# Twin Dark Matter

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# Outline

- Twin Higgs Mechanism — Z.Chacko, H-S.Goh, R.Harnik (hep-ph/0506256)
  - how does it work?
  - why does it solve the little hierarchy problem?
- Fraternal Twin Higgs — N. Craig et al. (hep-ph/1501.05310)
  - what is the minimal implementation of the Twin Higgs idea?
- Dark Matter
  - twin WIMPs — IGG, RL, JMR (hep-ph/1505.07109)
  - twin asymmetric DM — IGG, RL, JMR (hep-ph/1505.07410)
- Conclusions

# Twin Higgs

( Higgs as PNGB of approximate SU(4) )

Necessary ingredients:

(i) twin sector — copy of the SM → $SU(3)' \times SU(2)' \times U(1)'$ ; $H'$ (twin Higgs) ; $t'$, $b'$, etc…

both matter and gauge interactions

(ii) $\mathbb{Z}_2$ symmetry between twin and SM sectors → $g_i = g_i'$ ; $y_t = y_t'$ etc…

makes couplings in both sectors equal

(iii) Higgs quadratic term satisfies an accidental SU(4) global symmetry due to $\mathbb{Z}_2$

the Higgs particle we have observed is realised as a Pseudo-Nambu-Goldstone boson of the approximate SU(4)

- Tree-level Higgs scalar potential (fully SU(4)-symmetric):

8 real dof → $\Phi = \begin{pmatrix} H \\ H' \end{pmatrix}$ transforms as fundamental of global SU(4)

$$V_{tree}(\Phi) = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$= -m^2(|H|^2 + |H'|^2) + \lambda(|H|^4 + |H'|^4 + 2|H|^2|H'|^2)$$

SU(4)-invariant quartic

$$\Rightarrow \quad \langle|\Phi|^2\rangle = \langle|H|^2\rangle + \langle|H'|^2\rangle = \frac{m^2}{2\lambda} \equiv \left(\frac{f}{\sqrt{2}}\right)^2$$

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SU(4) → SU(3) ➡ 7 Goldstone bosons

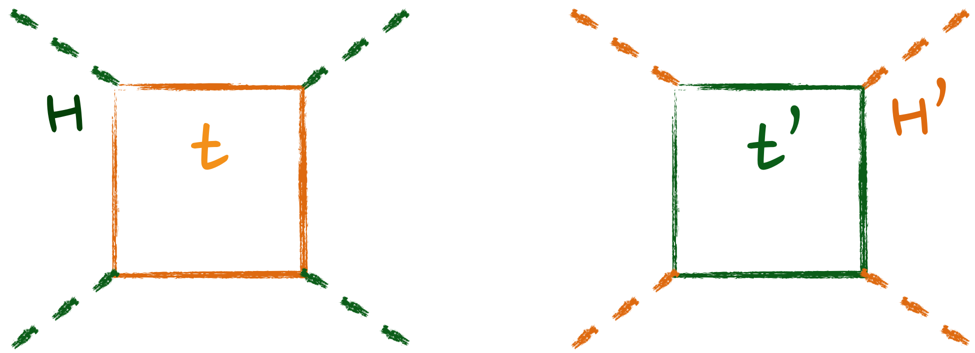
( rather: O(8) → O(7) )

→ 3 eaten by SU(2)
→ 3 eaten by SU(2)'
→ 1 left: the Higgs we've seen

2 uneaten scalars:

- Goldstone $\hat{m}^2 = 0$
- 'Normal' $\hat{M}^2 = 2\lambda f^2$

- SU(4)-breaking quartic (generated at 1-loop):




Yukawa and gauge interactions break SU(4)

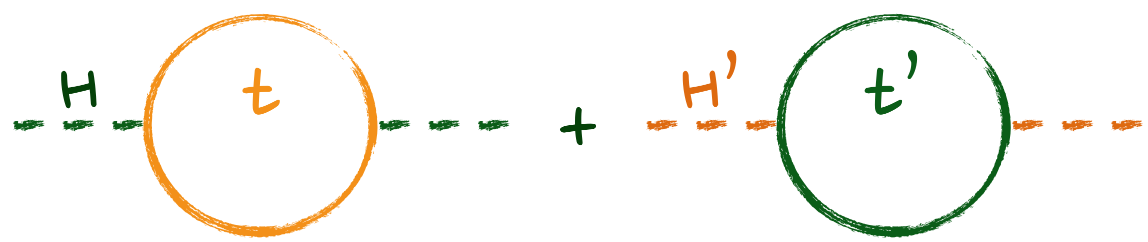
$$V(H,H') = V_{tree}(\Phi) + \delta(|H|^4 + |H'|^4)$$

SU(4)-breaking quartic

small mass for the pseudo-Goldstone

$$\Rightarrow \quad \langle |H|^2 \rangle = \langle |H'|^2 \rangle \approx \frac{1}{2}\left(\frac{f}{\sqrt{2}}\right)^2 \qquad \begin{cases} \hat{m}^2 = \delta f^2 \\ \hat{M}^2 = 2\lambda f^2 \end{cases}$$

But, crucially:




$$\Rightarrow \quad \delta V \sim -\frac{3y_t^2}{16\pi^2}\Lambda^2|H|^2 - \frac{3y_t'^2}{16\pi^2}\Lambda^2|H'|^2 = -\frac{3y_t^2}{16\pi^2}\Lambda^2(\underbrace{|H|^2+|H'|^2}_{|\Phi|^2})$$

Sensitivity of the quadratic term in the potential to the cutoff scale is SU(4)-symmetric!

→ Radiative corrections to the quadratic piece don't affect the mass of the pseudo-Goldstone

→ The vev f gets pulled up: cutoff ~ 5-10 TeV

But, crucially:

Partners of SM particles (twins) that stabilise the weak scale are not charged under SM group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**Neutral Naturalness!**

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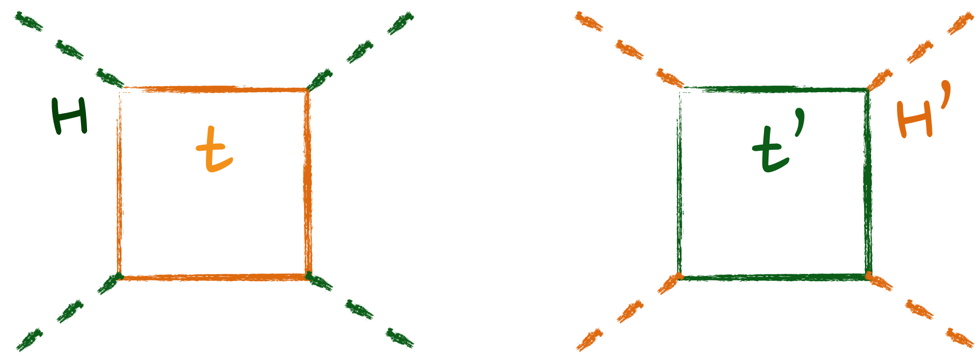
Radiative corrections to the quadratic piece don't affect the mass of the pseudo-Goldstone!

The vev f gets pulled up: cutoff ~ 5-10 TeV

Top partner not coloured – very much unlike SUSY

- SU(4)-breaking quartic (generated at 1-loop):

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$$\begin{cases} \hat{m}^2 = \delta f^2 \\ \hat{M}^2 = 2\lambda f^2 \end{cases} \qquad \begin{aligned} \hat{h} &= (h - h')/\sqrt{2} \\ \hat{H} &= (h + h')/\sqrt{2} \end{aligned}$$

This is experimentally ruled out.
The Higgs we have observed doesn't have BR($\hat{h} \to$ invisible) = 50%

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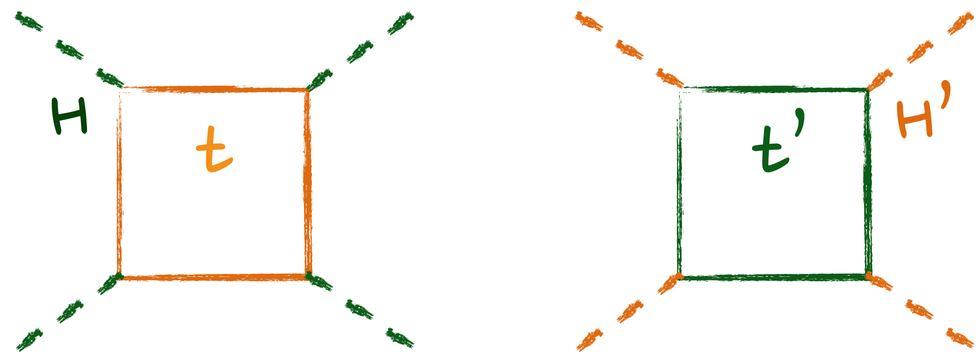


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$Z_2$ must be broken to allow for different vev's

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- $\mathbb{Z}_2$ symmetry must be broken (we will be agnostic about breaking mechanism):

$$V(H,H') = V_{tree}(\Phi) + \delta(|H|^4 + |H'|^4) + \mu^2|H|^2$$

$\mathbb{Z}_2$ breaking term

$$\Rightarrow \quad \langle |H|^2\rangle + \langle |H'|^2\rangle \approx \left(\frac{f}{\sqrt{2}}\right)^2$$

$$\langle |H|^2\rangle \approx \frac{1}{2}\left(\frac{f}{\sqrt{2}}\right)^2 - \frac{\mu^2}{4\delta} \equiv \left(\frac{v}{\sqrt{2}}\right)^2$$

$$\langle |H'|^2\rangle \approx \frac{1}{2}\left(\frac{f}{\sqrt{2}}\right)^2 + \frac{\mu^2}{4\delta} \equiv \left(\frac{f}{\sqrt{2}}\right)^2 - \left(\frac{v}{\sqrt{2}}\right)^2$$

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This is where the tuning in the Twin Higgs mechanism arises: need to tune size of $\mathbb{Z}_2$ breaking term to get right vev!

Tuning: $\Delta \sim \frac{2v^2}{f^2}$ $\sim 20\%$ for $f/v = 3$

Mass eigenvalues and eigenstates are now given by

$$\left\{ \begin{aligned} \hat{m}^2 &= 4\delta v^2 \\ \hat{M}^2 &= 2\lambda f^2 \end{aligned} \right.$$

$$\hat{h} = \cos\left(\frac{v}{f}\right) h \; - \sin\left(\frac{v}{f}\right) h'$$

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couplings to visible sector modified by a factor $\cos(\frac{v}{f})$

couplings to twin sector suppressed by a factor $\sin(\frac{v}{f})$

Two very important features of Twin Higgs models:

- Higgs portal
  - → Interactions between visible and twin sector only through the Higgs
- Collider signatures
  - → Twins not produced very much at LHC - they are SM neutral!
  - → Higgs coupling measurements should deviate from SM prediction
  - → Non-zero Higgs invisible width

# Fraternal Twin Higgs

N. Craig et al. (hep-ph/1501.05310)

( Minimal implementation of Twin Higgs mechanism )

Minimum necessary ingredients:

(i) twin SU(2) with twin *H'* in the fundamental

( at the heart of the Twin Higgs mechanism)

(ii) partial twin 3rd generation → $Q'$, $t'_R$ → $b'_R$, $L'$ (anomaly cancellation) → RH leptons optional

(iii) couplings in the two sectors similar to a high degree

⇒ (iv) twin SU(3) gauge group. → so that running of top Yukawas is similar

- How similar do the couplings need to be?

(e.g. for a 5 TeV cutoff)

- Top Yukawas:

$$\left|\frac{y_t'(\Lambda) - y_t(\Lambda)}{y_t(\Lambda)}\right| \lesssim 0.01$$

the two yukawas must be equal within 1% !

- SU(2) couplings:

$$\left|\frac{g_2'(\Lambda) - g_2(\Lambda)}{g_2(\Lambda)}\right| \lesssim 0.1$$

- SU(3) couplings (feeds into running of $y_t$):

$$\left|\frac{g_3'(\Lambda) - g_3(\Lambda)}{g_3(\Lambda)}\right| \lesssim 0.15$$

- other Yukawa couplings allowed to differ from SM (as long as $y_{b'}, y_{\tau'}, y_{\nu'} \ll y_{t'} \approx 1$ ).

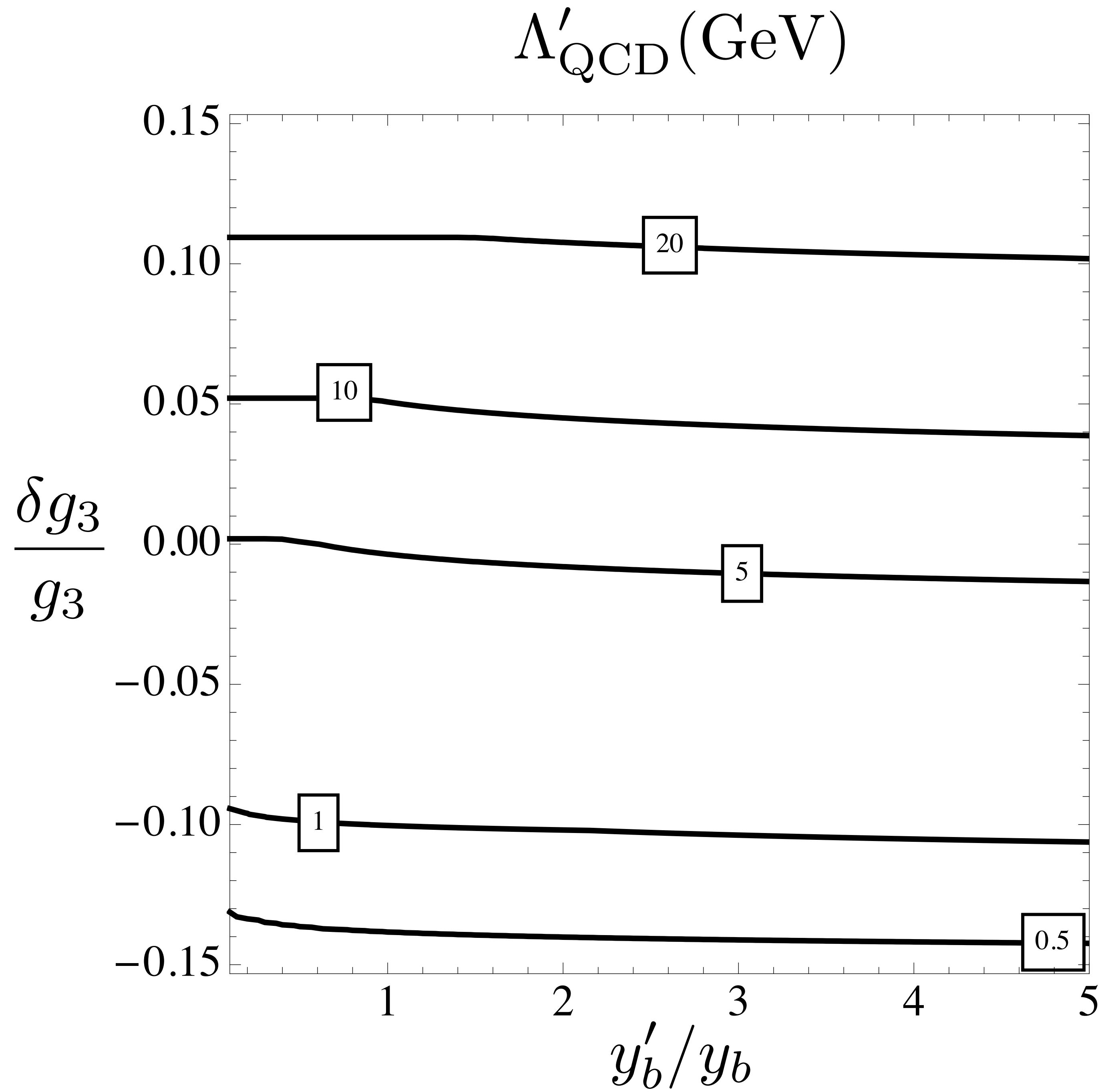
- Twin SU(3)

  - less twin quarks
    $\Rightarrow g_3'$ coupling runs quicker to large values in the IR.

    Twin SU(3) confinement scale $\Lambda'_{QCD}$ is bigger !

  - no light pions in the twin sector (regardless of $m_{b'}$): there is only one generation of quarks.

    No flavour symmetry is recovered in the limit $m_{b'} \to 0$ !




(for $\Lambda = 5$ TeV, $\frac{f}{v} = 3$)

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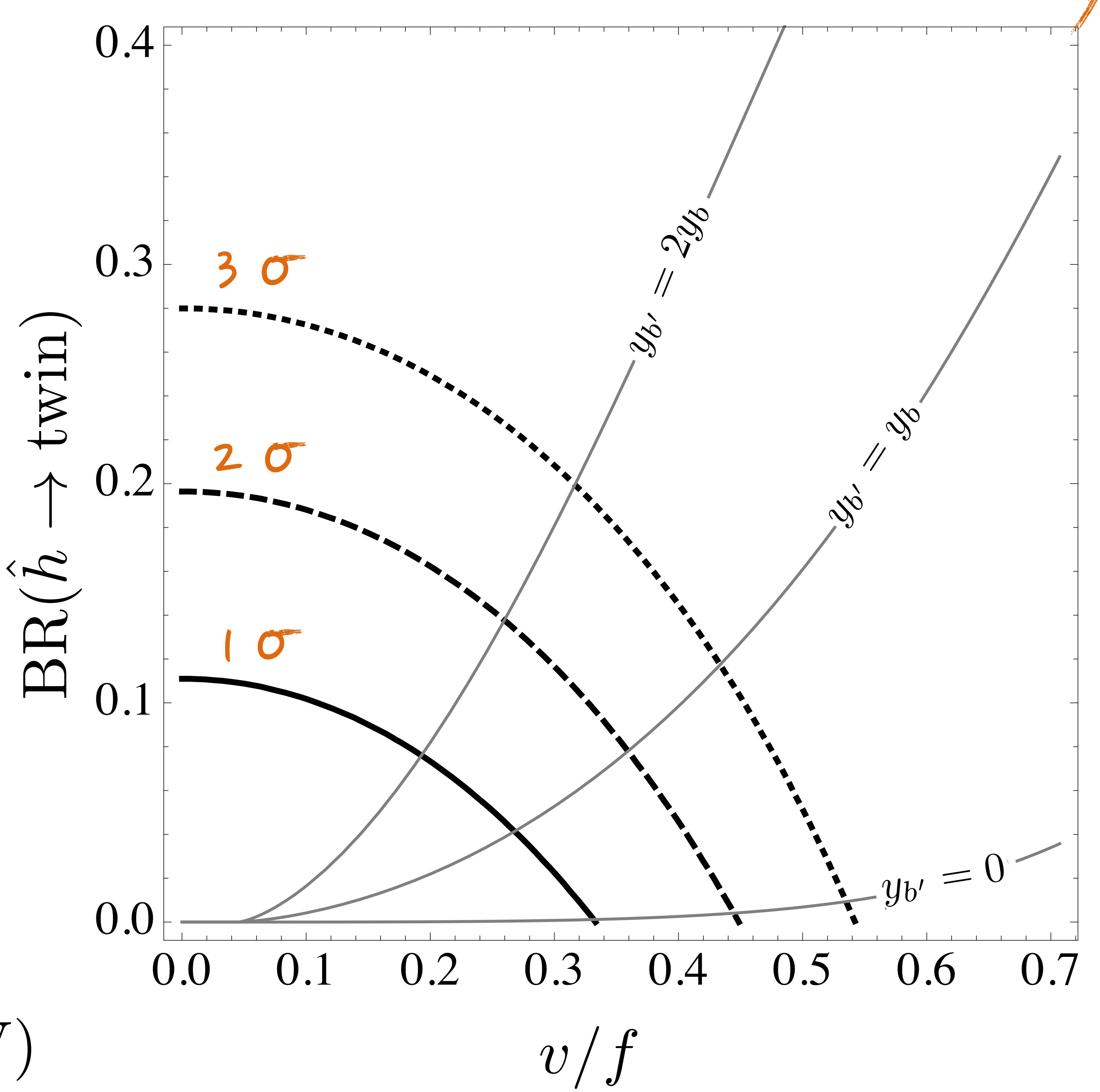
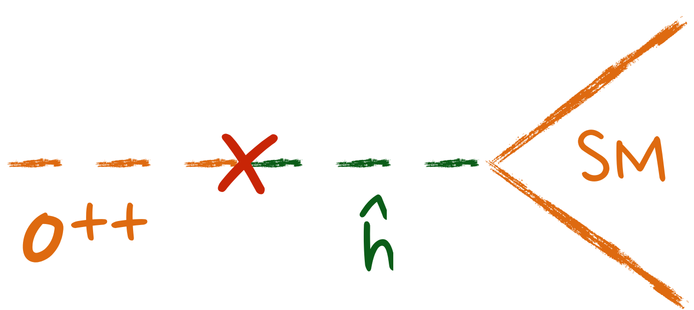
- Collider signatures/constraints:
  - twins not very produced at LHC
  - deviations from Higgs coupling measurements.
    $\Rightarrow f/v \gtrsim 3$
  - Higgs invisible width.
    constrains twin Yukawas (other than $y'_t$)
  - Twin glueball/ quarkonium

(for $m_0 \lesssim 40$ GeV, $\Lambda'_{\rm QCD} \lesssim 6$ GeV)




$$\tau_{0^{++}} \approx 10 \text{ cm} \left(\frac{21 \text{ GeV}}{m_0}\right)^7 \left(\frac{f/v}{3}\right)^4$$

# Twin WIMPs

IGG, RL, JMR (hep-ph/1505.07109)

( most natural DM candidates in a Fraternal Twin Higgs scenario )

Simplest possibility:

- First, we assume no asymmetry in the twin sector

  → final abundance determined purely by annihilation cross section

- Heavy quark limit ($m_{b'} \gg \Lambda'_{\rm QCD}$), naturally the case for $y_{b'} \approx y_b$ and $f/v \gtrsim 3$ ($\Rightarrow m_{b'} \gtrsim 15$ GeV)

- Symmetries $\begin{cases} \text{global: } U(1)_{B'}, U(1)_{L'}, U(1)_{Q'} \\ \text{discrete: } C', P' \text{ broken; } CP' \text{ may be conserved.} \end{cases}$

  focus on this case, but interesting things can potentially occur if CP' is broken

- Natural Dark Matter candidates:

  - Lepton sector:

    $\tau', \nu'$ (assume $m_{\nu'} \lesssim m_{\tau'}$ for simplicity)

    Since $m_{W'} = g_2' f/2 \gtrsim 240$ GeV, both twin leptons are naturally stable

    → automatic DM candidates

    We take

$$\begin{cases} m_{\tau'} \gtrsim m_h/2 \\ m_{\nu'} \gtrsim m_h/2 \quad \text{or massless.} \end{cases}$$

→ evades Higgs invisible width constraints

→ $N_{eff}$ within bounds

- Natural Dark Matter candidates:

  - Strong sector:

    Twin baryon $\Delta' \sim b'b'b'$ is the lightest state with $B' \neq 0$ but $\bar{b}'b'$ annihilation to twin gluons is very efficient

    $\Rightarrow \Delta'$ irrelevant as DM candidate unless $m_{b'} \gtrsim 1$ TeV.

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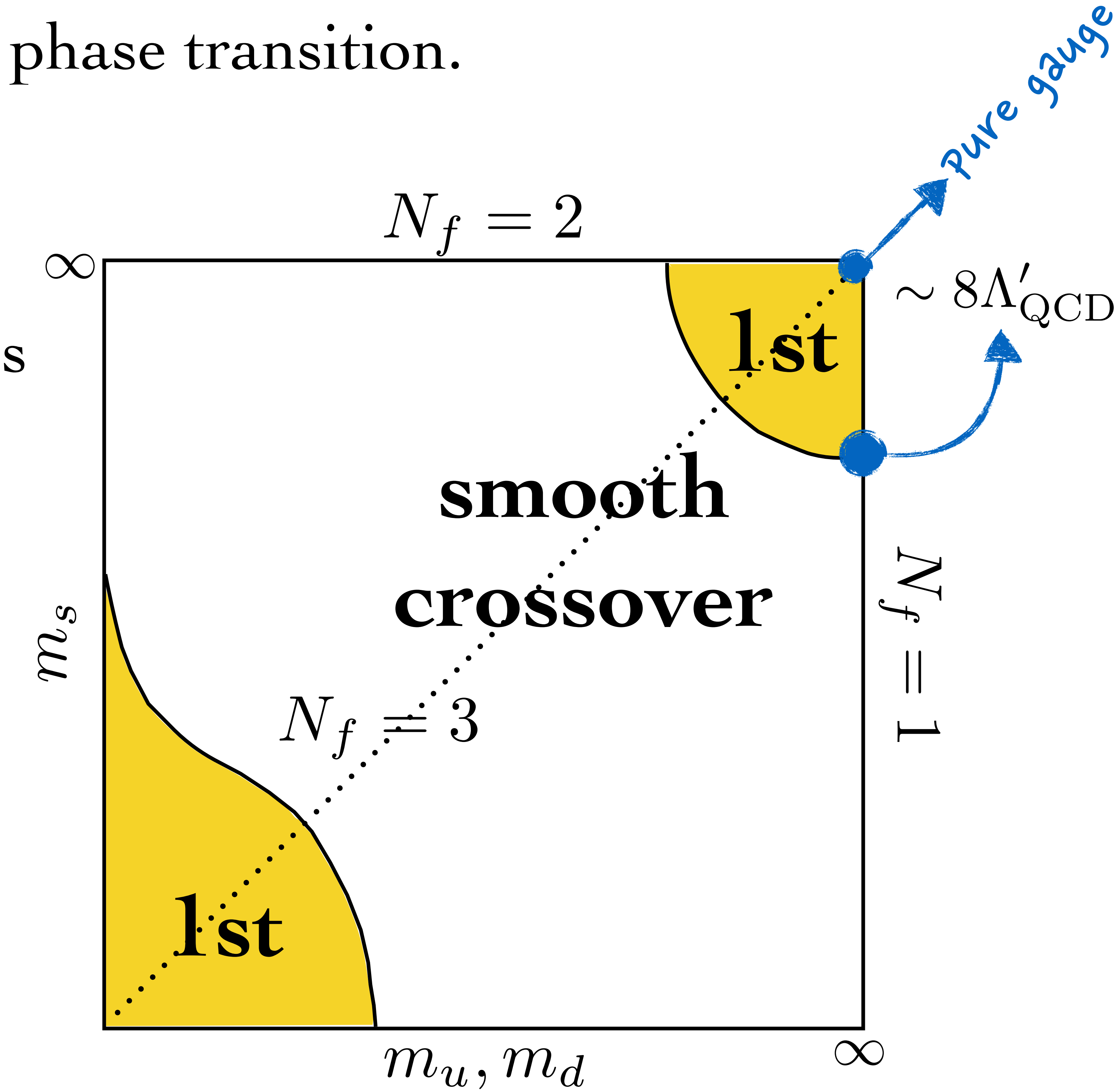
- Comment on SU(3)' phase transition.

  - 1 flavour QCD: expect smooth crossover for masses up to $\sim 8\Lambda'_{\mathrm{QCD}}$



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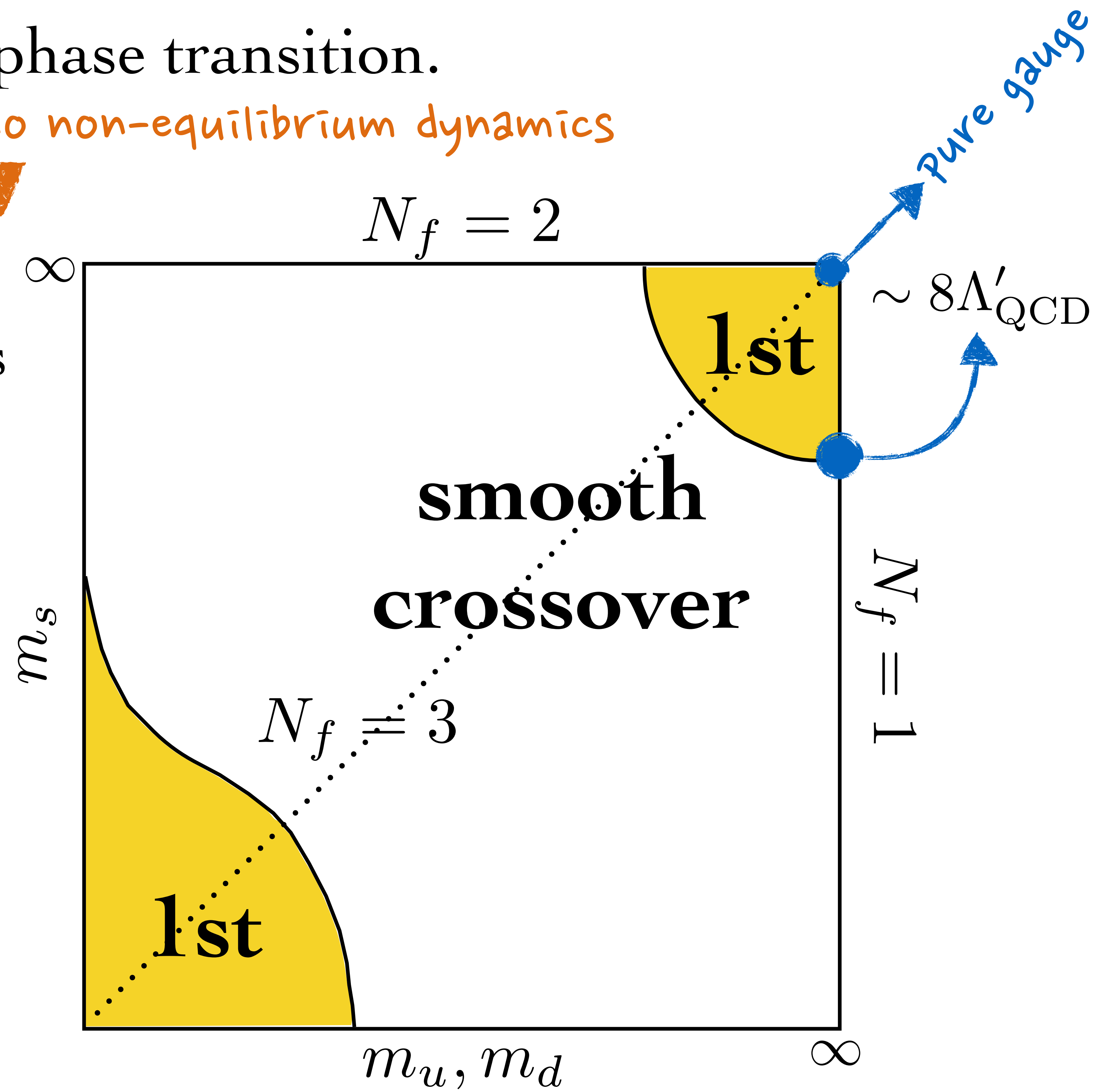

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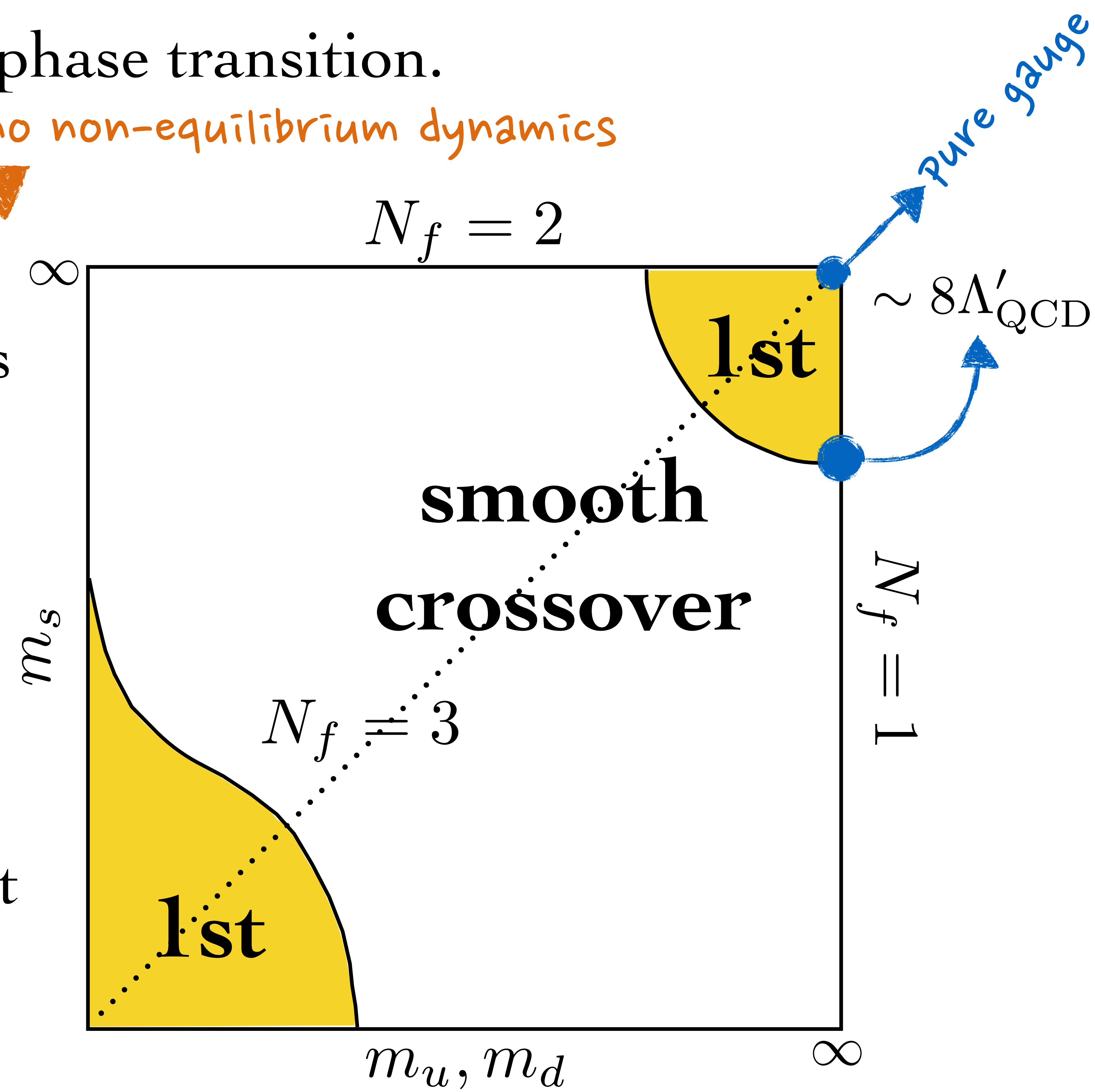

- why *weakly* first order?

Consider pure SU(3) phase transition. Most recent & detailed lattice studies tell us following facts

$$T_c \simeq 1.26\Lambda_{QCD'}^{\bar{M}S}$$ 'formal' Tc (equal free energy densities of confined and plasma phases)

$$\sigma \simeq 0.0155T_c^3$$ bubble wall surface tension (small)

$$\rho_L \simeq 1.4T_c^4$$ latent heat

We care about amount of supercooling of actual transition in expanding universe

$$T_{nuc} = (1-\delta)T_c$$

A bubble of the confined phase can expand if the pressure difference $\Delta P$ between phases overcomes surface tension

$$\Delta P = P_{conf}(T) - P_{plas}(T) \simeq -\delta\, T_c(s_{conf}(T_c) - s_{plas}(T_c)) = \delta \rho_L$$

This happens for bubbles of size greater than critical

$$R_c = \frac{2\sigma}{\Delta P}$$

The free energy to temperature ratio of such a critical bubble is

$$\frac{\Delta F_c}{T} \simeq \frac{16\pi}{3} \frac{\sigma^3}{\rho_L^2 T_c} \delta^{-2} \simeq 3 \times 10^{-5} \delta^{-2}$$

Nucleation in an expanding universe happens when

$$\frac{\Delta F_c}{T} \leq \log\left(\frac{T^4}{H^4}\right) \longrightarrow \delta \geq \delta_{nuc} \simeq 4 \times 10^{-4}$$

Thus nucleation occurs after a very small amount of supercooling and nucleations quickly become very efficient [for $\delta \sim 10\delta_{nuc}$ have $\exp(-\Delta F_c/T) \sim \mathcal{O}(1)$ ]

But latent heat of nucleations *heats surrounding plasma back up to* $T_c$ unless heat capacity of supercooled unconfined phase just below $T_c$ *very* large (lattice studies indicate not, but relatively poorly determined)

Bubbles stop expanding apart from slow quasi-equilibrium growth with Hubble (phase separation dynamics with tiny gravity wave signals)

In any case the entropy production is bounded and *small*

$$10^{-7} \simeq \frac{\delta_{nuc}^2 \rho_L}{T_c^4} \leq \frac{\Delta s}{T_c^3} \leq \text{few} \times \frac{\delta_{nuc}\rho_L}{T_c^4} \simeq 10^{-3}$$

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no non-equilibrium dynamics

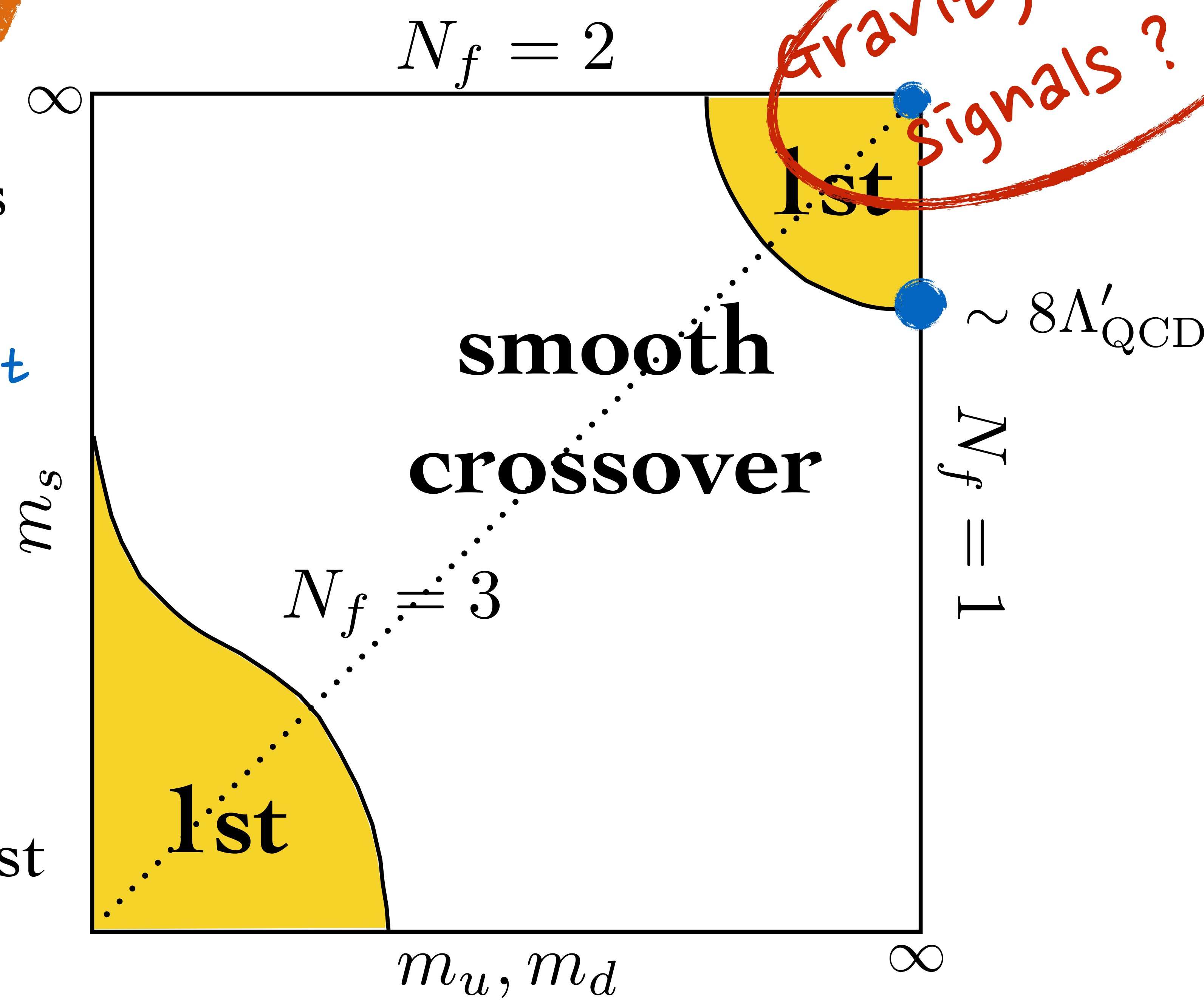
- 1 flavour QCD: expect smooth crossover for masses up to $\sim 8\Lambda'_{\rm QCD}$

even in the heavy quark limit

( we are typically in that regime )

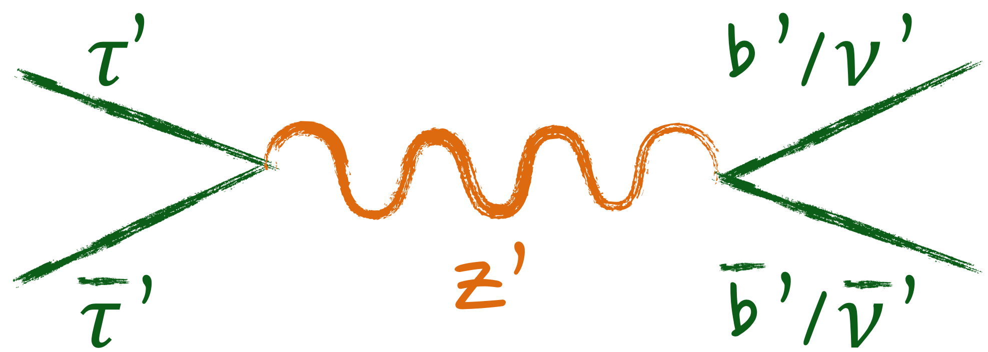
- even if we go above $\sim 8\Lambda'_{\rm QCD}$, the phase transition is weakly 1st order, with negligible entropy production.

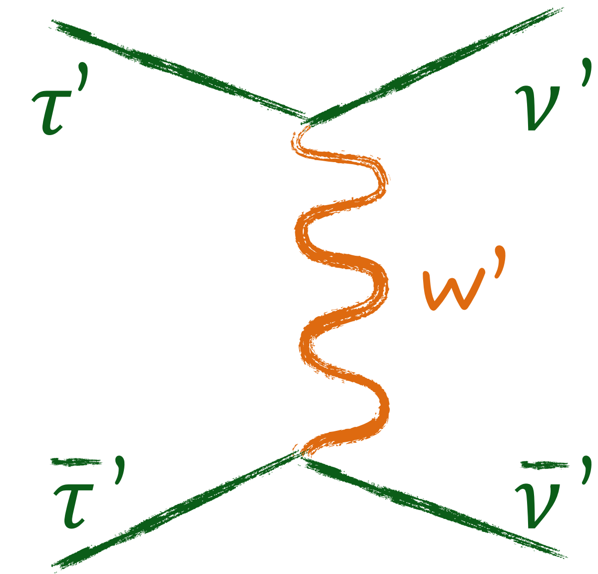
no dilution of relics

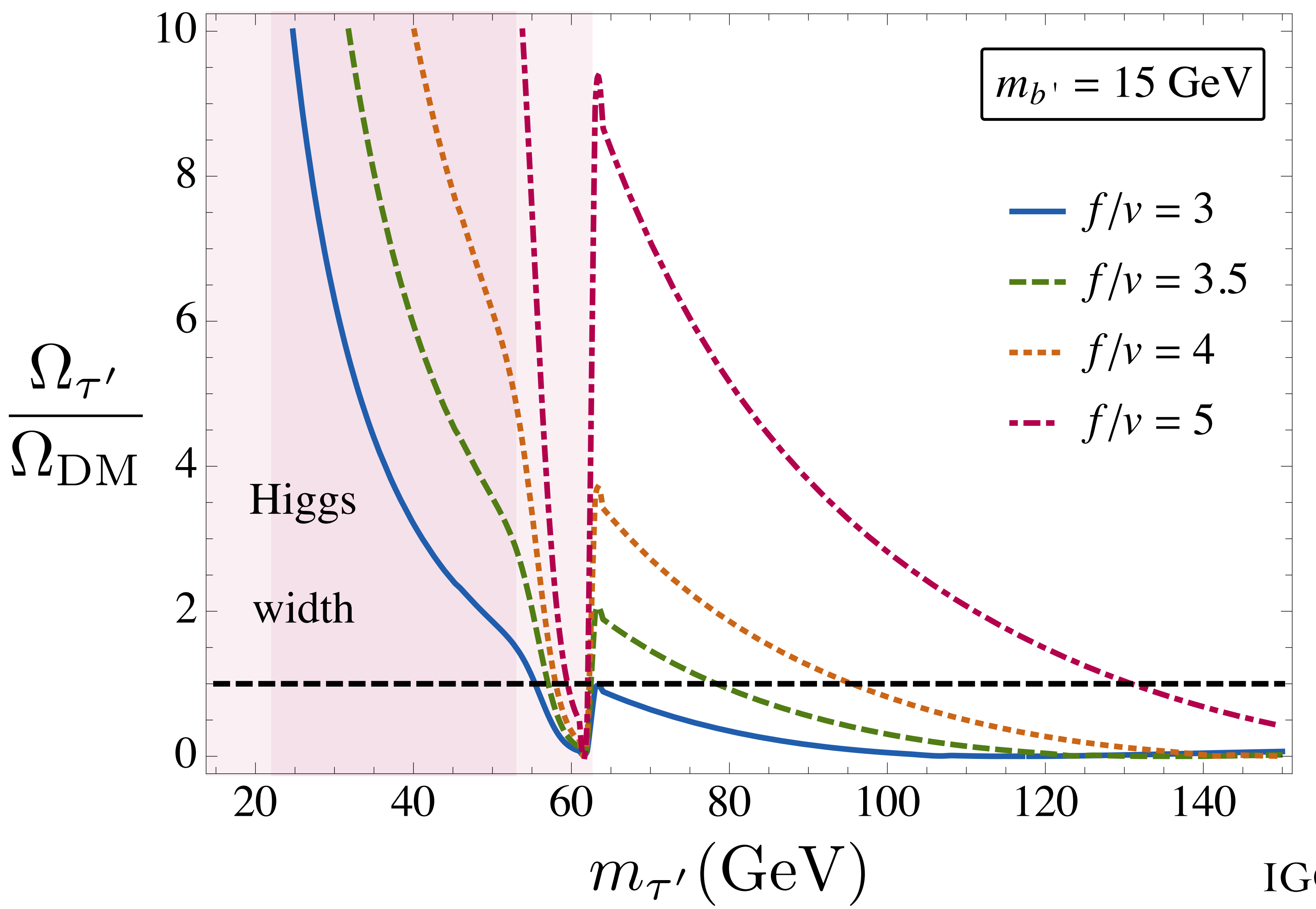


- Twin $\tau$ Dark Matter:

  - Annihilation cross section:




IGG, RL, JMR (hep-ph/1505.07109)

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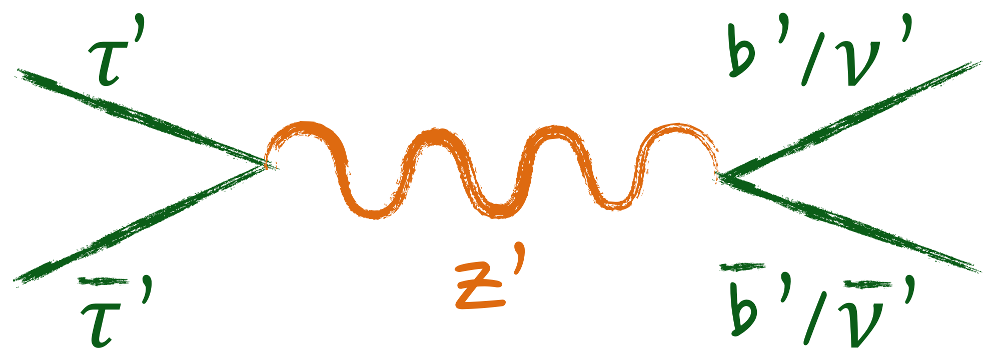


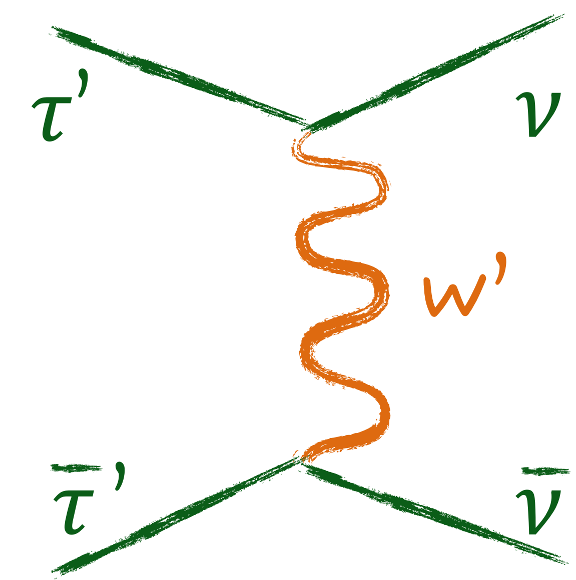


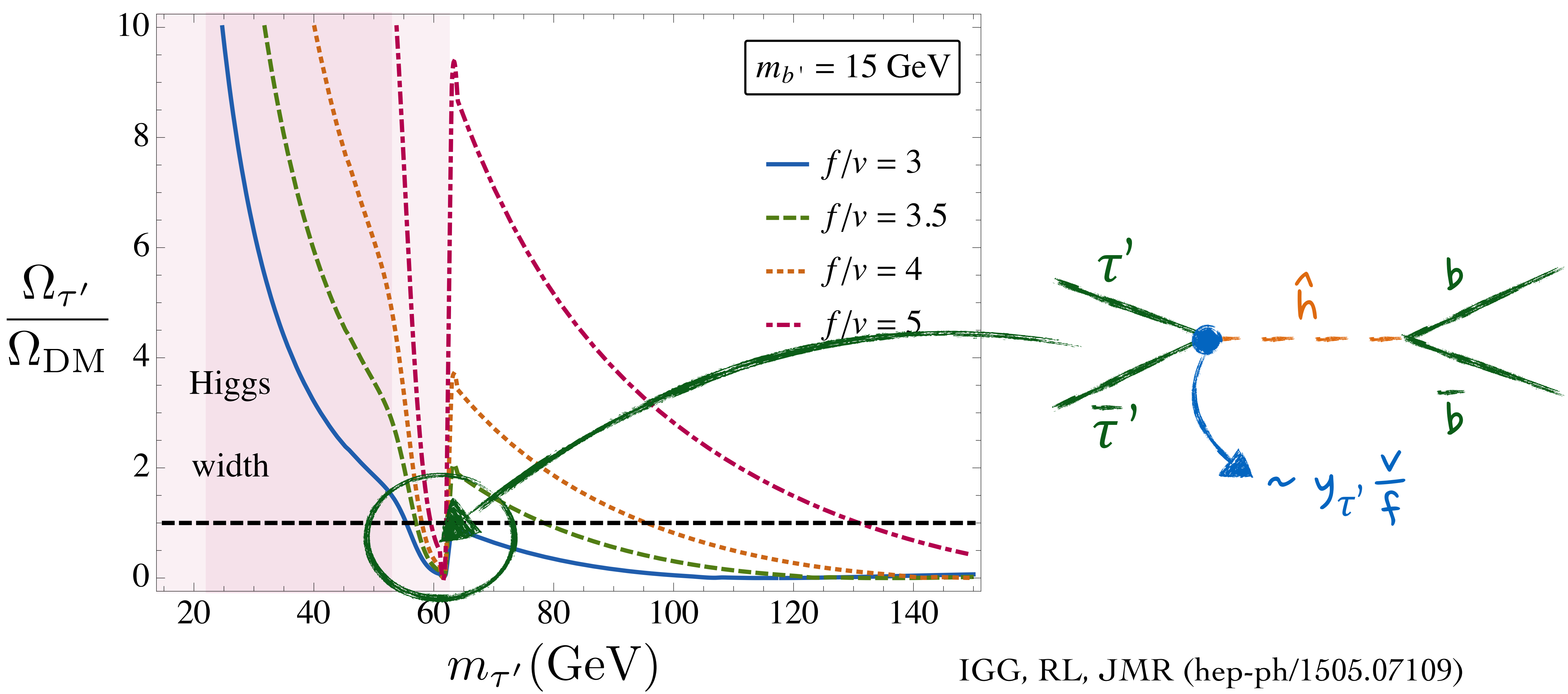


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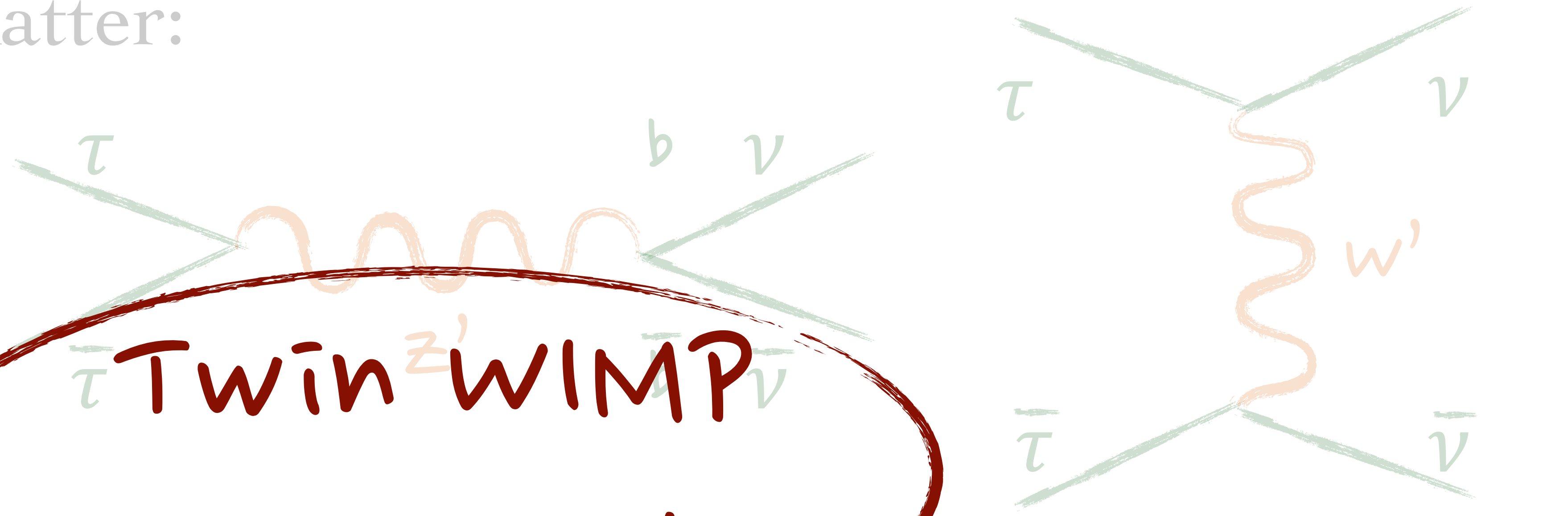
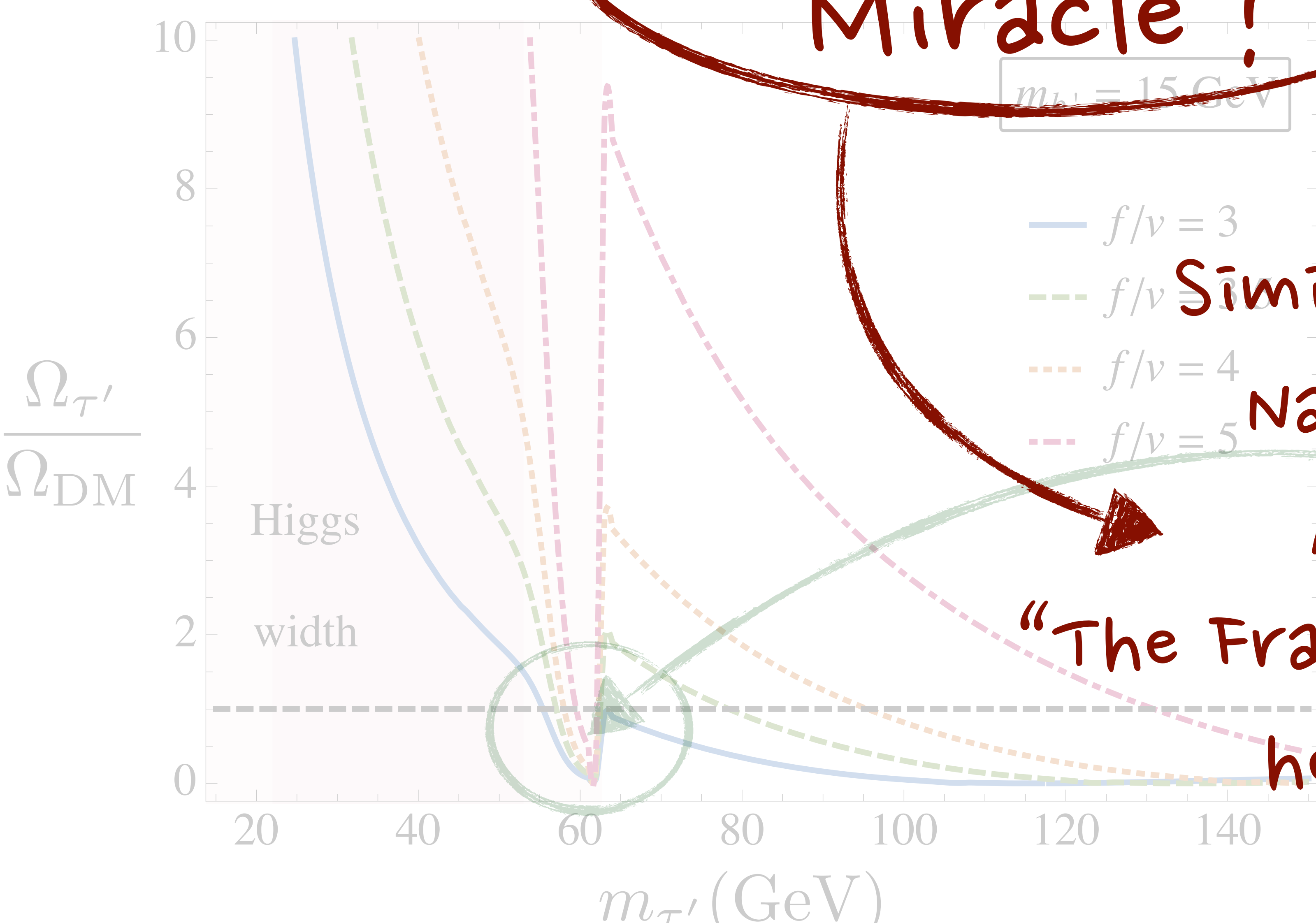





**Twin WIMP Miracle !**

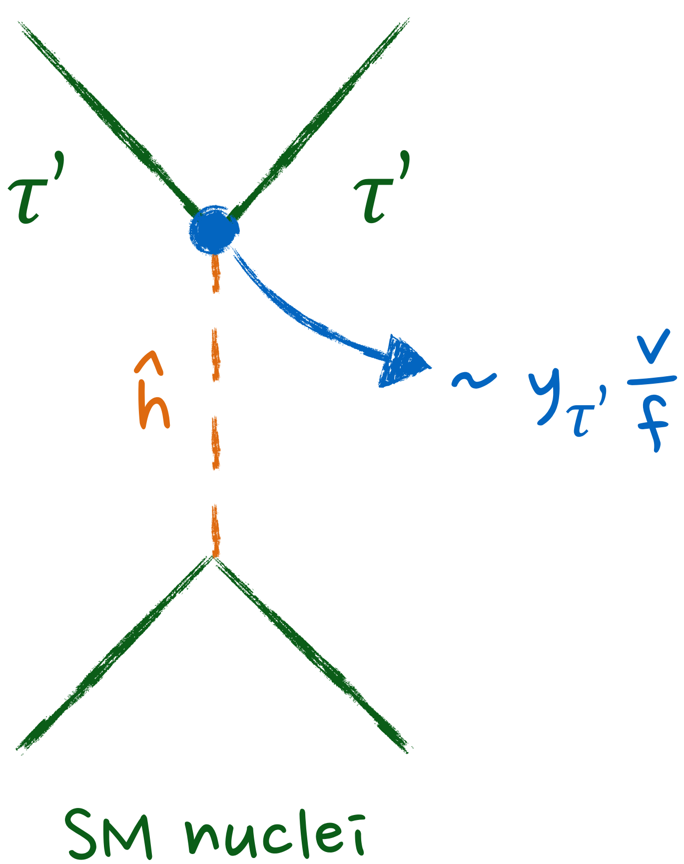
Similar work done by Nathaniel Craig & Andrey Katz:

“The Fraternal WIMP Miracle”

hep-ph/1505.07113

- Twin $\tau$ Dark Matter:

  - Direct Detection: purely Higgs portal.

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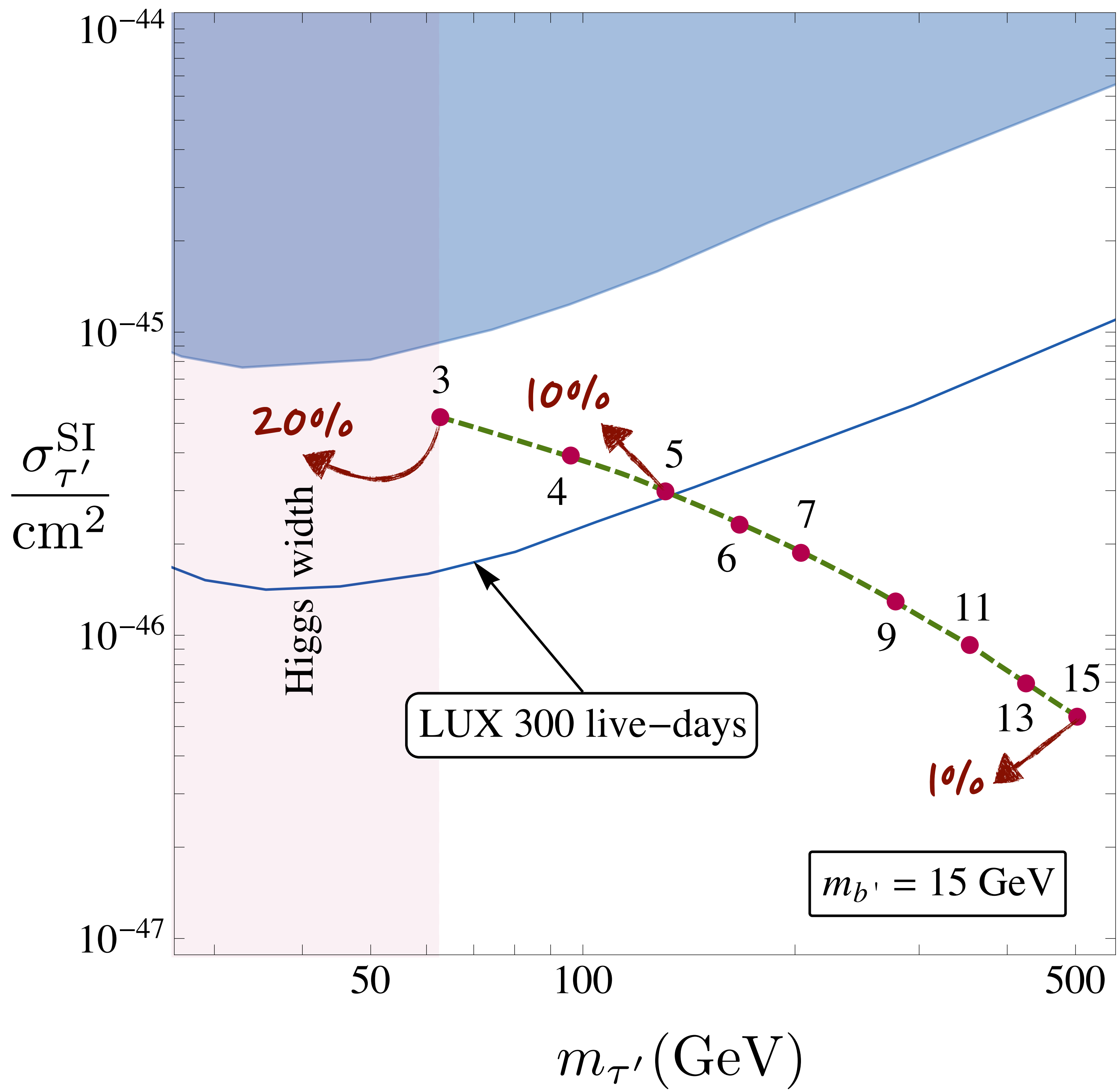

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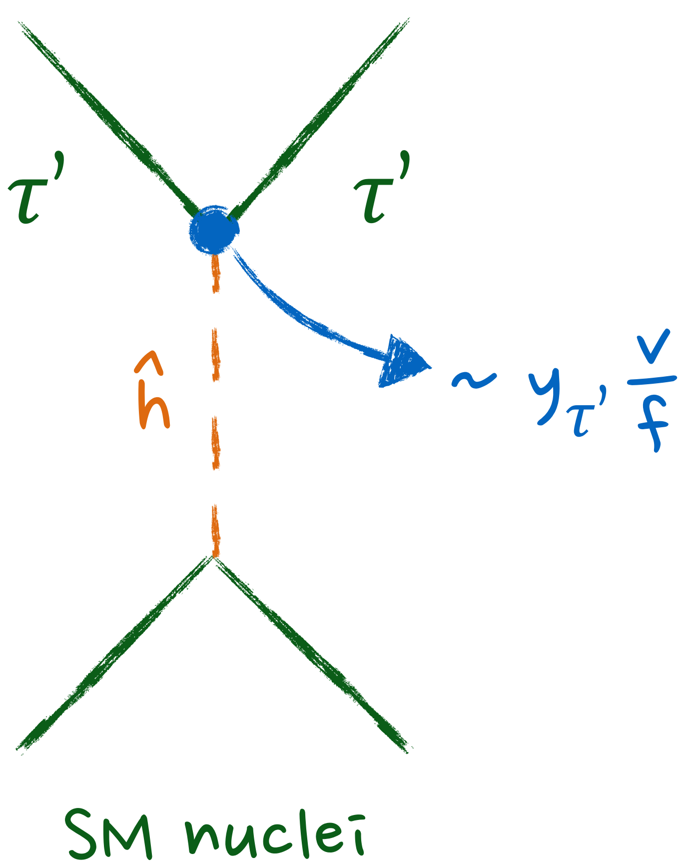


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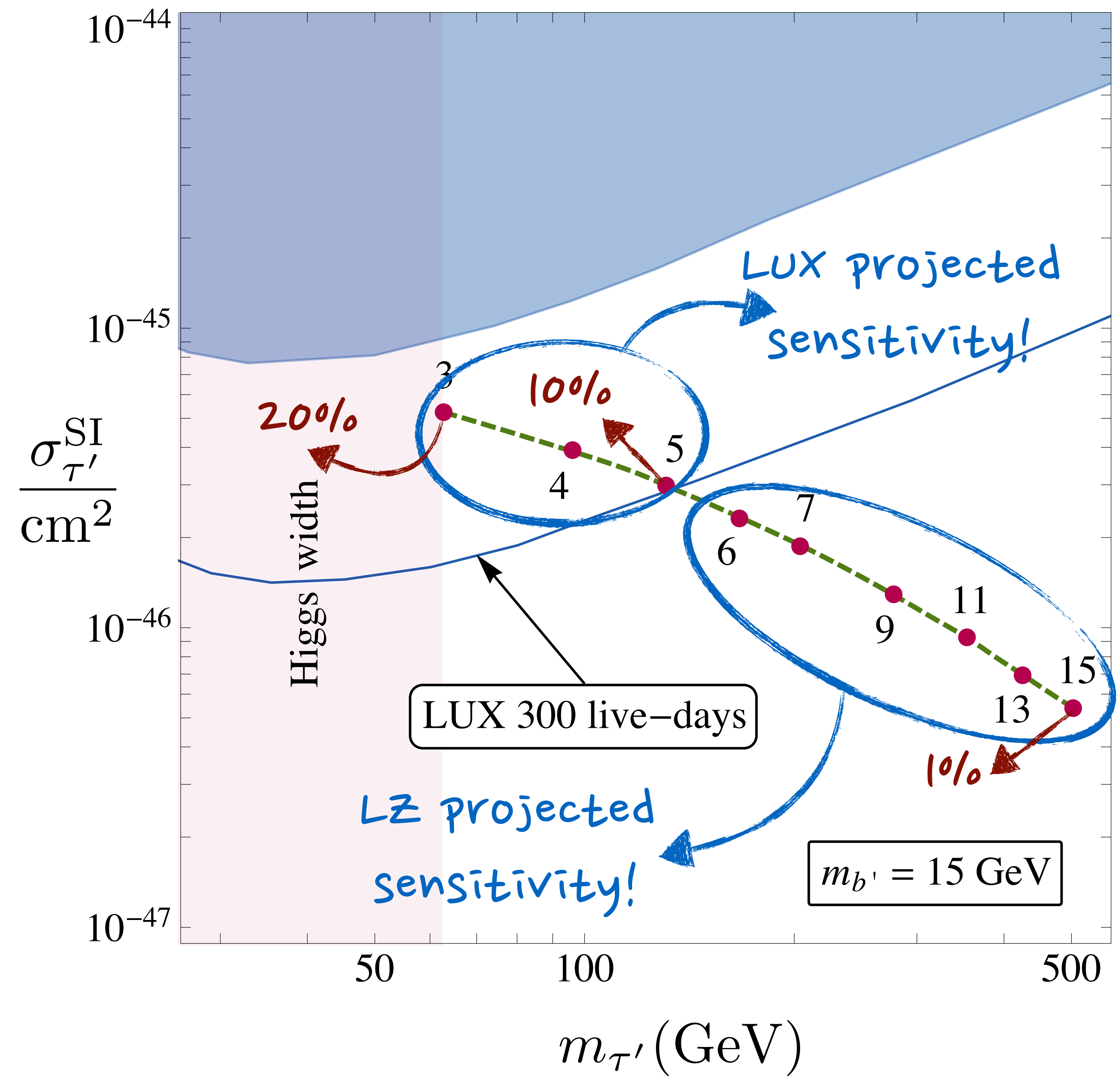

- *Multicomponent* Dark Matter is a very natural possibility

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    2-component DM scenario
    very similar to
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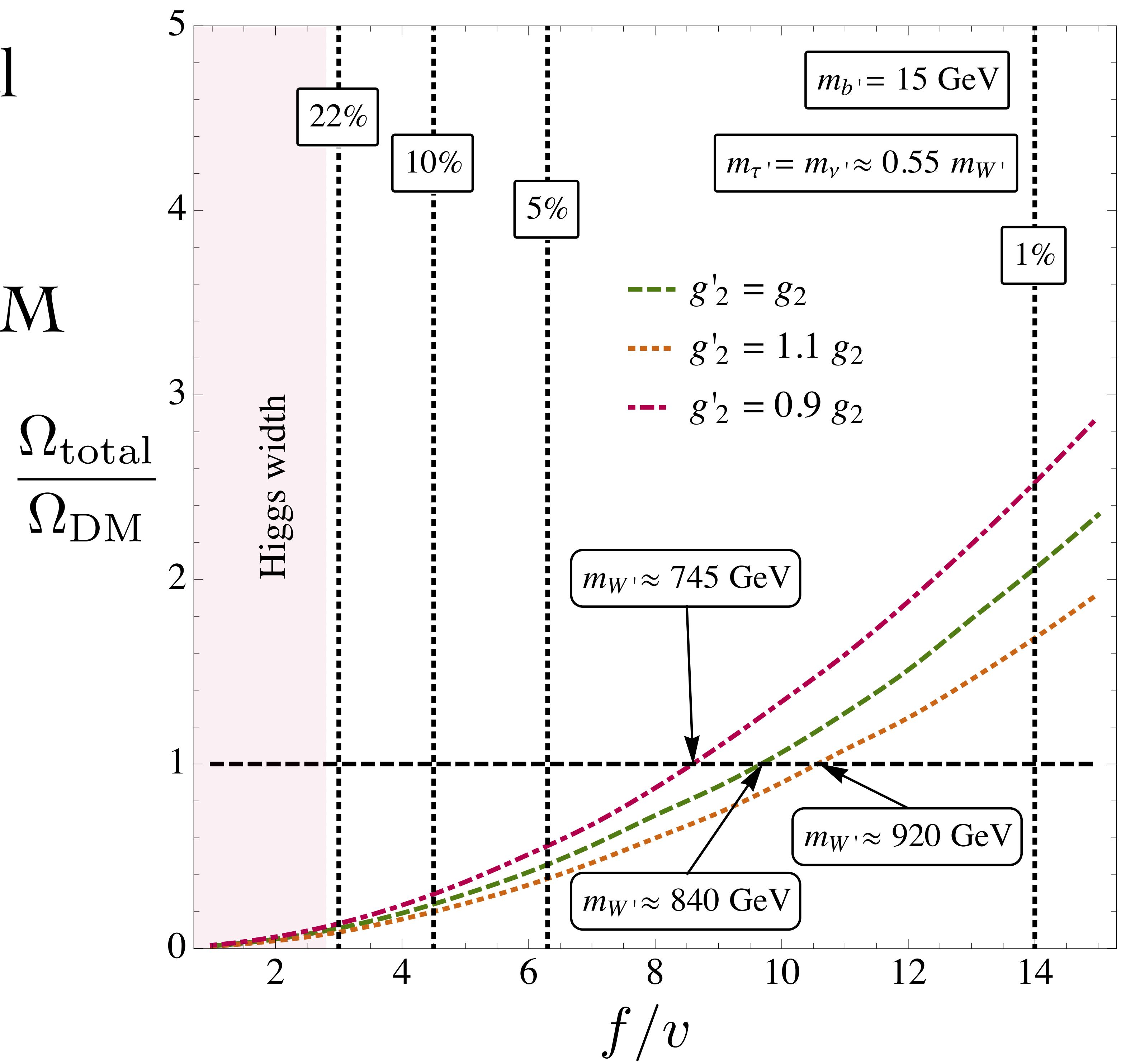
    2-component DM scenario very similar to single-component case ( not very exciting··· )

  - if $m_{\tau'} + m_{\nu'} \gtrsim m_{W'}$

    $\Rightarrow \tau', \nu', W'^{\pm}$ DM

    3-component scenario

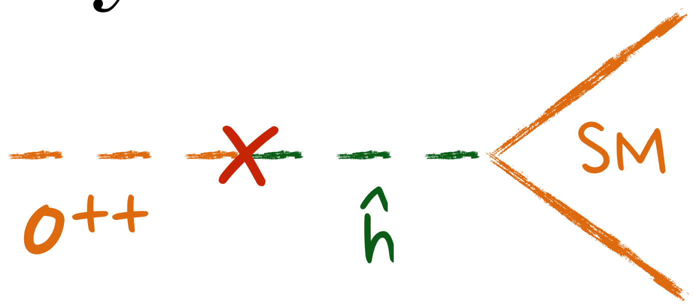
IGG, RL, JMR (hep-ph/1505.07109)

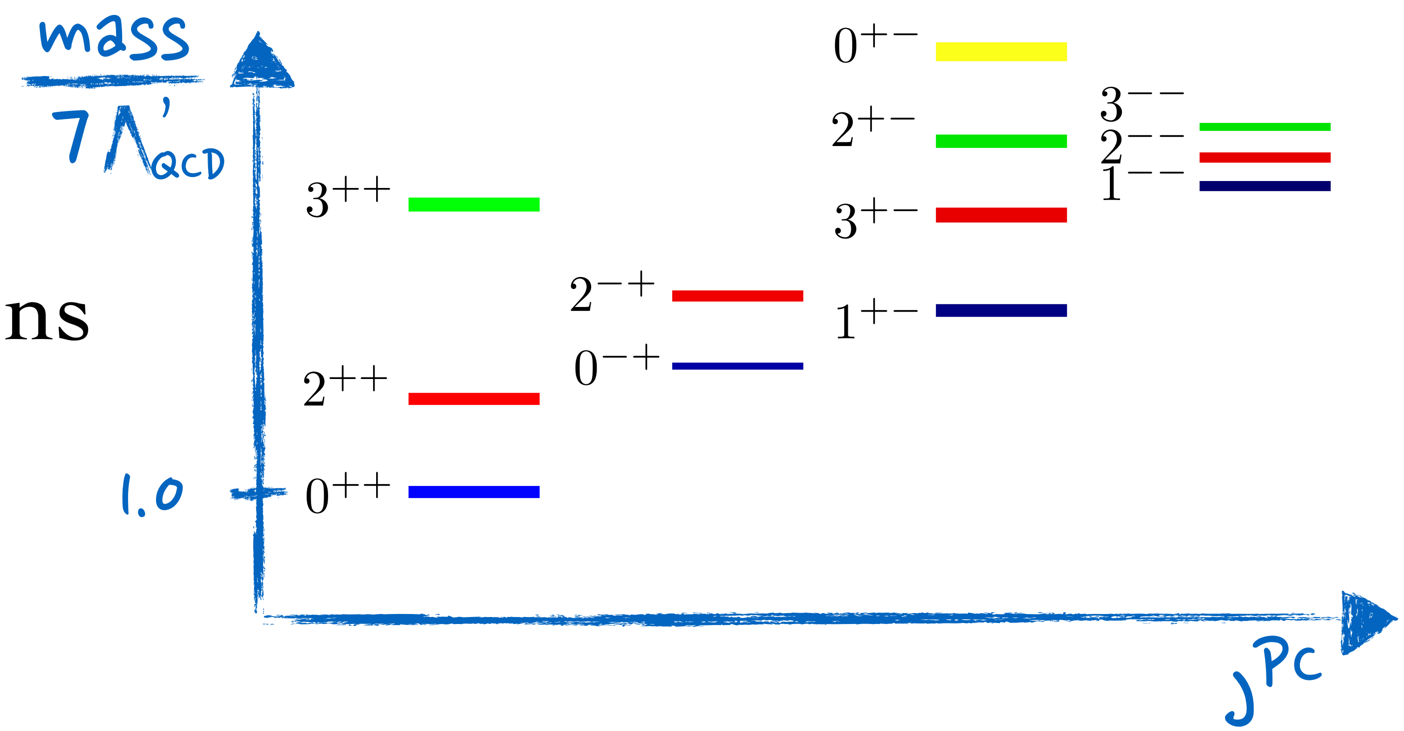



Though tuning is bad··· (large f/v needed)

- Twin glueballs: in the heavy quark limit, lightest twin strong-sector states are glueballs.

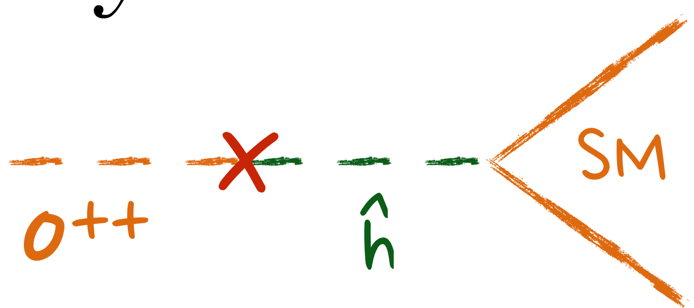
  - lightest twin glueball: If $0^{++} \to \bar{b}'b'$ not allowed kinematically, decay happens mostly to SM states.

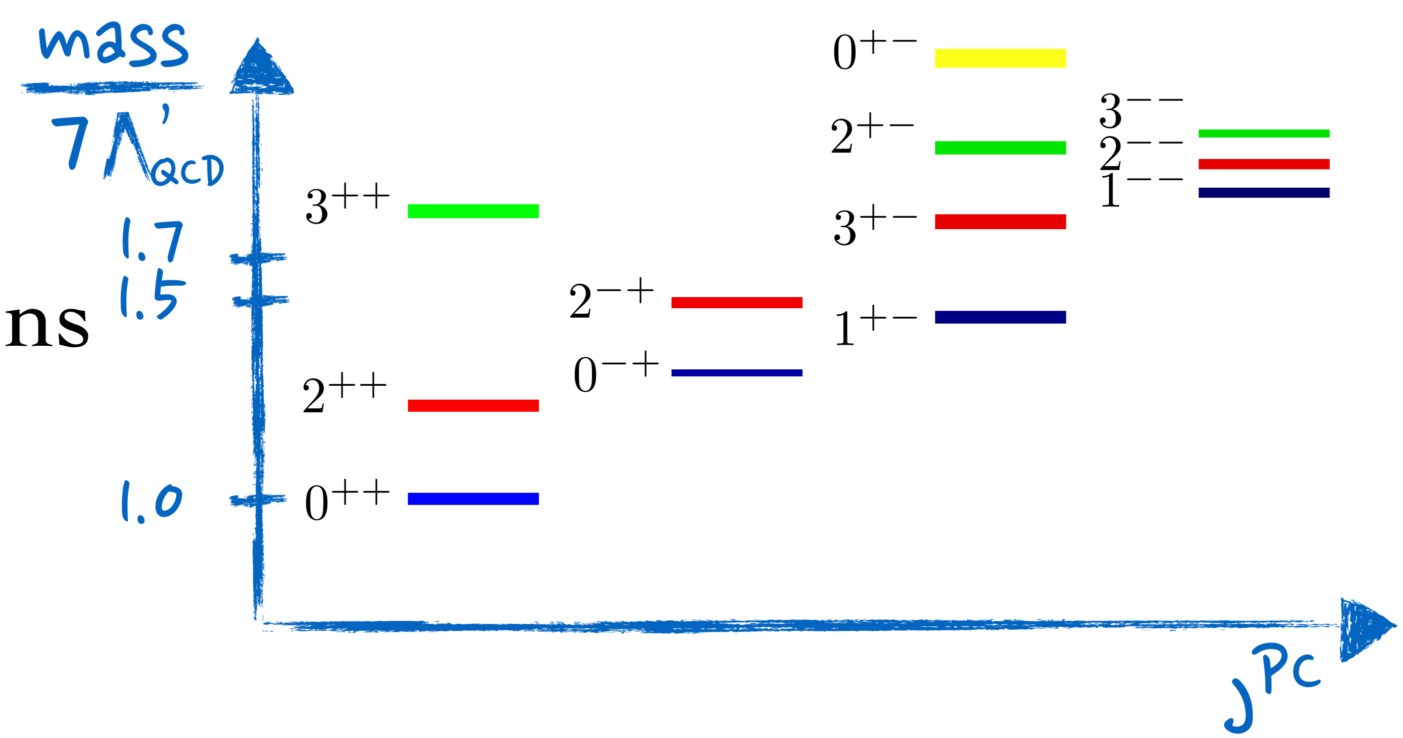


- Twin glueballs: in the heavy quark limit, lightest twin strong-sector states are glueballs

  - lightest twin glueball: If $0^{++} \to \bar{b}'b'$ not allowed kinematically, decay happens mostly to SM states



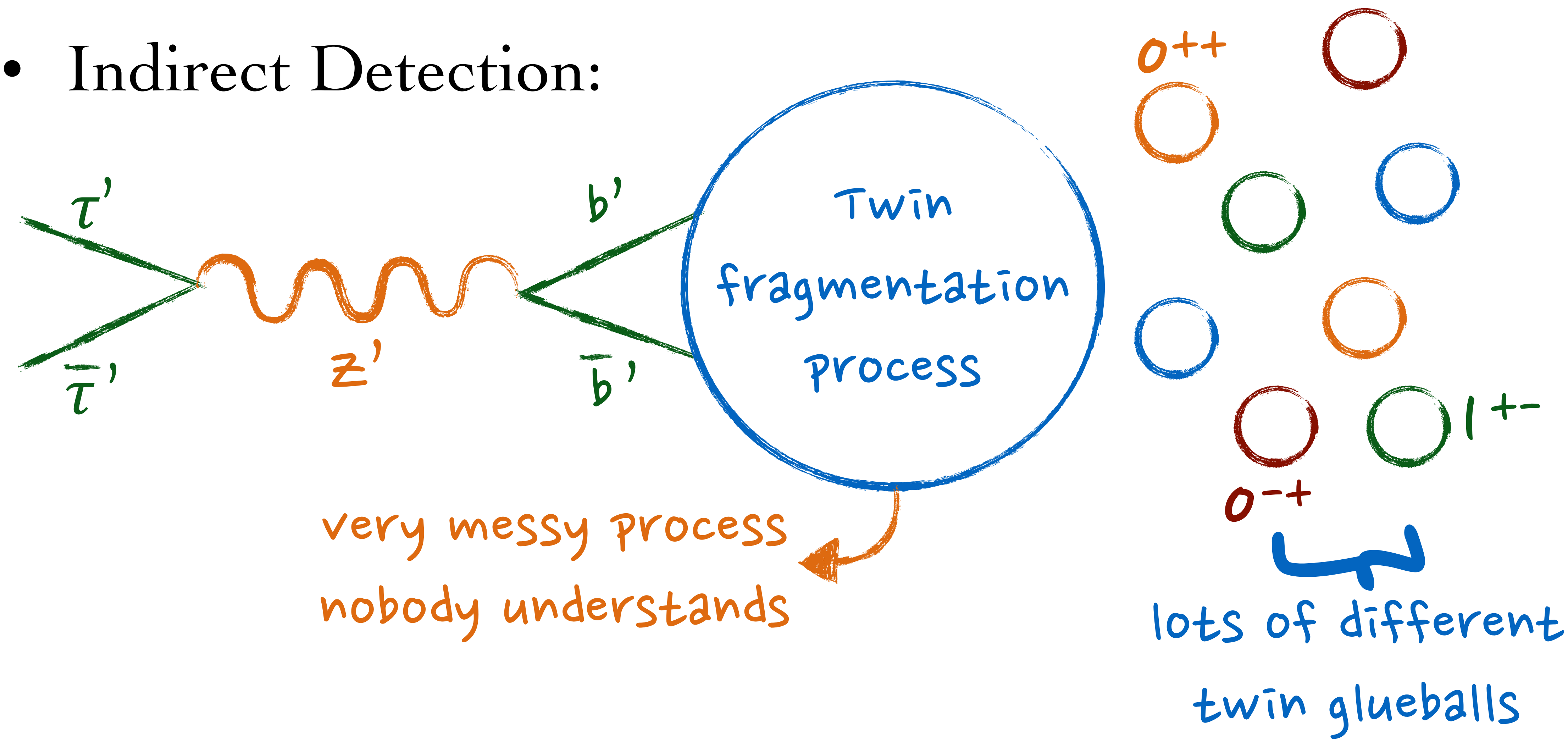

  - if there are no light states in the twin sector, two other glueballs become interesting: $0^{-+}$ and $1^{+-}$

potentially very long lived !

$0^{-+}$ may be cosmologically stable
$1^{+-}$ lifetime depends strongly on $\Lambda'_{QCD}$.

} very UV-dependent

- Indirect Detection:



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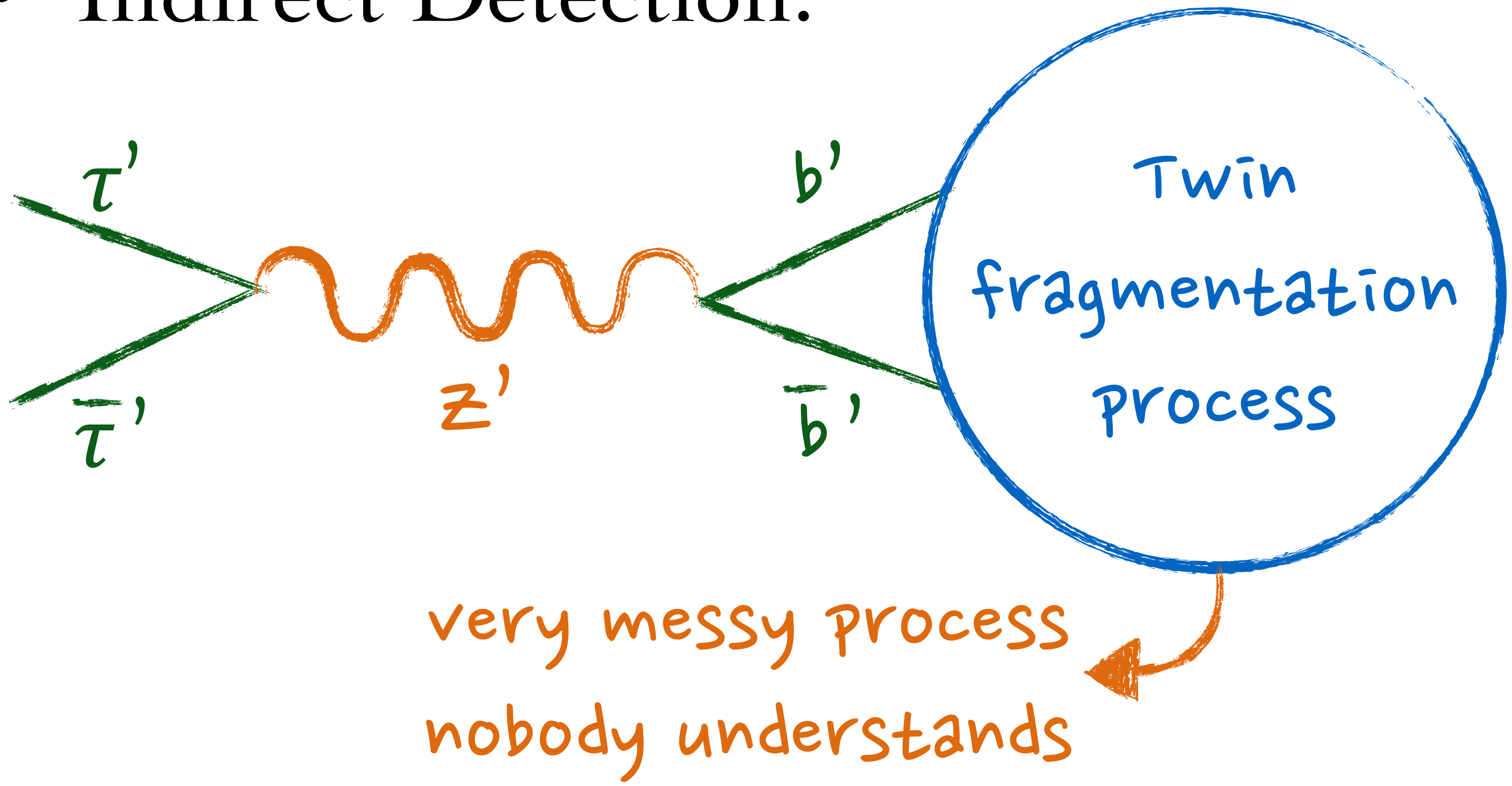
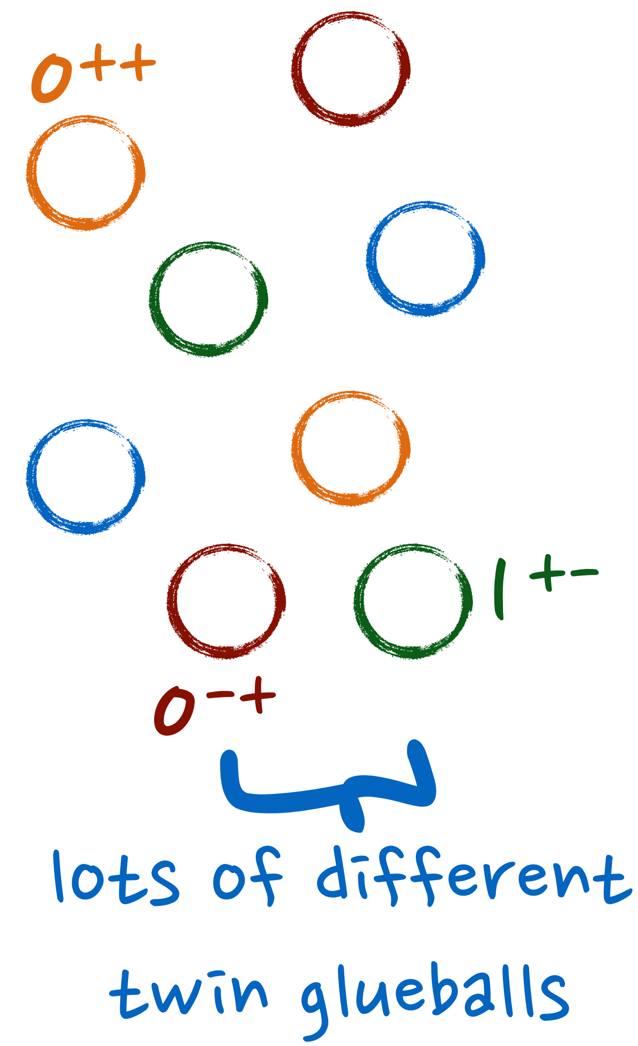



Glueballs will finally decay…

- quickly to $0^{++}$ plus $\bar{\nu}'\nu'$ pairs if $m_{\nu'} \approx 0$

- some metastable states might hang around if there are no light twins ( late decays might provide striking signatures ! )

- $0^{++}$ will decay mostly to $\bar{b}b \Rightarrow$ strongest constraints come from antiproton injection and gamma rays

seems fine with current bounds but better understanding of twin fragmentation needed

# Relativistic DOF?

You might be worried that with light dof in twin sector we have too large changes to $N_{eff}$ (as SM-Twin sectors weakly coupled via Higgs portal)

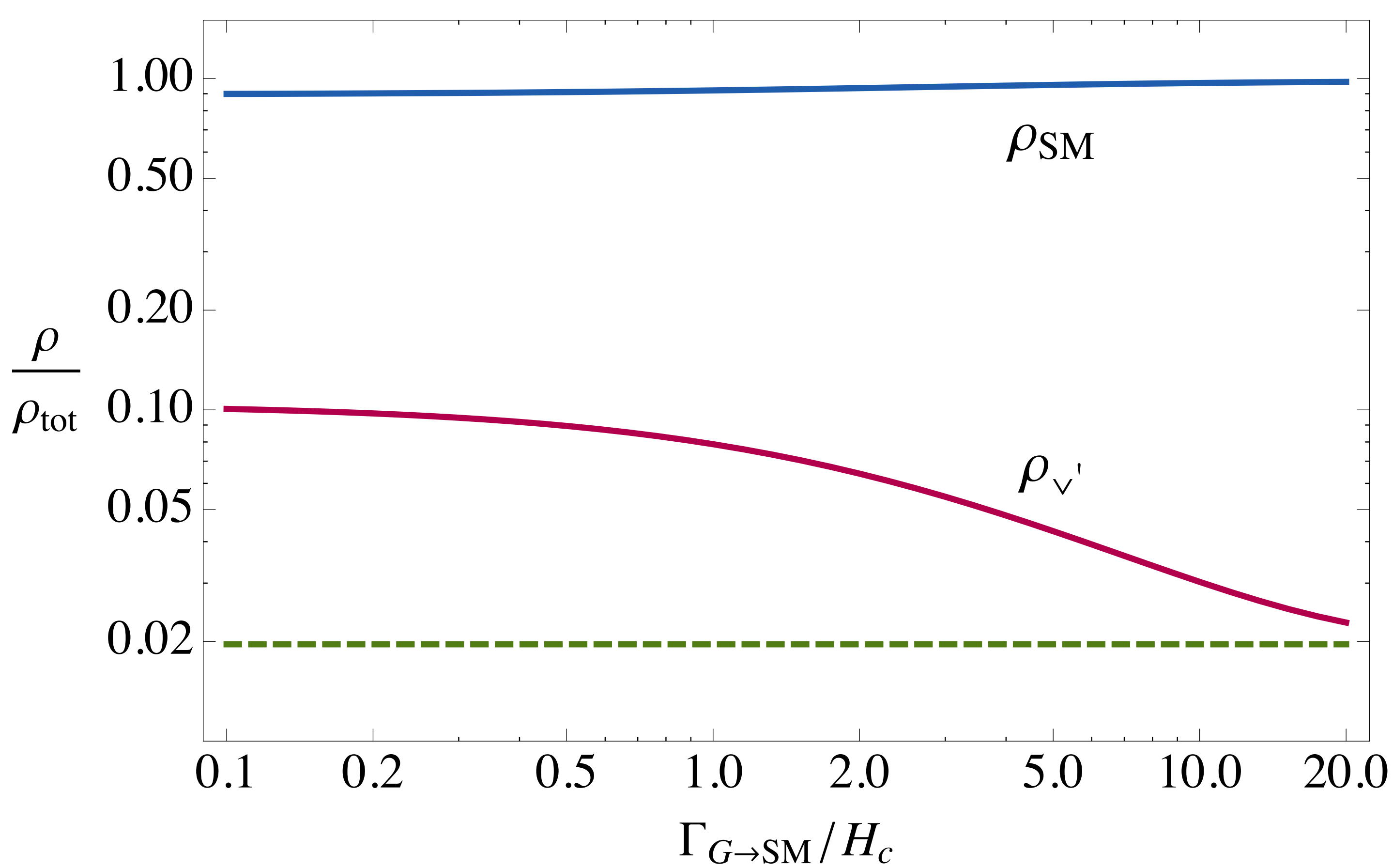
Even if glueball decay rate to light twin dof >> glueball rate to SM as long as glueball rate to SM >> H then re-equilibriate after twin-QCD PT. Requires $\hat{\Lambda}_{QCD} \geq 2.5$ GeV if f/v~3

$$\Gamma_{0^{++}\to SM} \simeq 10^{-9}\,\mathrm{eV}\left(\frac{m_0}{7\,\mathrm{GeV}}\right)^7\left(\frac{750\,\mathrm{GeV}}{f}\right)^4$$

$$H \simeq 10^{-9}\mathrm{eV}\left(\frac{T}{\mathrm{GeV}}\right)^2$$

$$\Delta N_{eff} \geq 0.075$$

( minimum possible from single light twin neutrino )



# Twin Asymmetric DM

IGG, RL, JMR (hep-ph/1505.07410)

- Asymmetric DM: tries to explain why $\Omega_{\rm DM}/\Omega_{\rm baryon} \approx 5$ by assuming a non-zero asymmetry in the DM sector.

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm baryon}} \approx \frac{m_{\rm DM}}{m_N}\frac{\eta_{\rm DM}}{\eta_{\rm baryon}}$$

A model with $m_{\rm DM} \sim m_N$ and $|\eta_{\rm DM}| \sim |\eta_{\rm baryon}|$ naturally explains the $\mathcal{O}(1)$ ratio of energy densities.

Important that symmetric component annihilates very efficiently, so that final DM abundance is mostly set by the asymmetry

- Twin Baryon Asymmetric DM:

  - We consider the case where only the twin baryon $\Delta' \sim b'b'b'$ is affected by the asymmetry, which can be achieved if $\eta_{B'} \approx -\eta_{Q'} \neq 0$ and $m_{\nu'} \approx 0$ .

  - Concentrate on light quark limit: $m_{b'} \ll \Lambda'_{\rm QCD} \Rightarrow$ twin hadron masses set by $\Lambda'_{\rm QCD}$ and spectrum of quarkonia is lighter than glueballs.

$$\left\{\begin{array}{l}\hat{\eta} \text{ with } m_{\hat{\eta}} \approx 2\Lambda'_{\rm QCD} \\ \hat{\chi} \text{ with } m_{\hat{\chi}} \approx 3\Lambda'_{\rm QCD} \\ \Delta' \text{ with } m_{\Delta'} \approx 5\Lambda'_{\rm QCD} \sim \mathcal{O}(1-10) \text{ GeV}\end{array}\right.$$

$\hat{\eta}$ → pseudoscalar

$\hat{\chi}$ → scalar

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$\hat{\eta}$ with $m_{\hat{\eta}} \approx 2\Lambda'_{\rm QCD}$ → pseudoscalar

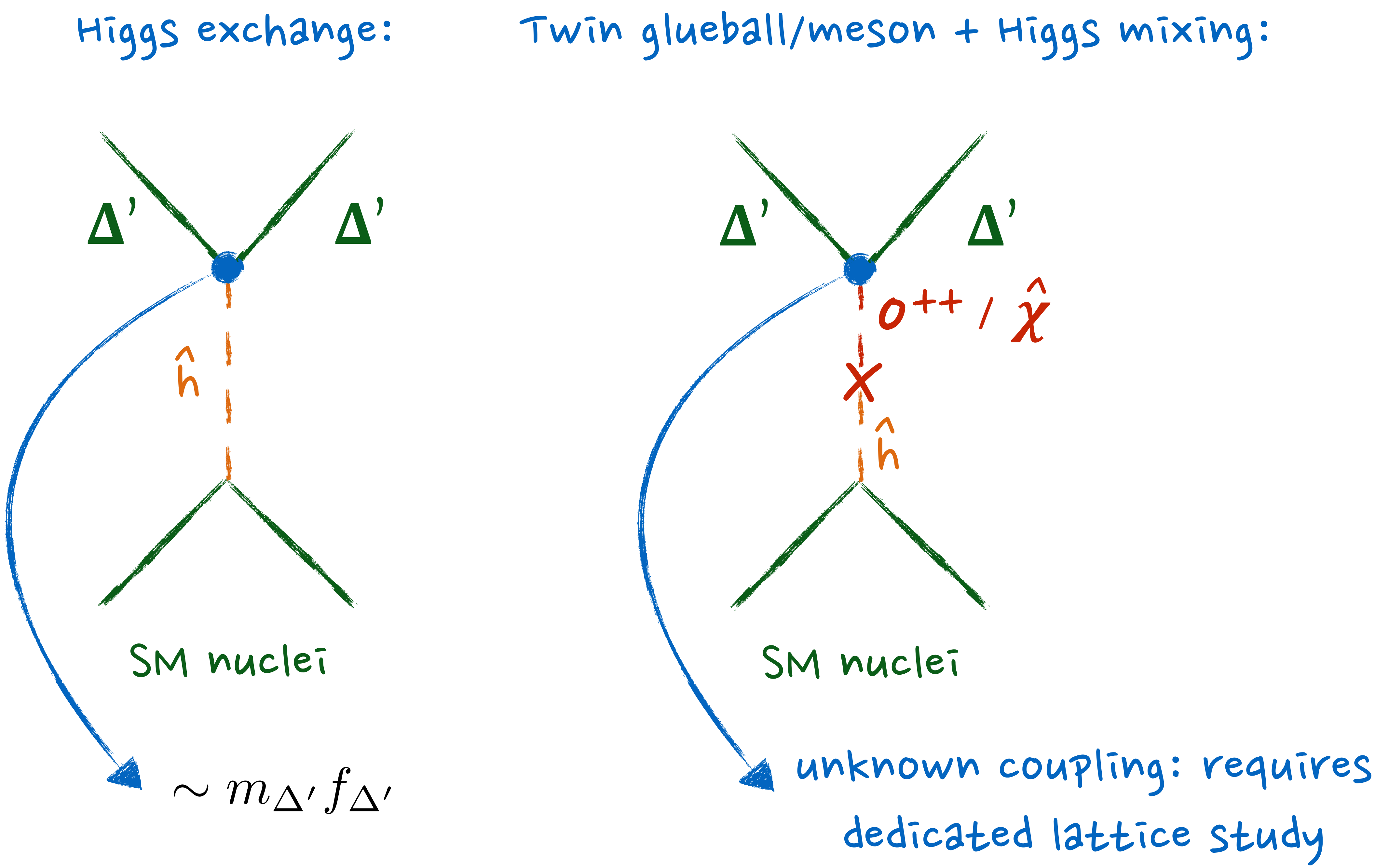
$\hat{\chi}$ with $m_{\hat{\chi}} \approx 3\Lambda'_{\rm QCD}$ → scalar

$\Delta'$ with $m_{\Delta'} \approx 5\Lambda'_{\rm QCD} \sim \mathcal{O}(1-10)$ GeV

attractive ADM mass that is set by twin confinement scale

- Direct Detection:

Scattering off SM nuclei happens via Higgs portal.



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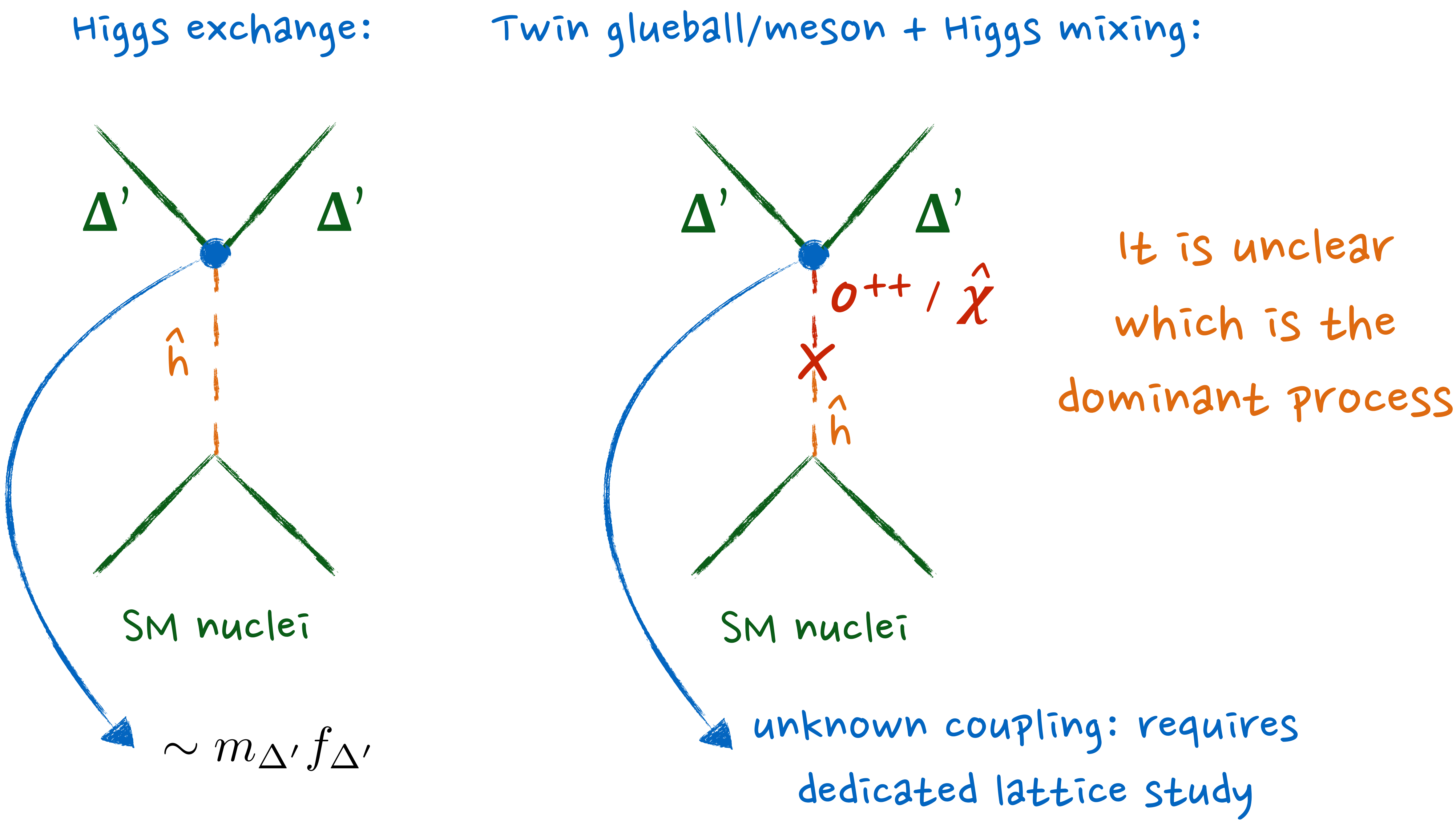
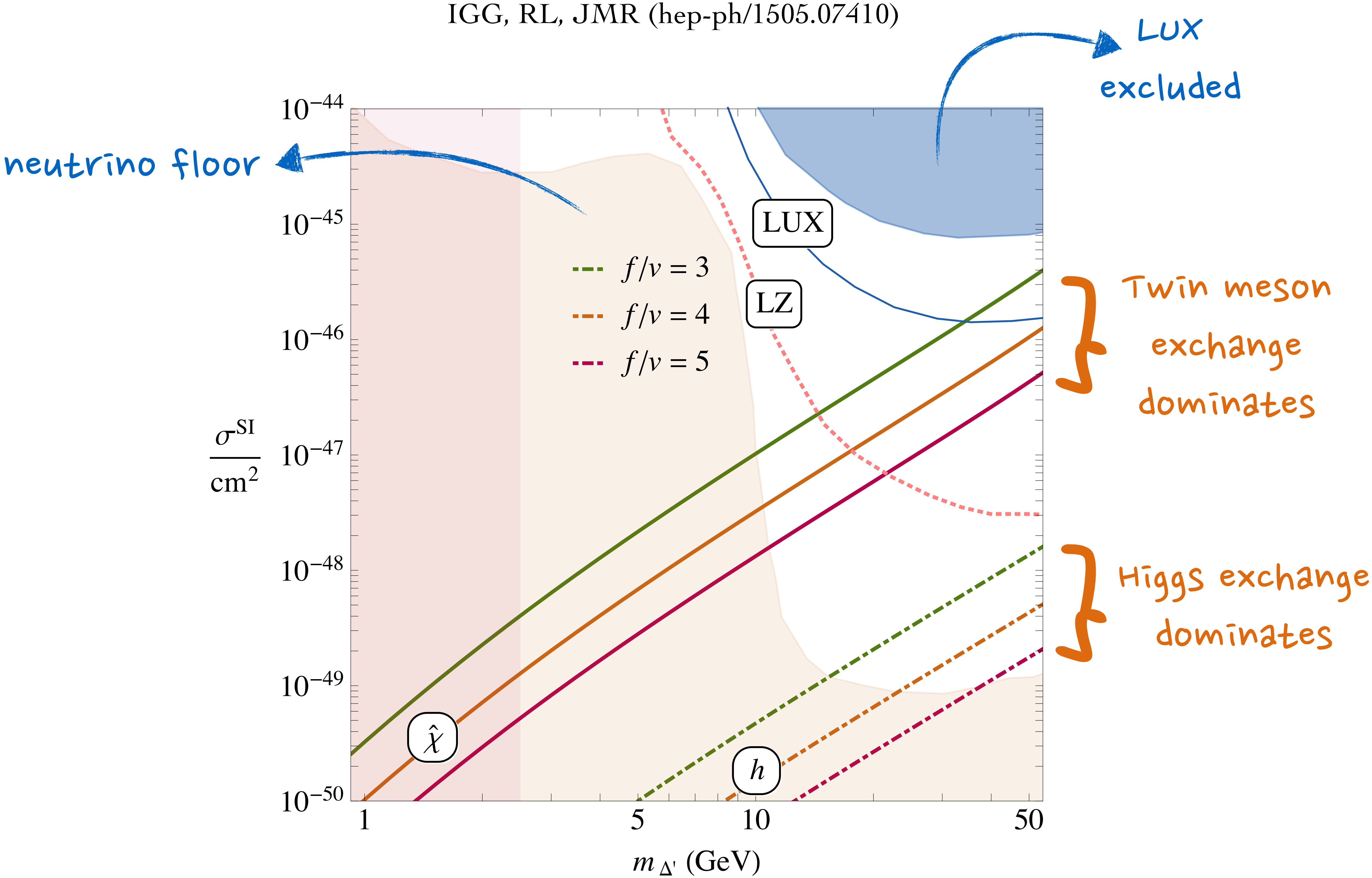


IGG, RL, JMR (hep-ph/1505.07410)




(twin baryon - twin meson coupling: $\lambda = 4\pi$ )

- Natural modification: gauged *U(1)'*

Physics changes a lot

- Neutrality of the Universe under twin electromagnetic charge requires $\eta_{Q'} = 0$

$\Rightarrow$ Asymmetric population of $\Delta'$ needs to be compensated by an equal population of $\bar{\tau}'$

- $\Delta'$ - $\bar{\tau}'$ form bound states

twin atoms

In fact, they'd better form atoms: DM in plasma form is very constrained from plasma instability effects

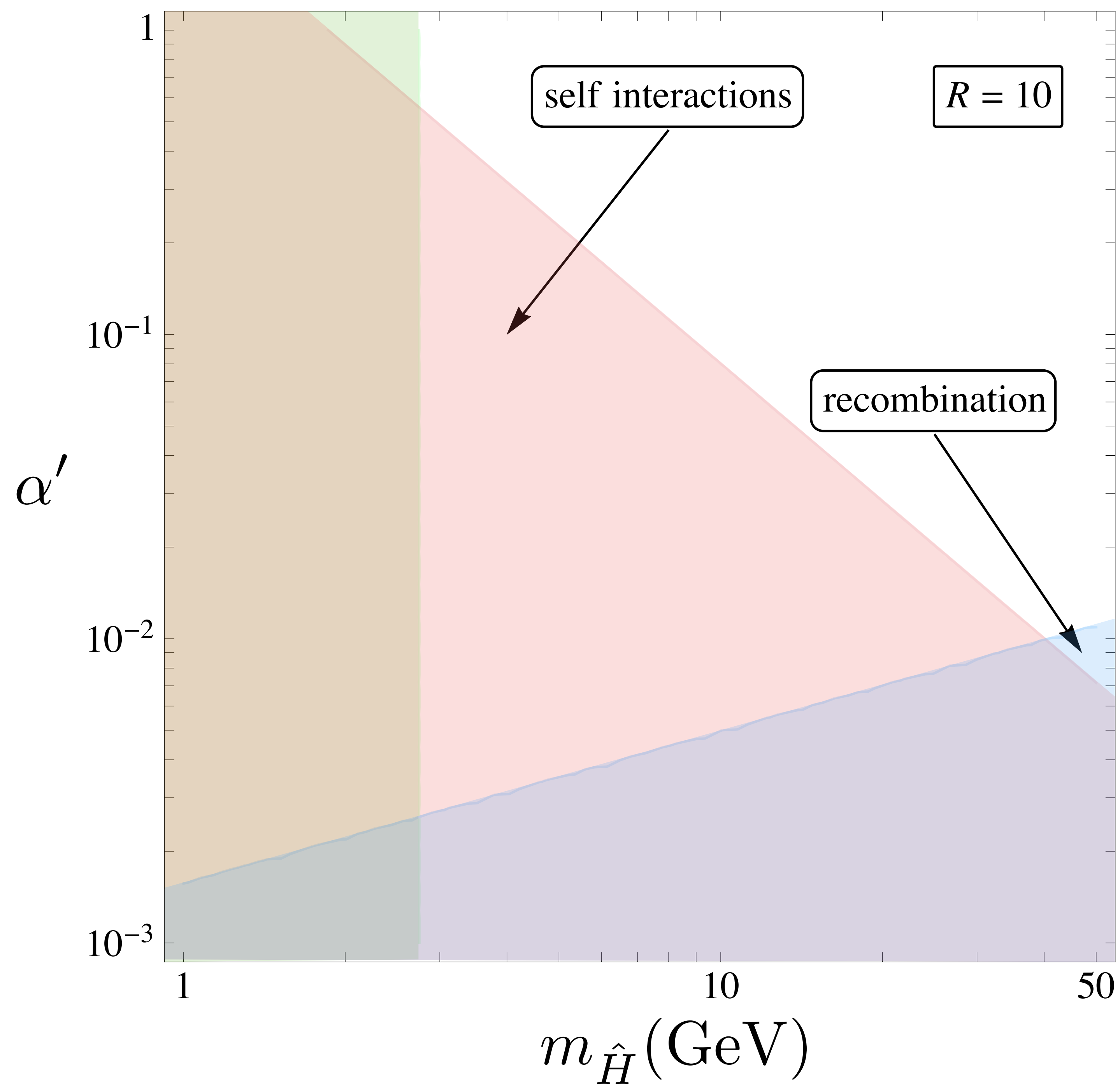
- Constraints on Twin Atom DM:

  - Sufficient recombination

    so that there is little plasma left

  - DM self-interactions

IGG, RL, JMR (hep-ph/1505.07410)




In the allowed region of parameter space, annihilation of the symmetric components happen very efficiently (even for light $\tau'$)

- Direct Detection:

  - Via Higgs portal interactions, very similar to twin baryon DM

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  - Via Higgs portal interactions, very similar to twin baryon DM

- Kinetic Mixing:

  Twin and visible sector photons are massless and it is possible to have a term

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

$\Rightarrow$ twins pick up charges $\sim \epsilon e'$ , but atoms are neutral and have zero electric dipole moments

magnetic dipole moments will provide the leading constraint

Moreover, radiative contributions to $\epsilon$ absent up to 3 loop order: at most, expect $\epsilon \sim \mathcal{O}(10^{-9})$

seems totally OK with current bounds

# Twin Nuclear DM?

In just 3rd generation case don't form significant di-B and beyond as even with photon present the radiative capture rate too slow (both M1 and E1 processes zero by fact that B is only (semi-)stable nucleon)

Can get twin nuclear DM — possibly with large nucleon number A if turn back on 2nd generation with now both "p" and "n" like states (if $m_p > m_n$ so that p eventually decays to n + twin leptons no Coulomb barrier at large A, and no dark atoms either)

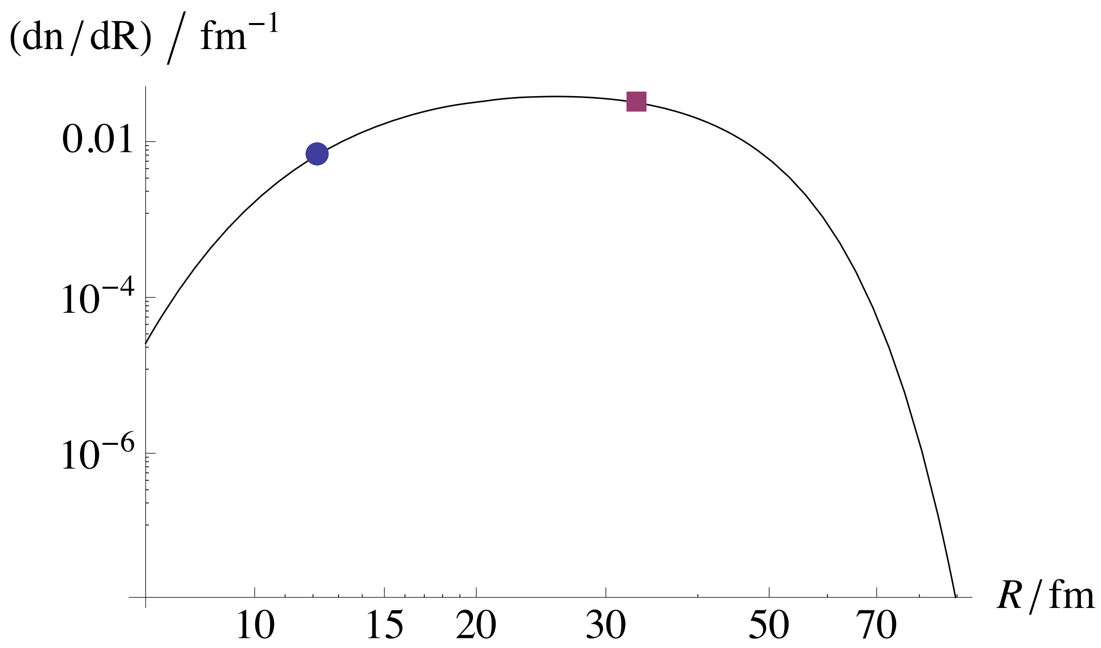
# Twin Nuclear DM

Comment: Get all the attractiveness of ADM with $m_B = 5$GeV without having halo DM states actually at mass 5GeV. They can have much bigger mass Ax5GeV with baryon number A (potentially changes DD region/pheno a lot)

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

This would still be true with $\eta_X = \eta_B$

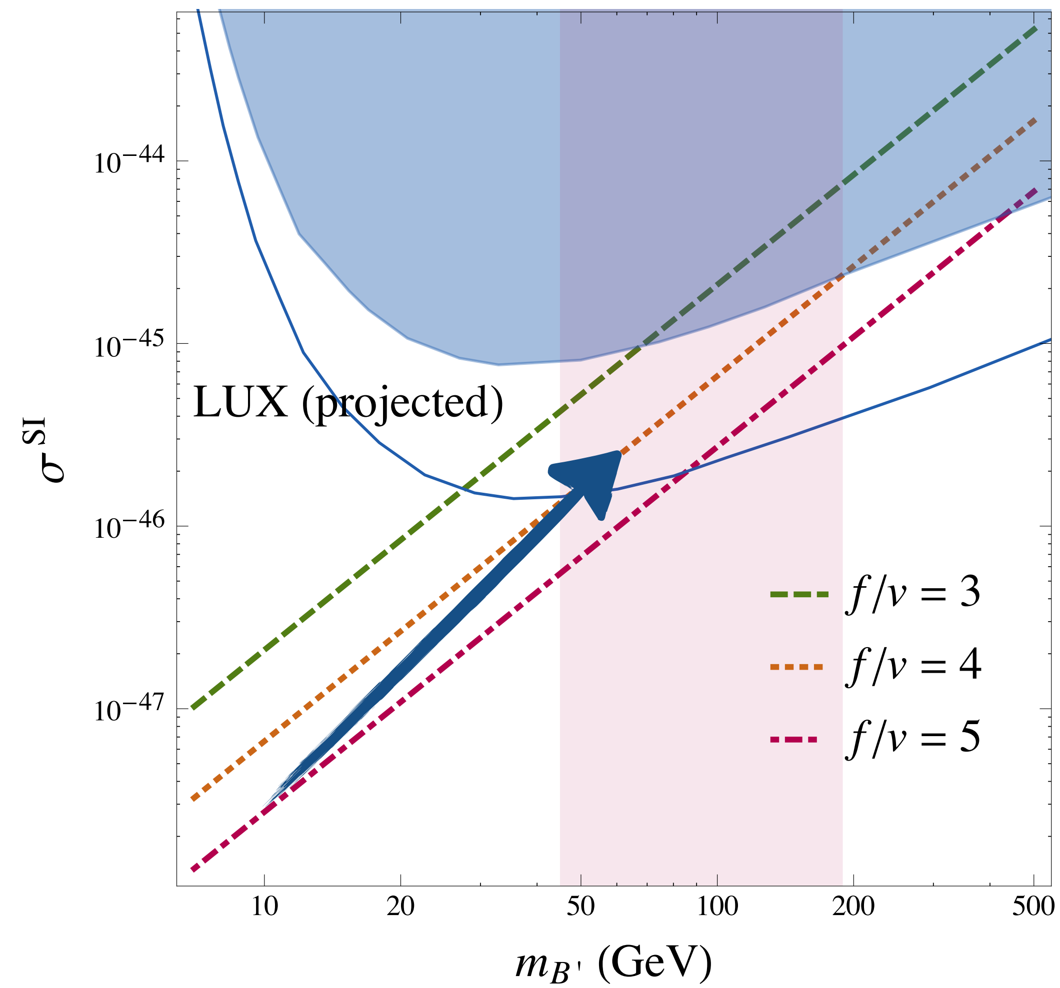
Note: example of dark-sector BBN result for number dist'n



# Twin Nuclear DM

If get through bottleneck region at small A number then can potentially build up large nuclei. Interesting case for us is A~10

Such large-A, and thus spatially extended, dark nuclei have effective coherent enhancement of DD cross section by $A^2$ (but more massive by A)




Can effectively move DD signal to higher mass and cross section even if $m_B$=5GeV

# Twin Dark Matter

## comments

When you twin the SM there are (unsurprisingly) a huge range of possibilities for stable states with rich dynamics (variety of WIMP's but also nucleon DM, atomic DM, nuclear DM, meson DM, spin 1 DM,$\cdots$)

In many parts of parameter space the DM is a multi-component cocktail. Sub-dominant parts can be interesting (halo dynamics, late decays & BBN, spectrum of states in direct or indirect detection, inelasticity,$\cdots$)

Higgs portal gives definite and very interesting predictions for DD and ID signals even in most minimal vanilla cases

# Conclusions

- Theories based on the Twin Higgs mechanism have very rich physics

even richer as soon as you add more generations

e.g. M. Farina hep-ph/1506.03520

IGG, RL, JMR…

- Lots of things left to do

uv completion

twin hadronisation

better understanding of twin phase transition

???…