Non-thermal Dark Matter and Baryogenesis

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Outline:

- Introduction

- Non-thermal DM from EMD
  the scenario, freeze-out/in production, direct production, the importance of EMD and pre-EMD details, constraints

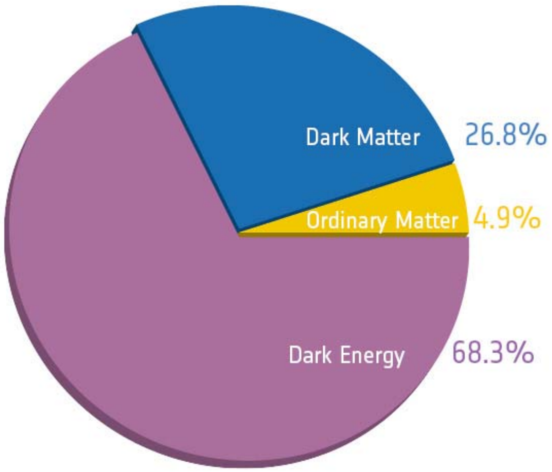
- EMD and baryogenesis
  a minimal model, baryon-DM coincidence, testable predictions, complementarity of cosmological and experimental constraints

- Conclusion and Outlook

- Possible observable signatures of EMD (Discussion Session?).

Introduction:

The present universe according to observations:



Two big problems to address:

Dark Matter (DM)

What is its nature? How was it produced?

Baryon Asymmetry of Universe (BAU)

Why is it nonzero? How was it generated?

Also, a possible coincidence puzzle:

Why the DM and baryons have comparable energy densities?

Answers have profound consequences for:

Particle Physics (BSM), Cosmology (thermal history)

Thermal DM:

Starting in a RD universe:

$$\dot{n}_\chi + 3Hn_\chi =< \sigma_{ann} v >_f (n^2_{\chi,eq} - n^2_\chi)$$

1) $T \gg m_\chi$: $\chi\chi \leftrightarrow f\bar{f} \implies n_\chi \propto T^3$

2) $T \lesssim m_\chi$: $\chi\chi \longrightarrow f\bar{f} \implies n_\chi \propto \exp(-\frac{m_\chi}{T})$

3) $T \approx T_f$: $\implies \frac{n_\chi}{s} = const.$

$$\boxed{< \sigma_{ann} v >_f = 3 \times 10^{-26}\ cm^3\ s^{-1}}$$

WIMP miracle:

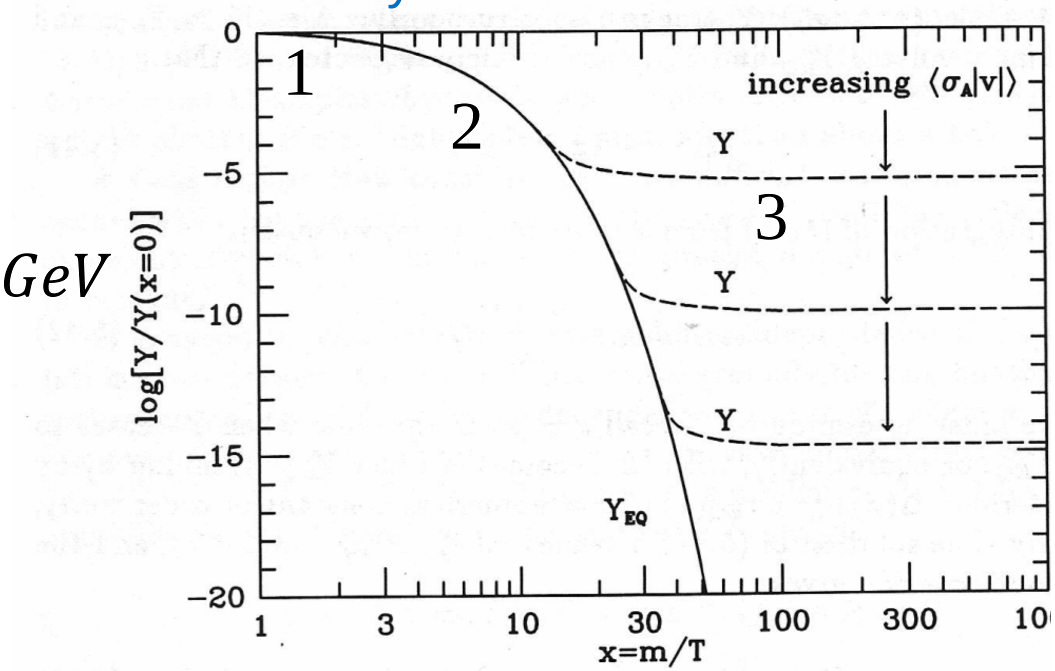
$$< \sigma_{ann} v >_f = \frac{\alpha^2_\chi}{m^2_\chi}$$

$$\alpha_\chi \sim O(10^{-2}), m_\chi \sim 10 - 10^3\ GeV$$

$$\Omega_\chi h^2 \sim 10^{-3} - 1$$

$$\boxed{t_f \lesssim 10^{-7}\ s}$$

“The Early Universe” Kolb & Turner



In principle, thermal DM is a very attractive scenario:
- Predictive
- Robust

However:
Annihilation rate tightly constrained by indirect detection searches

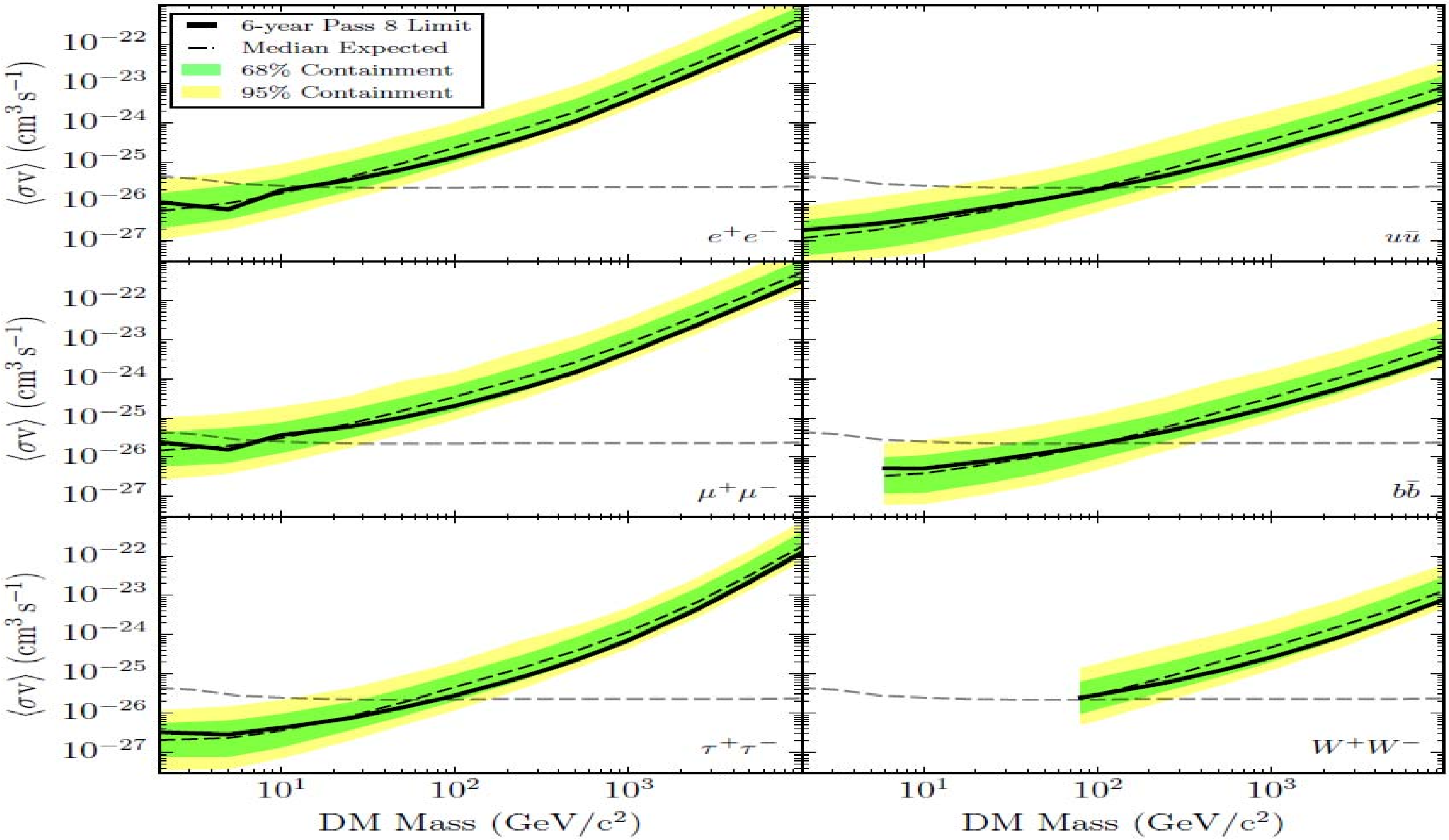
More importantly:
Freeze-out during RD is an assumption. Currently, we have no observational probe of the early universe prior to one second.

In fact, in a well-motivated class of particle physics models a RD universe is established much later than the freeze-out.

Studying alternatives to thermal DM is well motivated.

Indirect detection experiments

Fermi Collaboration PRL 115, 231301 (2015)



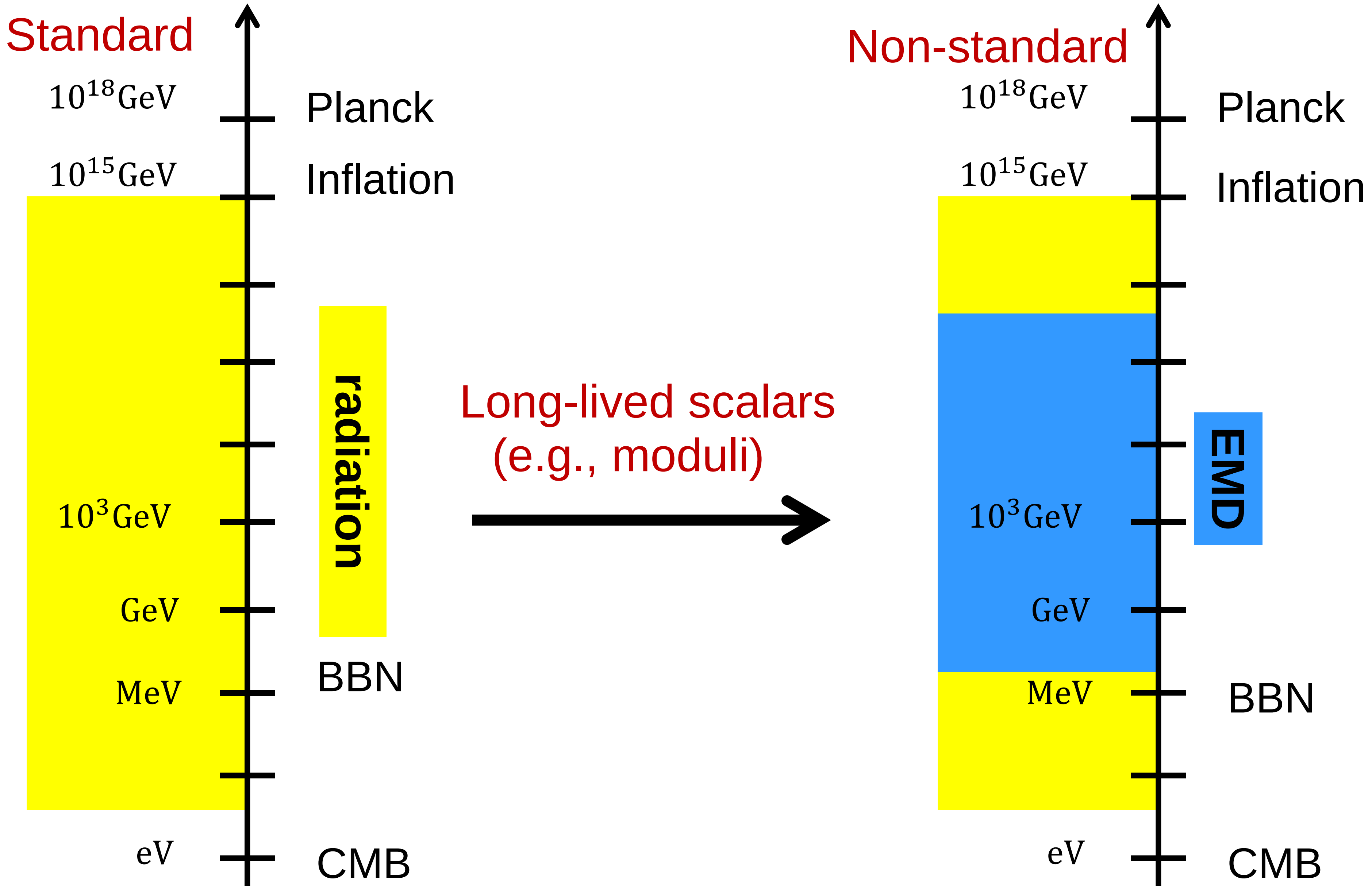
For DM masses *< 20 GeV*:

$$<\sigma_{ann} v>_f \; < 3\times10^{-26}\ cm^3 s^{-1}$$

(assuming S-wave annihilation)

R. Leanne, T. Slatyer, J. Beacom, K. Ng PRD 98, 023016 (2018)

Standard thermal history altered in well-motivated models



G. Kane, K. Sinha, S. Watson IJMPD 8, 1530022 (2015)

Non-thermal DM from Early Matter Domination:

Consider a scalar field ϕ with mass m_ϕ and decay width Γ_ϕ .

Modulus fields in string theory are natural candidates for ϕ :

$$\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2} \qquad c \sim O(1)$$

Dynamics of ϕ in the early universe:

$H \gg m_\phi$: Displaced from the minimum during inflation

$H \simeq m_\phi$: Starts oscillating, behaves like matter, and dominate

$H \simeq \Gamma_\phi$: Decays and forms a RD universe

$$T_R \sim 0.1\,(\Gamma_\phi M_P)^{1/2} \sim \left(\frac{m_\phi}{50\ TeV}\right)^{\frac{3}{2}} \times 3\ MeV \ \Longrightarrow m_\phi \gtrsim 50\ TeV$$

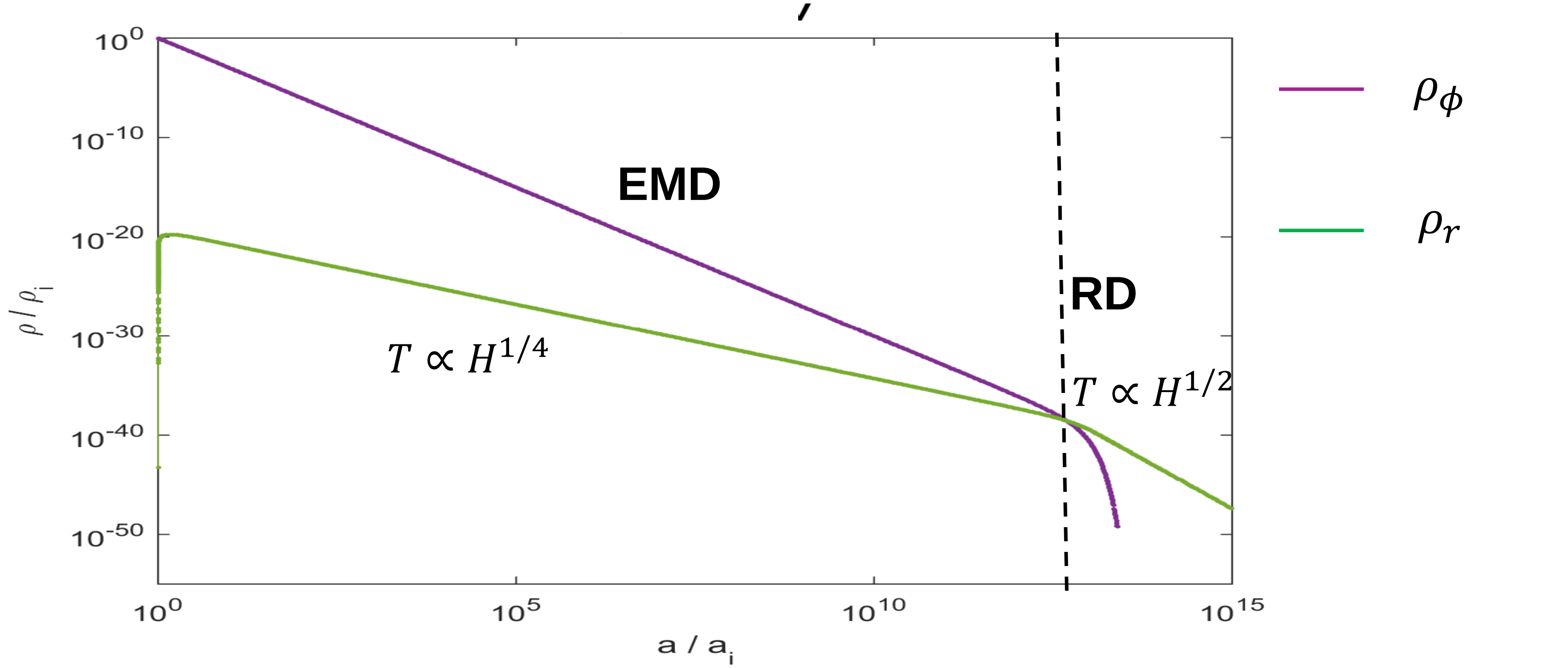
Evolution of matter and radiation energy densities:

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\dot{\rho}_r + 4H\rho_r = +\Gamma_\phi \rho_\phi$$

$$H^2 = \frac{\rho_\phi + \rho_r}{3M_P^2}$$

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$



The abundance of non-thermal DM follows:

$$\dot{n}_\chi + 3Hn_\chi = < \sigma_{ann} v >_f (n_{\chi,eq}^2 - n_\chi^2) + Br_\chi \Gamma_\phi n_\phi$$

Br_χ: number of DM quanta produced per decay of ϕ quanta

Production from thermal processes:

D. Chung, E. Kolb, A. Riotto PRD 60, 063504 (1999)

G. Giudice, E. Kolb, A. Riotto PRD 64, 043512 (2001)

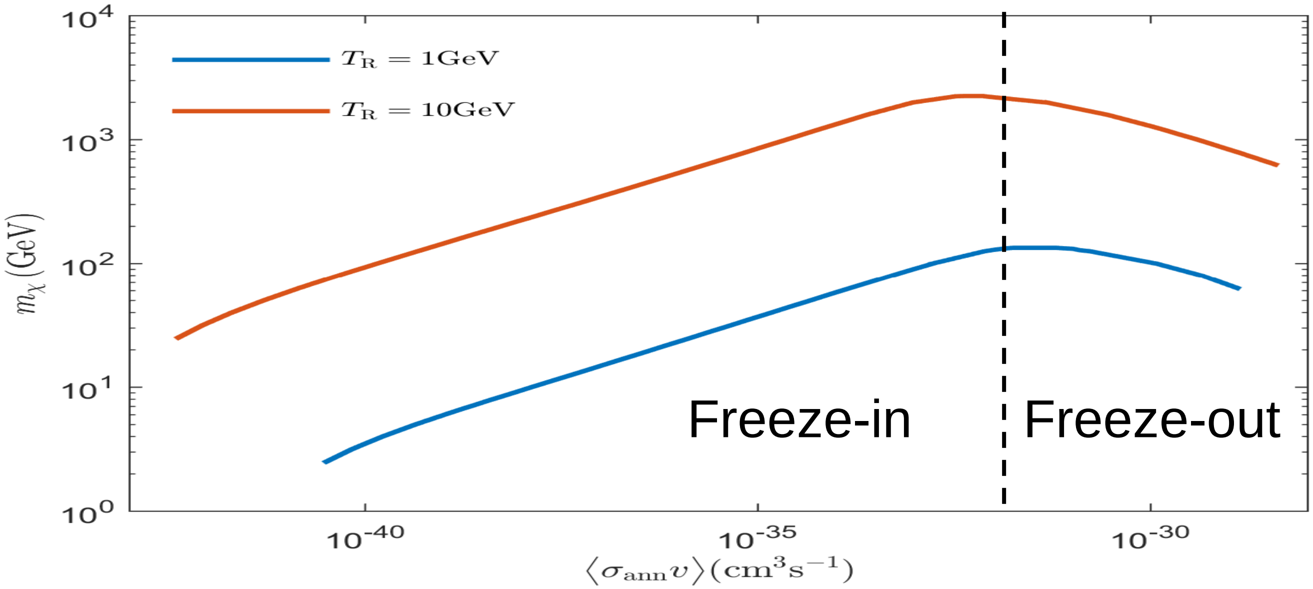
A. Erickcek PRD 92, 103505 (2015)

(1) Freeze-out:

$$(\Omega_\chi h^2)_{fo} \sim 1.6 \times 10^{-4} \left(\frac{m_\chi/T_f}{15}\right)^4 \left(\frac{150}{m_\chi/T_R}\right)^3 \left(\frac{3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>_f}\right)$$

(2) Freeze-in:

$$(\Omega_\chi h^2)_{fi} \sim 0.062 \left(\frac{150}{m_\chi/T_R}\right)^5 \left(\frac{T_R}{5\ \mathrm{GeV}}\right)^2 \left(\frac{<\sigma v>_f}{3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}\right)$$



Freeze-out/in production of DM during EMD is sensitive to the relation between H and T.

The relation depends on the details of EMD and pre-EMD history.

For example:

(1) More than one scalar field may be present during EMD
Multiple string moduli, visible sector fields (AD field)

(2) EMD preceded by other phases
Prior RD phase after inflationary reheating

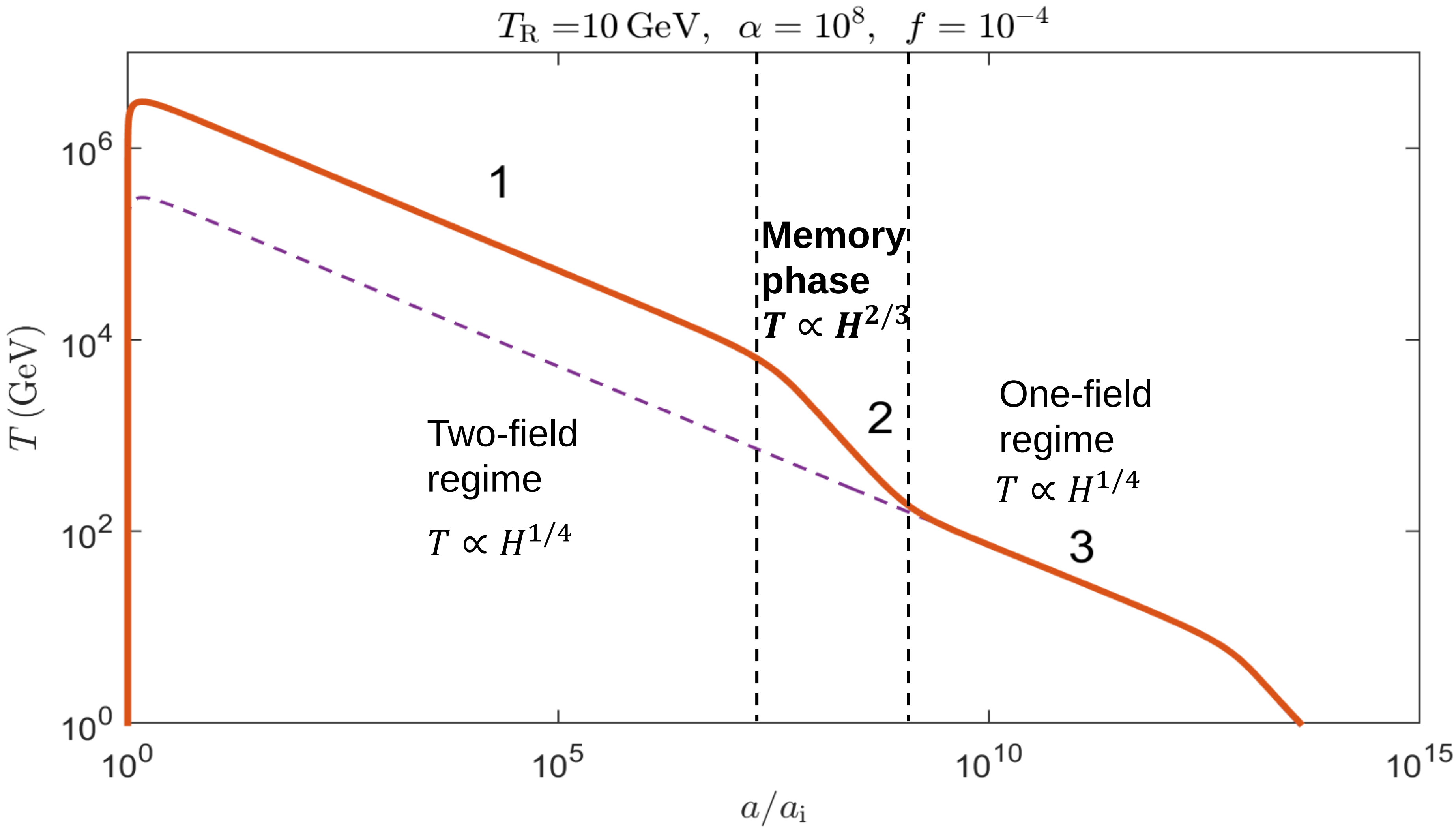
In both of these cases, there will be deviation from the $T \propto H^{1/4}$ relation. This will affect freeze-out/in production of DM.

The allowed parameter space may be significantly different from the simple picture.

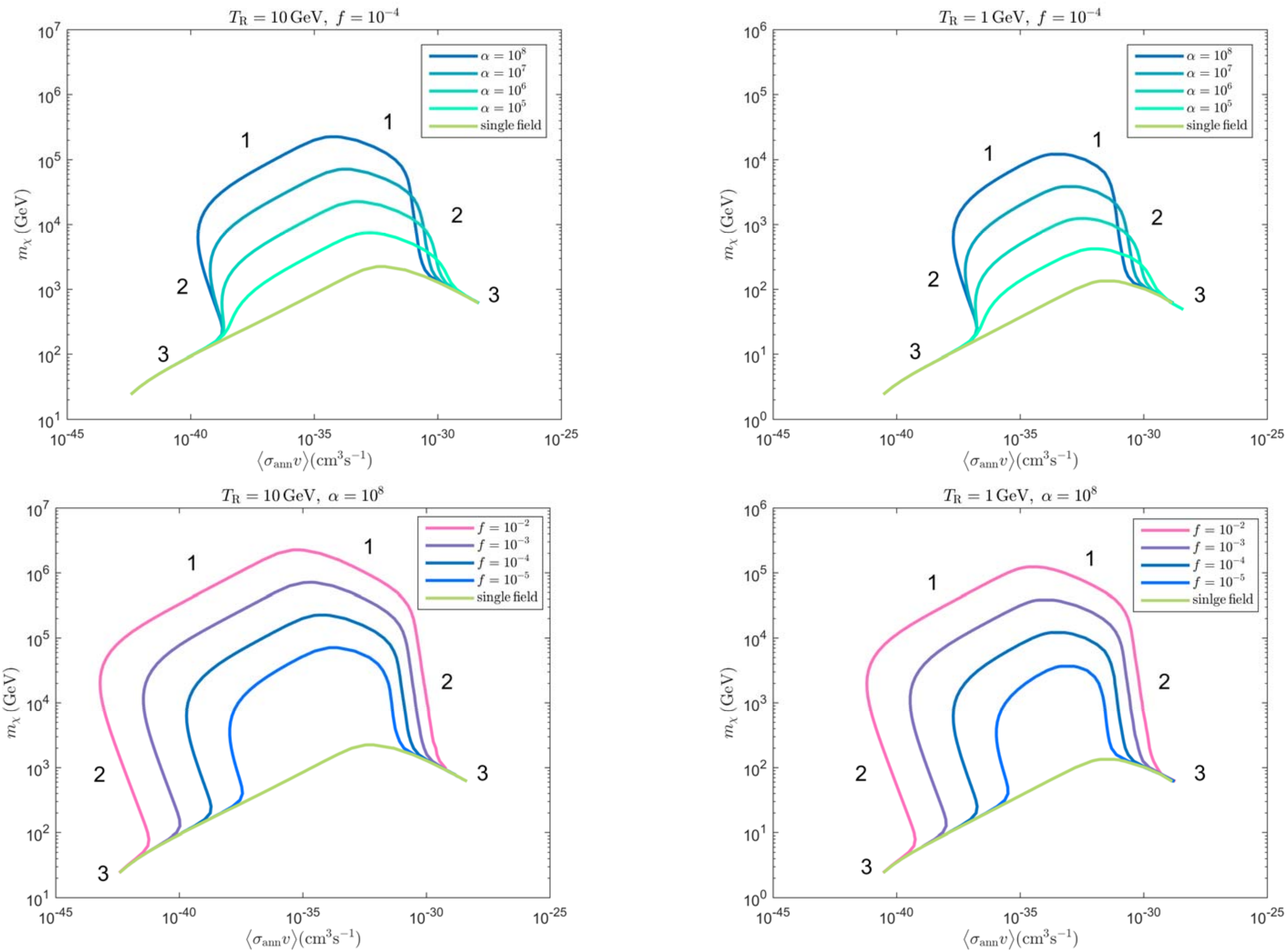
Two field EMD:

$$\rho_\varphi = f\rho_\phi \qquad \Gamma_\varphi = \alpha\Gamma_\phi$$

$$f \ll 1 \qquad \beta \equiv \alpha f \gg 1$$

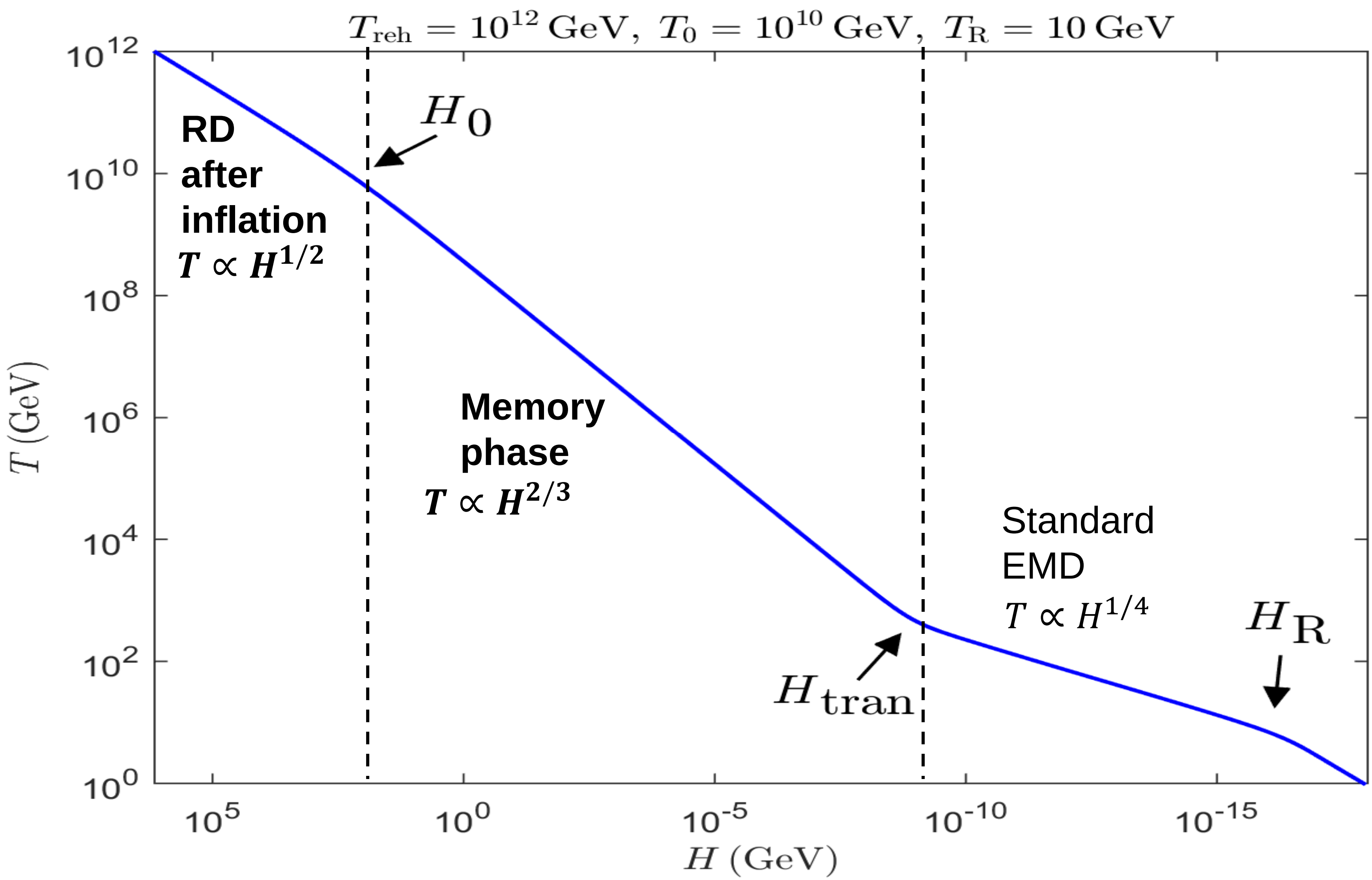


R.A., J. Osinski PRD 99, 083517 (2019)

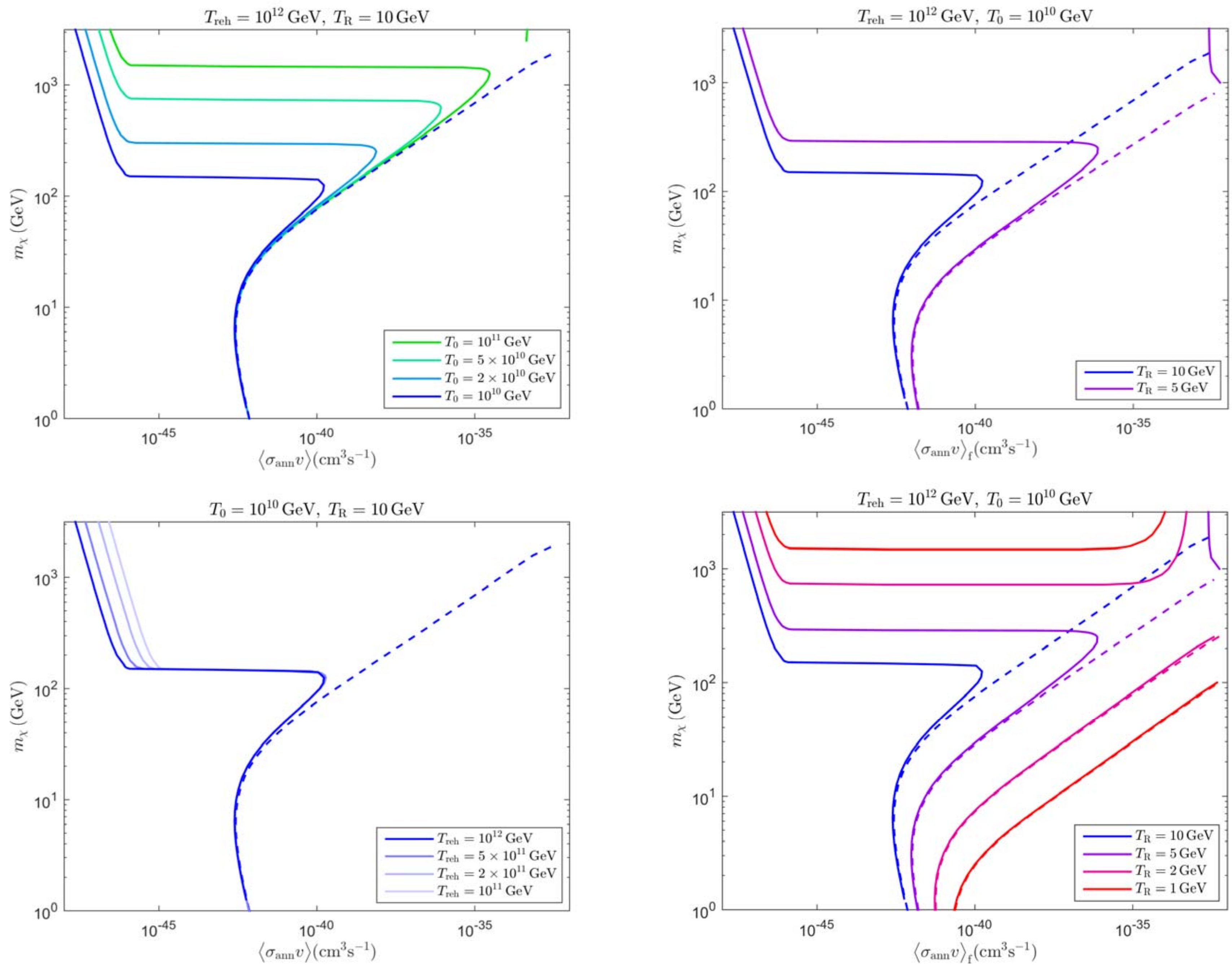


R.A., J. Osinski PRD 99, 083517 (2019)

Pre-EMD effect:



R.A., J. Osinski arXiv: 1909.01457 [hep-ph]



R.A., J. Osinski arXiv:1909.01457 [hep-ph]

Production from direct decay:

(1) Annihilation scenario:

$$< \sigma_{ann} v >_f Br_\chi n_\phi \gtrsim \Gamma_\phi$$

M. Kawasaki, T. Moroi, T. Yanagida PLB 370, 52 (1996)
T. Moroi, L. Randall NPB 570, 455 (2000)
...

$$\boxed{\left(\frac{n_\chi}{s}\right)_{ann} = \left(\frac{n_\chi}{s}\right)_{obs} \frac{3 \times 10^{-26}\ cm^3\ s^{-1}}{< \sigma_{ann} v >_f} \frac{T_f}{T_R}}$$

(2) Branching scenario:

$$< \sigma_{ann} v >_f Br_\chi n_\phi \ll \Gamma_\phi$$

G. Gelmini, P. Gondolo PRD 74, 023510 (2006)
R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)
...

$$\boxed{\left(\frac{n_\chi}{s}\right)_{br} = \frac{3T_R}{4m_\phi} Br_\chi}$$

DM abundance totally decoupled from annihilation rate!

The observed relic abundance can be obtained from non-thermal production for both small and large annihilation rates:

(1) Large annihilation rate: $< \sigma_{ann} v >_f > 3 \times 10^{-26}\ cm^3\ s^{-1}$

FO/FI during EMD is negligible, only direct decay matters (either of "annihilation/branching scenario" can work)

$$\left(\frac{n_\chi}{s}\right)_{non-th} = \min\left[\left(\frac{n_\chi}{s}\right)_{obs} \frac{3 \times 10^{-26}\ cm^3\ s^{-1}}{< \sigma_{ann} v >_f} \frac{T_f}{T_R}, \frac{3T_R}{4m_\phi}\ Br_\chi\right]$$

(2) Small annihilation rate: $< \sigma_{ann} v >_f < 3 \times 10^{-26}\ cm^3\ s^{-1}$

FO/FI during EMD and direct decay both can be significant (only "branching scenario" can work)

$$\left(\frac{n_\chi}{s}\right)_{non-th} = \frac{3T_R}{4m_\phi}\ Br_\chi + \left(\frac{n_\chi}{s}\right)_{fo/fi}$$

Constraints:

(1) Gravitino production must be suppressed.

$\phi \longrightarrow \tilde{G}\tilde{G}$ is the main source of gravitino production.

M. Endo, K. Hamaguchi, F. Takahashi PRL 96, 211301 (2006)

Helicity-1/2 gravitinos pose the main threat.

M. Dine, R. Kitano, A. Morisse, Y. Shirman PRD 73, 123518 (2006)

(2) Br_χ must be small enough for the "branching scenario".

2-body decays can be suppressed.

T. Moroi, L. Randall NPB 570, 455 (2000)

M. Cicoli, A. Mazumdar JCAP 1009, 025 (2010)

However, saturation from 3-body decays $Br_\chi \gtrsim 3 \times 10^{-3}$.

R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)

Challenge: successful realization in explicit models.

R.A., B. Dutta, K. Sinha PRD 86, 095016 (2012)

R.A., B. Dutta, K. Sinha PRD 87, 075024 (2013)

R.A., M. Cicoli, B. Dutta, K. Sinha PRD 88, 095015 (2013)

R.A., M. Cicoli, B. Dutta, K. Sinha JCAP 1410, 002 (2014)

Generation of BAU in Early Matter Domination:

Dilution by modulus decay washes any pre-existing asymmetry:

$$\left(\frac{s_{after}}{s_{before}}\right) \sim \frac{M_P}{m_\phi} \quad (>> 10^{10})$$

How to generate the desired BAU?

- At the end of EMD:

Non-thermal post-sphaleron baryogenesis

R.A., B. Dutta, K. Sinha   PRD 81, 053538 (2010)

- Or, from a mechanism that has its associated entropy:

Affleck-Dine baryogenesis

G. Kane, J. Shao, S. Watson, H-B Yu   JCAP 1111, 012 (2011)

R.A., M. Cicoli, F. Muia   JHEP 1606, 153 (2016)

A non-thermal origin may also help the DM-baryon coincidence.

R.A., B. Dutta, K. Sinha   PRD 83, 083502 (2011)

A Minimal Model:

B and *L* are accidental symmetries of SM at the perturbative level.

We adopt a bottom-up approach and consider a minimal extension of the SM with renormalizable $\cancel{B}$ interactions:

R.A., B. Dutta PRD 88, 023525 (2013)

$$\mathcal{L} \supset (\lambda_{\alpha i} X_\alpha \psi u^c_i + \lambda'_{\alpha ij} X^*_\alpha d^c_i d^c_j + \frac{m_\psi}{2} \bar{\psi}^c \psi + \mathrm{H.c.})$$
$$+ \; m^2_{X_\alpha} |X_\alpha|^2 + (\text{kinetic terms})\,.$$

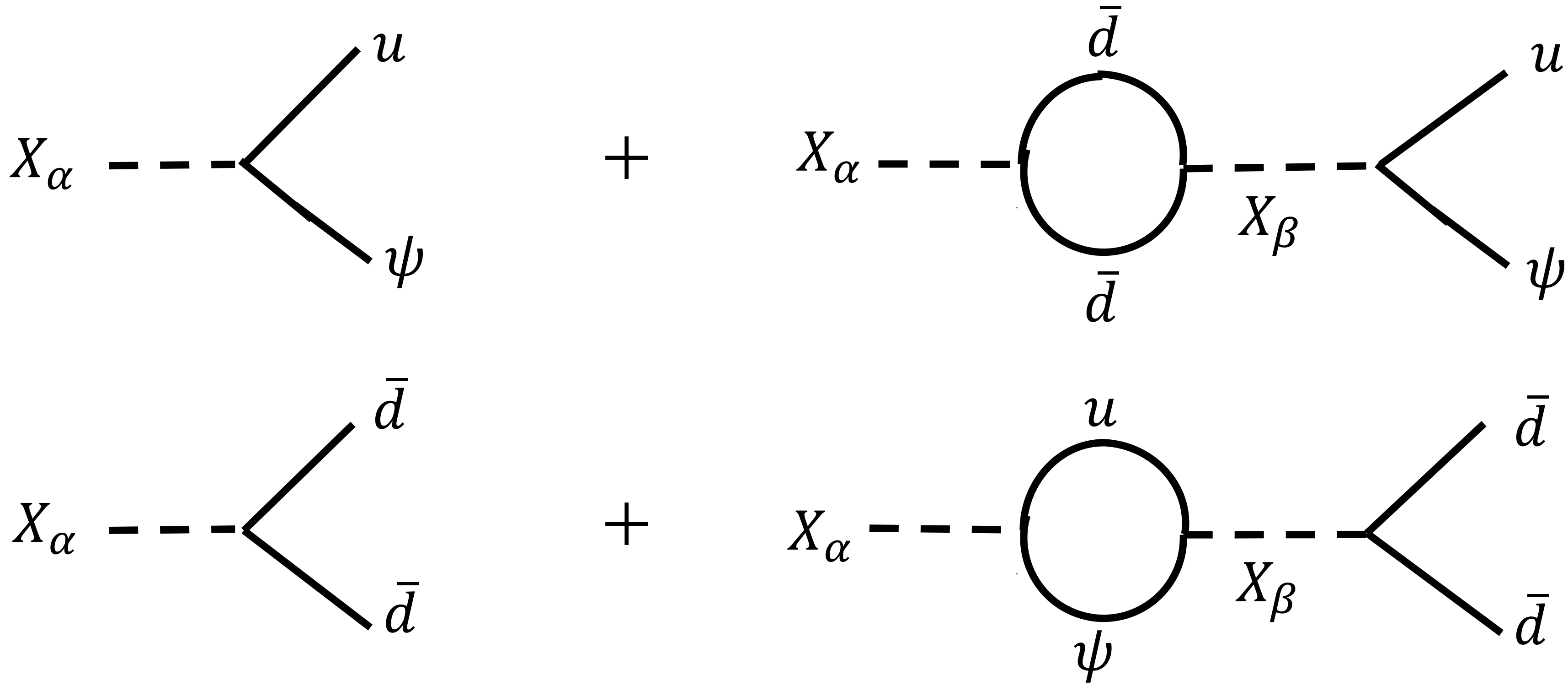
$X_{1,2}$: Iso-singlet color-triplet scalars Y =+4/3

ψ: Singlet fermion

Two color triplets are required in order to generate a nonzero baryon asymmetry via out-of-equilibrium decay of *X*.

E. Kolb, S. Wolfram NPB 172, 224 (1980); Erratum-ibid 195, 542 (1982)

Baryogenesis:



$$\epsilon_\alpha = \frac{1}{8\pi}\frac{\sum_{ijk}\mathrm{Im}(\lambda^*_{\alpha k}\lambda_{\beta k}\lambda'^*_{\alpha ij}\lambda'_{\beta ij})}{\sum_i|\lambda_{\alpha i}|^2+\sum_{ij}|\lambda'_{\alpha ij}|^2} \times \frac{(m^2_{X_\alpha}-m^2_{X_\beta})m_{X_\alpha}m_{X_\beta}}{(m^2_{X_\alpha}-m^2_{X_\beta})^2+m^2_{X_\alpha}\Gamma^2_{X_\beta}}$$

$$\Gamma_{X_\alpha} = \frac{m_{X_\alpha}}{16\pi}\left(\sum_i|\lambda_{\alpha i}|^2+\sum_{ij}|\lambda'_{\alpha ij}|^2\right)$$

$$\Delta m_X \equiv |m_{X_1}-m_{X_2}| \sim \frac{\Gamma_X}{2} \ll m_{X_{1,2}} \quad \rightarrow \epsilon_{max}\sim O(0.1)$$

$|\lambda_1 \lambda'_{12}|$ severely constrained by $\Delta B = 2$, $\Delta S = 2$ processes:

1) $n - \overline{n}$ oscillations.

2) Double proton decay $pp \rightarrow K^+ K^+$.

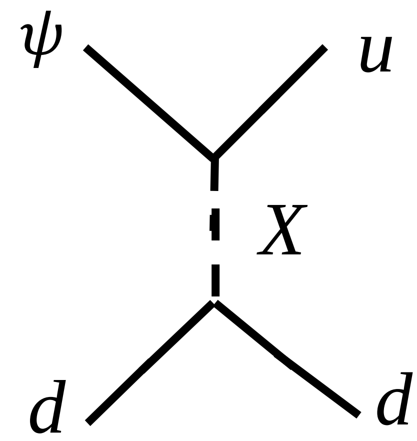
For $m_\psi \sim O(GeV), m_X \sim O(TeV)$ double proton decay requires:
$|\lambda_1 \lambda'_{12}| < 10^{-6}$

Experimental bounds on $K_s^0 - \overline{K}_s^0$ and $B_s^0 - \overline{B}_s^0$ oscillations are also satisfied (loop suppressed).

EDM constraints not strong since the new interactions involve only one chirality of quarks.

4-fermion interaction at low energies:

$$\frac{\lambda\lambda'}{m_X^2}\psi u d d$$



This operator results in the following decays:

$$m_\psi > m_p + m_e\text{:}\quad \psi \to p + e^- + \bar{\nu}_e\,, \bar{p} + e^+ + \nu_e$$

$$m_\psi < m_p - m_e\text{:}\quad p \longrightarrow \psi + e^+ + \nu_e\,, \psi + e^+ + \bar{\nu}_e$$

ψ is stable and becomes a viable dark matter (DM) candidate if:

$$m_p - m_e < m_\psi < m_p + m_e$$

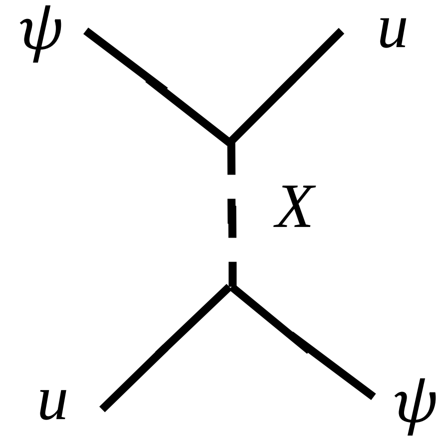
Stability of DM is tied to the stability of the proton.

Vicinity of DM and proton mass also useful for the DM-baryon coincidence puzzle.

Direct Detection:

Effective interaction at low energies:

$$\frac{1}{m_X^2 - (p_\psi - p_u')^2} (\bar{\Psi}_\psi P_L \Psi_\psi) \, (\bar{\Psi}_u P_R \Psi_u)$$



Spin-independent piece:

$$\frac{1}{m_X^4} (\bar{\Psi}_\psi \, \gamma^\mu \, \partial^\nu \Psi_\psi) \, [(\bar{\Psi}_u \gamma_\mu \partial_\mu \Psi_u) - (\partial_\nu \bar{\Psi}_u \gamma_\mu \Psi_u)]$$

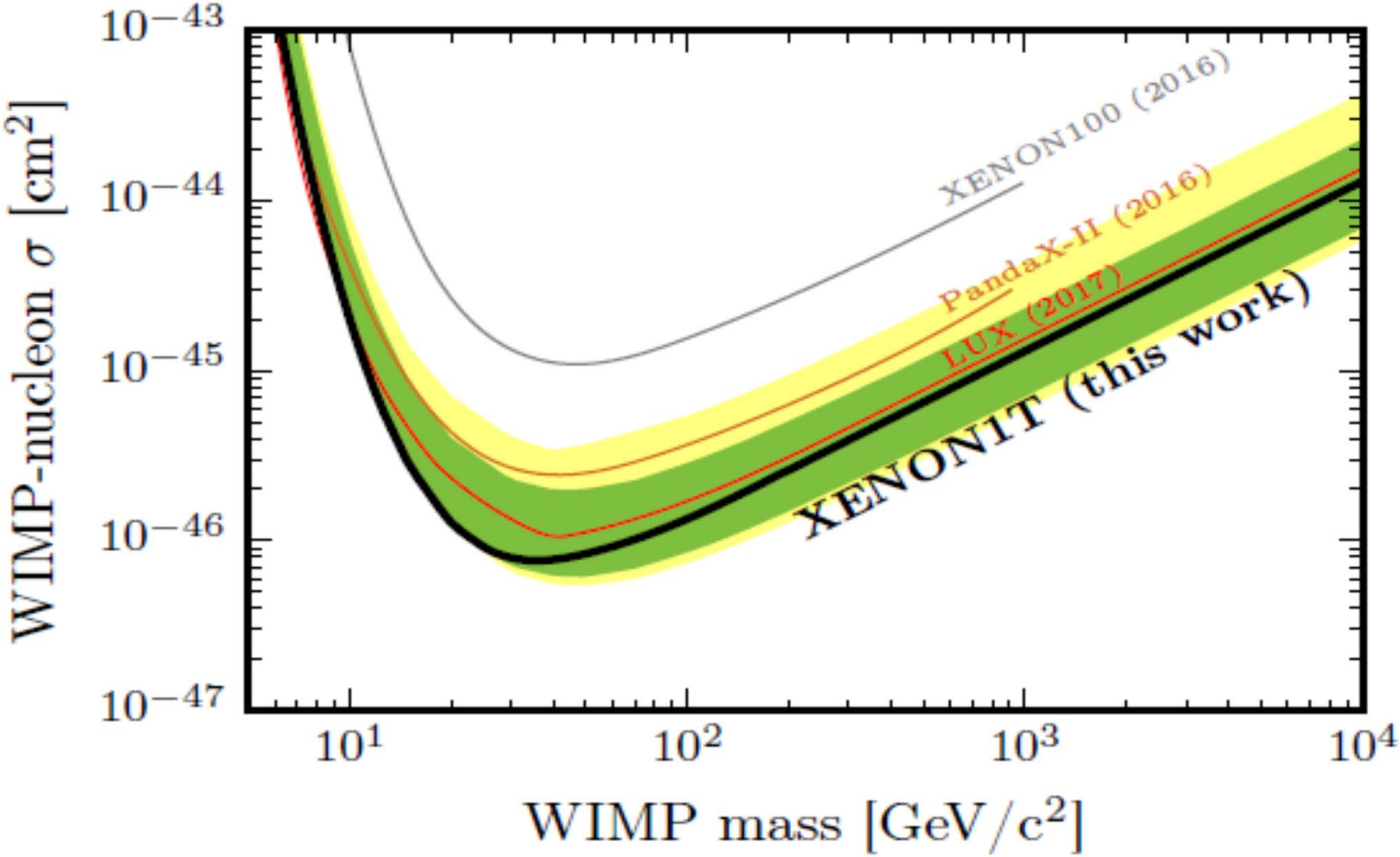
$$\sigma_{SI} \sim |\lambda|^4 \frac{O(GeV)^6}{m_X^8}$$

Spin-dependent piece:

$$\frac{1}{m_X^2} (\bar{\Psi}_\psi \, \gamma^\mu \, \gamma^5 \Psi_\psi) \, (\bar{\Psi}_u \gamma_\mu \gamma^5 \Psi_u)$$

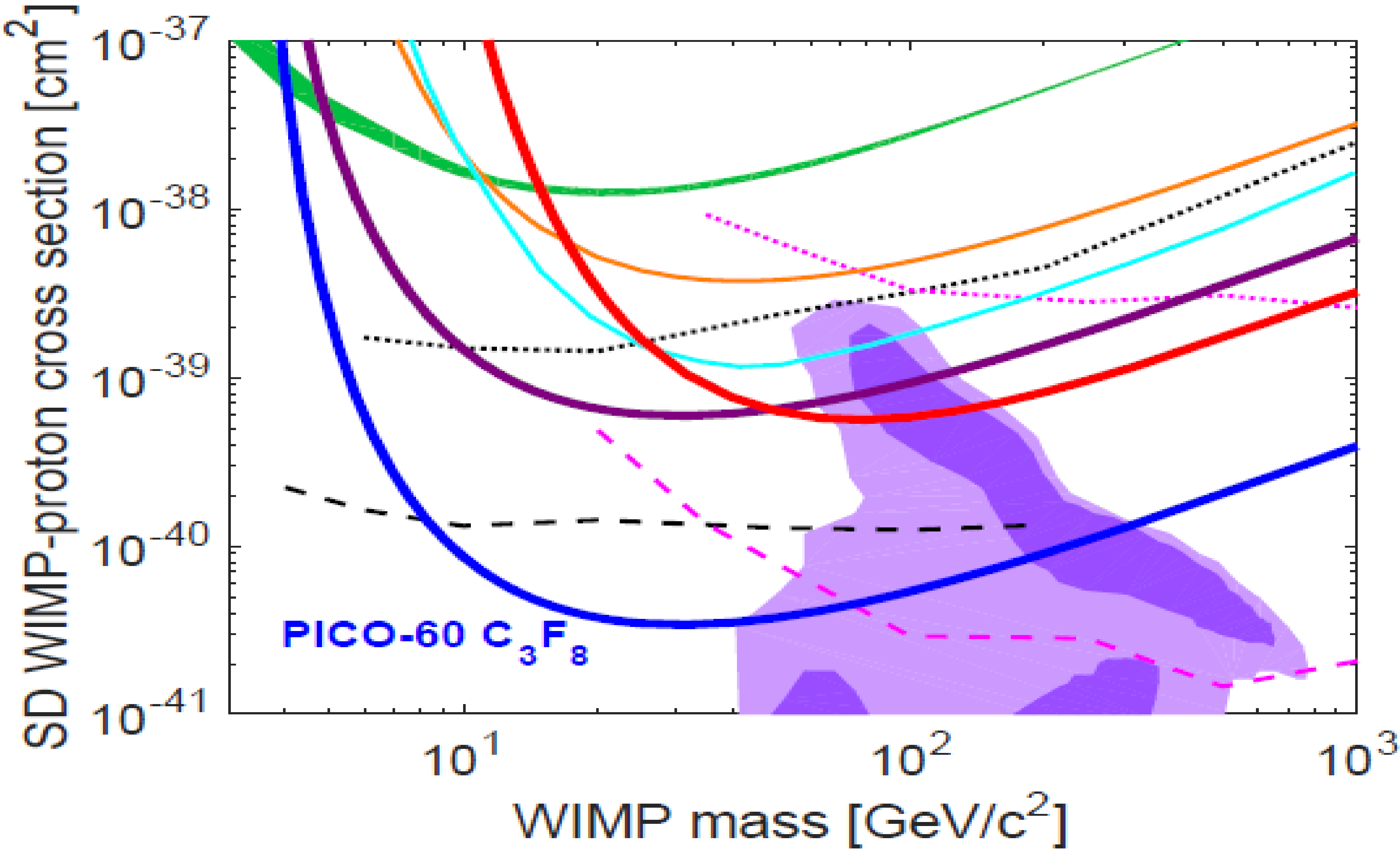
$$\sigma_{SD} \sim |\lambda|^4 \frac{O(GeV)^4}{m_X^4}$$

XENON Collaboration PRL 119, 181301 (2017)



$$m_X \sim O(TeV) \Rightarrow \sigma_{SI} < 10^{-52} cm^2$$

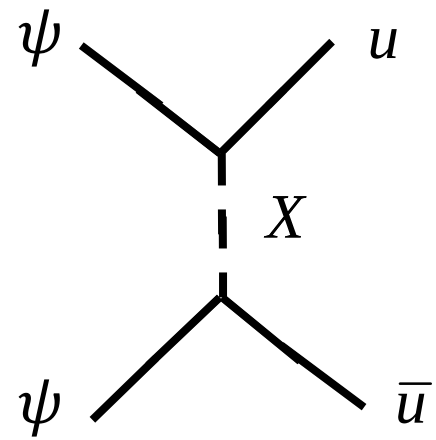
PICO Collaboration PRD 93, 052014 (2016)



$$m_X \sim O(TeV) \Rightarrow \sigma_{SD} < 10^{-40} cm^2$$

Indirect Detection:

$$\langle \sigma_{\rm ann} v \rangle \sim \frac{|\lambda_{\alpha 1}|^4}{8\pi} \frac{m_\psi^2}{m_{X_\alpha}^4}$$



$$m_X \sim O(TeV) \Longrightarrow <\sigma_{ann} v> \ll 3 \times 10^{-26}\ cm^3 s^{-1}$$

Neutrino or gamma-ray signals from galactic or extragalactic DM annihilation far below detectable levels.

Neutrino signal from solar DM annihilation also negligible:

1) σ_{ann} and $\sigma_{SD,SI}$ are .very small.

2) Evaporation dominates for $O(GeV)$ DM mass.

Low prospect for direct or indirect detection of DM in the model.

Relic Abundance:

Thermal freeze-out results in overproduction of DM.

A non-standard thermal history with EMD can help.

Consider a scenario where a scalar field ϕ drives an era of EMD.

ϕ decay reheats the universe to a temperature $T_R \ll 1\, GeV$.

The decay also produces ψ (DM) and *X* particles.

Subsequent decay of *X* generates the BAU.

$$\frac{n_\psi}{s} = \frac{n_\phi}{s}\frac{n_\psi}{n_\phi} = \frac{3T_{\rm R}}{m_\phi}\,{\rm Br}_{\phi\to\psi} \equiv Y_\phi\,{\rm Br}_{\phi\to\psi}$$

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq Y_\phi \sum_\alpha {\rm Br}_{\phi\to X_\alpha}\epsilon_\alpha$$

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq \frac{\mathrm{Br}_{\phi\to\psi}}{\sum_\alpha \epsilon_\alpha \mathrm{Br}_{\phi\to X_\alpha}}$$

$$\mathrm{Br}_{\phi\to\psi} = \mathrm{Br}^{\rm direct}_{\phi\to\psi} + \sum_\alpha \mathrm{Br}_{\phi\to X_\alpha}\mathrm{Br}_{X_\alpha\to\psi} \geq \sum_\alpha \mathrm{Br}_{\phi\to X_\alpha}\mathrm{Br}_{X_\alpha\to\psi}\,,$$

$$\mathcal{L} \supset (\lambda_{\alpha i} X_\alpha \psi u^c_i + \lambda'_{\alpha ij} X^*_\alpha d^c_i d^c_j + \frac{m_\psi}{2}\bar{\psi}^c\psi + \mathrm{H.c.}) + m^2_{X_\alpha}|X_\alpha|^2 + (\text{kinetic terms})\,.$$

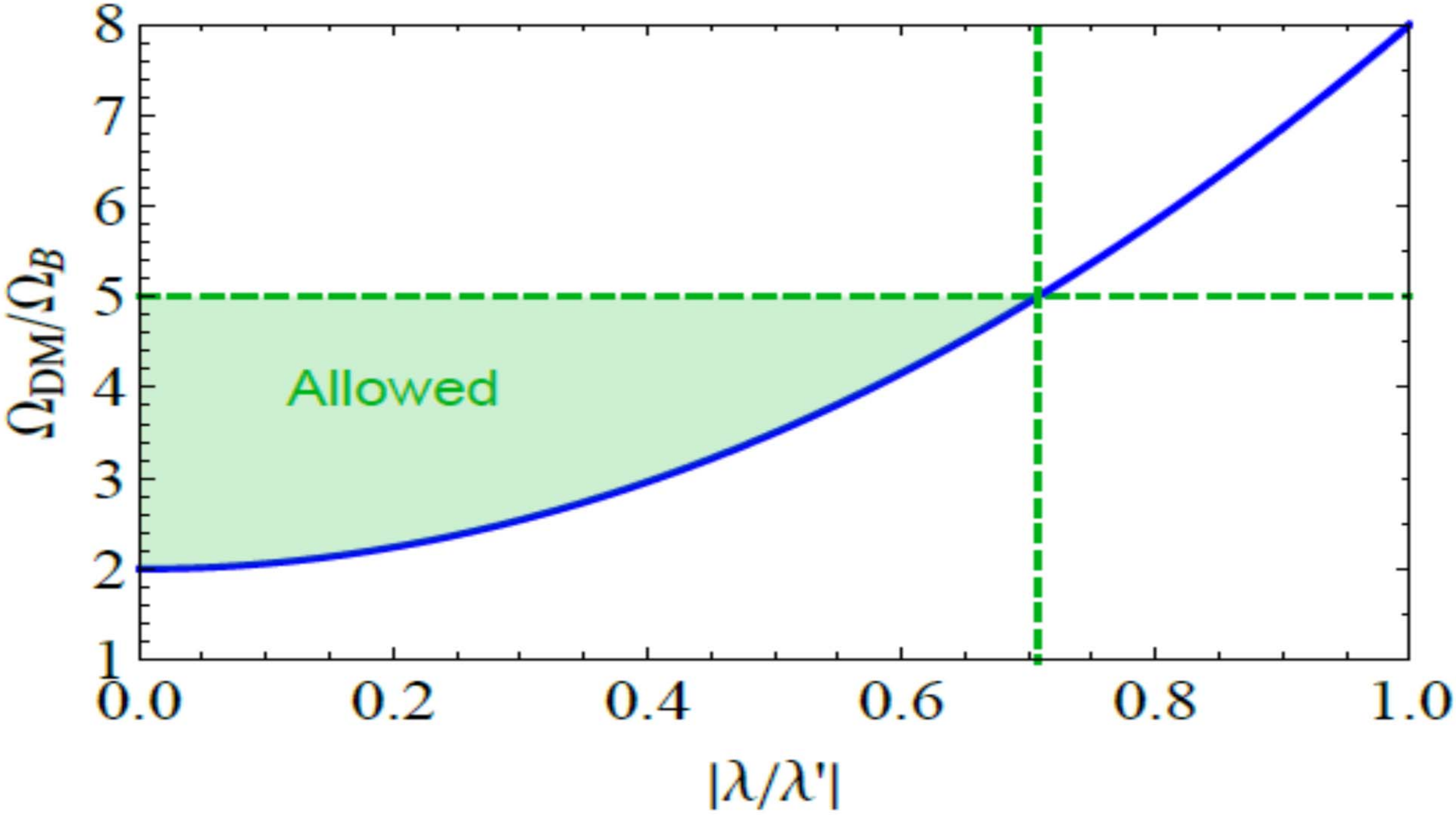
$$\mathrm{Br}_{X_\alpha\to\psi} = \frac{\sum_i |\lambda_{\alpha i}|^2}{\sum_{ij}|\lambda'_{\alpha ij}|^2 + \sum_i |\lambda_{\alpha i}|^2}$$

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \gtrsim \frac{\mathrm{Br}_{X_\alpha\to\psi}}{\epsilon_\alpha}$$

We need $\frac{\Omega_{DM}}{\Omega_B} \approx 5$.

General constraint on the couplings:

$$\lambda \equiv |\lambda_1| = |\lambda_2| = |\lambda_3| \qquad \lambda' \equiv \sqrt{|\lambda'_{13}|^2 + \lambda'_{23}|^2}$$

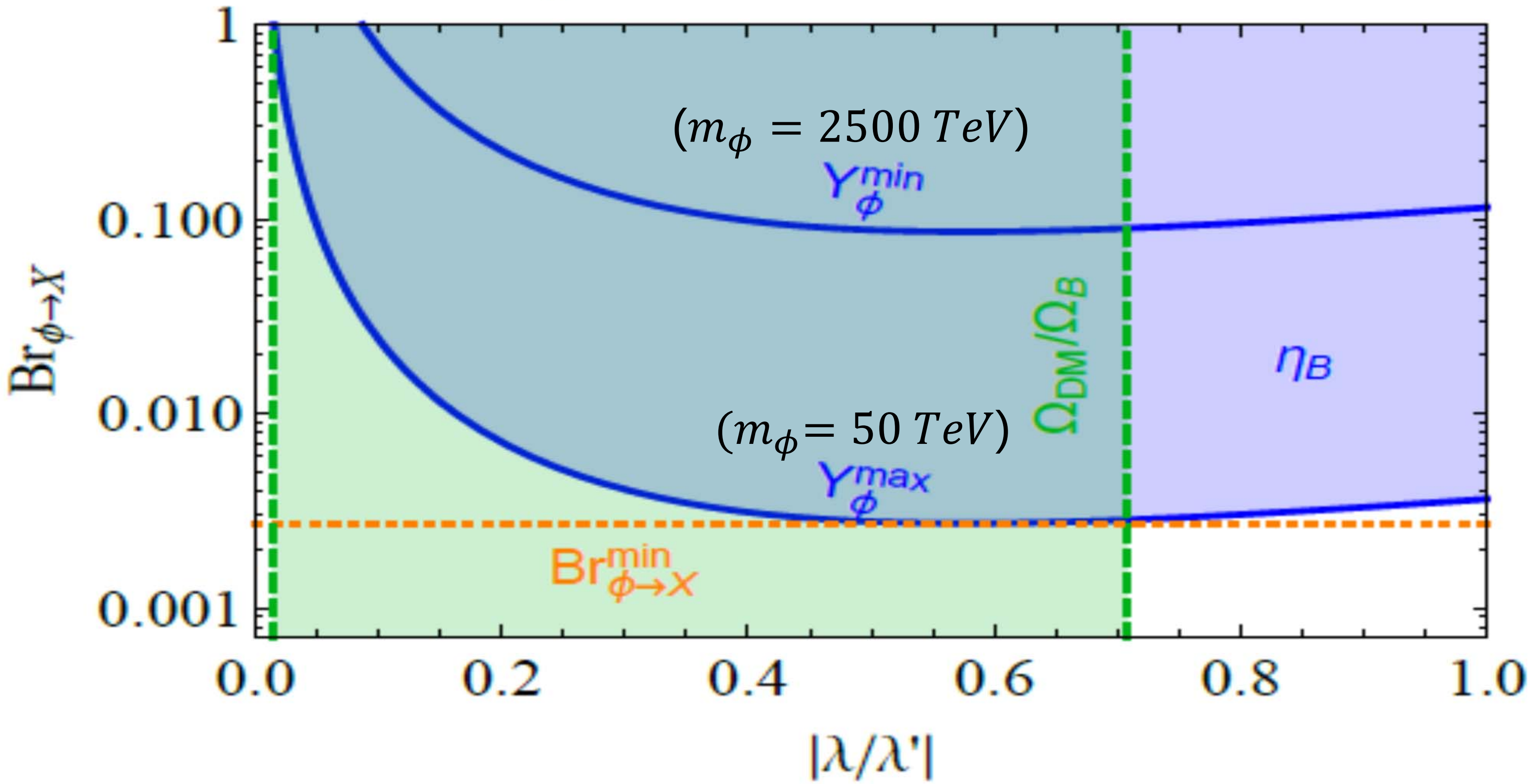


R.A., P. S. Bhupal Dev, B. Dutta PLB 779, 262 (2018)

Further constraints obtained by considering a modulus field:

$$\Gamma_\phi = \frac{c_\phi}{2\pi}\frac{m_\phi^3}{M_{\rm Pl}^2} \qquad T_{\rm R} \sim c_\phi^{1/2}\left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{m_\phi}{50\ {\rm TeV}}\right)^{3/2}(3\ {\rm MeV})$$

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq Y_\phi \sum_\alpha {\rm Br}_{\phi\to X_\alpha}\epsilon_\alpha \qquad Y_\phi \equiv \frac{3T_R}{4m_\phi} \qquad \varepsilon \geq 0.1$$



R.A., P. S. Bhupal Dev, B. Dutta PLB 779, 262 (2018)

Low-energy Signals:

$n - \overline{n}$ Oscillations:

$$G_{n\bar{n}} \simeq \frac{\lambda^2 \lambda'^4_{13} m_\psi}{16\pi^2 m_X^6} \ln\left(\frac{m_X^2}{m_\psi^2}\right)$$

$$\tau_{n\bar{n}} \sim (\Lambda_{QCD}^6 G_{n\bar{n}})^{-1}$$

Note that only λ'_{13} matters for $n - \overline{n}$ oscillations.

Current experimental limits:

$$\tau_{n\bar{n}} \geq 3 \times 10^8 \ s$$

Super-K Collaboration PRD 91, 072006 (2015)
SNO Collaboration arXiv:1705.00696

Next generation experiments:

$$\tau_{n\bar{n}} \geq 5 \times 10^{10} \ s$$

D. G. Phillips et al Phys. Rept. 612, 1 (2016)

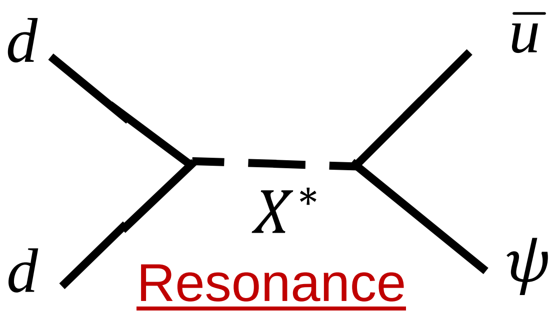
Collider Signals:

Both odd & even number of DM particles are produced from the interactions of the SM particles:

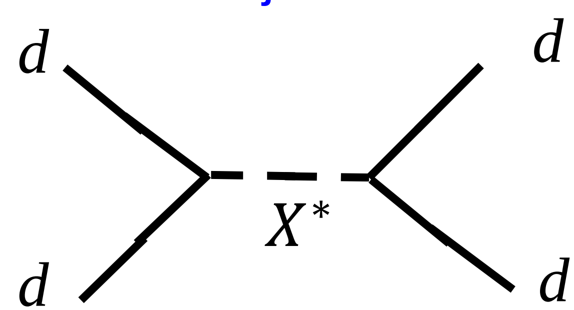
Monojets (including monotops) & dijets plus missing energy.

B. Dutta, Y. Gao, T. Kamon PRD 89, 096009 (2014)

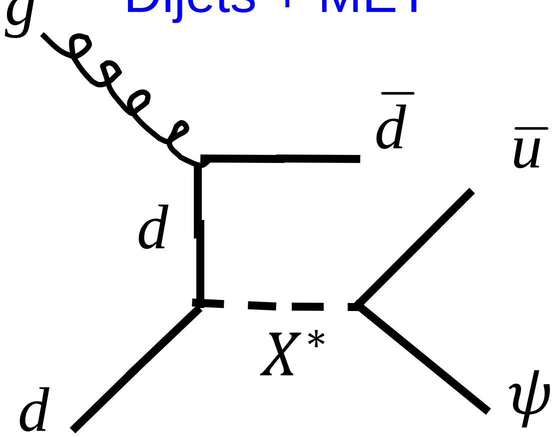
Monojets + MET



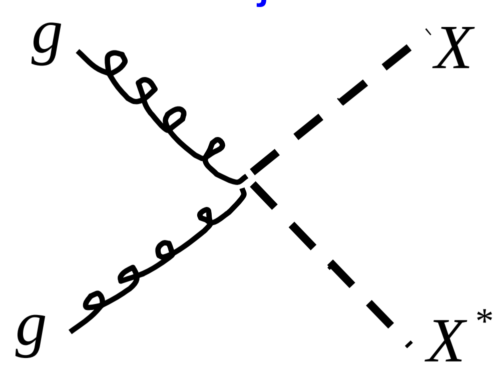
Dijets



Dijets + MET



Paired dijets + MET



Complementarity of cosmological considerations and experimental limits to constrain the parameter space of the model.

CMS & ATLAS dijet constraints

CMS Collaboration arXiv:1611.03568

ATLAS Collaboration arXiv:1711.02692

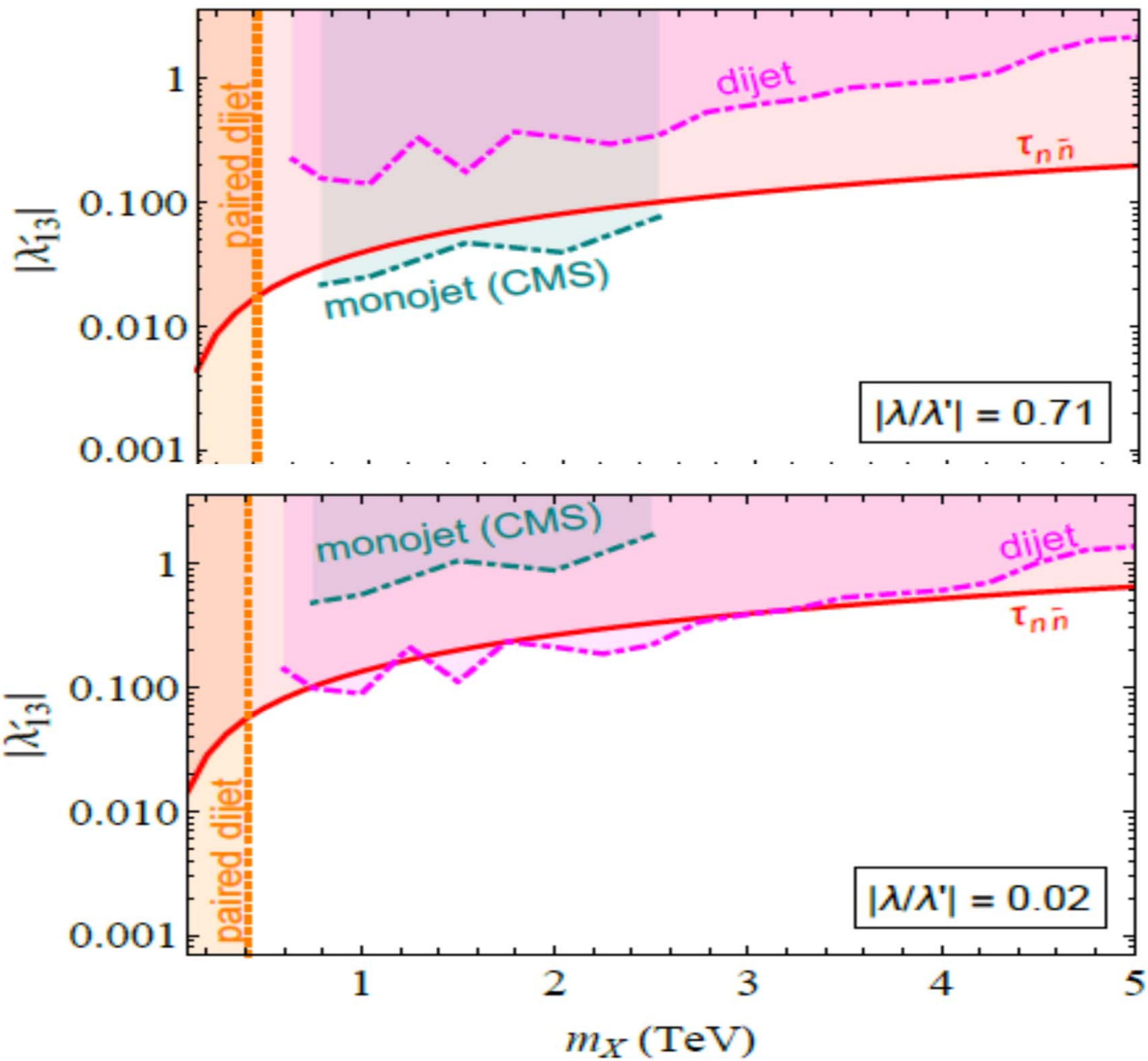
ATLAS analysis of pair-produced resonances

ATLAS Collaboration arXiv:1710.07171

A dedicated CMS monojet analysis

CMS Collaboration PRD 97, 092005 (2018)

We have also included the constraints from $n-\overline{n}$ oscillations and DM and baryogenesis, with λ'_{13} set to zero.



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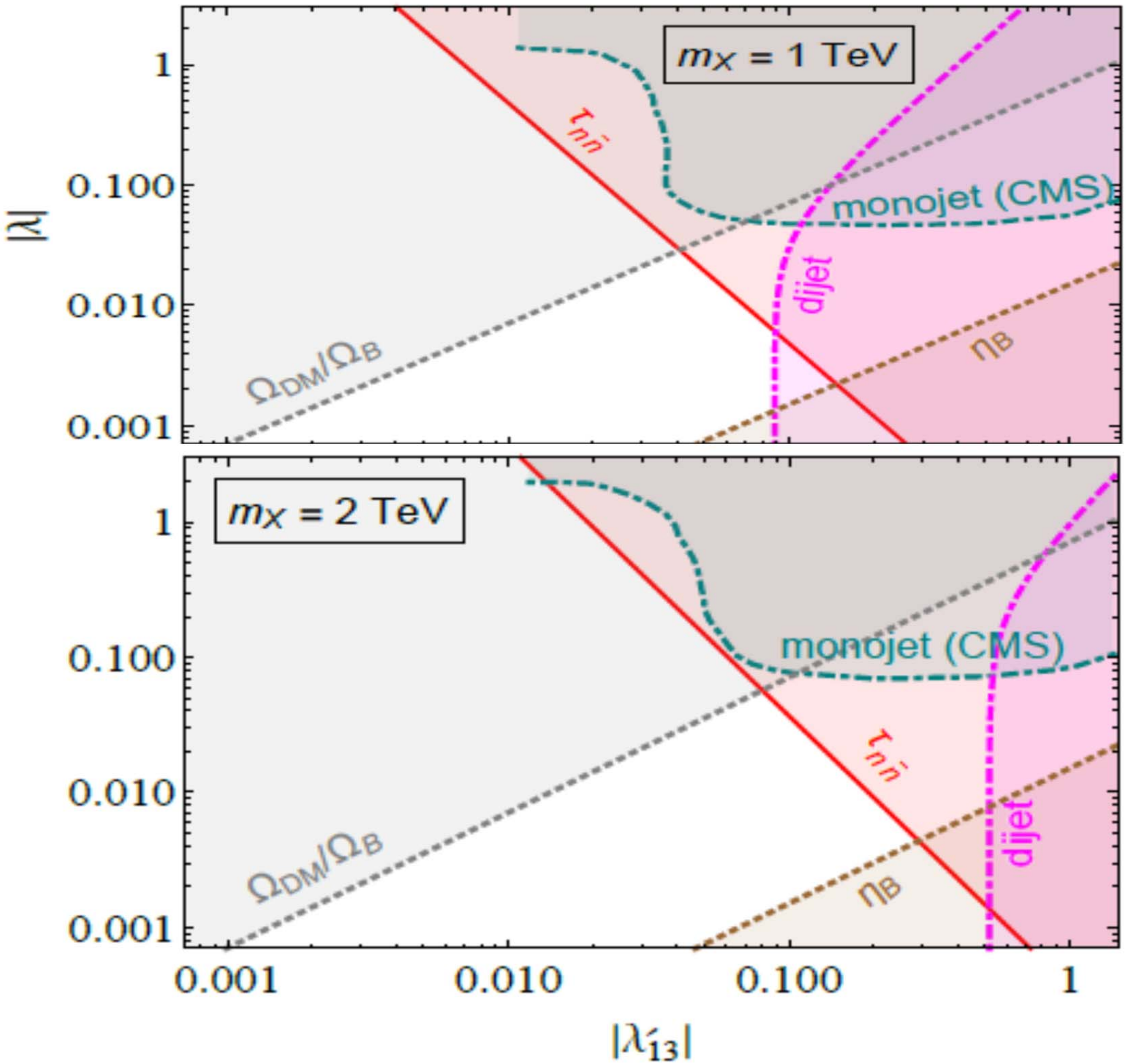

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Conclusion and Outlook:

- Thermal DM is an attractive scenario
  Coming under increasing scrutiny, relies on certain assumptions

- EMD provides a suitable framework for non-thermal DM
  Typically arises in a well-motivated class of UV complete models

- Can yield the correct relic abundance for large and small σ_{ann}
  Details of EMD and pre-EMD important for precise predictions

- EMD requires non-thermal baryogenesis
  Same origin for DM & BAU may explain baryon-DM coincidence

- A minimal predictive model for baryogenesis and DM presented
  Novel complementarity of experimental and cosmological limits