Indirect detection as a probe of the spectrum of primordial perturbations on small scales

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Based on Bringmann, PS, Akrami, in prep.
PS & Sivertsson, Phys Rev Lett 103:211301 (arXiv:0908.4082)

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

What is an *ultracompact* minihalo?

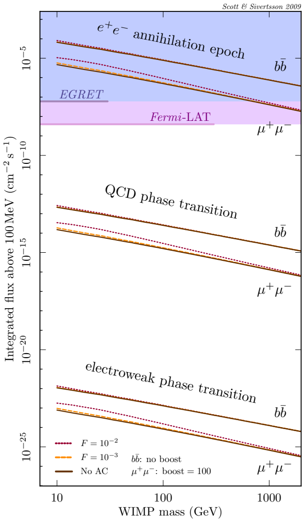
- Small-scale, large amplitude density perturbations in the early Universe create ultracompact minihalos (UCMHs)
  Ricotti & Gould (2009), Berezinsky et al. (multiple earlier papers)
- 'Failed primordial black holes'
- Very dense dark matter minihalos
- Enhanced perturbations produced by e.g. inflaton potential or phase transitions
- Non-baryonic, diffuse MACHOs
- Also excellent indirect detection targets

UCMH formation

- Formed (or at least 'seeded') well before matter-radiation equality
- Full gravitational collapse before $z = 1000$
- Requires $\delta \gtrsim \mathcal{O}(10^{-3})$
  (compare with normal inflationary perturbations $\delta \sim 10^{-5}$)
- $\longrightarrow$ much more likely than PBH formation ($\delta \gtrsim 0.3$)
- UCMH mass is set by horizon scale at time of transition
- $\implies$ specific UCMH mass $\equiv$ specific cosmological scale
- $\implies$ limit on abundance of specific mass halo $\equiv$ limit on power on specific scale k
  (Recent limits from Josan & Green (2010), improved analysis here)

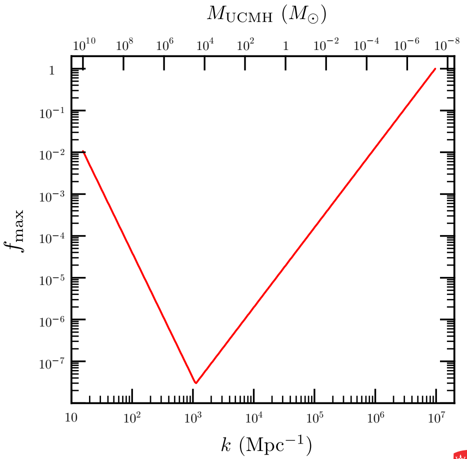
Gamma-ray fluxes from UCMHs

- Take e.g. $d = 100\,\mathrm{pc}$
- Minihalos produced at e.g. time of the e^+e^- annihilation epoch should be visible today by *Fermi* or HESS, or even in *EGRET* data
- Strongly constrains spectrum of perturbations formed at time of e^+e^- annihilation phase
- Gravitational contraction of UCMHs makes little difference



Limits on present-day UCMH abundance with *Fermi*

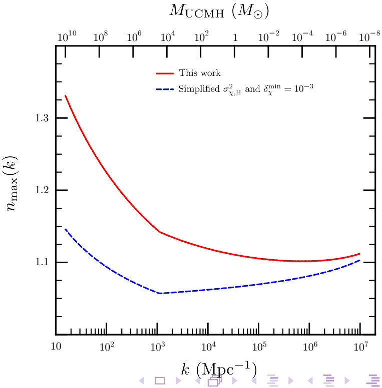
- 1-year, 5σ upper limits
- Based on public *Fermi* point source sensitivity
- Proper statistical treatment of observable limit
- Rather conservative assumptions:
  - 100% $b\bar{b}$
  - $\langle\sigma v\rangle = 3 \,.\, 10^{-26}\,\mathrm{cm^3\,s^{-1}}$
  - $m_\chi = 5\,\mathrm{TeV}$
  - no DM minihalo detected
- Limits essentially identical for e.g. $\mu^+\mu^-$ with $B = 100$



Scale-free (power law) spectrum

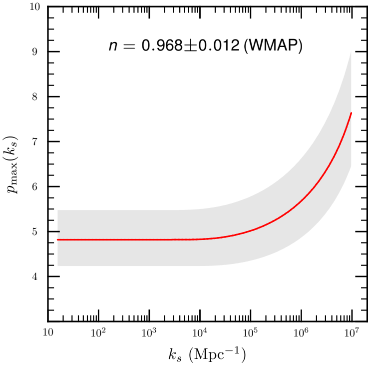
$$\sigma^2_{\chi,H}(R) \approx \delta^2_H(t_{k_0}) \left(\frac{k}{k_0}\right)^{n-1} \underbrace{\int_0^\infty x^{n+2}\, T^2_\chi(x)\, W^2_{\mathrm{TH}}(x)/\,T^2_\chi(1)\,\mathrm{d}x}_{\alpha^2_\chi} \qquad (1)$$

- Improved $\sigma^2_{\chi,H}$ using top hat window function
- Explicit calculation of δ_{min} (Solution to linear growth eqs; $\delta = 1.686$ during matter domination in linear approx $\implies \delta \to \infty$ in non-linear regime)



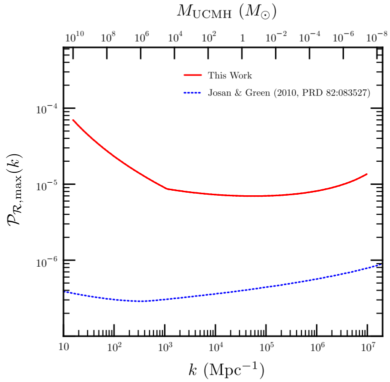
Spectrum with a step

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

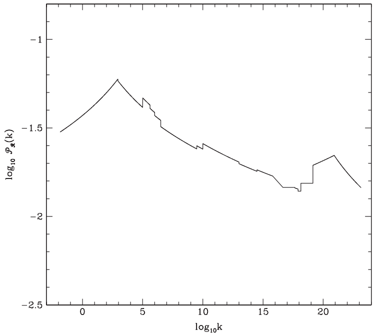


General spectrum and curvature perturbation limits

$$\sigma^2_{\chi,\mathrm{H}}(R) = \frac{1}{9}\mathcal{P}_\mathcal{R}(k_\mathrm{R}) \int_0^\infty x^{n_\mathrm{R}+2} W^2_\mathrm{TH}(x) W^2_\mathrm{TH}(x/\sqrt{3})\,\mathrm{d}x \qquad (3)$$



PBH limits – Josan, Green & Malik (2009)



Summary

- Ultracompact minihalos are promising indirect detection targets
- Could be visible by *Fermi*/VERITAS/HESS/CTA
- Assuming DM annihilates, non-observation places limits on primordial perturbations at small scales
- Derived limits are much tighter than existing ones from primordial black holes
- ...but weakened slightly by careful treatment of mass variance, radial profile and minimum density contrast required for formation

UCMH density profiles

- Initially single UCMH per horizon, minimal initial angular momentum
- $\implies$ UCMHs form via radial infall
- $\implies$ Very steep radial density profile

$$\rho_\chi(r) = \frac{3 f_\chi M_{\mathrm{UCMH}}}{16\pi R_{\mathrm{UCMH}}^{\frac{3}{4}} r^{\frac{9}{4}}}, \tag{4}$$

- Truncated at self-annihilation radius r_{SA}, and radius r_{AM} where gas angular momentum violates radial infall approx.

$$\rho(r_{\mathrm{SA}}) = \frac{m_\chi}{\langle\sigma v\rangle(t - t_{\mathrm{i}})}, \qquad r_{\mathrm{AM}} = \frac{\sigma_{\mathrm{DM}}^{\frac{8}{7}} R_{\mathrm{UCMH}}^{\frac{11}{7}}}{G^{\frac{4}{7}} M_{\mathrm{UCMH}}^{\frac{4}{7}}} \tag{5}$$

UCMH relic density calculation

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

$$f_{\mathrm{UCMH}} = \left(\frac{1+z_{\mathrm{eq}}}{1+z_{\mathrm{stop}}}\right)\int_{\delta_{\mathrm{min}}}^{\delta_{\mathrm{PBH}}} \mathrm{pdf}(\delta)\,\mathrm{d}\delta \qquad (6)$$

- For Gaussian perturbations,

$$\mathrm{pdf}(\delta) = \frac{1}{\sqrt{2\pi}\sigma^2_{\chi,H}(z_{\mathrm{X}},R)}\exp\left(-\frac{\delta^2}{2\sigma^2_{\chi,H}(z_{\mathrm{X}},R)^2}\right) \qquad (7)$$

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

Best scale for limits on step spectrum

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