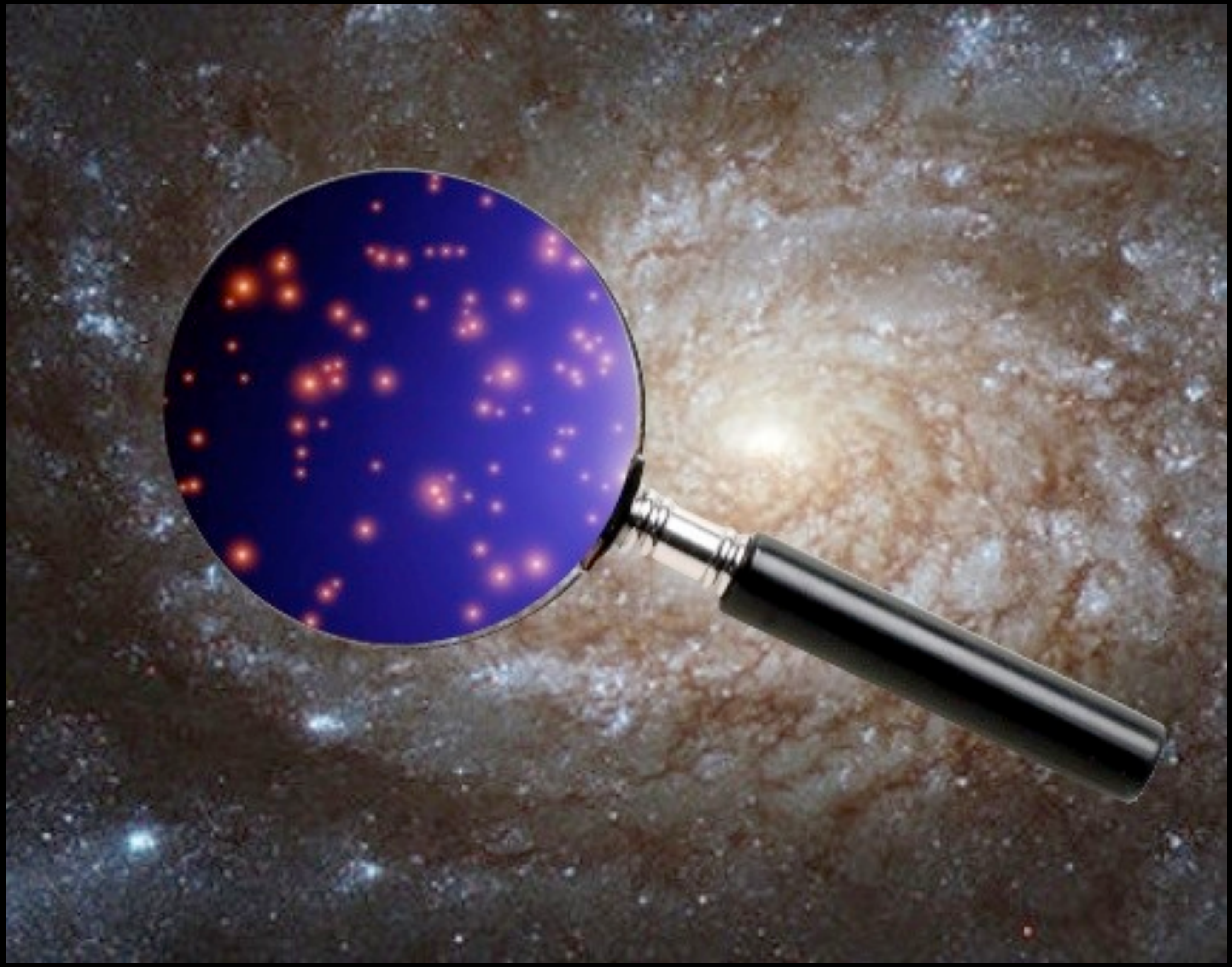
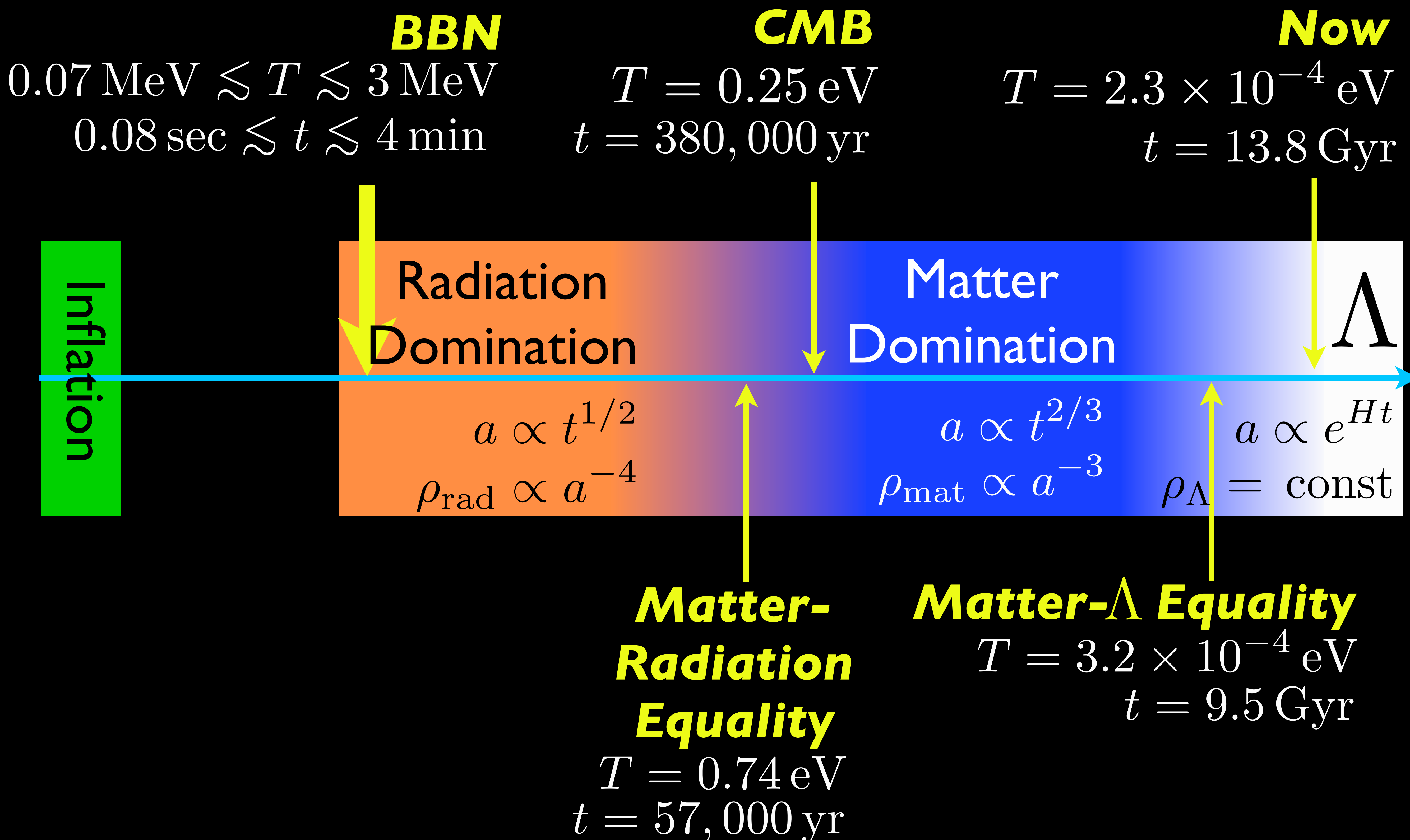
Microhalos: Messengers from the Early Universe



Adrienne Erickcek
CITA
Perimeter Institute

University of Illinois Astrophysics Colloquium
March 6, 2012

Cosmic Timeline



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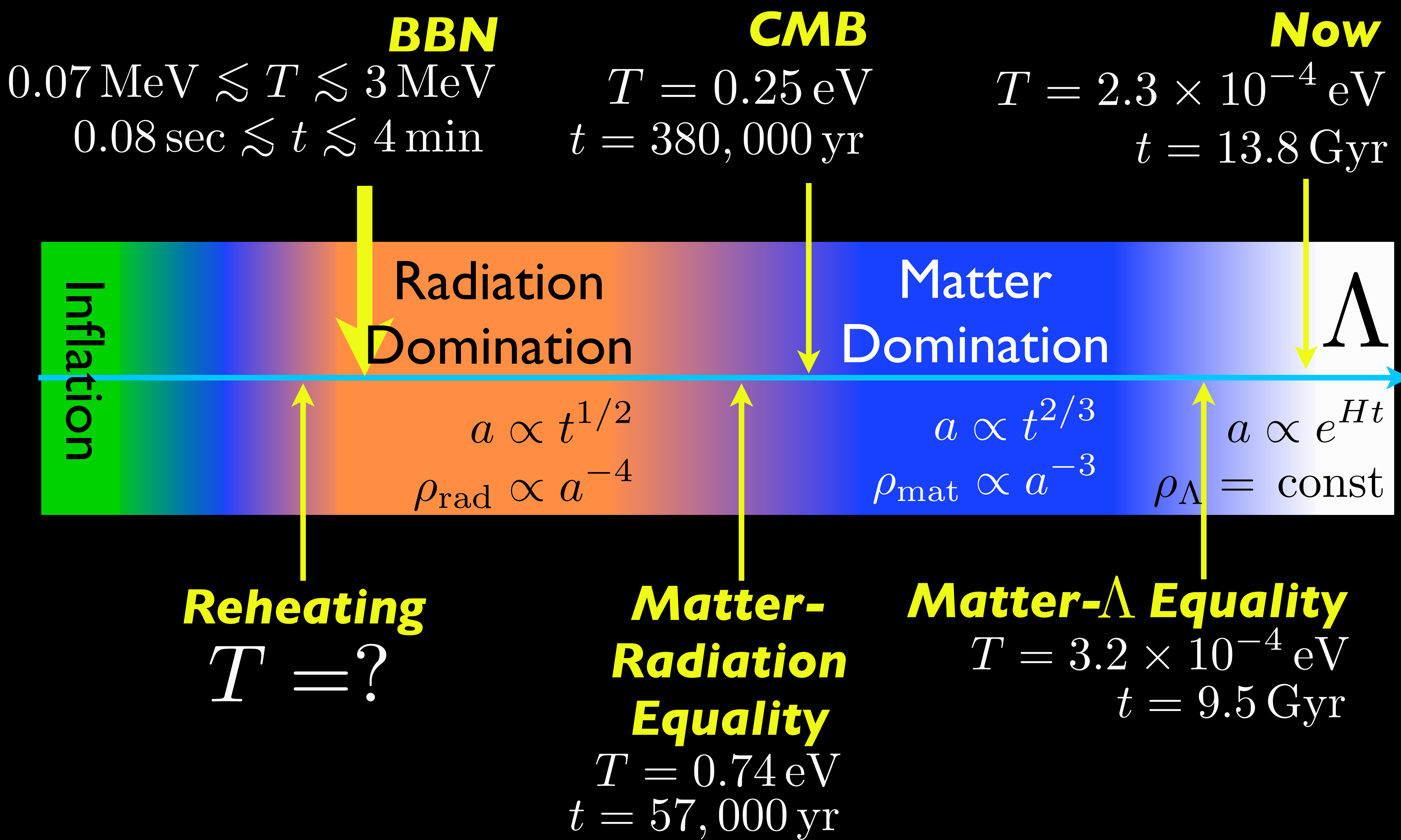
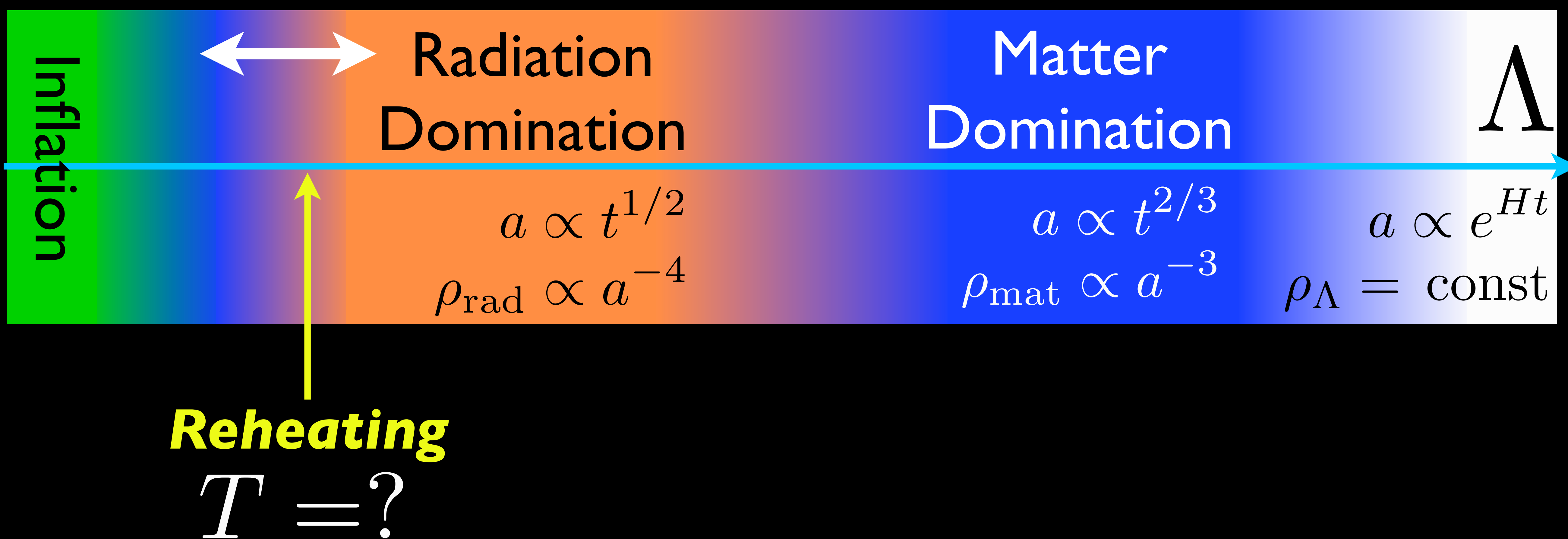


Colloquium Timeline

Part I: What can microhalos tell us about reheating?

with Kris Sigurdson

How does reheating change the small-scale matter power spectrum?
Microhalos from reheating; what substructures should we be looking for?



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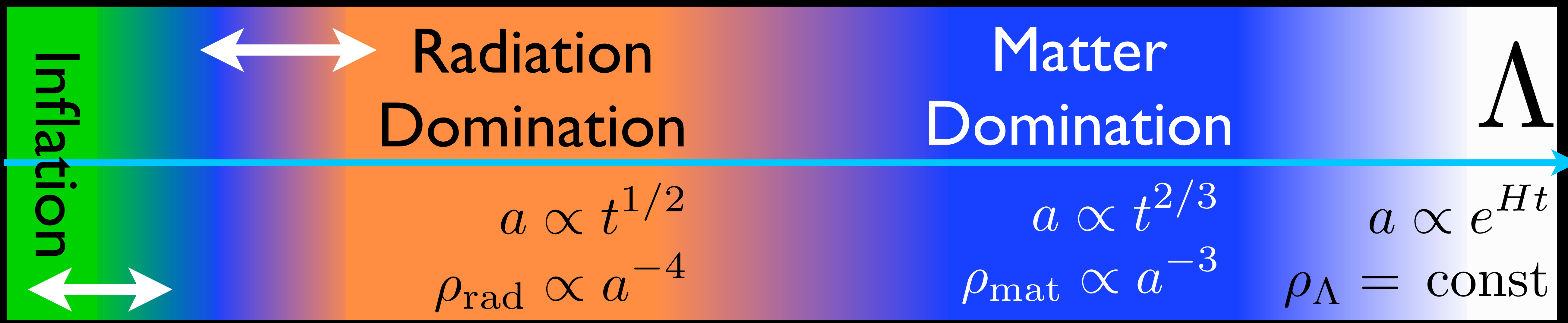


Part II: What can microhalos tell us about inflation?

with Fangda Li and Nicholas Law

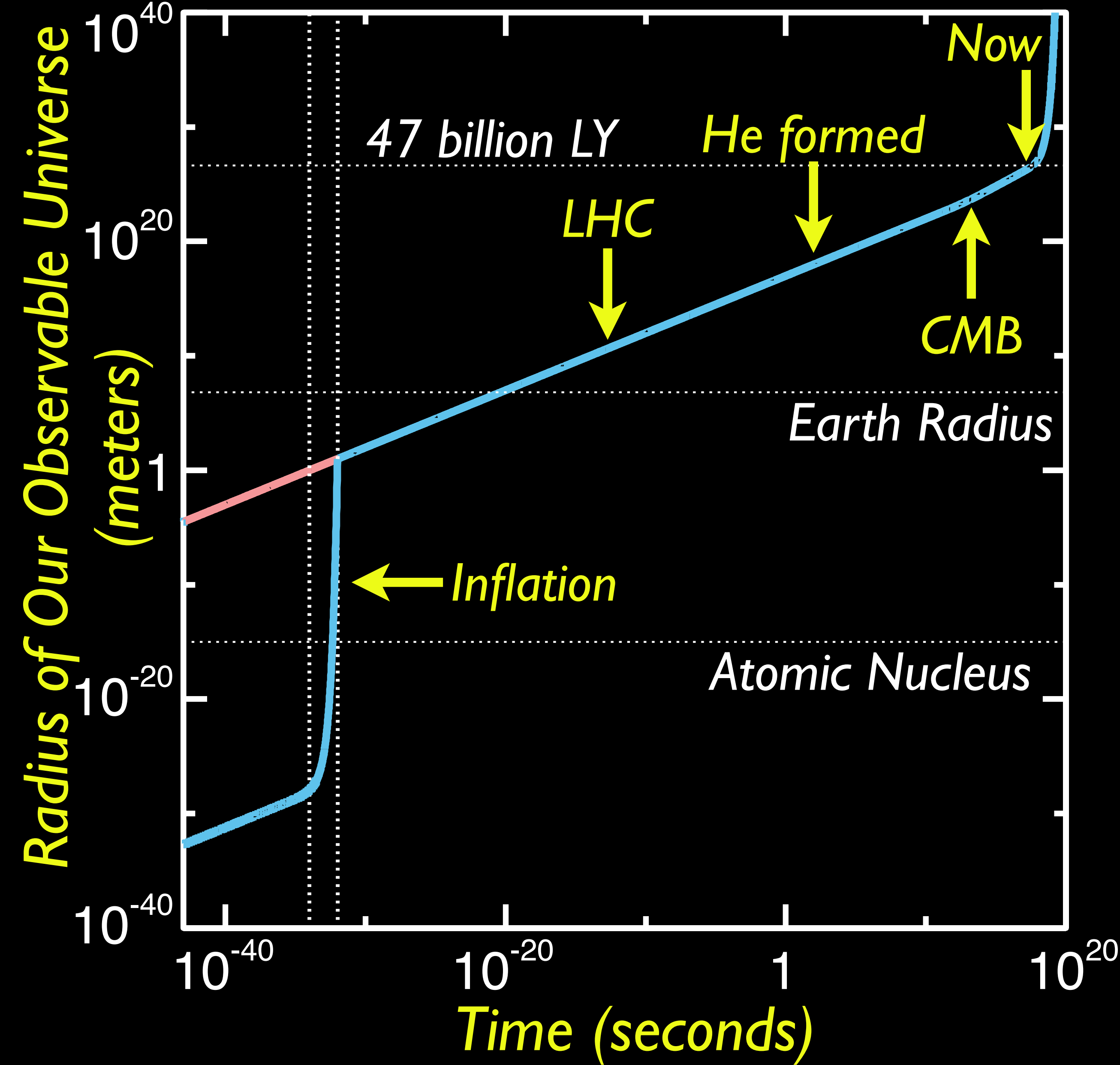
If inflation is a movie, how do we watch?

What are UCMHs? What happens when one passes in front of a star?

If Gaia doesn't detect an UCMH, what have we learned?

Inflation: the Universe's Growth Spurt

Inflation: an instant of accelerated expansion just after the Big Bang.



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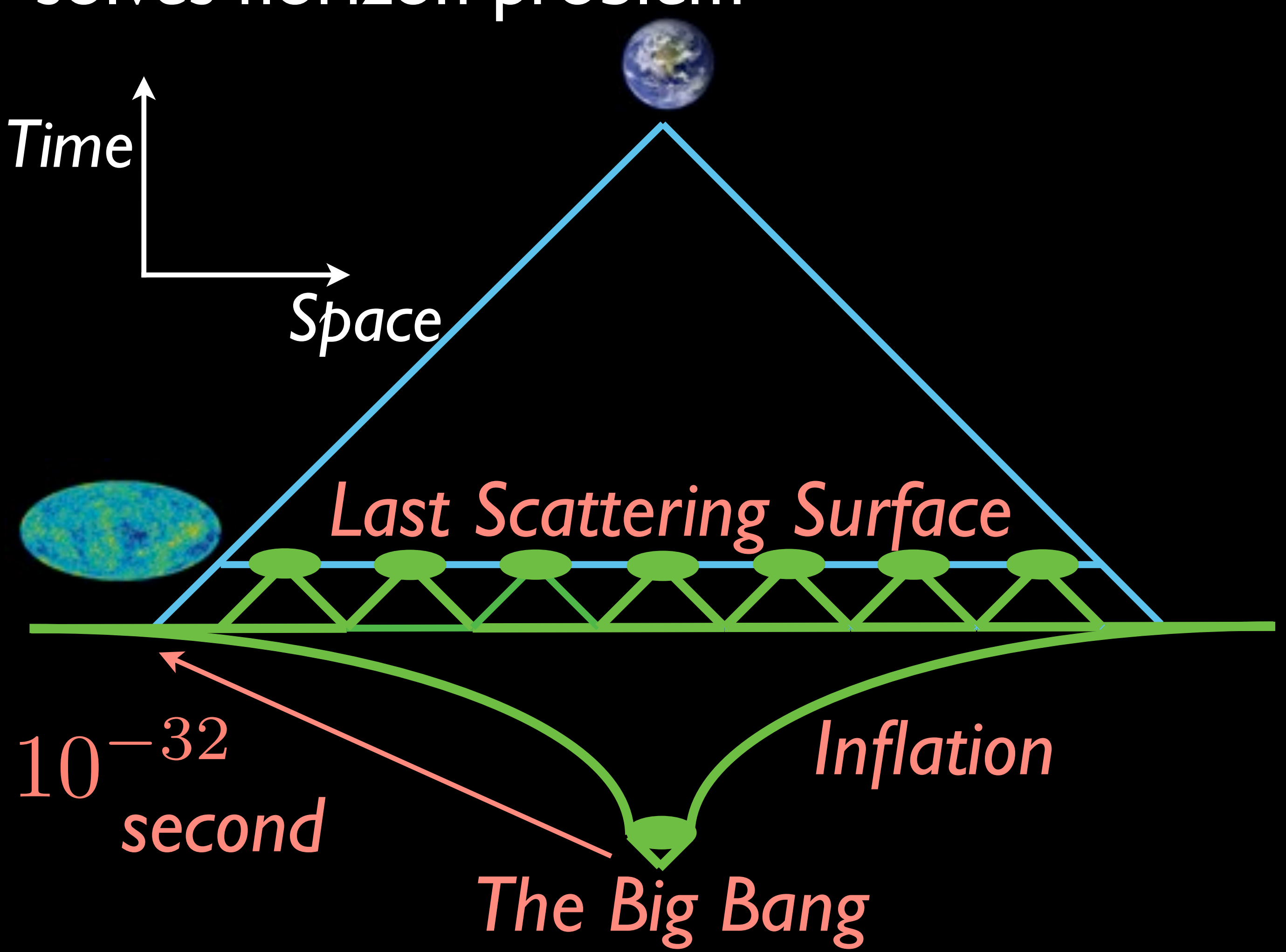

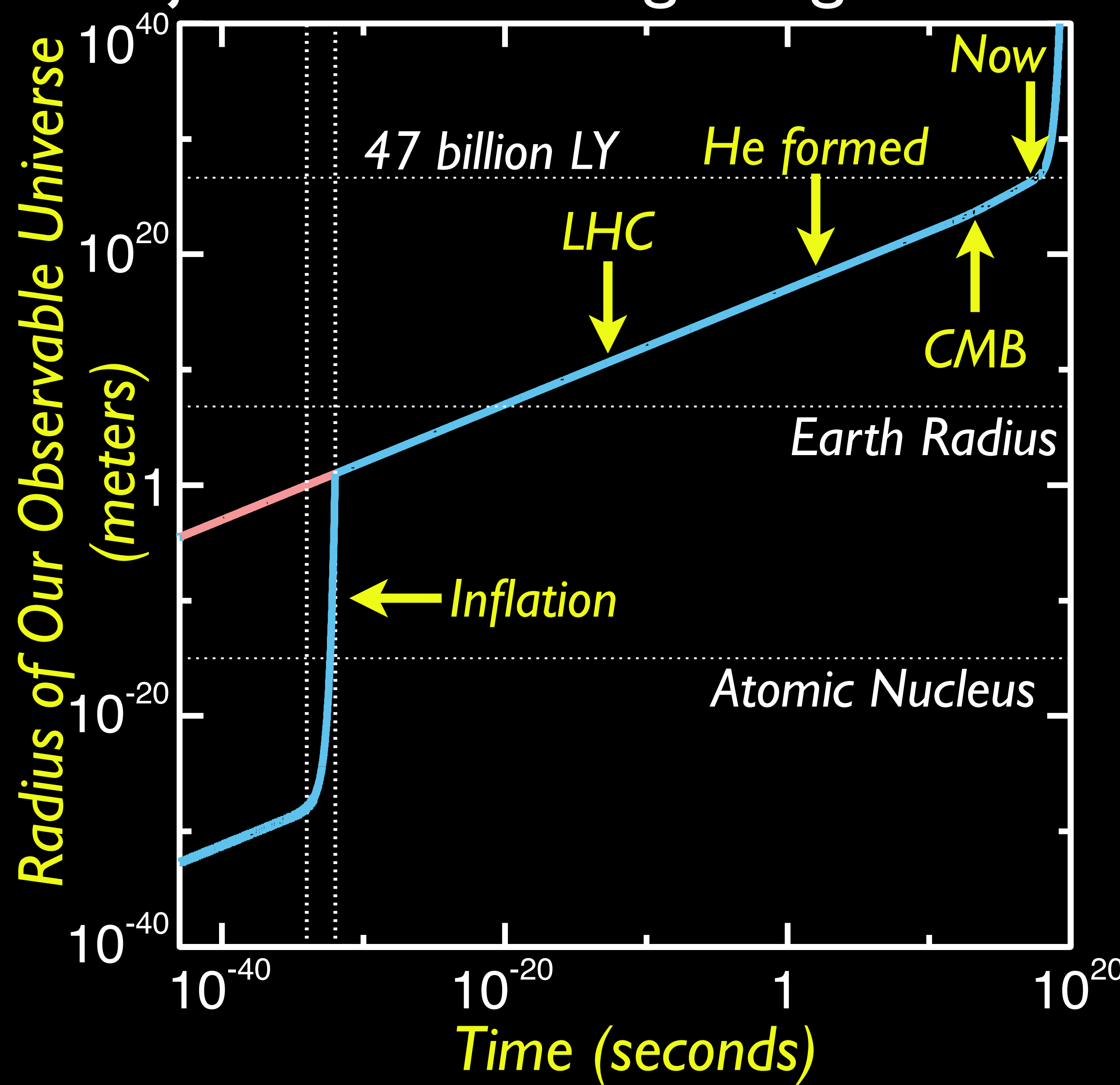

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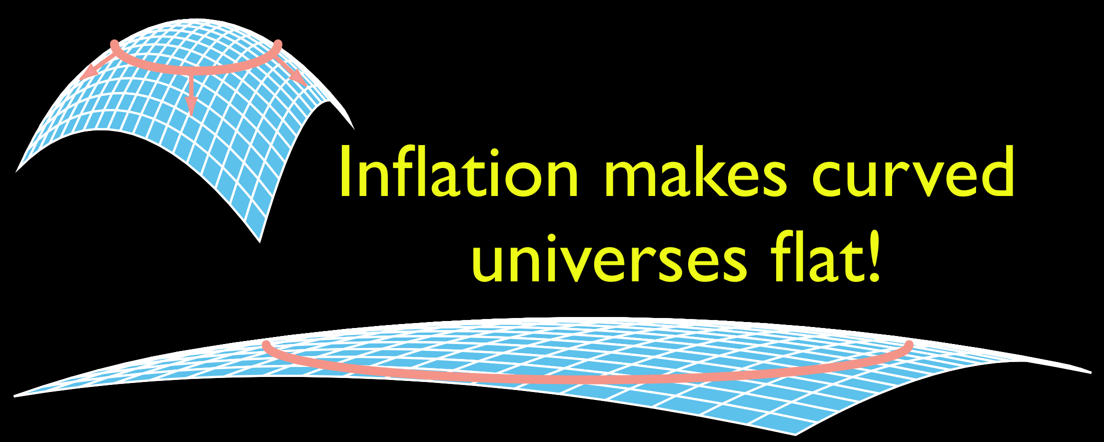

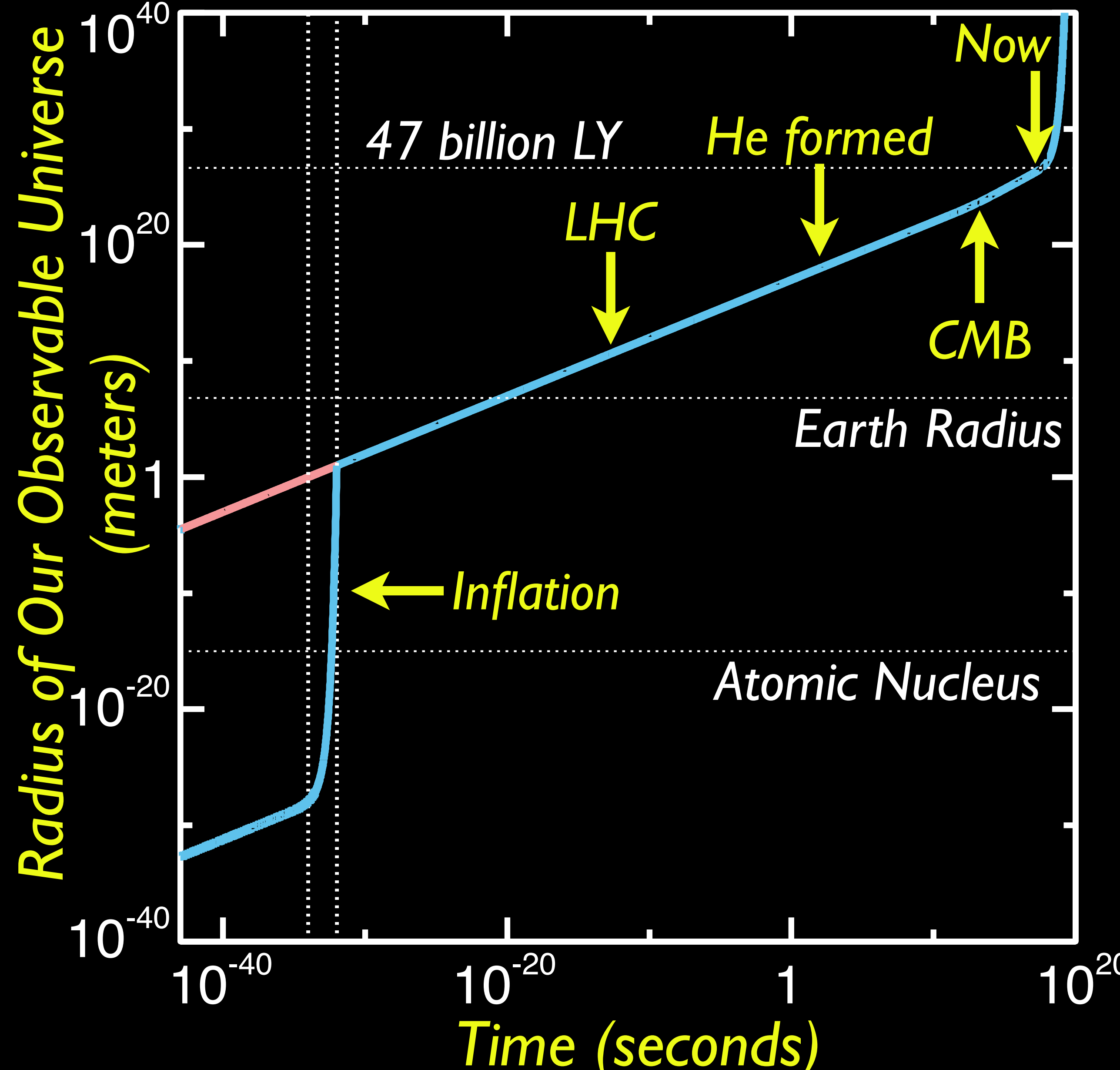

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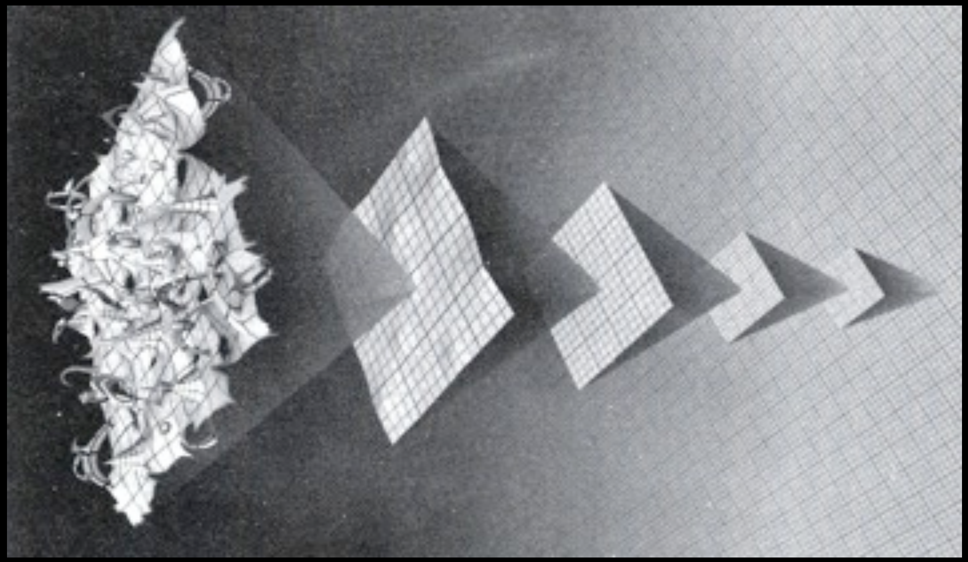
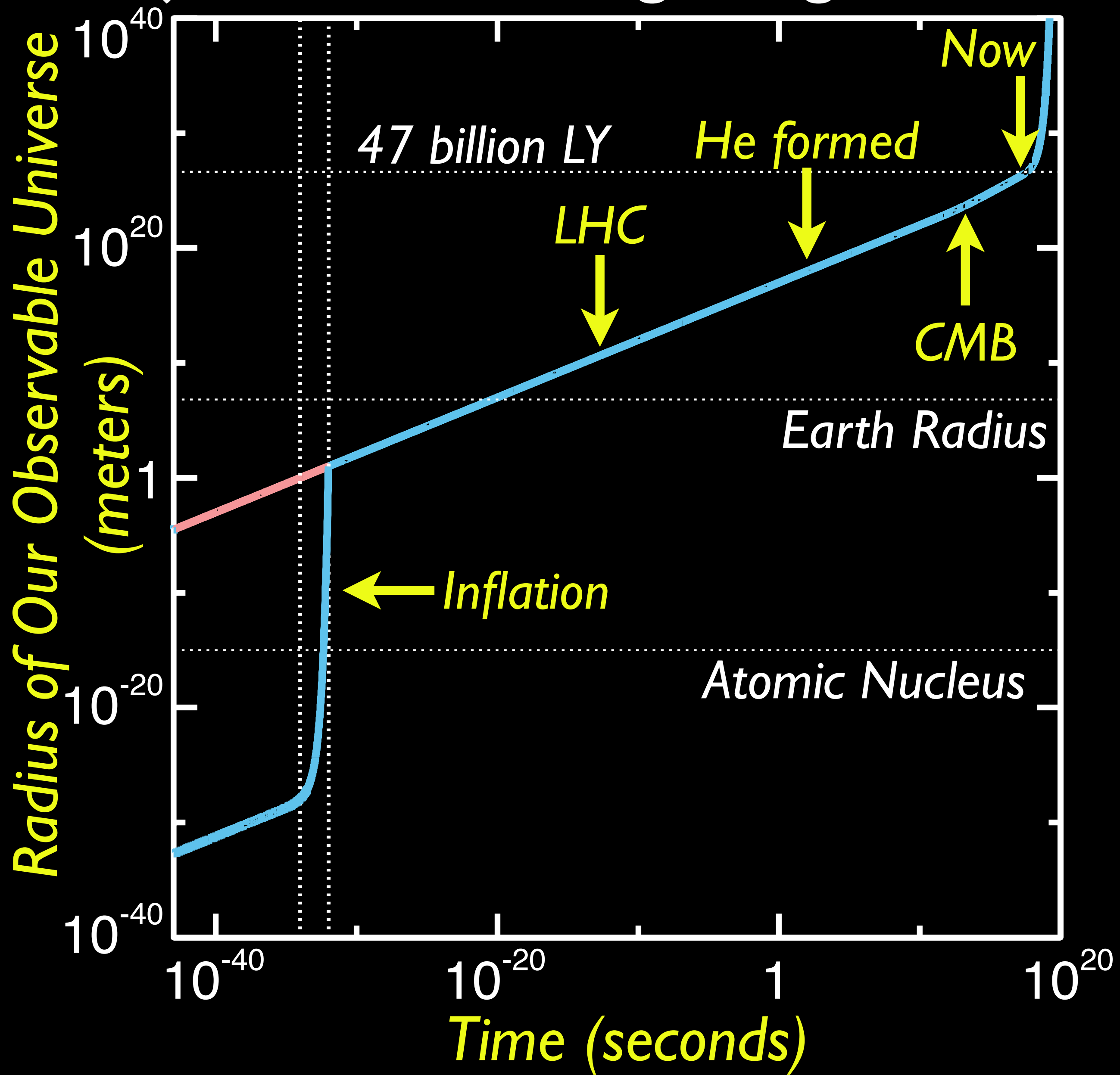


Initial density perturbations are quantum energy fluctuations stretched to cosmic scales during inflation.



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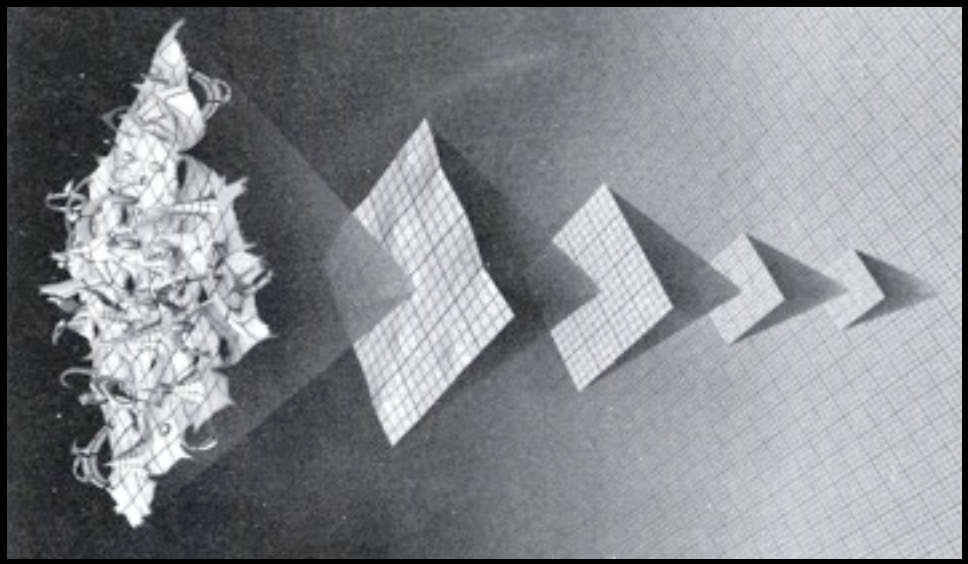

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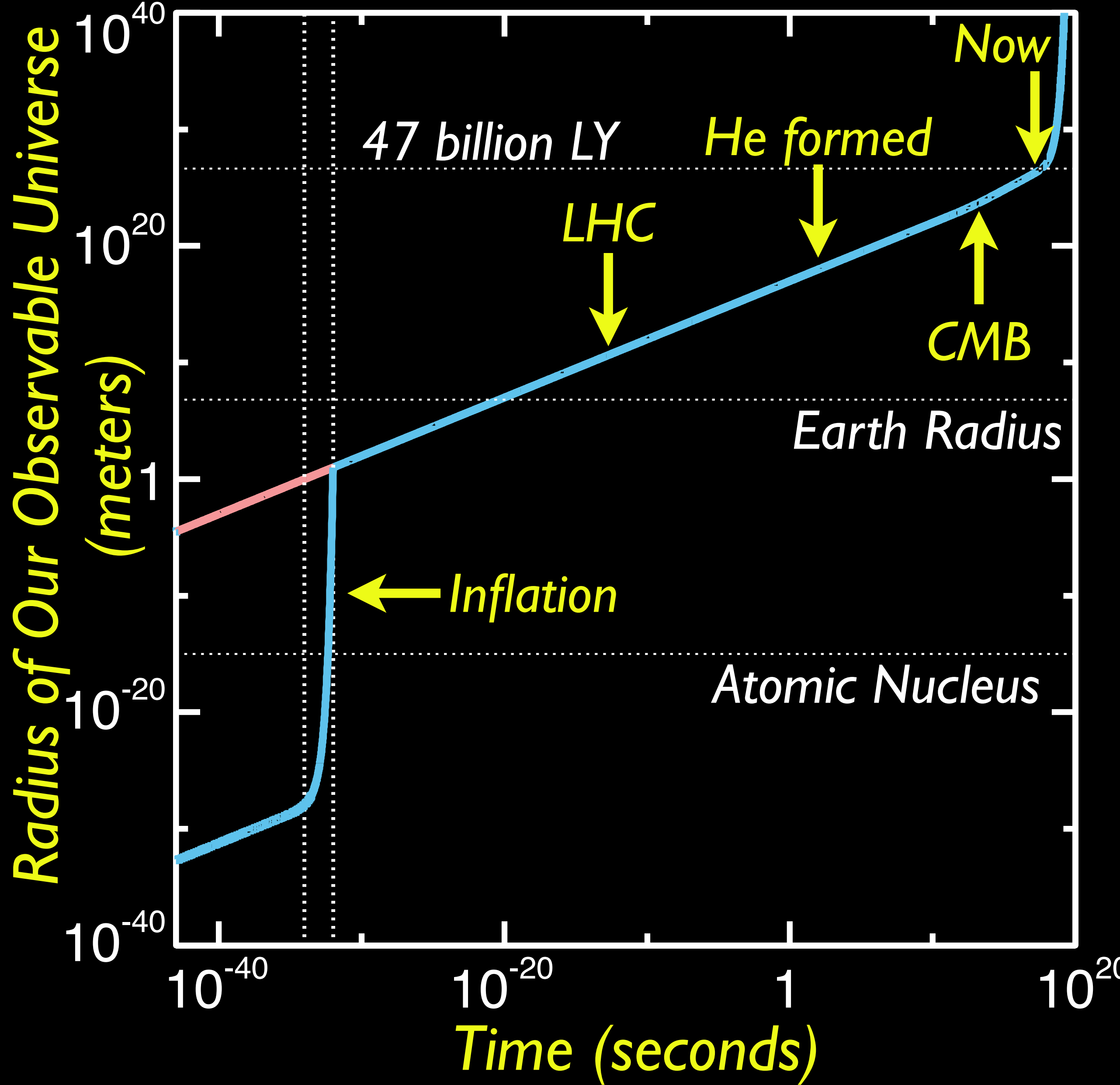

Just One Problem:
We don't know what caused inflation!

Scalar Fields: Cosmology's WD-40

"When cosmologists want something to move, they add a scalar field"

- Rocky Kolb (as best I can recall)

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \quad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Energy Density *Pressure*

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) = -\frac{8\pi G}{3}\left[\dot{\phi}^2 - V(\phi)\right]$$

Accelerated expansion if $\dot{\phi}^2 < V(\phi)$: slowly rolling scalar field

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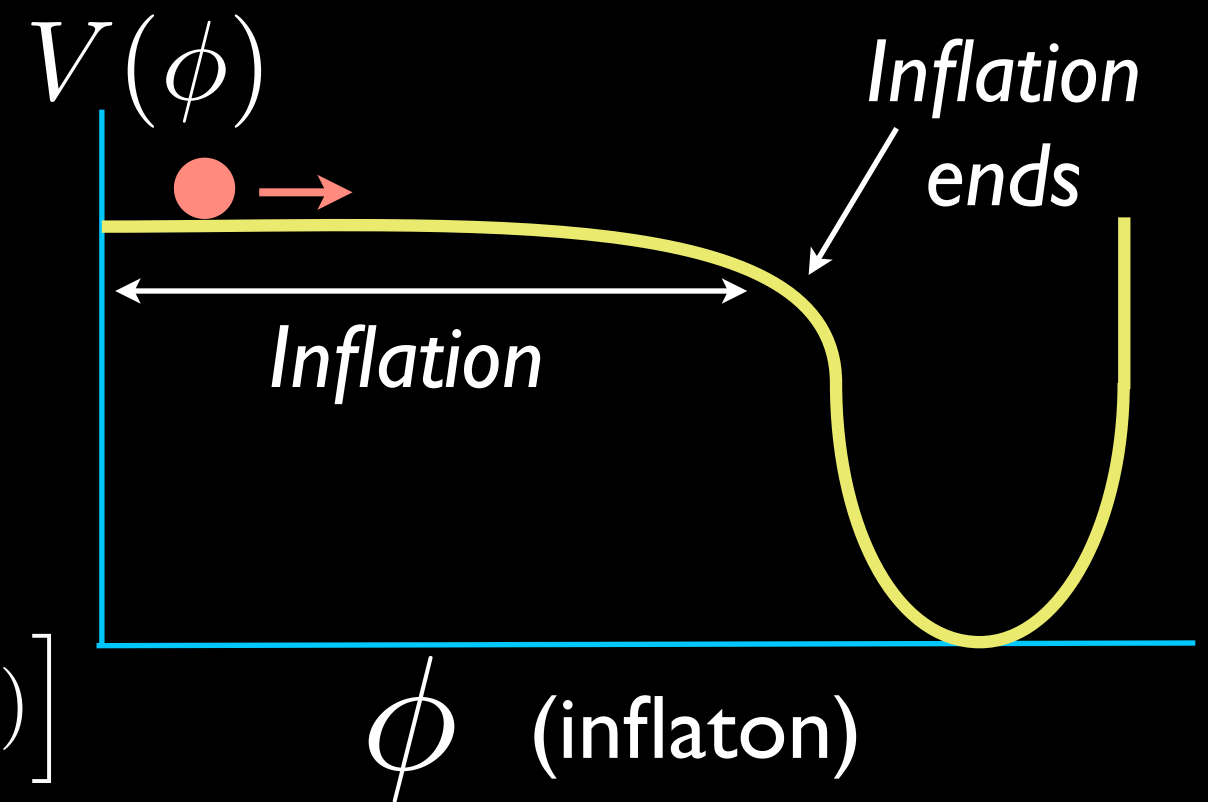


Accelerated expansion if $\dot{\phi}^2 < V(\phi)$: slowly rolling scalar field

Why slowly "rolling?"

Scalar field equation of motion: $$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

Acceleration *Hubble "drag"* *Force*

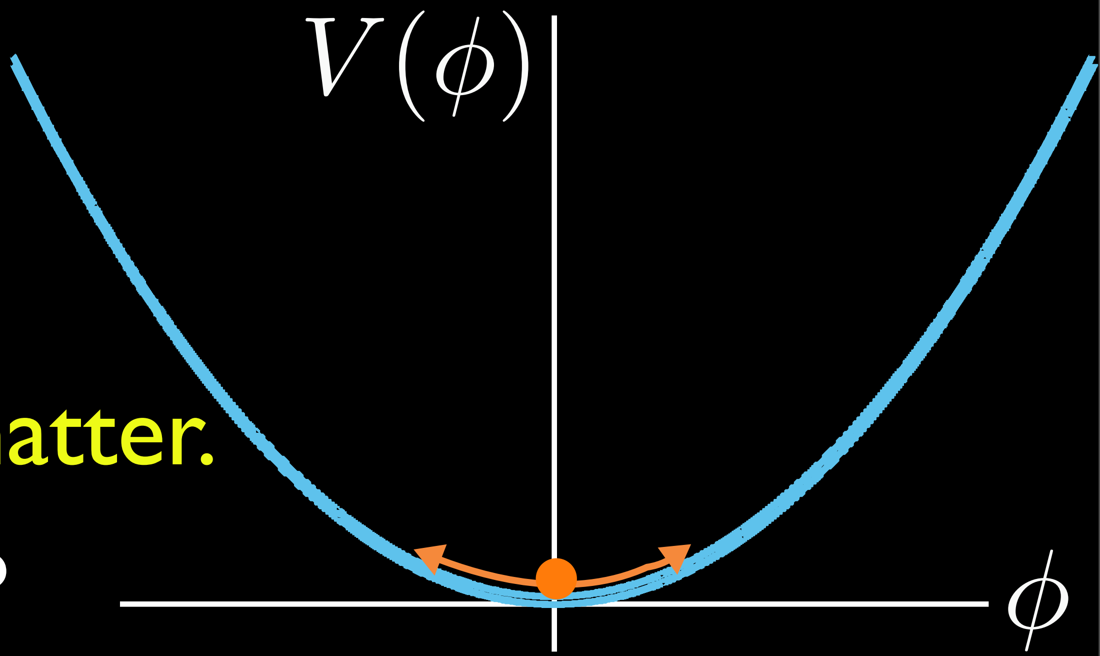
Inflation ends when $\dot{\phi}^2 > V(\phi) \Longleftrightarrow \frac{1}{16\pi G}\left[\frac{V'(\phi)}{V(\phi)}\right]^2 > 1$

Inflation ends when inflaton potential is too steep for field to roll slowly.

After Inflation: "Matter" Domination

In many models, inflation ends when the inflaton reaches its potential's minimum and begins to oscillate.

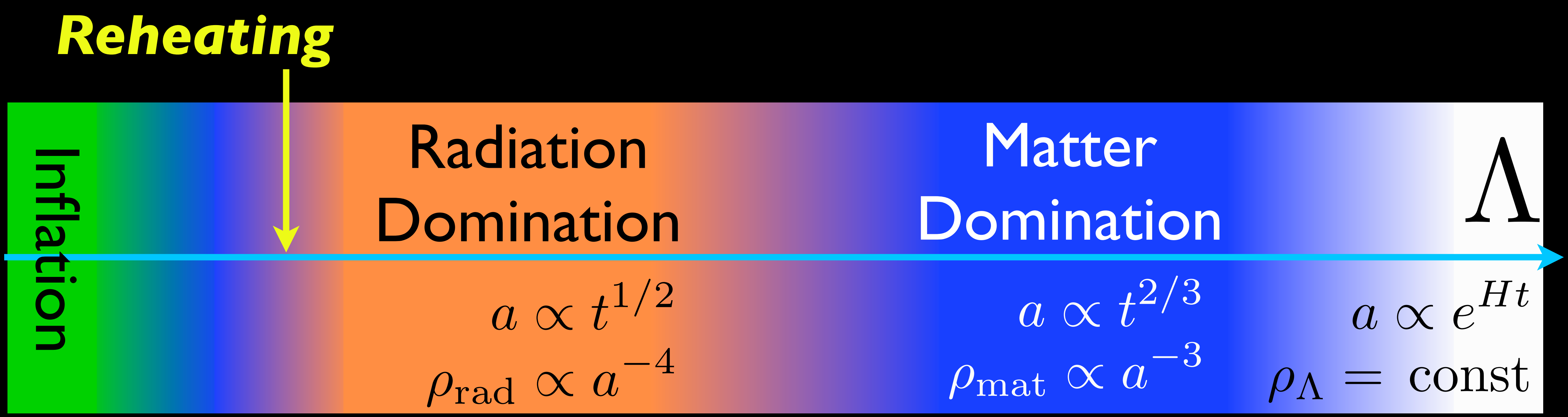
For $V \propto \phi^2$, oscillating scalar field $\simeq$ matter.



- over many oscillations, average pressure is zero
- density in scalar field evolves as $\rho_\phi \propto a^{-3}$
- scalar field density perturbations grow as $\delta_\phi \propto a$

Jedamzik, Lemoine, Martin 2010; Easther, Flauger, Gilmore 2010

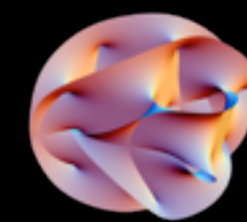
What happens to perturbations after reheating?



After Inflation: "Matter" Domination

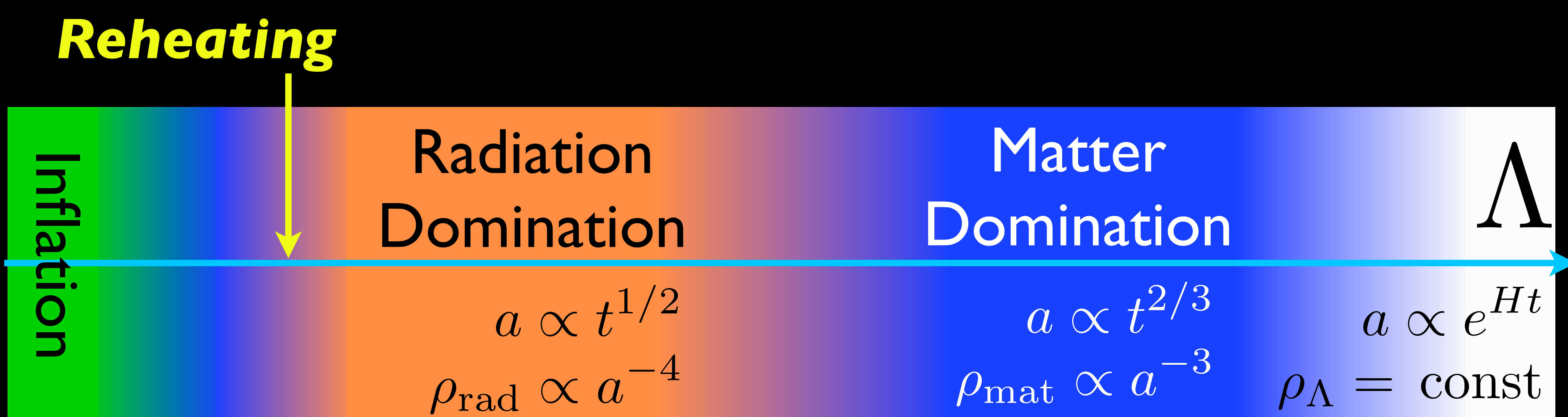
Other epochs of early "matter" domination?

- other oscillating scalar fields: curvatons, string moduli
- heavy particles created from inflaton decays



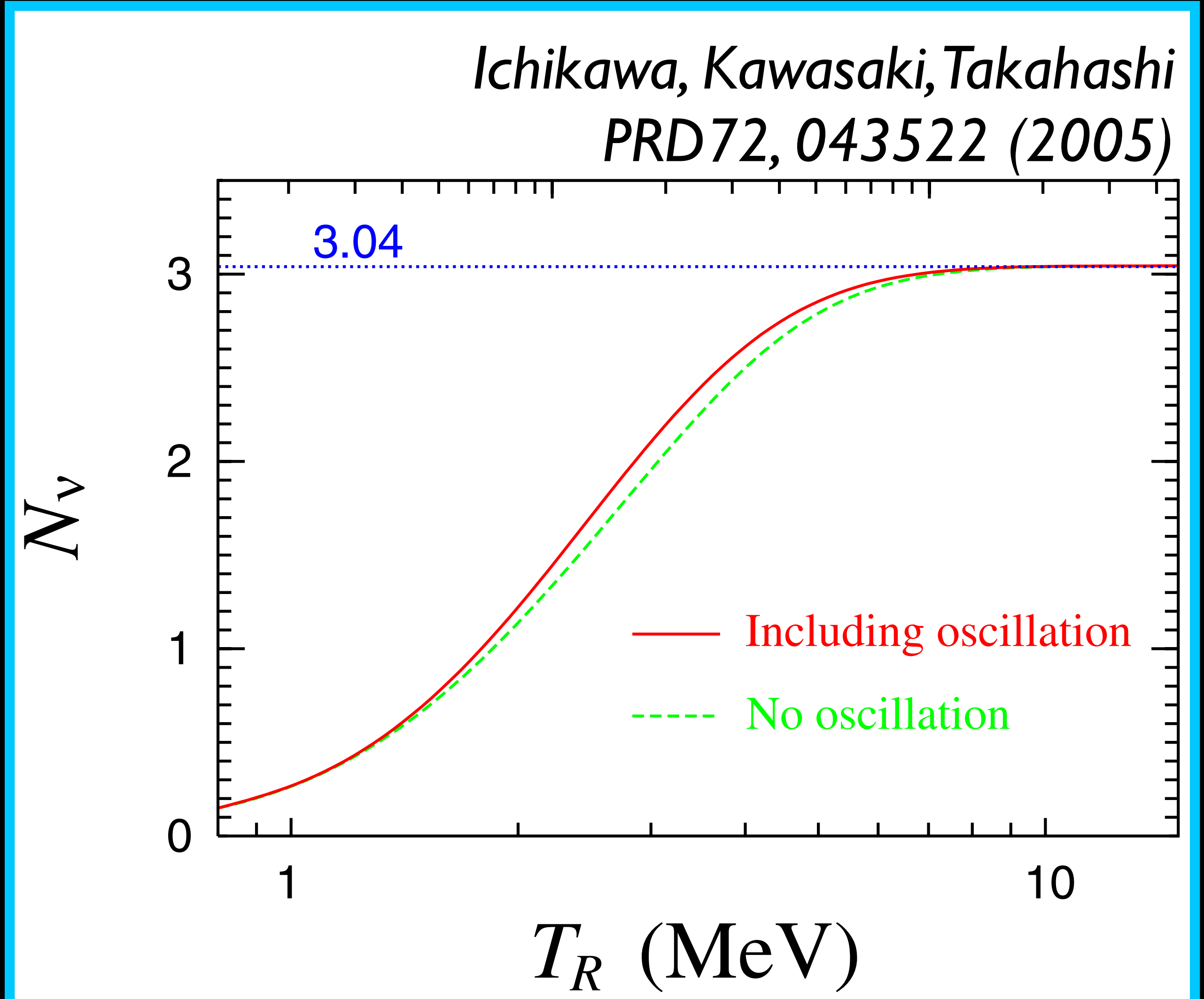
Scalar domination ended when the scalar decayed into radiation, reheating the Universe.

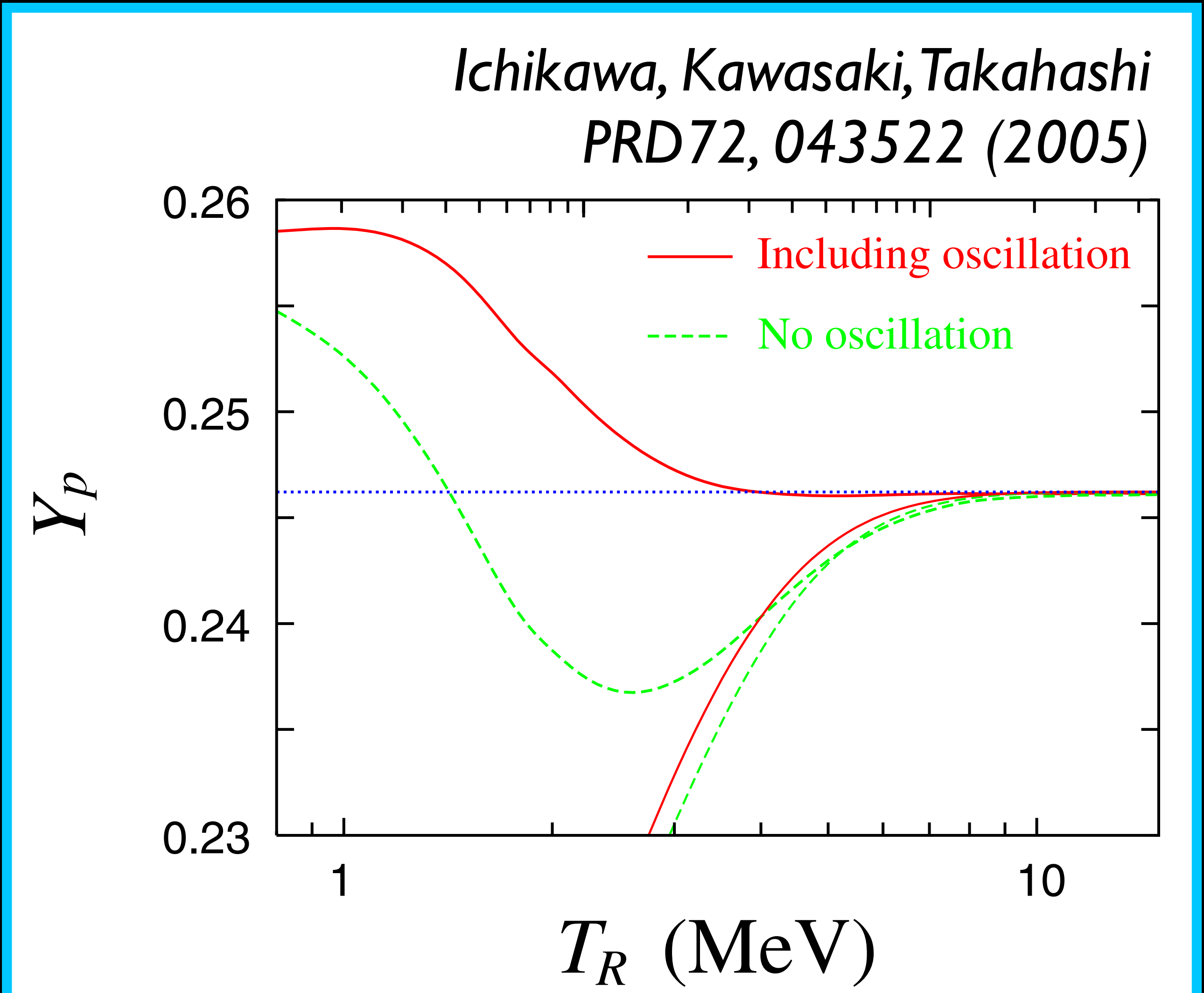
- assume perturbative decay; requires small decay rate
- scalar decays can also produce dark matter
- unknown reheat temperature, but the Universe must be hot for BBN.



Don't Mess with BBN

Reheat Temperature = Temperature at Radiation Domination





Lowering the reheat temperature results in fewer neutrinos.

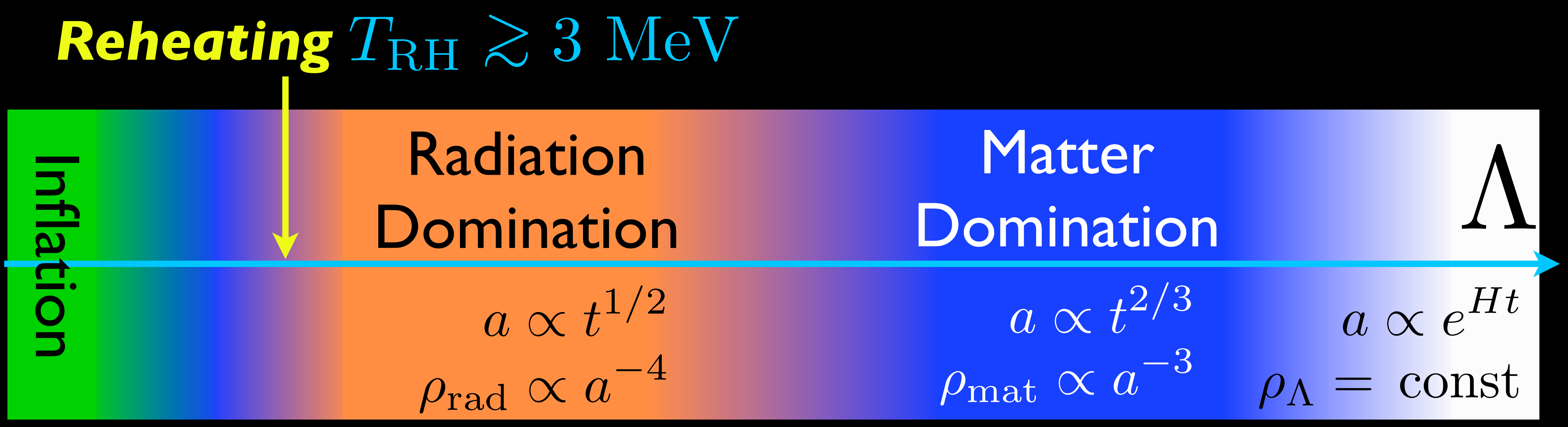
- slower expansion rate during BBN
- earlier neutron freeze-out; more helium
- earlier matter-radiation equality

$$T_{\rm RH} \gtrsim 3\ \text{MeV}$$

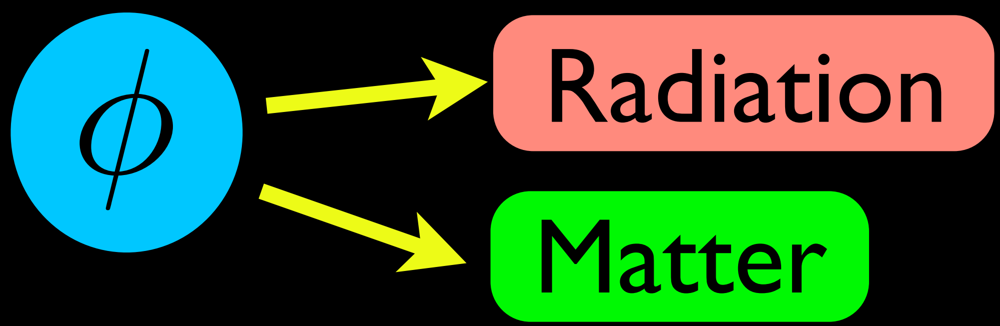
Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008

Microhalos from Reheating

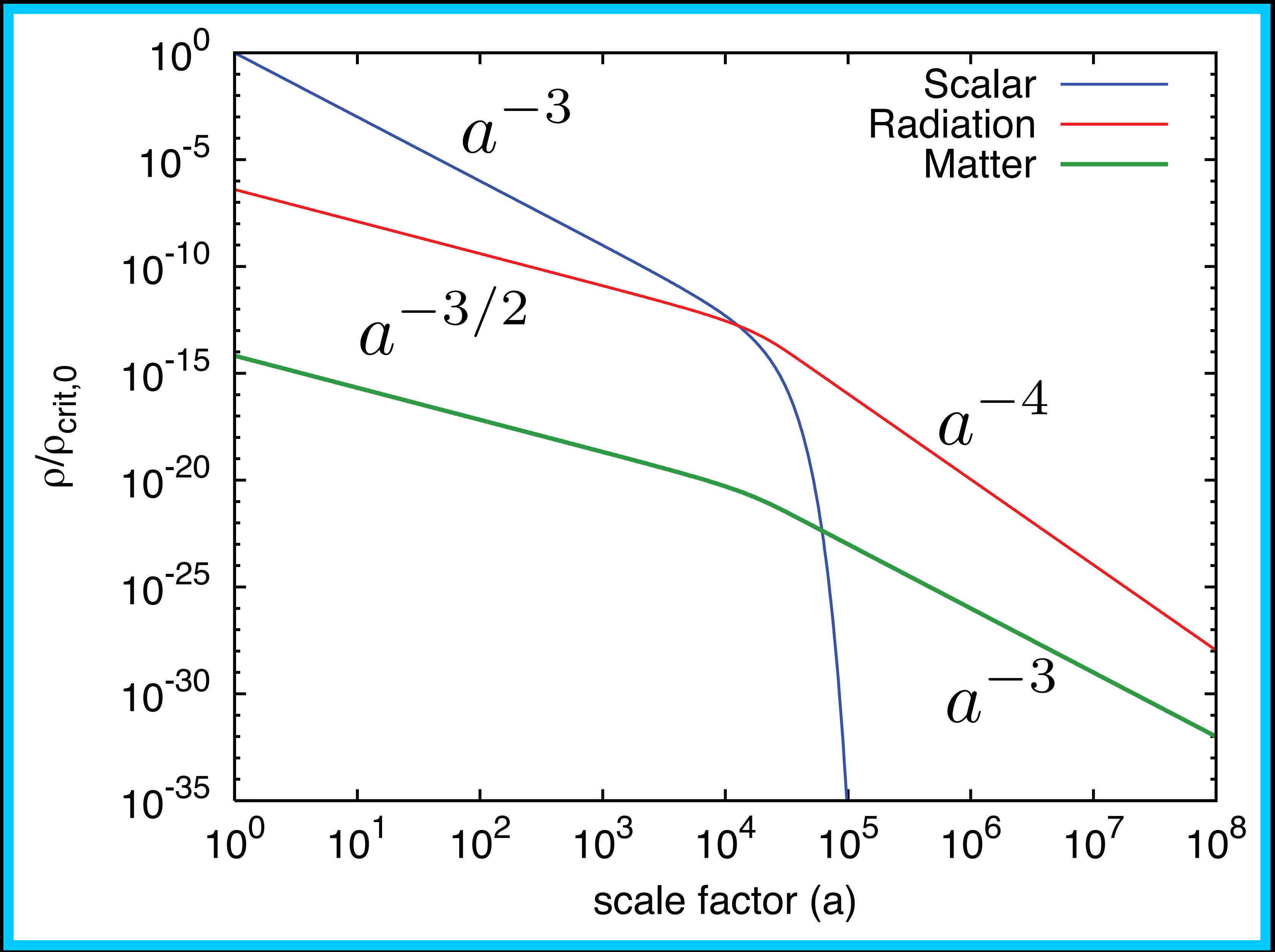
Erickcek & Sigurdson PRD 84, 083503 (2011)



Scalar Field Decay



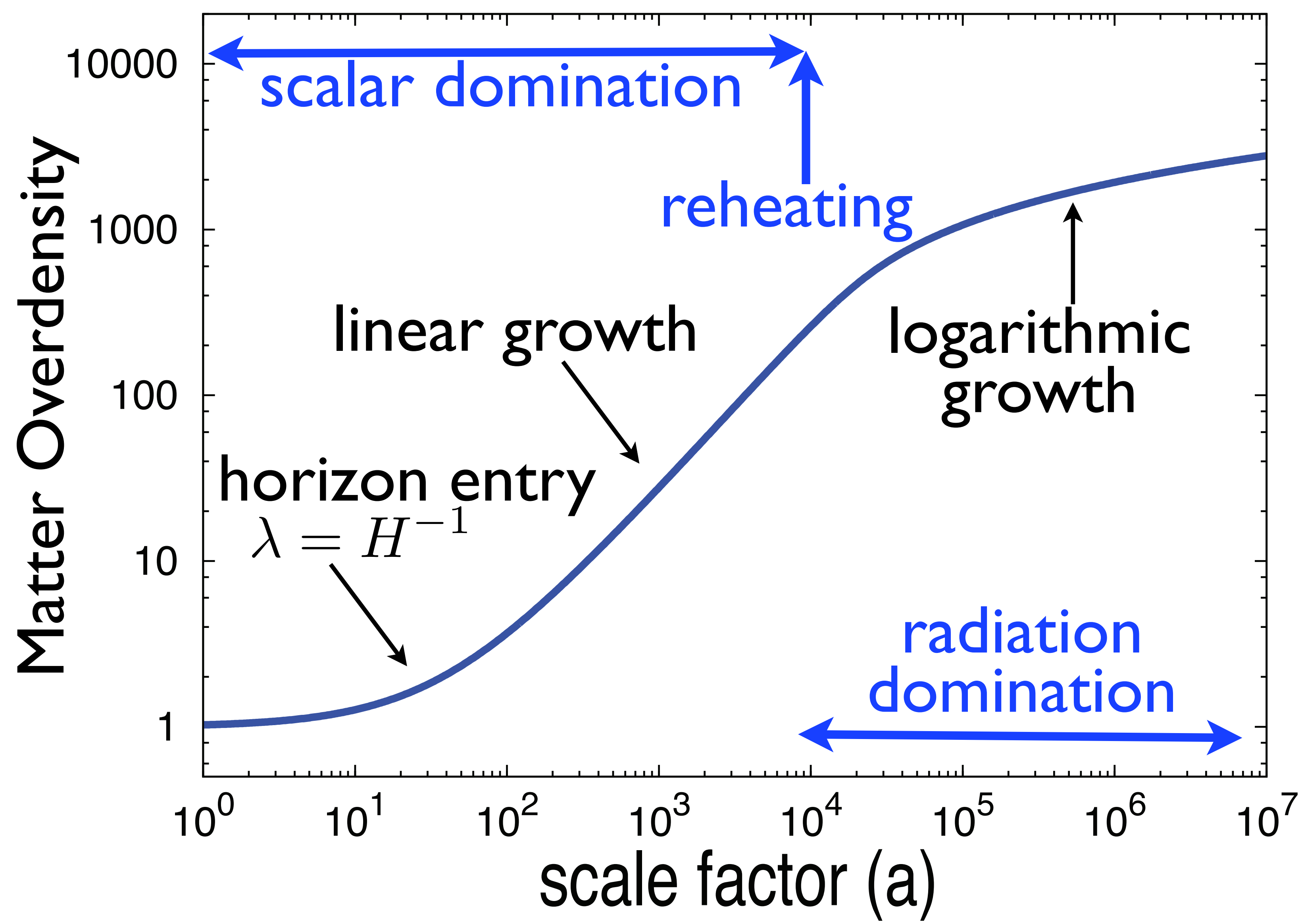
$$(1-f)\rho_\phi \longrightarrow \rho_{\rm rad}$$
$$f\rho_\phi \longrightarrow \rho_{\rm mat}$$



The Matter Perturbation

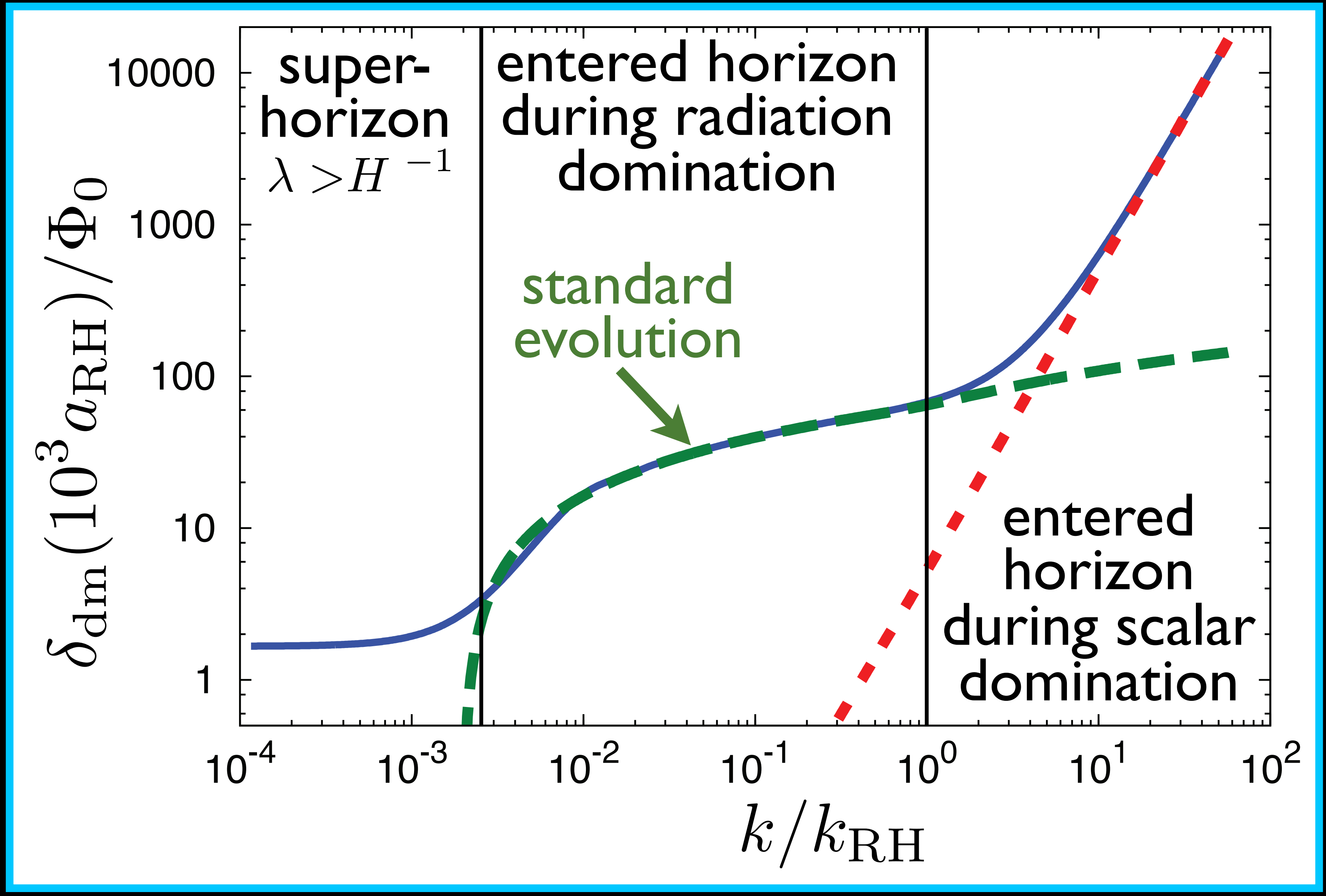
Scalar domination affects the growth of density fluctuations.

Evolution of the Matter Density Perturbation



The Matter Perturbation

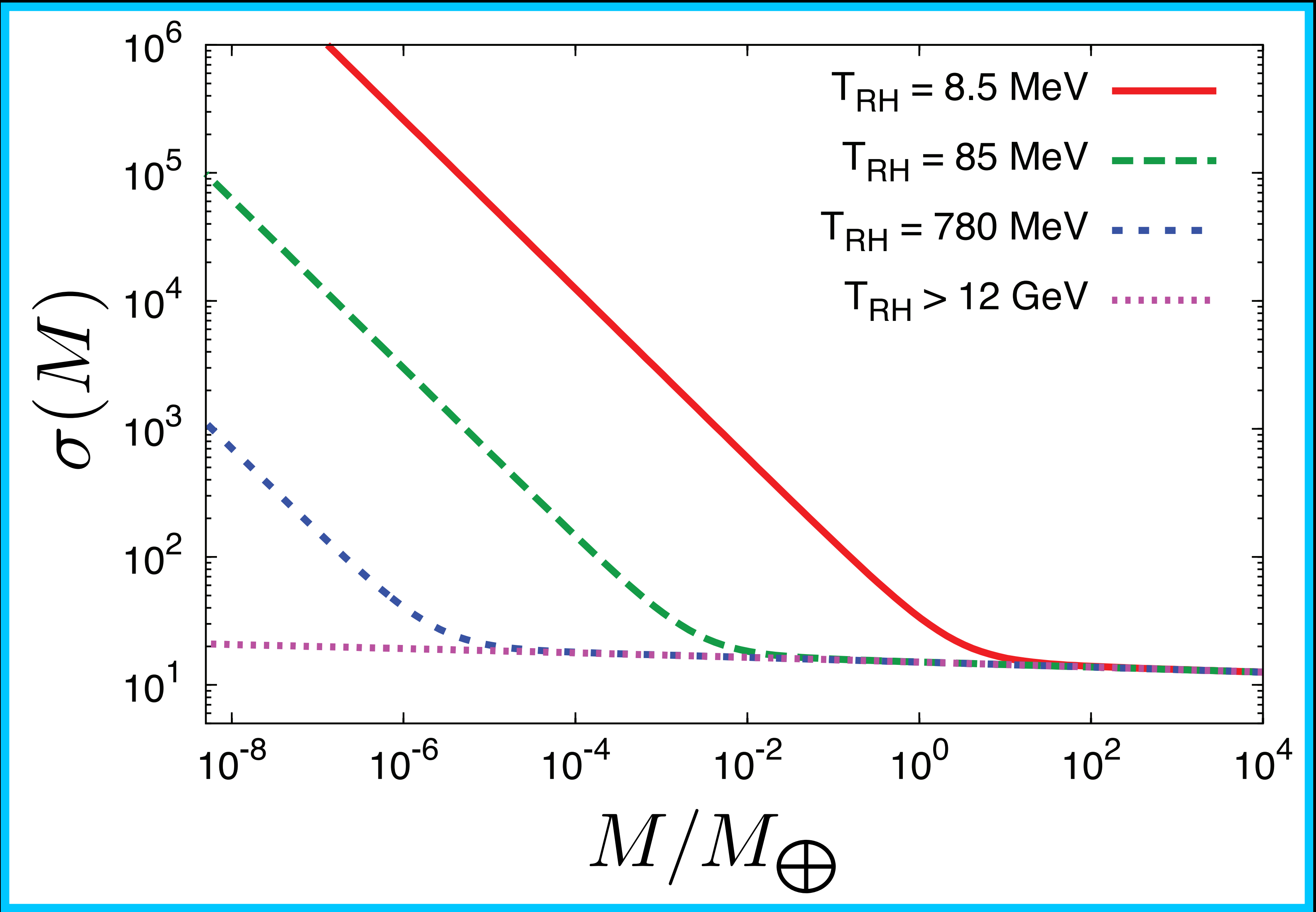
The Matter Density Perturbation during Radiation Domination



$$k_{\rm RH} = 35\ (T_{\rm RH}/3\,{\rm MeV})\ \ {\rm kpc}^{-1}$$

Wavenumber of mode that enters horizon at reheating

RMS Density Fluctuation



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

$$M_{\rm RH} \simeq 32.7 M_\oplus \left(\frac{10\,{\rm MeV}}{T_{\rm RH}}\right)^3$$

From Perturbations to Microhalos

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

$$\frac{df}{d\ln M} = \sqrt{\frac{2}{\pi}} \left| \frac{d\ln\sigma}{d\ln M} \right| \frac{\delta_c}{\sigma(M,z)} \exp\left[-\frac{1}{2} \frac{\delta_c^2}{\sigma^2(M,z)} \right]$$

differential bound fraction

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Key ratio: $\frac{\delta_c}{\sigma(M,z)}$

- Halos with $\sigma(M,z) < \delta_c$ are rare.
- Define $M_*(z)$ by

$$\sigma(M_*, z) = \delta_c$$

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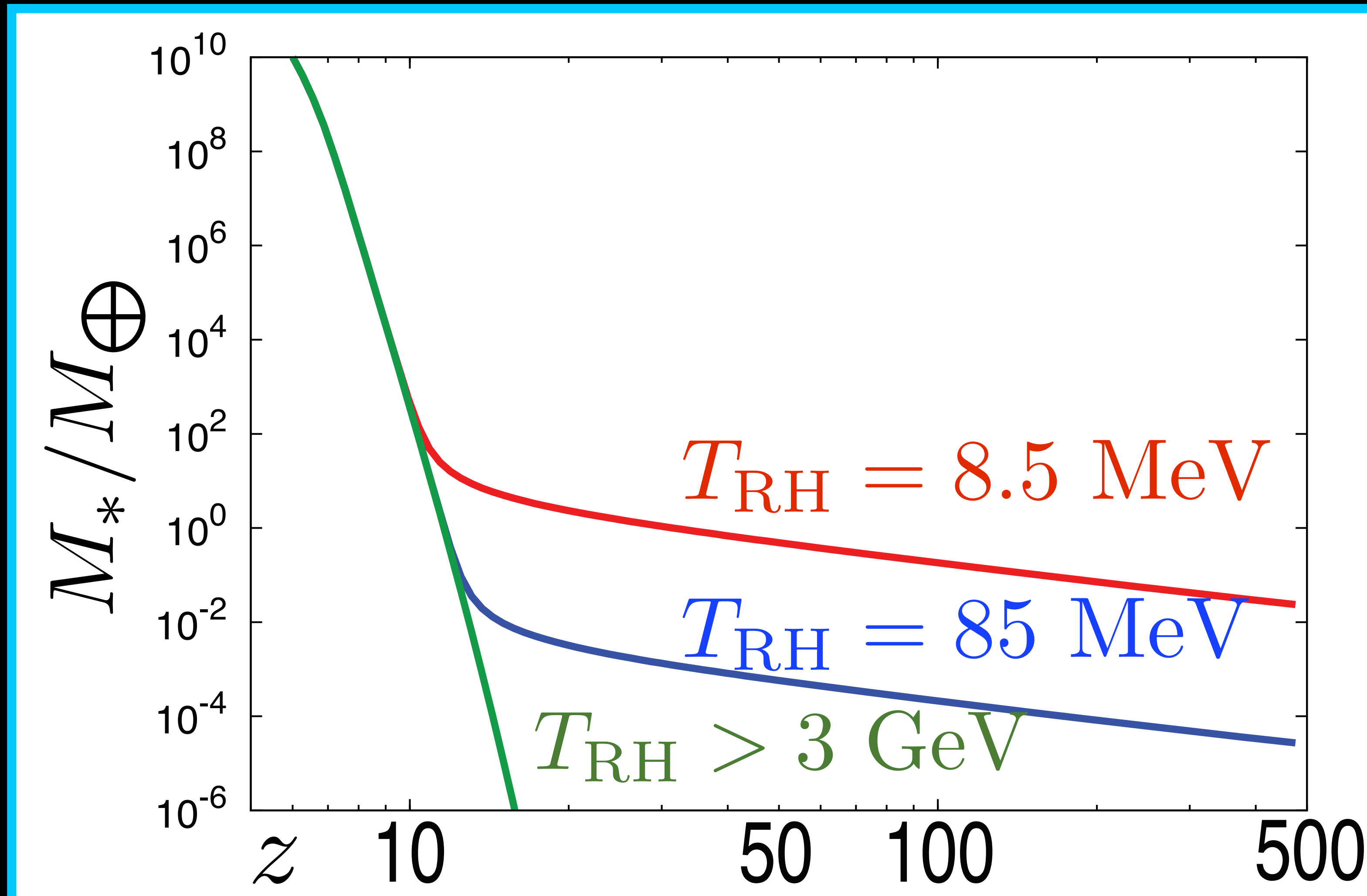
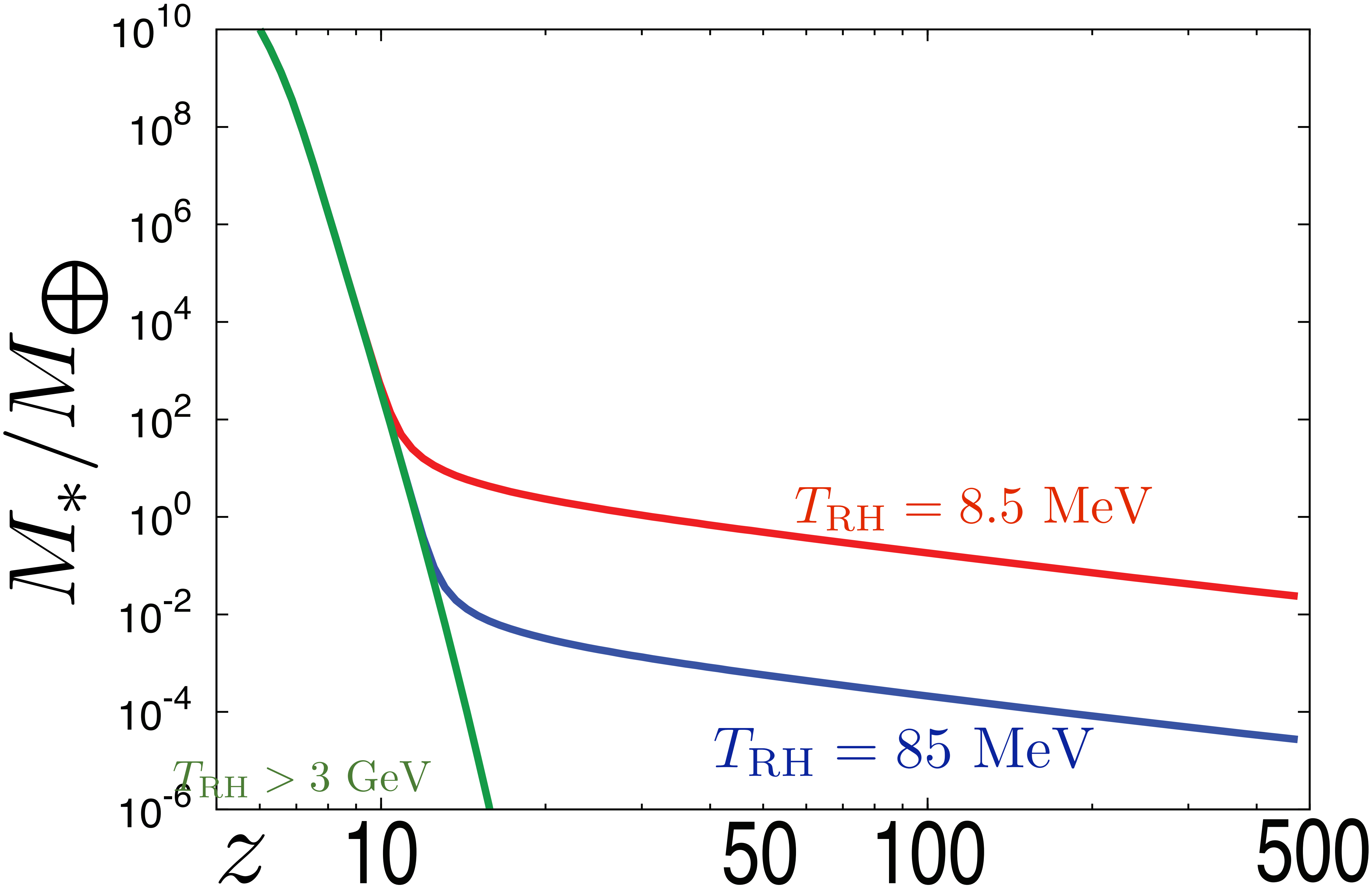


M_* Properties

$M_*(z)$ is the largest halo that is common at a given redshift.



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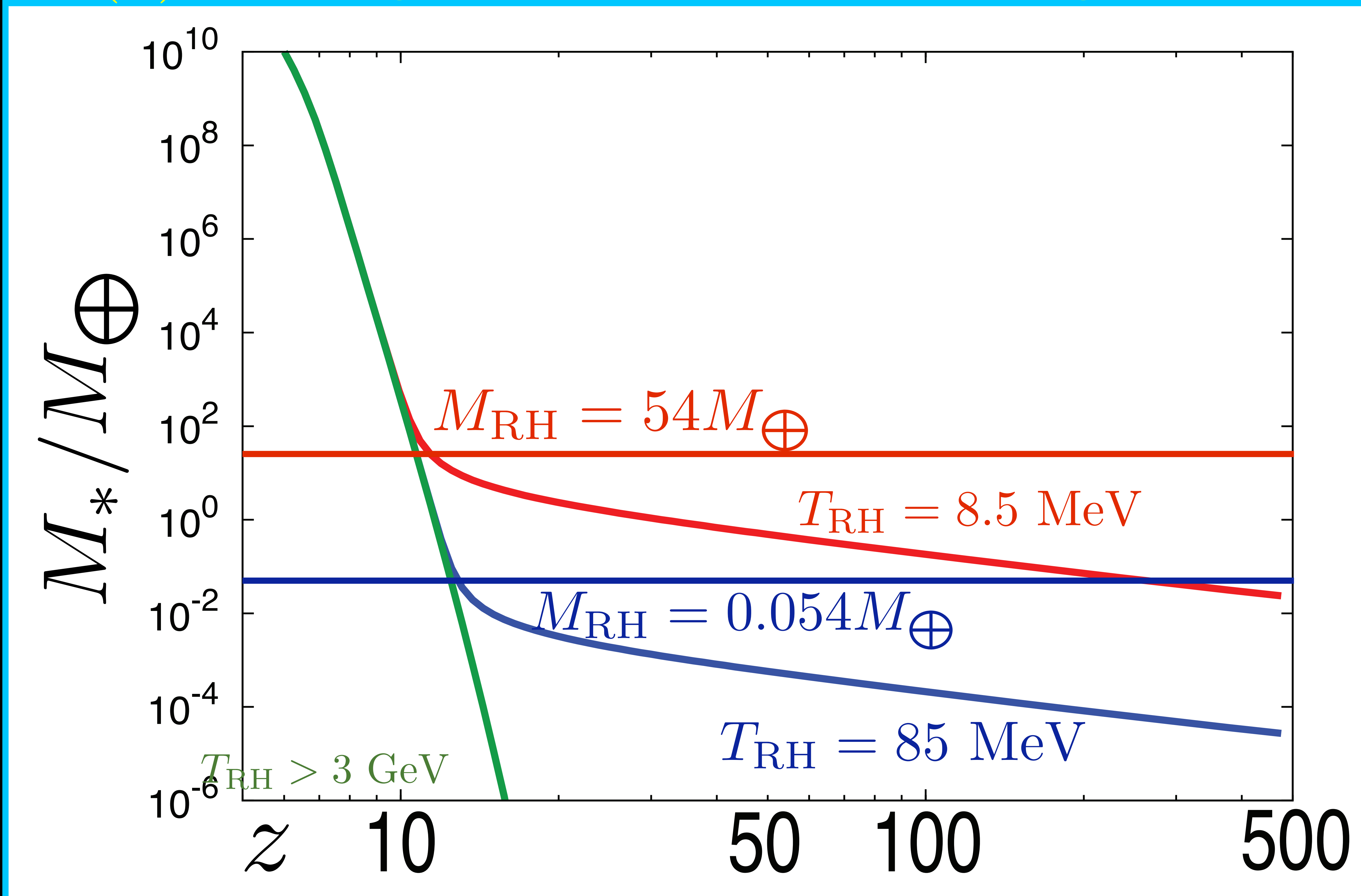

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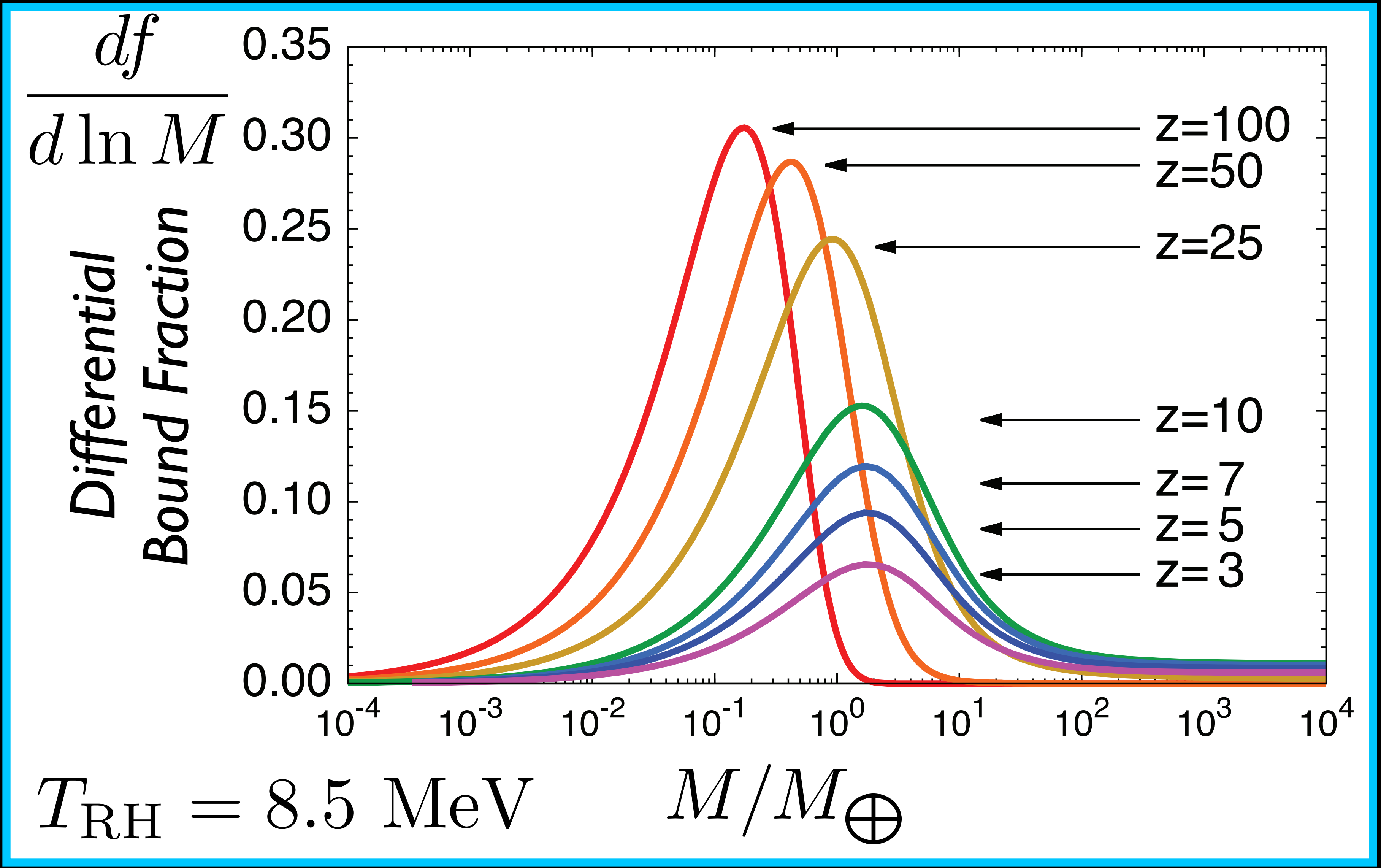

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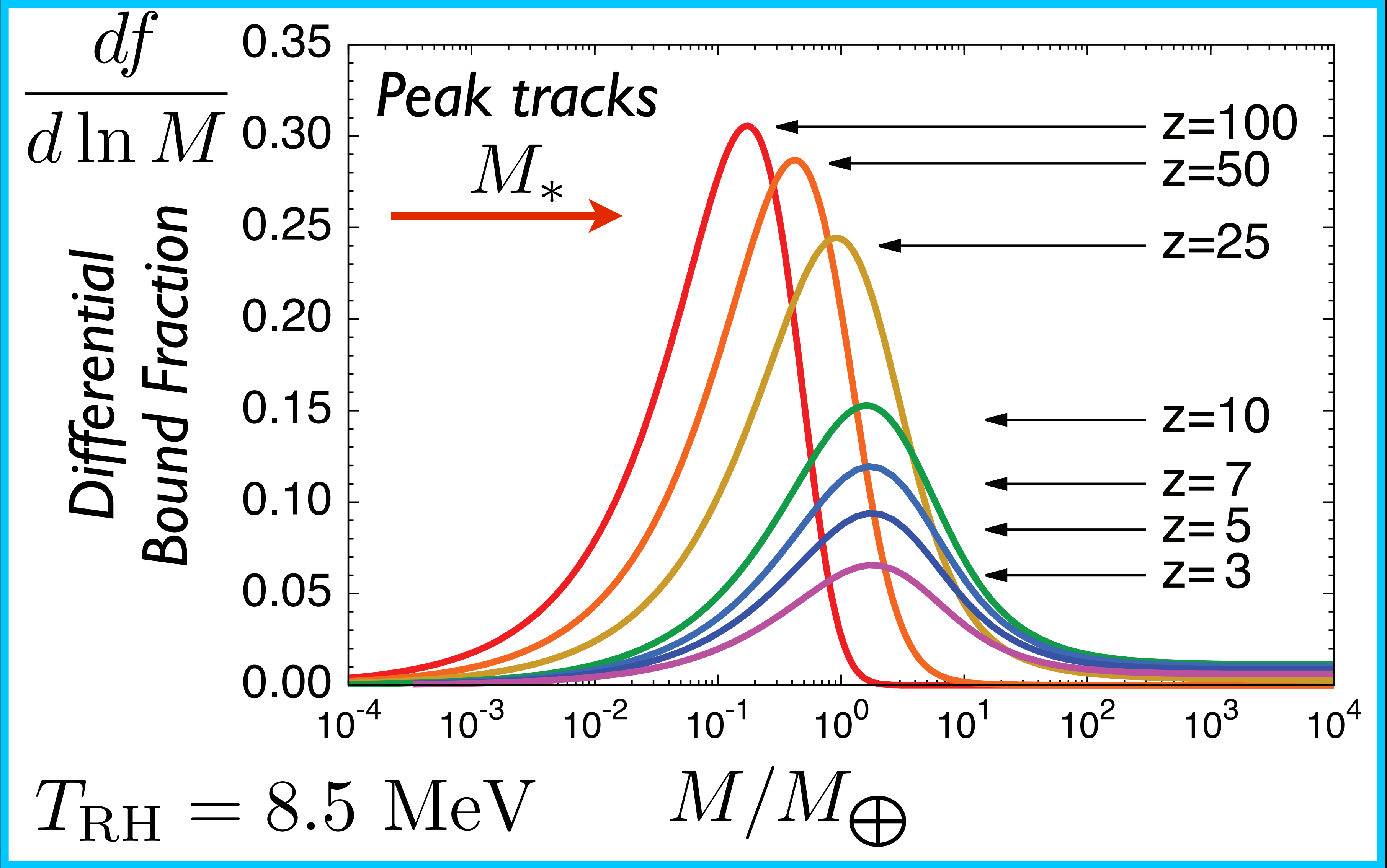

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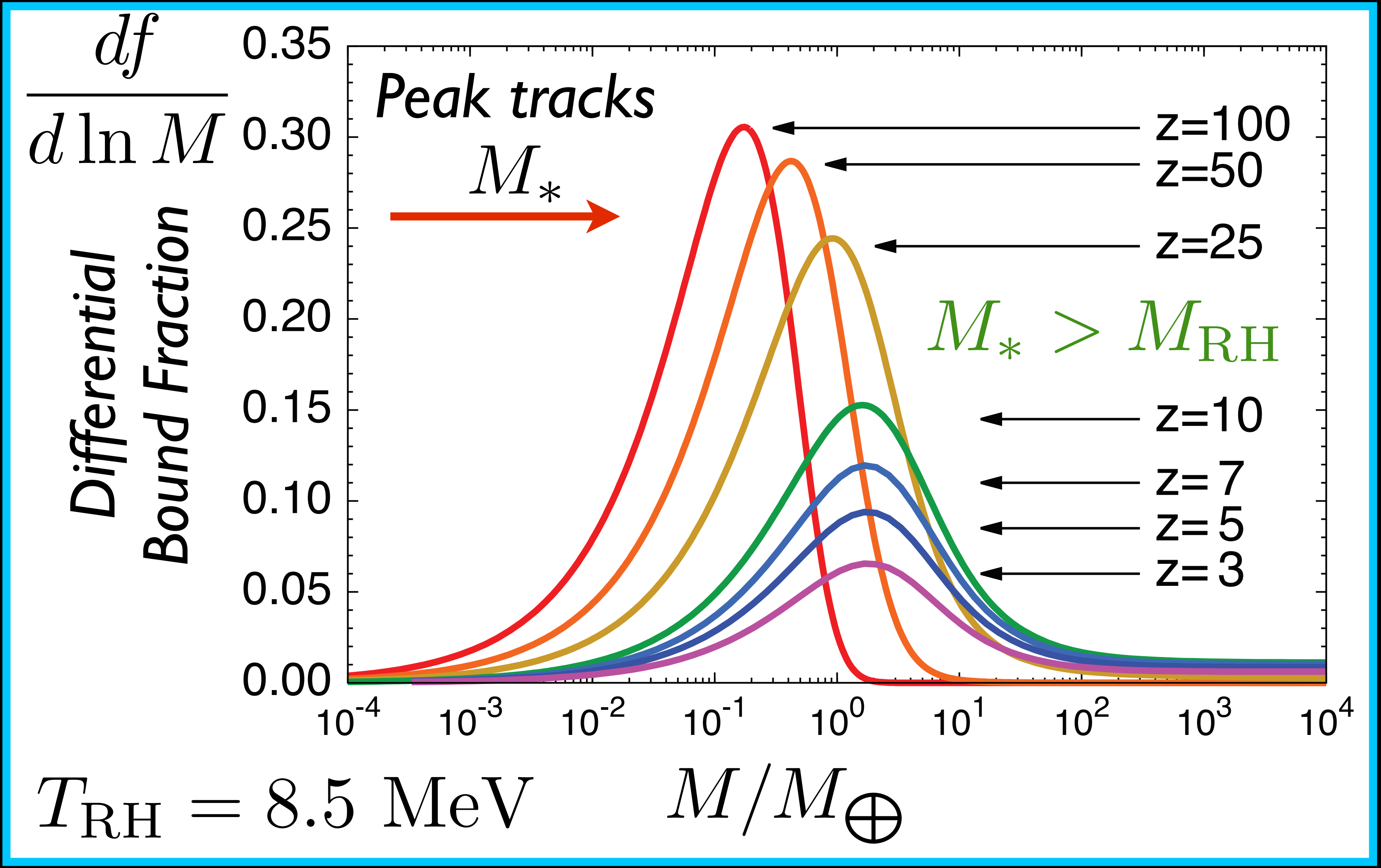

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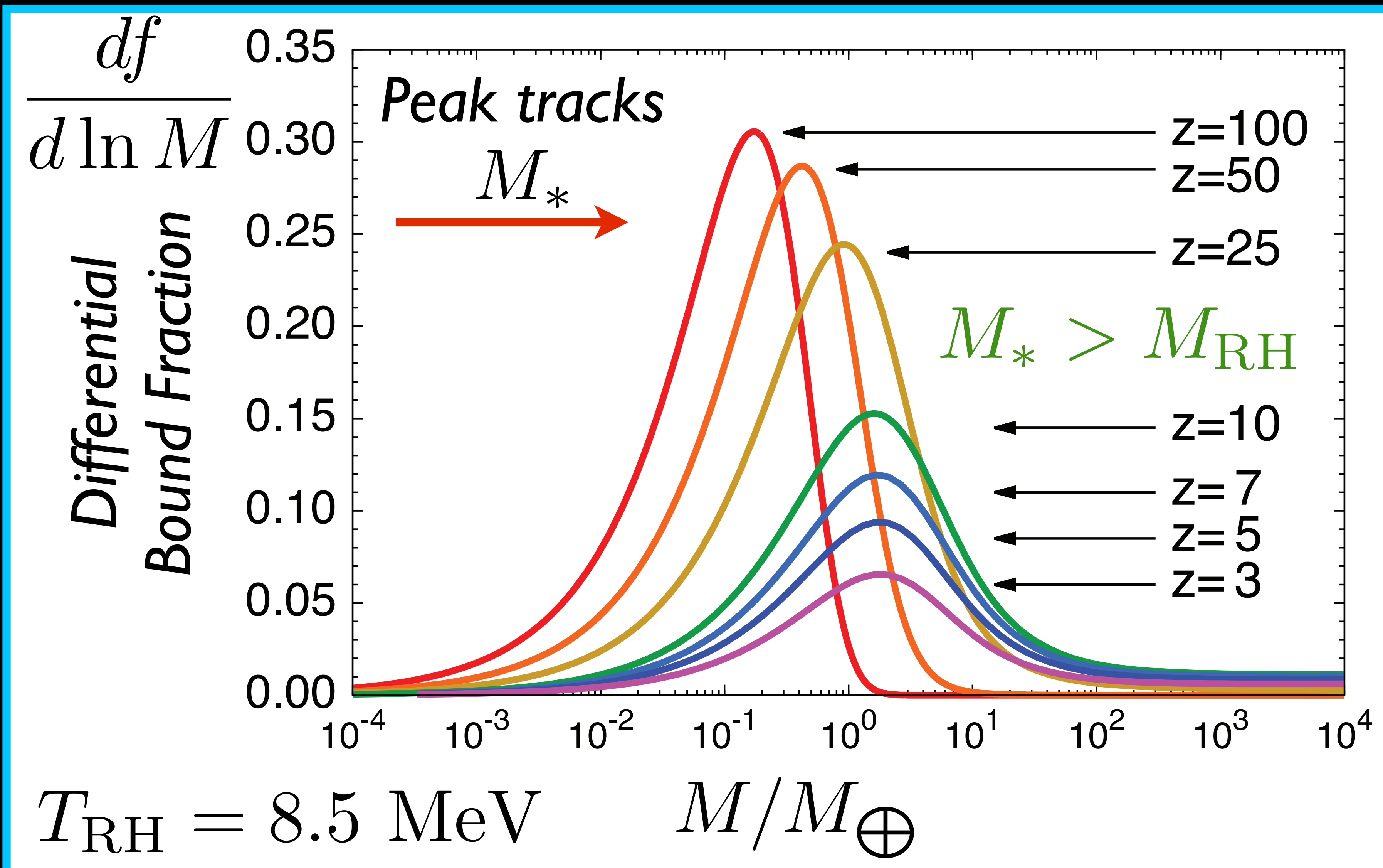

Fraction bound in halos with $M > 0.1\,M_\oplus$

z	Std	8.5 MeV
100	10^{-10}	0.49
50	10^{-3}	0.71
25	0.06	0.83

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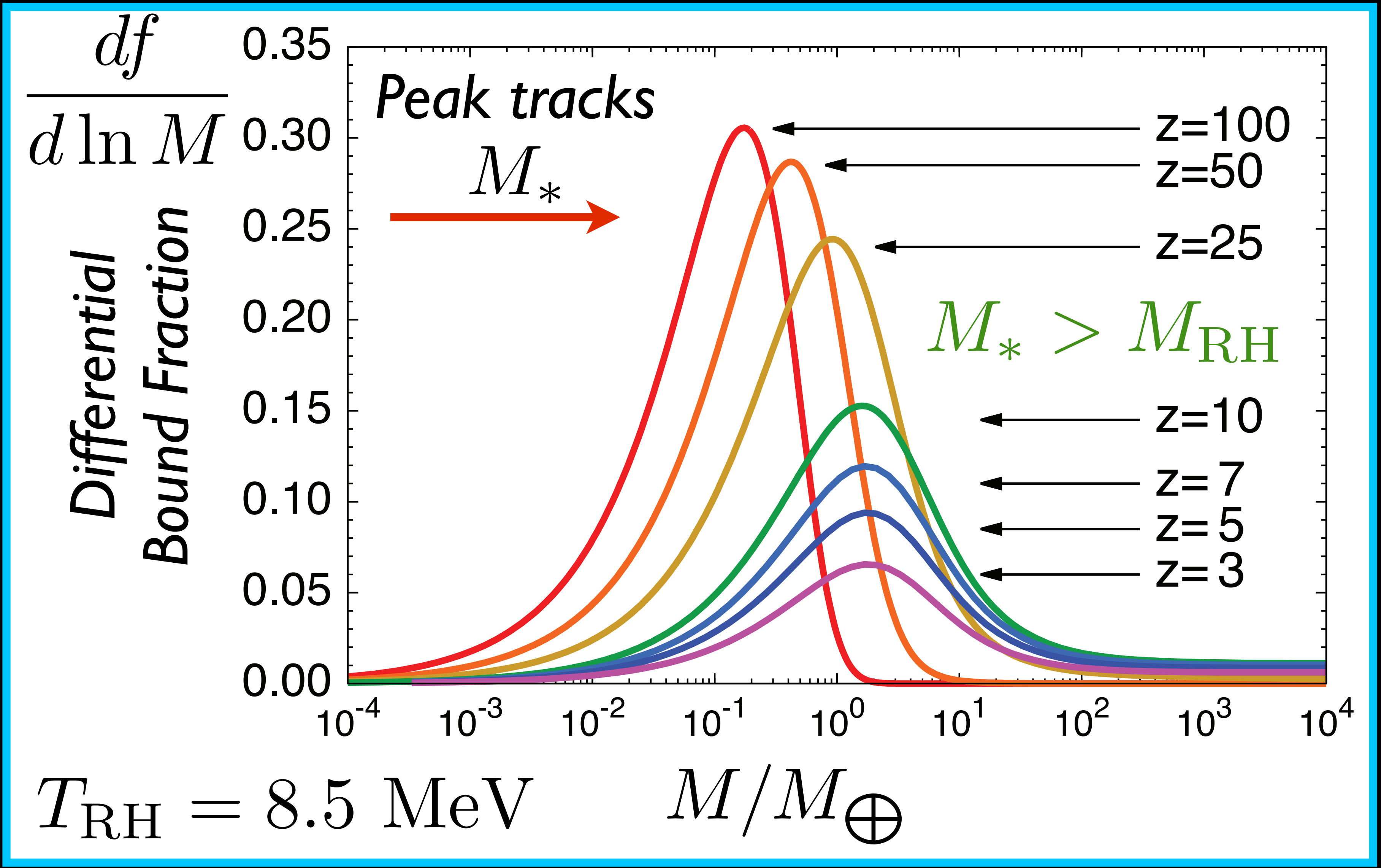

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Most dark matter is bound into microhalos after $z = 100$!

What about free-streaming?

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

Specify average particle velocity at reheating:

$$\langle v \rangle = \langle v_{\rm RH} \rangle \left(a_{\rm RH}/a\right)$$

For range of reheat temperatures,

$$\frac{k_{\rm RH}}{k_{\rm fsh}} \simeq \frac{\langle v_{\rm RH} \rangle}{0.06}$$

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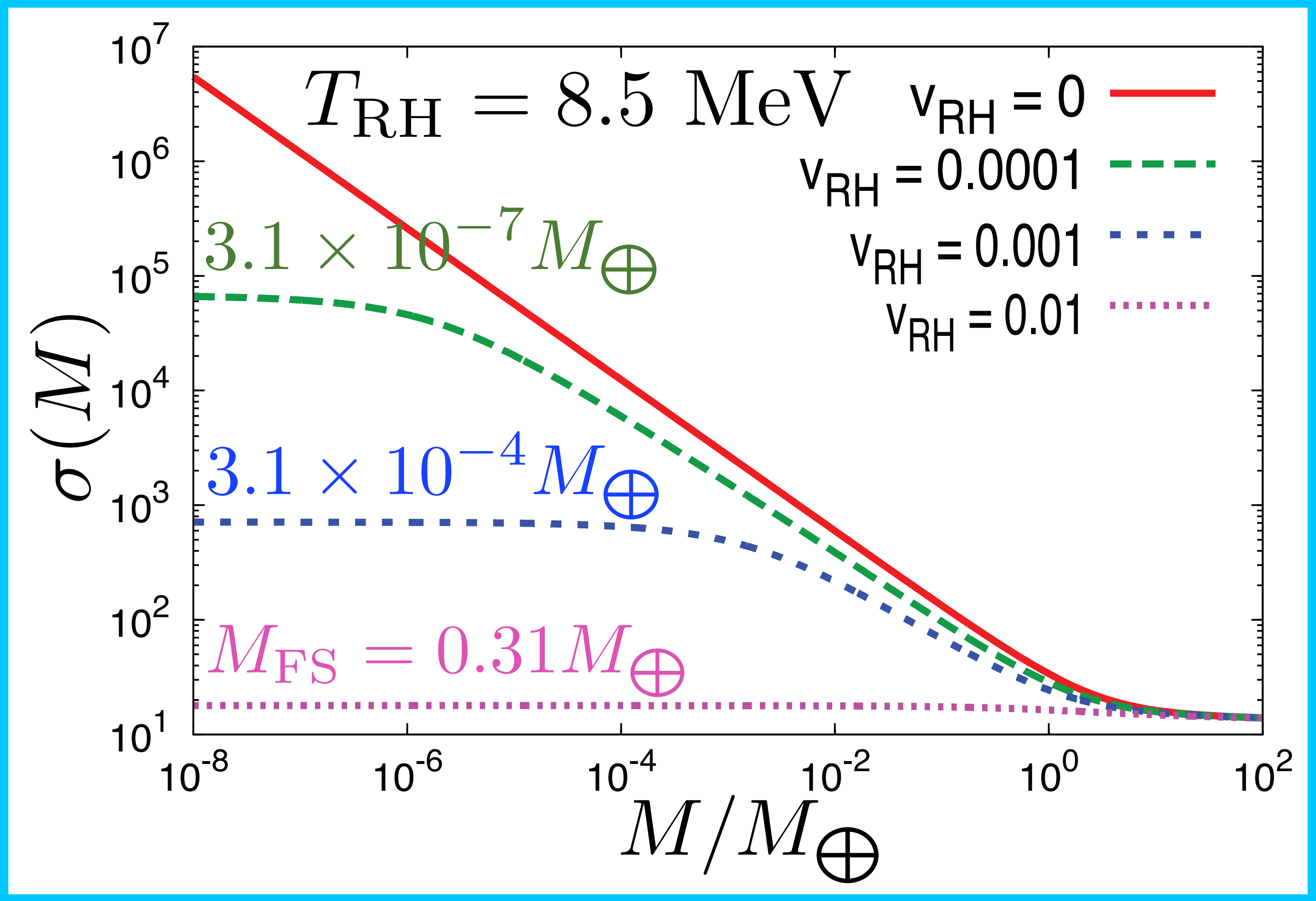

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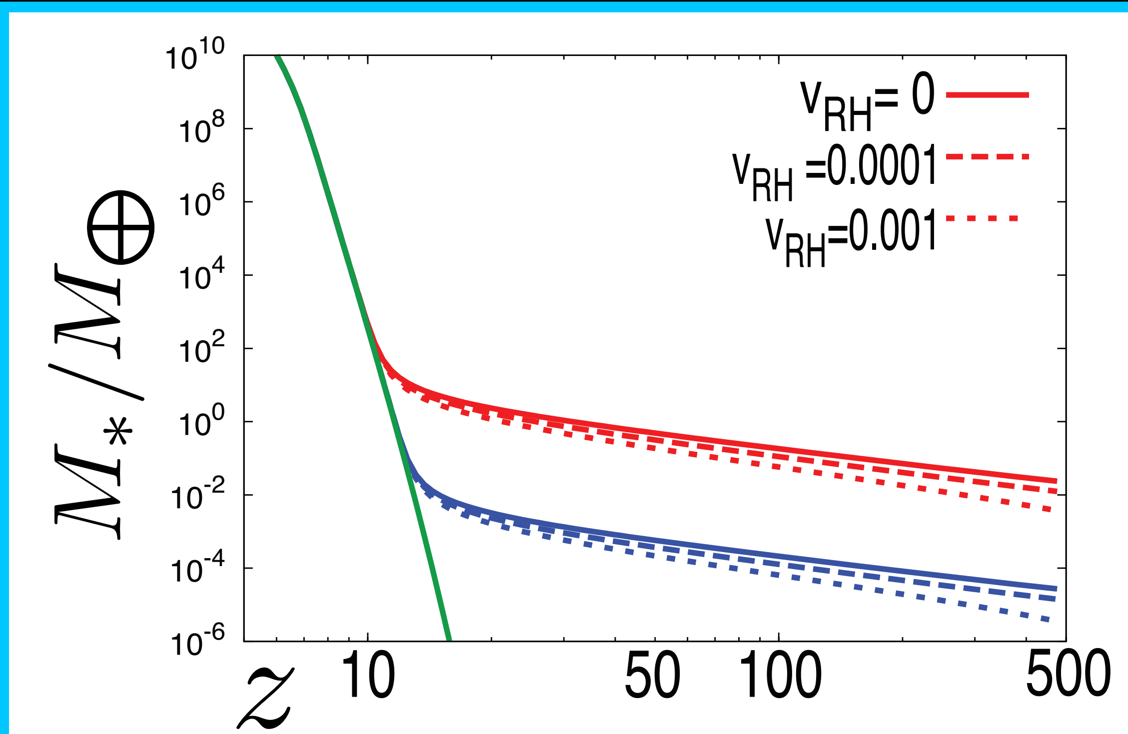
Structures grown during reheating only survive if $\langle v_{\rm RH} \rangle \lesssim 0.001c$

- dark matter from scalar decay: nearly degenerate decay or rapid energy loss
- spectator dark matter: dark matter decoupled long before reheating

Microhalos with Free-Streaming

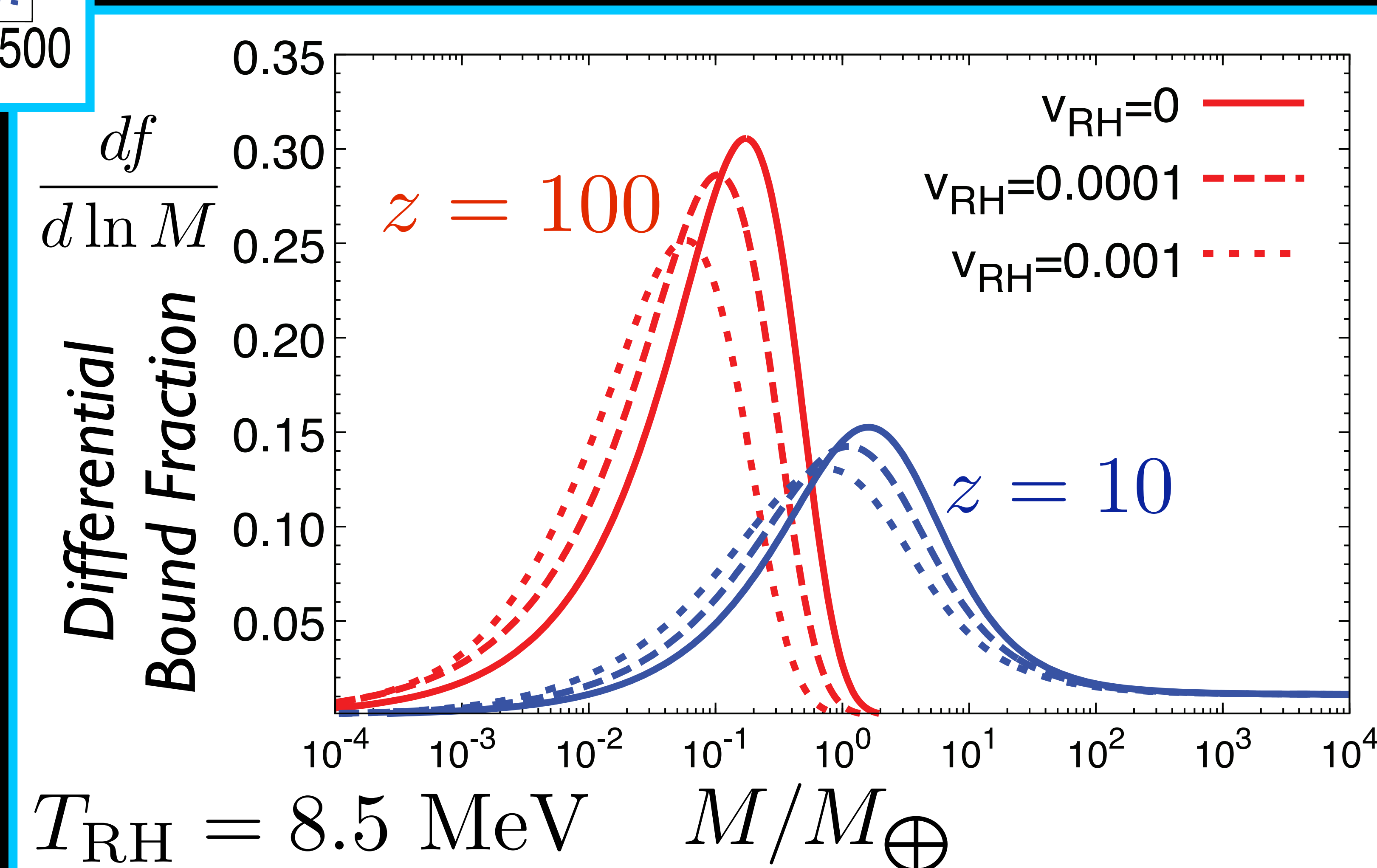


Giving the dark matter particles a small velocity at reheating slightly reduces M_* and $\left|\frac{d\ln\sigma}{d\ln M}\right|$.

Consequently, free-streaming leads to microhalos that

- have smaller masses
- are less abundant

$$\frac{df}{d\ln M} \propto \left|\frac{d\ln\sigma}{d\ln M}\right|$$



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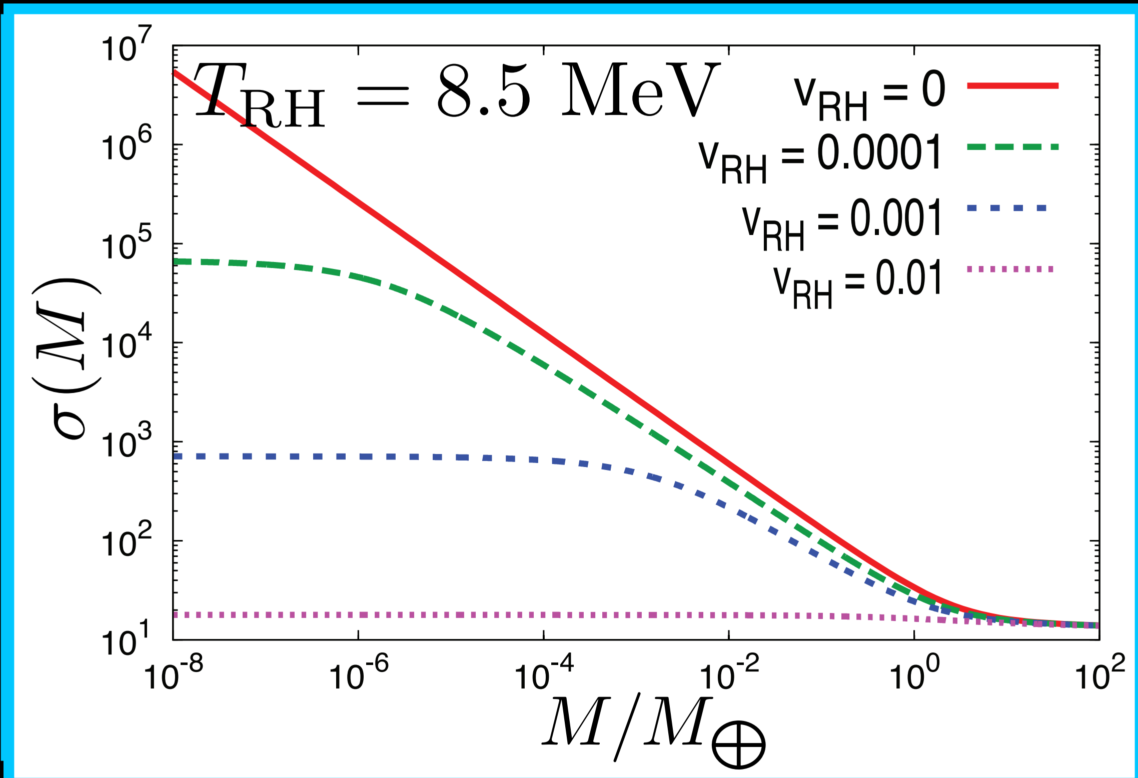

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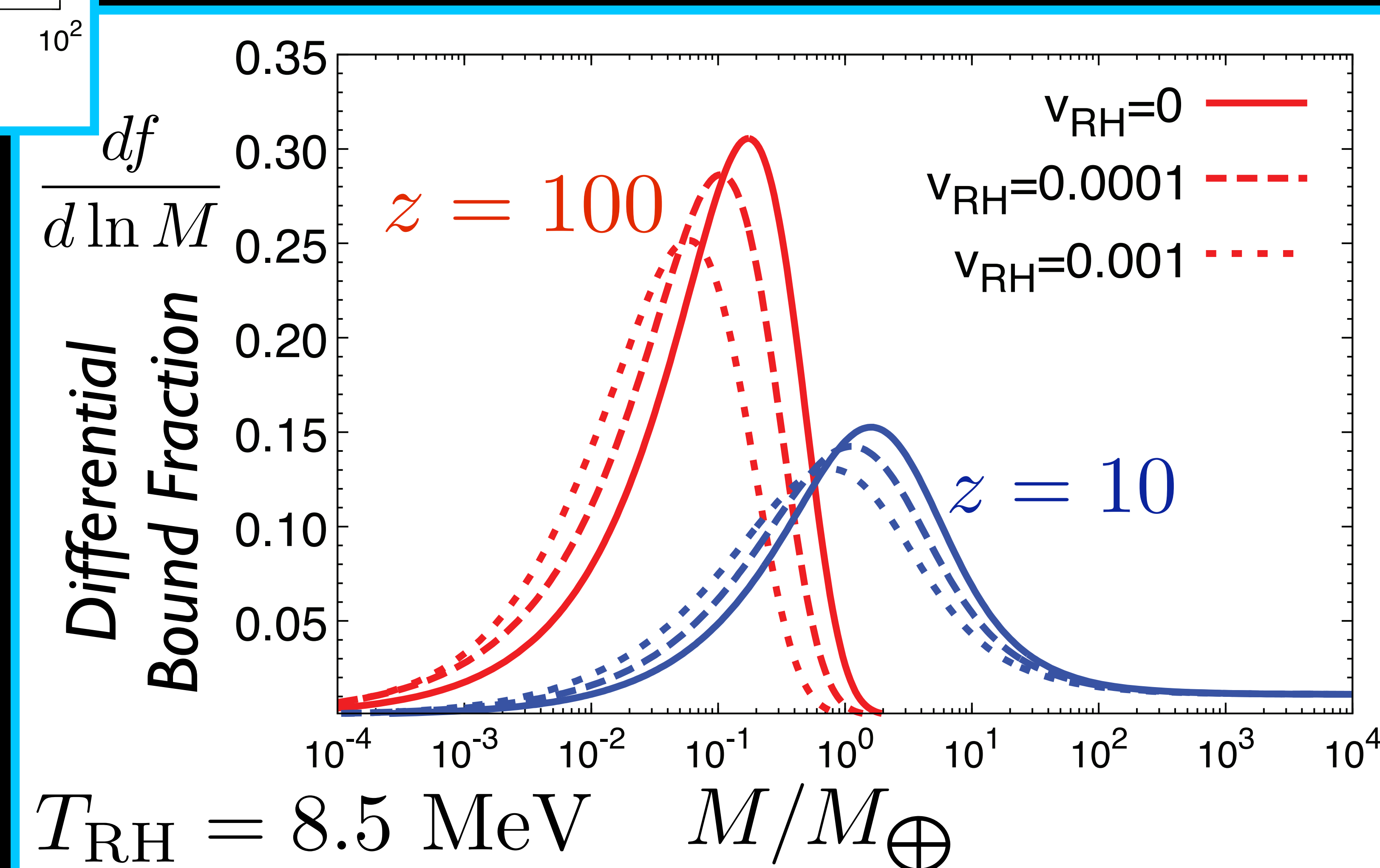
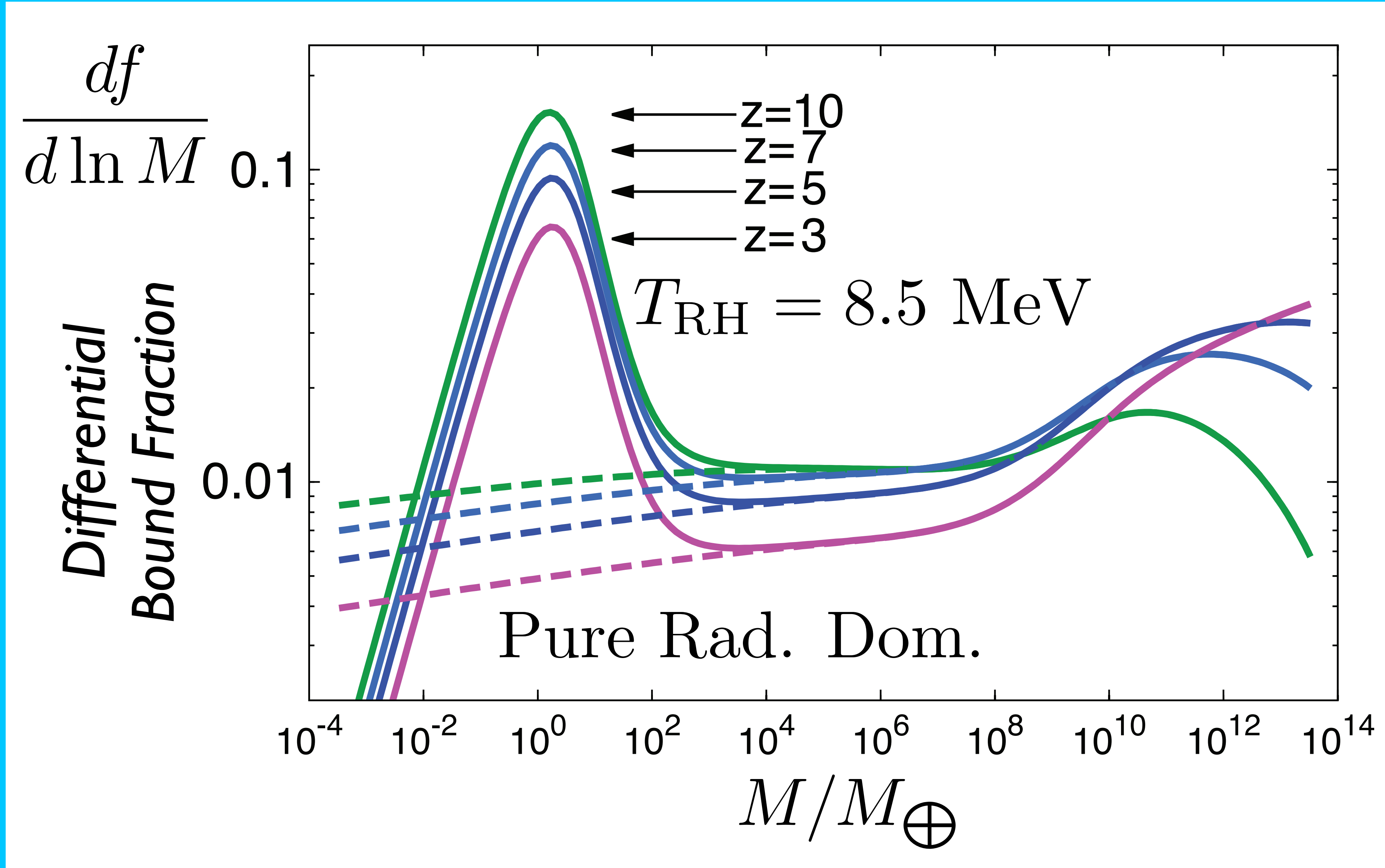


From Microhalos to Subhalos

After $M_* > M_{\rm RH}$, standard structure growth takes over, and larger-mass halos begin to form. The microhalos are absorbed.



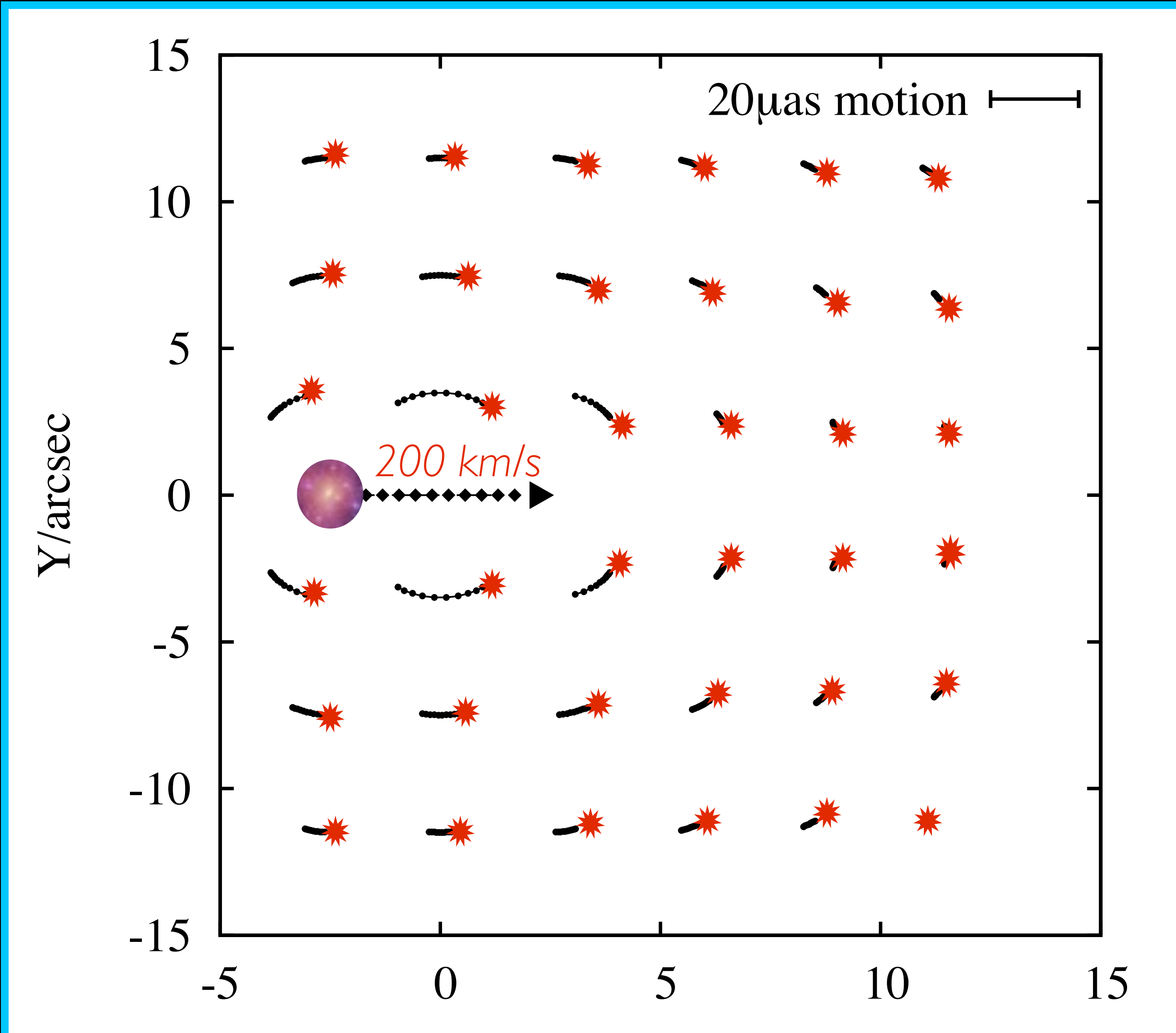
Since these microhalos formed at high redshift, they are far denser than standard microhalos and are more likely to survive.

Berezinsky, et al. 2010

Detection Prospects

The only guaranteed signatures are gravitational.

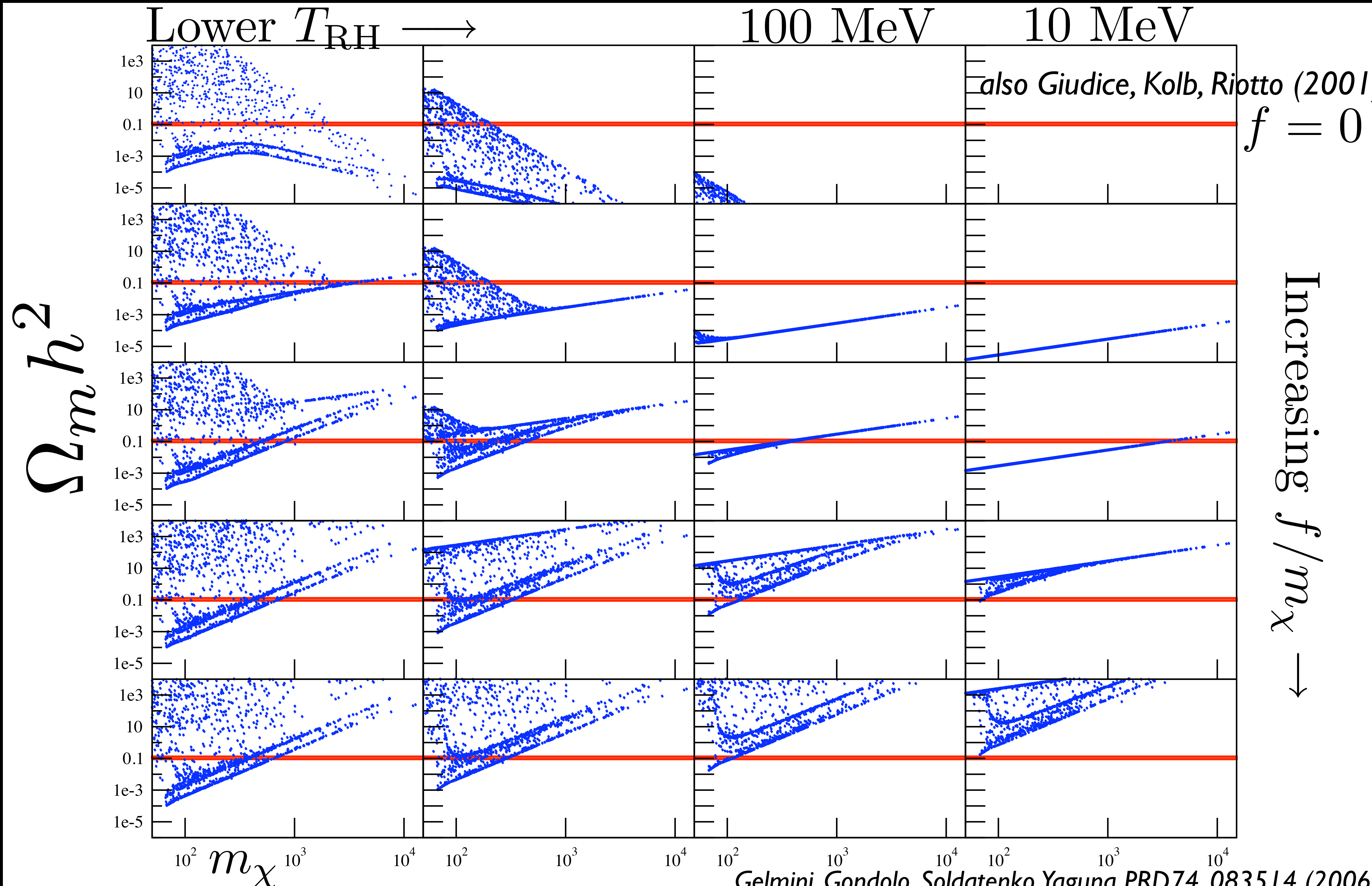
- Astrometric Microlensing — *Erickcek & Law 2011; Li, Erickcek Law 2012*
- Pulsar Timing Residuals — *Baghram, Afshordi, Zurek 2011*
- Photometric Microlensing — *Ricotti & Gould 2009*



Erickcek & Law 2011

If dark matter self-annihilates...

WIMP Dark Matter?



Gelmini, Gondolo, Soldatenko, Yaguna PRD74, 083514 (2006)

Summary: A New Window on Reheating

Perturbations that enter the horizon prior to reheating are very different from larger perturbations.

- Prior to reheating, subhorizon perturbations in the scalar field grow.
- If the scalar decays into cold dark matter, the matter directly inherits the scalar's enhanced inhomogeneity.

The enhancement in the dark matter power spectrum on small scales leads to an abundance of microhalos.

- At high redshift, half of the dark matter is bound into microhalos with masses smaller than the horizon mass at reheating.
- Are these microhalos detectable through gravitational lensing?
- Indirect detection can probe reheat history and origin of dark matter.

STAY TUNED

Part II
Ultracompact Minihalos and the Primordial Power Spectrum

Li, Erickcek & Law 1202.1284

Fangda Li
U of Toronto
3rd year undergrad

Quantum Fluctuations Revisited

Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

Hawking 1982; Starobinsky 1982; Guth 1982; Bardeen, Steinhardt, Turner 1983

$$\frac{\dot{a}}{a} \equiv H = \sqrt{\frac{8\pi G}{3}\rho}$$

expansion rate of the Universe

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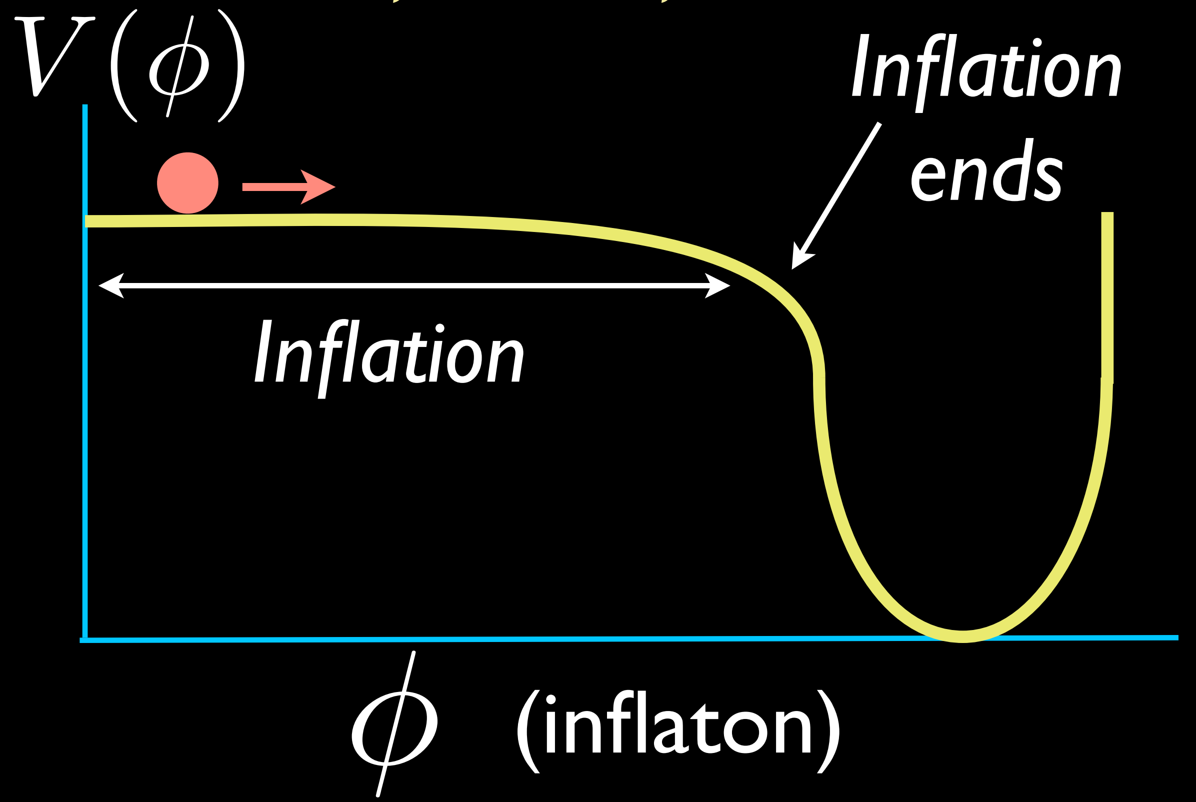
energy density of the Universe

During inflation: $\rho \simeq V(\phi)$ *nearly constant*



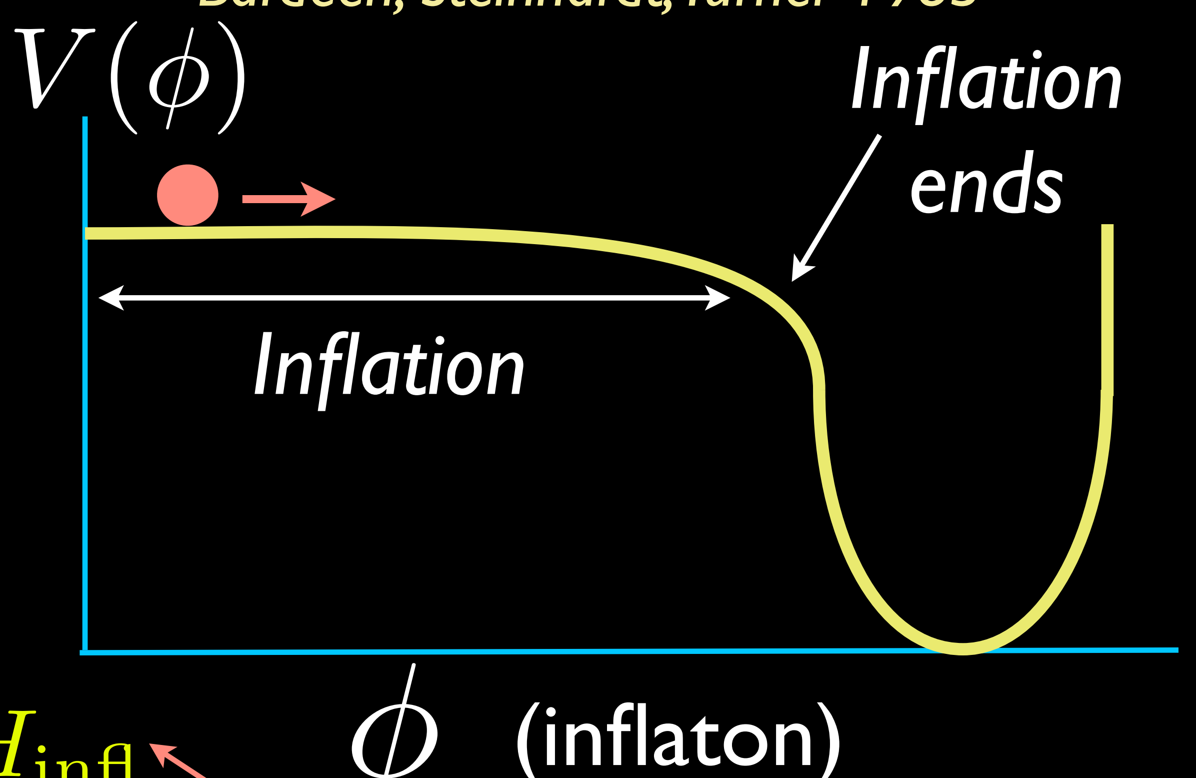
Quantum Fluctuations Revisited

Quantum fluctuations during inflation are the seeds of the CMB temperature fluctuations.

Hawking 1982; Starobinsky 1982; Guth 1982; Bardeen, Steinhardt, Turner 1983

$$\frac{\dot{a}}{a} \equiv H = \sqrt{\frac{8\pi G}{3}\rho}$$

expansion rate of the Universe — *energy density of the Universe*



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Fluctuations in ϕ are equivalent to fluctuations in time: $\delta t = \frac{\delta\phi}{\dot{\phi}}$

$$\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} = -\frac{1}{5}\frac{\delta a}{a} = -\frac{1}{5}H\delta t$$

how much space has expanded

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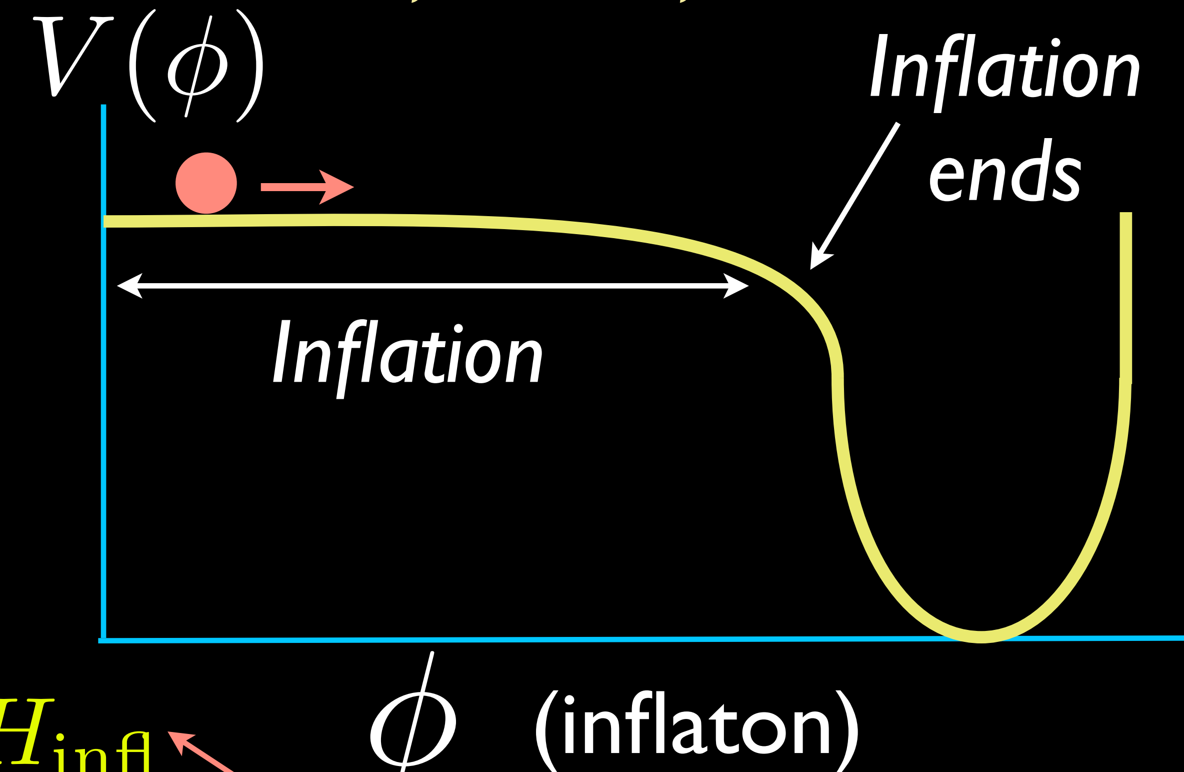

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how much space has expanded — *connection to quantum fluctuations*

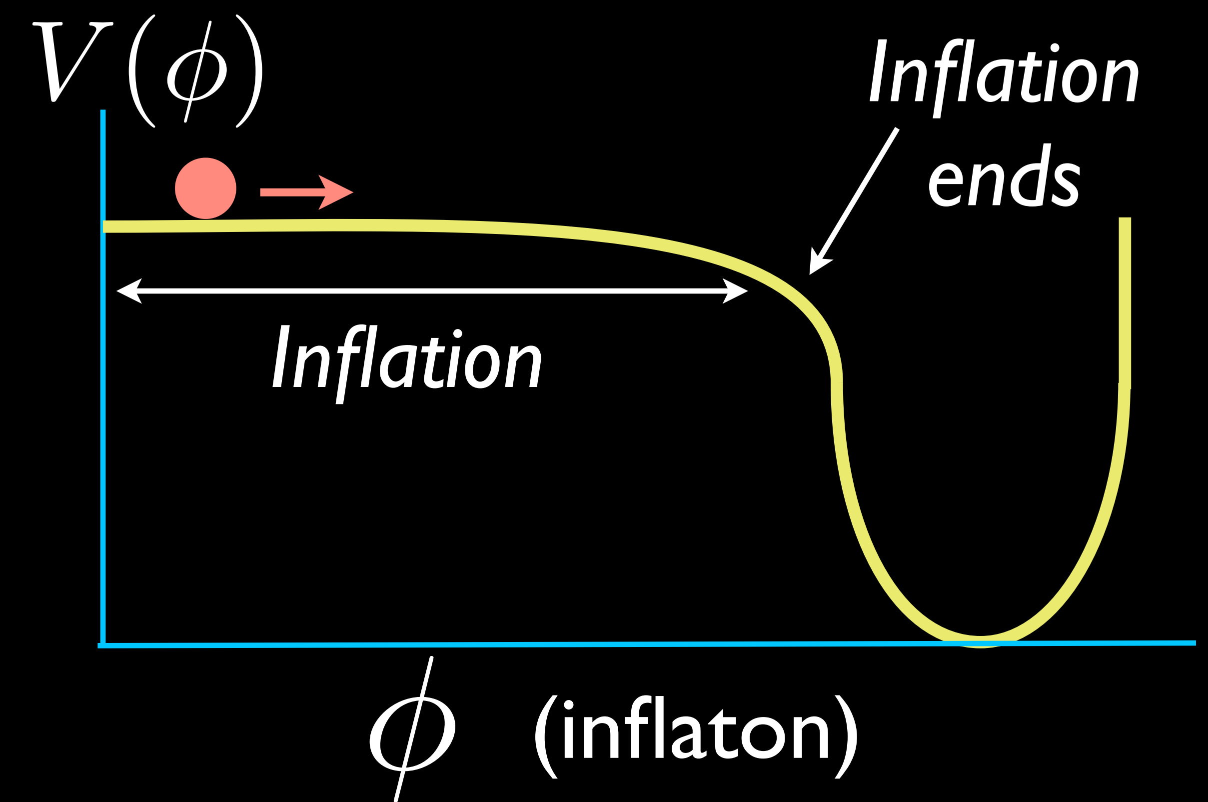
Probing Inflation with Perturbations

Density perturbations tell us about the inflaton's evolution:

$$\frac{\delta\rho}{\rho} \propto G\frac{V(\phi)}{\dot{\phi}}$$

nearly *constant during inflation*

When should this be evaluated?



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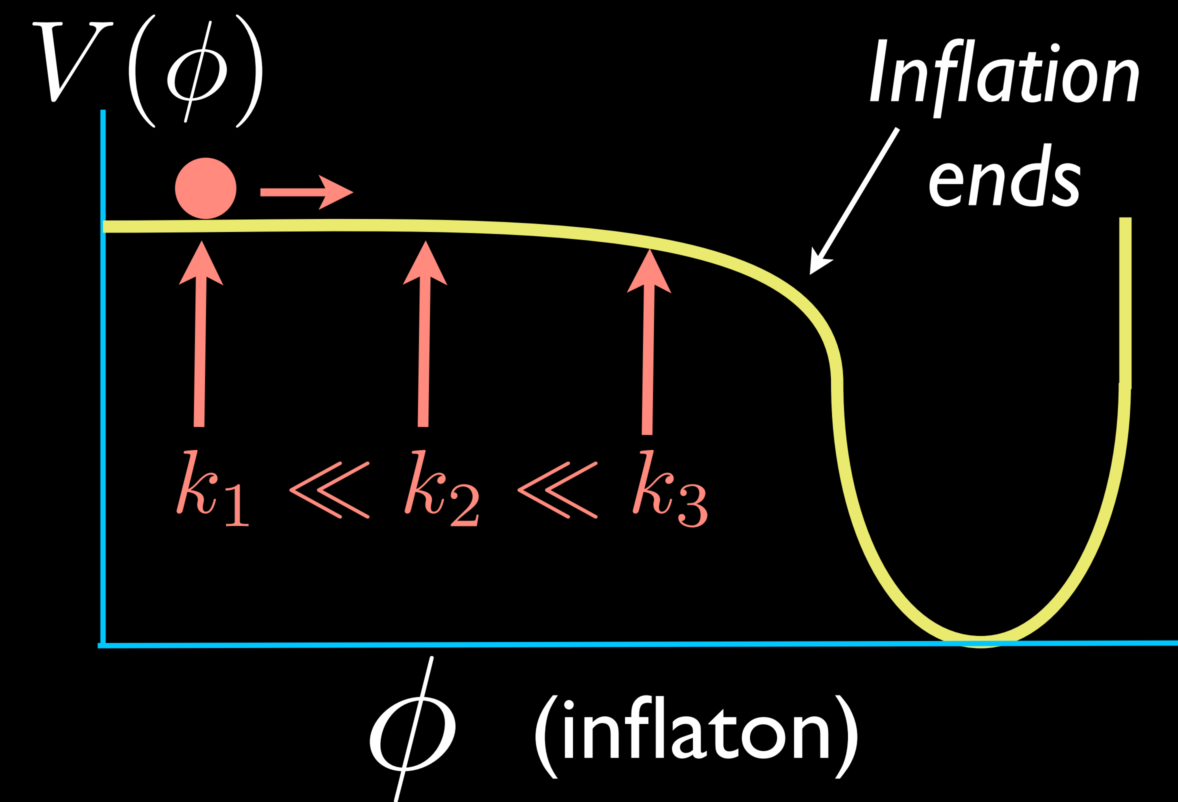

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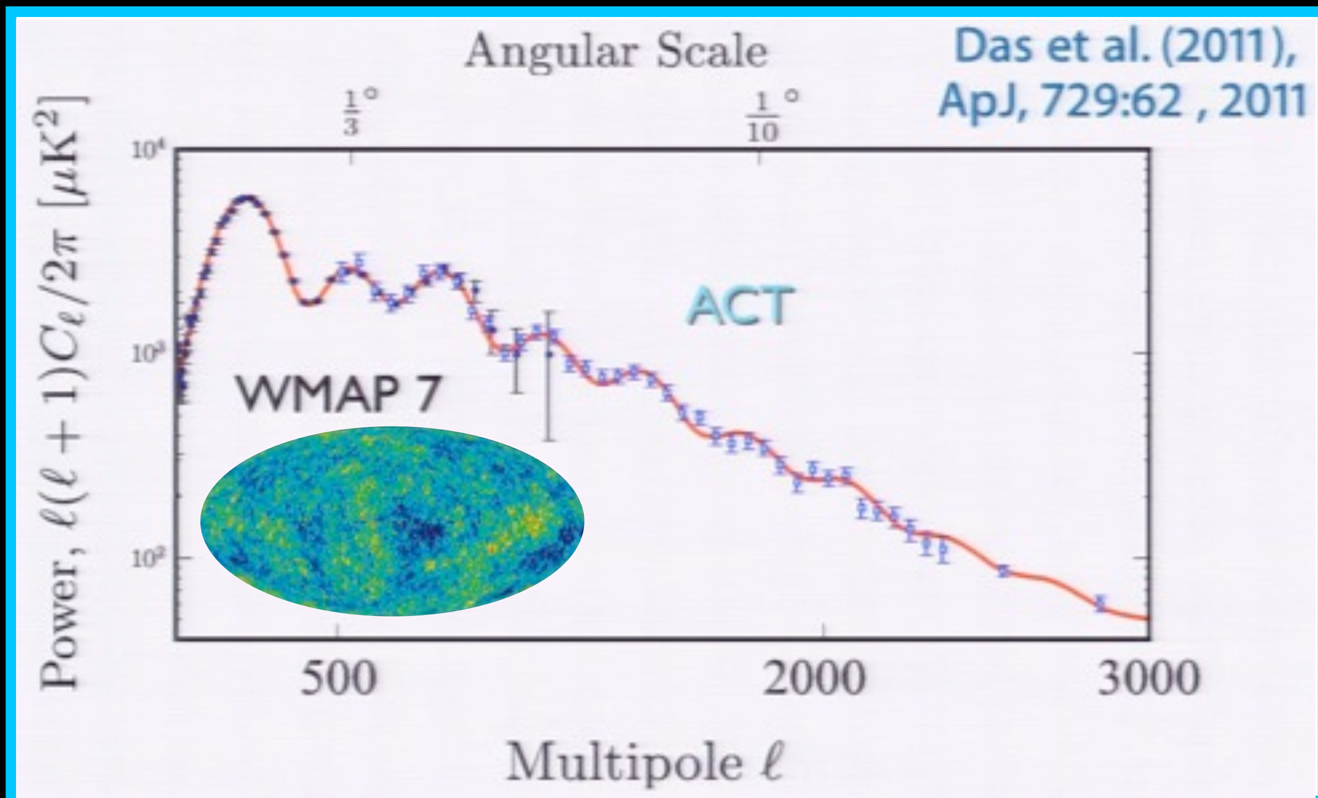
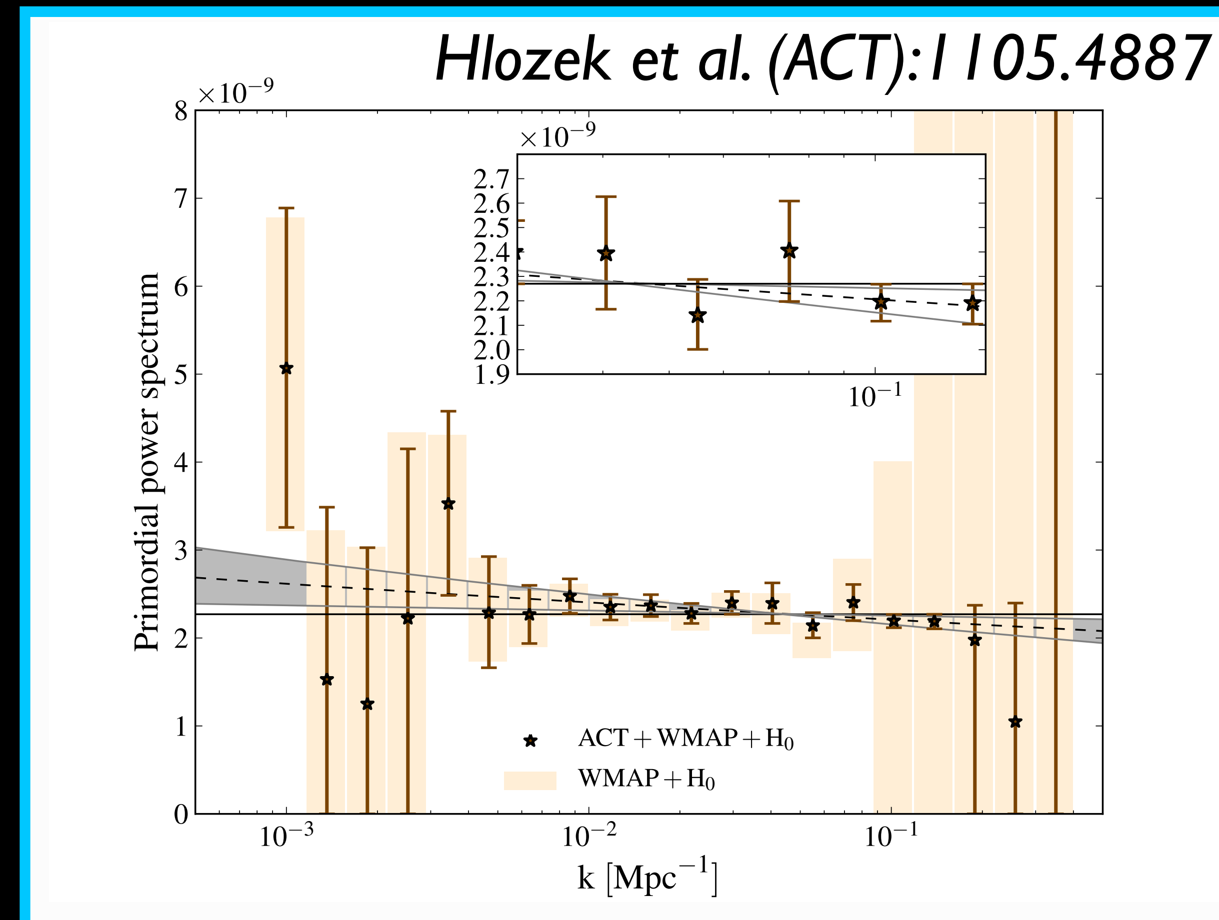
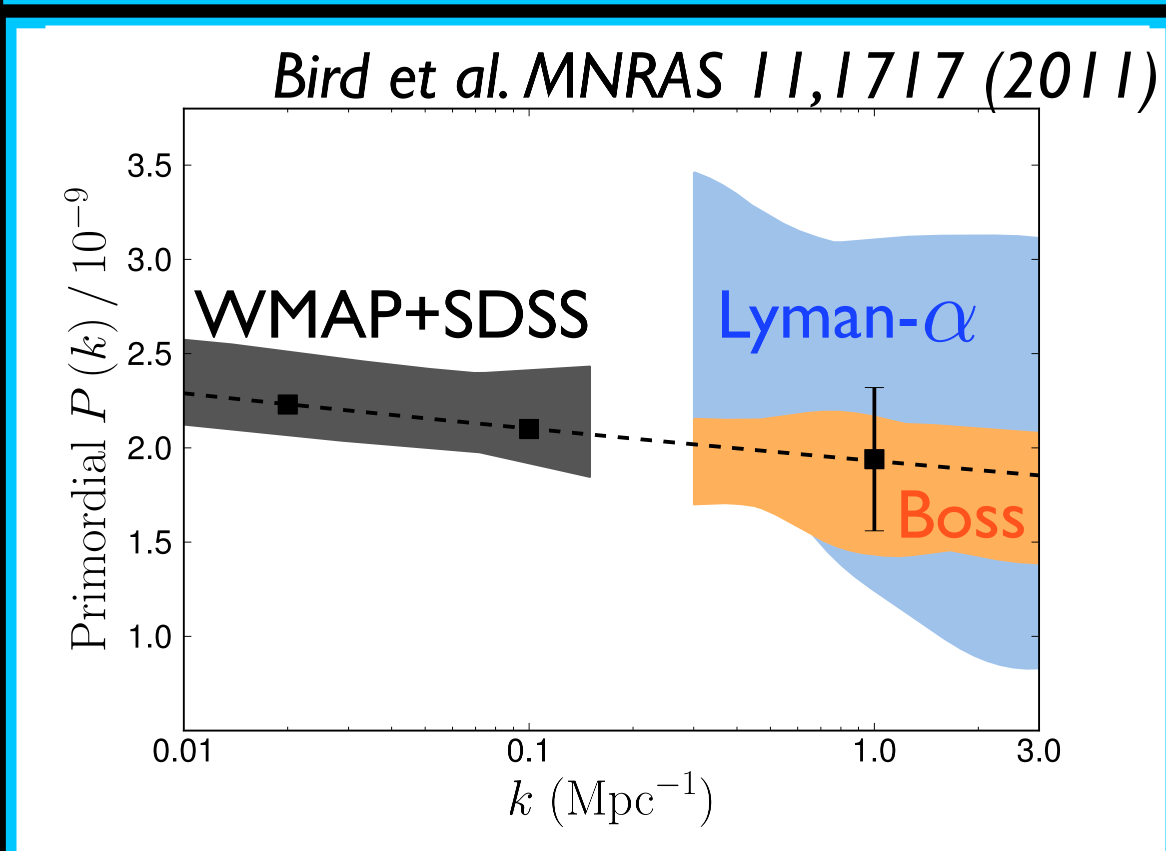
Perturbations on different scales probe different times during inflation!

- during inflation, $a \simeq e^{Ht} \Longrightarrow$ very short time span = wide range of scales
- the smaller scales probe the later stages of inflation

Large-Scale Perturbations





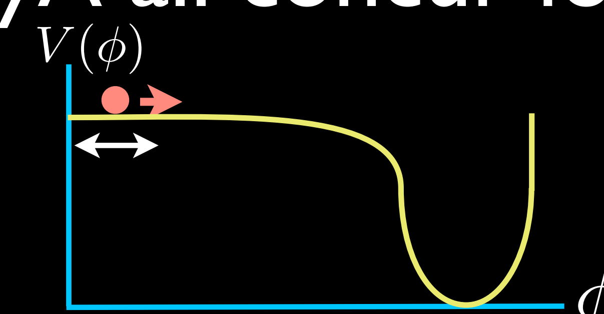


WMAP7+H0+BAO:

$$\mathcal{P}_\mathcal{R}(k) = (2.4\times10^{-9})\left(\frac{k}{k_0}\right)^{-0.037\pm0.012}$$

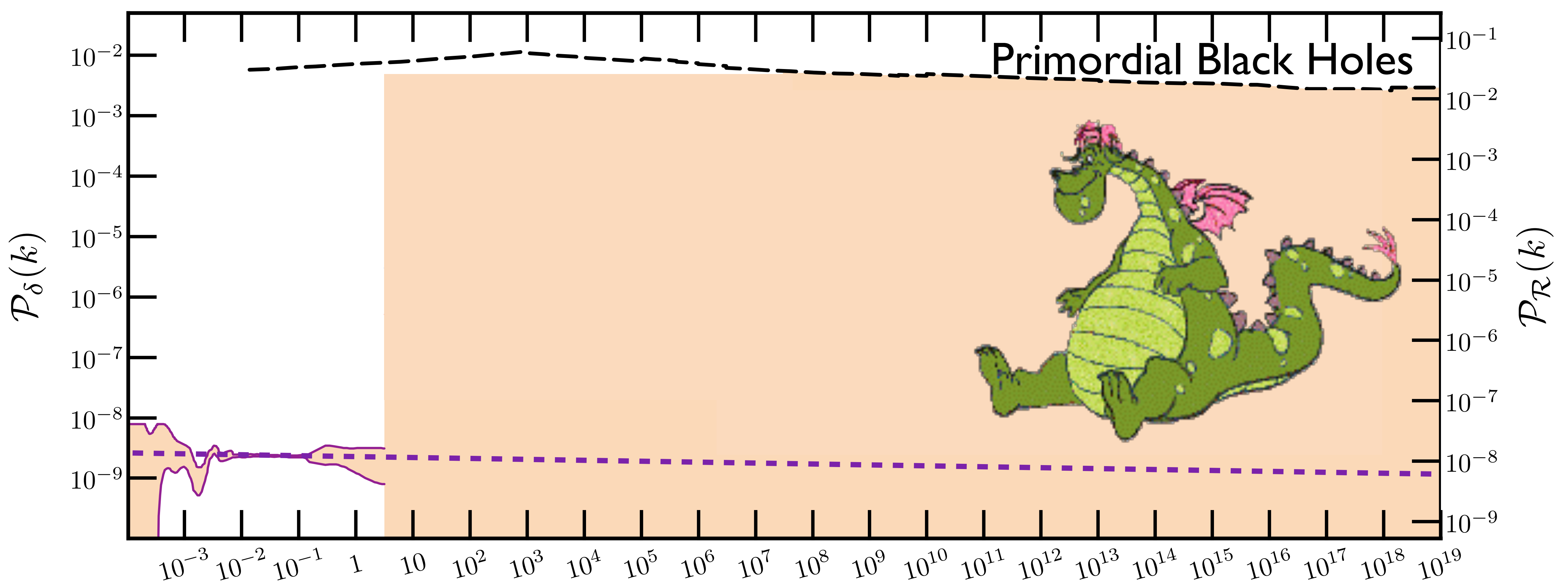
ACT, SDSS, and LyA all concur for

$$k \lesssim 3\,\mathrm{Mpc}^{-1}$$



Small scales: Here there be dragons

Several inflationary models predict excess small-scale power.



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- any theory with a potential that gets flatter: running mass inflation
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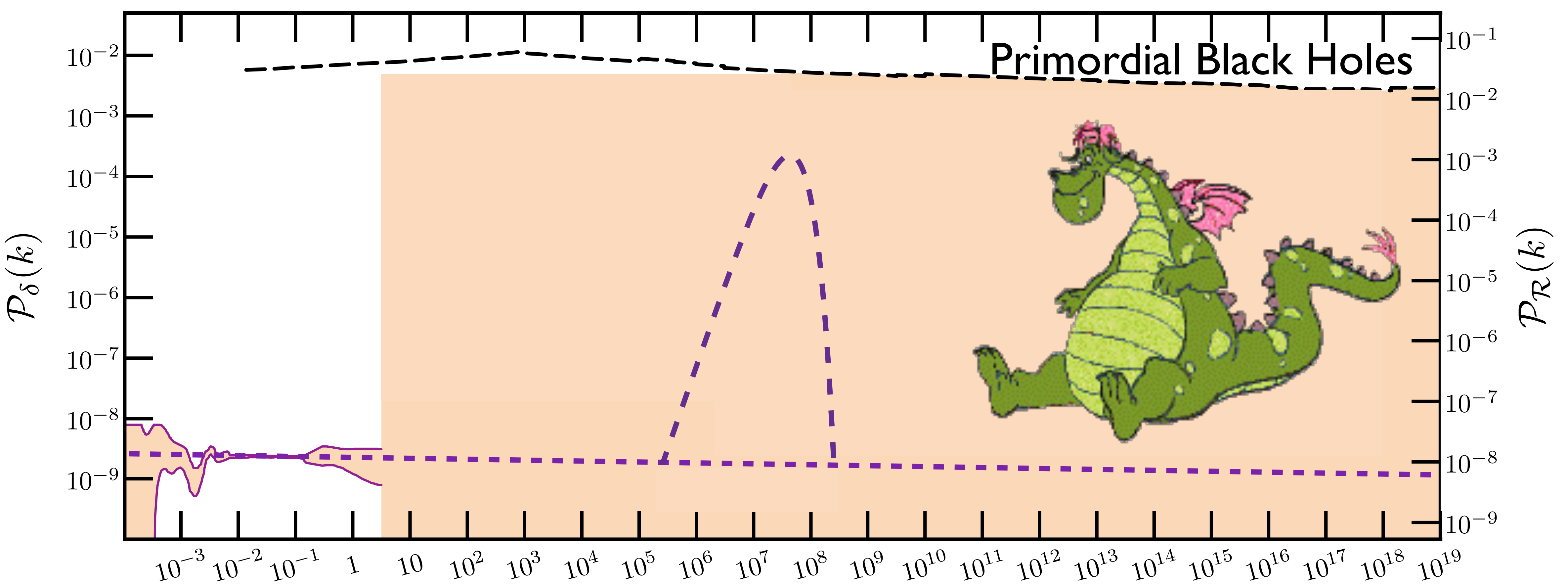

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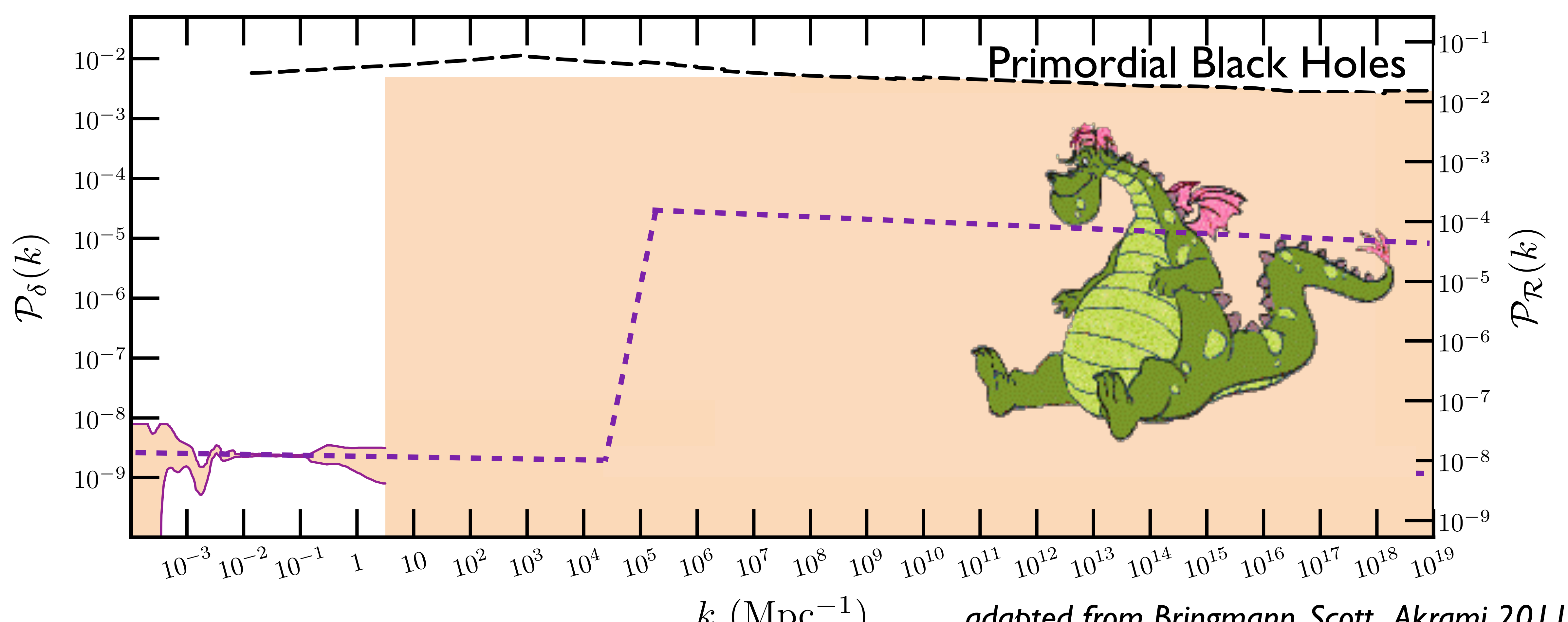

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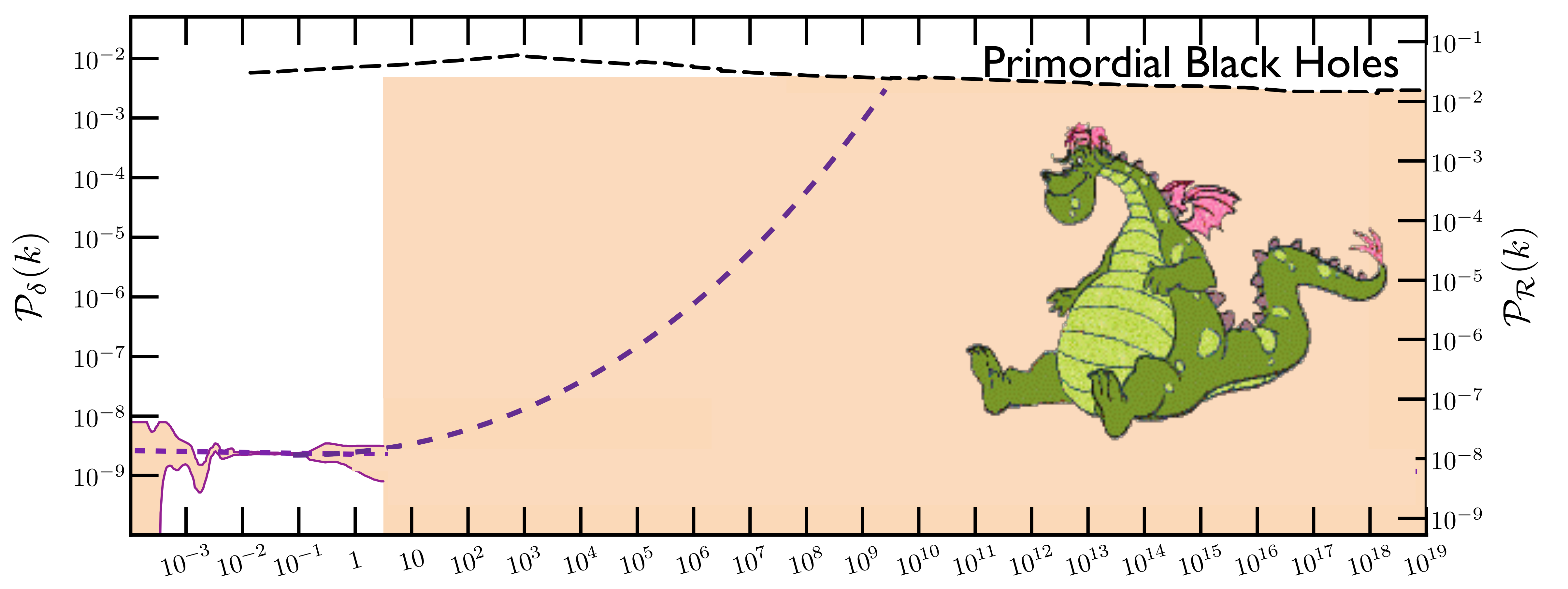

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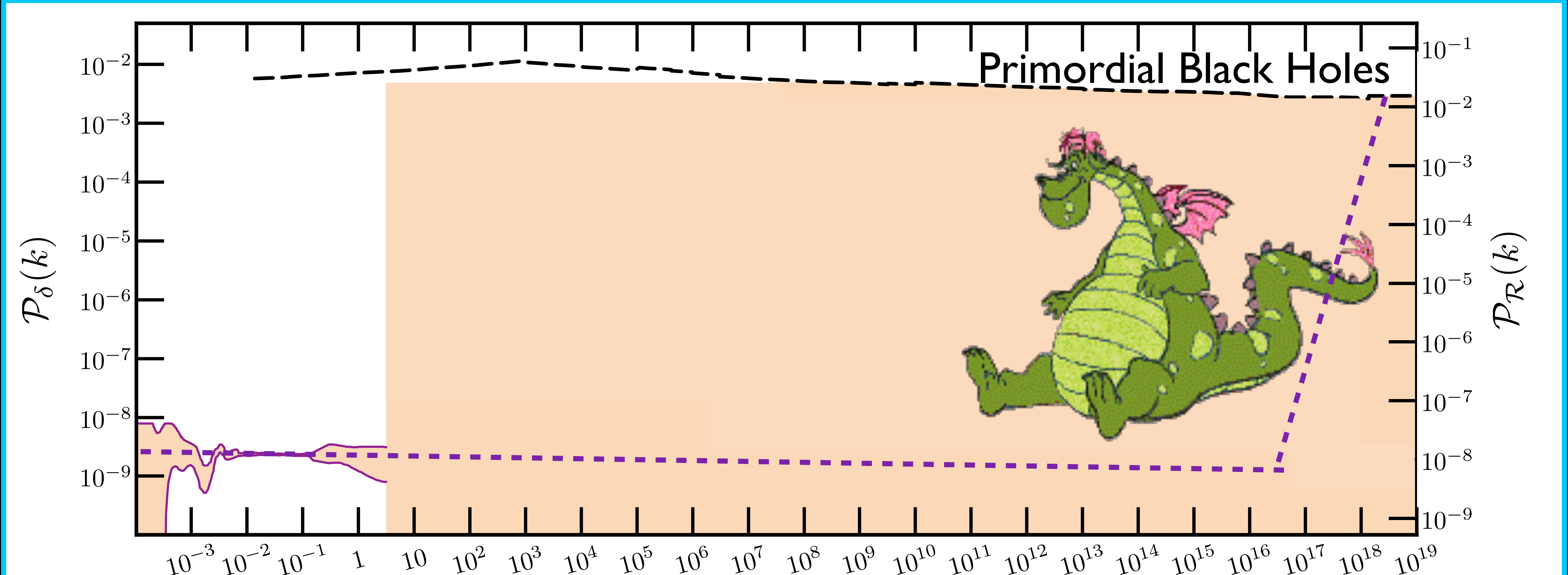

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UCMH=Ultra-Compact Mini-Halo

If a region enters the cosmological horizon with an overdensity $\delta \gtrsim 10^{-3}$, the dark matter in this region collapses prior to $z \sim 1000$ and forms an UCMH.

Ricotti & Gould 2009

- much lower overdensity than required to form a primordial black hole
- if dark matter self-annihilates, these UCMHs are gamma-ray sources

Scott & Sivertsson 2009

- the absence of UCMHs constrains the amplitude of the primordial power spectrum on small scales

Josan & Green 2010

Bringmann, Scott, Akrami 2011

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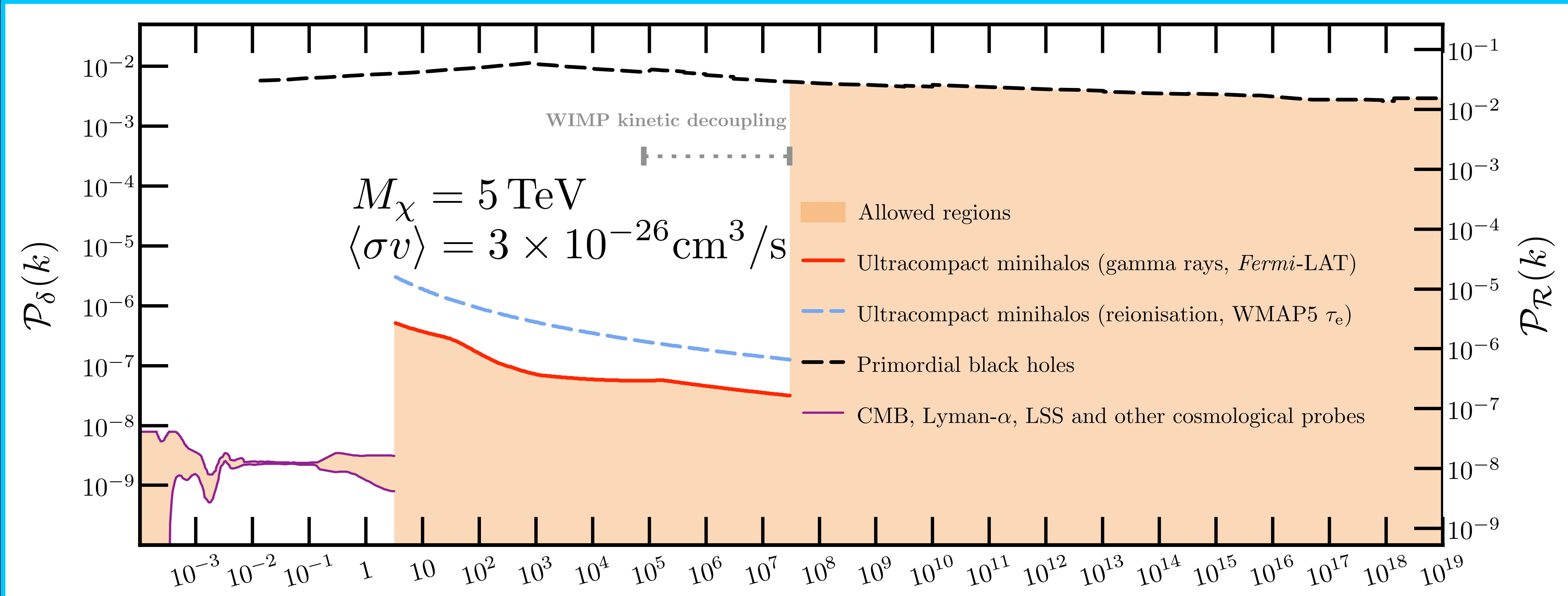

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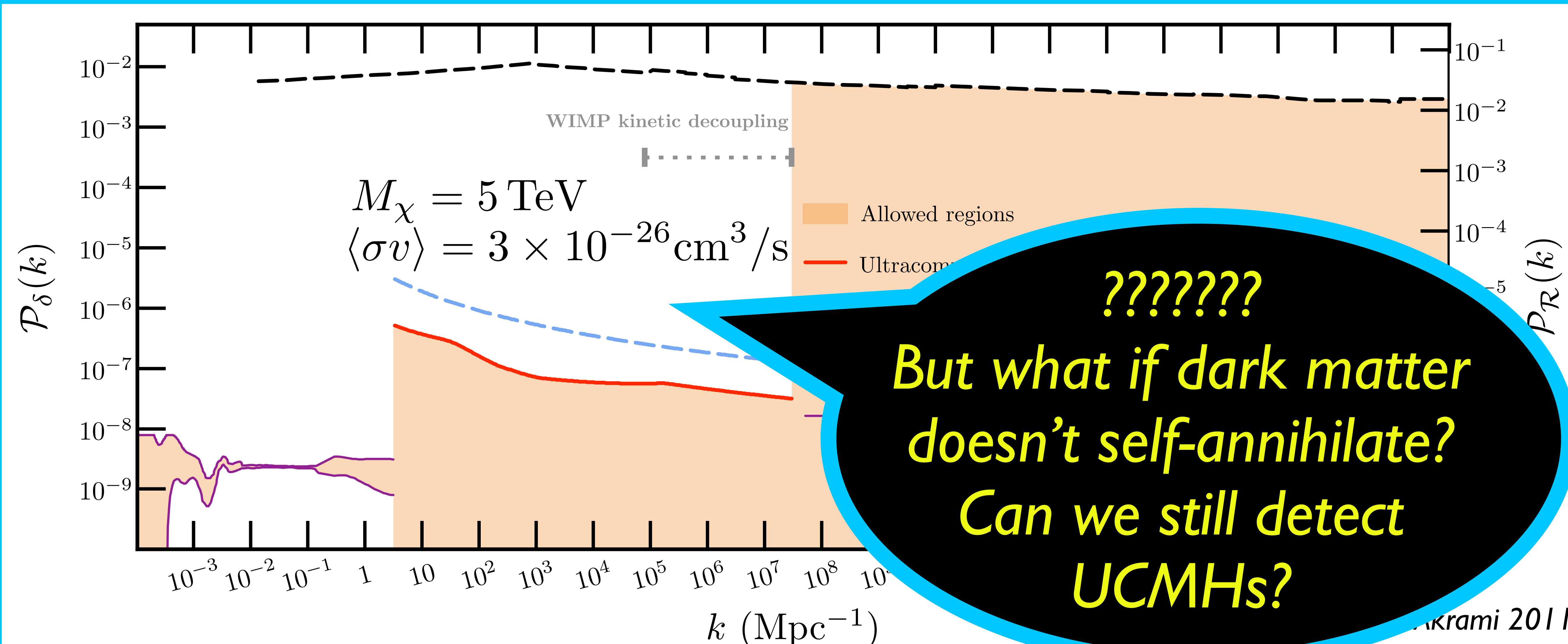


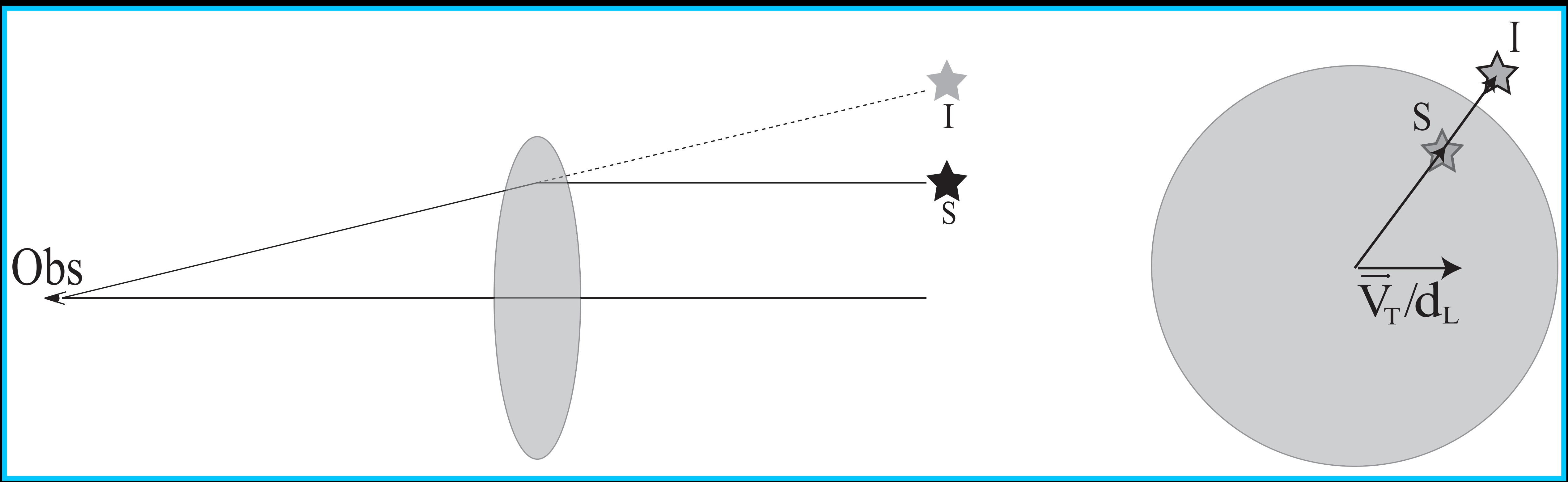
???????
But what if dark matter doesn't self-annihilate?
Can we still detect UCMHs?

krami 2011

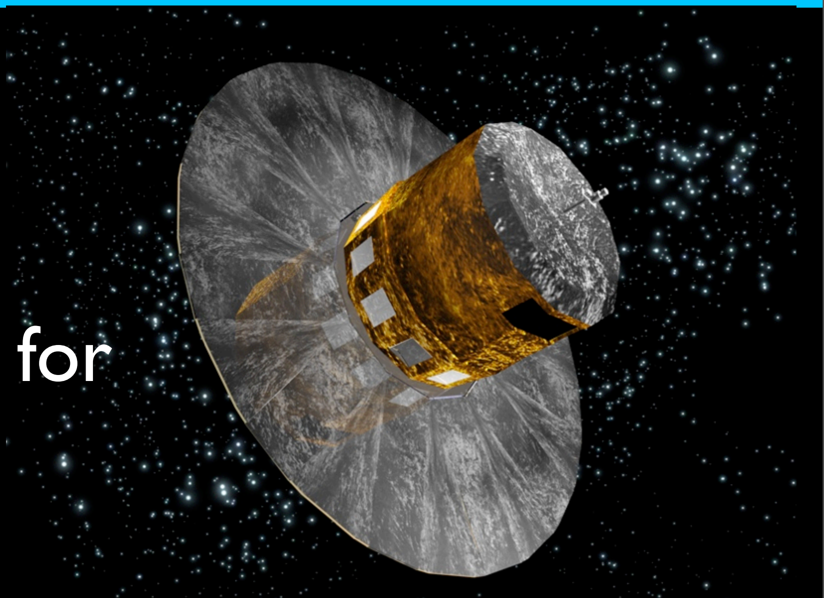
Astrometric Microlensing

The only sure bet in the dark matter game is gravity!

- UCMHs are too diffuse to be detected through photometric microlensing: $R_{\rm UCMH} \gg R_E$
- Local subhalos can be detected via astrometric microlensing, but they are too rare to be found in a blind search. *Erickcek & Law 2011*
- Nearby UCMHs produce bigger lensing signals, and they may be more numerous than standard subhalos.

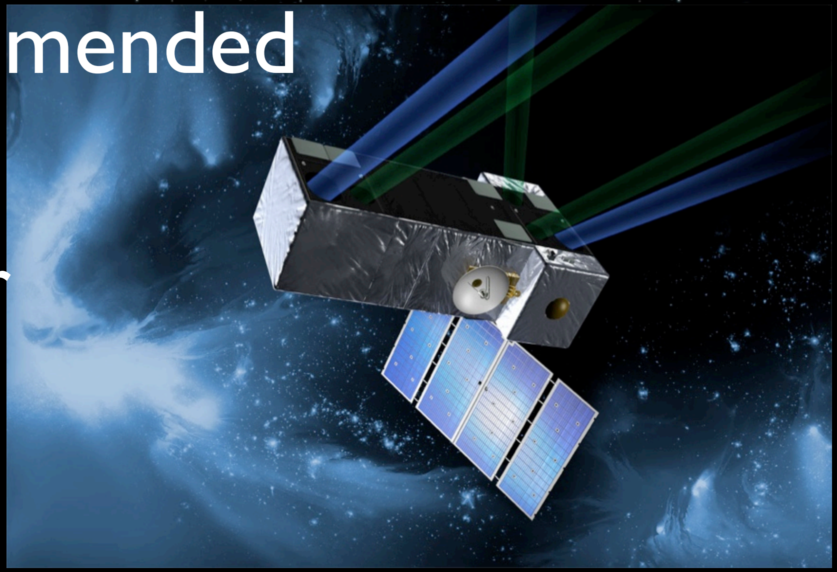


High Precision Astrometry



Gaia is an ESO satellite scheduled to launch in late 2013.

- astrometric precision per epoch: ~29 ***micro***arcseconds for its brightest targets (~7 million stars)



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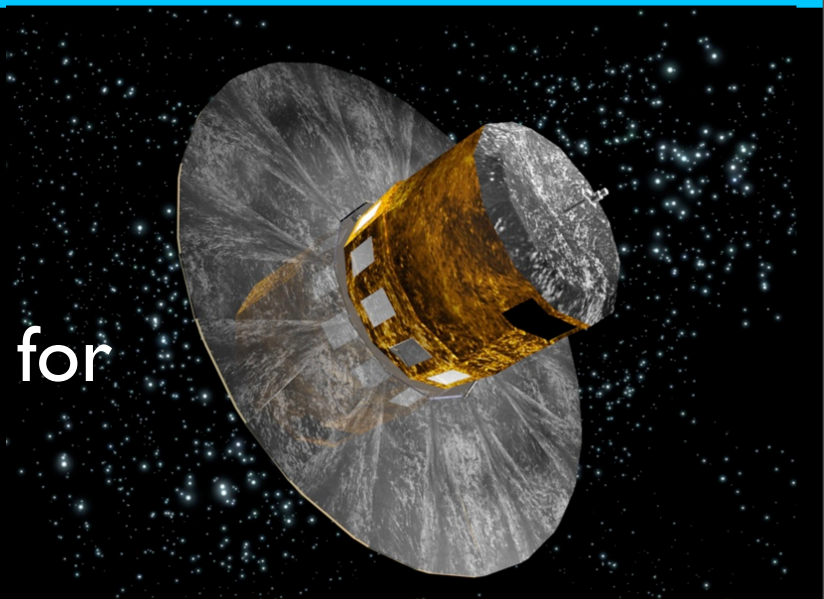

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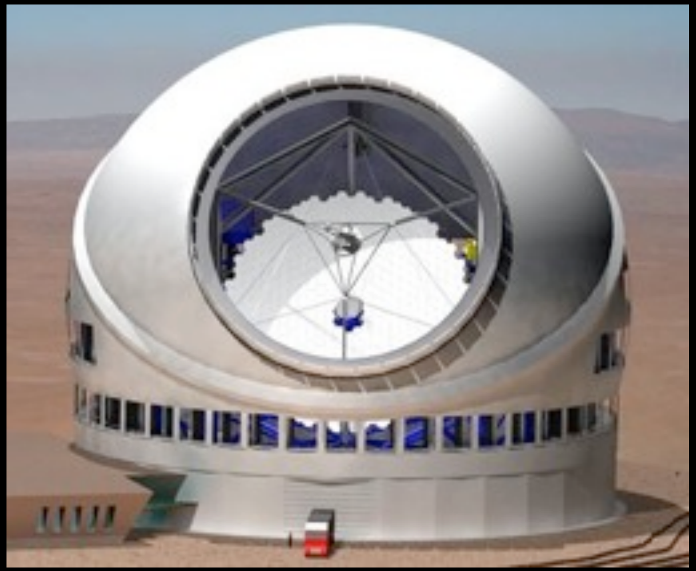


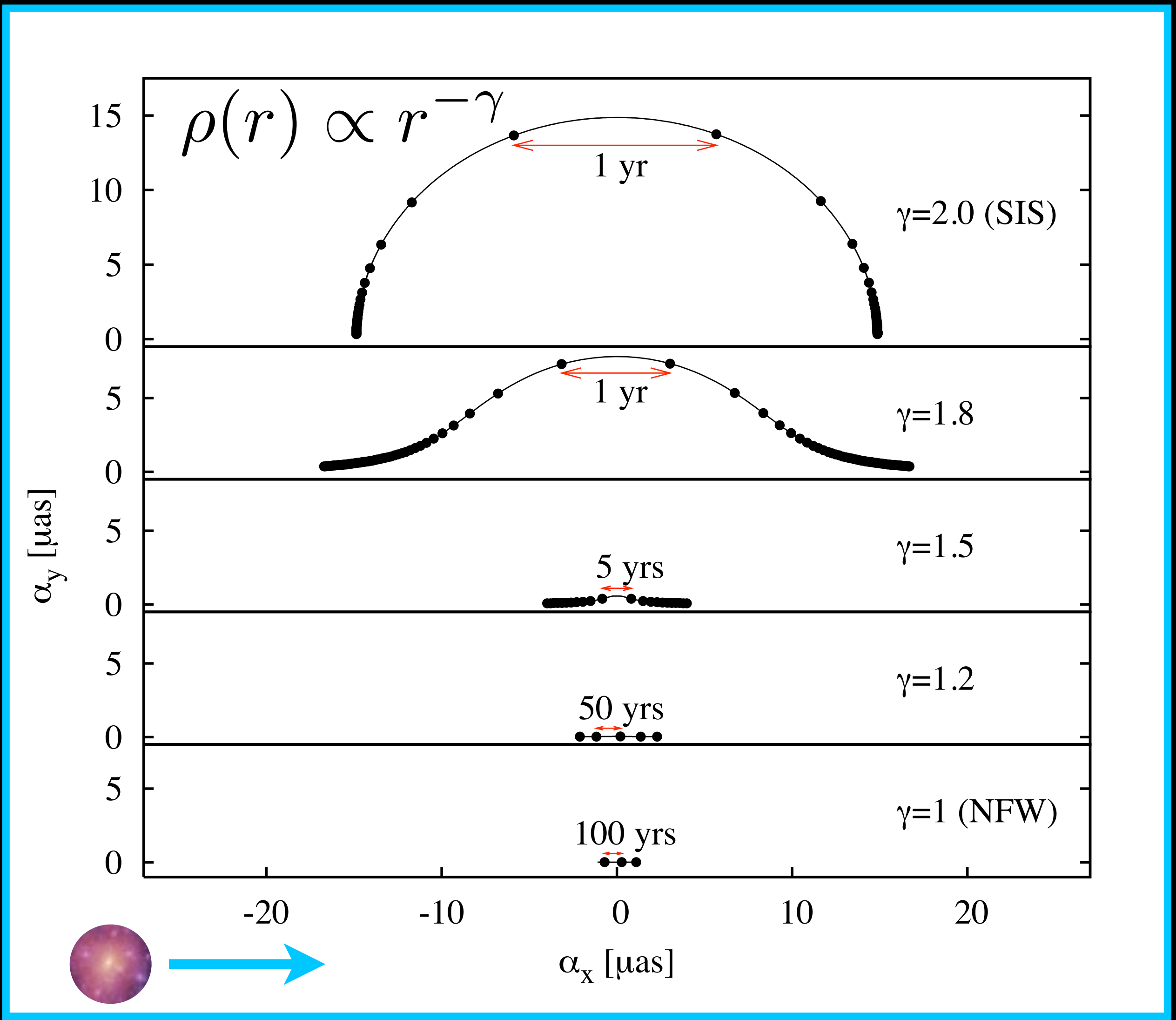
Ground-based telescopes have great potential.

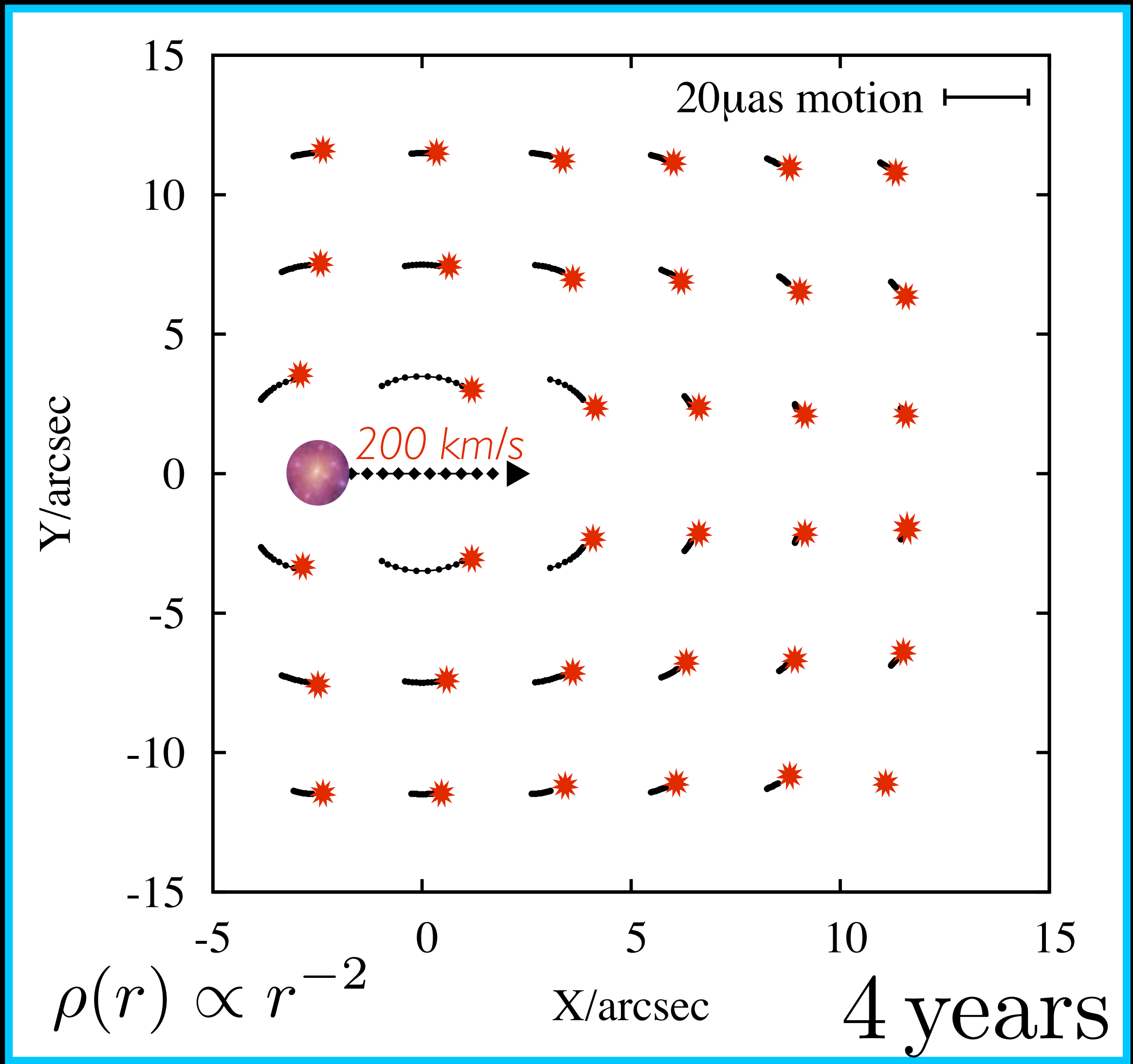
- Keck can reach ~100 ***micro***arcsecond precision
- TMT is designed for 50 ***micro***arcsecond precision and could reach much higher precision (Cameron *et al.* 2009)

Astrometric Microlensing by Subhalos

Lessons learned from standard subhalos:

Erickcek & Law 2011





The steepness of the density profile determines the shape of the image's path across the sky and the rate of its motion.

Only stars very near the subhalo center are deflected; a blind search requires a lot of stars and a lot of subhalos.

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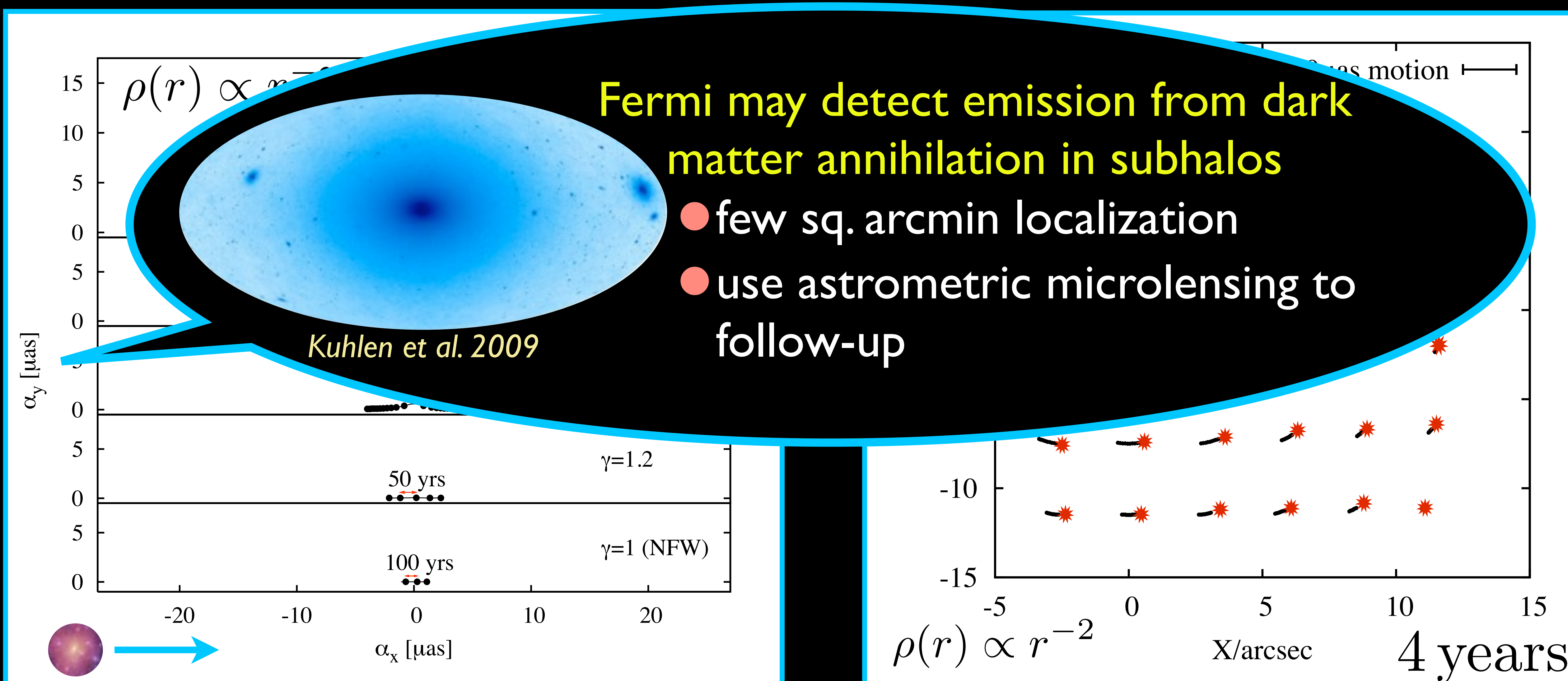

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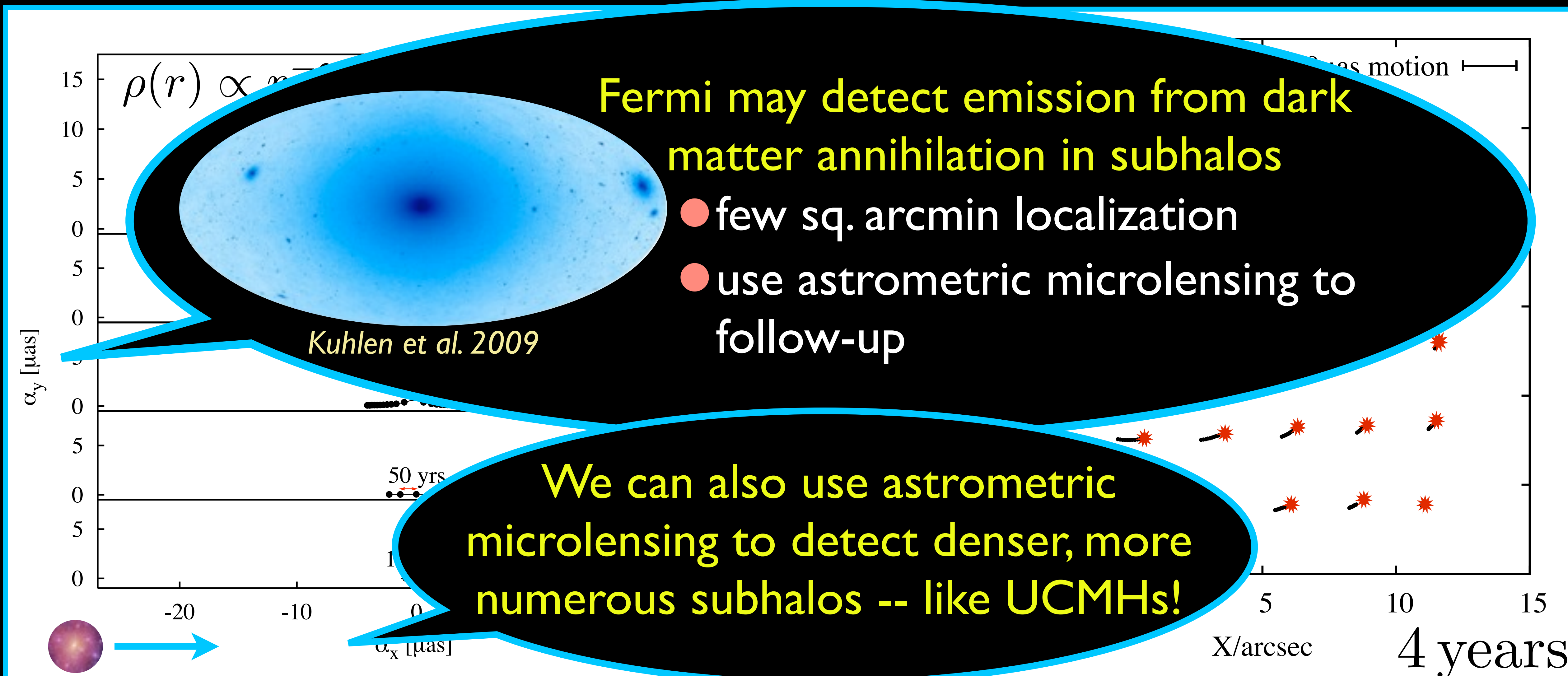

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UCMH Density Profiles

Secondary radial infall: constant UCMH density profile

- steep profile: $\rho \propto r^{-9/4}$ *Fillmore & Goldreich 1984; Bertschinger 1985; Ricotti & Gould 2009*
- $\rho \propto M_i$ (initial UCMH mass = dm mass within overdense region)
- UCMHs grow by increasing radius; accreted matter doesn't reach center

$$r_{\rm UCMH}(z) = 0.03 \left(\frac{1000}{1+z}\right)^{4/3} \left(\frac{M_i}{M_\odot}\right)^{1/3} \, {\rm pc}$$

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Non-radial infall: $(v_{\rm tan} > v_{\rm Kep})$ *Ricotti, Ostriker & Mack 2008; Ricotti & Gould 2009*

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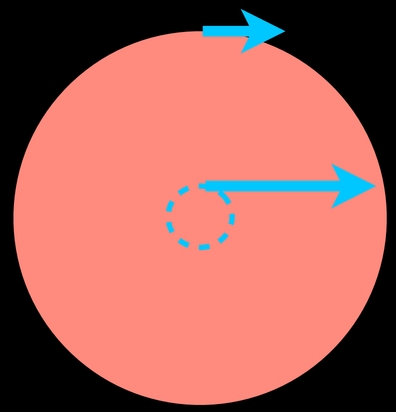

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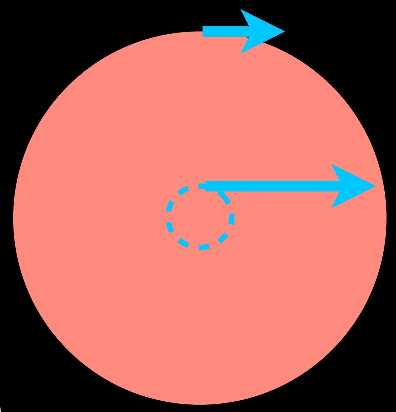

Dark matter self-annihilation: $\rho > m_\chi/(\langle\sigma v\rangle t)$

$$r_{\rm c,ann} = 3.0 \times 10^{-4} \left(\frac{M_i}{M_\odot}\right)^{1/3} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{-4/9} \left(\frac{\langle\sigma v\rangle}{3\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}\right)^{4/9} \mathrm{pc}$$

Lensing Trajectories

As UCMH passes beneath a star, the star moves!

Trajectory depends on

- initial microhalo mass
- impact parameter
- core radius

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

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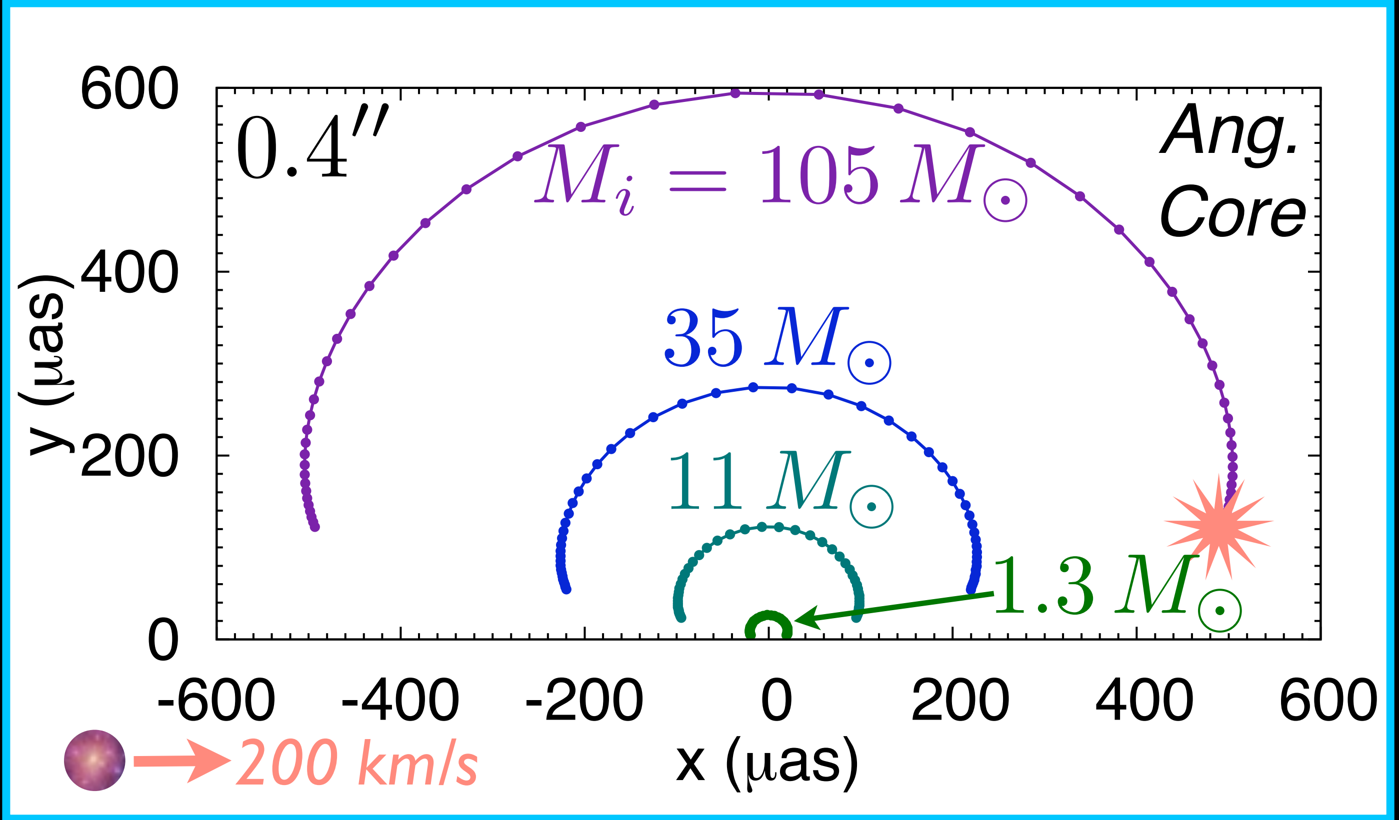

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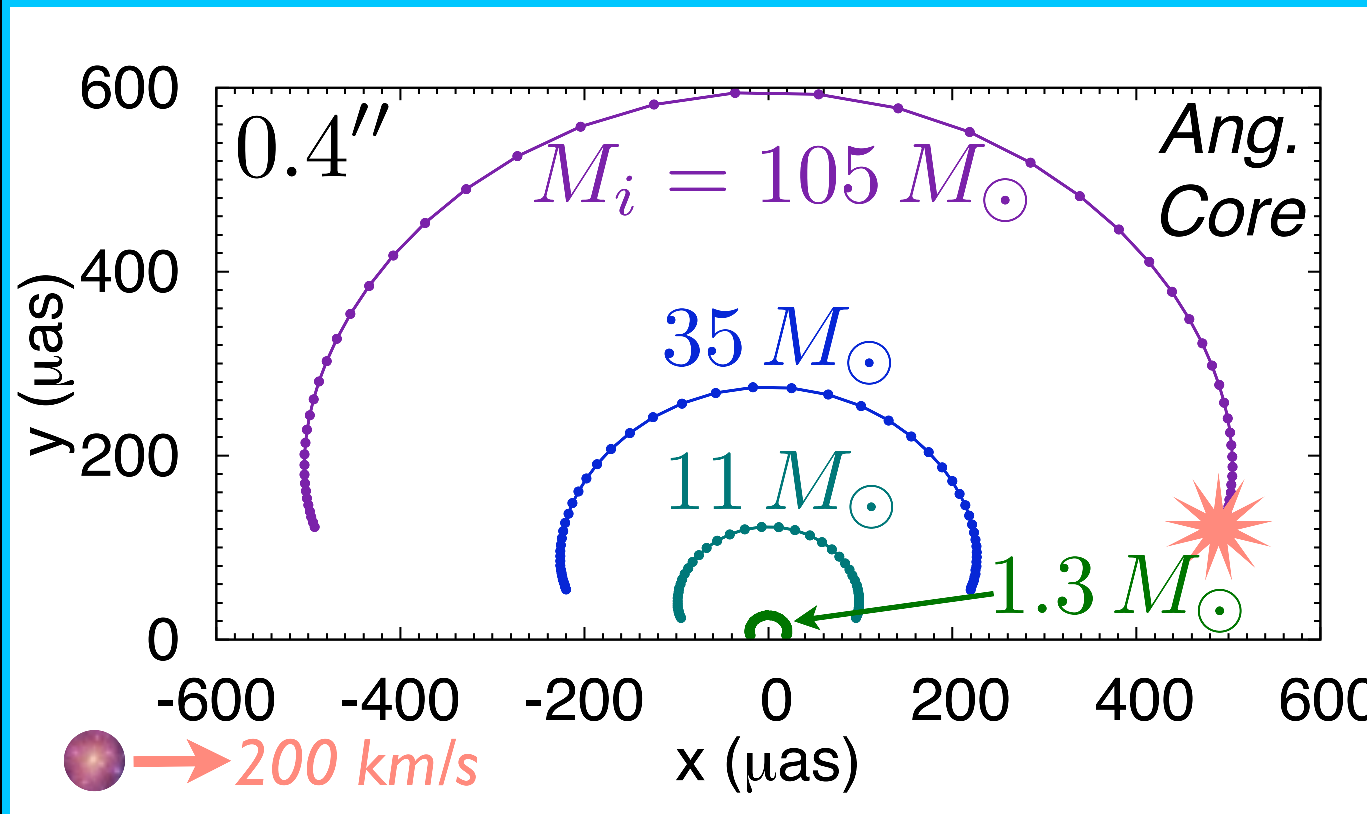

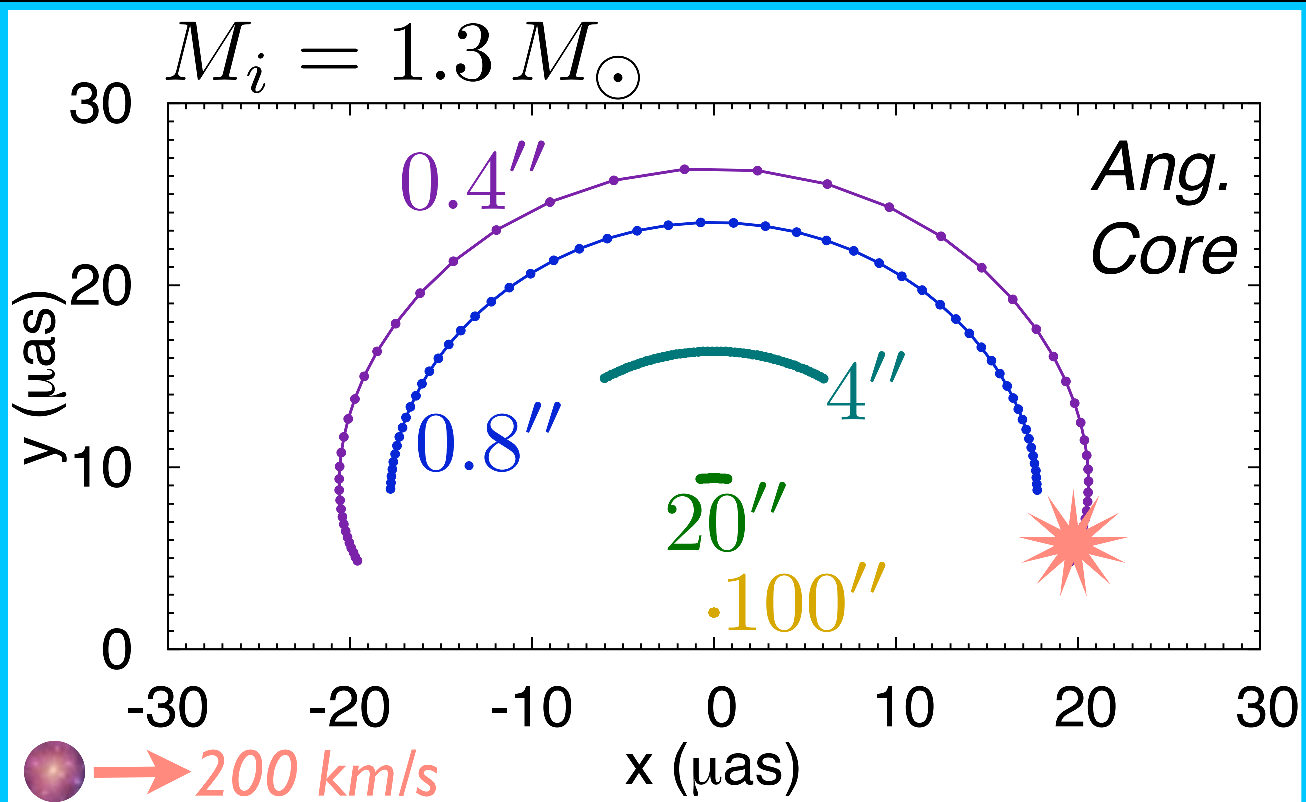

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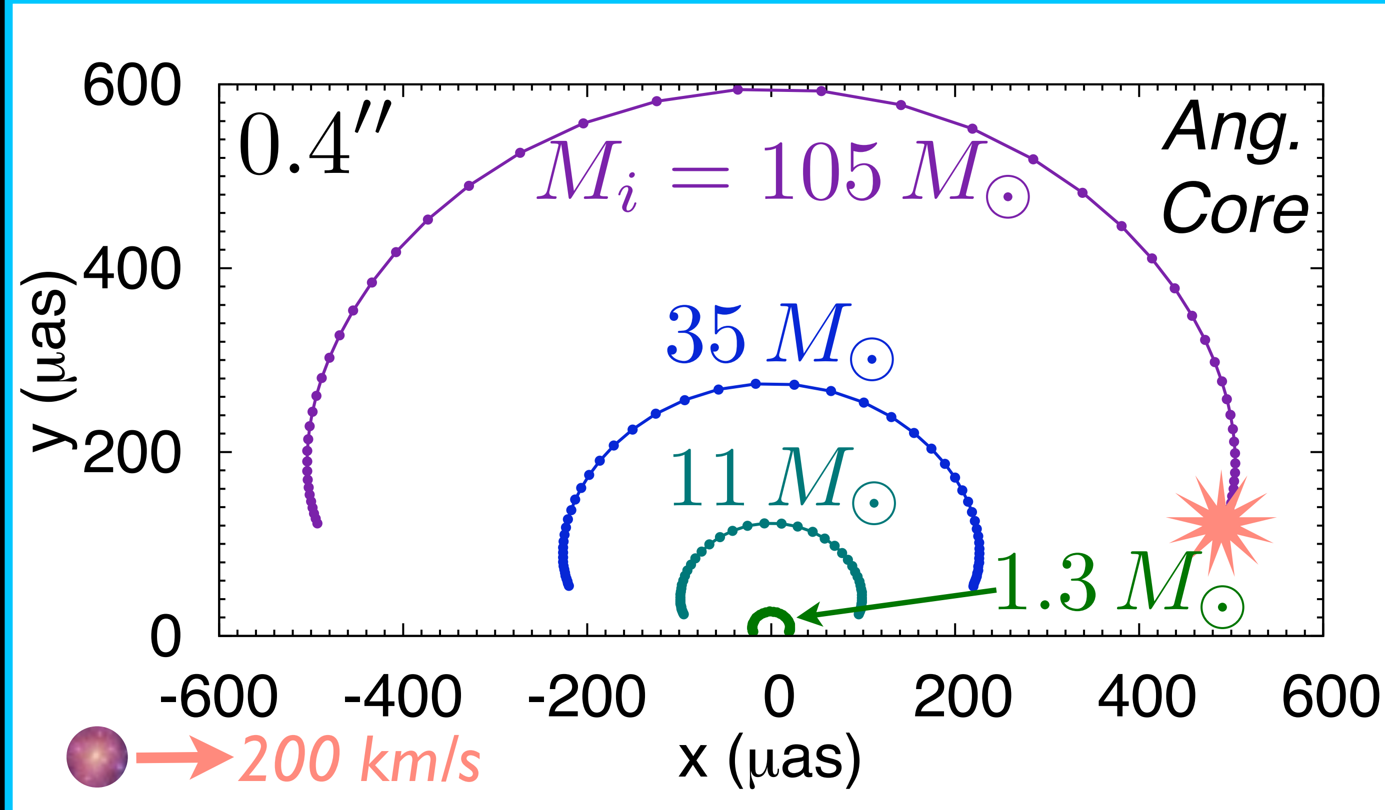
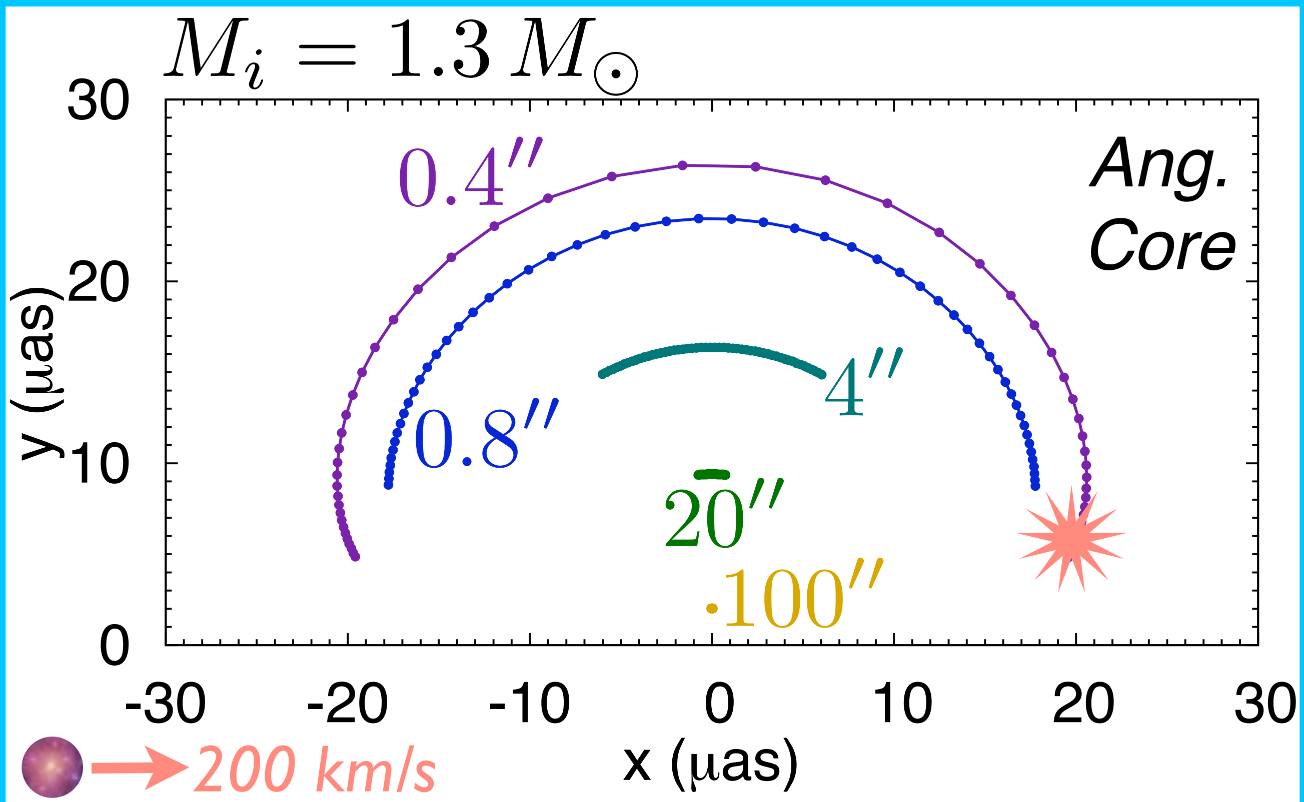
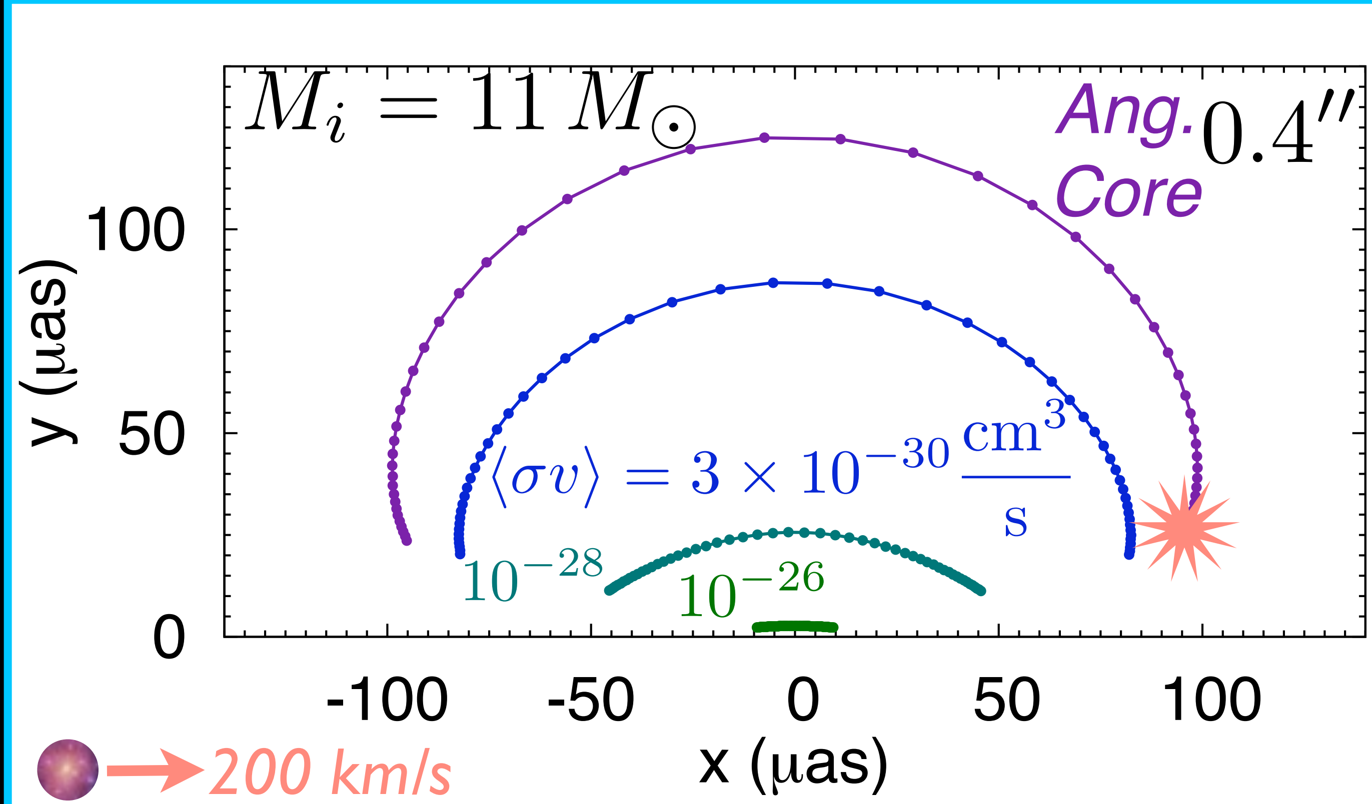
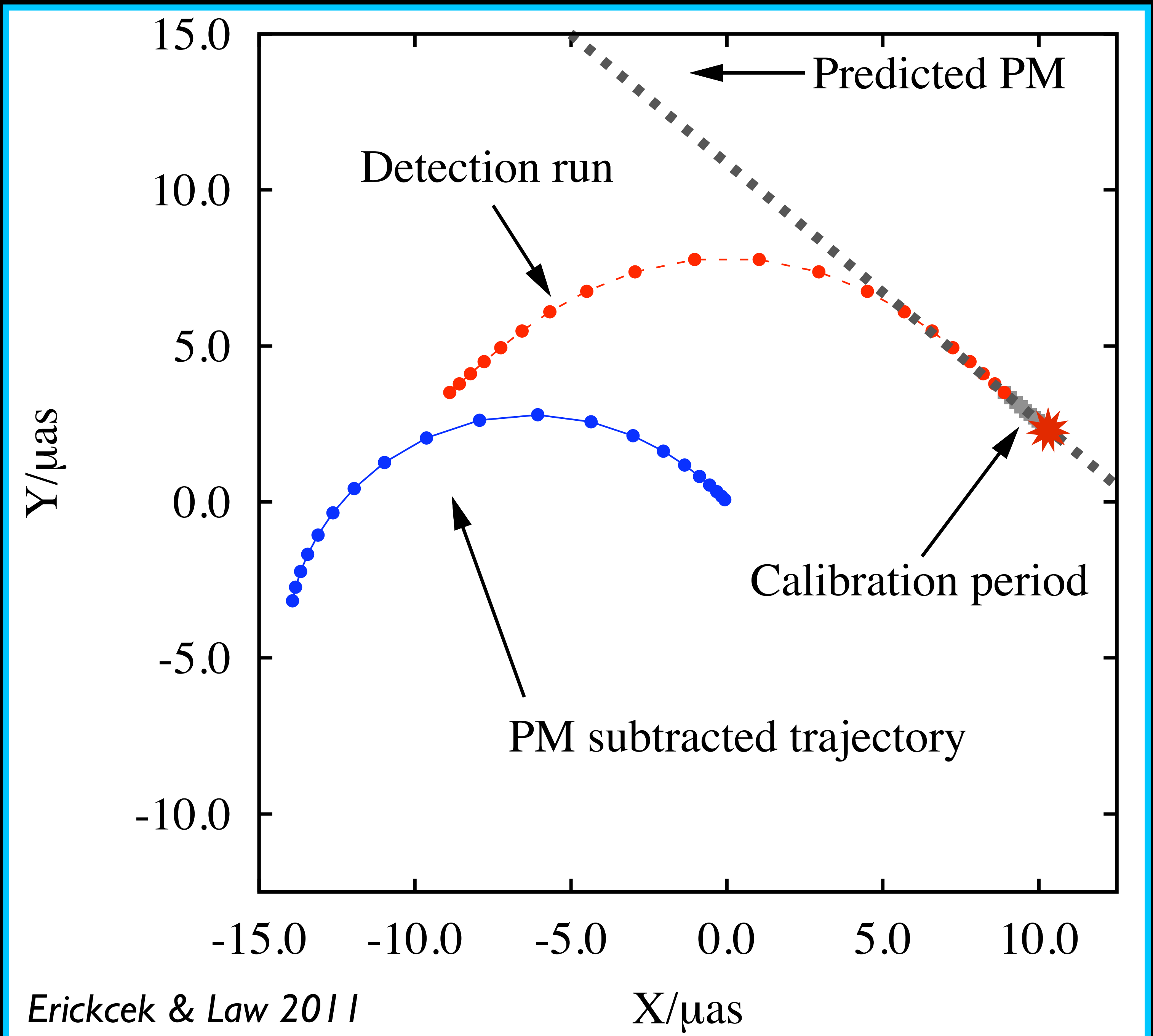






Our Detection Strategy

To detect this image motion, we propose a simple strategy:



1. Observe stars for a calibration period (2 years).
2. Reject stars that significantly accelerate during the calibration period (including binaries).
3. Measure each star's proper motion and parallax, and predict its future trajectory.
4. Observe the star during the detection run (4 years).
5. Measure deviations from the predicted trajectory.

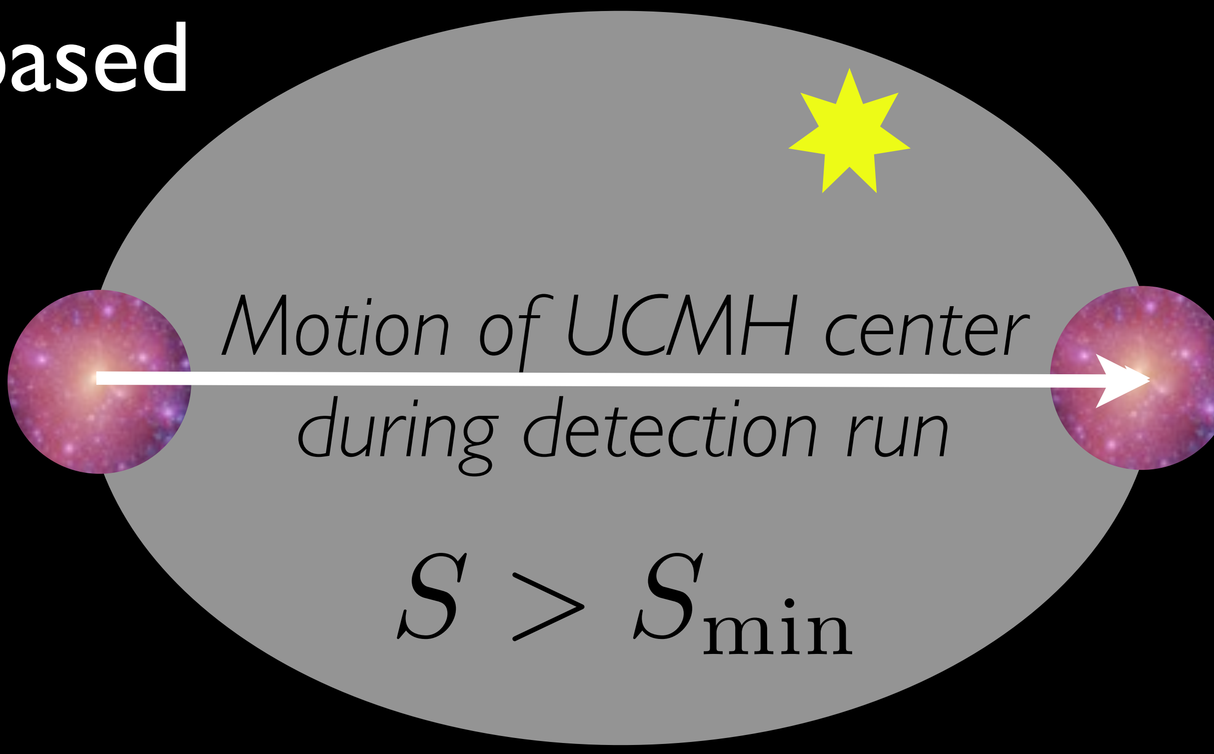
Star's true position is at the origin.
Subhalo center passes star two years into the detection run.

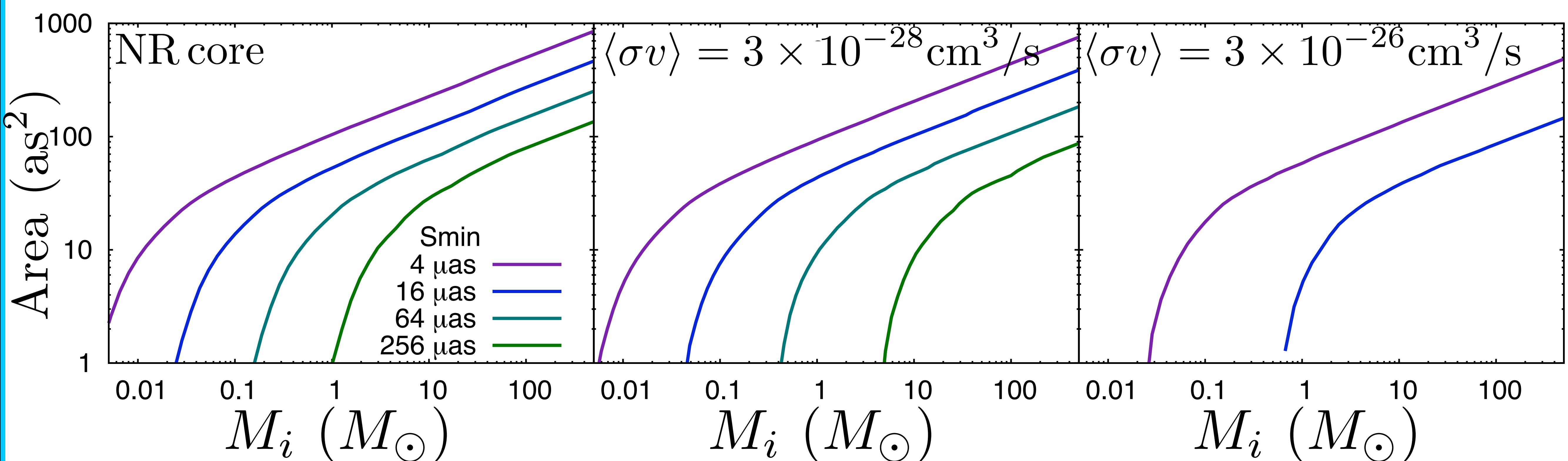
Lensing Cross Sections

We define a lensing cross-section based on a minimum value for the lensing signal; all stars within this area will produce $S > S_{\rm min}$.

$$S_{\rm min} \simeq {\rm SNR} \times 1.5\sigma_{\rm inst}$$

Gaia at $6\sigma: 256\mu{\rm as}$





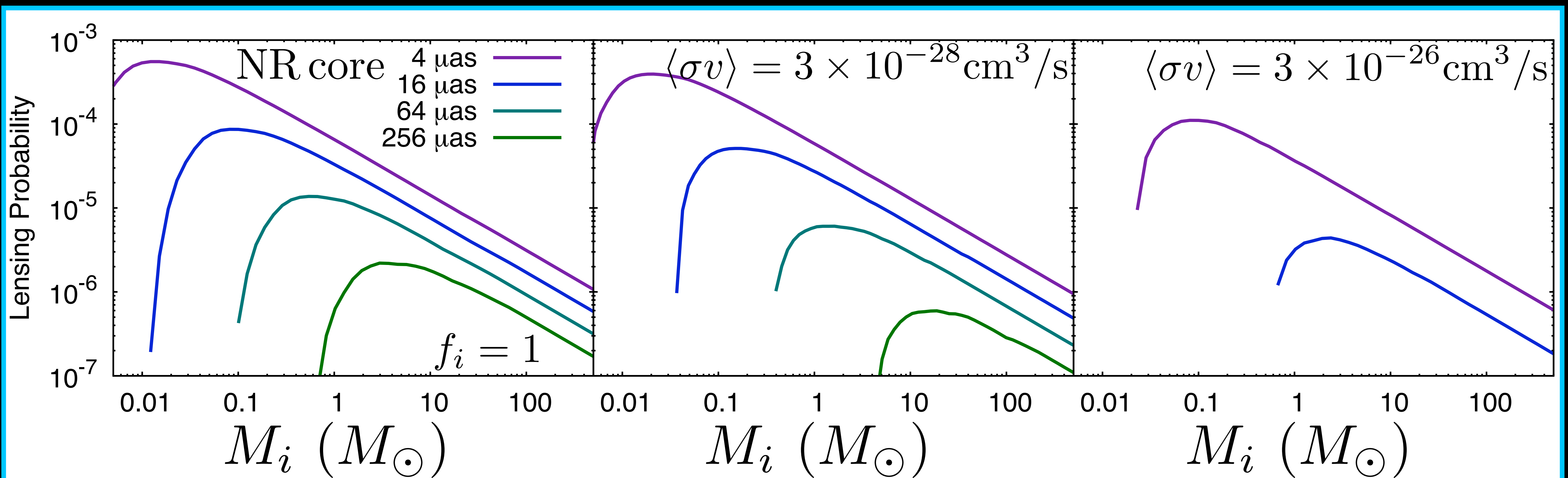
Lens distance: 50 pc; Lens velocity: 200 km/s; Source Distance: 2 kpc

Lensing Probability

We can combine the lensing cross sections with an **UCMH number density** to calculate the **fraction of the sky** that is detectably lensed ($S > S_{\rm min}$) by an UCMH.

$$n_{\rm UCMH} = f_0 \times \frac{\rho_{\rm dm}}{M_{\rm UCMH}} \qquad M_{\rm UCMH} = \begin{cases} 300 M_i \text{ if } f_i < 1/300 \\ M_i/f_i \text{ if } f_i > 1/300 \end{cases}$$

$f_0 \equiv$ *fraction of DM in UCMHs today* $\qquad f_i \equiv$ *fraction of DM in UCMHs initially*



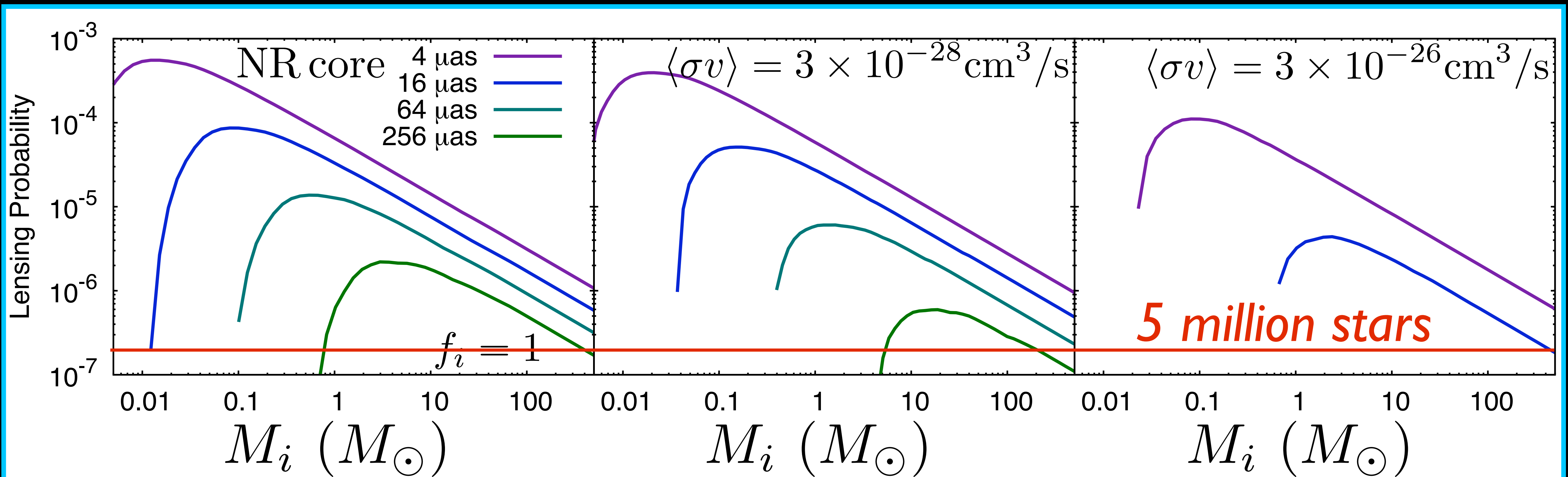
Lens velocity: 200 km/s; Source Distance: 2 kpc

Lensing Probability

We can combine the lensing cross sections with an UCMH number density to calculate the fraction of the sky that is detectably lensed ($S > S_{\rm min}$) by an UCMH.

$$n_{\rm UCMH} = f_0 \times \frac{\rho_{\rm dm}}{M_{\rm UCMH}} \qquad M_{\rm UCMH} = \begin{cases} 300 M_i \text{ if } f_i < 1/300 \\ M_i/f_i \text{ if } f_i > 1/300 \end{cases}$$

$f_0 \equiv$ fraction of DM in UCMHs today *$f_i \equiv$ fraction of DM in UCMHs initially*



Lens velocity: 200 km/s; Source Distance: 2 kpc

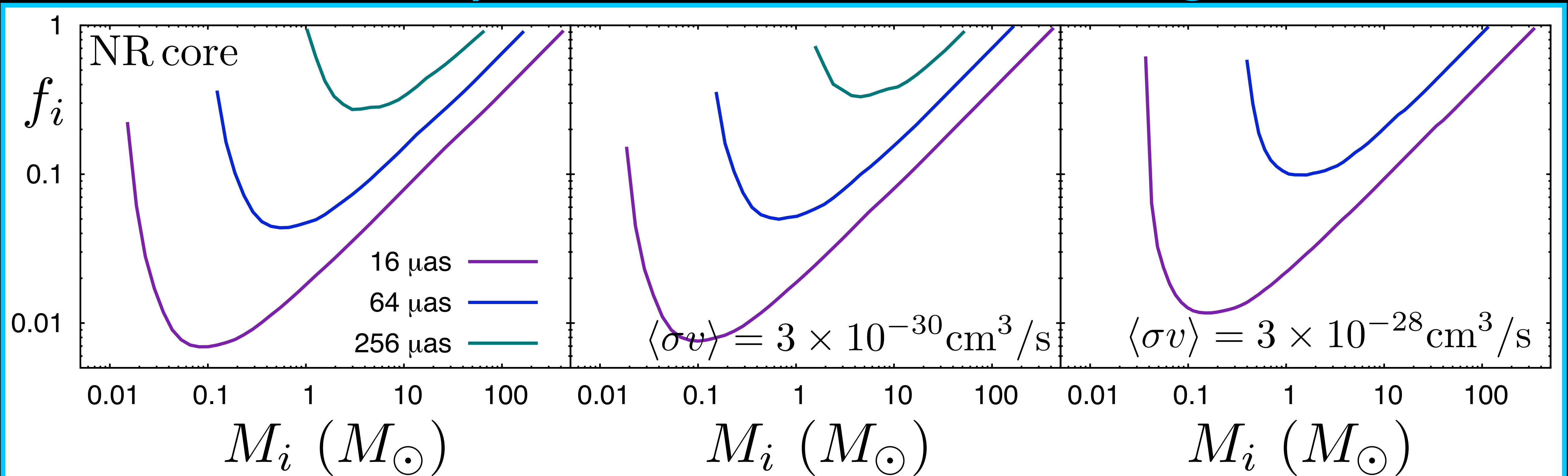
Constraining the UCMH fraction

If a search of $N_{\rm stars}$ stars fails to find a lensing event, we can conclude at 95% confidence that $\mathrm{Prob}_{\rm lens} < 3/N_{\rm stars}$.

If $f_i \gtrsim 0.003,\ f_0 \simeq 1$: all DM is currently in UCMHs

$$M_{\rm UCMH} = M_i/f_i \Longrightarrow n_{\rm UCMH} \propto f_i \Longrightarrow \mathrm{Prob}_{\rm lens} \propto f_i$$

Upper Bound on fraction of dark matter initially in UCMHs from a survey 5 million stars with no lensing events



$f_i \equiv$ *fraction of DM in UCMHs initially*

Lens velocity: 200 km/s; Source Distance: 2 kpc

Constraining the Power Spectrum

An upper bound on the initial UCMH mass fraction leads to an upper bound on the primordial power spectrum:

Josan & Green 2010
Bringmann, Scott, Akrami 2011

fraction of DM in UCMHs initially

Threshold overdensity for PBH formation

$$f_i(R) = \frac{2}{\sqrt{2\pi\sigma^2_{\mathrm{hor}}(R)}} \int_{10^{-3}}^{1/3} \mathrm{Exp}\left[-\frac{\delta^2_{\mathrm{hor}}(R)}{2\sigma^2_{\mathrm{hor}}(R)}\right] d\delta_{\mathrm{hor}}(R)$$

Comoving radius containing dark matter mass M_i

Threshold overdensity for UCMH formation

Proportional to $P_{\mathcal{R}}(k = R^{-1})$

Constraining the Power Spectrum

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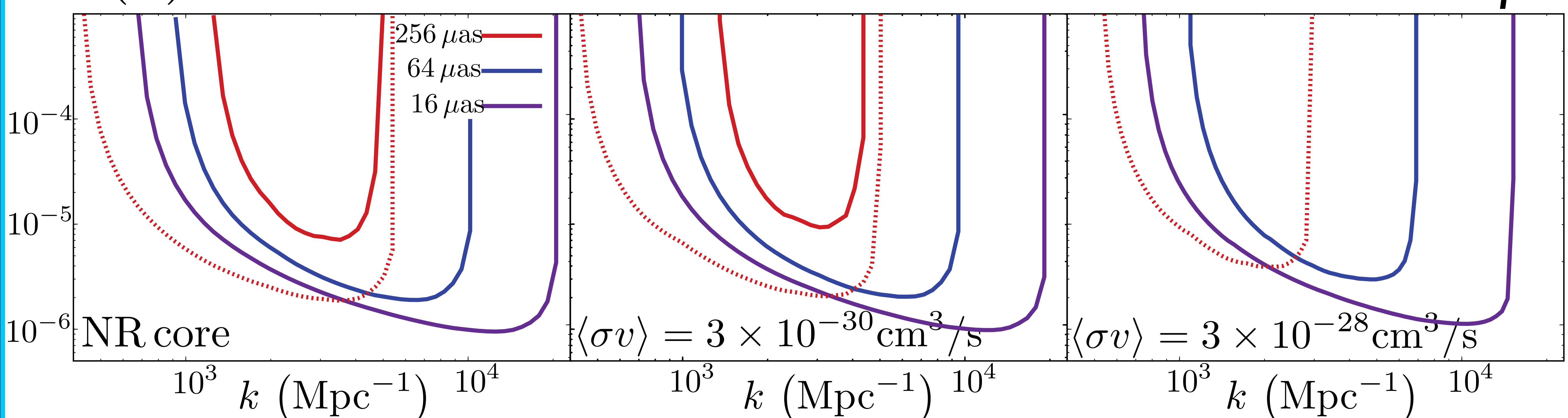
Comoving radius containing dark matter mass M_i

Threshold overdensity for UCMH formation

Proportional to $P_\mathcal{R}(k=R^{-1})$

5 million stars at ~2 kpc



Summary: Messages from Microhalos

The abundance of earth-mass and sub-earth-mass microhalos encodes information about the thermal history prior to BBN and the origin of dark matter. *AE, Sigurdson 1106.0536*

Astrometric microlensing by ultra-compact minihalos can provide new constraints on the primordial power spectrum.

- UCMHs produce distinctive astrometric microlensing signatures when they pass between us and a star.
- The astrometric lensing signal is strongest if the dark matter is not self-annihilating.
- If dark matter is not self-annihilating, a Gaia search for astrometric microlensing by UCHMs can reduce the upper bound on the primordial power spectrum on scales of $10^3 - 10^4\,\mathrm{Mpc}^{-1}$ by three orders of magnitude compared to the constraints from primordial black holes.

Li, AE, Law 1202.1284

Jedamzik, Lemoine, Martin 2010;
Easther, Flauger, Gilmore 2010

potential near minimum $V(\phi) \simeq \frac{1}{2} m^2 \phi^2 \implies \phi(t) \simeq \phi_0 \sin(mt)$

Pressure $p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$ $\langle p \rangle = \langle \frac{1}{2}\dot{\phi}^2 \rangle - \langle \frac{1}{2} m^2 \phi^2 \rangle = 0$