ELECTROWEAK-SYMMETRIC DARK MONOPOLES FROM PREHEATING

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MOTIVATION

Can there be pockets of the universe with a different electroweak VEV?

Even with electroweak symmetry restoration?

Yes!

Only requirement is dark sector with two simple ingredients:

1. Dark ‘t Hooft-Polyakov monopoles
2. A Higgs-portal coupling to the visible sector

OUTLINE

- Review of ‘t Hooft-Polyakov monopoles
- Higgs-portal dark monopoles
  - Modified EW VEV inside monopole
- Cosmological monopole production
  - Production during a thermal phase transition
  - Production during preheating
- Phenomenology

‘T HOOFT-POLYAKOV MONOPOLES

‘T HOOFT-POLYAKOV MONOPOLES

Consider the gauge symmetry breaking SU(2)/U(1) by a triplet scalar:

$$\mathcal{L}_{\text{dark}} = \frac{1}{2}(D_\mu \Phi)^2 - \frac{1}{4}\text{Tr}(F_{\mu\nu}F^{\mu\nu}) - \frac{\lambda}{4}\left(|\Phi|^2 - f^2\right)^2$$

In the “hedgehog gauge”

$$\Phi^a = \hat{r}^a\, f\, \phi(r)\,, \qquad A_i^a = \frac{1}{g}\,\epsilon^{aij}\,\hat{r}^j\left(\frac{1-u(r)}{r}\right)$$

The time-independent equations of motion are

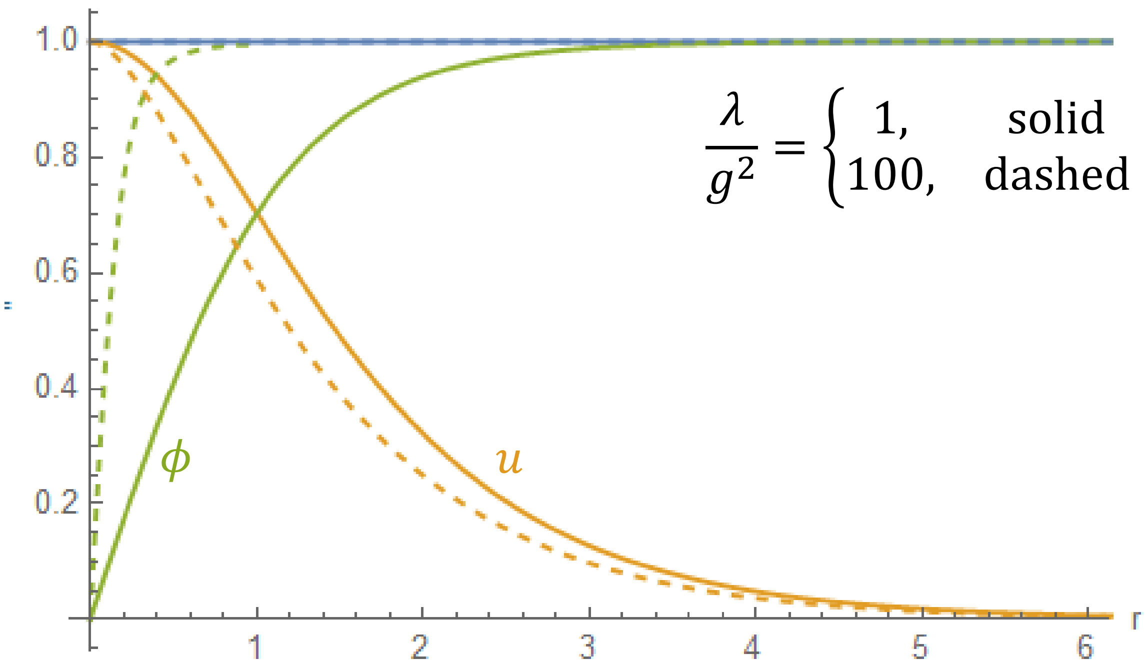
$$\begin{aligned} \frac{d^2\phi}{d\bar{r}^2} + \frac{2}{\bar{r}}\frac{d\phi}{d\bar{r}} &= \frac{2\,u^2\,\phi}{\bar{r}^2} + \frac{\lambda}{g^2}\phi\,(\phi^2 - 1)\,, \\ \frac{d^2 u}{d\bar{r}^2} &= \frac{u\,(u^2-1)}{\bar{r}^2} + u\,\phi^2\,, \end{aligned}$$

$$\left\{\bar{r} \equiv g\,f\,r = m_{W'}\,r\right\}$$

Want to solve with boundary conditions

$$\phi(0) = 0\,, \quad \phi(\infty) = 1\,, \quad u(0) = 1\,, \quad u(\infty) = 0$$

‘T HOOFT-POLYAKOV MONOPOLES



Large-radius behavior:

$$u \propto e^{-m_{W'} r}$$

$$1 - \phi \simeq \frac{c_1}{m_{W'} r} e^{-m_{h'} r} + \frac{c_2}{m_{h'}^2 r^2} e^{-2 m_{W'} r}$$

$$\left\{ \begin{aligned} m_{W'} &= g f \\ m_{h'} &= \sqrt{2\lambda} f \end{aligned} \right\}$$

‘T HOOFT-POLYAKOV MONOPOLES

The monopole radius, defined by the ϕ profile, is

$$R_{\text{Ⓜ}} \simeq \min[m_{h'}^{-1}, m_{W'}^{-1}]$$

The monopole mass is

$$\begin{aligned} M_{\text{Ⓜ}} &= \int 4\,\pi\, r^2 \left(\frac{1}{2} B_i^a\, B_i^a + \frac{1}{2} (D_i \Phi^a)(D_i \Phi^a) + V(\Phi) \right) \\ &= \frac{4\pi f}{g} \int d\bar{r} \bar{r}^2 \left(\frac{\bar{r}^2\, \phi'^2 + 2\, u^2 \phi^2}{2\, \bar{r}^2} + \frac{(1-u^2)^2 + 2\, \bar{r}^2\, u'^2}{2\, \bar{r}^4} + \frac{\lambda}{4 g^2} (\phi^2 - 1)^2 \right) \equiv \frac{4\pi f}{g} Y(\lambda/g^2) \end{aligned}$$

Both can be large, even macroscopic, given suitably small g and λ.

We’ll take $\lambda \lesssim g^2$ so that the radius is maximized for given g, f.

HIGGS-PORTAL DARK MONOPOLES

HIGGS PORTAL

Higgs portal couplings at the renormalizable level:

$$V(\Phi, H) = \frac{\lambda_\phi}{4}\,|\Phi|^4 - \frac{1}{2}\,\mu_\phi^2\,|\Phi|^2 + \lambda_h\,(H^\dagger H)^2 + \mu_h^2\,H^\dagger H - \frac{1}{2}\,\lambda_{\phi h}|\Phi|^2 H^\dagger H + V_0$$

VEVs:

$$f^2 = \frac{2\,\mu_\phi^2 + \lambda_{\phi h} v^2}{2\,\lambda_\phi}\,, \qquad v^2 = \frac{-2\,\mu_h^2 + \lambda_{\phi h} f^2}{2\,\lambda_h}$$

Cases with non-zero VEVs:

EW restoration	Case I :	$\mu_\phi^2 > 0\,,$	$\mu_h^2 > 0\,,$	$\lambda_{\phi h} > 0$	
	Case II :	$\mu_\phi^2 > 0\,,$	$\mu_h^2 < 0\,,$	$\lambda_{\phi h} > 0$	← Smaller EW VEV
Larger EW VEV	Case III :	$\mu_\phi^2 > 0\,,$	$\mu_h^2 < 0\,,$	$\lambda_{\phi h} < 0$	
	Case IV :	$\mu_\phi^2 < 0\,,$	$\mu_h^2 < 0\,,$	$\lambda_{\phi h} > 0$	←

EQUATIONS OF MOTION

Recall the EOM without the Higgs portal

$$\begin{aligned}
\frac{d^2\phi}{d\bar{r}^2} + \frac{2}{\bar{r}}\frac{d\phi}{d\bar{r}} &= \frac{2\,u^2\,\phi}{\bar{r}^2} + \frac{\lambda}{g^2}\phi\,(\phi^2 - 1)\,, \\
\frac{d^2u}{d\bar{r}^2} &= \frac{u\,(u^2 - 1)}{\bar{r}^2} + u\,\phi^2\,,
\end{aligned}$$

With boundary conditions

$$\phi(0) = 0\,, \quad \phi(\infty) = 1\,, \quad u(0) = 1\,, \quad u(\infty) = 0$$

EQUATIONS OF MOTION

Adding the Higgs portal:

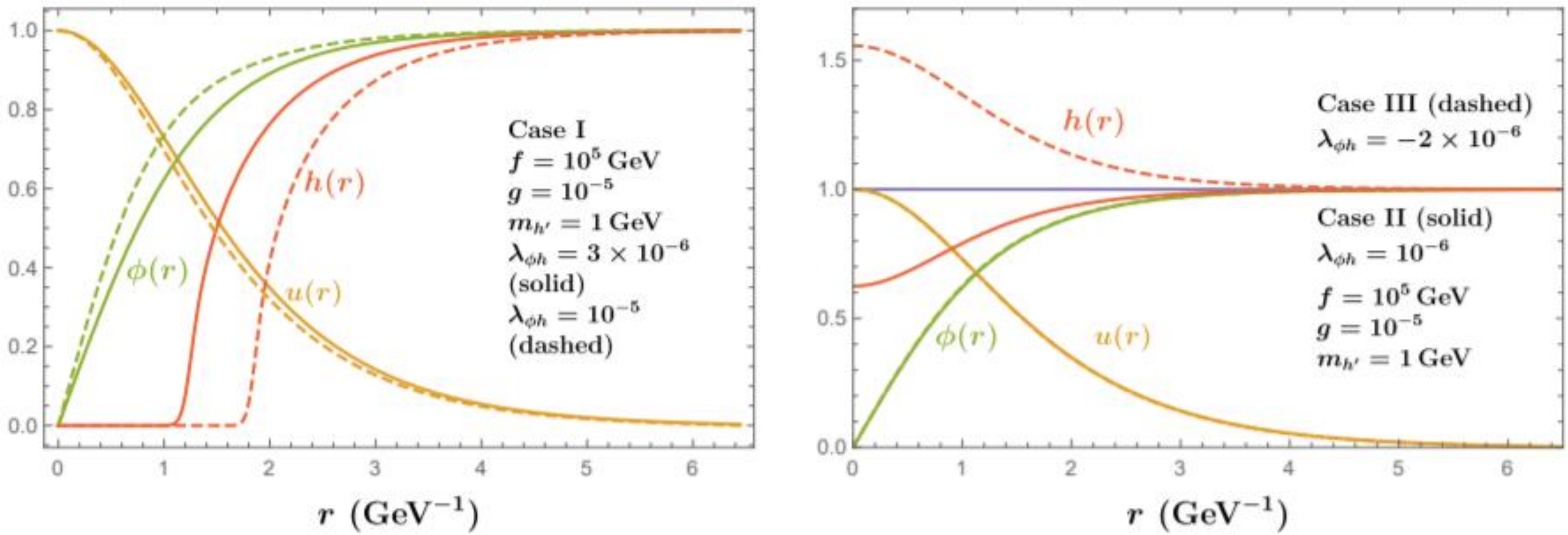
$$\begin{aligned}
\frac{d^2\phi}{d\bar{r}^2} + \frac{2}{\bar{r}}\frac{d\phi}{d\bar{r}} &= \frac{2\,u^2\phi}{\bar{r}^2} + \frac{\lambda_\phi}{g^2}\phi^3 - \frac{\mu_\phi^2\,\phi}{g^2 f^2} - \underline{\frac{\lambda_{\phi h}}{2g^2}\frac{v^2}{f^2}\,\phi\, h^2}\,, \\
\frac{d^2 u}{d\bar{r}^2} &= \frac{u(u^2-1)}{\bar{r}^2} + u\,\phi^2\,, \\
\underline{\frac{d^2 h}{d\bar{r}^2} + \frac{2}{\bar{r}}\frac{dh}{d\bar{r}}} &\underline{= \frac{\lambda_h}{g^2}\frac{v^2}{f^2}h^3 + \frac{\mu_h^2}{g^2 f^2}h - \frac{\lambda_{\phi h}}{2\,g^2}\phi^2\,h\,.}
\end{aligned}$$

With boundary conditions

$$\phi(0)=0\,,\ \phi(\infty)=1\,,\ \underline{h'(0)=0\,,\ h(\infty)=1}\,,\ u(0)=1\,,\ u(\infty)=0$$

$$\left\{\text{rescaling } \sqrt{H^\dagger H} = h(r)v/\sqrt{2}\right\}$$

FIELD PROFILES



Small g has been chosen to give large radius $\gg v^{-1}$.

To prevent tunings, we have chosen $\lambda_{\phi h} \sim \frac{\mu_h^2}{f^2}$.

(We could also get a larger radius by a fine-tuned cancellation of $\lambda_{\phi h} f^2 - 2\mu_h^2$)

PRODUCTION

PRODUCTION

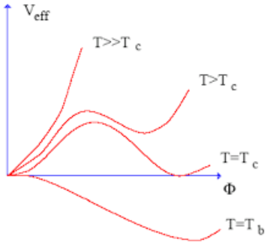
Your intuition may be that dark monopoles would be overproduced.

This intuition comes from the GUT monopole problem.

However, thermal phase transitions will tend to <u>underproduce</u> large-radius monopoles.

Monopole-antimonopole <u>annihilations</u> play an important role.

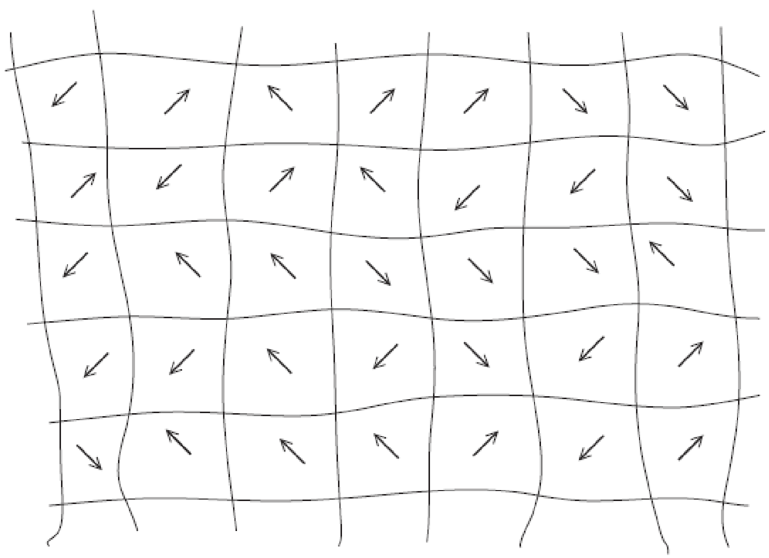
KIBBLE-ZUREK MECHANISM



Thermal phase transitions lead to different symmetry-breaking phases in different patches of the universe.

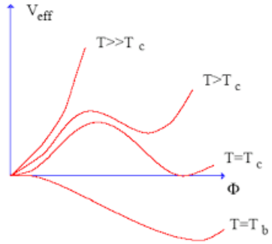
Kibble limit: at least one monopole per Hubble volume at the time of the thermal phase transition

$$n_{\text{Ⓜ}} \sim \xi^{-3} \qquad\qquad \xi < d_H(T_c')$$



U(1) example. Weinberg, *Classical Solution in Quantum Field Theory Solitons and Instantons*

KIBBLE-ZUREK MECHANISM



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$$n_{Ⓜ} \sim \xi^{-3} \qquad\qquad \xi < d_H(T'_c)$$

First order phase transition: bubble radius gives log enhancement [Guth, Weinberg '83]

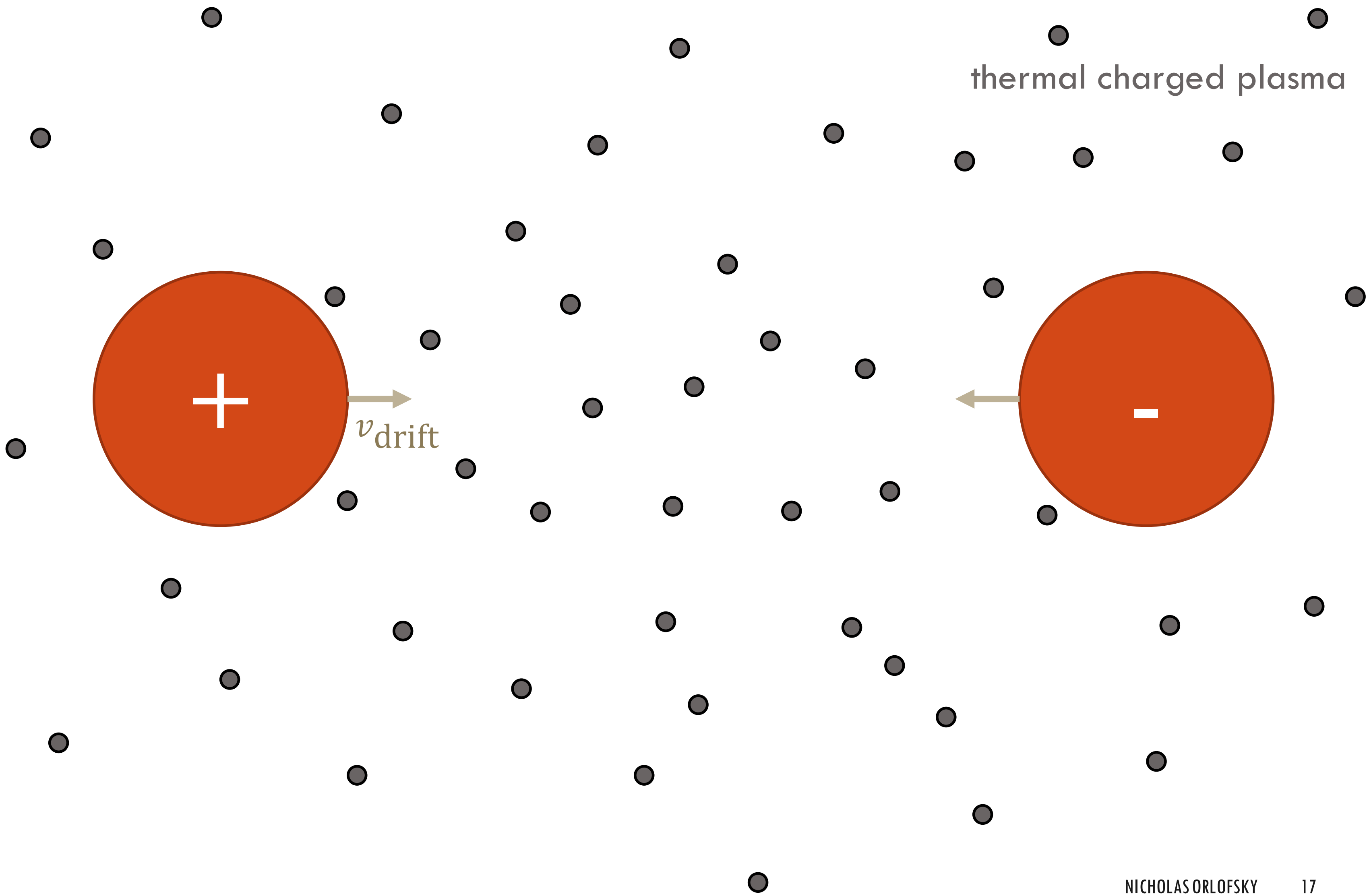
$$\xi \sim r_{\rm bubble} \simeq (M_{\rm pl}/T_c'^2)/\ln(M_{\rm pl}^4/T_c'^4) \ll d_H(T'_c)$$

$$Y(T_c) \equiv \frac{n_{Ⓜ}}{s} \simeq g_{*s}^{-1}\,\kappa^3 \left[\left(\frac{T'_c}{M_{\rm pl}}\right) \ln\left(\frac{M_{\rm pl}^4}{T_c'^4}\right)\right]^3$$

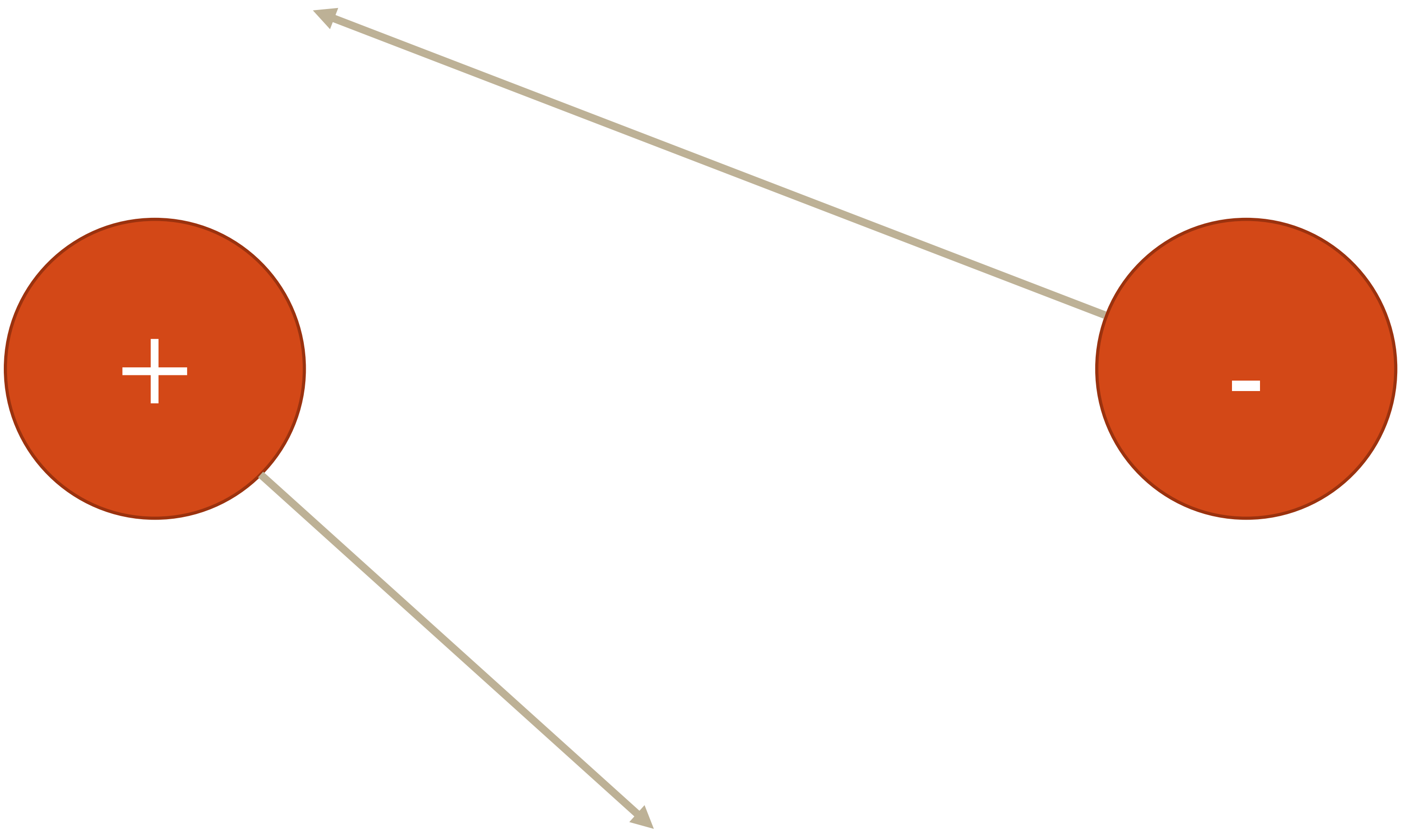
Second order phase transition: finite relaxation time gives enhancement [Zurek '85]

$$Y(T_c) \;\simeq\; g_{*s}^{-1}\, g_*^{1/2}\, \kappa\, \lambda\, \frac{T'_c}{M_{\rm pl}}$$

ANNIHILATIONS



ANNIHILATIONS



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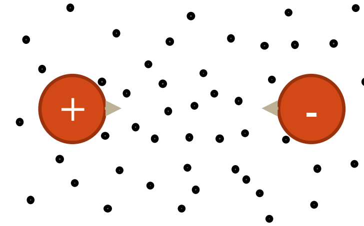


Abundance after annihilations, assuming freeze-out temperature $T_F' \sim m_{W'} \sim gf$ [Preskill '79]

$$\Omega_{\textcircled{\scriptsize M}} h^2 \approx 0.112 \times \left(\frac{\kappa}{1/10}\right)\left(\frac{g\,f}{1.5 \times 10^6\,\mathrm{GeV}}\right)^2$$

Independent of abundance after phase transition

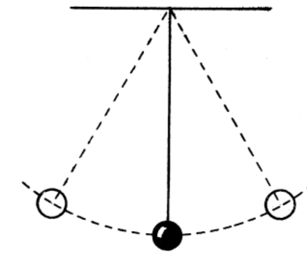
(assuming the phase transition abundance is greater than this)

This gives a small monopole radius if it is a sizeable fraction of DM:

$$R_{\textcircled{\scriptsize M}} \approx (g\,f)^{-1} \approx 7 \times 10^{-7}\,\mathrm{GeV}^{-1}$$

(Aside: large-radius monopoles could still be a tiny fraction of DM)

PREHEATING



Coupling to the oscillating inflaton field can induce exponential growth.

$$V \supset \frac{1}{2}\, m_{\mathcal{I},0}^2\, \mathcal{I}^2 \;+\; \frac{1}{2}\, \lambda_{\mathcal{I}\phi}\, \mathcal{I}^2\, |\Phi|^2$$

Near the origin:
$\lambda_{\mathcal{I}\phi} f^2 \gg m_{\mathcal{I},0}^2$

Equations of motion with $\langle \Phi_1 \rangle = f$:

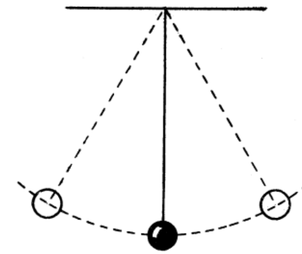
$$\begin{aligned} \delta\varphi''_{1\,k} \;+\; \left[A_{1\,k} + 2\,q\,\cos(2z)\right]\delta\varphi_{1\,k} \;&=\; 0 \\ \delta\varphi''_{2,3\,k} \;+\; \left[A_{2,3\,k} + 2\,q\,\cos(2z)\right]\delta\varphi_{2,3\,k} \;&=\; 0 \end{aligned}$$

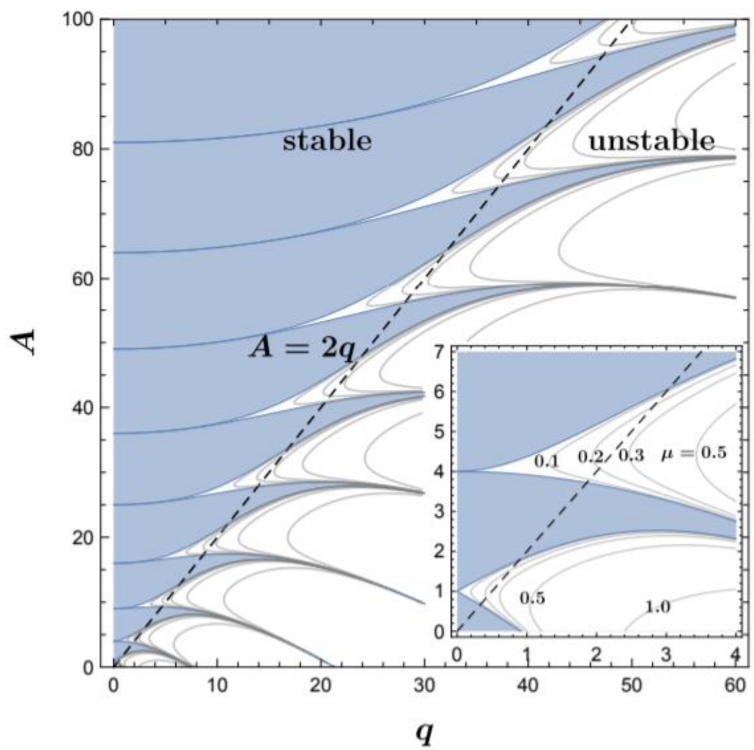
Mathieu equation

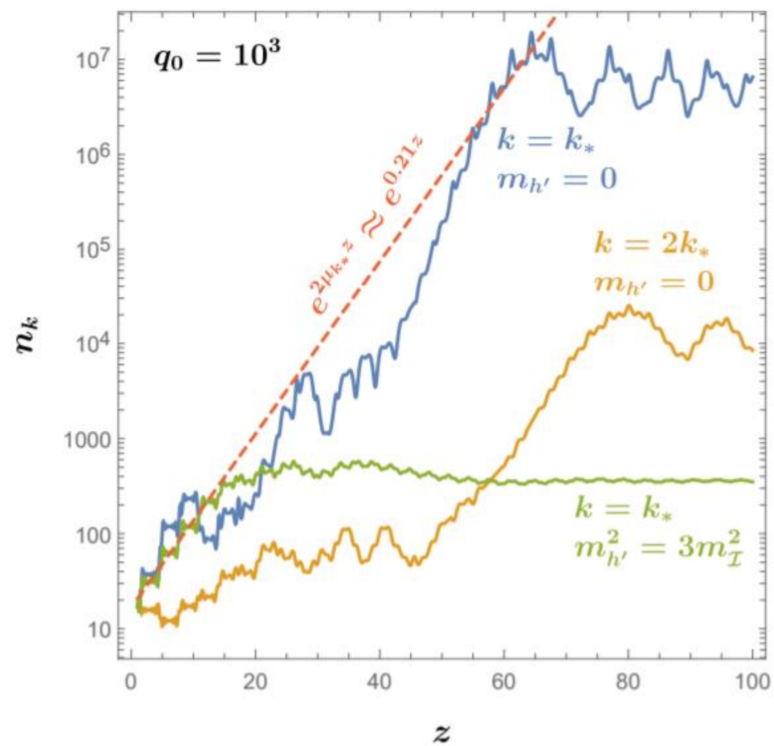
$$\left\{ \begin{array}{c} \delta\varphi_{i,k} \;\equiv\; a^{3/2}\,\delta\Phi_{i,k} \qquad\qquad z \;\equiv\; m_{\mathcal{I}}\,(t - t_0) \\ q_0 \equiv \dfrac{\lambda_{\mathcal{I}\phi}\,\mathcal{I}_0^2}{4\,m_{\mathcal{I}}^2}\,, \quad q \equiv \dfrac{q_0}{a^3}\,, \quad A_{1\,k} = 2\,q + \dfrac{k^2}{a^2\,m_{\mathcal{I}}^2} + \dfrac{m_{h'}^2}{m_{\mathcal{I}}^2}\,, \quad A_{2,3\,k} = 2\,q + \dfrac{k^2}{a^2\,m_{\mathcal{I}}^2} \end{array} \right\}$$

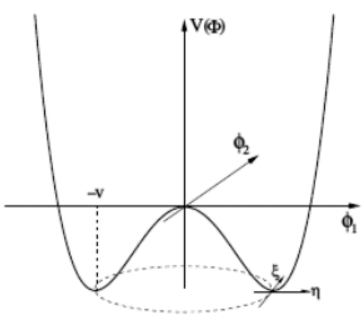
On preheating: [Kofman, Linde, Starobinsky '94; '97]
On topological defect production: during preheating: [Kasuya, Kawasaki '97; '98; '99; Khlebinov, Kofman, Linde, Tkachev '98; '98; Rajantie, Copeland '00; Kawasaki, Yanagida, Yoshino '13; …]

PREHEATING







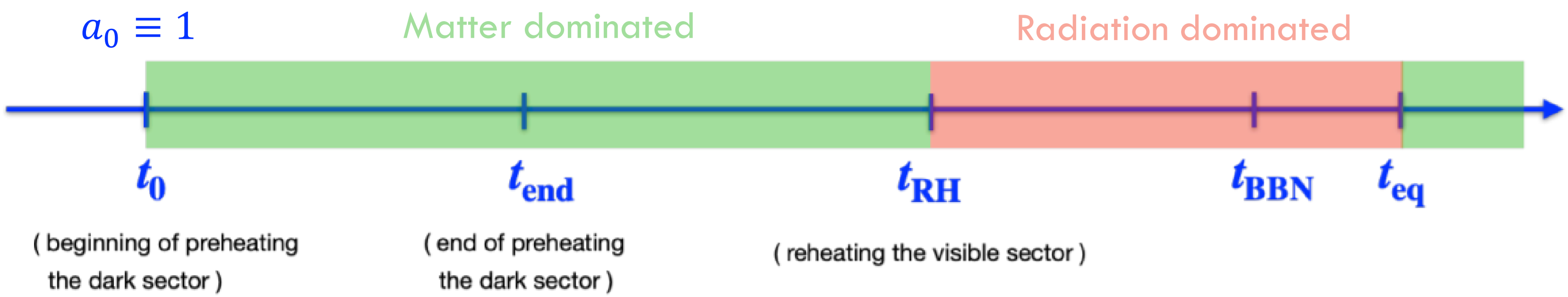


$$\langle|\delta\Phi|^2\rangle \simeq \frac{1}{2\,a^3\sqrt{\pi\,\mu_{k_*} z}}\left(\frac{H_{\mathcal{I}}}{2\pi}\right)^2 e^{2\,\mu_{k_*} z}$$

Get monopole production when $\langle|\delta\Phi|^2\rangle \simeq f^2$

Gives a modest requirement on $q_0 \gtrsim \text{few} \times 10^2$

PREHEATING



Number density at end of preheating can be much larger:

$$n_{\text{M}}(t_{\mathrm{end}}) \simeq \xi^{-3} \simeq p^3_{*\,\mathrm{end}} = (k_*/a_{\mathrm{end}})^3$$

$$k_* \simeq m_{\mathcal{I}}\, q_0^{1/4}$$ Most enhanced mode

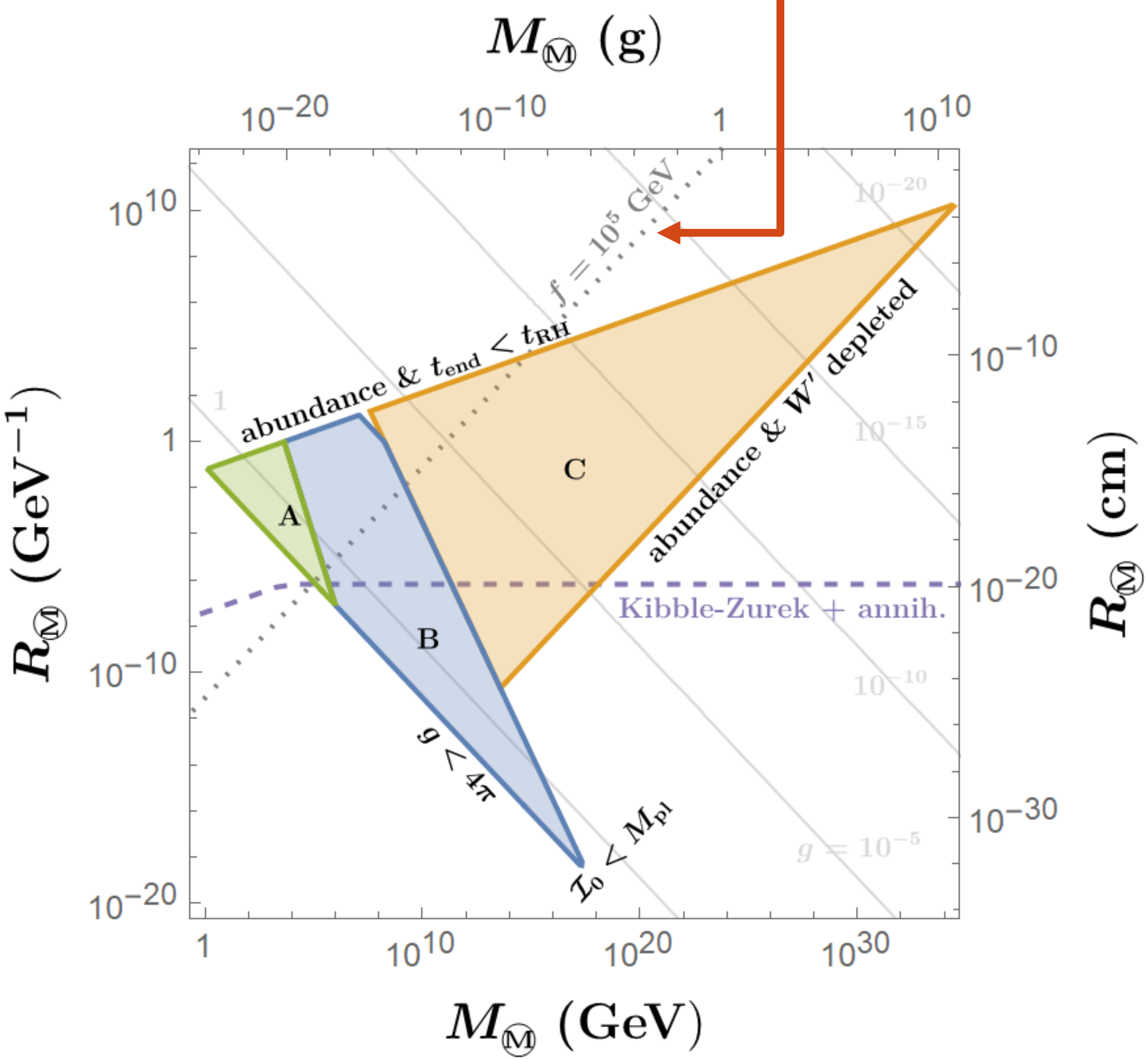
Abundance:

$$\Omega_{\text{M}} h^2 \simeq 0.120 \times \left(\frac{10^3}{q_0}\right)^{1/4} \left(\frac{\lambda^{1/2}_{\mathcal{I}\phi}/g}{2\times 10^{-7}}\right) \left(\frac{T_{\mathrm{RH}}}{1\,\mathrm{MeV}}\right)$$

No longer depends on radius

PREHEATING

Dark sector decoupling ($\lambda_{\phi h} \lesssim 10^{-5}$) + EW restoration ($\lambda_{\phi h} f^2 \gtrsim \mu_h^2$) requires $f \gtrsim 10^5$ GeV (below this line).



All points choose $\lambda_{I\phi}$ so monopoles are 100% DM.

$T_{RH} = 1$ MeV and $\lambda_\phi = g^2$.

A. Dark sector in kinetic and chemical equilibrium with itself.
B. Only kinetic equilibrium
C. No kinetic or chemical equilibrium

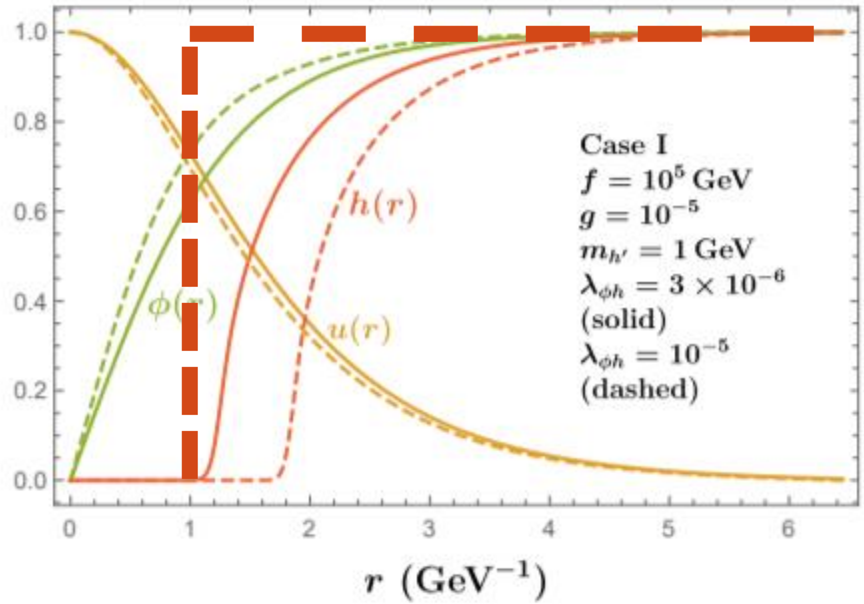
PHENOMENOLOGY

DIRECT DETECTION

We will focus on the EW-symmetric monopole.

Approximate the potential for a nucleon as a spherical well:

$$V(r) = A\, y_{hNN}\left(h(r) - v\right) \approx -V_0\, \Theta(r - R_{Ⓜ})$$



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Using the Born approximation:

$$\begin{aligned}
\sigma^{\text{elastic}}_{NⓂ} &\approx \frac{\sigma^{\text{elastic}}_{AⓂ}}{A^2} = 4\pi\, \frac{1}{A^2} \left| \frac{m_A}{q} \int_0^\infty dr\, r\, \sin(qr)\, V(r) \right|^2 \\
&\approx \frac{16\pi}{9}\, m_N^2\, A^2\, y_{hNN}^2\, v^2\, R_{Ⓜ}^6 \approx (2.5 \times 10^{-42}\,\text{cm}^2) \left(\frac{A}{131}\right)^2 \left(\frac{R_{Ⓜ}}{10^{-3}\,\text{GeV}}\right)^6
\end{aligned}$$

This growns as $R_{Ⓜ}^6$ until it saturates to the geometric cross section:

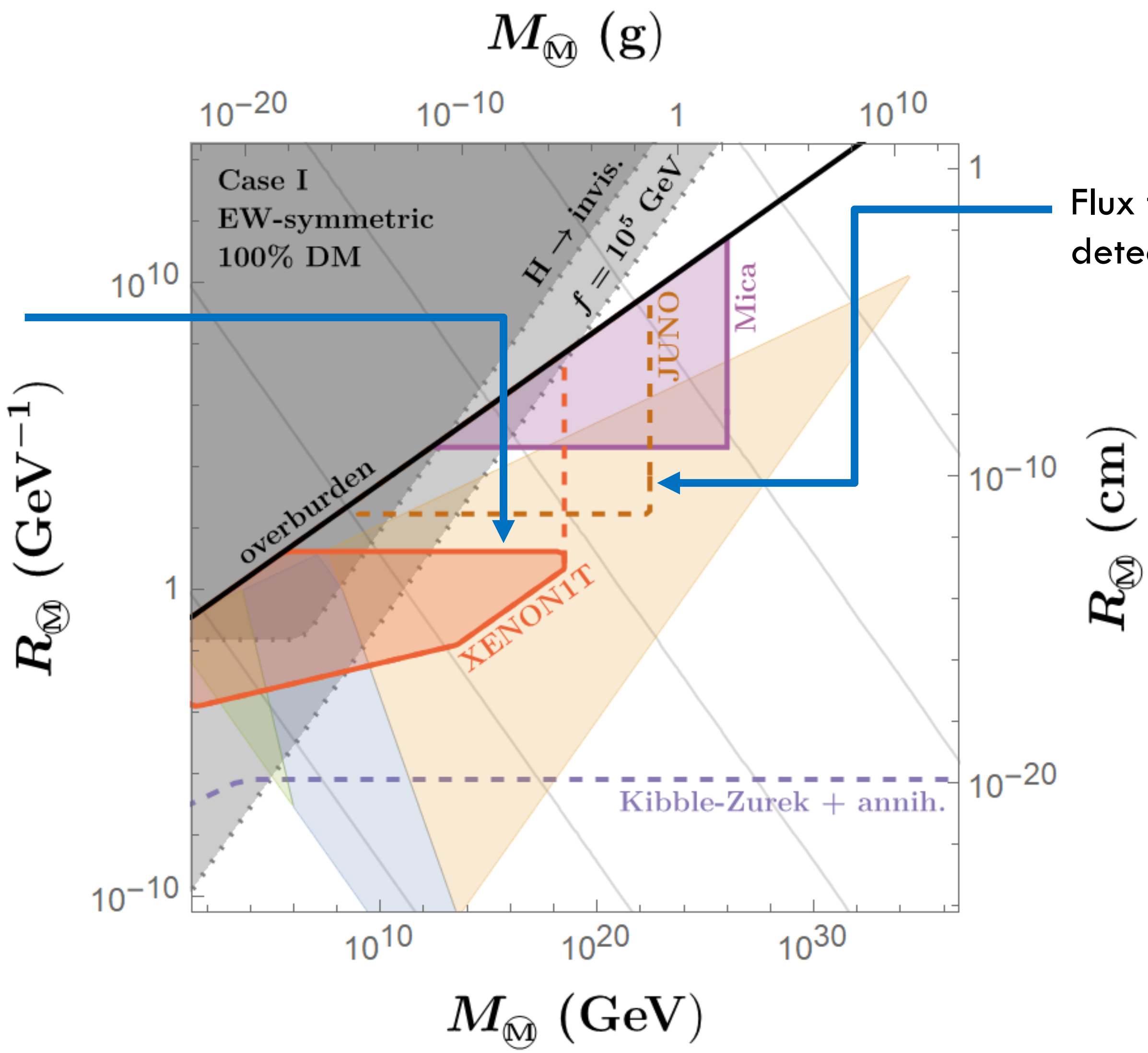
$$\sigma^{\text{elastic}}_{AⓂ} \approx 2\pi\, R_{Ⓜ}^2$$

However, bound states also form. See Yang Bai's talk after this!

DIRECT DETECTION

Multi-hit signal:

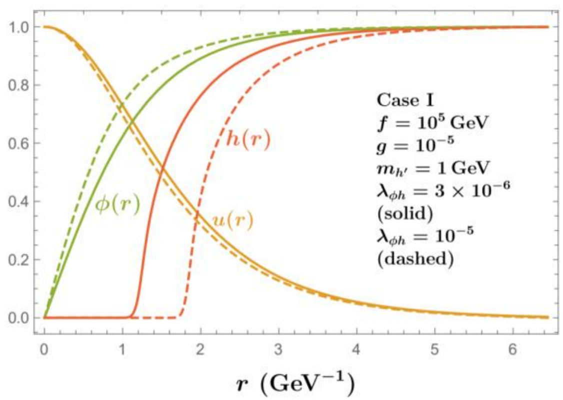
$\sigma_{A Ⓜ}^{\text{elastic}} n_{\text{det}} L_{\text{det}} \gtrsim 1$



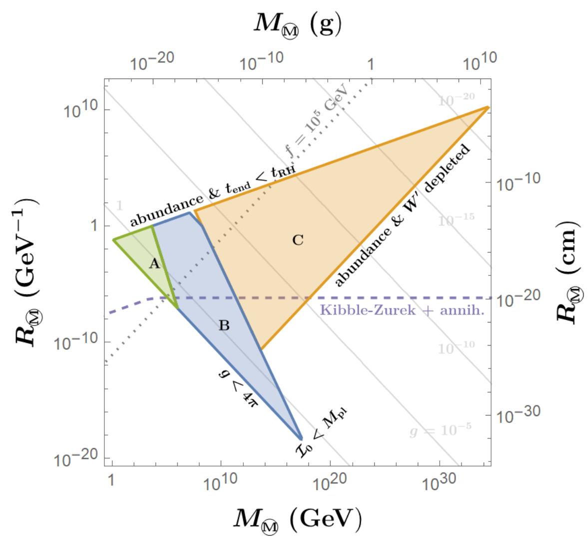
Flux too small for detector exposure

SUMMARY

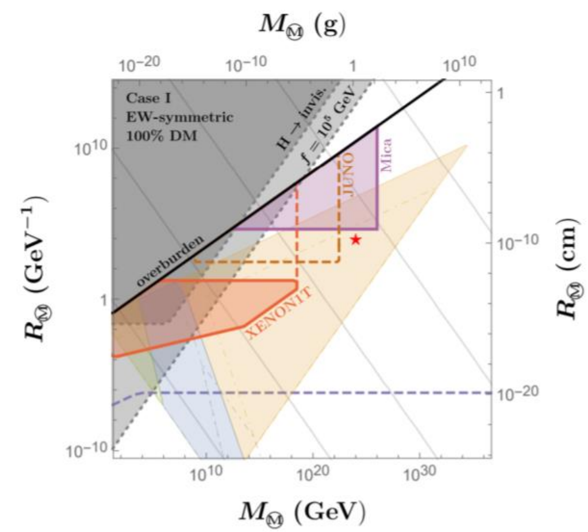
SUMMARY



1. Higgs portal gives EW symmetry modifications in dark monopole interiors.



2. Thermal phase transitions underproduce, preheating expands possible radii.



3. Large-volume terrestrial experiments are sensitive to single- and multi-hit signals.

Thank you