Electroweak Symmetric Ball

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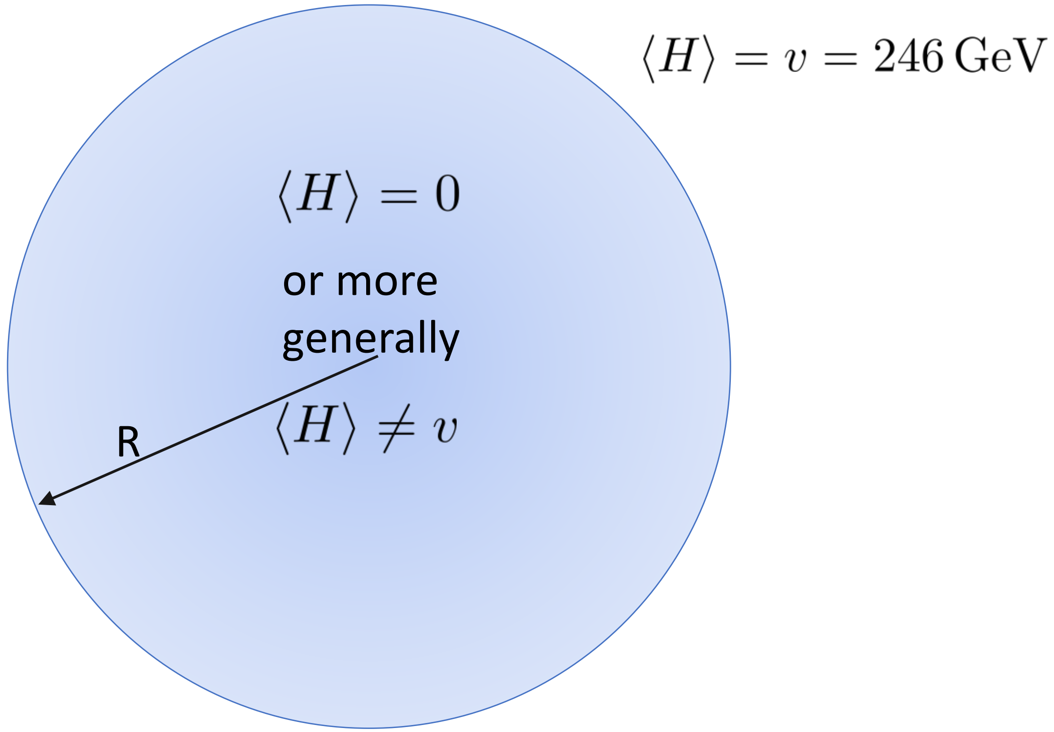
Phase Transitions and Topological Defects in the Early Universe

Based on work with Yang Bai, Joshua Berger, and Nicholas Orlofsky

Introduction

- Soliton with Electroweak Symmetry completely or partially restored

- Phenomenology: M, R, $\langle H \rangle$



Brief Summary

• How to get it from microscopic physics?	**Dark Monopole** or Dark Soliton ✚ **Higgs-portal** Interaction
• Early universe formation Can it be relic DM?	Thermal Phase Transition, Preheating Mechanism
• Catalyzed Baryogenesis	EW Sphaleron rate is unsuppressed inside EWS object
• Direct Detection	Multi-hit signatures in Large volume neutrino detectors

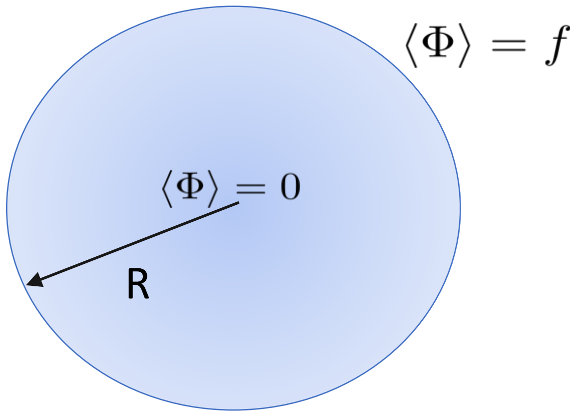
How to get it from microscopic physics?

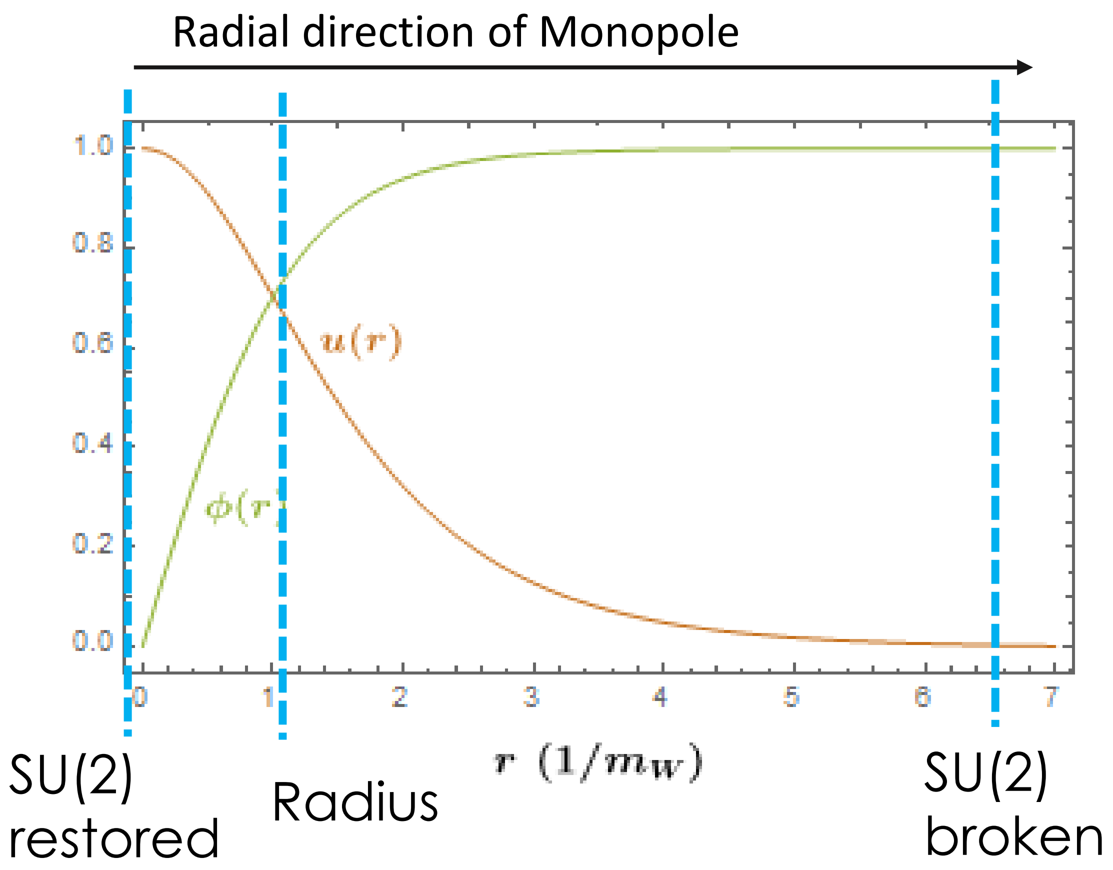
Dark Monopoles

- SSB $SU(2) \rightarrow U(1)$ by a triplet scalar $\langle \Phi^a \rangle \neq 0$
- Field profiles for Monopole

$$\Phi^a = f\phi(r)\hat{r}^a \qquad A_i^a = \epsilon^{aim}\frac{1-u(r)}{gr}\hat{r}^m$$

$$M \approx 4\pi f/g \qquad R \approx 1/gf = 1/m_{W'}$$





Higgs-portal dark monopoles

- Higgs portal interaction between SM higgs and Φ^a

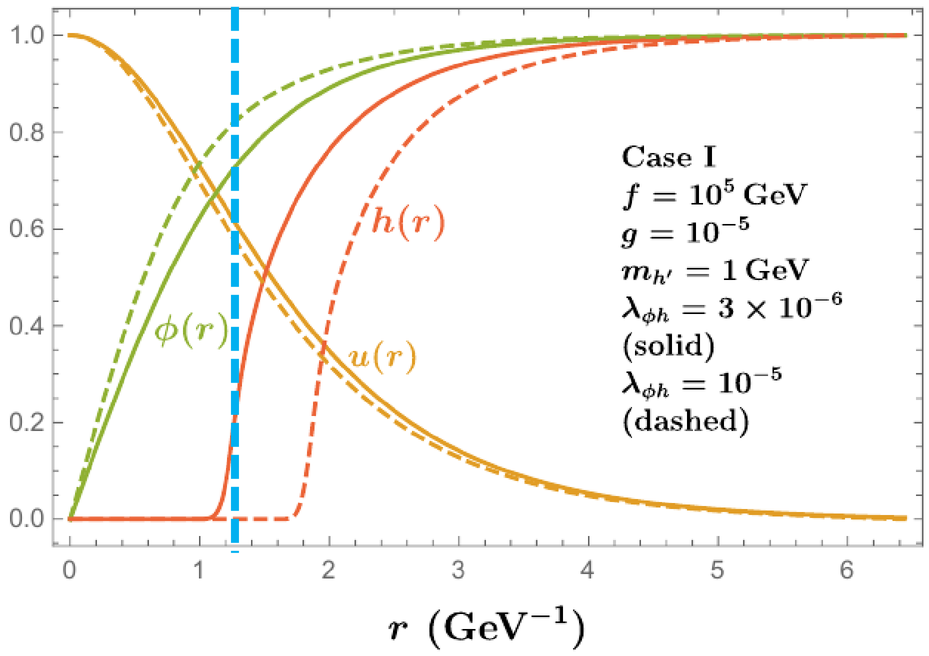
$$V(\Phi, H) = \frac{\lambda_\phi}{4}\,|\Phi|^4 - \frac{1}{2}\,\mu_\phi^2\,|\Phi|^2 + \lambda_h\,(H^\dagger H)^2 + \mu_h^2\,H^\dagger H - \frac{1}{2}\,\lambda_{\phi h}|\Phi|^2 H^\dagger H + V_0$$

(Bai, **MK**, Orlofsky' 20)

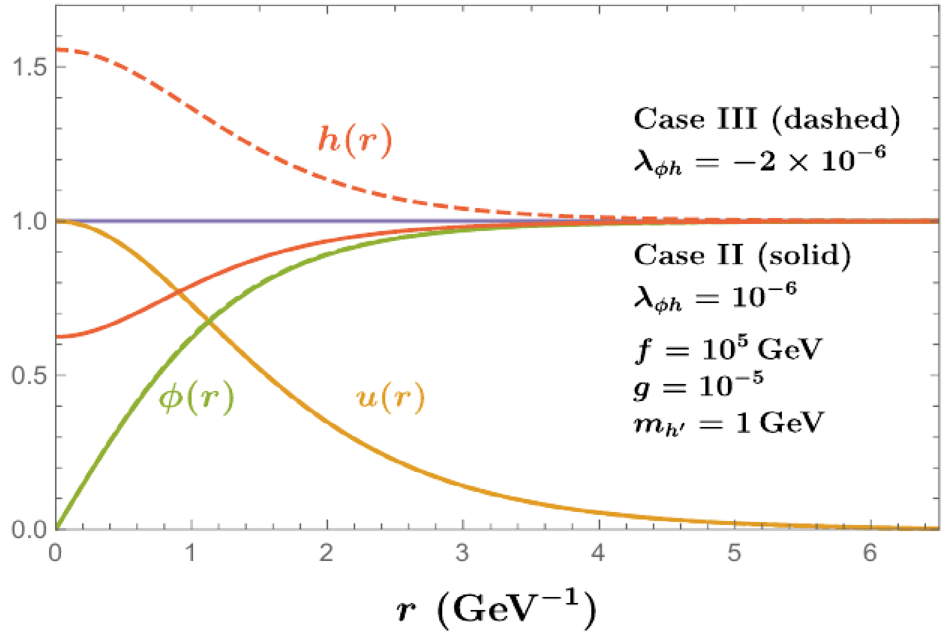
Case I: $\mu_\phi^2 > 0, \mu_h^2 > 0, \lambda_{\phi h} > 0$

Case II: $\mu_\phi^2 > 0, \mu_h^2 < 0, \lambda_{\phi h} > 0$

Case III: $\mu_\phi^2 > 0, \mu_h^2 < 0, \lambda_{\phi h} < 0$



Electroweak Symmetric Case

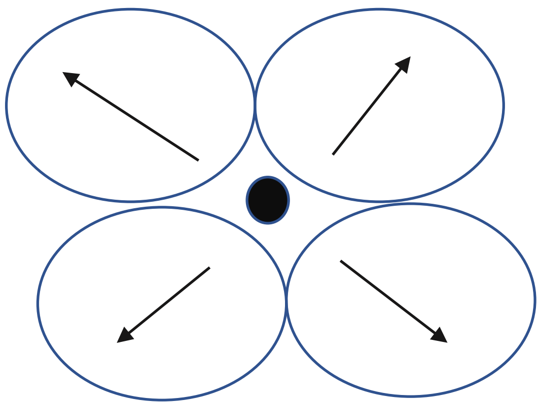


Partially Electroweak Symmetric/Broken Case

Early universe formation: Can it be relic DM?

Formation I: Kibble-Zurek + Annihilations

- After thermal PT patches separated by correlation length have random direction of $\langle \Phi^a \rangle$



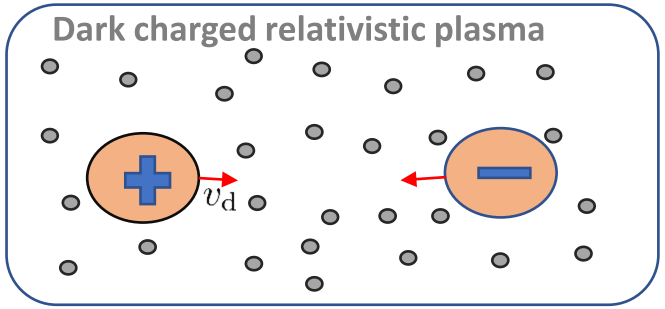
(Kibble' 76, Zurek' 85)

- Initial formation Yield depends on order of PT and $\kappa \equiv T'/T$

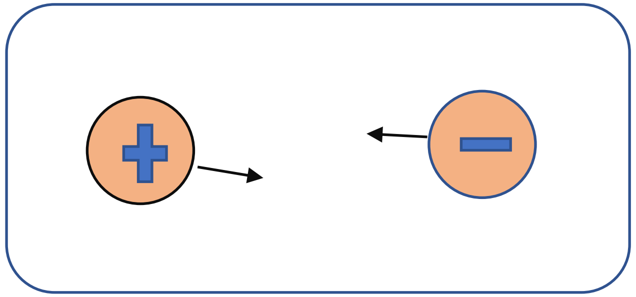
$$Y(T_c) \equiv \frac{n_M}{s} \simeq \begin{cases} g_{*s}^{-1}\,\kappa^3 \left[\left(\frac{T_c'}{M_{\rm pl}}\right) \ln\left(\frac{M_{\rm pl}^4}{T_c'^4}\right)\right]^3 & \text{first-order PT} \\ g_{*s}^{-1}\, g_*^{1/2}\, \kappa\, \lambda\, \frac{T_c'}{M_{\rm pl}} & \text{second-order PT} \end{cases}$$

- Annihilations:

$l_{\rm free} < l_{\rm cap}$



$l_{\rm free} > l_{\rm cap}$



(Preskill' 79)

$$\Omega_M h^2 \approx 0.112 \times \left(\frac{\kappa}{1/10}\right) \left(\frac{g\, f}{1.5 \times 10^6\ \text{GeV}}\right)^2$$

Only complete DM if radius of Dark Monopole is small

Formation II: Preheating

- SSB before the end of inflation so uniform direction of $\langle \Phi^a \rangle$ in Hubble patch

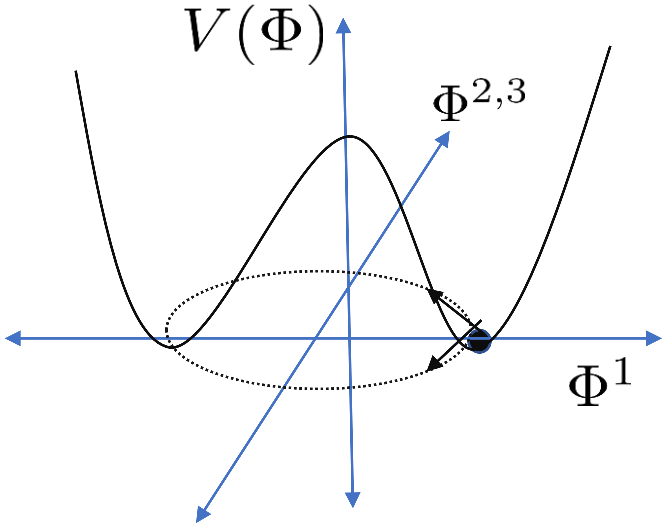
- Consider inflaton ($\mathcal{I}$) coupling to scalar (Φ^a)

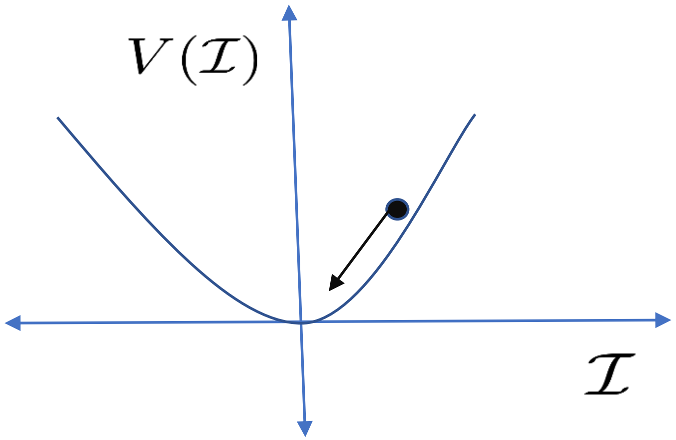
$$V_{\mathcal{I}\Phi} \supset \frac{1}{2} \lambda_{\mathcal{I}\phi} \mathcal{I}^2 \, |\Phi|^2$$

- Fluctuations in $\delta\Phi^a$ until $\delta\Phi^a \approx f$

- At the end of preheating different sub-horizon patches have different direction of vev $\langle \Phi^a \rangle$, producing monopole

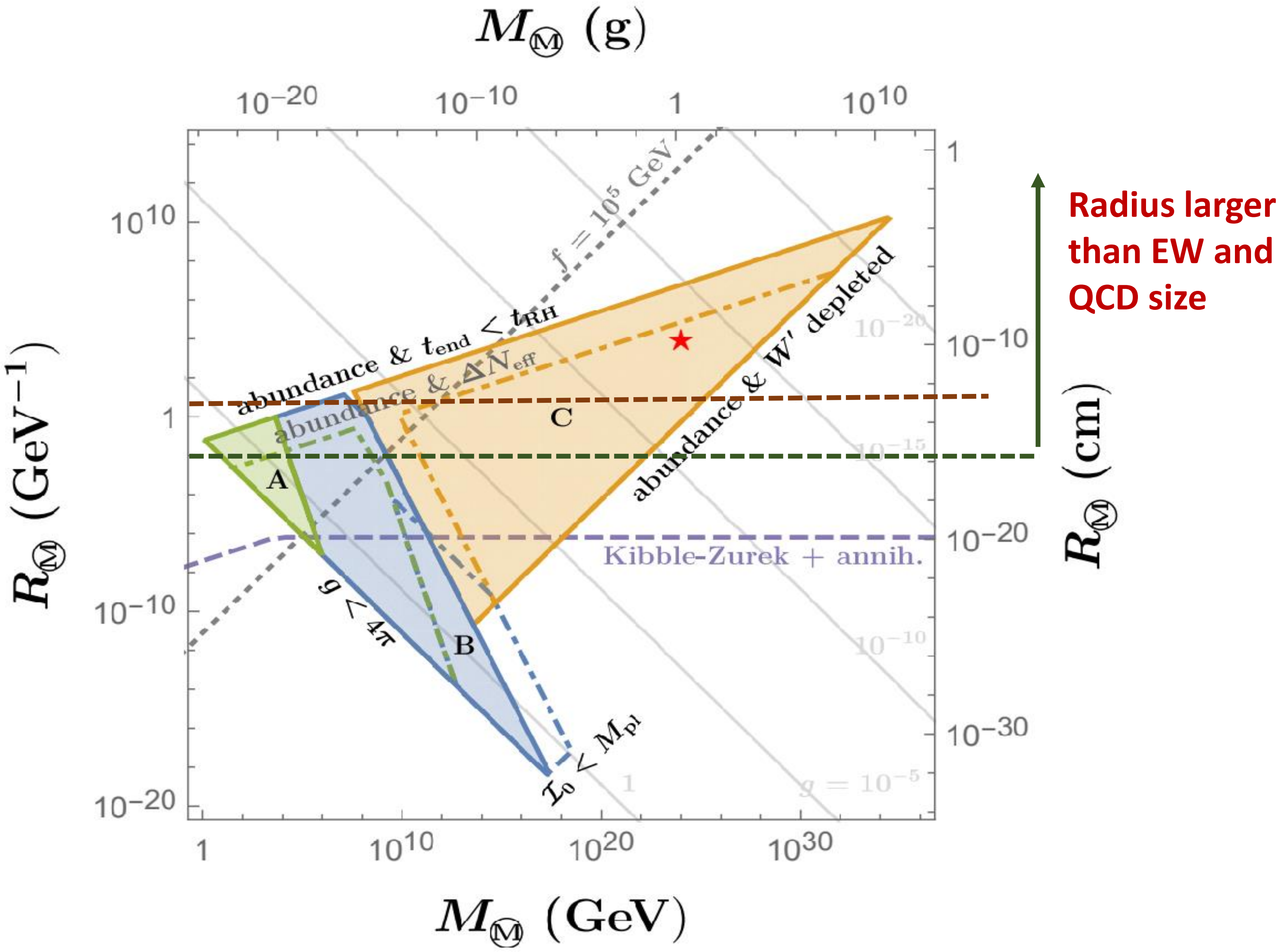
- Reheat dark sector to smaller temperatures, no relativistic plasma





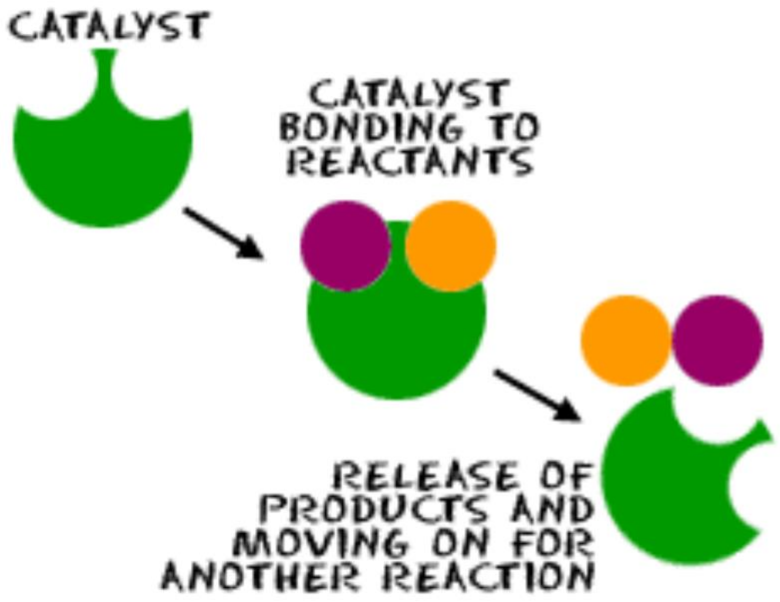
(Kawasaki et al.’ 97, Linde et al.’ 98, Rajantie 2000, Bai, **MK**, Orlofsky’ 20)

Parameter space as DM relic



(Bai, **MK**, Orlofsky' 20)

Catalyzed Baryogenesis

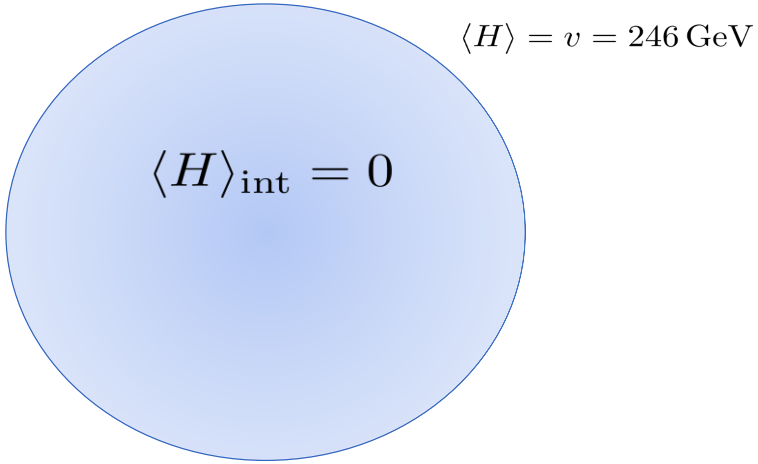


Chem4kids.com

Catalyzed Baryogenesis : Sakharov Conditions

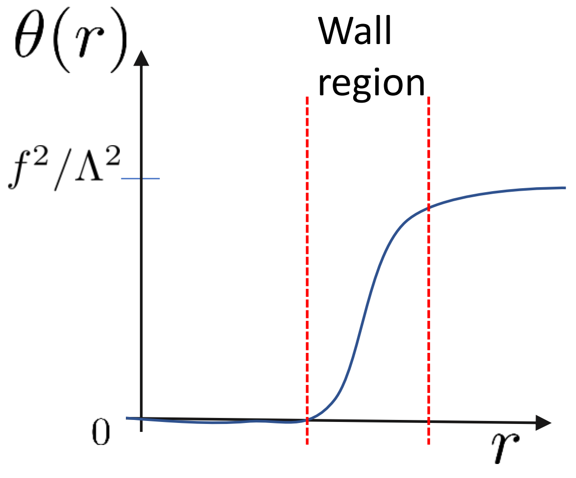
- Baryon number violation via EW Sphaleron

$$\Gamma_{\rm sph} \propto \exp(-E_{\rm sph}/T) \qquad E_{\rm sph} = \frac{8\pi\langle H\rangle}{g_2}$$



- CP violating interaction at the wall of the EWS ball

$$\mathcal{L} = y_t \overline{Q}_L \widetilde{H}\left(1+\eta\frac{\Phi\Phi^\dagger}{\Lambda^2}\right) t_R + h.c. \xrightarrow{\Phi=\phi(r)} m_t(r) = |m_t(r)| e^{i\theta(r)}$$



- Local out-of-equilibrium from movement of wall w.r.t plasma same as in case of Electroweak Baryogenesis

(Bai, Berger, **MK**, Orlofsky' 21)

Baryon Asymmetry

- **Diffusion equation:**

CP asymmetry inside the ball contributes to sphaleron process

$$\frac{\partial n_{\rm CP}(\vec{x},t)}{\partial t} - D\,\nabla^2 n_{\rm CP}(\vec{x},t) + \Gamma\, n_{\rm CP}(\vec{x},t) = S(\vec{x},t)$$

$$\mu_{\rm CP} \approx \frac{v_{\rm w}^2\,\Delta\theta}{R_{\rm ball}}$$

$$S(x) \approx \frac{v_{\rm w}\, y_f^2\, D\, T^2\, \theta'''}{6}$$

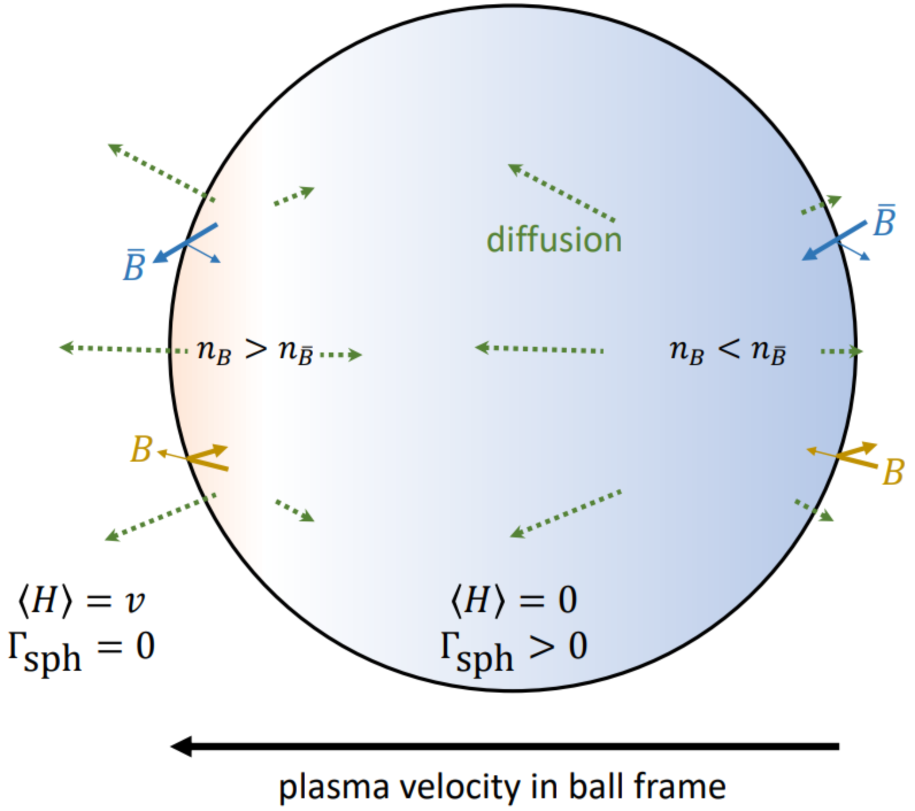
Opposite sign at the front and back wall

- **Baryon asymmetry:**

$$\frac{dN_B}{dt} \approx -\Gamma_{\rm sph}\, R_{\rm ball}^3\, \frac{\mu_{\rm CP}}{T}$$

→ Baryon asymmetry generated per ball

$$Y_B = 1.9\times 10^{-10}\, f_{\rm DM} \left(\frac{R_{\rm ball}}{1\,{\rm GeV}^{-1}}\right)^2 \left(\frac{10^8\,{\rm GeV}}{M_{\rm ball}}\right)^2 \left(\frac{\Delta\theta}{-1}\right) \left(\frac{T_i}{100\,{\rm GeV}}\right)^2$$



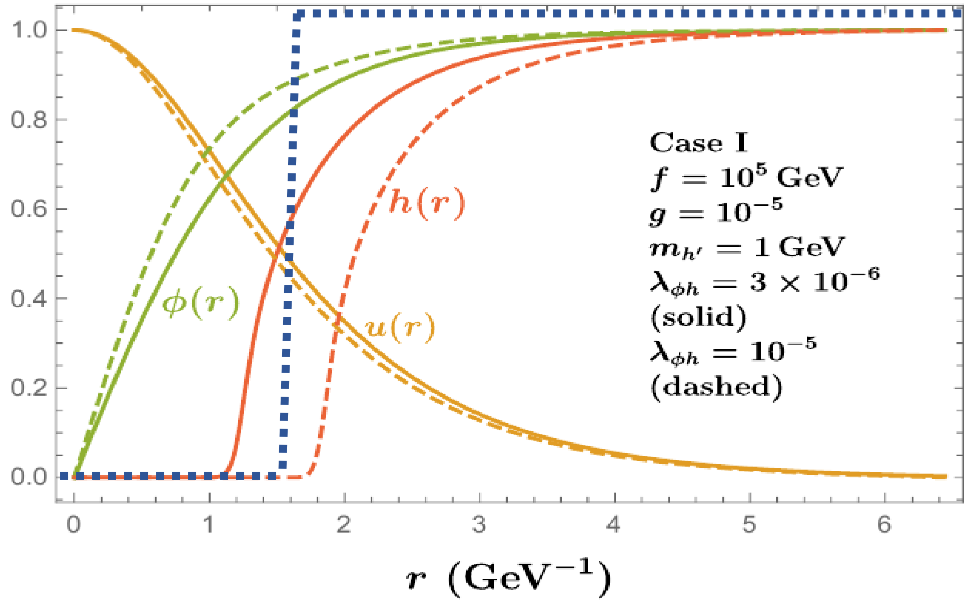
(Cline et al.' 99,
Bai, Berger, **MK**, Orlofsky' 21)

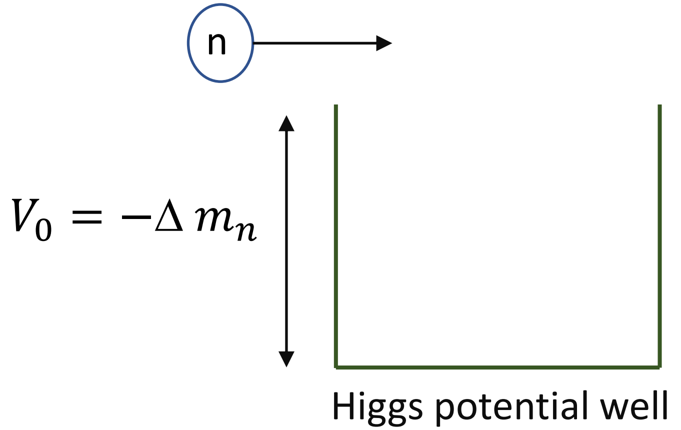
Direct Detection

Direct Detection: Elastic Scattering

- Nucleons scatter from higgs potential well created by EWS ball

$$V(r) = A y_{\rm hNN}(h(r) - v) \approx -V_0 \theta(r - R_{\rm ball})$$





- Cross-section

$$\sigma_{\rm N}^{\rm elastic} \approx (2.5 \times 10^{-42}\,{\rm cm}^2) \left(\frac{A}{131}\right)^2 \left(\frac{R_{\rm ball}}{10^{-3}\,{\rm GeV}^{-1}}\right)^6$$

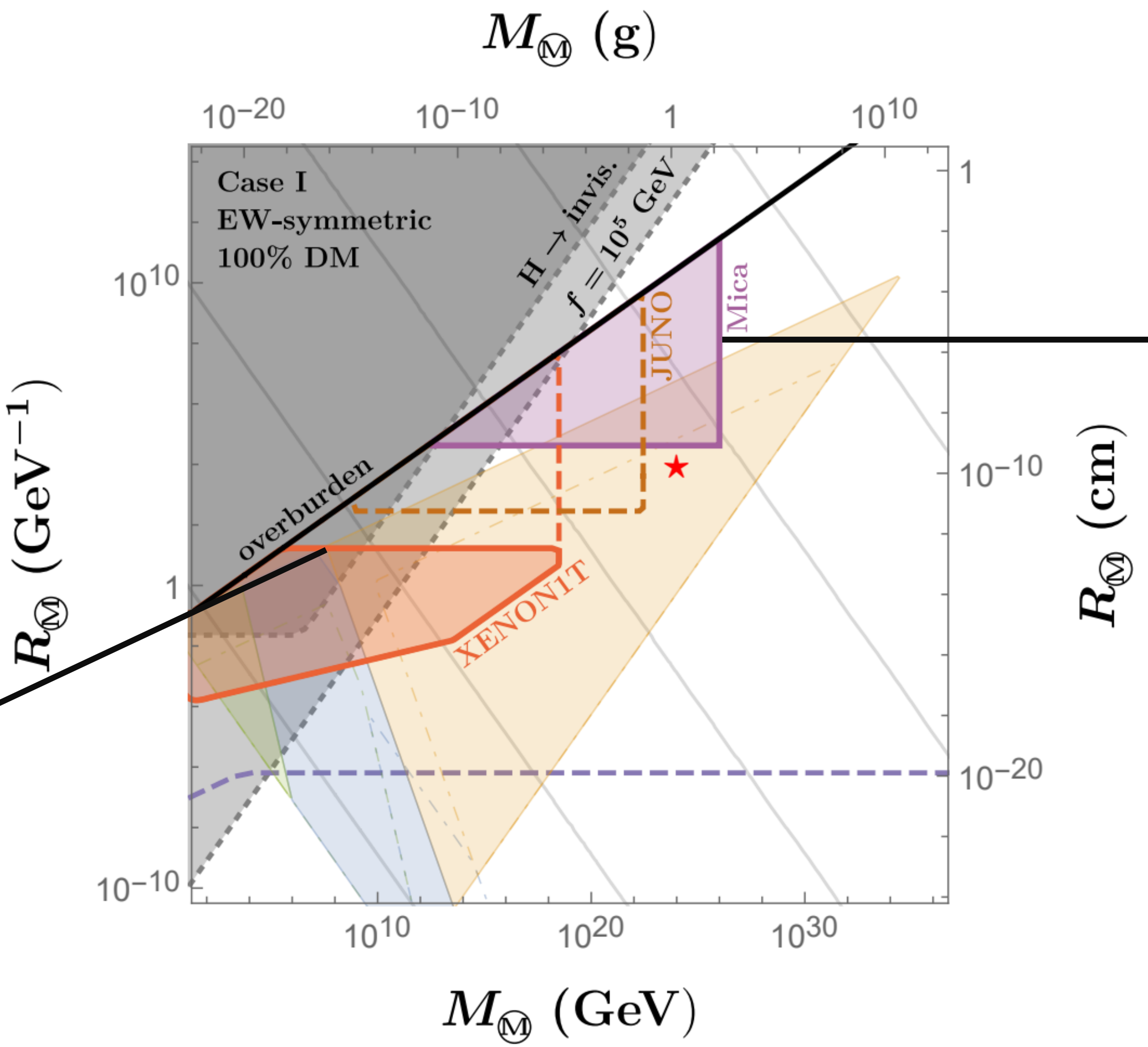
Small radius

$$\sigma \approx 2\pi R_{\rm ball}^2 \approx 10^{-27} {\rm cm}^2 \left(\frac{\rm R_{ball}}{1\,{\rm GeV}^{-1}}\right)^2$$

Large radius

(Ponton, Bai, Jain ’ 19)

Direct Detection: Limit Plot



Flux too small to detect

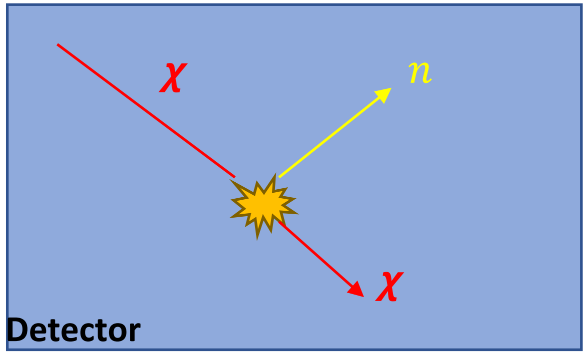
Multi-hit scattering

$\sigma n_{\rm det} L_{\rm det} > 1$

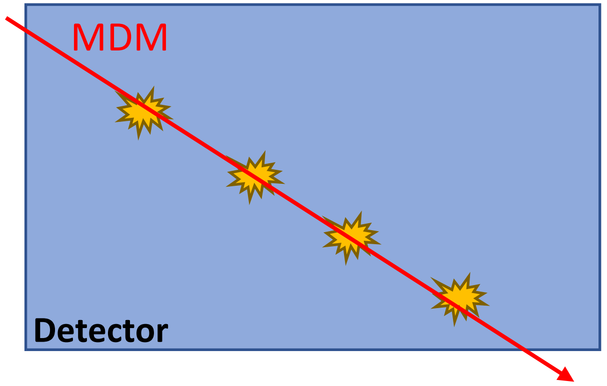
(Bai, **MK**, Orlofsky' 20)

Multi-hit + Inelastic Scattering

- Multi-hit signature in detector

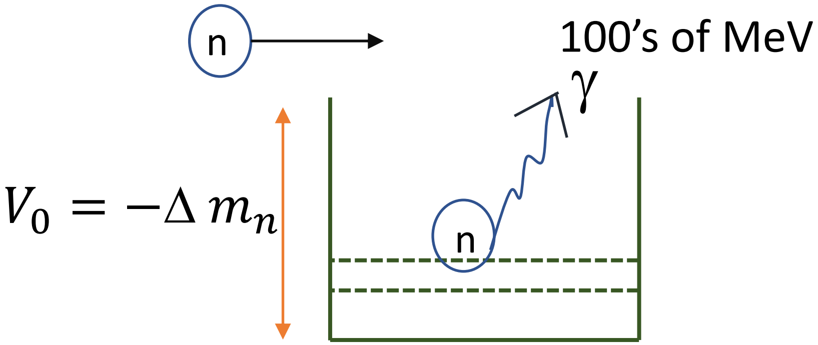


Single Hit (usual Particle DM)



Multi-hit (EWS DM)

- Inelastic Scattering : Bound state formation



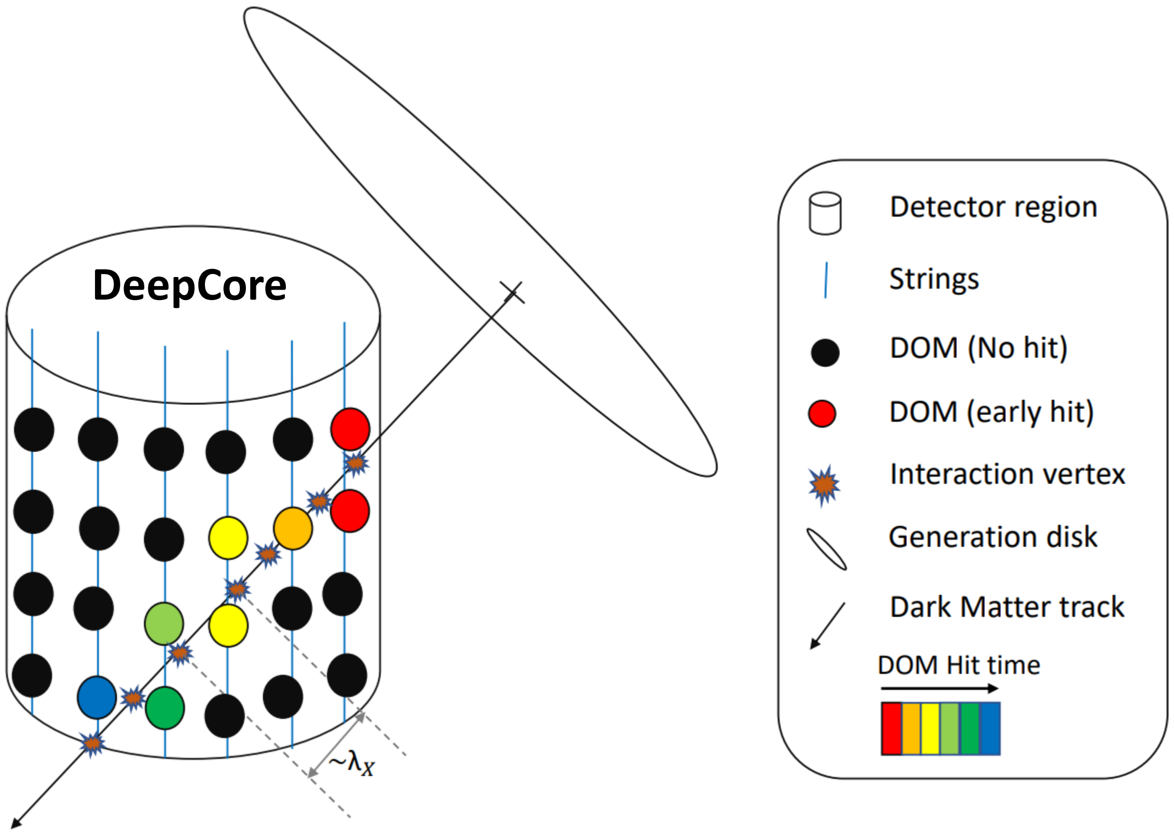
Higgs potential well

Multi-hit + Inelastic scattering searched at Large Volume Neutrino detectors

(Bai, Berger ' 19)

Search at IceCube detector

- Released energy leads to EM cascade producing Cerenkov radiation which is detected by PMT/DOM.
- Both the spatial and time info is necessary to build trigger and cuts.
- **SLOP trigger**:- Trigger to detect slow-moving particles like monopoles
- Dominant background is random noise from radioactive decay in the DOM



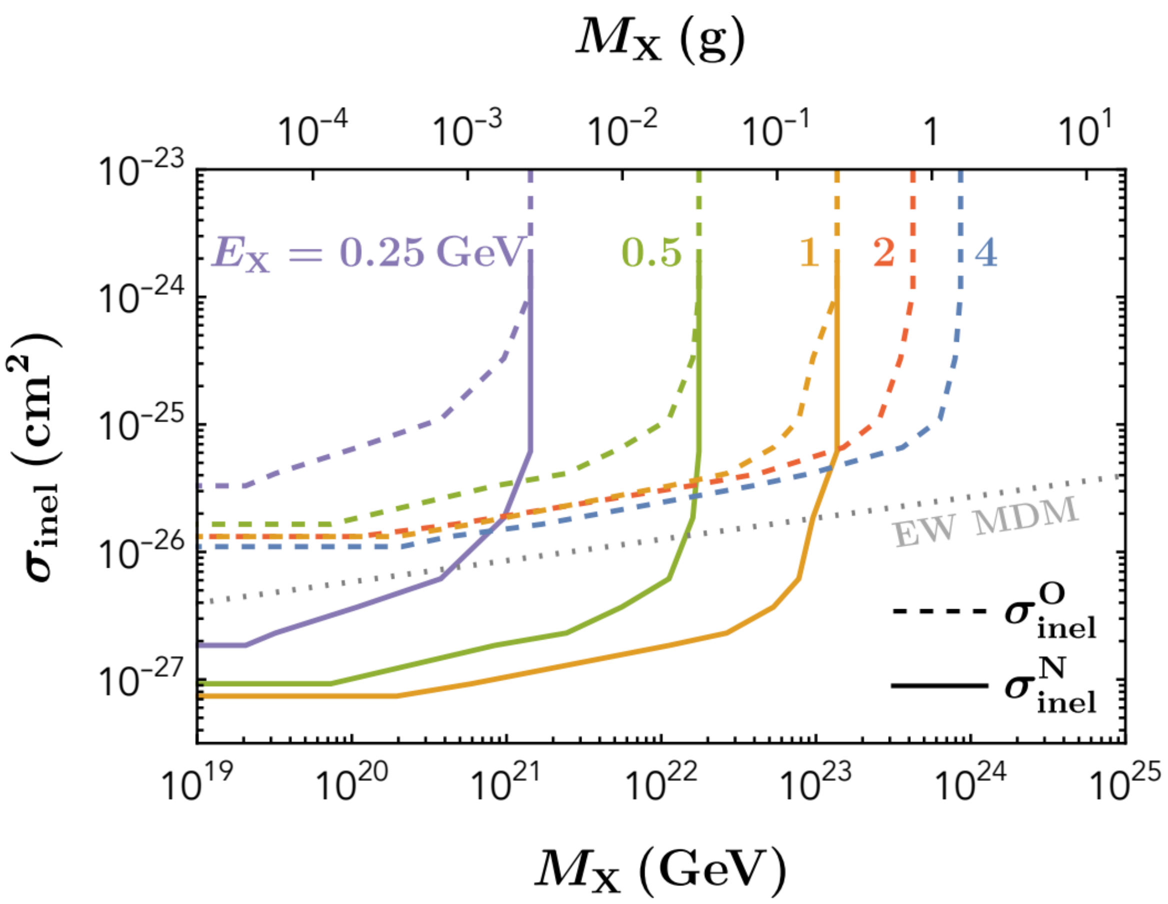
(Bai, Berger, **MK** ' 22)

Constraints

- Projected 90% CL limits with 10-yr runtime
- Probe upto few gram mass

$$M_X > 3 \times 10^{24}\,\mathrm{GeV} \times \left(\frac{\rho_{\rm DM}}{0.4\,\mathrm{GeV/cm^3}}\right)\left(\frac{A_{\rm gen}}{2\times 10^5\,\mathrm{m}^2}\right)\left(\frac{T}{10\,\mathrm{yrs}}\right) \times \int dv_X\, f_{\rm DM}(v_X)\,\epsilon_{\rm eff}(v_X,\lambda_X,E_X)\left(\frac{v_X}{300\,\mathrm{km/s}}\right)$$

Can not probe beyond few grams



(Bai, Berger, **MK** ' 22)

Future Direction

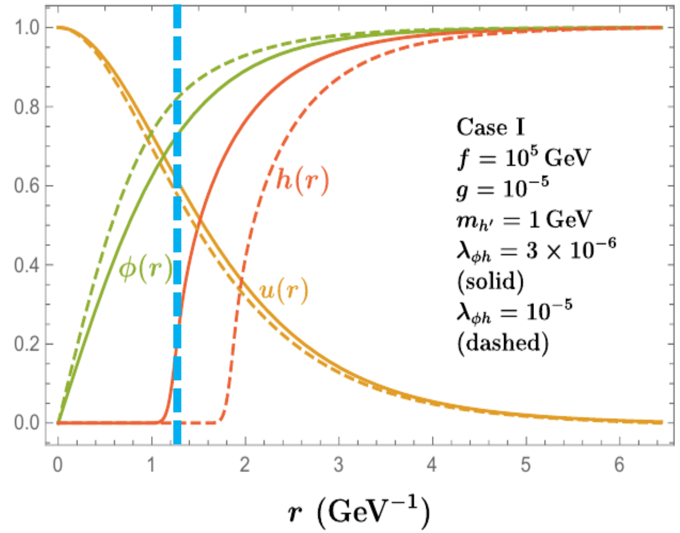
- **New ways to get EWS ball:** Changes the parameter space (radius and mass) where EWS can be formed (EWS Fermi ball?). Can we get Electroweak Symmetric Stars?

- **Triggers and Searches using exp data:** Neutrino detectors such as DUNE, HyperK**.** Search for track like signatures at these experiments

- **Astrophysical searches:** Probe beyond few gram mass

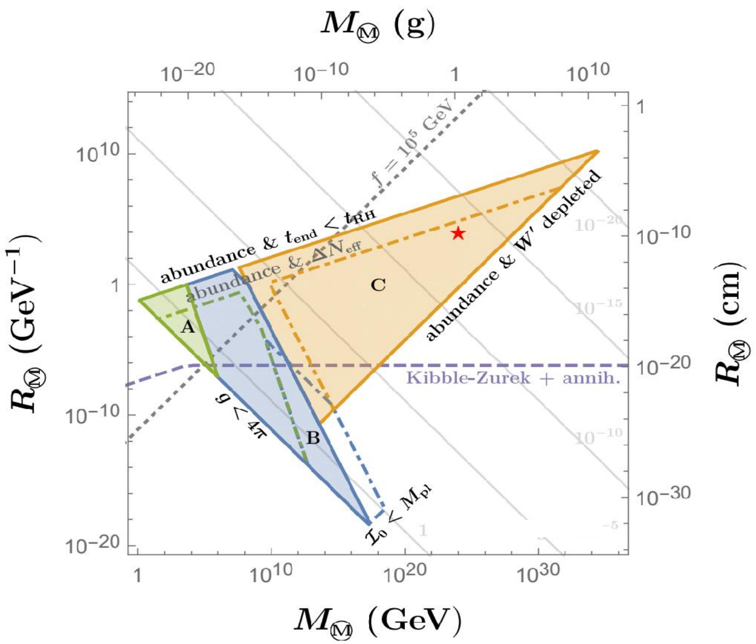
Summary : Electroweak Symmetric Ball

How to get it from microscopic physics?

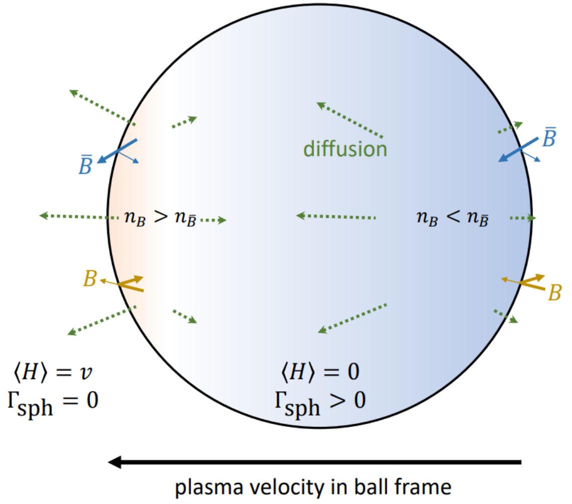


Electroweak Symmetric Case

Early universe formation
Can it be relic DM?



Catalyzed Baryogenesis



Direct Detection