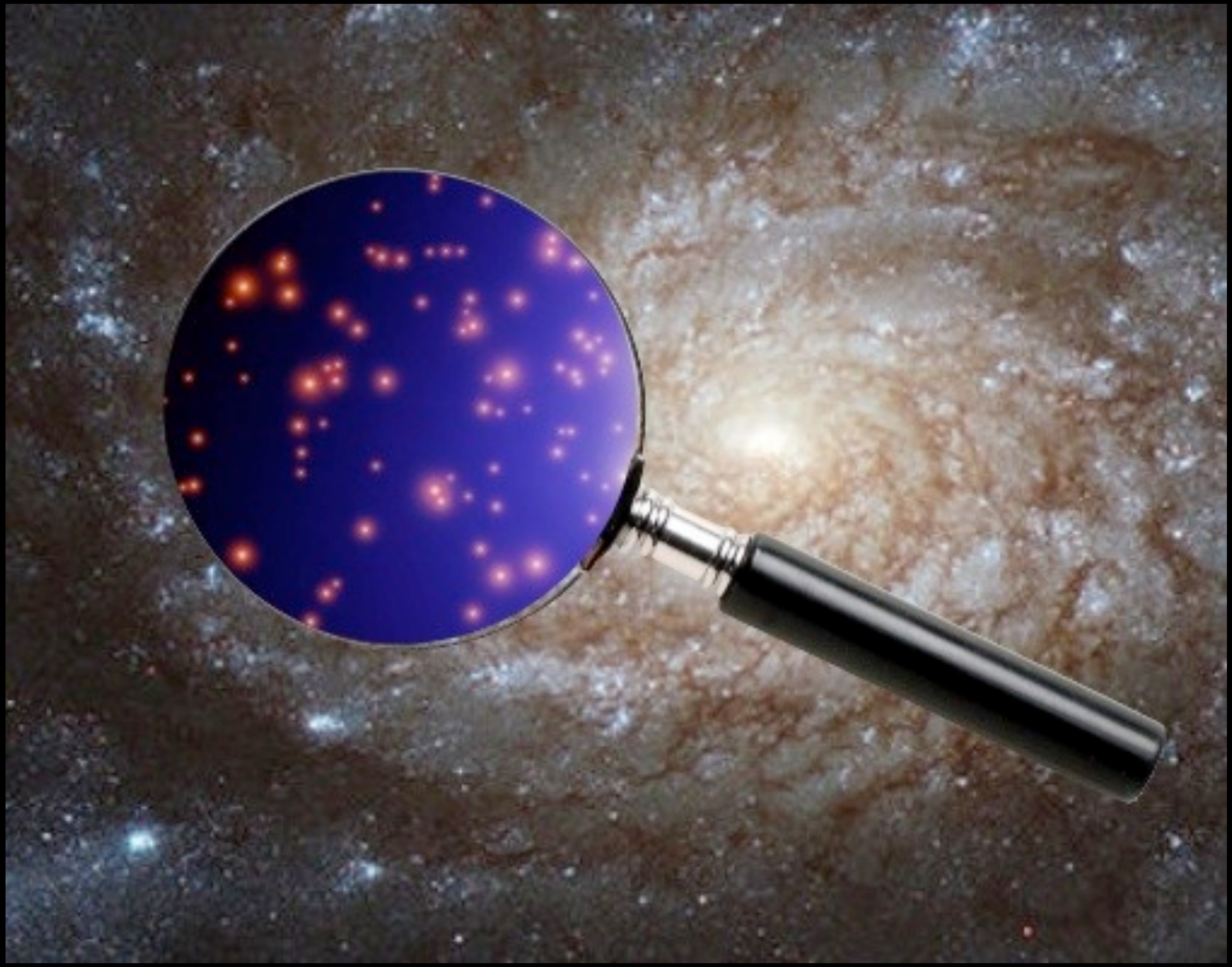
# The Power of Small Scales to Probe Inflation

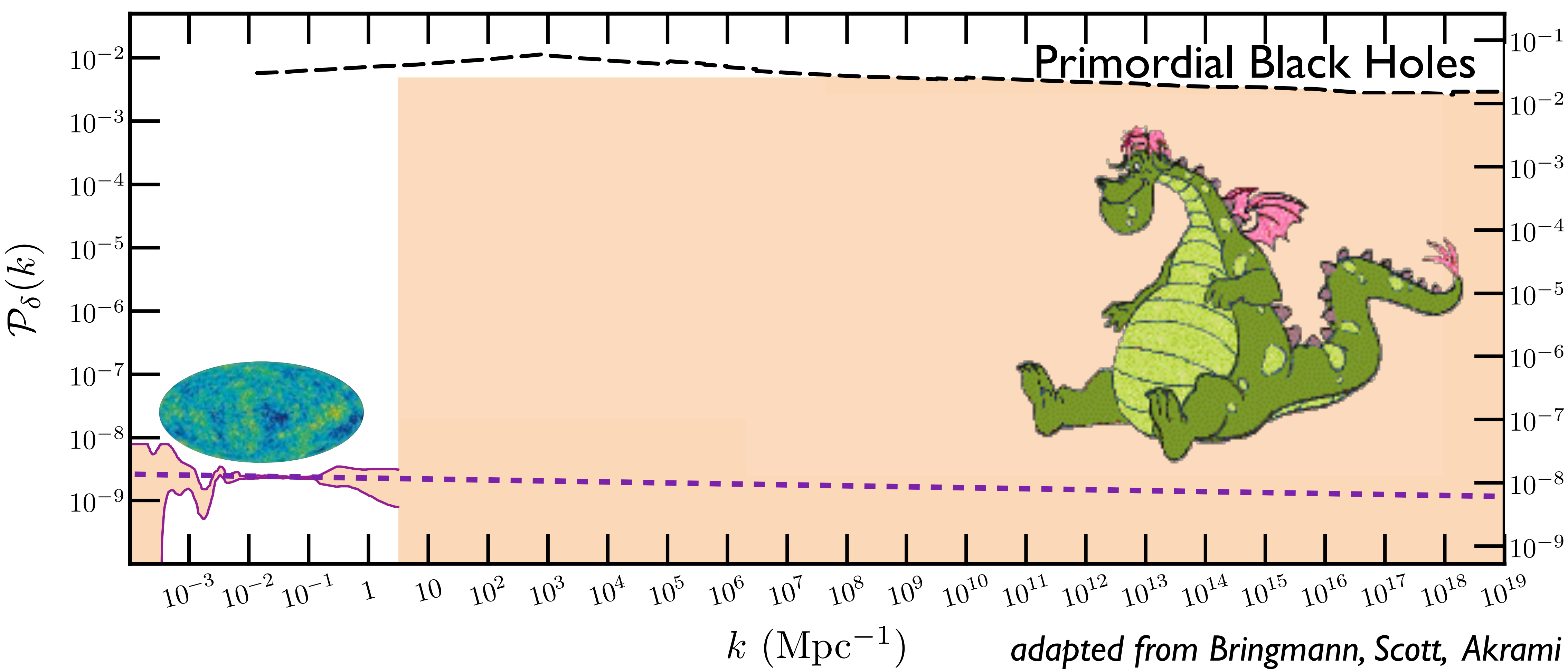


Adrienne Erickcek
CITA
Perimeter Institute

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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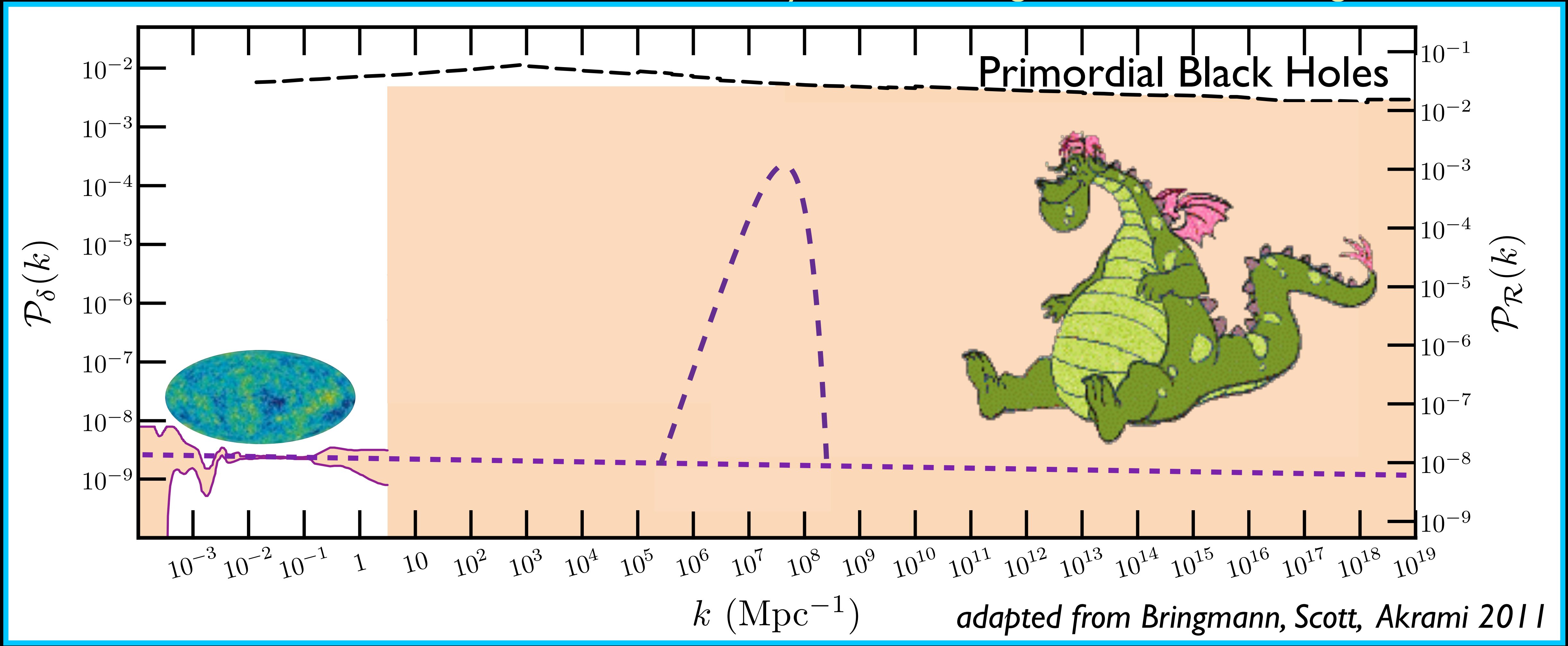

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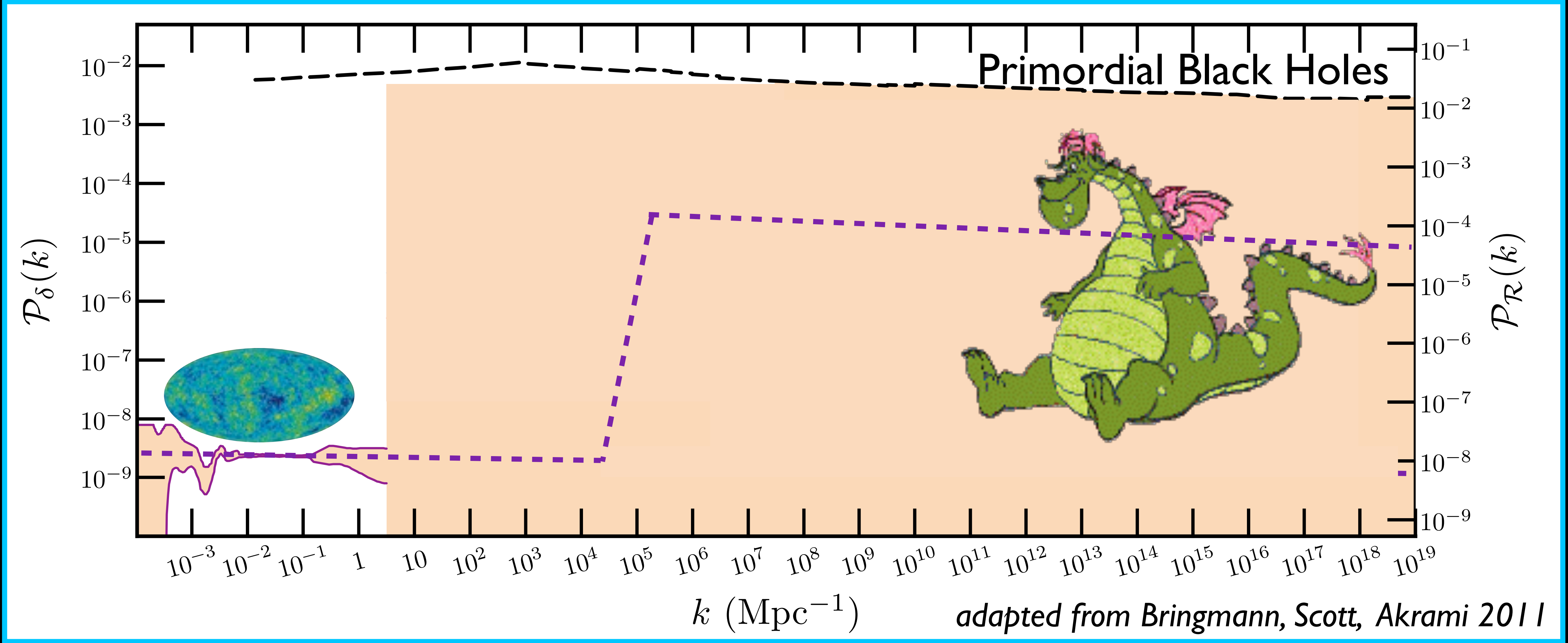

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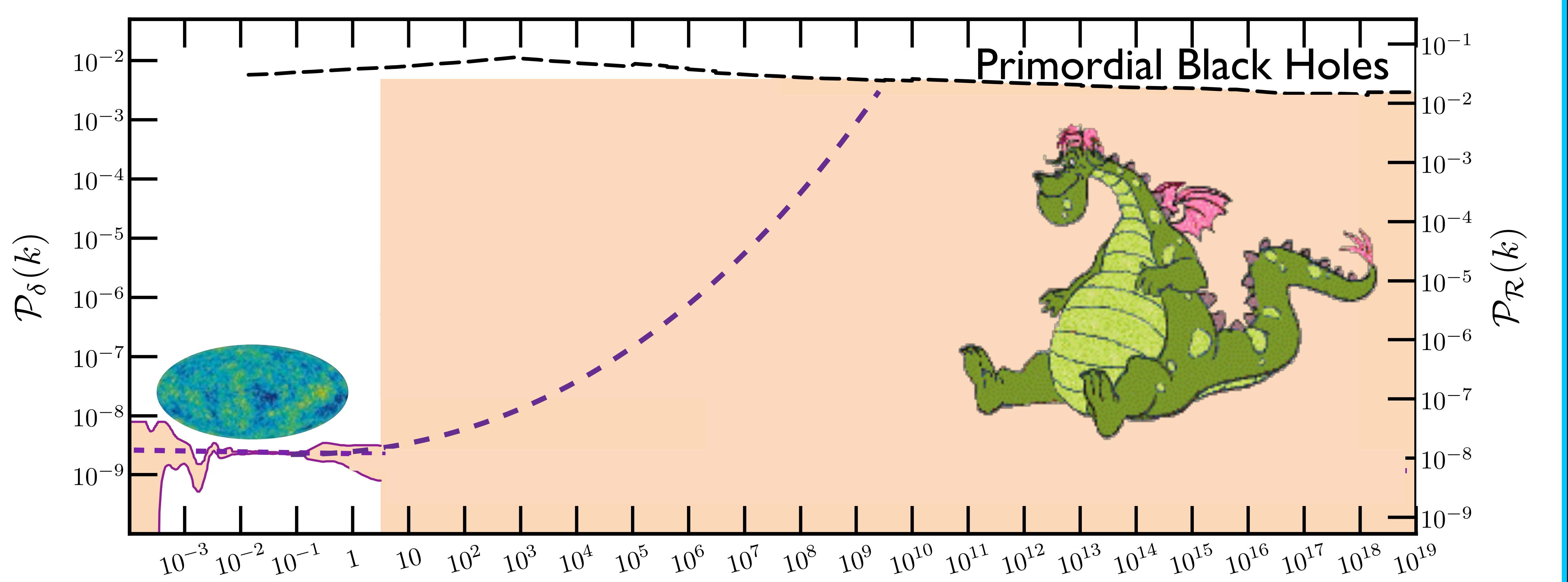

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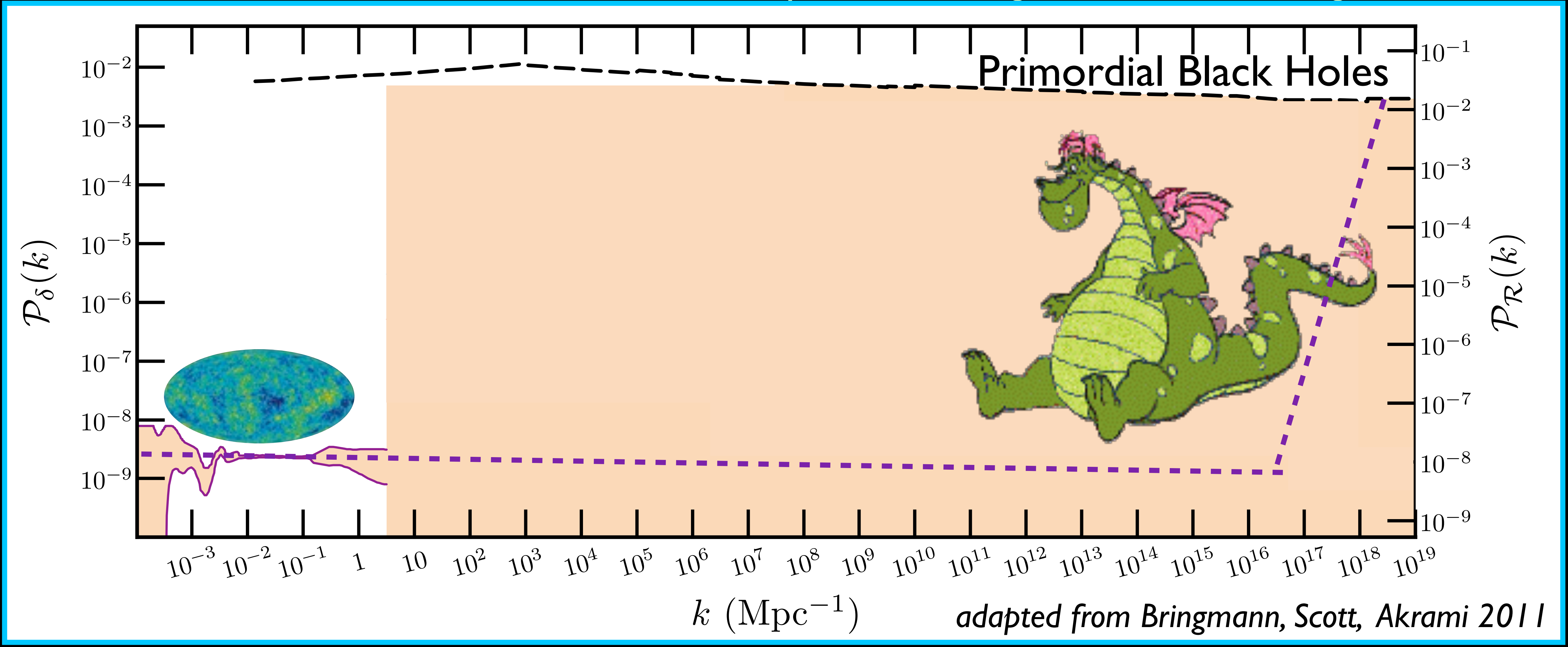


# Outline

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

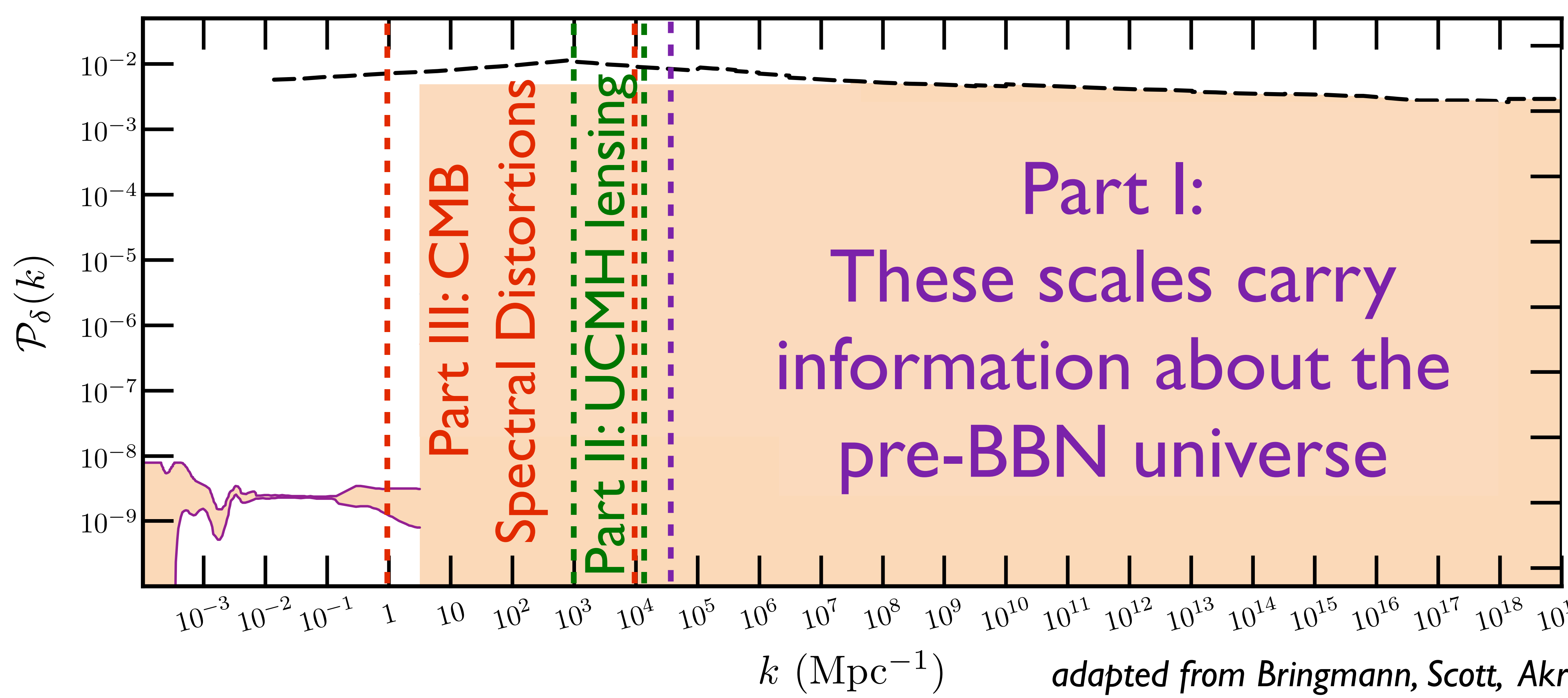
*Collaborators: Kris Sigurdson (UBC)*

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)*



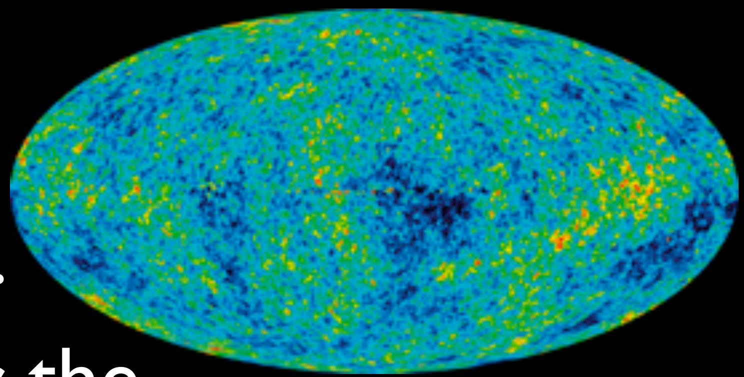

*adapted from Bringmann, Scott, Akrami 2011*

# What Happened Before BBN?

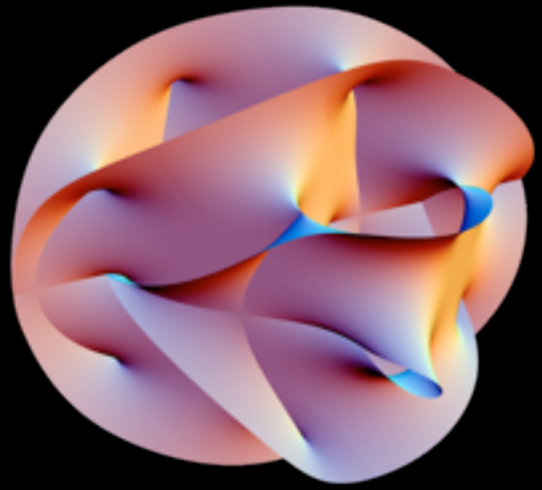
The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology's crowning achievements.

- 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.

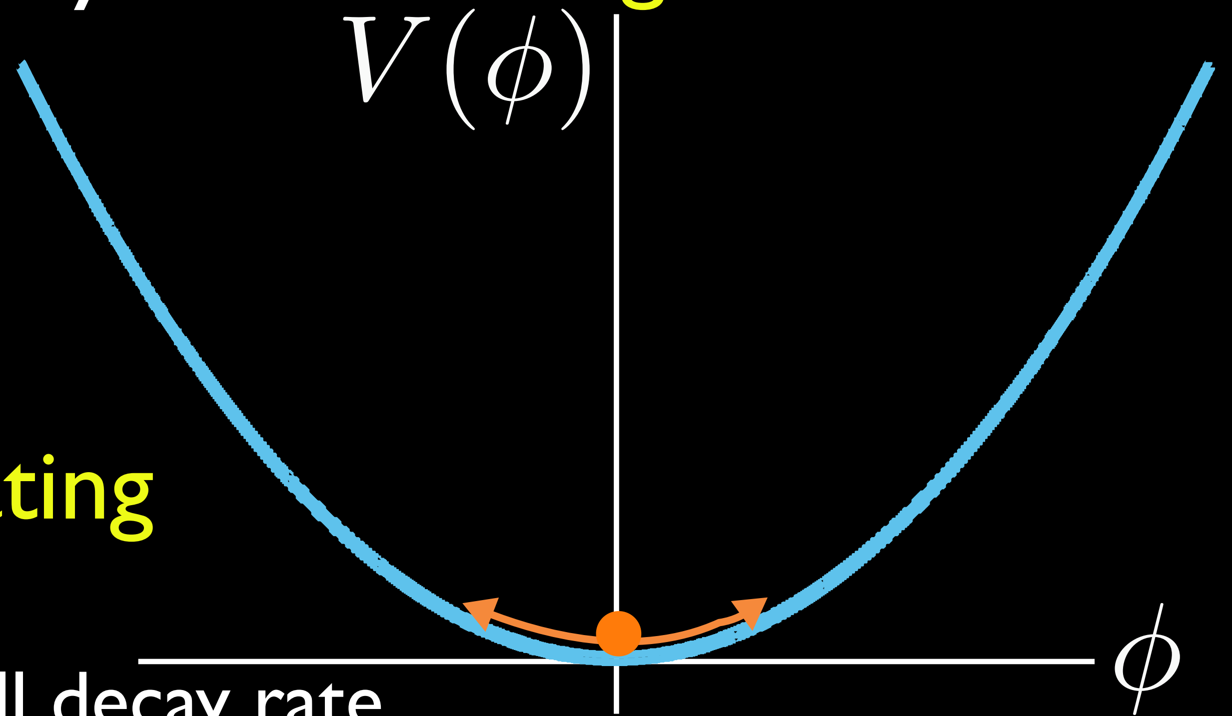


*Carlos, Casas, Quevedo, Roulet 1993*
*Banks, Kaplan, Nelson 1994*
*Acharya, Kane, Kuflik 2010*

# 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: $T_{\rm RH} \gtrsim 3$ 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 $\delta_\phi \propto a$

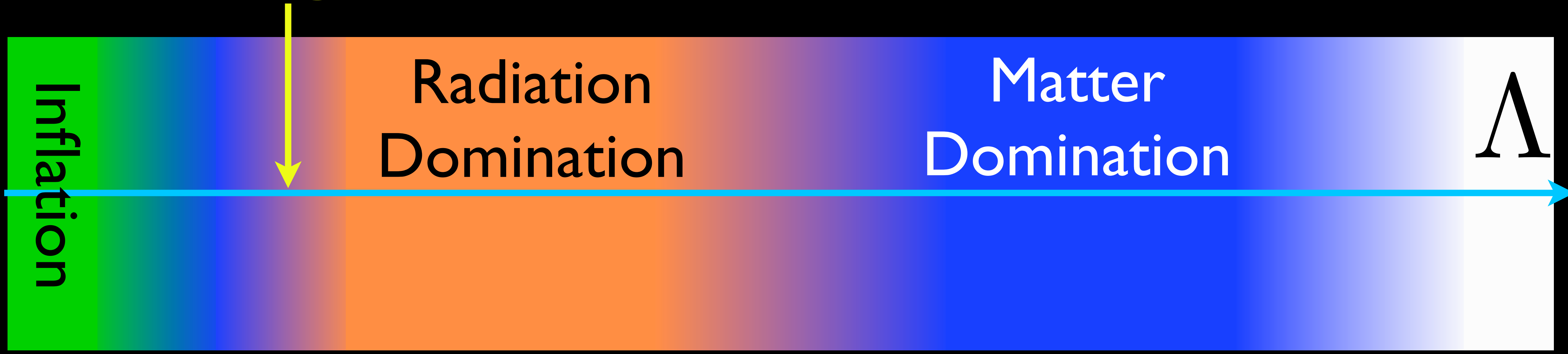
*Jedamzik, Lemoine, Martin 2010; Easther, Flauger, Gilmore 2010*

***What happens to these perturbations after reheating?***

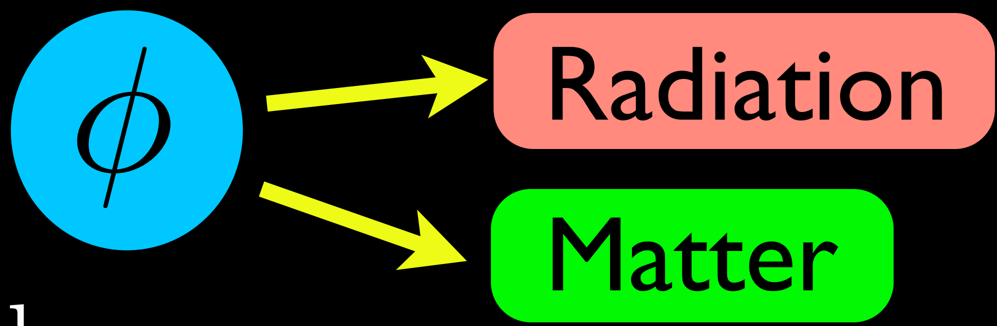
# *Microhalos from Reheating*

Erickcek & Sigurdson PRD 84, 083503 (2011)

***Reheating*** $T_{\rm RH} \gtrsim 3\ {\rm MeV}$



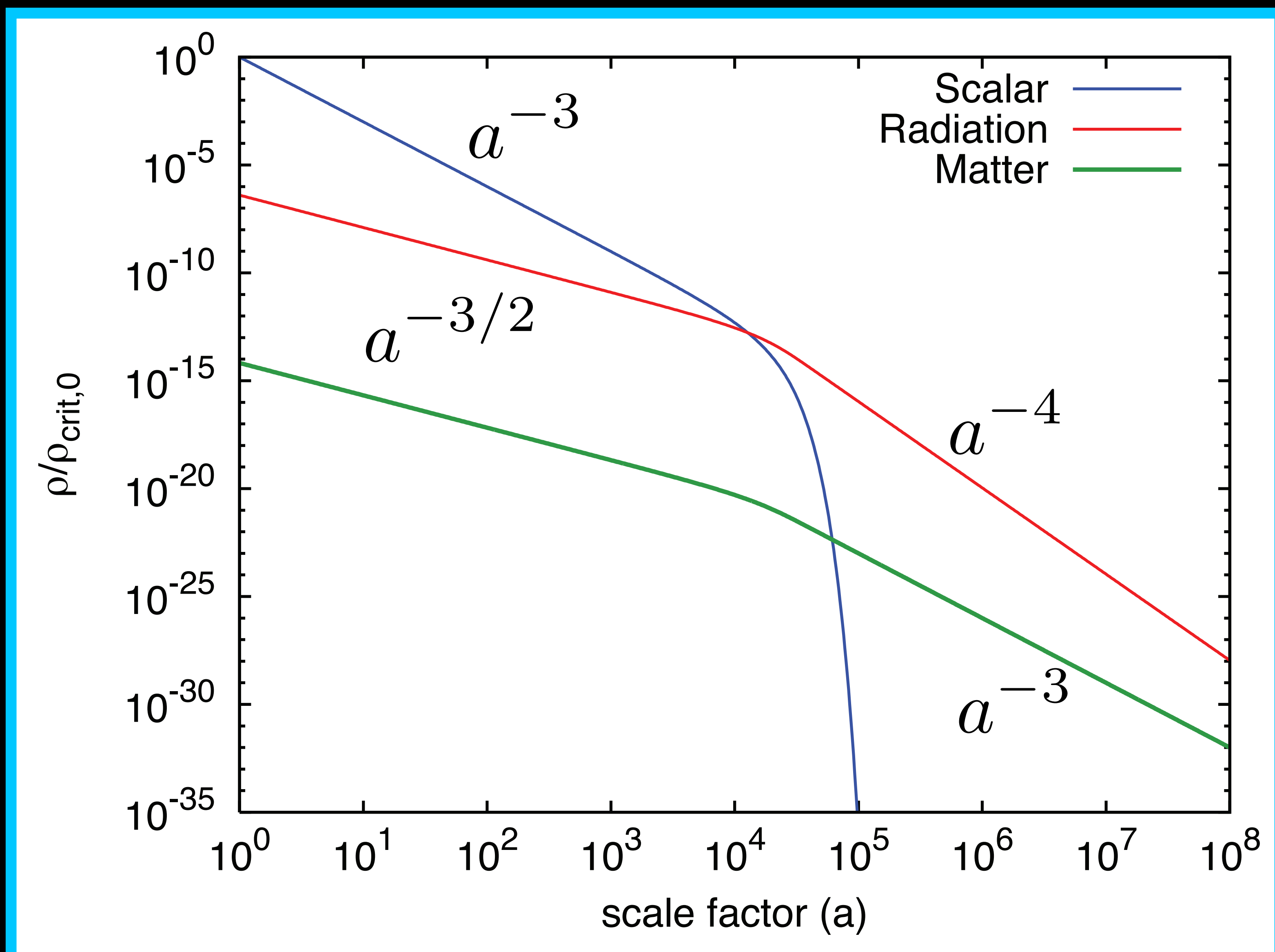
# Perturbative Scalar Decay




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

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

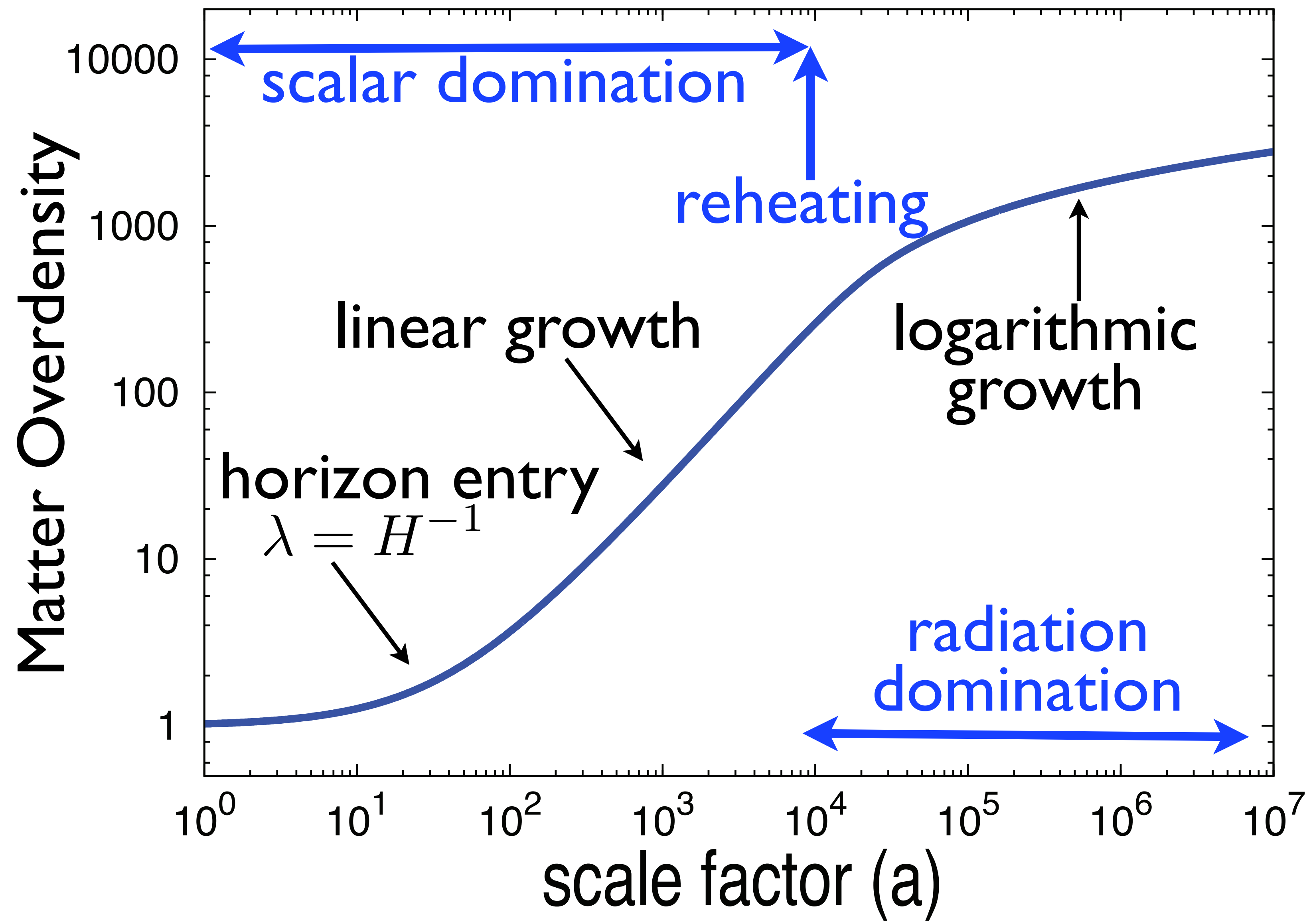
$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$



# The Matter Perturbation

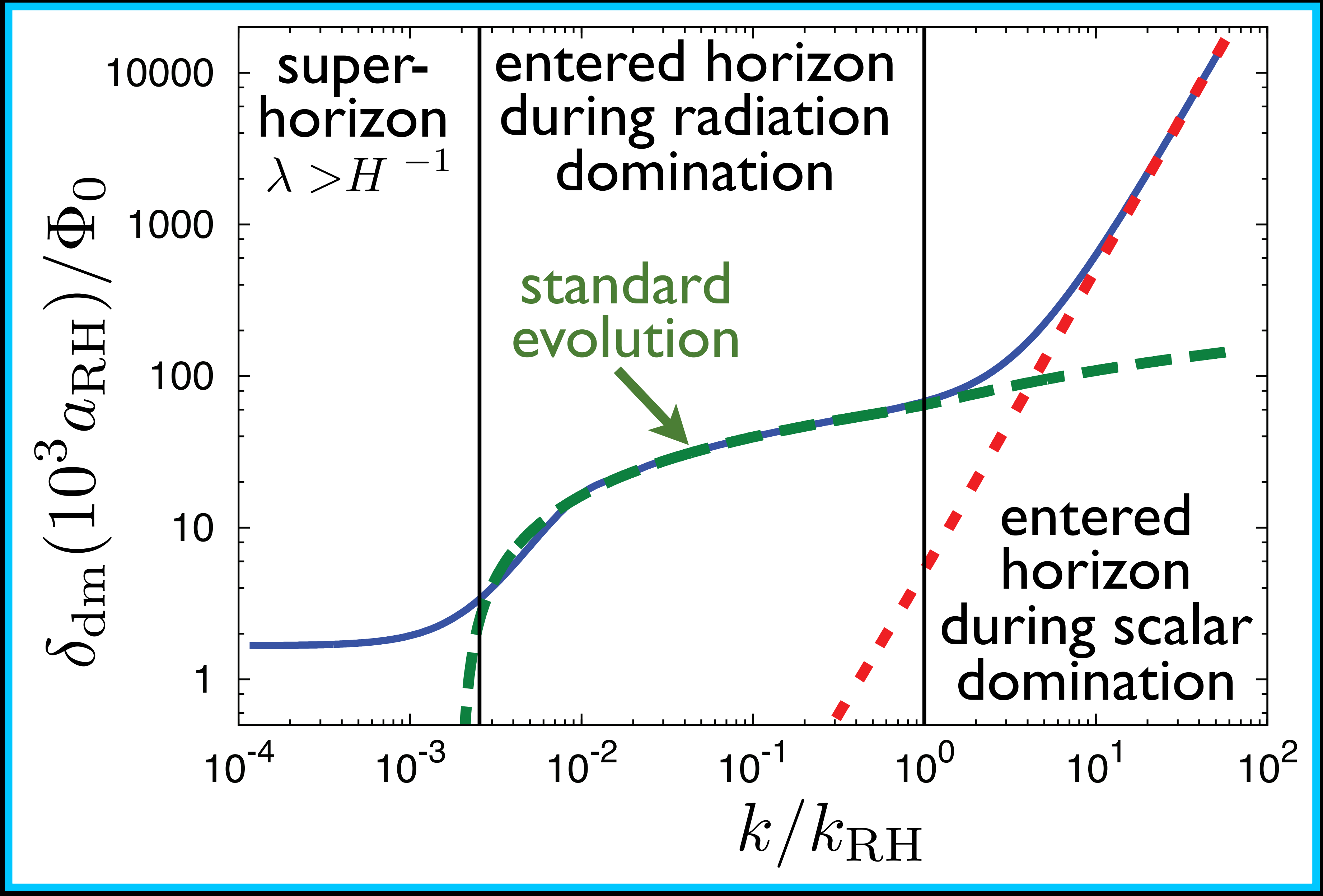
Scalar domination affects the growth of density fluctuations.

Evolution of the Matter Density Perturbation



# The Matter Perturbation

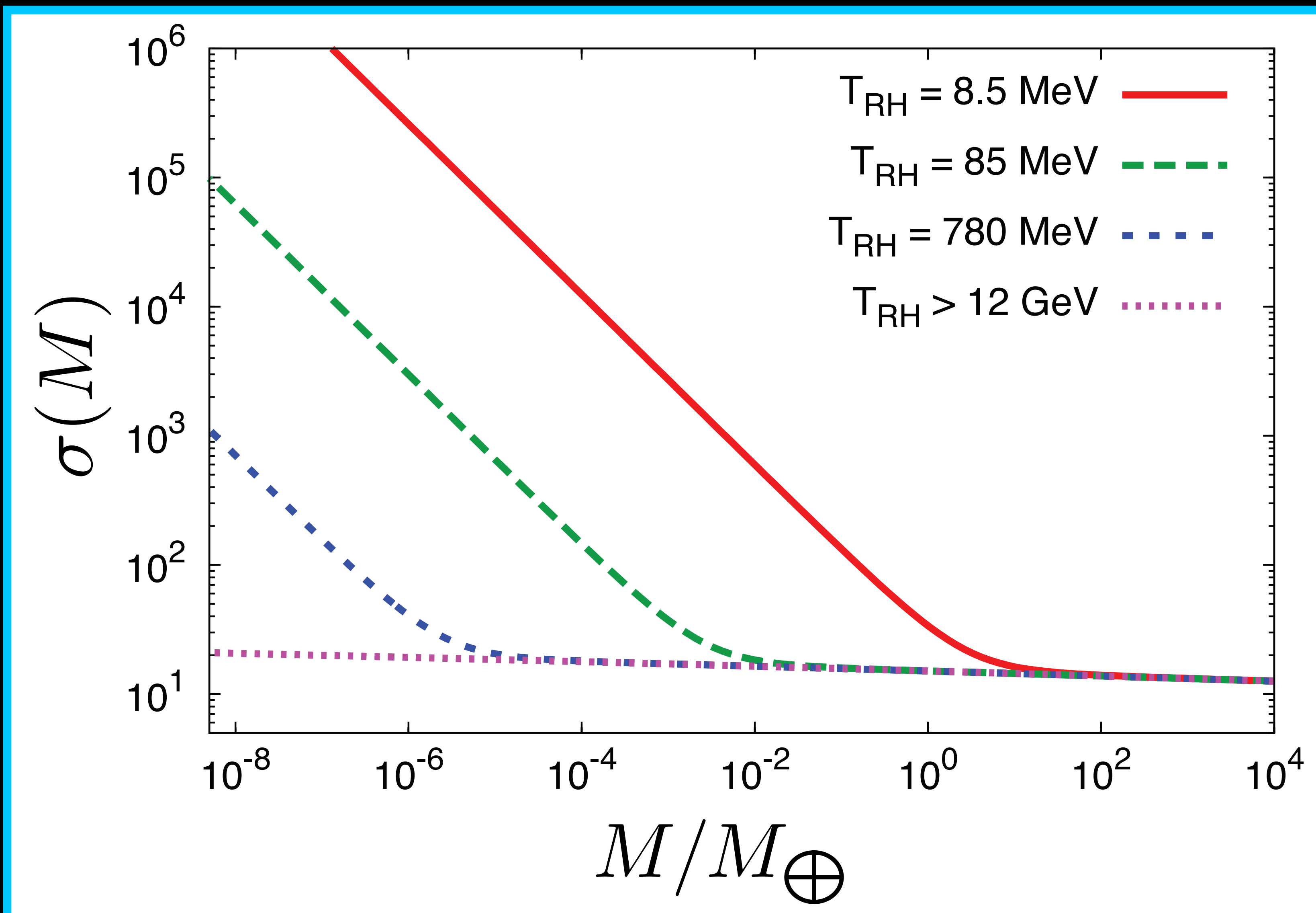
## The Matter Density Perturbation during Radiation Domination




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

Wavenumber of mode that enters horizon at reheating

# RMS Density Fluctuation

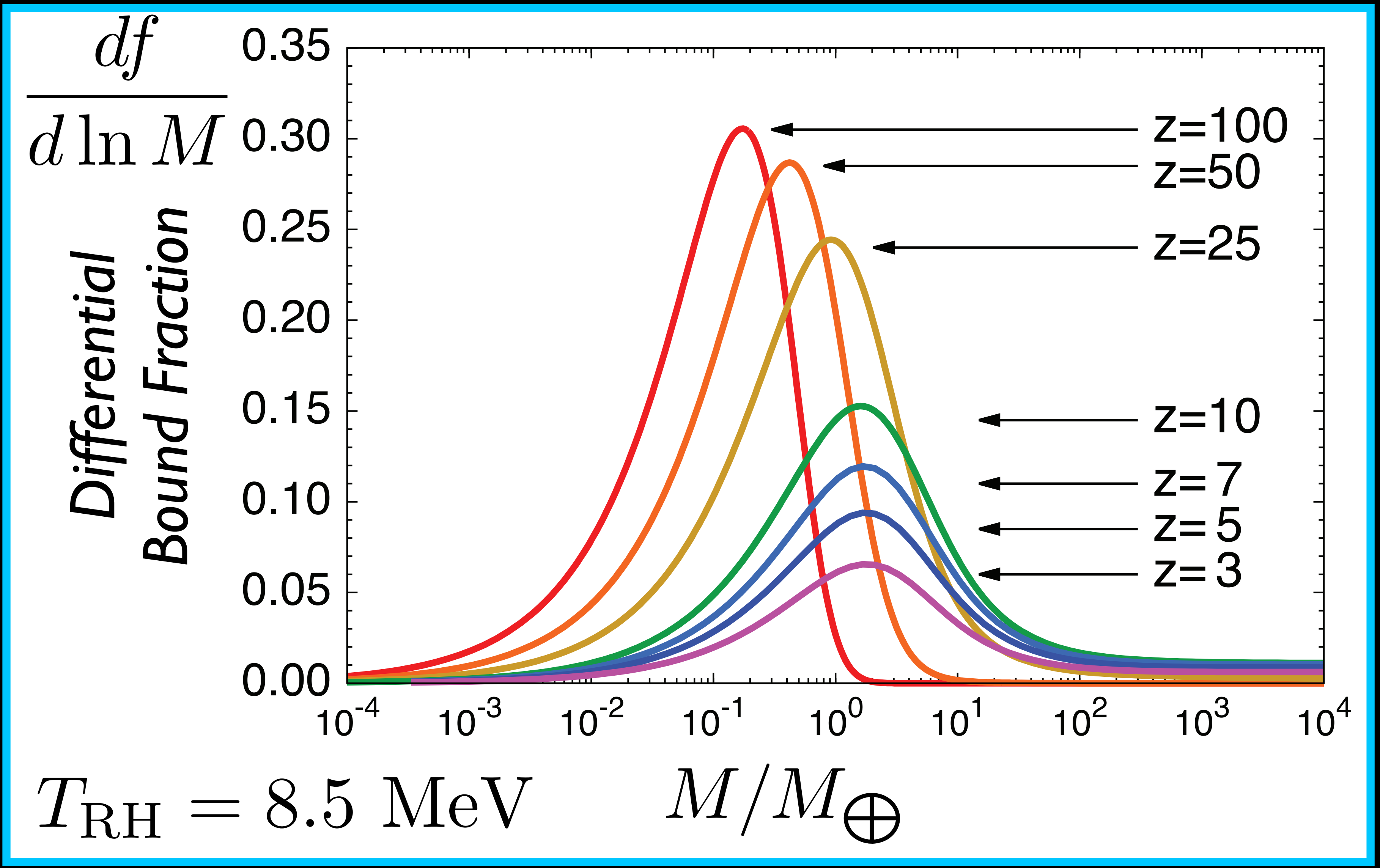



- Enhanced perturbation growth affects scales with $R \lesssim k_{\rm RH}^{-1}$
- Define $M_{\rm RH}$ to be dark matter mass within this comoving radius.

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

# 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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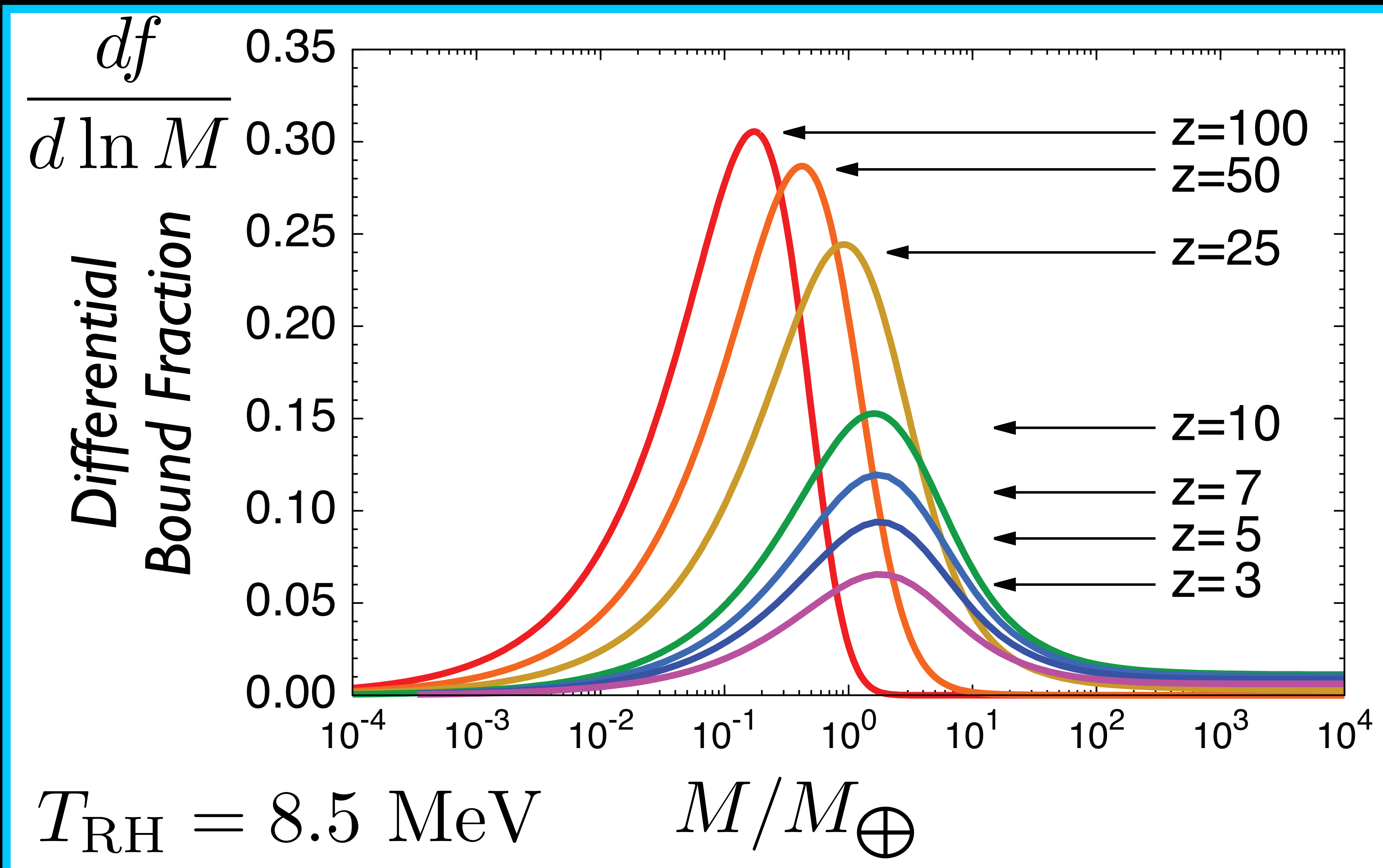



Fraction bound in halos with $M > 0.1\, M_{\oplus}$

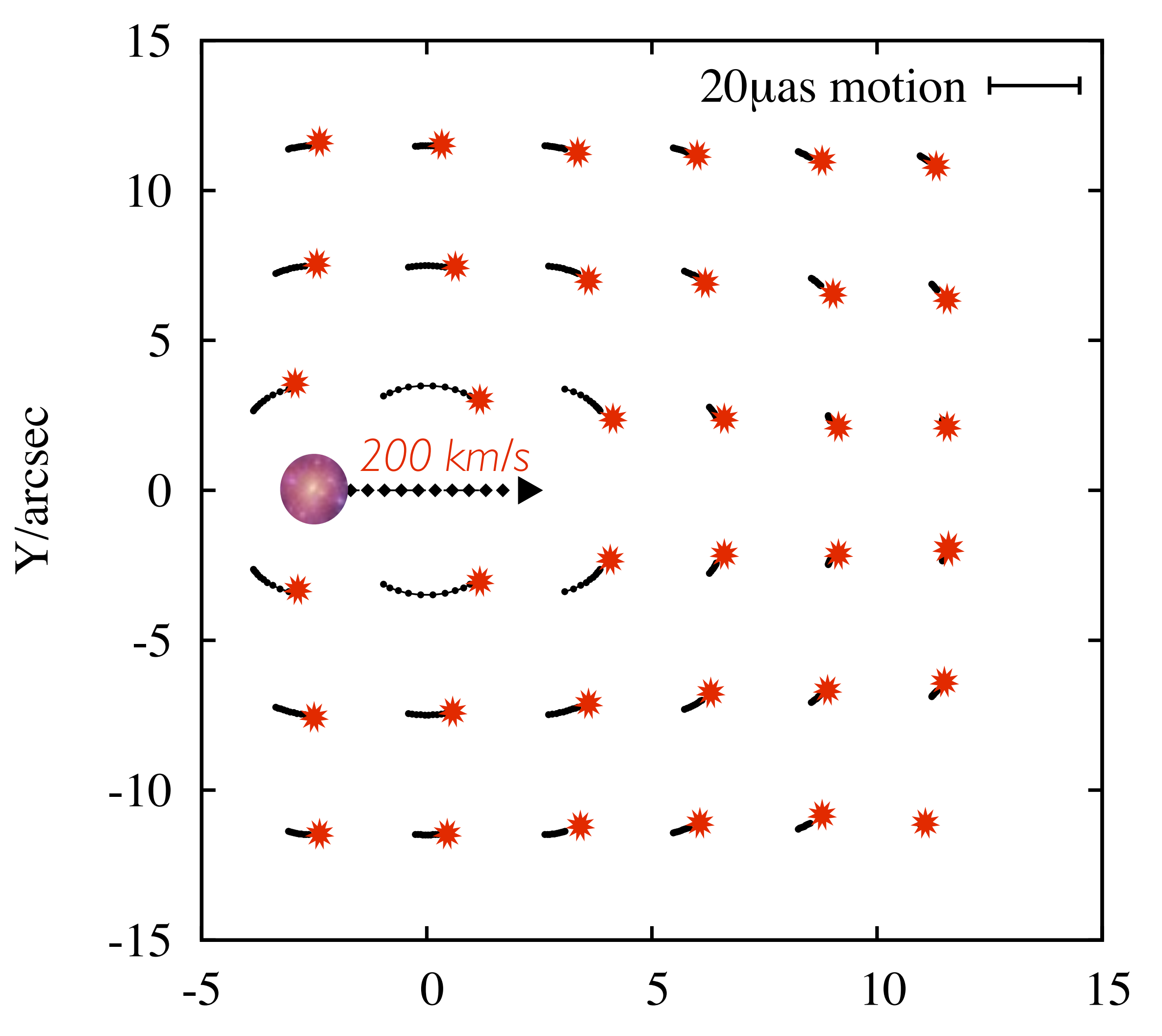
| z | Std | 8.5 MeV |
|---|---|---|
| 100 | $10^{-10}$ | 0.49 |
| 50 | $10^{-3}$ | 0.71 |
| 25 | 0.06 | 0.83 |

***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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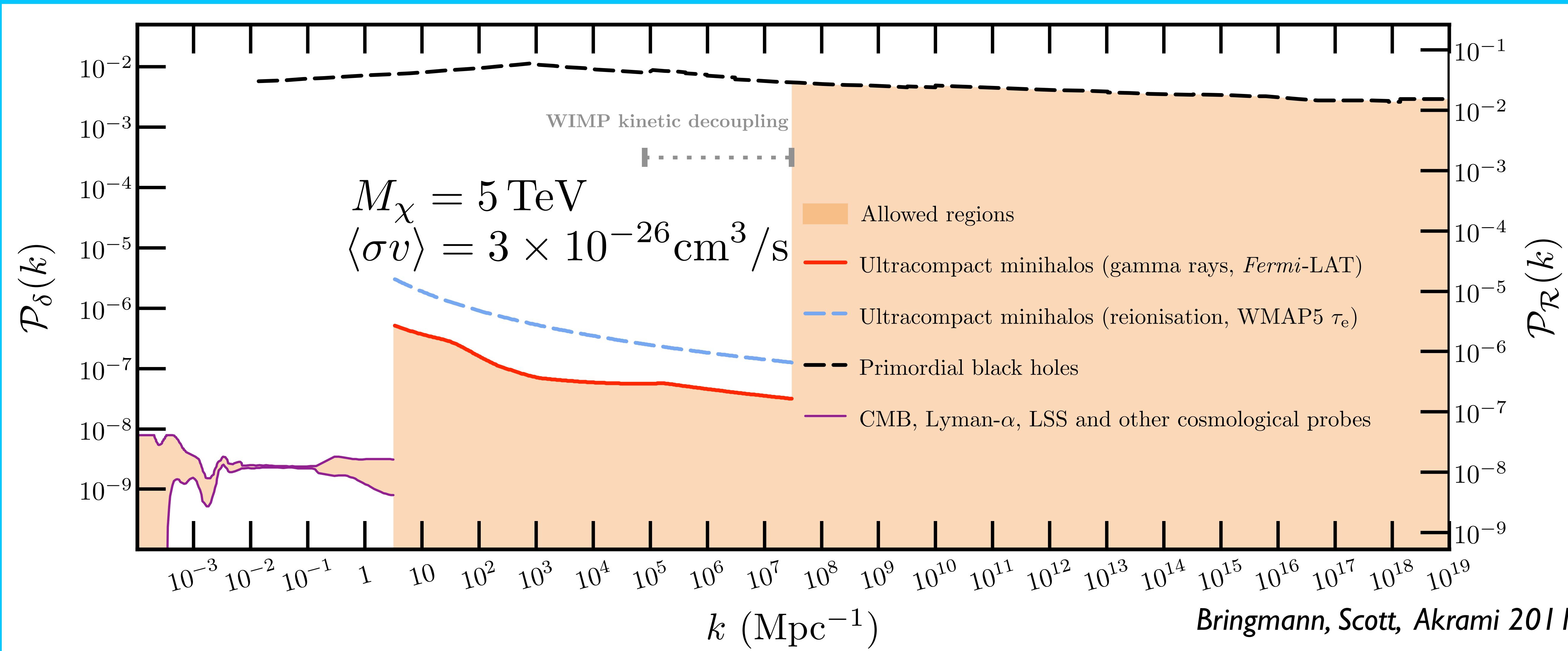


*Bringmann, Scott, Akrami 2011*

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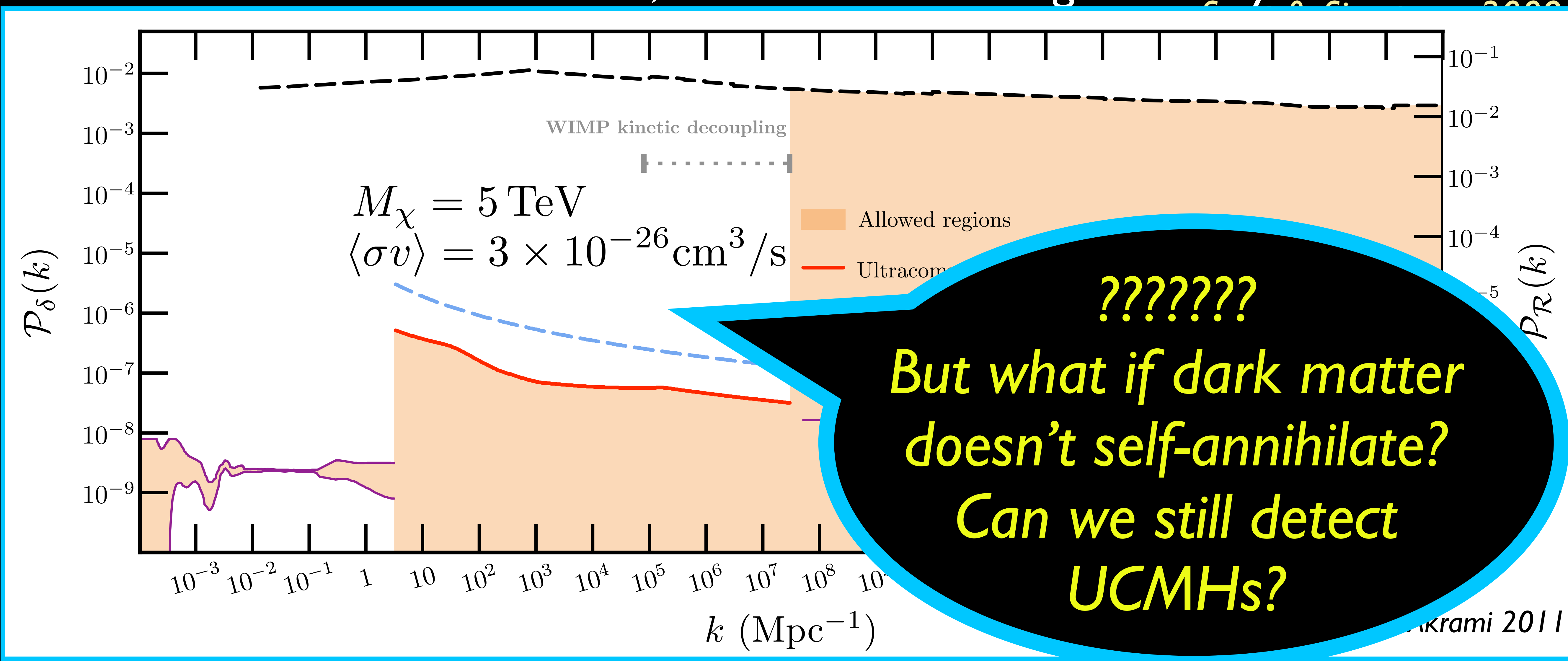


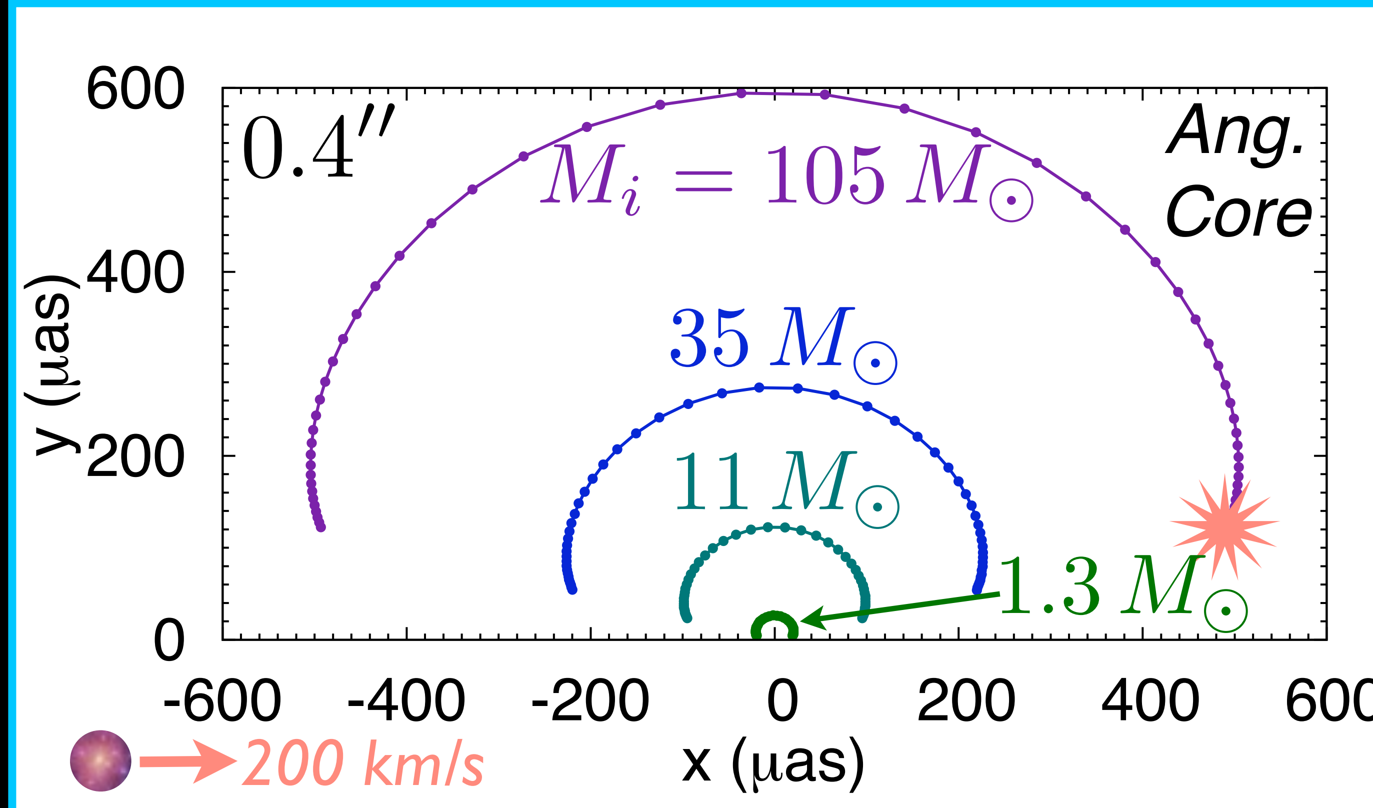
# Astrometric Microlensing by UCMHs

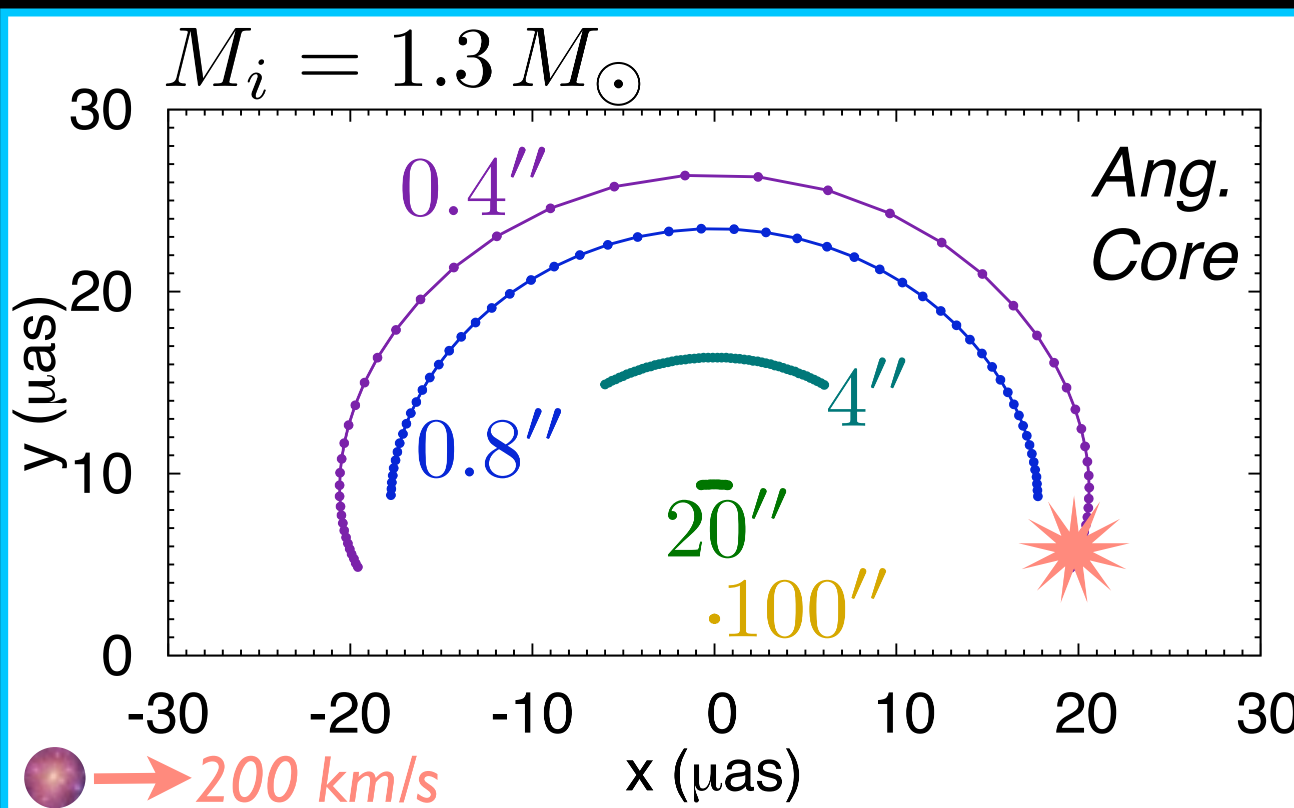
As UCMH passes in front of a star, the star moves!

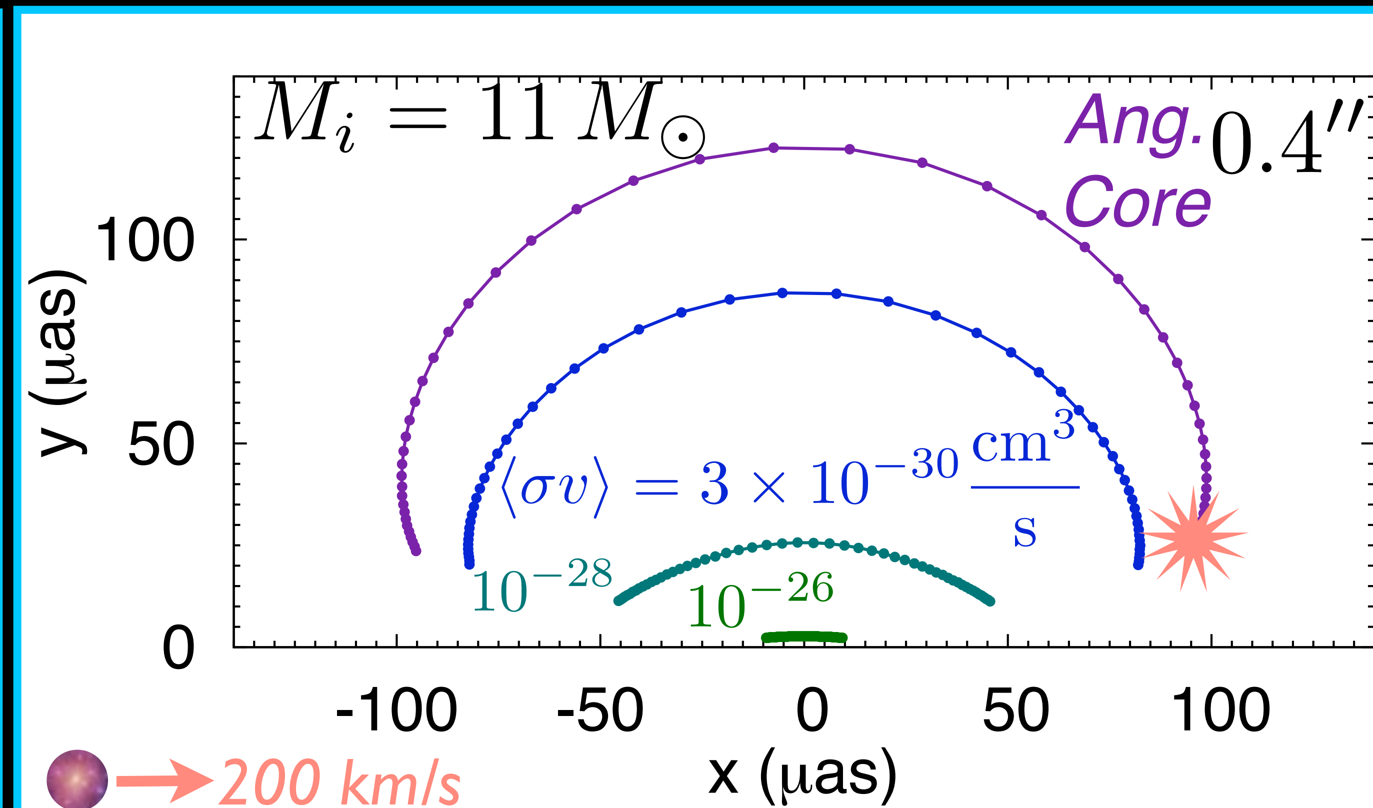
Trajectory depends on

- initial microhalo mass
- impact parameter
- core radius

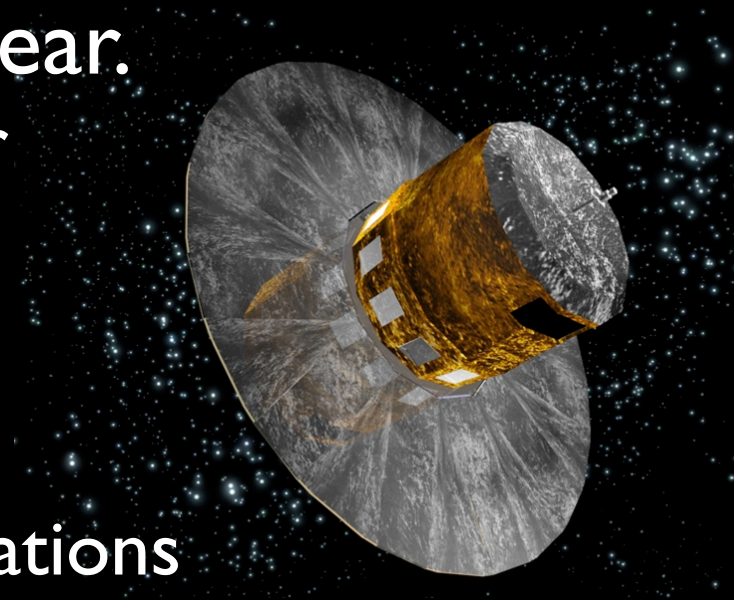
*4 yrs, monthly obs;*
*Lens distance: 50 pc;*
*Source Distance: 2 kpc*



# 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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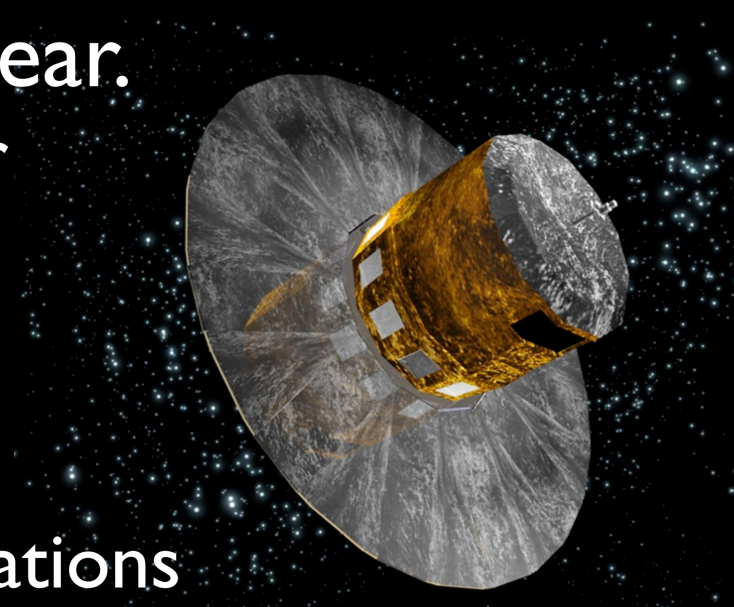

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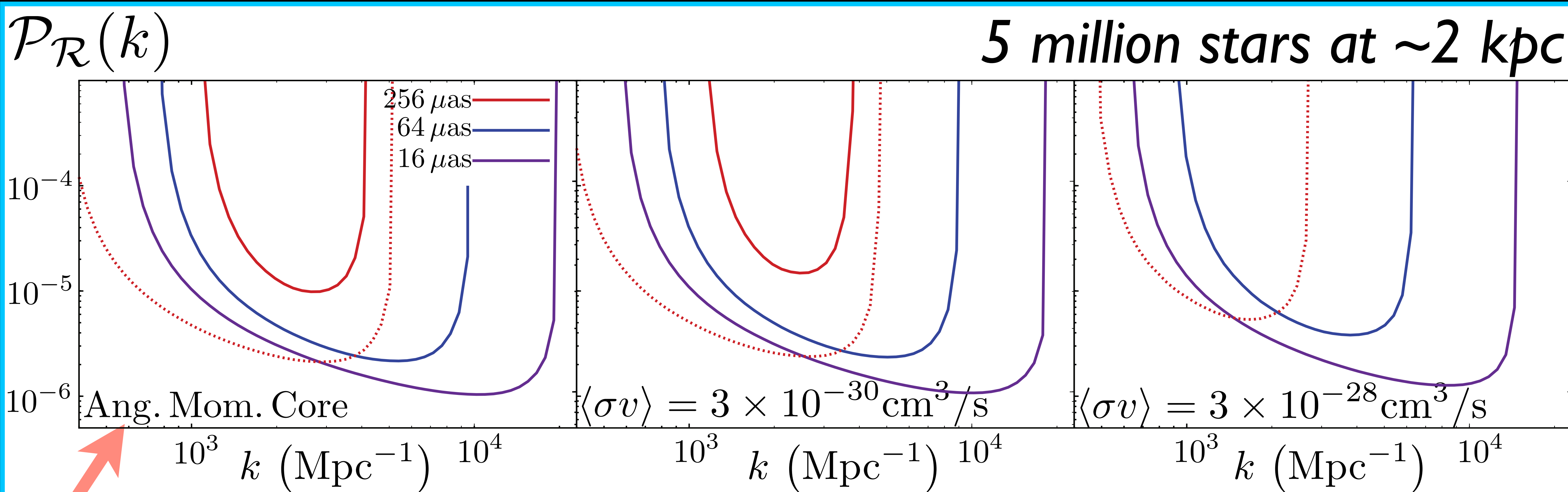


*Most conservative case: Fermi gives a stronger bound if DM self-annihilation diminishes lensing signal.*

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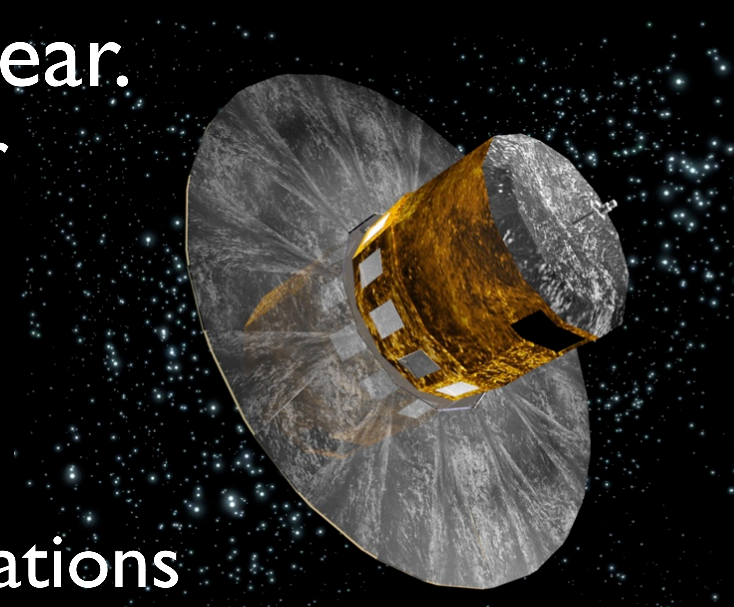

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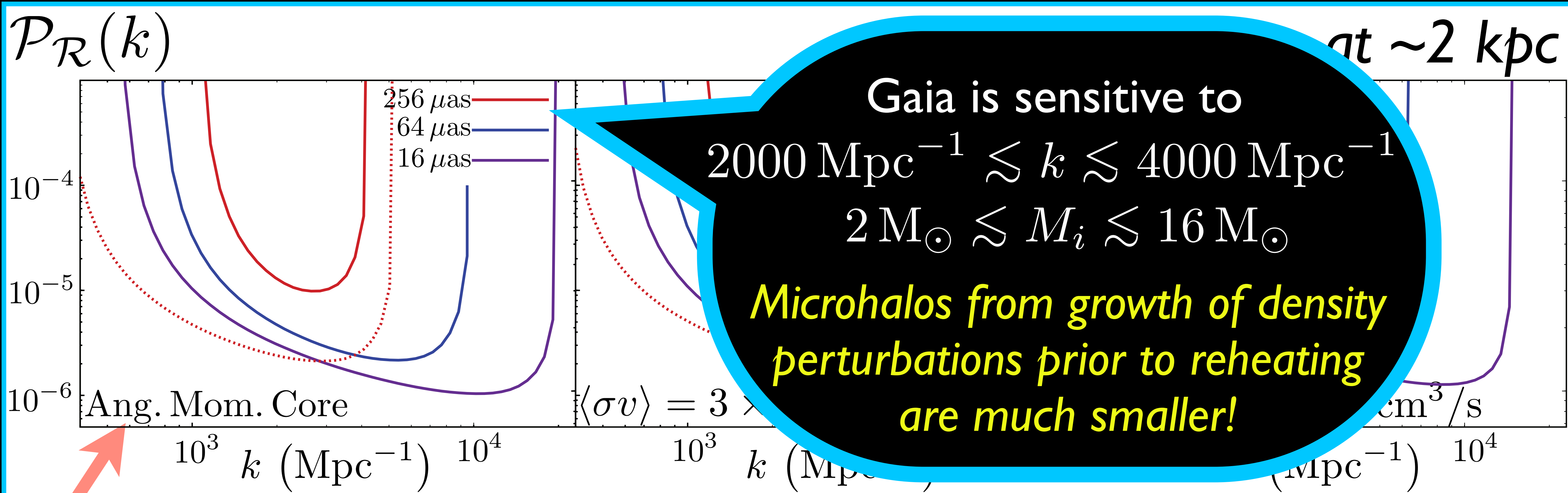


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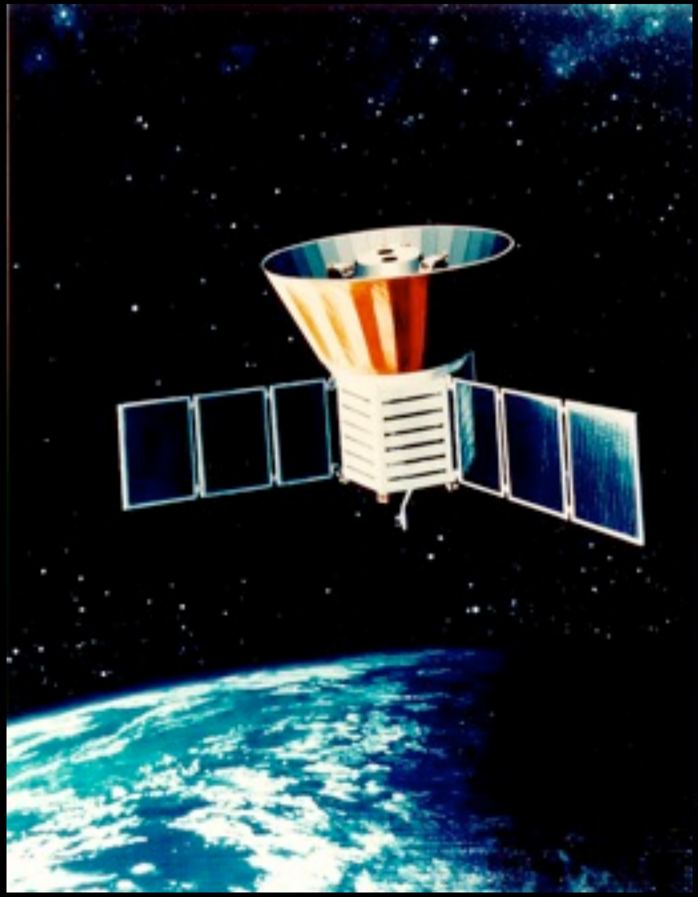
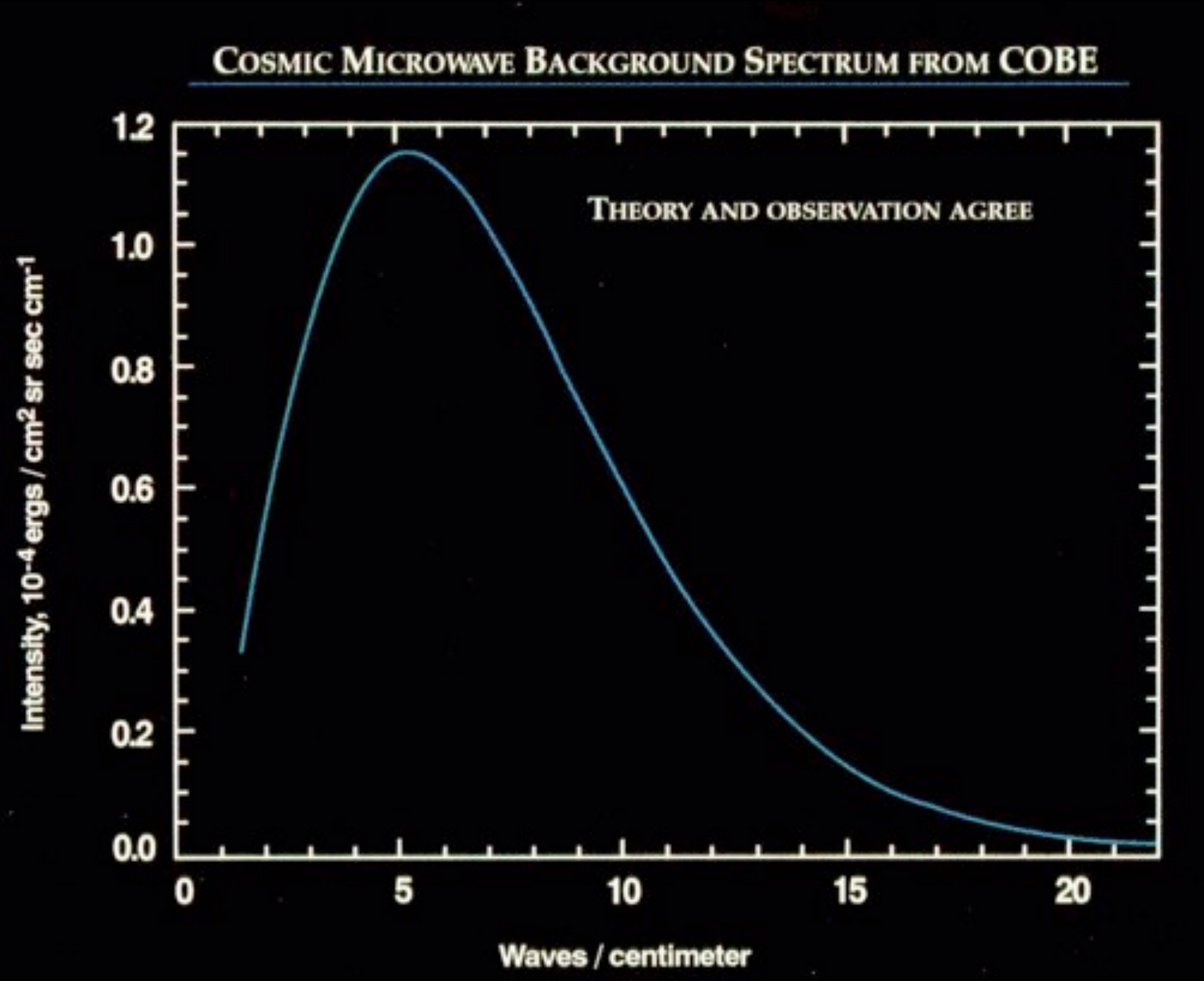
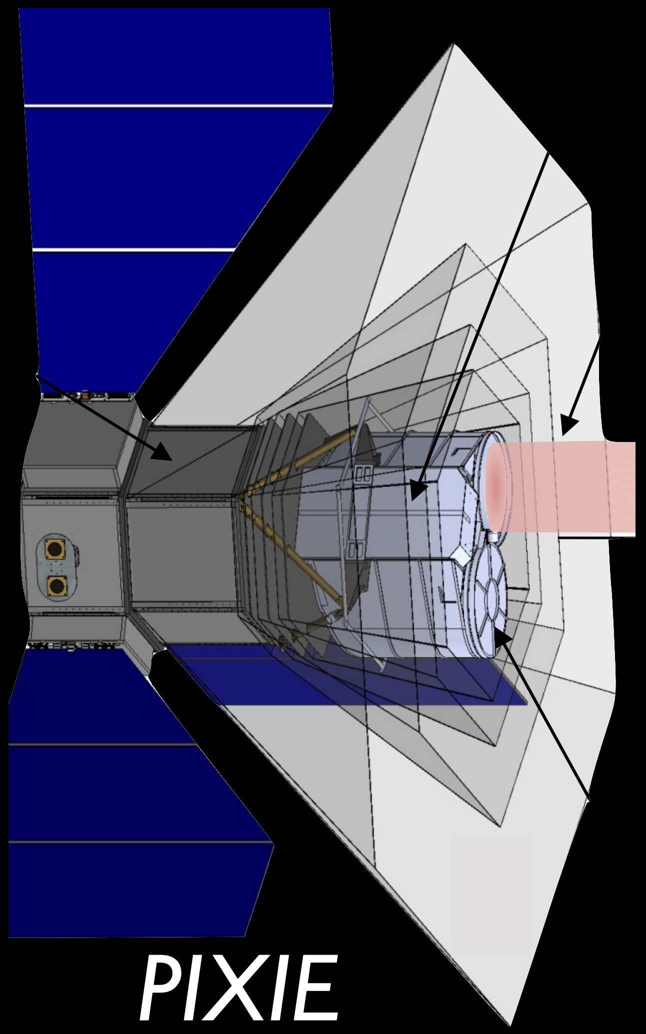
# Part III
# Probing the Primordial Power Spectrum with CMB Spectral Distortions

Chluba, Erickcek & Ben-Dayan 1203.2681



COBE FIRAS

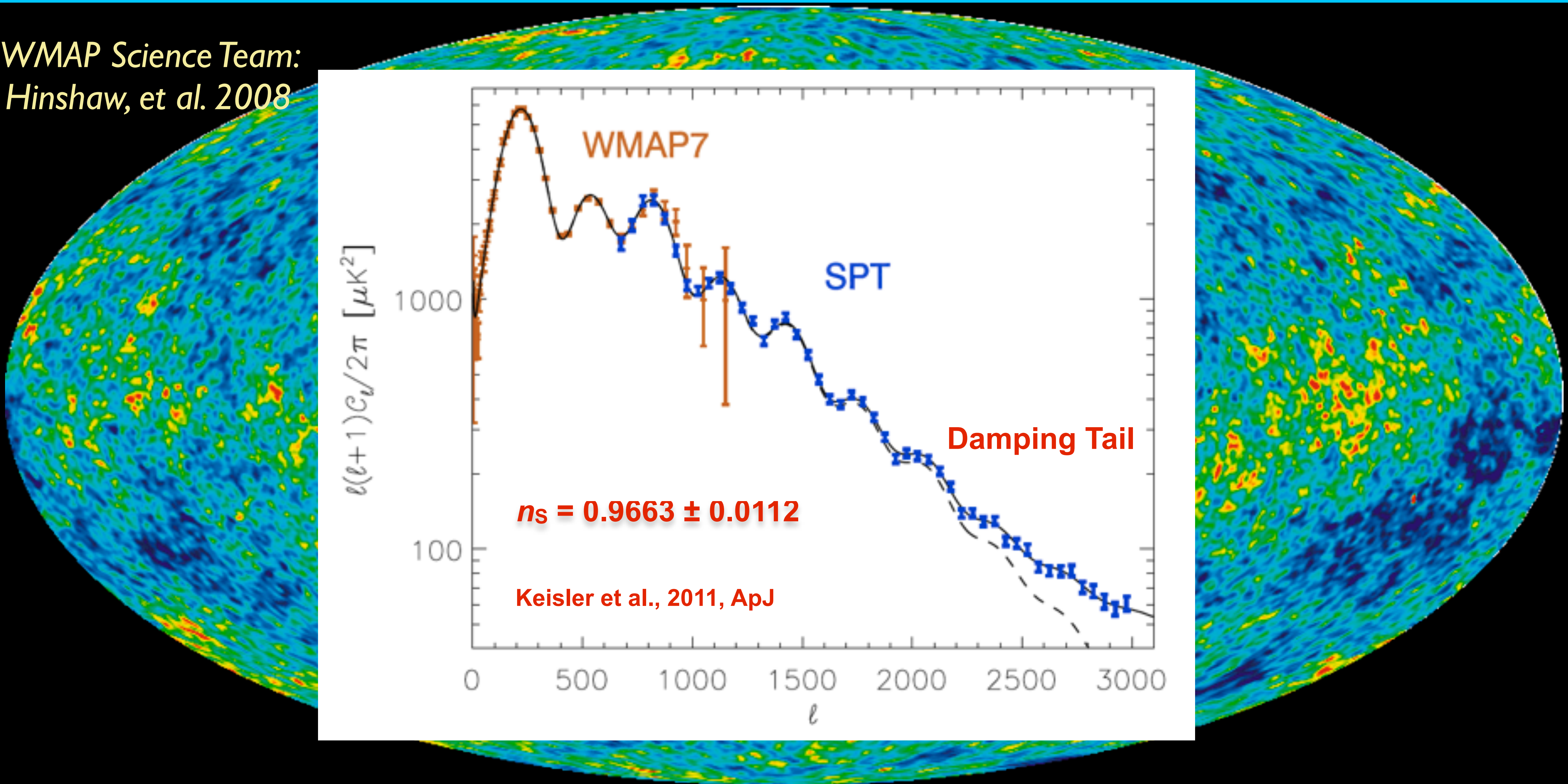


PIXIE
Kogut+ 2011

# Spectral Distortions from Diffusion

*WMAP Science Team: Hinshaw, et al. 2008*



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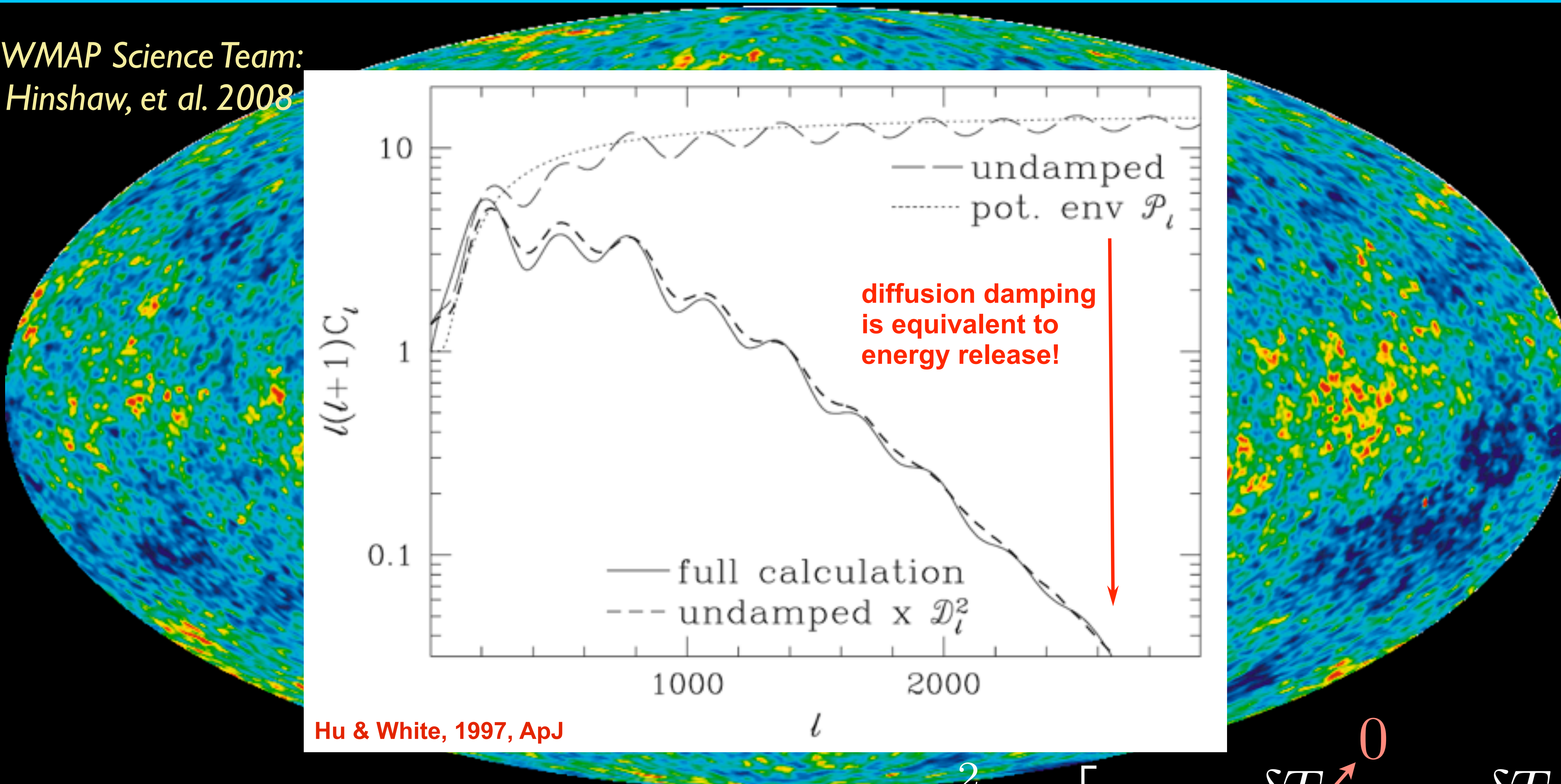



Energy stored in perturbations: $\langle\rho_\gamma\rangle = \frac{\pi^2}{15}\bar{T}^4\left[1+\cancelto{0}{4\langle\frac{\delta T}{\bar{T}}\rangle}+6\langle\frac{\delta T}{\bar{T}}\rangle^2\right]$

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 $\mu$-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:

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

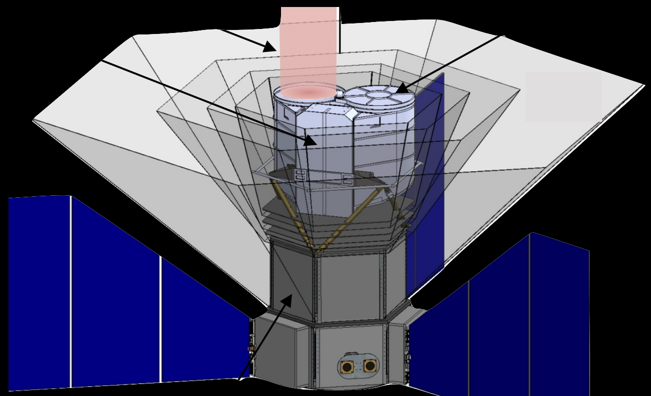
$$y \approx 0.4 \int_{k_{\mathrm{min}} = 1\,\mathrm{Mpc}^{-1}}^{\infty} \mathcal{P}_\zeta(k) \exp\left(-\left[\frac{k\,\mathrm{Mpc}}{31.6}\right]^2\right) \mathrm{d}\ln k$$

COBE FIRAS

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

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

*Fixsen et al. 1996*



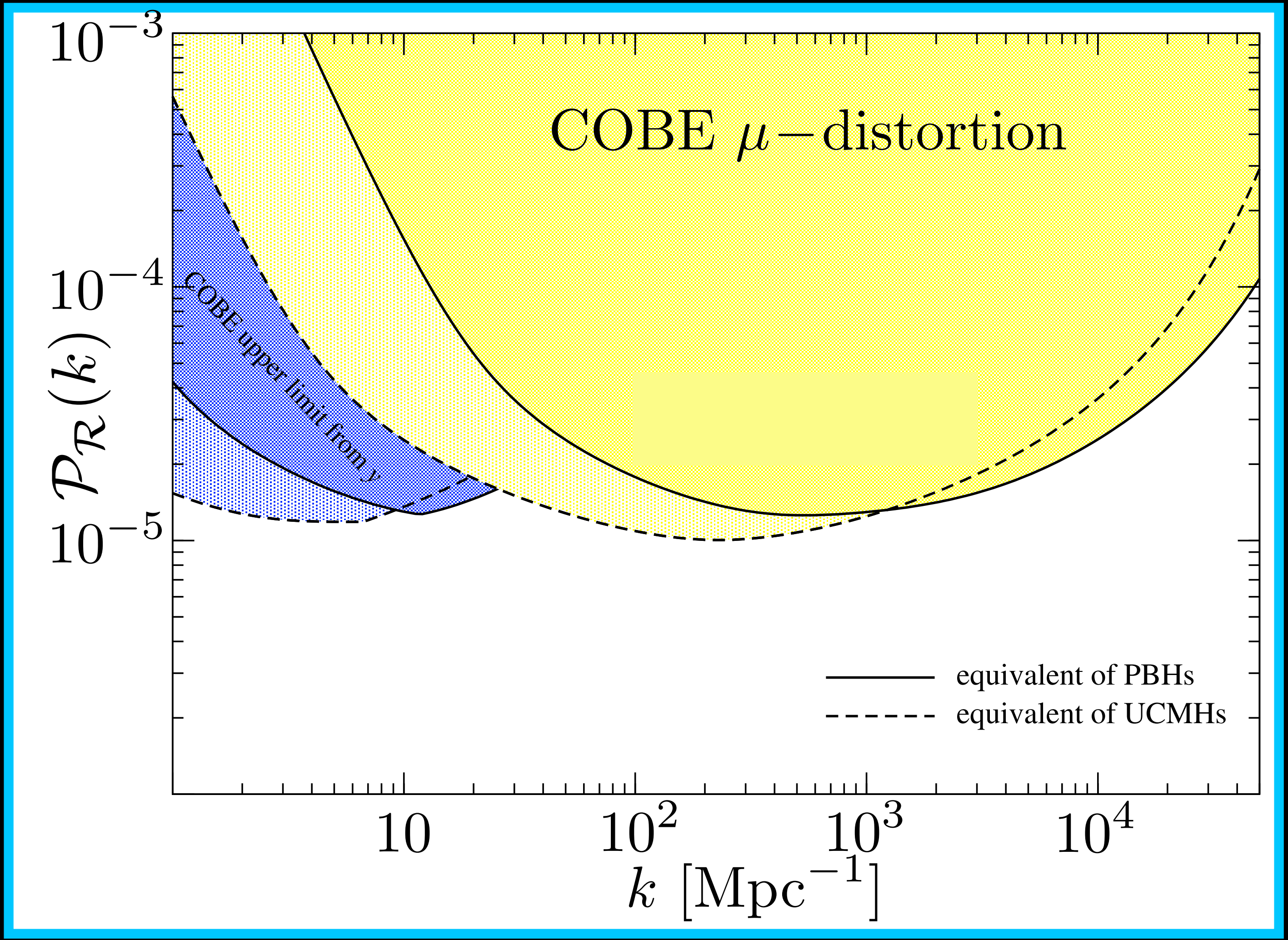
PIXIE

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

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

*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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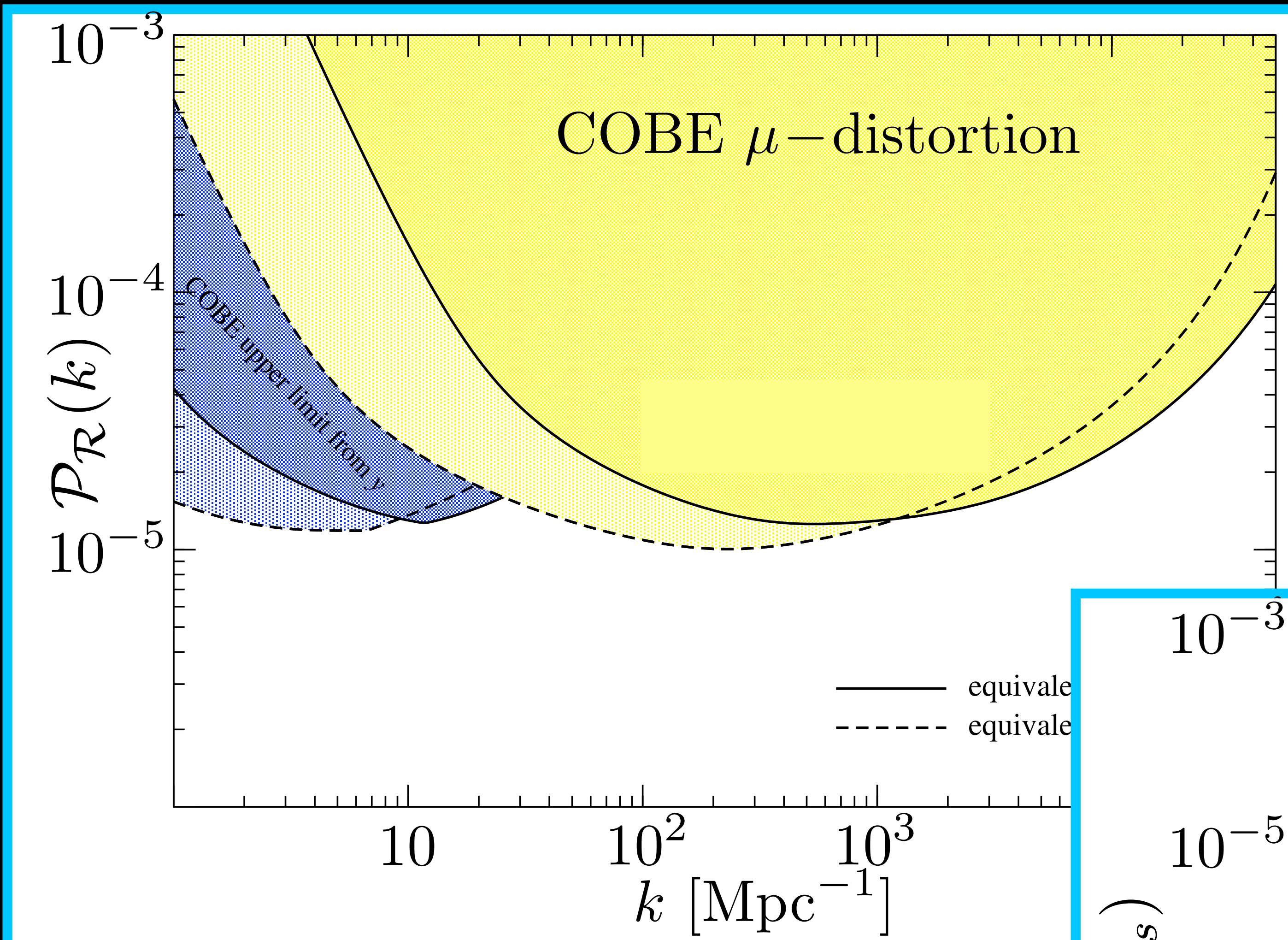


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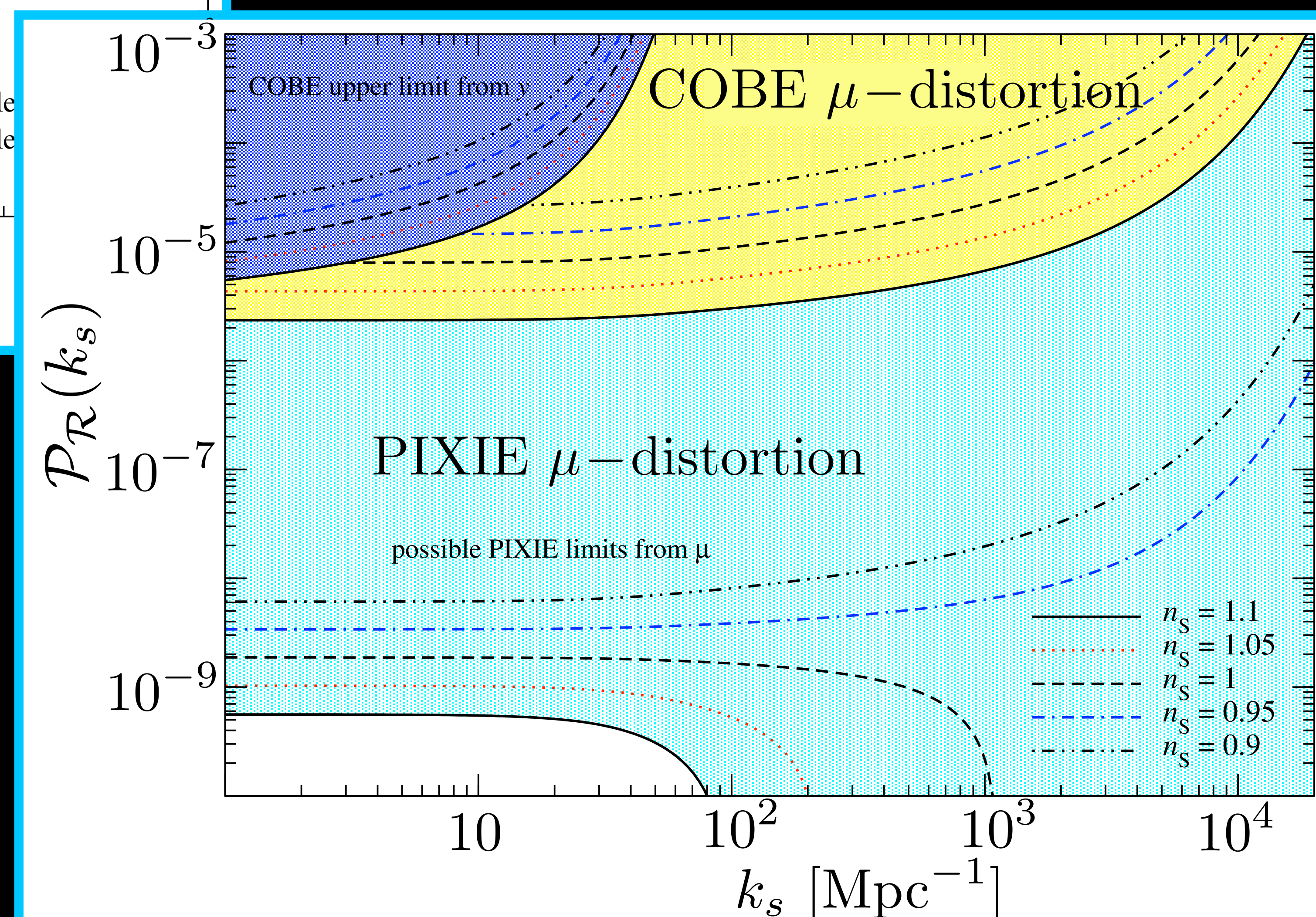


## Constrain a step in the primordial power spectrum

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

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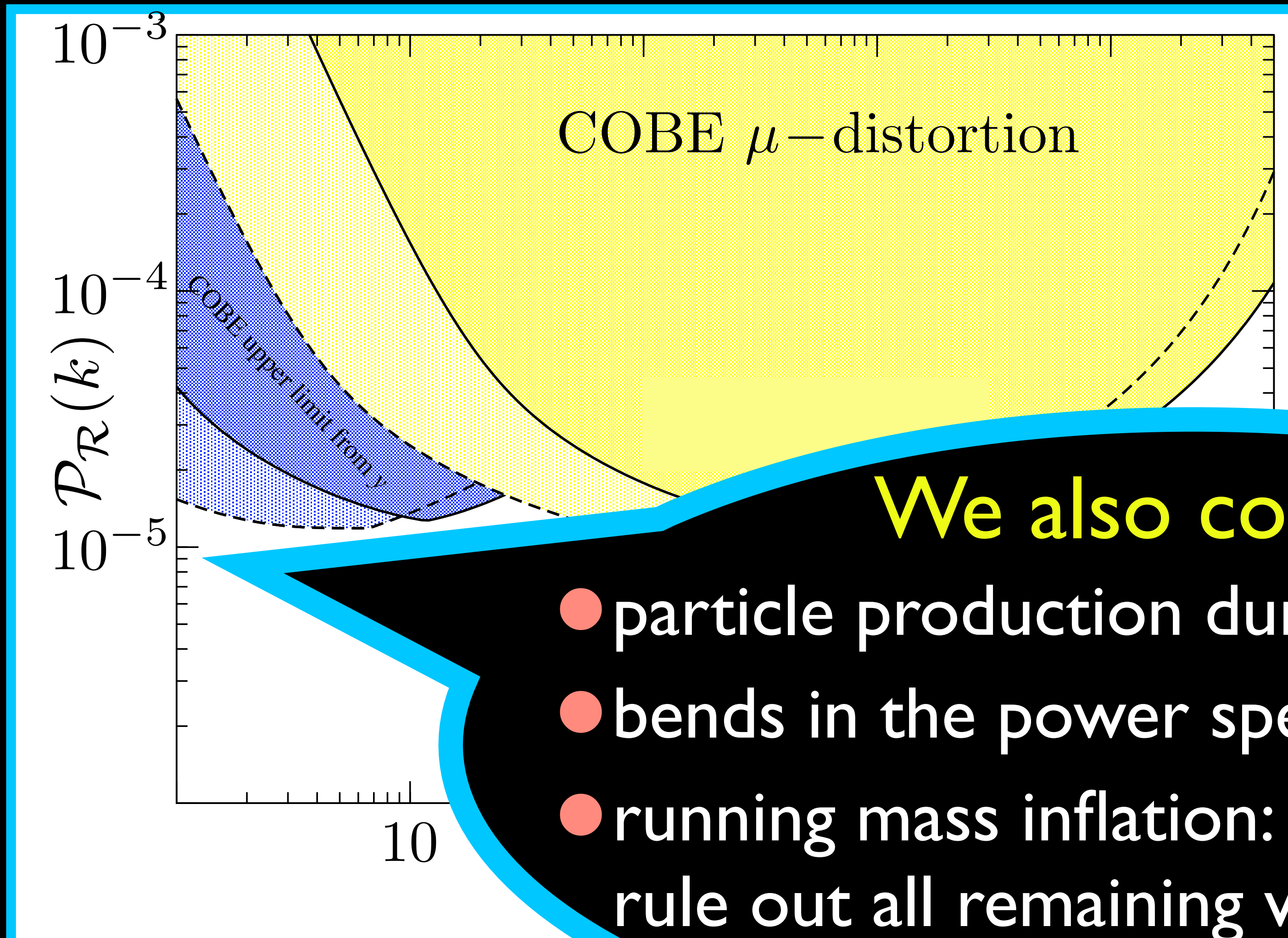


## Comparison to bounds from PBHs and UCMHs

- assume "local scale invariance"
- apply the same minimal assumption ...hen computing bounds from ...ortions

## We also consider

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

## Constrain a step in th... primordial power spectrum

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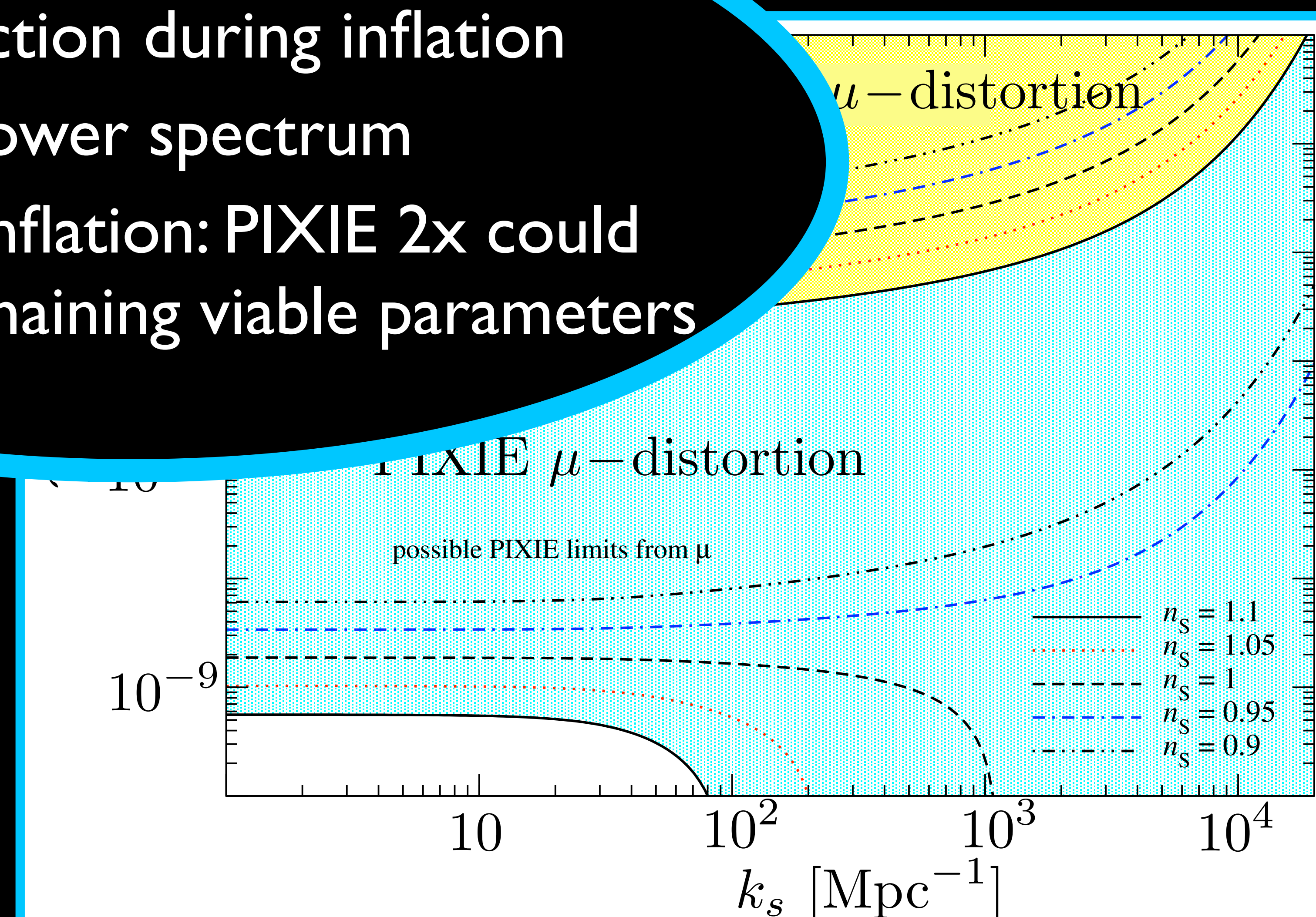
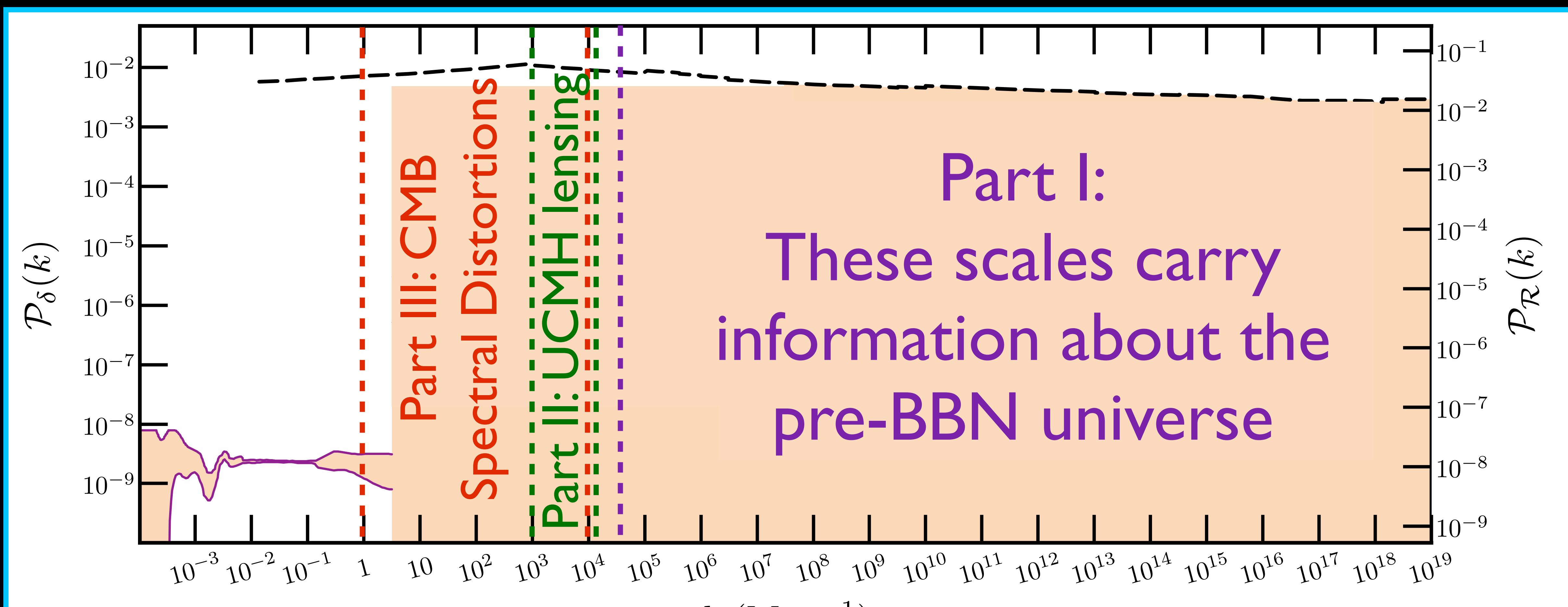


# Summary: Small Scales Probe the EU

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*