Probing dark matter above TeV and below meV

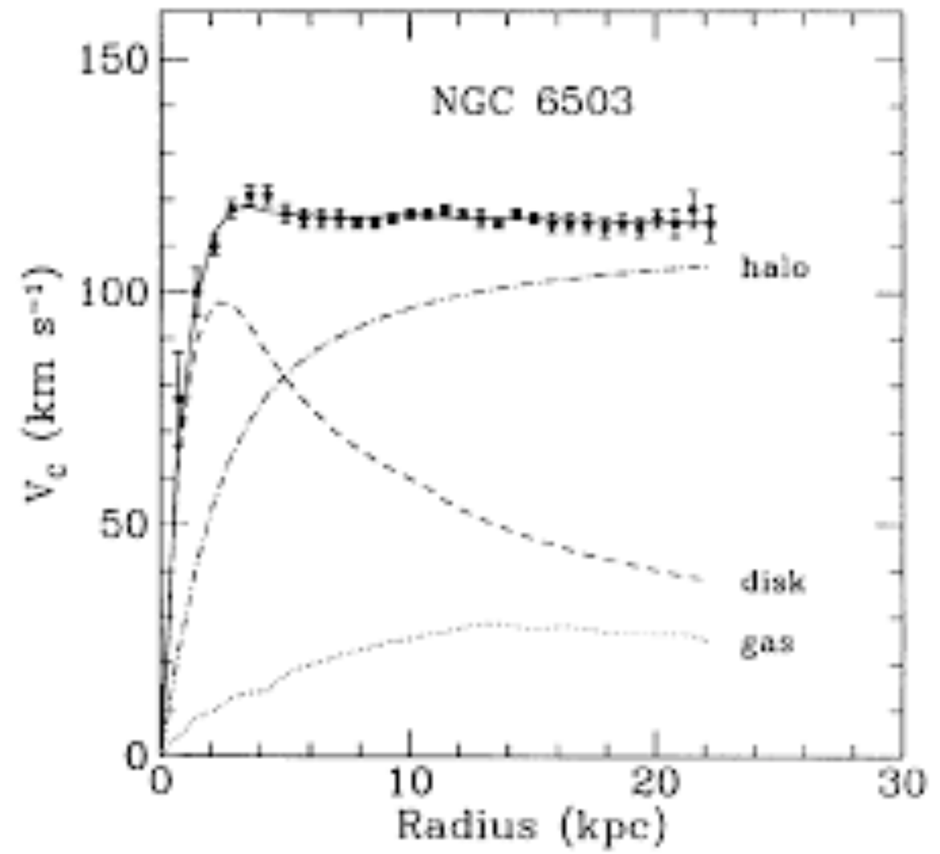
Giovanni Grilli di Cortona

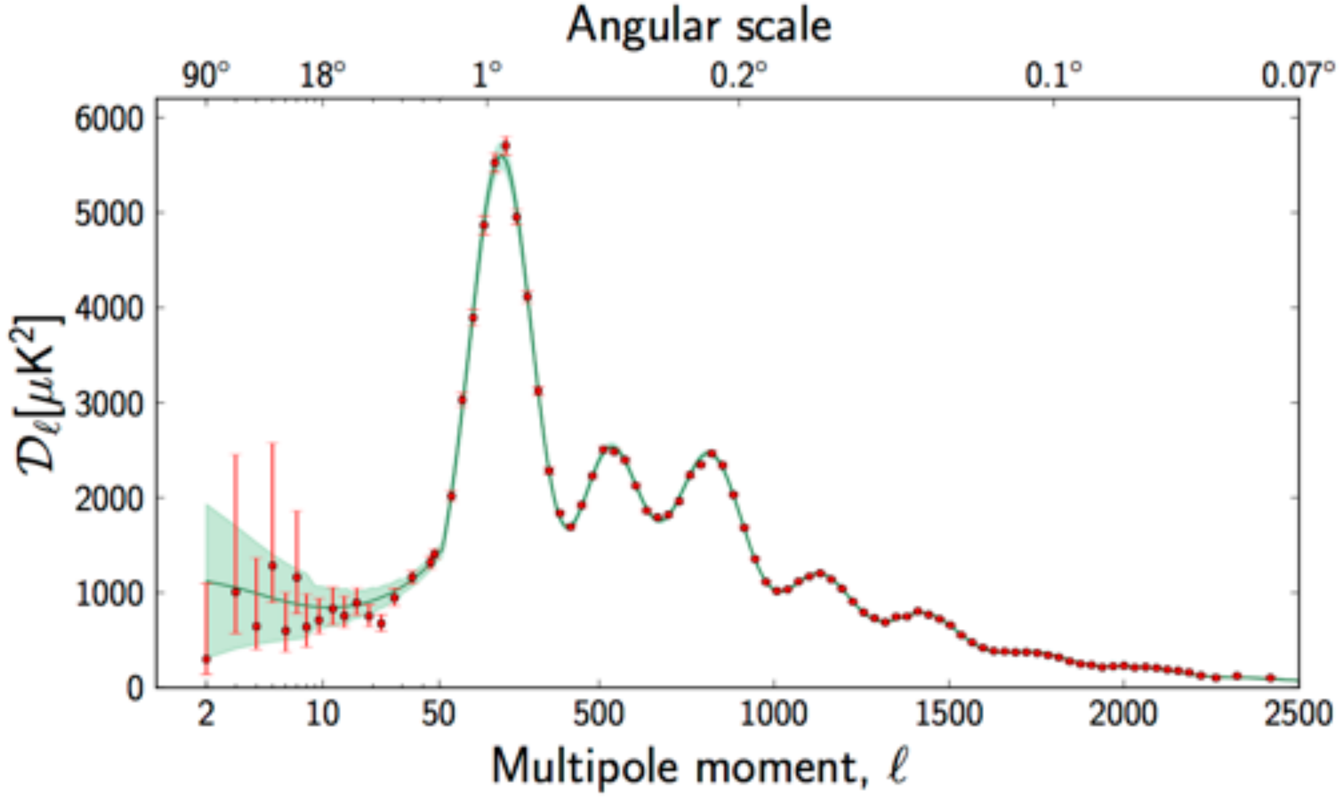
based on:
- JHEP 1505(2015)035 (arXiv: 1412.5952)
- work in progress with E. Hardy, J. Pardo Vega and G. Villadoro

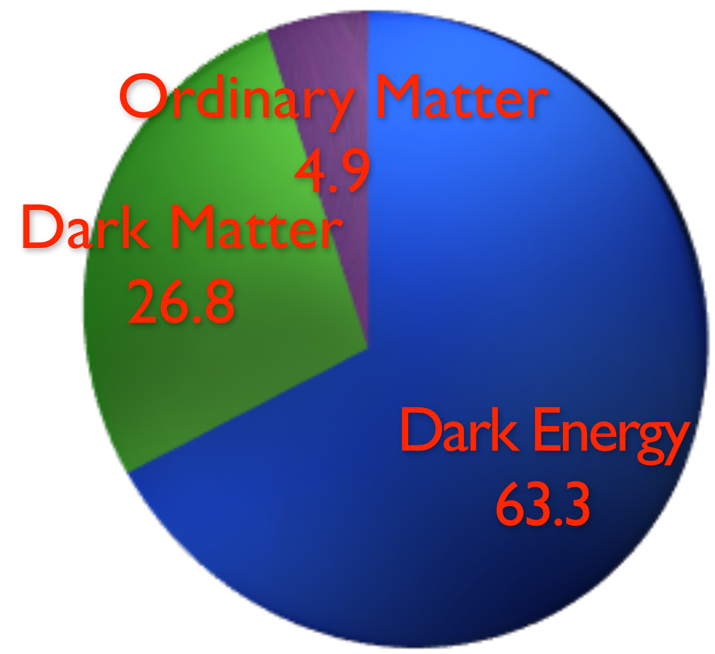
INFN Istituto Nazionale di Fisica Nucleare

ma per seguir virtute e canoscenza
SISSA

Evidences for dark matter







Dark matter candidates

DM properties:

- stable
- electrical and color neutral
- not relativistic today -> Cold DM
- collision-less

several candidates:

WIMPs gravitino

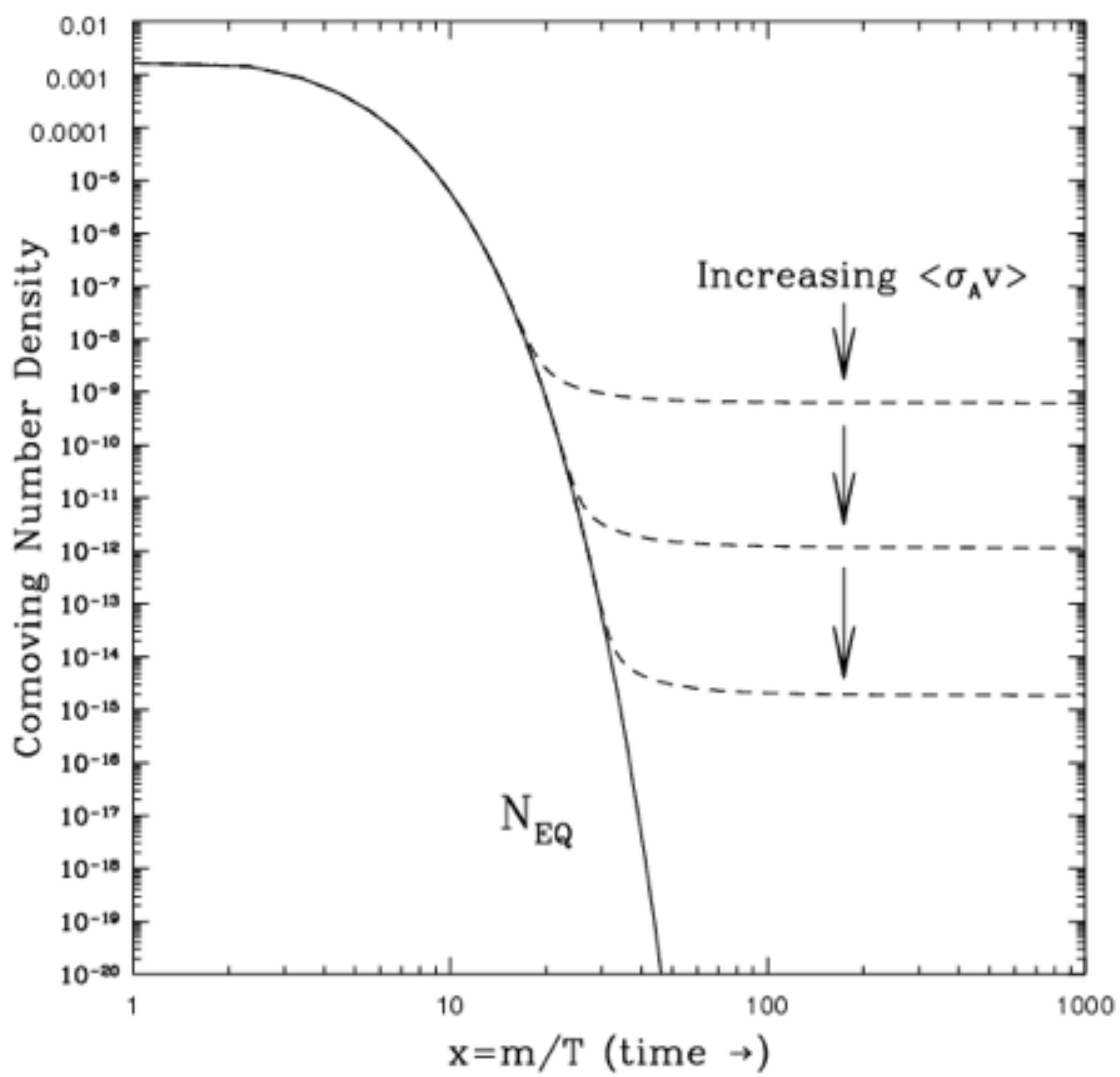
axino axion ...

Outline

- TeV dark matter: split SUSY
  - Motivations
  - Anomaly mediation
  - Universal gaugino masses
- meV dark matter: QCD axion
  - Motivations
  - Axion properties
- Conclusions

Above the TeV...

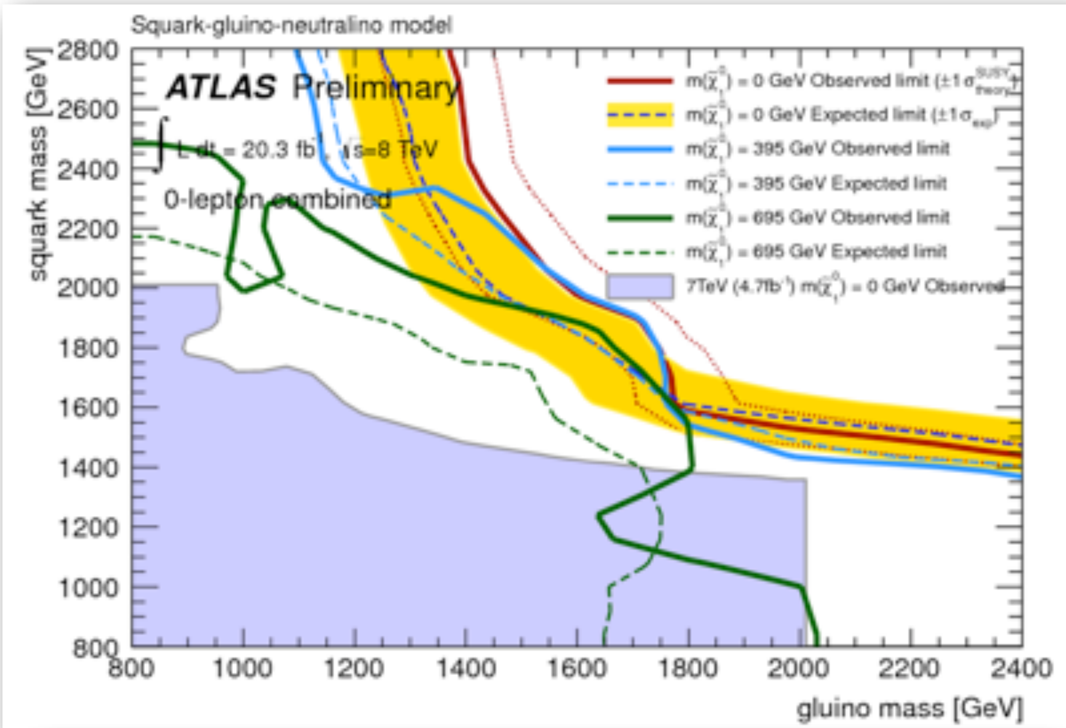
Dark matter relic density: WIMP

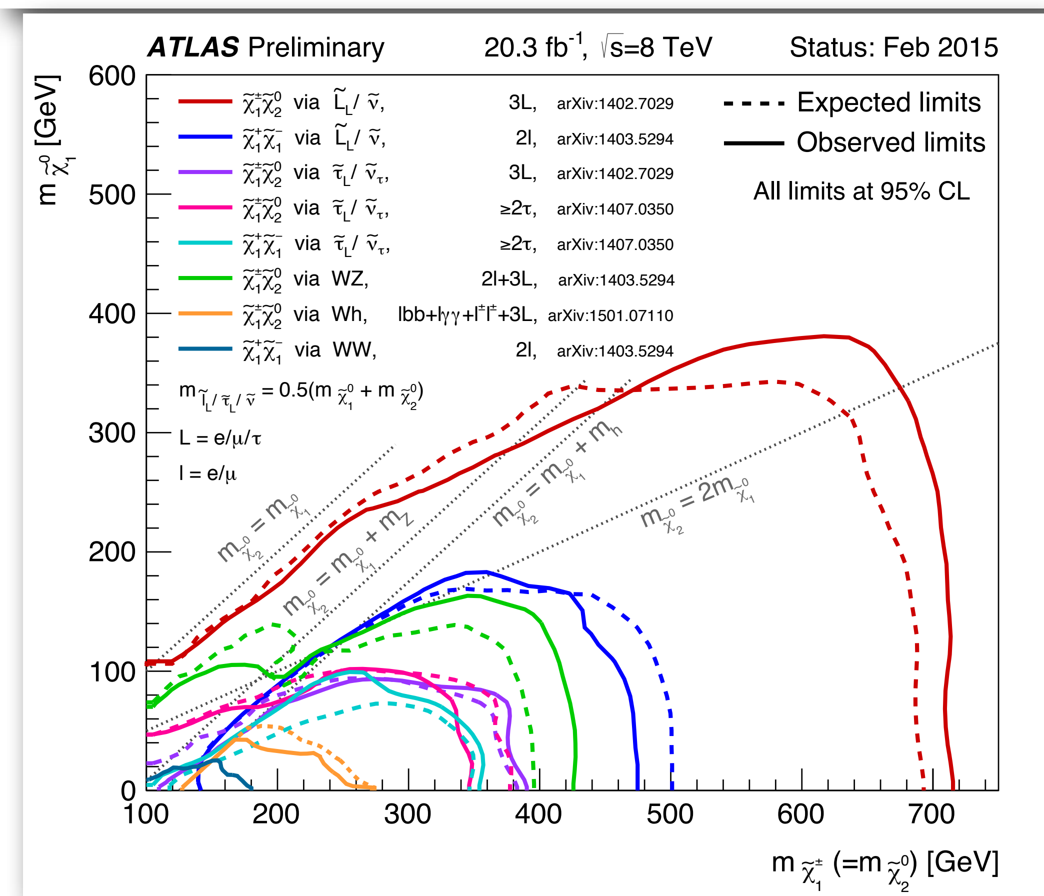


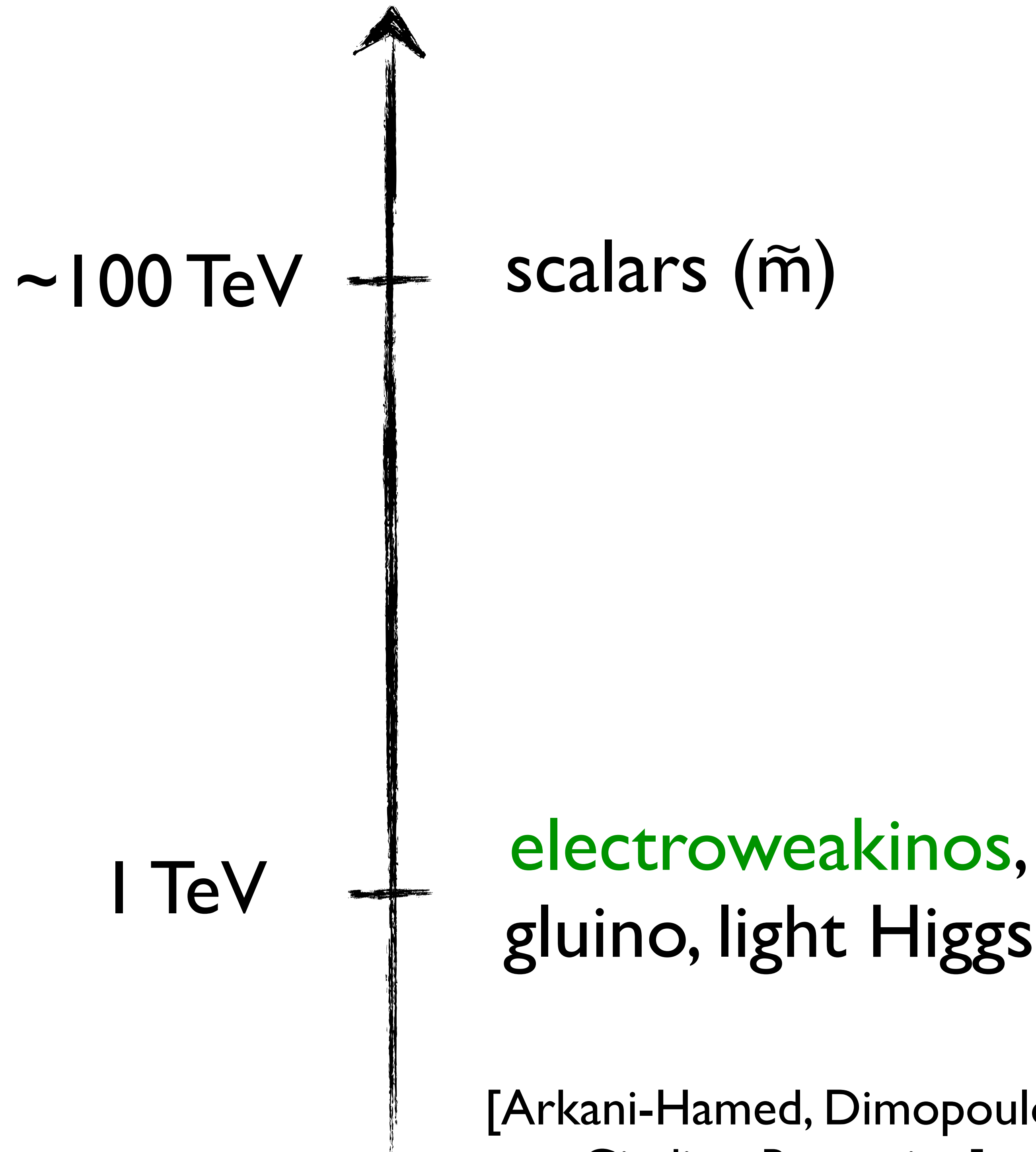
$$\begin{cases} \Omega h^2 \simeq 0.1 \dfrac{3\times10^{-26}\mathrm{cm}^3/s}{\sigma_0} \\ \sigma_0 \sim \dfrac{g^4}{m_\chi^2} \end{cases}$$

DM mass GeV-TeV

Split SUSY: motivations







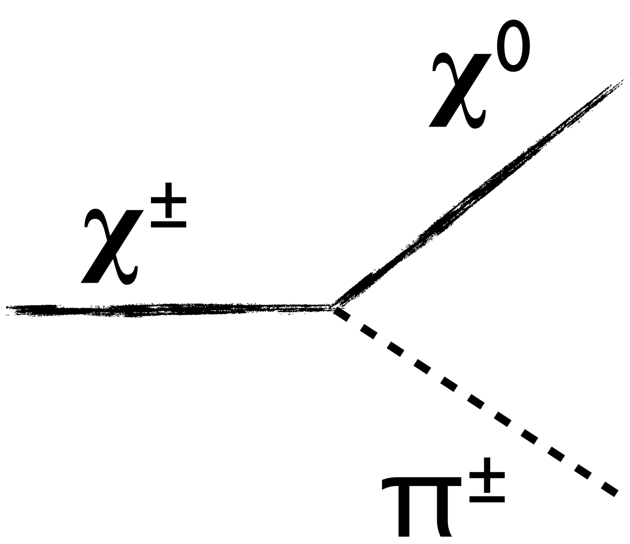
[Arkani-Hamed, Dimopoulos, Giudice, Romanino]

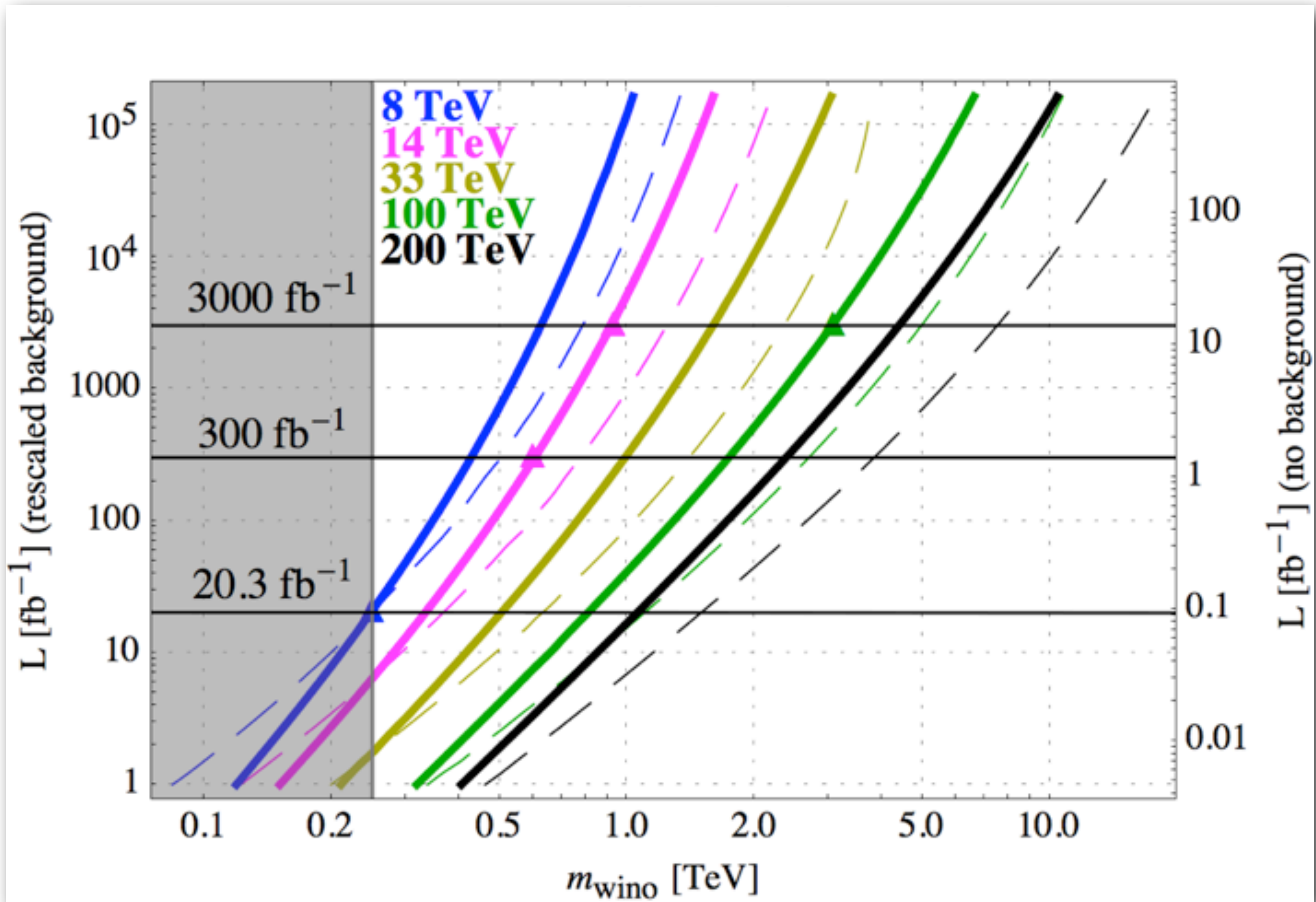
Anomaly mediation

$$\begin{cases} M_{1,2} = \dfrac{\beta_{1,2}}{g_{1,2}} m_{3/2} + \dfrac{\alpha_{1,2}}{2\pi} \dfrac{(\tilde{m}^2 + \mu^2)\mu \tan\beta}{(\tan^2\beta + 1)\tilde{m}^2 + \mu^2} \ln\left[(1 + \tan^{-1}\beta)\left(1 + \dfrac{\tilde{m}^2}{\mu^2}\right)\right] \\ M_3 = \dfrac{\beta_3}{g_3} m_{3/2} \end{cases}$$

[Randall, Sundrum ’98]
[Giudice, Luty, Murayama, Rattazzi ’98]
[Arkani-Hamed, Dimopoulos, Giudice, Romanino]

Long-lived Winos





see also
[Low, Wang '14]
[Cirelli, Sala, Taoso '14]

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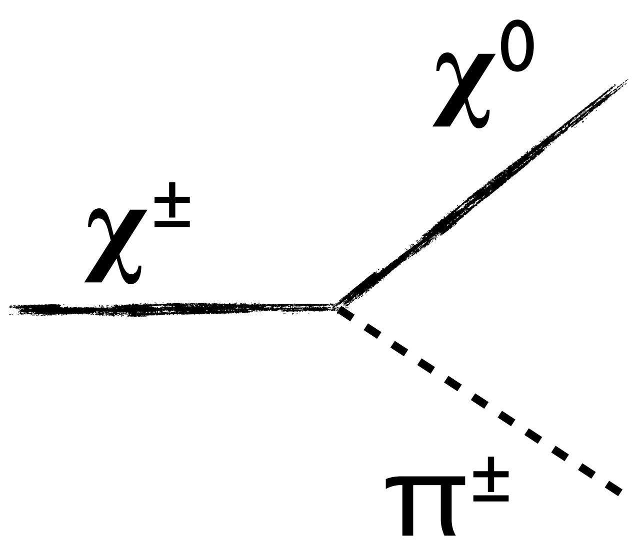

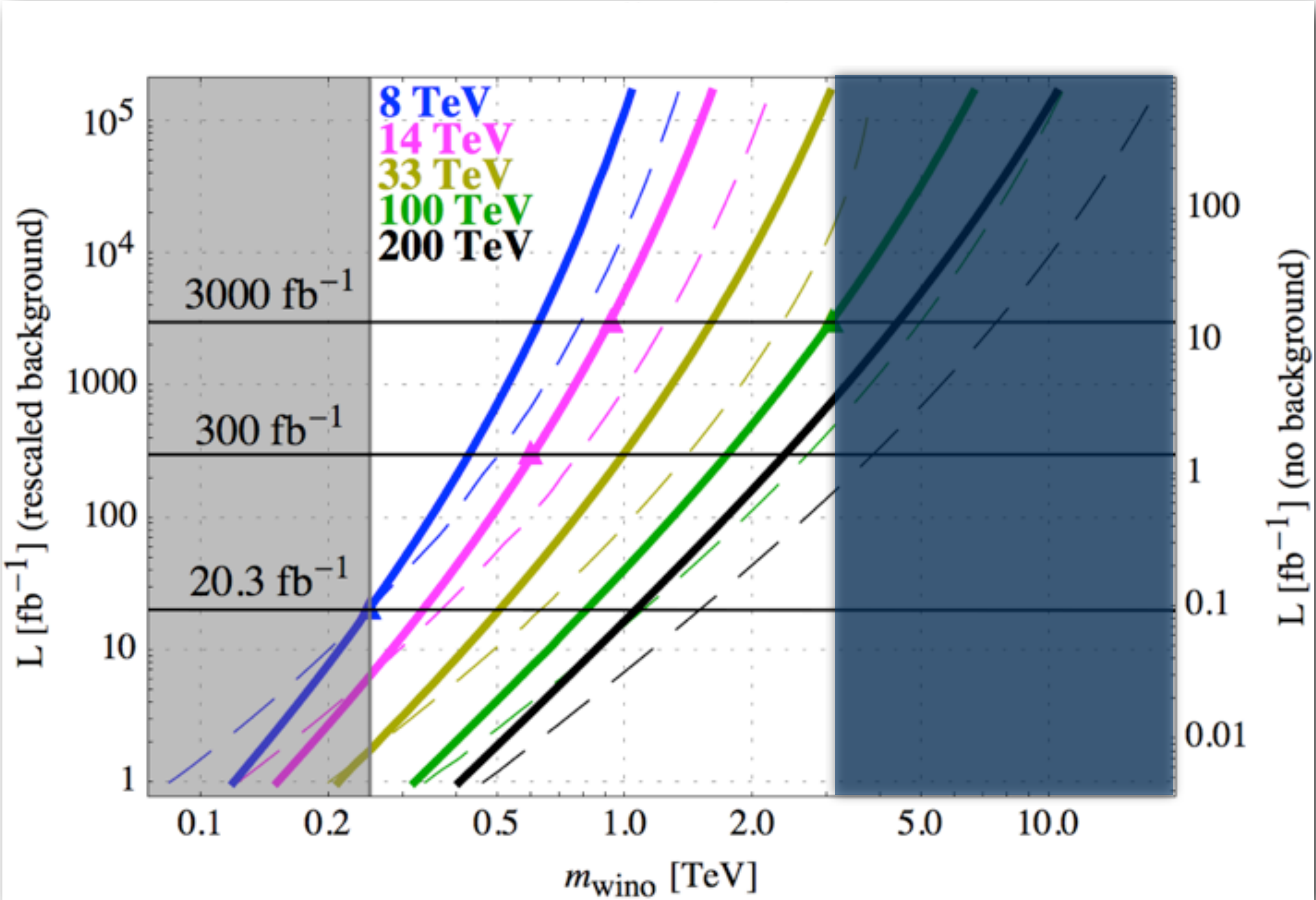

see also
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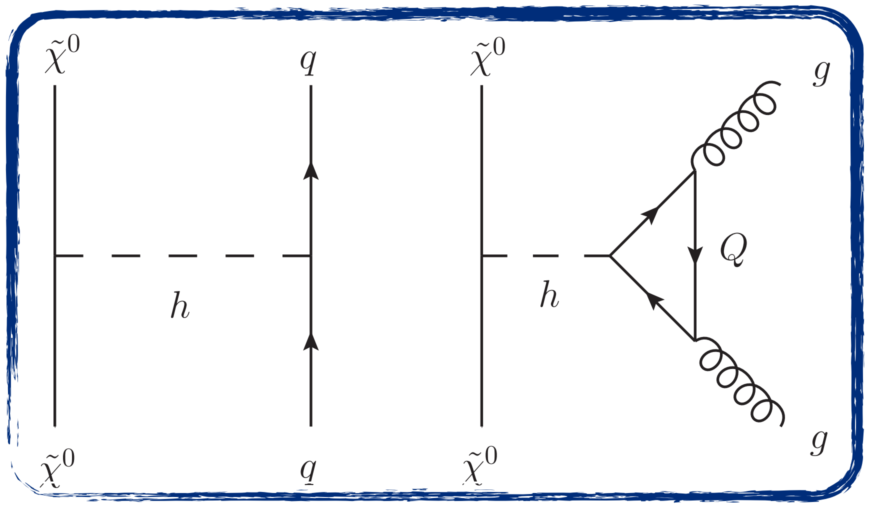
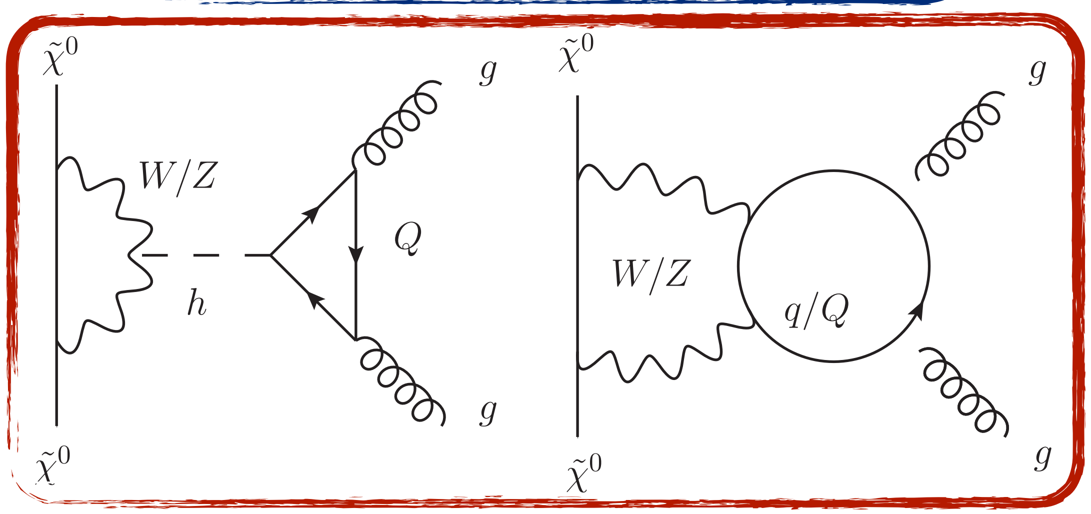
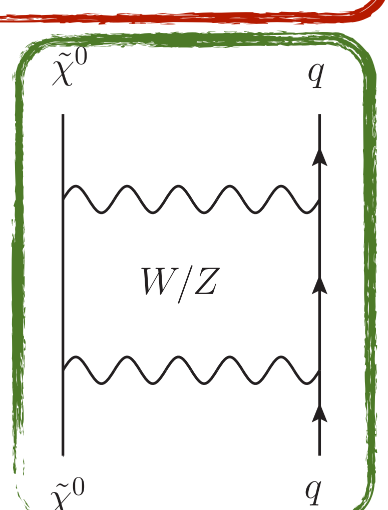
Direct detection

σ_{SI}=|Higgs+gluon+twist-2|^2





[Hisano, Ishiwata, Nagata, Takesako '11]



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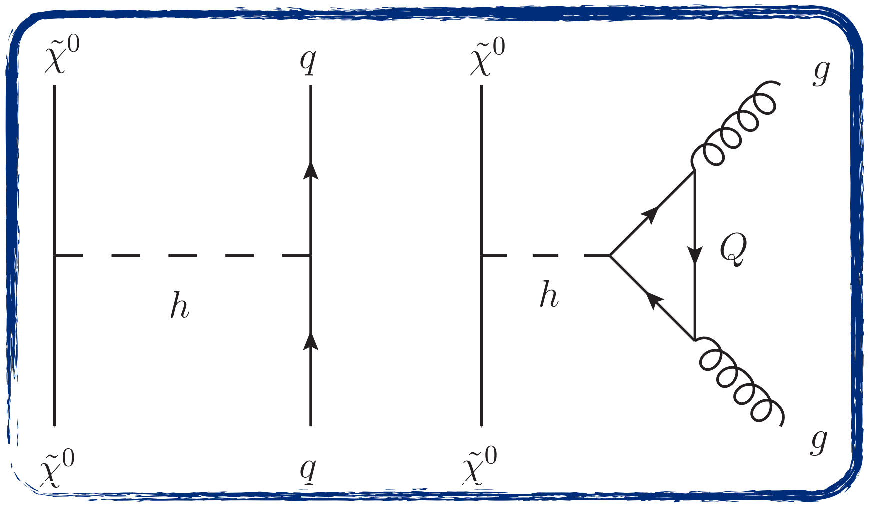

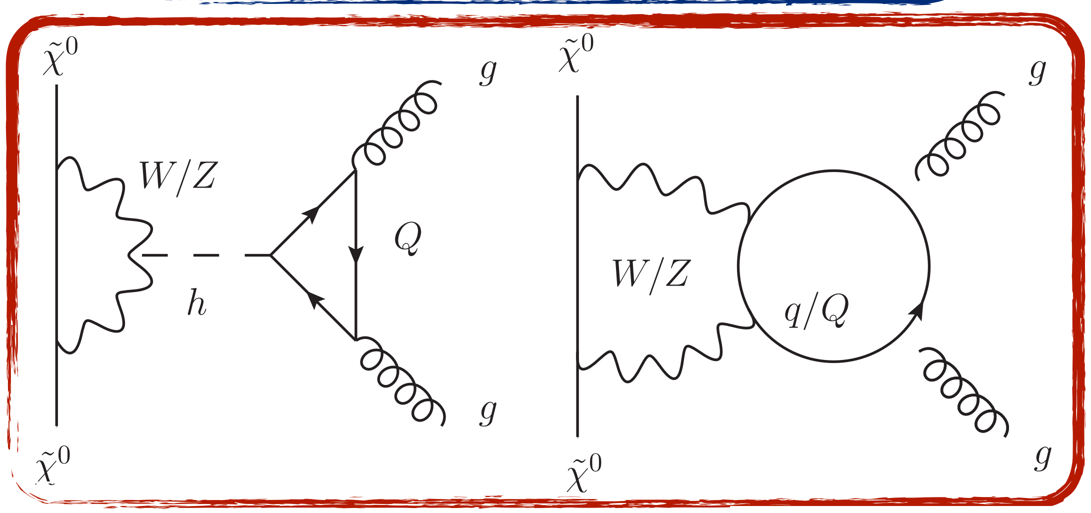

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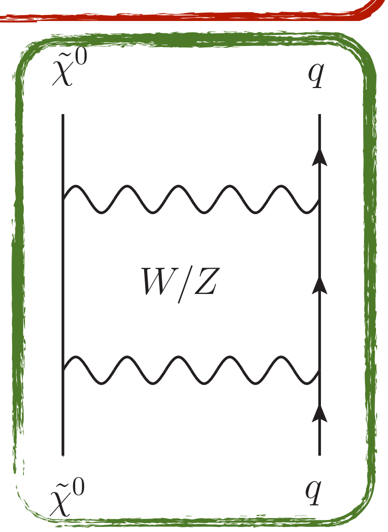

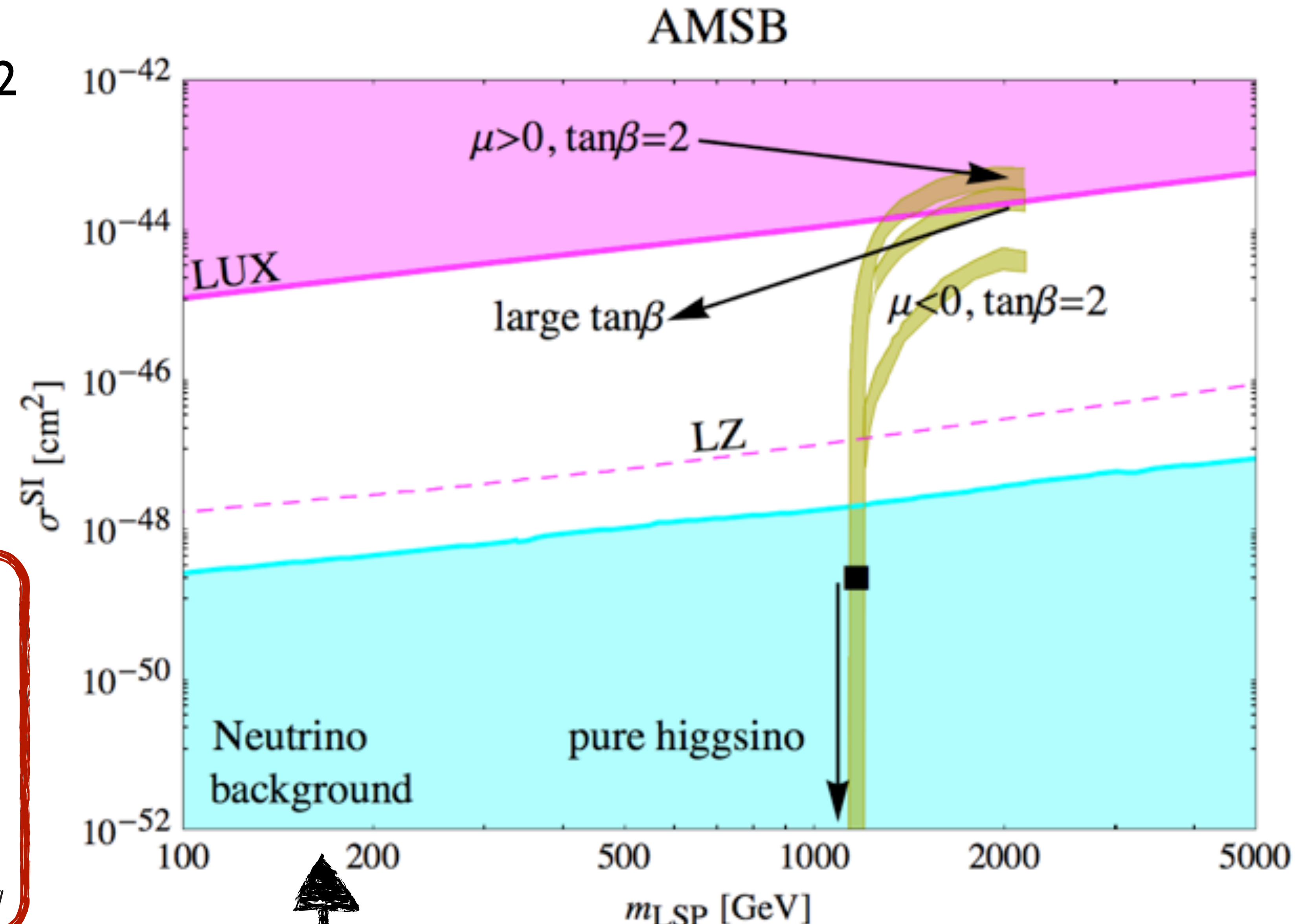

gluino

Bino

Wino

higgsino

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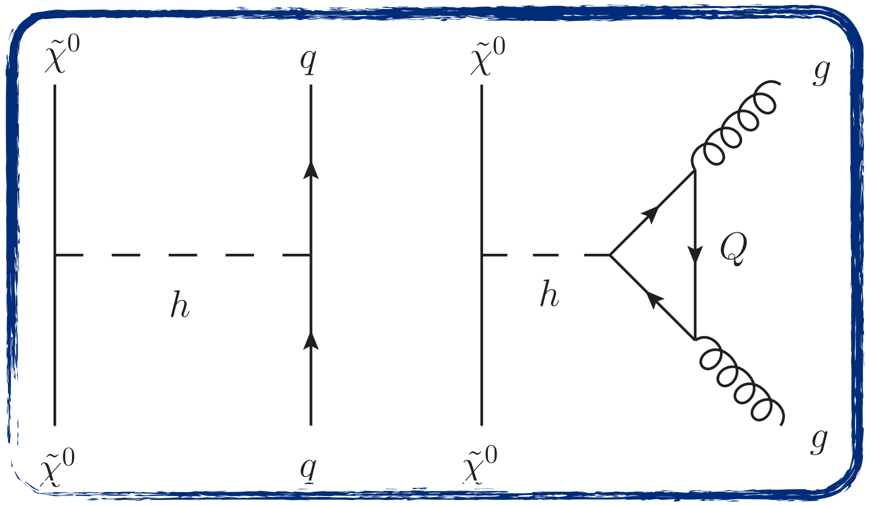

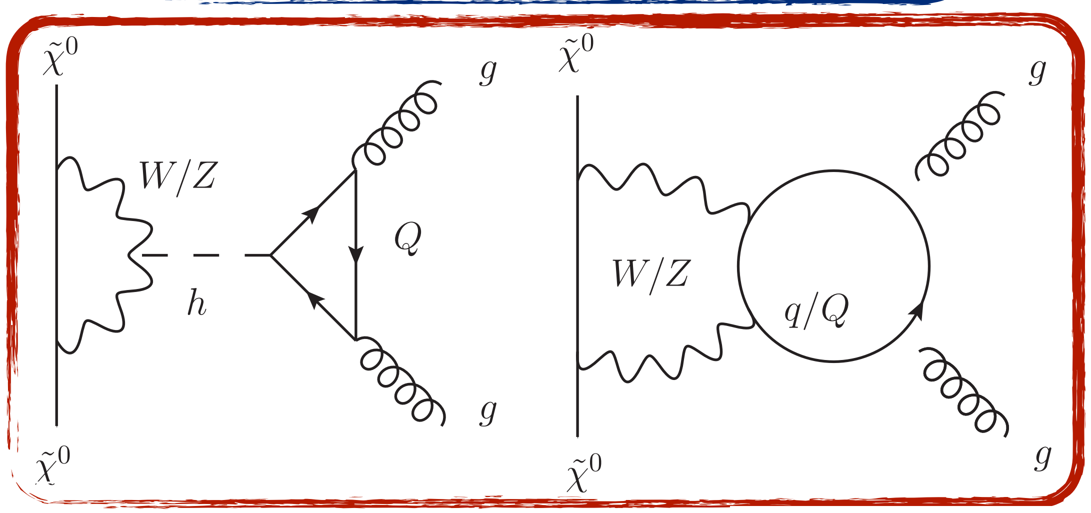

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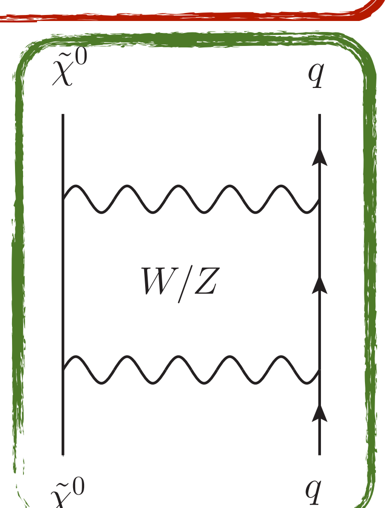

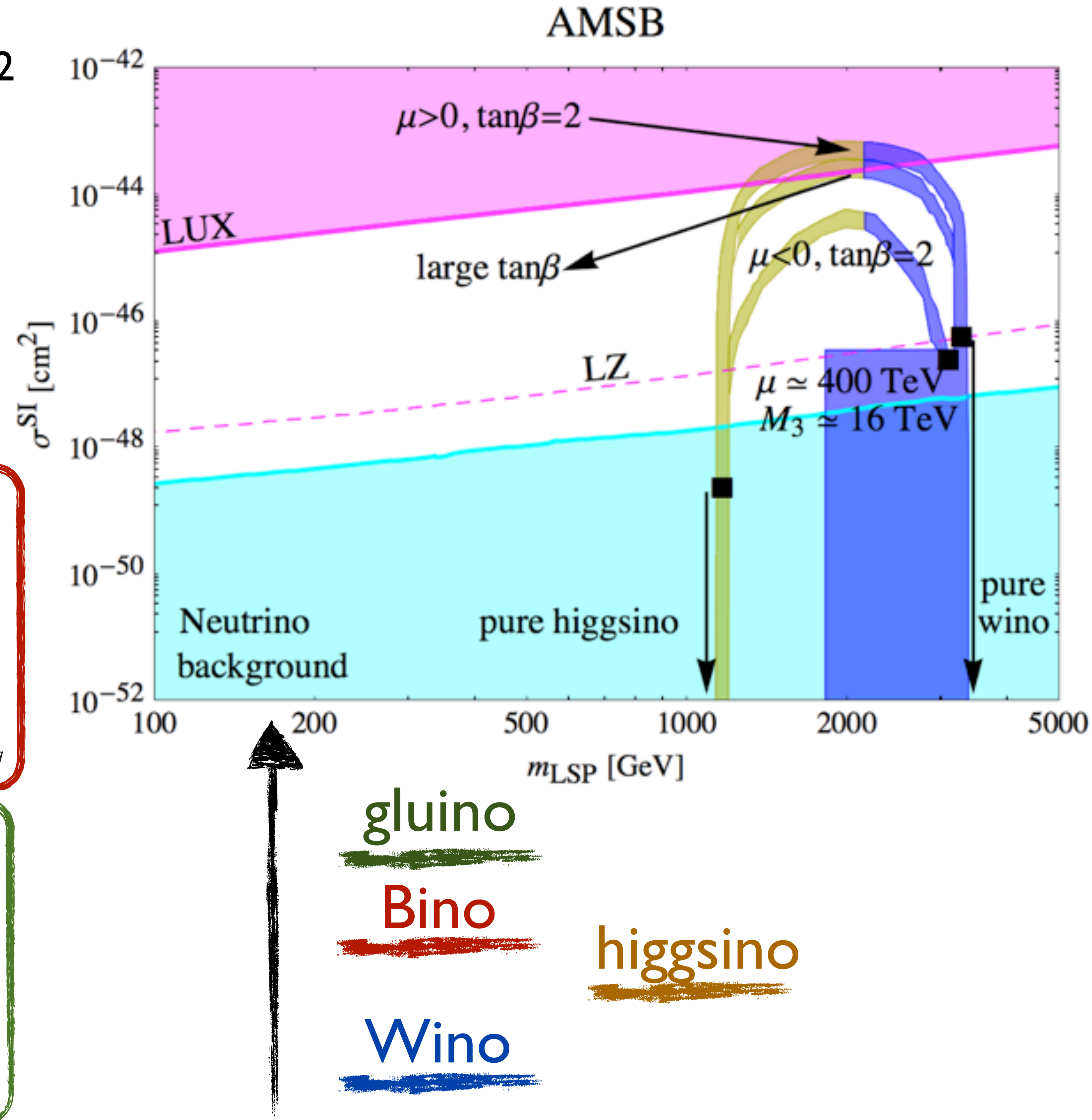

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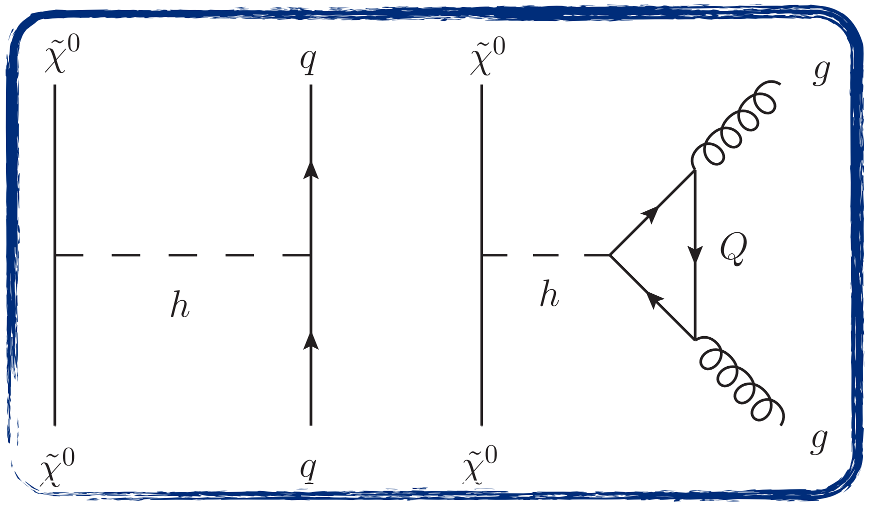

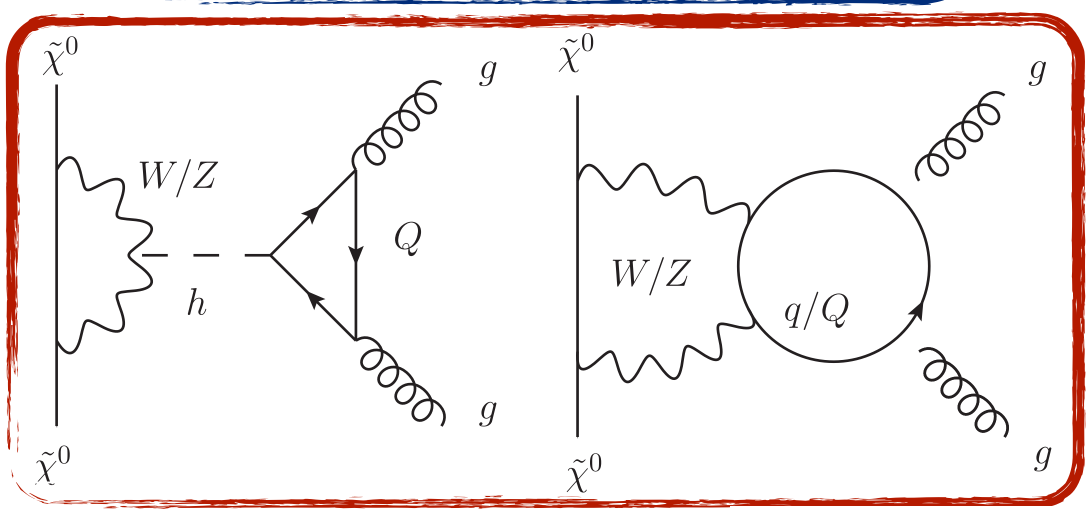

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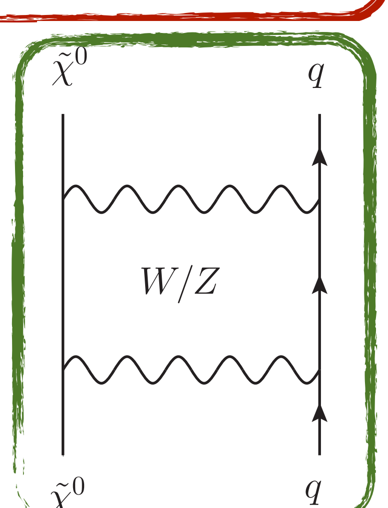
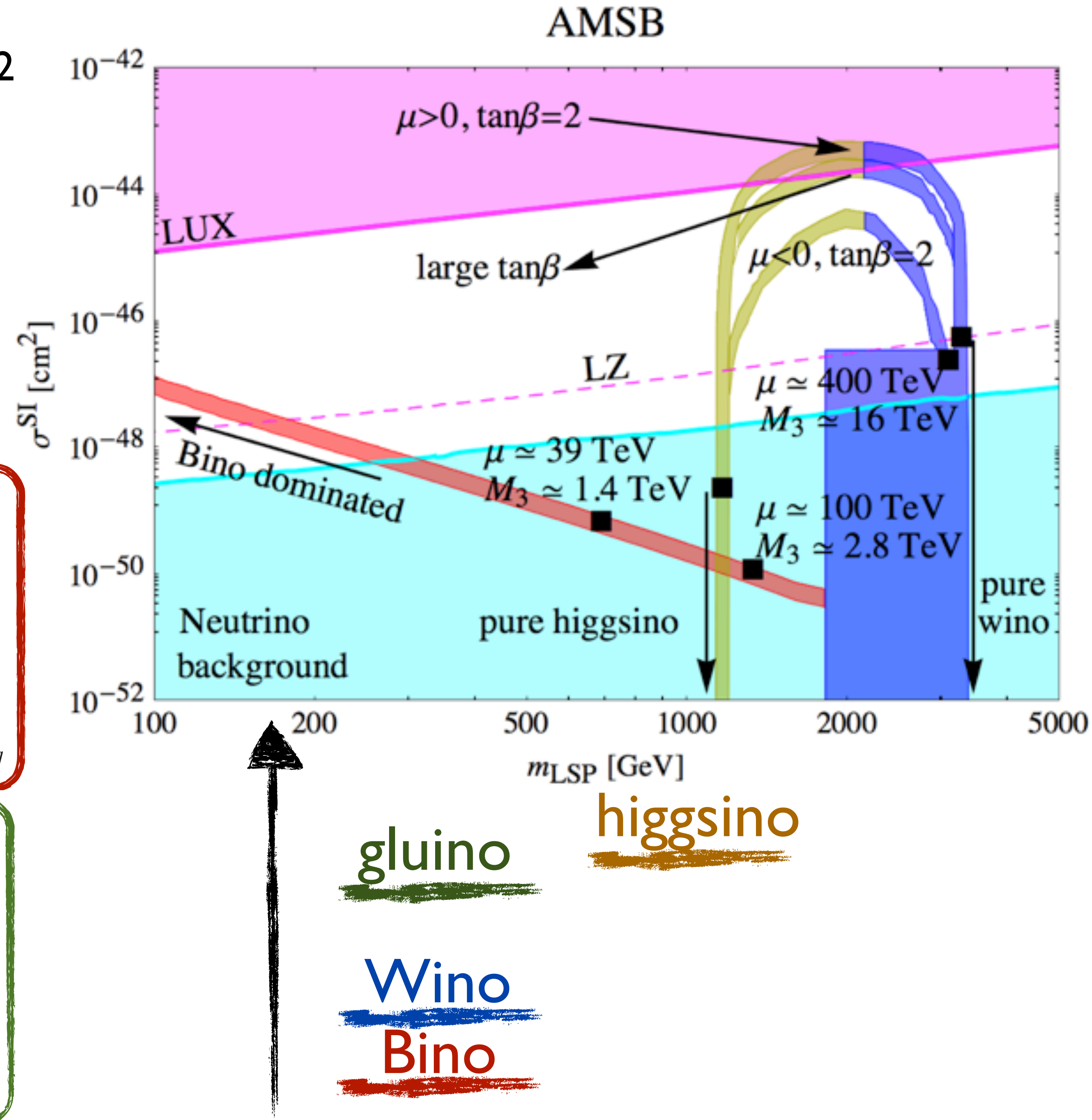
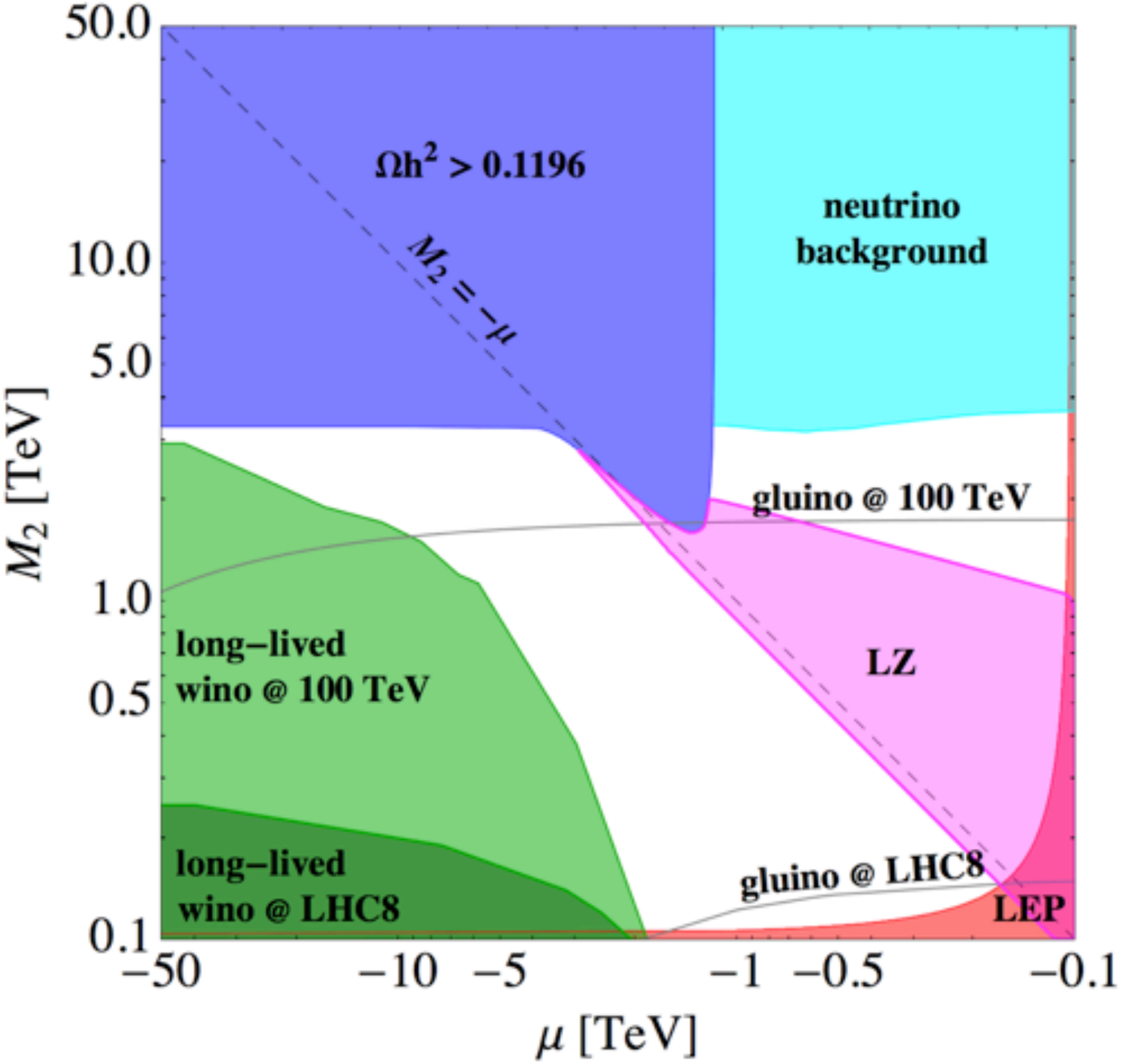
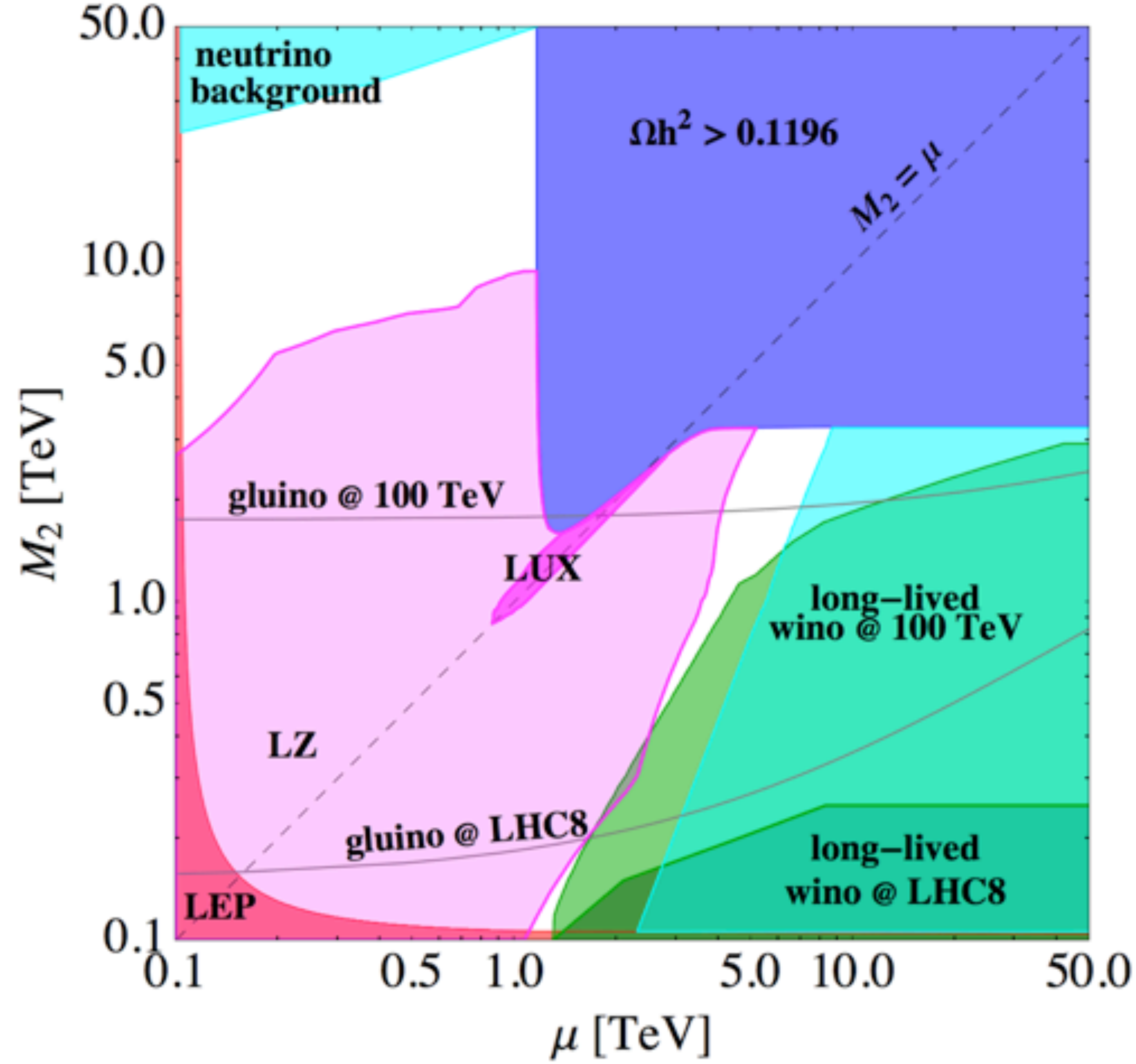




Collider vs direct detection





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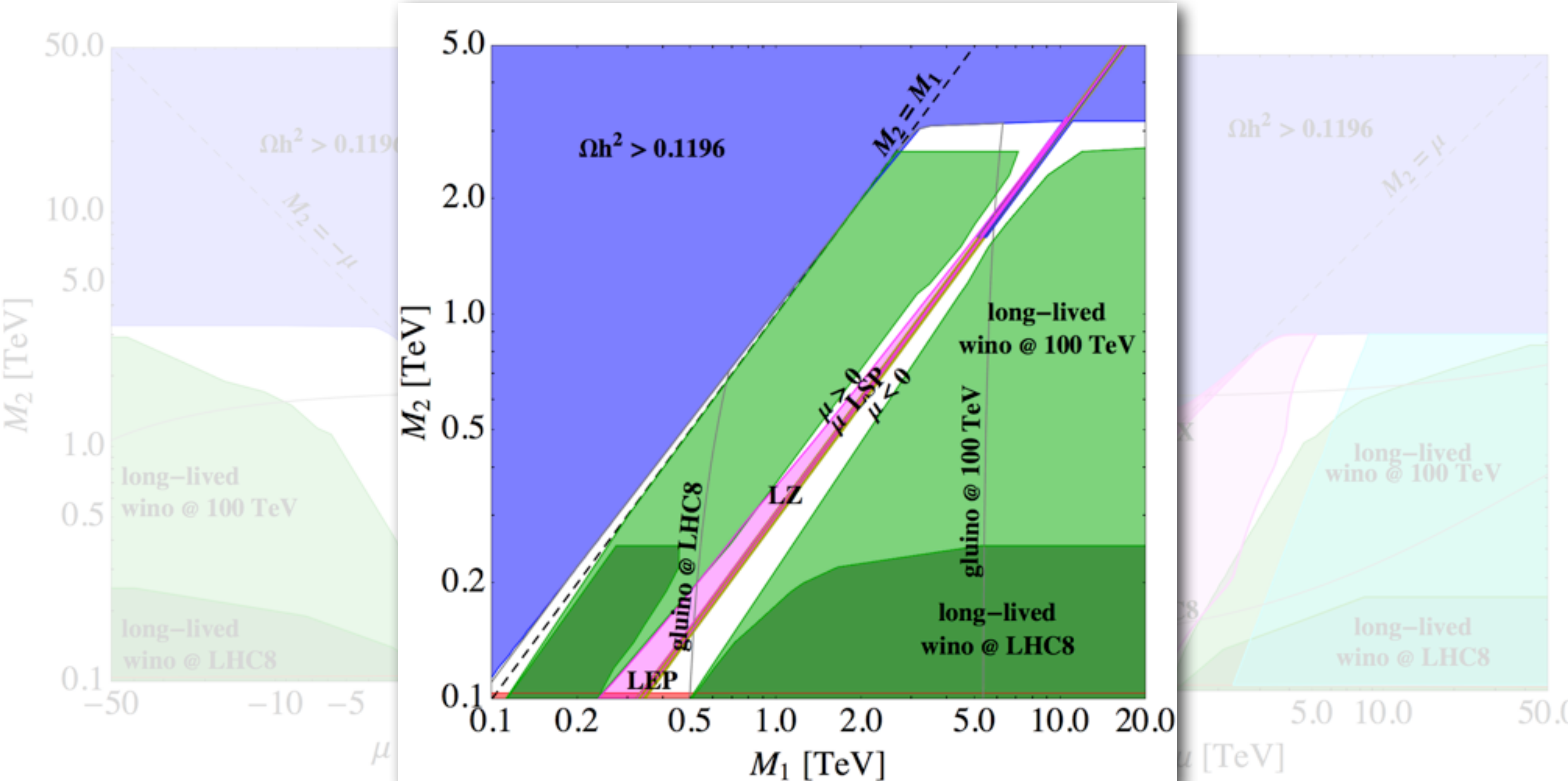
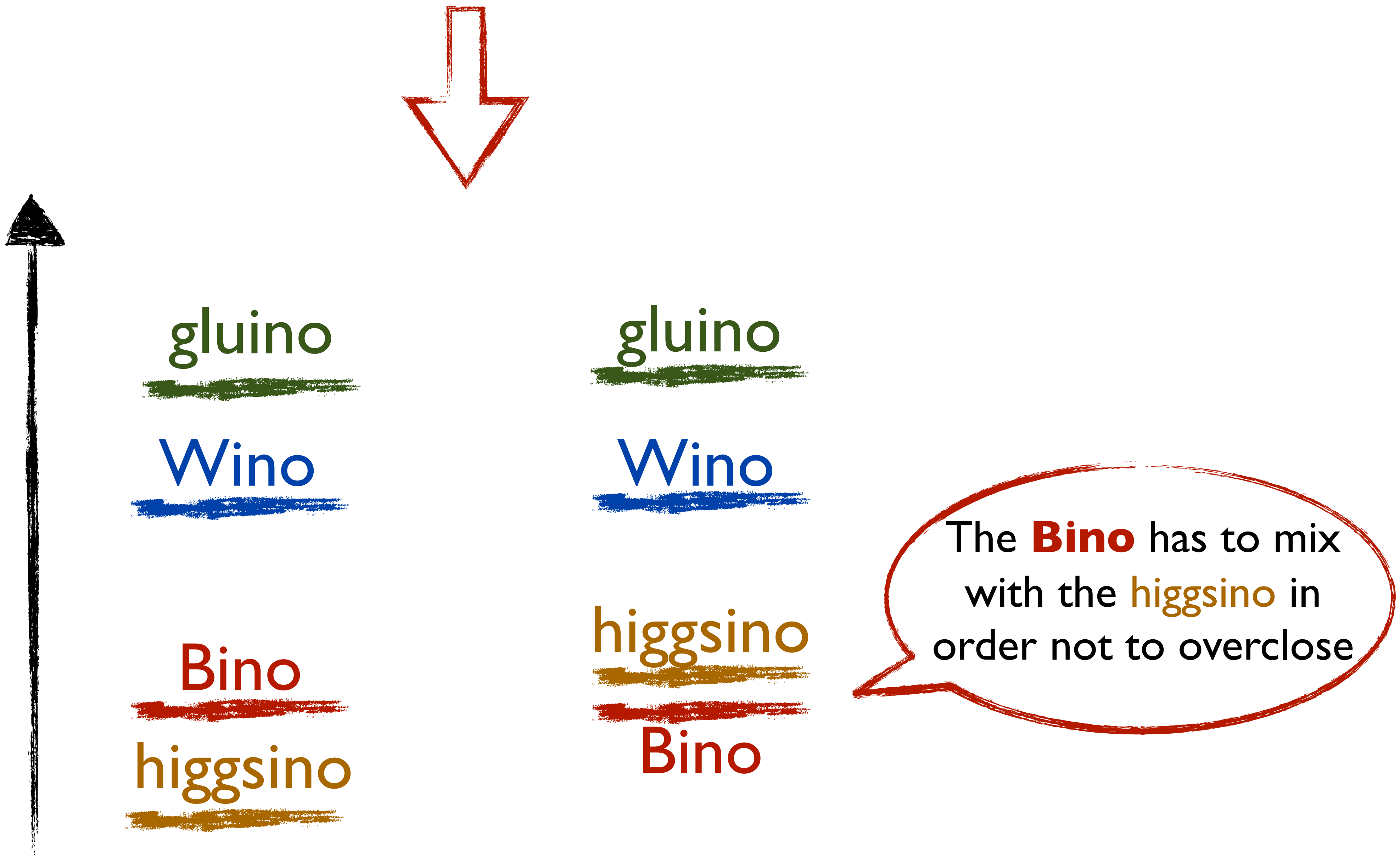


Universal gaugino masses

$$M_i \propto \alpha_i M_0$$



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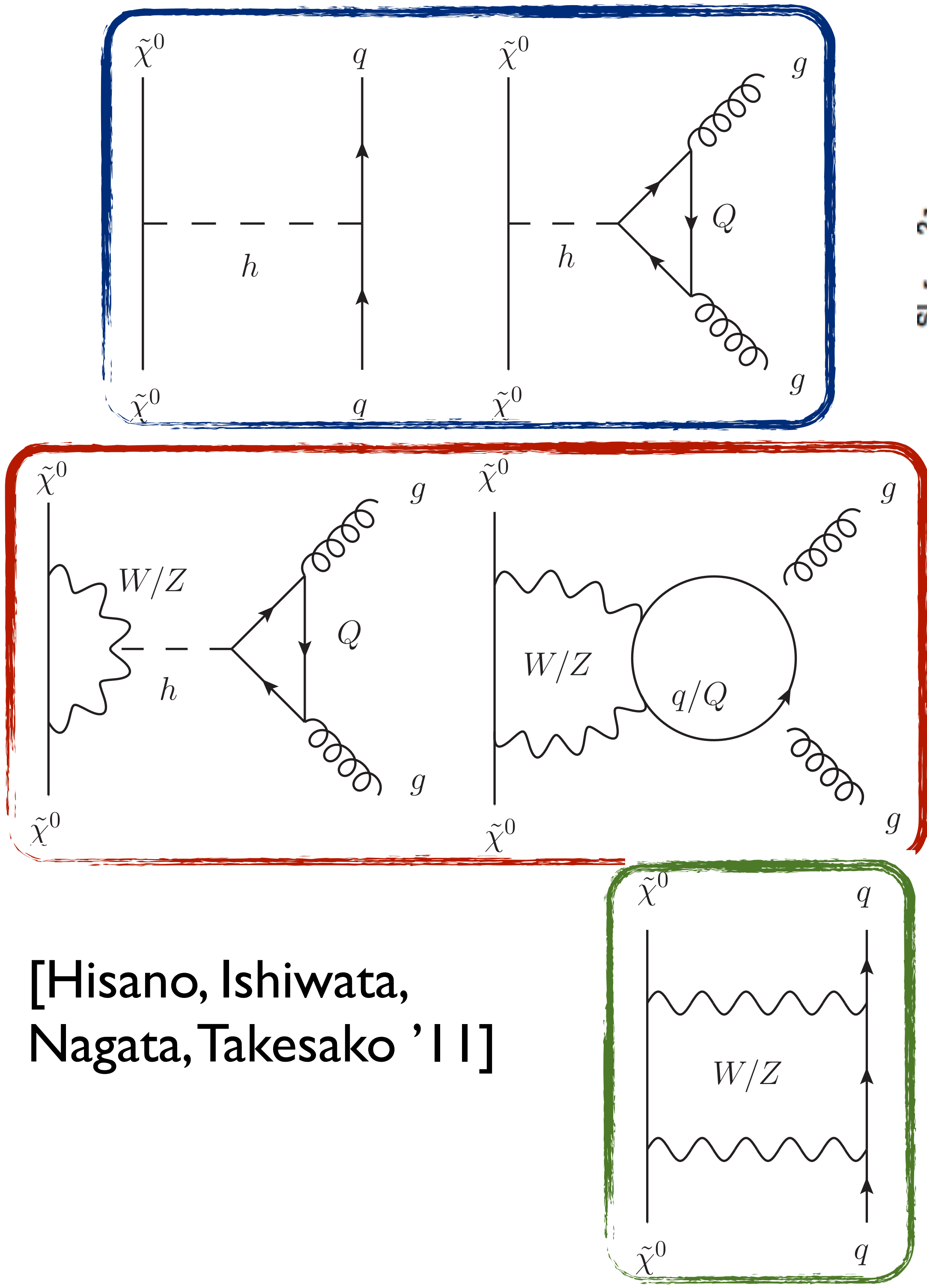

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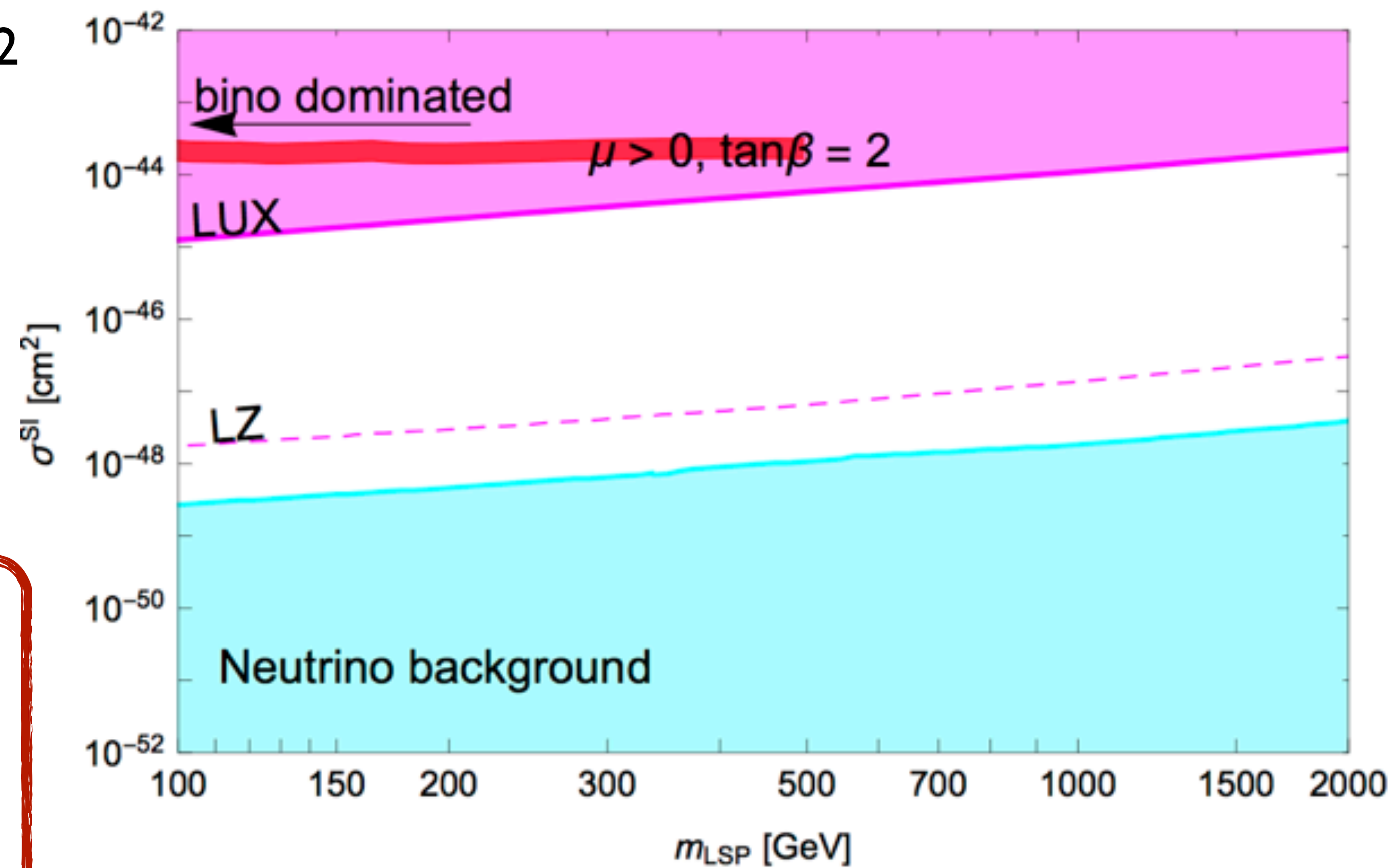

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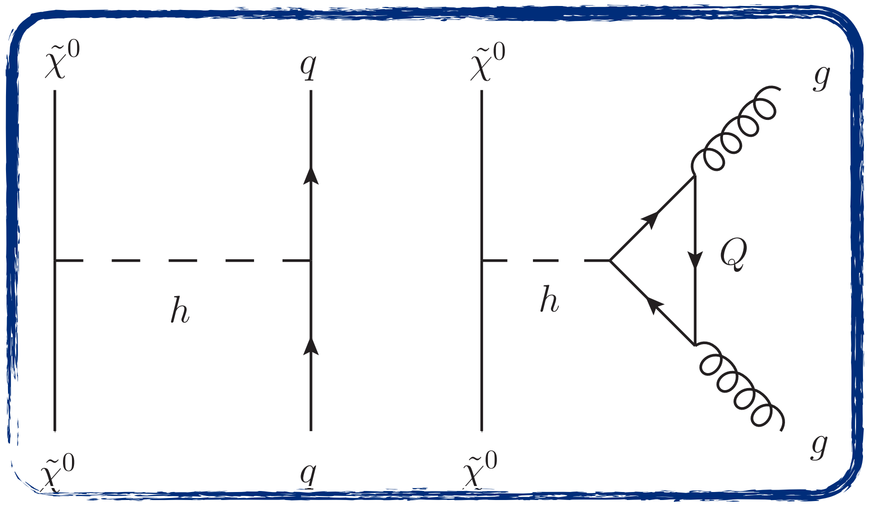

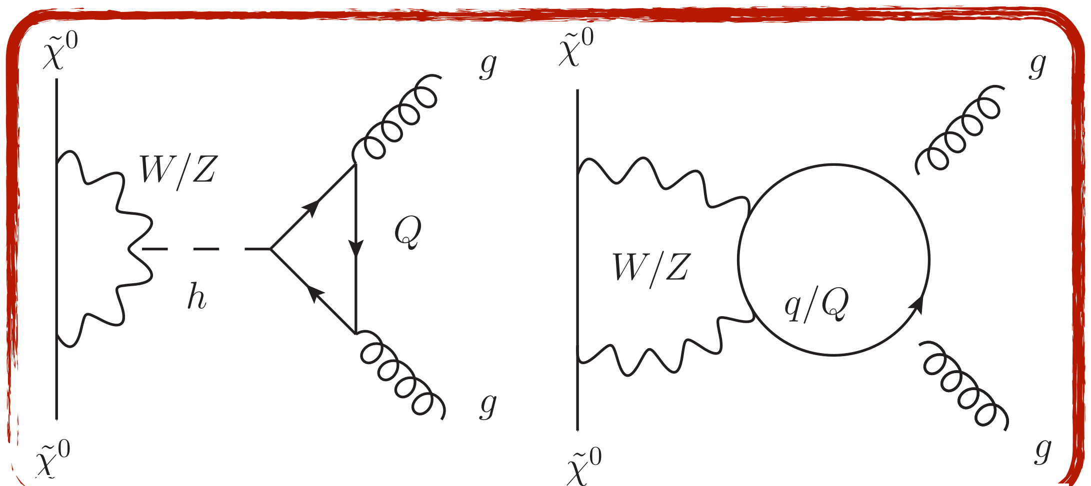

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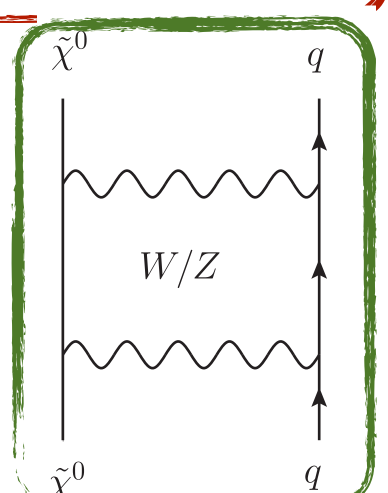

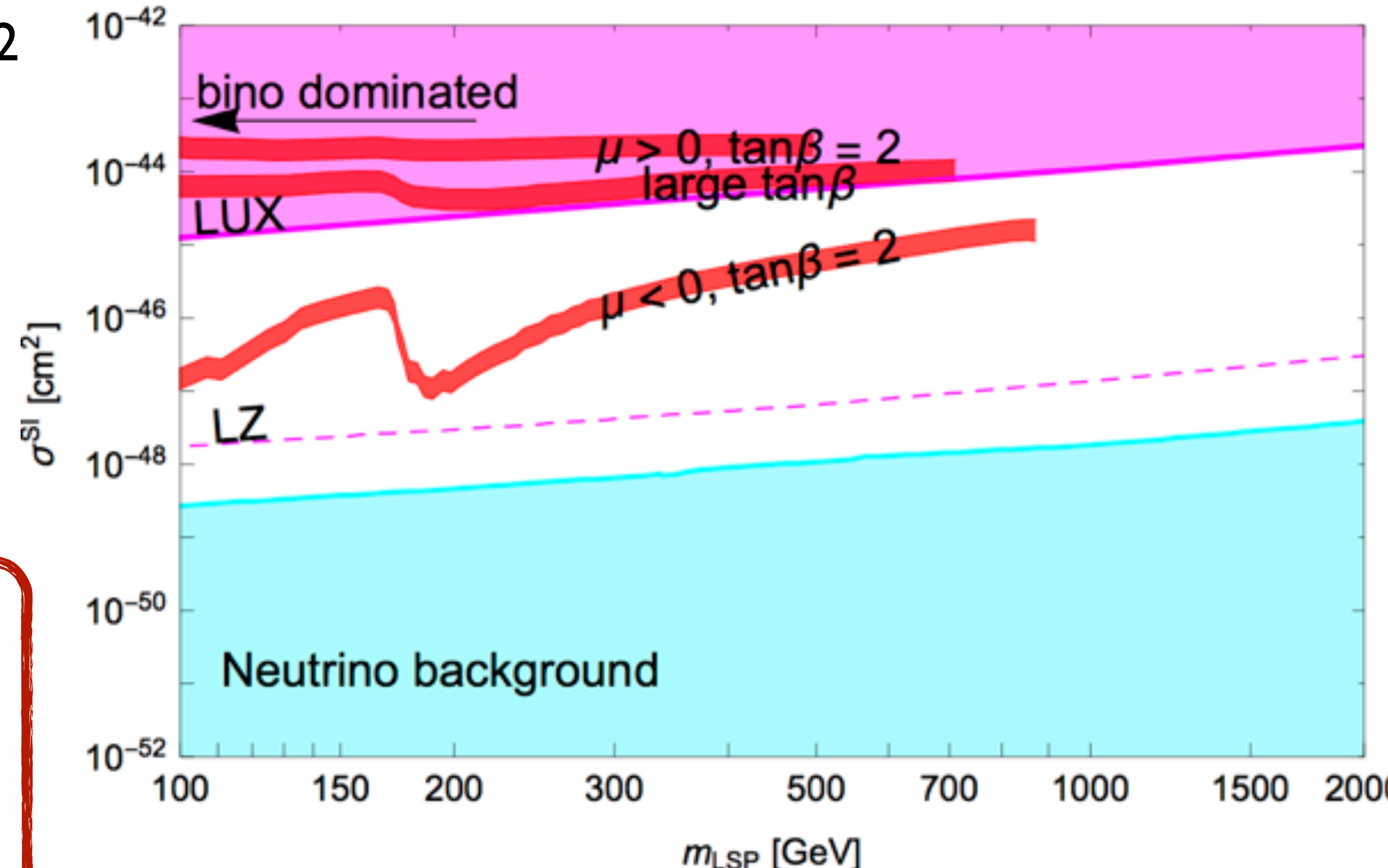

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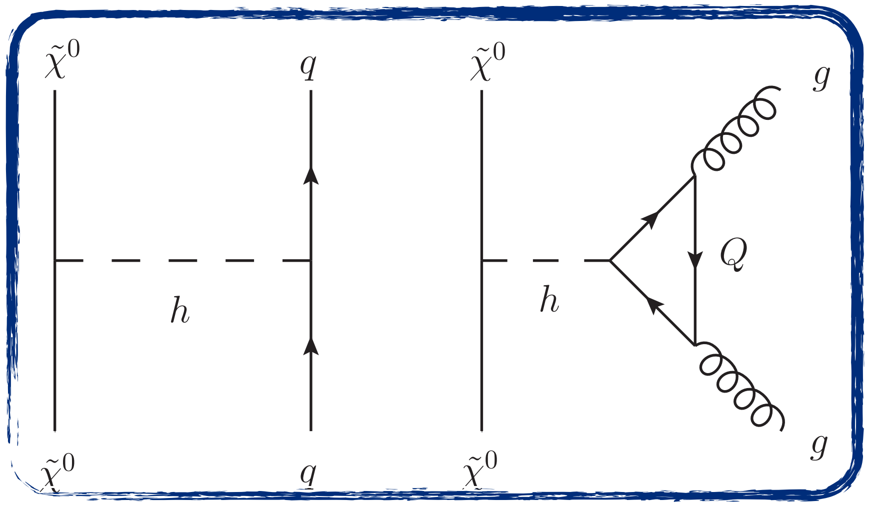

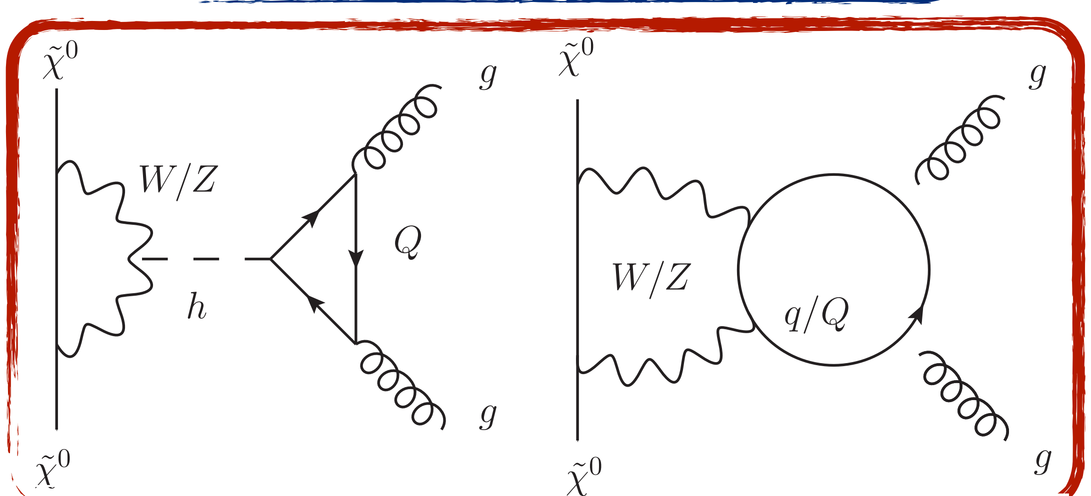

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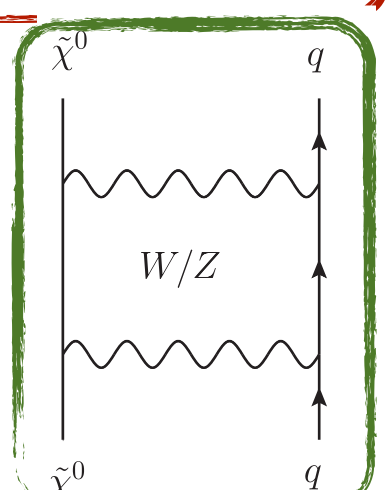

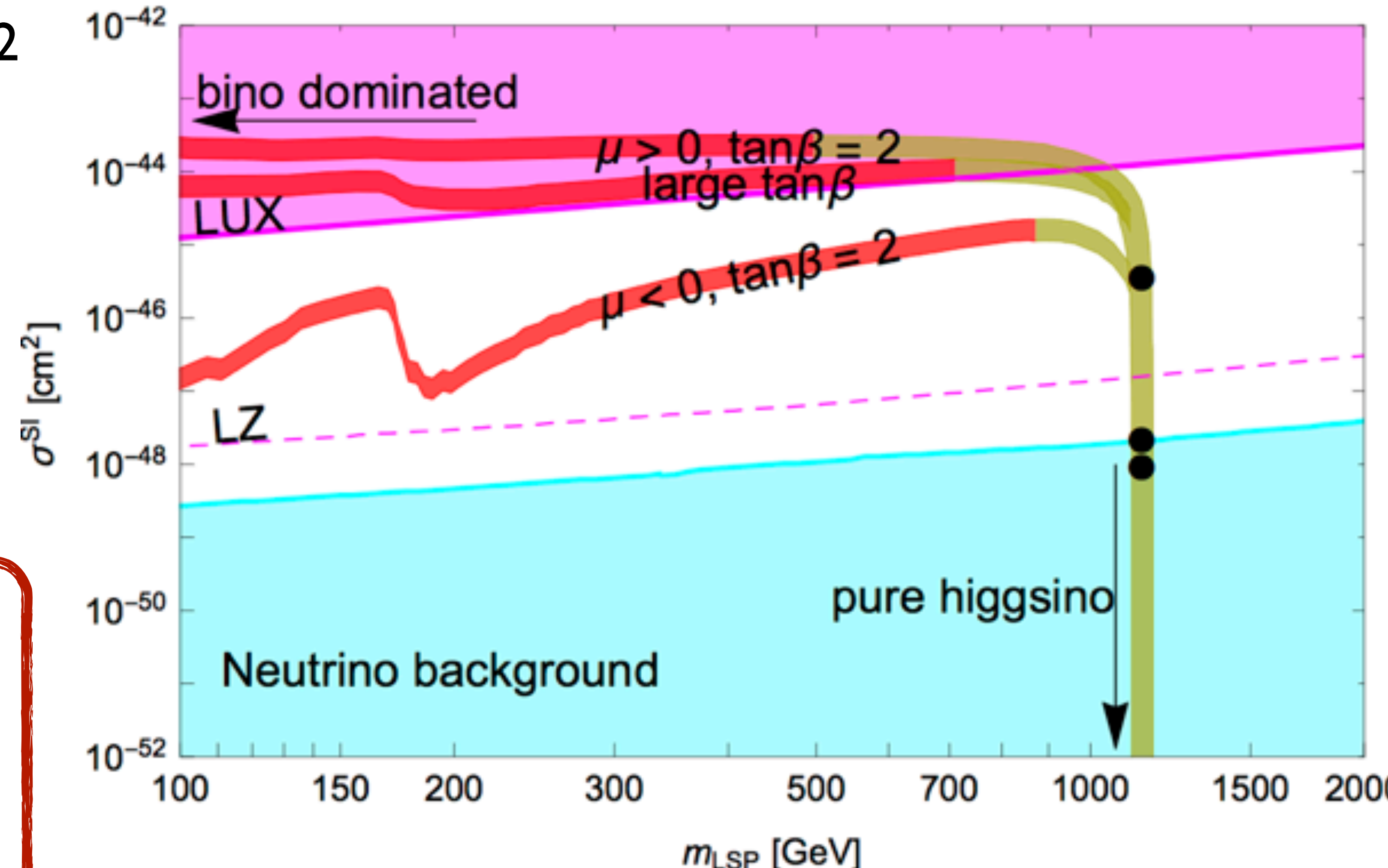

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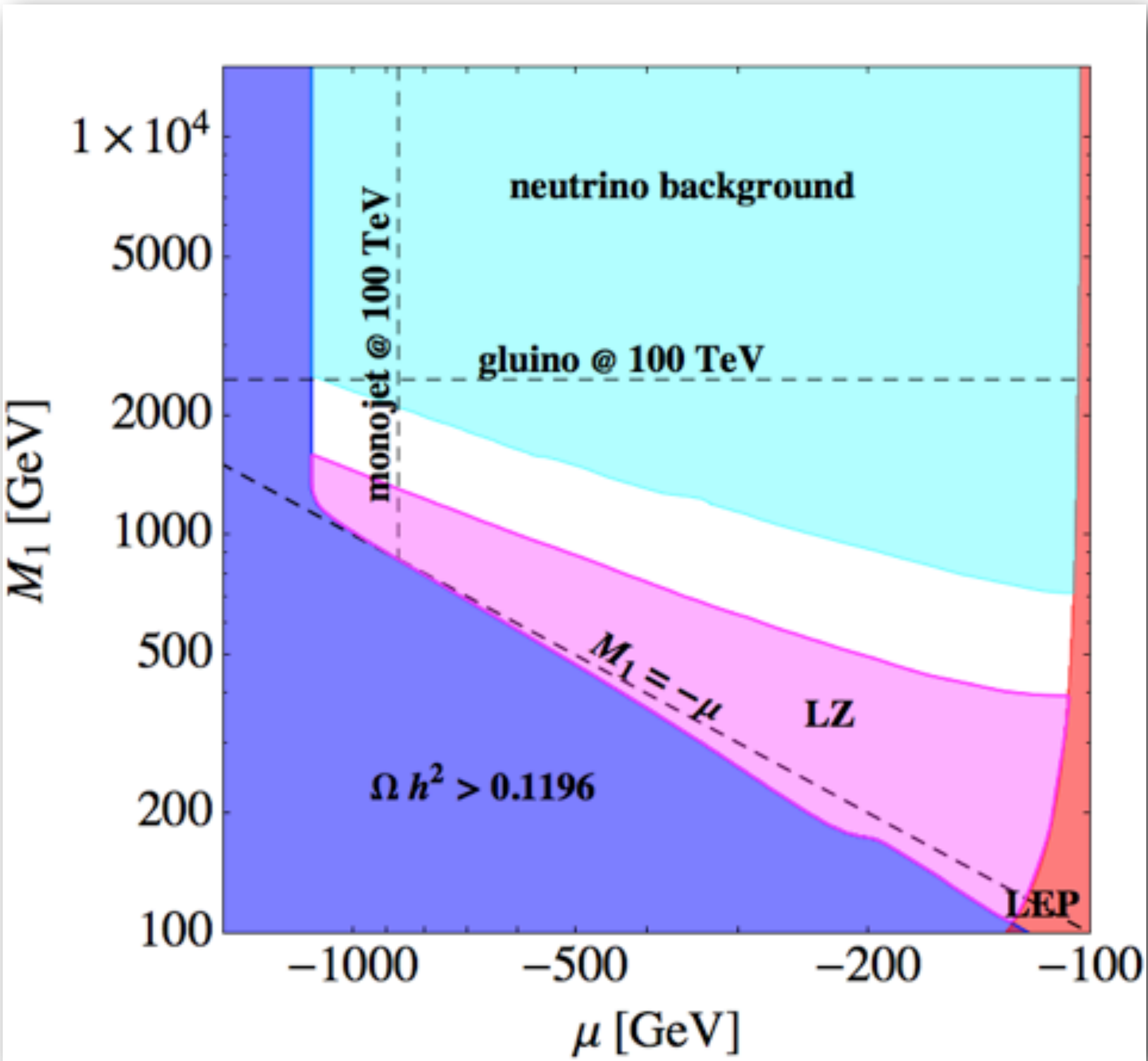

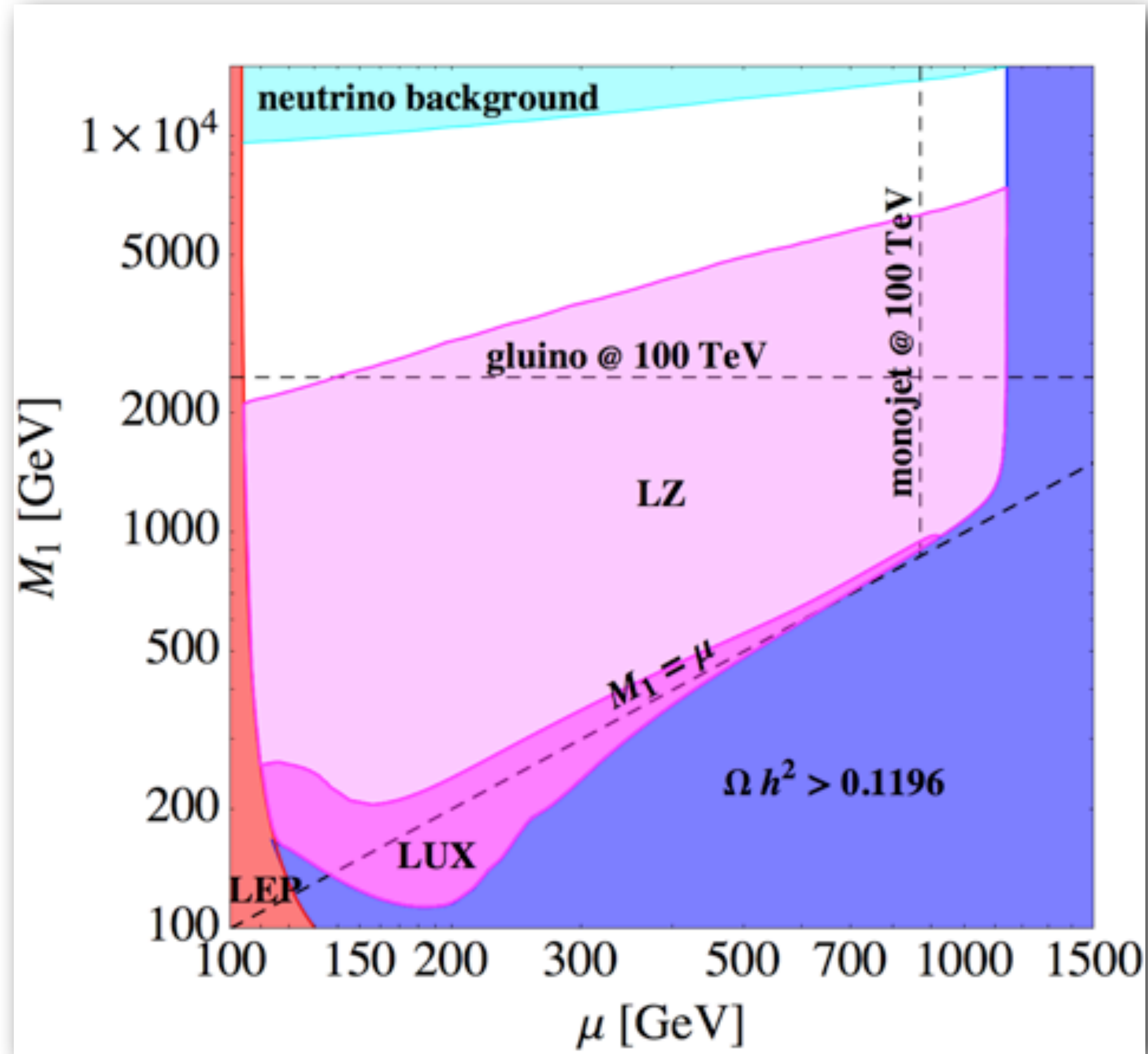

… and below meV

Strong CP problem...

$$\mathcal{L} \supset -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \frac{\theta g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} + \sum_{j=1}^{n} \left[i\bar{q}_j \gamma^\mu D_\mu q_j - (m_j q_{Lj}^\dagger q_{Rj} + \text{h.c.}) \right]$$

$$\overline{\theta} = \theta + \arg(\det(m_j))$$

CP violation

$$d_n \simeq \overline{\theta} \times 10^{-16} \text{e cm}$$

$$d_n^{\text{exp}} < 3 \cdot 10^{-26} \text{cm e}$$

$$\overline{\theta} \leq 10^{-10}$$

Why the quark masses and the theta term should cancel so exactly even if they come from completely different sources?

... axion as a solution

[Peccei, Quinn '77]
[Wilczek '78]
[Weinberg '78]

$$\mathcal{L} \supset -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$
$$+ \sum_{j=1}^{n}\left[i\bar{q}_j\gamma^\mu D_\mu q_j - (m_j q_{Lj}^\dagger q_{Rj} + \text{h.c.})\right]$$

$$\bar{\theta} + \frac{a}{f_a} = 0$$

minimize the energy density

Chiral perturbation theory

$$Z(j) = \int \delta q \delta \bar{q} \delta G \, e^{iS_{QCD}(\phi,j)} = \int \delta\pi \, e^{iS(\pi,j)}$$

$SU(N_f)_L x SU(N_f)_R \longrightarrow SU(N_f)_V$

$$\mathcal{L} = \frac{f_a^2}{4}\left[\mathrm{Tr}(\partial_\mu U \partial^\mu U) + 2B_0 \mathrm{Tr}(M_0^\dagger U + M_0 U^\dagger)\right]$$

$$U = e^{i\Pi/f_\pi}$$

$$\Pi = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

$$M_0 = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

Chiral perturbation theory

$$\mathcal{L} = \frac{f_\pi^2}{4}\left[\mathrm{Tr}(D_\mu U D^\mu U) + 2B_0 \mathrm{Tr}(M U^\dagger + M^\dagger U)\right]$$

$$M = e^{i\frac{a}{2f_a}Q_a} M_0 e^{i\frac{a}{2f_a}Q_a}$$

and in order to avoid axion-pion mixing:

$$Q_a = \frac{M_0^{-1}}{\mathrm{Tr}(M_0^{-1})}$$

$$\mathcal{L}_4 = \sum_{i=1}^{12} l_i \mathcal{O}_i^l + \sum_{i=1}^{7} h_i \mathcal{O}_i^h \qquad \mathcal{L}_6^W = \sum_{i=1}^{13} c_i \mathcal{O}_i^c$$

Axion mass

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} \left[1 + 2 \frac{m_\pi^2}{f_\pi^2} \left(h_1^r - h_3^r - l_4^r + \frac{m_u^2 - 6 m_u m_d + m_d^2}{(m_u + m_d)^2} l_7^r \right) \right]$$

Axion mass

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$$l_7^r = 7(4) \cdot 10^{-3} \qquad h_1^r - h_3^r - l_4^r = (4.8 \pm 1.4) \cdot 10^{-3}$$

$$z = \frac{m_u^{\overline{MS}}(2\,\mathrm{GeV})}{m_d^{\overline{MS}}(2\,\mathrm{GeV})} = 0.48(3)$$

Axion mass

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$$z = \frac{m_u^{\overline{MS}}(2\,\mathrm{GeV})}{m_d^{\overline{MS}}(2\,\mathrm{GeV})} = 0.48(3)$$

$$m_a = 5.70(6)(4)\ \mu\mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right) = 5.70(7)\ \mu\mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$$

Coupling to photons

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

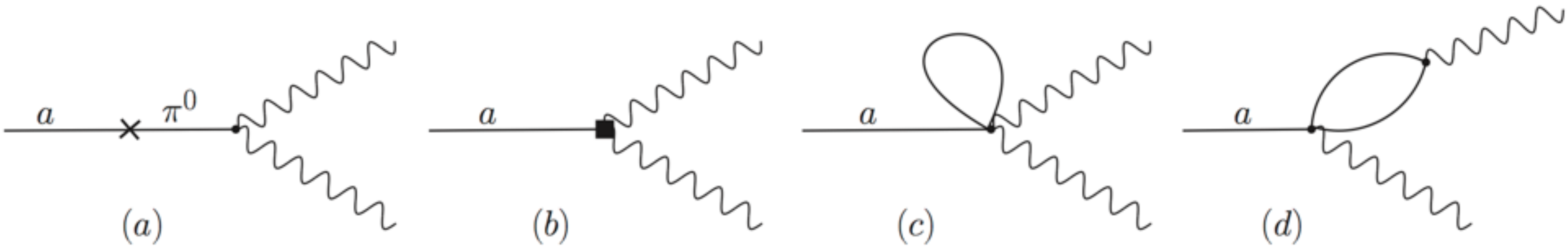
$$Q_e = \mathrm{diag}(2/3, -1/3)$$

$$g_{a\gamma\gamma} \to g_{a\gamma\gamma} - \frac{\alpha}{2\pi} \frac{1}{f_a} \mathrm{Tr}(Q_a Q_e Q_e)$$

$$Q_a = \frac{1}{2} \frac{M^{-1}}{\mathrm{Tr}(M^{-1})}$$

$$g_{a\gamma\gamma} = \frac{a}{2\pi} \frac{1}{f_a} \left(\frac{E}{N} - \frac{2}{3} \frac{4+z}{1+z} \right)$$

Coupling to photons



$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}\left[\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z} - \frac{8m_\pi^2}{f_\pi^2}\frac{z(1-z)}{(1+z)^3}l_7^r + \frac{1024}{9}\frac{z\,\pi^2 m_\pi^2}{(1+z)^2}(5c_3^W + c_7^W + 2c_8^W)\right]$$

$$g_{a\gamma\gamma} = \frac{\alpha_{\rm em}}{2\pi f_a}\left[\frac{E}{N} - 1.92(4)\right] = \left[0.203(3)\frac{E}{N} - 0.39(1)\right]\frac{m_a}{\rm GeV^2}$$

Coupling to nucleons

$$\frac{\partial_\mu a}{2f_a} c_N \overline{N} \gamma^\mu \gamma_5 N$$

$$\begin{aligned} c_p &= -0.48(3) + 0.89(2)c_u^0 - 0.38(2)c_d^0 - 0.036(4)c_s^0 \\ &\quad - 0.013(5)c_c^0 - 0.009(2)c_b^0 - 0.0036(4)c_t^0 \\ c_n &= -0.03(3) + 0.89(2)c_d^0 - 0.38(2)c_u^0 - 0.036(4)c_s^0 \\ &\quad - 0.013(5)c_c^0 - 0.009(2)c_b^0 - 0.0036(4)c_t^0 \end{aligned}$$

[Kim '79]
[Shifman, Vainshtein & Zakharov '80]

$c_q^0 = 0$

$$\begin{aligned} c_p^{\rm KSVZ} &= -0.48(3) \\ c_n^{\rm KSVZ} &= 0.03(3) \end{aligned}$$

$c_q^0 \neq 0$

[Dine, Fishler & Srednicki '81]
[Zhitnitsky '80]

$$\begin{aligned} c_p^{\rm DFSZ} &= -0.622 + 0.434 \sin^2\beta \pm 0.024 \\ c_n^{\rm DFSZ} &= 0.249 - 0.415 \sin^2\beta \pm 0.024 \end{aligned}$$

Detecting axions...

$$\mathcal{L} \supset \frac{g}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} = g a \vec{E} \cdot \vec{B}$$

$$\mathcal{L} \supset -\frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

In a static magnetic field, the oscillating axion field generates EM-fields, oscillating at a frequency given by m_a: **ADMX, CAST, IAXO, dish antenna**...

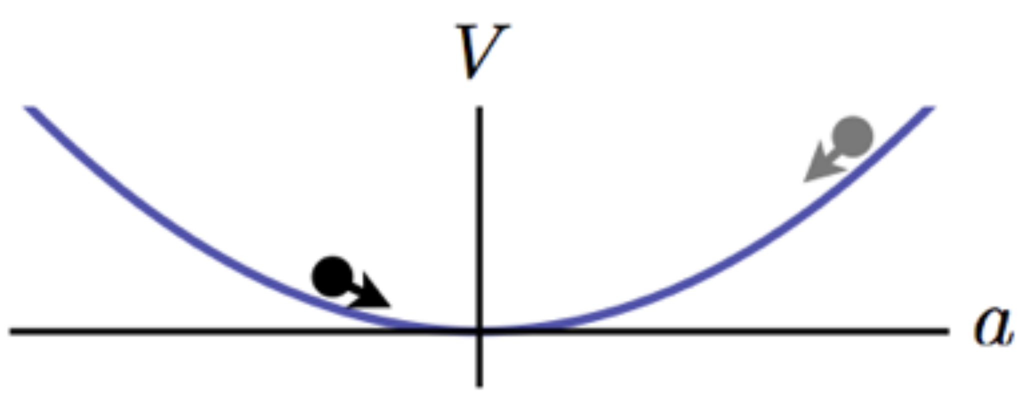
NMR searches:

- Axion gives all nucleons an oscillating EDM independent of f_a: **CASPEr**.
- Axion mediates short ranges spin-dependent forces between objects: **ARIADNE**.

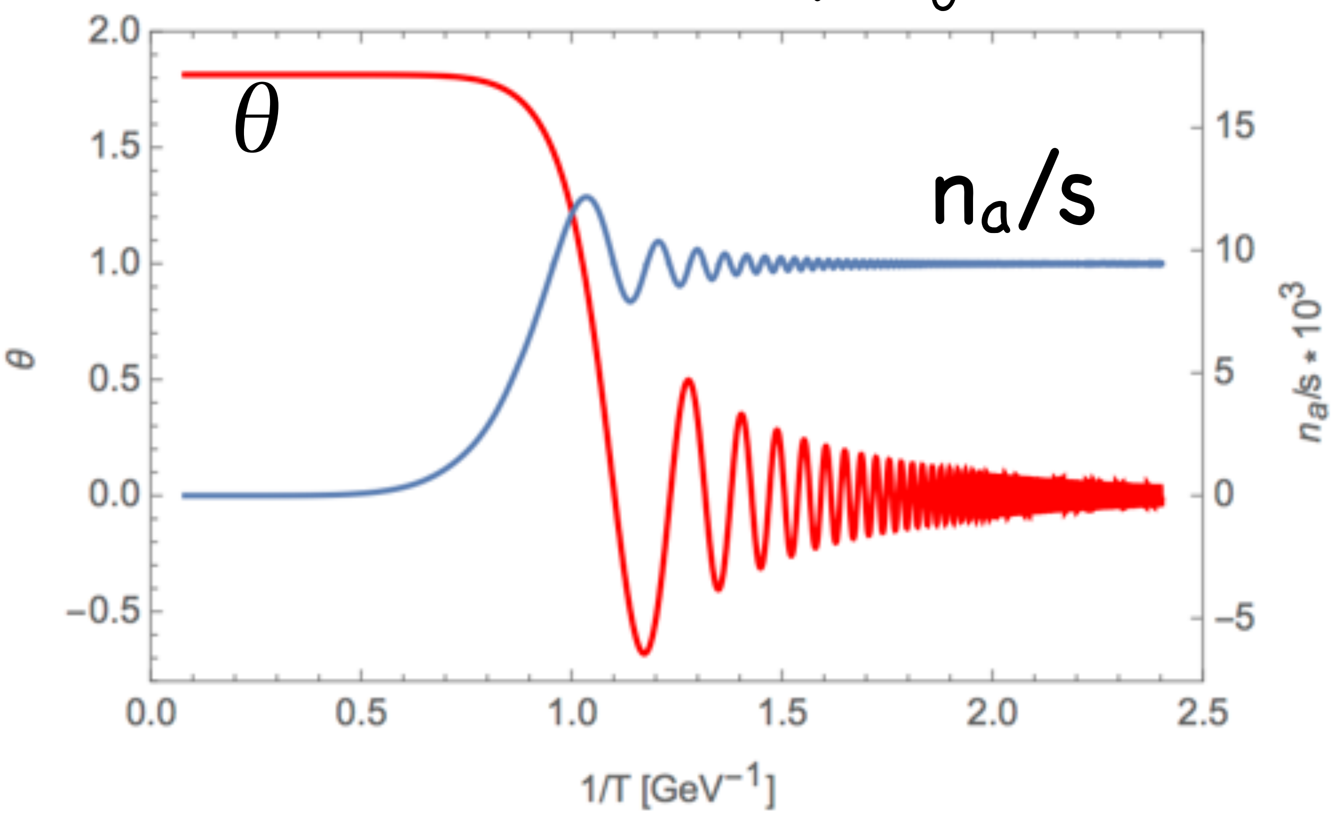
Dark matter relic density

Misalignment mechanism

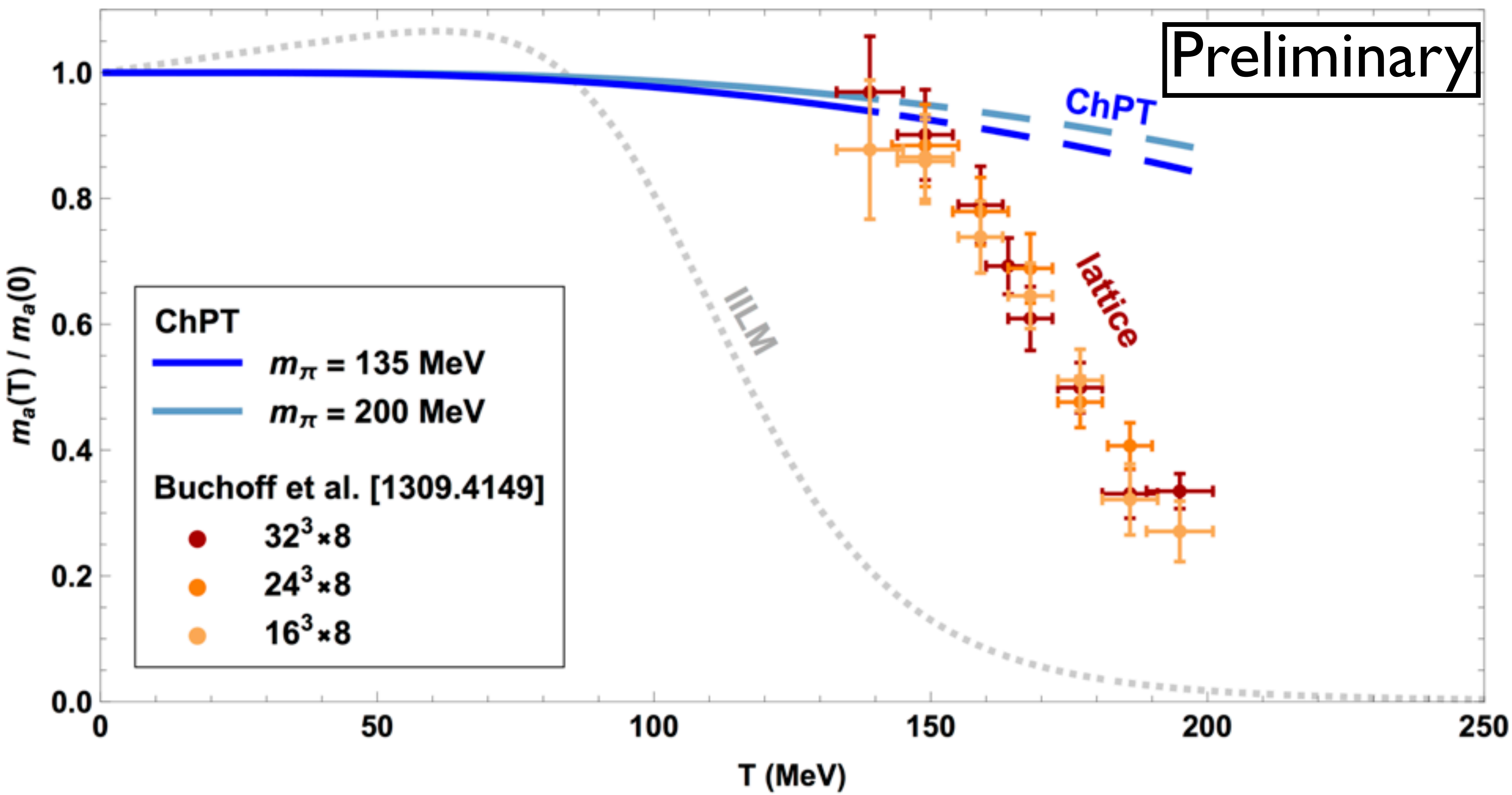
$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$



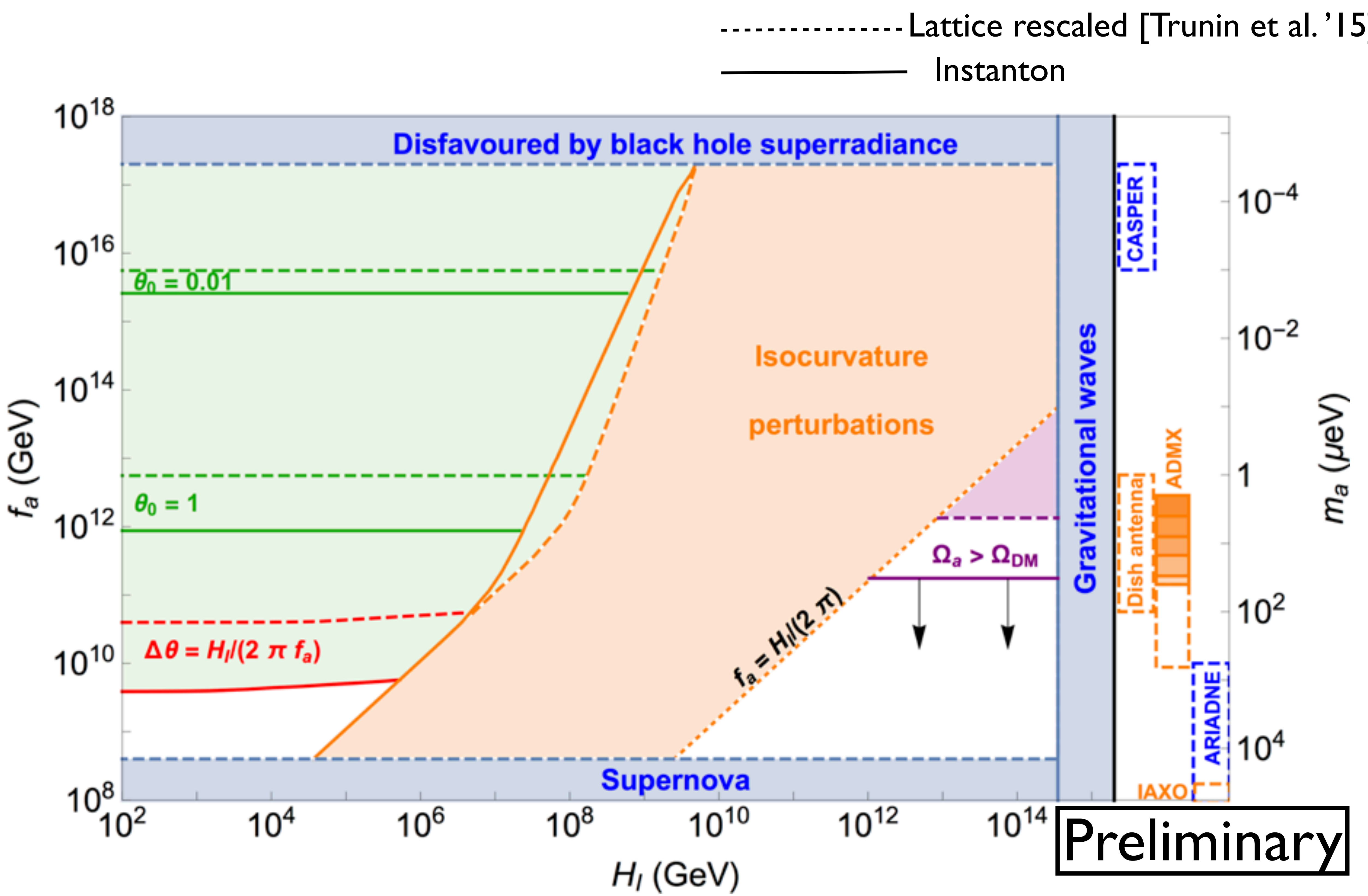
$f_a \simeq 10^{11}$, $\theta_0 \simeq \pi/\sqrt{3}$



Axion mass at finite T



Axion dark matter



Conclusions

- LHC14 might probe Winos up to ~1 TeV with 3000 fb^{-1}, while a 100 TeV collider may reach 3 TeV Winos.
- Direct detection experiments can probe complementary area of the parameter space for higgsino DM.
- In order to explore all the parameter space for Wino and higgsino DM, a 100 TeV collider seems to be a necessary tool.

- We showed that it is possible to achieve high precision in the axion physics. Improvement in lattice calculation will increase more the precision on the mass and the couplings of the axion.
- Lattice studies on the chiral susceptibility at $T > T_c$ will lead to higher precision in the axion mass at finite T and therefore smaller uncertainty on the relic density.