Composite Dark Matter

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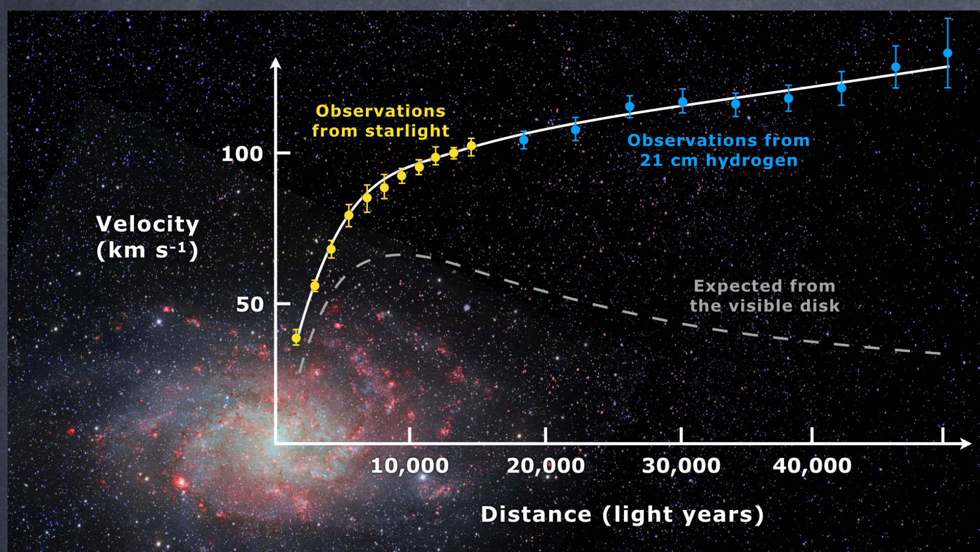
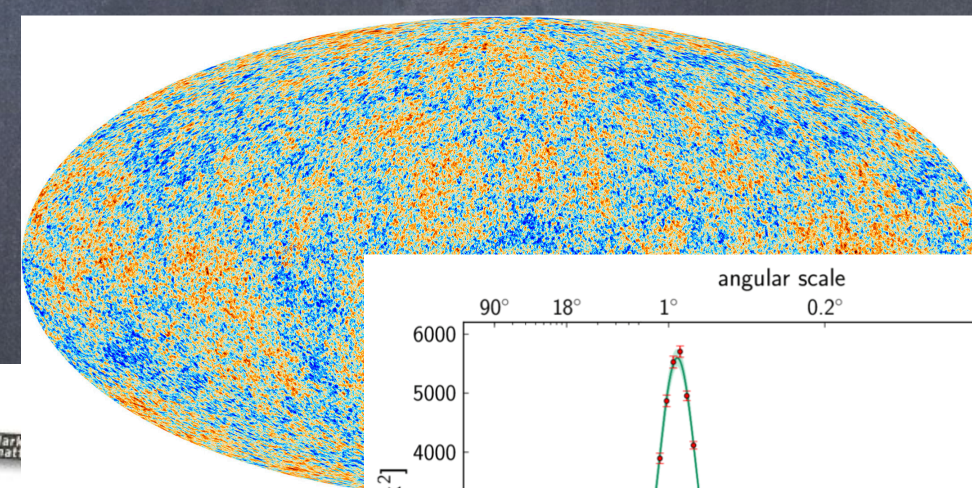
LFC22 @ ECT*, Trento

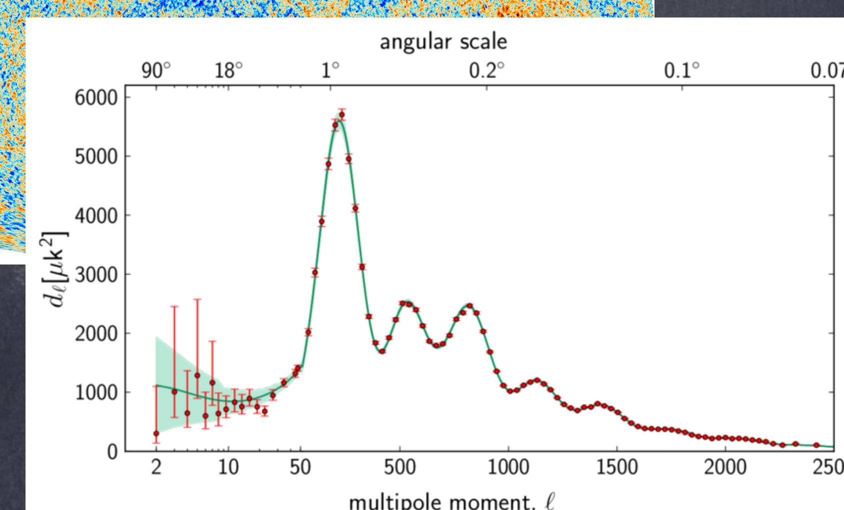
Dark Matter: where are we?

Indirect evidence in astrophysics and cosmology.



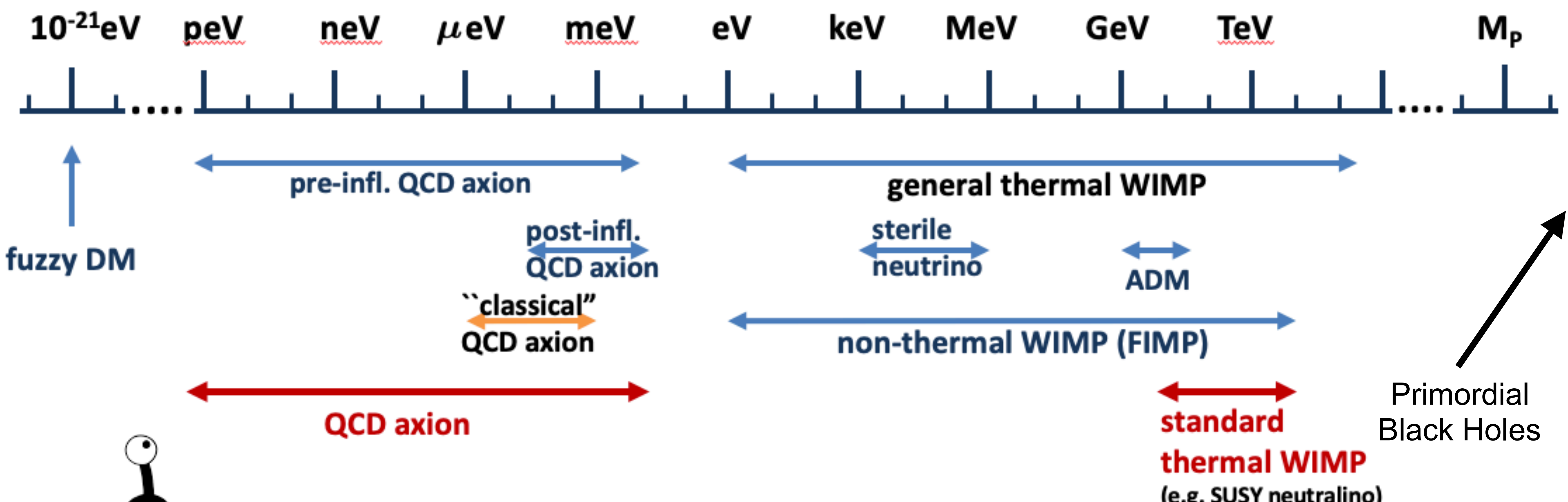
25% of our Universe is made of Dark Matter!





Dark Matter: where are we?

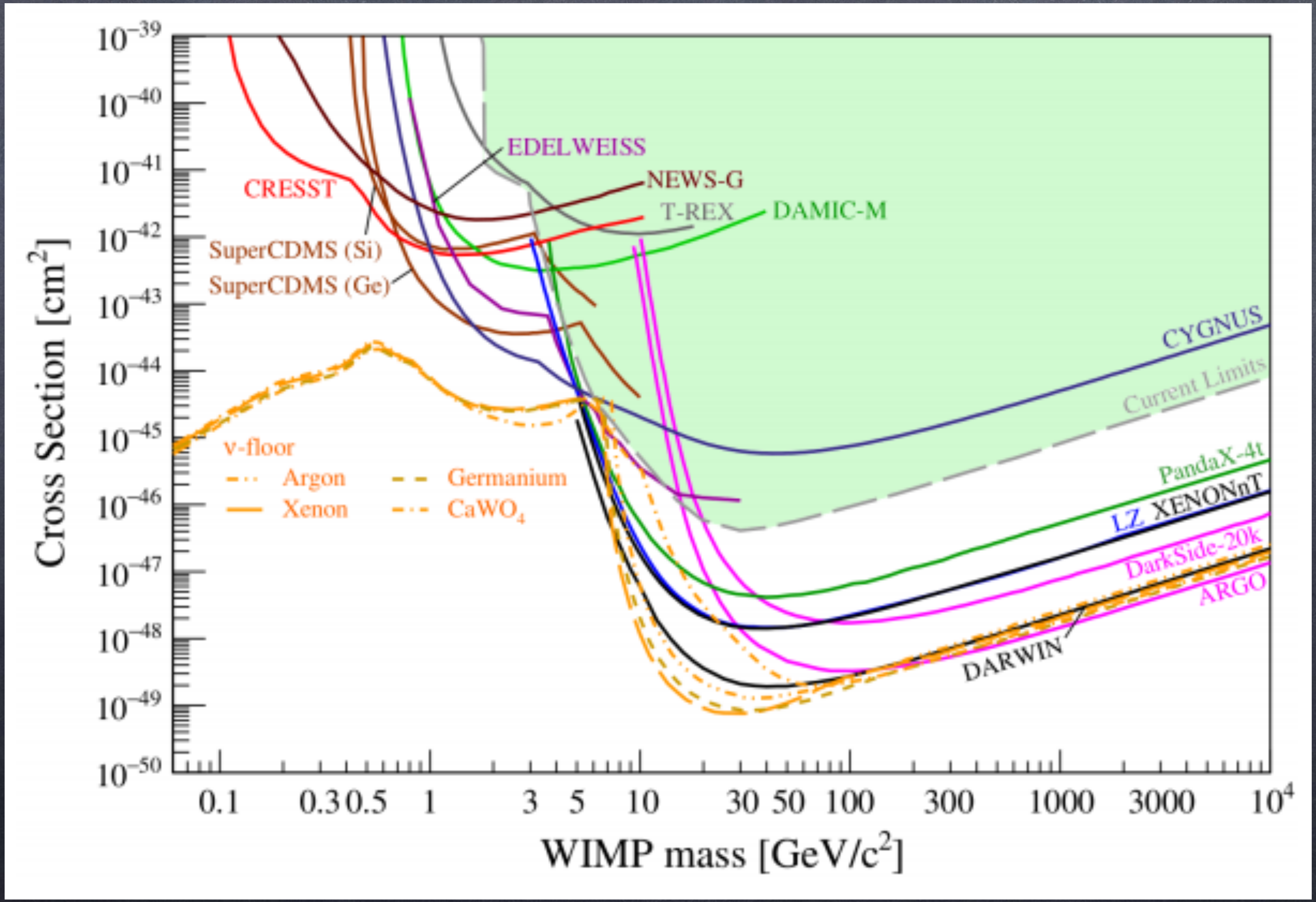
- Very wide 'available' mass range:



From the APPEC DM report

Dark Matter: where are we?

- Strong constraints from Direct Detection:

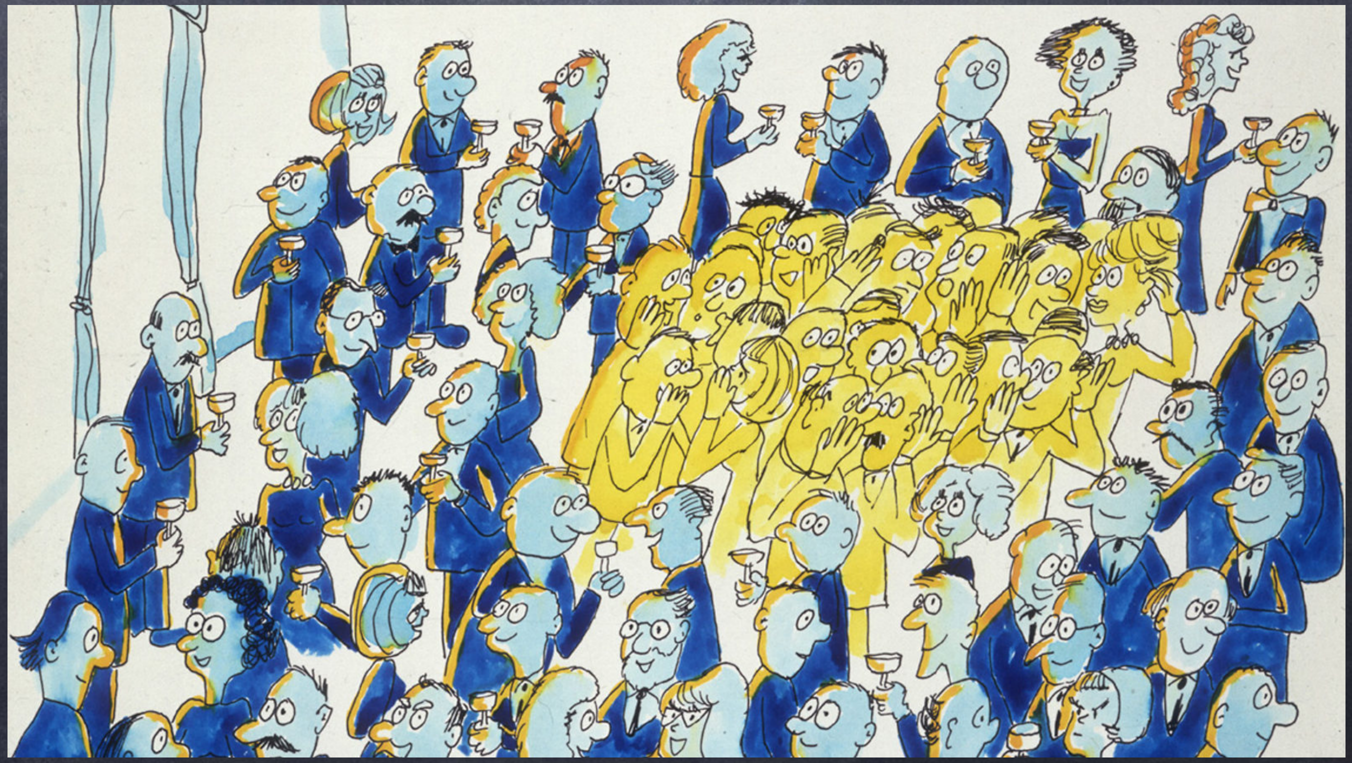


From the APPEC DM report

Benefits of compositeness:

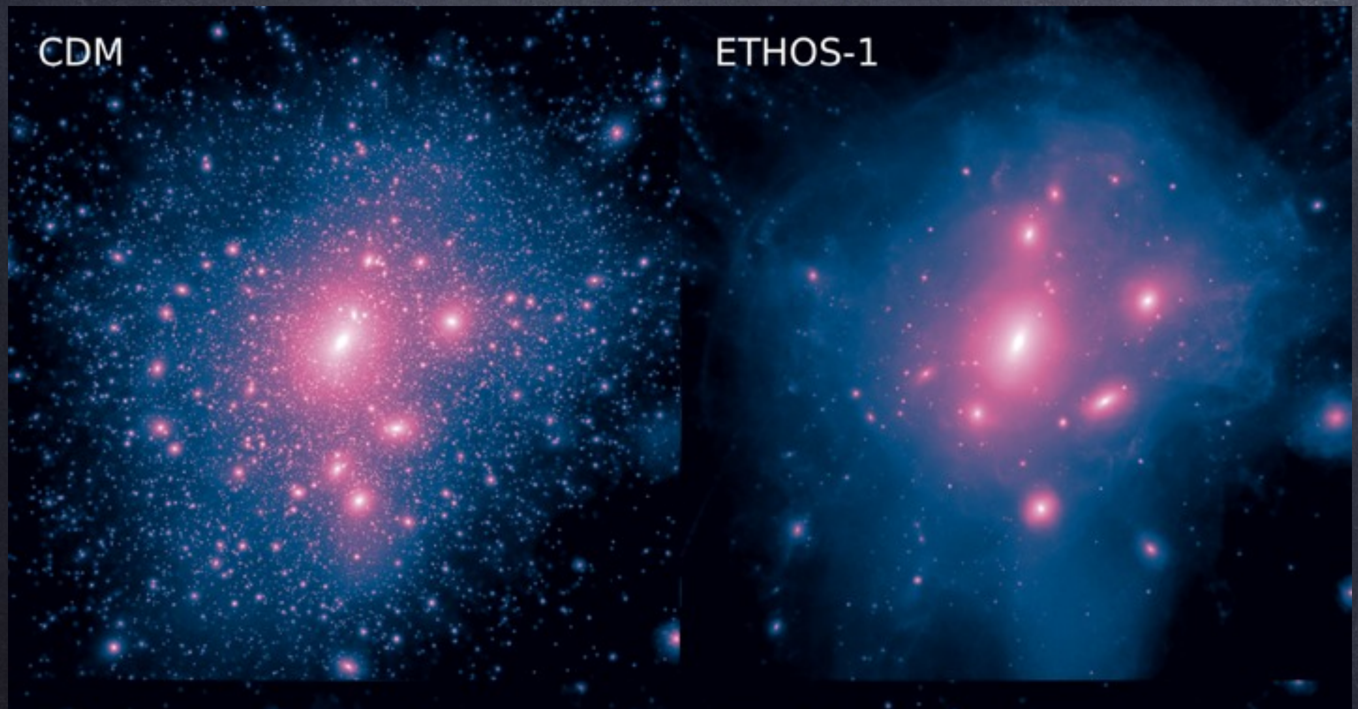
- Dynamical mass generation

A DM state can be made of massless fundamental particles, no need to generate mass!



Benefits of compositeness:

- Dynamical mass generation
- Self-interactions naturally present

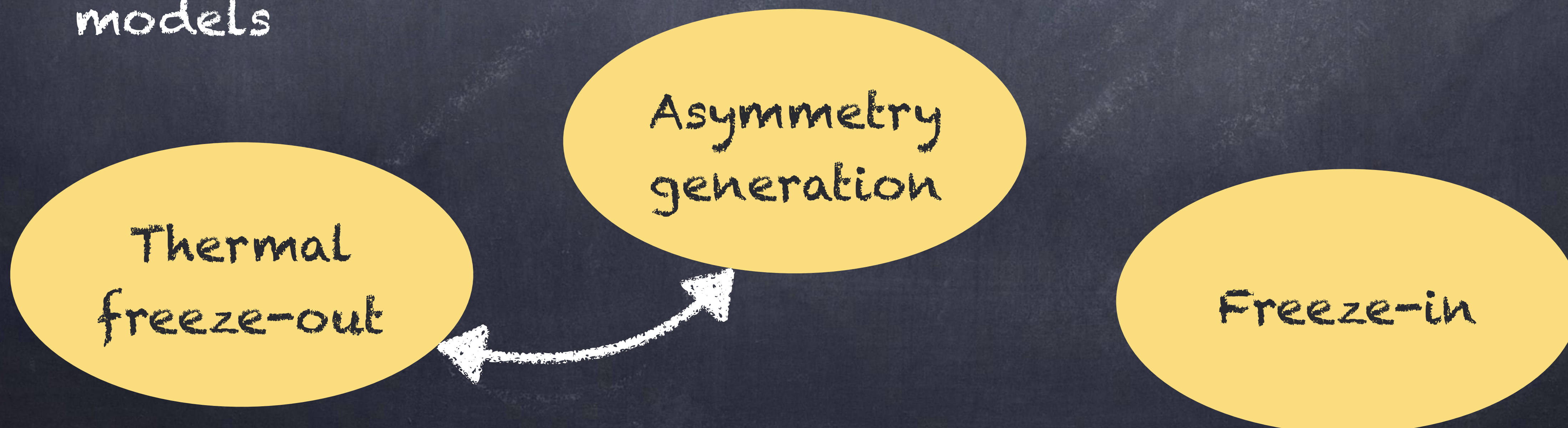


Collision-less DM
predicts too many small
structures around Galaxies

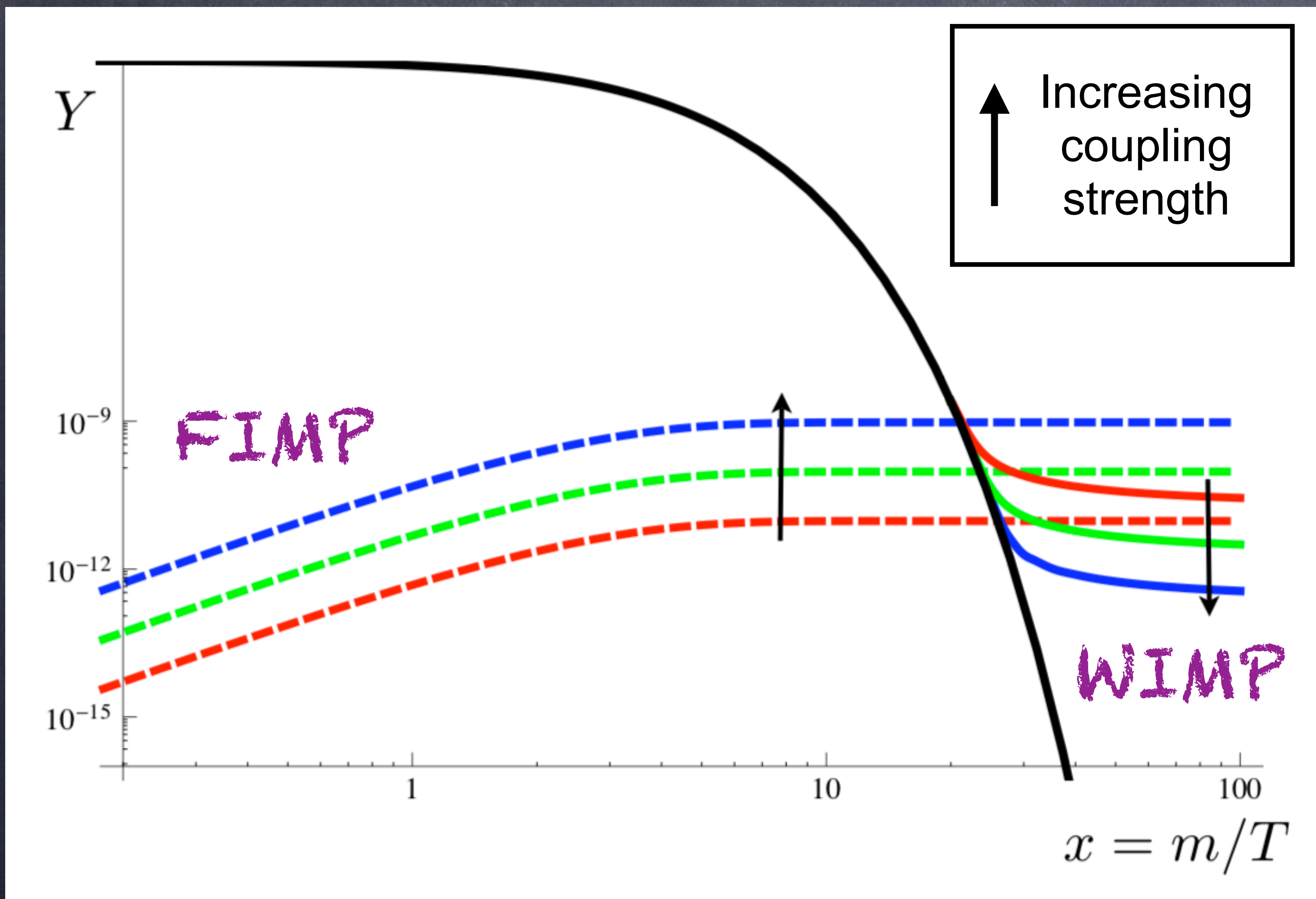
+ other issues...

Benefits of compositeness:

- Dynamical mass generation
- Self-interactions naturally present
- Many production mechanisms can be included in the models



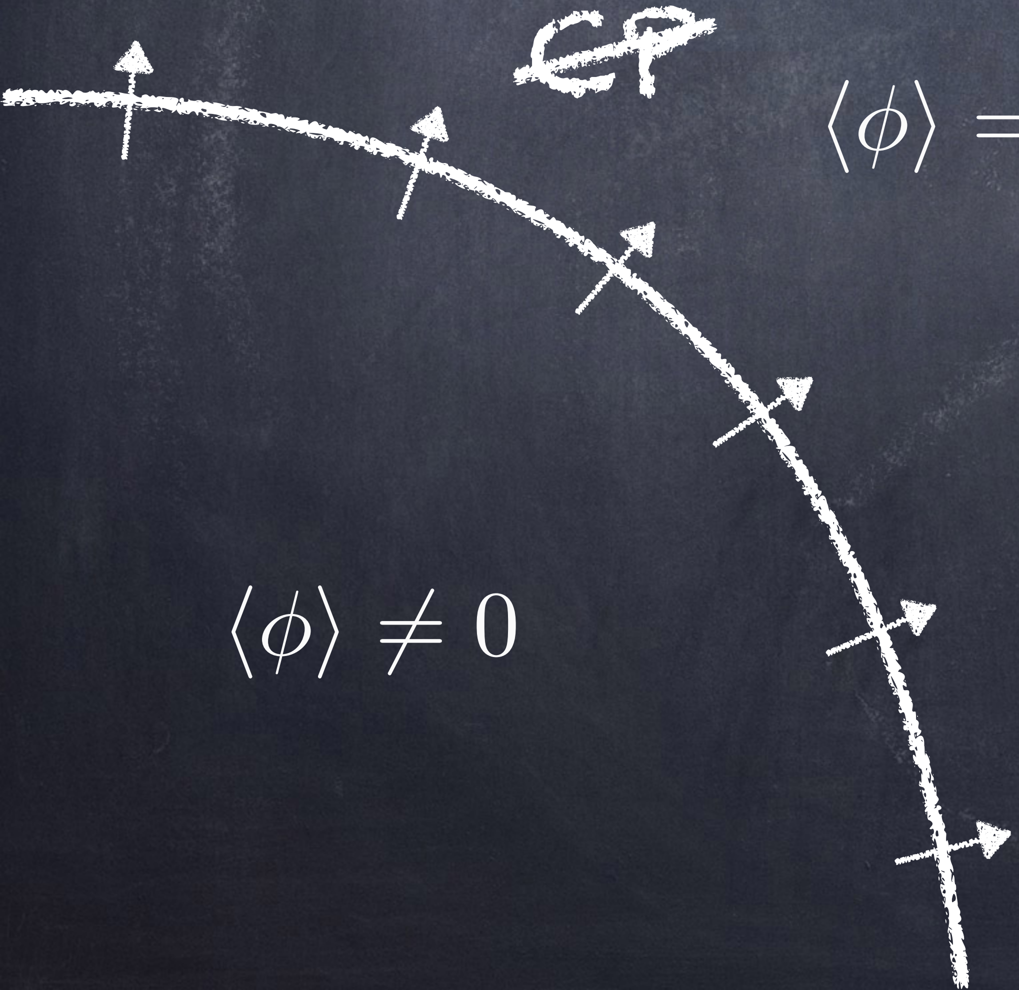
Production mechanisms



- Freeze-out: weak strength couplings to the SM required
- Freeze-out: feeble couplings to the SM needed.

Production mechanisms

- Asymmetric production: similar in nature to baryogenesis (might be related)



$\langle \phi \rangle = 0$

$\langle \phi \rangle \neq 0$

Tunneling produces net baryon number

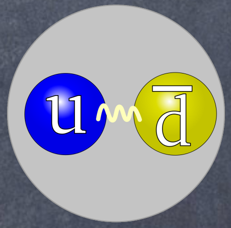
Credit: XKCD

How to couple the strong dark sector to the SM?

- DM emerging from composite Higgs models (or Technicolor-like)
- Confining fermions/scalars charged under SM gauge symmetries
- Portal couplings via (suppressed) higher dimensional operators.

Composite Higgs models 101

- Symmetry broken by a condensate (of TC-fermions)
- Higgs and longitudinal Z/W emerge as mesons (pions)



Scales:

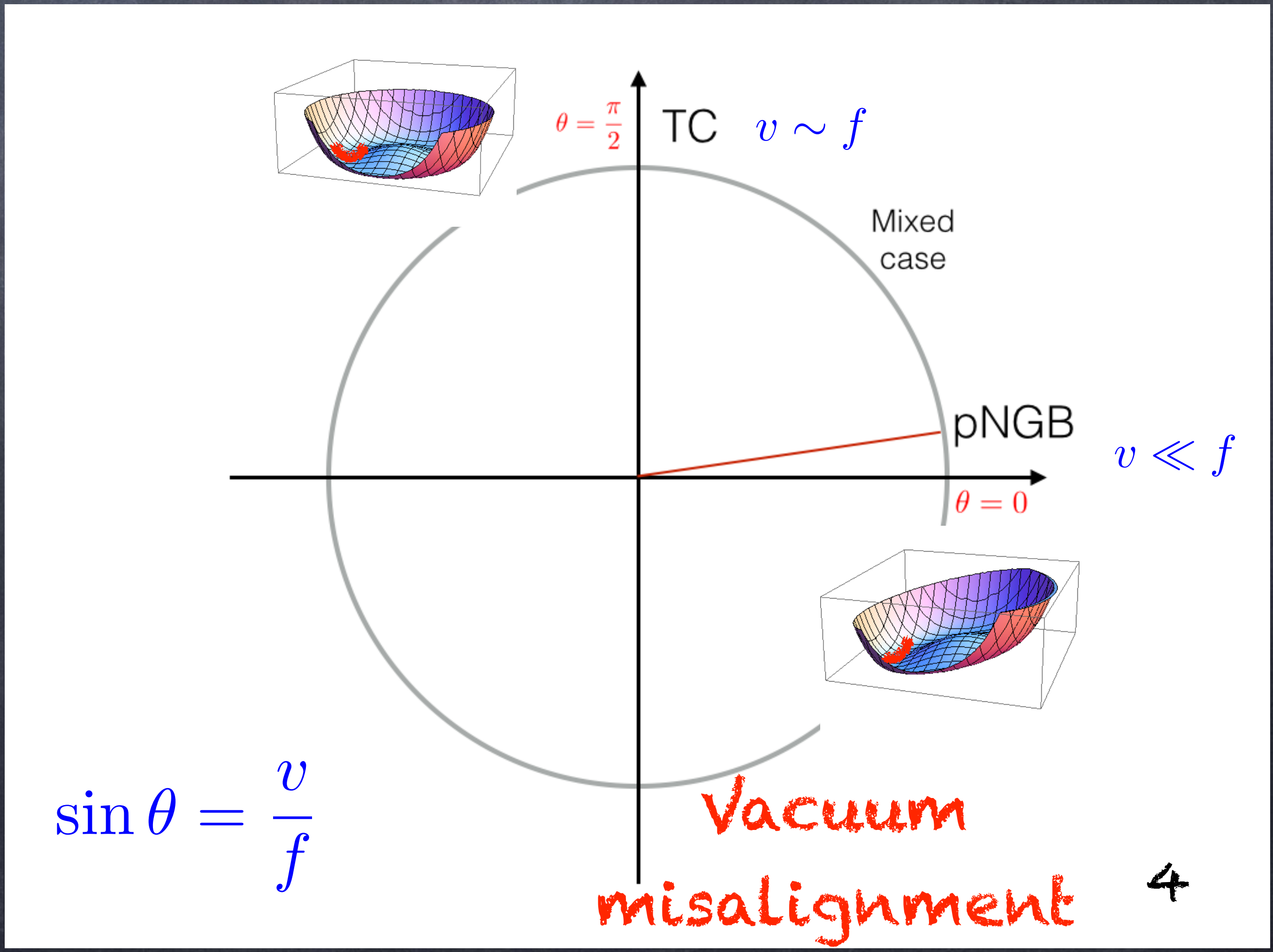
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

EWPTs + Higgs coupl. limit:

$$\boxed{f \gtrsim 4v \sim 1 \text{ TeV}}$$



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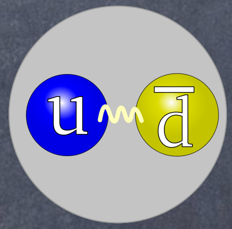
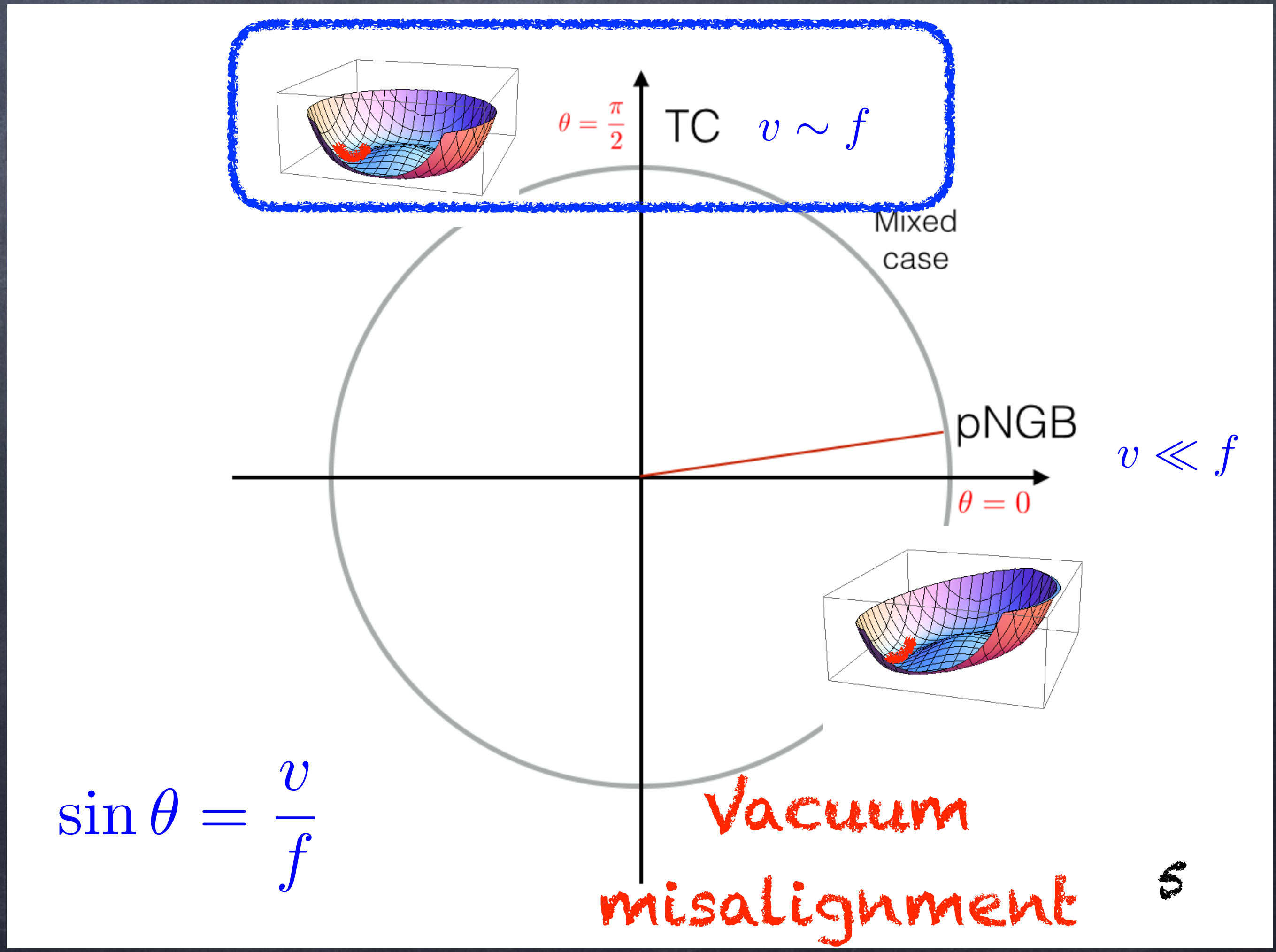


In the TC limit:

$$f = v$$

The Higgs is a light scalar resonance (dilaton?)

$m_\rho \sim 4\pi f$ ~ 2 TeV



A minimal case

T.Ryttov, F.Sannino 0809.0713
Galloway, Evans, Luty, Tacchi 1001.1361

	$SU(2)_{TC}$	$SU(4)_\psi$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix}\psi^1\\ \psi^2\end{pmatrix}$	$\square$	$\square$	**2**	0
ψ^3	$\square$		**1**	-1/2
ψ^4	$\square$		**1**	1/2

This theory is
Asymptotic Free
and confines in the IR!

Antisymmetric matrix

$$\langle \psi^i \psi^j \rangle = \Sigma_0$$

Under the global symmetry SU(4):

$$\Sigma_0 \to U \cdot \Sigma_0 \cdot U^T$$

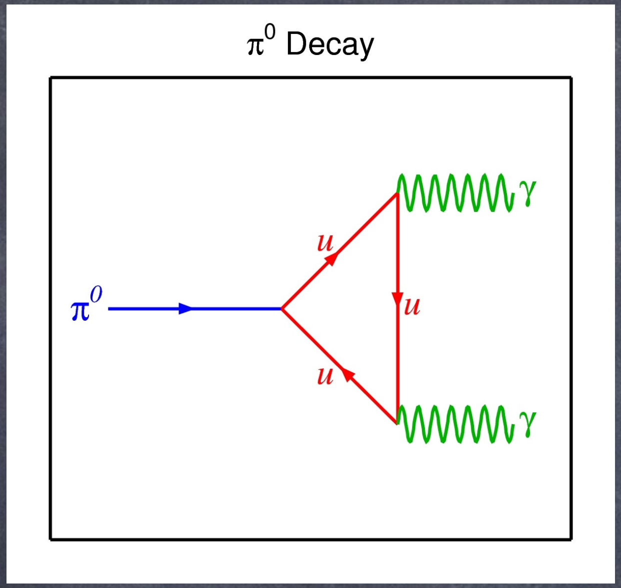
SU(4) -> Sp(4)

$$5_{\mathrm{Sp}(4)} \to (2,2) \oplus (1,1)$$

Higgs

DM?

WZW matters!



In QCD, coupling of the pions to EW gauge bosons are generated by (global) anomalies!

$$\mathcal{L}_{WZW} = \frac{d_\psi}{64\pi^2}\frac{\eta}{f}\left(g^2 W_{\mu\nu}\tilde{W}^{\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

$d_\psi = 2$

Dimension of TC rep

- Predictive power!
- Coupling to 2 photons vanishes!

A minimal case

TC limit: $\theta = \dfrac{\pi}{2}$

$$
\begin{aligned}
f^2\,\mathrm{Tr}(D_\mu\Sigma)^\dagger D^\mu\Sigma \;=\;& \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2 \\
&+\frac{1}{48 f^2}\left[-(h\partial_\mu\eta - \eta\partial_\mu h)^2\right] + \mathcal{O}(f^{-3}) \\
&+\left(2g^2 W^+_\mu W^{-\mu} + (g^2+g'^2)Z_\mu Z^\mu\right)\Bigg[f^2 s_\theta^2 + \cancel{\frac{s_{2\theta} f}{2\sqrt{2}} h\left(1 - \frac{1}{12 f^2}(h^2+\eta^2)\right)} \\
&+\frac{1}{8}\left(\overset{-1}{c_{2\theta}} h^2 - \overset{1}{s_\theta^2}\eta^2\right)\left(1 - \frac{1}{24 f^2}(h^2+\eta^2)\right) + \mathcal{O}(f^{-3})\Bigg] \,. \qquad (25)
\end{aligned}
$$

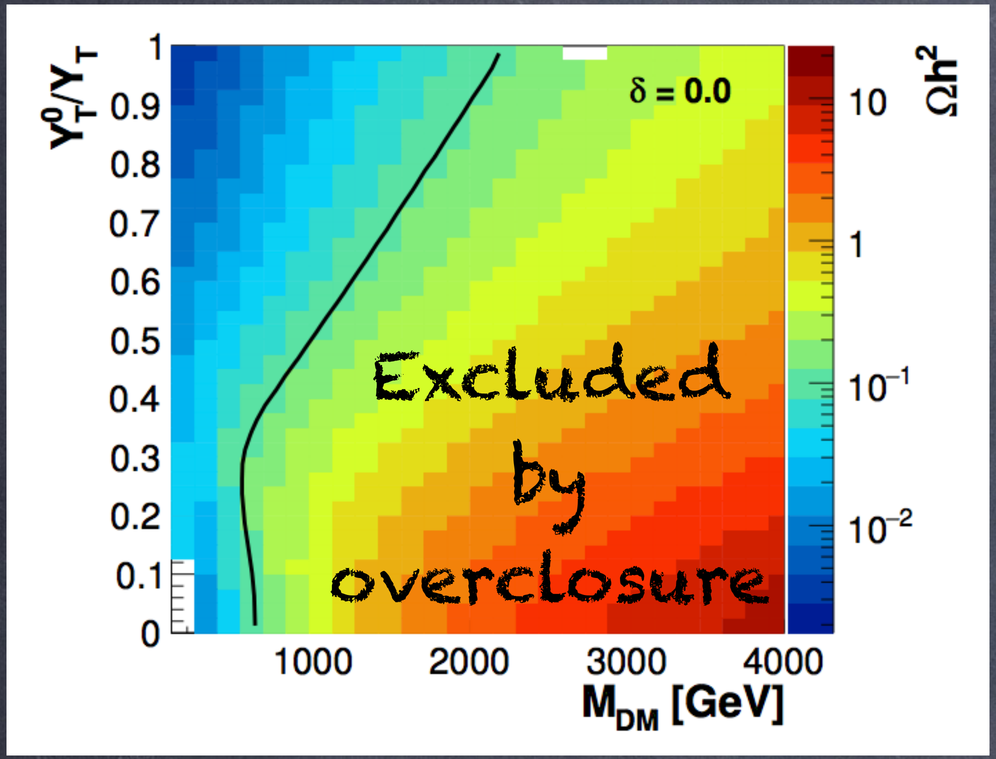
$$\mathcal{L}_{\mathrm{WZW}} = \cancel{\frac{d_\psi \cos\theta}{64\pi^2}\frac{\eta}{f}}\left(g^2\, W_{\mu\nu}\tilde{W}^{\mu\nu} - g'^2\, B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

Ryttov, Sannino
0809.0713

In the TC limit, Sp(4) ⊂ $U(1)_{em} \times U(1)_{DM}$

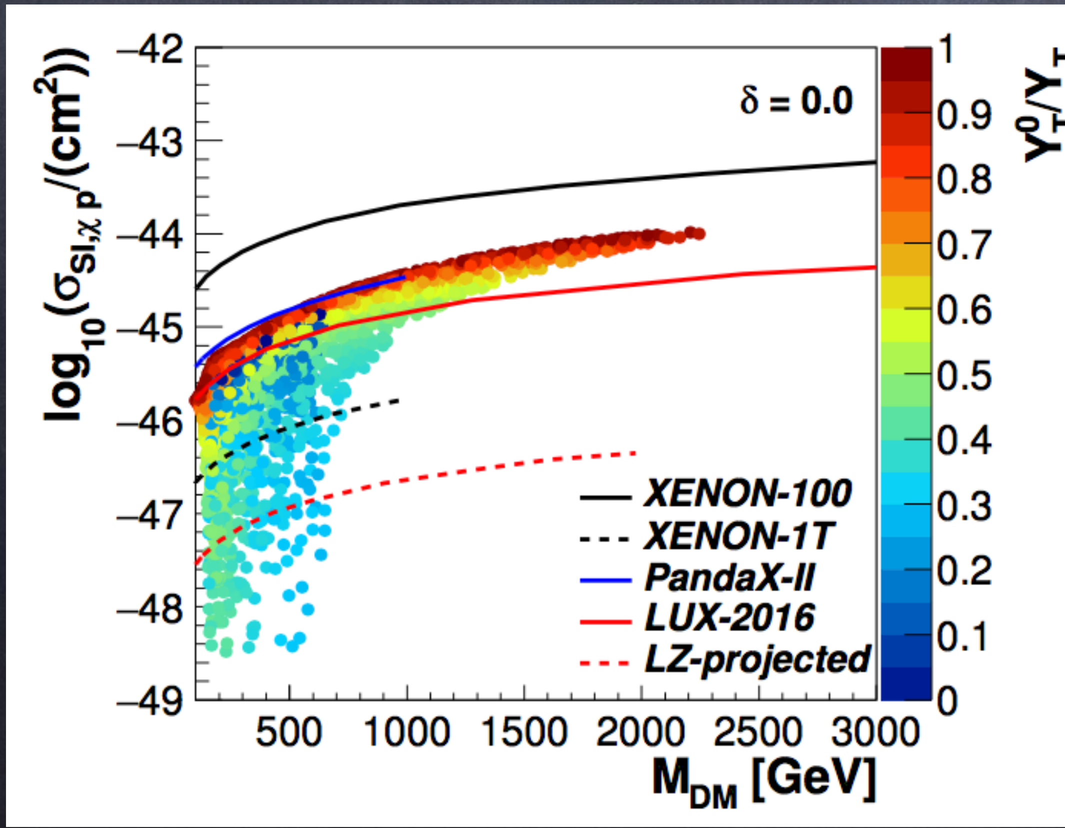
$\phi = \dfrac{h + i\eta}{\sqrt{2}}$ is charged under the unbroken $U(1)_{DM}$, and thus stable (TIMP).

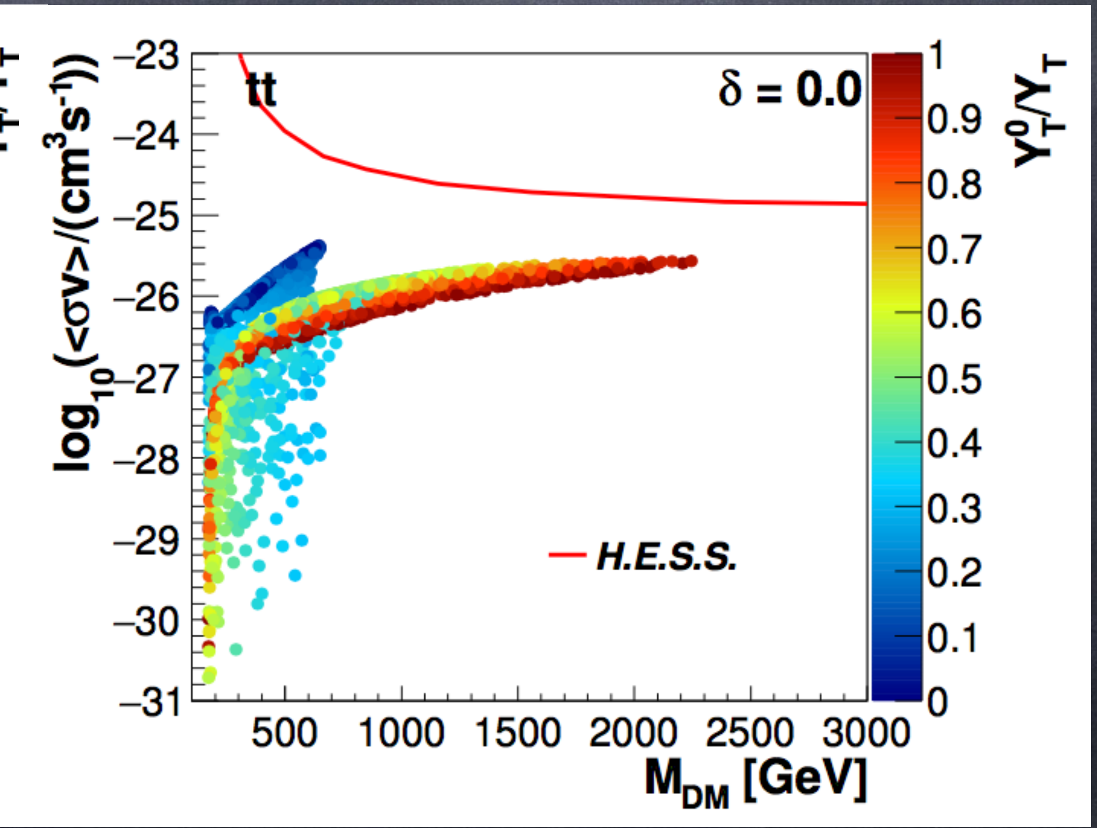
Composite Dark Matter (and Higgs)
as thermal relic



- Additional pNGBs may be (accidentally) stable
- Need extended global symmetry (ex. SU(4)xSU(4)/SU(4))

1703.06903





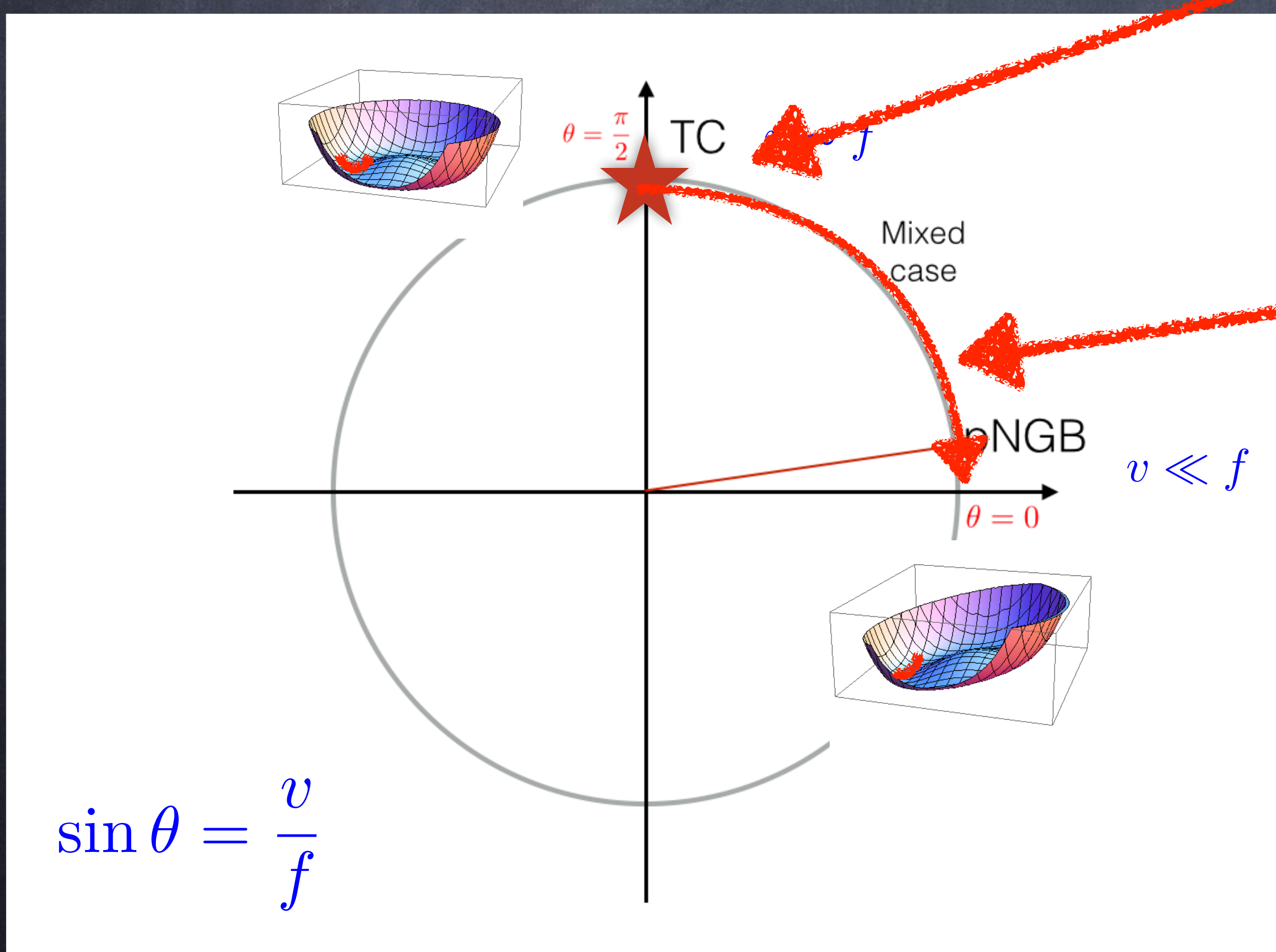
Asymmetric production

- What is the vacuum alignment at the confinement scale?

Alignment at condensation scale: baryogenesis!

Crossover towards the CHM vacuum

Servant et al
1804.07314



Asymmetric production

Cai, Zhang et al
1911.12130

T_{HL} — Higgsless theory in the TC limit → Asymmetry generated as in TIMP model

Ryttov, Sannino
0809.0713

$$V(\theta, T) = -a(T)\ \sin^2\theta + \frac{1}{2} b(T)\ \sin^4\theta$$

$$\frac{a(T_{\rm HL})}{b(T_{\rm HL})} > 1 \quad \text{and} \quad \frac{a(0)}{b(0)} \ll 1$$

T_{dc} — Z_2-odd states decouple from TIMP

$$\mathcal{L} \supset -i\frac{g}{\sqrt{2}} W^+_\mu \left(\Theta^* \overleftrightarrow{\partial}^\mu \Theta^-\right) + \frac{\xi}{2} f\ \phi^*_X \Theta\Theta + \text{h.c.} - \frac{g^2}{2}\ \phi^*_X \phi_X \left(W^+_\mu W^{-,\mu} + \frac{1}{2} Z_\mu Z^\mu\right)$$

T_F — Freeze-out kills symmetric part

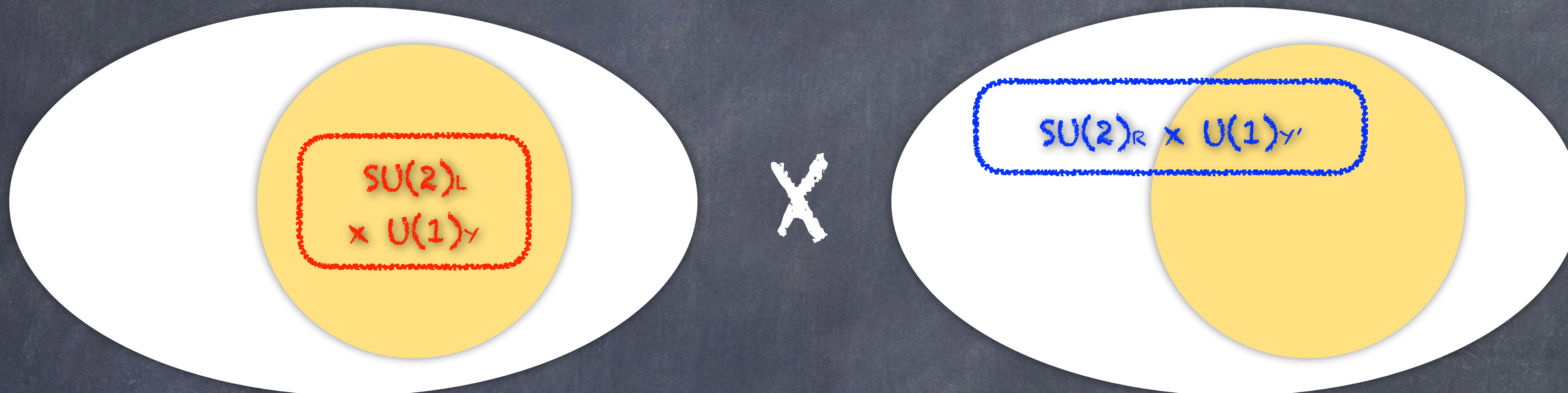
TIMP

T_* — Crossover tw. CHM

$$\left(\begin{array}{c|c} \mathcal{G}_0/\mathcal{H}_0 & \mathbb{Z}_2\text{–odd pNGBs} \\ \hline \mathbb{Z}_2\text{–odd pNGBs} & \mathbb{Z}_2\text{–even pNGBs} \end{array}\right)$$

$T=0$ — CHM: ex. SU(6)/Sp(6)

New C. Dark Matter production

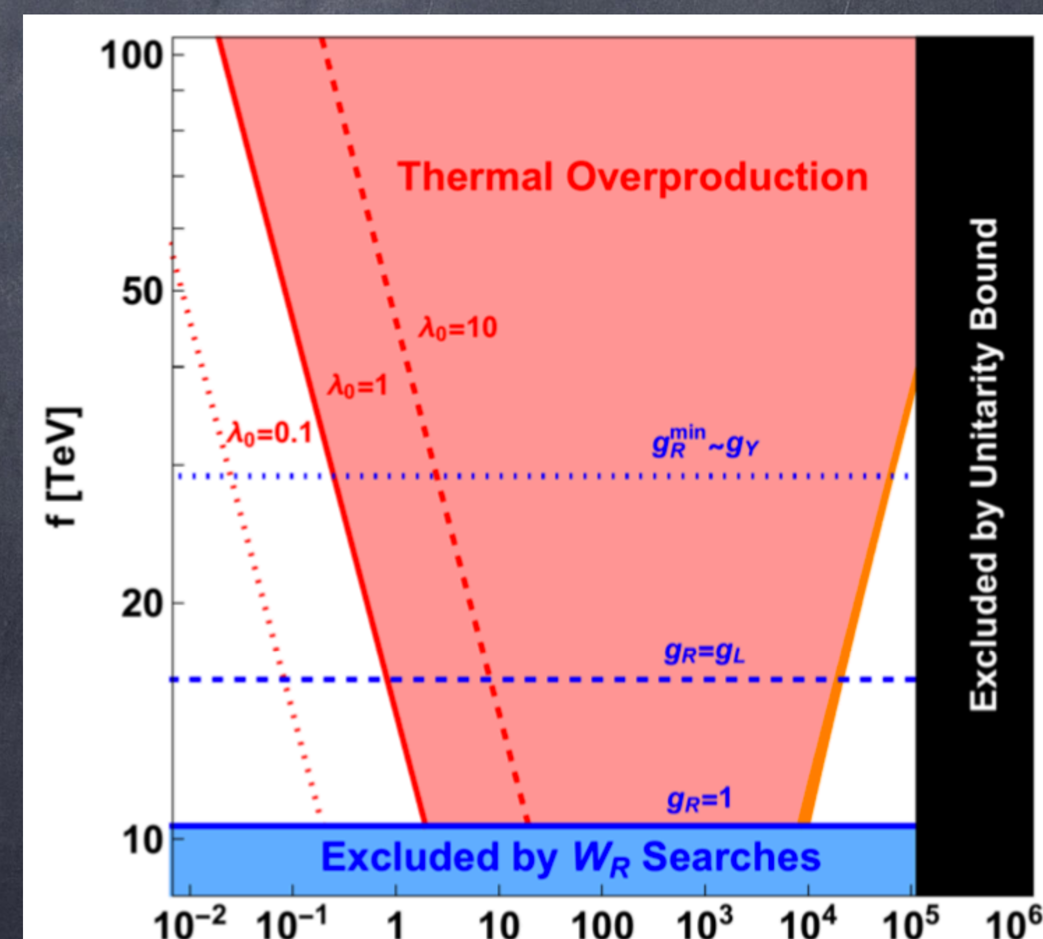


$SU(2)_R \times U(1)_{Y'} \to U(1)_Y$ by TC-vacuum

"Dark" $U(1)_X$ remains unbroken (global)

DM-genesis via strong phase transition + anomaly

2111.09319: G.C., M.Frandsen et al



Emancipation from composite Higgses

Antipin, Redi, Strumia
1503.08749

- Renounce to a composite Higgs sector

$$\mathcal{L}_{\rm DS} = -\frac{1}{2}{\rm Tr}[\mathcal{G}_{\rm D}^{\mu\nu}\mathcal{G}_{{\rm D},\mu\nu}] + \overline{\Psi}_i(i\not{D} - m_\Psi)\Psi_i + y_{ij}\overline{\Psi}_i\Psi_j H + {\rm h.c.}$$

- Global (accidental) symmetry on fermions ensure stability of baryons or pNGBs
- Thermal production, with the usual problems...
- No asymmetric production: vector-like fermions!

Accidental asymmetry?

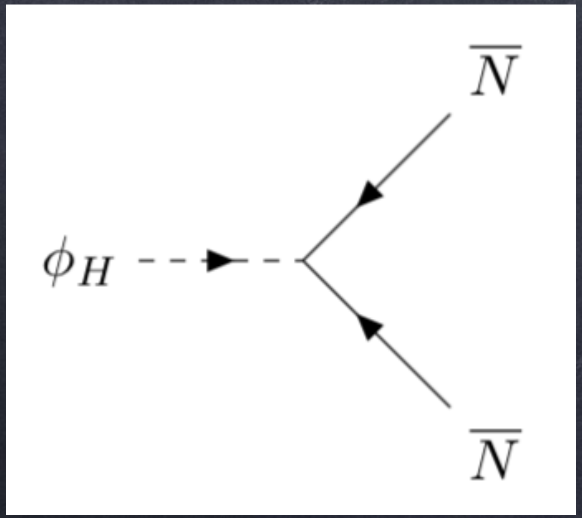
- Asymmetric production can be produced by explicit breaking of the D-number

Bottaro, Costa, Popov
2104.14244

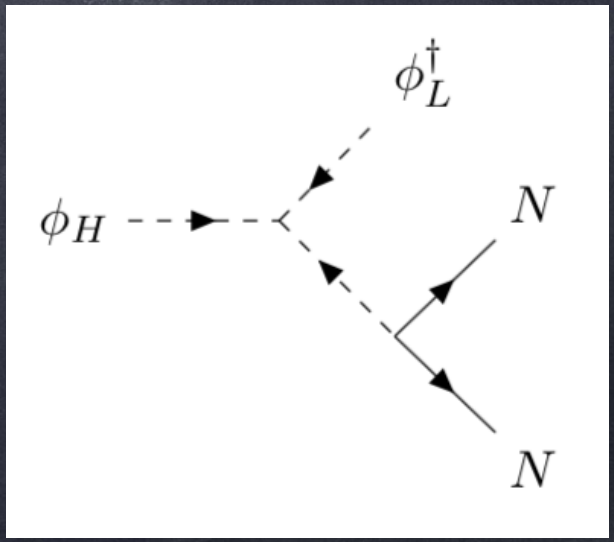
Field	$SU(3)_{DC}$	$(SU(3)_c, SU(2)_L)_Y$	$U(1)_{DB}$ (D)
N	3	$(1,1)_0$	1
ϕ	$\bar{6}$ (sym)	$(1,1)_0$	-2

Two scalar fields with D-violating couplings: mechanism similar to Leptogenesis

$\Delta D = 0$:



$\Delta D = 6$:



Chiral-isation

- Render the fermions chiral by introducing a new gauged symmetry

Contino, Podo, Revello
2008.10607

Type I

	G_{DC}	$\mathrm{U}(1)_D$	G_{SM}	$\mathrm{U}(1)_{3V}$	$\mathrm{U}(1)_V$
ψ_1	R	$+1$	r	$+1$	$+1$
ψ_2	R	-1	r	-1	$+1$
χ_1	$\bar{R}$	$-a$	$\bar{r}$	-1	-1
χ_2	$\bar{R}$	$+a$	$\bar{r}$	$+1$	-1

And permutations of the charge assignments

- $\mathrm{U}(1)_D$ broken dynamically: dark photon (possibly light)
- Both dark baryons - $\mathrm{U}(1)_V$ - and mesons - $\mathrm{U}(1)_{3V}$ - present: pandora box of possibilities!

Feebly interacting composite DM

- Consider a strong dark sector decoupled from the SM
- Only coupling may come from gravity
- Consider a tensor glueball as the lightest state: can it be a DM candidate?

Chiral enhancement on the rescue

Cai, Lee, Cacciapaglia
2107.14548

- What happens for light spin-2 resonances (gravitons)?
- We consider a general case, one massive graviton and no parity.

$$\mathcal{L}_{eff} = C_H \, G^{\mu\nu}_{(n)} \, T^{\rm SM}_{\mu\nu} \qquad C_H \sim \frac{1}{M_{\rm Pl}}$$

- Let's consider the process: $q + \bar{q} \to \text{gluon} + G$

For massless fermion:

$$\mathcal{A}^0_{\bar{q}q} = \frac{128\pi}{3} C_H^2 g_s^2 s$$

(in line with the naive expectation)

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For massive fermion:

$$\boxed{\mathcal{A}_{\bar{q}q} = \frac{256\pi C_H^2 g_s^2 m_q^2 s \left(s + 2m_q^2\right)}{9 M_G^4}}$$

(applies below the EW phase transition)

Chiral enhancement on the rescue

Cai, Lee, Cacciapaglia
2107.14548

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Huge enhancement!

$$\left(\frac{m_b}{M_G \sim 2\ \mathrm{MeV}}\right)^4 \sim 10^{12}$$

- Easy to understand: it comes from the longitudinal mode of the massive graviton

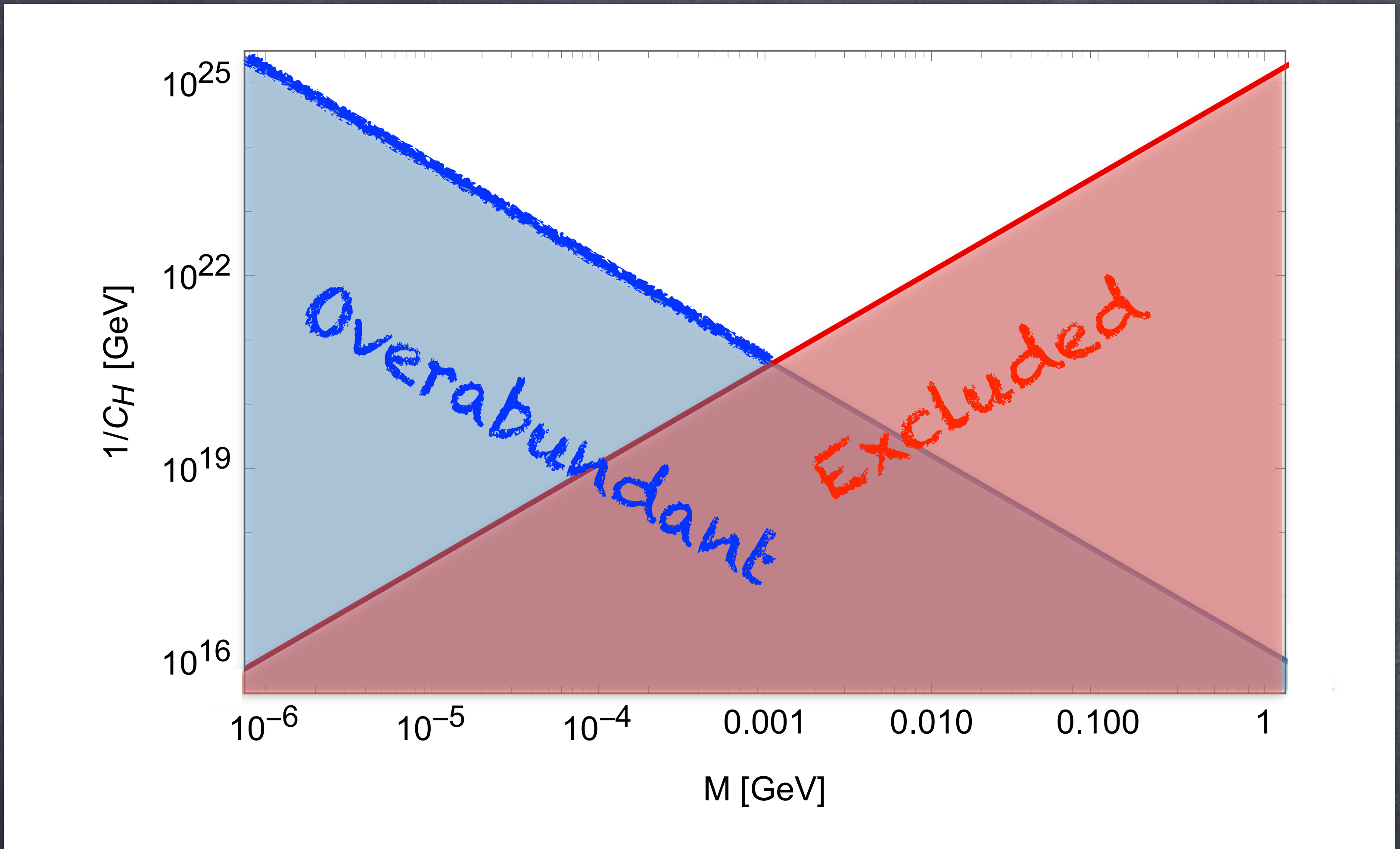
Sum over graviton polarisations:

$$P_{\mu\nu,\alpha\beta} = \frac{1}{2}\left(P_{\mu\alpha}P_{\nu\beta} + P_{\nu\alpha}P_{\mu\beta} - \frac{2}{3}P_{\mu\nu}P_{\alpha\beta}\right),$$

$$P_{\mu\nu} = \eta_{\mu\nu} - \frac{k_\mu k_\nu}{M_G^2}$$

$$M \sim \frac{m_q^2}{M_G^2}$$

Parameter space:



$$\Omega_{\rm IR} h^2 \lesssim 0.12 \times \left(\frac{1.6 \text{ MeV}}{M_G}\right)^6 \frac{10^{27} \text{ Sec}}{\tau_G}$$

MeV is the right mass scale to solve the large scale problem!

Outlook

- Strong dark sectors are popular
- An (accidental) dark symmetry always needs to be imposed
- Many model-building possibilities: cherry-picking of recent ideas.
- Interplay with Lattice could be very useful!