Gravitino or Axino Dark Matter with Reheat Temperature as high as 10^{16} GeV

Francesco D'Eramo

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

IBS-CTPU Focus Workshop on Particle Physics and Cosmology
5 December 2016

Very Small Numbers

Hierarchy Problem

$$\frac{m_{\text{weak}}^2}{M_{\text{Pl}}^2} \simeq 10^{-32}$$

Strong CP Problem

$$\theta \lesssim 10^{-10}$$

Motivated BSM Physics

Hierarchy Problem

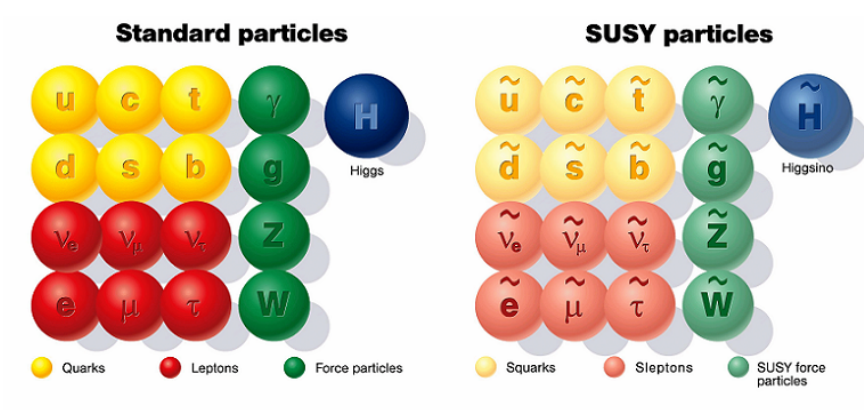


Image credit: DESY at Hamburg

Strong CP Problem

Image credit: http://motls.blogspot.com

SUSY: solution to the hierarchy problem, Higgs mass and gauge coupling unification

Peccei-Quinn: solution to the strong CP problem, relaxes the QCD ϴ angle to zero

Motivated BSM Physics

Hierarchy Problem

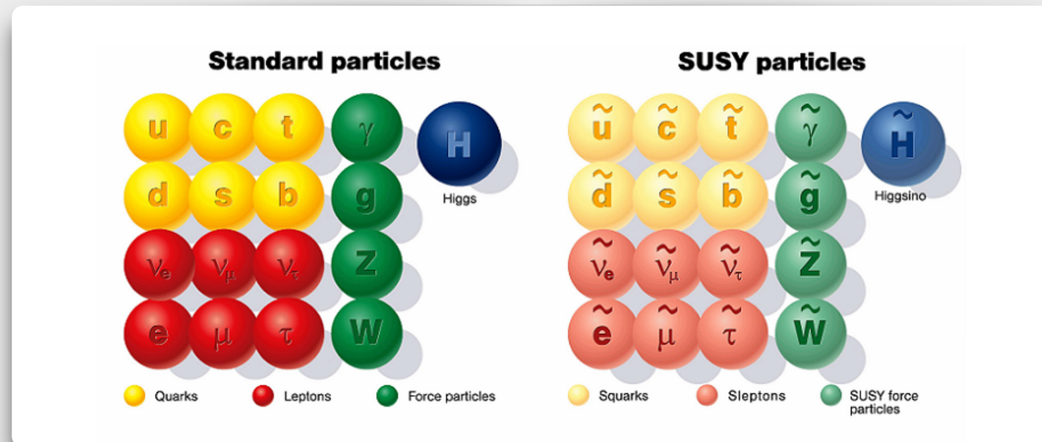
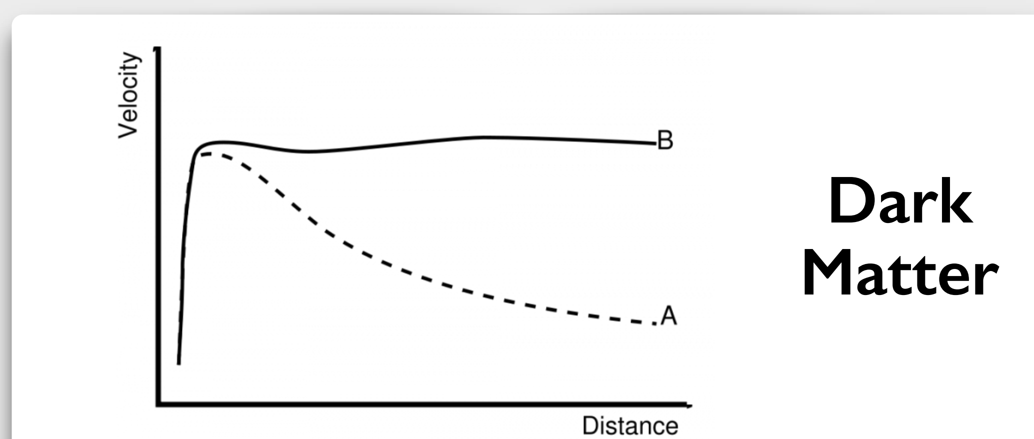


Image credit: DESY at Hamburg

Strong CP Problem

Image credit: http://motls.blogspot.com

A 3rd BSM Motivation



Motivated BSM Physics

Hierarchy Problem

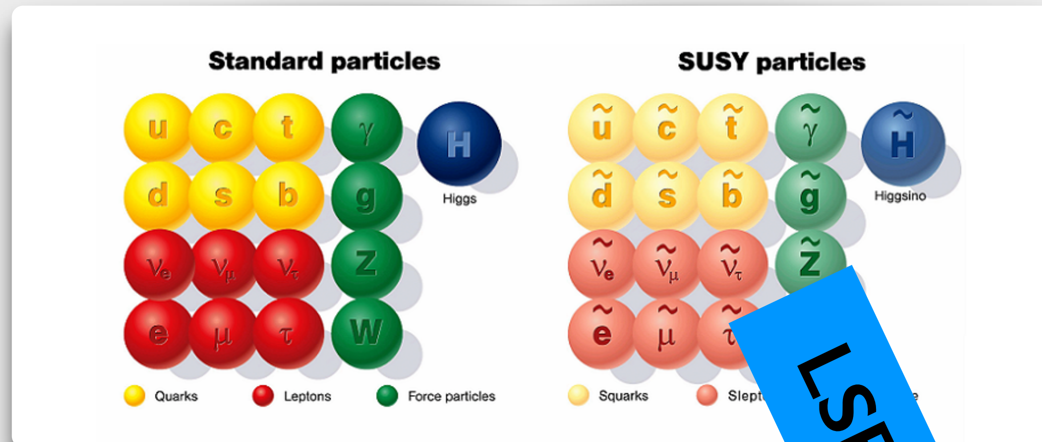


Image credit: DES amburg

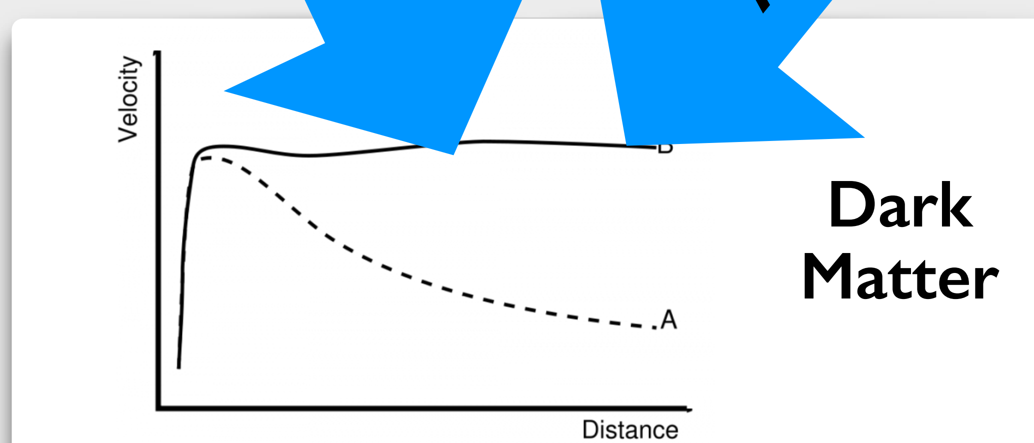
Strong CP Problem

credit: http://motls.blogspot.com

LSP Dark Matter

Axion Dark Matter

A 3rc SM Moti ion



Dark Matter

Motivated BSM Physics

Hierarchy Problem

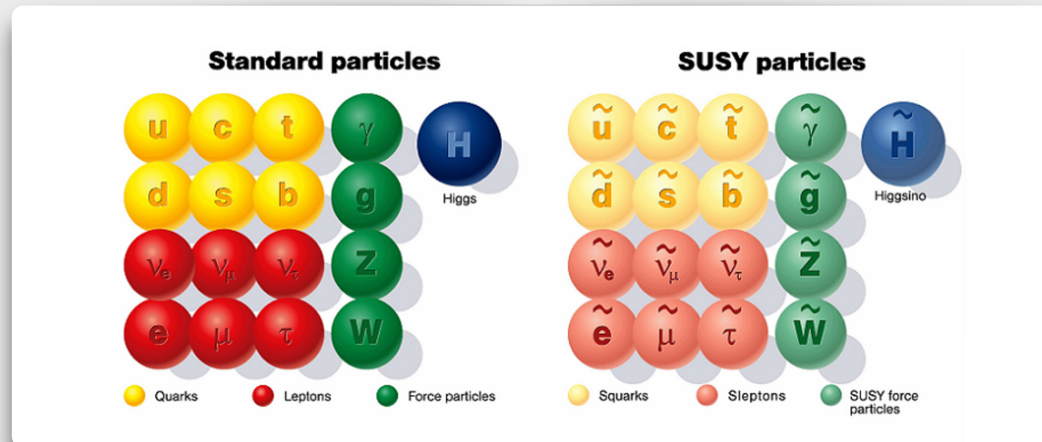


Image credit: DESY at Hamburg

Strong CP Problem

Image credit: http://motls.blogspot.com

SUSY and the Peccei-Quinn mechanism provide the two best motivated dark matter candidates

SUSY PQ Theories

Hierarchy Problem

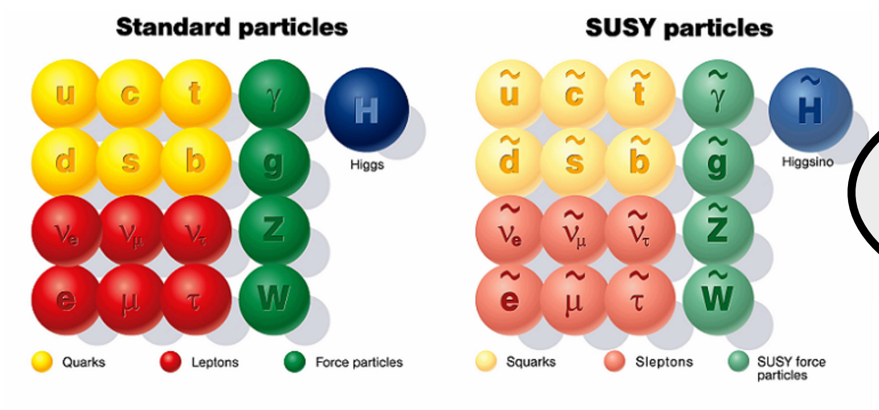


Image credit: DESY at Hamburg

&

Strong CP Problem

Image credit: http://motls.blogspot.com

SUSY PQ Theories

Hierarchy Problem

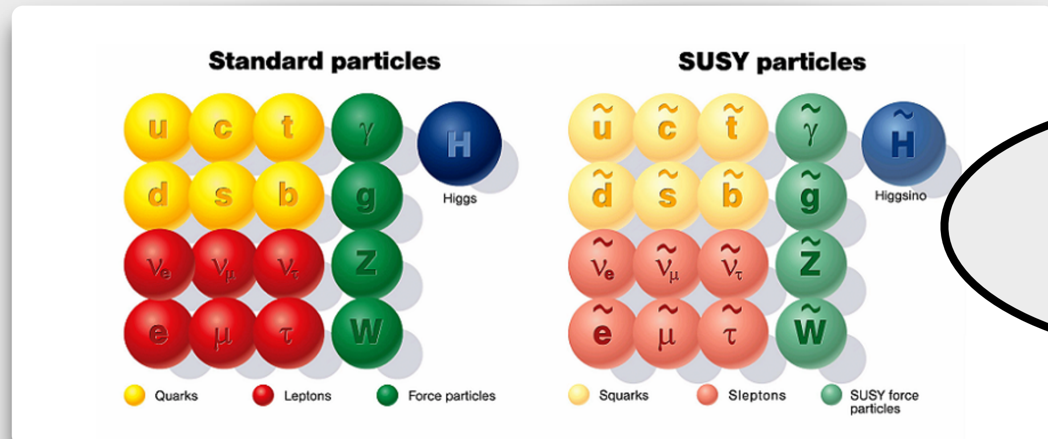


Image credit: DESY at Hamburg

&

Strong CP Problem

Image credit: http://motls.blogspot.com

The axion a does not come alone…

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

…but with its superpartners, the saxion and the axino

SUSY PQ Theories

Hierarchy Problem

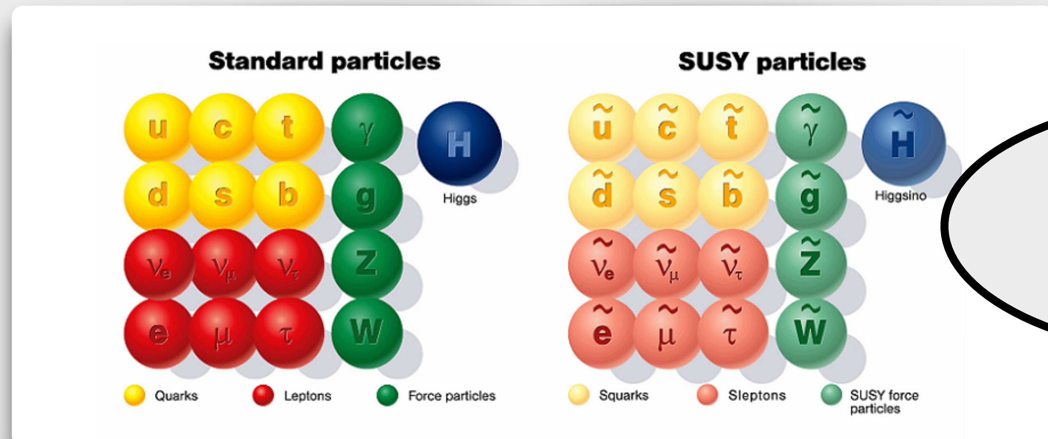


Image credit: DESY at Hamburg

&

Strong CP Problem

Image credit: http://motls.blogspot.com

The axion a does not come alone…

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

…but with its superpartners, the saxion and the axino

Soft masses, very weakly coupled, *dramatic effects*

Hashimoto, Izawa, Yamaguchi, Yanagida, PLB437 (1998)(hep-ph/9803263); Kawasaki, Nakayama, PRD77 (2008) (arXiv:0802.2487); Kawasaki, Kitajima, Nakayama, PRD83 (2011) (arXiv:1104.1262); Asaka, Yanagida, PLB494 (2000) (hep-ph/0006211); Baer, Lessa, Sekmen, JCAP1104 (2011) (arXiv:1012.3760); Baer, Lessa, JHEP1106 (2011) (arXiv:1104.4807); Bae, Baer, Lessa, Serce, JCAP1410 (2014) (arXiv:1406.4138); Hasenkamp Kersten, PRD82 (2010) (arXiv:1008.1740)

SUSY PQ Theories

Hierarchy Problem

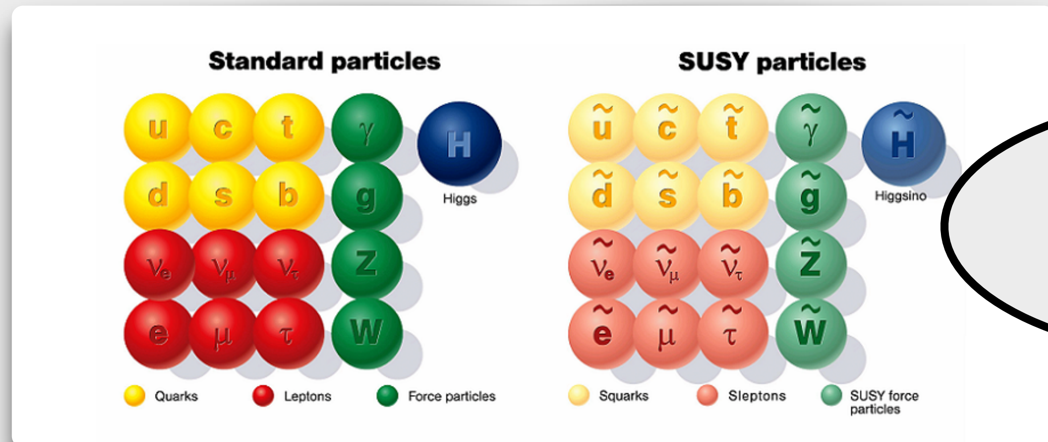


Image credit: DESY at Hamburg

&

Strong CP Problem

Image credit: http://motls.blogspot.com

Today's Talk

Gravitino and Axino DM scenarios for theories with *both* SUSY and PQ?

Observable signatures?

Raymond Co, FD, Lawrence Hall, arXiv:1611.05028

Dark Matter in SUSY PQ

DFSZ theories

Dine, Fischler, Srednicki, PLB104 (1981)
Zhitnitsky, SJNP31(1980)

$$W_{\rm DFSZ} = \mu H_u H_d + q_\mu \frac{\mu}{V_{PQ}} A\, H_u H_d + \ldots$$

Dark Matter in SUSY PQ

DFSZ theories

Dine, Fischler, Srednicki, PLB104 (1981)
Zhitnitsky, SJNP31(1980)

$$W_{\mathrm{DFSZ}} = \mu H_u H_d + q_\mu \frac{\mu}{V_{PQ}} A\, H_u H_d + \ldots$$

Axion Dark Matter

Bae, Huh, Kim, JCAP 0809 (2008) (arXiv:0806.0497)

$$f_a = \sqrt{2} V_{\mathrm{PQ}} / N_{\mathrm{DW}}$$

$$\Omega_a h^2 \simeq \theta_i^2 \; (f_a / 10^{12}\,\mathrm{GeV})^{1.18}$$

Dark Matter in SUSY PQ

DFSZ theories

Dine, Fischler, Srednicki, PLB104 (1981)
Zhitnitsky, SJNP31(1980)

$$W_{\mathrm{DFSZ}} = \mu H_u H_d + q_\mu \frac{\mu}{V_{PQ}} A\, H_u H_d + \ldots$$

Axion Dark Matter

Bae, Huh, Kim, JCAP 0809 (2008) (arXiv:0806.0497)

$f_a = \sqrt{2} V_{\mathrm{PQ}}/N_{\mathrm{DW}}$

$$\Omega_a h^2 \simeq \theta_i^2 \, (f_a/10^{12}\,\mathrm{GeV})^{1.18}$$

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\mathrm{F.O.})} h^2 \simeq 0.1\,(1\,\mathrm{pb}/\langle \sigma v_{\mathrm{rel}} \rangle)$$

Lee, Weinberg, PRL39 (1977)

Gravitino UV Production

$$\Omega_{3/2}^{(\mathrm{UV})} h^2 \simeq 0.1\,(1\,\mathrm{GeV}/m_{3/2})\,(T_{\mathrm{RH}}/10^6\,\mathrm{GeV})$$

Strumia, Rychkov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\mathrm{F.I.})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(\mu/300\,\mathrm{GeV})\,(10^{13}\,\mathrm{GeV}/V_{\mathrm{PQ}})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

$$\Omega_{\tilde{a}}^{(\mathrm{UV})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(10^{12}\,\mathrm{GeV}/f_a)^2 (T_{\mathrm{RH}}/10^4\,\mathrm{GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Dark Matter in SUSY PQ

Present also in the MSSM alone

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\mathrm{F.O.})} h^2 \simeq 0.1 \, (1\,\mathrm{pb}/\langle \sigma v_{\mathrm{rel}} \rangle)$$

Lee, Weinberg, PRL39 (1977)

Gravitino UV Production

$$\Omega_{3/2}^{(\mathrm{UV})} h^2 \simeq 0.1 \, (1\,\mathrm{GeV}/m_{3/2}) \, (T_{\mathrm{RH}}/10^6\,\mathrm{GeV})$$

Strumia, Rychkov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\mathrm{F.I.})} h^2 \simeq 0.1 \, (m_{\tilde{a}}/1\,\mathrm{GeV}) \, (\mu/300\,\mathrm{GeV}) \, (10^{13}\,\mathrm{GeV}/V_{\mathrm{PQ}})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

$$\Omega_{\tilde{a}}^{(\mathrm{UV})} h^2 \simeq 0.1 \, (m_{\tilde{a}}/1\,\mathrm{GeV}) \, (10^{12}\,\mathrm{GeV}/f_a)^2 (T_{\mathrm{RH}}/10^4\,\mathrm{GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Dark Matter in SUSY PQ

Present also in the MSSM alone (with their issues…)

Neutralino has to be *well-tempered*

Arkani-Hamed, Giudice, Delgado, NPB741 (2006) (hep-ph/0601041)

Gravitino *abundance* and *late-time decays* severely constrained

Moroi, Murayama, Yamaguchi, PLB303 (1993)
Kawasaki, Kohri, Moroi, Yotsuyanagi, PRD78 (2008) (arXiv:0804.3745)

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\mathrm{F.O.})} h^2 \simeq 0.1\,(1\,\mathrm{pb}/\langle \sigma v_{\mathrm{rel}}\rangle)$$

Lee, Weinberg, PRL39 (1977)

Gravitino UV Production

$$\Omega_{3/2}^{(\mathrm{UV})} h^2 \simeq 0.1\,(1\,\mathrm{GeV}/m_{3/2})\,(T_{\mathrm{RH}}/10^6\,\mathrm{GeV})$$

Strumia, Rychkov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\mathrm{F.I.})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(\mu/300\,\mathrm{GeV})\,(10^{13}\,\mathrm{GeV}/V_{\mathrm{PQ}})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

$$\Omega_{\tilde{a}}^{(\mathrm{UV})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(10^{12}\,\mathrm{GeV}/f_a)^2 (T_{\mathrm{RH}}/10^4\,\mathrm{GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Dark Matter in SUSY PQ

A new R-odd particle in SUSY PQ theories

Both IR and UV axino production mechanisms

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\mathrm{F.O.})} h^2 \simeq 0.1\,(1\ \mathrm{p} \ldots \langle\sigma v_{\mathrm{rel}}\rangle)$$

...einberg, PRL39 (1977)

Gravitino U... ...roduction

$$\Omega_{3/2}^{(\mathrm{UV})} h^2 \simeq 0.1\,(1 \ldots \mathrm{V}/m_{3/2})\,(T_{\mathrm{RH}}/10^6\,\mathrm{GeV})$$

Strumia, ...ov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\mathrm{F.I.})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(\mu/300\,\mathrm{GeV})\,(10^{13}\,\mathrm{GeV}/V_{\mathrm{PQ}})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

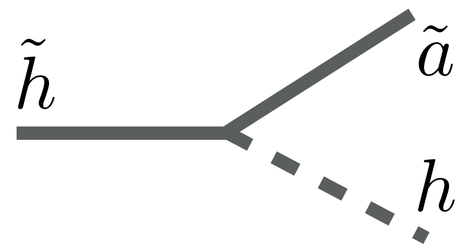
$$\Omega_{\tilde{a}}^{(\mathrm{UV})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(10^{12}\,\mathrm{GeV}/f_a)^2 (T_{\mathrm{RH}}/10^4\,\mathrm{GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Dark Matter in SUSY PQ

DFSZ Axino Freeze-In

$$W_{\mathrm{DFSZ}} \supset q_\mu \frac{\mu}{V_{PQ}} A\, H_u H_d$$



EWinos in thermal equilibrium decaying to axinos

Production dominated at TeV scale (IR)

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\mathrm{F.O.})} h^2 \simeq 0.1\,(1\,\mathrm{pb}/\langle \sigma v_{\mathrm{rel}} \rangle)$$

Lee, Weinberg, PRL39 (1977)

Gravitino UV Production

$$\Omega_{3/2}^{(\mathrm{UV})} h^2 \simeq 0.1\,(1\,\mathrm{GeV}/m_{3/2})\,(T_{\mathrm{RH}}/10^6\,\mathrm{GeV})$$

Strumia, Rychkov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\mathrm{F.I.})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(\mu/300\,\mathrm{GeV})\,(10^{13}\,\mathrm{GeV}/V_{\mathrm{PQ}})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

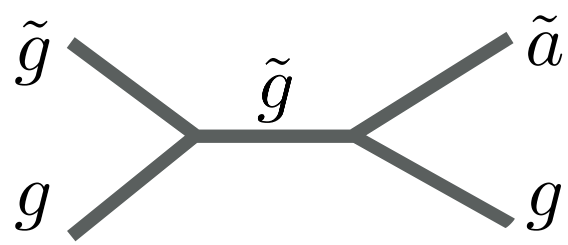
$$\Omega_{\tilde{a}}^{(\mathrm{UV})} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,\mathrm{GeV})\,(10^{12}\,\mathrm{GeV}/f_a)^2 (T_{\mathrm{RH}}/10^4\,\mathrm{GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Dark Matter in SUSY PQ

Axino UV Production

$$\mathcal{L}_{\rm UV} \propto \frac{g_3^2}{v_{\rm PQ}} \int d^2\theta A W^\alpha W_\alpha$$



Model dependent
Fermion content of PQ sector
Not present in minimal DFSZ

Bae, Choi, Im, JHEP1108 (2011) (arXiv:1106.2452)

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\rm F.O.)} h^2 \simeq 0.1\,(1\,{\rm pb}/\langle\sigma v_{\rm rel}\rangle)$$

Lee, Weinberg, PRL39 (1977)

Gravitino UV Production

$$\Omega_{3/2}^{(\rm UV)} h^2 \simeq 0.1\,(1\,{\rm GeV}/m_{3/2})\,(T_{\rm RH}/10^6\,{\rm GeV})$$

Strumia, Rychkov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\rm F.I.)} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,{\rm GeV})\,(\mu/300\,{\rm GeV})\,(10^{13}\,{\rm GeV}/V_{\rm PQ})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

$$\Omega_{\tilde{a}}^{(\rm UV)} h^2 \simeq 0.1\,(m_{\tilde{a}}/1\,{\rm GeV})\,(10^{12}\,{\rm GeV}/f_a)^2 (T_{\rm RH}/10^4\,{\rm GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Dark Matter in SUSY PQ

They all contribute to LSP dark matter abundance, regardless of the LSP nature

LSP Dark Matter

Neutralino Freeze-Out

$$\Omega_{\tilde{N}}^{(\mathrm{F.O.})} h^2 \simeq 0.1 \, (1 \, \mathrm{pb} / \langle \sigma v_{\mathrm{rel}} \rangle)$$

Lee, Weinberg, PRL39 (1977)

Gravitino UV Production

$$\Omega_{3/2}^{(\mathrm{UV})} h^2 \simeq 0.1 \, (1 \, \mathrm{GeV} / m_{3/2}) \, (T_{\mathrm{RH}} / 10^6 \, \mathrm{GeV})$$

Strumia, Rychkov, PRD75 (2007) (hep-ph/0701104)

Axino Freeze-In

$$\Omega_{\tilde{a}}^{(\mathrm{F.I.})} h^2 \simeq 0.1 \, (m_{\tilde{a}} / 1 \, \mathrm{GeV}) \, (\mu / 300 \, \mathrm{GeV}) \, (10^{13} \, \mathrm{GeV} / V_{\mathrm{PQ}})^2$$

Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Axino UV Production

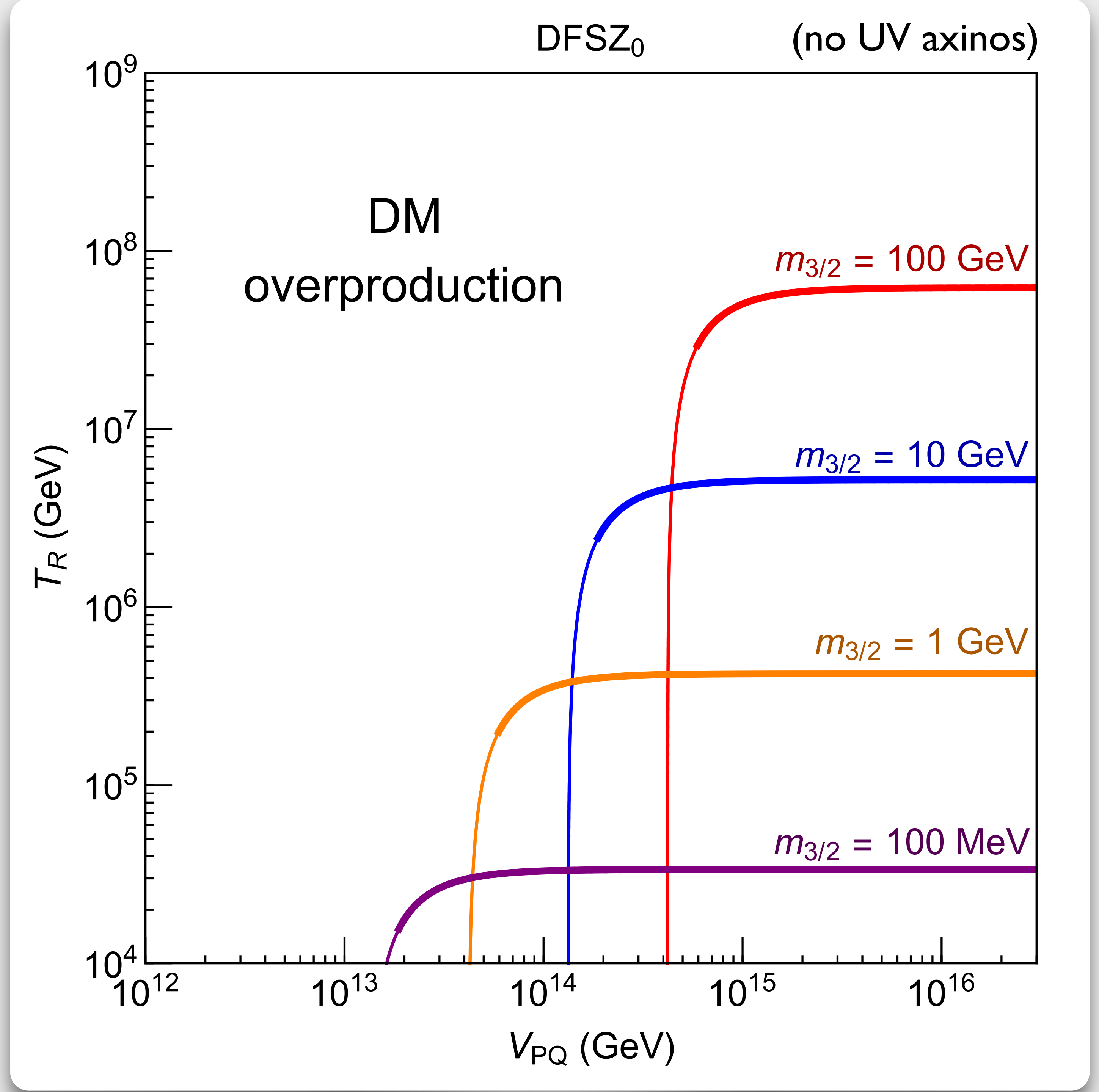
$$\Omega_{\tilde{a}}^{(\mathrm{UV})} h^2 \simeq 0.1 \, (m_{\tilde{a}} / 1 \, \mathrm{GeV}) \, (10^{12} \, \mathrm{GeV} / f_a)^2 (T_{\mathrm{RH}} / 10^4 \, \mathrm{GeV})$$

Strumia, JHEP1006 (2010) (arXiv:1003.5847)

Cosmological Disaster?

Typical TeV SUSY spectrum with LSP gravitino

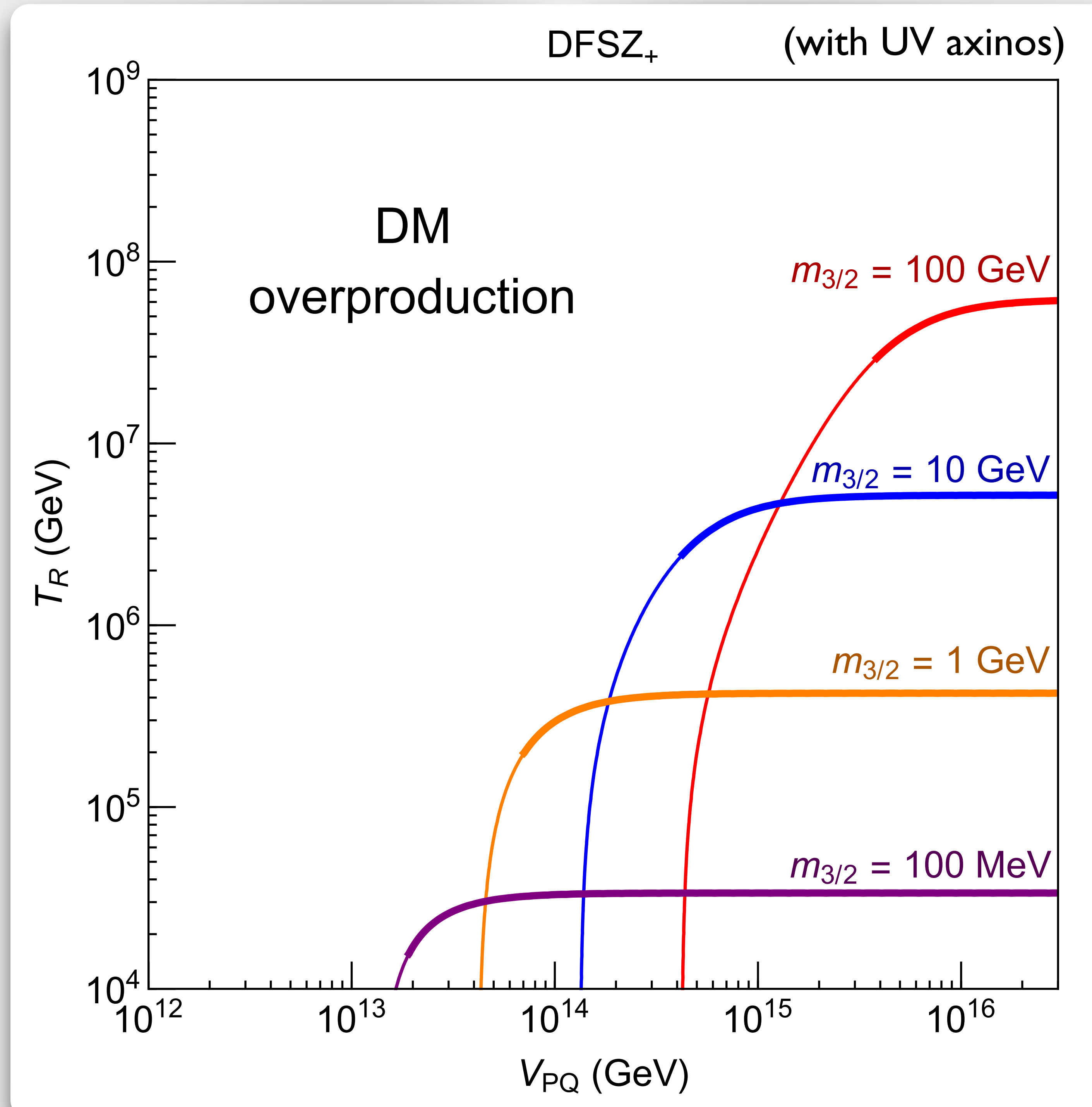
DM relic density: low reheat temperature (UV gravitino) and large V_{PQ} (IR axino freeze-in)



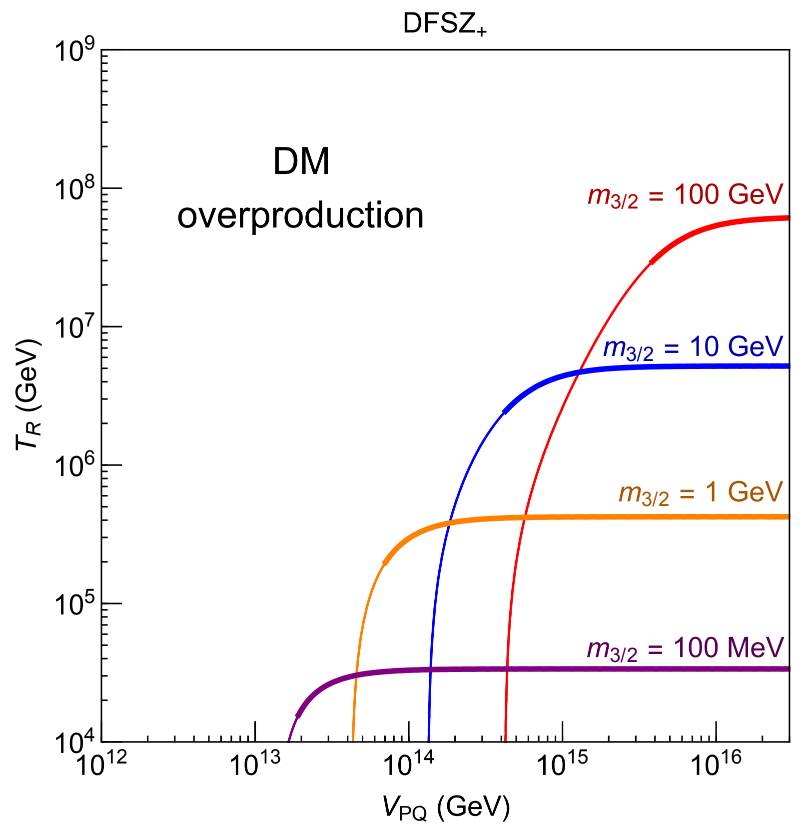
Cosmological Disaster?

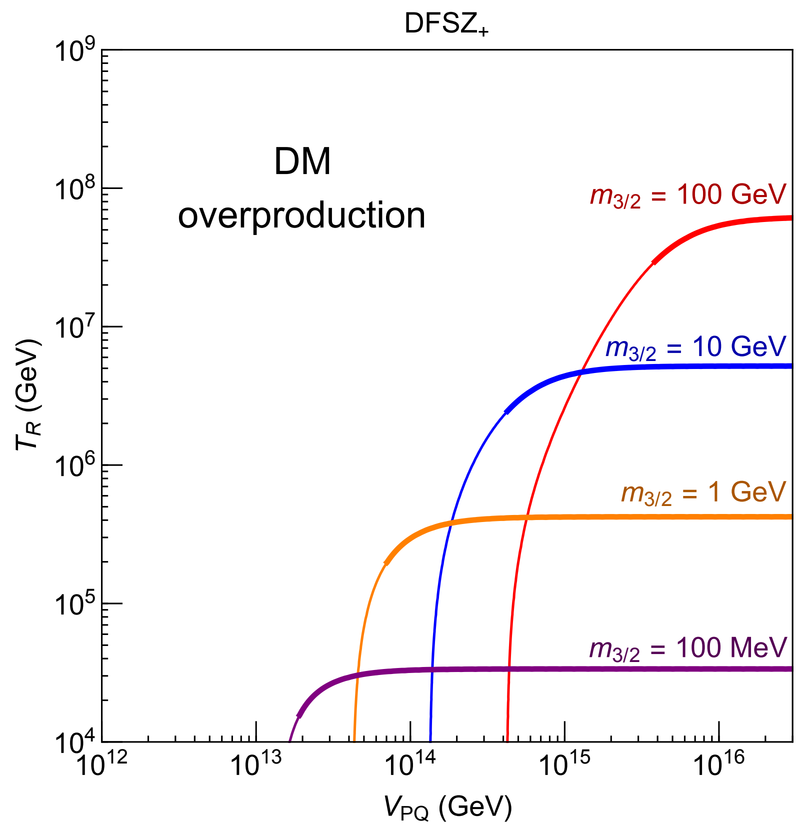
Typical TeV SUSY spectrum with LSP gravitino

Adding UV axinos only makes things worse



Cosmological Disaster?

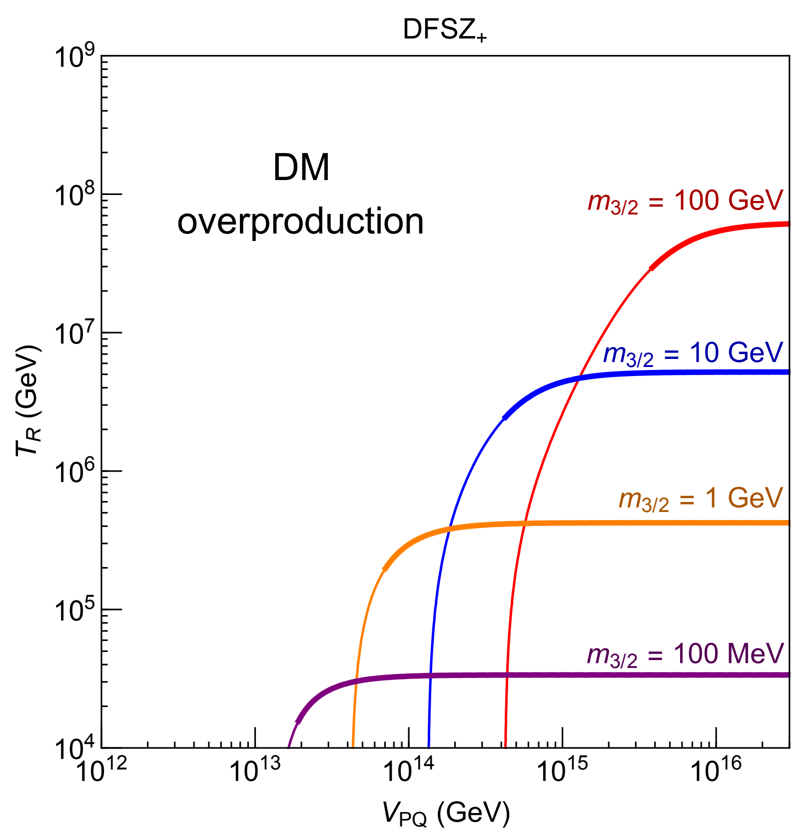


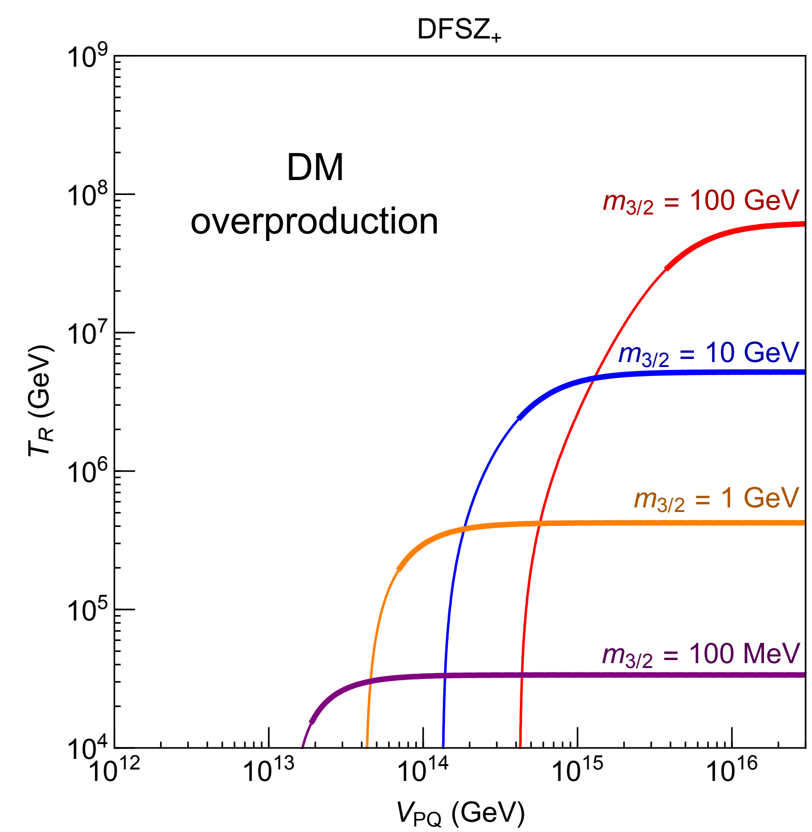


LSP Dark Matter in SUSY PQ:

low T_R (no leptogenesis) and large V_{PQ} (axion overproduction)?

Cosmological Disaster?



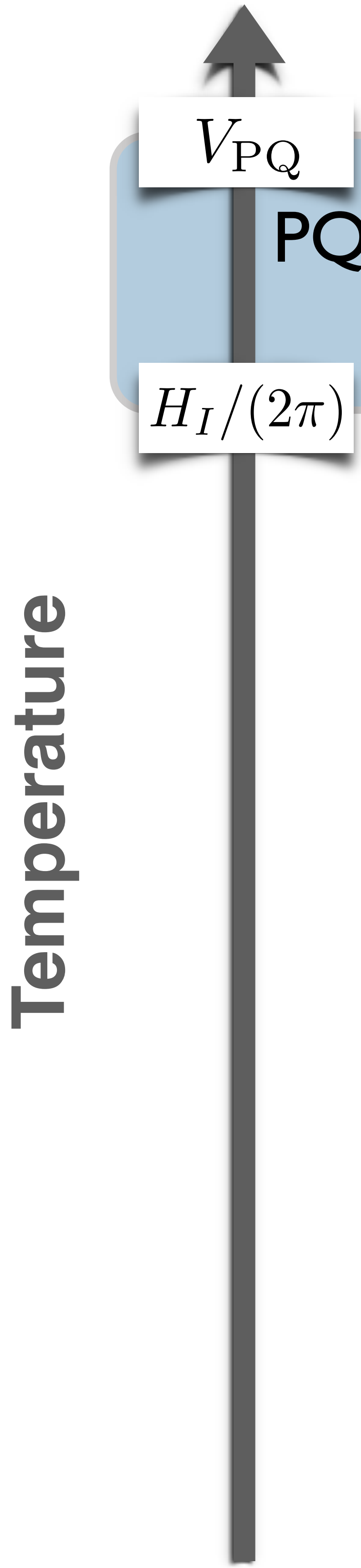


LSP Dark Matter in SUSY PQ:

low T_R (no leptogenesis) and large V_{PQ} (axion overproduction)?

Wait… Saxion effects not accounted for!

Saxion Cosmology



PQ broken during inflation and not restored afterwards (domain wall)

Saxion develops a large condensate: $s_I = V_{PQ}$ or M_*

Saxion Cosmology

V_{PQ}

PQ broken during inflation and not restored afterwards (domain wall)

Saxion develops a large condensate: $s_I = V_{PQ}$ or M_*

$H_I/(2\pi)$

After inflationary reheating saxion stuck by Hubble friction

Temperature

Saxion Cosmology

Temperature

$V_{\rm PQ}$

PQ broken during inflation and not restored afterwards (domain wall)

Saxion develops a large condensate: $s_I = V_{PQ}$ or M_*

$H_I/(2\pi)$

After inflationary reheating saxion stuck by Hubble friction

$T_{\rm osc}$

Universe cools enough that saxion starts oscillating

Energy density stored in oscillations red-shifts as NR matter

Saxion Cosmology

Temperature

$V_{\rm PQ}$

PQ broken during inflation and not restored afterwards (domain wall)

Saxion develops a large condensate: $s_I = V_{PQ}$ or M_*

$H_I/(2\pi)$

After inflationary reheating saxion stuck by Hubble friction

$T_{\rm osc}$

Universe cools enough that saxion starts oscillating

Energy density stored in oscillations red-shifts as NR matter

T_M

Universe enters an early matter dominated (MD epoch),

lasting until the saxion condensate decays to Standard Model

T_{Rs}

Saxion Cosmology

Temperature

V_{PQ}

PQ broken during inflation and not restored afterwards (domain wall)

Saxion ... ndensate: $s_I = V_{PQ}$ or M_*

$H_I/(2\pi)$

After in ... onary reheating saxion st ... k by Hubble friction

T_{osc}

Universe c ... n starts oscillating

Energy density stored in oscillation ... hifts as NR matter

T_M

Universe enters an early matter domin ... epoch),

lasting until the saxion condensate decays to ... Model

T_{Rs}

Saxion Cosmology

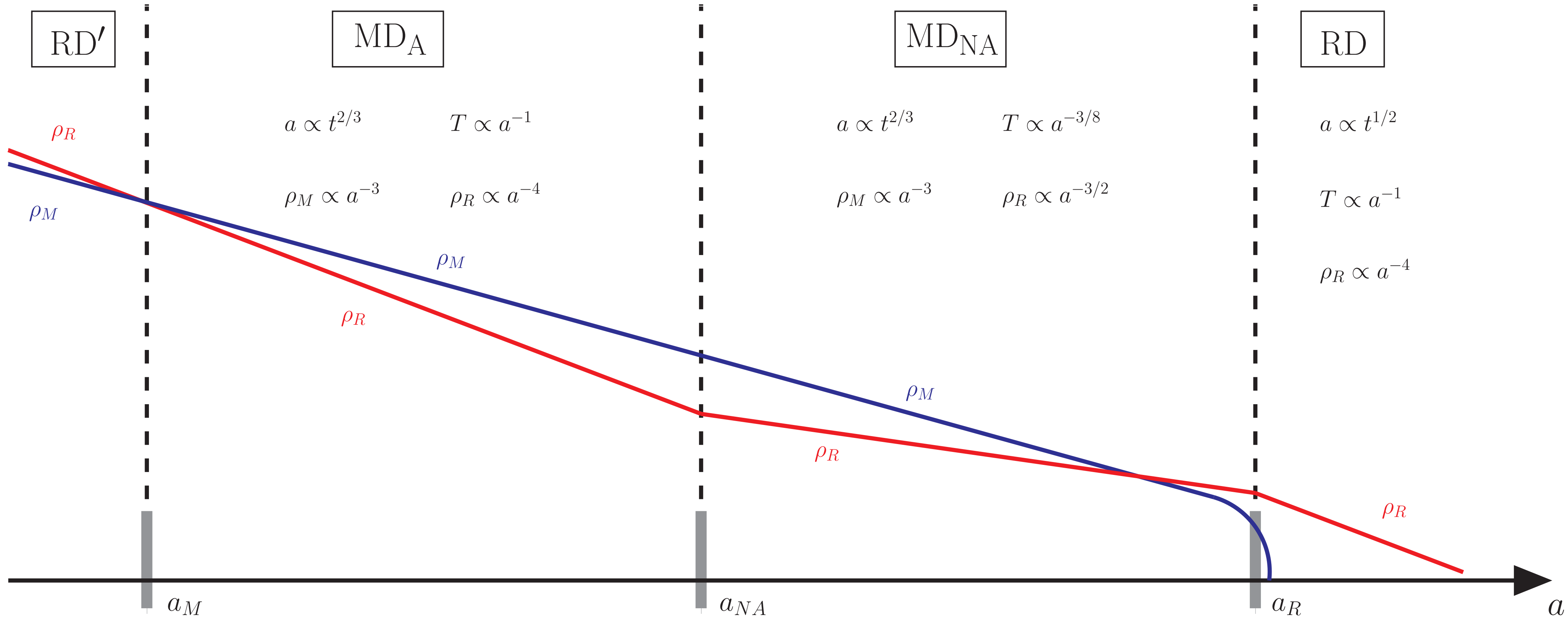


Figure from Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

Saxion Cosmology

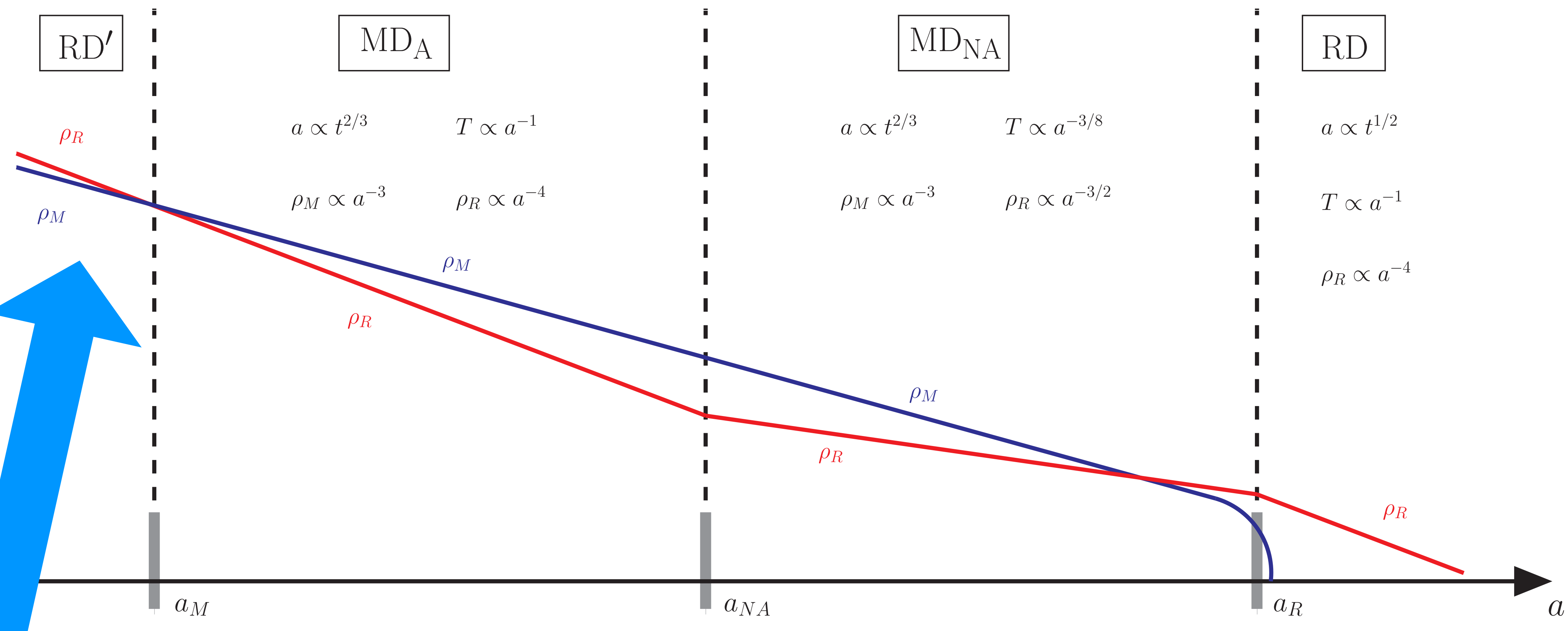


Figure from Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

RD'

Radiation energy still dominates

Saxion Cosmology

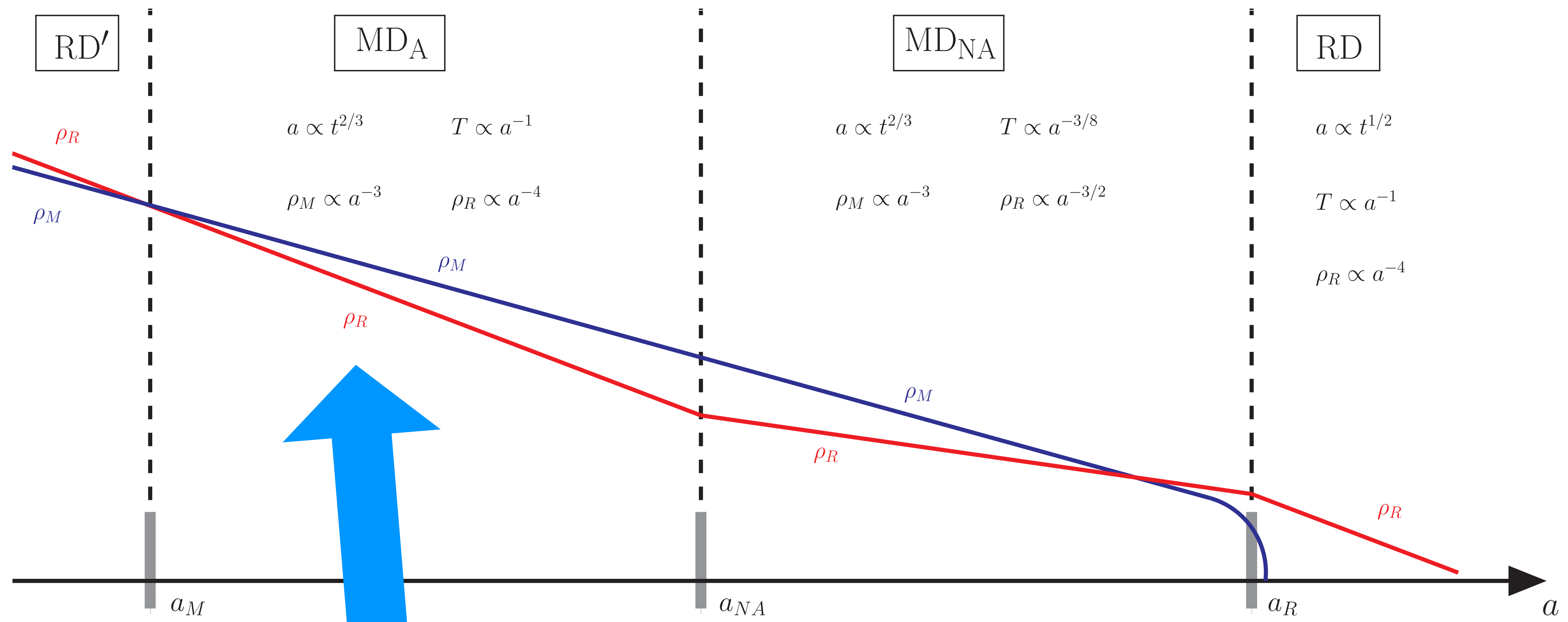


Figure from Co, FD, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

RD'

Radiation energy still dominates

MD$_A$

Saxion oscillations take over the energy budget

Saxion Cosmology

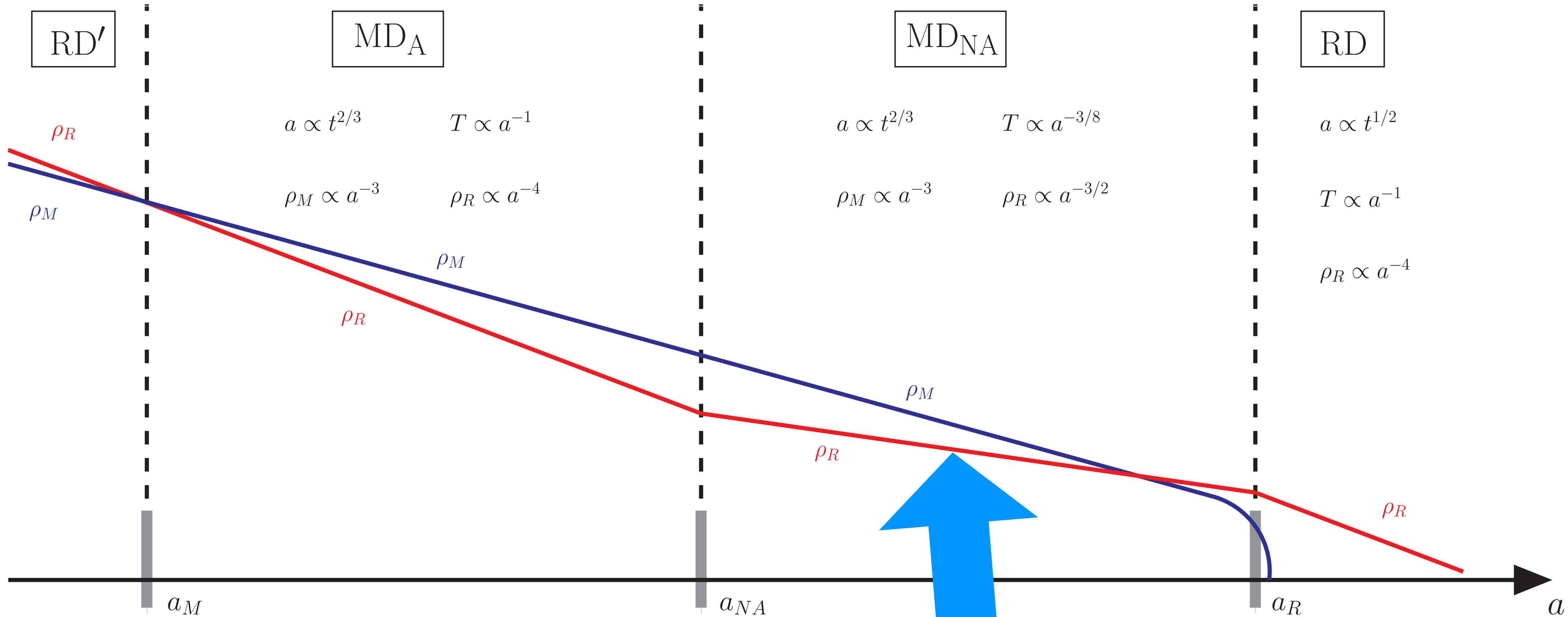


Figure from C[illegible]D, Hall, Pappadopulo, JCAP1512 (2015) (arXiv:1506.07532)

RD'

Radiation energy still dominates

MD$_A$

Saxion oscillations take over the energy budget

MD$_{NA}$

Radiation dominated by saxion decay products, entropy not conserved

Saxion Cosmology

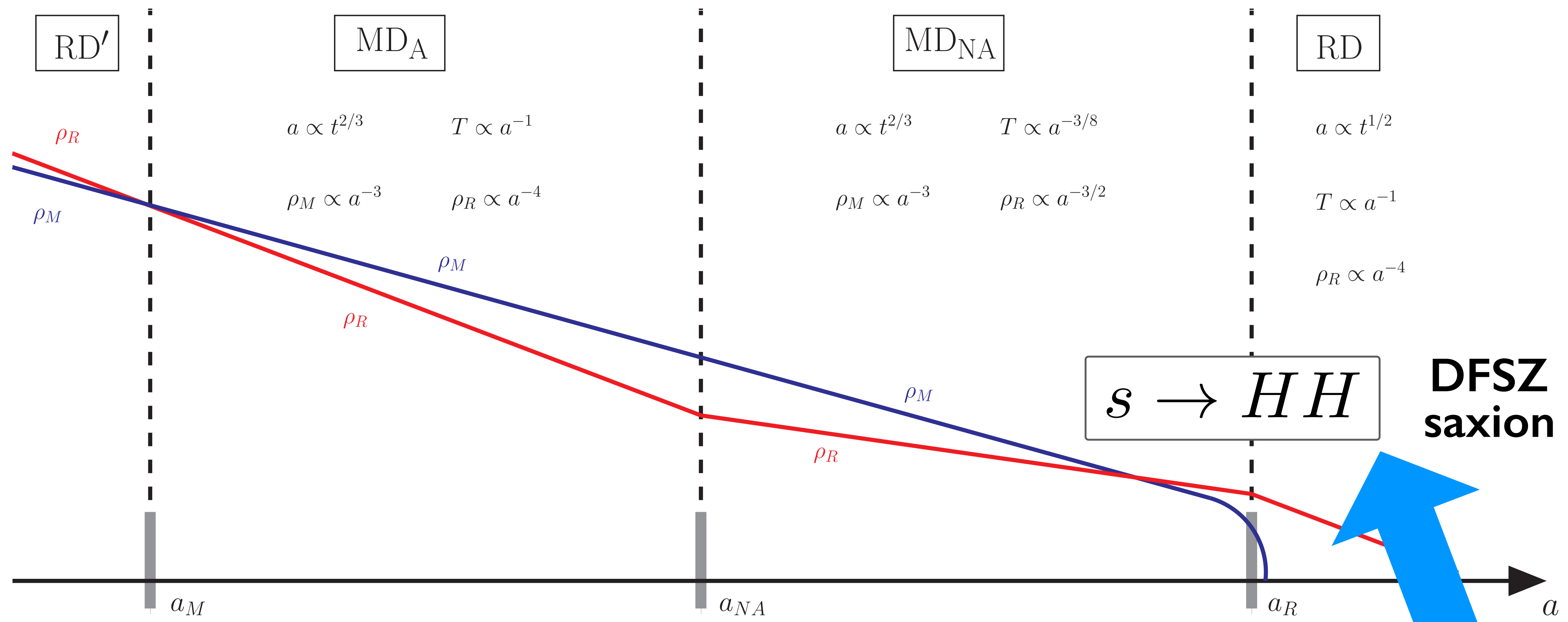


Figure from Co, FD, Hall, Pappadopulo, JCAP1512 (20… arXiv:1506.07532)

RD'
Radiation energy still dominates

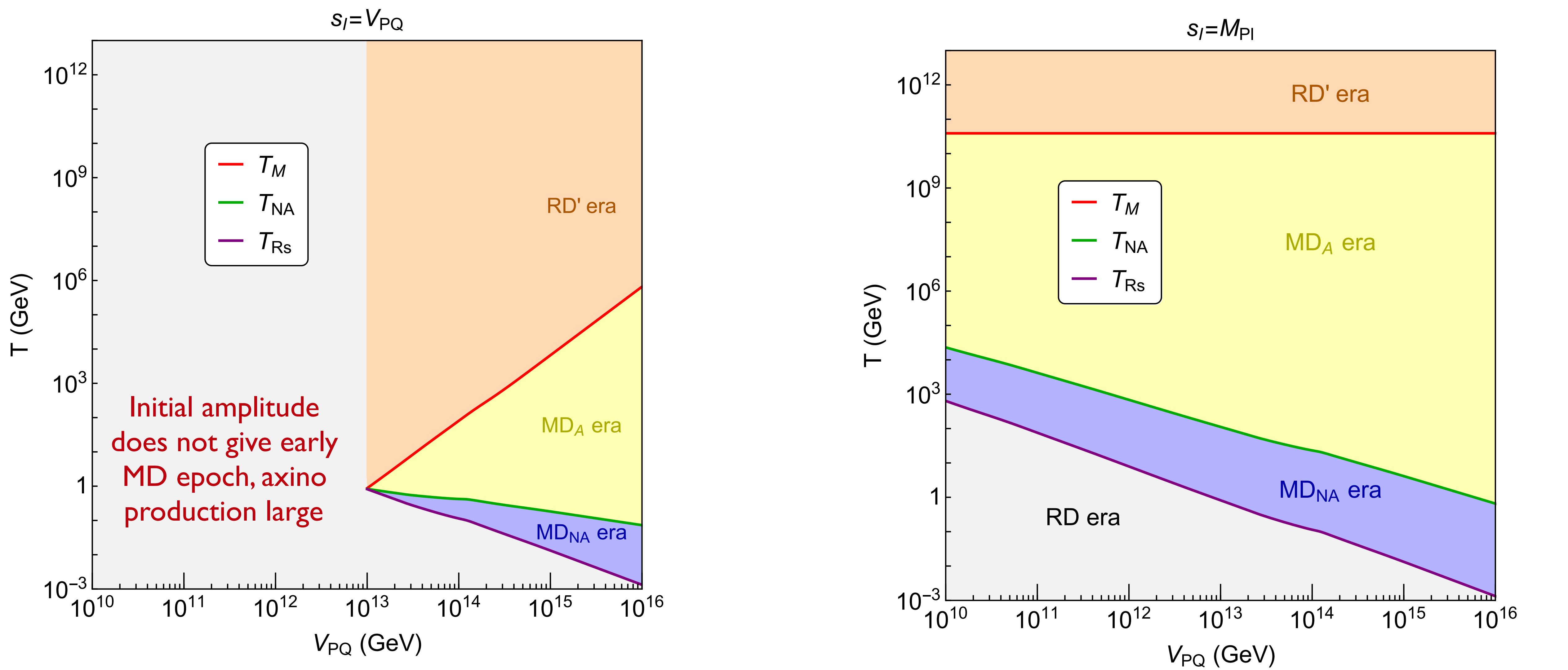
MDA
Saxion oscillations take over the energy budget

MDNA
Radiation dominated by saxion decay products, entropy not conserved

RD
Saxion condensate decays

Saxion Cosmology

Characteristic Temperatures



Each UV production mechanism diluted by $D = T_M / T_{Rs}$

Saxion Cosmology

Temperature

$V_{\rm PQ}$

PQ broken during inflation and not restored afterwards (domain wall)

Saxion develops a large condensate: $s_I = V_{PQ}$ or M_*

$H_I/(2\pi)$

After inflationary reheating saxion stuck by Hubble friction

$T_{\rm osc}$

Universe cools enough that saxion starts oscillating

Energy density stored in oscillations red-shifts as NR matter

T_M

Universe enters an early matter dominated (MD epoch),

lasting until the saxion condensate decays to Standard Model

T_{Rs}

$$T_{Rs} \simeq 10\,\mathrm{MeV}\left(\frac{\mu}{\mathrm{TeV}}\right)^{3/2}\left(\frac{\mu}{m_s}\right)^{1/2}\left(\frac{10^{15}\,\mathrm{GeV}}{V_{PQ}}\right)$$

$T_{\rm BBN}$

DM Scenarios

What are the viable DM scenarios in the presence of a large dilution by the saxion condensate?

DM Scenarios

What are the viable DM scenarios in the presence of a large dilution by the saxion condensate?

Misalignment Axions with large V_{PQ}

GUT and PQ broken together ("SaxiGUTs")

$$\Omega_a h^2 \simeq 0.1\ \theta_i^2 \left(\frac{f_a}{10^{15}\,\mathrm{GeV}} \right)^2 \left(\frac{T_{Rs}}{3\,\mathrm{MeV}} \right) \qquad f_a = \sqrt{2} V_{\mathrm{PQ}} / N_{\mathrm{DW}}$$

Raymond Co, FD, Lawrence Hall, PRD94 (2016) (arXiv:1603.04439)

DM Scenarios

What are the viable DM scenarios in the presence of a large dilution by the saxion condensate?

Misalignment Axions with large V_{PQ}

GUT and PQ broken together ("SaxiGUTs")

$$\Omega_a h^2 \simeq 0.1\ \theta_i^2 \left(\frac{f_a}{10^{15}\,\mathrm{GeV}}\right)^2 \left(\frac{T_{Rs}}{3\,\mathrm{MeV}}\right) \qquad f_a = \sqrt{2} V_{\mathrm{PQ}}/N_{\mathrm{DW}}$$

Raymond Co, FD, Lawrence Hall, PRD94 (2016) (arXiv:1603.04439)

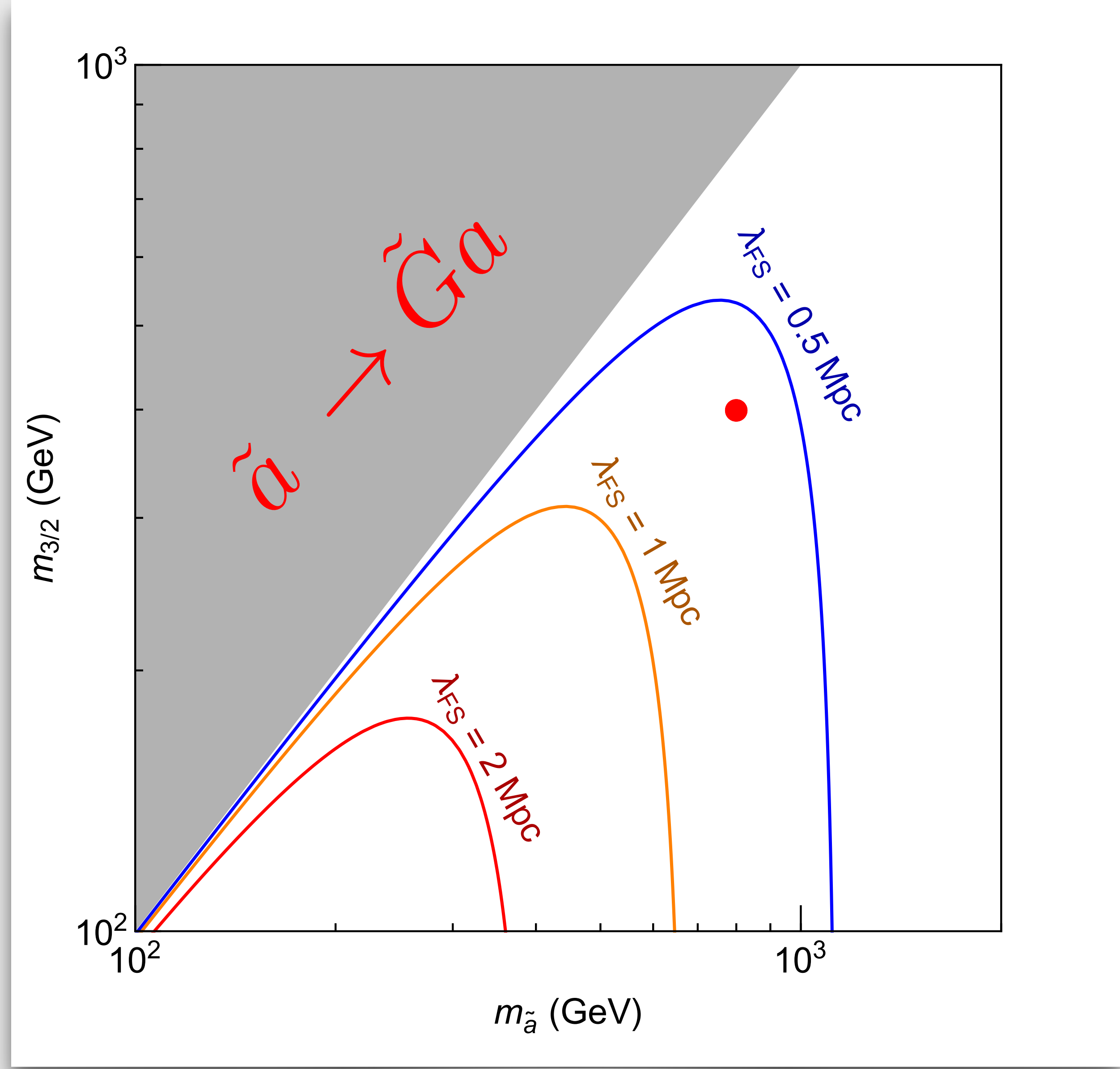
Remaining part of this talk: LSP dark matter

- Gravitino and axino two lightest R-odd states
- LOSP freeze-out highly diluted
- R-odd particles produced by processes with axino and gravitino in the final state

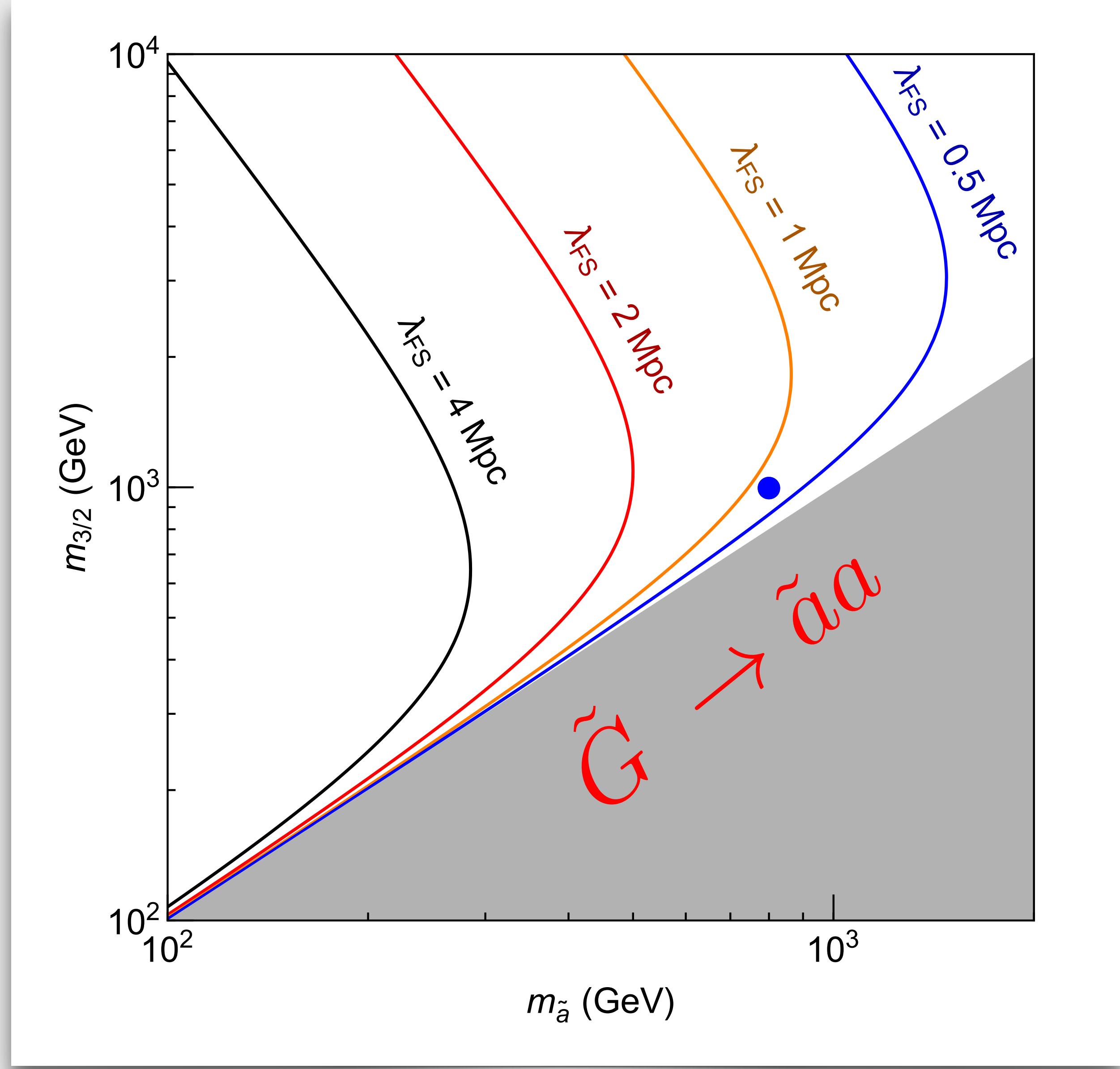
Raymond Co, FD, Lawrence Hall, arXiv:1611.05028

Cold and Warm DM

LSP Gravitino

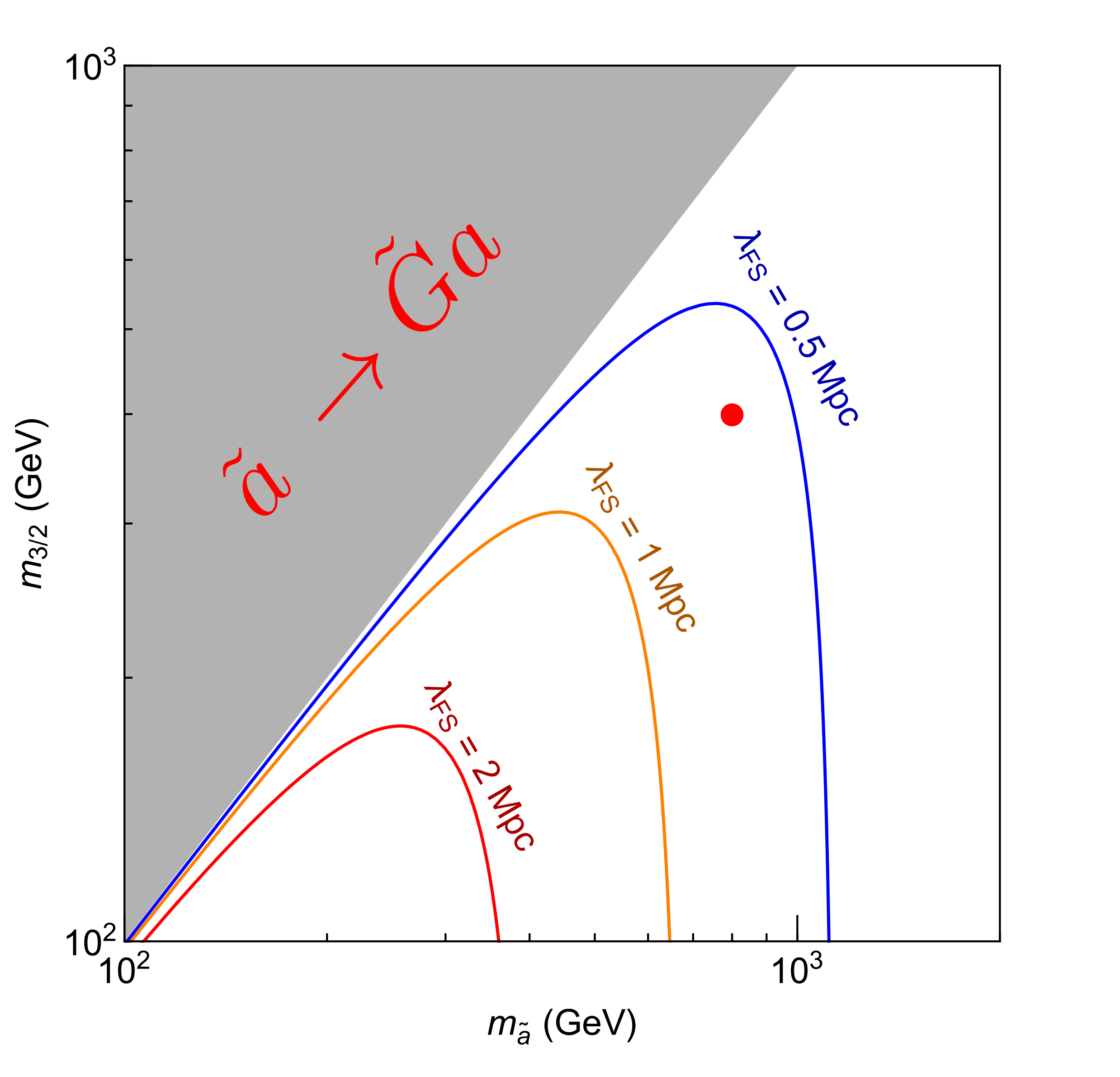


LSP Axino

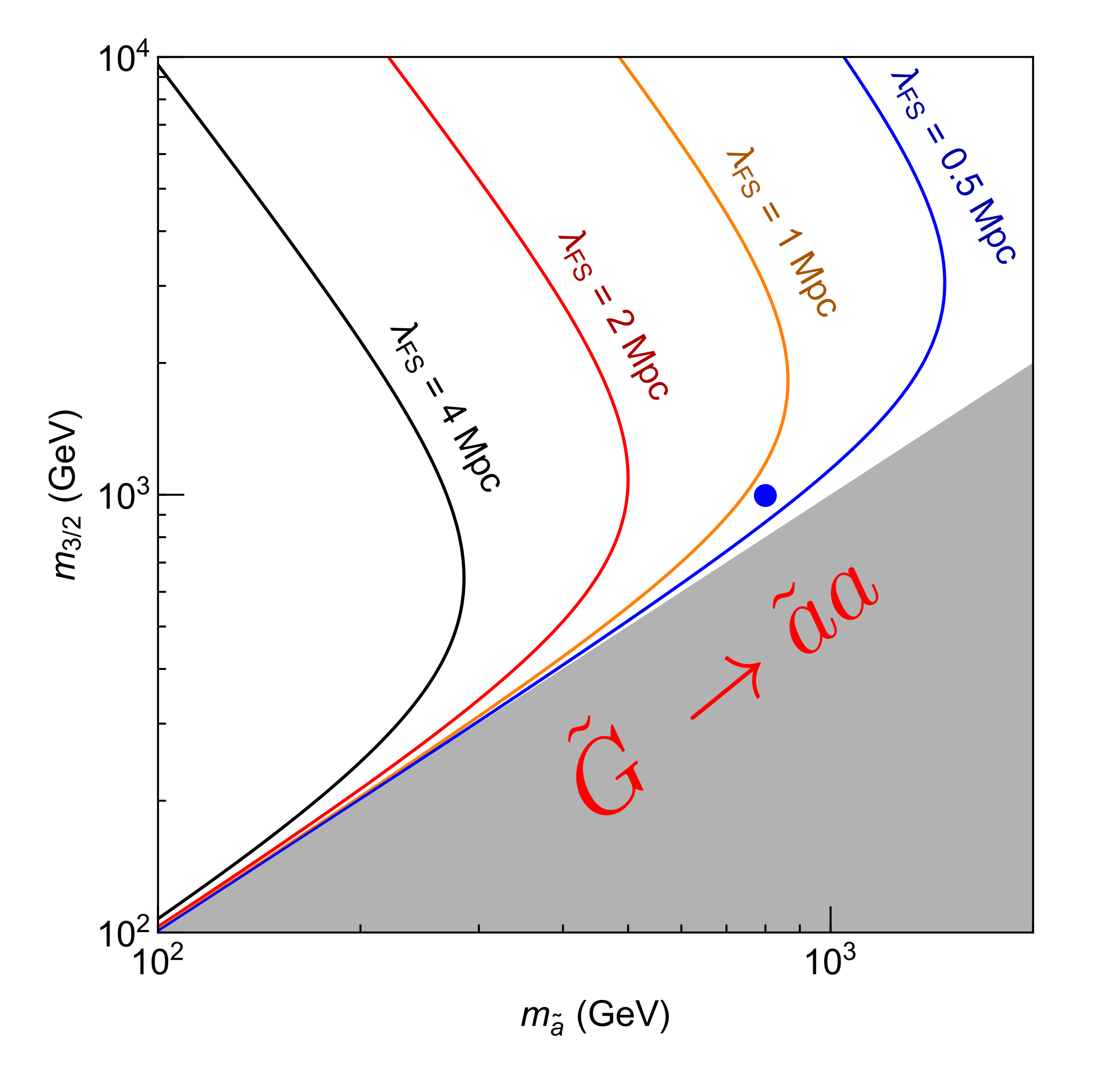


Cold and Warm DM

LSP Gravitino



LSP Axino



Decays harmless for BBN (gravitino problem solved)

Axion Dark Radiation

$$s \to aa$$

$$K = A^\dagger A + \frac{\kappa}{2} A^\dagger A \left(A + A^\dagger\right) + \dots$$

$$\kappa = \sum_i \frac{q_i^3 v_i^2}{V_{PQ}^3} \simeq \mathcal{O}(1)$$

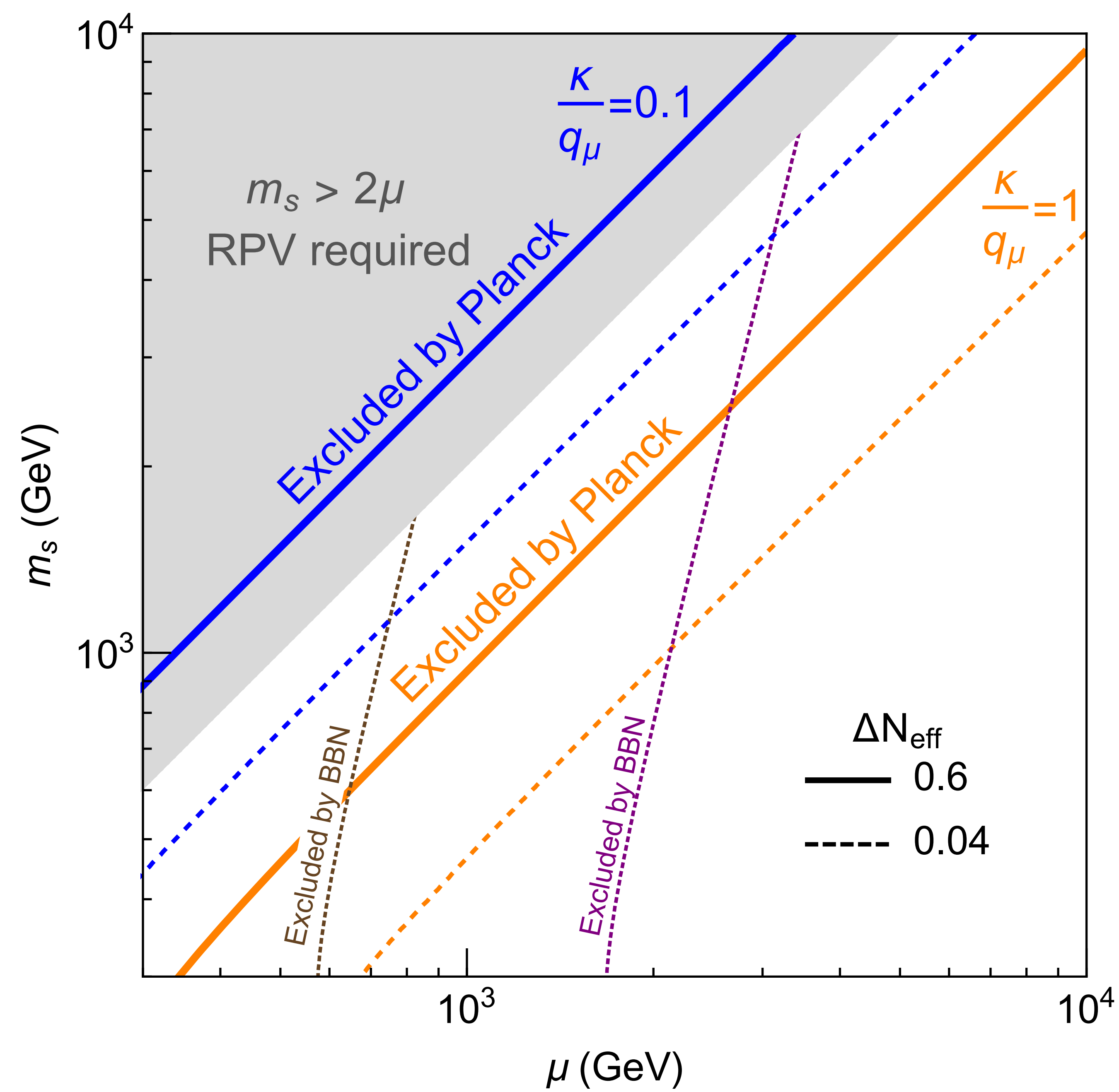
Axion Dark Radiation

$$s \to aa$$

$$K = A^\dagger A + \frac{\kappa}{2} A^\dagger A \left(A + A^\dagger\right) + \ldots$$

$$\kappa = \sum_i \frac{q_i^3 v_i^2}{V_{PQ}^3} \simeq \mathcal{O}(1)$$

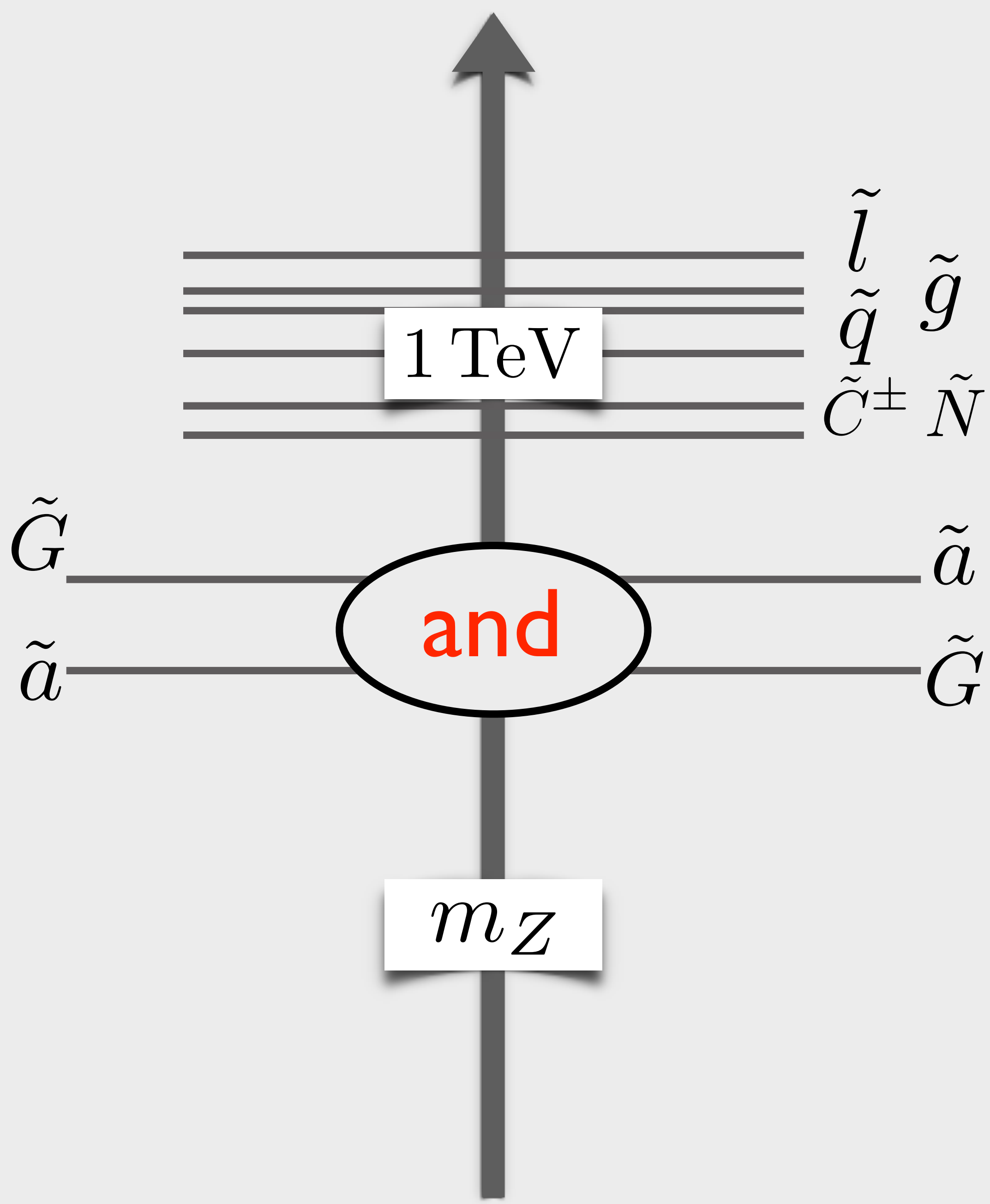
$$\Delta N_{eff} \simeq 0.4 \left(\frac{\kappa}{q_\mu}\right)^2 \left(\frac{m_s}{\mu}\right)^4$$



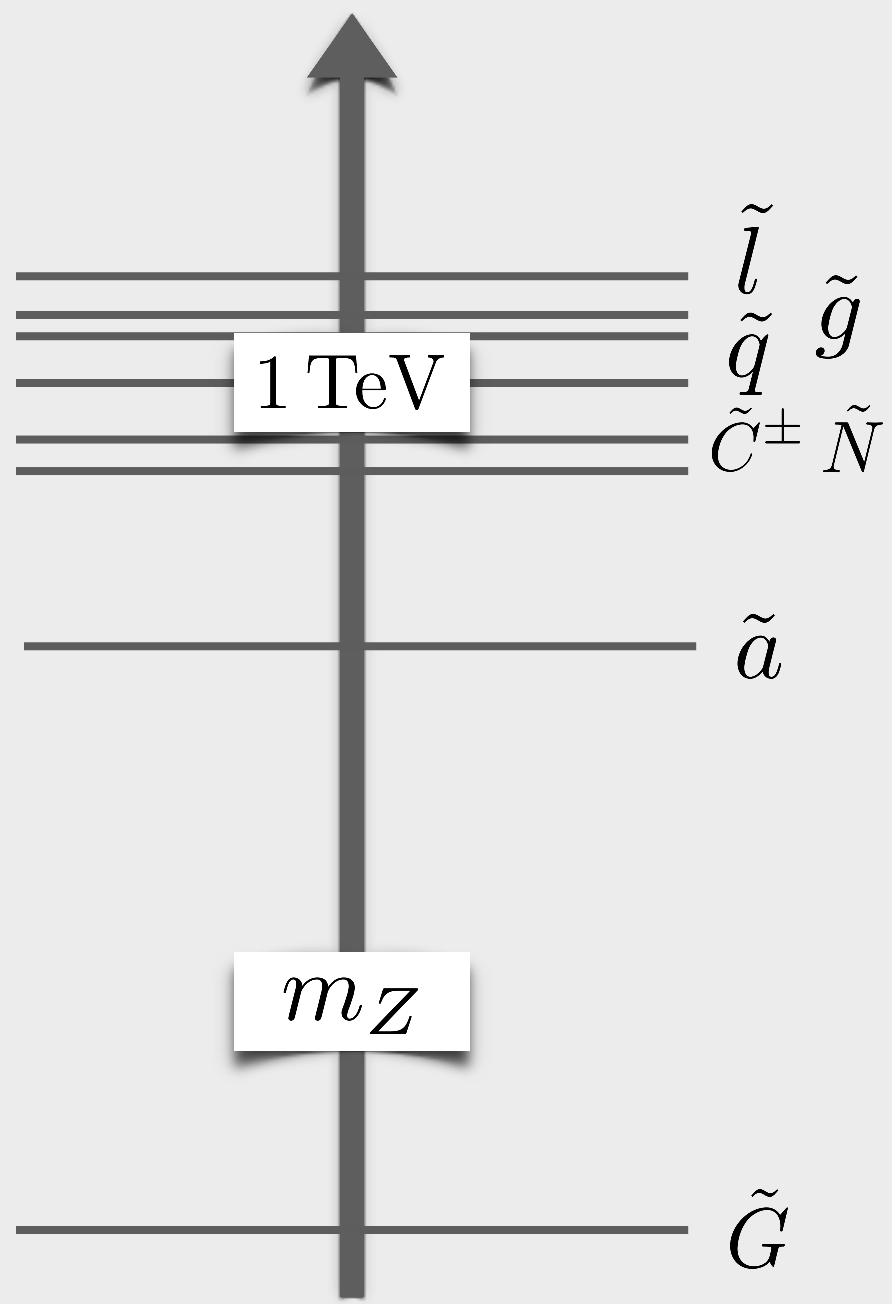
Raymond Co, FD, Lawrence Hall, PRD94 (2016) (arXiv:1603.04439)

Two Classes of Spectra

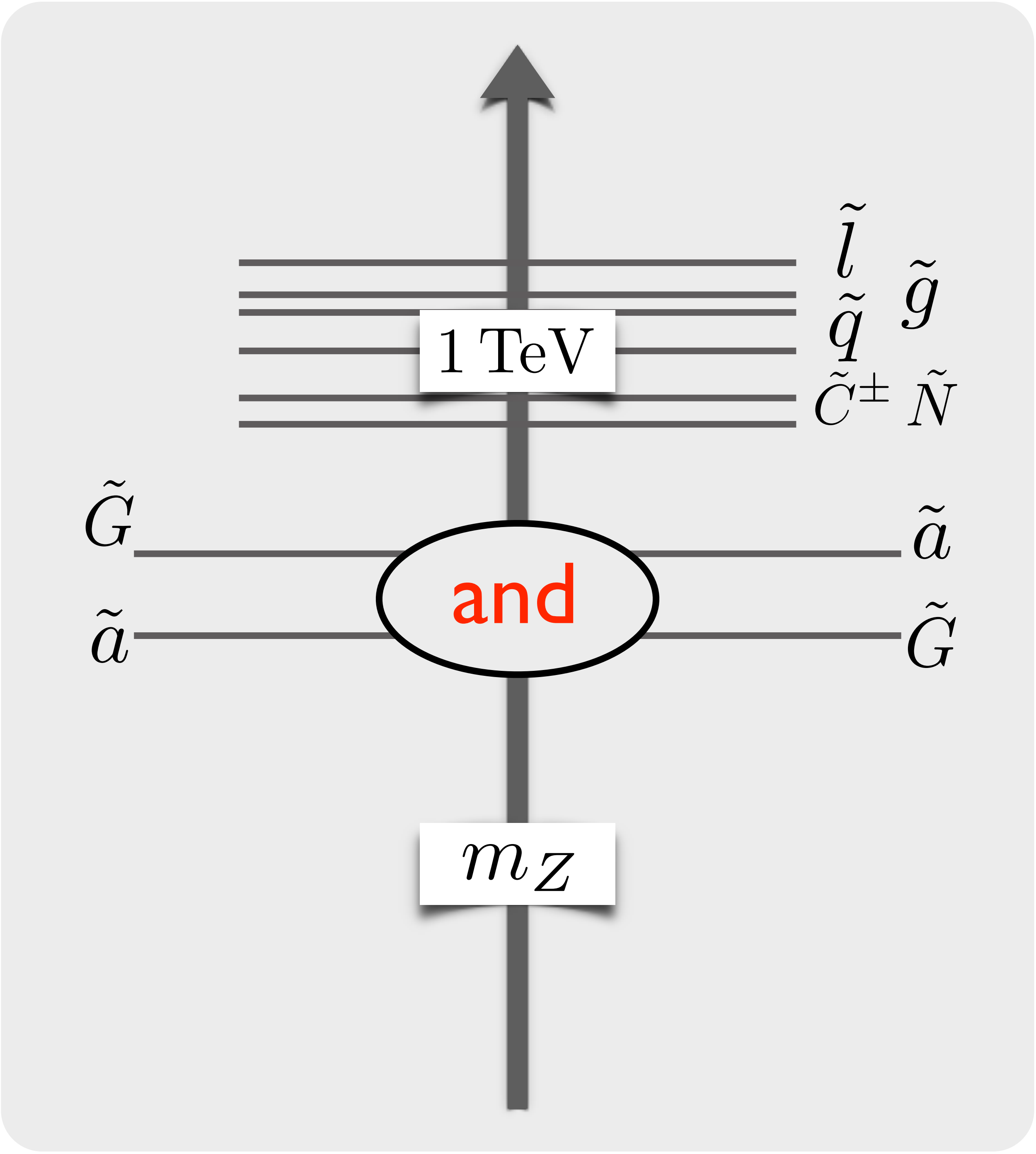
High Scale Mediation ("gravity")



Low Scale Mediation ("gauge")

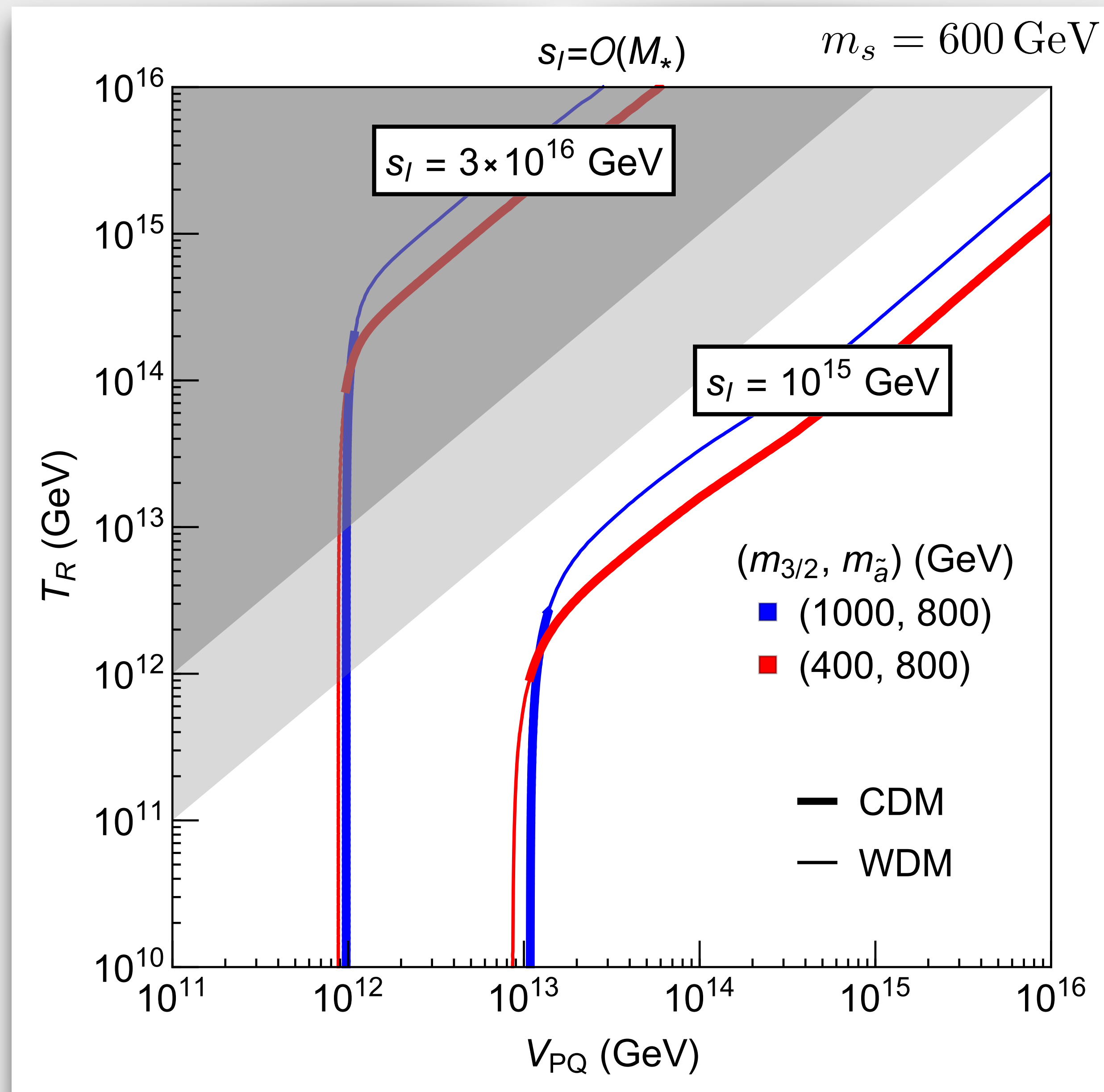


High Scale Mediation



High Scale Mediation

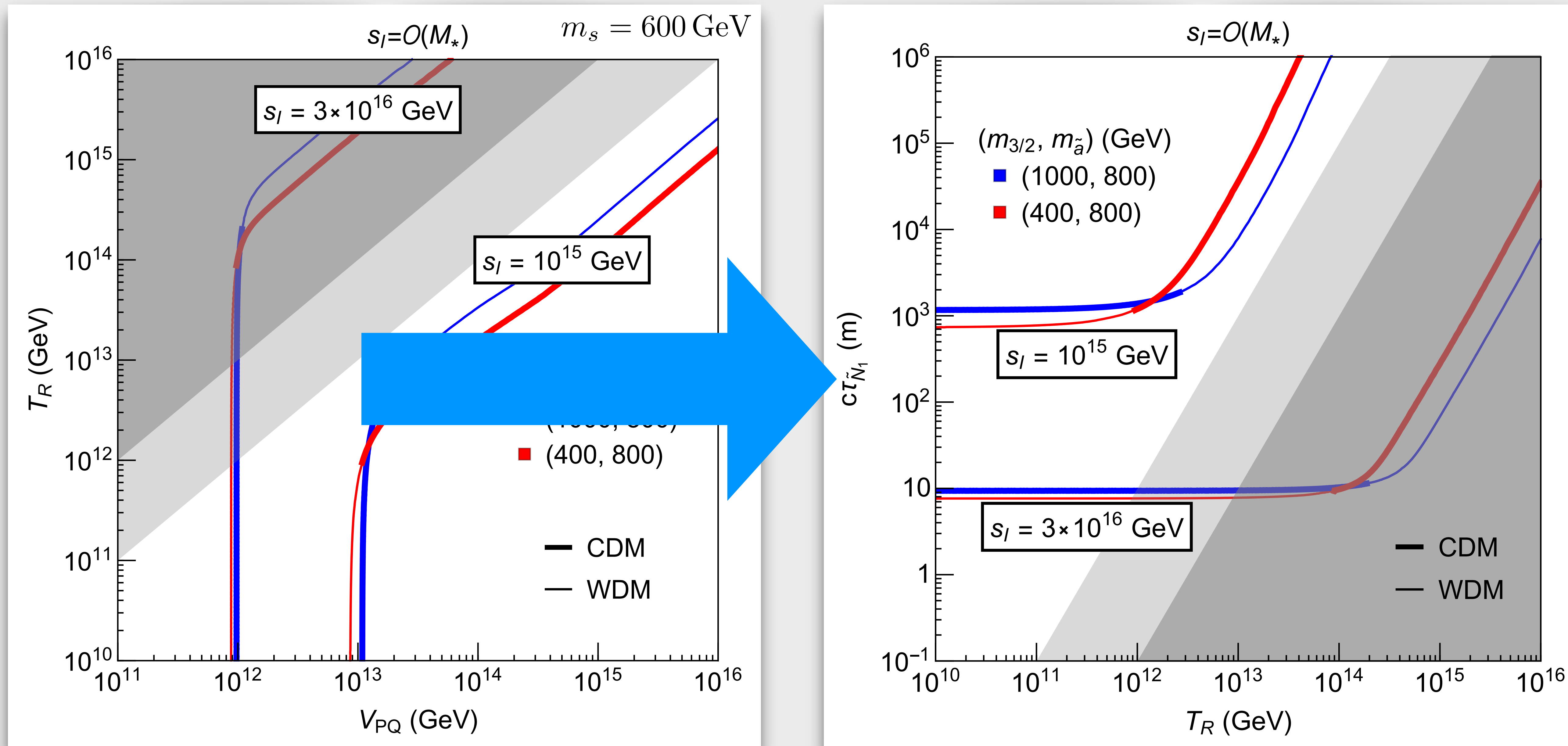
TeV SUSY Spectrum, no axino UV production



- Vertical Lines: Axino Freeze-In (smaller v_{PQ} needs larger s_I)
- For $s_I > 10^{16}$ GeV unmodified
- Diagonal Lines: Gravitino UV ($\Omega h^2 \propto T_R / V_{PQ}$)
- Saxion condensate opens up the region at high T_R!

High Scale Mediation

TeV SUSY Spectrum, no axino UV production

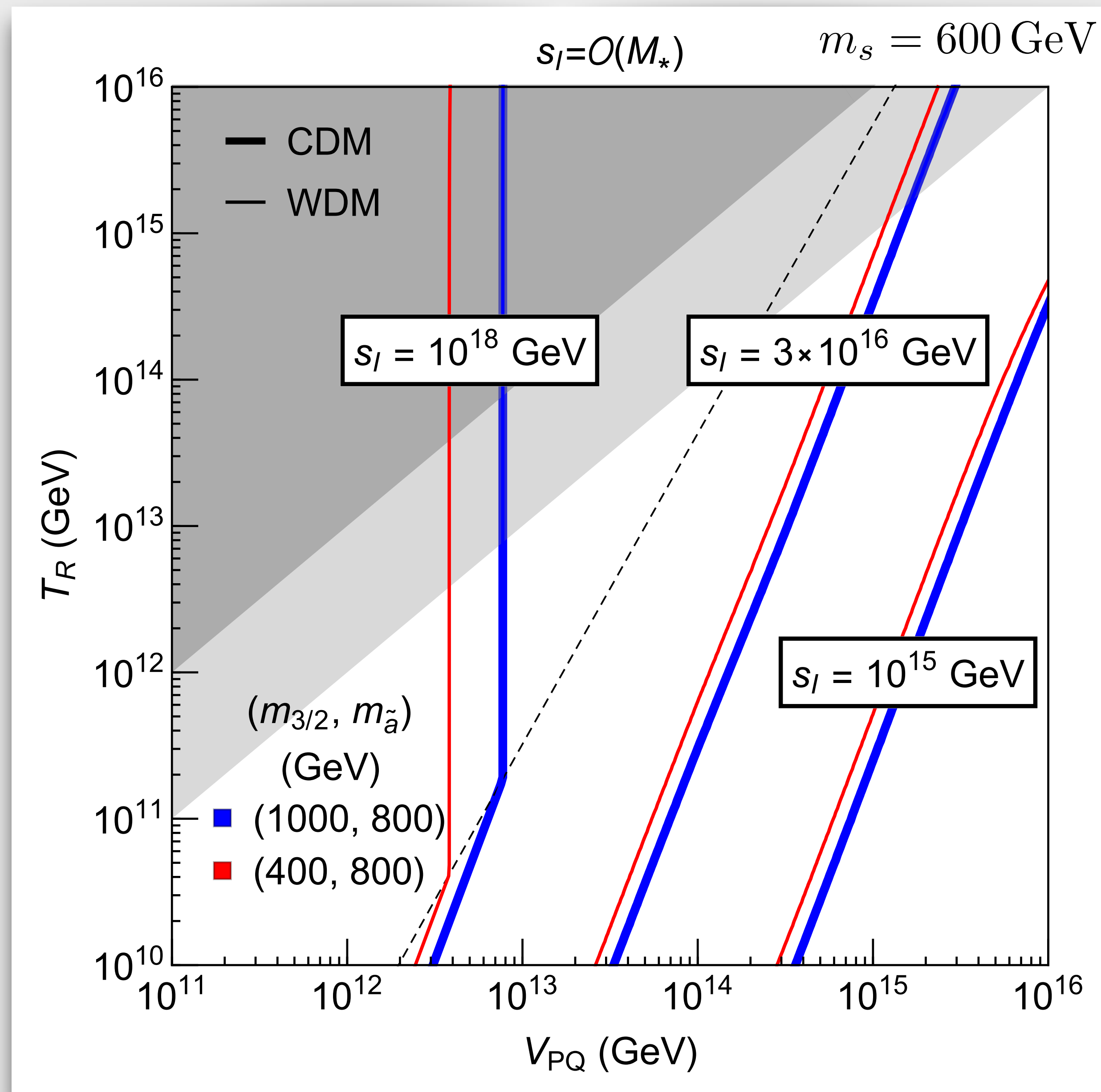


Displaced Axinos at Colliders!

MATHUSLA detector (Chou, Curtin, Lubatti, arXiv:1606.06298)

High Scale Mediation

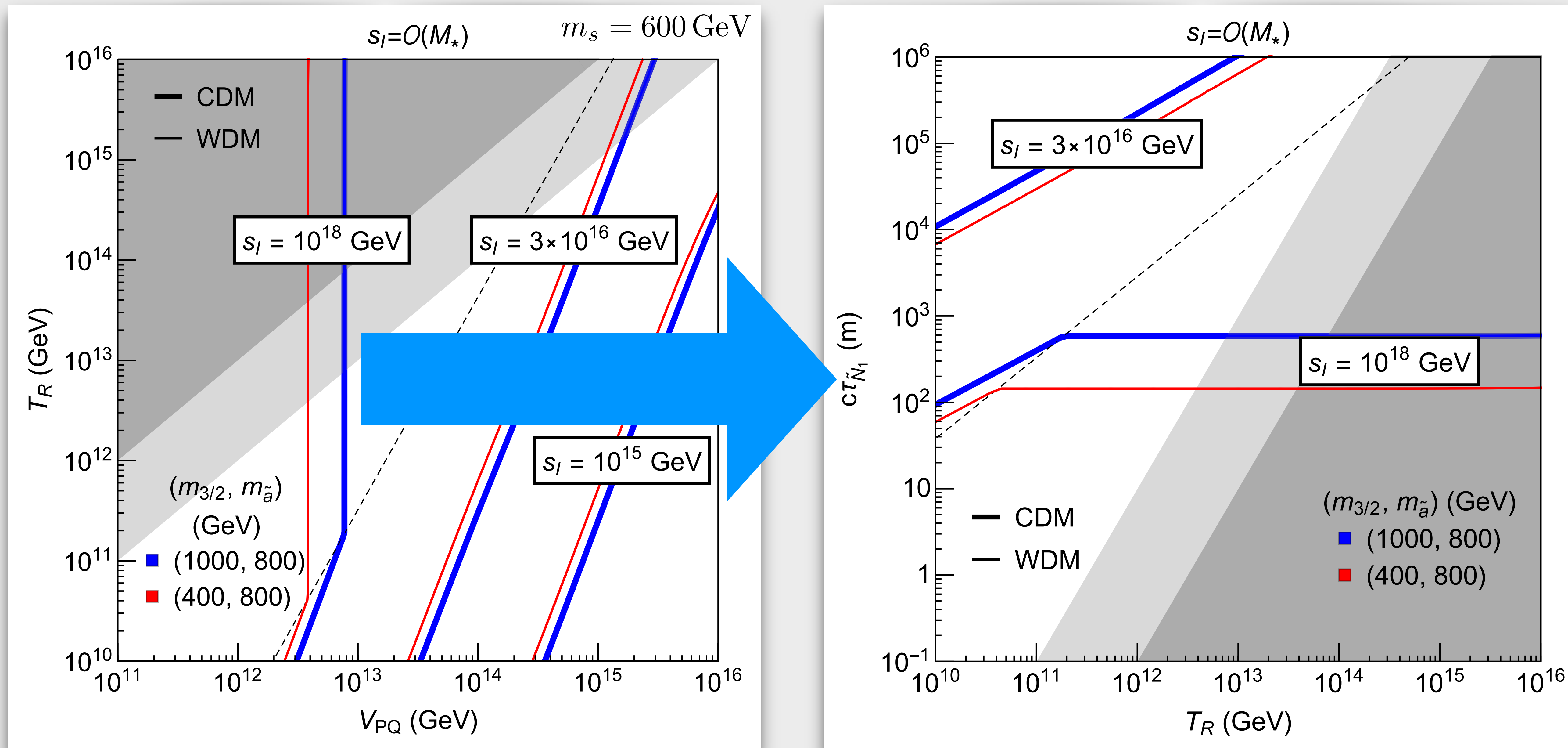
TeV SUSY Spectrum, with axino UV production



- Production always dominated by Axino UV production ($\Omega h^2 \propto T_R / V_{PQ}^3$)
- Axinos thermalize in the UV for small enough V_{PQ} DA
- More dilution needed then without Axino UV
- Region at high T_R still opened!

High Scale Mediation

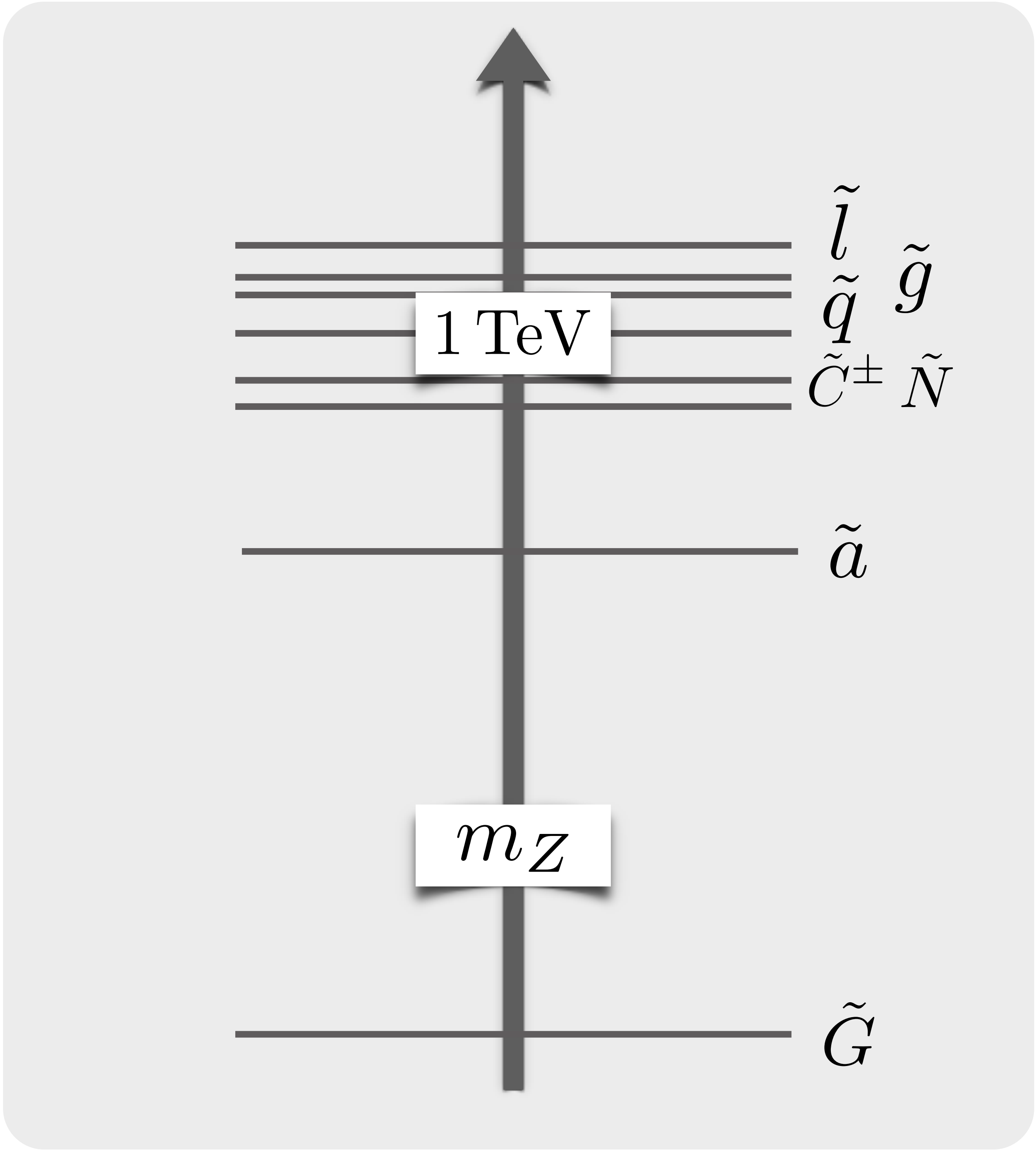
TeV SUSY Spectrum, with axino UV production



Displaced Axinos at Colliders!

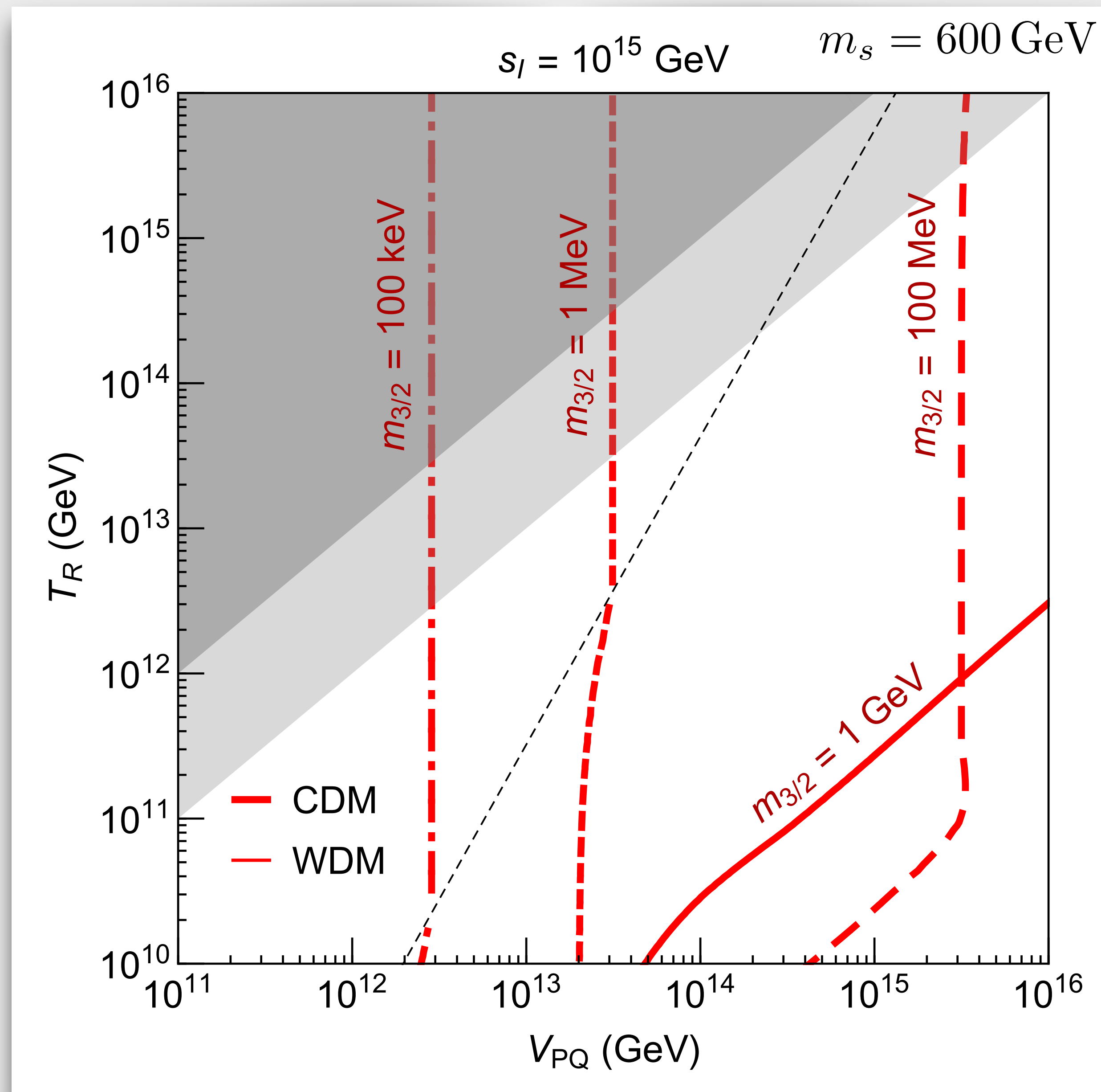
MATHUSLA detector (Chou, Curtin, Lubatti, arXiv:1606.06298)

Low Scale Mediation



Low Scale Mediation

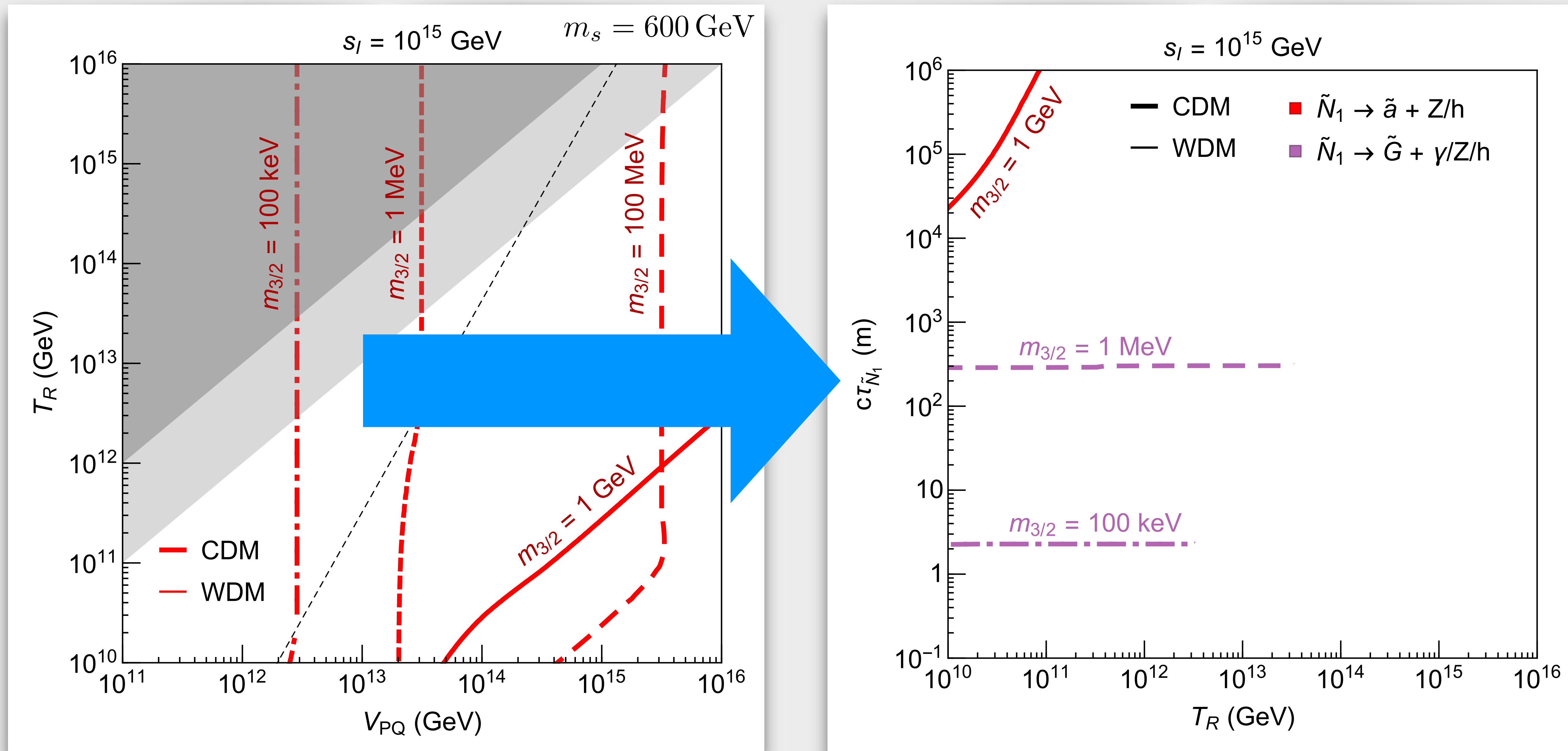
TeV SUSY Spectrum, with axino UV production



- Gravitino UV production enhanced, axino sub-dominant
- Large $m_{3/2}$: gravitino UV with $\Omega h^2 \propto T_R / V_{PQ}$
- Low $m_{3/2}$: gravitinos thermalize
- Very low $m_{3/2}$: V_{PQ} small enough that axinos thermalize
- T_R can still be large!

Low Scale Mediation

TeV SUSY Spectrum, with axino UV production

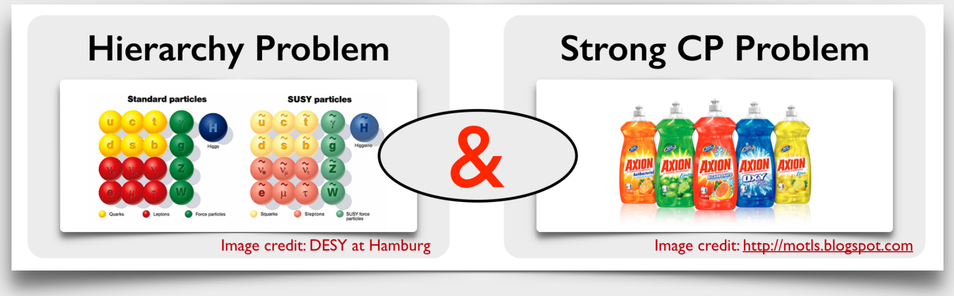


Displaced Axinos and Gravitinos at Colliders!

MATHUSLA detector (Chou, Curtin, Lubatti, arXiv:1606.06298)

Outlook

SUSY PQ Theories



PQ broken during inflation:
large saxion condensate with dramatic effects on dark matter relic density

New scheme for gravitino or axino dark matter

- No gravitino problem (LOSP decays before BBN)
- T_R can be as high as 10^{16} GeV!
- Cold and/or warm dark matter
- Axion dark radiation
- Displaced signals at colliders

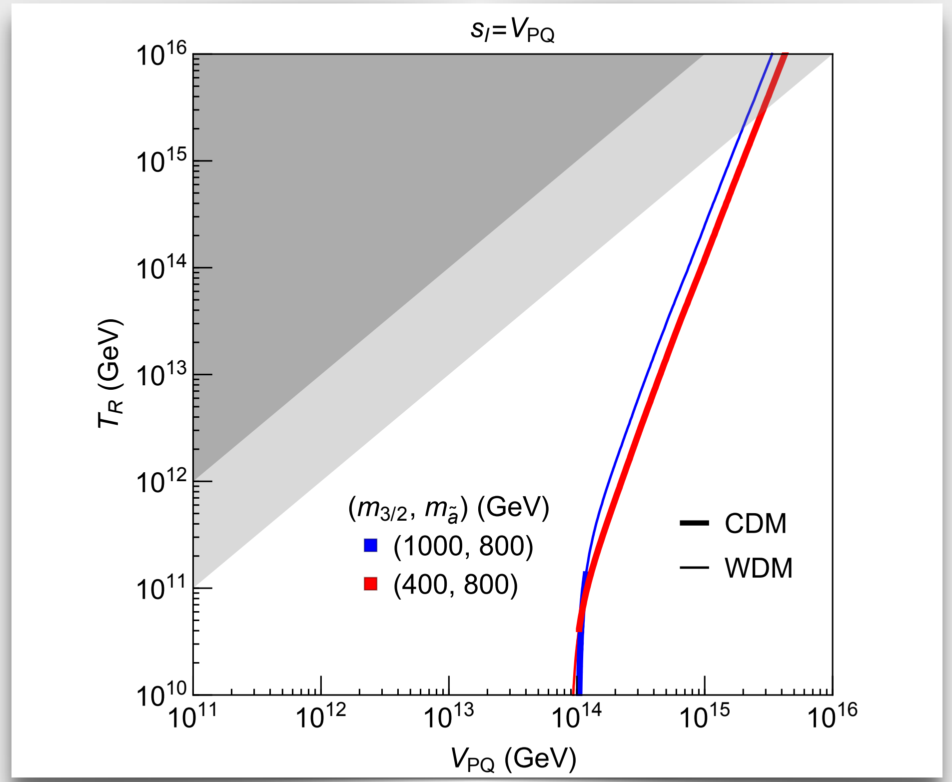
Raymond Co, FD, Lawrence Hall, arXiv:1611.05028

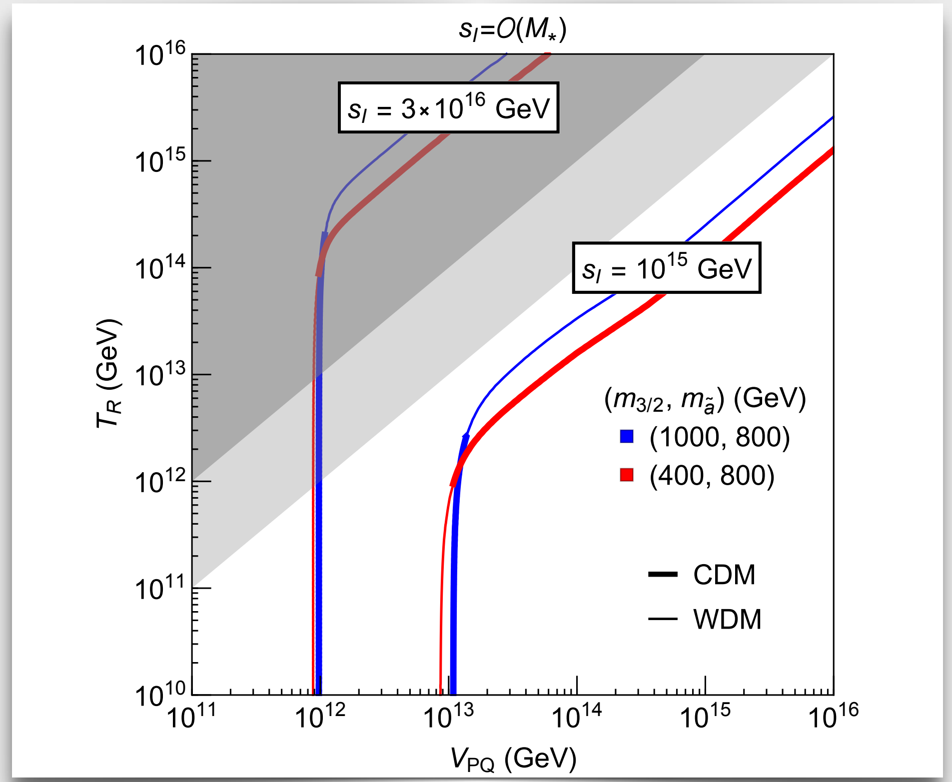
Thank You!

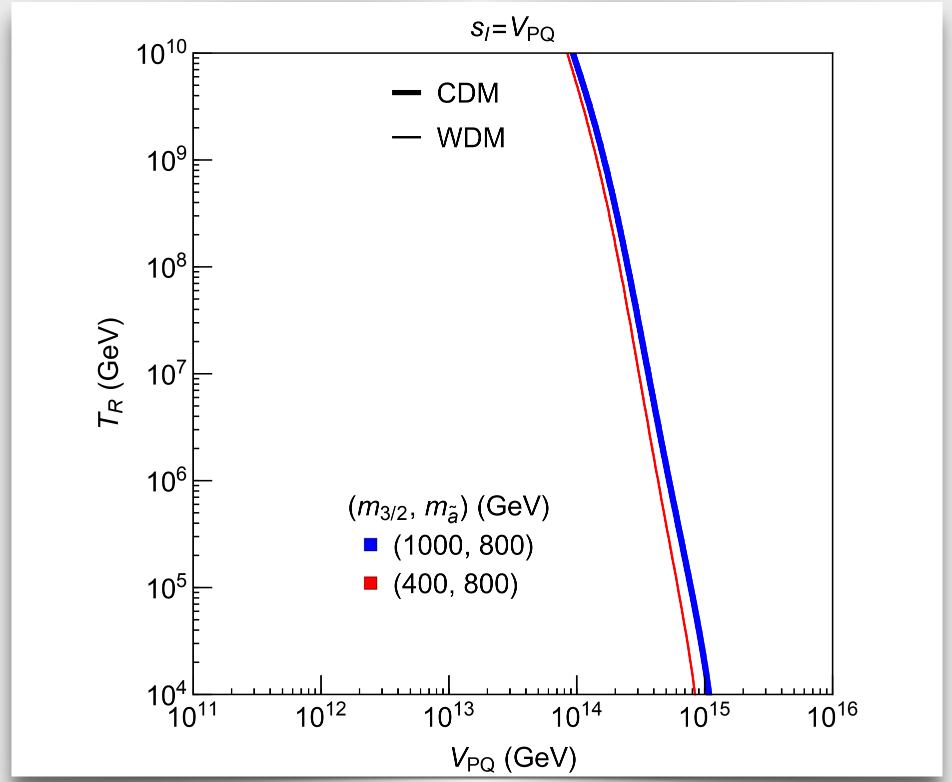
고맙습니다

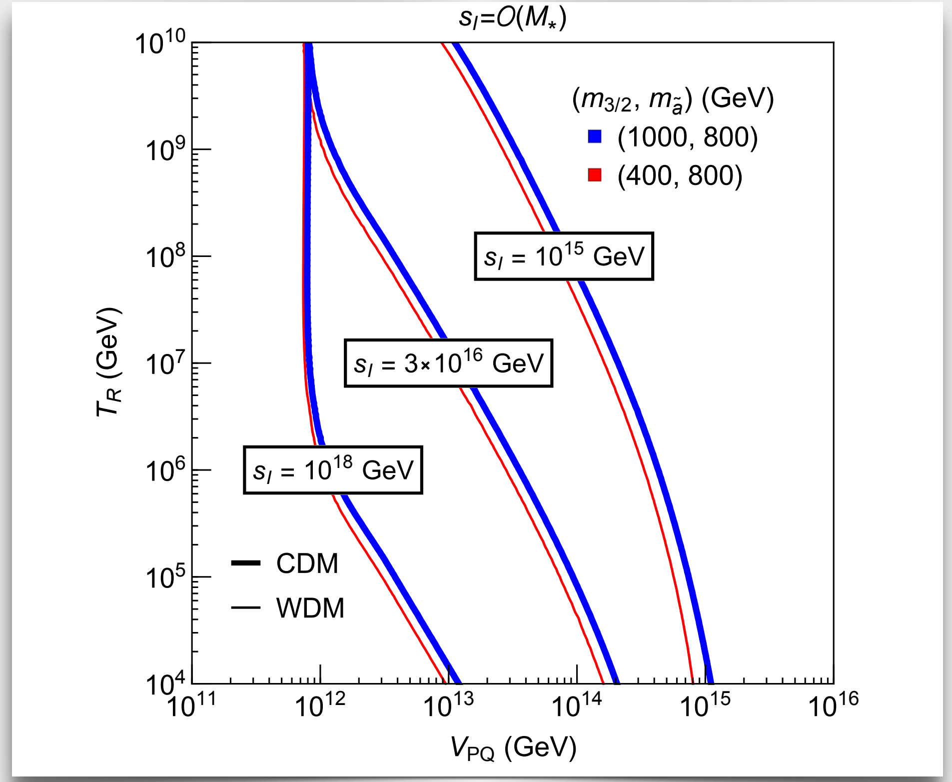
BACKUP SLIDES

High Scale – DFSZ$_0$



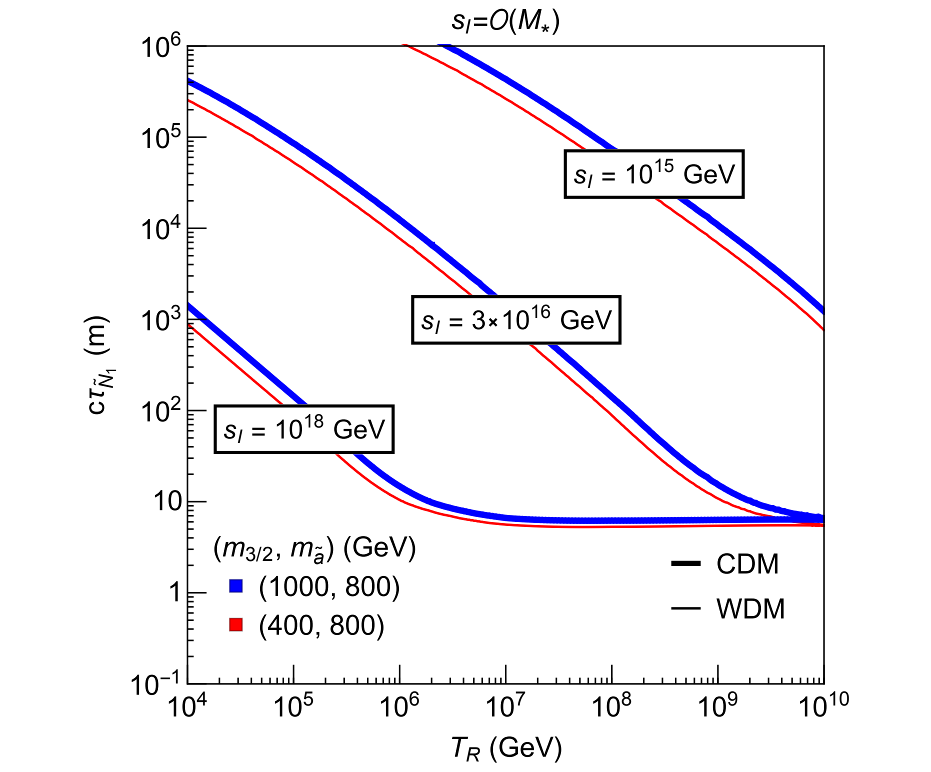


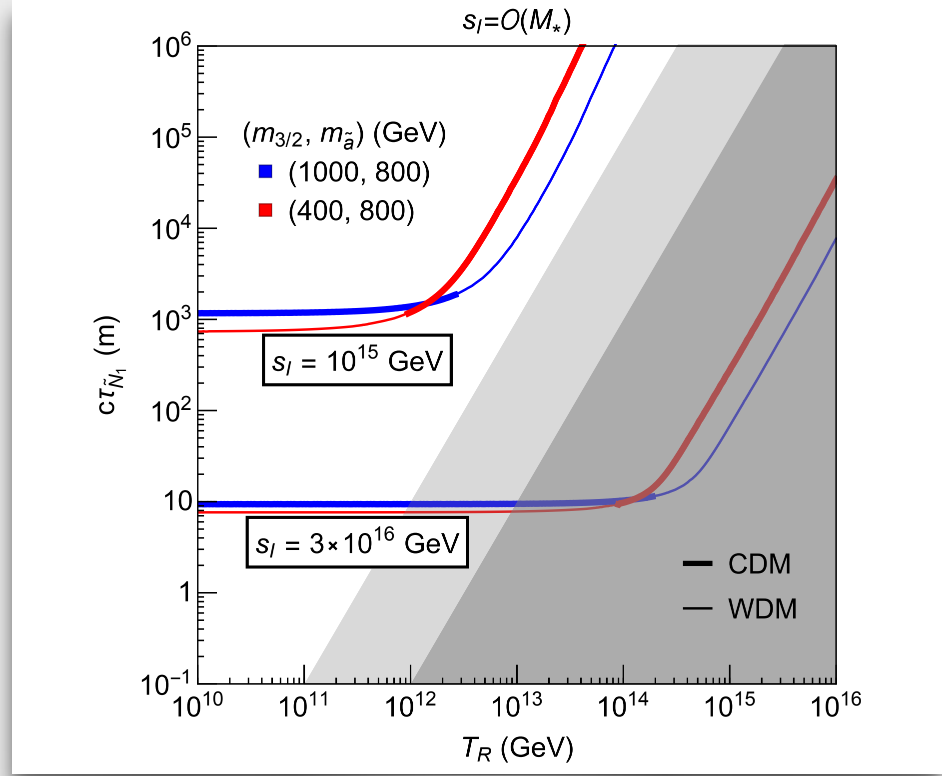




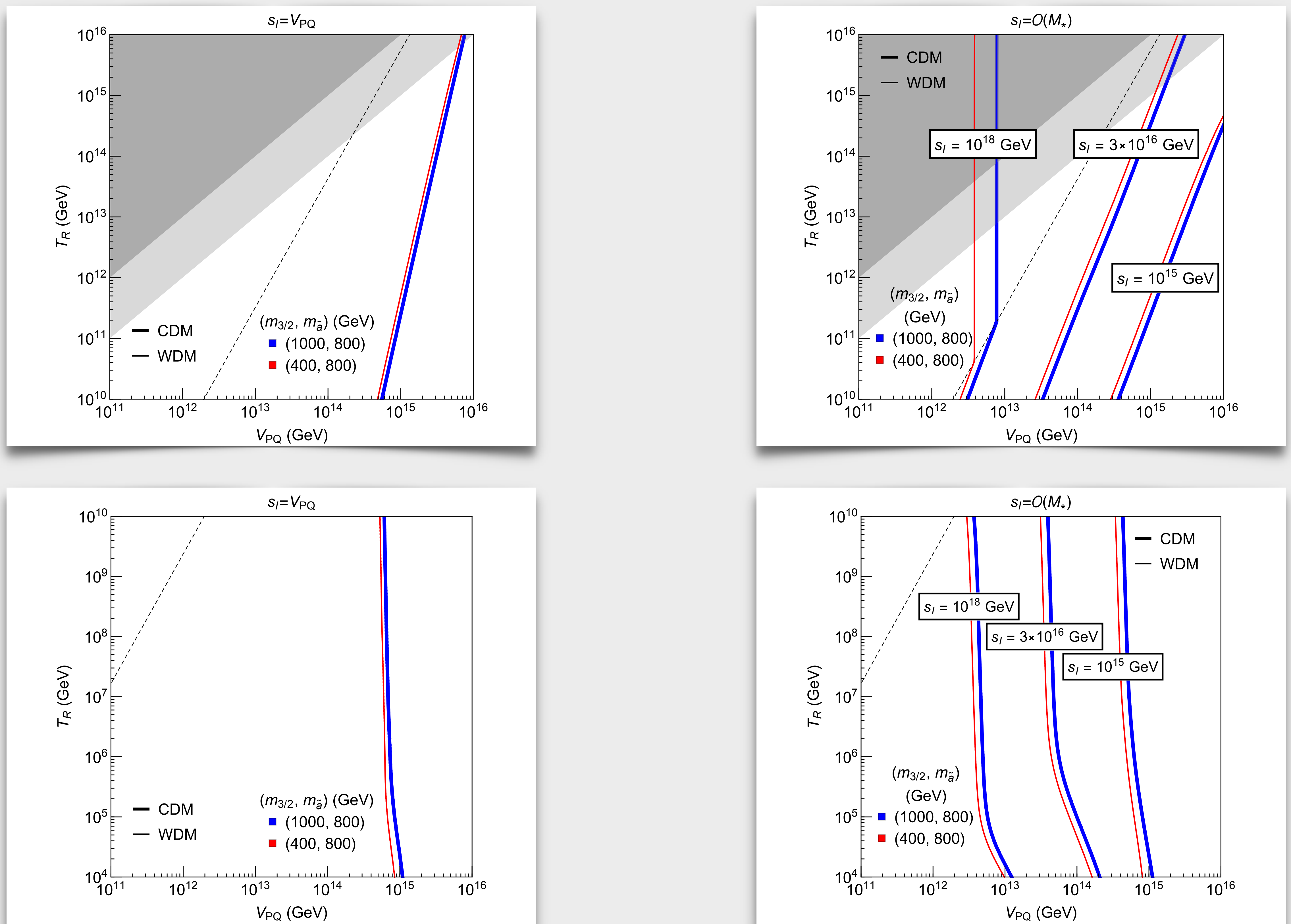
High Scale – DFSZ$_0$

Displaced Signals



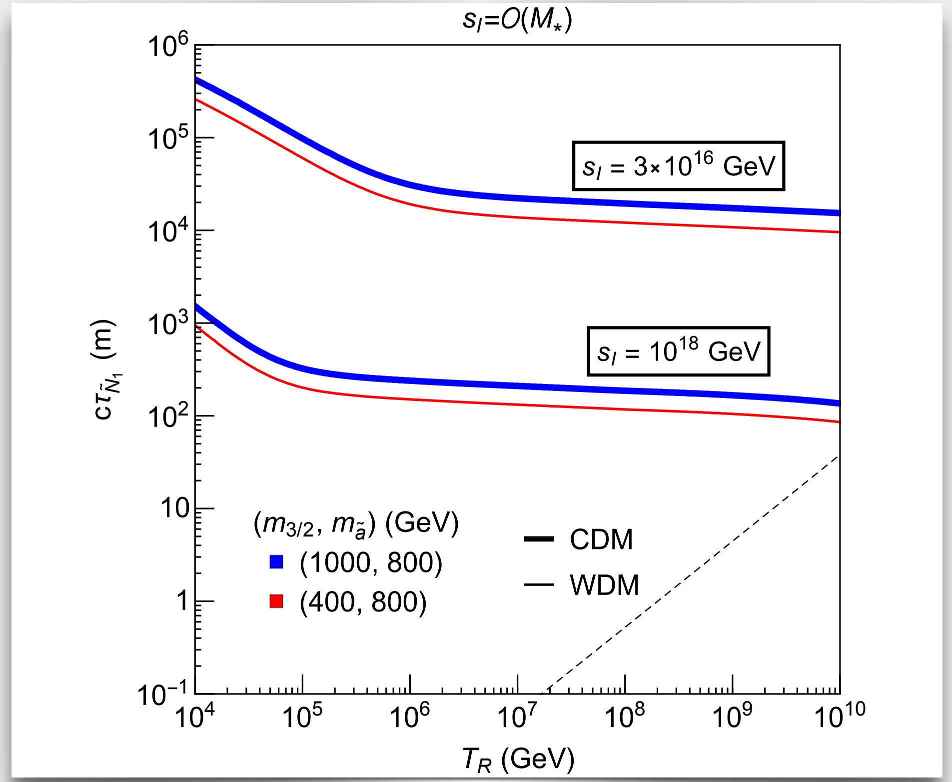


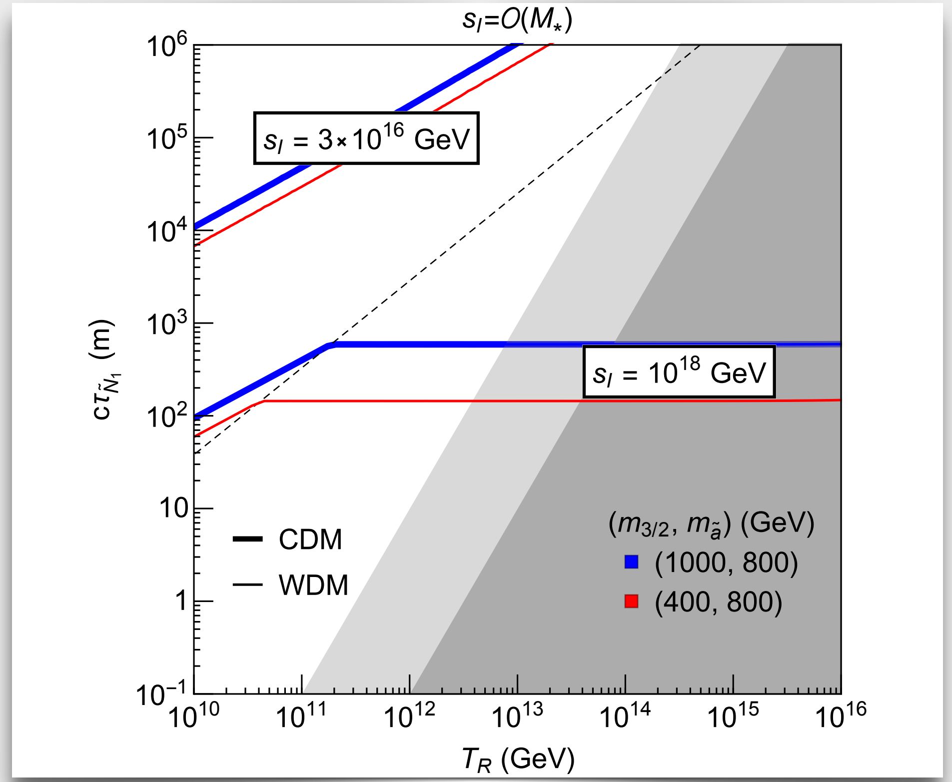
High Scale – DFSZ+



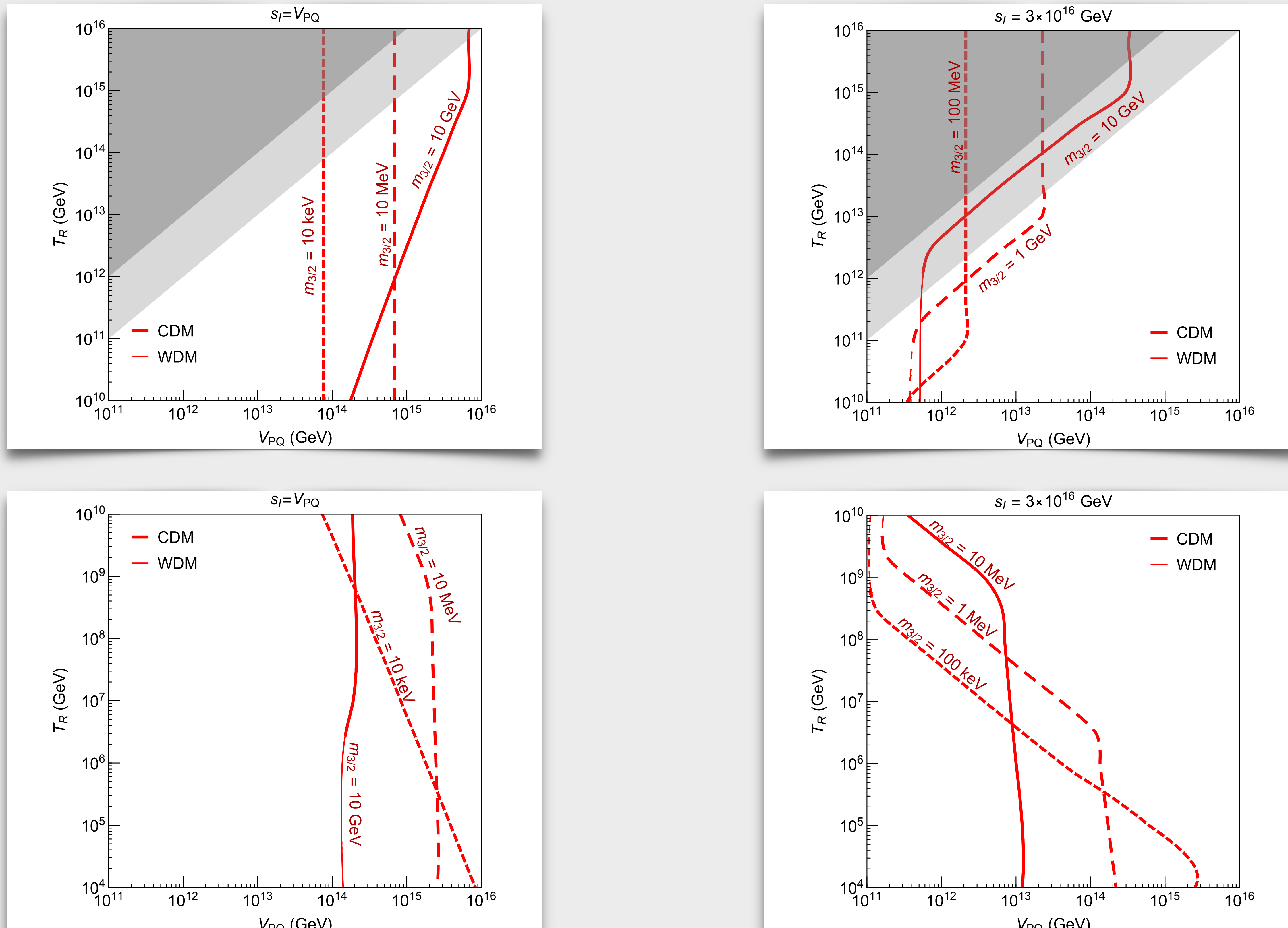
High Scale – DFSZ+

Displaced Signals



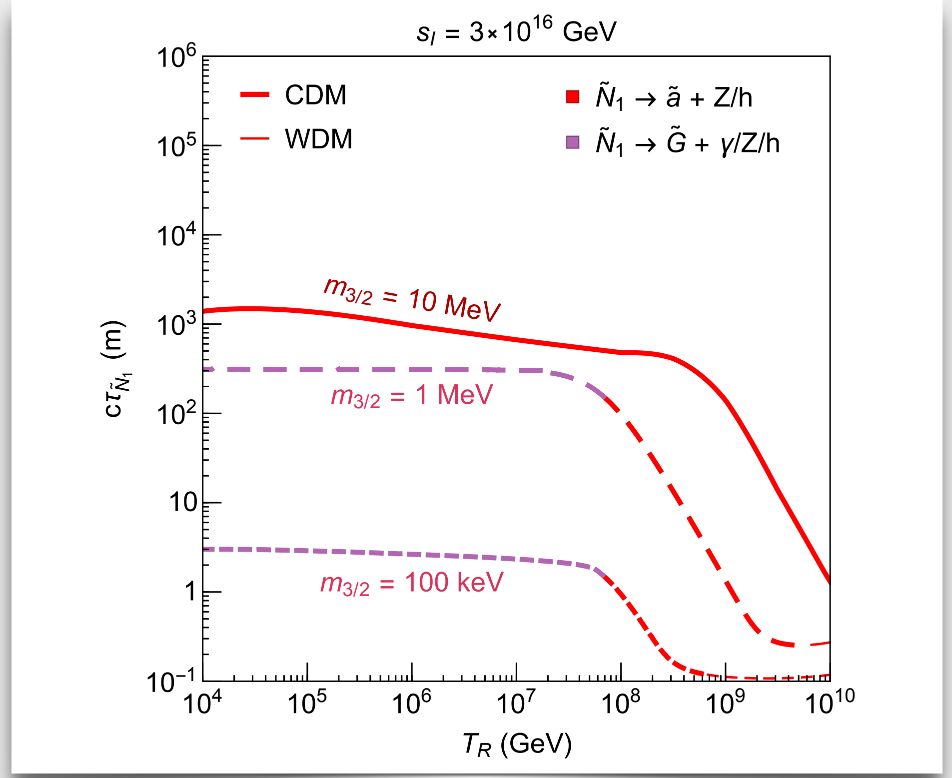


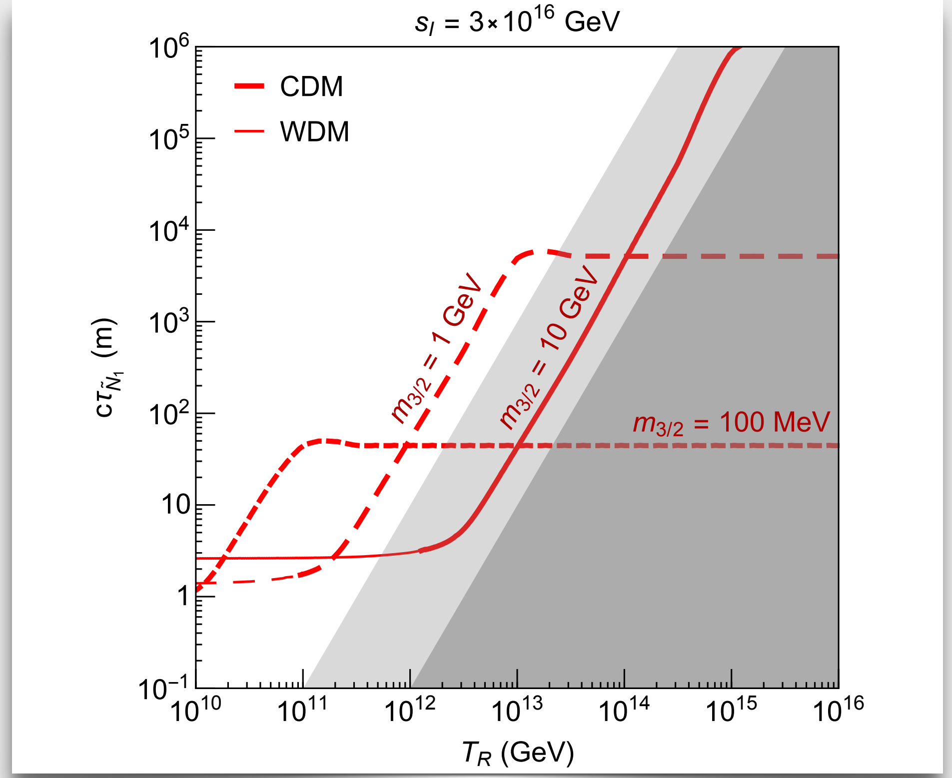
Low Scale – DFSZ$_0$



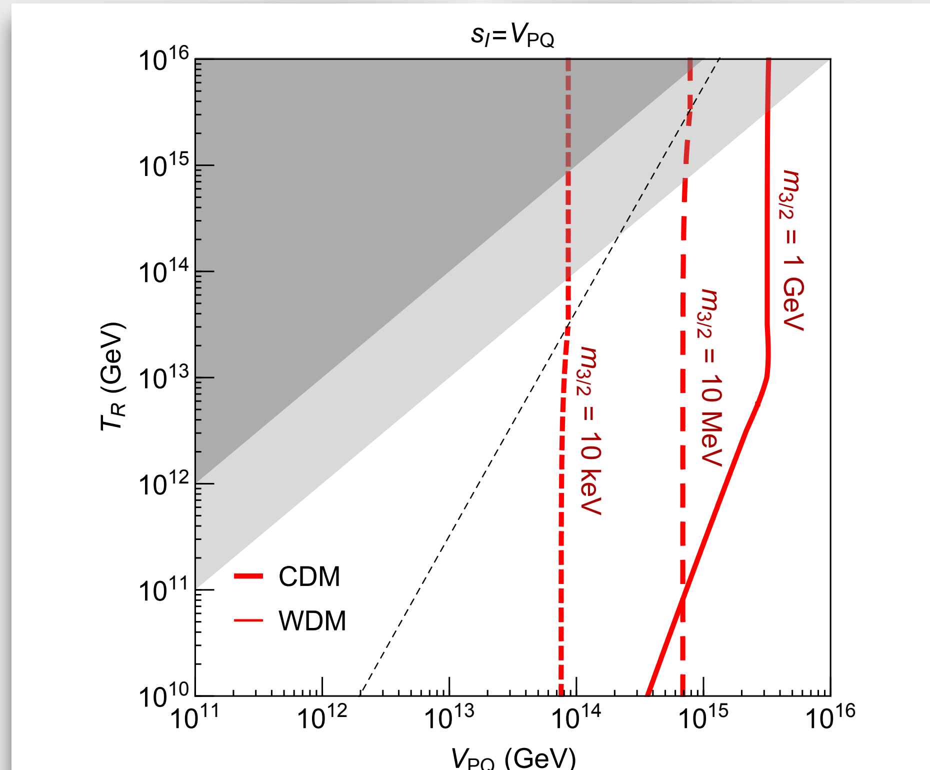
Low Scale – DFSZ$_0$

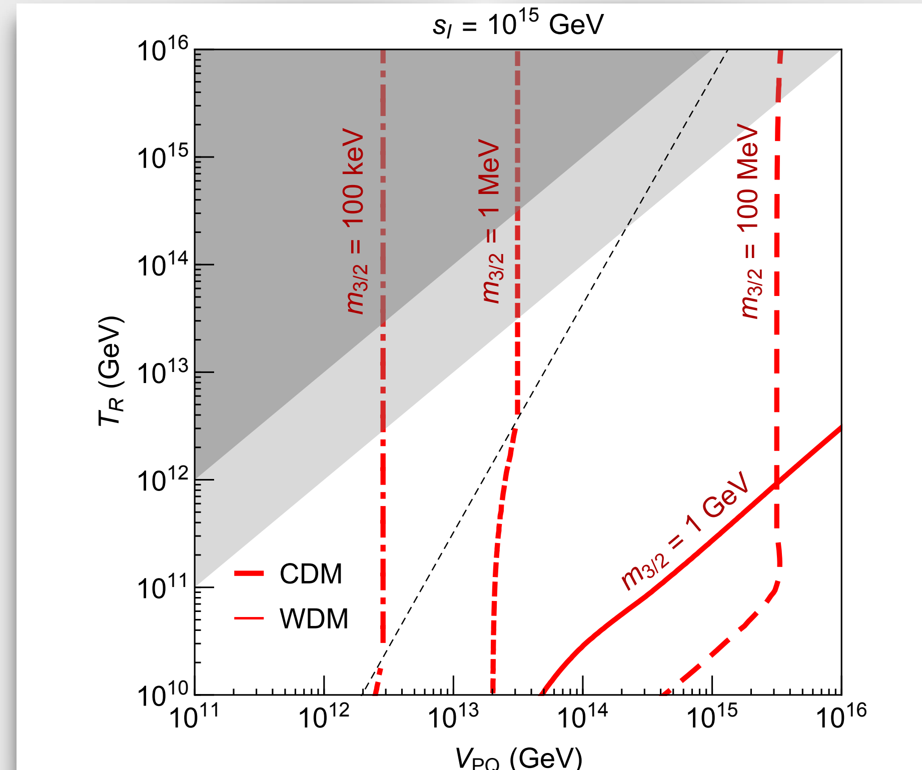
Displaced Signals

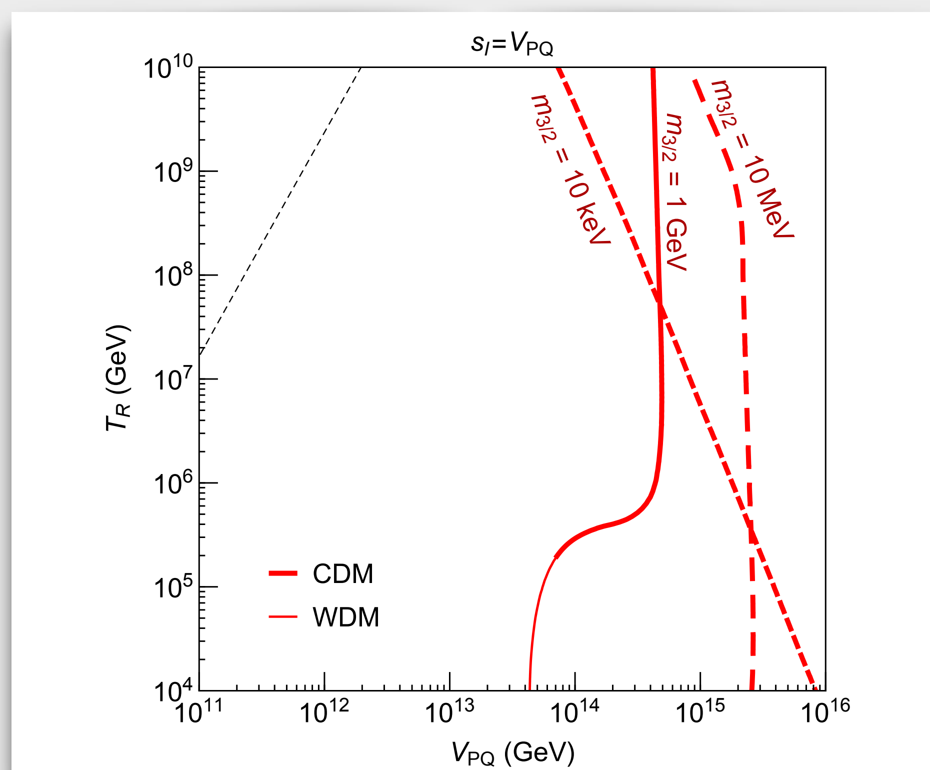


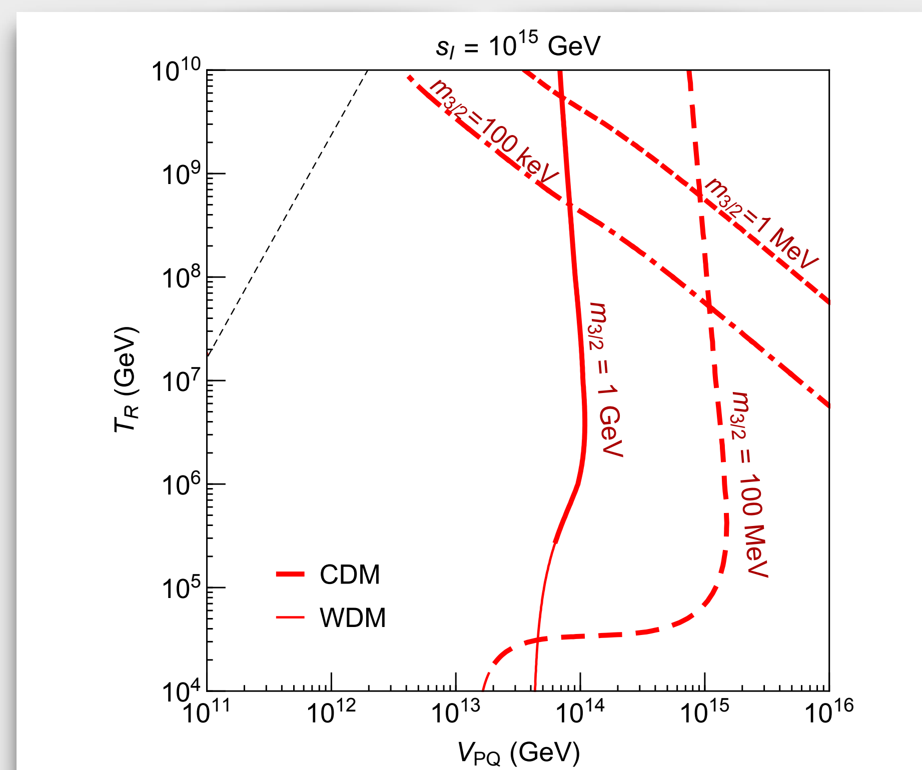


Low Scale – DFSZ$_+$









Low Scale – DFSZ$_+$

Displaced Signals