Cosmology with ultracompact minihalos

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Based on:

PS, Adams, Bringmann & Easther, in prep.
Shandera, PS & Erickcek, in prep.
Bringmann, PS & Akrami, *Phys. Rev. D*, 2012 arXiv:1110.2484
PS & Sivertsson, *Phys. Rev. Lett.*, 2009 arXiv:0908.4082

Slides available from http://www.physics.mcgill.ca/~patscott

Outline

1. Background and observational limits
2. Cosmological implications

Background

Question

What is an *ultracompact* minihalo (UCMH)?

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Answer

A DM halo that collapses shortly after matter-radiation equality

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Answer

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'Shortly' means z_{collapse} is $O(100)$ or more

$\Longrightarrow$ isolated collapse

$\Longrightarrow$ formation by radial infall

$\Longrightarrow$ very steep density profile $\rightarrow \rho \propto r^{-9/4}$

$\Longrightarrow$ excellent indirect detection targets

PS & Sivertsson *Phys. Rev. Lett.* 2009
Lacki & Beacom *ApJL* 2010

Also good lensing prospects Ricotti & Gould *ApJ* 2009; Li et al *Phys. Rev. D* 2012

Background

Question

How would UCMHs be created?

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Answer

Large amplitude density perturbations in the early Universe (e.g. on small scales)

- Small-scale power in primordial perturbation spectrum (e.g. features in the inflaton potential)
- Phase transitions
- Other seeds (e.g. cosmic strings)

UCMH formation

Conditions for formation

- Seeded well before matter-radiation equality
- Requires $\delta \gtrsim \mathcal{O}(10^{-3})$
(compare with normal inflationary perturbations $\delta \sim 10^{-5}$)
- $\longrightarrow$ much more likely than PBH formation ($\delta \gtrsim 0.3$)

Usefulness

- UCMH mass is set by horizon scale at time of horizon entry
- $\implies$ specific UCMH mass $\equiv$ specific cosmological scale
- $\implies$ limit on abundance of specific mass halo $\equiv$ limit on power on specific scale *k*

UCMH relic density calculation

- For some distribution of perturbations $\mathrm{pdf}(\delta)$

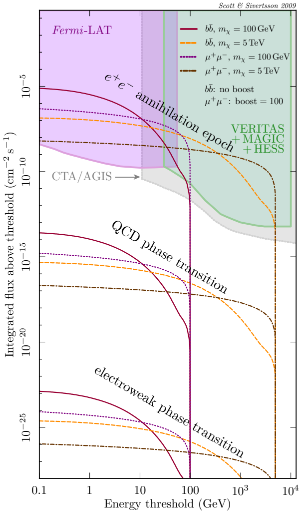
$$f_{\mathrm{UCMH}} = \left(\frac{1+z_{\mathrm{eq}}}{1+z_{\mathrm{stop}}}\right) \int_{\delta_{\mathrm{min}}}^{\delta_{\mathrm{PBH}}} \mathrm{pdf}(\delta)\, \mathrm{d}\delta \qquad (1)$$

- For Gaussian perturbations,

$$\mathrm{pdf}(\delta) = \frac{1}{\sqrt{2\pi}\sigma^2_{\chi,H}(z_{\mathrm{X}}, R)} \exp\left(-\frac{\delta^2}{2\sigma^2_{\chi,H}(z_{\mathrm{X}}, R)^2}\right) \qquad (2)$$

- Improved $\sigma^2_{\chi,H}$ using top hat window function
- Explicit calculation of δ_{min}

Observability in gamma-rays

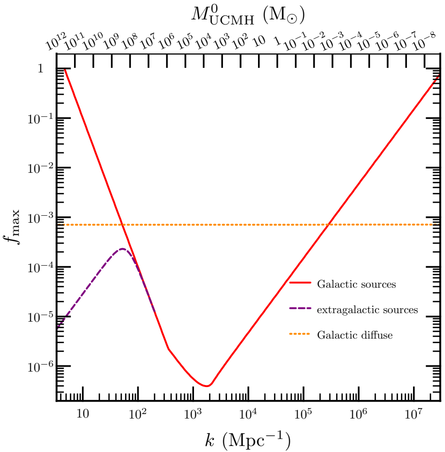


- Potential sources for *Fermi*, VERITAS, HESS & MAGIC
- Detectability depends mostly on
  - UCMH formation time ($\equiv$ mass)
  - UCMH abundance ($\equiv$ mean distance from us)
- Not ***strongly*** dependent on the WIMP model employed

PS & Sivertsson, *Phys. Rev. Lett.* 2009

Limits on present-day UCMH abundance with *Fermi*

- 1-year, 95% CL upper limits
- Based on public *Fermi* point source sensitivity
- Proper statistical treatment of observable limit
- Rather conservative assumptions:
  - 100% $b\bar{b}$
  - $\langle \sigma v \rangle = 3 \,.\, 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
  - $m_\chi = 1$ TeV
  - no DM minihalo detected[a]



Bringmann, PS & Akrami, *Phys. Rev. D* 2012

[a] 2FGL has $\leq$9, $\sim$60% expected to be blazars $\Longrightarrow$ $\lesssim$ 1 or 2 in 1FGL; see 1111.2613 & 1007.2644

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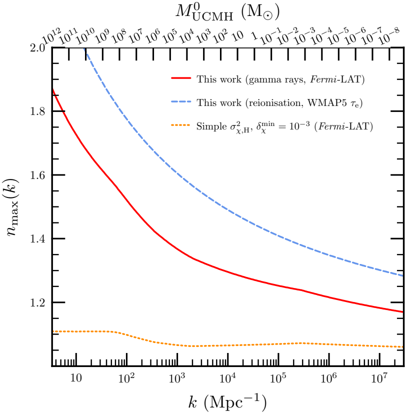
Limits on scale-free primordial power spectrum

$$\sigma^2_{\chi,H}(R) \propto \delta^2_H(t_{k_0}) \left(\frac{k}{k_0}\right)^{n-1}$$

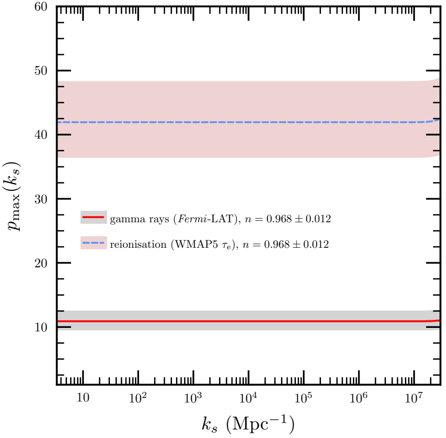
- Improved $\sigma^2_{\chi,H}$ using top hat window function
- Explicit calculation of $\delta_{\rm min}$
  (Solution to linear growth eqs; $\delta = 1.686$ during matter domination in linear approximation $\implies \delta \to \infty$ in non-linear regime)
- Contribution of UCMHs to reionisation at $z \lesssim 30$ is constrained by WMAP τ (Zhang 2010)



Bringmann, PS & Akrami, *Phys. Rev. D* 2012

Limits on power spectrum with a step

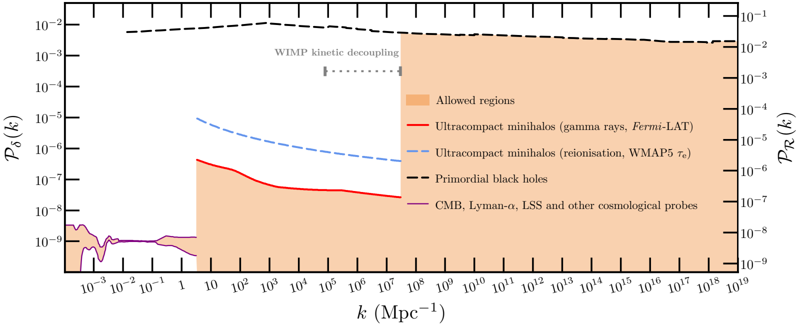
$$\delta_H^2(k) \rightarrow \delta_H^2(k)\left\{\theta\left(k_s - k\right) + p^2\theta\left(k - k_s\right)\right\} \quad (3)$$



Bringmann, PS & Akrami, *Phys. Rev. D* 2012

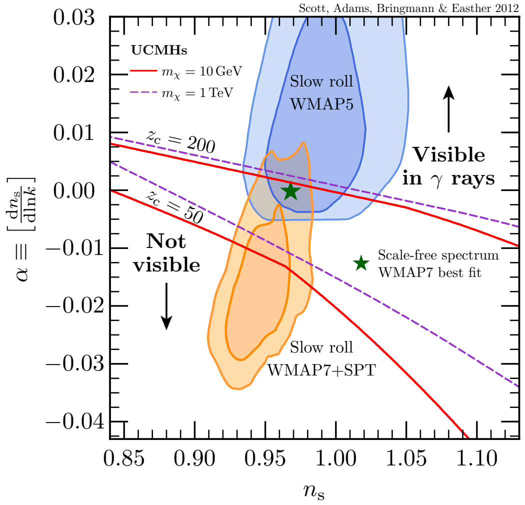
Generalised spectrum and curvature perturbation limits

Limits on $\mathcal{P}_\mathcal{R}$ from UCMHs ~5 orders better than from PBHs
$\implies$ strong limits on inflationary models



Bringmann, PS & Akrami, *Phys. Rev. D* 2012

Implications for inflation – slow-roll



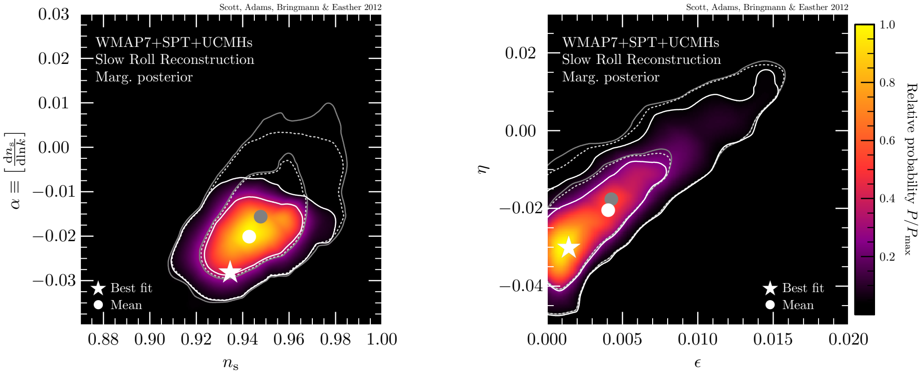
With $z_c = 200$ & $z_c = 50$ (vs 1000 in previous limits)

Excludes much of slow-roll inflationary parameter space

$\implies$ detection soon if $z_c \ll 200$ is reasonable

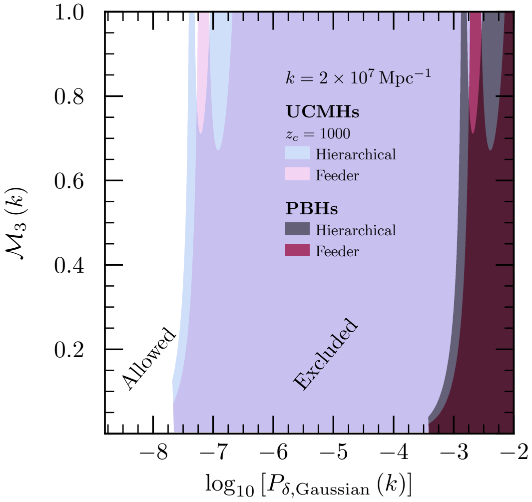
Otherwise, either slow-roll or WIMPs are starting to look a bit shaky…

Implications for inflation – slow-roll



Impacts on slow-roll reconstruction
(but beware extrapolation of α from WMAP scales)

Implications for inflation – non-gaussianities



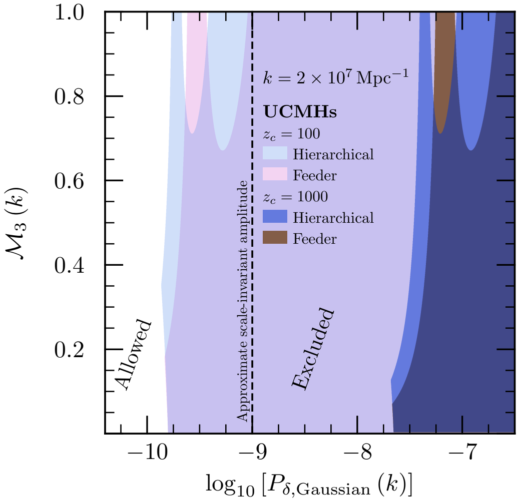
With $z_{\mathrm{c}} = 1000$

M_3 = parameter in NG expansion about Gaussian case ($\sim$ 'strength' of NG)

Expansion is not well-controlled everywhere

Can place limits on M_3 as function of Gaussian power

Implications for inflation – non-gaussianities



With $z_\mathrm{c} = 100$

Again, things get much more interesting with small z_c

→ can probe NG at the scale-invariant equivalent power level

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- Depending on formation scenario, limits are close to predictions of inflationary models
- Limits on non-gaussianities also possible
- *Much more detailed simulations of UCMH formation are required*

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3 Backup Slides

Implications of kinetic decoupling for step spectrum

$$\alpha_\chi^2 \rightarrow \int_0^\infty x^{n+2}\, T_\chi^2(x)\, W_{\mathrm{TH}}^2(x)/T_\chi^2(1) \left\{\theta\left(\frac{k_s}{k} - x\right) + p^2\theta\left(x - \frac{k_s}{k}\right)\right\} \mathrm{d}x$$