Strong Dynamics and Dark Matter

(a model-builder perspective)

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ECT*: Interdisciplinary approach to QCD-like composite dark matter (1/10/2018)

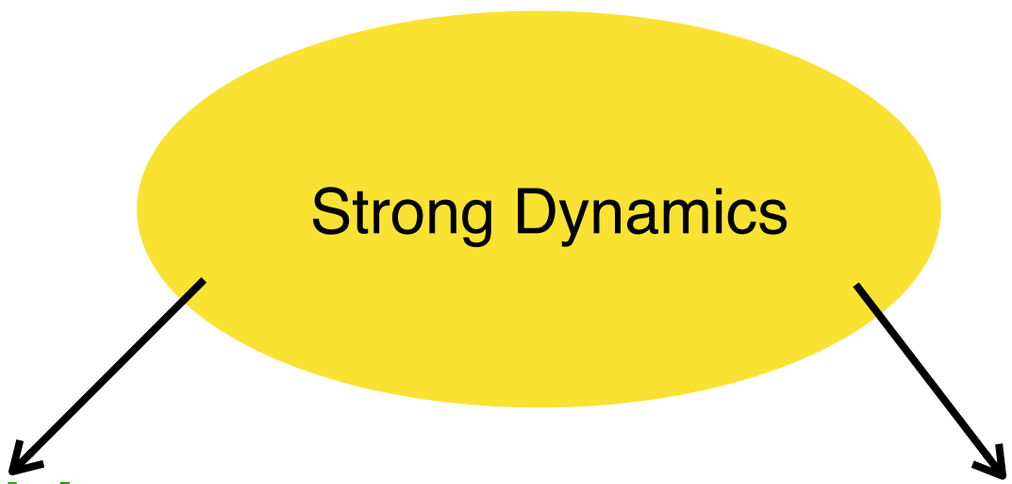
Outline

- **Strong Dynamics & Dark Matter**
  - Main candidates (baryons, pions, glueballs, axions)
  - Density, Detection, Pros and Cons

- **Strong Dynamics, Dark Matter, and…**
  - Solutions of the Hierarchy problem
  - Solutions of the Flavor problem
  - Solutions of the Strong CP problem
  - Solutions of the Baryogenesis problem

- **Conclusions**

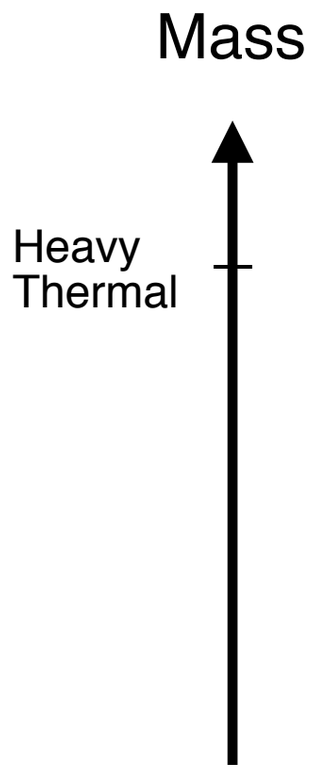
Strong Dynamics and Dark Matter



Stable particles
From accidental symmetries
(even anomalous: U(1)→Z_Nf)

Many candidates
From a rich spectrum:
baryons (baryon number),
pions (flavor symmetry),
glueballs (none)

(Ex: Baryons)



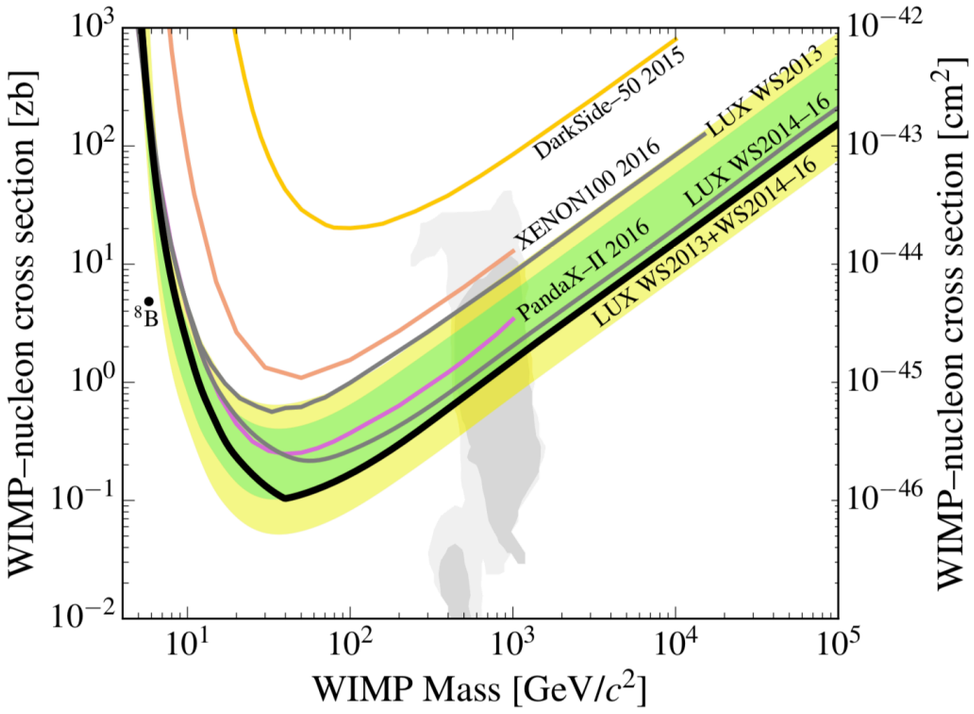
$$\sigma v \sim \frac{4\pi}{\Lambda^2}$$

Annihilation into lighter (non-dark matter…) composite states

$$\sigma v = \sigma v|_{\rm WIMP} \quad \Longrightarrow \quad \Lambda \sim 50 \text{ TeV}$$

Asymmetry relevant if $\sigma v > \sigma v|_{\rm WIMP}$

$$\Lambda \sim 5 \frac{\eta_b}{\eta} m_b < 50 \text{ TeV}$$

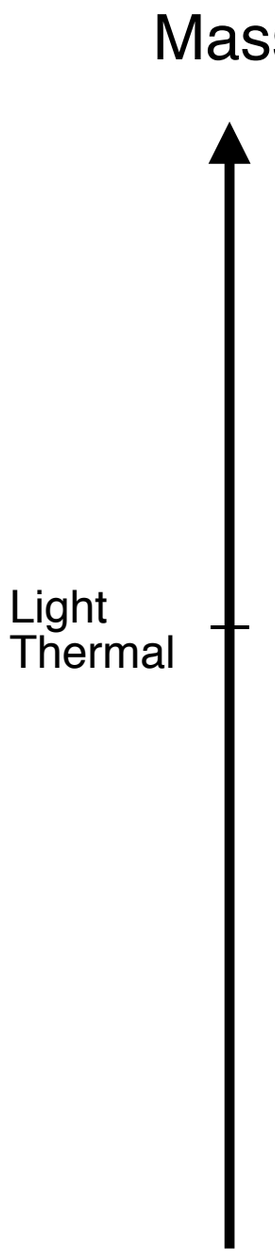


Direct and Indirect detection:

— typically too heavy (Ex: 50 TeV and dim-6 int $\sigma_n \lesssim \frac{\mu^2}{\Lambda^4} \sim 10^{-46}$ cm^2)

— some chance if couple to SM (ex: EDM)

(Ex: Pions)



$$\sigma v \sim \frac{g^4}{4\pi m^2}$$

$$100\ \mathrm{MeV} \lesssim m \sim 10 g^2\ \mathrm{TeV} \qquad m = \epsilon\Lambda,\ g = 4\pi\epsilon \implies \Lambda = 10^3 \epsilon\ \mathrm{TeV} \ll 10^3\ \mathrm{TeV}$$

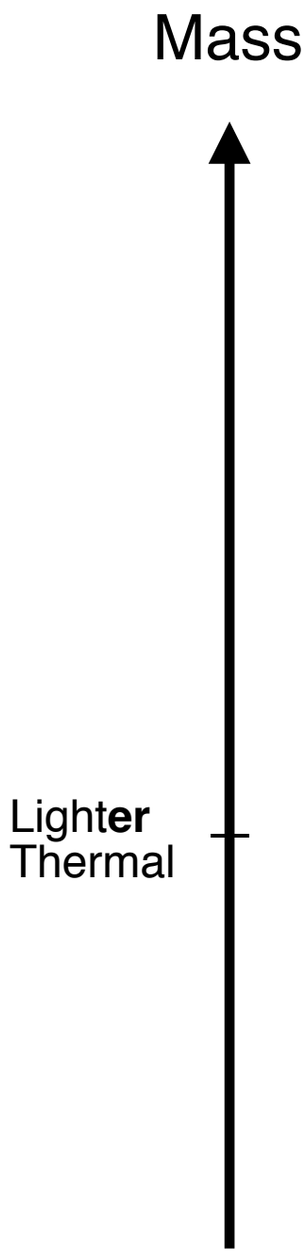
Annihilation into
— SM
— lighter exotic states

Asymmetry relevant if $\sigma v > \sigma v|_{\mathrm{WIMP}}$

$$100\ \mathrm{MeV} < m < 10 g^2\ \mathrm{TeV}$$

Direct and Indirect detection: optimal, colliders?

(Ex: Pions, Glueballs)



$\pi\pi\pi \to \pi\pi$ **Depletion "do-it-yourself"**
(watch the entropy…)

$$n^3\sigma \sim nH(m)$$
$$\sigma \sim g^6/m^5 \quad \Longrightarrow \quad m \sim g^2 \text{ GeV}$$

— Estimate ok for glueballs, not so for pions (selection rules)
— Possible implications in Astrophysics (bullet cluster, etc.)
— Direct and Indirect detection not likely (by construction)

(Ex: Axions)

Mass

Super-Light
Non-Thermal

Assume no thermal component
(not even of constituents!)

$$f^2 m^2 \left(\frac{T_{\rm eq}}{\sqrt{m M_{\rm Pl}}}\right)^3 \sim T_{\rm eq}^4$$

$$\left.\begin{array}{l} m < f \\ \sqrt{m M_{\rm Pl}} > T_{\rm eq} \end{array}\right\} \implies 10^7\ {\rm GeV} < f < 10^{17}\ {\rm GeV}$$

Example: $\delta\mathcal{L} = \dfrac{\Psi\Psi\Psi\Psi}{M_{\rm Pl}^2} \implies m^2 \sim \dfrac{\Lambda^2 f^2}{M_{\rm Pl}^2}$

$$\Lambda \sim 4\pi f \sim 10^{10}\ {\rm GeV} > T_{\rm re-heat}$$

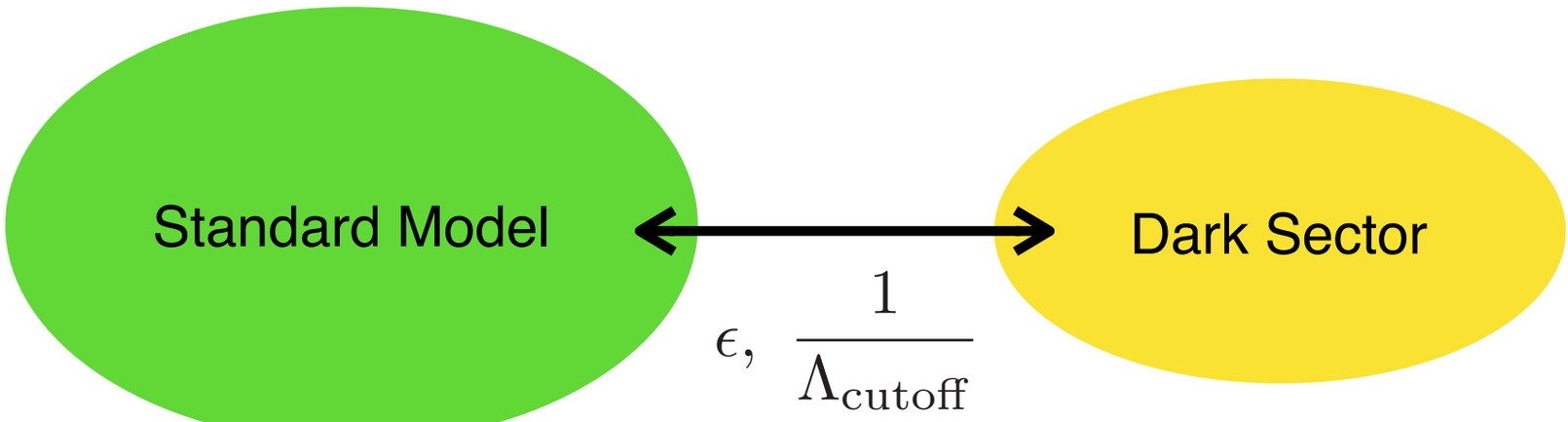
— Direct and Indirect detection not likely
— No obvious implications in Astrophysics (not the QCD axion!)

Detection:

Many opportunities: Direct/Indirect-detection, Colliders, Astrophysics, Cosmology.
But:

1) Some candidate is hard to see by construction:
   — Axions are extremely weakly-coupled
   — Baryons are heavy (small density)

2) Regarding thermal candidates: the “WIMP miracle” works fine even with a decoupled dark sector…
   (early decoupling plus small dark radiation)



Dark Matter from strong dynamics: Pros & Cons

Pros:
— many compelling candidates

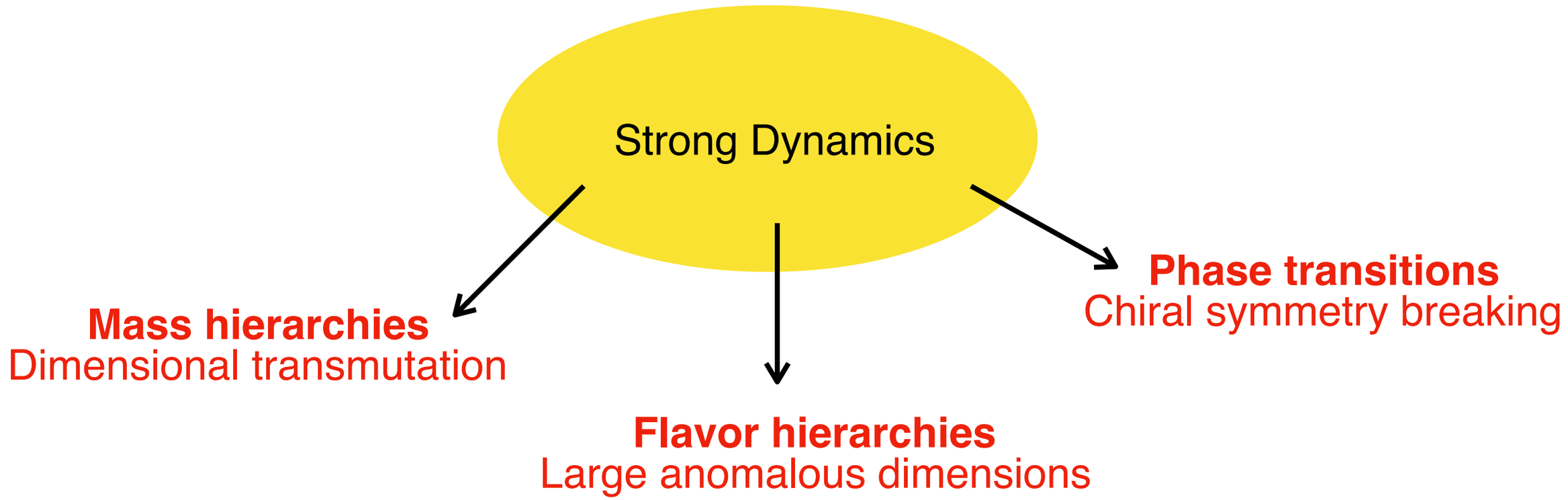
Cons:
— many compelling candidates

<u>What to do:</u>
— hope for the best
— investigate all candidates and “portals”
— **try adding more assumptions…**

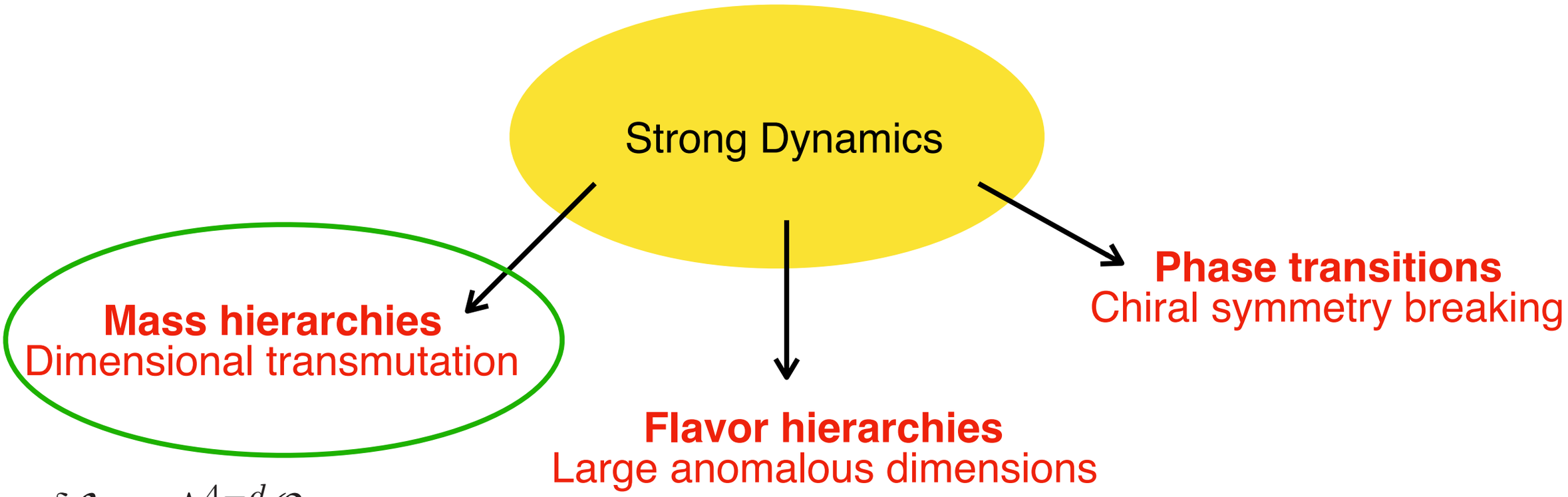
This is the dark matter business…

Strong Dynamics, Dark Matter, and…

Strong dynamics and model-building



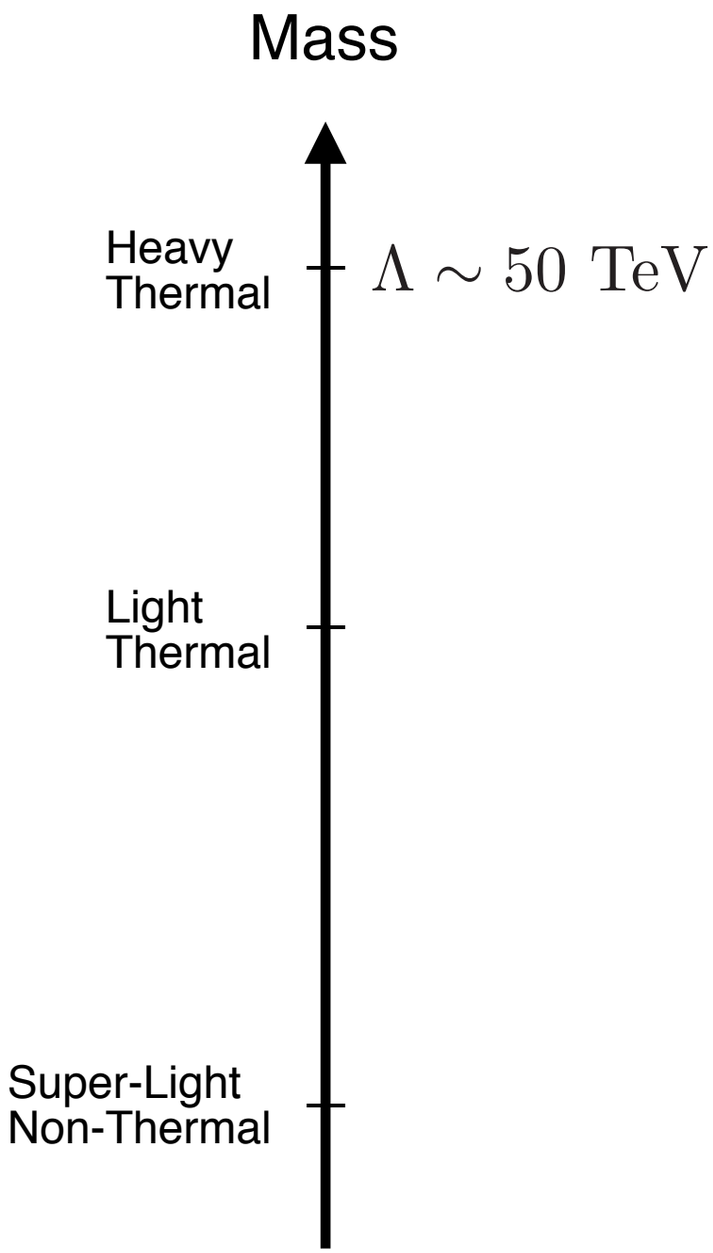
Strong dynamics and model-building



$$\delta\mathcal{L} = \epsilon\Lambda_{\rm UV}^{4-d}\mathcal{O}$$

$$\Lambda \sim \Lambda_{\rm UV}\epsilon^{1/(d-4)} \ll \Lambda_{\rm UV}$$

Composite Higgs (Technicolor)



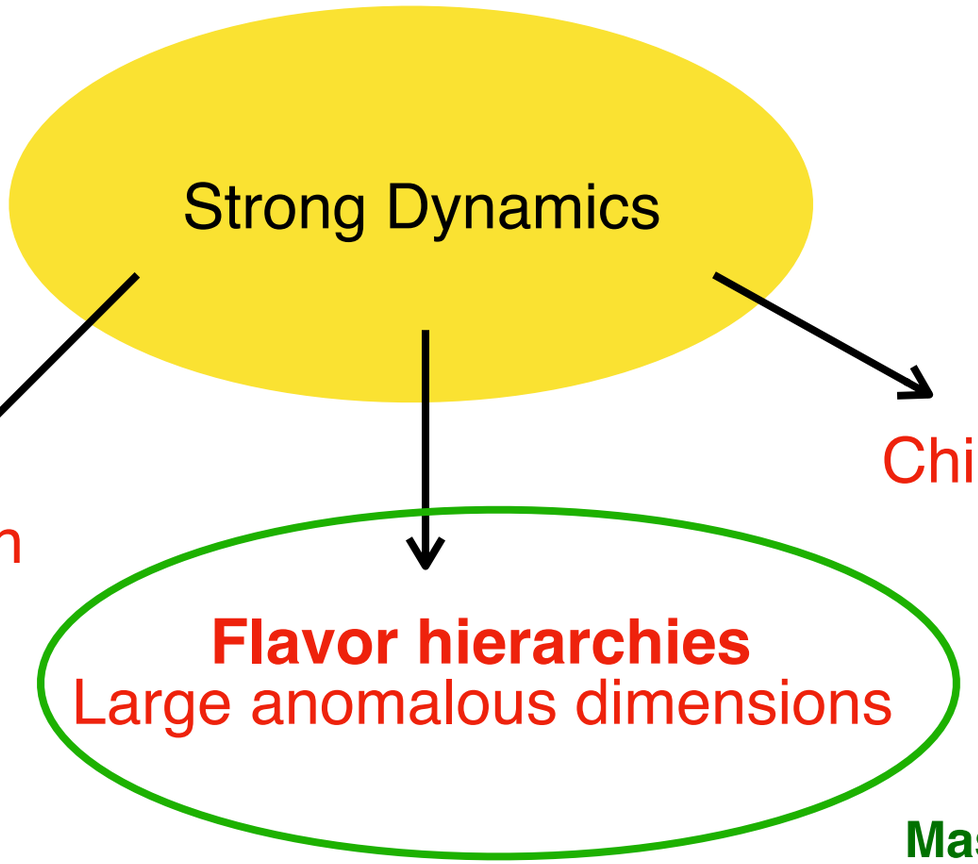
New constraints!

— EW data Λ > 5 TeV
— Flavor Λ > 1000 TeV (10 TeV if smart)
— CP violation Λ > 100 TeV
— Λ not too large for naturalness…

↕

…WIMPs survive, axion is in trouble

Strong dynamics and model-building



Mass hierarchies
Dimensional transmutation

Phase transitions
Chiral symmetry breaking

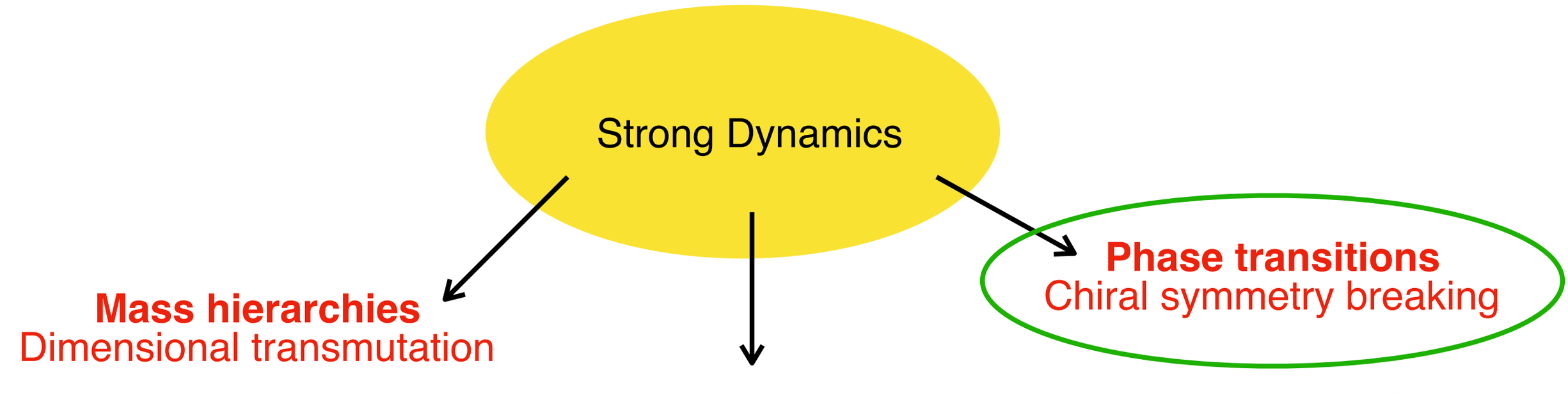
Flavor hierarchies
Large anomalous dimensions

Mass scale Λ is basically unconstrained
(decoupling of flavor problem)

$$y_{ij} \sim \left(\frac{\Lambda}{\Lambda_{\rm UV}}\right)^{\gamma_{ij}}$$

— Walking TC
— Randall-Sundrum
— Nelson-Strassler

Strong dynamics and model-building



Spontaneous CP breaking: strong CP a la Nelson-Barr

CP is exact

Spontaneous CP breaking — Λ

m_Ψ

CP-even ↓ $m_\Psi \Psi\Psi$ + CP-odd ↓ $\langle\Sigma\rangle \Psi q$ + $\cdots$

↑ SM fermion

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \cdots$$

with CP-odd phase in CKM and small QCD angle!

Constraints:

$$\theta \sim \frac{g_\Sigma^2}{16\pi^2} < 10^{-10}$$ Fine, but still…

$$\frac{g_s^2}{\Lambda_{\rm UV}^2}\langle\Sigma\rangle^2 G\tilde{G} \implies \langle\Sigma\rangle < 10^{-5}\Lambda_{\rm UV}$$

Strong CP problem not solved
unless you address the hierarchy problem!

Spontaneous CP breaking: strong CP a la Nelson-Barr

— VEV/cutoff hierarchy naturally addressed
— Spontaneous CP violation via the VEV of “pions”

$$\delta\mathcal{L} = \frac{\chi\chi\Psi\Psi}{\Lambda_{\rm UV}^2} + \frac{\chi'\chi'\Psi q}{\Lambda_{\rm UV}^2} + \frac{\Psi\Psi HH}{\Lambda_{\rm UV}} + \mathcal{O}\left(\frac{\chi^4, \chi'^4, q^4}{\Lambda_{\rm UV}^2}\right)$$

$$\Big\downarrow \Lambda$$

$$\delta\mathcal{L} = m_\Psi \Psi\Psi + \langle\Sigma\rangle \Psi q + \cdots$$

Constraints easily satisfied!

$$g_\Sigma \sim \frac{\Lambda^2}{\Lambda_{\rm UV}^2} \sim \frac{m_\Psi}{\Lambda} < 10^{-5} \quad \text{(neutron EDM)}$$

$$\frac{g_s^2}{\Lambda_{\rm UV}^6}\langle\chi'\chi'\rangle^2 G\widetilde{G} \qquad \langle\chi'\chi'\rangle \ll \Lambda_{\rm UV}^3$$

$$\Lambda > 10^5 m_\Psi > 10^5 \text{ TeV} \quad \text{(colliders)}$$

Solutions alternative to the QCD axion also favor an axion DM…

Baryogenesis

$T > 10^{11}$ GeV — High scale mechanisms are active: Leptogenesis, Affleck-Dine

$T < 10^{11}$ GeV — Realistic exotic sources of B and L breaking are out of equilibrium
Require a low scale mechanisms: **EW Baryogenesis** (B+L≠0 provided B-L=0)

↕

EW phase transition from a strong dynamics:
Composite Higgs

EW Baryogenesis from a strong dynamics at Λ<10^11 GeV?

Non-abelian gauge theories have all necessary ingredients:

1) first order chiral phase transitions (truly second order is rare) $\Longrightarrow$ departure from equilibrium
2) anomalous symmetries (when chiral symmetry is weakly-gauged) $\Longrightarrow$ charge violation
3) C & CP violation

However:

Anomalous symmetries
$\Longleftrightarrow$
Chiral fermions
$\Longrightarrow$
No CP phases
$\Longrightarrow$
No Baryogenesis

However, more structure is clearly needed to reproduce the SM (ex: Randall-Sundrum), then Baryogenesis can be achieved: no serious challenges here.

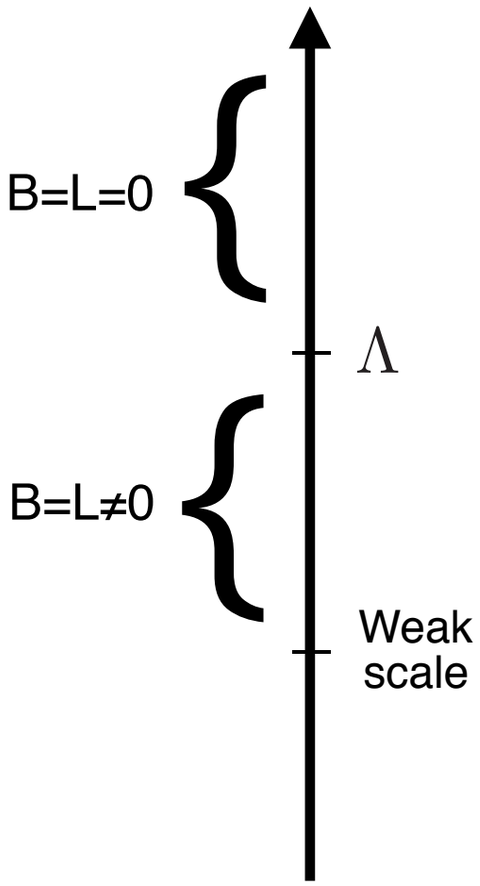
The strong dynamics was in thermal equilibrium: axion DM is unlikely

EW Baryogenesis at Λ<10^11 GeV?

The only serious challenge is the usual one: CP violation!

$$d_e = e\frac{g_*^2}{8\pi^2}\frac{m_e}{m_*^2} < 8.7\times 10^{-29} e\ \mathrm{cm} \qquad m_* > g_* 40\ \mathrm{TeV}$$

In our case something like… $100\ \mathrm{TeV} < \Lambda < 10^{11}\ \mathrm{GeV}$



Genesis at Λ>100 TeV

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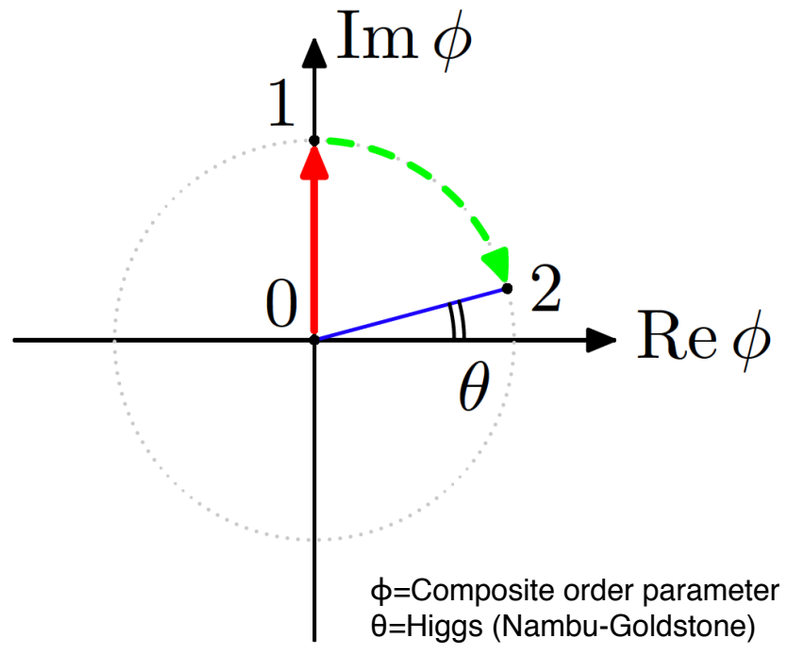
Need light sector that prevents washout

$$\Gamma_{\mathrm{sphaleron}} = (\cdots) T e^{-\frac{4\pi}{g}\frac{v}{T}} \ll H(T)$$



ϕ=Composite order parameter
θ=Higgs (Nambu-Goldstone)

Conclusions

- **Strong dynamics makes very compelling Dark Matter candidates:**
  - ✺ Baryons: heavy WIMPs (harder to detect) — for 100 MeV<Λ<50 TeV
  - ✺ Pions: WIMPs (DD, ID, colliders), otherwise astrophysics — for 100 MeV<Λ<<1000 TeV
  - ✺ Glueballs: constrained mostly by astrophysics and cosmology — for 1 GeV<Λ<100 GeV
  - ✺ Axions: very light (hard to detect) — for 10^8 GeV<Λ<Planck (Λ>T_reheat)

  $\Longrightarrow$ **More on this in the other talks…**

- **Add more assumptions, possibilities reduce… good news: discrimination power!**

  Exceptions always exist!
  - ✺ Models for the weak scale → prefer WIMPs (“WIMP miracle”)
  - ✺ Models for flavor are not structurally constraining → all candidates on the table…
  - ✺ (Non-SUSY) Solutions of the Strong CP (including Nelson-Barr) live in the far UV → prefer axions
  - ✺ Strong sectors can realize EW Baryogenesis → prefer WIMPs (since Λ<T_reheat)

  $\Longrightarrow$ **Observing Dark Matter might tell us more than we think…**

Thank You