Monopoles, VDMs & dark radiation

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(arXiv: 1311.1035, in collaboration with Seungwon Baek & Pyungwon Ko)

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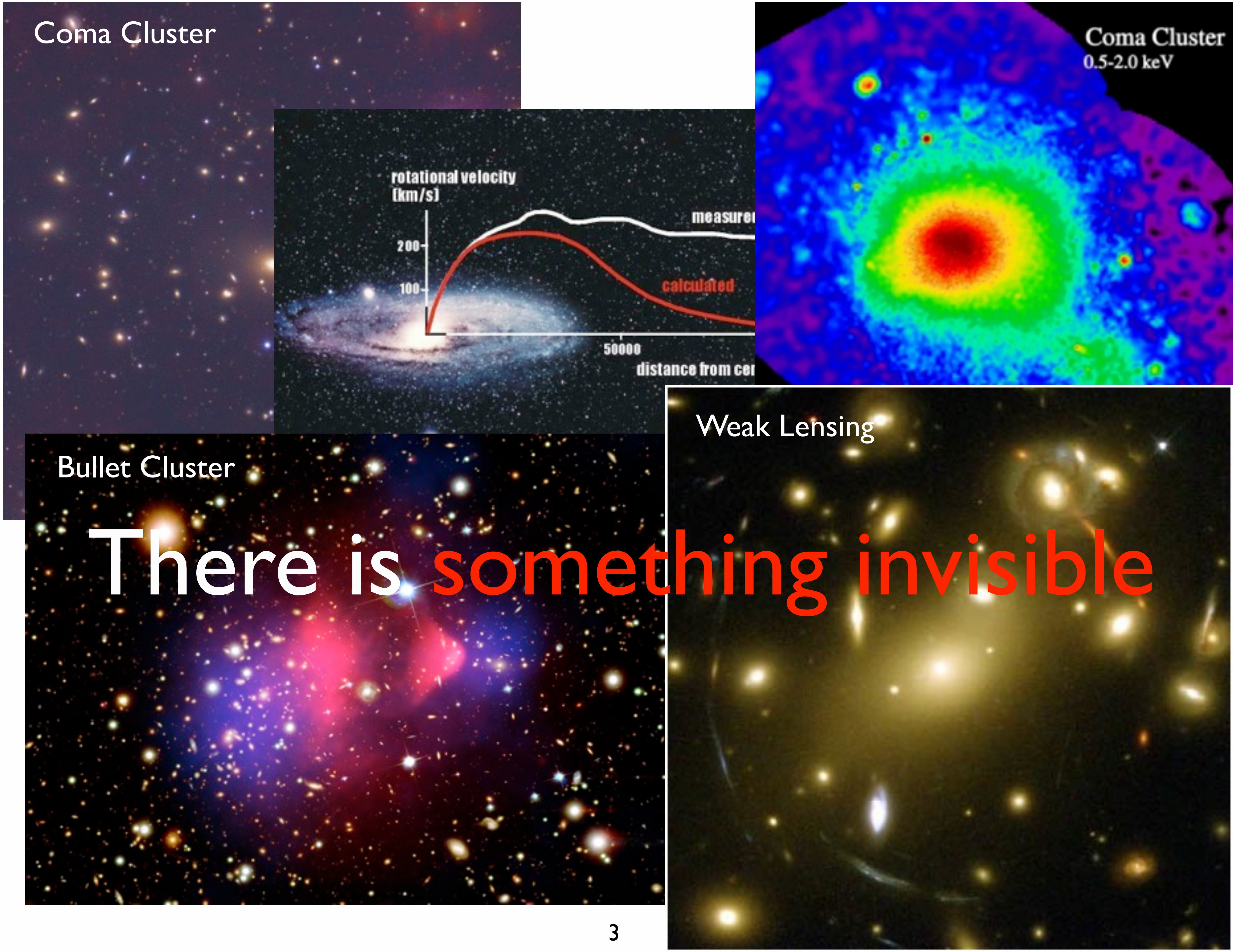
Dark matter

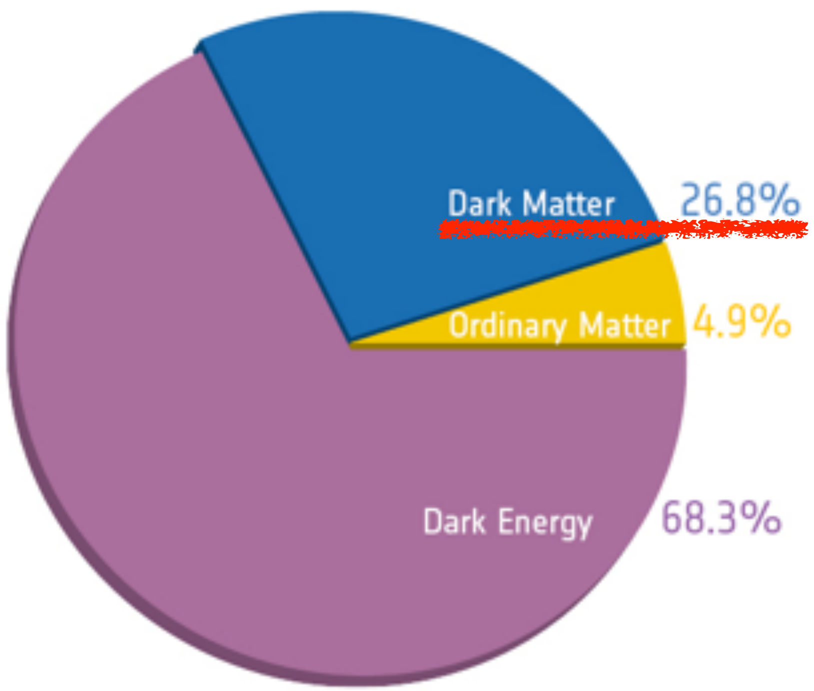


There is something invisible

Planck says ...

- Cosmological parameters (based on LCDM)

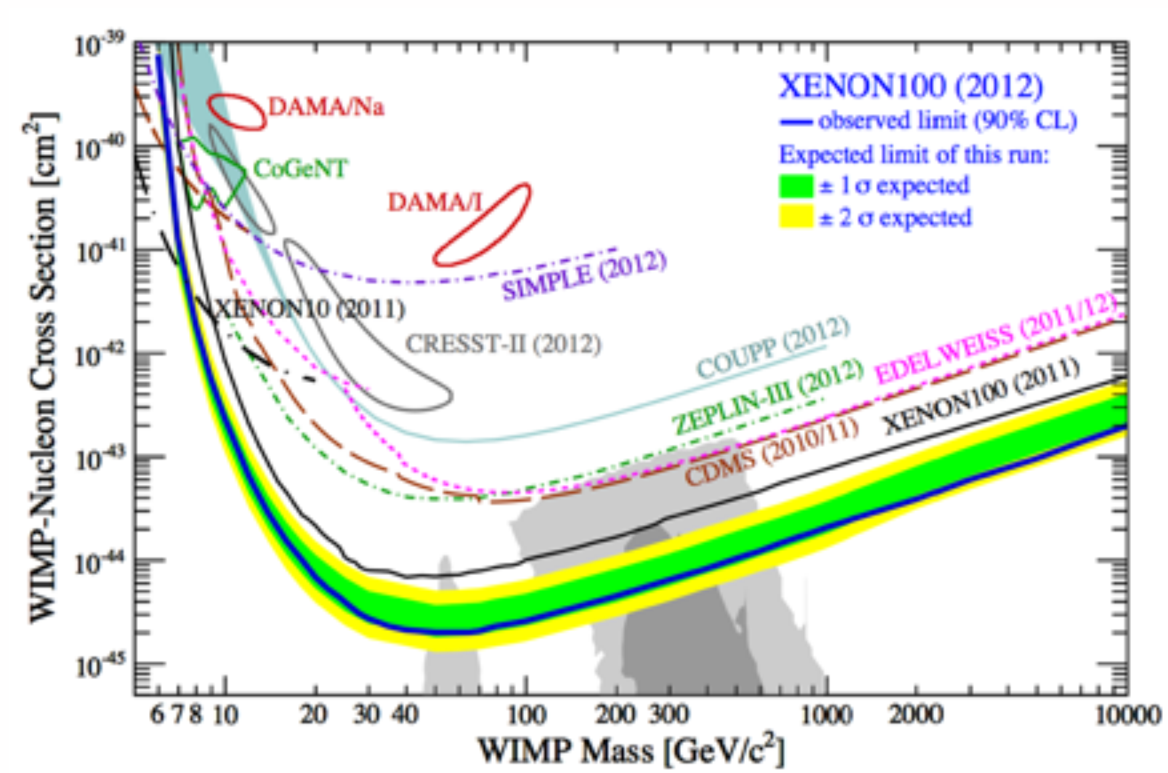
	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

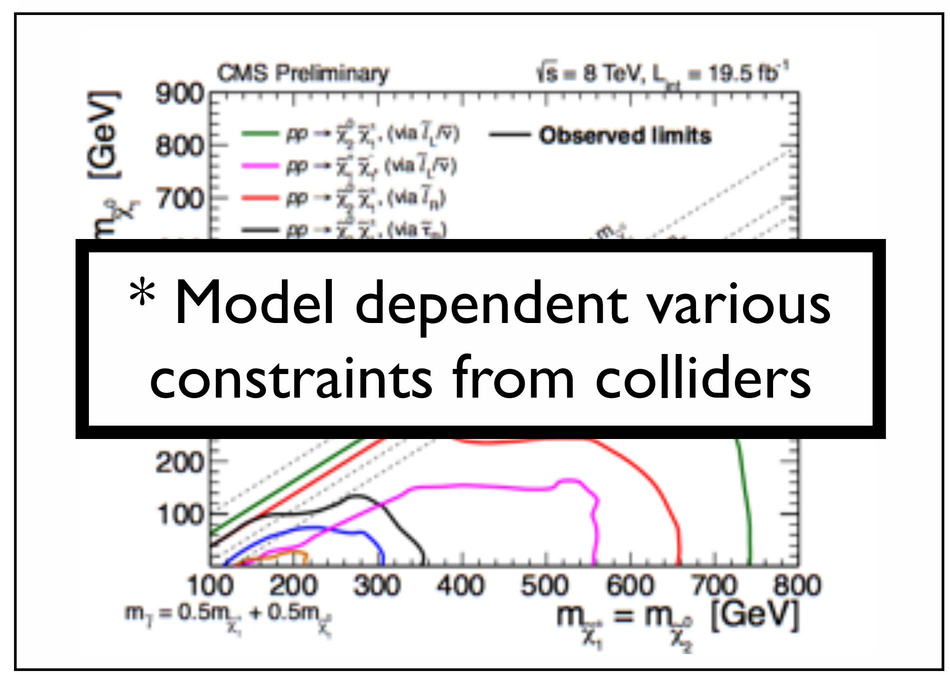


Energy budget

Dark matter is ...

- Properties
  - electromagnetically neutral (invisible)
  - matter-like (clustered)
  - long-living ($\tau \gtrsim 10^{26\text{-}30}$s) or absolutely stable
  - mostly cold
- Productions
  - thermal (freeze-in, freeze-out)
  - non-thermal
- Constraints





* Model dependent various constraints from colliders

Candidates of DMs

- Moduli, axion, ...
- LSP (gravitino, neutralino, sneutrino, singlino, axino, ...)
- LKP (eg, KK-photon)

or

- Scalar
- Fermion
- Vector

DM is stable because...

- Symmetries

  - (ad hoc) Z_2 symmetry
  - R-parity
  - Topology (from a broken sym.)

- Very small mass and weak coupling

  e.g: QCD-axion ($m_a \sim \Lambda_{QCD}^2/f_a$; $f_a \sim 10^{9\text{-}12}$ GeV)

  ⇨ $$\Gamma_a \sim \mathcal{O}(10^{-5})\frac{m_a^3}{f_a^2} \ll H_0 \sim 10^{-42}\mathrm{GeV}$$

But for WIMP ...

- Global sym. is not enough since

$$-\mathcal{L}_{\rm int} = \begin{cases} \lambda \frac{\phi}{M_{\rm P}} F_{\mu\nu} F \mu\nu & \text{for boson} \\ \lambda \frac{1}{M_{\rm P}} \bar{\psi} \gamma^\mu D_\mu \ell_{Li} H^\dagger & \text{for fermion} \end{cases}$$

Observation requires [M. Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\rm DM} \gtrsim 10^{26-30} {\rm sec} \Rightarrow \begin{cases} m_\phi \lesssim \mathcal{O}(10) {\rm keV} \\ m_\psi \lesssim \mathcal{O}(1) {\rm GeV} \end{cases}$$

$\Rightarrow$ WIMP is unlikely to be stable

- SM is guided by gauge principle

It looks natural and may need to consider a gauge symmetry in dark sector, too.

Principles for BSM

- Gauge symmetry

  - can make DM absolutely stable.

- Renormalizability

  - does not miss physics which EFT can not catch.

- Singlet portals

  - allows communication of DS to SM (thermalization, detectability, ...)

Dark gauge symmetry broken to a U(1)

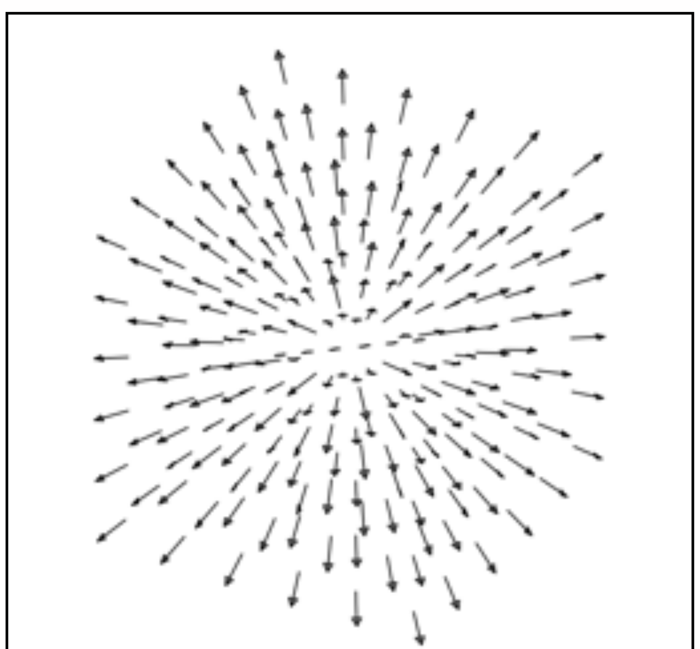
Magnetic monopoles

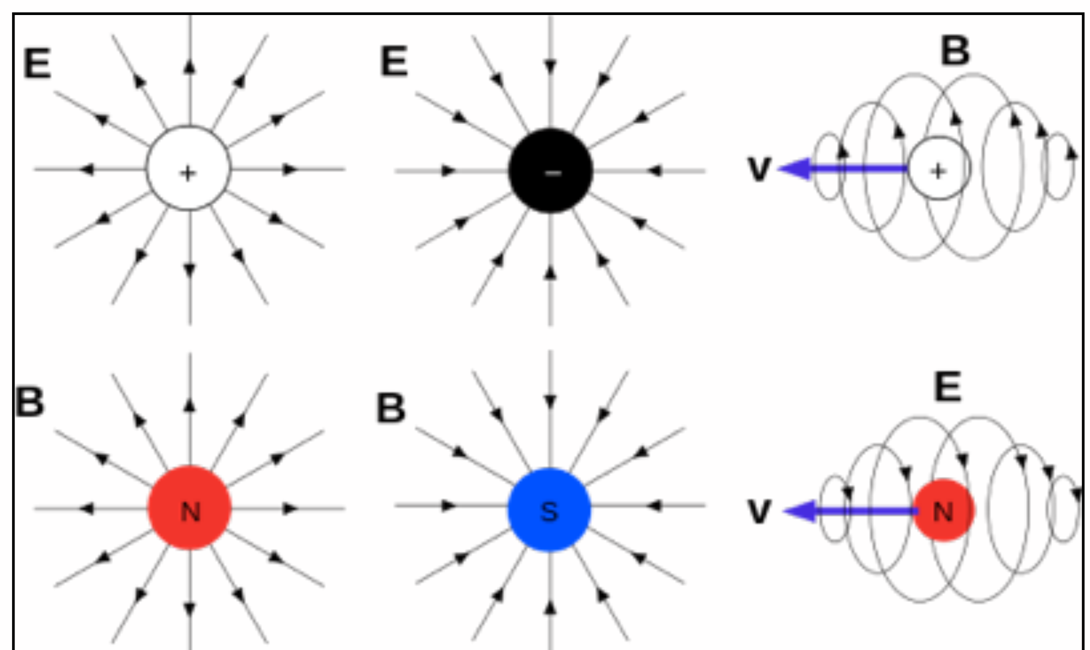
- ’t Hoft-Polyakov monopoles exist when vacuum manifold contains non-shrinkable surfaces.

⟺ $\Pi_2(\mathcal{M}) \neq \mathcal{I}$

⟺ (semi-) simple symmetry group broken to a subgroup with an U(1) factor

$$(\ \textit{hedgehog}\ \text{conf.} :\ \phi^a(\hat{r}) = v_\phi \hat{r}^a\ \text{with}\ (\phi^a(\hat{r}))^2 = v_\phi^2\ )$$





[wiki]

Vector dark matter(?)

- Renormalizable (?) model

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}(F_V)^2 - \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{1}{4}\lambda_V\,(V_\mu V^\mu)^2 - \frac{1}{2}\lambda_{VH} V_\mu V^\mu H^\dagger H$$

- not unitary!
- not gauge invariant!
- dark Higgs is needed.

- Corrected simple model

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}(F_V)^2 + (D\phi)^2 - \lambda_\phi|\phi|^4 - \lambda_{\phi H}|\phi|^2 H^\dagger H$$

SSB $\Rightarrow$ massive VDM! $\Rightarrow$ no dark radiation!

Dark Radiation

- Observations

$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \quad \Rightarrow \quad \Delta N_{\rm eff} = 0.254^{+0.54}_{-0.51}$$

(Planck+WP+highL+BAO, 95%CL)

- Sources

  - relativistic degrees of freedom other than SM photons (light sterile neutrinos, (QCD-) axions, ...)

- Size of contribution

  - assuming no more non-SM light degrees below $T_{\rm DR,kd}$,

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{g_{\rm DR}}{2} \left(\frac{g_{*S}(T_0)}{g_{*S}(T_{\rm DR,kd})}\right)^{4/3}$$

$SU(2)_h \rightarrow U(1)_h$

+

Higgs portal

The Model

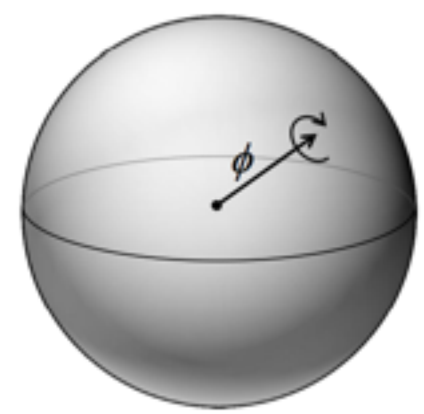
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} V^a_{\mu\nu} V^{a\mu\nu} + \frac{1}{2} D_\mu \vec{\phi} \cdot D^\mu \vec{\phi} - \frac{\lambda_\phi}{4} \left(\vec{\phi} \cdot \vec{\phi} - v_\phi^2 \right)^2 - \frac{\lambda_{\phi H}}{2} \vec{\phi} \cdot \vec{\phi} H^\dagger H$$

’t Hoot-Polyakov | Higgs portal

- Symmetry breaking

$$\phi^T = (0, 0, v_\phi) \Rightarrow SU(2) \rightarrow U(1)$$



- Particle spectra $\left(V^\pm \equiv \frac{1}{\sqrt{2}} (V_1 \mp i V_2) \,,\ \gamma' \equiv V_3,\ H_1,\ H_2 \right)$

$$m_V = g_X v_\phi$$

$$m_M = m_V / \alpha_X$$

$$m_{1,2} = \frac{1}{2} \left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{ \left(m_{hh}^2 - m_{\phi\phi}^2 \right)^2 + 4 m_{\phi h}^4 } \right]$$

DM self-interacts

- Constraint from dwarf galaxy scale halos

$$\sigma_T/m_V \lesssim 35\mathrm{cm}^2/g \Rightarrow g_X \lesssim 9\times 10^{-2}\left(\frac{m_V}{1\mathrm{TeV}}\right)^{3/4}$$

- Possible solutions to some puzzles of CDM

  - core/cusp problem: [S.-H Oh et al., arXiv:1011.0899]
    simulated cusp of DM density profile contrary to the cored one found in the obvserved LSB galaxies and dSphs

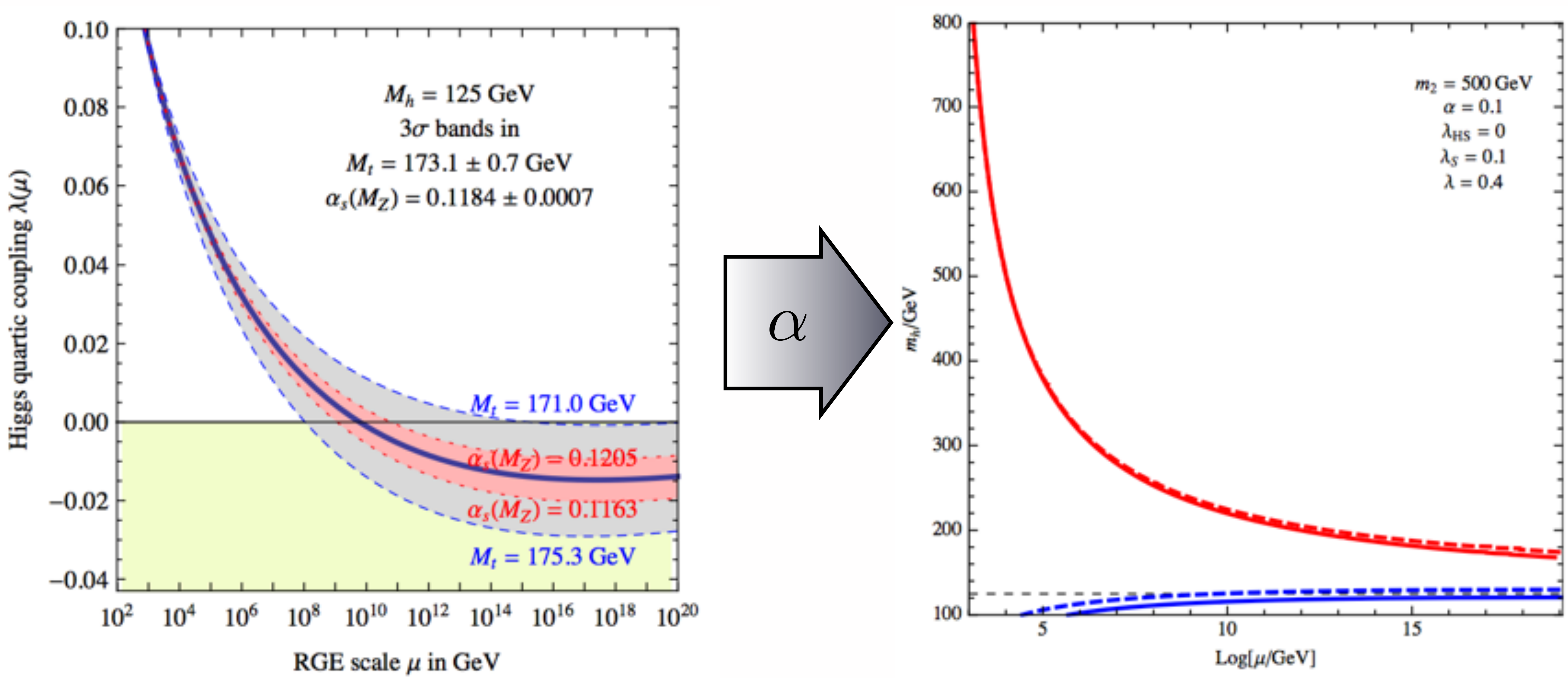
  - "too big to fail" problem: [M. Boylan-Kolchin et al., arXiv:1111.2048]
    simulated high internal density concentration of the subhalos in the MW-sized halos contrary to the observed brightest MW satellites

- Dark radiation ($\Leftarrow$ massless dark photon)

Vacuum stability

[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

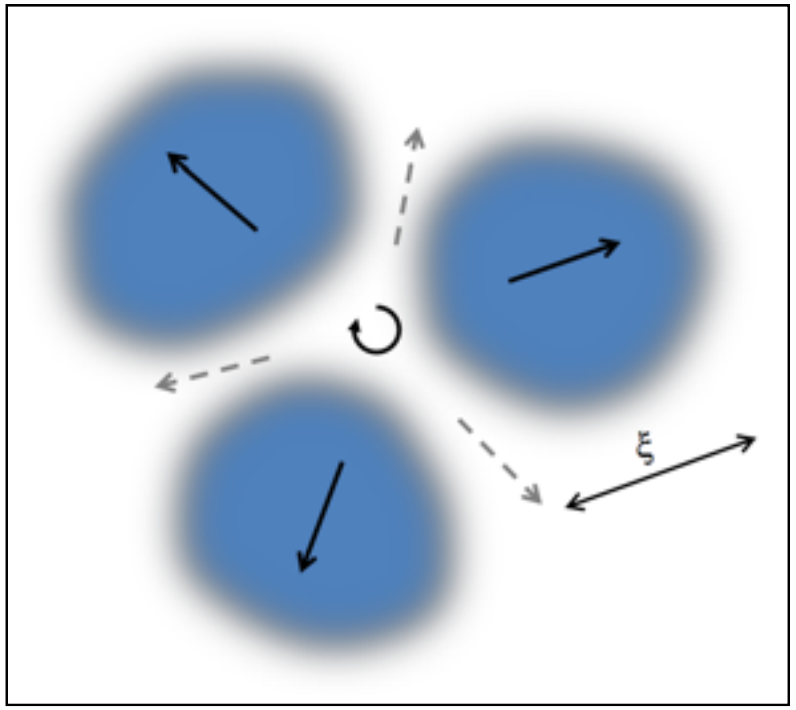
$$\lambda_H = \left[1 + \tan^2(\alpha)\frac{m_2^2}{m_1^2}\right]\cos^2(\alpha)\frac{m_1^2}{2v^2} \quad (\Leftarrow \lambda_{\phi h})$$



[G. Degrassi et al., 1205.6497]

Relic densities

- Monopoles (Kibble-Zurek mechanism)-1/2



$$\epsilon \equiv (T_c - T)/T_c$$

$$\xi = \xi_0 |\epsilon|^{-\nu}, \ \xi_0^{-1} \sim \sqrt{|m_\phi(0)^2|}$$

$$\tau = \tau_0 |\epsilon|^{-\mu}, \ \tau_0 \approx \xi_0$$

$$\tau_Q = (t - t_c)/|\epsilon| \to \tau_0 |\epsilon|^{-(1+\mu)}$$

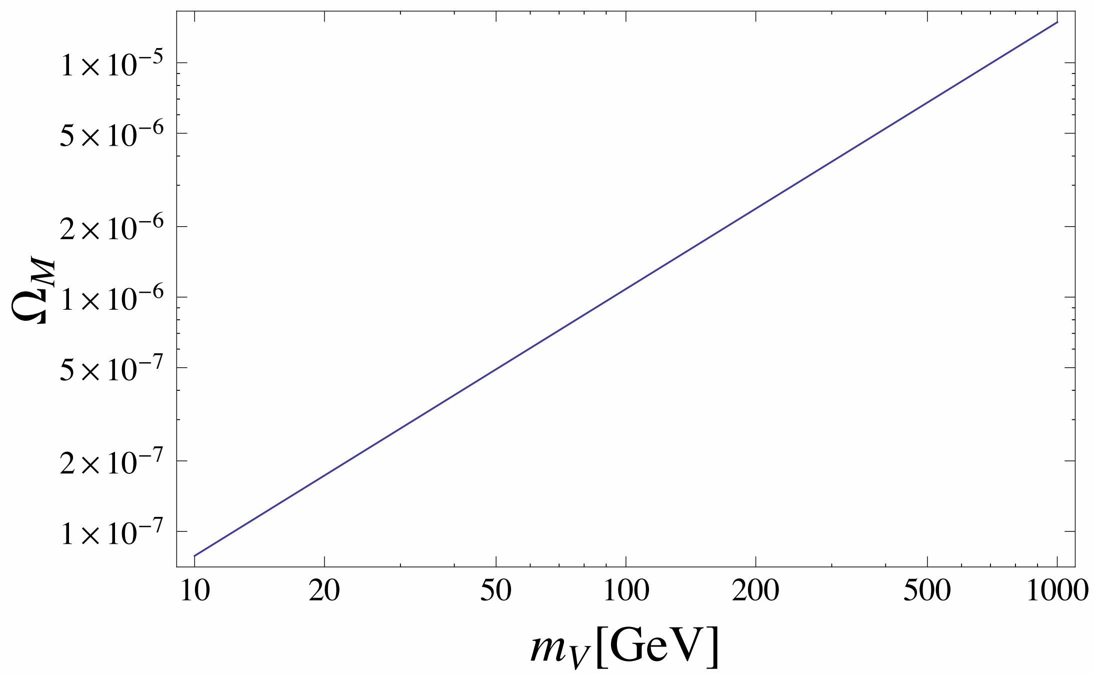
$$\Rightarrow \xi \sim \xi_0 (\tau_Q/\tau_0)^{-\frac{\nu}{1+\mu}}$$

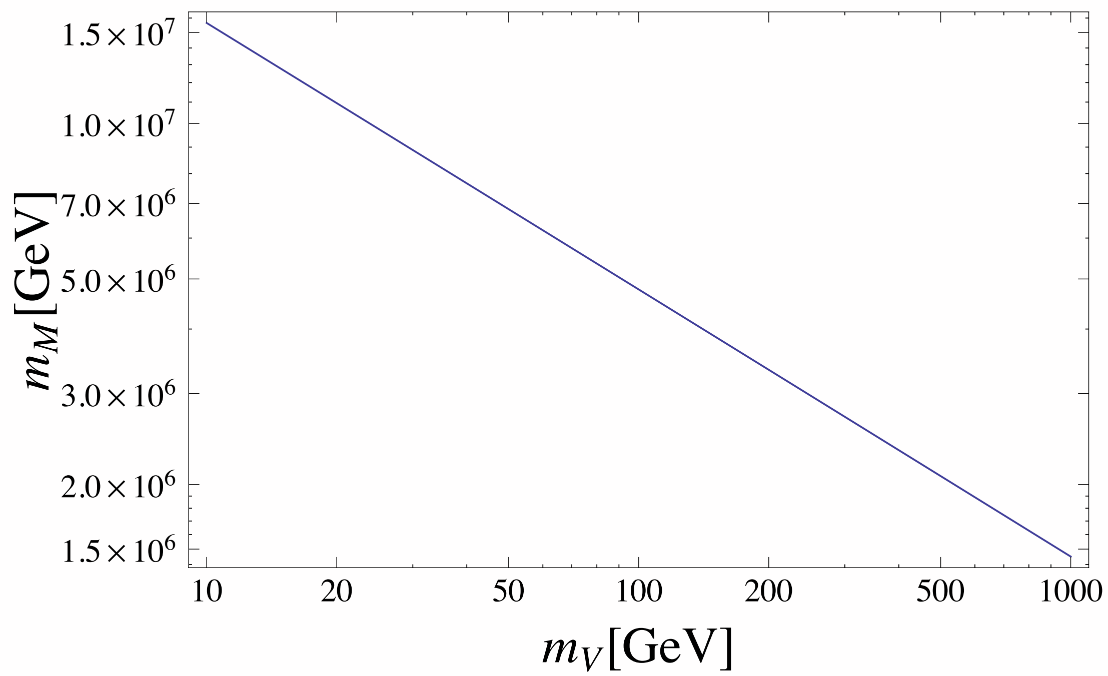
$$n \sim 1/\xi^3 \Rightarrow Y_i \approx \frac{\left(\sqrt{\lambda_\phi/2}\right)^3}{C_S} \left[\frac{1}{\sqrt{\lambda_\phi/2}} C_0^{1/2} \frac{m}{h M_P} \right]^{3\nu/(1+\mu)}$$

$$\text{Landau} - \text{Ginzburg form of } V(\phi) : \Rightarrow \nu = \mu = 1/2$$

$$\text{Quantum} - \text{corrected} : \Rightarrow \nu = \mu = 0.7$$

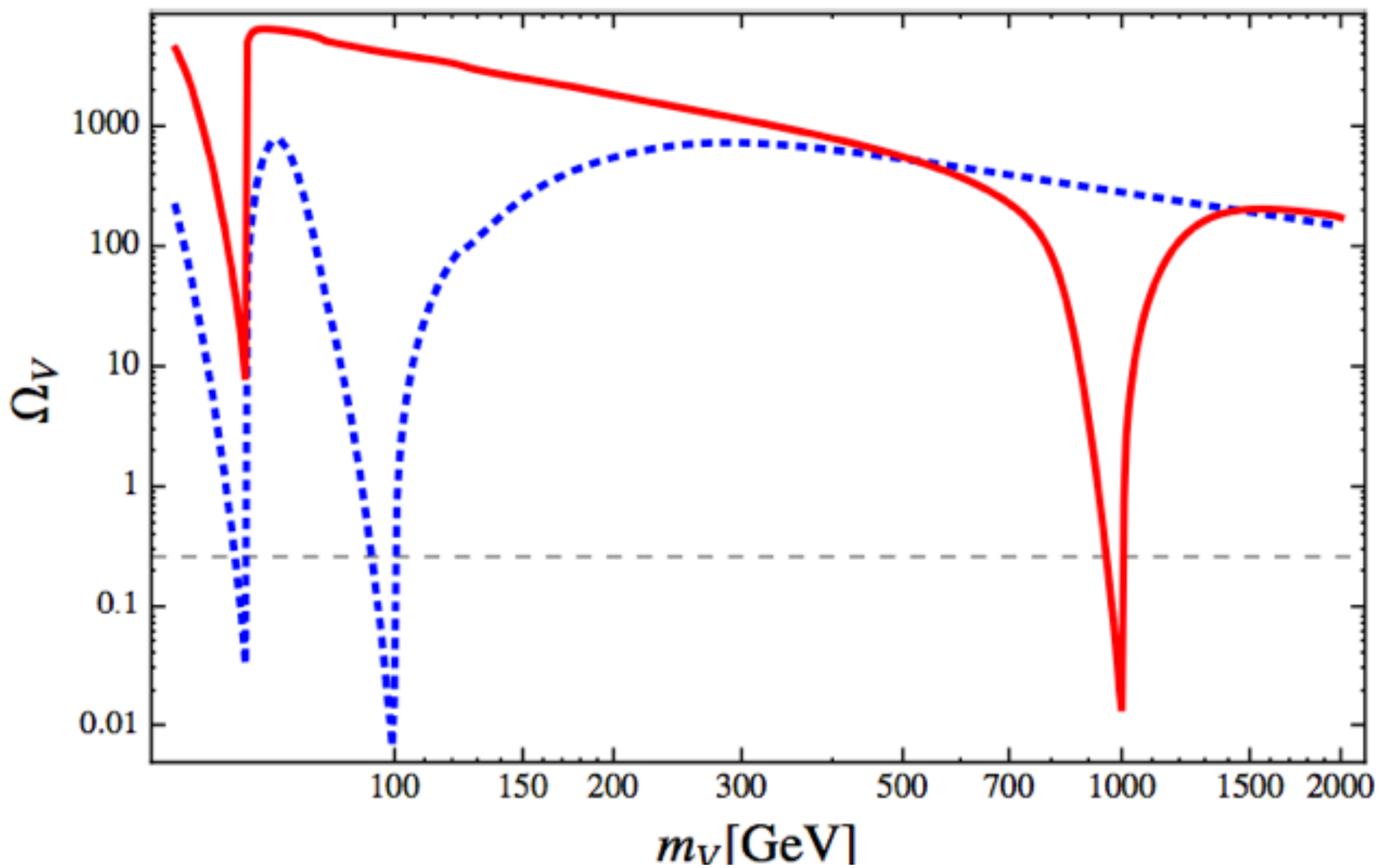
- Monopoles (relic density)-2/2





$$g_X = 9 \times 10^{-2}\,(m_V/1\mathrm{TeV})^{3/4} \Rightarrow v_\Phi = \mathcal{O}(1-10)\mathrm{TeV}$$

- VDM (thermal freeze-out)



$$m_V Y_{V,0}^{\rm res} \approx C_V \frac{m_V^2}{M_{\rm P}} \frac{m_{\rm R}}{\Gamma_{\rm R}} \frac{\epsilon_{\rm R}^{1/2}}{{\rm B}_i {\rm B}_f} \frac{\Theta(\epsilon_{\rm R})}{{\rm erfc}(\sqrt{x_{\rm fz}\epsilon_{\rm R}})}$$

$$\gtrsim 9.4 \times 10^{-12}\,{\rm GeV} \left(\frac{m_V}{1\,{\rm TeV}}\right)^{1/2} \frac{\Gamma_{\rm R}}{\Gamma_{\rm R}^{\rm SM}} \frac{\Theta(\epsilon_{\rm R})}{{\rm erfc}(\sqrt{x_{\rm fz}\epsilon_{\rm R}})} \quad (13)$$

$$\Delta m_V / m_V = \mathcal{O}(0.01 - 0.1)$$

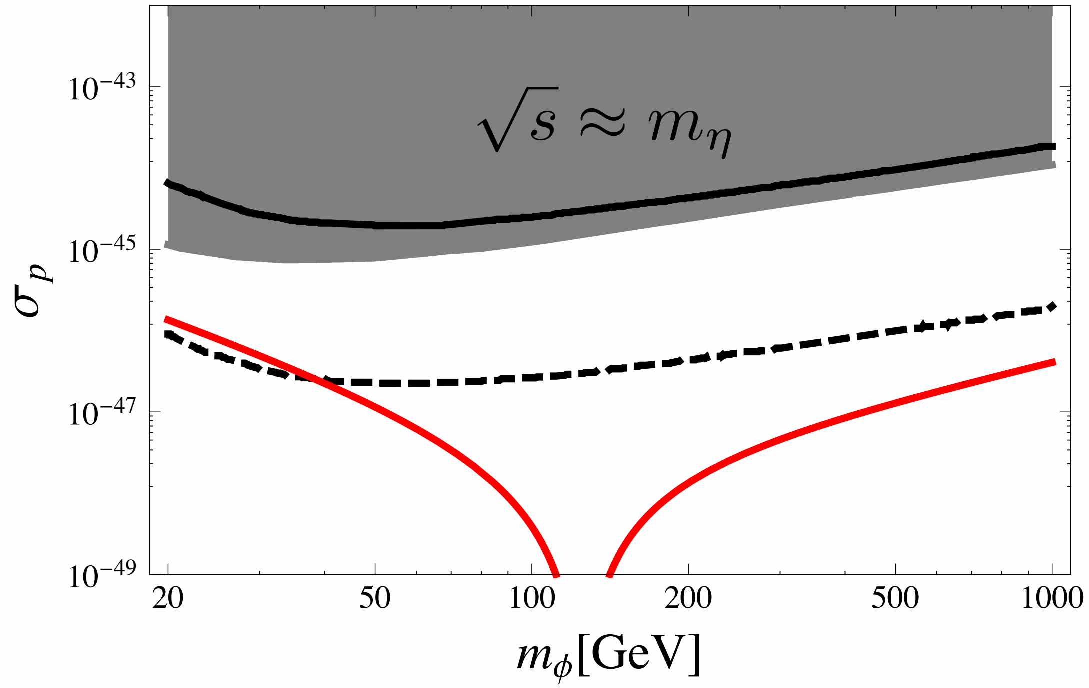
Direct detection

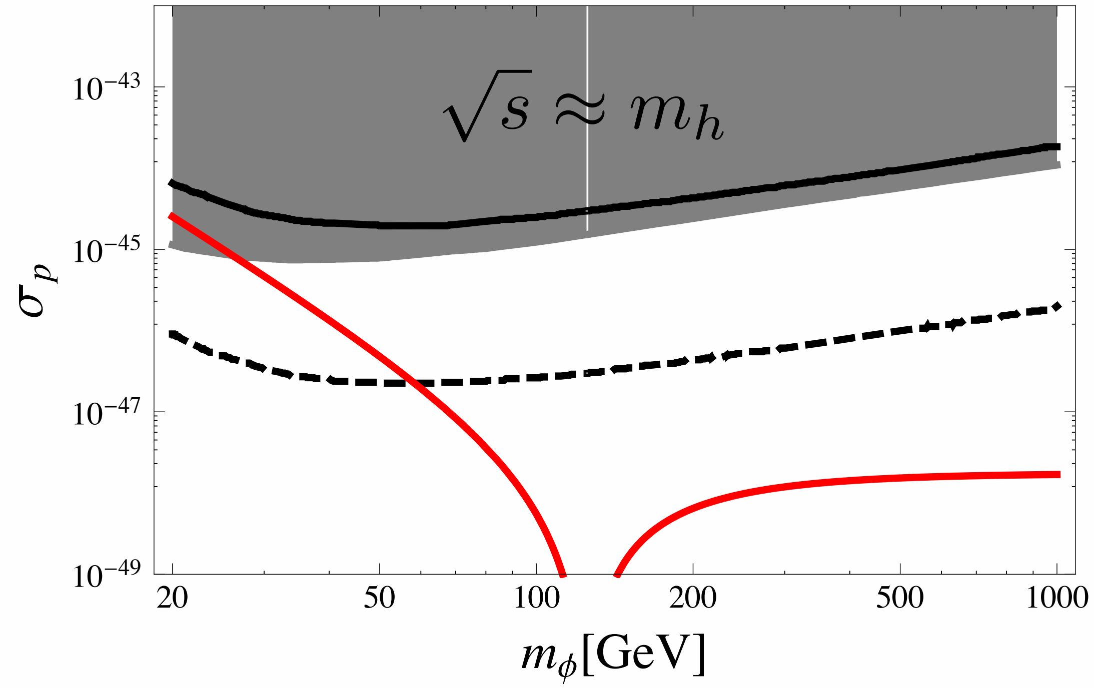
- Monopole-nucleon scattering cross section

$$\sigma_p \lesssim \frac{\lambda_{\Phi H}^2}{64\pi m_{\rm M}^2}\left(\frac{m_p}{m_h}\right)^4 f_p^2 \simeq \frac{3.4\times 10^{-28}}{\rm GeV^2}\left(\frac{\lambda_{\Phi H}}{0.1}\right)^2\left(\frac{10^7\,{\rm GeV}}{m_{\rm M}}\right)^2$$

- VDM-nucleon scattering cross section

$$\sigma_p = \frac{4\mu_V^2}{\pi}\left(\frac{g_X s_\alpha c_\alpha m_p}{2v_H}\right)^2\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)^2 f_p^2,$$

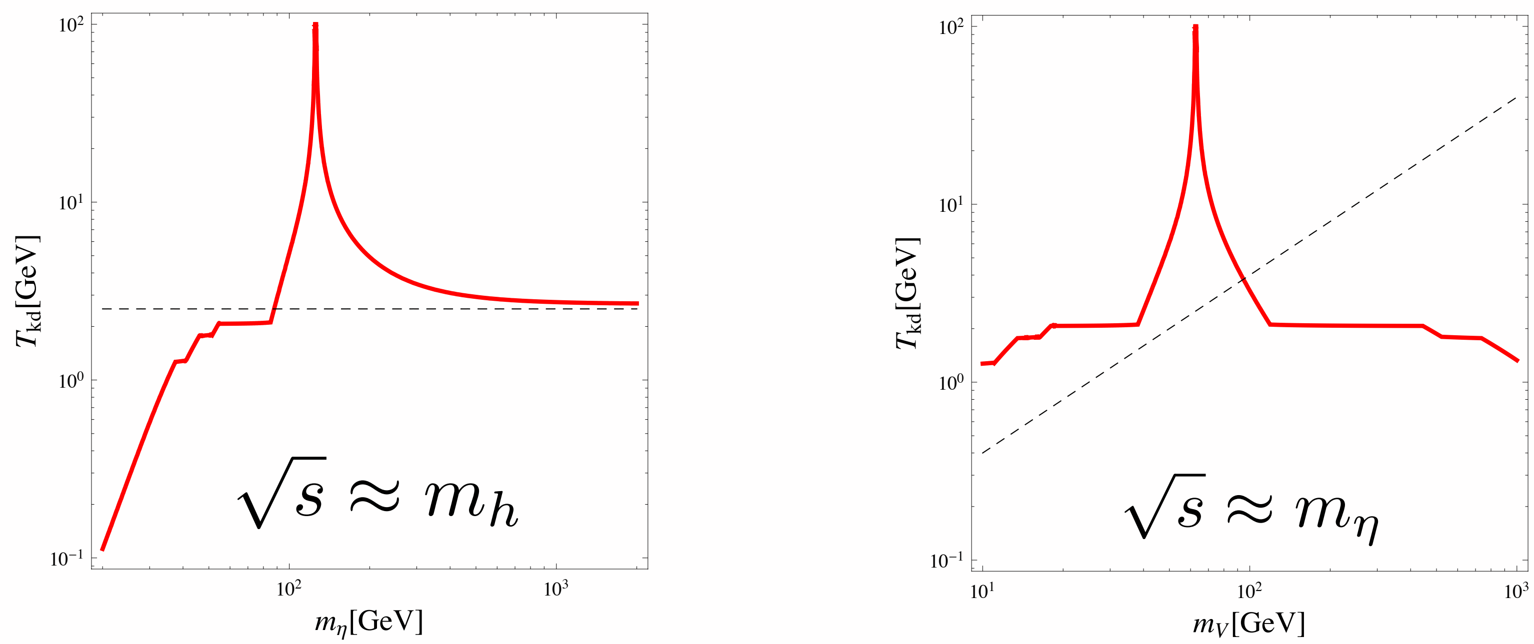




DR from dark photon

- T at kinetic decoupling of DR

Higgses mediate DM-SM scattering $\Rightarrow$ $\mathcal{M} = -v_\Phi g_X^2 \sin\alpha\cos\alpha \left(\frac{1}{t-m_1^2} - \frac{1}{t-m_2^2}\right)\frac{\sqrt{2}m_f}{v_H}$



$$T_{\rm QCD} < T_{\rm kd} \leq T_{\rm fz} \sim m_V/25$$

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{g_{\rm DR}}{2}\left(\frac{g_{*S}(T_0)}{g_{*S}(T_{\rm DR,kd})}\right)^{4/3} \approx 0.08 - 0.11$$

Conclusions

- t'Hoot-Polyakov monopole model is a nice example of VDM accompanying DR.
- The abundance of monopoles is $(10^{-6}\text{-}10^{-4})\times\Omega_{cdm}$
- CDM relic density is obtained from VDM via s-channel resonant annihilation thanks to Higgs portal interaction.
- Once m_V is known, m_η is known or vice versa.

Backup1

’t Hoot-Polyakov Monopoles

- Homotopy group & monopoles

Let $\mathcal{G} \to \mathcal{H}$ with $\mathcal{M} = \mathcal{G}/\mathcal{H}$

$$\Pi_2(\mathcal{G}/\mathcal{H}) = \begin{cases} \Pi_1(\mathcal{H}) & \text{for simply} - \text{connected } \mathcal{G} \\ \Pi_1(\mathcal{H})/\Pi_1(\mathcal{G}) & \text{for not} - \text{simply} - \text{connected } \mathcal{G} \end{cases}$$

$$\left.\begin{array}{l} \mathcal{G} = \text{semi} - \text{simple} \\ \mathcal{H} = \tilde{\mathcal{H}} \times U(1) \end{array}\right\} \Rightarrow \Pi_1(\mathcal{H}) \neq \mathcal{I} \Rightarrow \text{Monopole!}$$