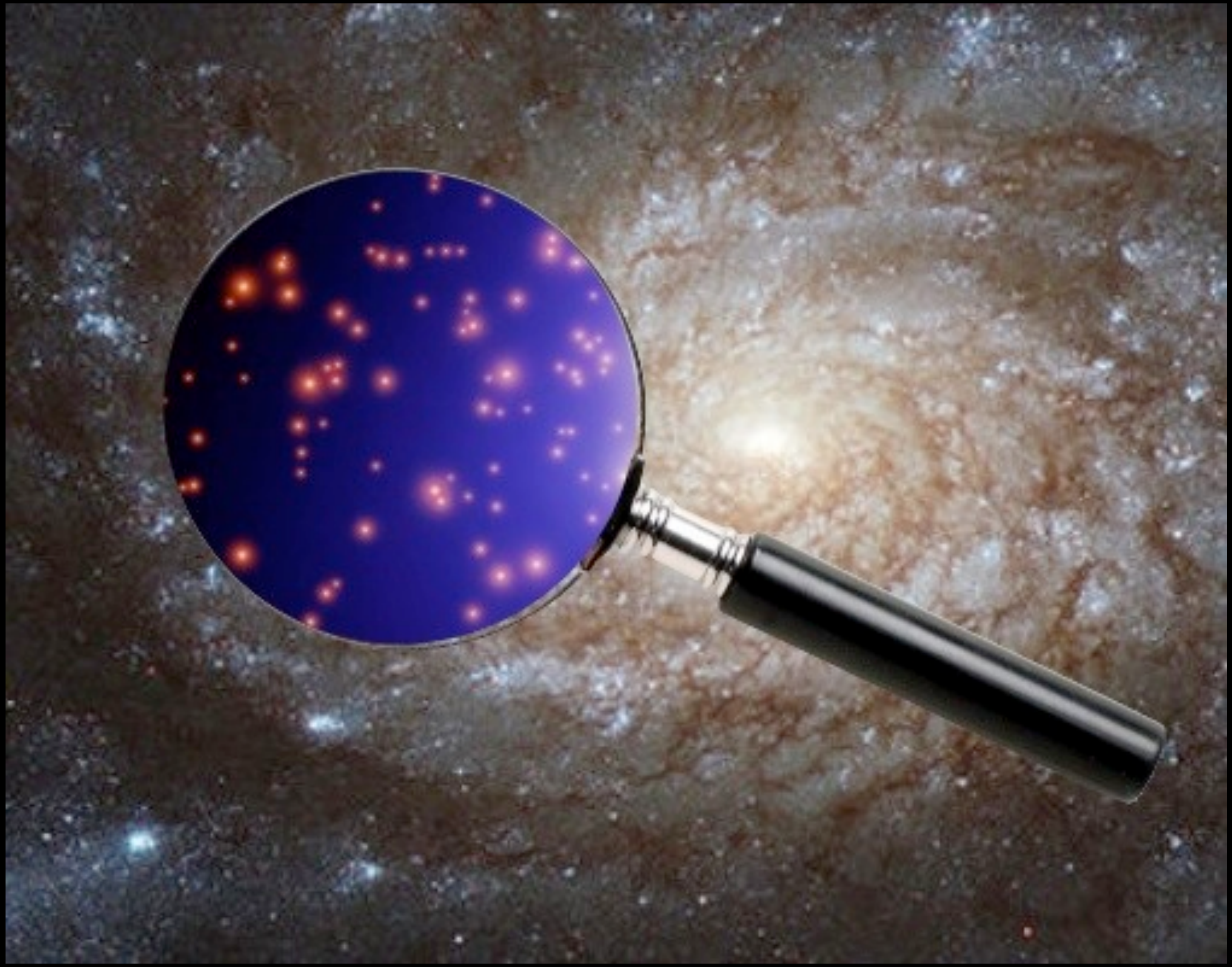
The Power of Small Scales to Probe Inflation

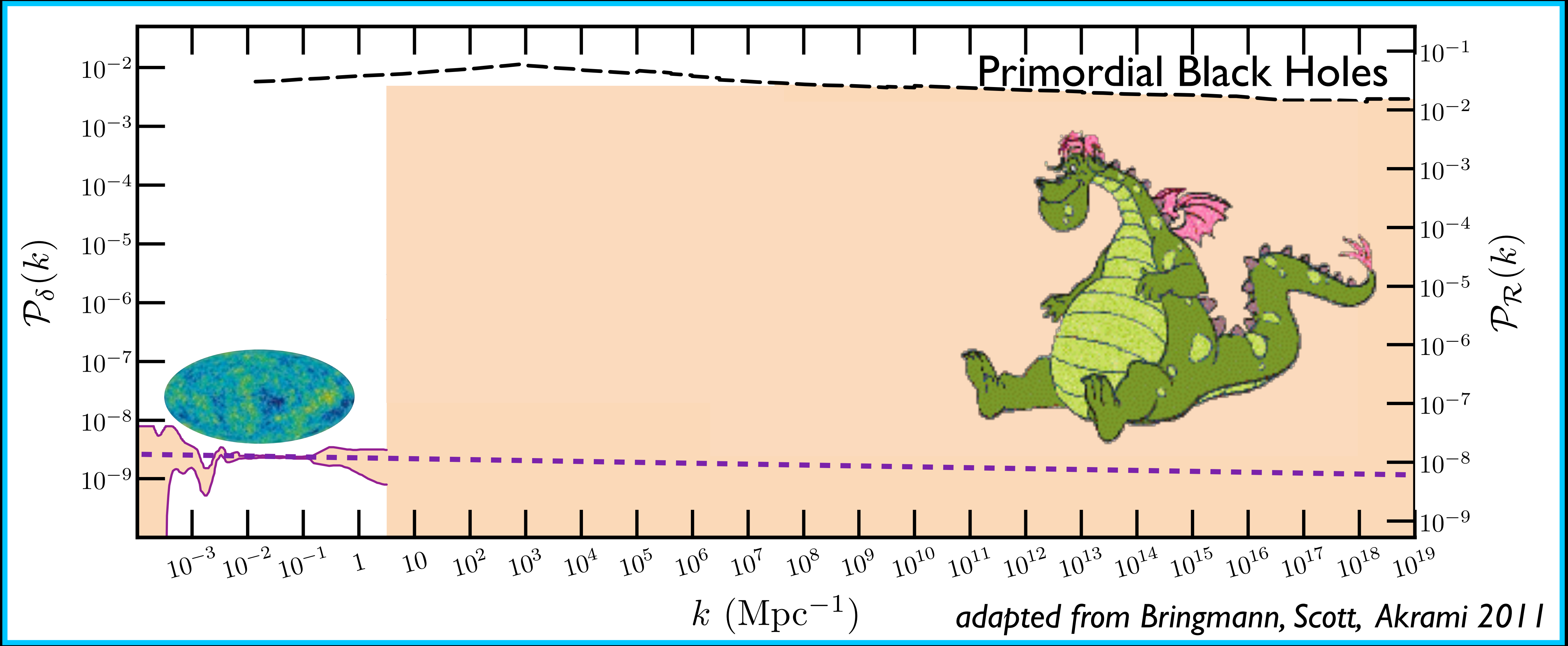


Adrienne Erickcek
CITA
Perimeter Institute

CMU Cosmic Acceleration Workshop
August 25, 2012

Small scales: Here there be dragons

Several inflationary models predict excess small-scale power.



adapted from Bringmann, Scott, Akrami 2011

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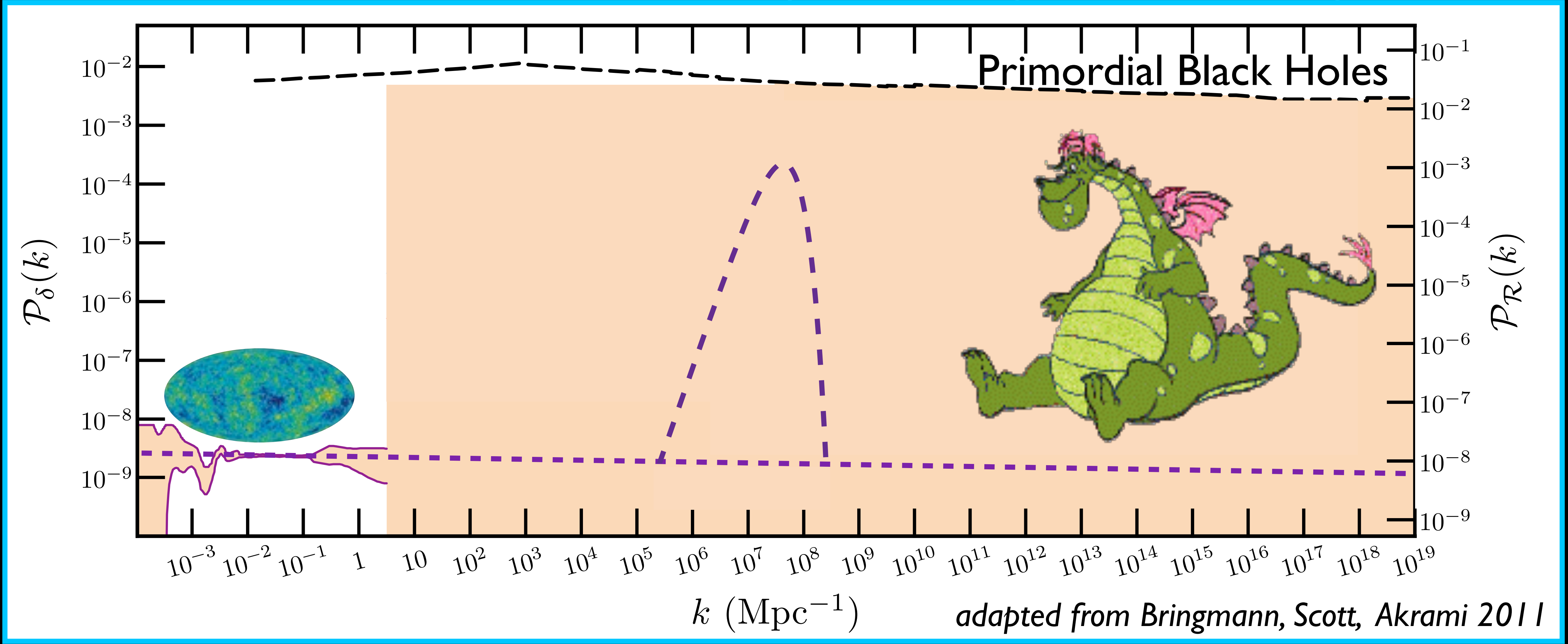

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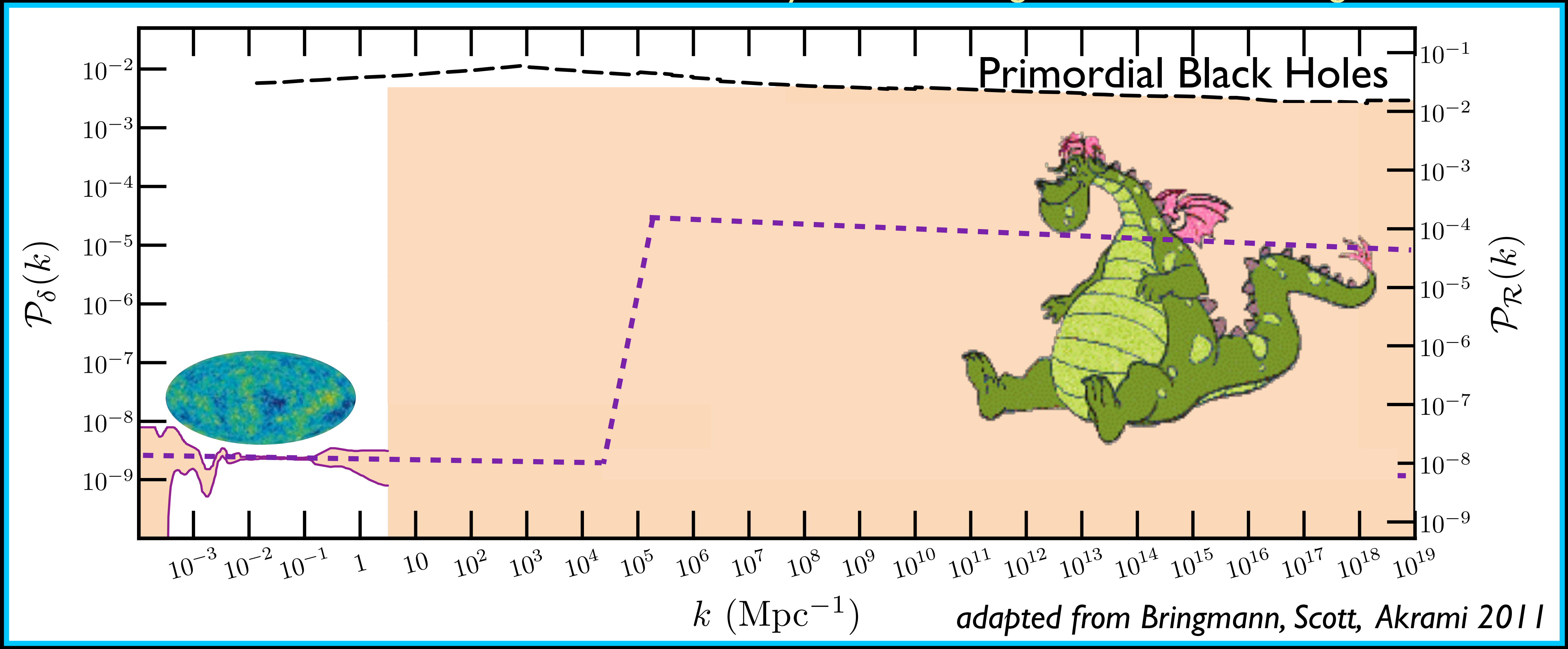

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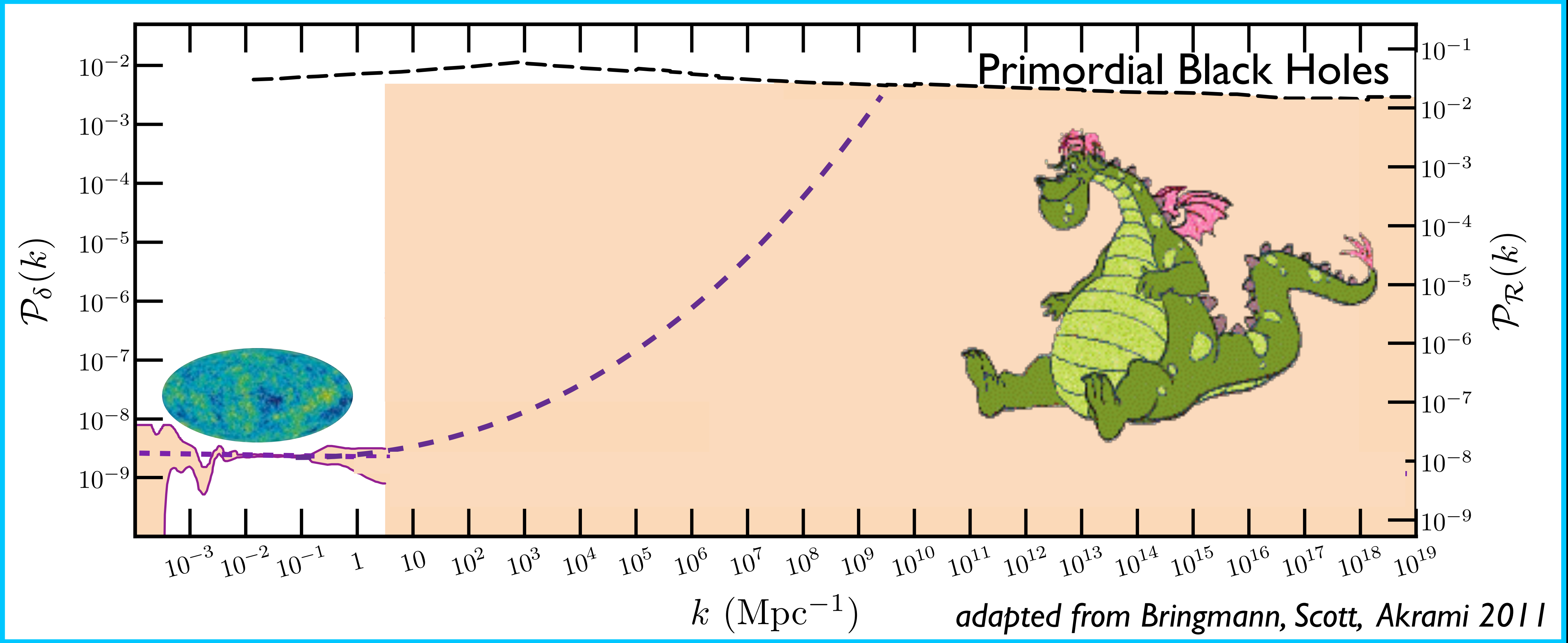

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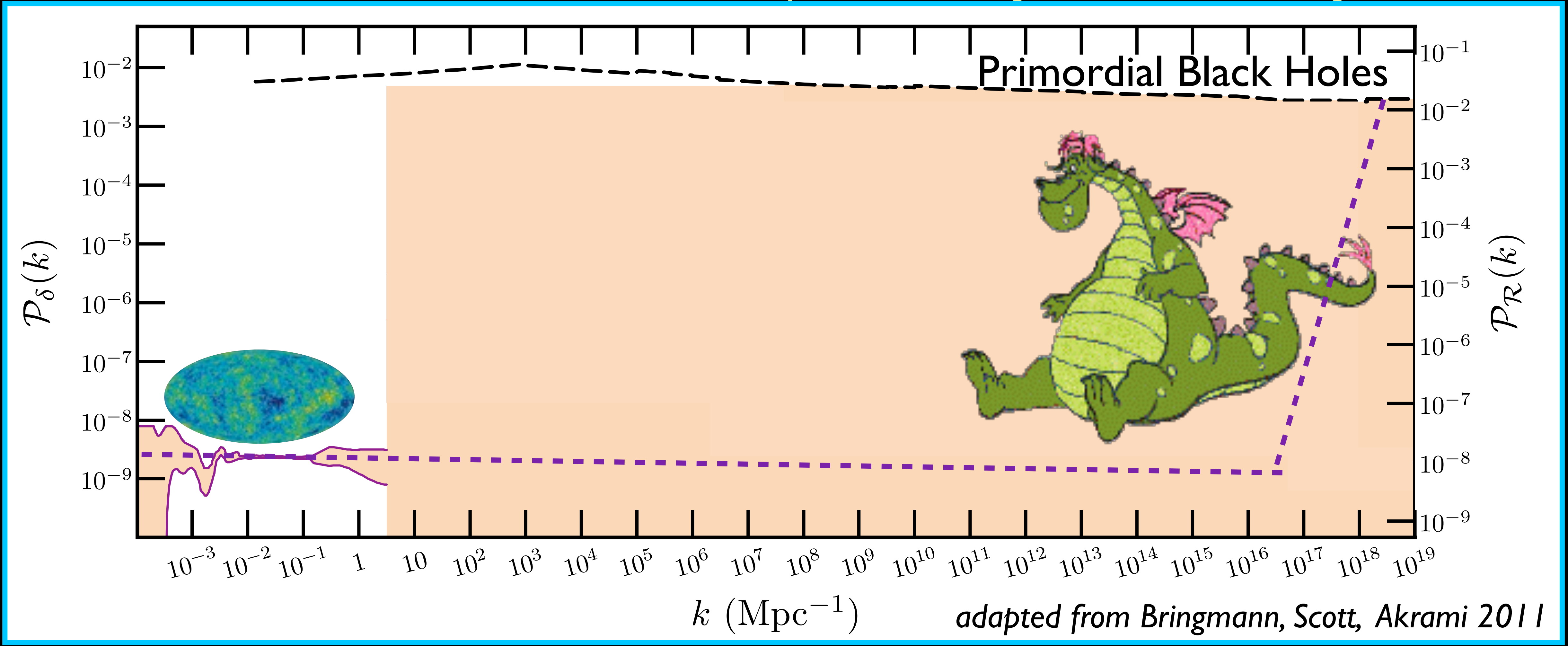

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Outline

Part I: What can small scales tell us about reheating?

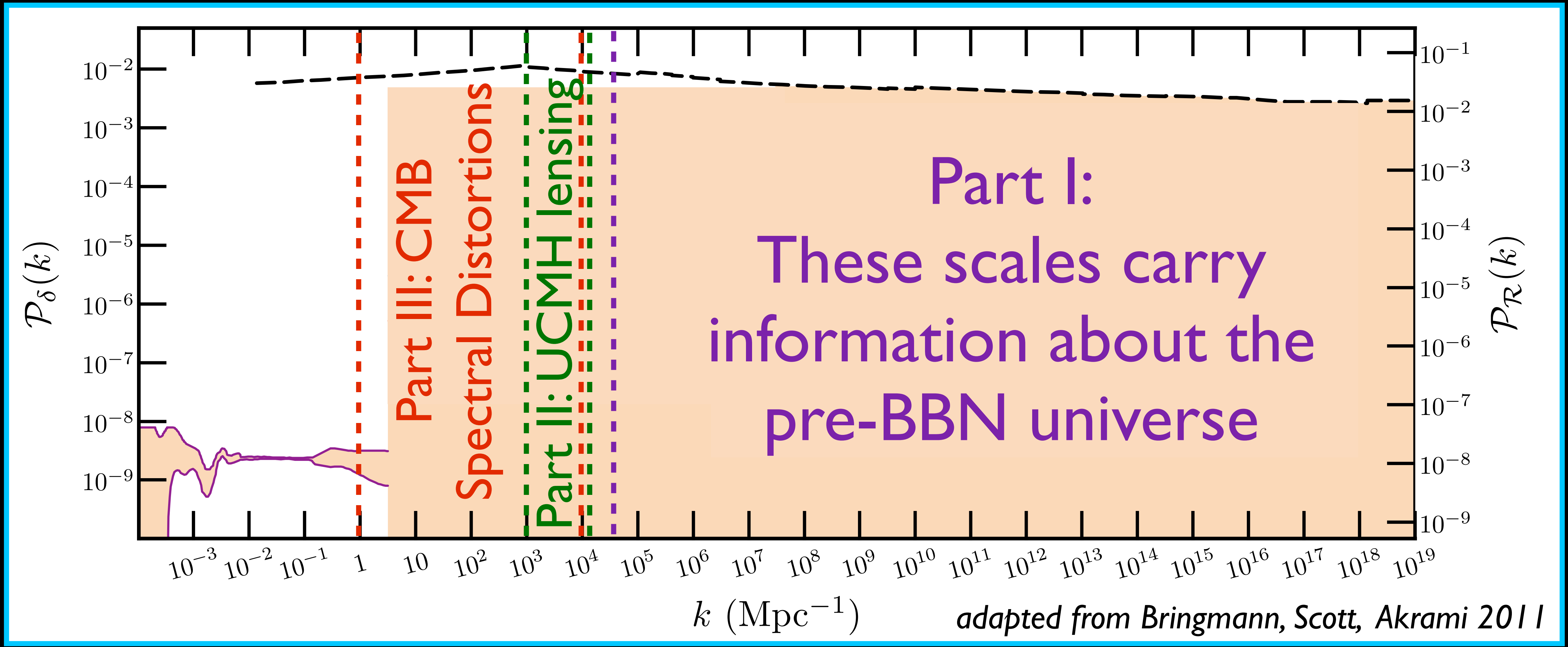
Collaborators: Kris Sigurdson (UBC)

Part II: Probing small scales with astrometric lensing by UCMHs

Collaborators: Fangda Li (UT undergrad) & Nicholas Law (DI Fellow)

Part III: Probing small scales with CMB spectral distortions

Collaborators: Jens Chluba (CITA) & Ido Ben-Dayan (CITA/PI)



Part III: CMB Spectral Distortions

Part II: UCMH lensing

Part I: These scales carry information about the pre-BBN universe

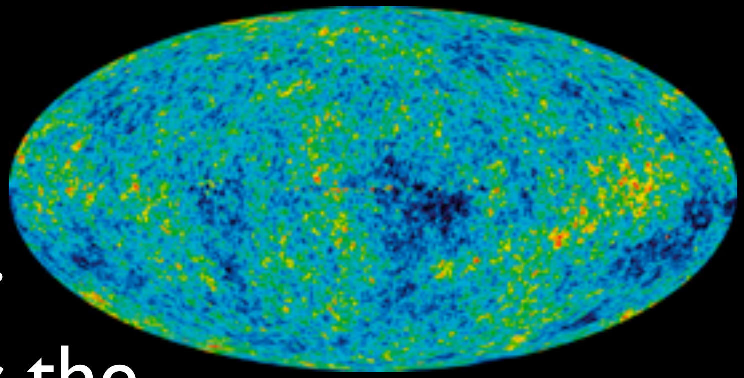
adapted from Bringmann, Scott, Akrami 2011

What Happened Before BBN?

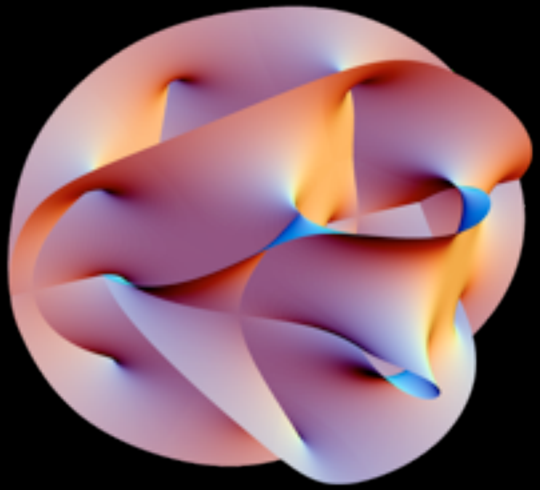
The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology's crowning achievements.

- The elements produced during Big Bang Nucleosynthesis are our first window on the Universe.
- They 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.
- During inflation, the Universe was scalar dominated.
- Other scalar fields may dominate the Universe after the inflaton decays.
- The string moduli problem: scalars with gravitational couplings come to dominate the Universe before BBN.

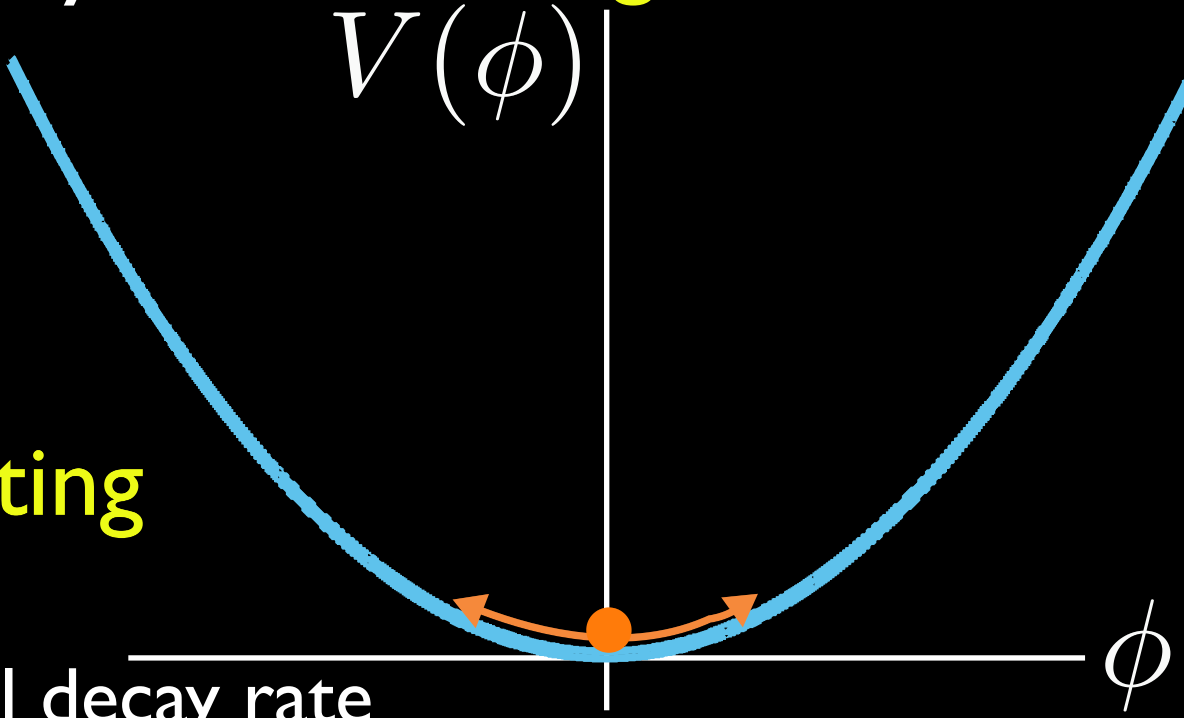


Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
Acharya, Kane, Kuflik 2010

Scalar Domination after Inflation

The Universe was once dominated by an oscillating scalar field.

- reheating after inflation
- curvaton domination
- string moduli



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

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

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

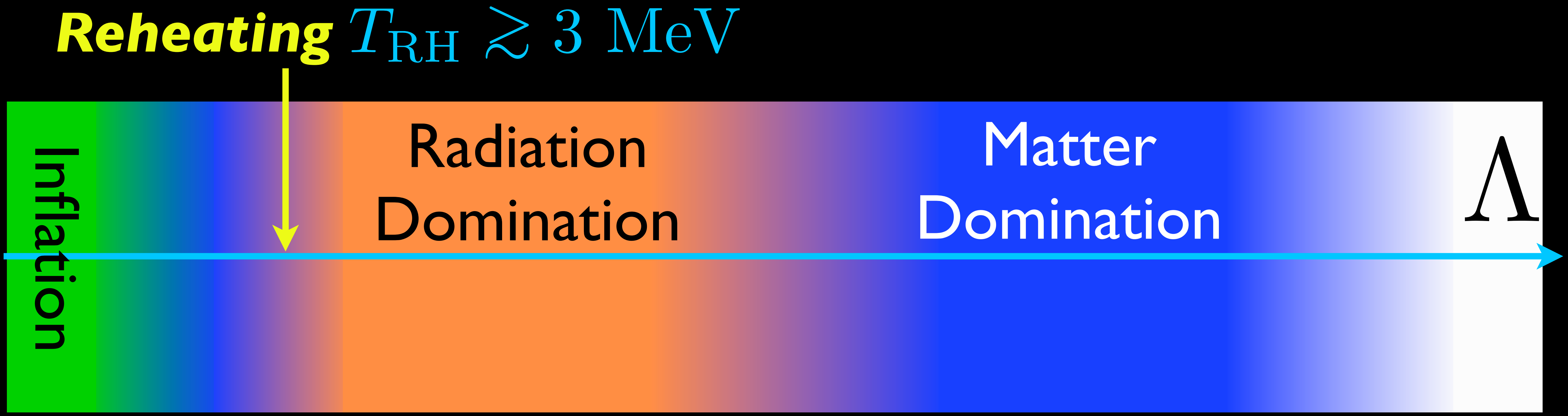
- over many oscillations, average pressure is zero.
- density in scalar field evolves as $\rho_\phi \propto a^{-3}$
- scalar field density perturbations grow as $\delta_\phi \propto a$

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

What happens to these perturbations after reheating?

Microhalos from Reheating

Erickcek & Sigurdson PRD 84, 083503 (2011)



Reheating $T_{\mathrm{RH}} \gtrsim 3\ \mathrm{MeV}$

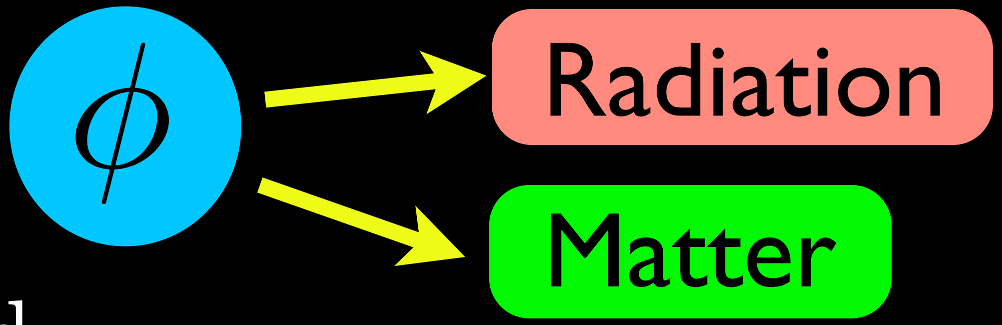
Inflation

Radiation Domination

Matter Domination

Λ

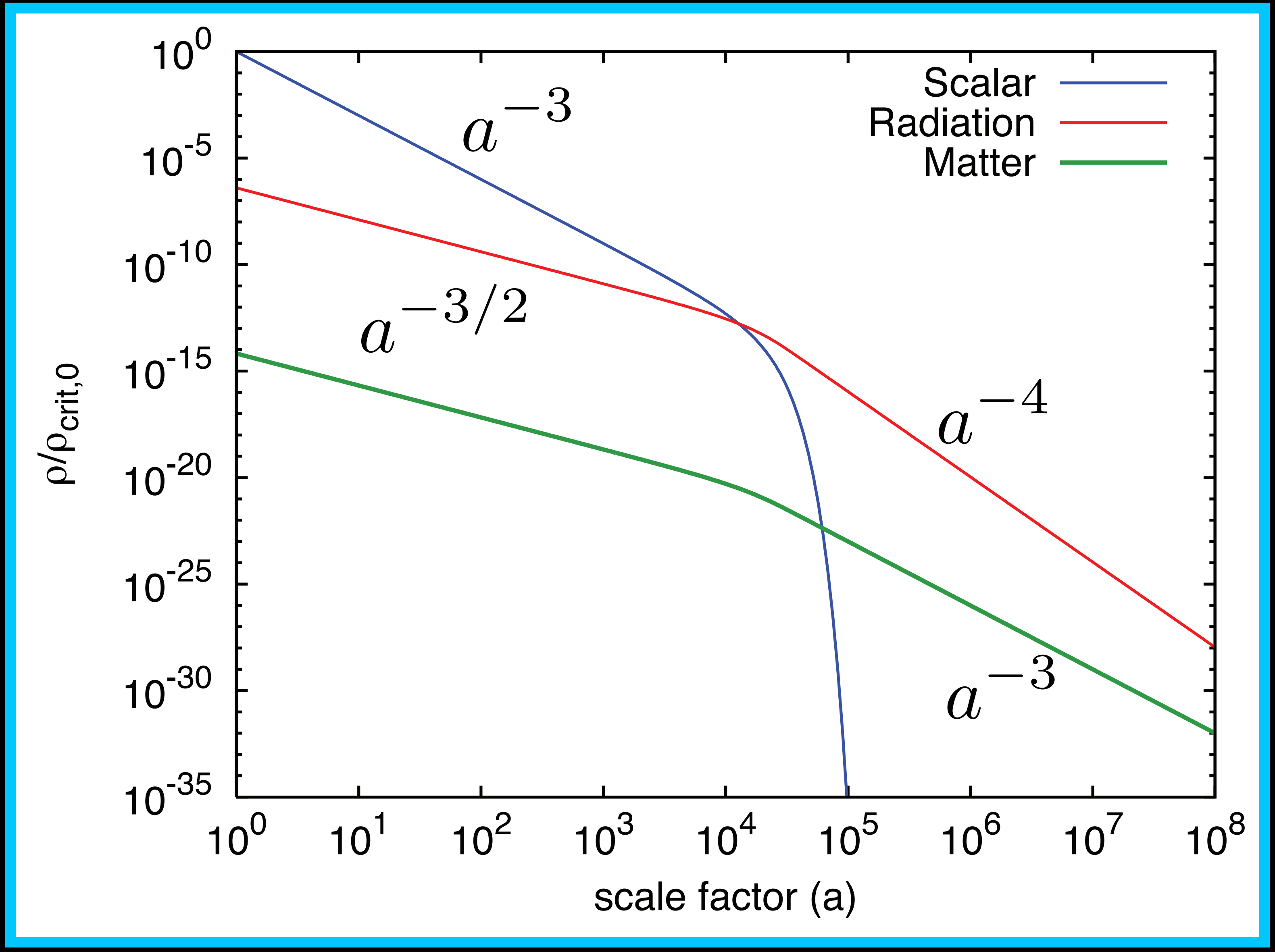
Perturbative Scalar Decay



$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_r + 4H\rho_r = (1-f)\Gamma_\phi\rho_\phi$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{\mathrm{dm}} + 3H\rho_{\mathrm{dm}} = f\Gamma_\phi\rho_\phi$$

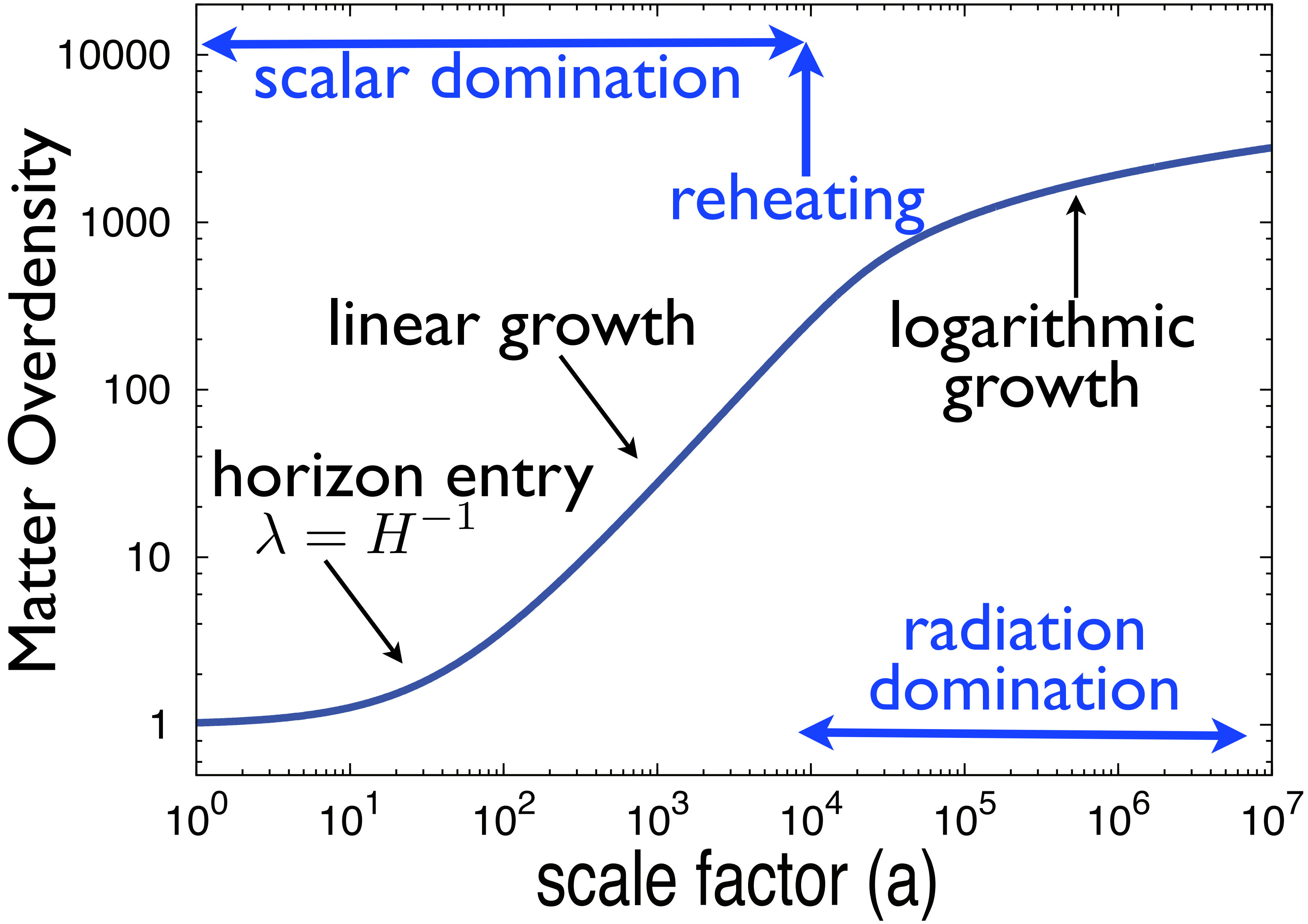
$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$



The Matter Perturbation

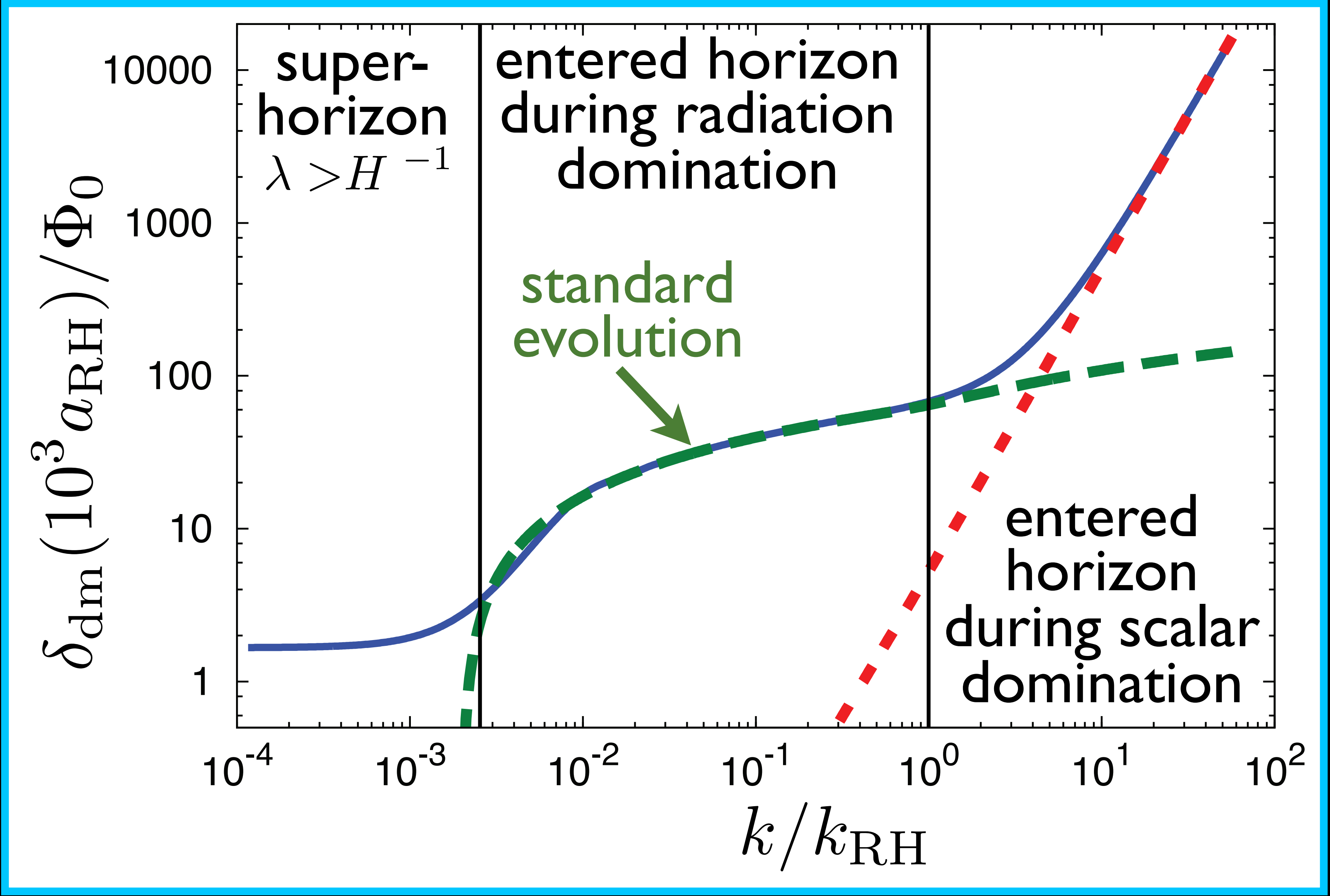
Scalar domination affects the growth of density fluctuations.

Evolution of the Matter Density Perturbation



The Matter Perturbation

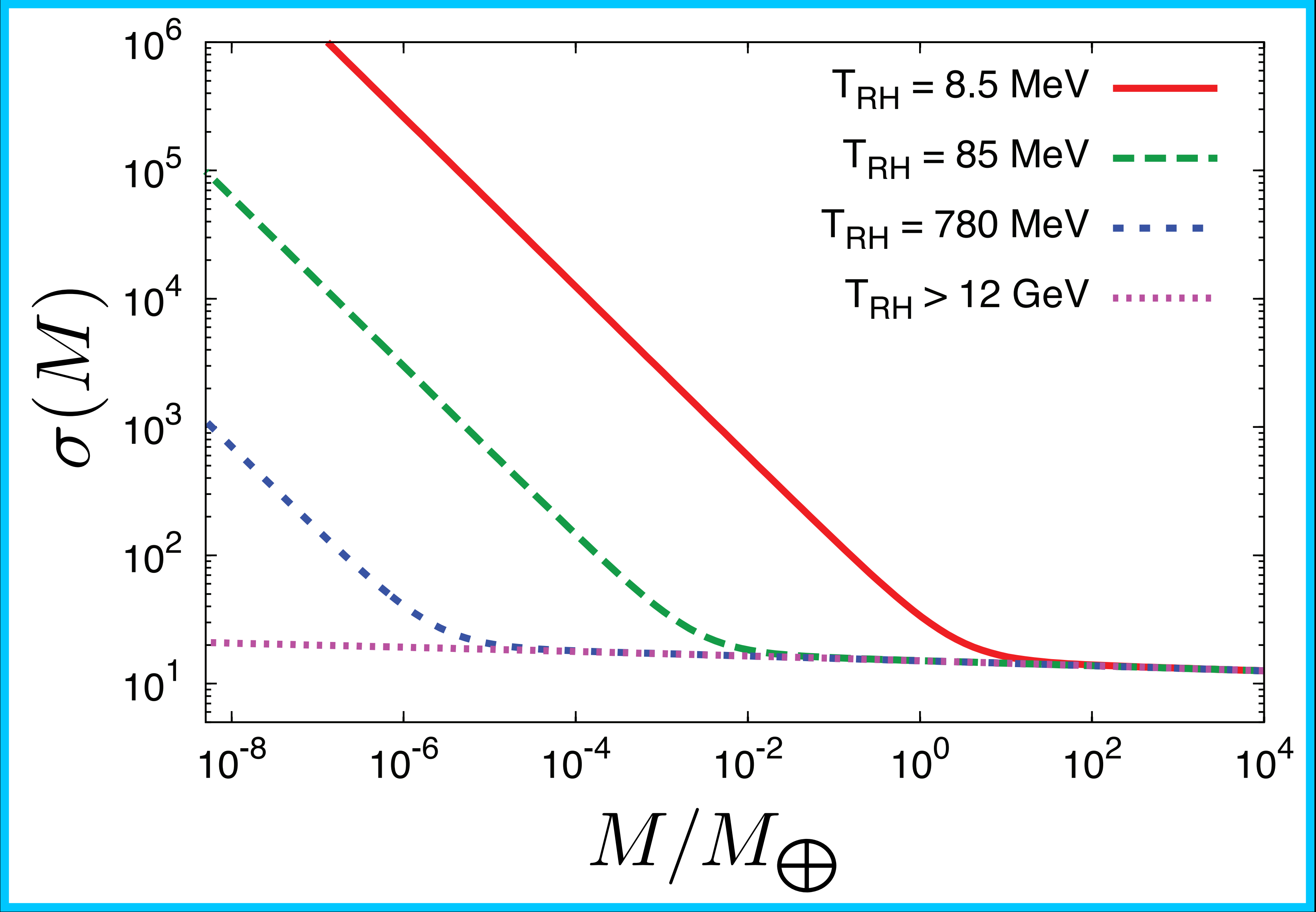
The Matter Density Perturbation during Radiation Domination



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

Wavenumber of mode that enters horizon at reheating

RMS Density Fluctuation

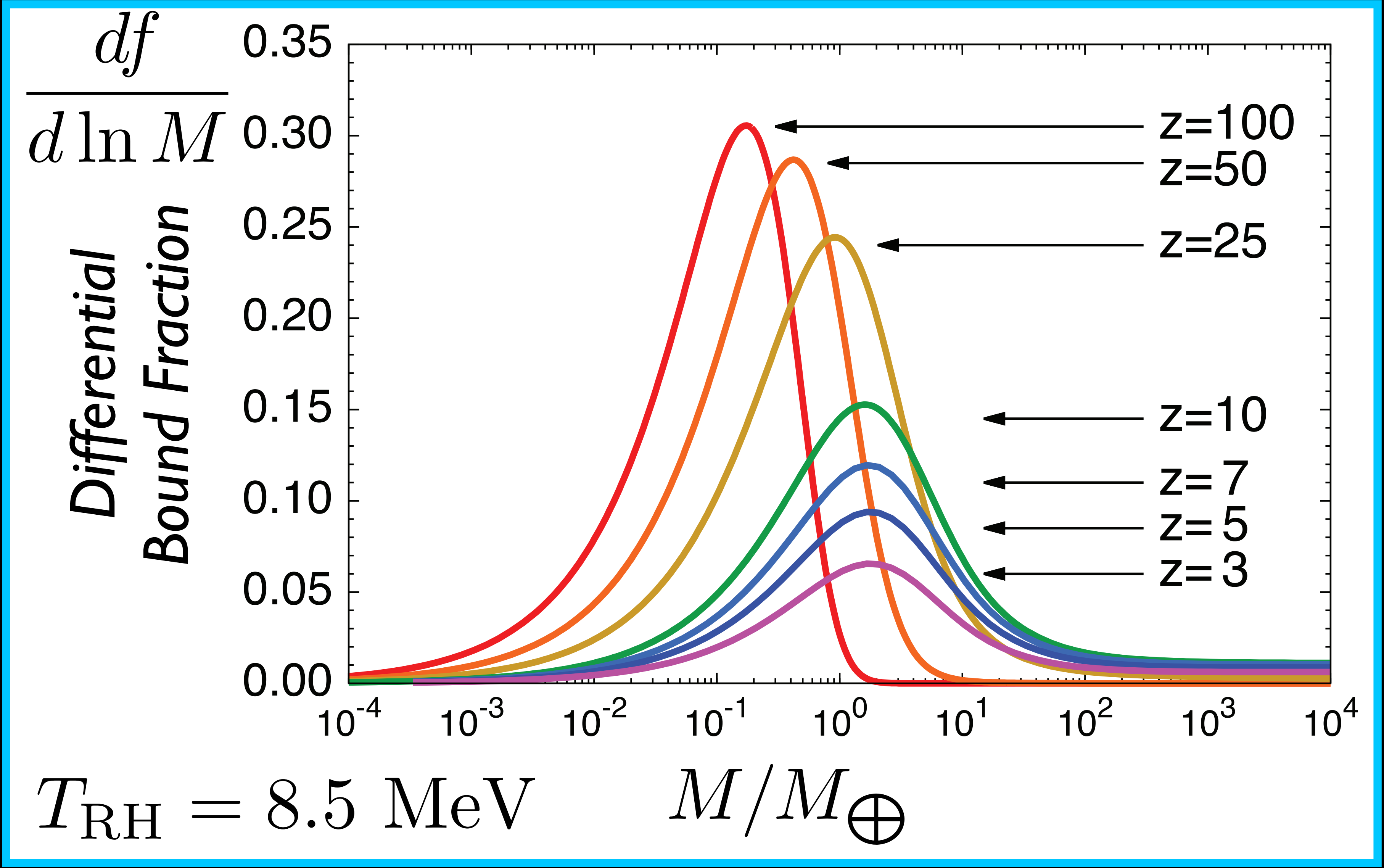


- Enhanced perturbation growth affects scales with $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be dark matter mass within this comoving radius.

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

Microhalos at High Redshift

We used the **Press-Schechter** mass function to calculate the **fraction of dark matter contained in halos of mass M.**



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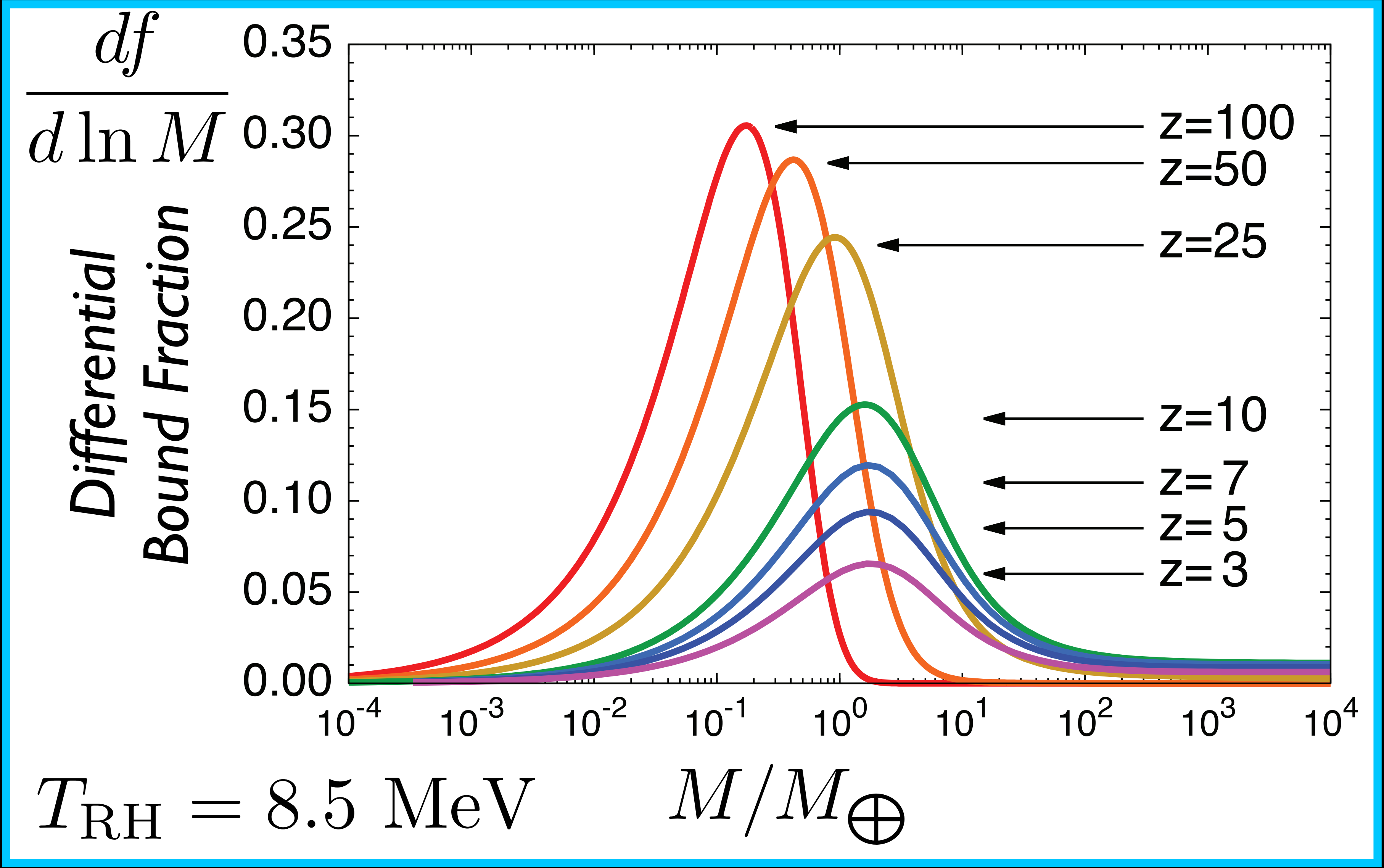


Fraction bound in halos with $M > 0.1\,M_\oplus$

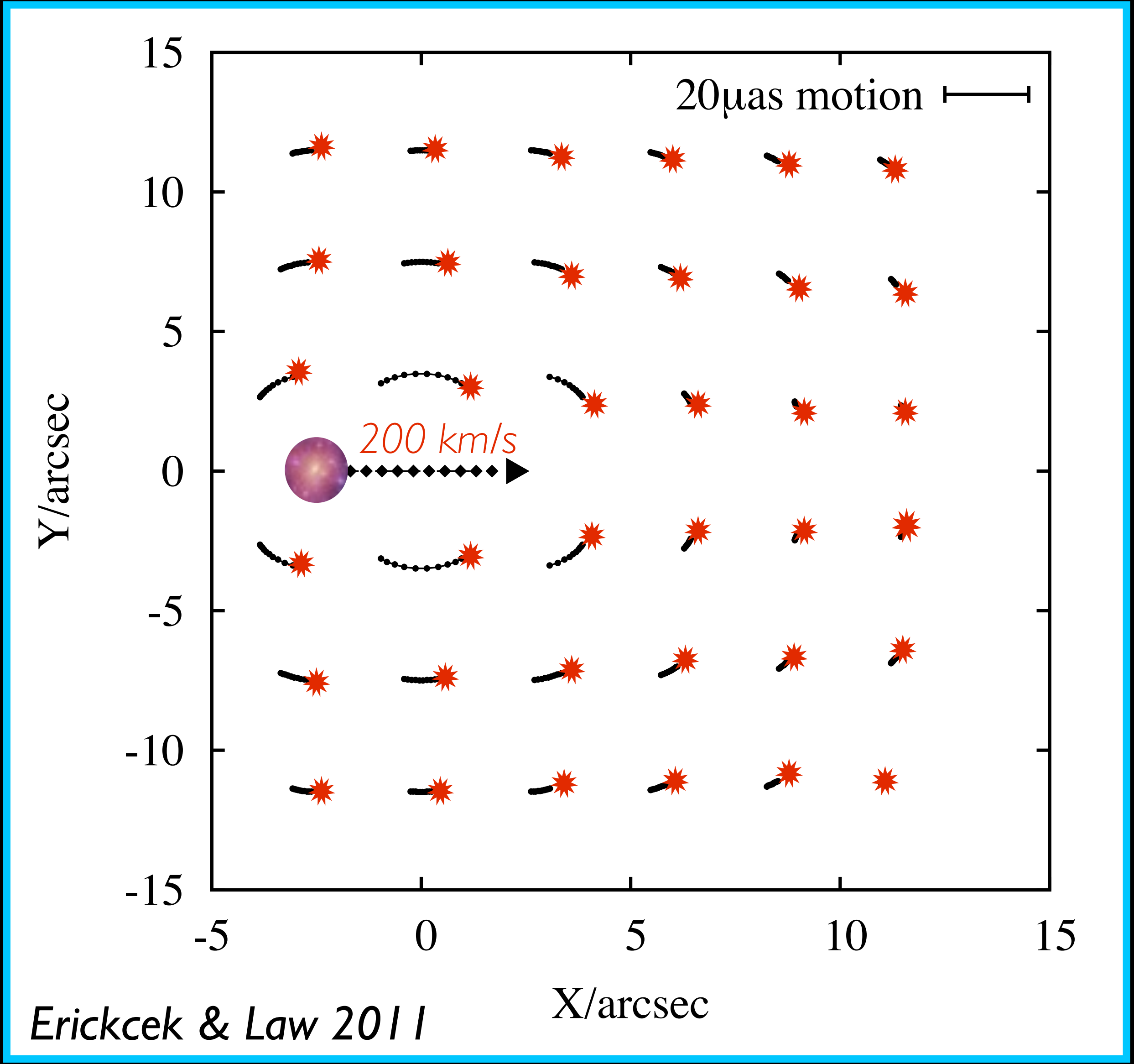
z	Std	8.5 MeV
100	10^{-10}	0.49
50	10^{-3}	0.71
25	0.06	0.83

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

Detection Prospects

The only guaranteed signatures are gravitational.

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



Erickcek & Law 2011

If dark matter self-annihilates...

Part II
Ultracompact Minihalos and the Primordial Power Spectrum

Li, Erickcek & Law PRD 86 043519 (2012)

Fangda Li
U of Toronto
3rd year undergrad

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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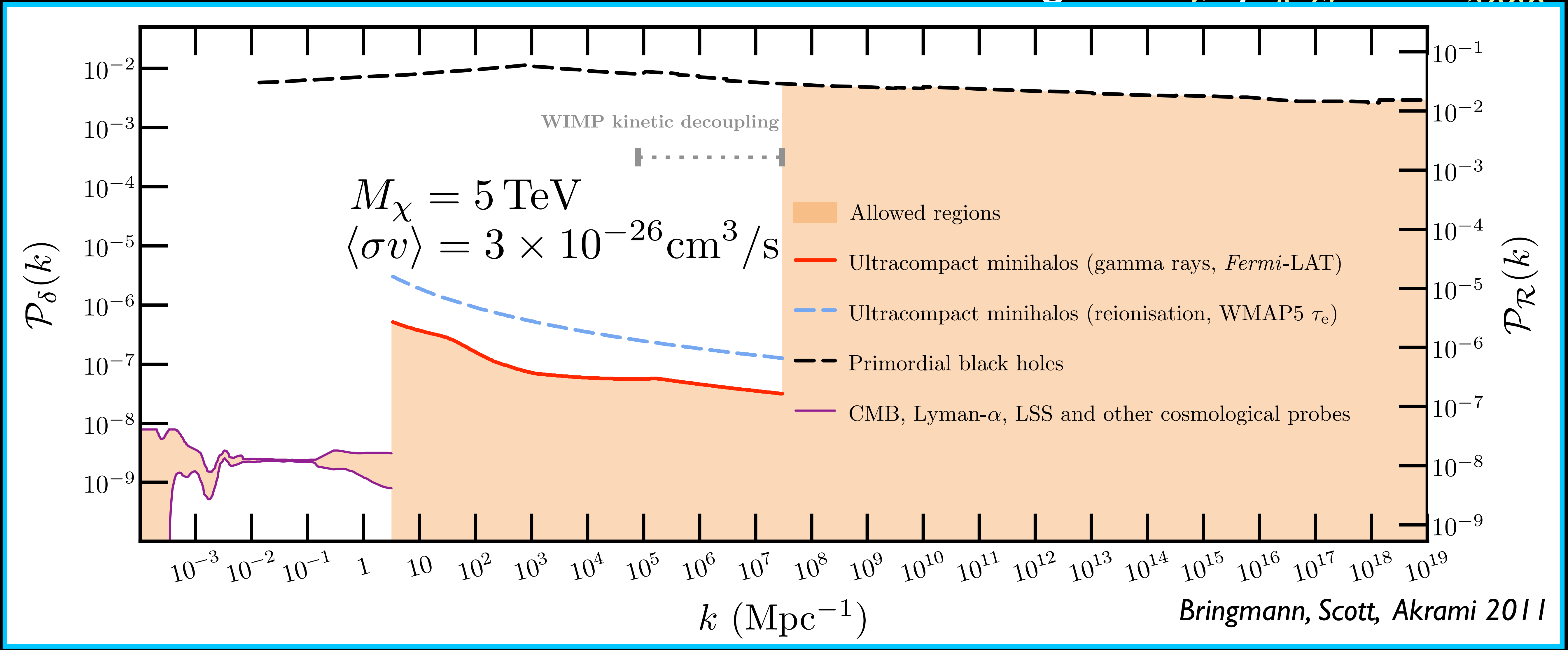

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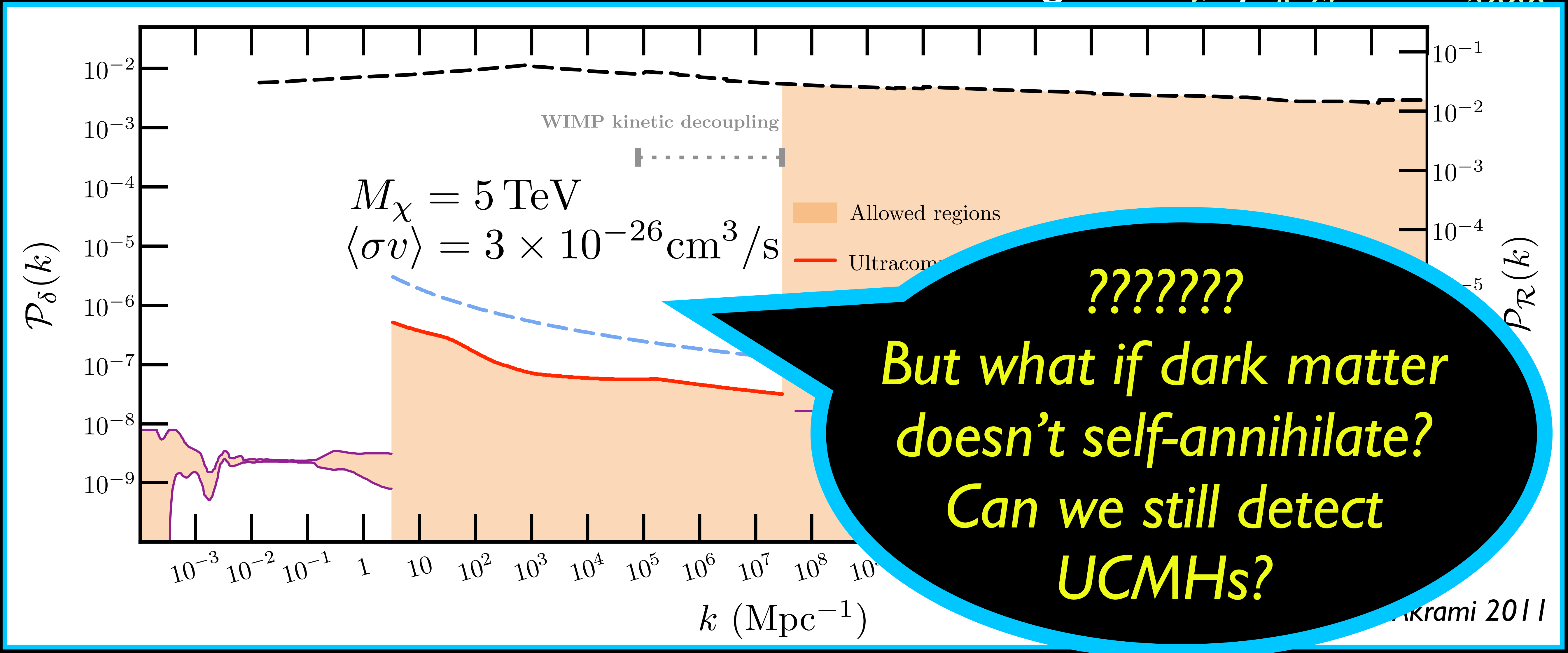


???????

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

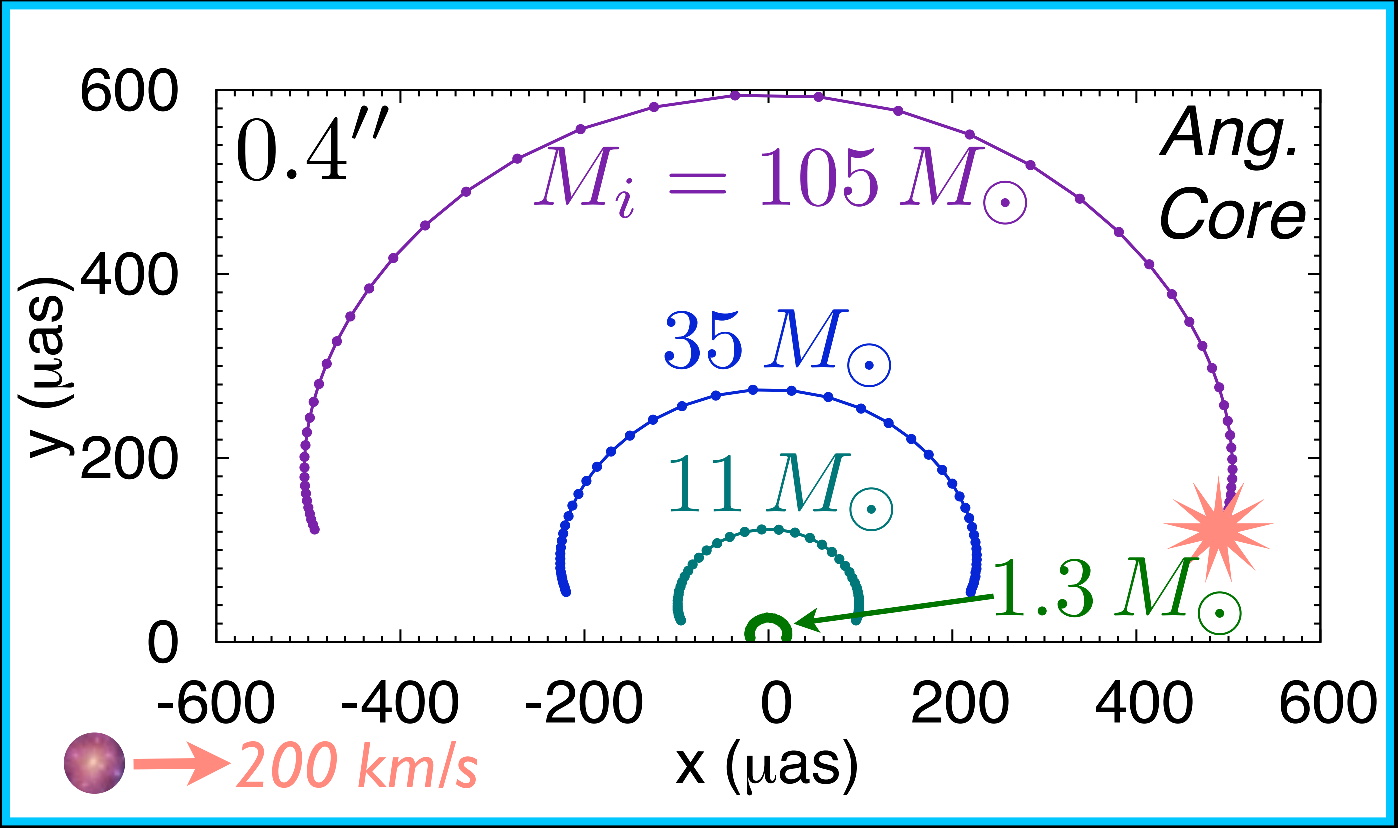
Astrometric Microlensing by UCMHs

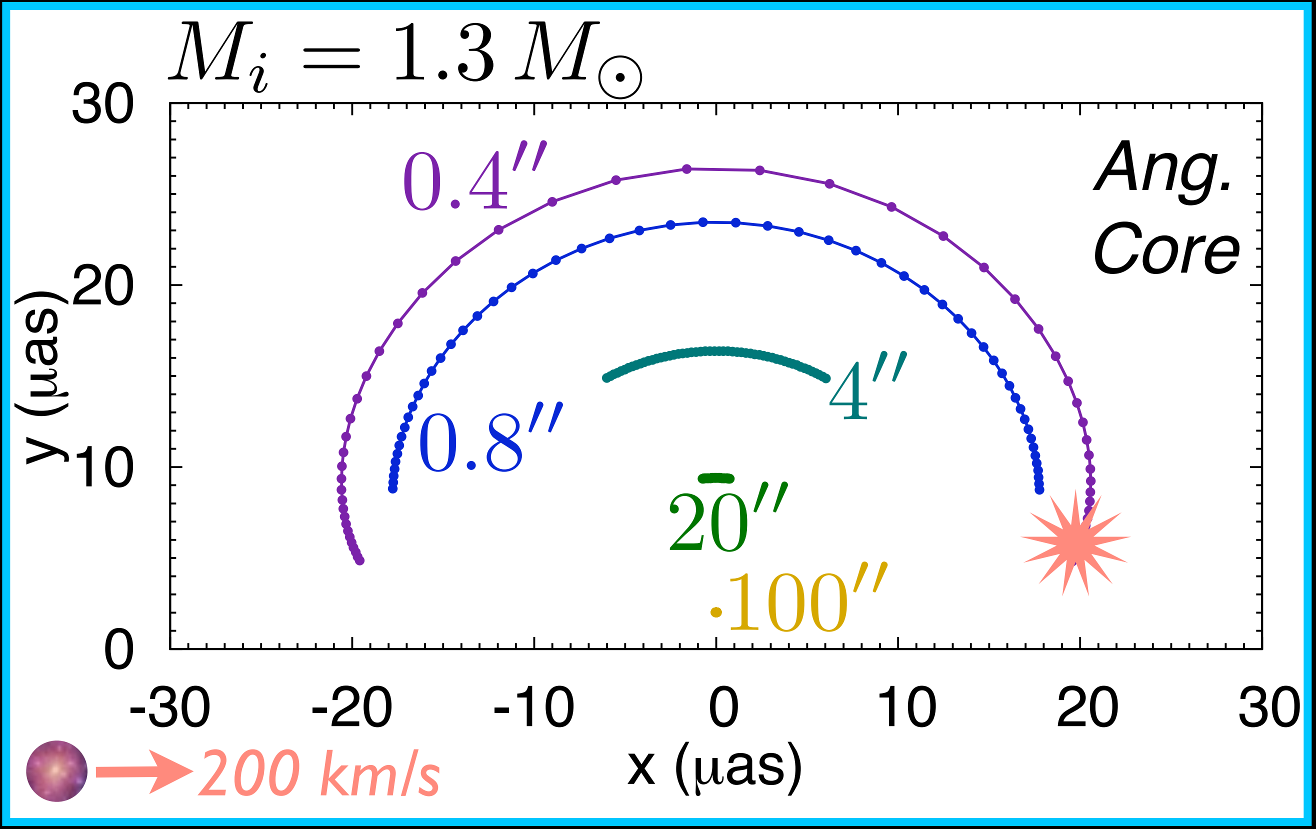
As UCMH passes in front of a star, the star moves!

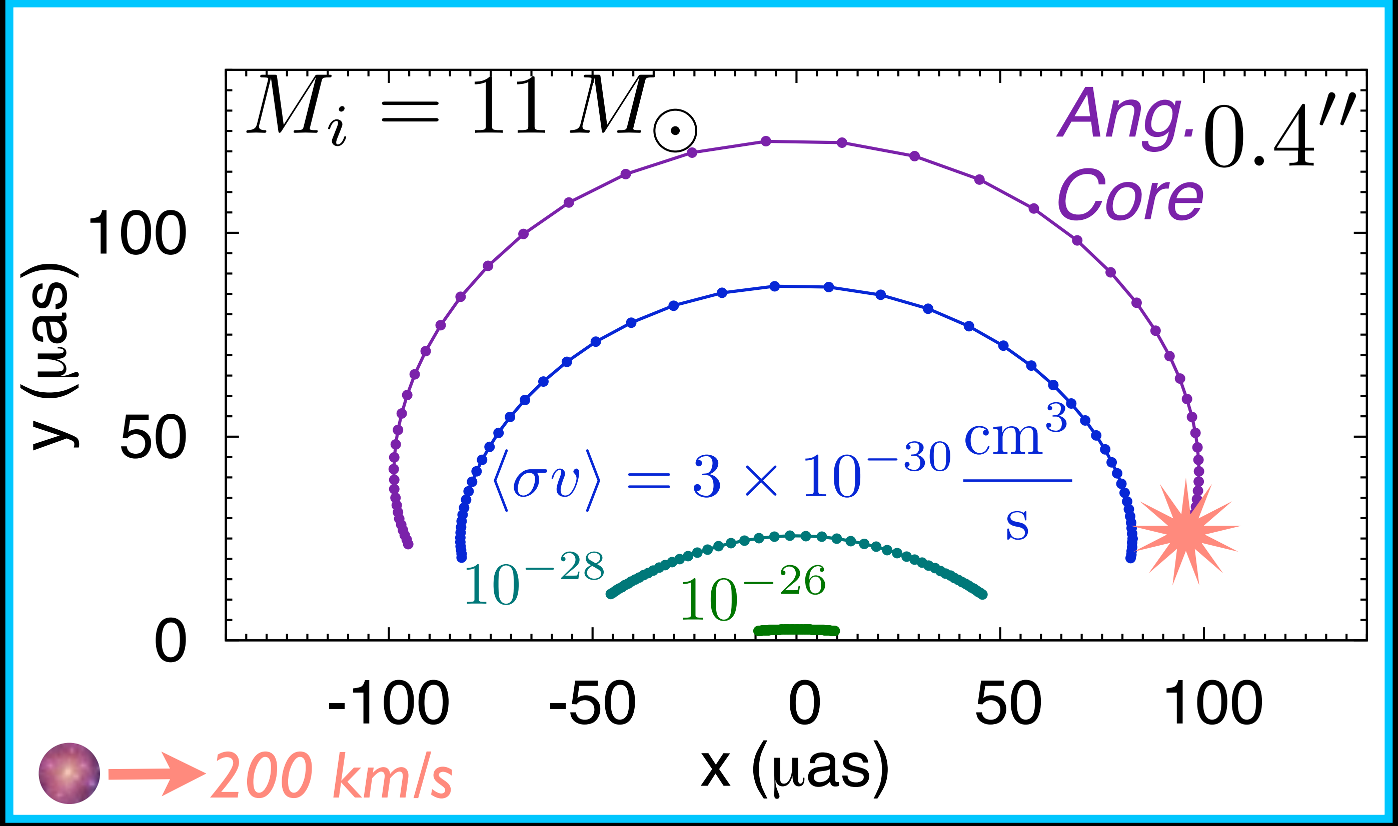
Trajectory depends on

- initial microhalo mass
- impact parameter
- core radius

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



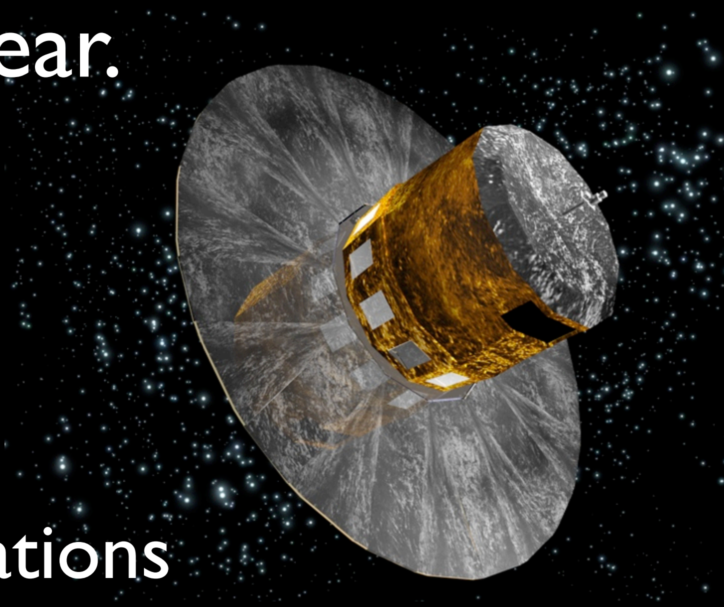




Probing the Primordial Perturbations

Gaia is an ESO satellite scheduled to launch next year.

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



If Gaia doesn't detect microlensing by UCMHs,

- upper bound on number density of UCMHs
- upper bound on the amplitude of small-scale density fluctuations

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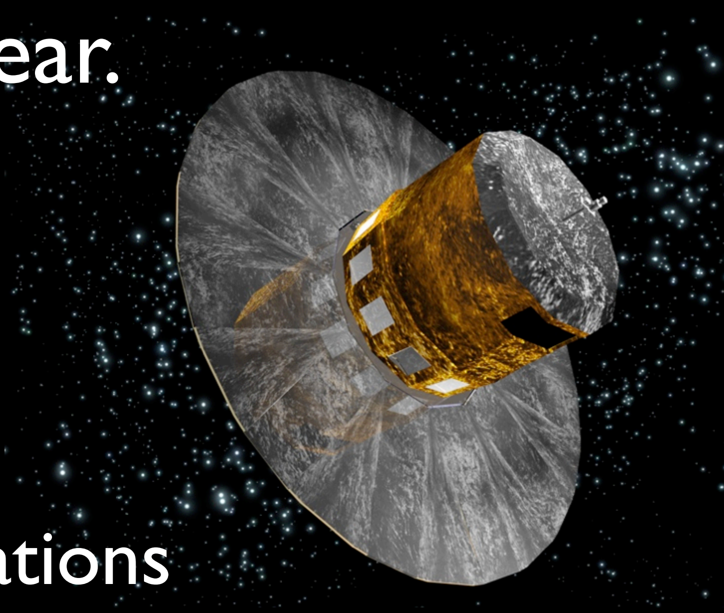

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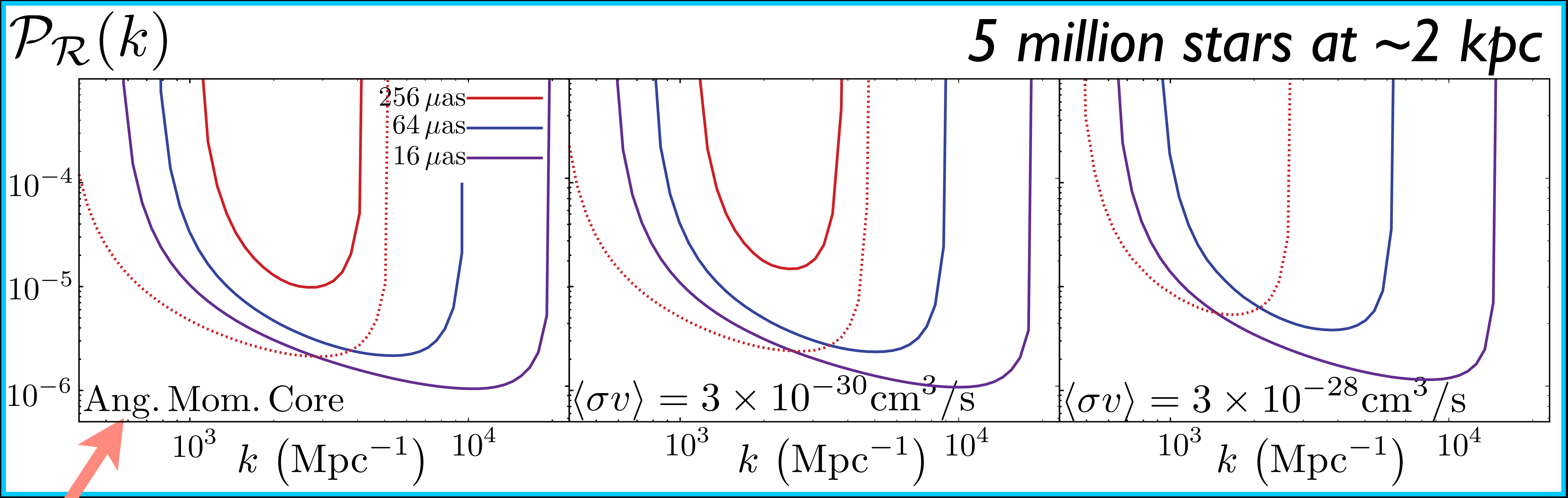

Most conservative case: Fermi gives a stronger bound if DM self-annihilation diminishes lensing signal.

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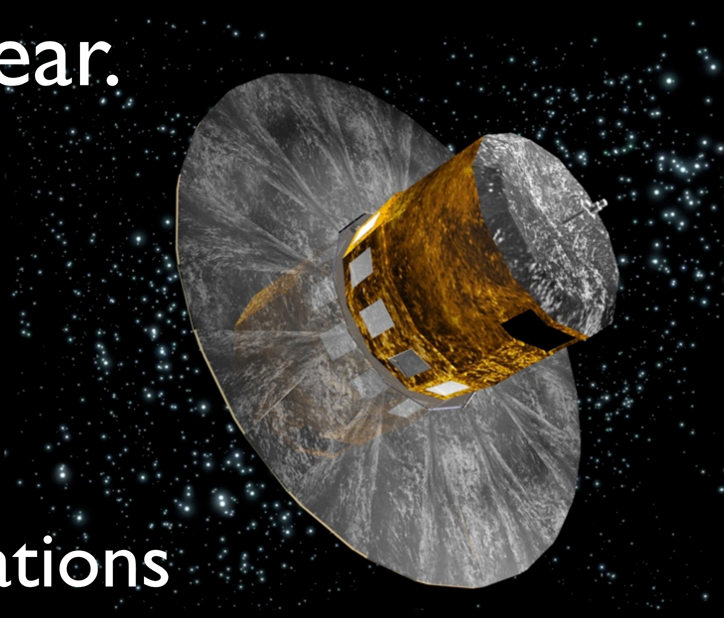

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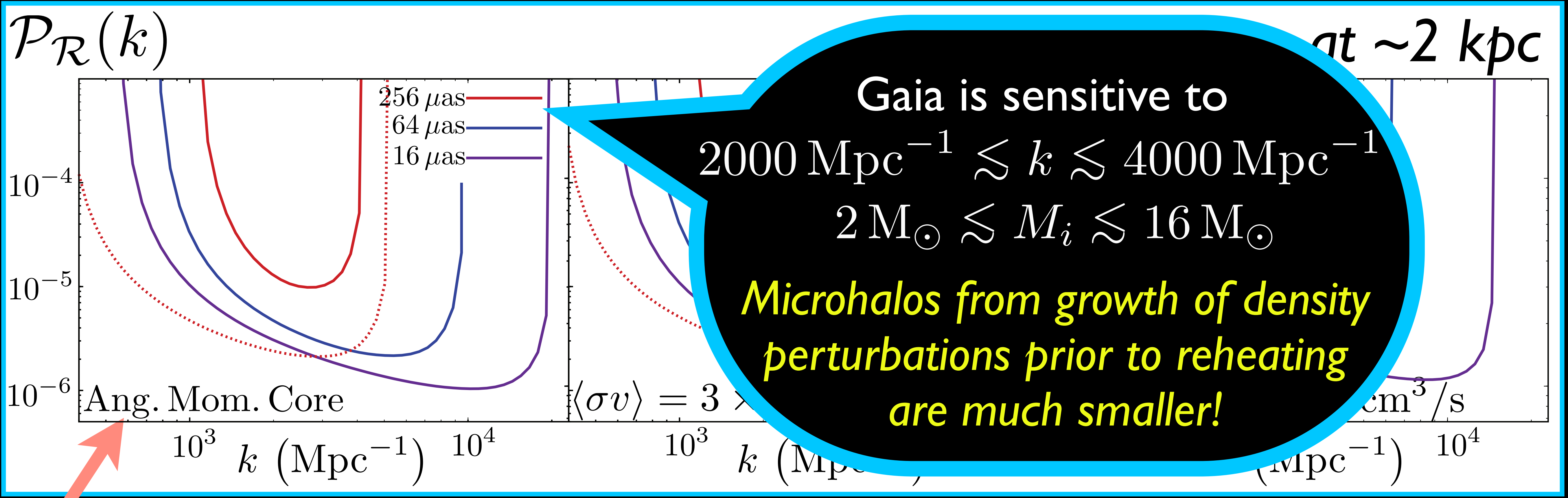


Gaia is sensitive to

$$2000\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 4000\,\mathrm{Mpc}^{-1}$$

$$2\,\mathrm{M}_\odot \lesssim M_i \lesssim 16\,\mathrm{M}_\odot$$

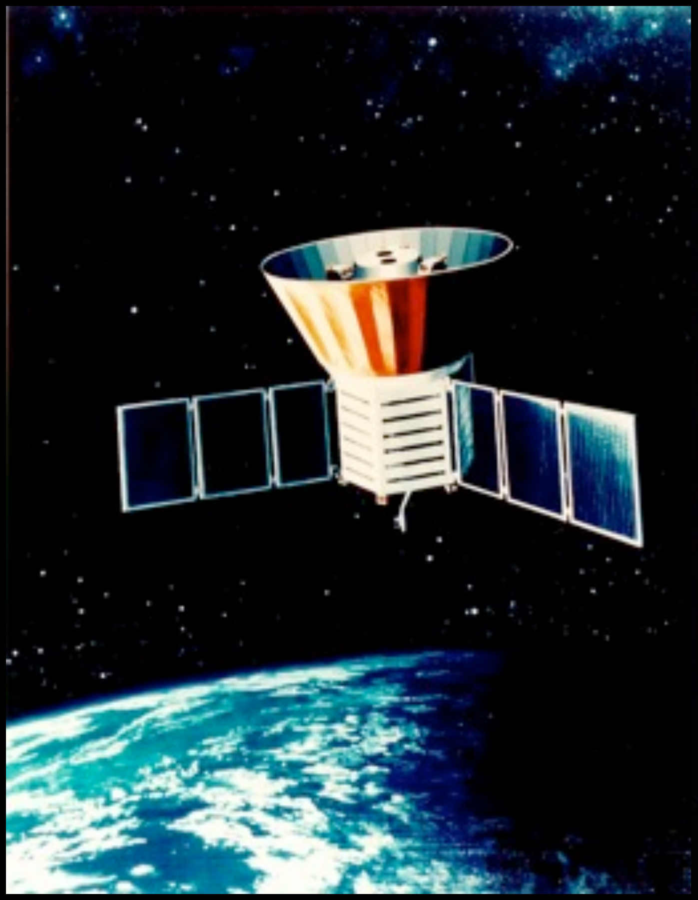
Microhalos from growth of density perturbations prior to reheating are much smaller!

Most conservative case: Fermi gives a stronger bound if DM self-annihilation diminishes lensing signal.

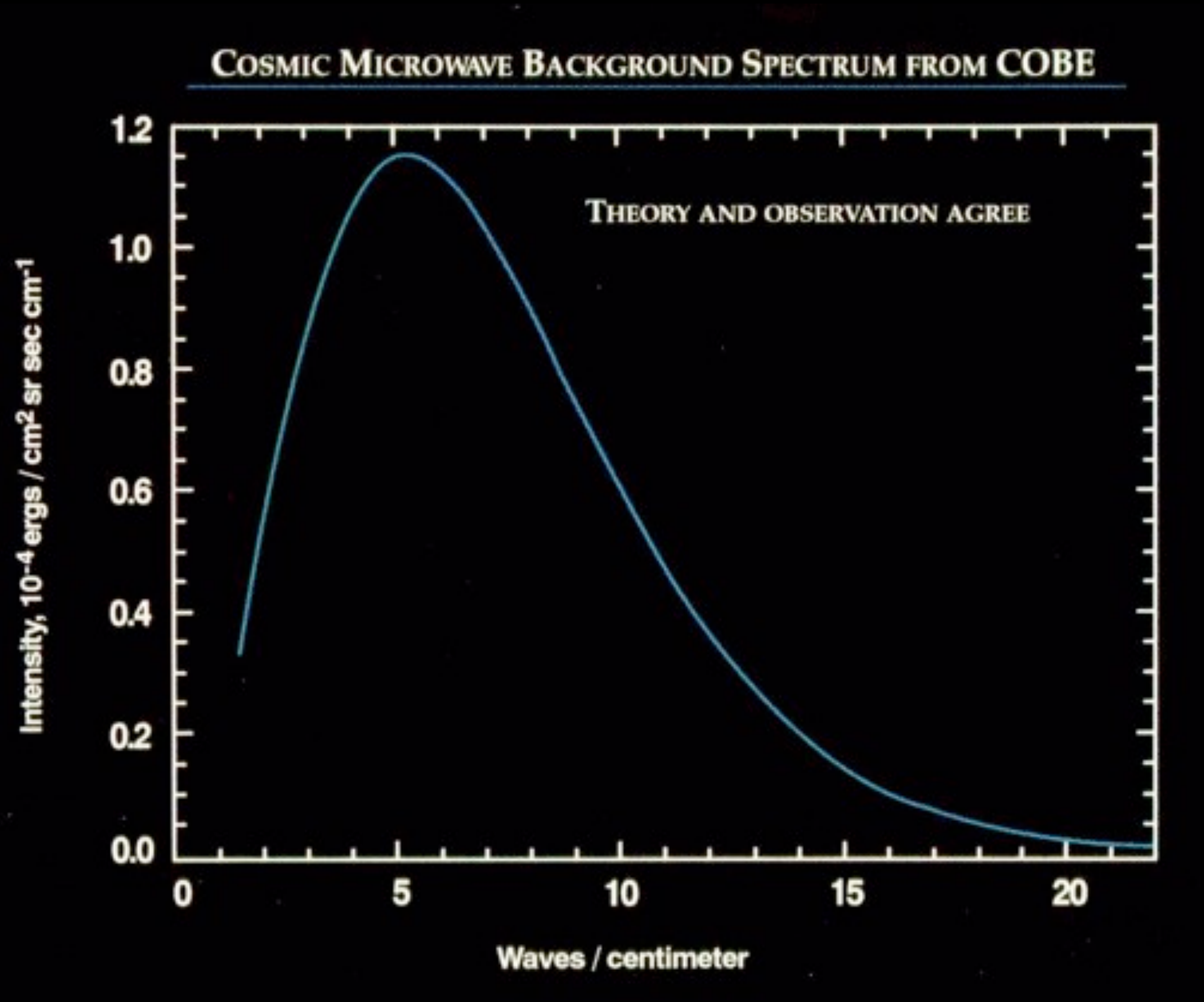
Part III

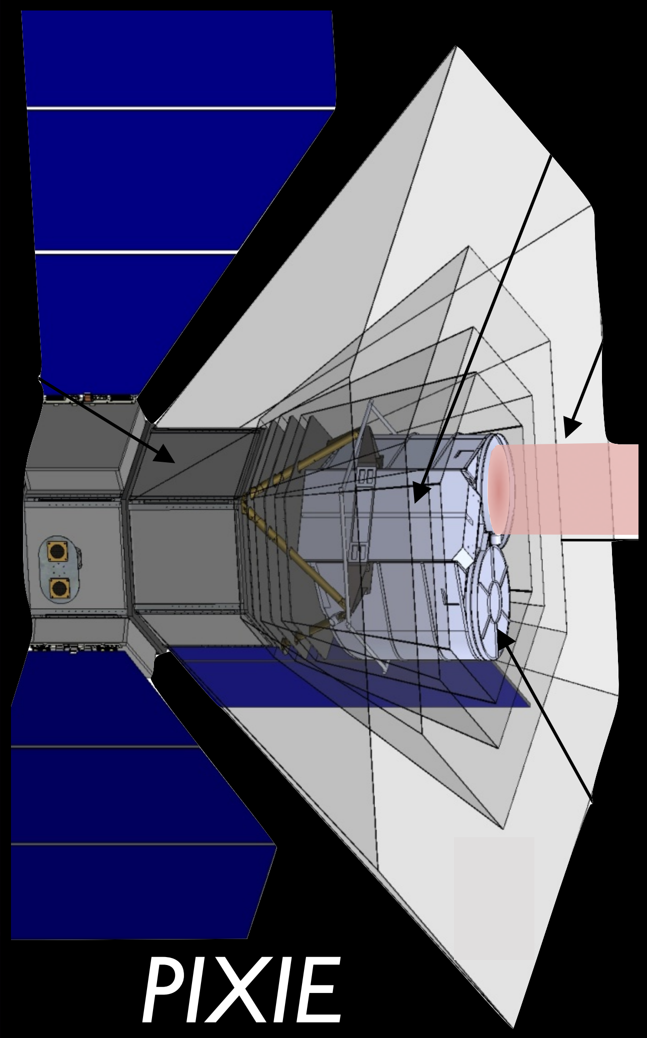
Probing the Primordial Power Spectrum with CMB Spectral Distortions

Chluba, Erickcek & Ben-Dayan 1203.2681



COBE FIRAS



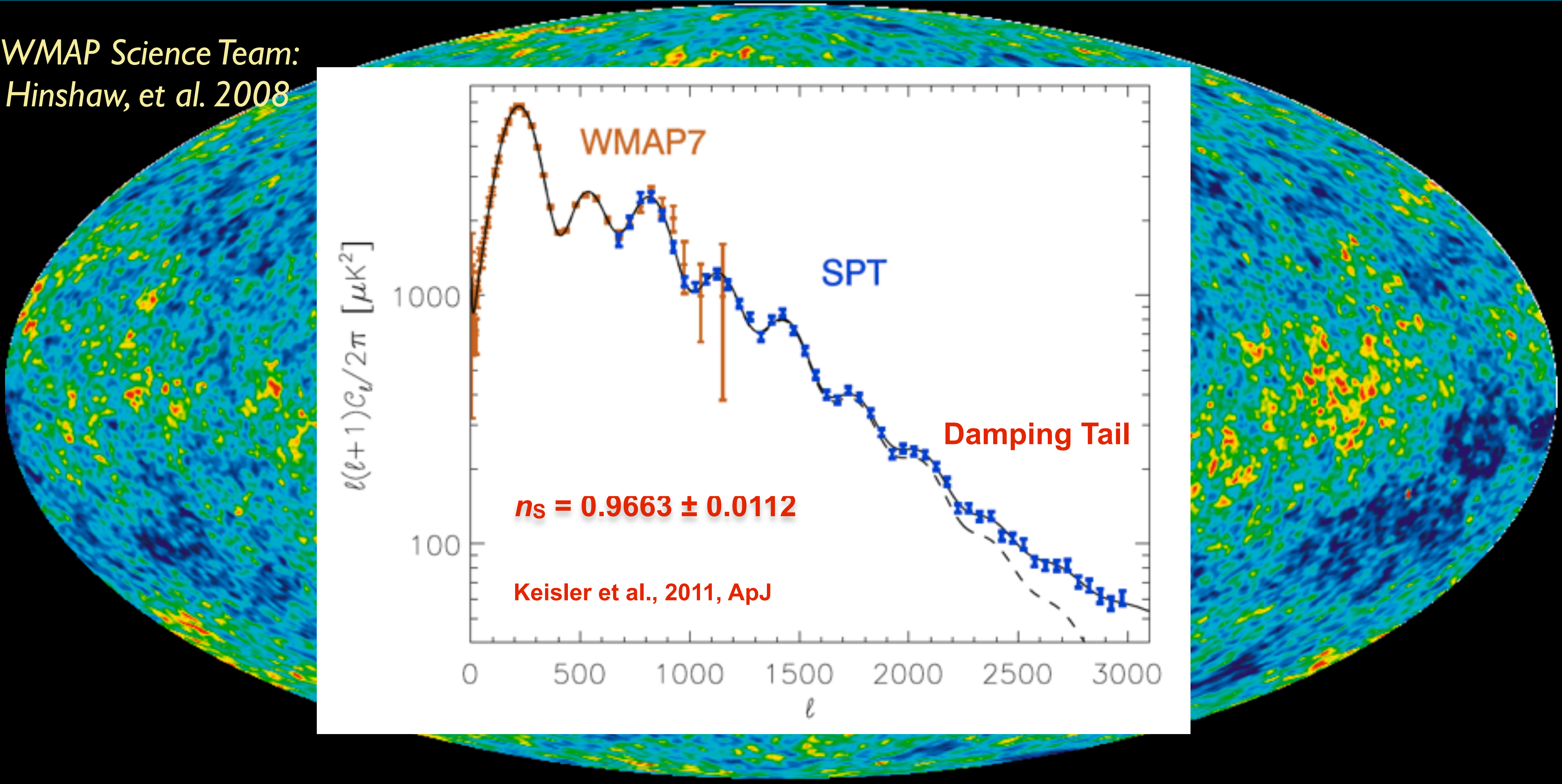


PIXIE

Kogut+ 2011

Spectral Distortions from Diffusion

WMAP Science Team: Hinshaw, et al. 2008



Damping Tail

$n_S = 0.9663 \pm 0.0112$

Keisler et al., 2011, ApJ

Spectral Distortions from Diffusion

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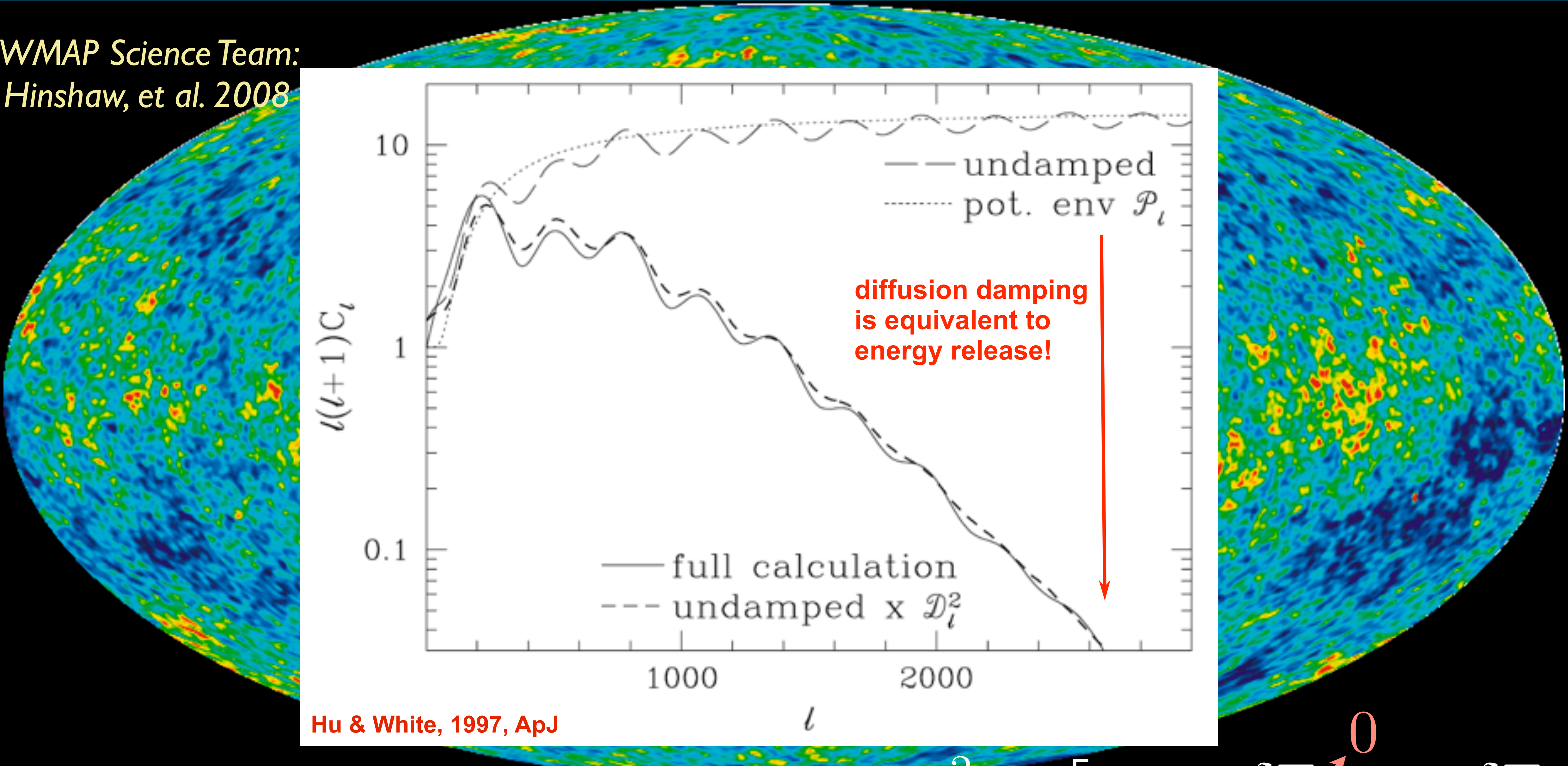


diffusion damping is equivalent to energy release!

Hu & White, 1997, ApJ

Energy stored in perturbations: $\langle\rho_\gamma\rangle = \frac{\pi^2}{15}\bar{T}^4\left[1 + \cancelto{0}{4\langle\frac{\delta T}{\bar{T}}\rangle} + 6\langle\frac{\delta T}{\bar{T}}\rangle^2\right]$

For diffusion after $z_\mu \simeq 2\times10^6$, CMB cannot re-thermalize!

Sunyaev & Zeldovich 1970; Hu, Scott, Silk 1994

$1/3$ of released energy sources spectral distortion. *Chluba, Khatri, Sunyaev 2012*

Spectral Distortions from Diffusion

Energy released when $k \simeq k_D(z) \simeq 4 \times 10^6 (1+z)^{3/2}\,\mathrm{Mpc}^{-1}$

- Modes with $50\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 10^4\,\mathrm{Mpc}^{-1}$ generate μ-distortions
- Modes with $k \lesssim 50\,\mathrm{Mpc}^{-1}$ dissipate at $z \lesssim 5 \times 10^4$, generating y-distortions

Spectral distortions yield an integral constraint on the primordial power spectrum:

$$\mu \approx 2.2 \int_{k_{\min}}^{\infty} \mathcal{P}_\zeta(k) \left[\exp\left(-\frac{k\,\mathrm{Mpc}}{5400}\right) - \exp\left(-\left[\frac{k\,\mathrm{Mpc}}{31.6}\right]^2\right)\right] \mathrm{d}\ln k$$

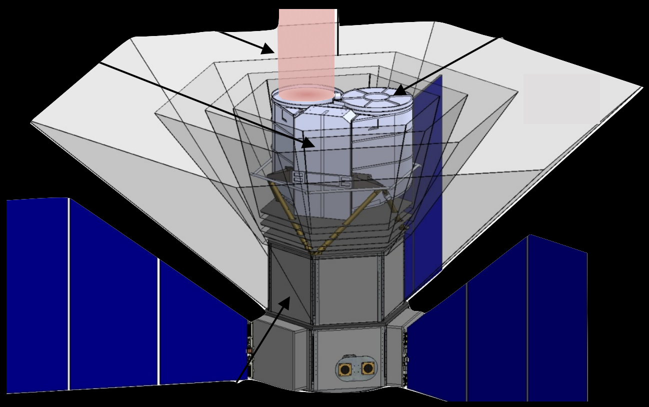
$$y \approx 0.4 \int_{k_{\min} = 1\,\mathrm{Mpc}^{-1}}^{\infty} \mathcal{P}_\zeta(k) \exp\left(-\left[\frac{k\,\mathrm{Mpc}}{31.6}\right]^2\right) \mathrm{d}\ln k$$

COBE FIRAS

$\mu \lesssim 9 \times 10^{-5}$

$y \lesssim 1.5 \times 10^{-5}$

Fixsen et al. 1996



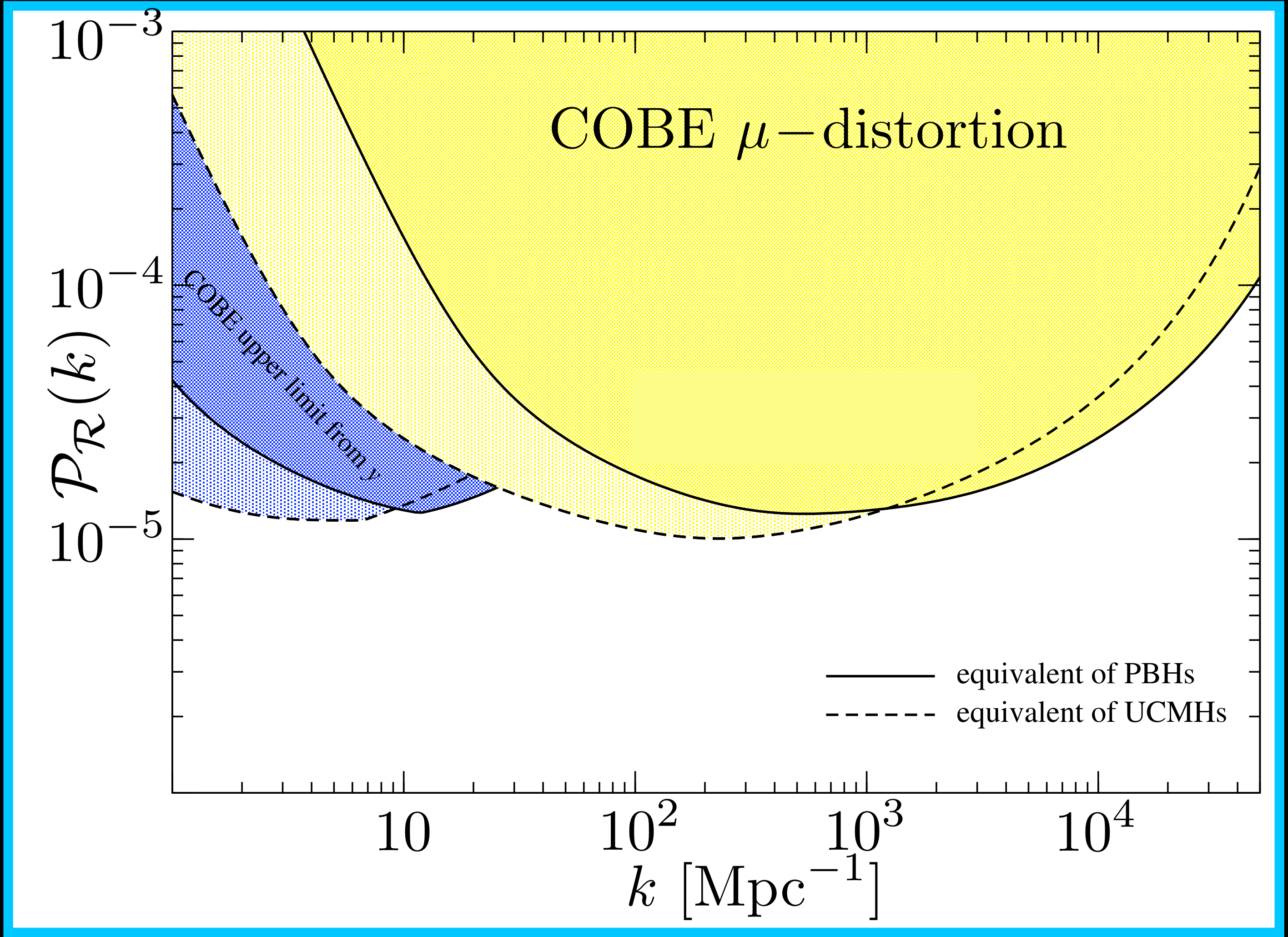
PIXIE

$\mu \lesssim 2 \times 10^{-8}$

$y \lesssim 4 \times 10^{-9}$

Kogut et al. 2011

Constraining Inflation



Comparison to bounds from PBHs and UCMHs

- assume "local scale invariance"
- apply the same minimal assumption when computing bounds from spectral distortions

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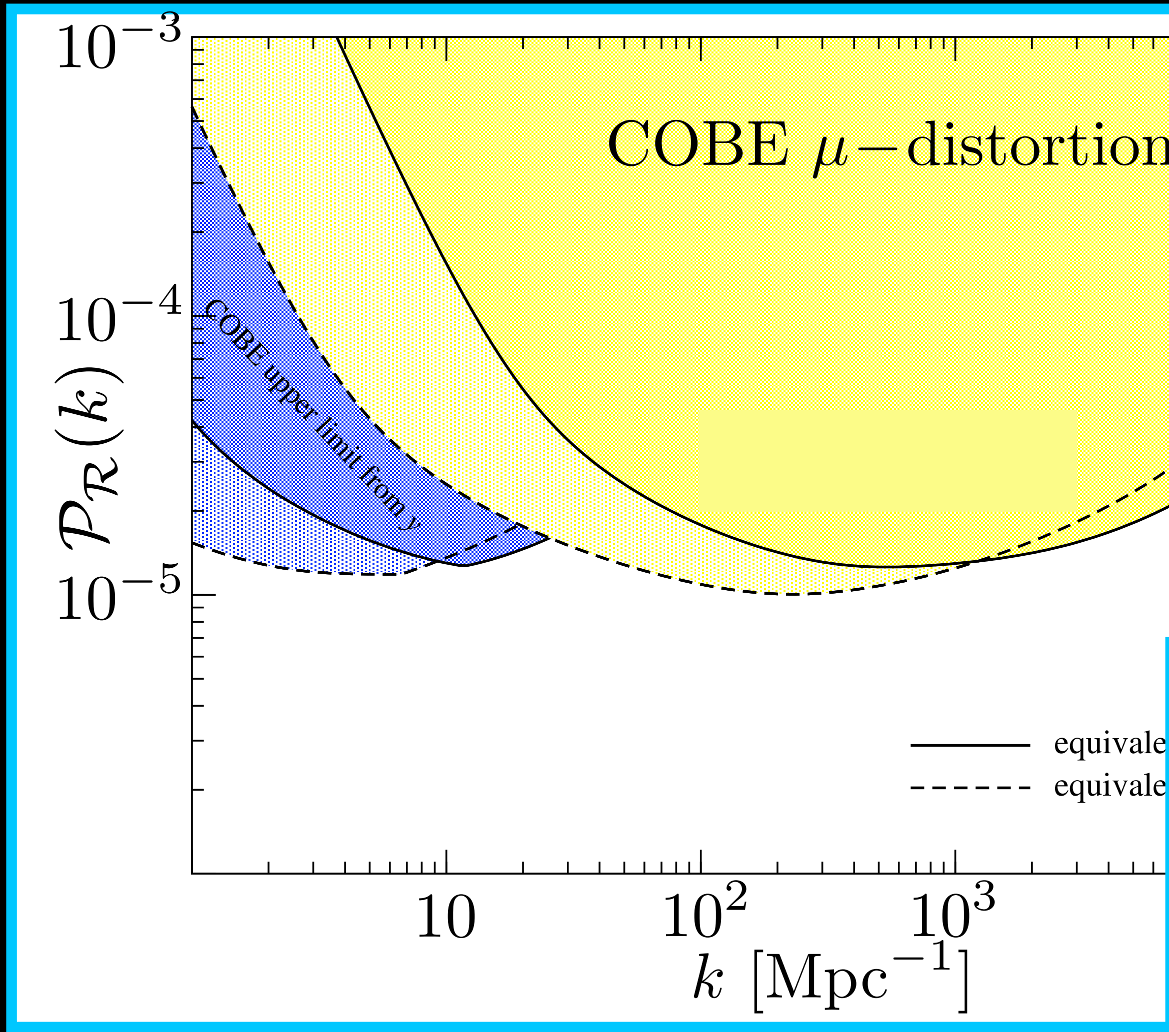

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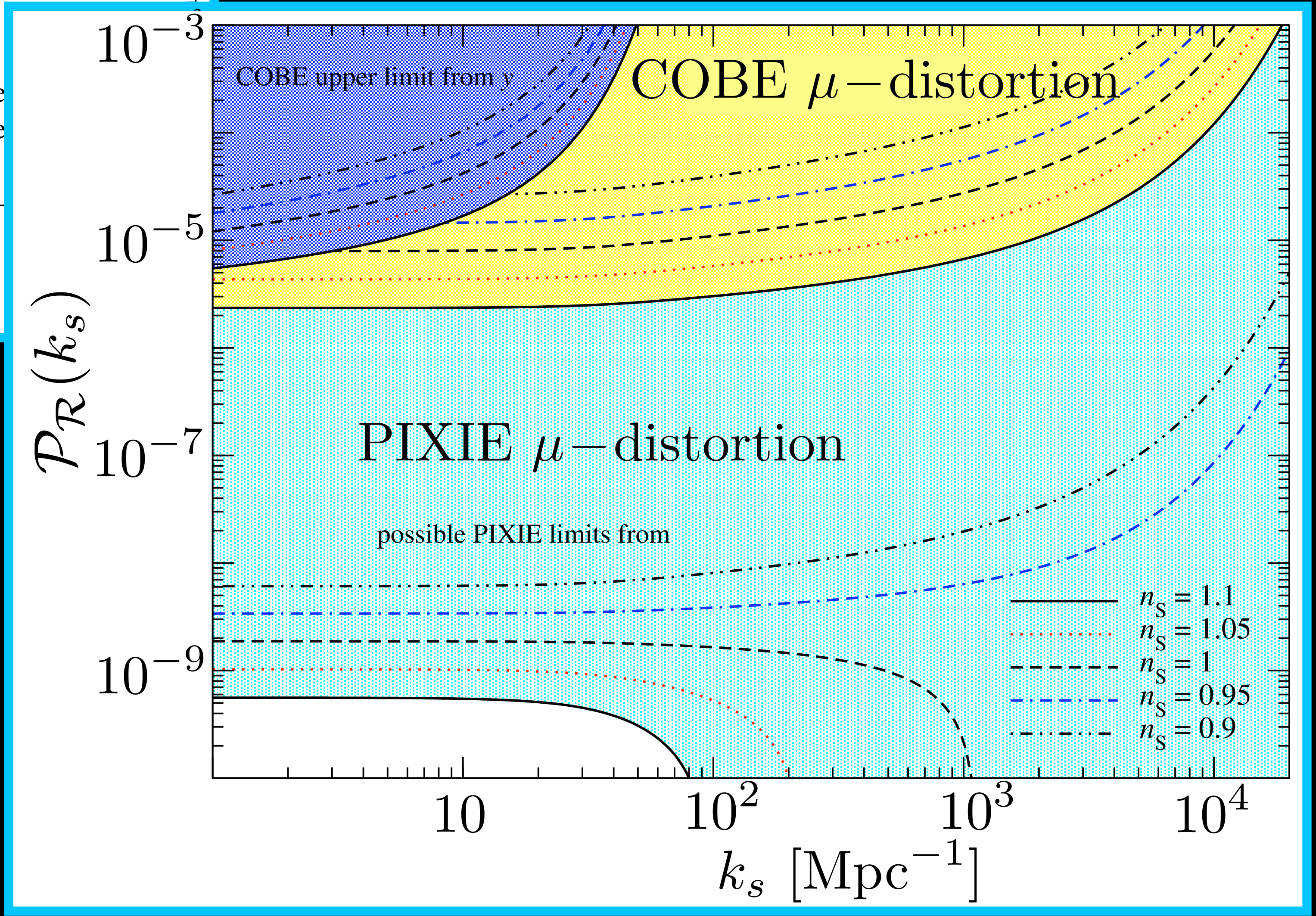
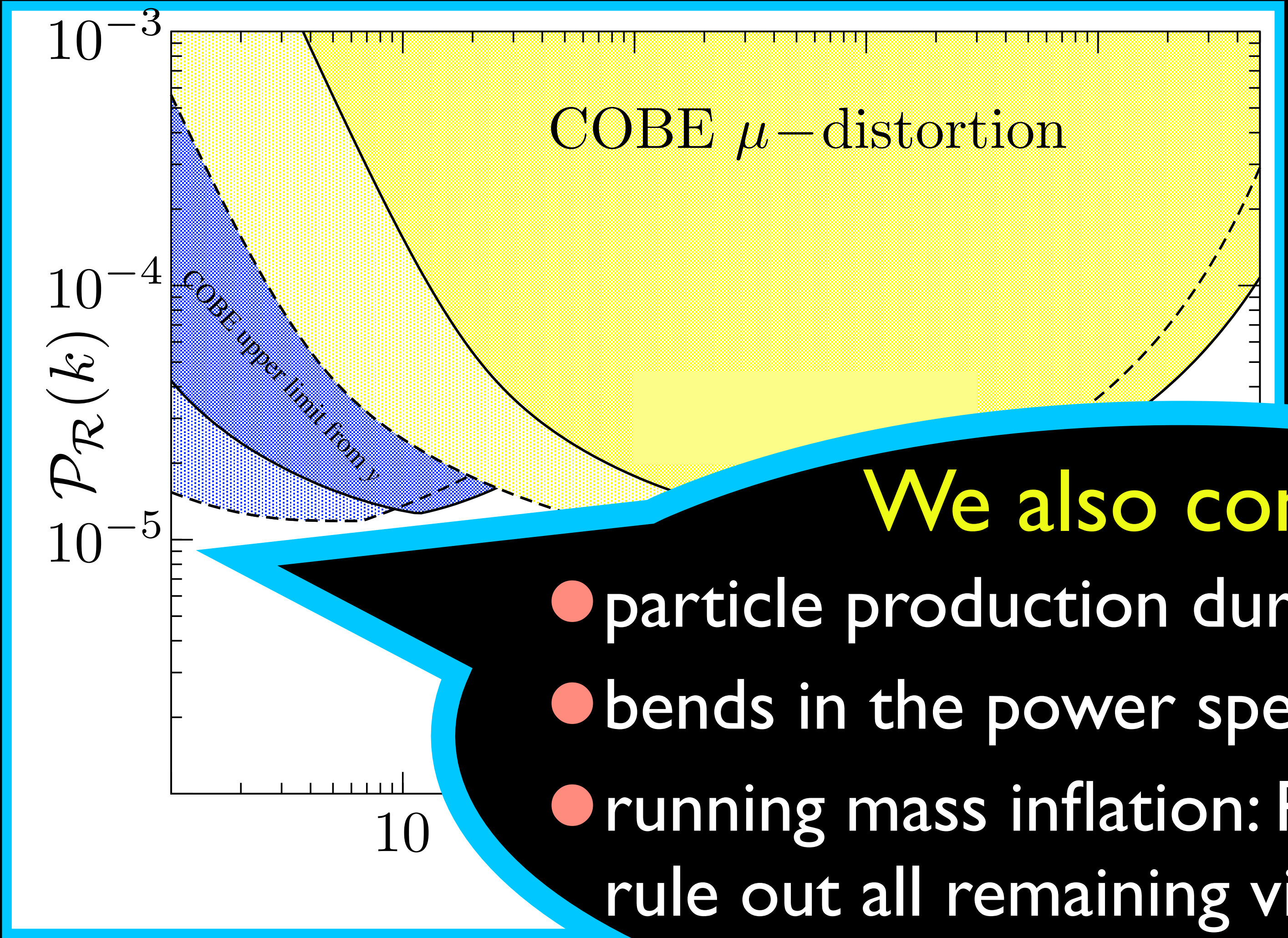


Constrain a step in the primordial power spectrum

- match CMB on large scales
- different amplitude for $k \geq k_s$
- constant spectral index

Constraining Inflation



Comparison to bounds from PBHs and UCMHs

- assume “local scale invariance”
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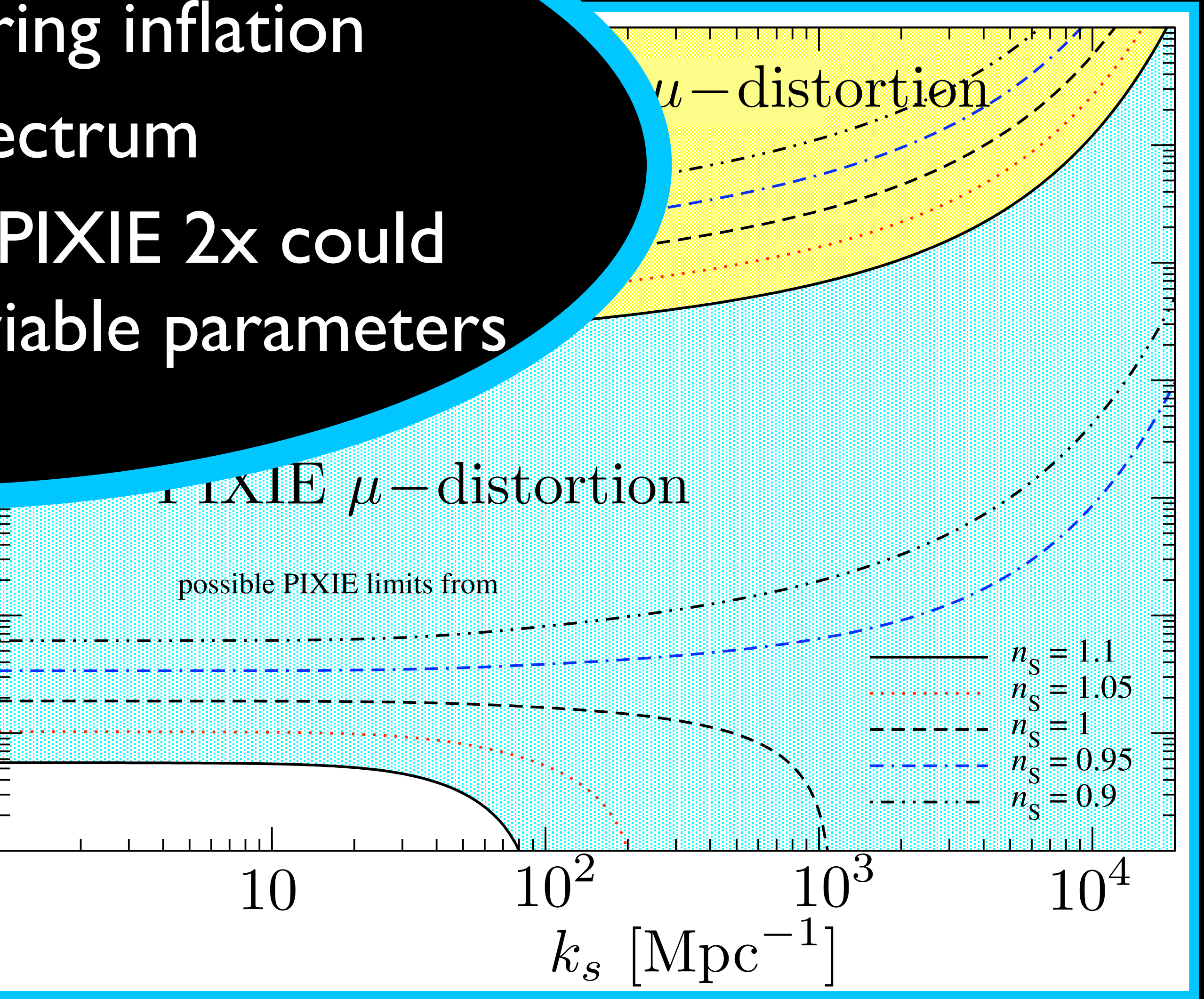
hen computing bounds from
tortions

We also consider

- particle production during inflation
- bends in the power spectrum
- running mass inflation: PIXIE 2x could rule out all remaining viable parameters



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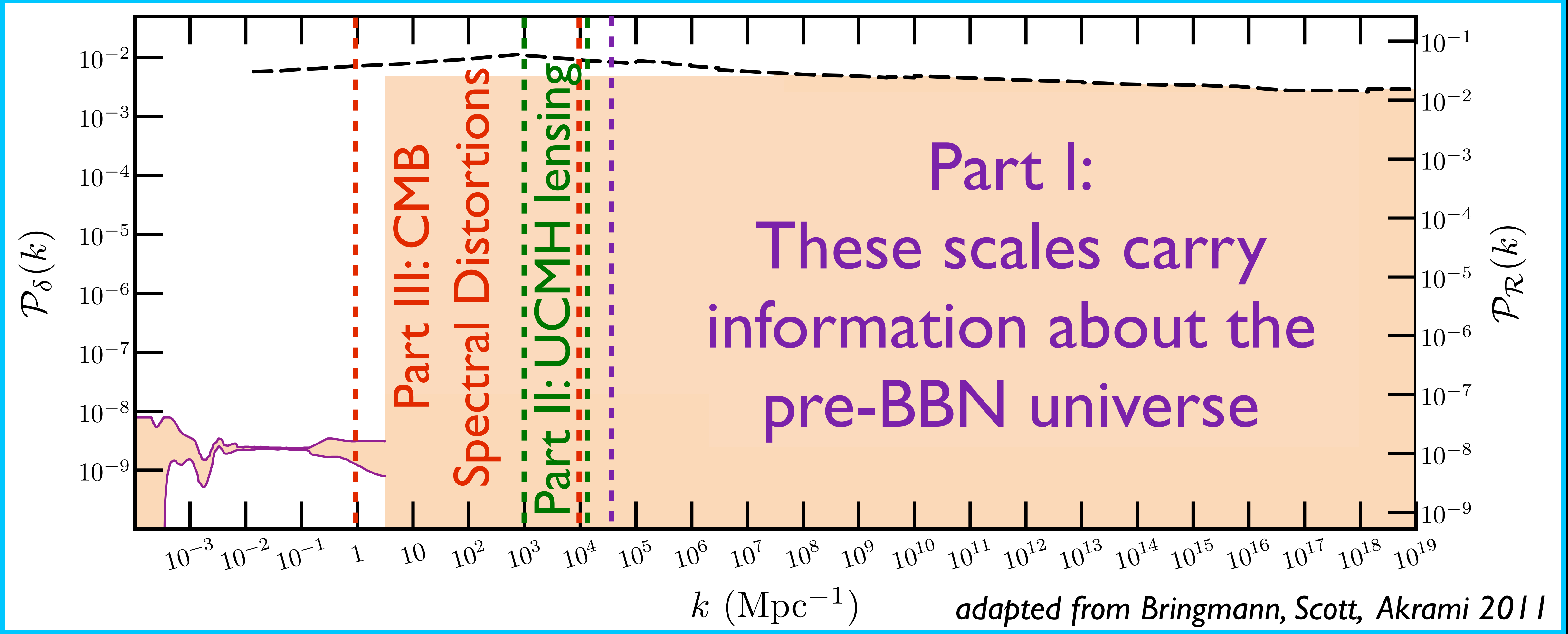
- constant spectral index

Summary: Small Scales Probe the EU

Part I: An early "matter" dominated era can produce numerous microhalos. *AE & Sigurdson PRD 84, 083503 (2011)*

Part II: Astrometric microlensing by UCMHs: using Gaia, constrain $\mathcal{P}_{\mathcal{R}}(k \simeq 2700\,\mathrm{Mpc}^{-1}) \lesssim 10^{-5}$ *Li, AE & Law PRD 86, 043519 (2012)*

Part III: Constrain $1\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 10^4\,\mathrm{Mpc}^{-1}$ with CMB spectral distortions *Chluba, AE & Ben-Dayan arXiv: 1203.2681, to appear in ApJ*



adapted from Bringmann, Scott, Akrami 2011