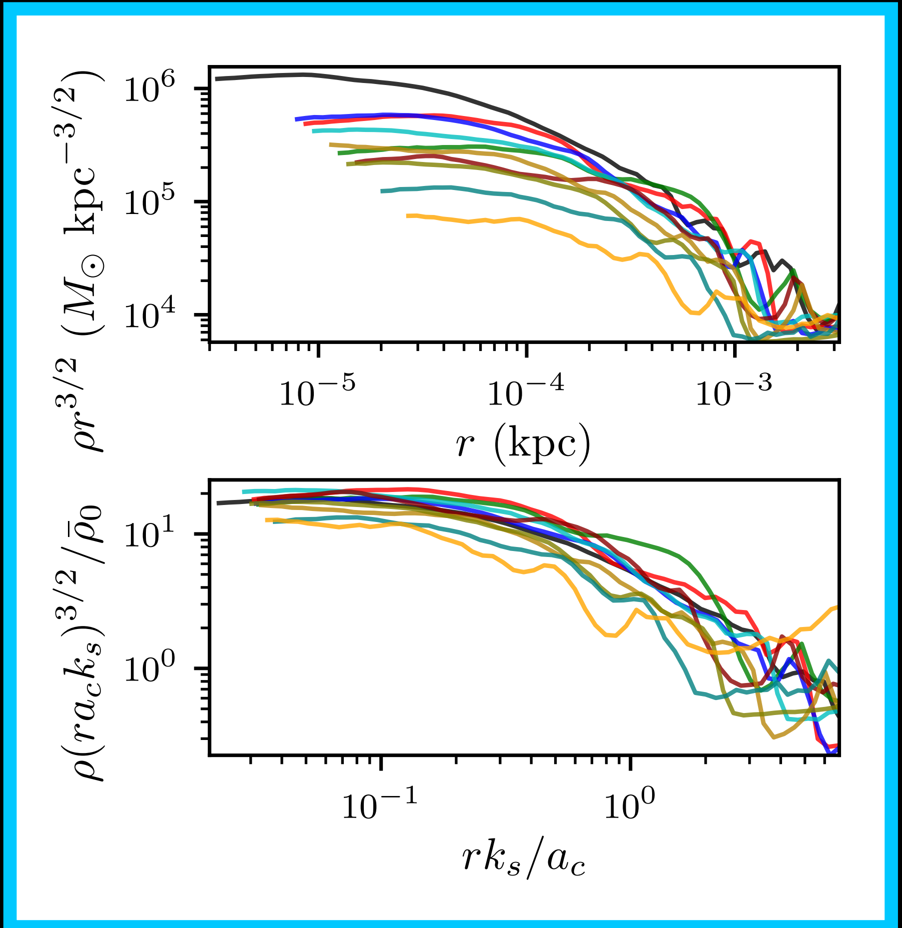
and these UCMHs have NFW proflies!



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...





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

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

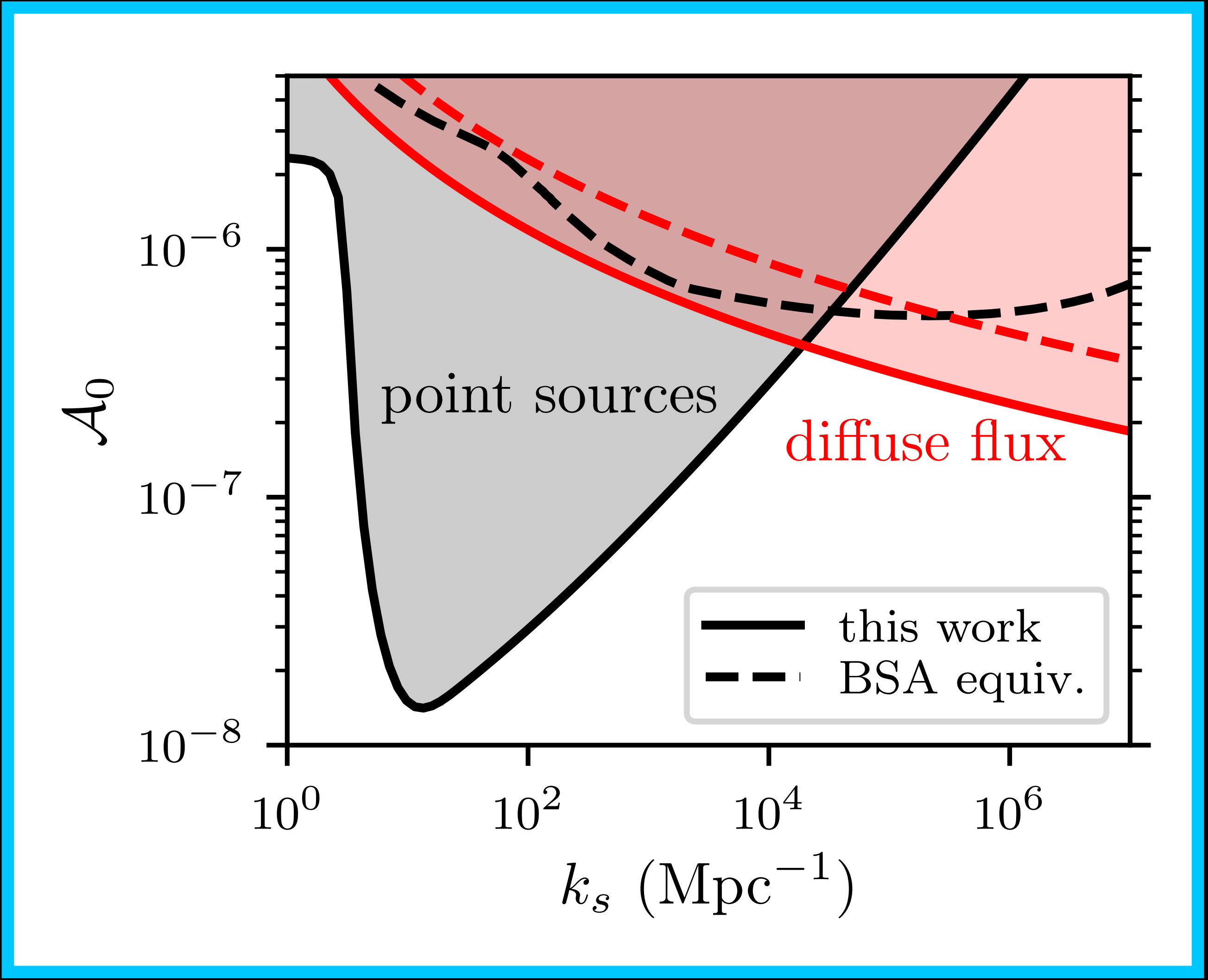
- We then use statistics of peaks to get the number density of halos as a function of formation time.

New Constraints on *P(k)*

Delos, ALE, Bailey, Alvarez
1806.07389

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

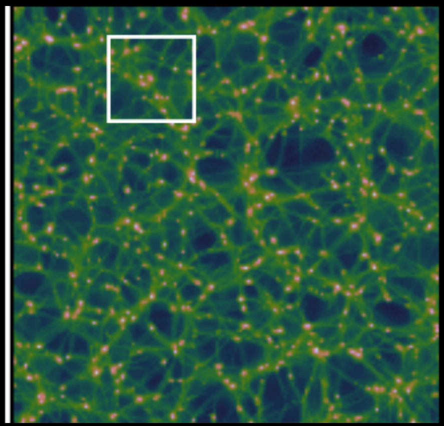
$$\mathcal{P}_\zeta(k) = \mathcal{A}_0 k_s \delta(k - k_s)$$



- For comparison, we also use the BSA 2012 UCMH abundance constraints to obtain a bound on this power spectrum.
- Including all minihalos more than compensates for the reduction in minihalo luminosity due to the shallower density profiles.
- Our *P(k)* bounds are more sensitive to changes in minihalo abundance limits.

Summary: Minihalos probe inflation

- 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 ($\rho \propto r^{-1}$).
- But if we include all the minihalos that form from an enhanced power spectrum, we can obtain stronger constraints on *P(k)*, in spite of the shallower density profiles.



M. Sten Delos, *ALE, Avery Bailey, Marcelo Alvarez*
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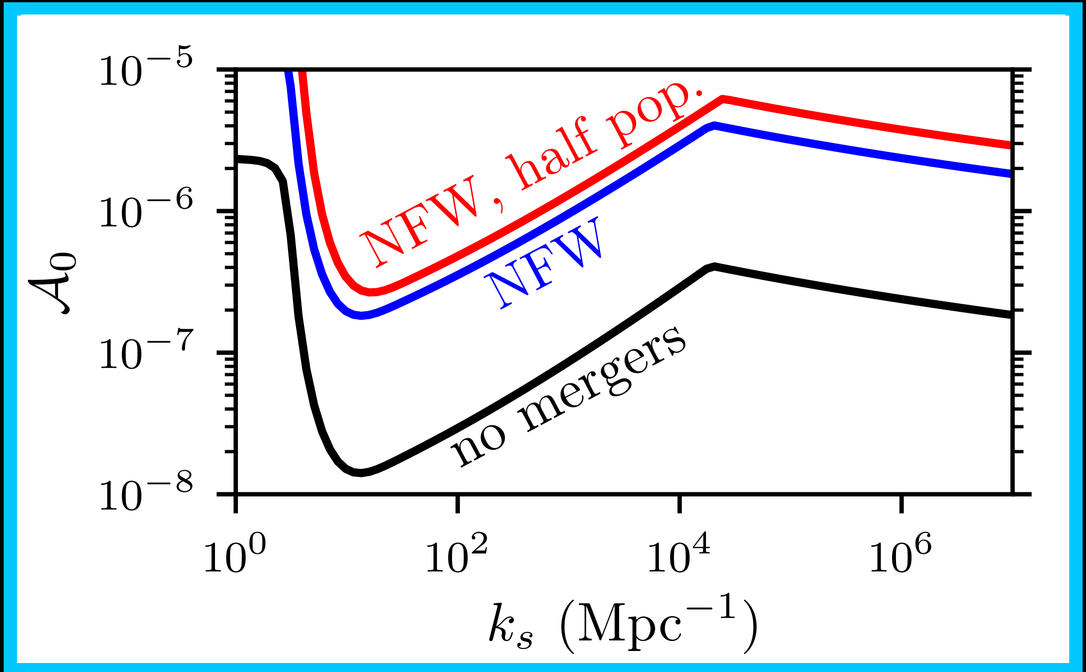
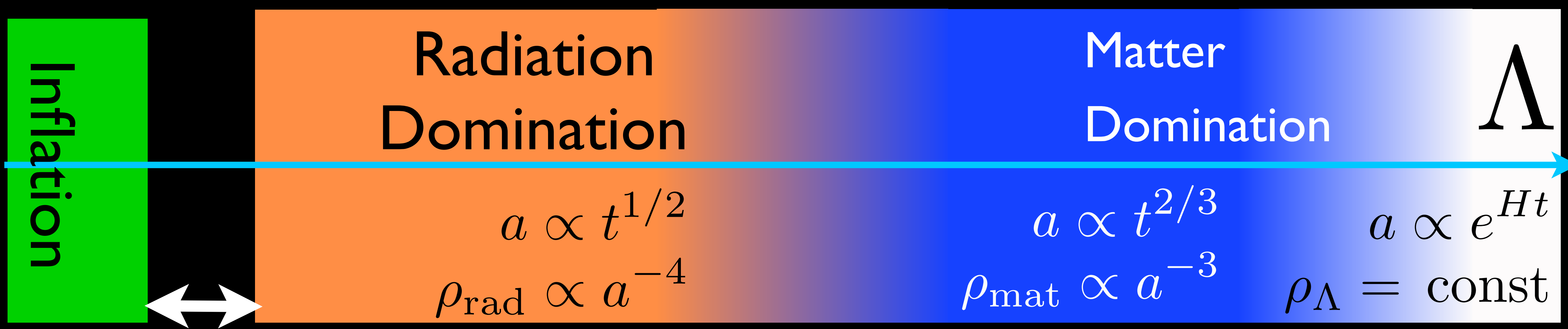
Looking forward:

- An improved and generic model for minihalo density profiles: *Delos et al. 1905.05766*
- Include the effects of minihalo mergers
- Look beyond a delta-function spike in *P(k)*
- Constrain inflation models



STAY TUNED

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



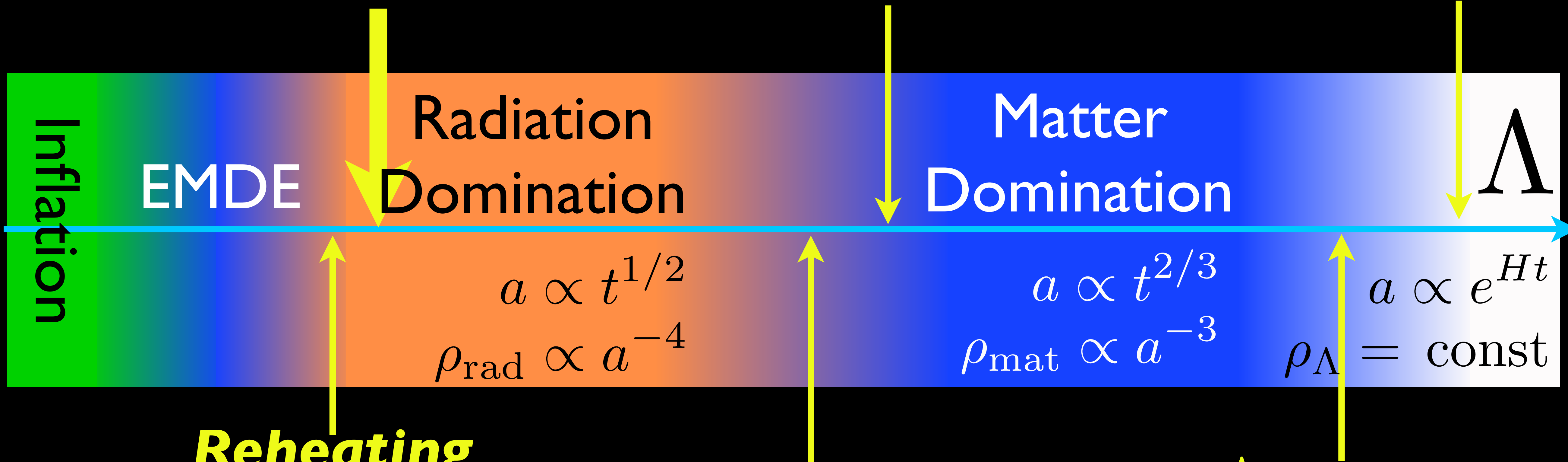
ALE & Kris Sigurdson; PRD 84, 083503 (2011)
ALE; PRD 92, 103505 (2015)
ALE, Kuver Sinha, Scott Watson; PRD 94, 063502 (2016)
Isaac Raj Waldstein, ALE, Cosmin Ilie; PRD 95, 123531 (2017)
Carlos Blanco, **M. Sten Delos**, ALE, Dan Hooper; PRD 100, 103010 (2019)
Carisa Miller, ALE, Riccardo Murgia; PRD 100, 123520 (2019)
M. Sten Delos, Tim Linden, ALE; PRD 100, 123546 (2019)
Work in progress with **Sheridan Green, Charlie Mace, Himanish Ganjoo**

Cosmic Timeline

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

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

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



Reheating
$T = ?$

Matter-Radiation Equality
$T = 0.74\,\mathrm{eV}$
$t = 57,000\,\mathrm{yr}$

Matter-Λ Equality
$T = 3.2 \times 10^{-4}\,\mathrm{eV}$
$t = 9.5\,\mathrm{Gyr}$

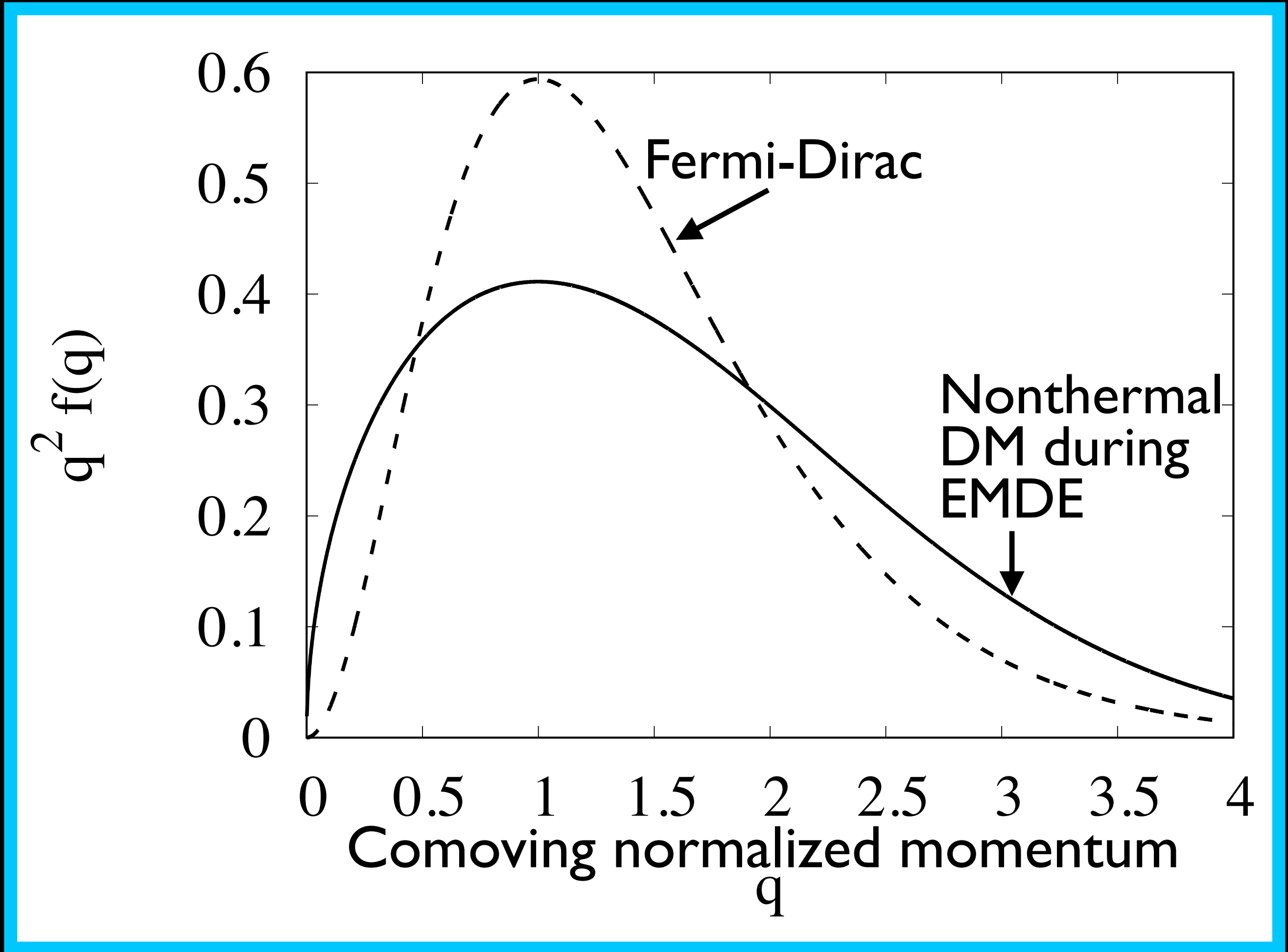
Implications:
1. Dark matter production
2. Early structure growth

Nonthermal DM during an EMDE

Dark matter may have been created directly from the decay of the heavier particle that dominated the Universe during the early matter-dominated era (EMDE).

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

Carisa Miller, *ALE, Riccardo Murgia, arXiv: 1908.10369*

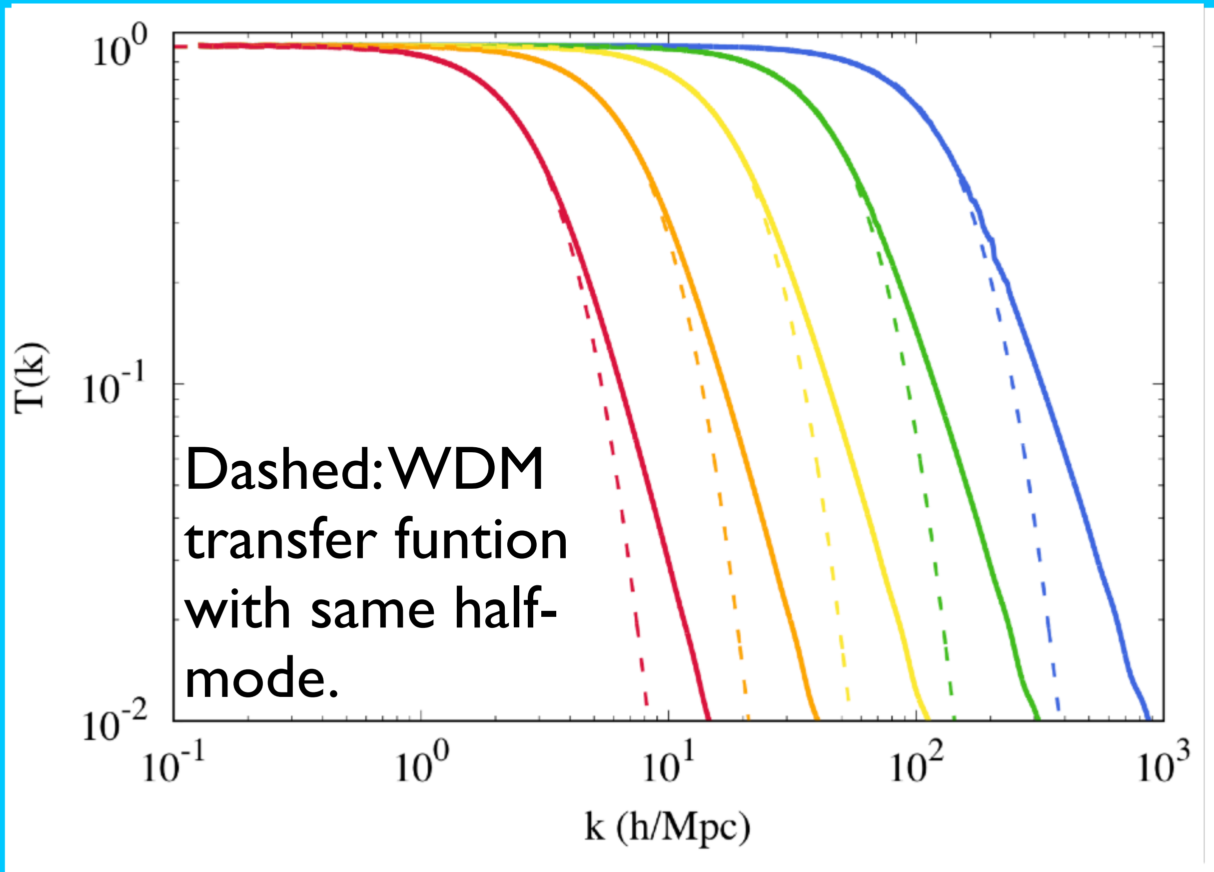


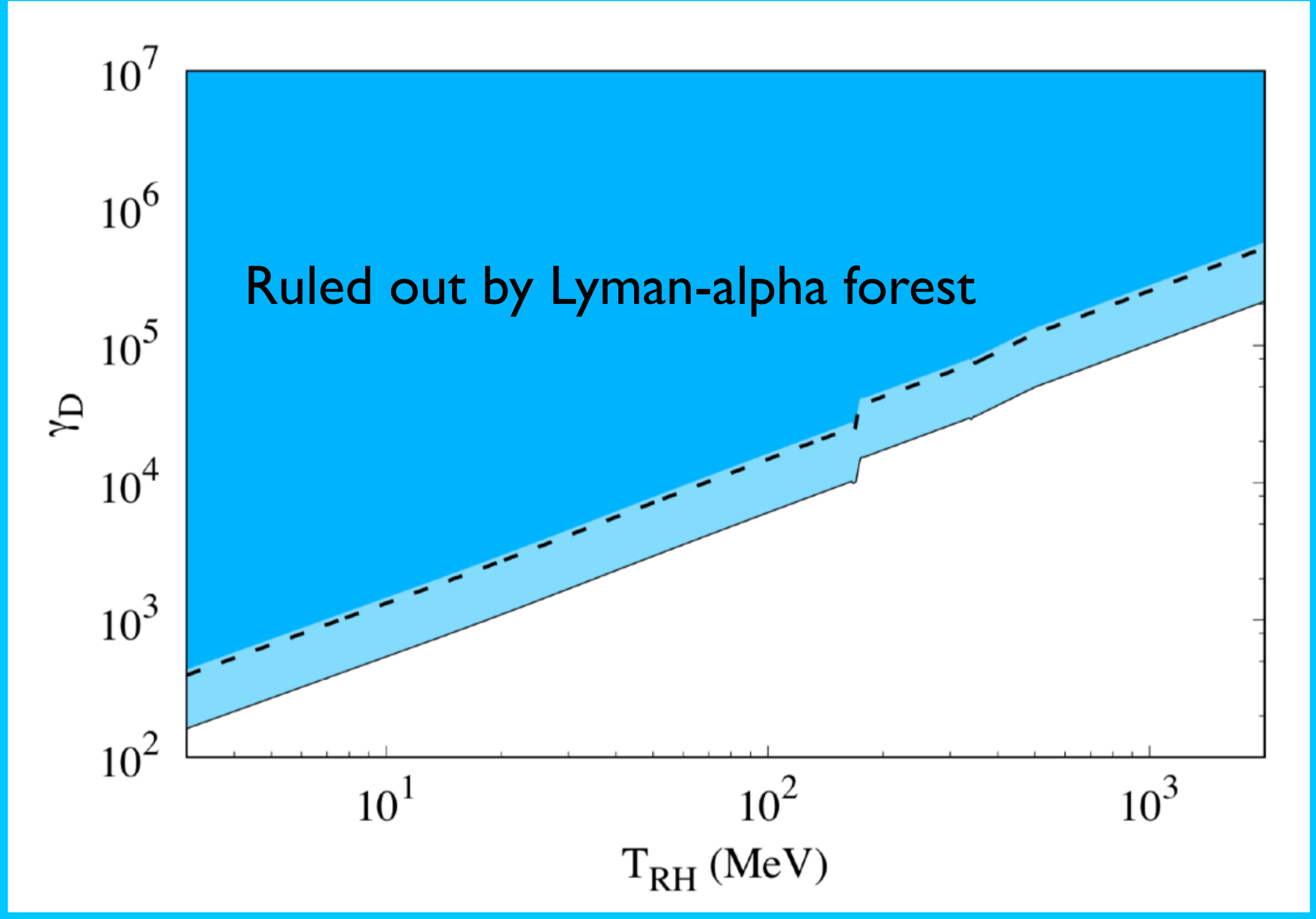
Probing nonthermal DM production

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

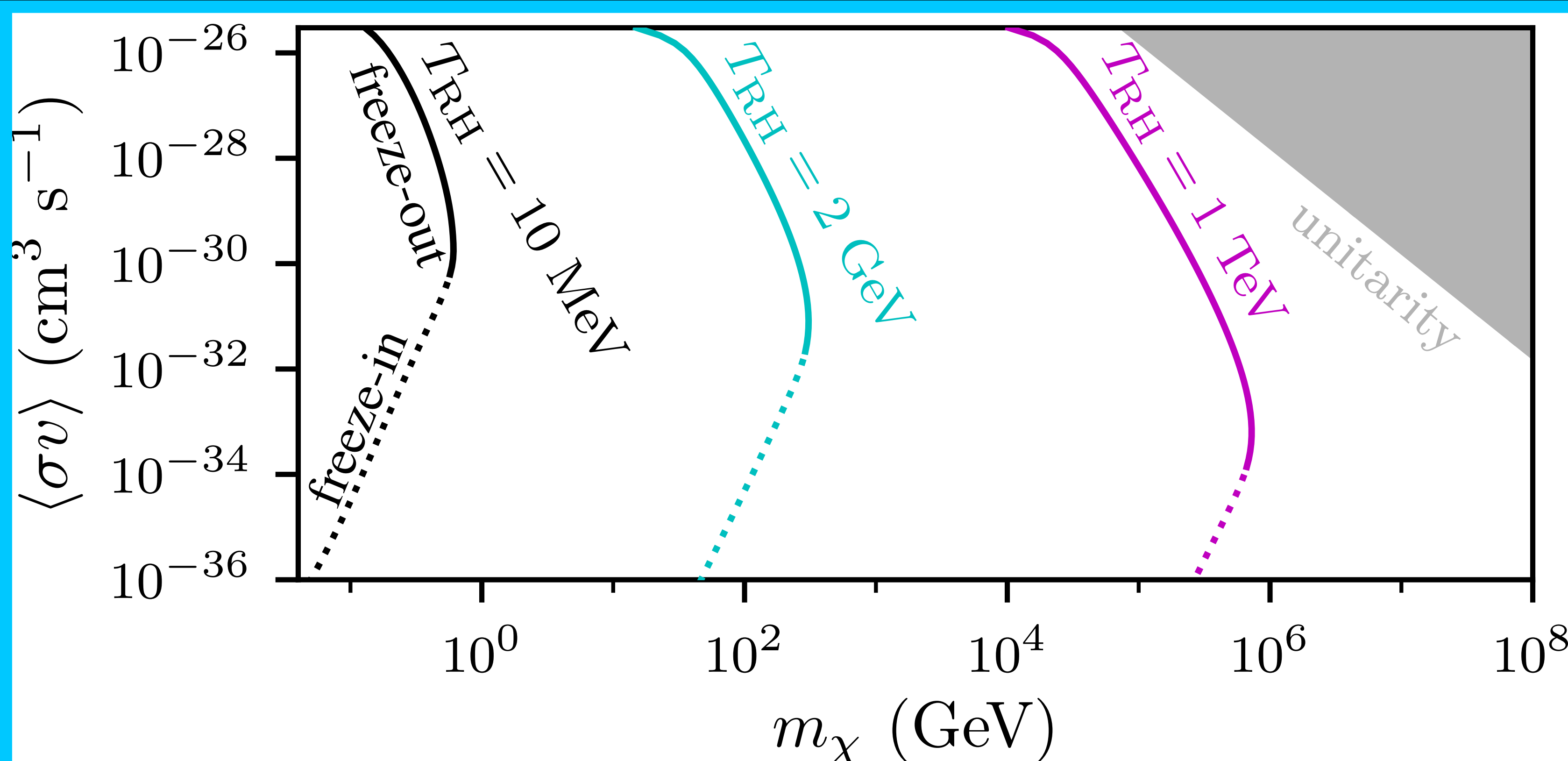
- Use CLASS to determine matter power spectrum.
- Free-streaming length predicts suppression scale.
- Apply bounds from observations of Lyman-alpha forest.

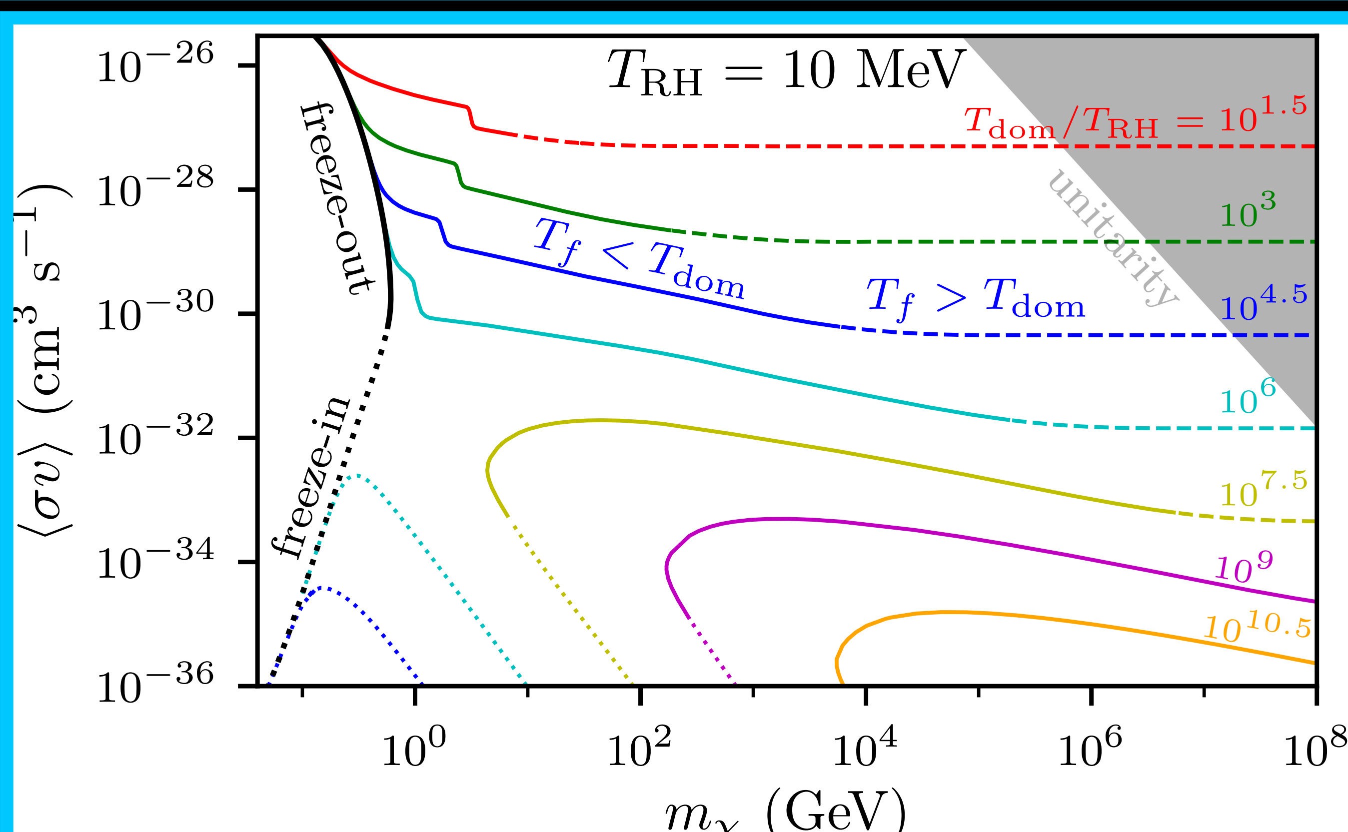
Carisa Miller,
Riccardo Murgia, ALE
arXiv: 1908.10369





Thermal DM Production with an EMDE





Giudice, Kolb, Riotto 2001
ALE 2015
M. Sten Delos, Tim Linden, ALE 2019

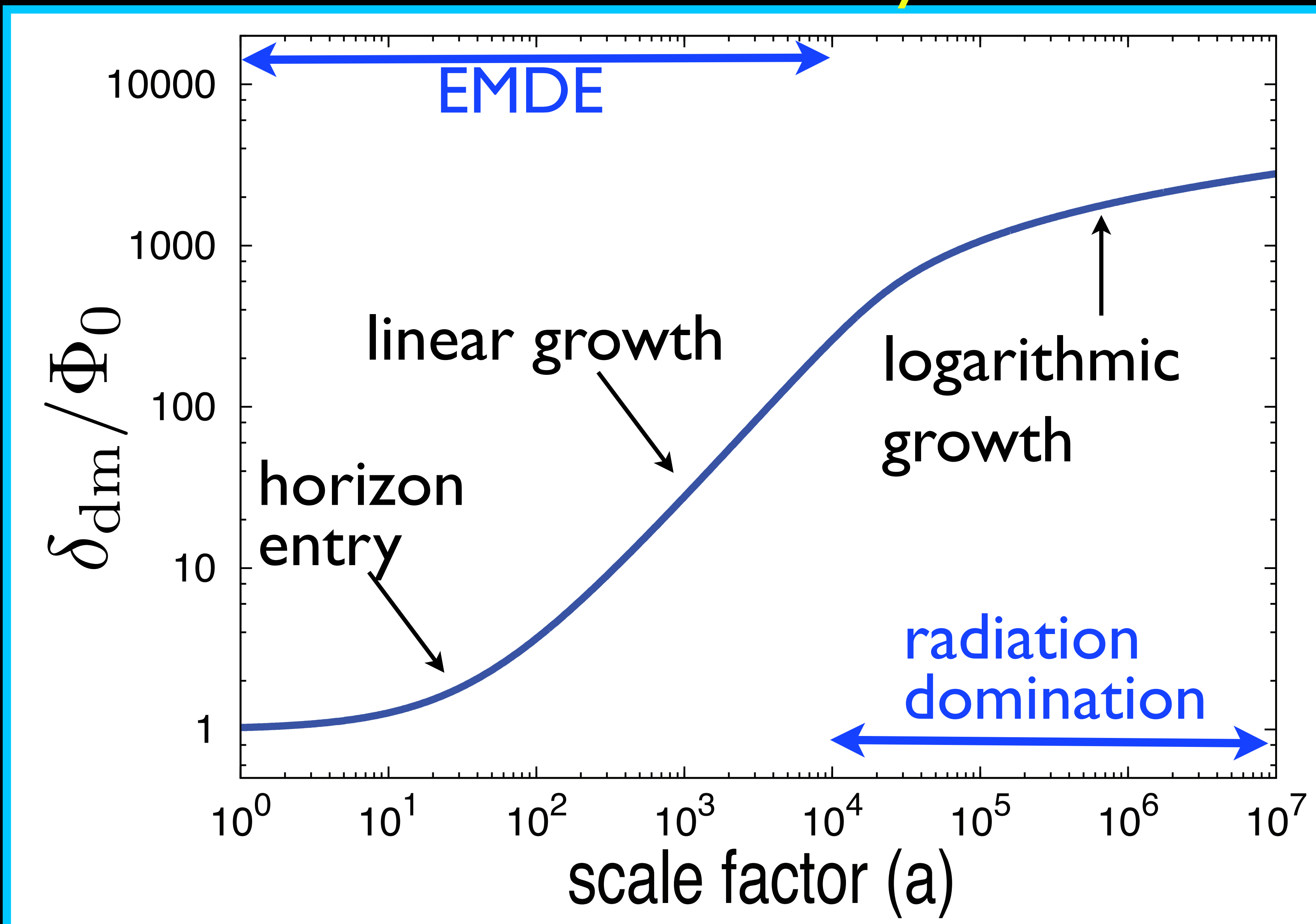
The creation of new SM particles during the EMDE dilutes the DM abundance after freeze-out, so smaller annihilation cross sections are needed to match DM density.

- A radiation-dominated era prior to the EMDE further widens the range of viable parameters.
- T_{dom} is the temperature at the start of the EMDE.

Another nightmare scenario?

Structure Growth during an EMDE

Evolution of the Matter Density Perturbation



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

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

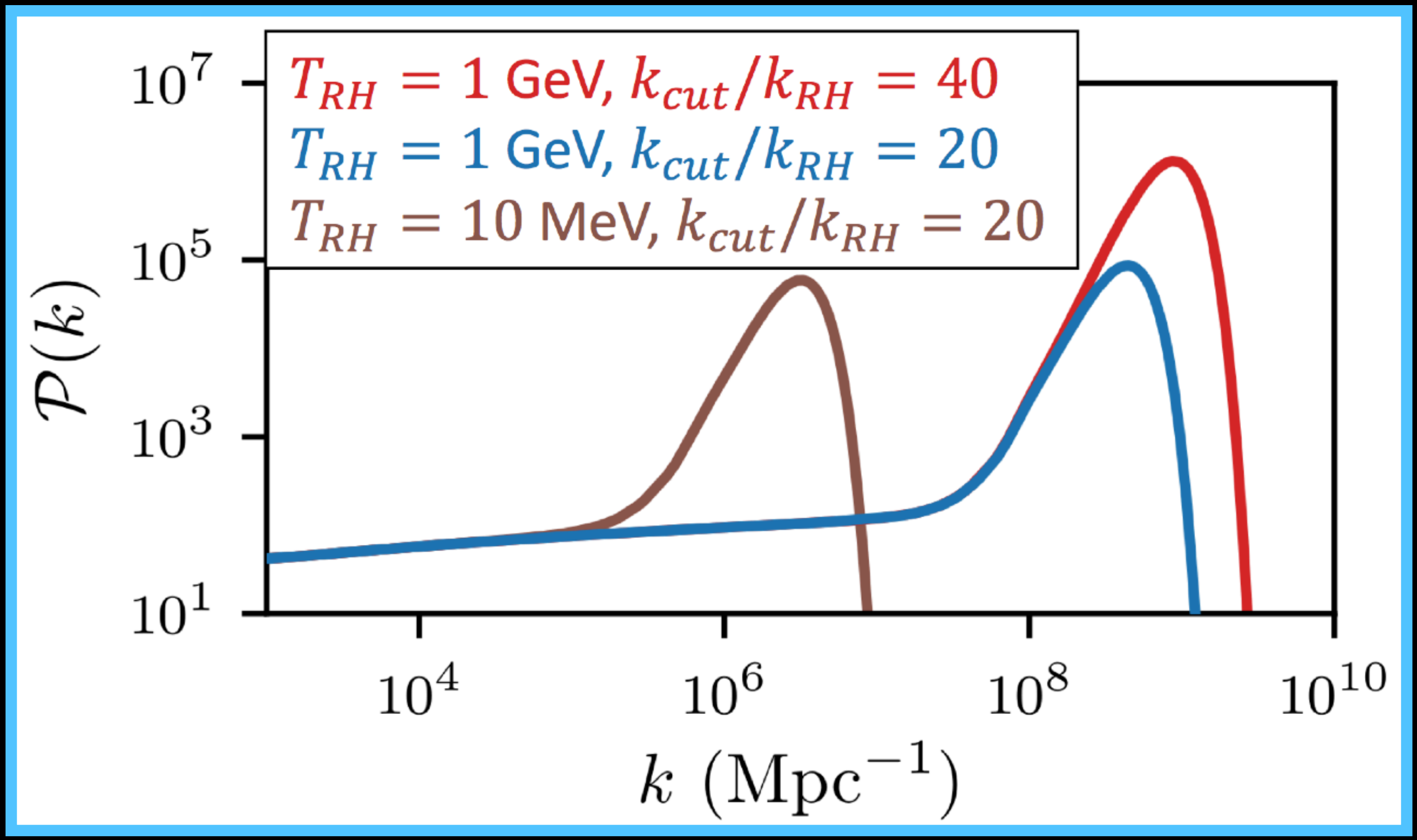
$$M_{\rm RH} \simeq 10^{-5}\, M_\oplus \left(\frac{1\,{\rm GeV}}{T_{\rm RH}}\right)^3$$

Microhalos!

The Small-Scale Cut-off

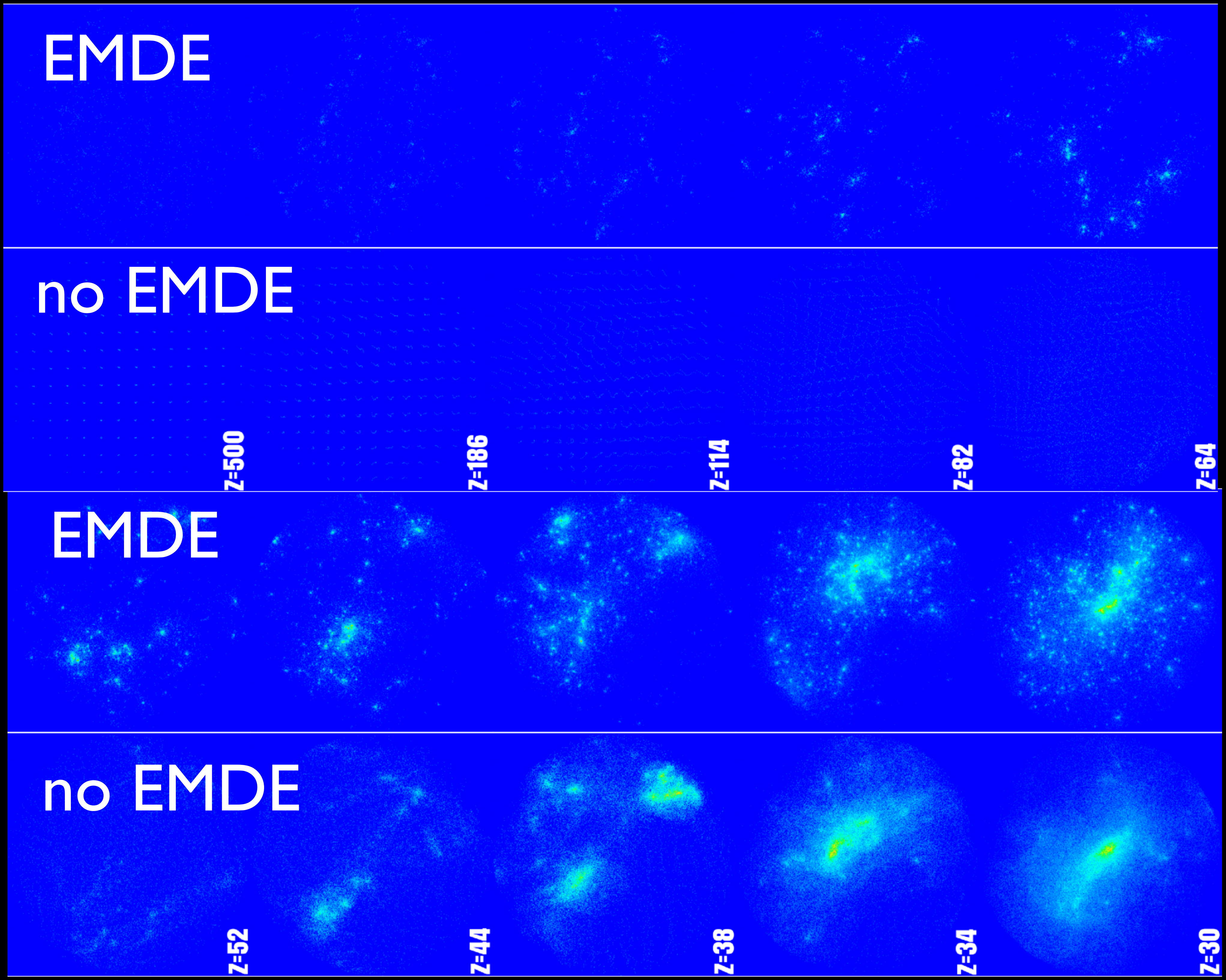
Free-streaming will exponentially suppress power on scales smaller than the free-streaming horizon: $\lambda_{\rm fsh}(t) = \int_{t_{\rm RH}}^{t} \frac{\langle v \rangle}{a}\,{\rm d}t$

The small-scale cut-off determines the mass and formation time of the first halos.



- For WIMP dark matter thermally produced during an EMDE, $k_{\rm fsh} \lesssim 80 k_{\rm RH}$
  ALE, Sinha, Watson 2016
- Dark matter in a hidden sector can be much colder; cut-off set by interactions within the hidden sector.

EMDE Microhalo Simulations



EMDE

$$T_{\rm RH} = 30 \text{ MeV}$$

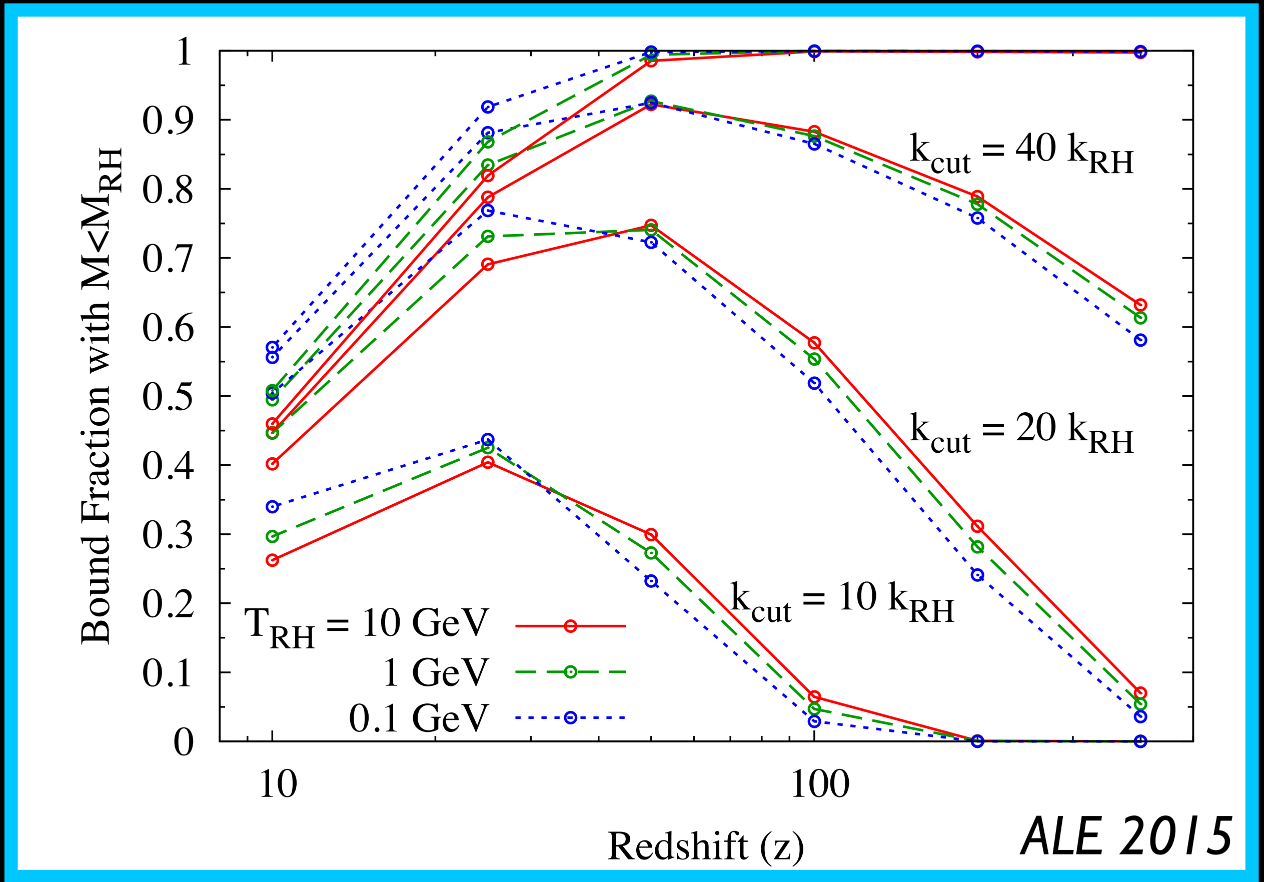
$$k_{\rm cut} = 20 k_{\rm RH}$$

Microhalos within microhalos!

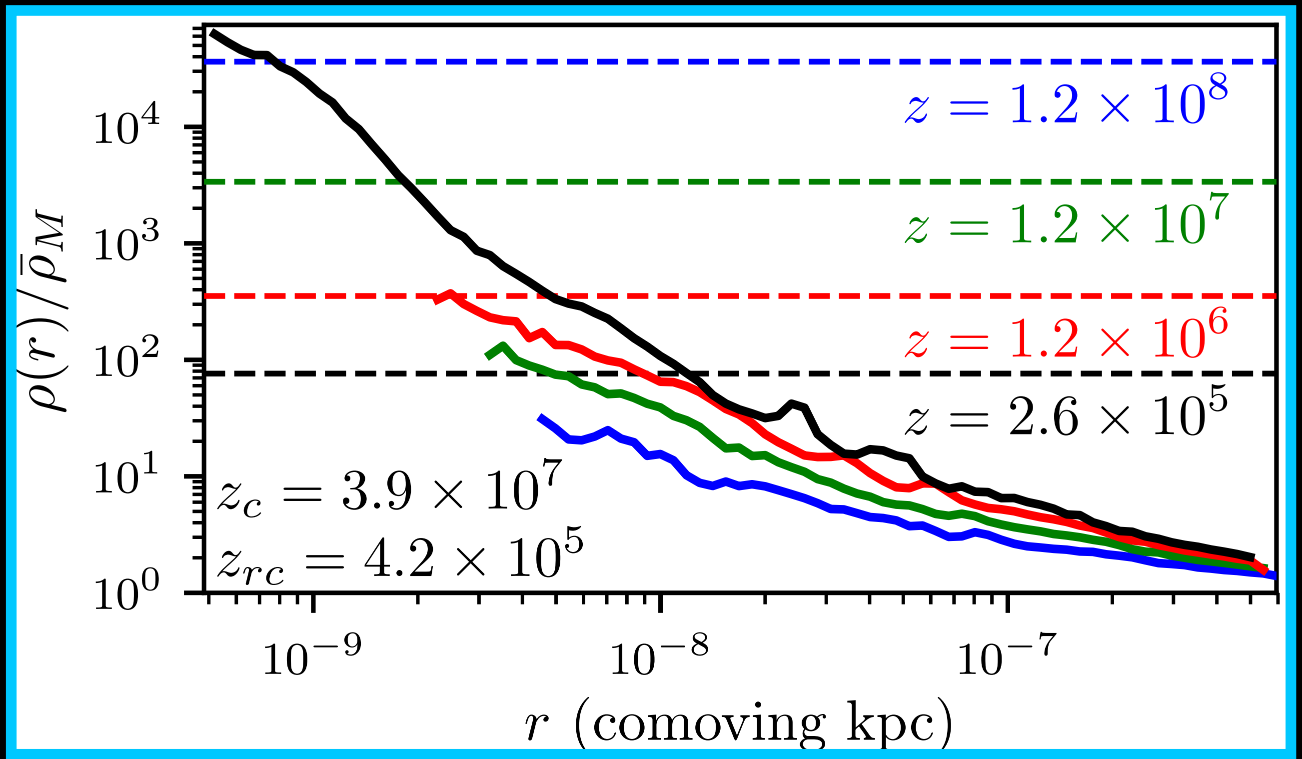
Simulations by ***Sheridan Green***

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.

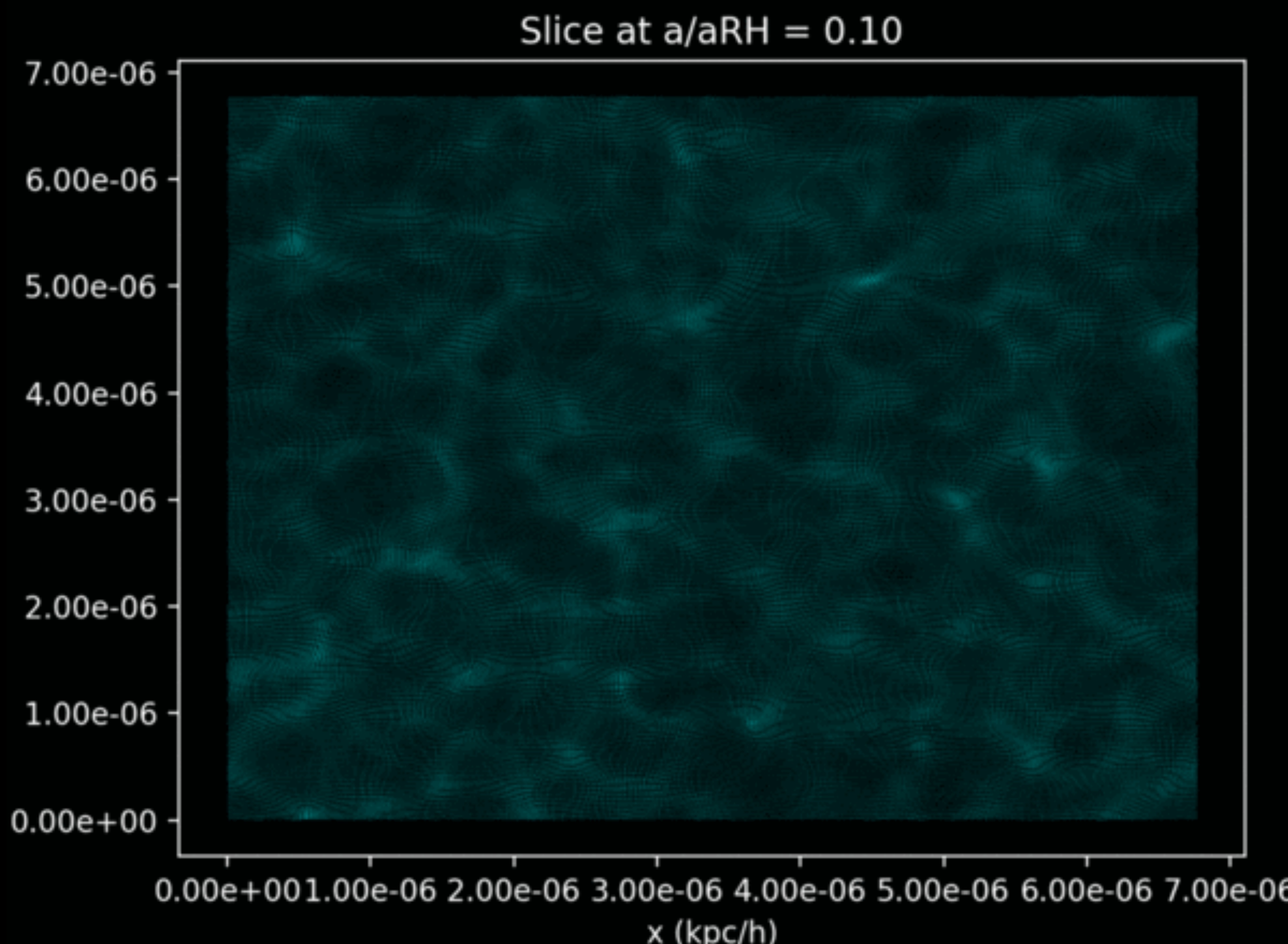


- For WIMP dark matter thermally produced during an EMDE, microhalos form during matter domination.
- With HS dark matter, we can form halos earlier, during radiation domination! *Blanco, Delos, ALE, Hooper 2019*



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

Gravitational Heating



*Simulations by **Himanish Ganjoo and M. Sten Delos***

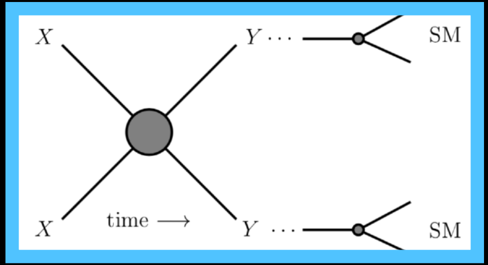
DM Annihilation within Microhalos

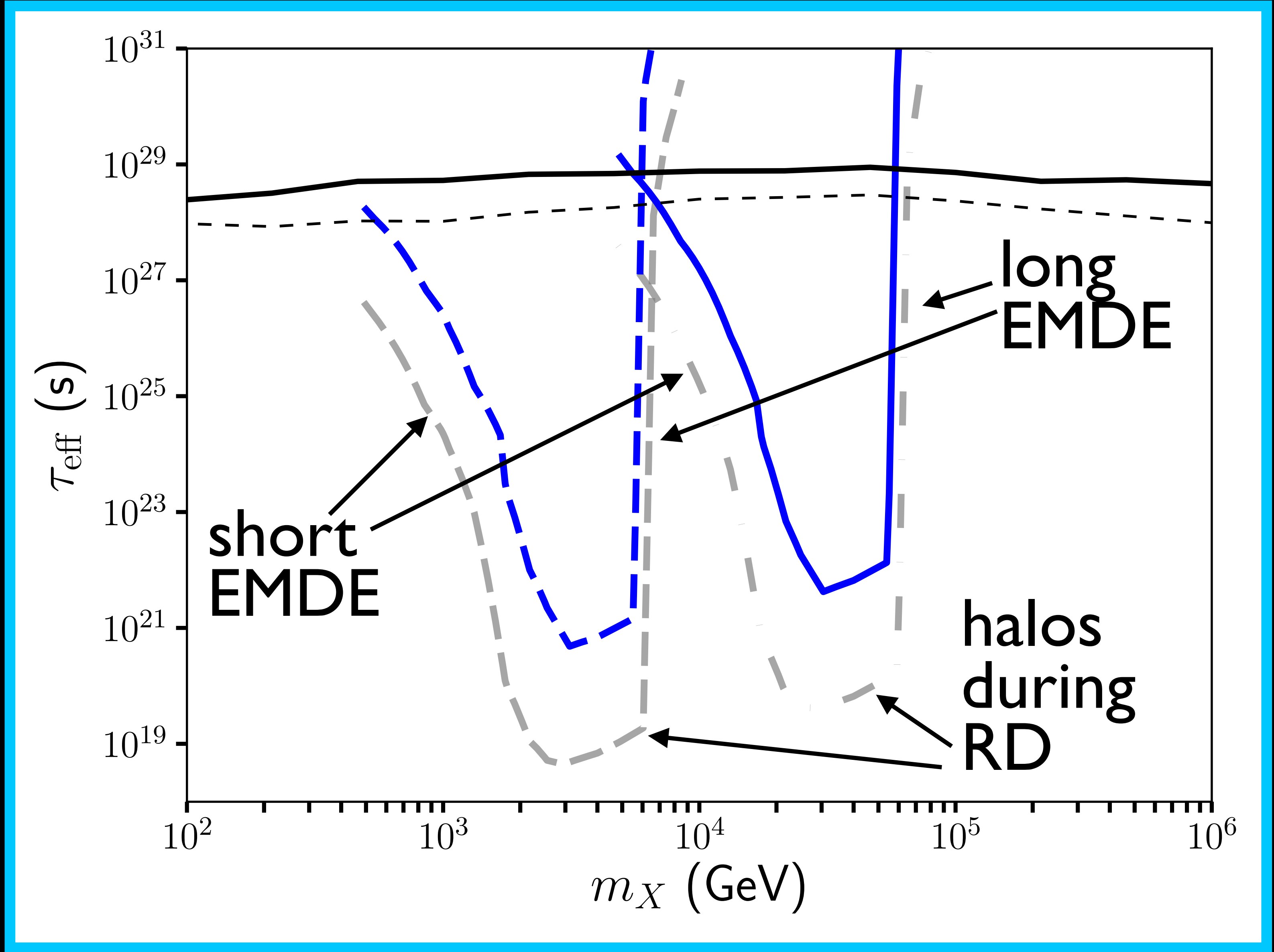
Dark matter annihilation within early-forming microhalos dominates all other emission, mimicking the signal of decaying dark matter.

- 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:

$$\tau_{\rm eff} = \frac{1}{2m_\chi(\Gamma/M_\chi)}$$

- For hidden sector dark matter, the isotropic gamma-ray background provides powerful constraints.





Blanco, Delos, ALE, Hooper 2019

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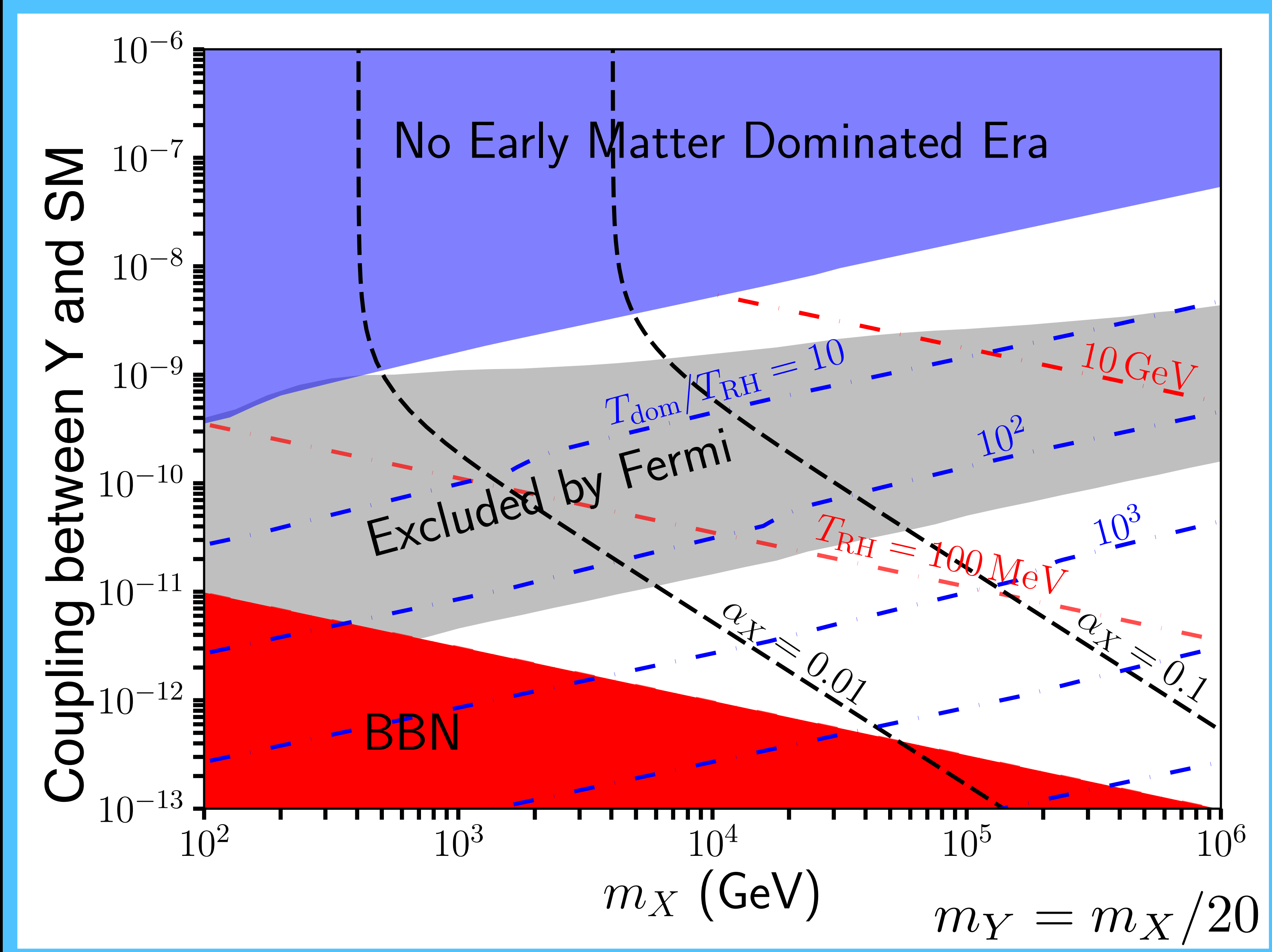
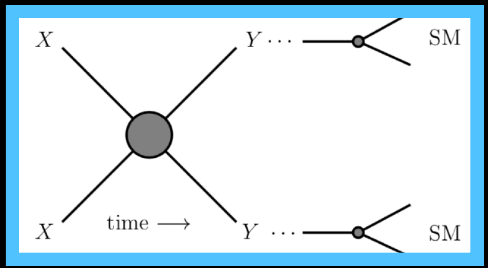




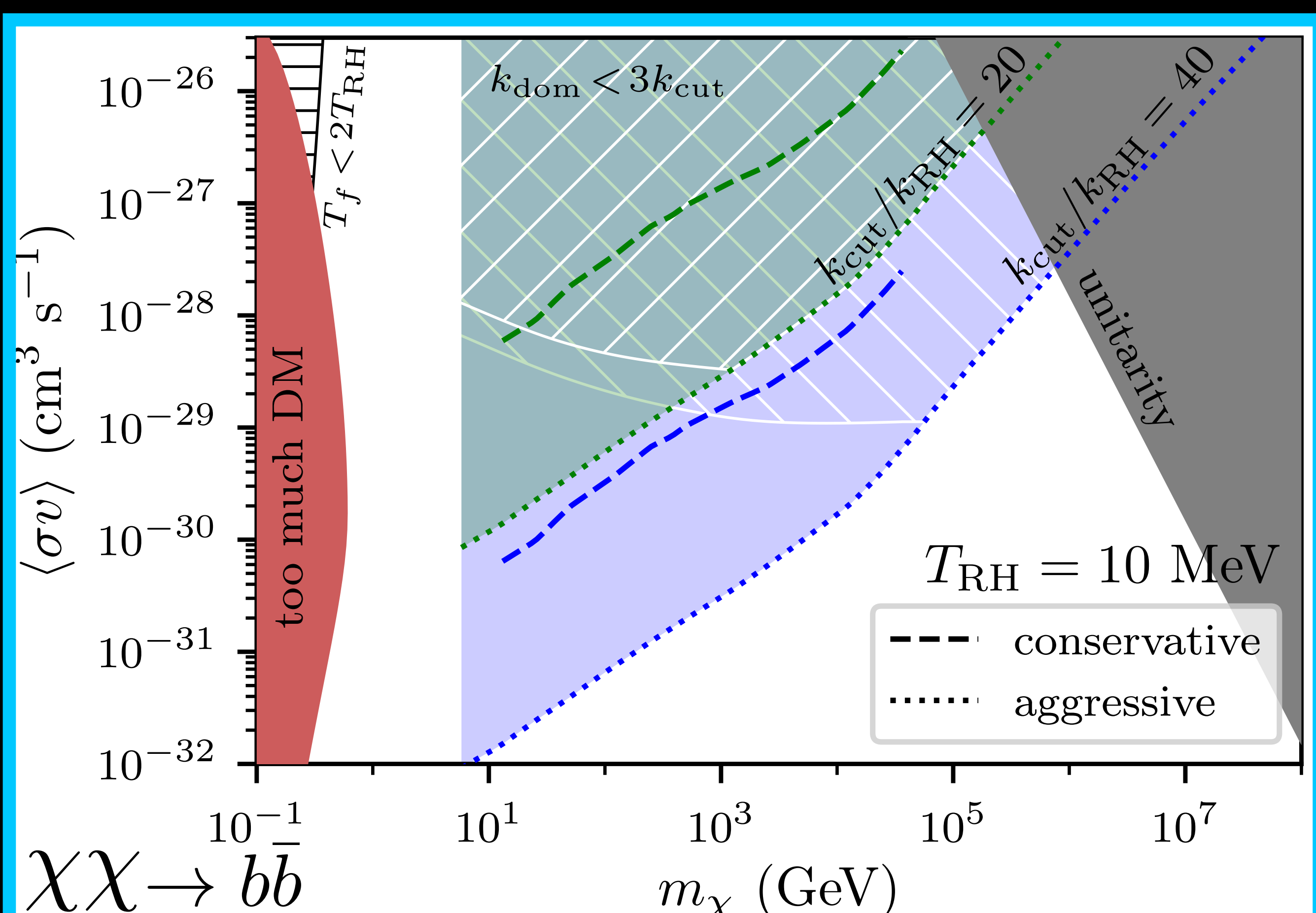
Blanco, Delos, ALE, Hooper 2019

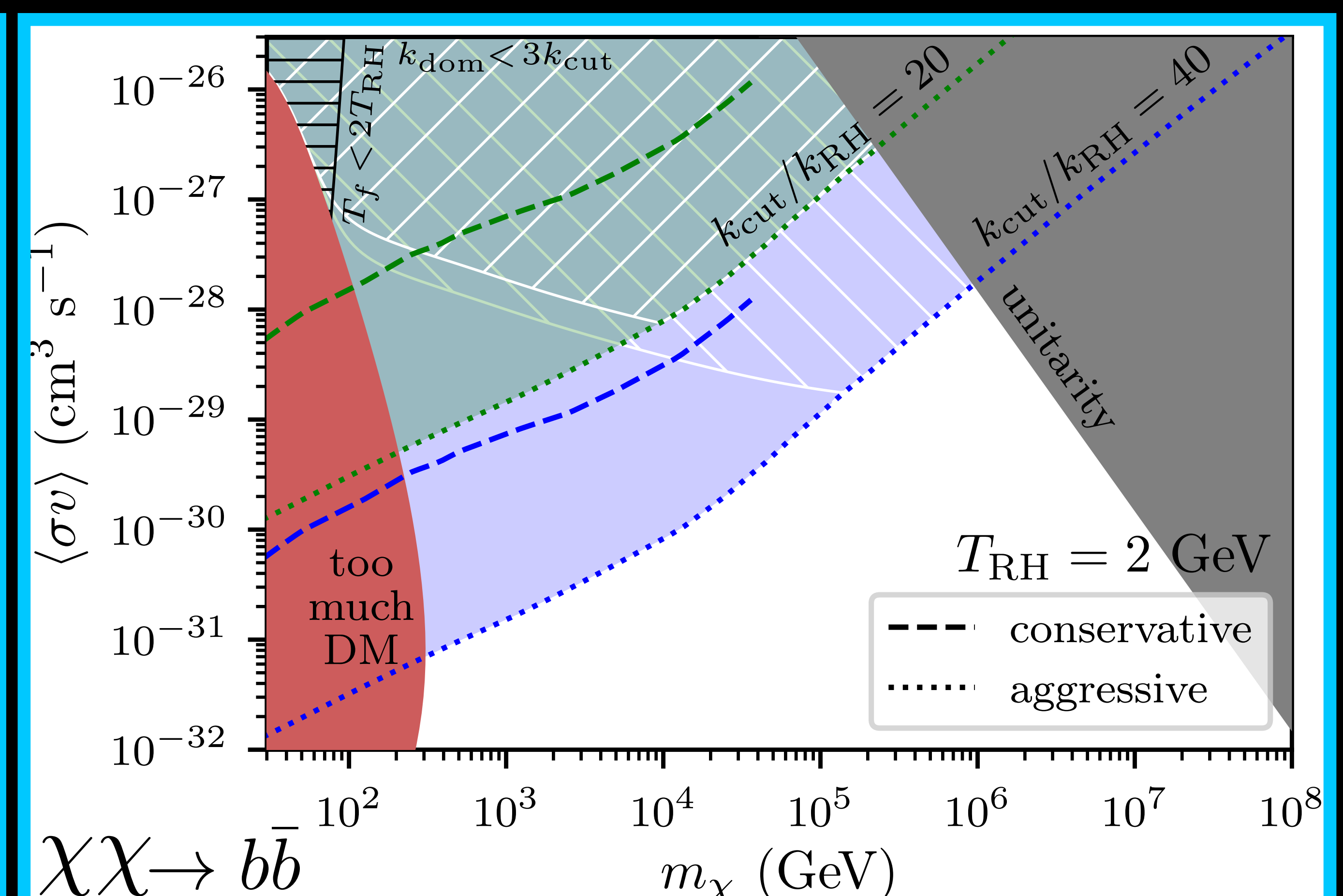
More constraints from the IGRB

Sten Delos, Tim Linden, ALE 2019

More generally, the isotropic gamma-ray background significantly restricts the field of viable thermal relics.

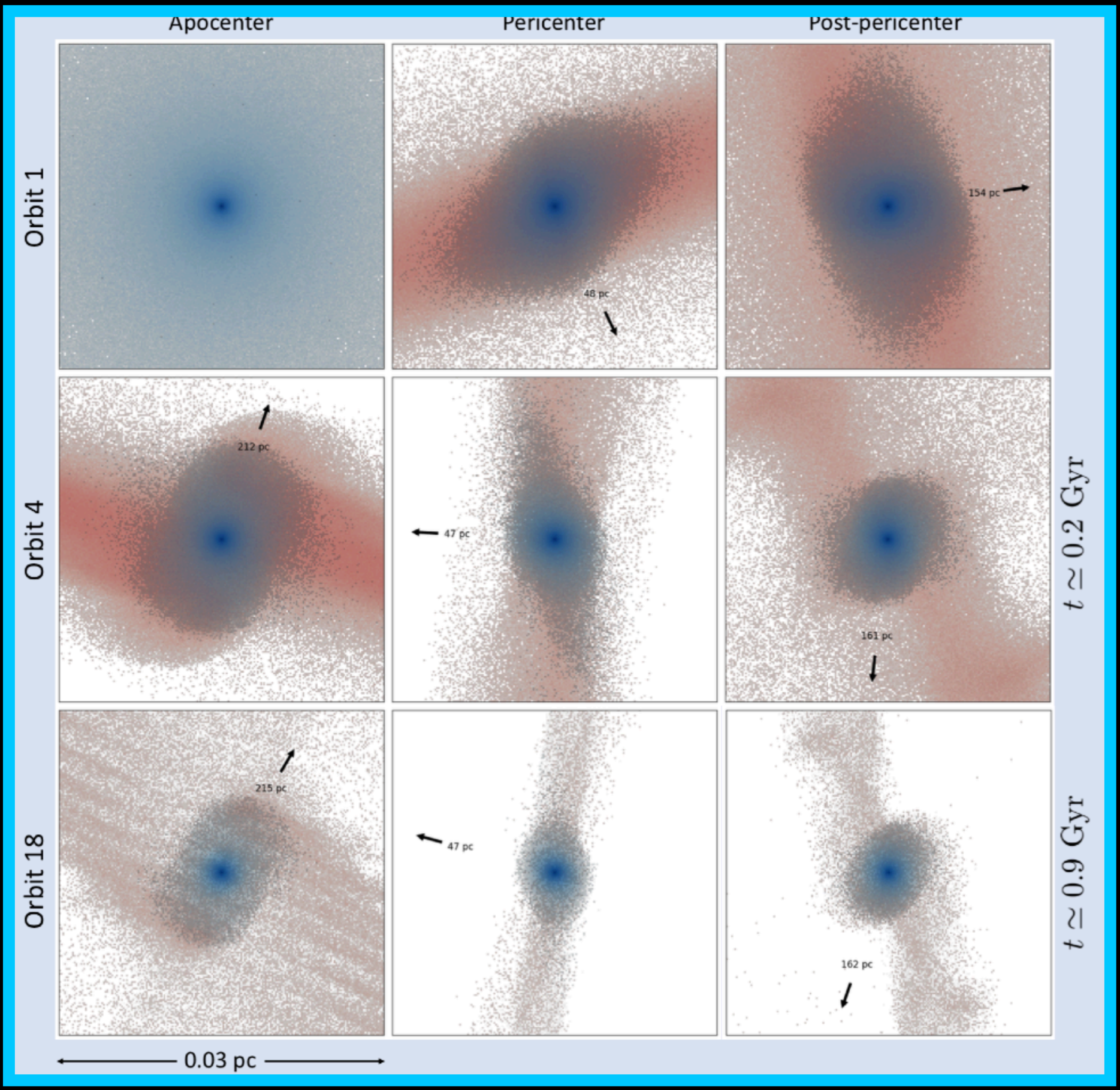
- Constraints use microhalo population predicted by Delos, Bruff, ALE 2019
- Constraints depend on $k_{\mathrm{cut}}/k_{\mathrm{RH}}$: larger means more dense microhalos
- Constraints are tentative for short EMDEs ($k_{\mathrm{dom}} < 3k_{\mathrm{cut}}$)

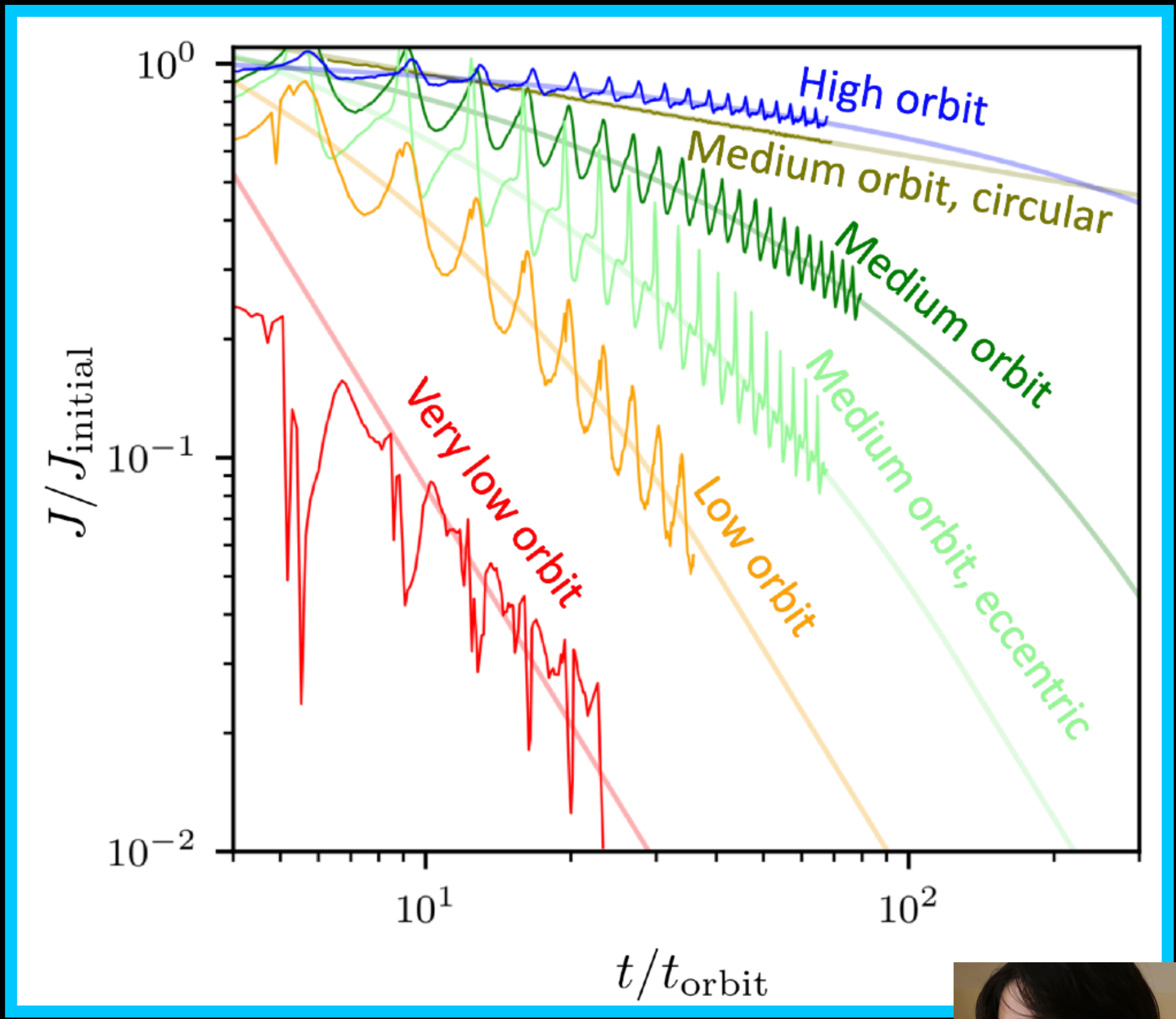




Microhalos within Galaxies

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





Sten Delos 1906.10690

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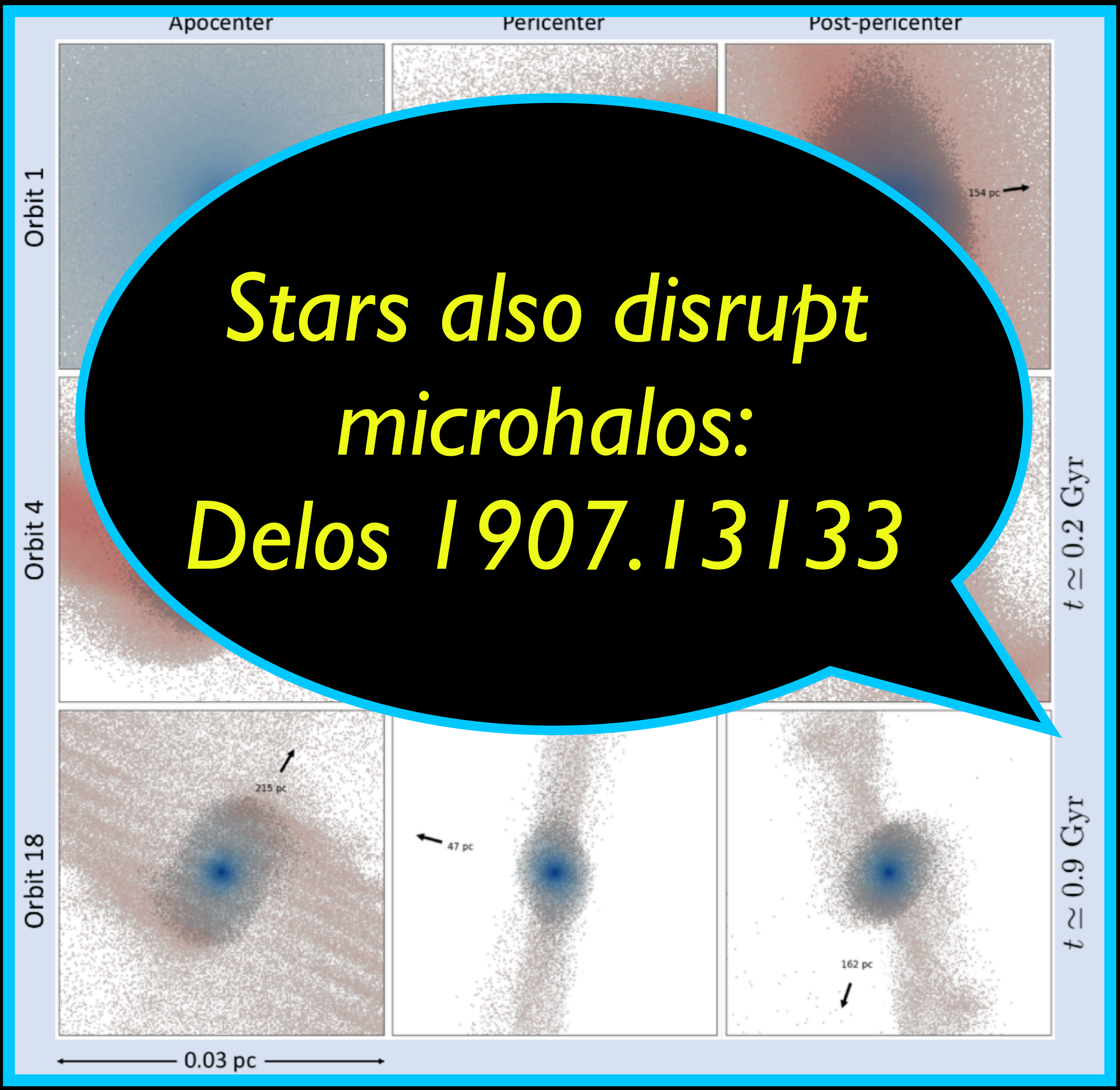
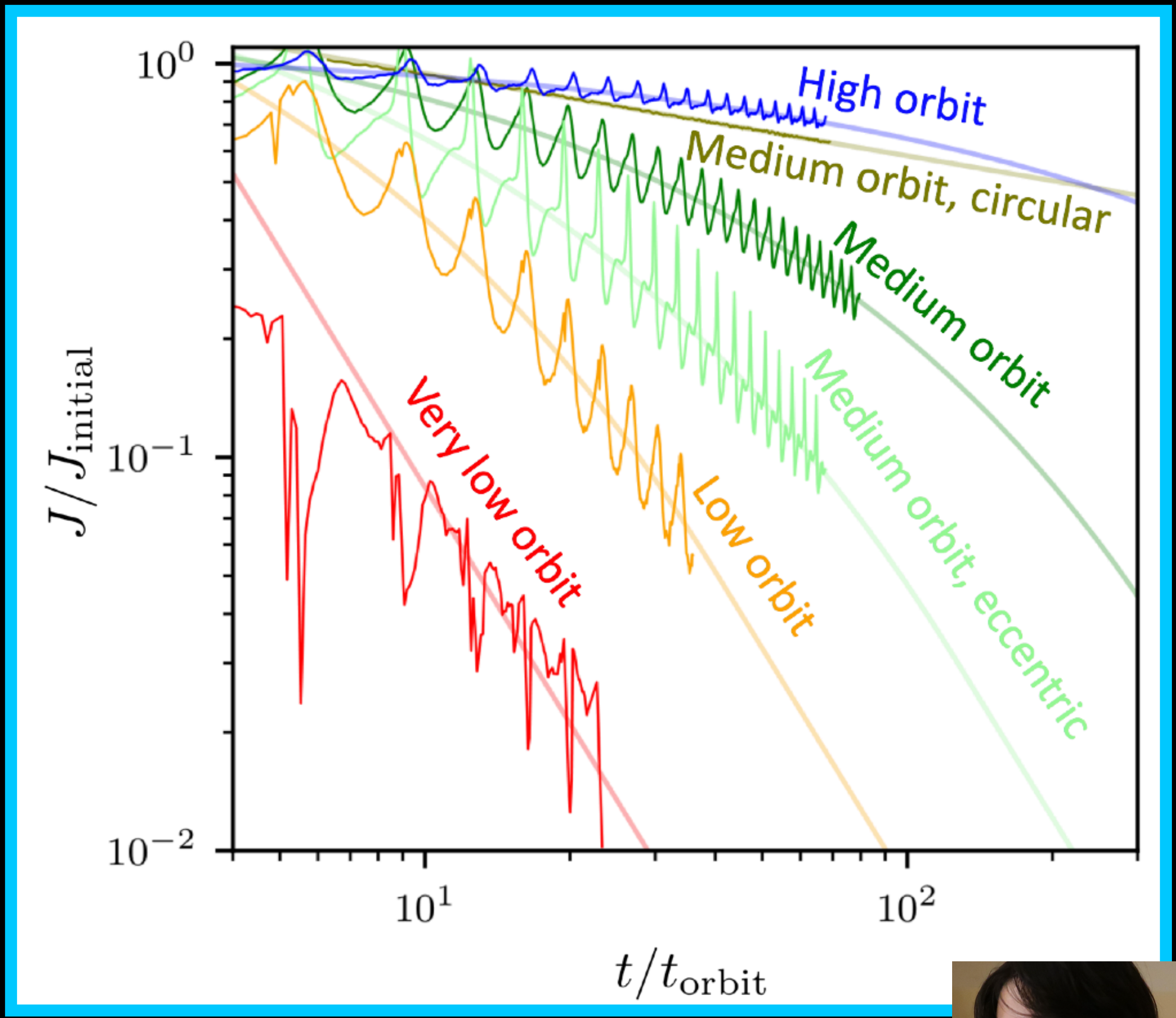




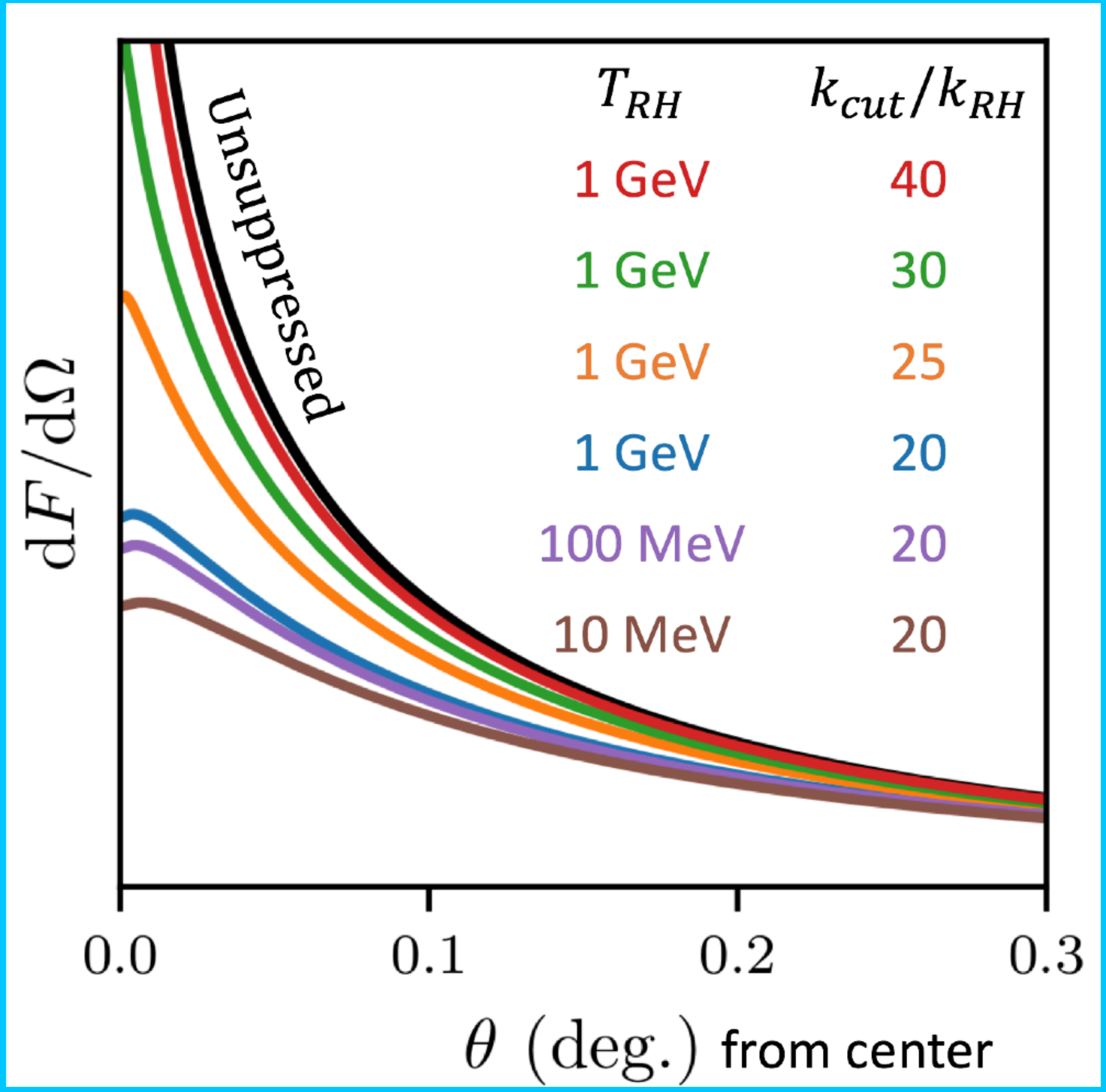
Sten Delos 1906.10690

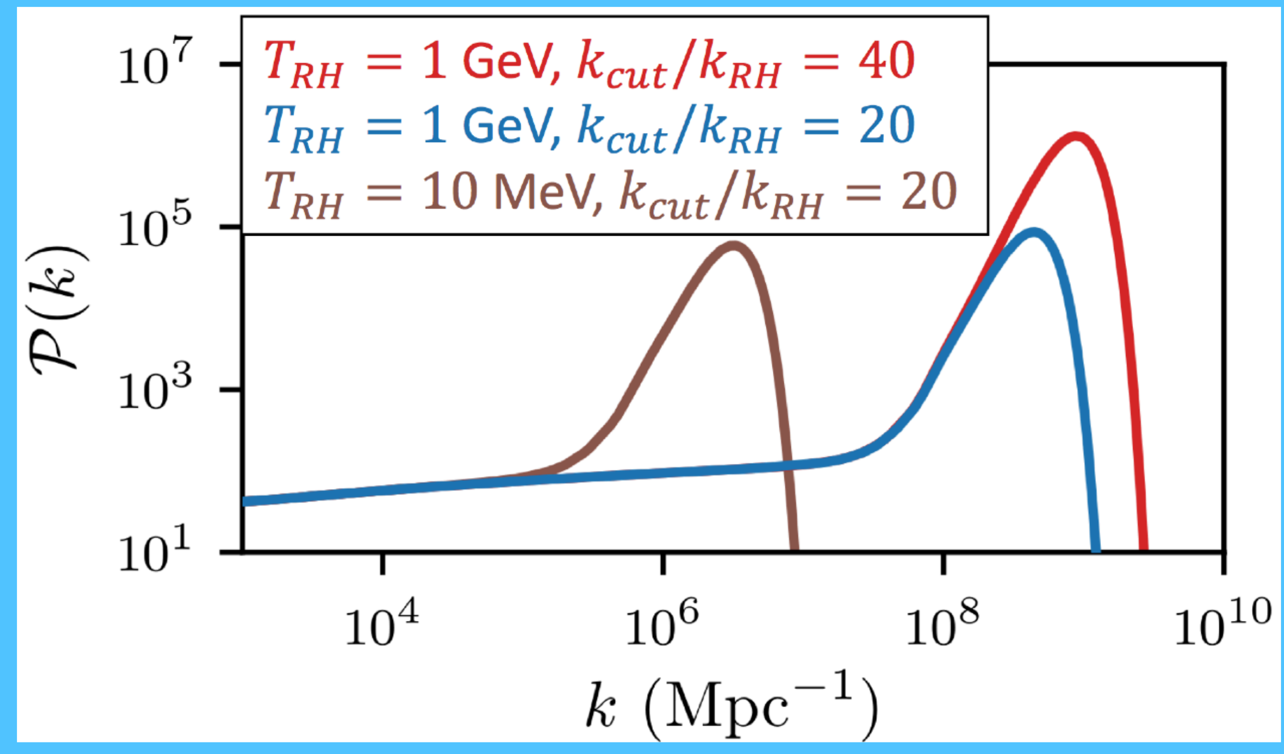
Observational Signatures and Constraints

Case study: Draco

Sten Delos, Tim Linden, ALE 2019

Microhalos in the central region are disrupted by stars and tides, reducing the annihilation signature.





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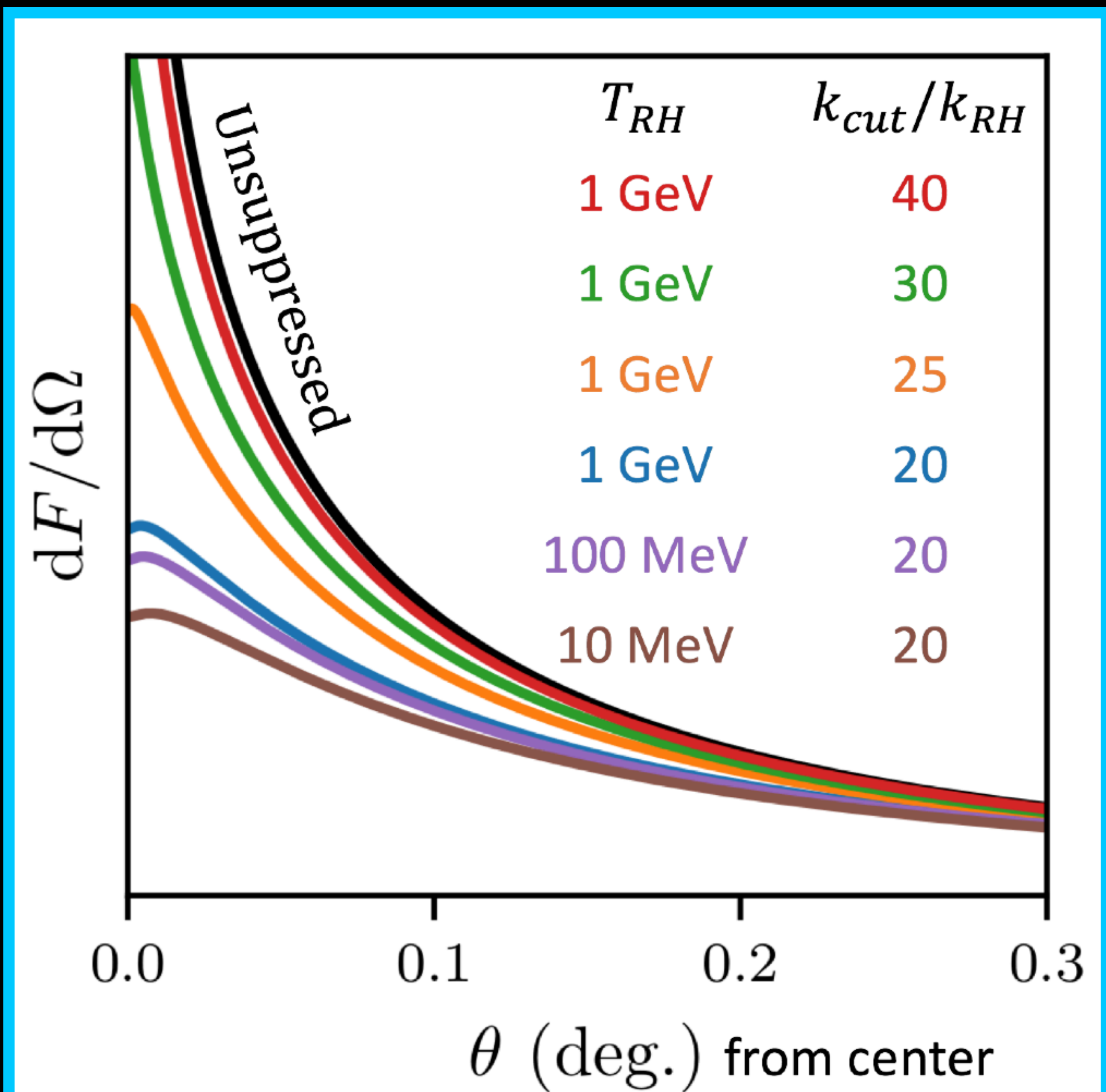

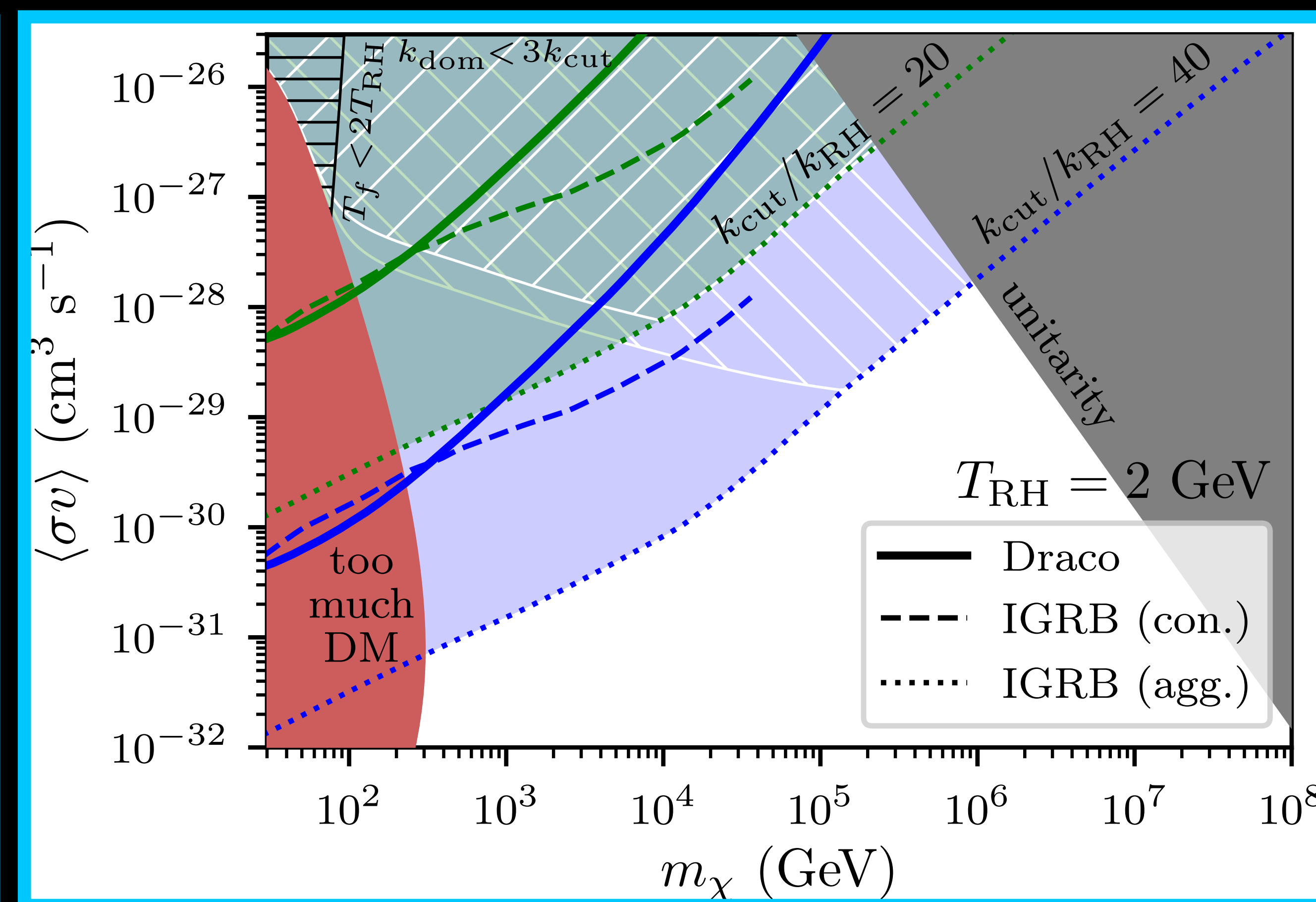

Fermi-LAT observations of Draco limit this emission profile, leading to constraints on EMDE cosmologies.

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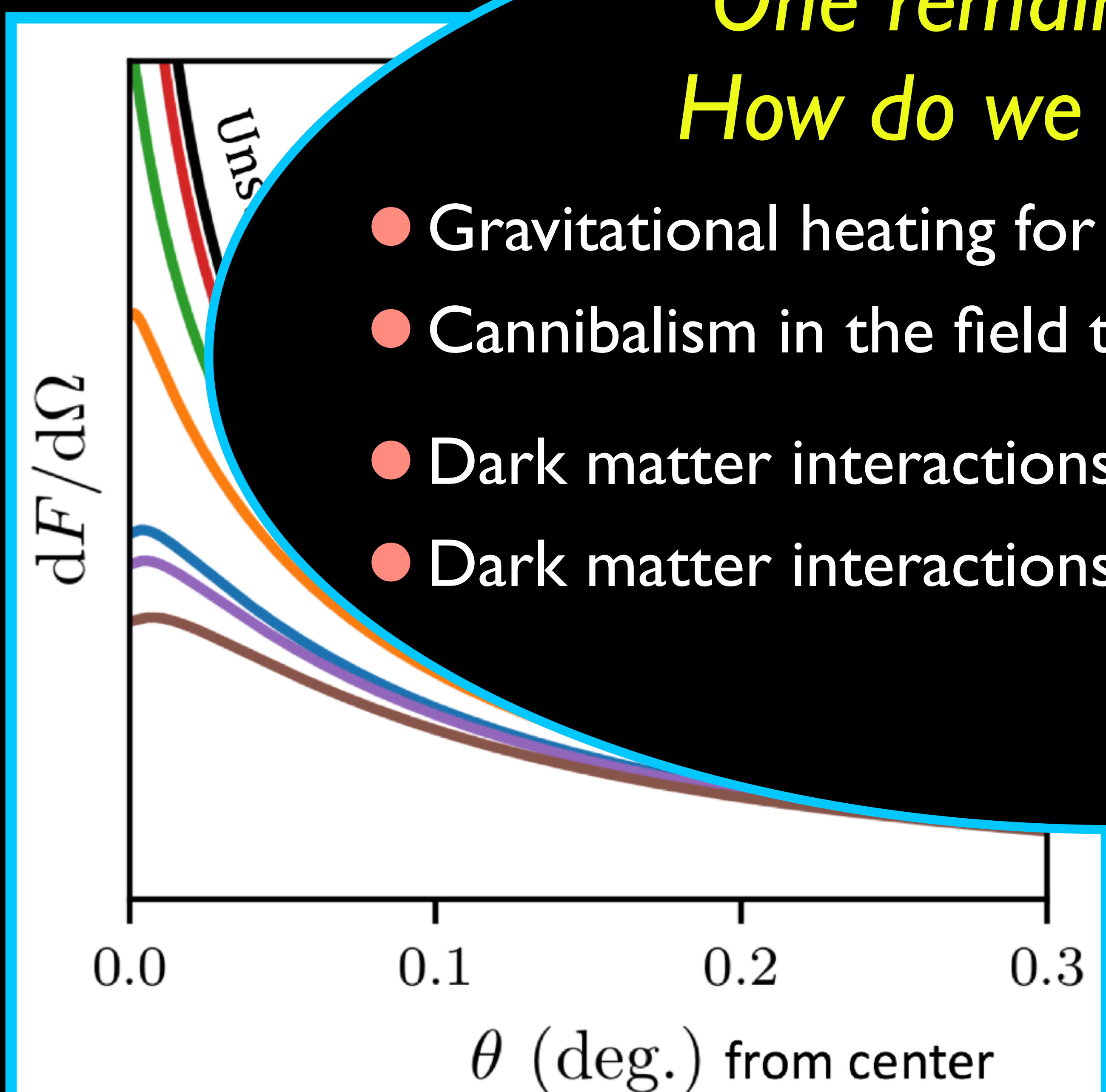
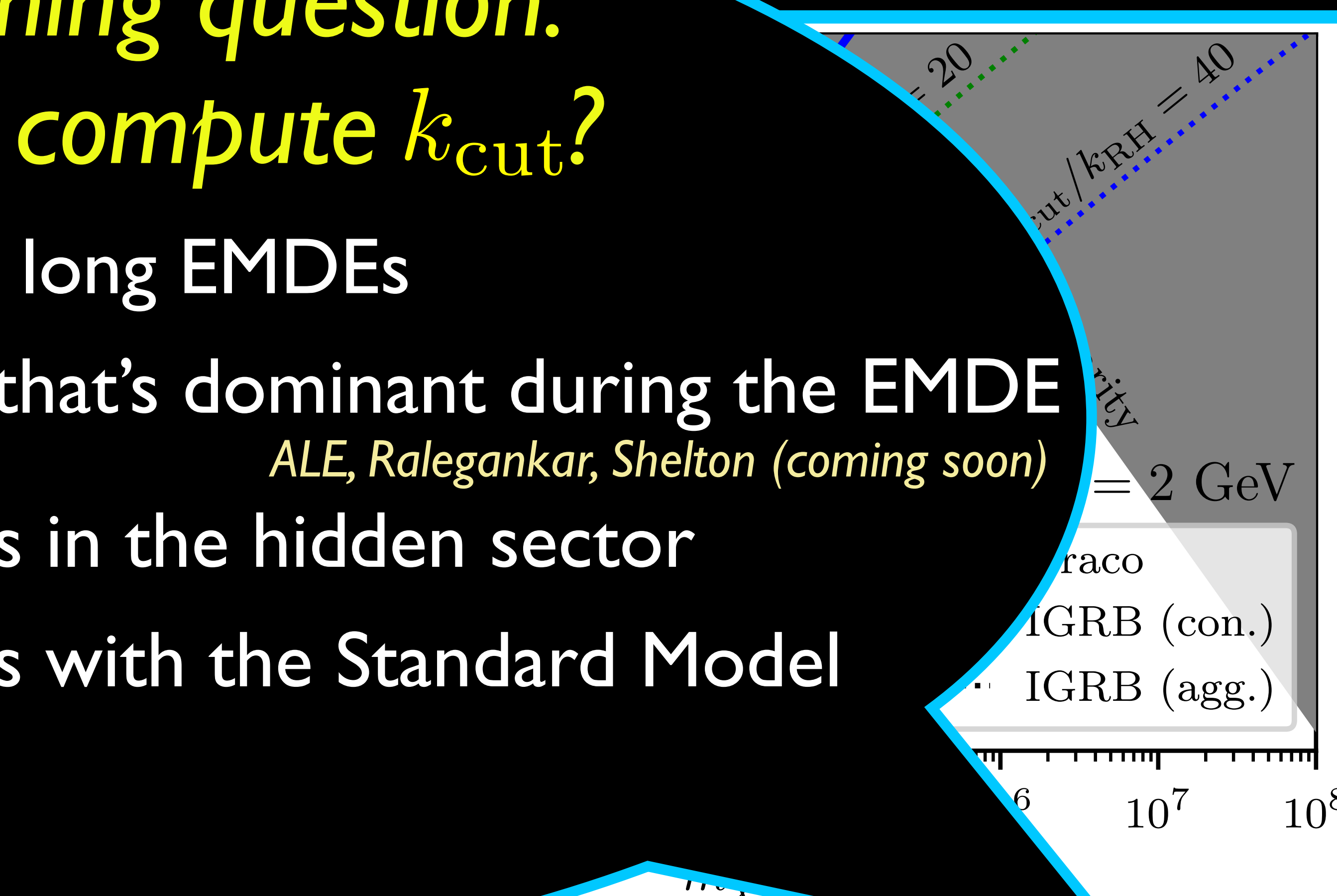


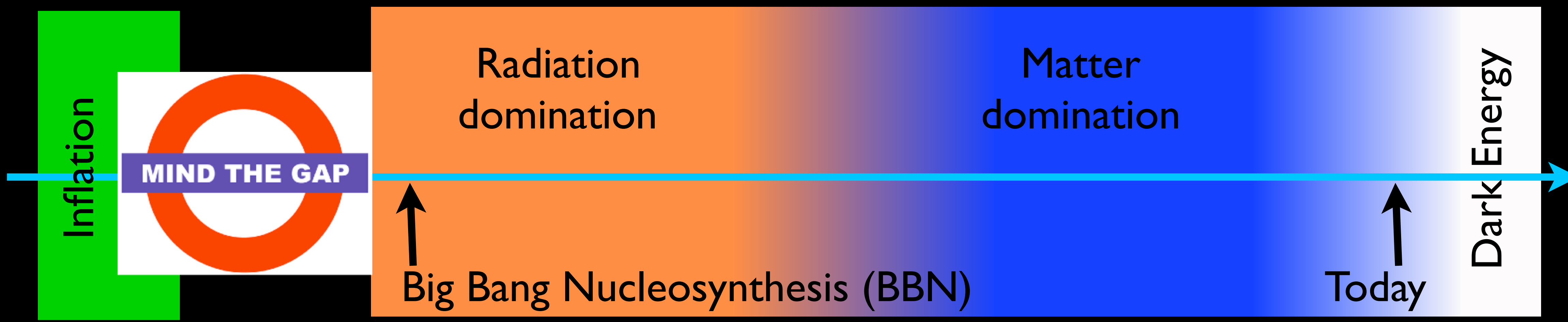


One remaining question:
How do we compute k_{cut}?

- Gravitational heating for long EMDEs
- Cannibalism in the field that's dominant during the EMDE
  ALE, Ralegankar, Shelton (coming soon)
- Dark matter interactions in the hidden sector
- Dark matter interactions with the Standard Model

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: $10^{15}\,\mathrm{GeV} \gtrsim T \gtrsim 10^{-3}\,\mathrm{GeV}$
- Dark matter microhalos offer hope of probing the gap.
- An early matter-dominated era (EMDE) enhances the growth of sub-horizon density perturbations.
- The microhalos that form after an EMDE significantly boost the dark matter annihilation rate.
- We can use gamma-ray observations to probe the evolution of the early Universe and narrow the field of thermal relics.
- Nonthermal DM production is constrained by the Lyman-alpha forest.