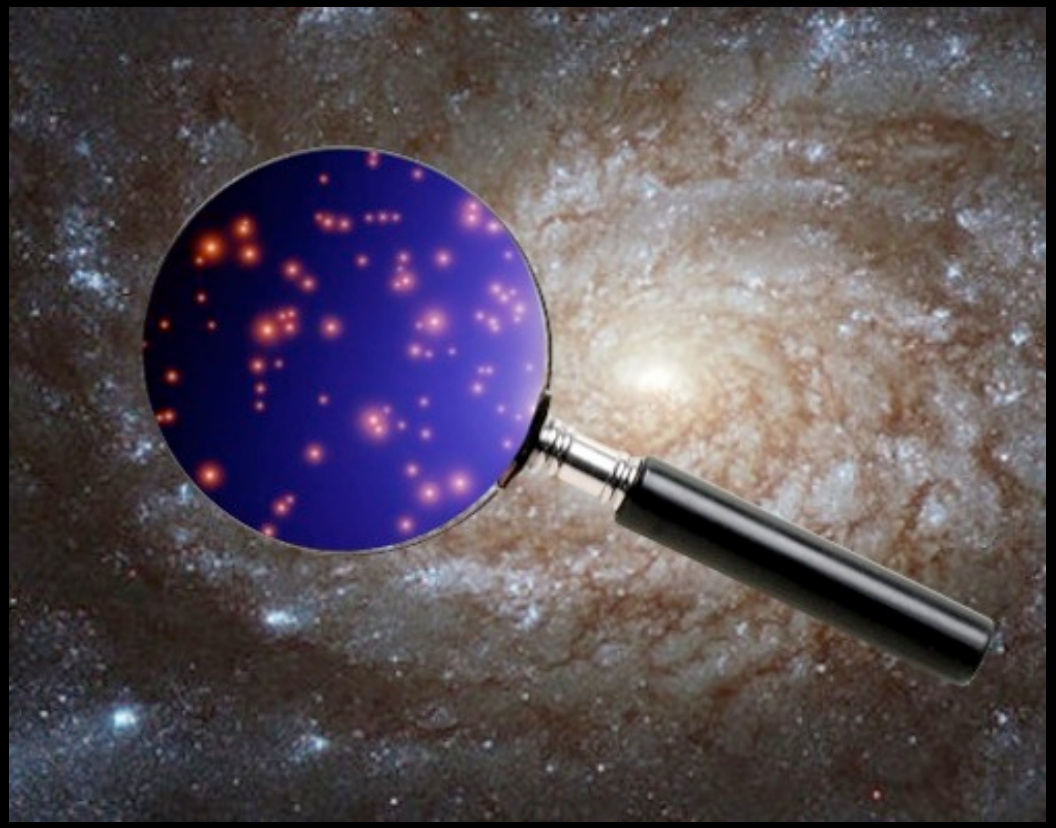
Astrometric Microlensing by UCMHs: a new probe of inflation



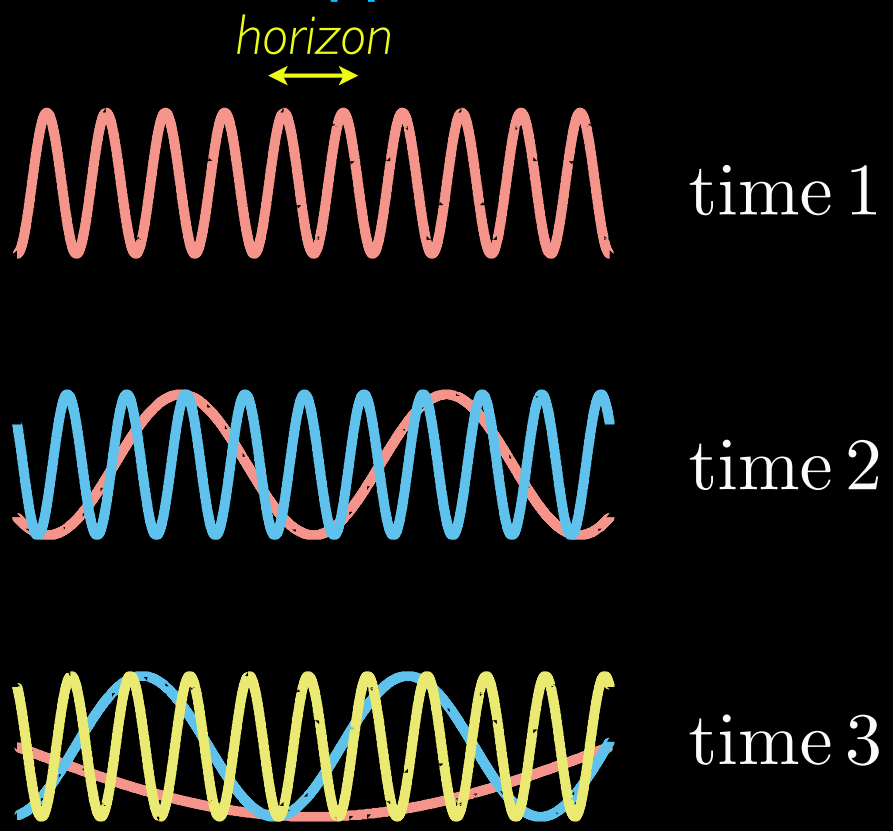
Adrienne Erickcek
UNC Chapel Hill

Theia Workshop
November 2, 2015

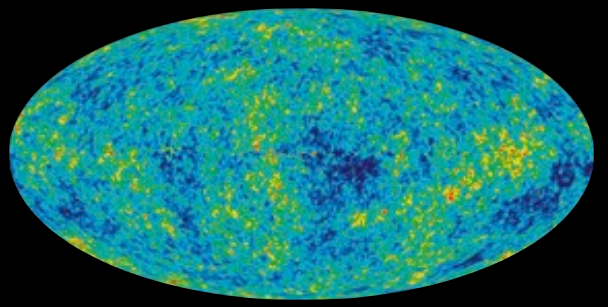
Probing Inflation Using Perturbations

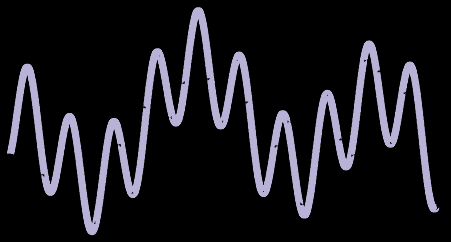
Perturbations "freeze" when their wavelengths become larger than the cosmological horizon during inflation.

What happened:



What we observe:



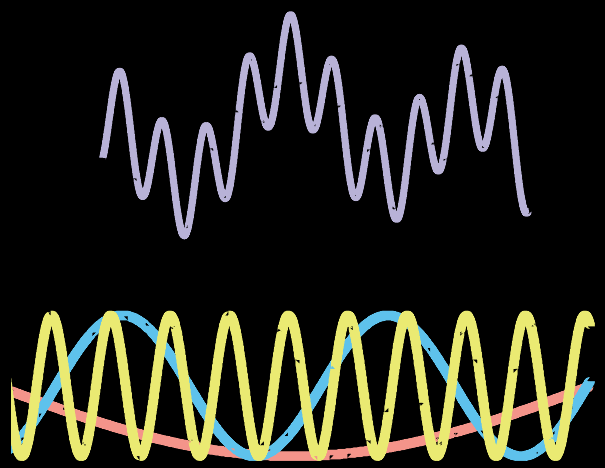


$$\mathcal{P}_{\mathcal{R}}\left(k = \frac{2\pi}{\lambda}\right)$$

Perturbations with different wavelengths probe different times:

smaller wavelengths (larger k) = later stages of inflation

The Primordial Power Spectrum



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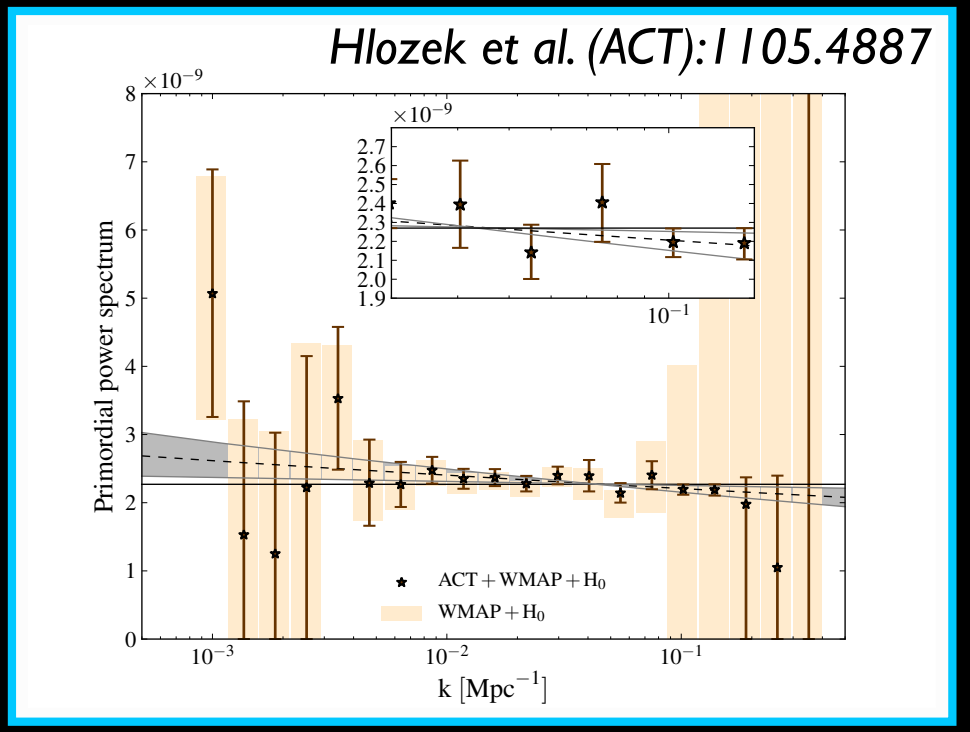
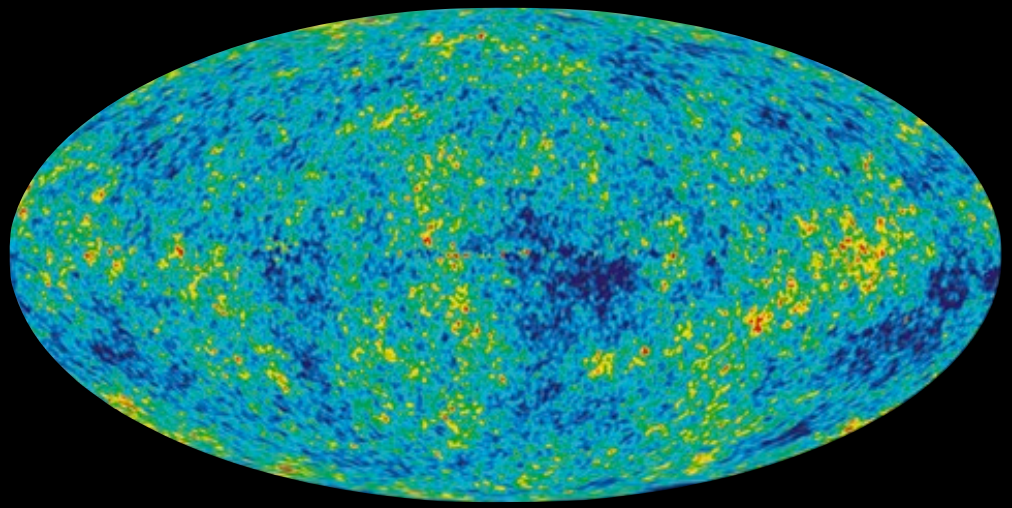
Curvature

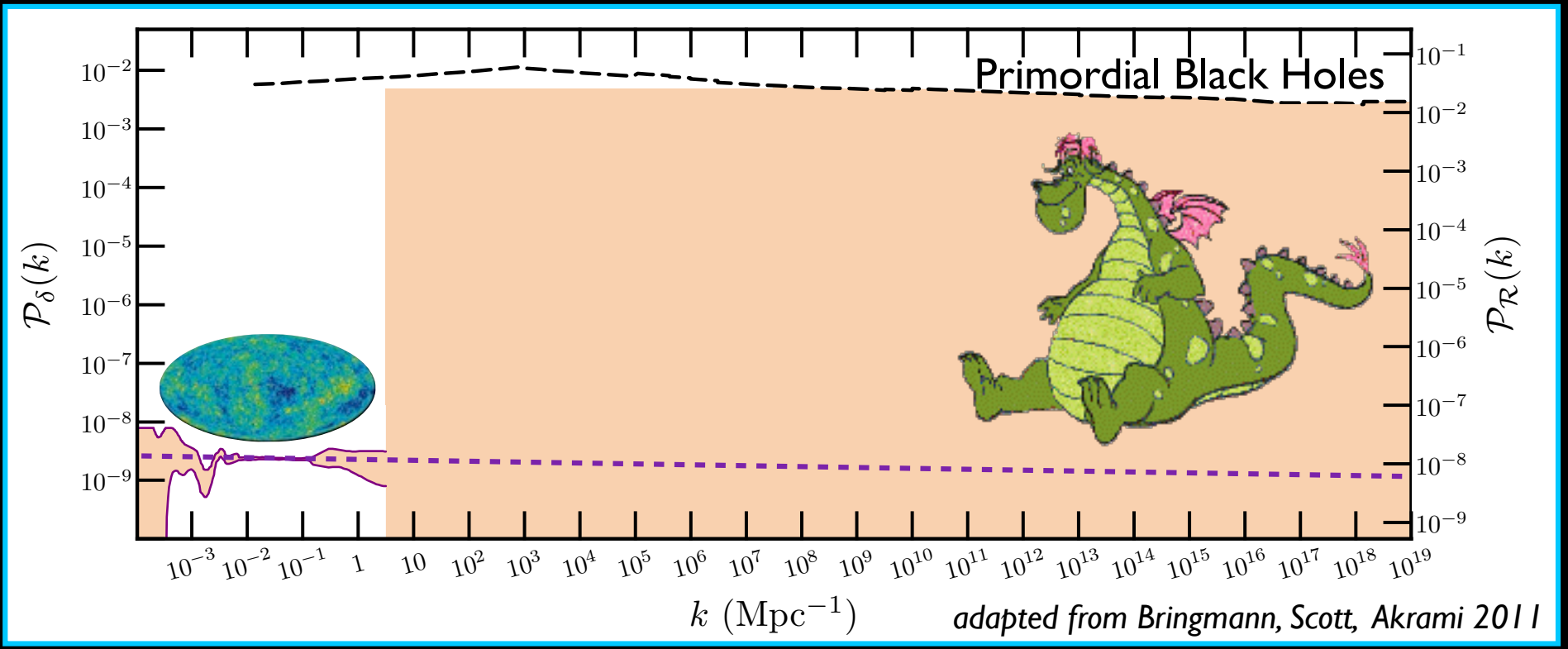




Measurements of the CMB temperature fluctuations and measurements of large-scale structures (galaxies + gas clouds) tell us about $k \lesssim 3\,\mathrm{Mpc}^{-1}$.

Small scales: Here there be dragons

Several inflationary models predict excess small-scale power.



adapted from Bringmann, Scott, Akrami 2011

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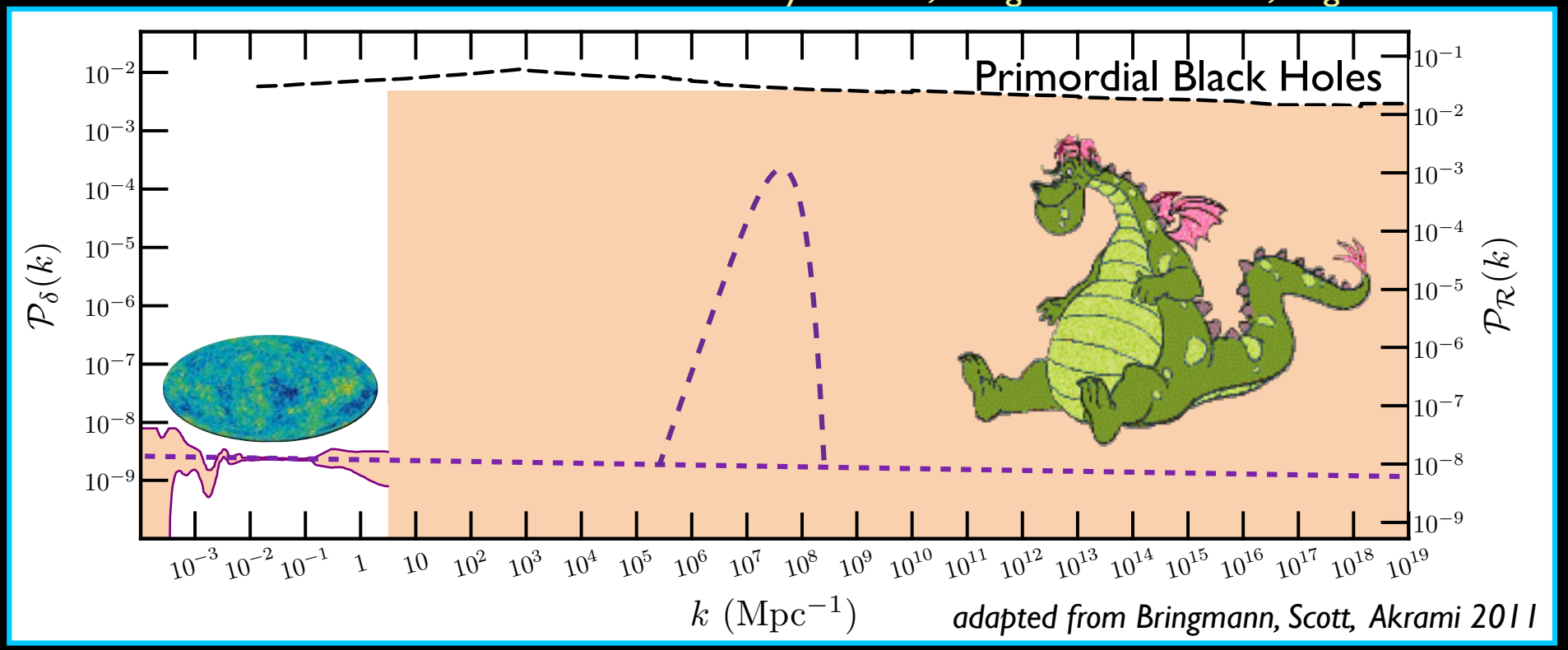

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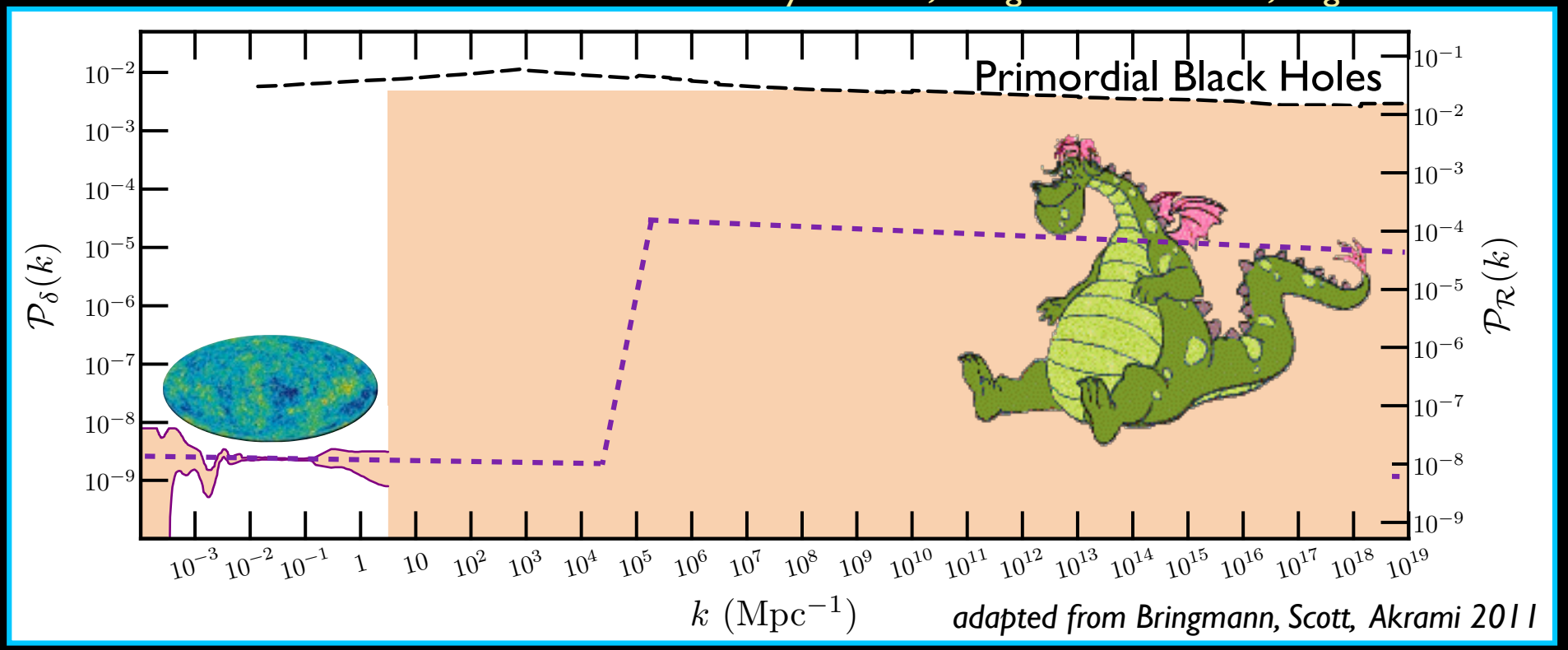

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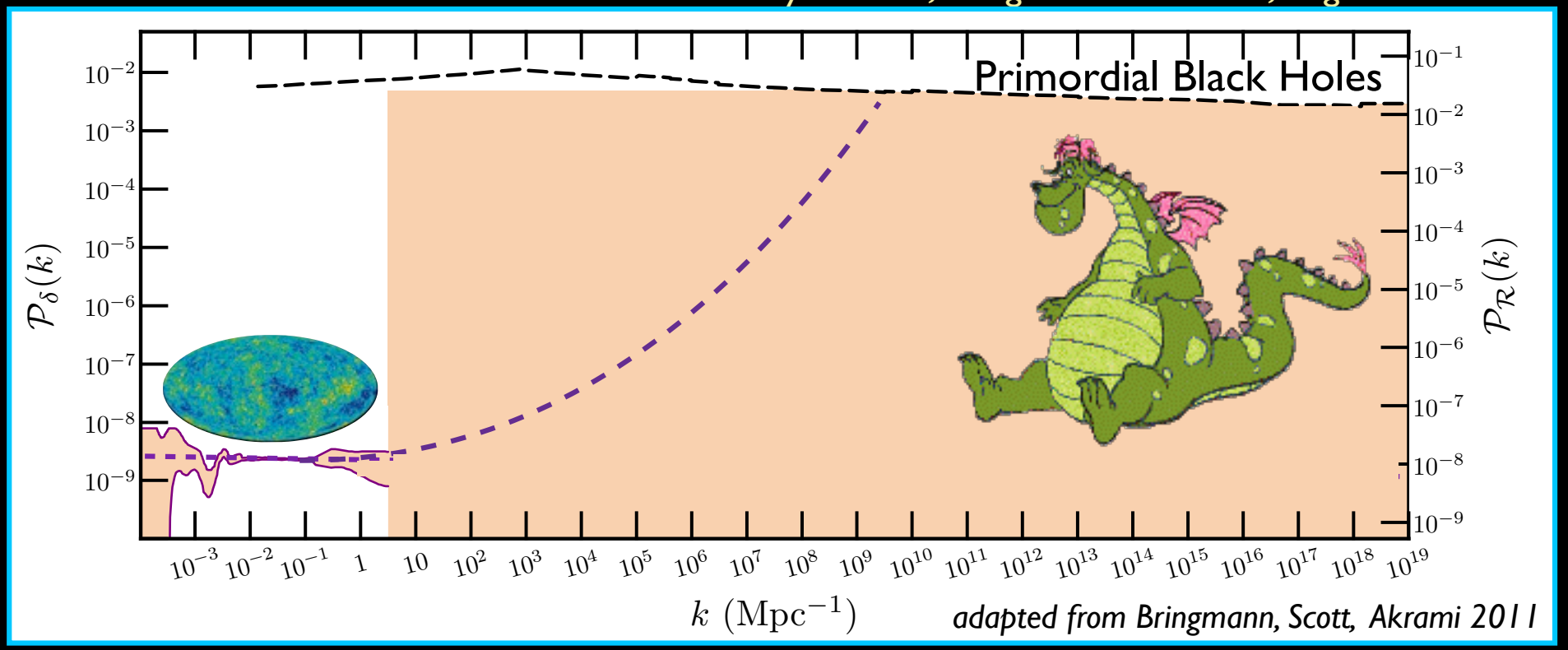

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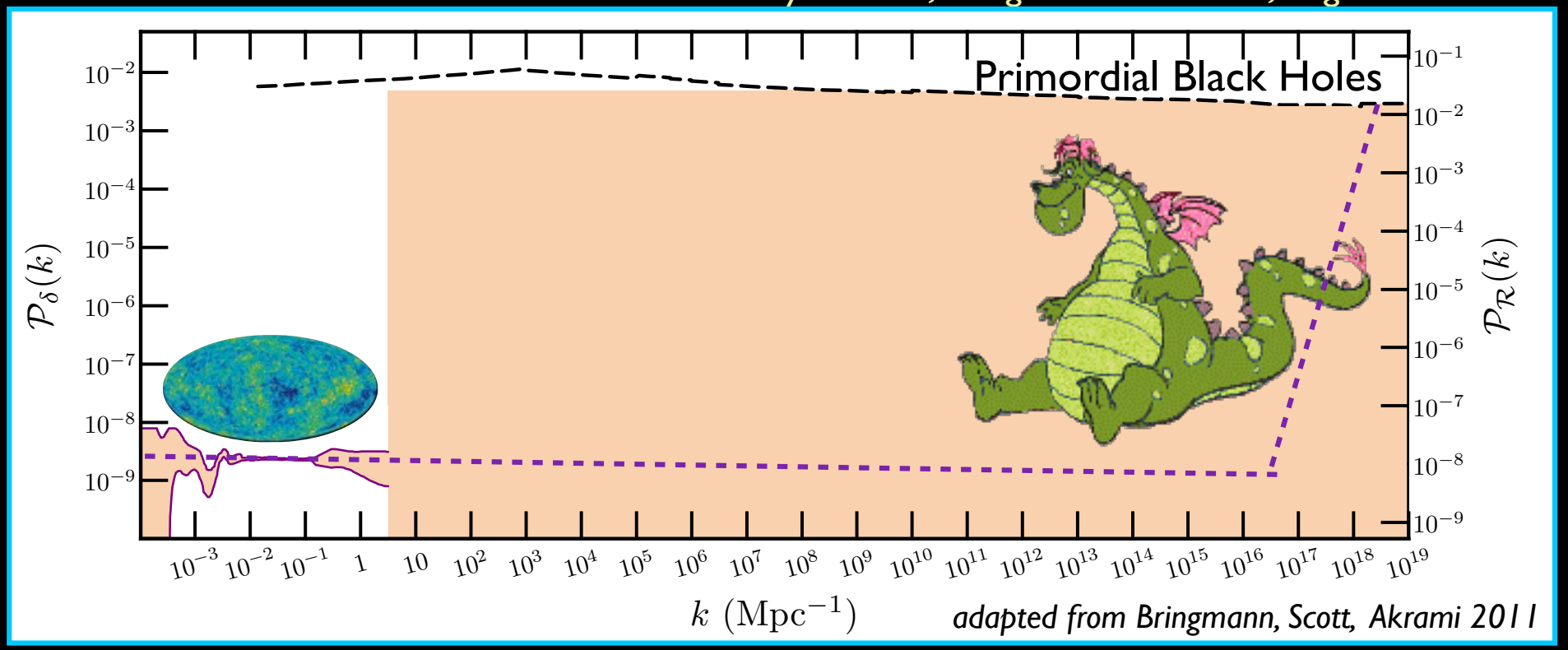

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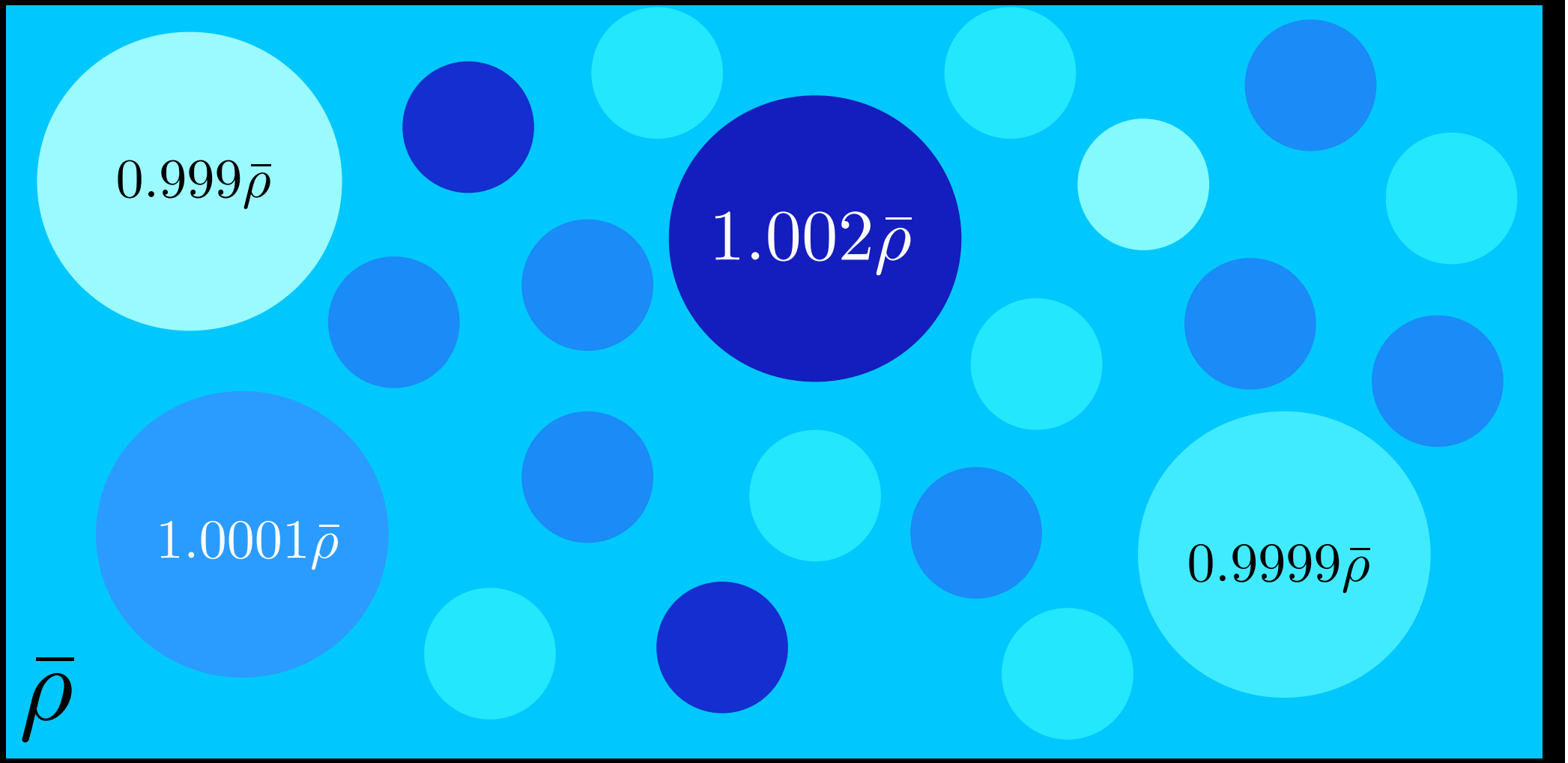
UCMH Formation

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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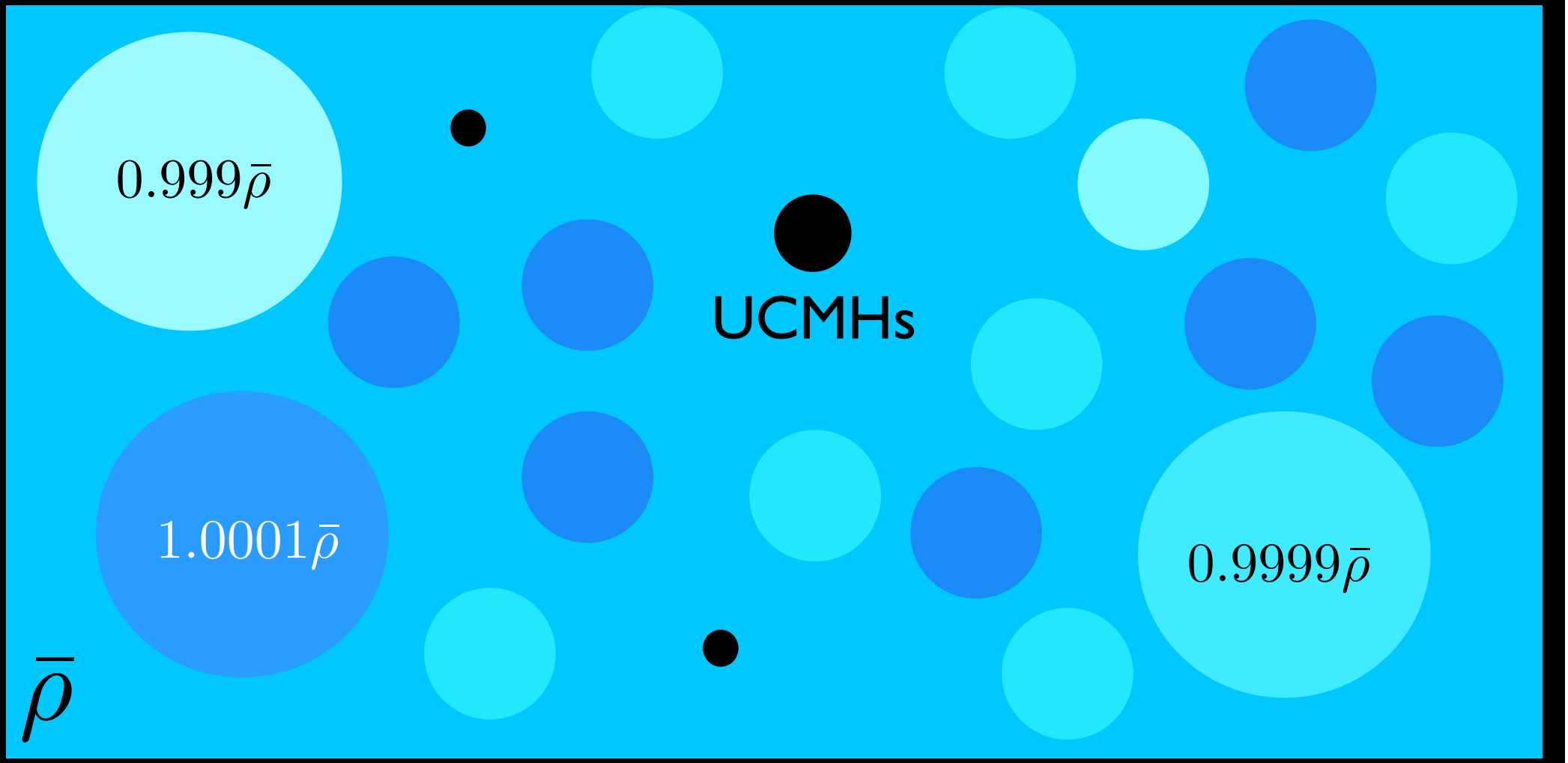
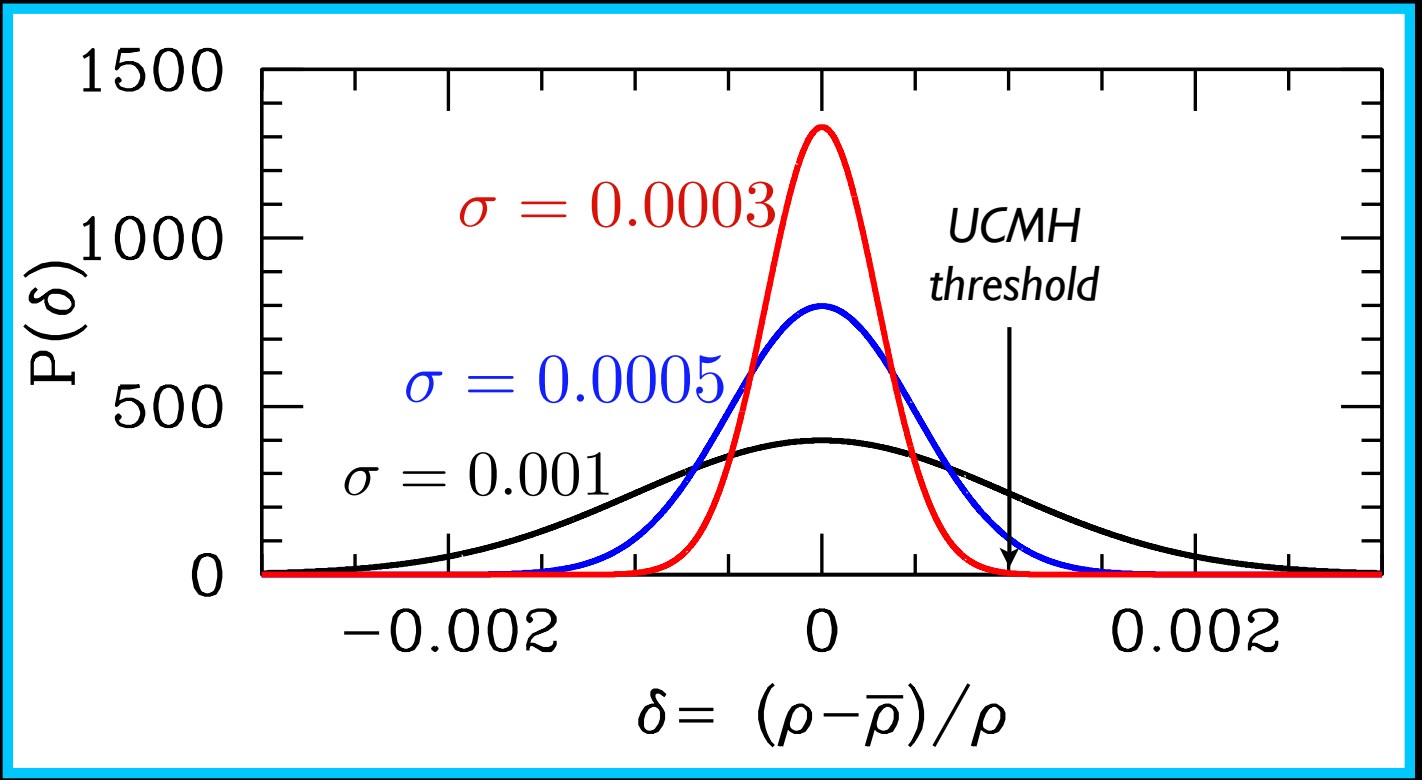


UCMHs Probe Power Spectrum Tail

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



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

directly related to primordial power spectrum

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

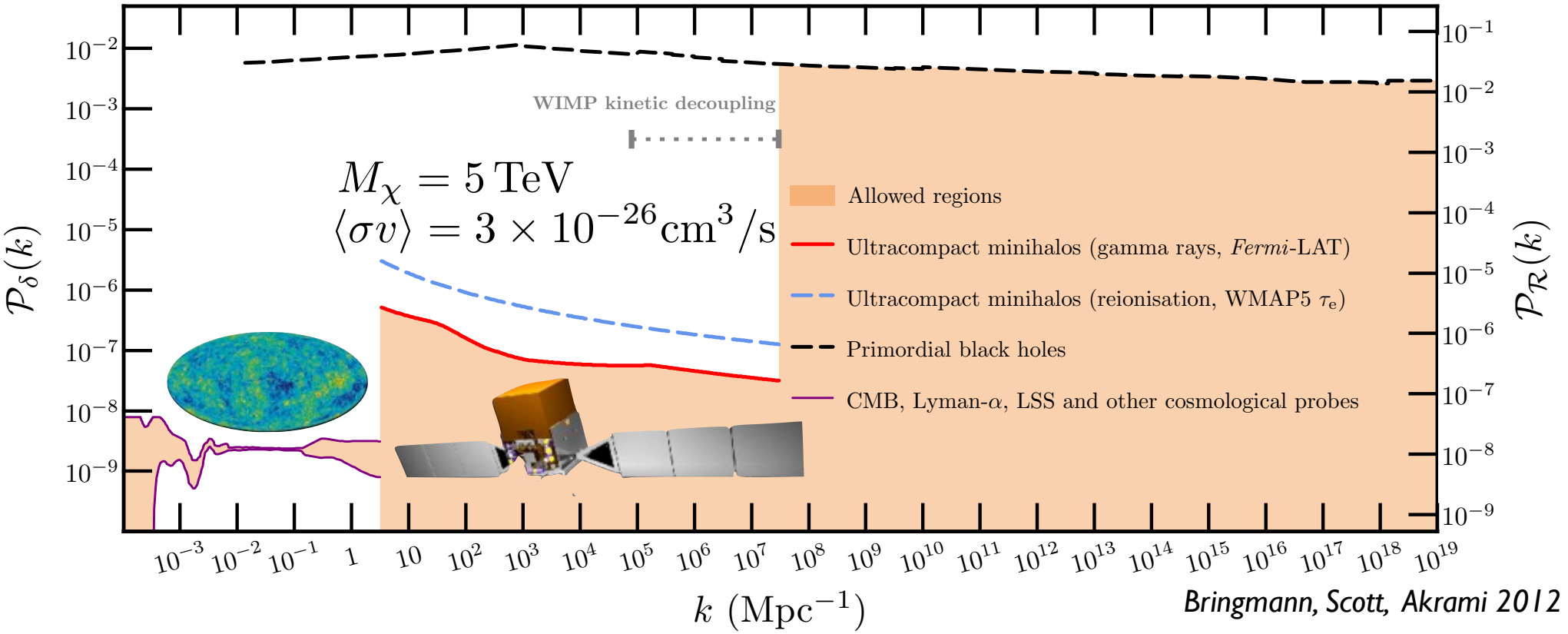
Josan & Green 2010; Bringmann, Scott, Akrami 2012

How to Detect UCMHs

Dark Matter Annihilations:

$$\chi\bar{\chi} \rightarrow \gamma\gamma$$

The dark matter density in UCMHs is much higher than in a normal galaxy. That makes it easier for the dark matter particles to collide.



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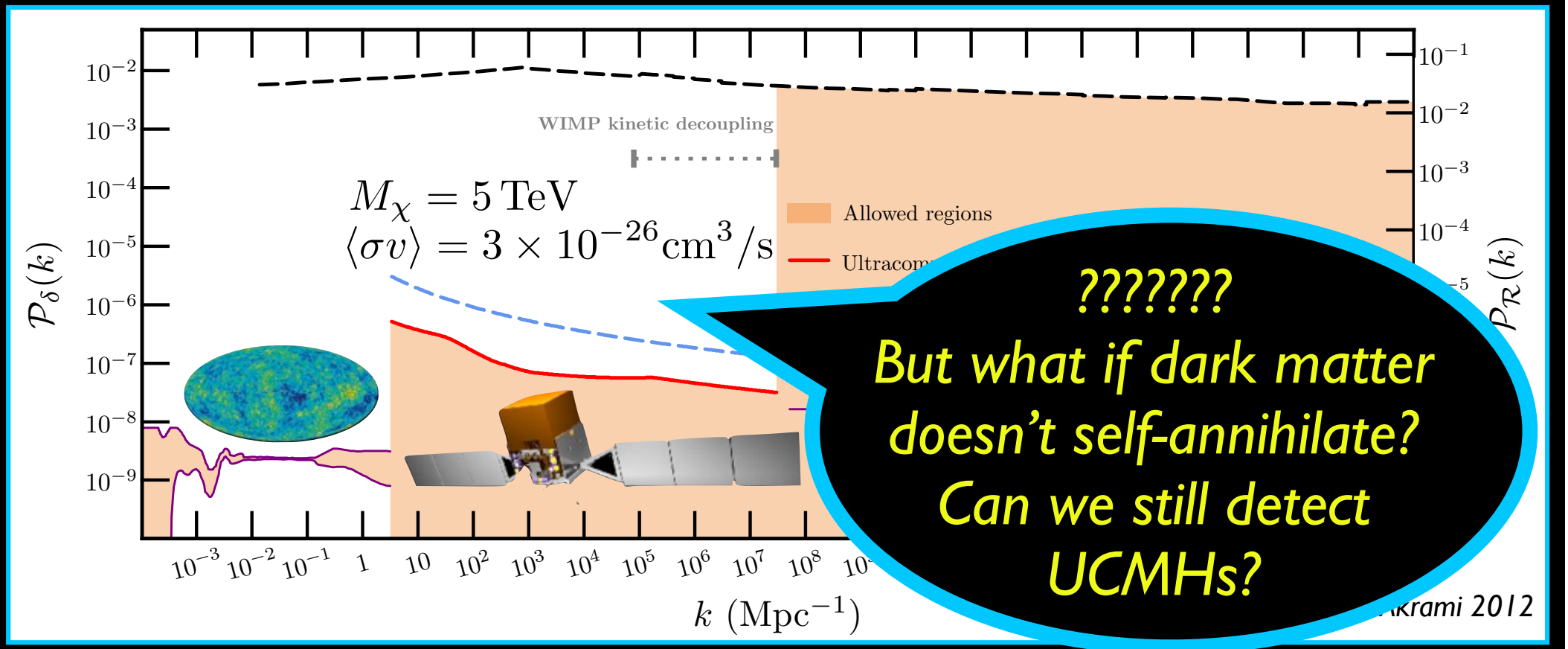


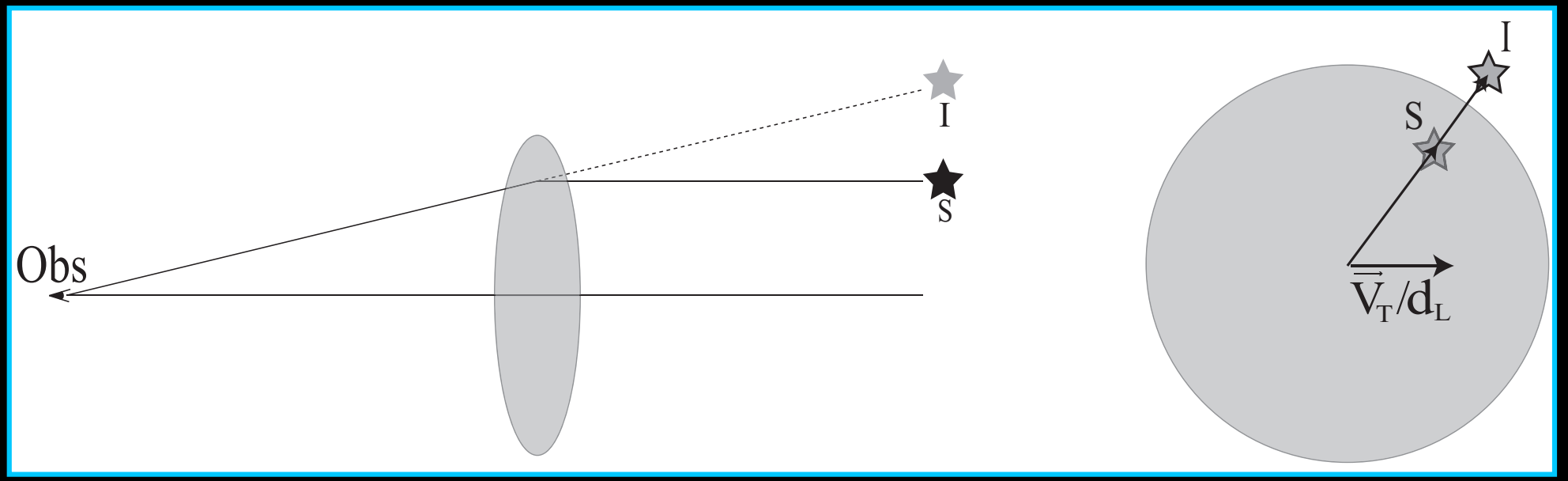
???????

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

Astrometric Microlensing

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

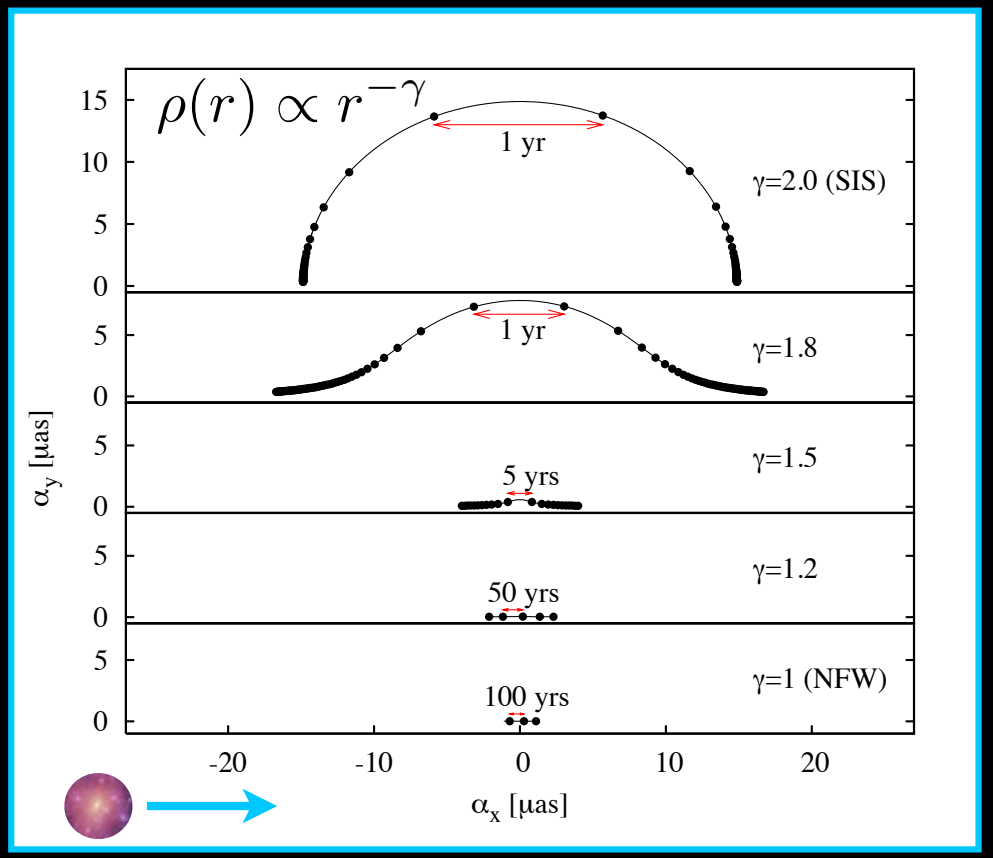
- UCMHs are too diffuse to be detected through photometric microlensing: $R_{\rm UCMH} \gg R_E$
- Local subhalos can be detected via astrometric microlensing, but they are too rare to be found in a blind search. *Erickcek & Law 2011*
- Nearby UCMHs produce bigger lensing signals, and they may be more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

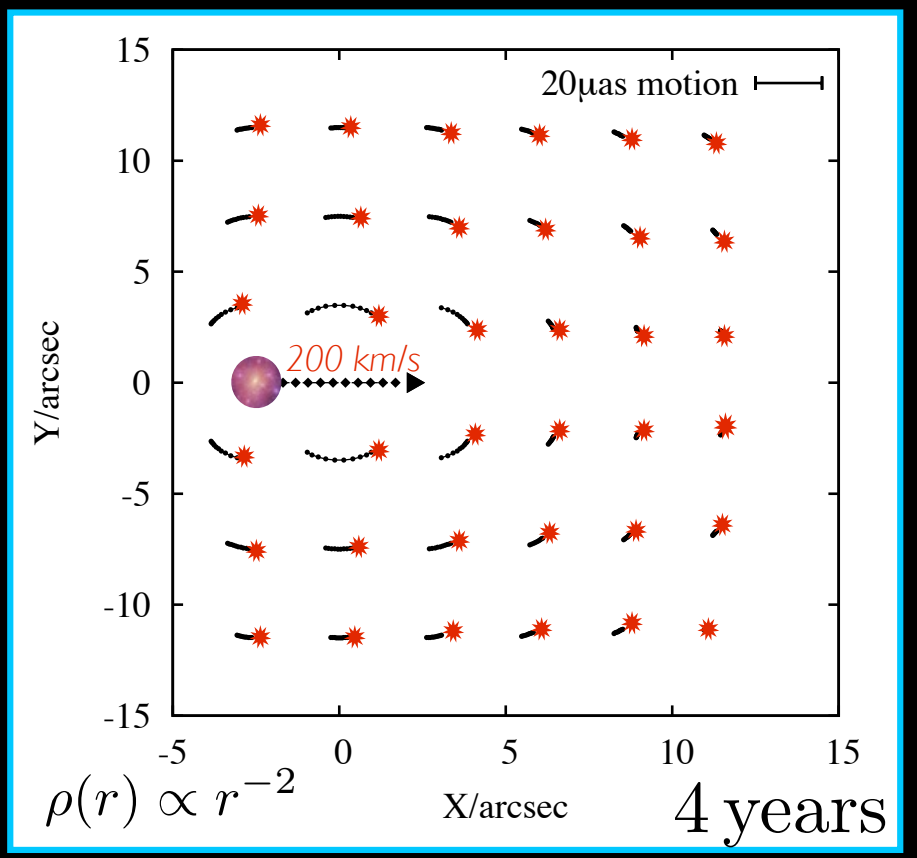


Astrometric Microlensing by Subhalos

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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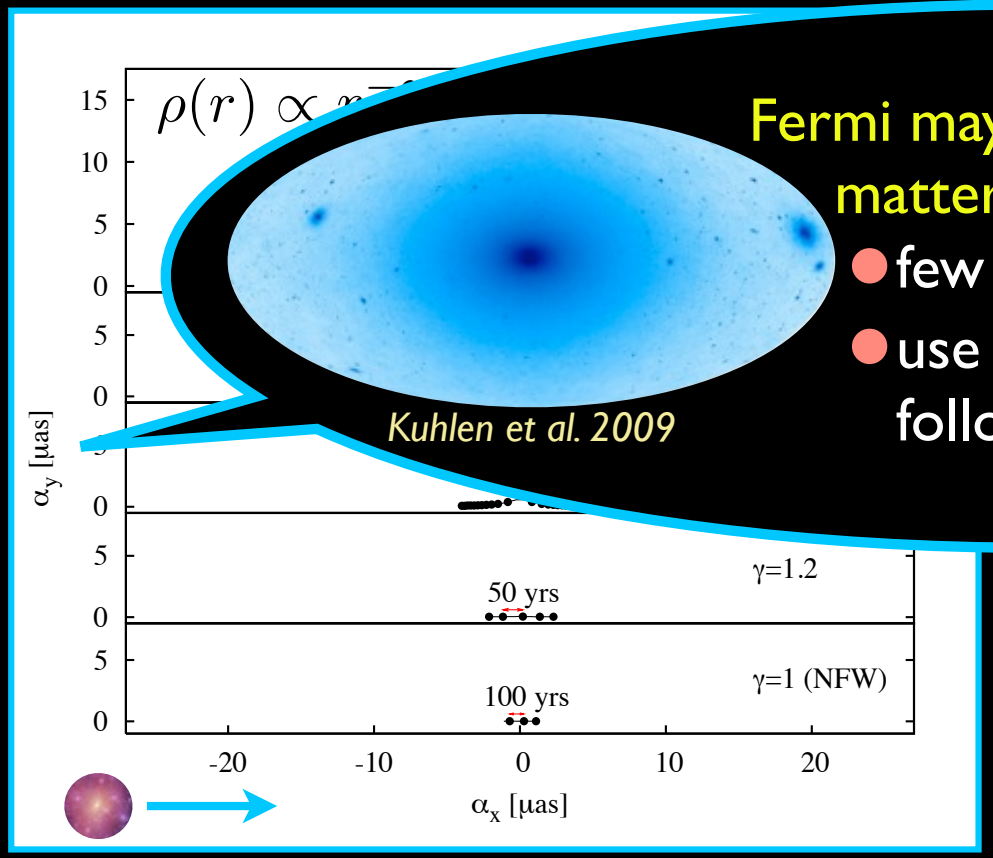

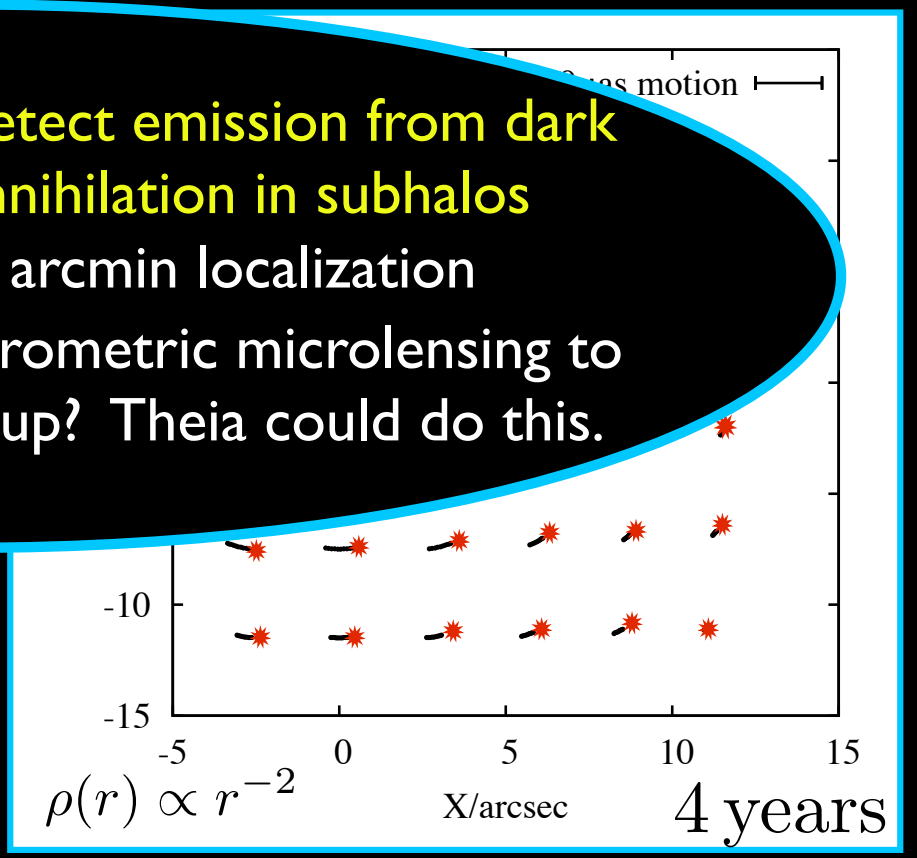

Kuhlen et al. 2009

Fermi may detect emission from dark matter annihilation in subhalos

- few sq. arcmin localization
- use astrometric microlensing to follow-up? Theia could do this.

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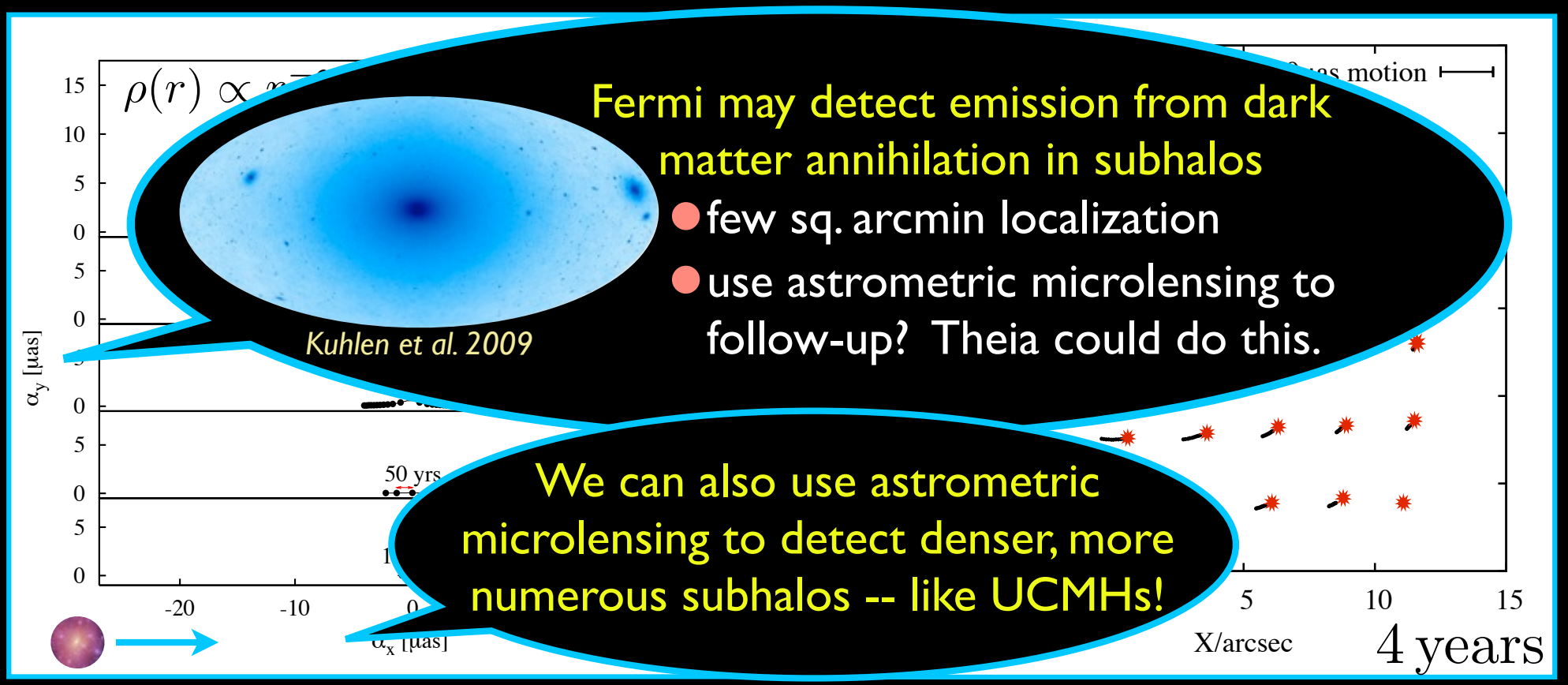

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UCMH Density Profiles

Microlensing depends on the UCMH density profile.

Secondary radial infall: $\rho(r) \propto \dfrac{M_{\rm UCMH}}{R_{\rm UCMH}^{3/4} r^{9/4}}$

Fillmore & Goldreich 1984
Bertschinger 1985
Ricotti & Gould 2009

$$M_{\rm UCMH}(z) = M_i \left(\frac{1+z_{\rm eq}}{1+z}\right)$$

UCMHs accrete mass

$$r_{\rm UCMH}(z) = 0.019 \left(\frac{1000}{1+z}\right) \left[\frac{M_{\rm UCMH}(z)}{M_\odot}\right]^{1/3} {\rm pc}$$

$\longrightarrow \rho(r)$ is constant

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Add a constant-density core: $\rho \propto \left(1 + \dfrac{r}{r_c}\right)^{-9/4}$

Ricotti, Ostriker & Mack 2008
Ricotti & Gould 2009

Non-radial infall: $(v_{\rm tan} > v_{\rm Kep})$

$$r_{\rm c,nr} = 1.5 \times 10^{-6} \left(\frac{1+z_t}{1000}\right)^{-2.41} \left(\frac{M_i}{M_\odot}\right)^{0.272} \text{pc}$$

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

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

UCMH 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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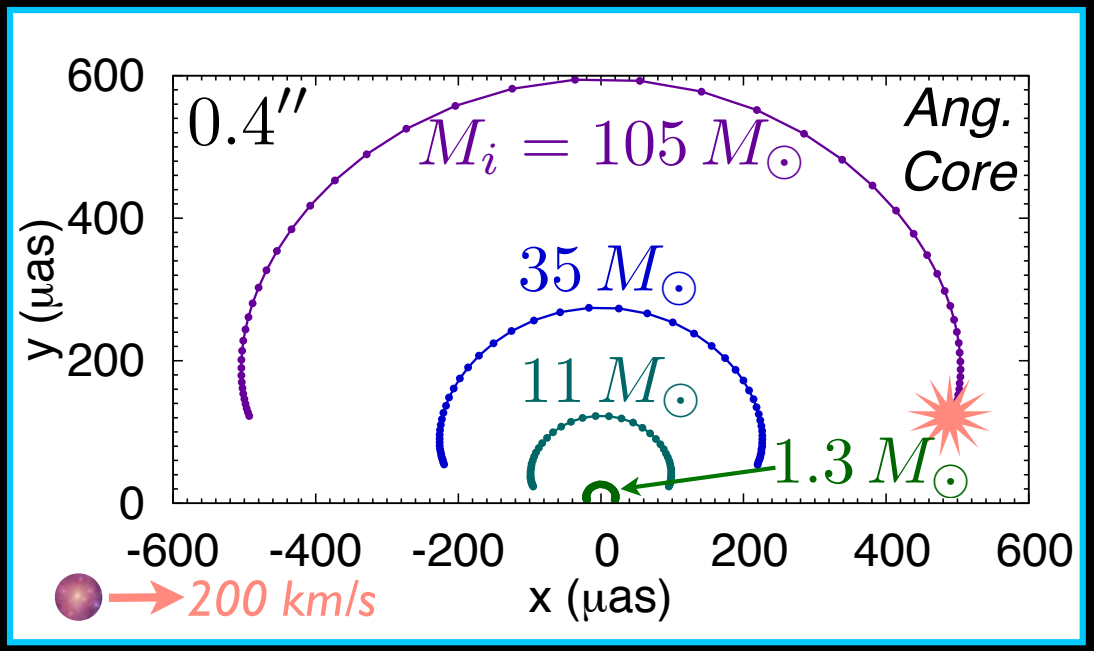

Li, Erickcek & Law 2012

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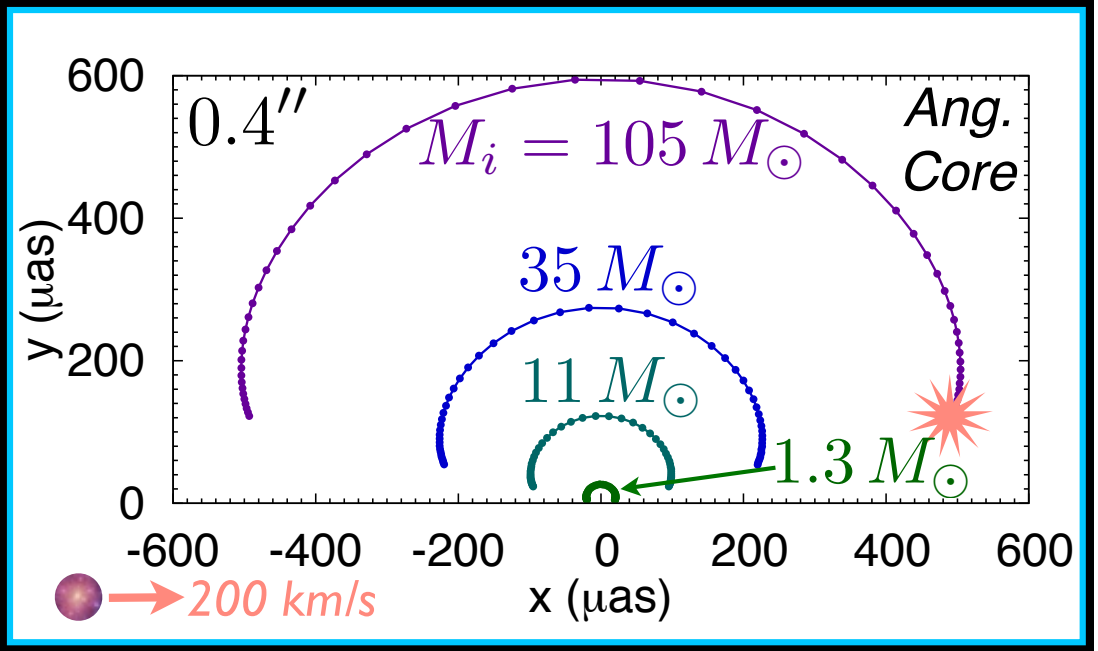

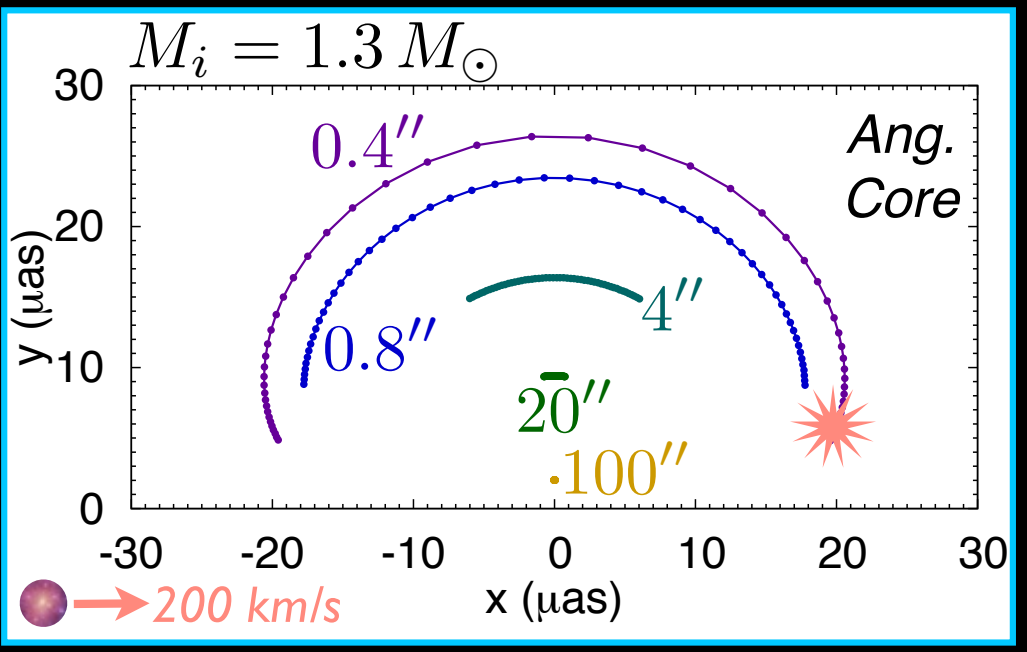

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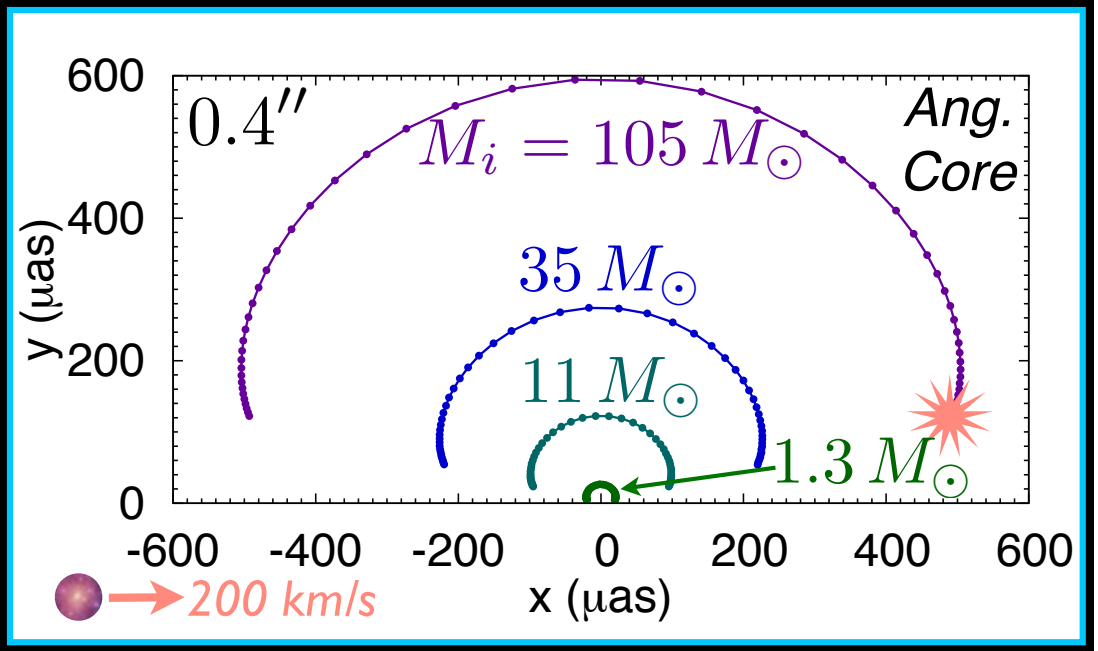
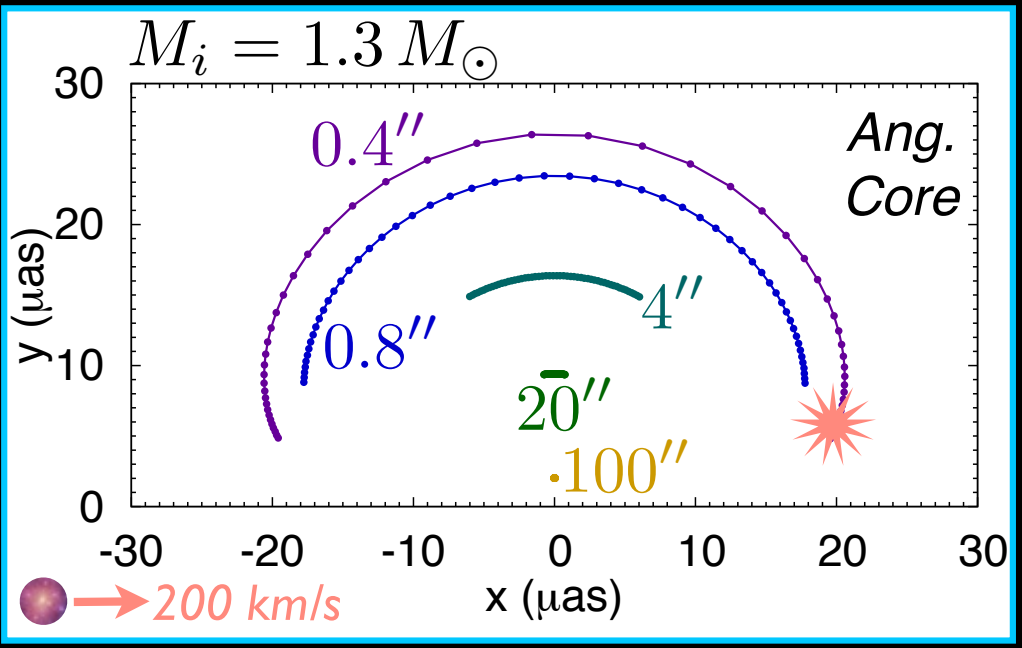
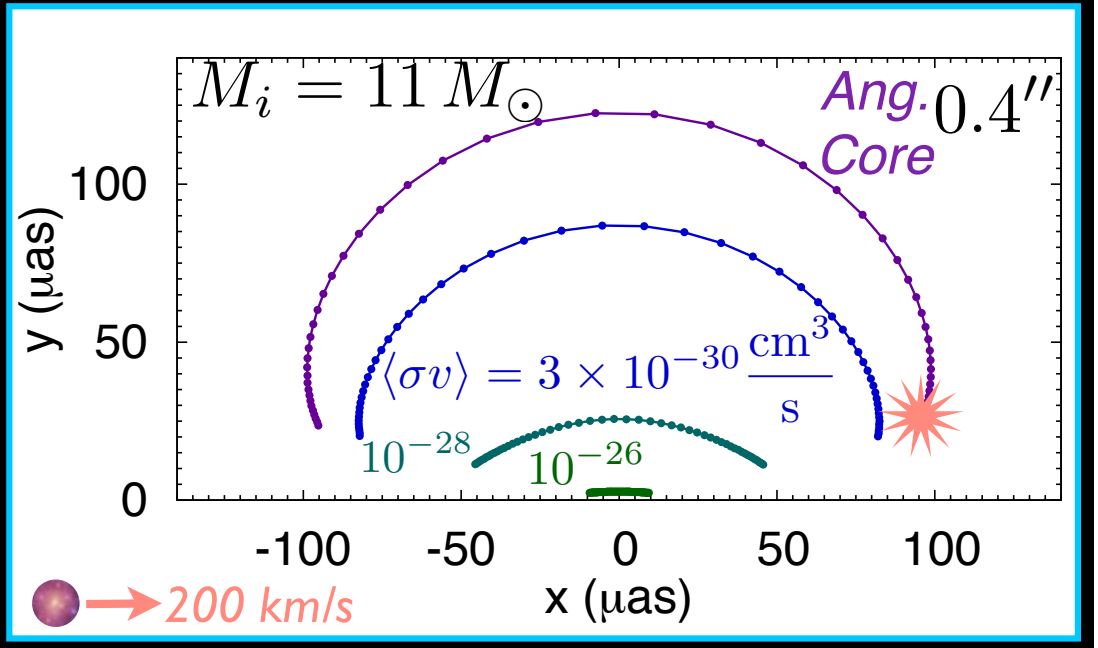
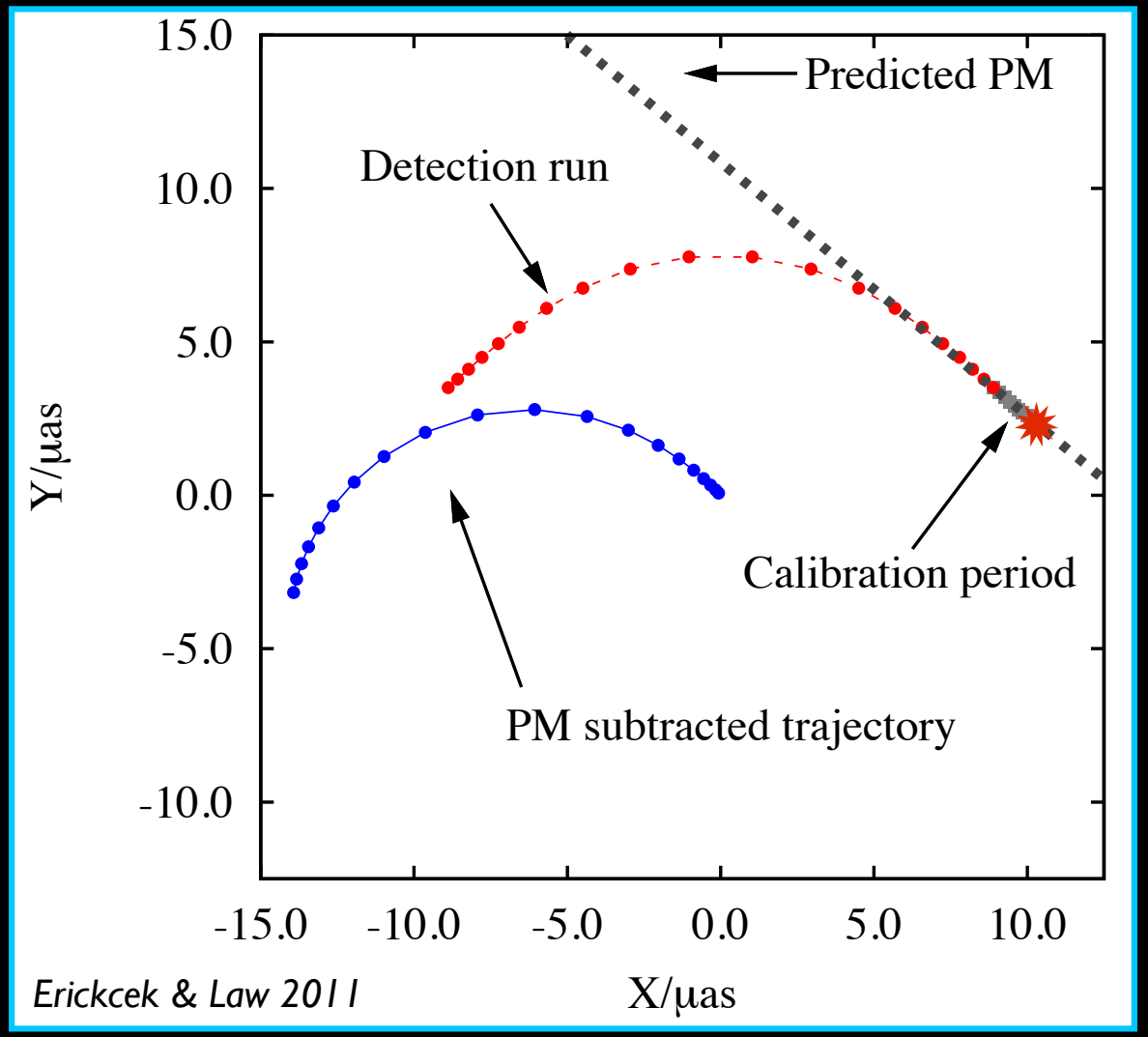






Our Detection Strategy

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.

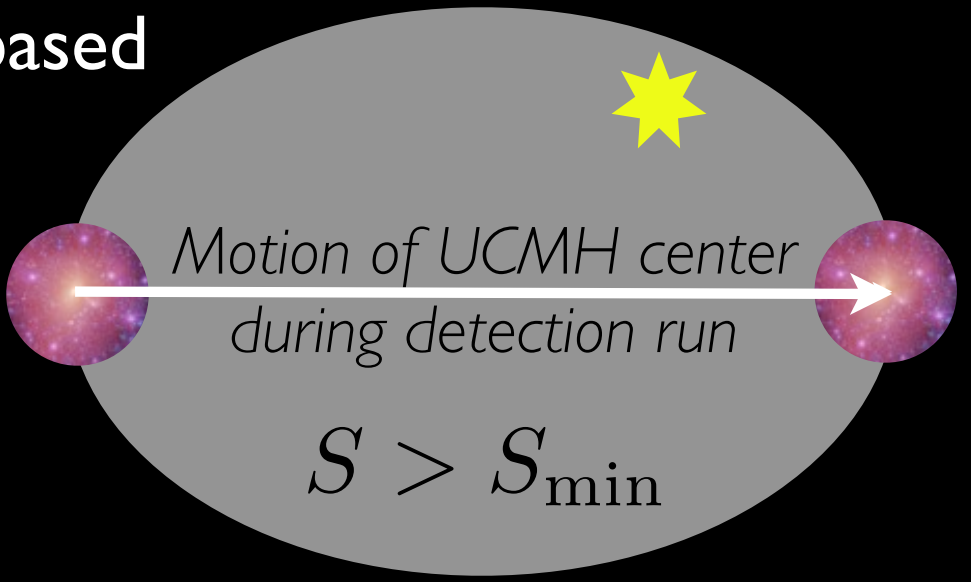
Star's true position is at the origin.
Subhalo center passes star two years into the detection run.

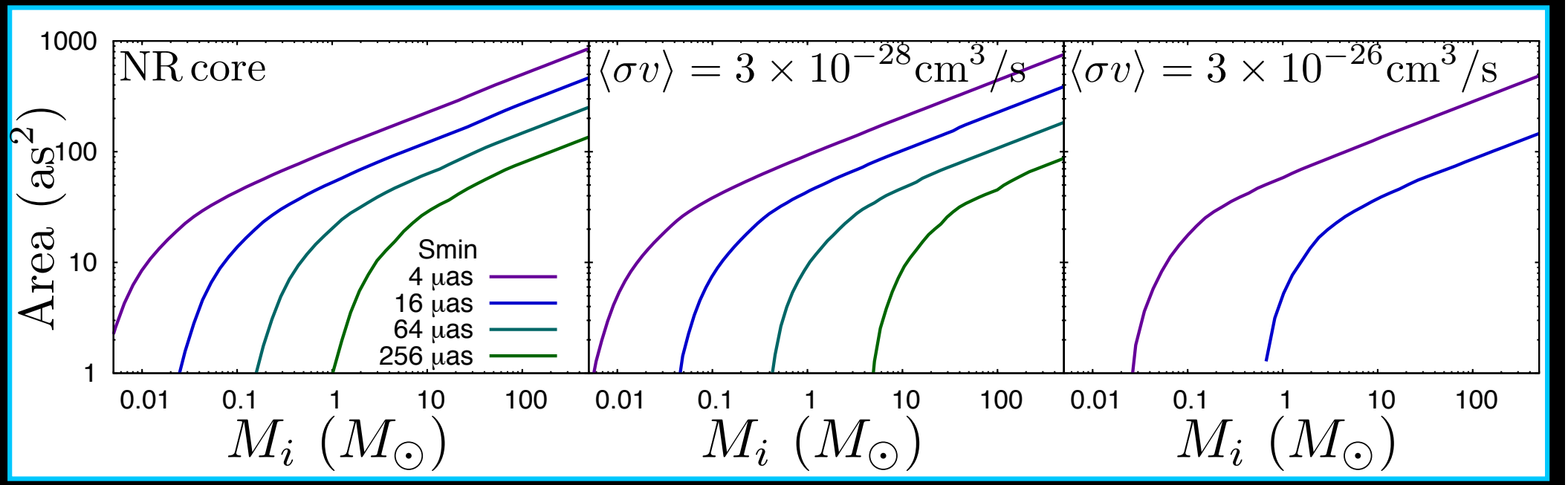
Lensing Cross Sections

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 $5\sigma : 256\mu{\rm as}$





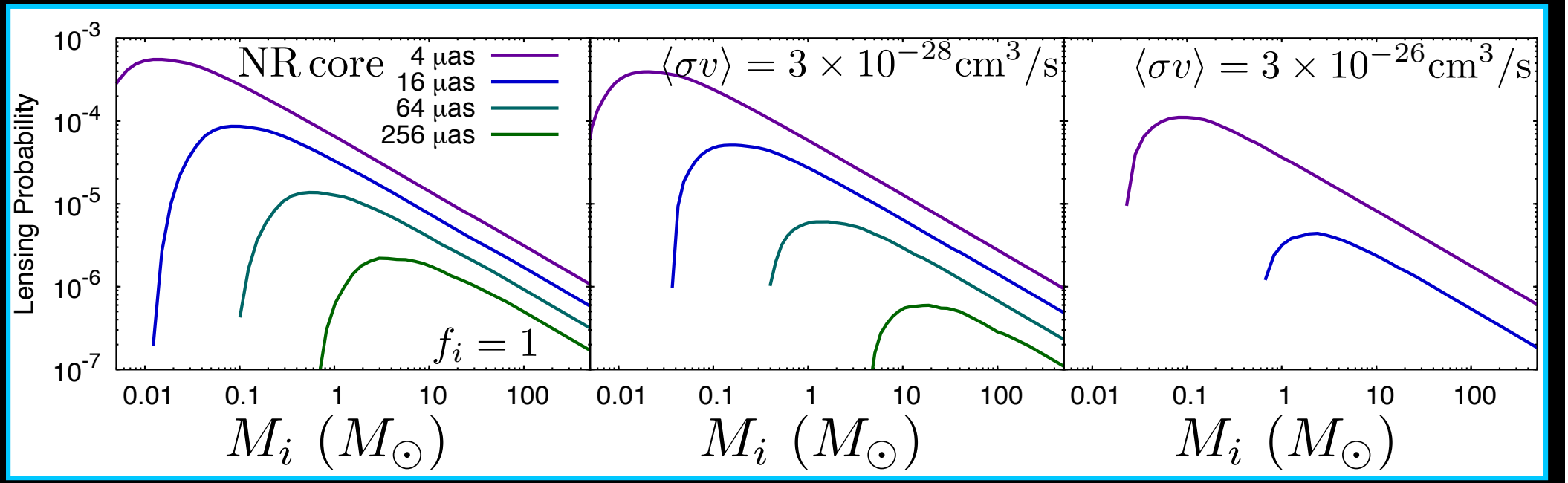
Lens distance: 50 pc; Lens velocity: 200 km/s; Source Distance: 2 kpc

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*



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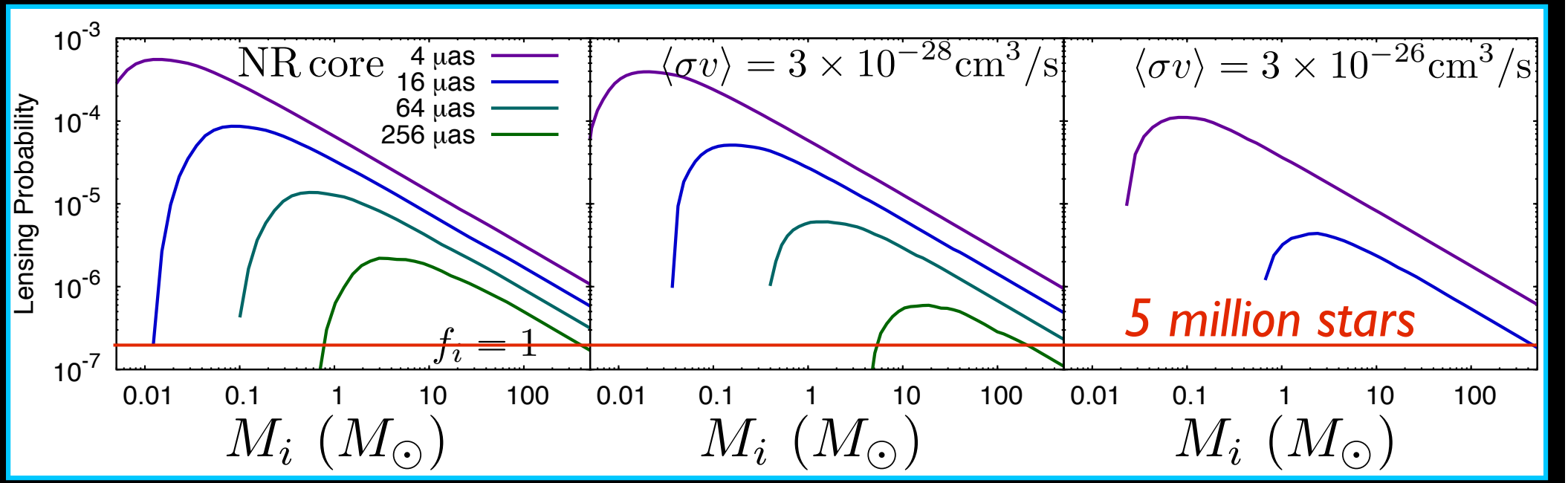


Lens velocity: 200 km/s; Source Distance: 2 kpc

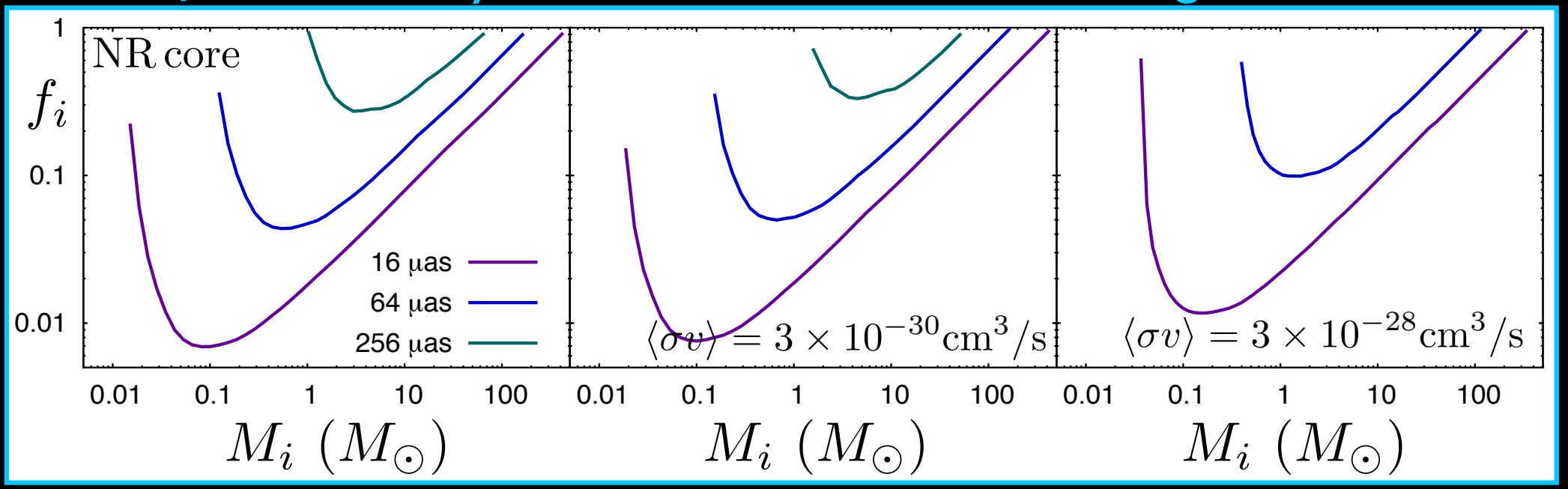
Constraining the UCMH fraction

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



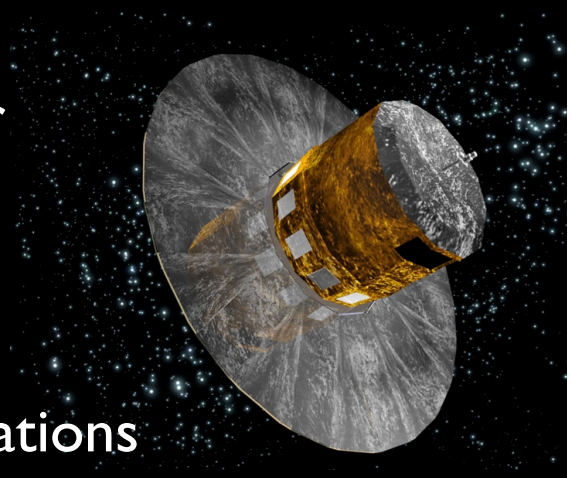
$f_i \equiv$ *fraction of DM in UCMHs initially*

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

Probing the Primordial Perturbations

Gaia specifications:

- 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

Li, Erickcek & Law 2012

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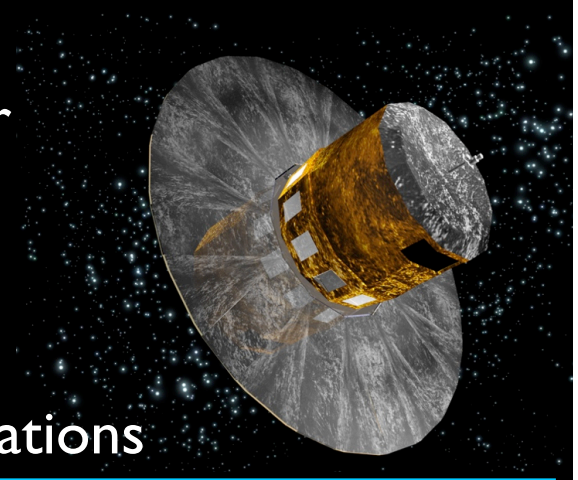

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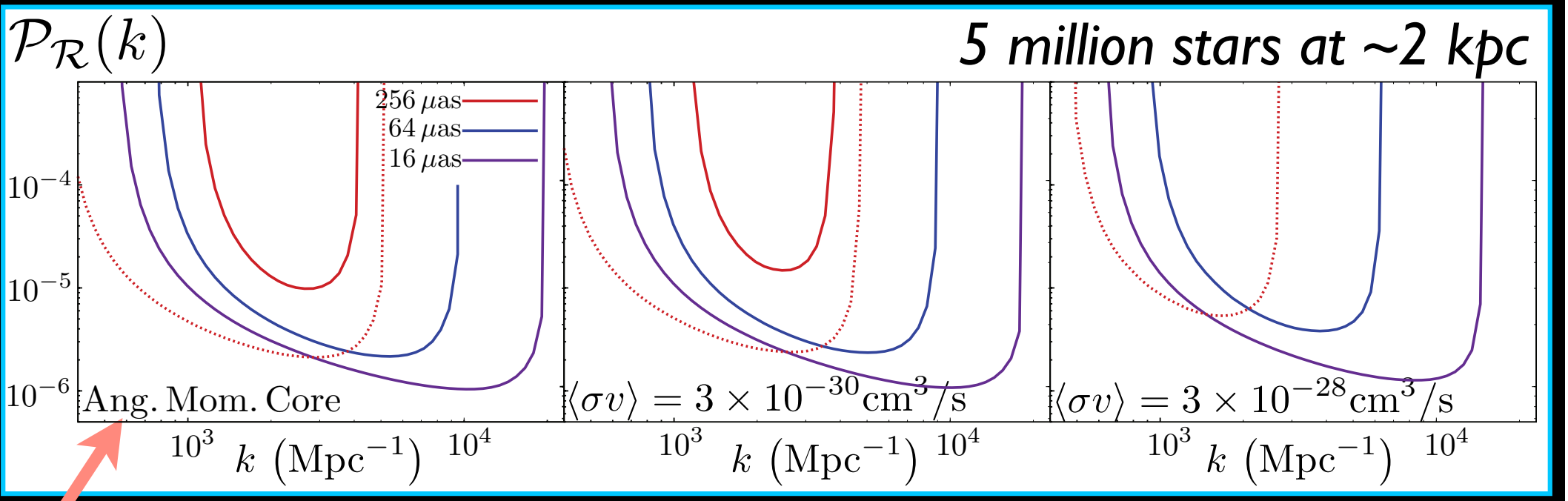


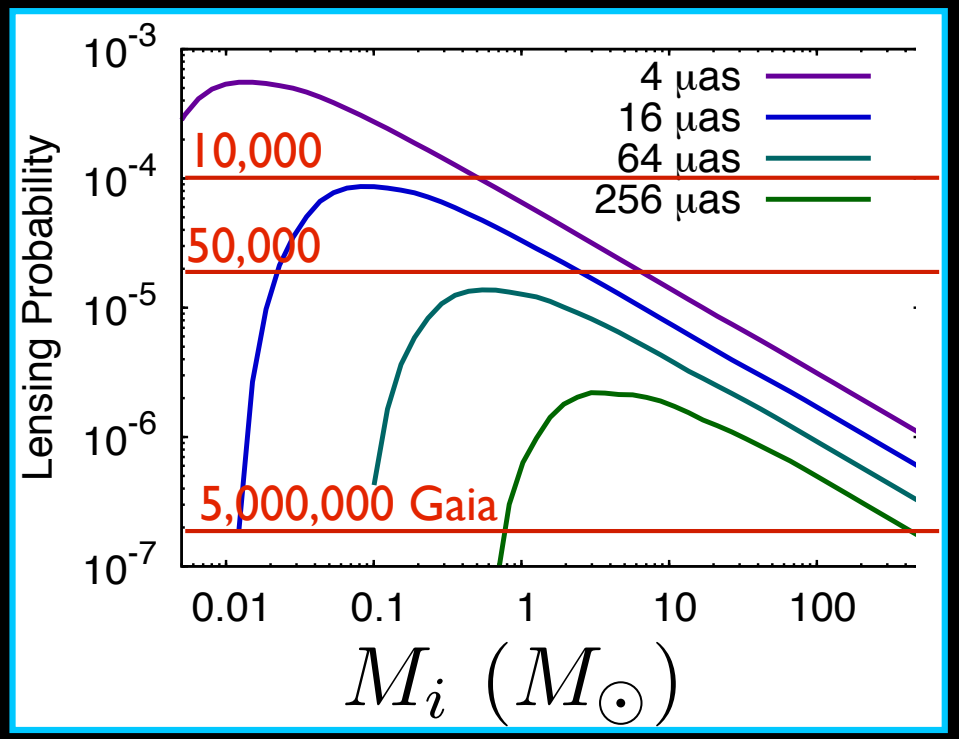
Most conservative case: Fermi gives a stronger bound if DM self-annihilation diminishes lensing signal.

Li, Erickcek & Law 2012

Possible Improvements with Theia

Theia's improved astrometric sensitivity makes it capable of detecting smaller UCMHs and thus probing smaller scales.

- Higher sensitivity increases the lensing probability, so fewer targets are needed.
- Fewer targets makes lower SNRs acceptable: $S_{\rm min} \simeq {\rm SNR} \times 1.5\sigma_{\rm inst}$
- 2uas precision (R=14) makes $S_{\rm min} = 16\mu{\rm as}\ \ (5\sigma)$: 50,000 targets
- 0.7uas precision (R=11) makes $S_{\rm min} = 4\mu{\rm as}\ \ (4\sigma)$: 10,000 targets



Li, Erickcek & Law 2012

- Gaia: $M_i \simeq 8M_\odot \Rightarrow k \simeq 3{\rm kpc}^{-1}$
- Theia $S_{\rm min} = 16\mu{\rm as}\ \ (5\sigma)$

  $M_i \simeq 0.06M_\odot \Rightarrow k \simeq 15{\rm kpc}^{-1}$
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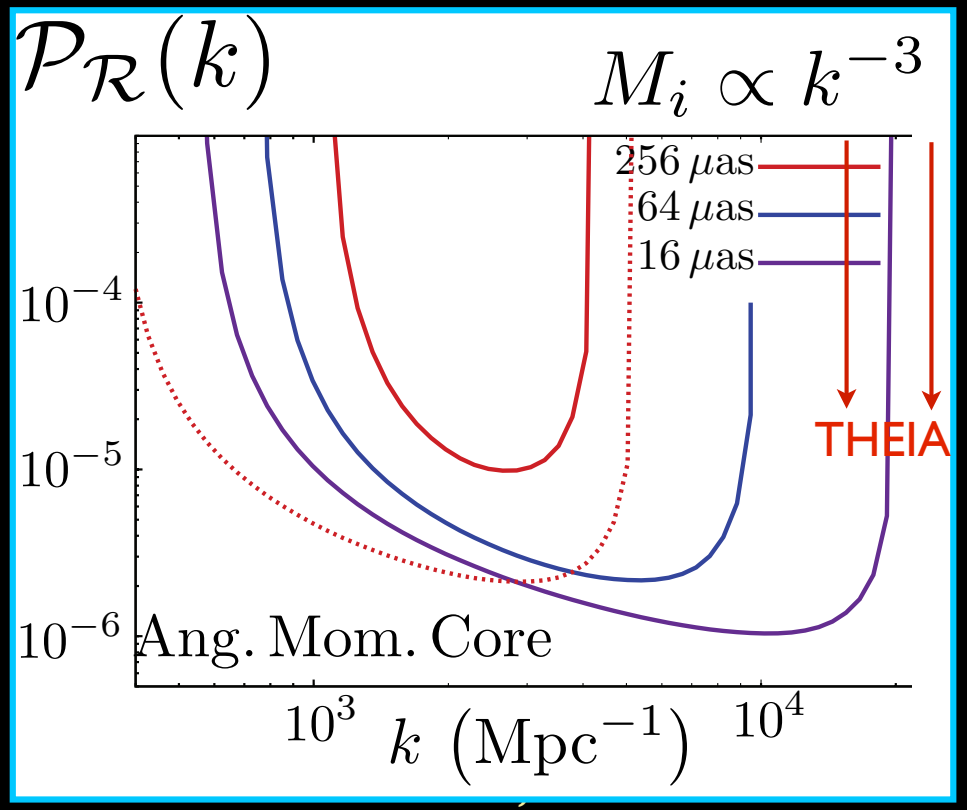

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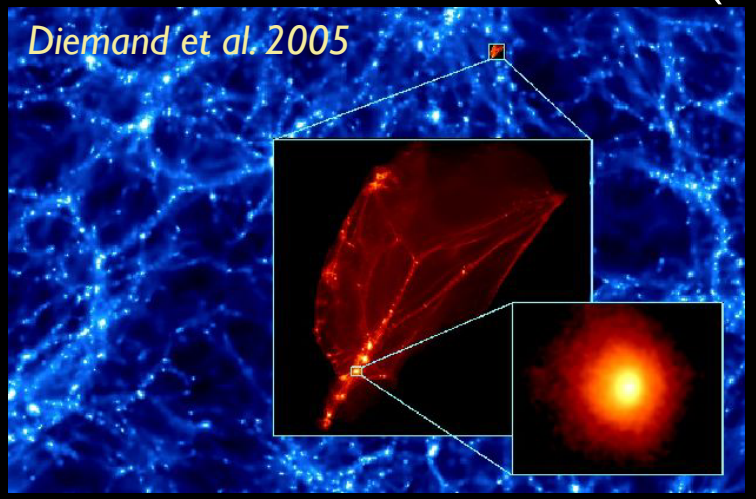
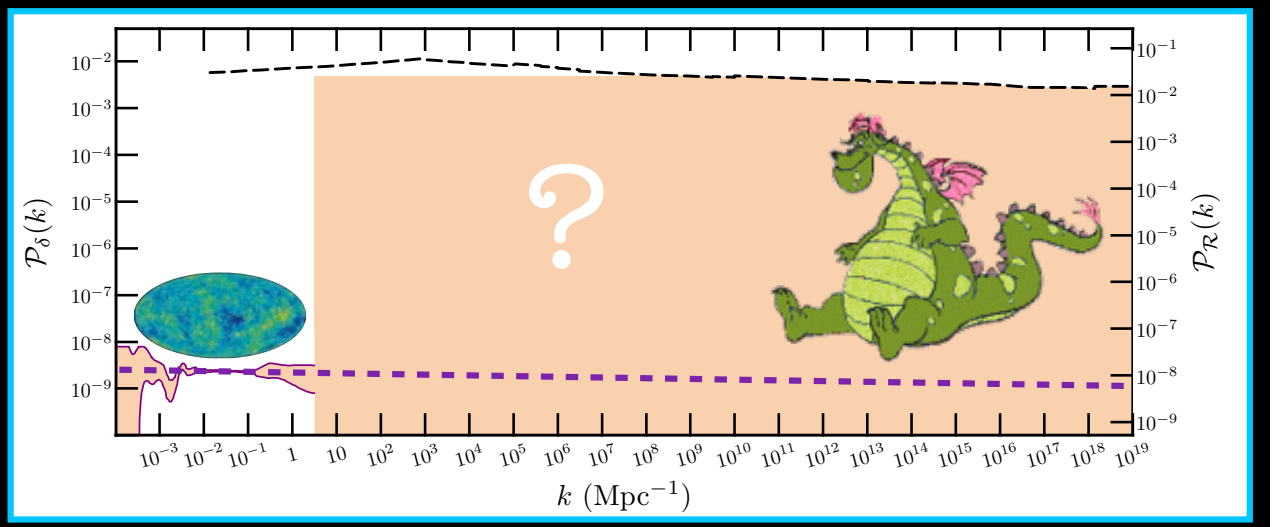
UCMHs Probe Inflation!

Searching for ultra-compact minihalos can provide new constraints on the primordial power spectrum generated during inflation. *Li, AE, Law (2012)*

- UCMHs produce distinctive astrometric microlensing signatures.
- 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.
- A Theia search could extend these bounds to scales of $10^4 - 10^5\,\mathrm{Mpc}^{-1}$
- But see Clark, Lewis, Scott (1509.02941) -- better limits from pulsar timing?





Useful Stuff

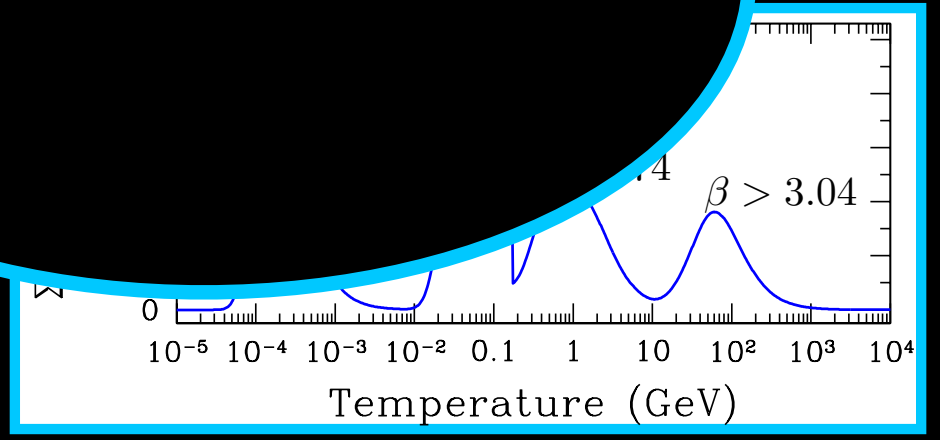
$V''(\phi)$

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

- stuff
- sfuff

Densities in both fram

Chameleon gravity

More stuff

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