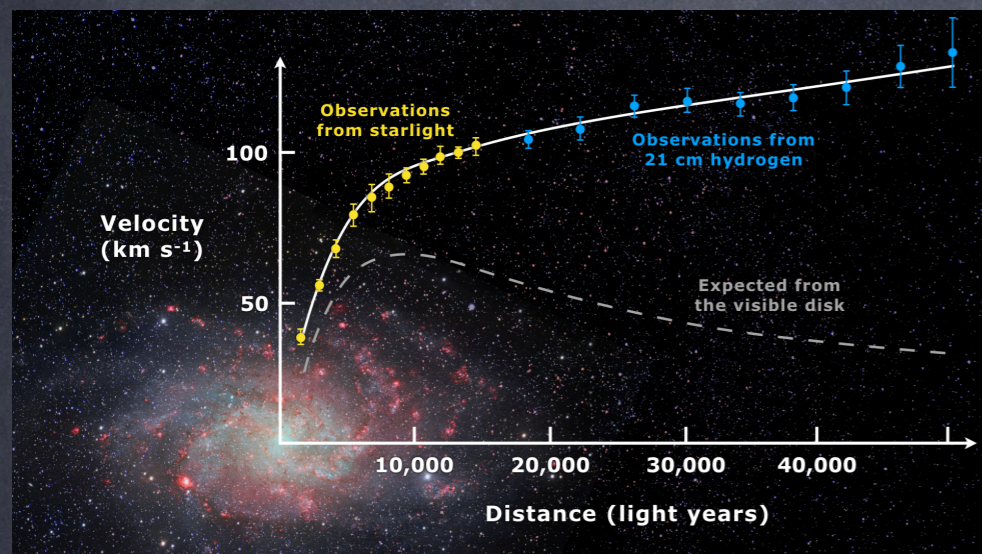# Strong Dark Matter

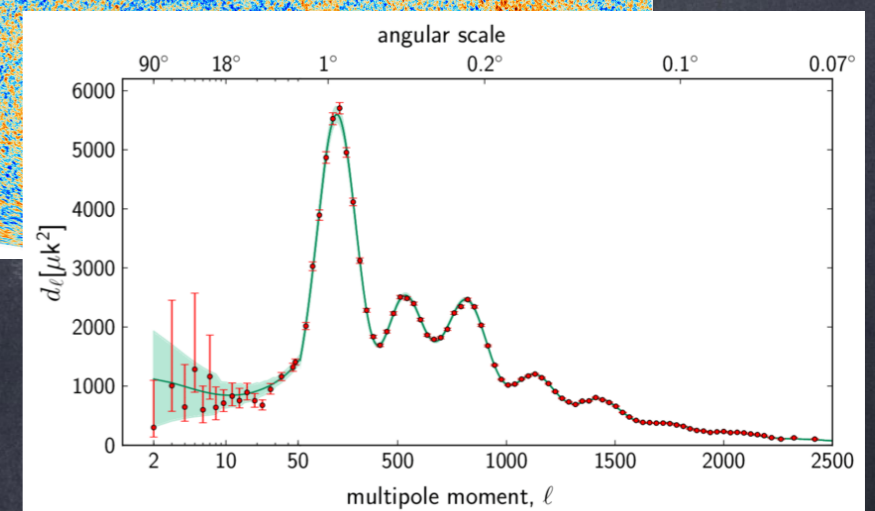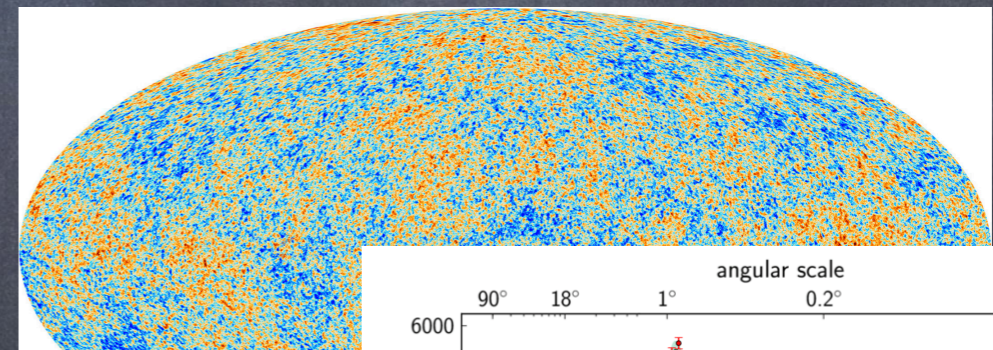## Giacomo Cacciapaglia (IP2I Lyon)

Confinement XV, Stavanger U.

Dark Matter: where are we?

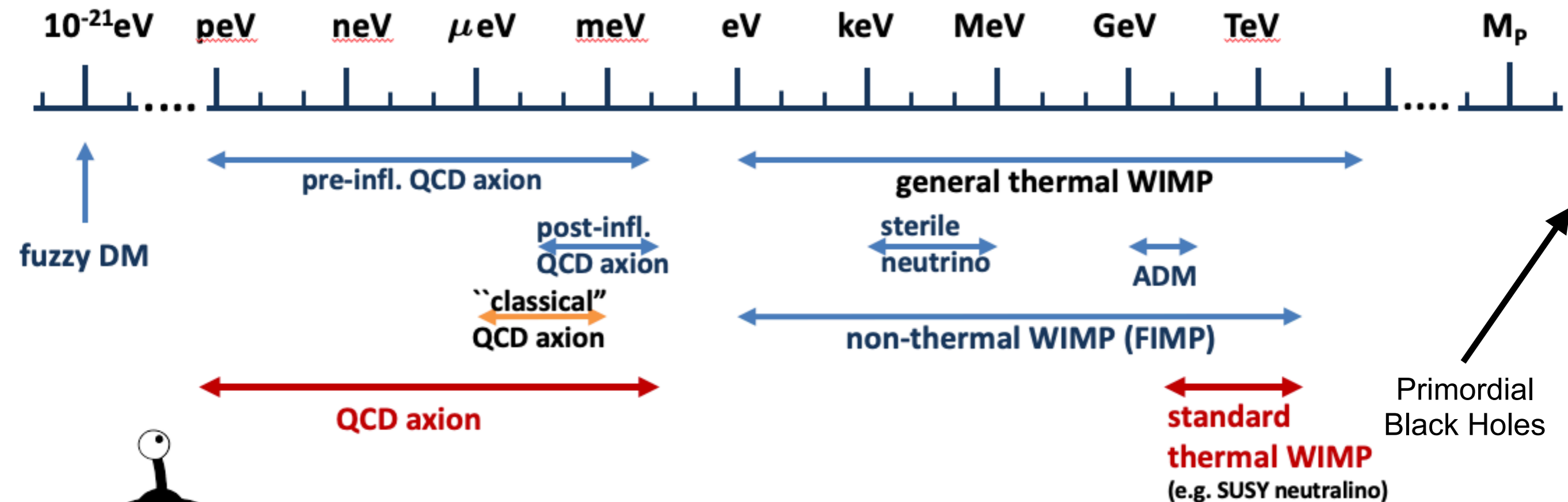## Indirect evidence in astrophysics and cosmology.

25% of our Universe is made of Dark Matter!

Dark Matter: where are we?

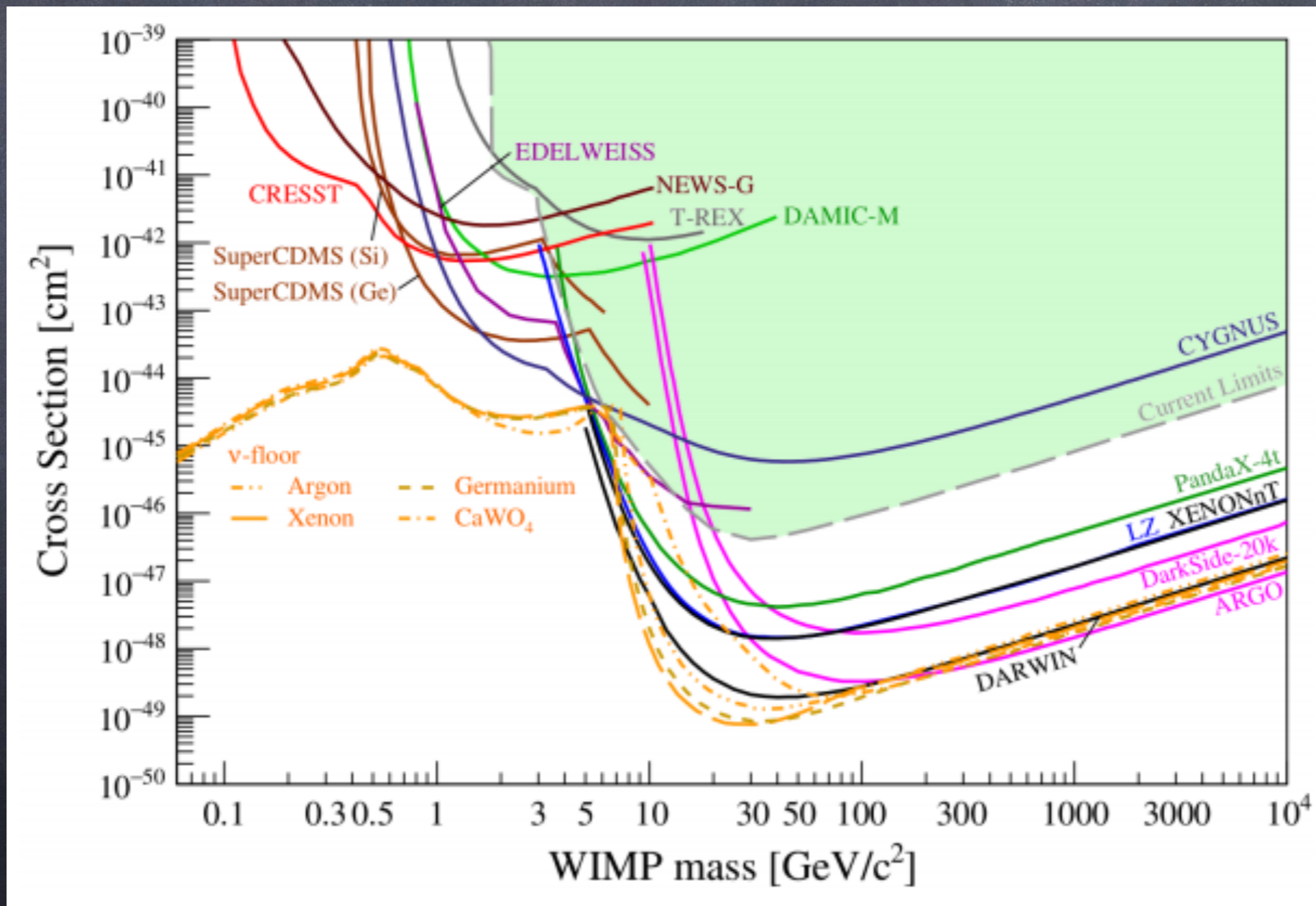- Very wide 'available' mass range:

From the APPEC DM report

Dark Matter: where are we?

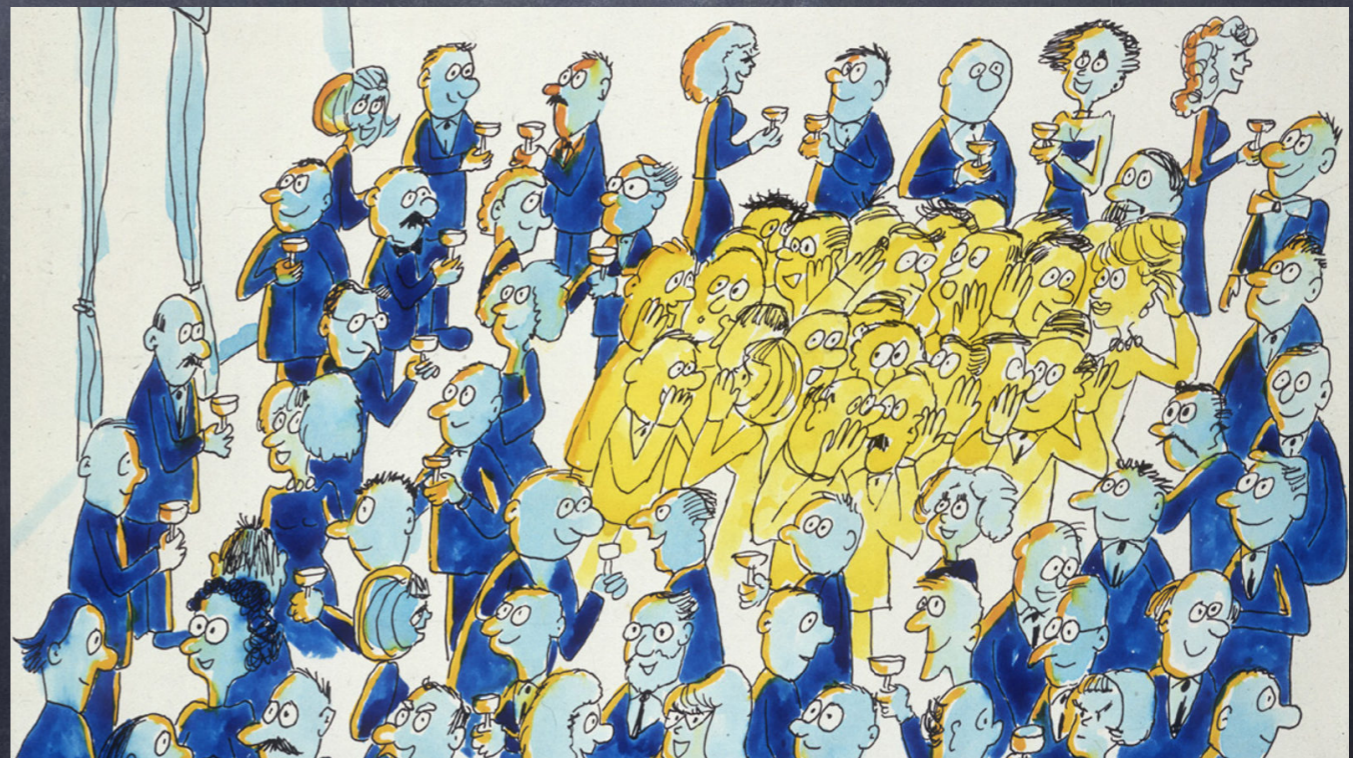- Strong constraints from Direct Detection:

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
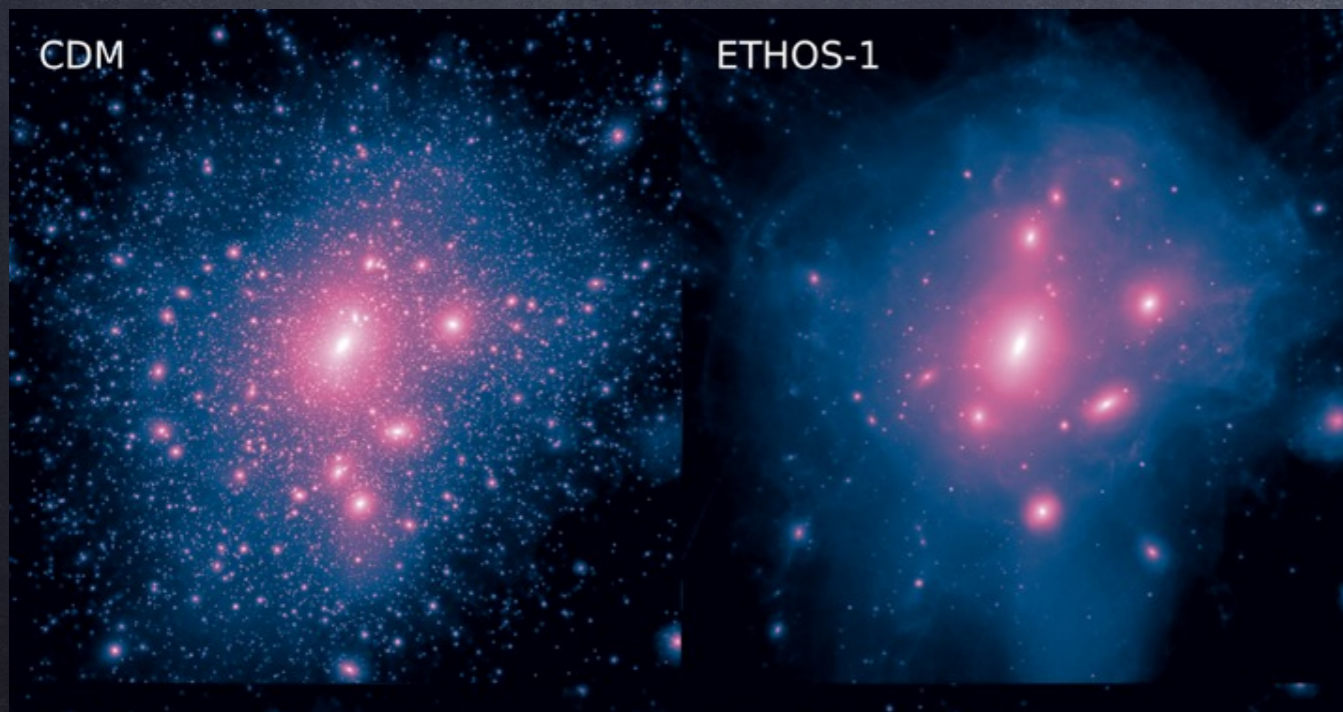
Collision-less DM predicts too many small structures around Galaxies
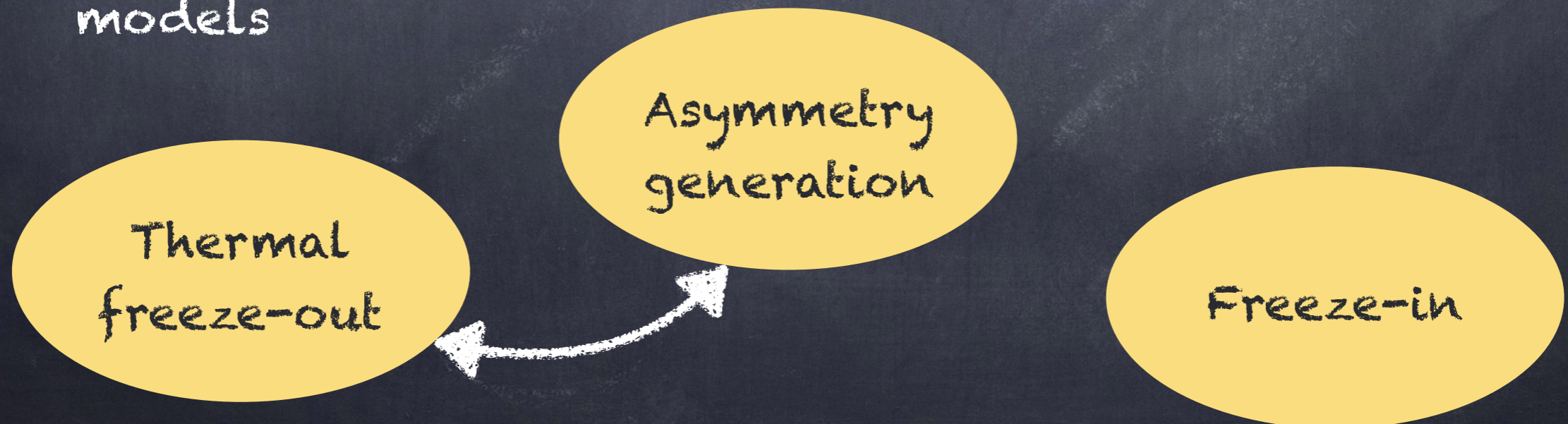
+ other issues...

Benefits of compositeness:

- Dynamical mass generation

- Self-interactions naturally present

- Many production mechanisms can be included in the models

Thermal freeze-out

Asymmetry generation

Freeze-in

Production mechanisms
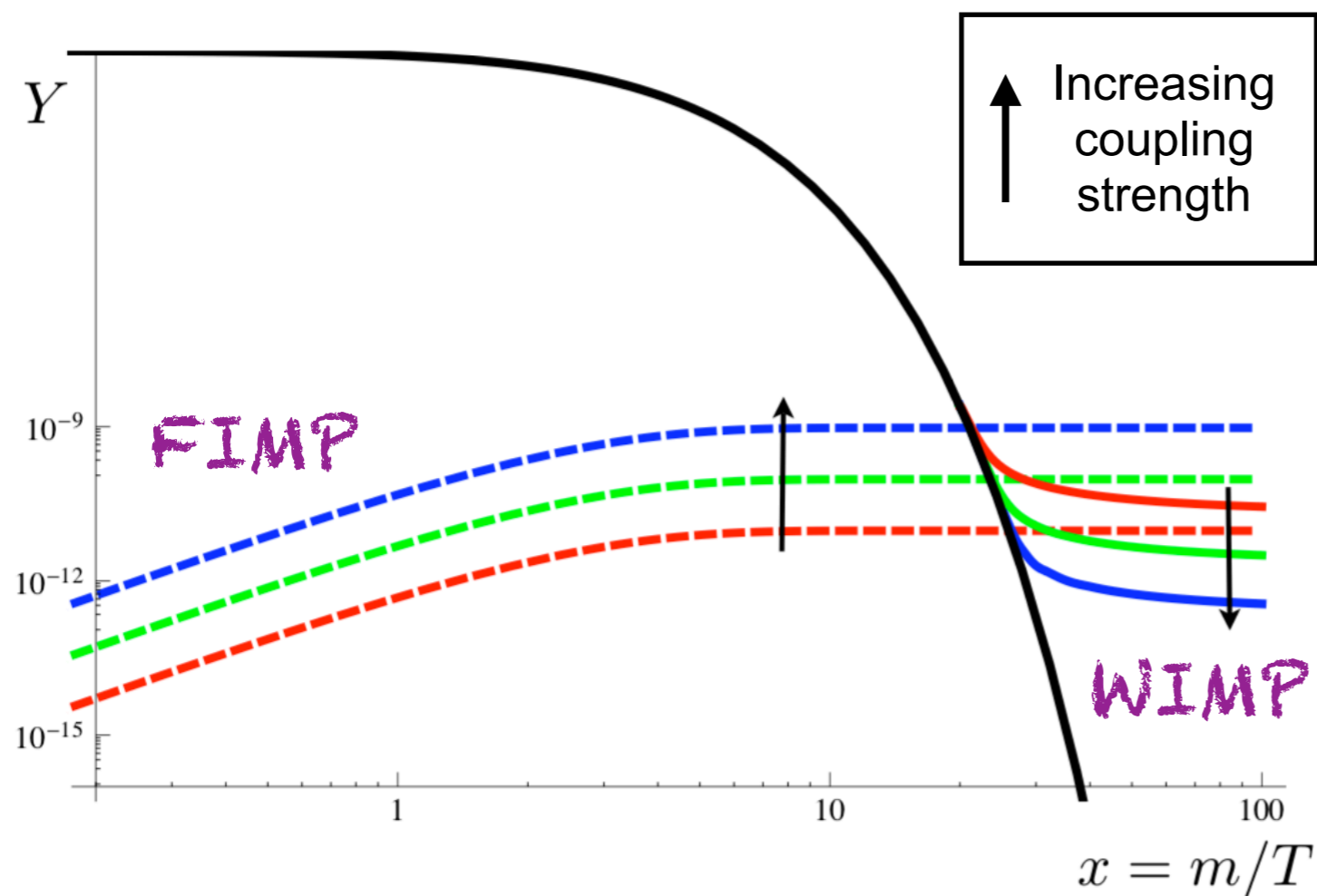
- Freeze-out: weak strength couplings to the SM required

- Freeze-out: feeble couplings to the SM needed.
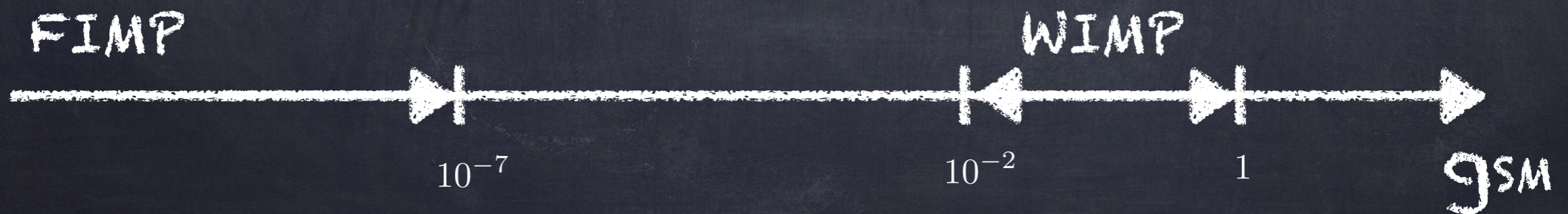
Production mechanisms

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

$\langle \phi \rangle = 0$

CP

$\langle \phi \rangle \neq 0$

Tunneling produces net baryon number
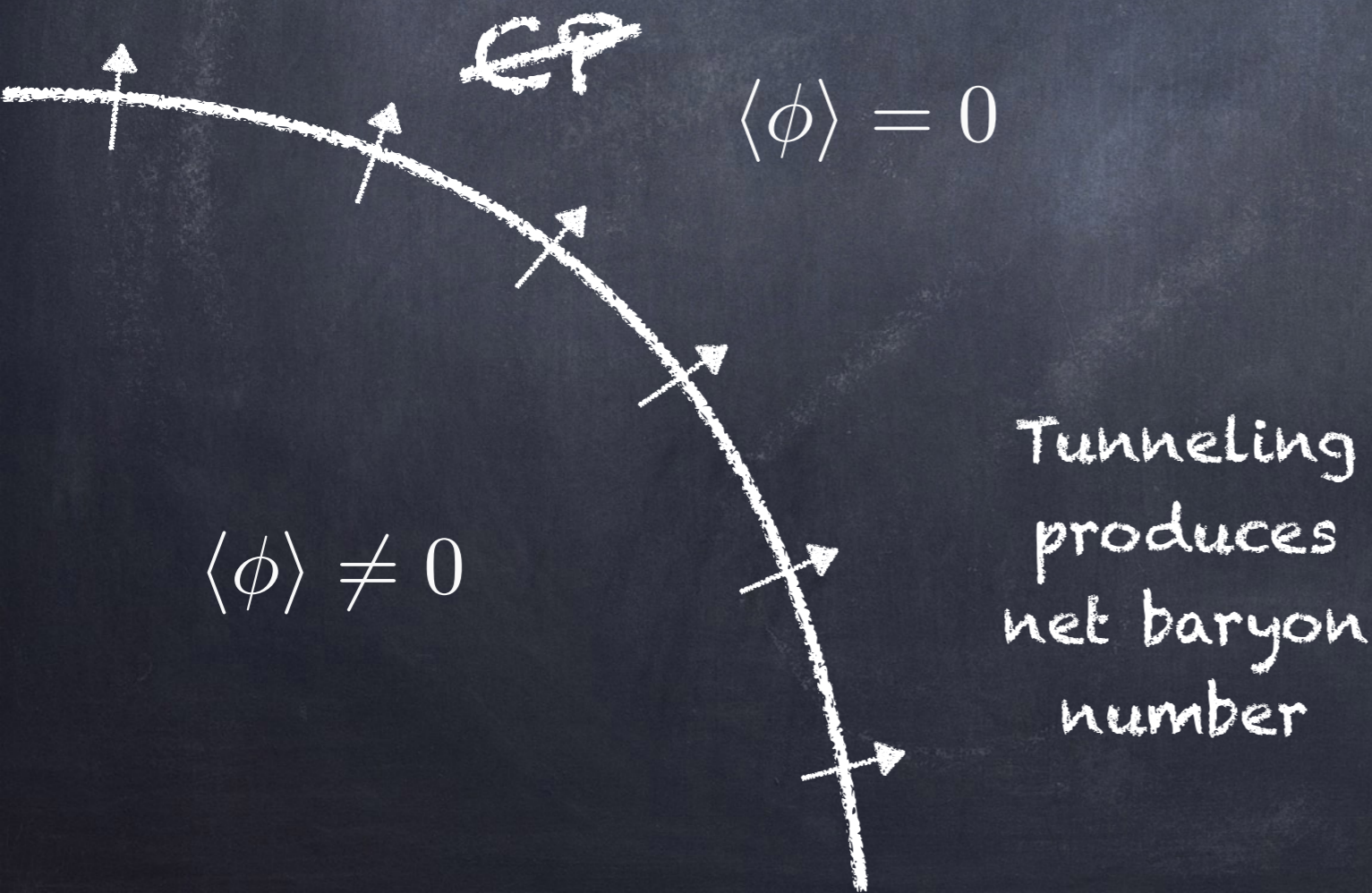
YEAH, I LEARNED ABOUT IT WHEN I WAS RESEARCHING ANOMALOUS ELECTROWEAK SPHALERON TRANSITION BARYOGENESIS.

COOOOL.

A-N-O-M-

Credit: XKCD

MY HOBBY: COLLECTING REALLY SATISFYING-SOUNDING FIVE-WORD TECHNICAL PHRASES.

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:

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

$\theta = \frac{\pi}{2}$ TC $\quad v \sim f$

Mixed case

pNGB $\quad v \ll f$

$\theta = 0$

$$\sin \theta = \frac{v}{f}$$

Vacuum misalignment

4

Composite Higgs models 101

- Symmetry broken by a condensate (of TC-fermions)

- Higgs and longitudinal Z/W emerge as mesons (pions)

In the TC limit:
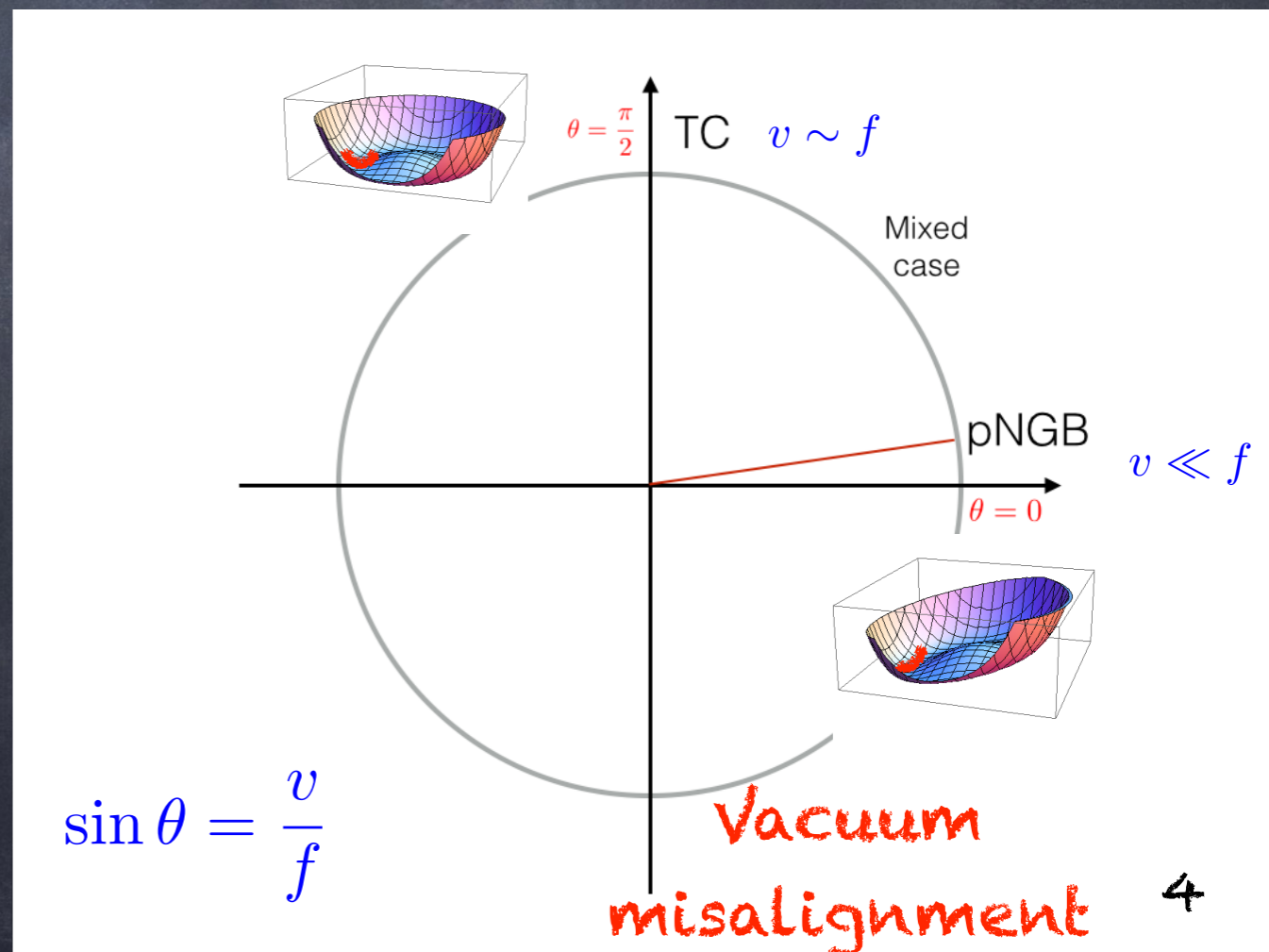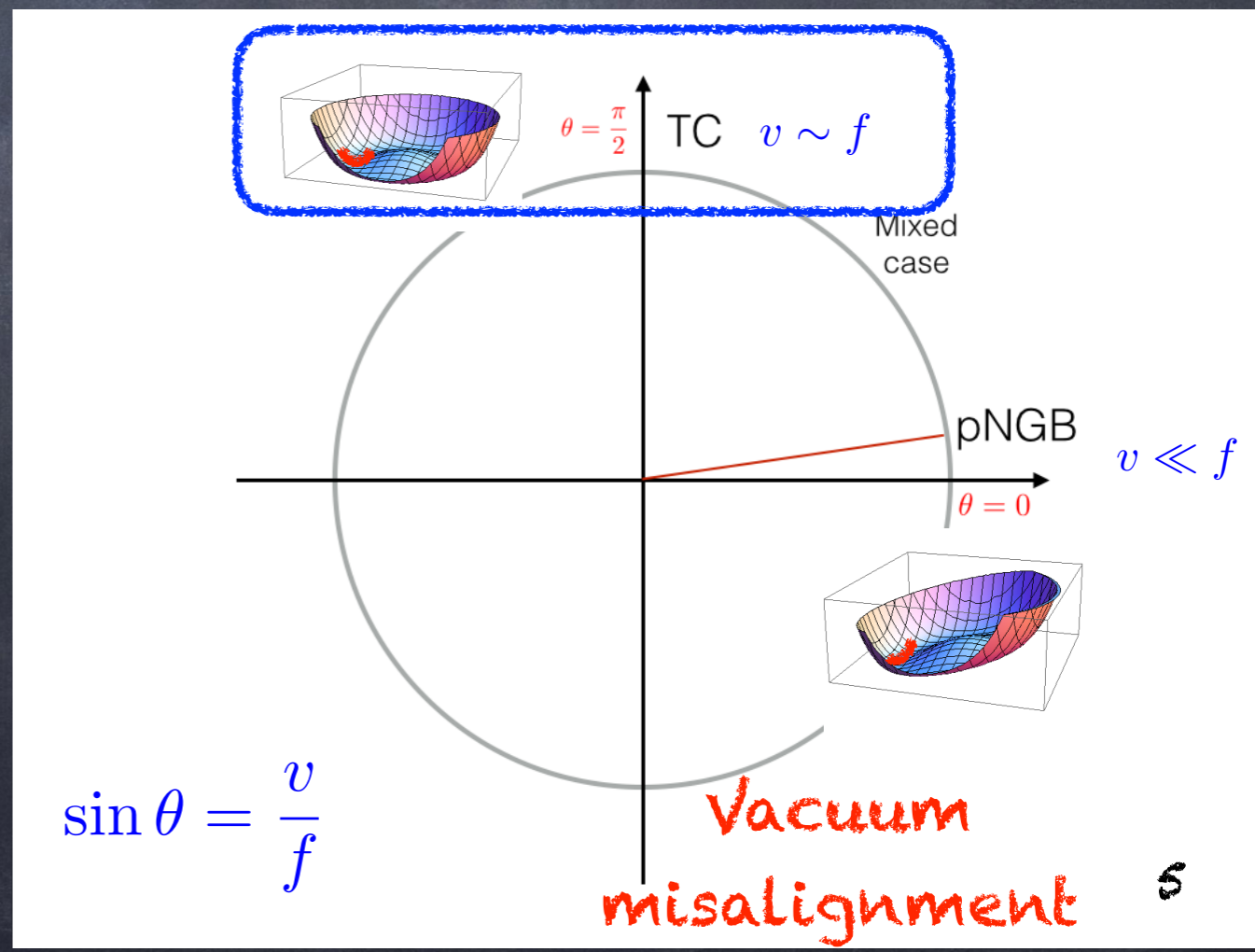
$$f = v$$

The Higgs is a light scalar resonance (dilaton?)

$$m_\rho \sim 4\pi f \sim 2\,\text{TeV}$$

TC $v \sim f$

Mixed case

pNGB $v \ll f$

$\theta = \frac{\pi}{2}$

$\theta = 0$

$\sin\theta = \dfrac{v}{f}$

Vacuum misalignment

5

A minimal case

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

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

Higgs

SU(4) -> Sp(4)

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

DM?

WZW matters!

π^0 Decay
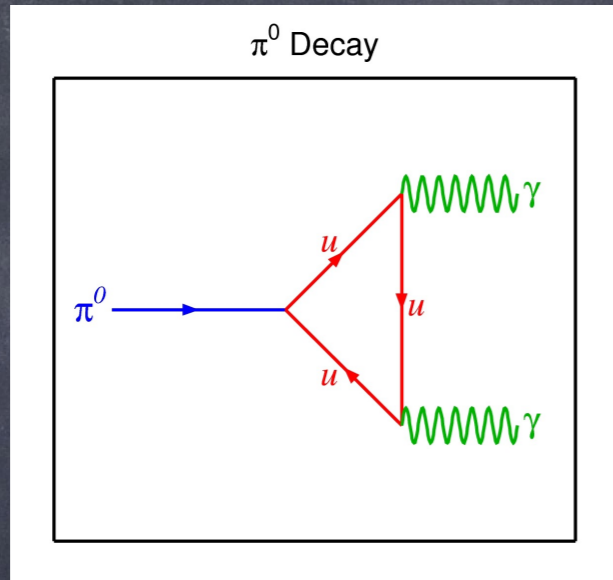
In QCD, coupling of the pions to EW gauge bosons are generated by (global) anomalies!

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

$d_\psi = 2$

Dimension of TC rep

- Predictive power!

- Coupling to 2 photons vanishes!

A minimal case

$$f^2 \, \mathrm{Tr}(D_\mu \Sigma)^\dagger D^\mu \Sigma = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2$$

$$+\frac{1}{48f^2}\left[-(h\partial_\mu\eta - \eta\partial_\mu h)^2\right] + \mathcal{O}(f^{-3})$$

$$+\left(2g^2 W_\mu^+ W^{-\mu} + (g^2 + g'^2)Z_\mu Z^\mu\right)\left[f^2 s_\theta^2 + \frac{s_{2\theta} f}{2\sqrt{2}}h\left(1 - \frac{1}{12f^2}(h^2 + \eta^2)\right)\right.$$

$$\left. + \frac{-1}{8}(\overset{1}{c_{2\theta}}h^2 - \overset{1}{s_\theta^2}\eta^2)\left(1 - \frac{1}{24f^2}(h^2 + \eta^2)\right) + \mathcal{O}(f^{-3})\right]. \tag{25}$$

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

Ryttov, Sannino
0809.0713

In the TC limit, Sp(4) ⊂ U(1)em x U(1)DM

$$\phi = \frac{h + i\eta}{\sqrt{2}}$$

is charged under the unbroken U(1)DM,
and thus stable (TIMP).

Composite Dark Matter (and Higgs)
as thermal relic
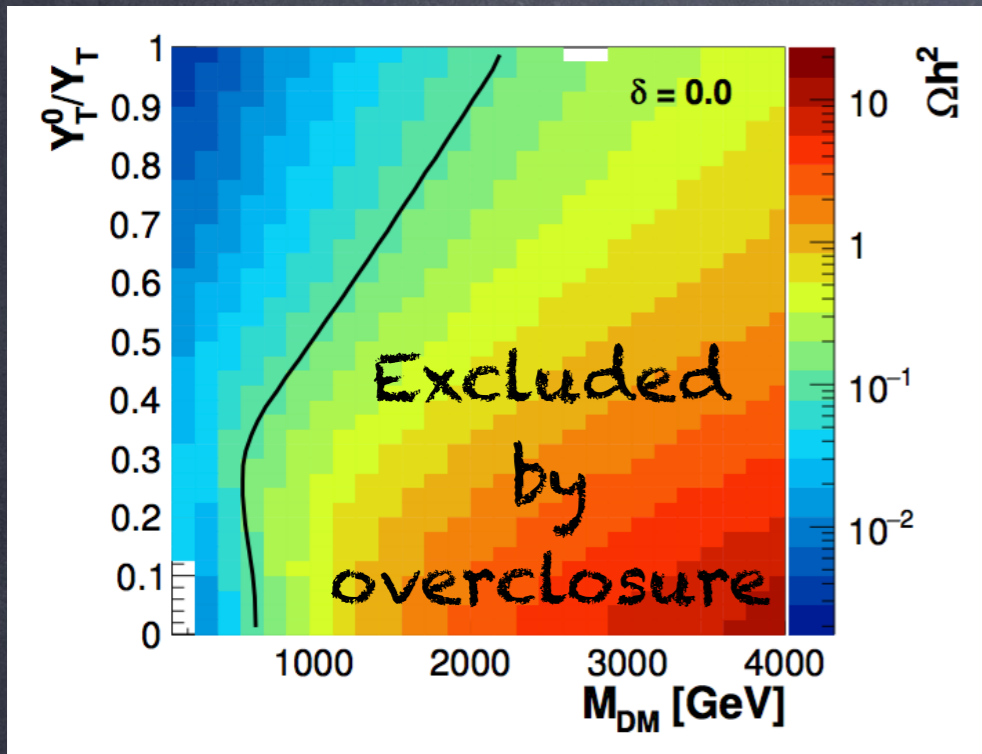
- Additional pNGBs may be (accidentally) stable

- Need extended global symmetry (ex. SU(4)xSU(4)/SU(4))

1703.06903
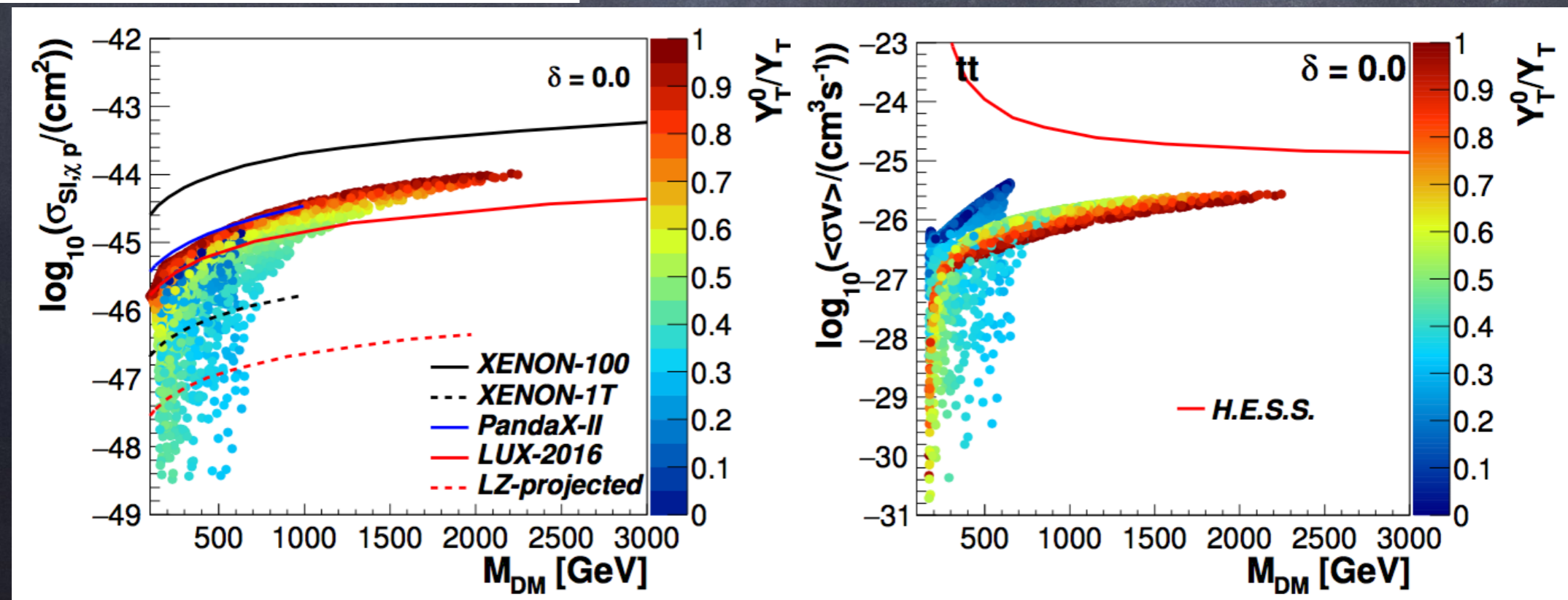
Asymmetric production

- What is the vacuum alignment at the confinement scale?

Alignment at condensation scale: baryogenesis!

Crossover towards the CHM vacuum

Servant et al
1804.07314

$$\sin\theta = \frac{v}{f}$$

Asymmetric production

Cai, Zhang et al
1911.12130

T_{HL}

Higgsless theory
in the TC limit → Asymmetry generated
as in TIMP model Ryttov, Sannino
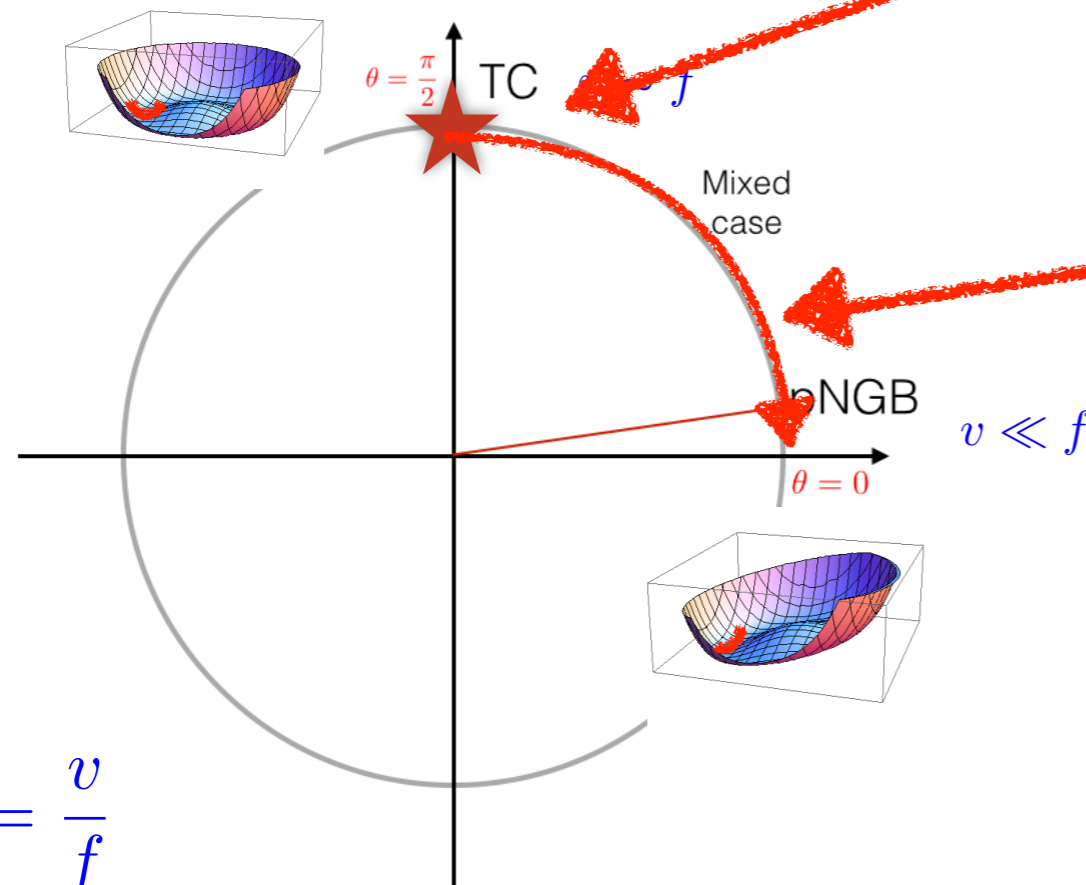0809.0713

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

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

T_{dc}

$\mathbb{Z}_2$-odd states
decouple from TIMP

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

T_F

Freeze-out kills
symmetric part

TIMP

T_*

Crossover tw. CHM

$T=0$

CHM: ex. SU(6)/Sp(6)

$$\begin{pmatrix} \mathcal{G}_0/\mathcal{H}_0 & \mathbb{Z}_2-\text{odd} \\ & \text{pNGBs} \\ \hline \mathbb{Z}_2-\text{odd} & \mathbb{Z}_2-\text{even} \\ \text{pNGBs} & \text{pNGBs} \end{pmatrix}$$

New C. Dark Matter production

SU(2)$_L$ × U(1)$_Y$

X
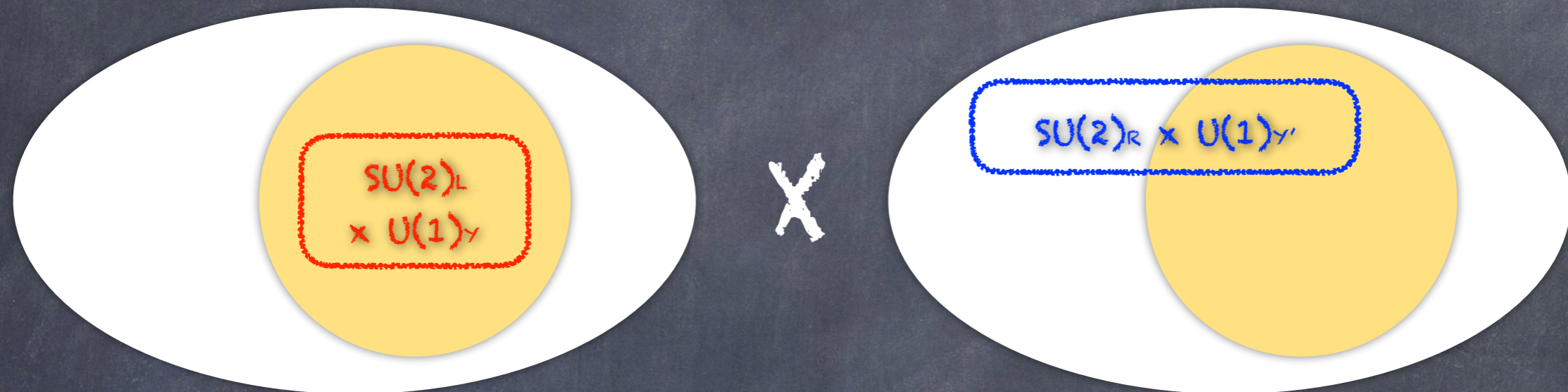
SU(2)$_R$ × U(1)$_{Y'}$

SU(2)$_R$×U(1)$_{Y'}$ ->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

- Renounce to a composite Higgs sector

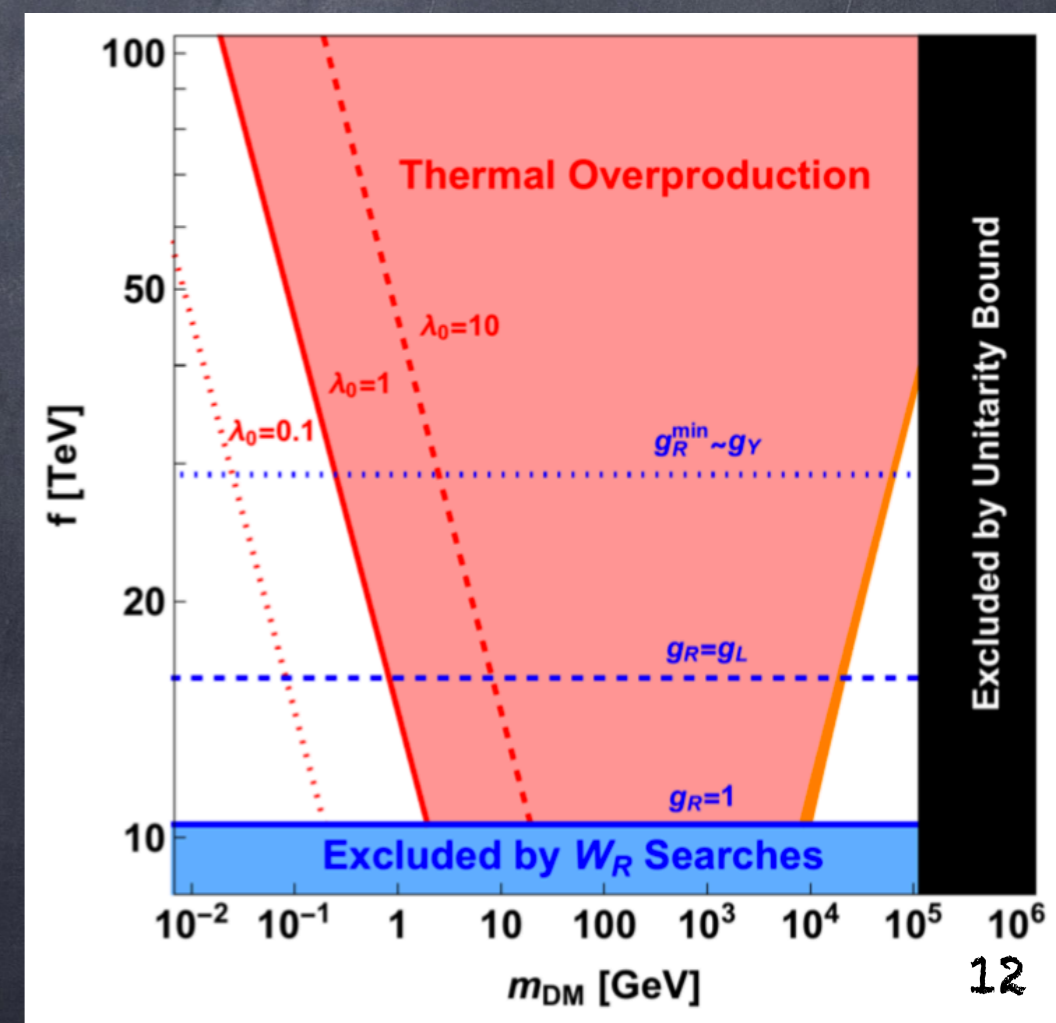$$\mathcal{L}_{\mathrm{DS}} = -\frac{1}{2}\mathrm{Tr}[\mathcal{G}_{\mathrm{D}}^{\mu\nu}\mathcal{G}_{\mathrm{D},\mu\nu}] + \overline{\Psi}_i(i\not{D} - m_\Psi)\Psi_i + y_{ij}\overline{\Psi}_i\Psi_j H + \mathrm{h.c.}$$

- 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

$\Delta D = 0$:
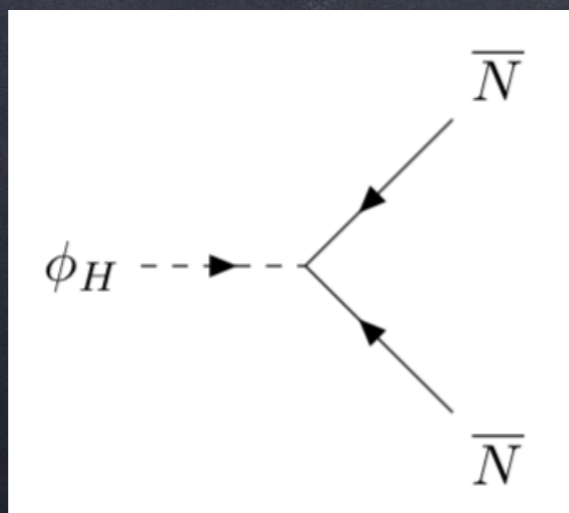
$\Delta D = 6$:
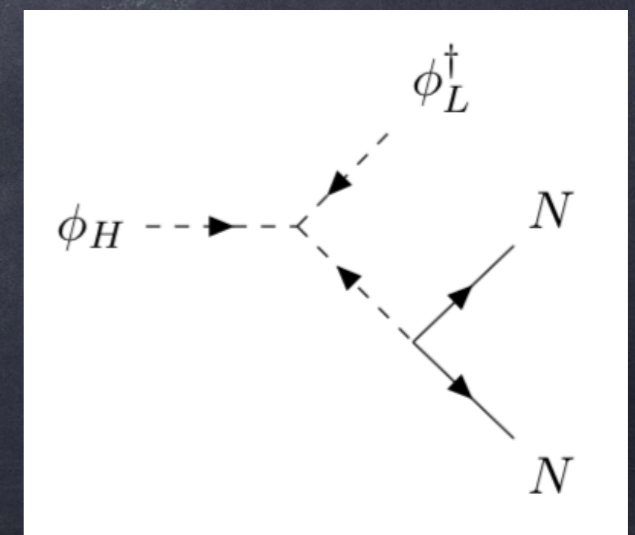
Chiral-isation

- Render the fermions chiral by introducing a new gauged symmetry

	G_{DC}	$U(1)_D$	G_{SM}	$U(1)_{3V}$	$U(1)_V$
			Type I		
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

- $U(1)_D$ broken dynamically: dark photon (possibly light)

- Both dark baryons – $U(1)_V$ – and mesons – $U(1)_{3V}$ – 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

- What happens for light spin-2 resonances (gravitons)?

- We consider a general case, one massive graviton and no parity.

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

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

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)

Chiral enhancement on the rescue

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(in line with the naive expectation)

For massive fermion:

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

(applies below the EW phase transition)

Chiral enhancement on the rescue

For massive fermion:

Huge enhancement!

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

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

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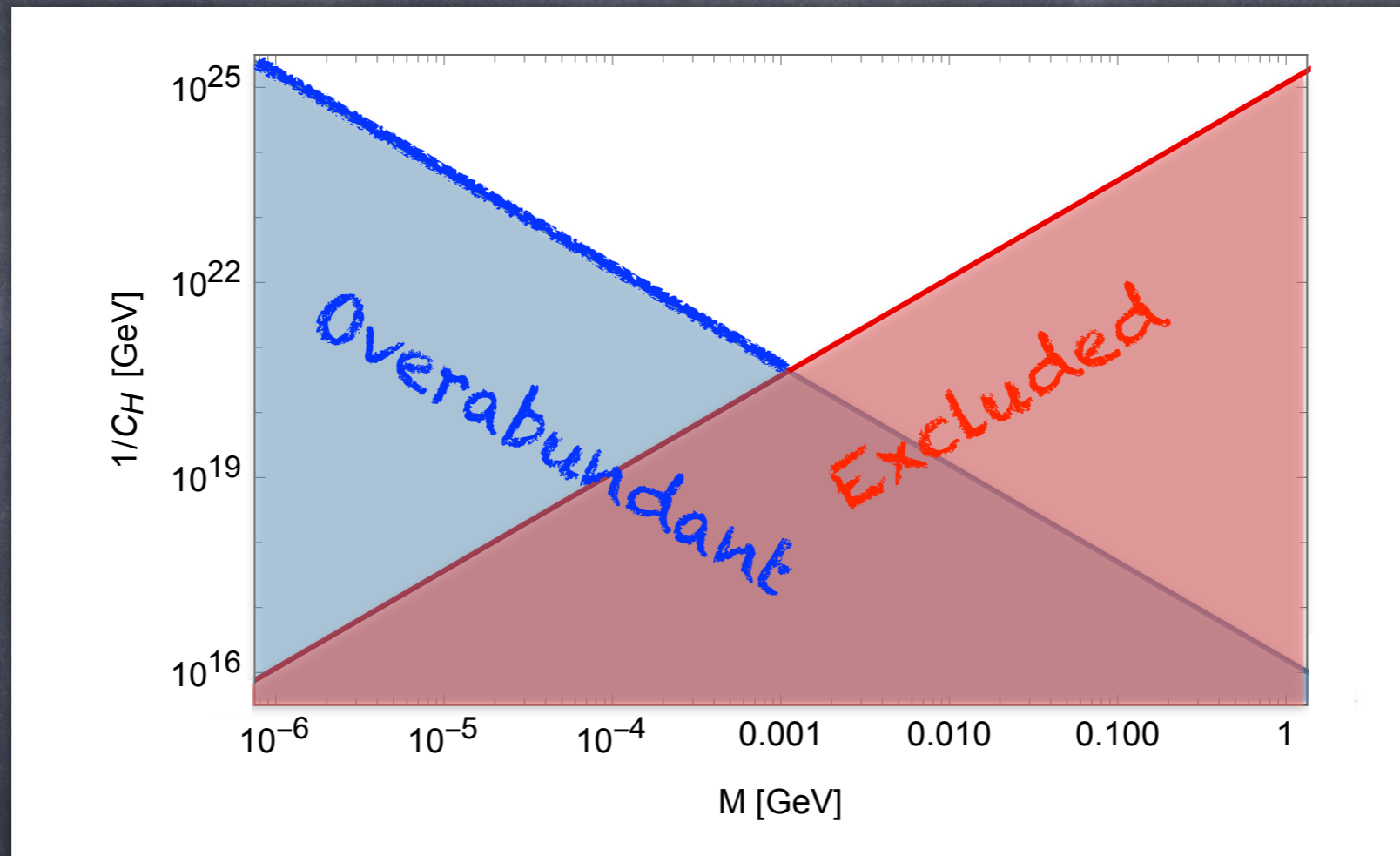
Sum over graviton polarisations:

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

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

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

Parameter space:

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

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!