Non-thermal WIMPs: Opportunities and Challenges

Rouzbeh Allahverdi

THE UNIVERSITY of NEW MEXICO

Exploring the Energy Ladder of the Universe

MITP, Johannes Gutenberg University of Mainz

May 30-June 10, 2016

Outline:

- Introduction
  WIMP miracle in principle & in practice, assumptions & limits

- Non-thermal DM from late reheating
  Different scenarios, constraints & challenges

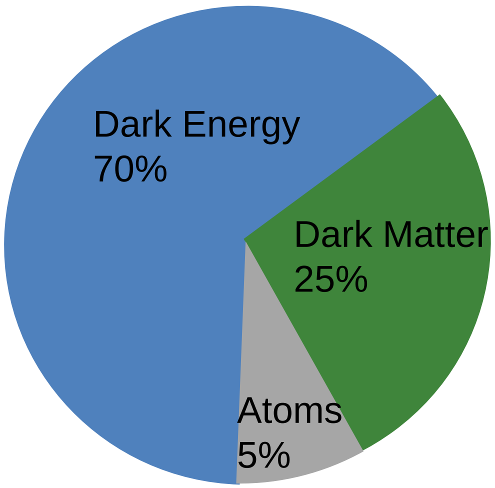
- An explicit model
  Successful realization in LVS

- Novel observational signatures
  Boosted DM annihilation, PBHs

- Summary and Outlook

Introduction:

The present universe according to observations:



BSM needed to explain 95% of the universe.

Important questions about DM:

What is the nature of DM?

How did it acquire its relic abundance?

Profound consequences for:

Particle Physics (BSM)

Cosmology (thermal history)

Focus of this talk is on WIMP(-like) DM

(will not consider sterile neutrino, axion, axino, gravitino, …)

Weakly Interacting Massive Particles (WIMPs) are promising DM candidates.

WIMPs arise naturally in extensions of the SM.

Consider a WIMP χ with mass m_χ that interacts with SM particles through a coupling g_χ .

The rate for WIMP interaction with SM particles at a temperature $T >> m_\chi$ is:

$$\Gamma \sim \alpha_\chi^2 T$$

For weak scale mass and coupling, the interaction is in equilibrium in the radiation-dominated phase:

$$\Gamma >> H \qquad (m_\chi << T < T_R)$$

Thermal DM:

Starting in thermal equilibrium at $T >> m_\chi$:

1) $T >> m_\chi : \quad \chi\chi \leftrightarrow f\bar{f},... \quad \Rightarrow \quad n_\chi \propto T^3 \;,\; n_\chi / s = const$

2) $T < m_\chi : \quad \chi\chi \rightarrow f\bar{f},... \quad \Rightarrow \quad n_\chi \propto \exp(-m_\chi / T)$

3) $T \approx T_f : \quad freeze-out \quad \Rightarrow \quad n_\chi / s = const$

$$\Omega_\chi h^2 \approx 10^{-1} \Rightarrow \boxed{<\sigma_{ann} v>_f = 3\times 10^{-26}\ cm^3 s^{-1}}$$

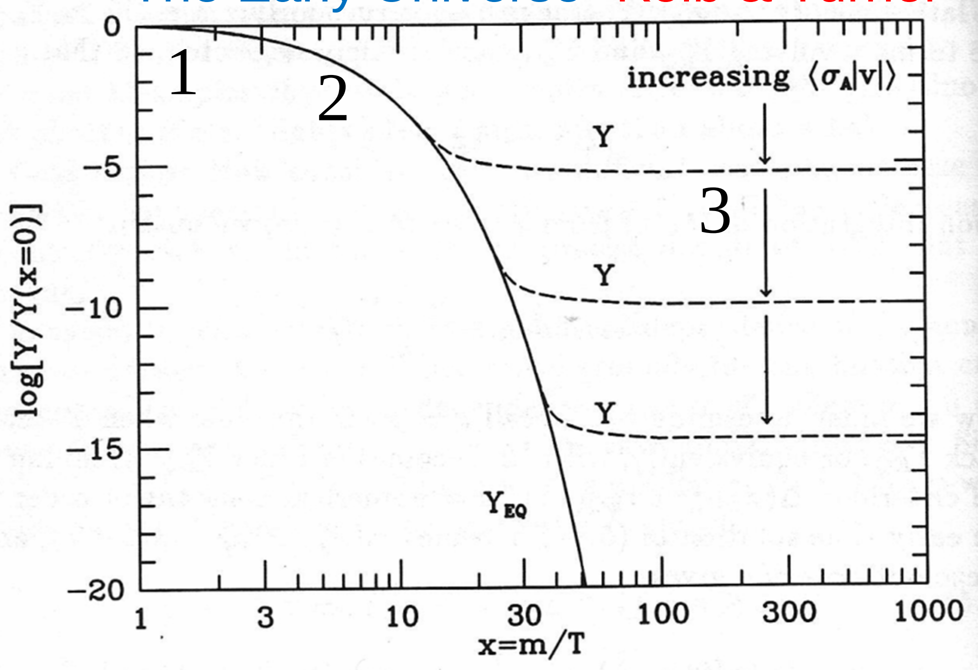
WIMP miracle:

$$<\sigma_{ann} v>_f = \frac{\alpha_\chi^2}{m_\chi^2}$$

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

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

“The Early Universe” Kolb & Turner



In principle, thermal DM is a very attractive scenario.

DM abundance insensitive to details of thermal history at $T > T_f$.

However, thermal equilibrium above T_f is an assumption.

WIMP freeze-out occurred when:

$$T_f \sim \frac{m_\chi}{20} \Rightarrow t_f \sim \frac{1}{H_f} \sim 400 \frac{M_P}{m_\chi^2} \qquad m_\chi \sim 100\, GeV \Rightarrow t_f \sim 10^{-7}\ s$$

We have no observational probe of the early universe before 1 *sec*.

The best experimental probes of the early universe at the present:

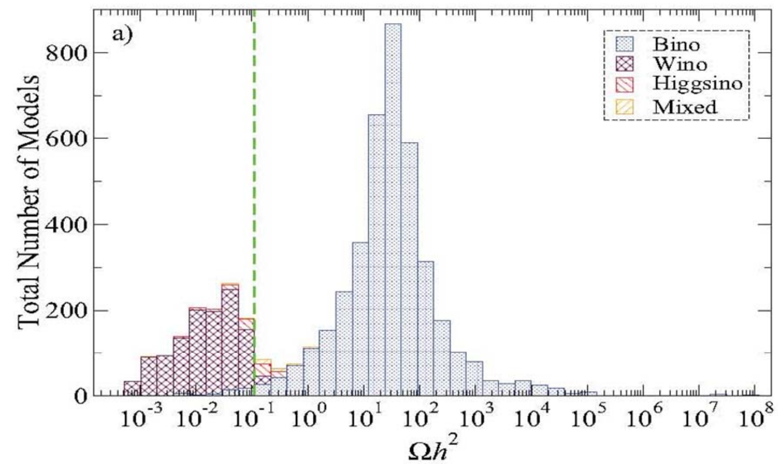
1) CMB: *t* ~ 400,000 *yr*
2) BBN: *t* ~ 1 *sec*

DM will be the strongest probe of the thermal history, but only **after** it is discovered and its properties are established**.**

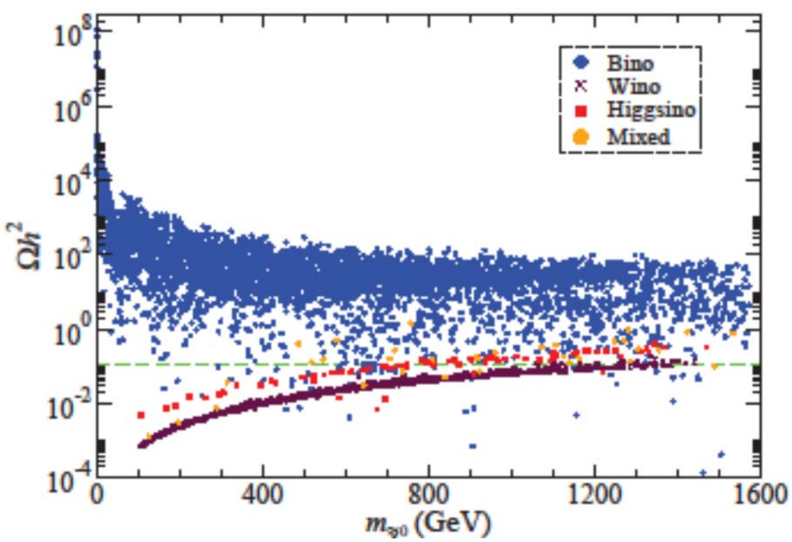
In practice, thermal DM is not a generic scenario.

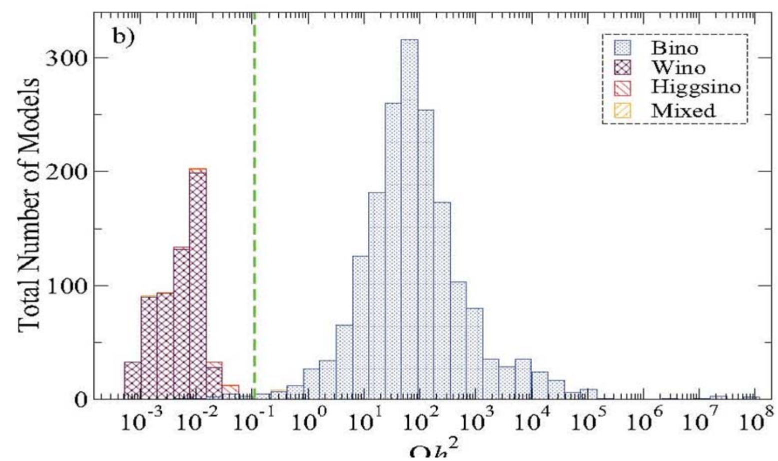
Example: pMSSM.

H. Baer, A. Box, H. Summy JHEP 1010, 023 (2010)



WIMP miracle needs real miracle!





Parametrization of annihilation rate is oversimplified:

$$< \sigma_{ann} v >_f = \frac{\alpha_\chi^2}{m_\chi^2}$$

1) It assumes DM mass is the only relevant mass scale.

2) It assumes there is no velocity dependence.

In MSSM:

1) Many annihilation diagrams with particles of different masses.

2) Annihilation is velocity suppressed in many cases.

$$< \sigma_{ann} v >_f = a + b v^2 + \ldots \qquad T = T_f \sim \frac{m_\chi}{20} \Rightarrow v^2 \sim 0.1$$

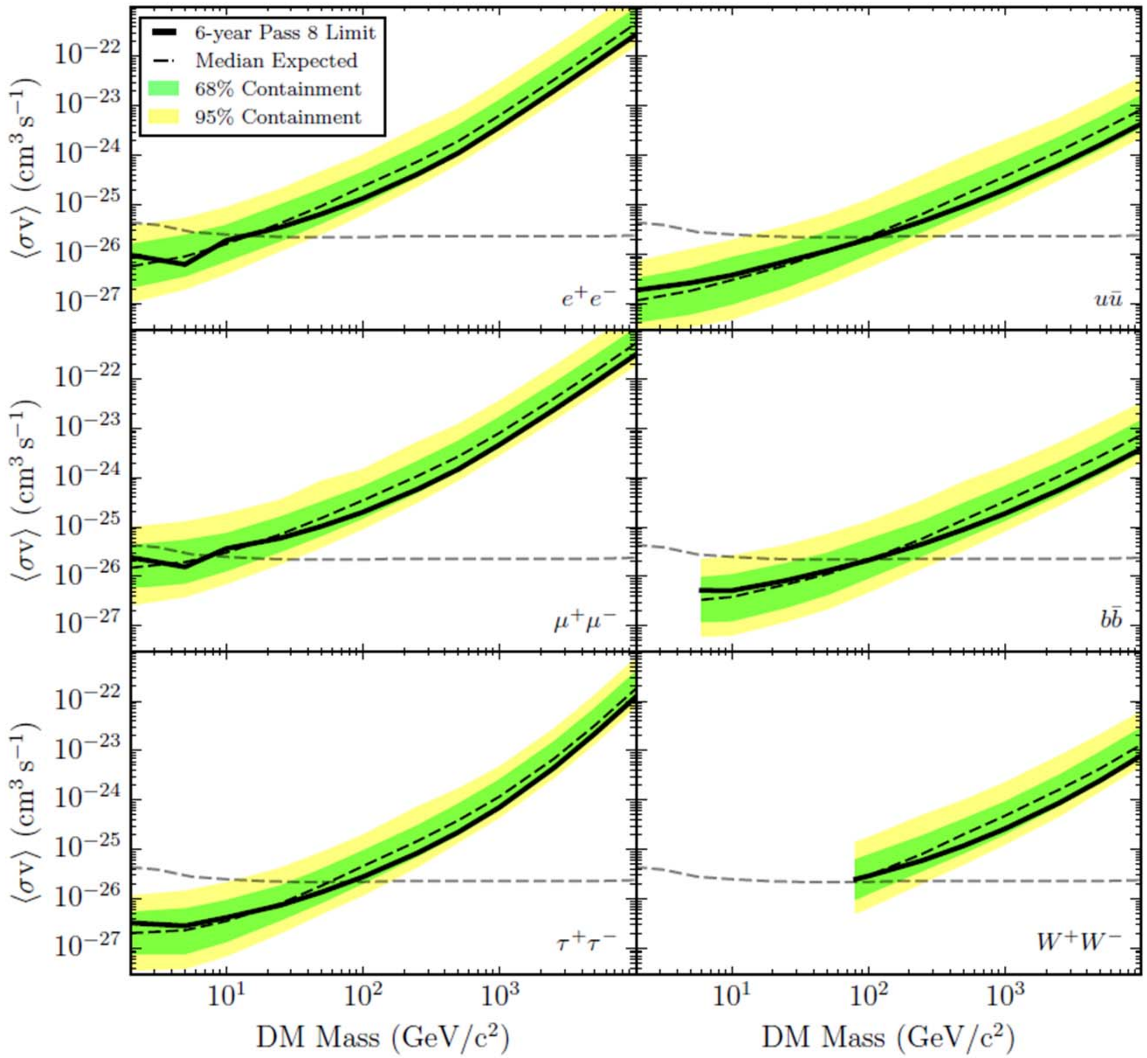
S-wave P-wave

Significant suppression of annihilation rate if $a << b$.

Indirect Detection Experiments:

Stringent bounds on annihilation rate from non-detection of gamma-rays from dwarf spheroidals.

Fermi Collaboration arXiv:1503.02632



WIMP miracle ruled out for smaller DM masses!

Assuming:

S-wave dominance

Single-component DM

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

Thermal overproduction

Collider Experiments:

Modifications of MSSM proposed after 125 GeV Higgs discovered.

Example: Natural SUSY

H. Baer, V. Barger, P. Huang, X. Tata JHEP 1205, 109 (2012)
M. Papucci, J. Ruderman, A. Weiler JHEP 1209, 035 (2012)
L. Hall, D. Pinner, J. Ruderman JHEP 1201, 134 (2012)

3rd generation squarks & EW gauginos $\sim O(TeV)$

Gluinos $\sim 3-4\ TeV$

1st and 2nd generation squarks & sleptons $>> 10\ TeV$

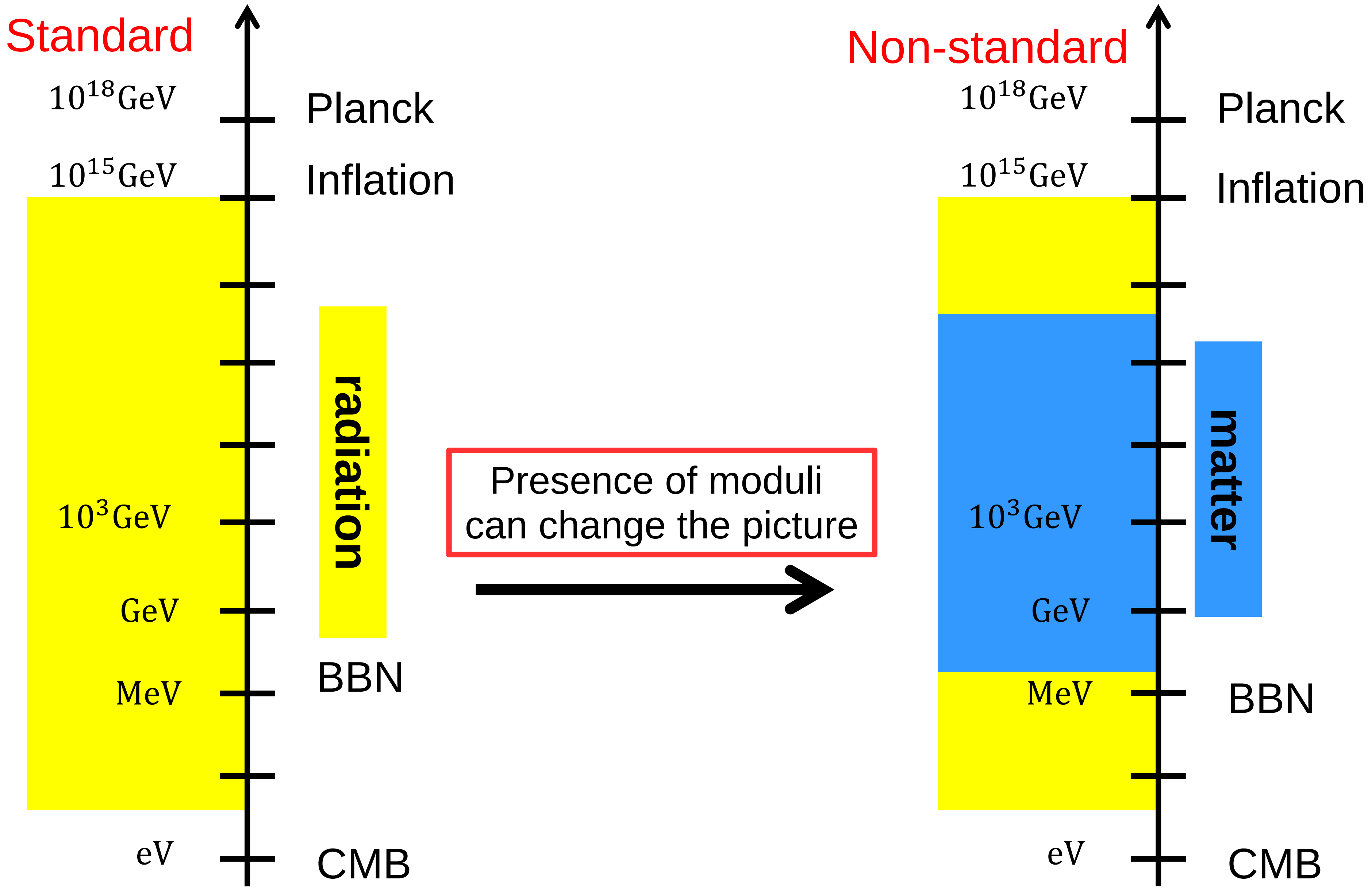
$\mu \sim 150-200\ GeV$

Higgsino is the DM candidate:

$$<\sigma_{ann} v>_f \sim \frac{\alpha_{EW}^2}{m_\chi^2} > 3\times 10^{-26}\ cm^3 s^{-1} \qquad (m_\chi < 1.2\ TeV)$$

Thermal underproduction

Thermal History of the Universe:



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

Obtaining correct relic density for $<\sigma_{ann} v>_f \neq 3\times 10^{-26}\ cm^3 s^{-1}$ within a standard thermal history:

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

Multi-component DM (WIMP + non-WIMP)

Example: mixed Higgsino/axion DM

H. Baer, A. Box, H. Summy JHEP 0908, 080 (2009)

Asymmetric DM (relic density not set by annihilation)

K. Zurek Phys. Rept. 537, 91 (2014)

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

Super/E-WIMP DM from WIMP decay

Examples:

Axino DM L. Covi, J. Kim, L. Roszkowski PRL 82, 4180 (1999)

Gravitino DM J. Feng, A. Rajaraman, F. Takayama PRL 91, 011302 (2003)

Non-thermal DM from Late Reheating:

DM relic density will be different in non-standard thermal histories (i.e., if there is entropy production at $T < T_f$).

J. Barrow NPB 208, 501 (1982)

M. Kamionkowski, M. Turner PRD 42, 3310 (1990)

Such a scenario can naturally arise from decay of a scalar field ϕ that reheats the universe to a temperature $T_r < T_f \ (\sim m_\chi / 20)$.

m_ϕ : Scalar mass

Γ_ϕ : Scalar decay width

$$T_r \sim (\Gamma_\phi M_P)^{1/2}$$

Late decay releases entropy:

$$s_{after} = \frac{2\pi^2}{45} T_r^3$$

Modulus fields are natural candidates for ϕ .

Commonly arise in SUSY and string models, and are long lived:

$$\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2}$$

(typically: $c \sim 0.1 - 1$)

Moduli dynamics in the early universe: $(m_\phi << H_{\inf})$

1) Displaced during inflation $\phi_0 \sim M_P$

2) Start oscillating when $H \approx m_\phi$

3) Decay and reheat the universe $T_r \sim \left(\frac{m_\phi}{50\ TeV}\right)^{3/2} \times 3\ MeV$

BBN requires that $T_r > 3\ MeV$.

Handicap (cosmological moduli problem) turned into virtue if:

$$\boxed{m_\phi > 50\ TeV}$$

Modulus decay releases huge entropy:

$$\frac{s_{after}}{s_{before}} = \left(\frac{\rho_{rad,after}}{\rho_{rad,before}} \right)^{3/4} = \left(\frac{\rho_{\phi}}{\rho_{rad,before}} \right)^{3/4}$$

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

Any DM relic abundance produced via thermal freeze-out prior to modulus decay is diluted by a huge factor.

This renders production prior to late reheating totally irrelevant.

DM relic density must be entirely produced by late reheating.

Sources of DM relic abundance in the late reheating scenario:

(1) DM particles directly produced in scalar decay.

$$\left(\frac{n_\chi}{s}\right)_{dec} = Y_\phi \; Br_\chi$$

$$Y_\phi \equiv \frac{n_\phi}{s} = \frac{3T_r}{4m_\phi}$$

Br_χ : Branching ratio to R-parity odd particles

It can account for the entire DM relic abundance, provided that:

$$\left(\frac{n_\chi}{s}\right)_{dec} \geq \left(\frac{n_\chi}{s}\right)_{obs} \approx 5\times 10^{-10}\left(\frac{1 \; GeV}{m_\chi}\right)$$

Two different scenarios are possible.

Annihilation Scenario:

$$\left(\frac{n_\chi}{s}\right)_{dec} > \left(\frac{n_\chi}{s}\right)_{obs} \quad , \quad <\sigma_{ann} v>_f \; > 3\times 10^{-26} \; cm^3 s^{-1} \left(\frac{T_f}{T_r}\right)$$

Residual annihilation is efficient, and can lower the abundance to the correct value.

M. Kawasaki, T. Moroi, T. Yanagida   PLB 370, 52 (1996)

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

…

Branching Scenario:

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

Annihilation is inefficient, scalar decay directly produces just the right DM abundance.

G. Gelmini, P. Gondolo   PRD 74, 023510 (2006)

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

Annihilation scenario only works for thermal underproduction:

$$T_r = T_f \left(\frac{3\times 10^{-26}\ cm^3 s^{-1}}{<\sigma_{ann} v>_f} \right)$$

Experimental constraints on $<\sigma_{ann} v>_f$ restrict T_r .

Branching scenario works for both thermal under/overproduction:

$$Br_\chi\ Y_\phi = (5\times 10^{-10}) \left(\frac{1\ GeV}{m_\chi} \right)$$

Insensitive to $<\sigma_{ann} v>_f$, restrictions for model building.

Task: Successful realization within realistic models.

(2) DM particles thermally produced during scalar decay.

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)

$$\Gamma_\phi << H << m_\phi \ :$$

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi \qquad H = 0.33 \frac{g_*(T)}{g_*^{1/2}(T_r)} \frac{T^4}{T_r^2 M_P}$$

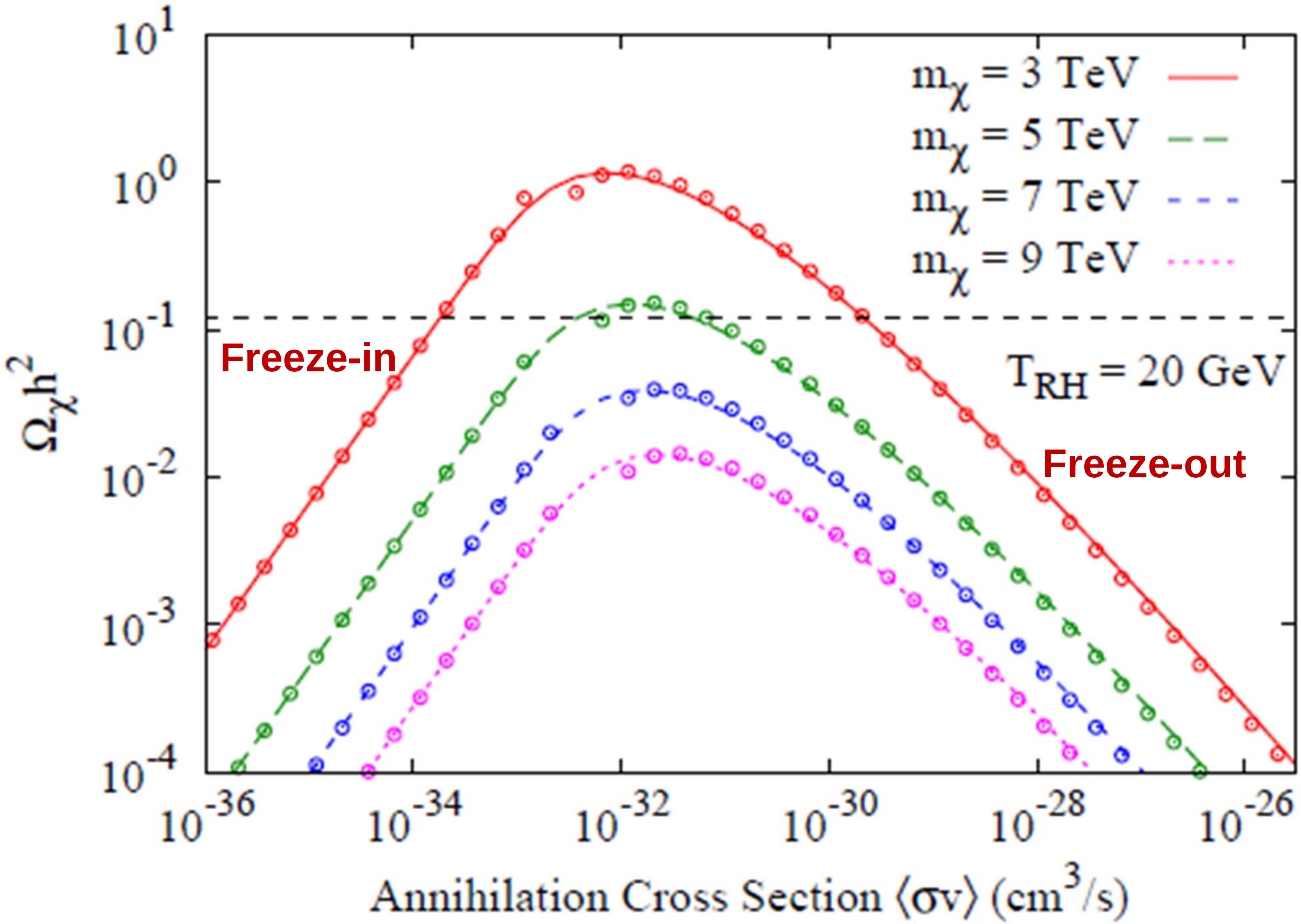
Assuming decay products instantly thermalize:

$$\dot{\rho}_r + 4H\rho_r = +\Gamma_\phi \rho_\phi \qquad \rho_r = \frac{\pi^2}{30} g_*(T)\ T^4$$

Production via freeze-out in the instantaneous thermal bath:

$$\left(\frac{n_\chi}{s}\right)_{fo} \approx \left(\frac{n_\chi}{s}\right)_{obs} \left(\frac{m_\chi / T_f}{15}\right)^4 \left(\frac{100}{m_\chi / T_r}\right)^3 \left(\frac{3\times 10^{-29} cm^3 s^{-1}}{< \sigma_{ann} v >}\right)$$

Works only for small cross sections (thermal overproduction).



A. Erickcek PRD 92, 103505 (2015)

Constraints and Challenges:

1) Suppressing gravitino production.

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

M. Endo, M. Yamaguchi, K. Yoshioka PRD 72, 015004 (2005)

Helicity-1/2 gravitinos pose the main threat.

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

$$\frac{n_{3/2}}{s} = Y_\phi \; Br_{3/2} < \frac{n_\chi}{s} \approx 5\times 10^{-10}\left(\frac{1 \; GeV}{m_\chi}\right)$$

$$Y_\phi \sim 7\times 10^{-8} c^{1/2}\left(\frac{m_\phi}{50 \; TeV}\right)^{1/2} \geq 7\times 10^{-8} \; c^{1/2}$$

$m_\chi \geq 10 \; GeV:$ $\boxed{Br_{3/2} < 7\times 10^{-4}}$ or $\boxed{c << 1}$

2) Obtaining the right relic density in "Branching" scenario.

$$\frac{n_\chi}{s} = Y_\phi \; Br_\chi \approx 5\times 10^{-10} \left(\frac{1 \; GeV}{m_\chi} \right)$$

$\boxed{Br_\chi < 7\times 10^{-4}}$ or $\boxed{c << 1}$

Typically, the main decay mode is to gauge/Higgs bosons.

2-body decays to gauginos and Higgsinos may be suppressed.

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

M. Cicoli, C. Burgess, F. Quevedo JHEP 1110, 119 (2011)

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

However, 3-body decays produce gauginos: $Br_\chi \sim 3\times 10^{-3}$.

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

Decay to particles with gauge charges must be suppressed

3) Generating the correct baryon asymmetry of the universe.

Recall the dilution factor from modulus decay:

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

This washes out any pre-existing, even $O(1)$, asymmetry.

How to obtain the observed BAU?

Non-thermal post-sphaleron baryogenesis
R.A., B. Dutta, K. Sinha PRD 81, 053538 (2010) & PRD 83, 083502 (2011)

Affleck-Dine baryogenesis
G. Kane, J. Shao, S. Watson, H-B Yu JCAP 1111, 012 (2011)
R.A., M. Cicoli, F. Muia arXiv:1604.03120

An Explicit Model:

As an explicit example, let us consider the volume modulus in the LARGE Volume Scenarios (LVS).

V. Balasubramanian, P. Berglund, J. Conlon, F. Quevedo
JHEP 0503, 007 (2005)

$$K \supset -3\ln(\tau_b + \bar{\tau}_b) \quad , \quad W \supset W_{flux} + Ae^{-a\tau_s}$$

Large volume can be obtained after stabilization of τ_b.

M. Cicoli, J. Conlon, F. Quevedo JHEP 0801, 052 (2008)

For large volume, one can have a sequestered scenario such that:

$$m_{soft} << m_{\tau_b} << m_{3/2} \qquad (m_{soft} m_{3/2} \sim m_{\tau_b}^2)$$

For example, TeV scale SUSY can be obtained for:

$$m_{3/2} \sim 10^{10}\ GeV \quad , \quad m_{\tau_b} \sim 5\times 10^{6}\ GeV \quad , \quad m_{soft} \sim 1\ TeV$$

Hierarchy of Scales:

$$M_P$$

$$M_S \sim \frac{M_P}{\mathcal{V}^{1/2}}$$

$$m_{3/2} \sim m_{\tau_s} \sim \frac{W_0 M_P}{\mathcal{V}}$$

$$m_{\tau_b} \sim \frac{W_0 M_P}{\mathcal{V}^{3/2}}$$

$$m_0, m_{1/2} \sim \frac{M_P}{\mathcal{V}^2}$$ MSSM

$$M_P$$

$$M_S \sim \frac{M_P}{\mathcal{V}^{1/2}}$$

$$m_{3/2} \sim m_{\tau_s} \sim \frac{W_0 M_P}{\mathcal{V}}$$

$$m_{\tau_b} \sim m_0 \sim \frac{W_0 M_P}{\mathcal{V}^{3/2}}$$

$$m_{1/2} \sim \frac{M_P}{\mathcal{V}^2}$$

Split SUSY

$$m_{\tau_b} < m_{3/2} \Rightarrow \boxed{Br_{3/2} = 0}$$

The decay to gauge bosons arises at one-loop level:

$$\Gamma_{\phi \to gg} \sim \left(\frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2} \qquad \phi = \sqrt{\frac{3}{2} \ln} \; (\tau_b + \bar{\tau}_b)$$

The decay to Higgs controlled by the Giudice-Masiero term:

$$\Gamma_{\phi \to H_u H_d} = \frac{Z^2}{24\pi} \frac{m_\phi^3}{M_P^2}$$

$\boxed{c << 1}$ is possible

The decay to gauginos (and Higgsinos) is mass suppressed:

$$\Gamma_{\phi \to \tilde{g}\tilde{g}} \propto \frac{m_\phi m_{soft}^2}{M_P^2} \Rightarrow \boxed{Br_\chi << 1}$$

LVS can accommodate both annihilation & branching scenarios.

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

DM-DR Correlation in LVS:

The axionic partner of τ_b , denoted by a_b , survives lifting by the non-perturbative effects and being eaten up by anomalous U(1)'s.

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

a_b acquires an exponentially suppressed mass $m_{a_b} \approx 0$.

$$\Gamma_{\phi\to a_b a_b} = \frac{1}{48\pi}\frac{m_\phi^3}{M_P^2}$$

M. Cicoli, J. Conlon, F. Quevedo PRD 87, 043520 (2013)

Bulk axions are ultra-relativistic and behave as DR.

They contribute to the effective number of neutrinos N_{eff} :

$$\Gamma_\phi = \frac{c}{48\pi}\frac{m_\phi^3}{M_P^2} \Rightarrow \Delta N_{eff} = \frac{43}{7(c-1)} \qquad (\Delta N_{eff} = N_{eff} - 3.04)$$

Decay to visible sector mainly produces gauge bosons and Higgs:

$$\Gamma_{\phi\to gg} \sim \left(\frac{\alpha_{SM}}{4\pi}\right)^2 \frac{m_\phi^3}{M_P^2} \qquad \Gamma_{\phi\to gg} << \Gamma_{\phi\to a_b a_b}$$

$$K \supset \frac{ZH_u H_d}{\tau_b + \bar{\tau}_b} + h.c. \qquad \Gamma_{\phi\to H_u H_d} = \frac{Z^2}{24\pi}\frac{m_\phi^3}{M_P^2}$$

Giudice-Masiero term needed to avoid a DR-dominated universe.

$$c = 2Z^2 + 1$$

2σ bound from Planck+WMAP9+ACT+SPT+BAO+HST:

$$\Delta N_{eff} = 0.48^{+0.48}_{-0.45}$$

$$\Delta N_{eff} < 1 \Rightarrow Z > \sqrt{3}$$

M. Cicoli, J. Conlon, F. Quevedo PRD 87, 043520 (2013)

T. Higaki, F. Takahashi JHEP 1211, 125 (2012)

$$T_r \approx \frac{1}{\pi}\left(\frac{10Z^2}{288 g_*(T_r)}\right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_P}}$$

$$O(MeV) \leq T_r \leq O(TeV) \Rightarrow 10.75 \leq g_* \leq 228.75$$

Abundance of DM particles produced from ϕ decay:

$$\frac{n_\chi}{s} = \frac{3T_r}{4m_\phi} Br_\chi$$

$$Z > \sqrt{3} \;,\; m_\phi \sim 5\times 10^6 \; GeV \;\; \Rightarrow T_r \geq O(GeV)$$

$$Br_\chi > 3\times 10^{-3} \;\; \Rightarrow \frac{n_\chi}{s} > \left(\frac{n_\chi}{s}\right)_{obs}$$

Avoiding excess of DR within LVS prefers “Annihilation” scenario, hence Higgsino-type DM.

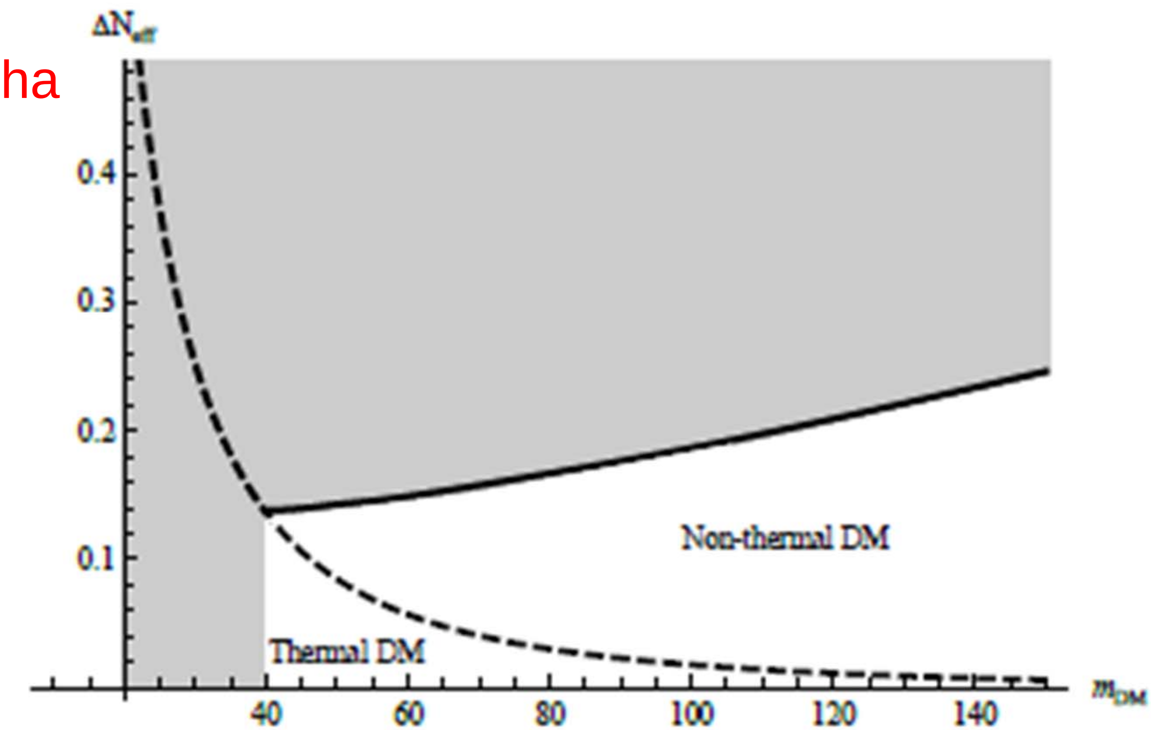
Obtaining the correct relic density in “Annihilation” scenario needs:

$$T_r = T_f \left(\frac{3\times10^{-26}\ cm^3 s^{-1}}{<\sigma_{ann} v>_f} \right) \qquad\qquad T_f \sim \frac{m_\chi}{20}$$

Assuming S-wave annihilation, which is valid for the Higgsino-type DM, $<\sigma_{ann} v>_f$ is directly constrained by Fermi.

The Fermi bound is translated to a constraint in $\Delta N_{eff} - m_\chi$ plane:

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



Novel Observational Signatures:

The universe dominated by scalar field oscillations has the same equation of state as a matter-dominated phase.

Subhorizon perturbations of DM grow in the matter-dominated era:

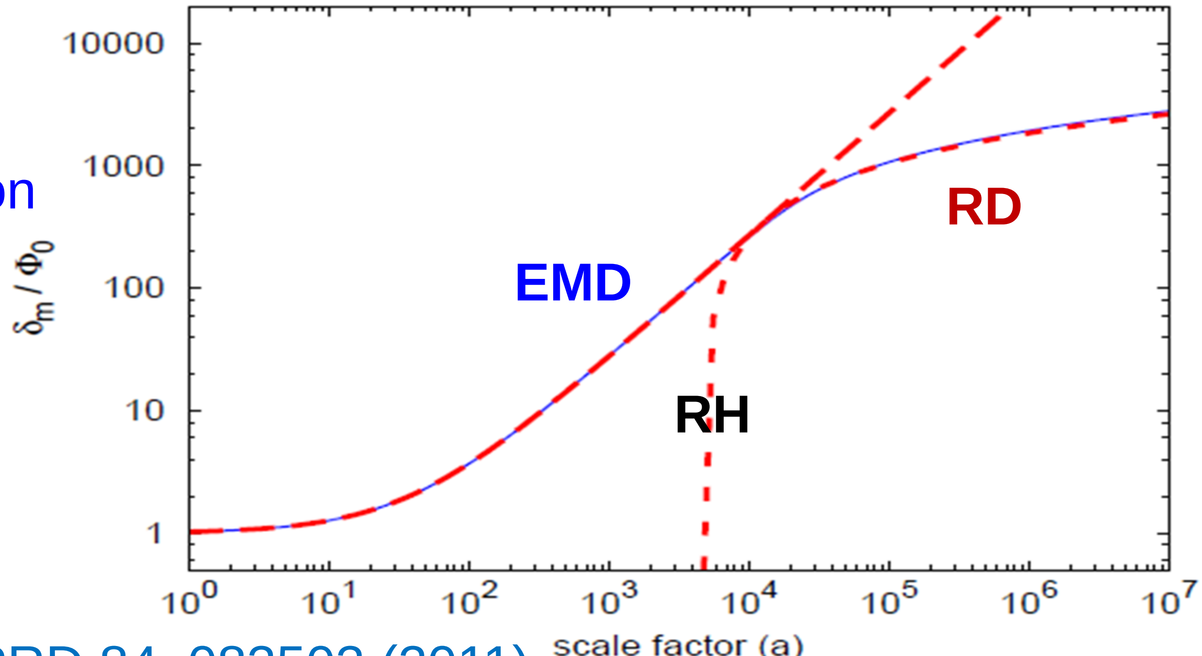
$$\ddot{\delta}_m + 2H\dot{\delta}_m - \frac{2}{3}H^2\delta_m = 0 \qquad H = \frac{2}{3t} \Rightarrow \delta_m \propto t^{2/3}$$

Subhorizon perturbations of ϕ grow during scalar domination.

EMD: Early Matter Domination

RH: Reheating

RD: Radiation Domination

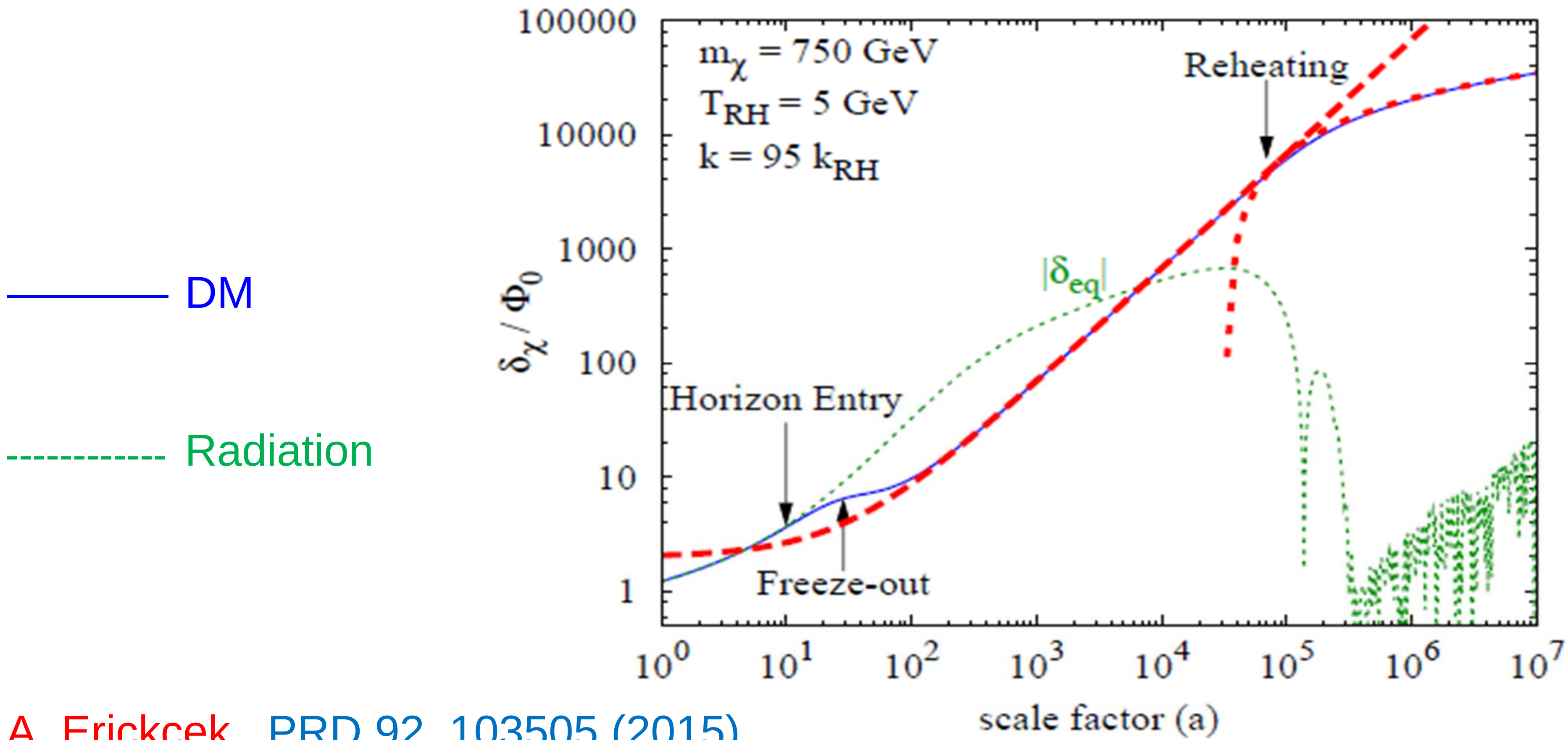


A. Erickcek, K. Sigurdson PRD 84, 083503 (2011)

During EMD perturbations of ϕ are transferred to radiation & DM.

DM perturbations inherit enhancement of ϕ perturbations upon production via freeze-out at $T = T_f$.

Modes that enter the horizon prior to reheating are enhanced if DM gets kinetically decoupled form radiation.



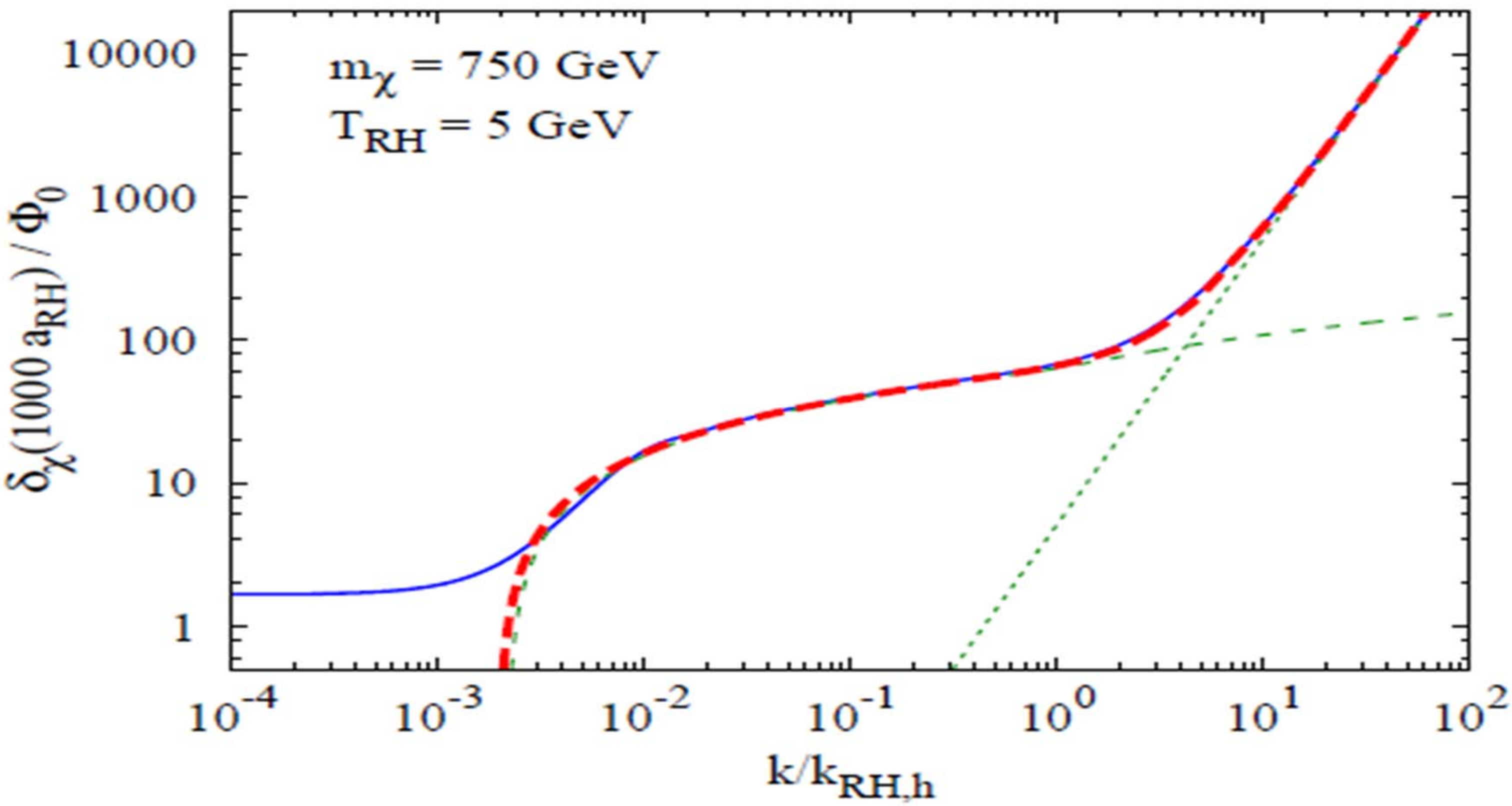
A. Erickcek PRD 92, 103505 (2015)

Kinetic decoupling happens at a temperature T_{kd} when:

$$\Gamma_{kin} = < \sigma_{el} v > n_{rel} \frac{T}{m_\chi} \approx H$$

In order to have enhancement, we need $T_r << T < T_f$.

All modes that satisfy this condition get enhanced.



A. Erickcek PRD 92, 103505 (2015)

The enhancement can compensate the small annihilation cross section, and boost the annihilation signal to detectable levels.

A well-motivated particle physics model to realize this scenario?
A. Erickcek, K. Sinha, S. Watson arXiv:1510.04291 [hep-ph]

Kinetic decoupling requires $< \sigma_{el} v >$ to be sufficiently small.

Successful freeze-out requires $< \sigma_{ann} v >$ to be large enough.

Can we satisfy both without too much tuning?
R.A., B. Dutta, A. Erickcek In Progress

Very small scale perturbations grow by a large factor during the modulus-dominated era.
This can lead to the formation of primordial black holes within a wide mass range, providing another possible observational probe.
J. Georg, G. Sengor, S. Watson arXiv: 1603.00023 [hep.ph]

Summary and Outlook:

- The origin of DM relic abundance an important question
  DM to be the strongest observational probe of the early universe

- Thermal DM scenario has driven much of the research
  Attractive, but relies on assumptions about thermal history

- Alternatives within a non-standard thermal history motivated
  Naturally arise in some UV complete high energy models
  Can ease the increasing tension with tight experimental limits

- Non-thermal DM from late reheating a viable scenario
  Can yield the correct density for large & small annihilation rates
  Successful embedding in explicit constructions is nontrivial

- Novel observational signatures can help us test the scenario
  Enhancement of DM substructure, DM-DR correlation, …