EeV scale dark matter: production mechanism and experimental signatures

In collaboration with **Fei Huang (University of Arizona)**, **Yann Mambrini (LPT, France), Mathias Pierre (IPT, Spain)**

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The dark sector is still quite obscure…

What is Dark Matter?

(One unique particle? A set of particles? Primordial black holes?...)

How is it produced?

(Thermal Freeze Out, Non-thermal/Freeze-In, dynamical dark matter , out-of-equilibrium decay …)

What is its mass?

(From micro-eV to EeV and further…)

The WIMP and beyond

- The WIMP miracle

$$m_{DM} \sim m_{EW} \quad \text{scale and} \quad \langle \sigma v \rangle \sim m_{EW}^{-2}$$

should have been detected already…

(According to [Slatyer, Beacom *et al.*, 18'] the WIMP isn't slightly ruled out though)

- Unitarity bound on thermal scenarios → $m_{DM} < 500\ \mathrm{TeV}$
- Non-WIMP scenarios allow a wider range of masses
- How to evade the WIMP paradigm?

→ Progressive thermal production ?

→ Out-of-equilibrium decay ? (Reheating?)

→ Hidden sector containing dark matter?

Can Dark Matter be (very) Heavy?

Two examples:

- WIMPzilla : Dark matter produced at the reheating time, in the right proportion.

→ Either under the form of an instantaneous decay at $T = T_{RH}$;

→ Or by an extended prodution during the reheating period $T_{RH} \lesssim T \lesssim T_{max}$.;

e.g., in [Dudas, Mambrini, Olive, 17'] An EeV gravitino is proposed as a DM candidate produced mainly during the reheating.

- The diluton [Hooper, 16'] is another option to generate thermally a DM relic density for DM particles as heavy as $m_{DM} \gtrsim PeV$

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If dark matter is heavy : The role played by the reheating might be of a crucial importance

Outline

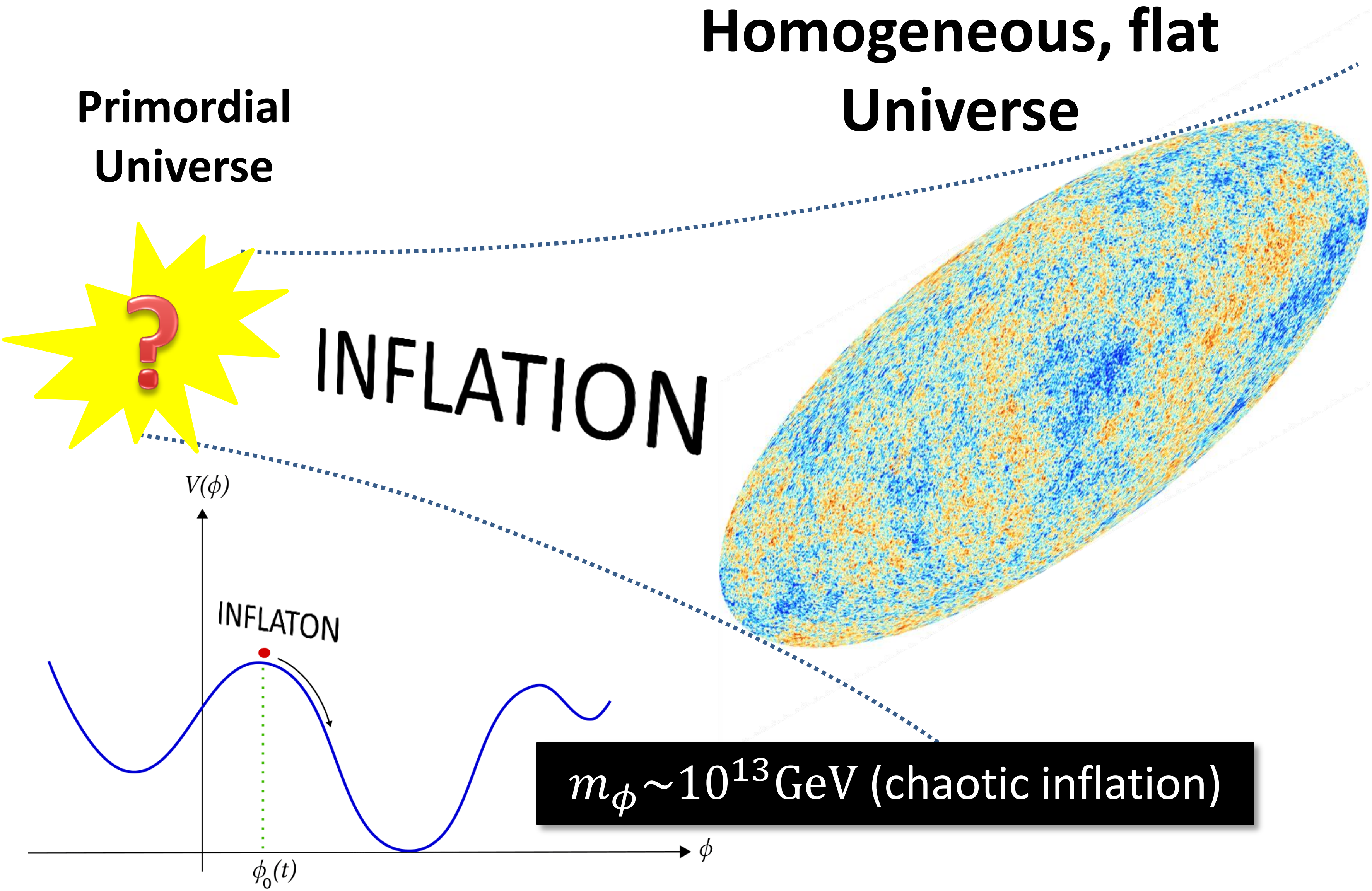
Part I

- Motivations: Connection between inflation and dark matter phenomenology
- The inflaton portal to dark matter: General Idea
- Study of a toy model: The inflaton miracle
- Cosmological Constraints

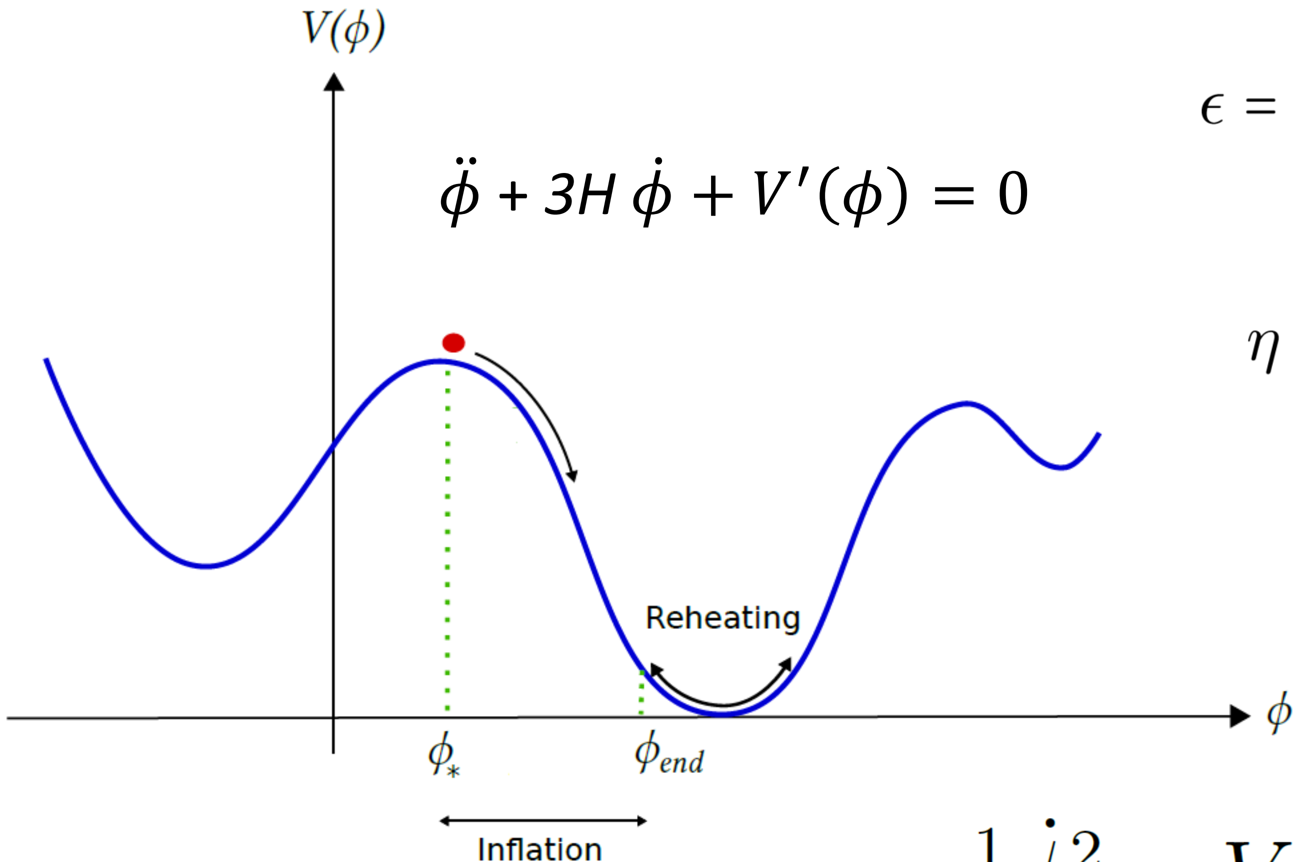
Part II

- UHECR detection with neutrino detectors
- ANITA anomalous events
- A (very) heavy dark matter explanation
- Complementarity with IceCube detection

The importance of the inflaton couplings



Single Field Inflation



$$\ddot{\phi} + 3H\,\dot{\phi} + V'(\phi) = 0$$

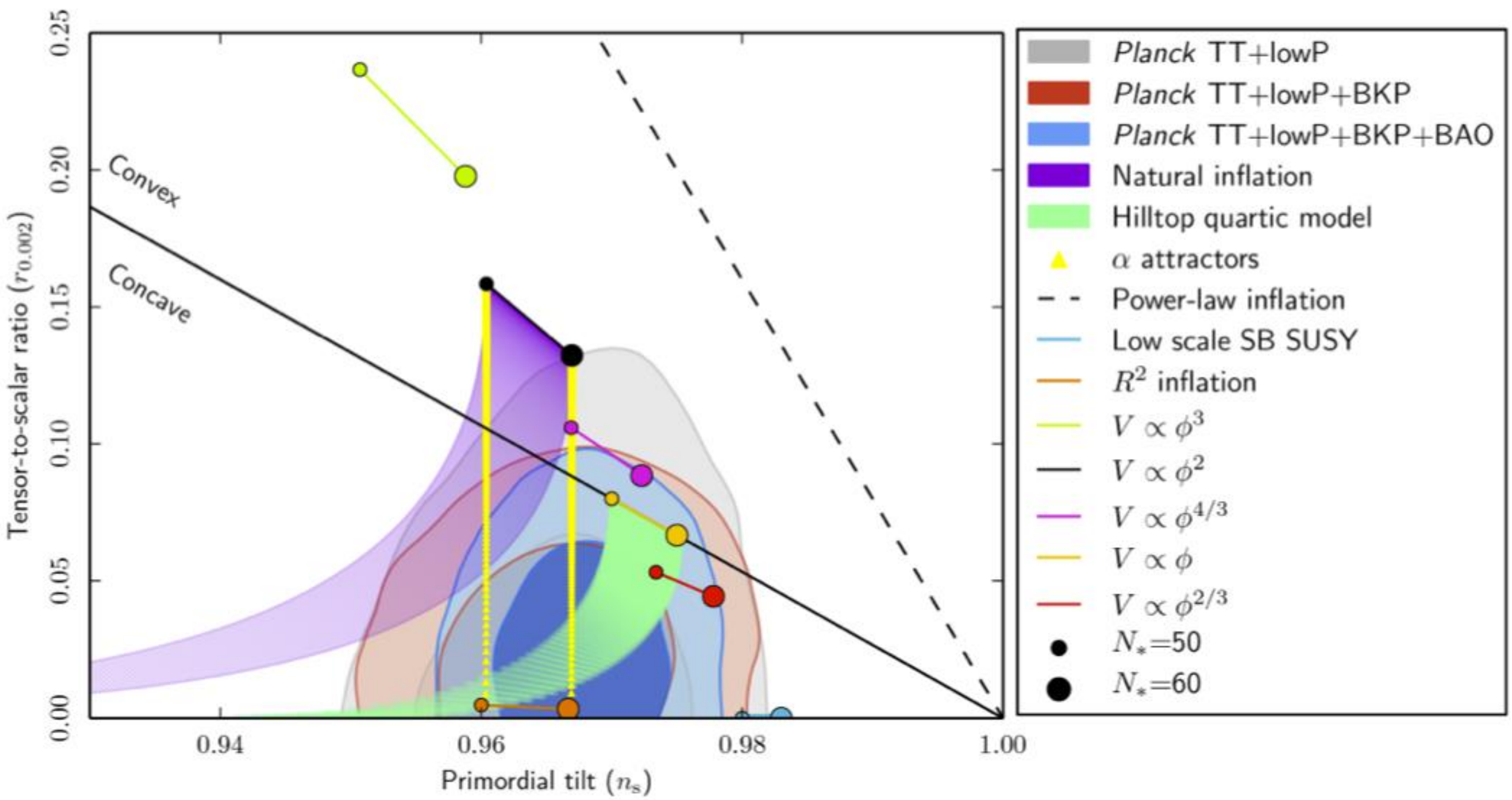
$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta = \left|\frac{V''}{V}\right| \ll 1$$

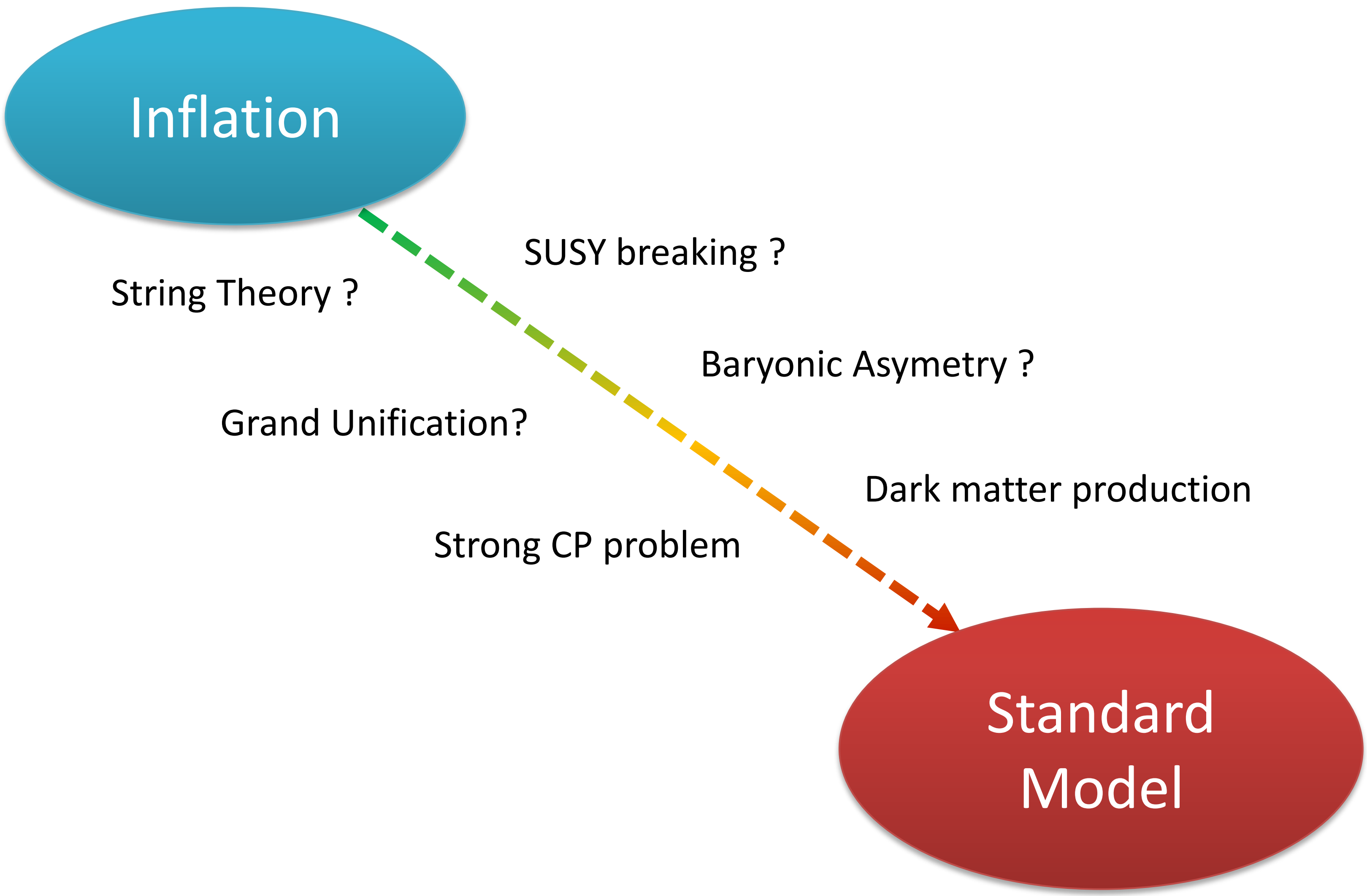
$$\omega_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \sim -1$$

Inflation constraints

- Tensor to scalar ratio : $r = 16\,\varepsilon$
- Spectral index : $n_s = 1 - 6\,\varepsilon + 2\,\eta$



From Inflation to Low energy physics



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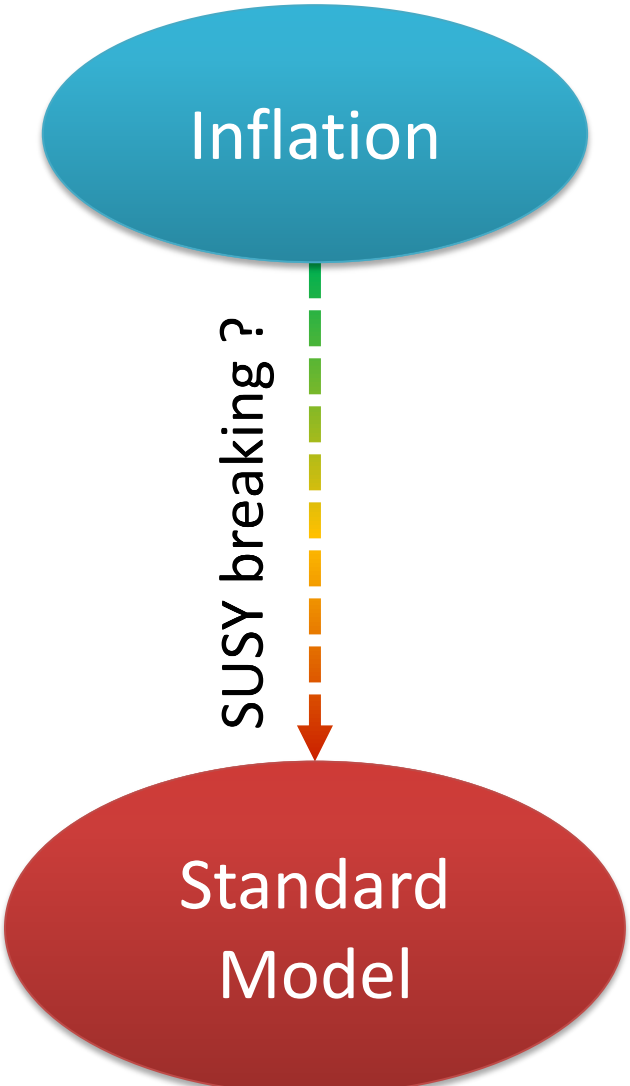


SUSY breaking **at the end of inflation** perturbs the inflaton trajectory

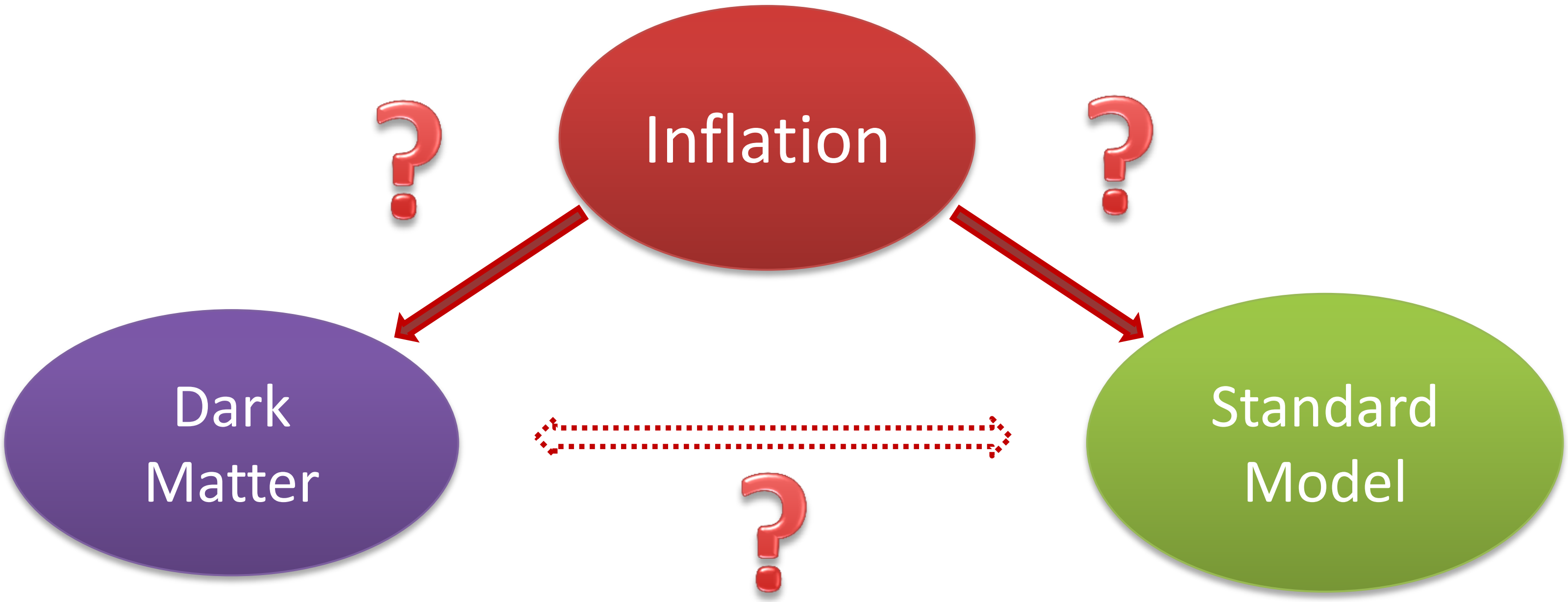
→ $f_{SUSY} > H$ can destabilize chaotic inflation for models with stabilizers ($W = mS\phi$)
[Buchmüller, Dudas, LH, Wieck, '14]

→ $f_{SUSY} \sim H$ can rescue models without stabilizers ($W = m\phi^2$)
[Buchmüller, Dudas, LH, Westphal, Wieck, Winkler '15]

→ In a complete model including low energy SUSY breaking and inflation: constraints from many different perspectives… [Argurio, Dries, LH, Mariotti '16]

The importance of the inflaton couplings

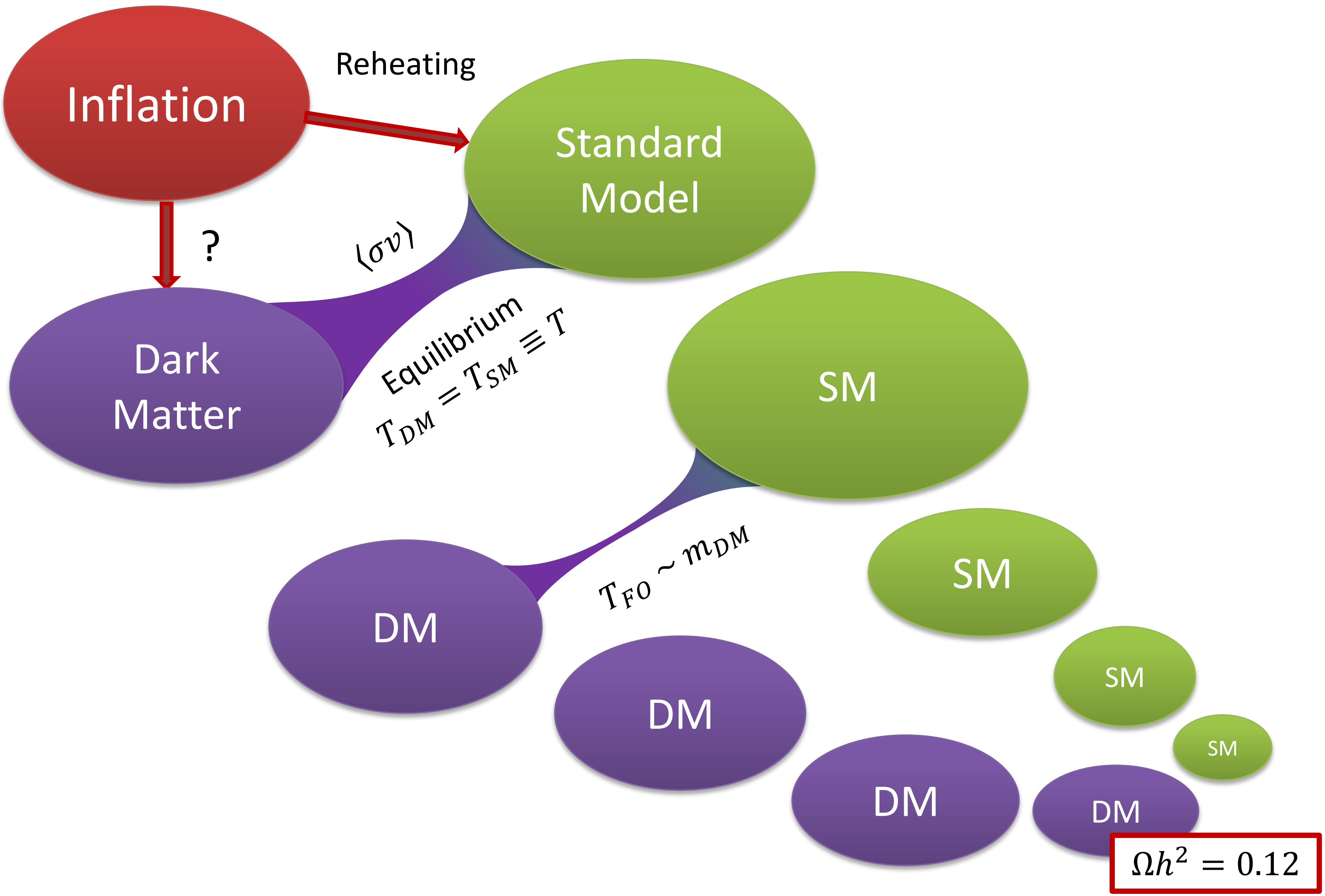
Inflaton Decay : Reheating



Being explicit about the reheating lagrangian fixes initial conditions for dark matter production …

When is it relevant to DM production ?

Thermal scenario of Dark matter production :



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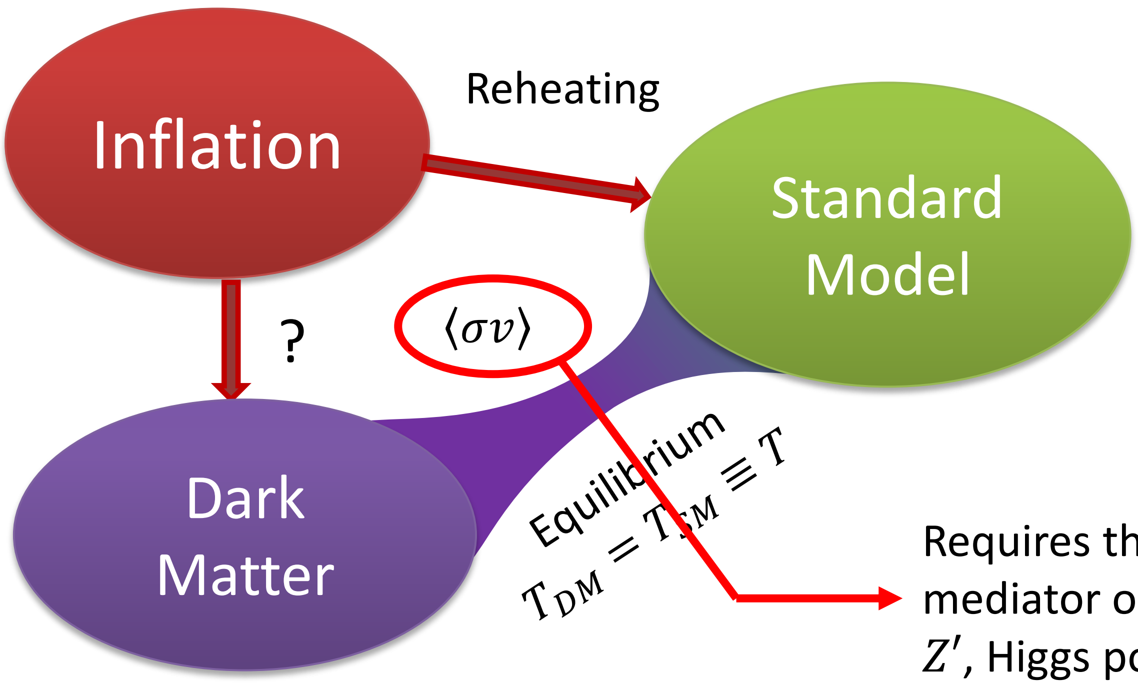

Requires the presence of a mediator or small coupling : Z', Higgs portal, etc.

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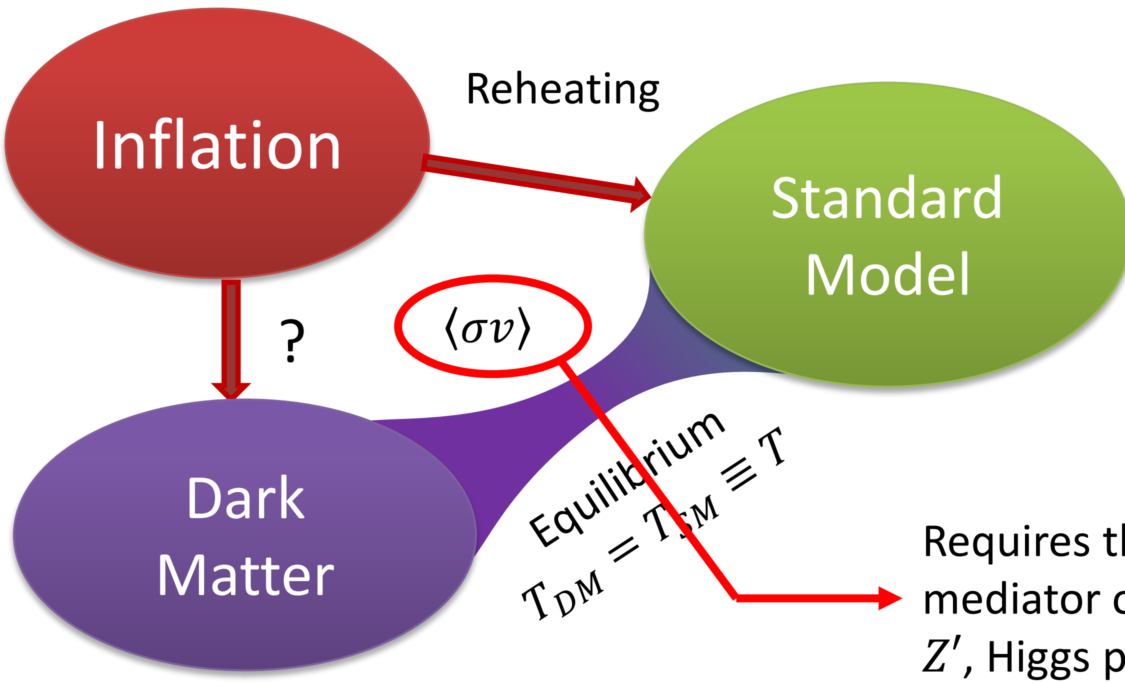


Requires the presence of a mediator or small coupling : Z', Higgs portal, etc.

More and more disfavored by direct detection experiments…

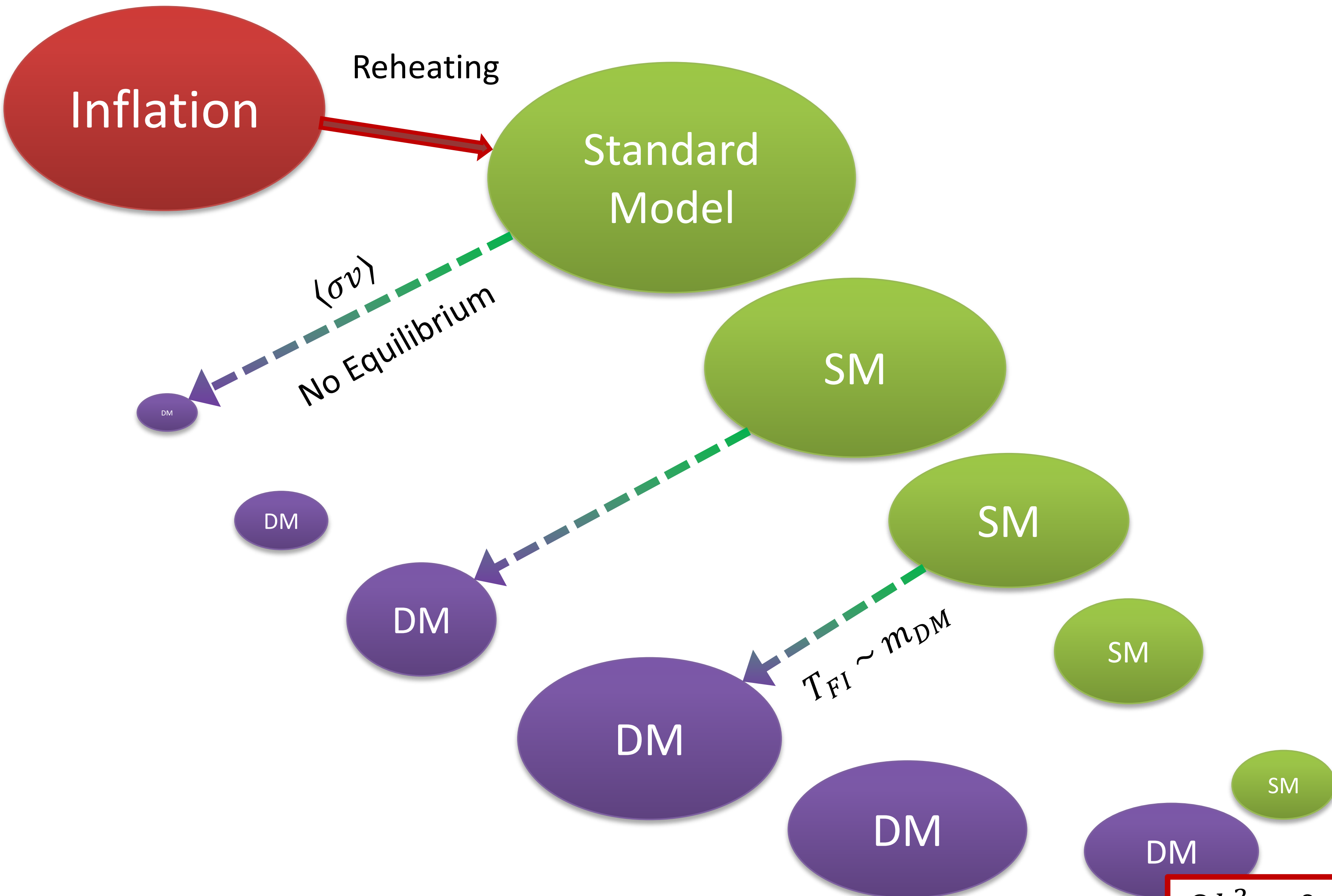
WIMP miracle:

$\langle \sigma v \rangle \sim \langle \sigma v \rangle_{EW}$ and $m_{DM} \sim \mathcal{O}(100)$ GeV

$$\Downarrow$$

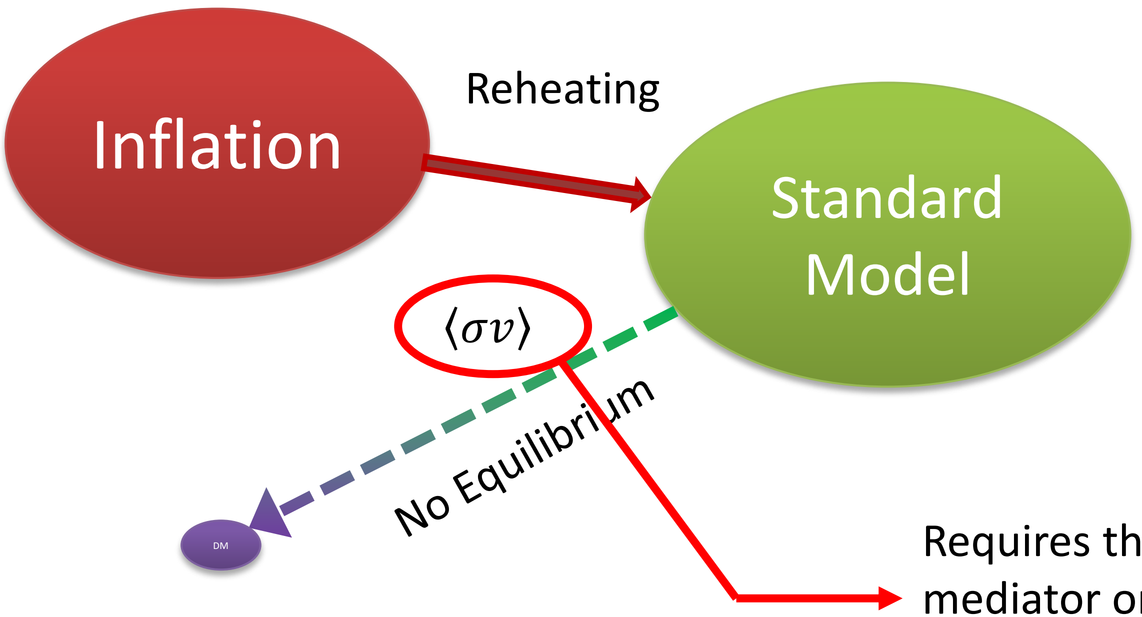
$$\Omega h^2 \sim 0.12$$

Non-Thermal scenario of Dark matter production :



$\Omega h^2 = 0.12$

Non-Thermal scenario of Dark matter production :



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$\langle \sigma v \rangle_{non-Th} \ll \langle \sigma v \rangle_{Th}$

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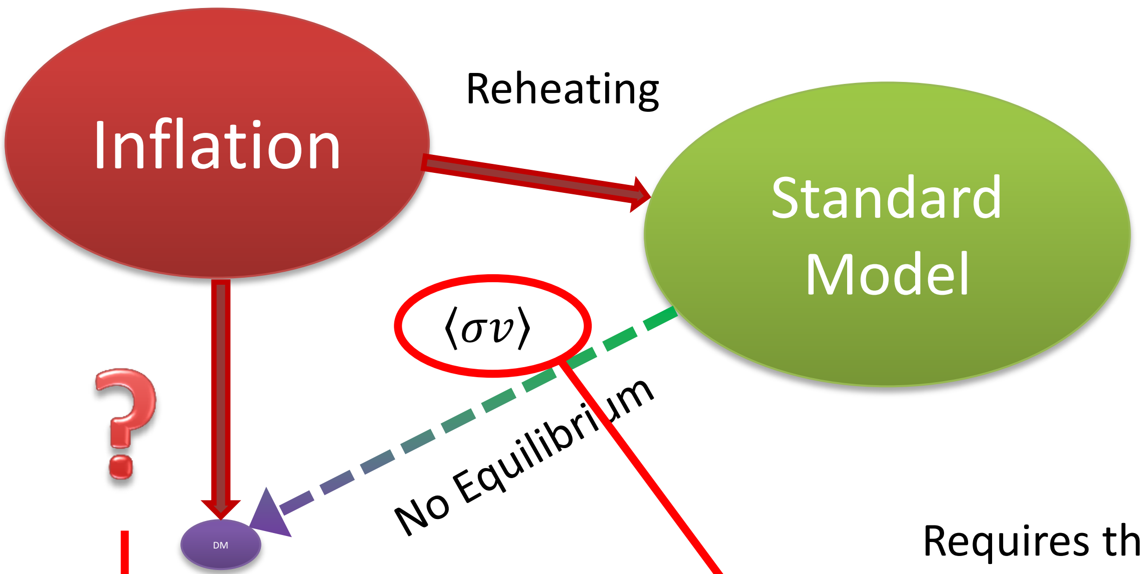


Requires the presence of a mediator or small coupling : Z', Higgs portal, etc.

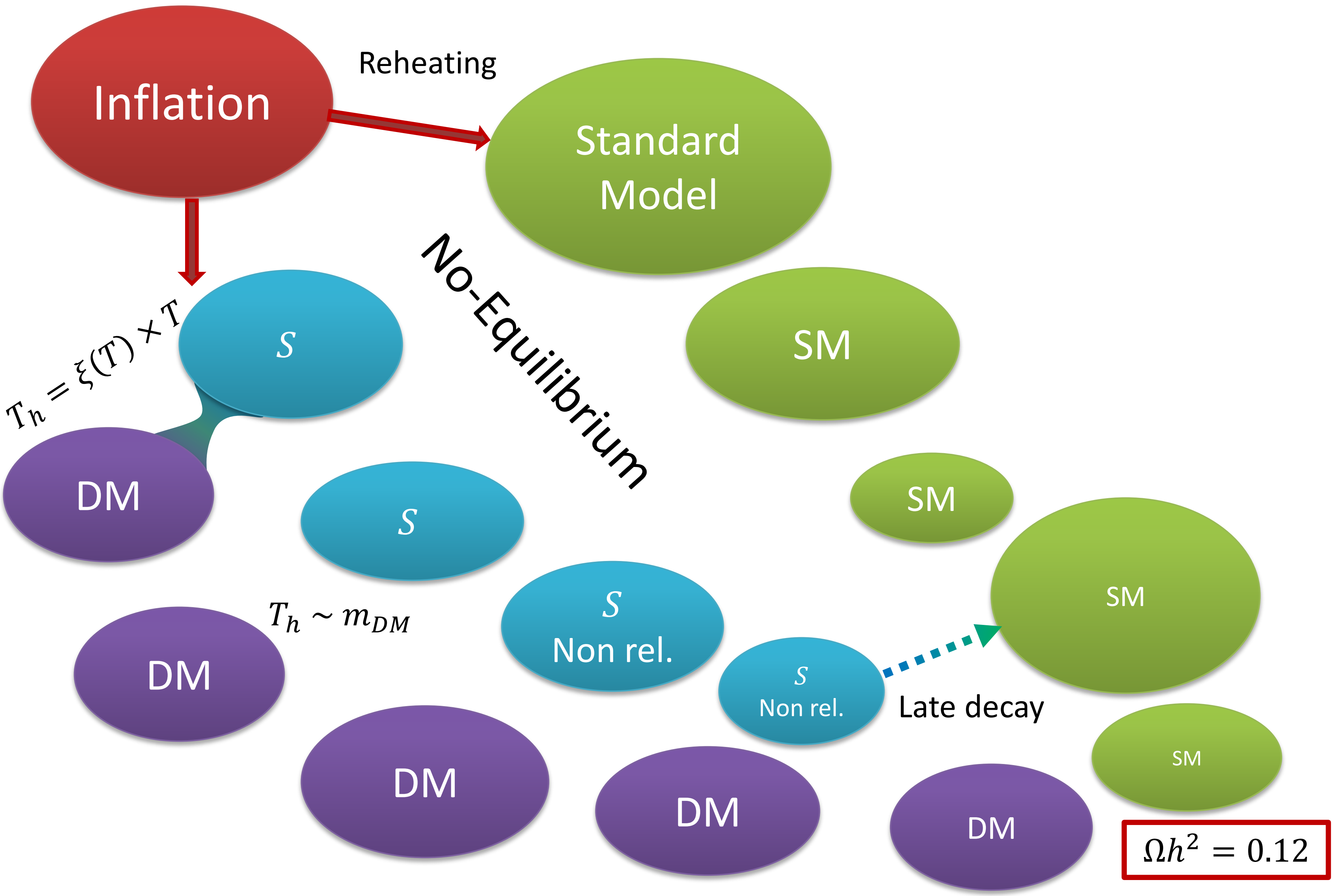
$\langle \sigma v \rangle_{non-Th} \ll \langle \sigma v \rangle_{Th}$

No reason a priori to suppress the production of DM through inflaton decay…

Such coupling HAS to be there at the loop level in many models of reheating …

[Kaneta, Mambrini, Olive '19]

Decoupled Hidden sector [Hooper et al., '16]



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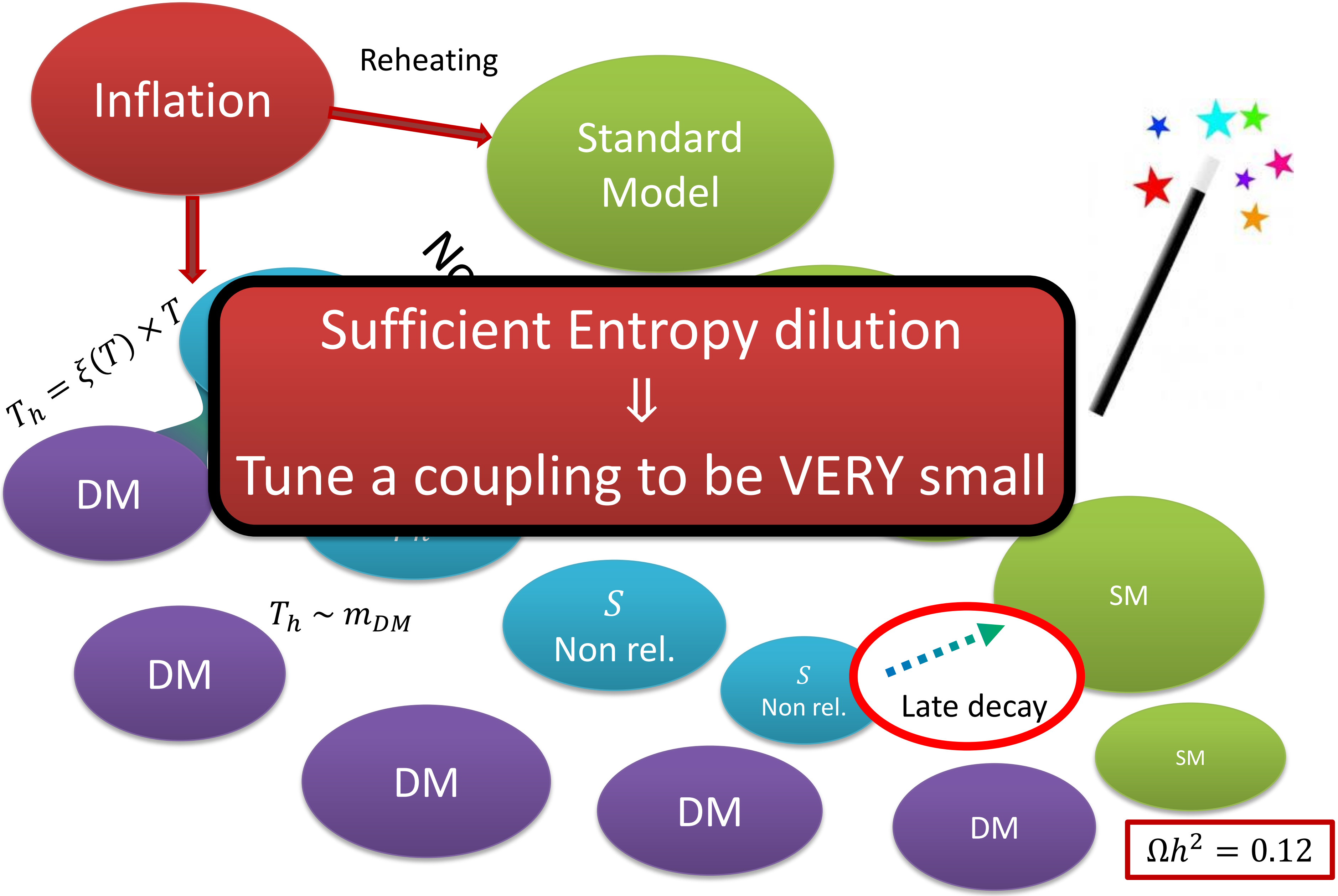
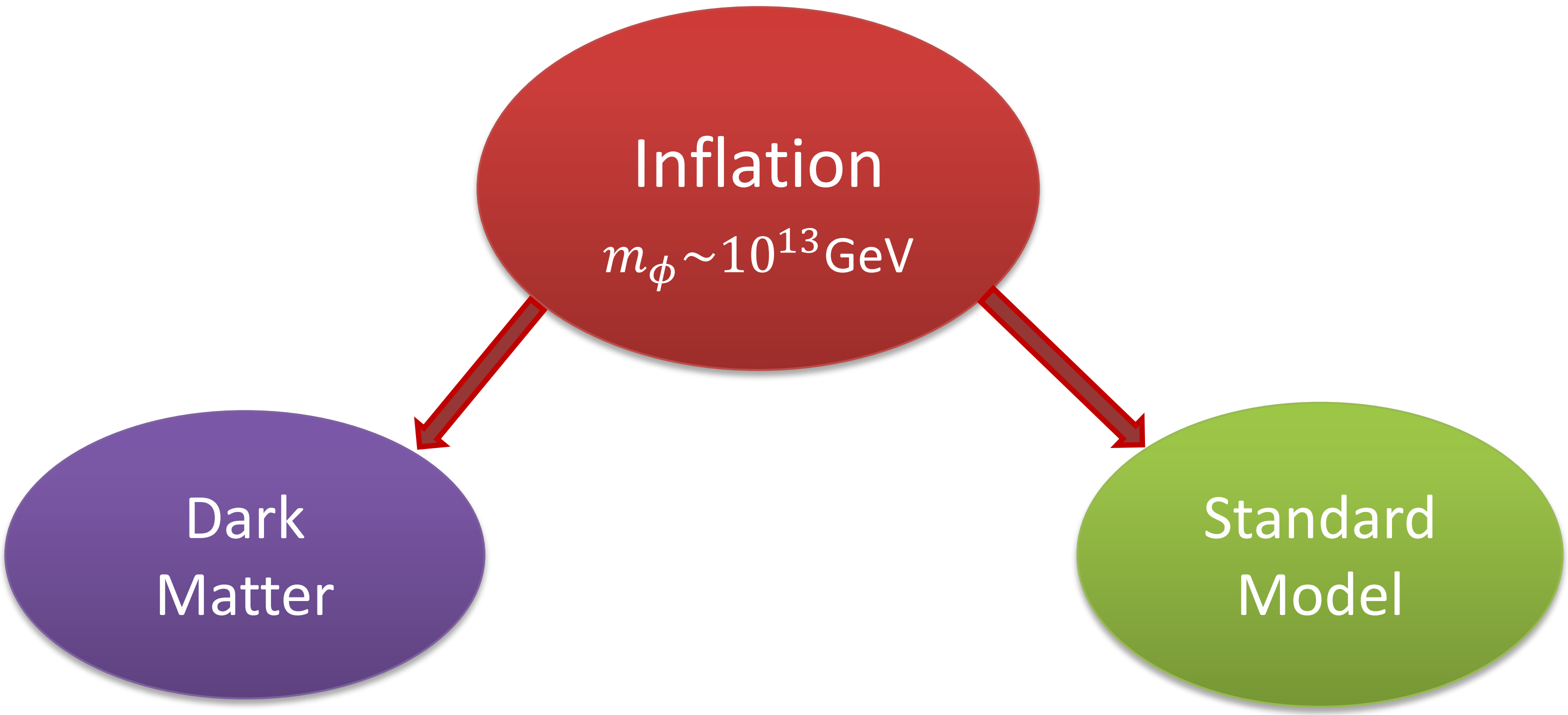


Part I

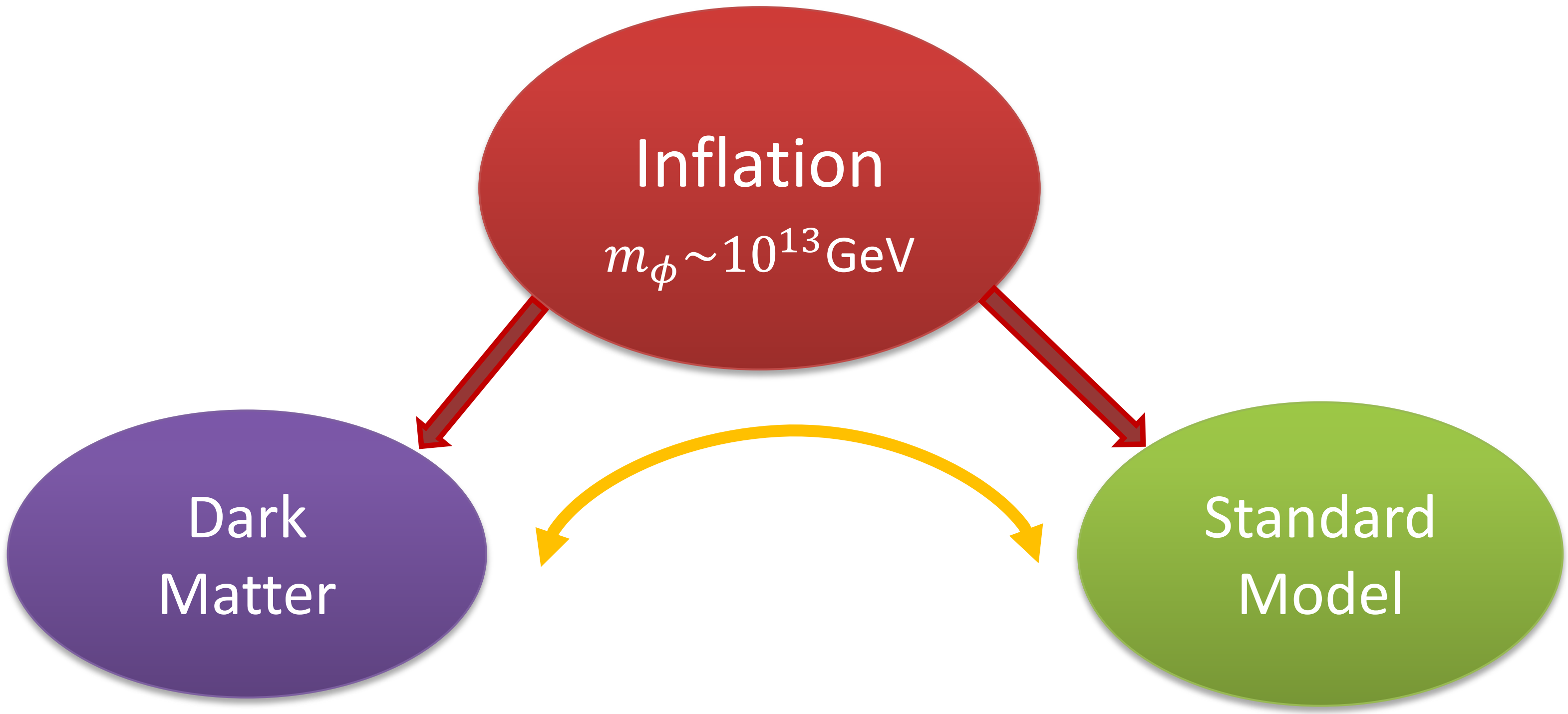
The Inflaton Portal to Dark Matter

The inflaton portal to DM



[Dev, Mazumdar, Qutub 13’], [Heurtier 17’]

The inflaton portal to DM



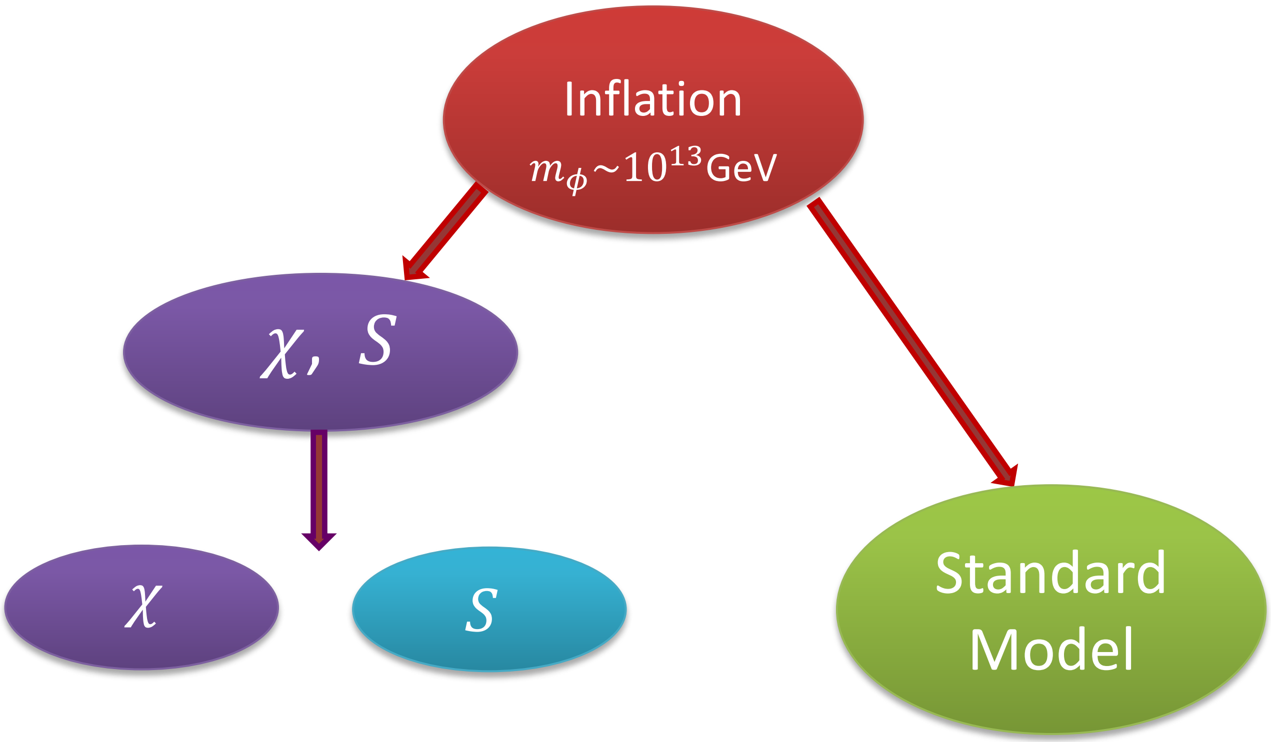
$m_\phi \sim 10^{13}$GeV $\rightarrow$ Annihilation cross section feeble

$\rightarrow$ No possible thermal scenario

[Dev, Mazumdar, Qutub 13'], [Heurtier 17']

The inflaton portal to DM

Highly decoupled sectors?



The inflaton portal to DM

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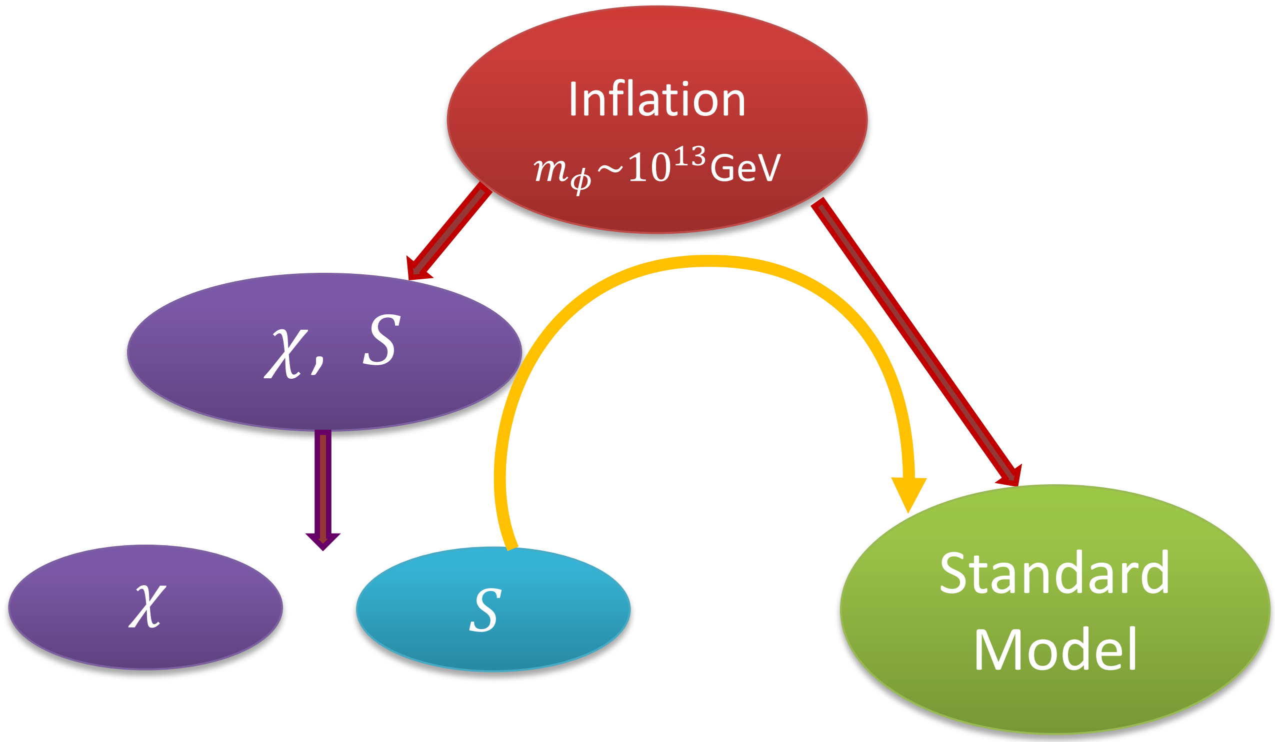
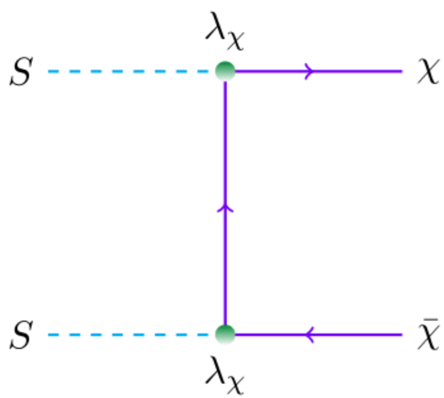
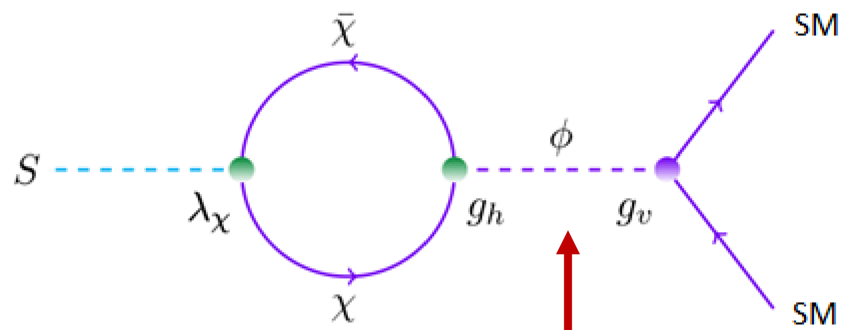


$m_\phi \sim 10^{13}$GeV → Late decay of the hidden sector

The Model

[F.Huang, L.H., coming soon]





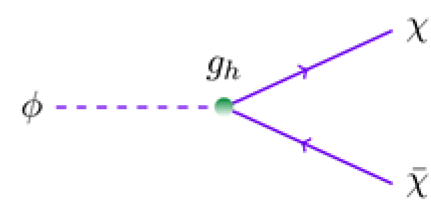
$m_\phi = 10^{13} GeV$

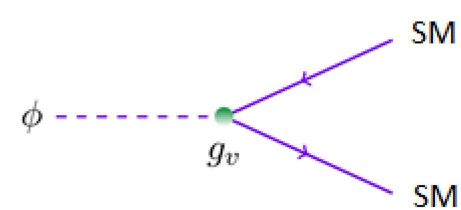
Thermal decoupling of dark matter in the dark sector

Natural suppression of the hidden scalar decay width…

$g_h/g_v \longrightarrow T_h/T_v$ after inflation

$$\xi_{\rm inf} \equiv \left(\frac{T_h}{T}\right)_{\rm inf} = \left(\frac{g^\star_{\rm inf}}{g^\star_{h,\,\rm inf}}\right)^{1/4} \times \left(\frac{\rho_h}{\rho_v}\right)^{1/4}$$





Relic Density

[F.Huang, L.H., coming soon]

$$\Omega_\chi h^2 \longrightarrow \Omega_\chi h^2 \times \frac{S_i}{S_f}$$

Thermal decoupling in the dark sector

Entropy Suppression

$$\Omega_\chi h^2 \approx 8.5\times 10^{-11} \frac{m_\chi \sqrt{g_\star + g_\star^h \xi^4}}{T_f^h g_\star} \left(\frac{a + 3\xi b m_\chi / T_f^h}{\mathrm{GeV}^{-2}} \right)^{-1}$$

$$\frac{S_f}{S_i} \approx 1.83 \langle g_\star{}^{1/3} \rangle^{3/4} \frac{m_S Y_S \tau_S^{1/2}}{m_p^{1/2}}$$

$$a \sim b \sim \alpha_\chi^2 / m_\chi^2$$

Inflaton suppressed decay rate

$$\Gamma_S \sim (g_h g_v)^2 \frac{m_S^5}{m_\phi^4}$$

Relic Density

[F.Huang, L.H., coming soon]

$$\Omega_\chi h^2 \longrightarrow \Omega_\chi h^2 \times \frac{S_i}{S_f}$$

Generic range of masses

$$\frac{\Omega_\chi h^2}{S_f/S_i} \approx 0.38 \left(\frac{10^{13}\mathrm{GeV}}{m_\phi}\right)^2 \left(\frac{g_h g_v}{(0.1)^2}\right) \left(\frac{m_\chi}{10\mathrm{PeV}}\right)^{7/2} \left(\frac{m_\chi/m_S}{10}\right)^{-3/2} \left(\frac{0.1}{\alpha_\chi}\right)^2$$

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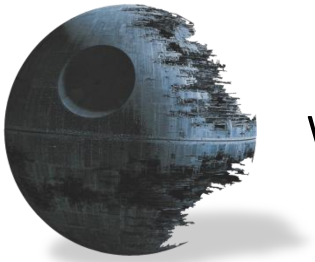

WIMP miracle → **The Inflaton miracle**

Relic Density

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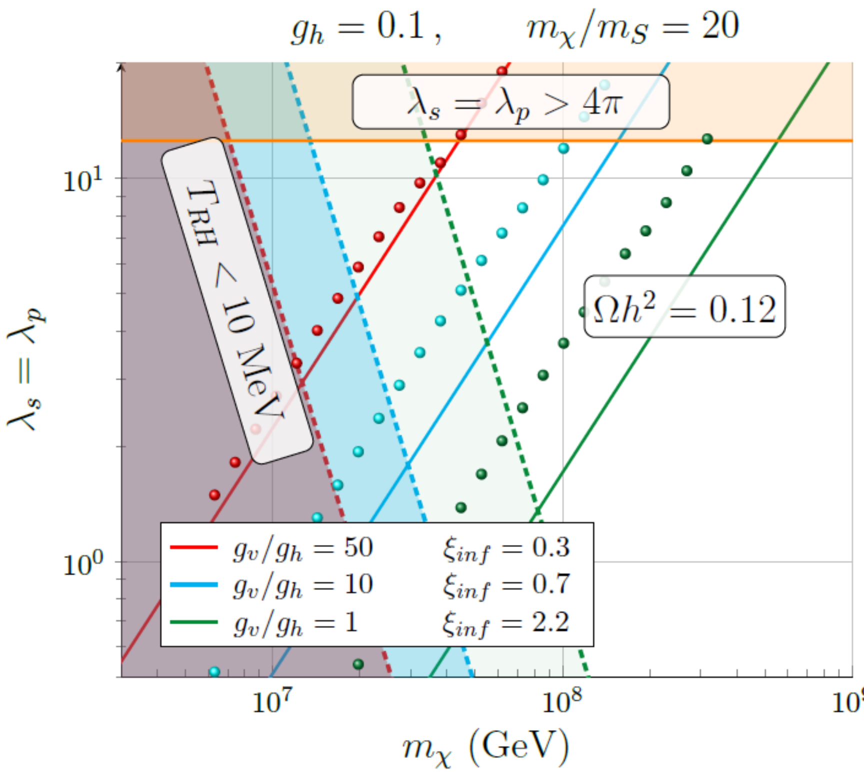
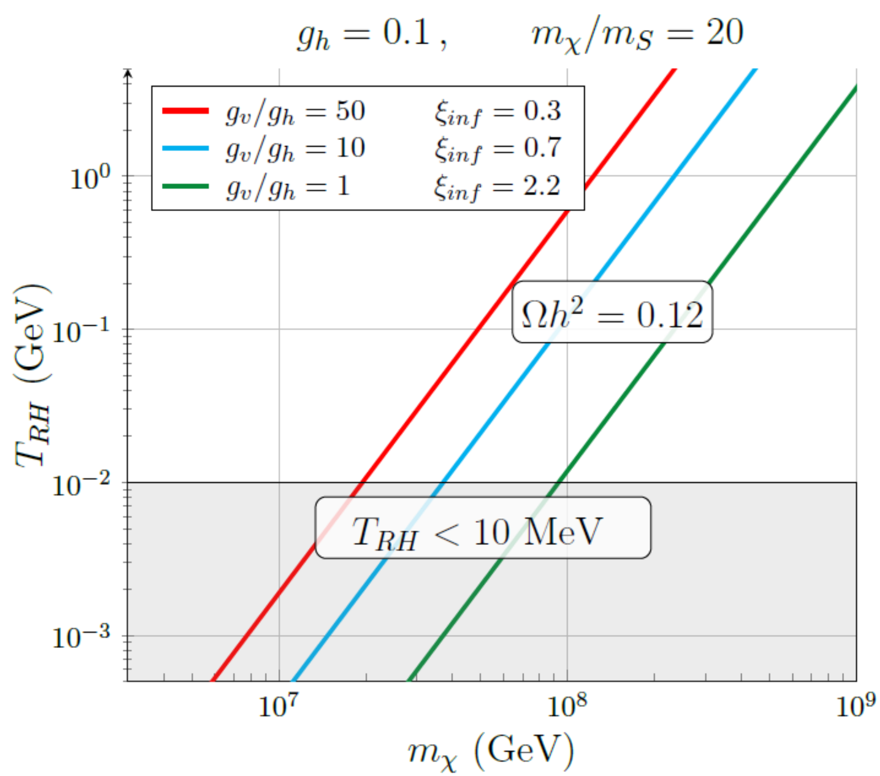
$$T_{RH} \equiv \left(\frac{90}{8\pi^3 g_\star}\right)^{1/4} \sqrt{\frac{M_p}{\tau_s}} > 10 \text{ MeV}$$

$$\frac{\Omega_\chi h^2}{S_f/S_i} \approx 0.16 \quad \times \xi_f^{-2} \left(\frac{T_R}{10\mathrm{MeV}}\right) \left(\frac{m_\chi}{50\mathrm{PeV}}\right) \left(\frac{m_\chi/m_S}{20}\right) \left(\frac{0.8}{\alpha_\chi}\right)^2$$

Relic Density

[F.Huang, L.H., coming soon]





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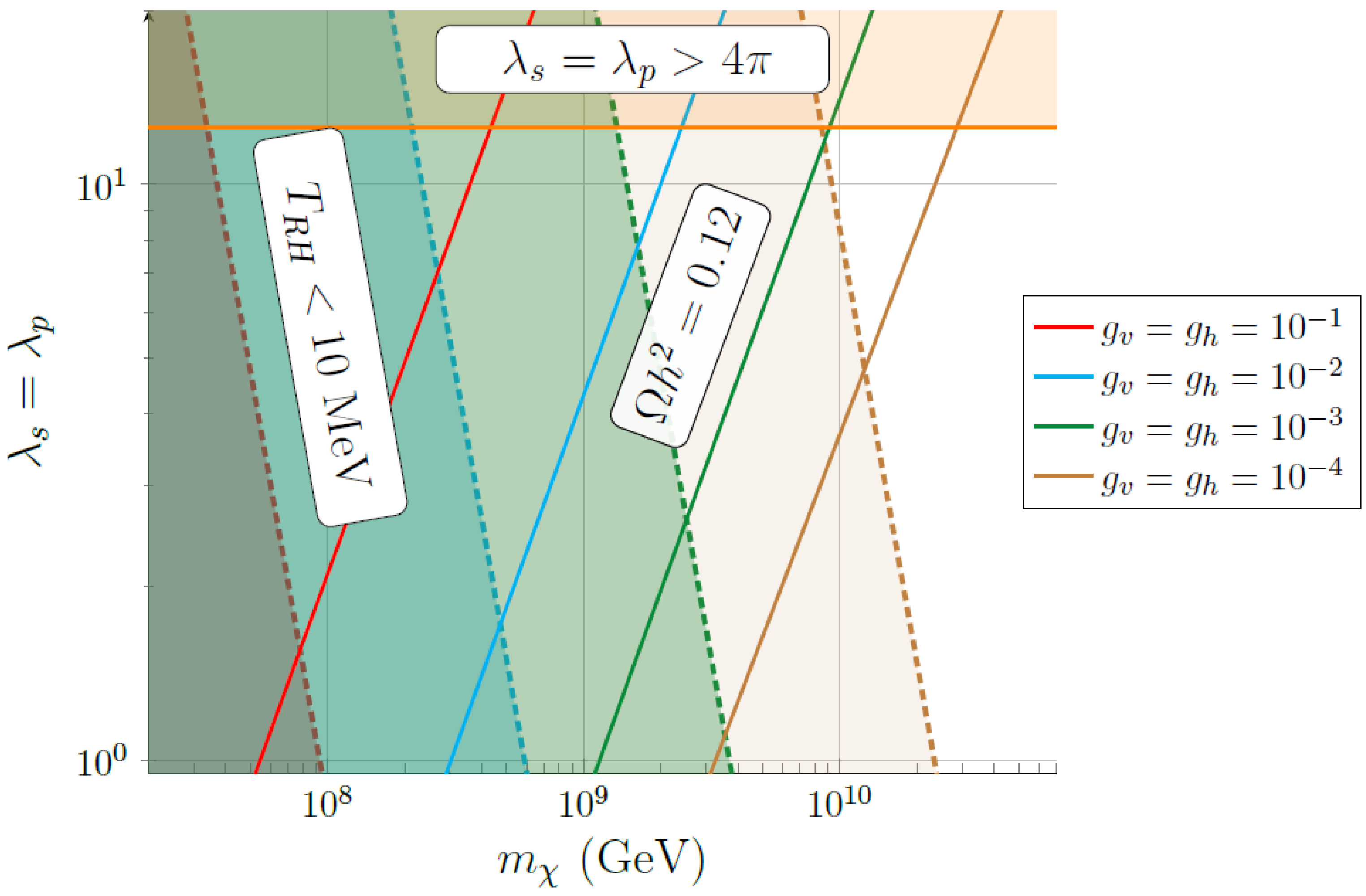


Experimental signatures ?

Dark matter features :

- 10 PeV – EeV dark matter
- Very feeble interaction with the standard model

→ **No Direct Detection constraints**

- Significant annihilation into dark scalars
- Dark scalar lifetime < 0.01s

→ **Indirect Detection ?** Same problem: Low DM number density, low flux of decay products, extremely hard to detect.

Vacuum mass versus inflation parameters

- In most minimal models, the inflaton mass in the vacuum is given by the inflation scenario

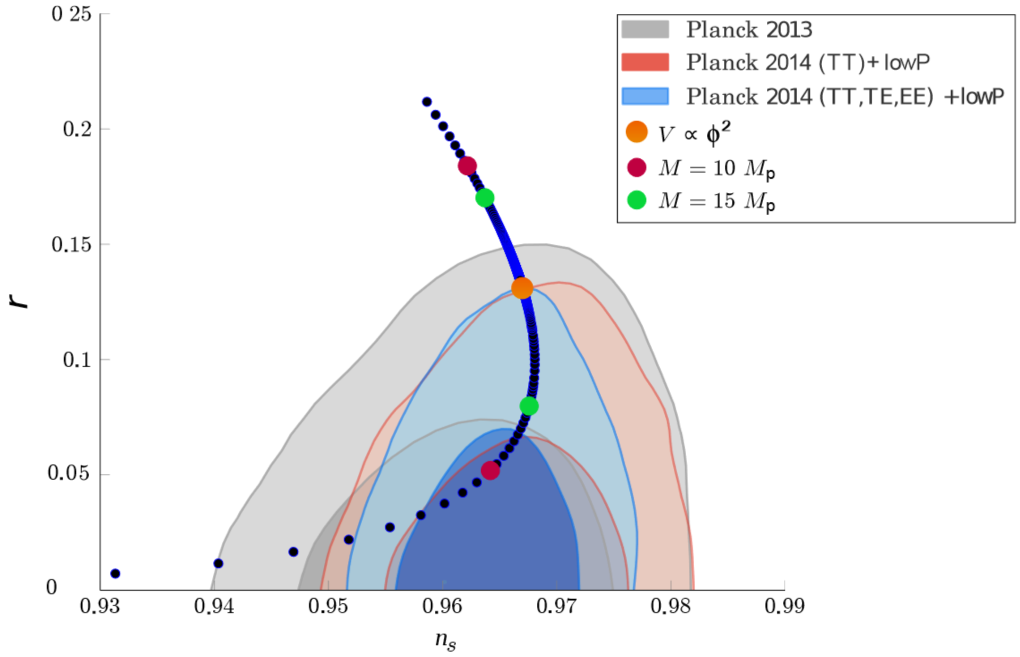
$$V(\phi) \longrightarrow m_\phi^2 = V''(\phi)\Big|_{\phi=0}$$

Chaotic inflation is the simplest option….

Vacuum mass versus inflation parameters

- Quadratic / quartic models

$$V(\varphi) = \frac{\lambda}{4}\left(\phi^2 - v^2\right)^2$$



[Linde '07]
[LH, Moursy '15]

Vacuum mass versus inflation parameters

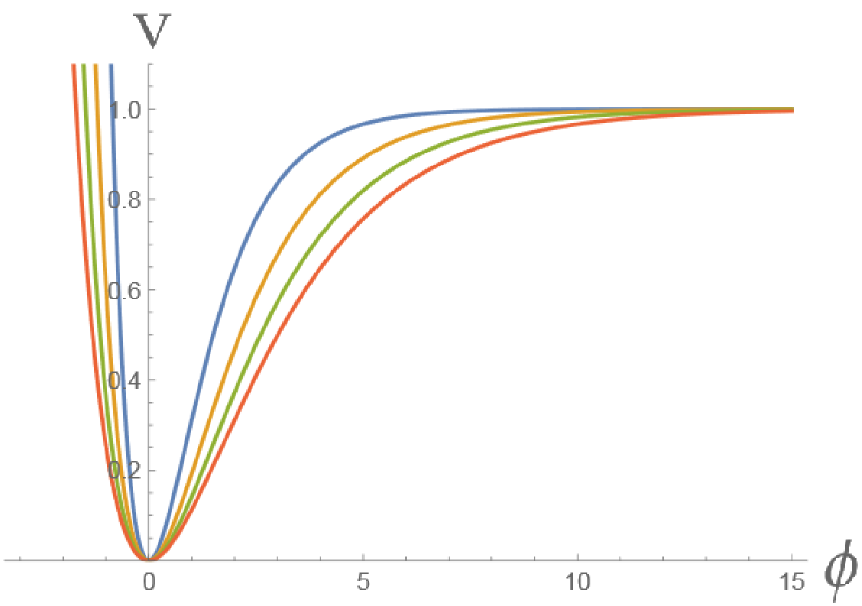
- α-attractors (E-model)

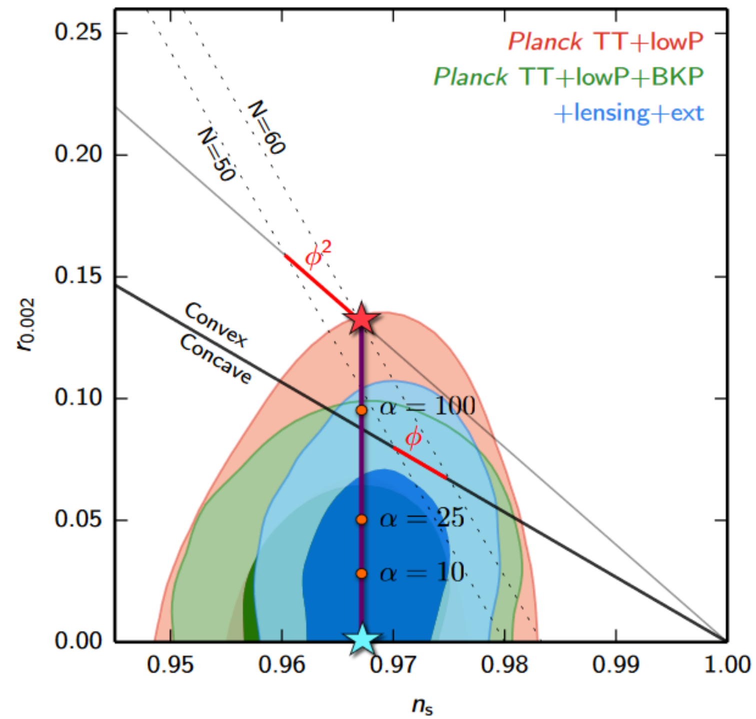
$$V(\phi) = V_0 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{Pl}}}\right)^2$$

$$m_\phi^2 = \left.\frac{\partial^2 V}{\partial \phi^2}\right|_{\phi=0} = \frac{4V_0}{3\alpha M_{Pl}^2} = \frac{m^2}{\alpha}$$

$$m \sim 3 \cdot 10^{13}\ GeV$$

[Carrasco, Kallosh, Linde '15]

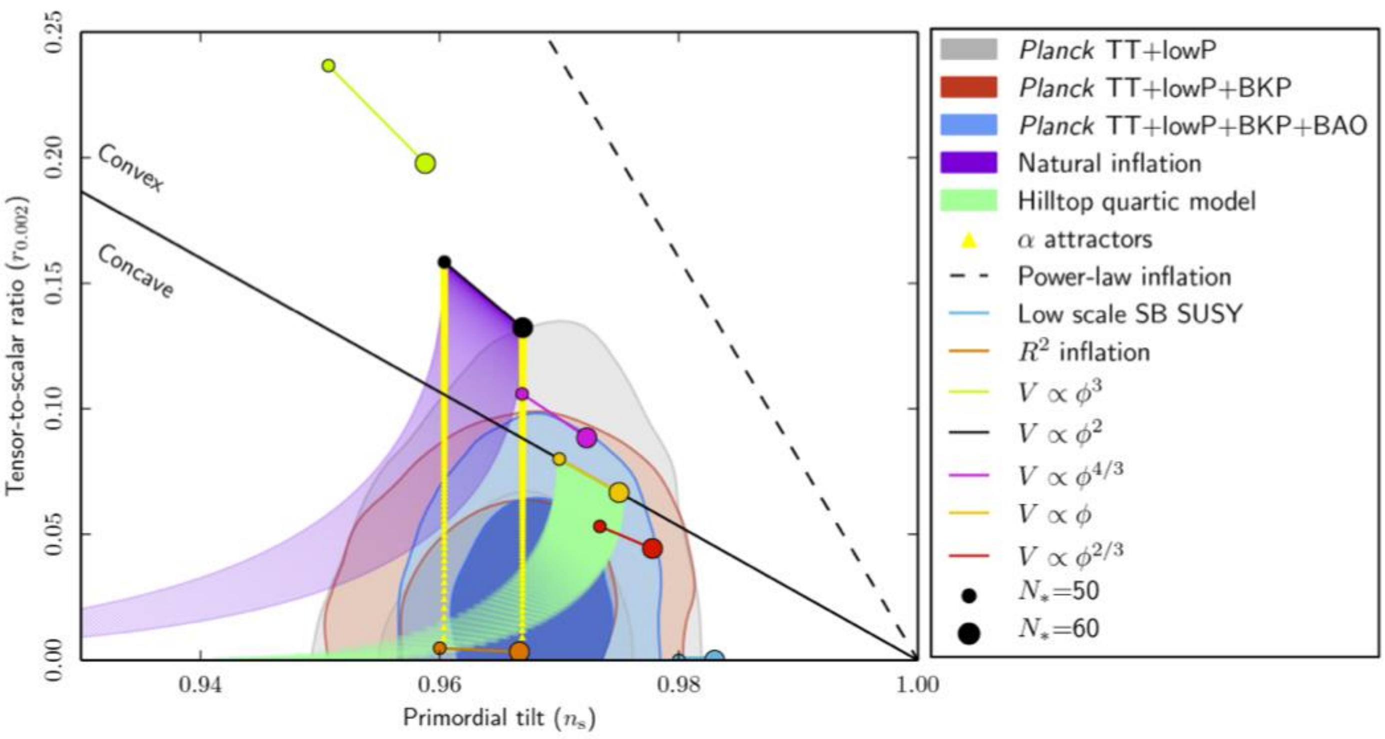




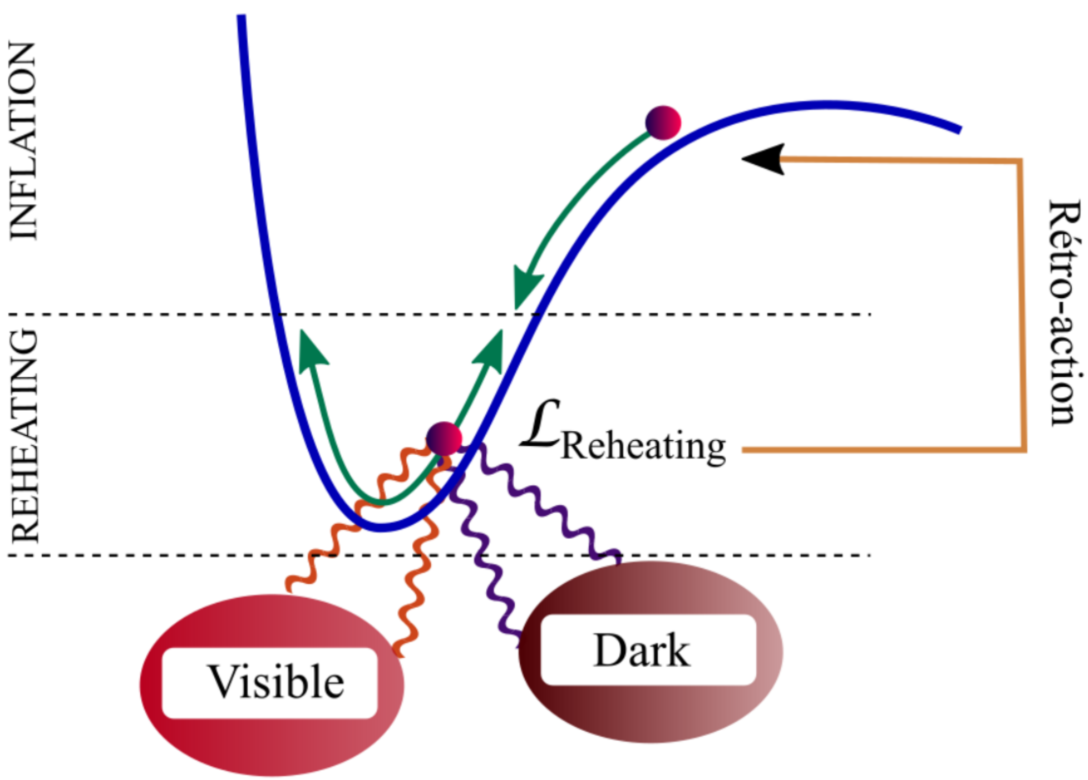
Vacuum mass versus inflation parameters

- Natural inflation

$$V(\phi) = \Lambda^4 \left[1 \pm \cos\left(a\frac{\phi}{f}\right)\right] \quad m_\phi \sim M_{GUT}^2/M_{Pl} \sim 4\times 10^{13}\ GeV$$



What on the inflation side?



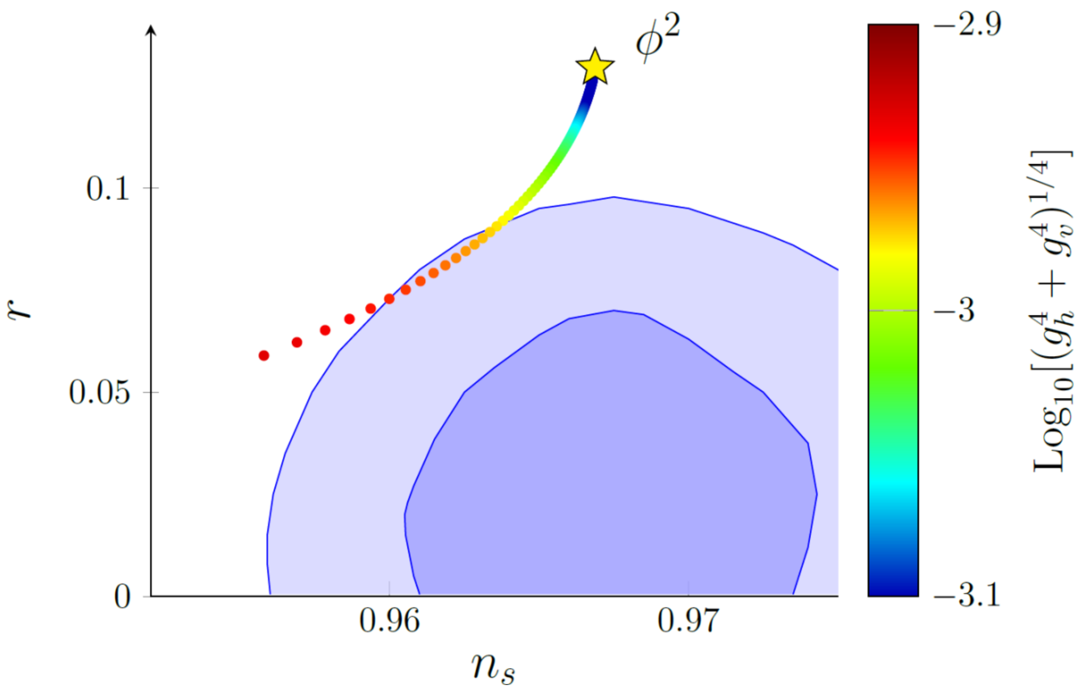
Loop corrections backreact on the inflationary trajectory

Destabilizes the inflaton at large field values

Modifies the predictions fof inflation observables (r, ns)

What on the inflation side?

Ne = 60 e-folds



Loop corrections backreact on the inflationary trajectory

Destabilizes the inflaton at large field values

Modifies the predictions fof inflation observables (r, ns)

What about the primordial universe?

After dark matter decouples, the light dark component becomes non-relativistic and dominates the energy density before decaying…

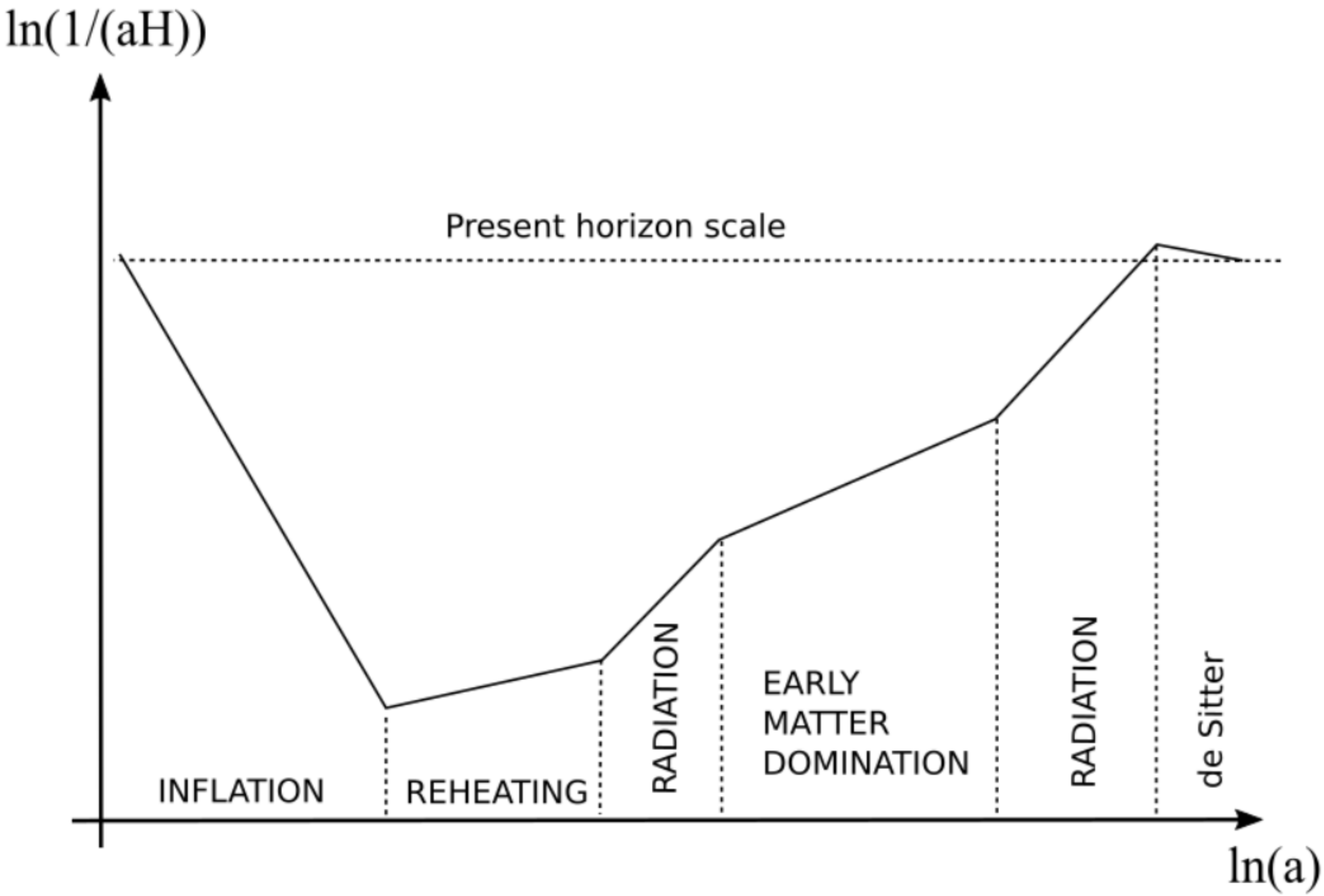
↓

Period of early matter domination

↓

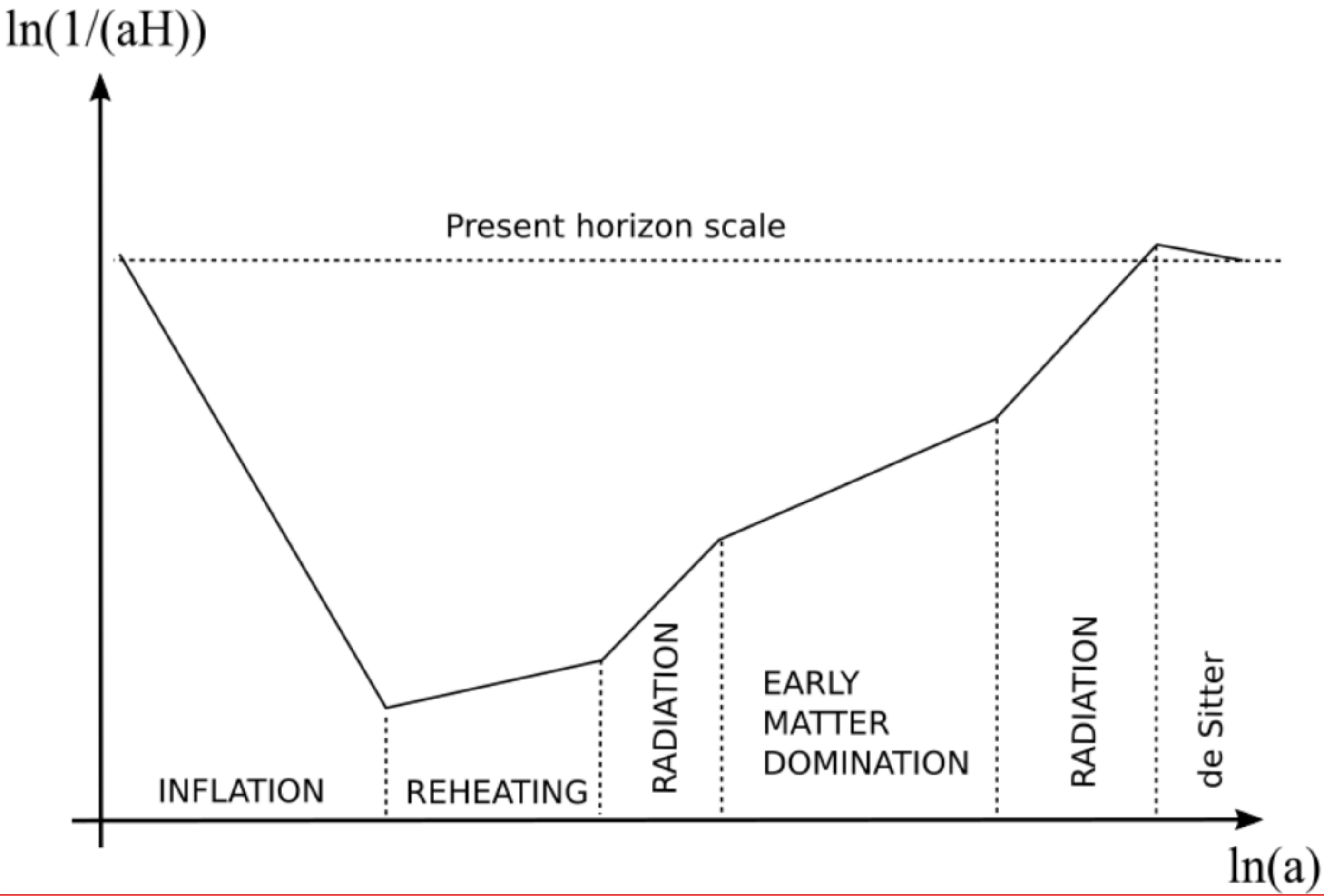
Modifies the number of e-folds

What about the primordial universe?



$$\frac{k}{a_0 H_0} = \frac{a_k H_k}{a_0 H_0} = e^{-N(k)} \frac{a_{\rm end}}{a_{\rm reh}} \frac{a_{\rm reh}}{a_{\rm dom}} \frac{a_{\rm dom}}{a_{\rm eq}} \frac{H_k}{H_{\rm eq}} \frac{a_{\rm eq} H_{\rm eq}}{a_0 H_0}$$

What about the primordial universe?



Chaotic inflation → N < 50 e-folds **EXCLUDED**

Other inflation scenarios : To appear soon !

Conclusion(I)

- Dark matter production usually requires fine tuning or the introduction of arbitrary mass scales

- We propose an ***inflaton portal*** to a highly decoupled dark sector

→ **Reheating process explicitely present in the scenario**

→ **Natural choices of couplings lead to the correct relic abundance**

- The model escapes any direct or indirect detection

- The presence of light fields and of an early matter domination period provides strong constrains on the inflationary sector…

- Chaotic inflation is ruled out in this framework

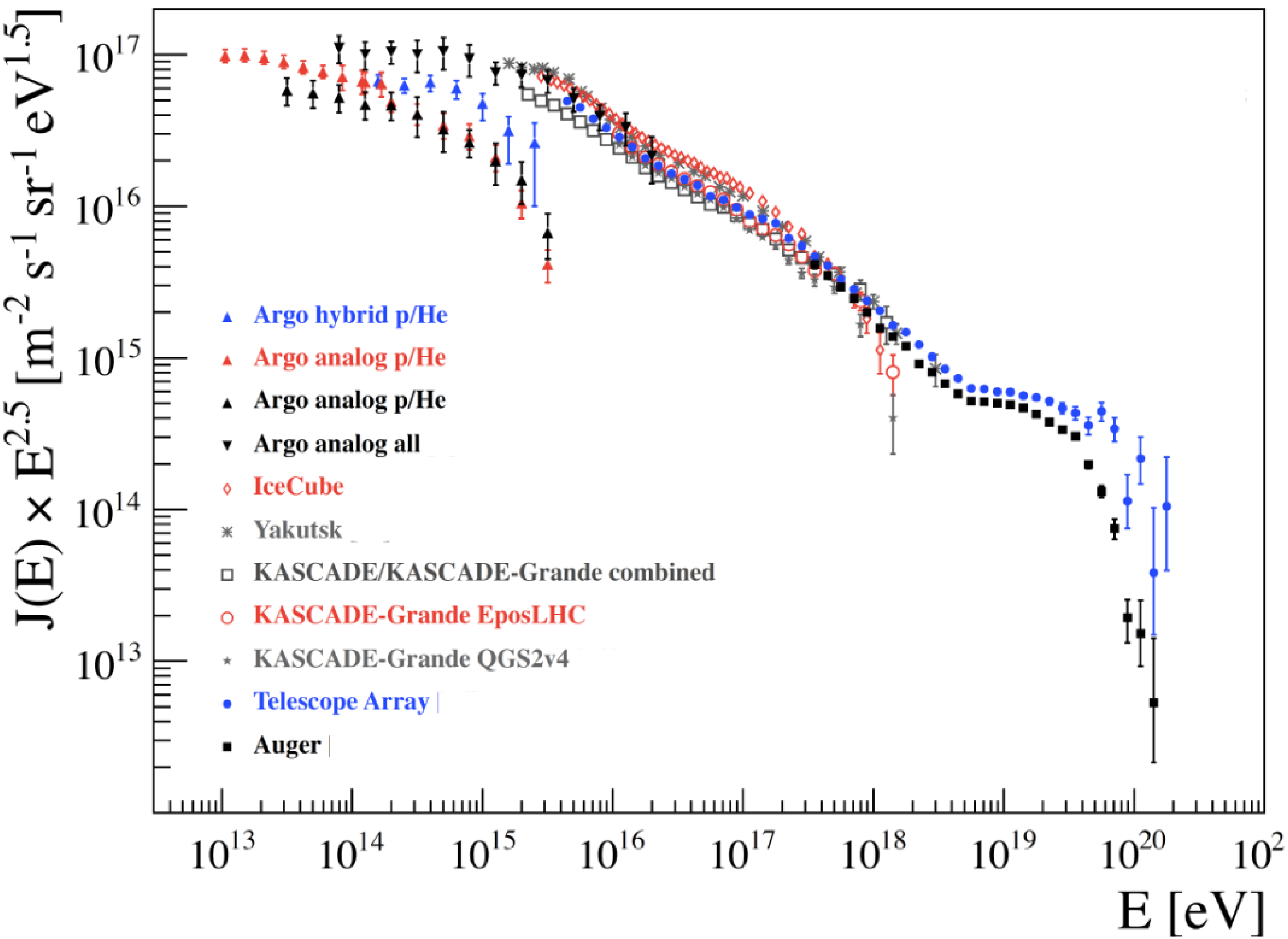
Part II

Signatures of EeV scale dark matter in the neutrino sector

What do we expect at ultra high energy?

Up to $\mathrm{E} < 5 \times 10^{19}$GeV, primary proton cosmic rays can propagate (also known as Greisen-Zatsepin-Kuzmin (GZK) limit)

Above such energy, primary cosmic rays scatter on the CMB to produce *cosmogenic* neutrinos which remain yet undetected…



J(E) × E^2.5 [m^-2 s^-1 sr^-1 eV^1.5]
E [eV]
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Argo hybrid p/He
Argo analog p/He
Argo analog p/He
Argo analog all
IceCube
Yakutsk
KASCADE/KASCADE-Grande combined
KASCADE-Grande EposLHC
KASCADE-Grande QGS2v4
Telescope Array
Auger

Searching for Heavy Dark Matter in the Neutrino Sector

- Presence of decaying HDM in the galaxy

→ Ultra-High-Energy Cosmic Rays

At energies larger than >TeV **photons scatter on the CMB**…

… but **neutrinos can propagate**!

→ Search for decay products in the neutrino sector !

Experimental Status

- IceCube, Auger and ANITA have been operating for several years

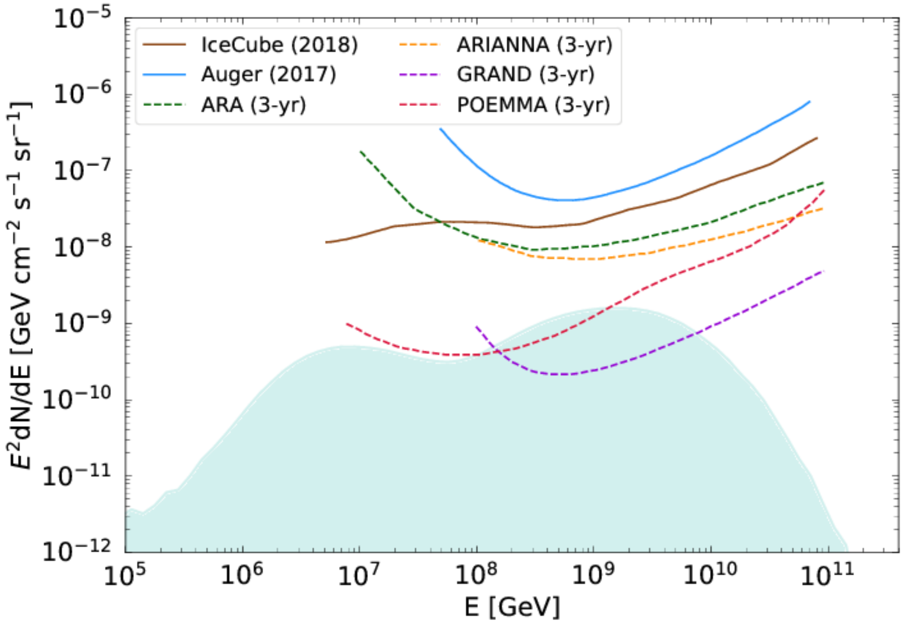
<u>Signals:</u>

→ IceCube : A few PeV events in ten years

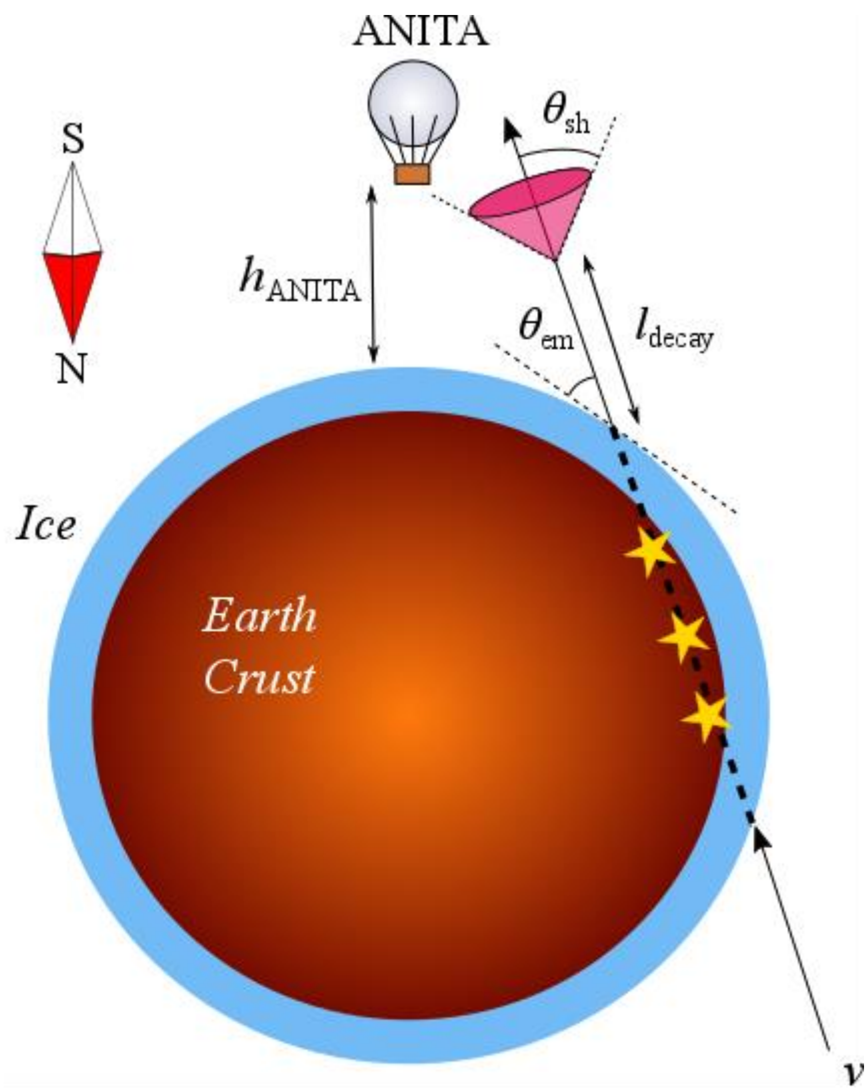
→ ANITA : 2 anomalous upgoing EeV events in 85 days

Future detectors:

POEMMA, GRANDE, …



The ANITA experiment



Three types of interactions in the SM:

- Charged current: Neutrinos → leptons
- Neutral current : Neutrinos → Neutrinos
- Regeneration: Lepton → Neutrino + sh.

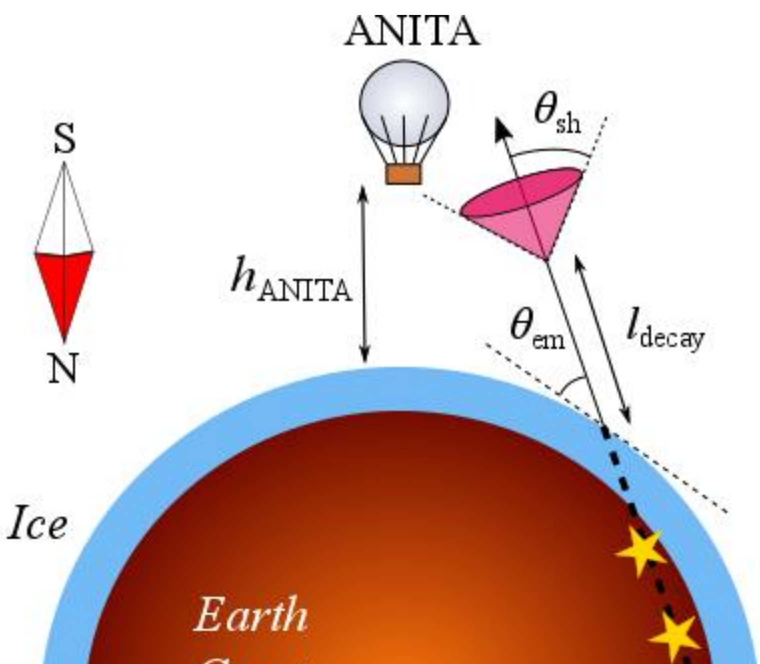
Propagation depends on the particle energy, local density, and particle interactions…

Two anomalous events with emergence angles 27° and 35° and energies O(1)EeV.

At such emergence angles, a SM neutrino cannot cross the Earth.

No astrophysical source identified.

The ANITA experiment



Three types of interactions in the SM:

- Charged current: Neutrinos → leptons
- Neutral current : Neutrinos → Neutrinos
- Regeneration: Lepton → Neutrino + sh.

Propagation depends on the particle energy, local density, and particle interactions…

Property	AAE 061228	AAE 141220
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. 282°.14064, Dec. +20°.33043	R.A. 50°.78203, Dec. +38°.65498
Energy ε_{cr}	0.6 ± 0.4 EeV	$0.56^{+0.30}_{-0.20}$ EeV
Zenith angle z'/z	117°.4 / 116°.8 ± 0°.3	125°.0 / 124°.5 ± 0°.3
Earth chord length ℓ	5740 ± 60 km	7210 ± 55 km
Mean interaction length for $\varepsilon_\nu = 1$ EeV	290 km	265 km
$p_{SM}(\varepsilon_\tau > 0.1\,\text{EeV})$ for $\varepsilon_\nu = 1$ EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{SM}(z > z_{obs})$ for $\varepsilon_\nu = 1$ EeV, $\varepsilon_\tau > 0.1$ EeV	6.7×10^{-5}	3.8×10^{-6}
$n_\tau(1\text{–}10\,\text{PeV}) : n_\tau(10\text{–}100\,\text{PeV}) : n_\tau(> 0.1\,\text{EeV})$	34 : 35 : 1	270 : 120 : 1

The ANITA experiment

[Fox, Sigurdson, Murase *et al., Nov 18'*]

The SM can't explain ANITA events.

+

A re-analysis of IceCube data

→ two upgoing events : energies O(0.01)EeV

Property	IceCube-140611	IceCube-140109	IceCube-121205
EHE Northern Track ID	#27	#24	#20
Date & Time (UTC or MJD)	2014-06-11 04:54:24	56666.5	56266.6
Equatorial coordinates (J2000)	R.A. $110^\circ.34 \pm 0^\circ.22$,	R.A. $293^\circ.29$,	R.A. $169^\circ.61$,
	Dec. $+11^\circ.42 \pm 0^\circ.08$	Dec. $+32^\circ.82$	Dec. $+28^\circ.04$
Zenith angle z	$101^\circ.42$	$122^\circ.82$	$118^\circ.04$
Earth chord length ℓ	2535 km	6910 km	5990 km
As tau: $\varepsilon_{\tau,\mathrm{obs}}$ (median)	70 PeV	13 PeV	12 PeV
Mean interaction length for $\varepsilon_\nu = 1\,\mathrm{EeV}$	340 km	270 km	285 km
$p_{\mathrm{SM}}(\varepsilon_\tau > \varepsilon_{\tau,\mathrm{obs}})$ for $\varepsilon_\nu = 1\,\mathrm{EeV}$	2.2×10^{-4}	3.8×10^{-6}	1.0×10^{-5}
$p_{\mathrm{SM}}(z > z_{\mathrm{obs}})$ for $\varepsilon_\nu = 1\,\mathrm{EeV}$, $\varepsilon_\tau > \varepsilon_{\tau,\mathrm{obs}}$	5.0×10^{-3}	4.5×10^{-5}	1.8×10^{-4}

Question: Can both signals have a common origin?

A right-handed neutrino interpretation

Consider:

- A right-handed neutrino mixes with the tau neutrino
- A scalar dark-matter particle decays into sterile neutrinos in the galaxy

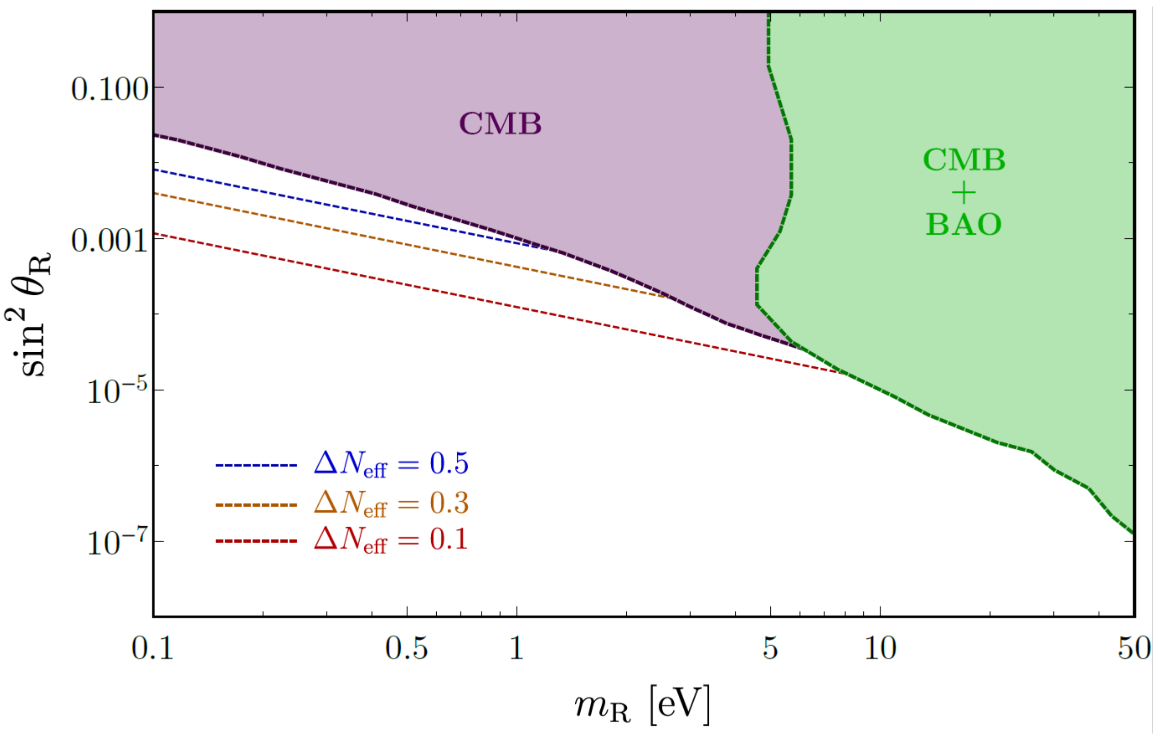
One needs:

→ RH neutrinos sufficiently long lived

→ To satisfy observational bounds (BBN, CMB, direct searches)

A right-handed neutrino interpretation

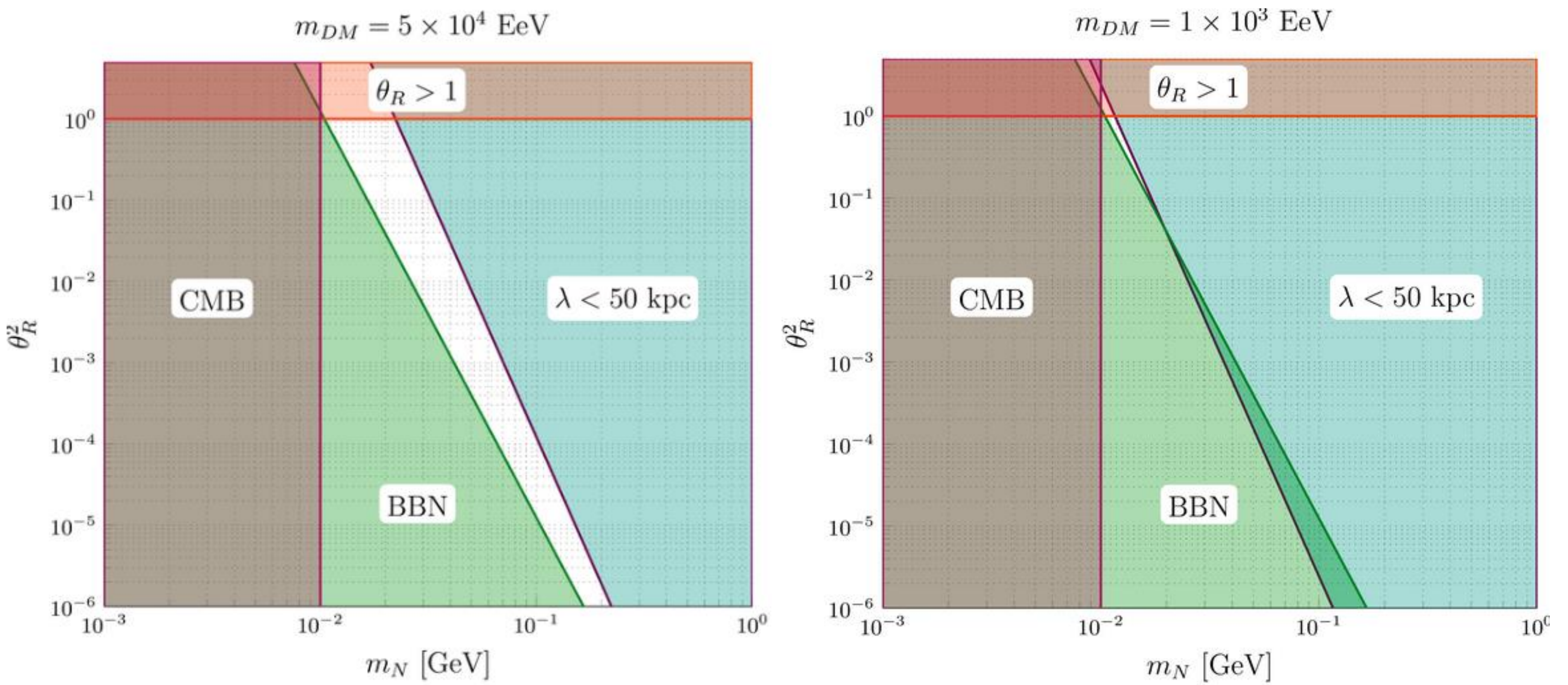
$m_R < 10$ eV or $m_R \sim 0.1$ GeV



$m_R < 10$ eV → $m_{DM} \sim 10$ EeV

A right-handed neutrino interpretation

$m_R < 10$ eV or $m_R \sim 0.1$ GeV

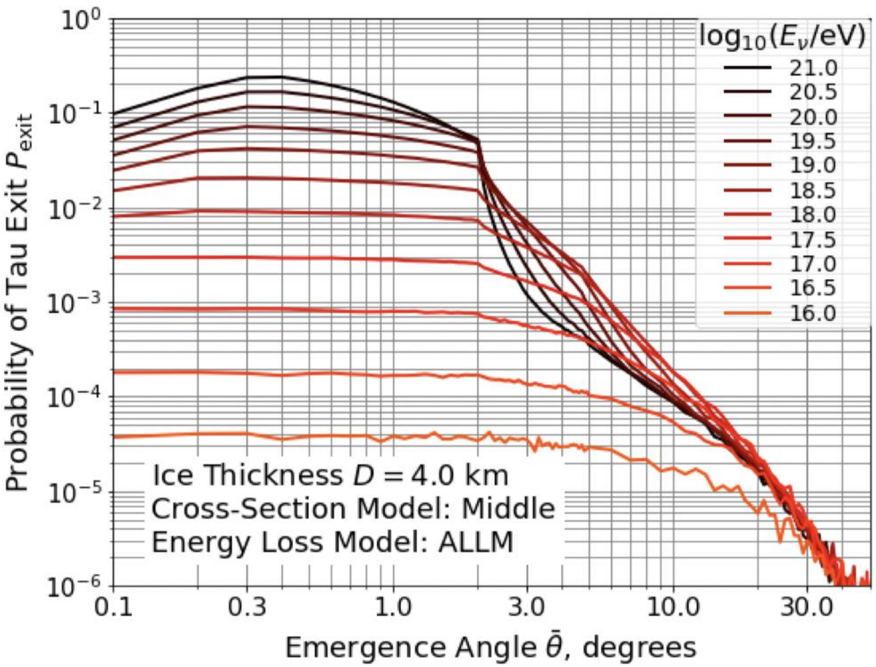


$m_R \sim 0.1$ GeV → $m_{DM} \gtrsim 10^3$ EeV $= 10^{12}$ GeV

Approaches the inflaton mass…

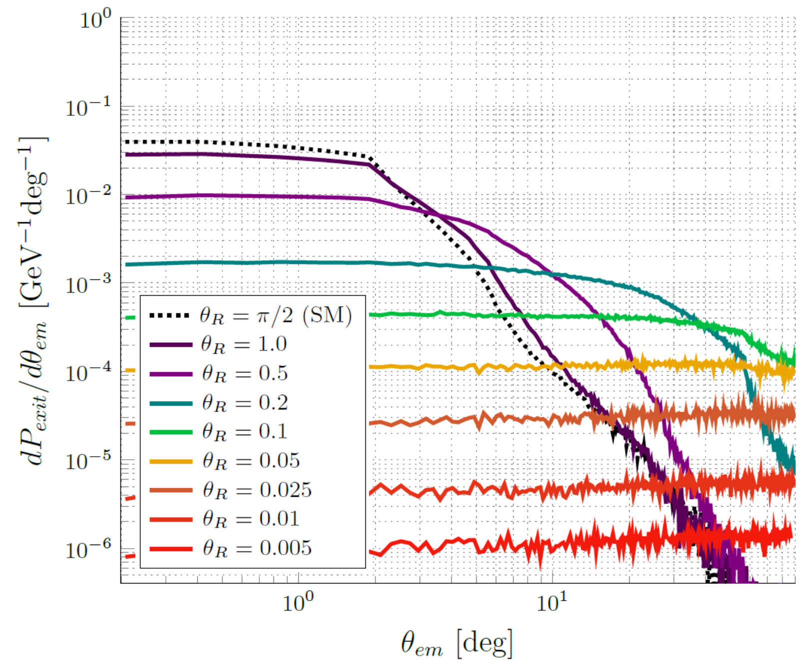
A right-handed neutrino interpretation

Propagation and conversion into tau's



SM

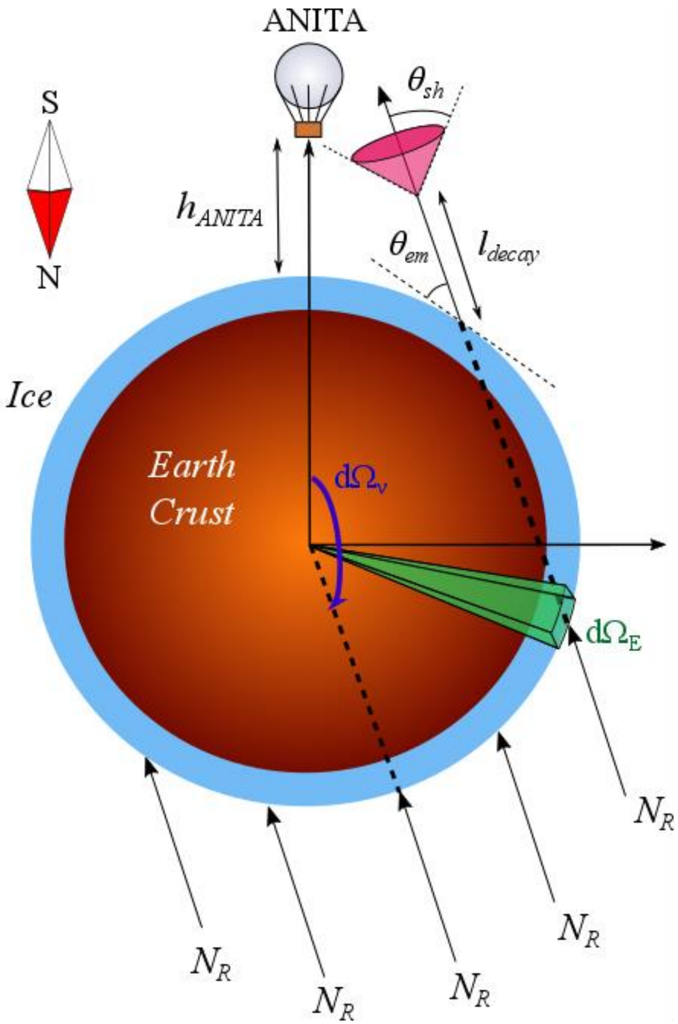
[Romero-Wolf *et al.*, Dec 17']



SM + RH neutrinos and mixing angle

[**LH**, Y. Mambrini, M. Pierre, To appear]

Effective Area Calculation



$$\frac{\mathrm{d}^2 A_{\mathrm{eff}}}{\mathrm{d}E_{\mathrm{exit}}\mathrm{d}\theta_{\mathrm{em}}}(E_{\mathrm{exit}}, \theta_{\mathrm{em}} \mid E_{\mathrm{N}}, \theta_{\mathrm{N}}, \phi_{\mathrm{N}})$$

$$= R_{\mathrm{E}}^2 \int \mathrm{d}\Omega_{\mathrm{E}} \vec{n}_{\mathrm{N}} \cdot \vec{n}_E$$

$$\times \int \mathrm{d}E_{\mathrm{exit}} \frac{\mathrm{d}P_{\mathrm{exit}}}{\mathrm{d}E_{\mathrm{exit}}}(E_{\mathrm{exit}}, \theta_{\mathrm{em}} \mid E_{\mathrm{N}}, \theta_{\mathrm{N}}, \phi_{\mathrm{N}}, \theta_{\mathrm{E}}, \phi_{\mathrm{E}})$$

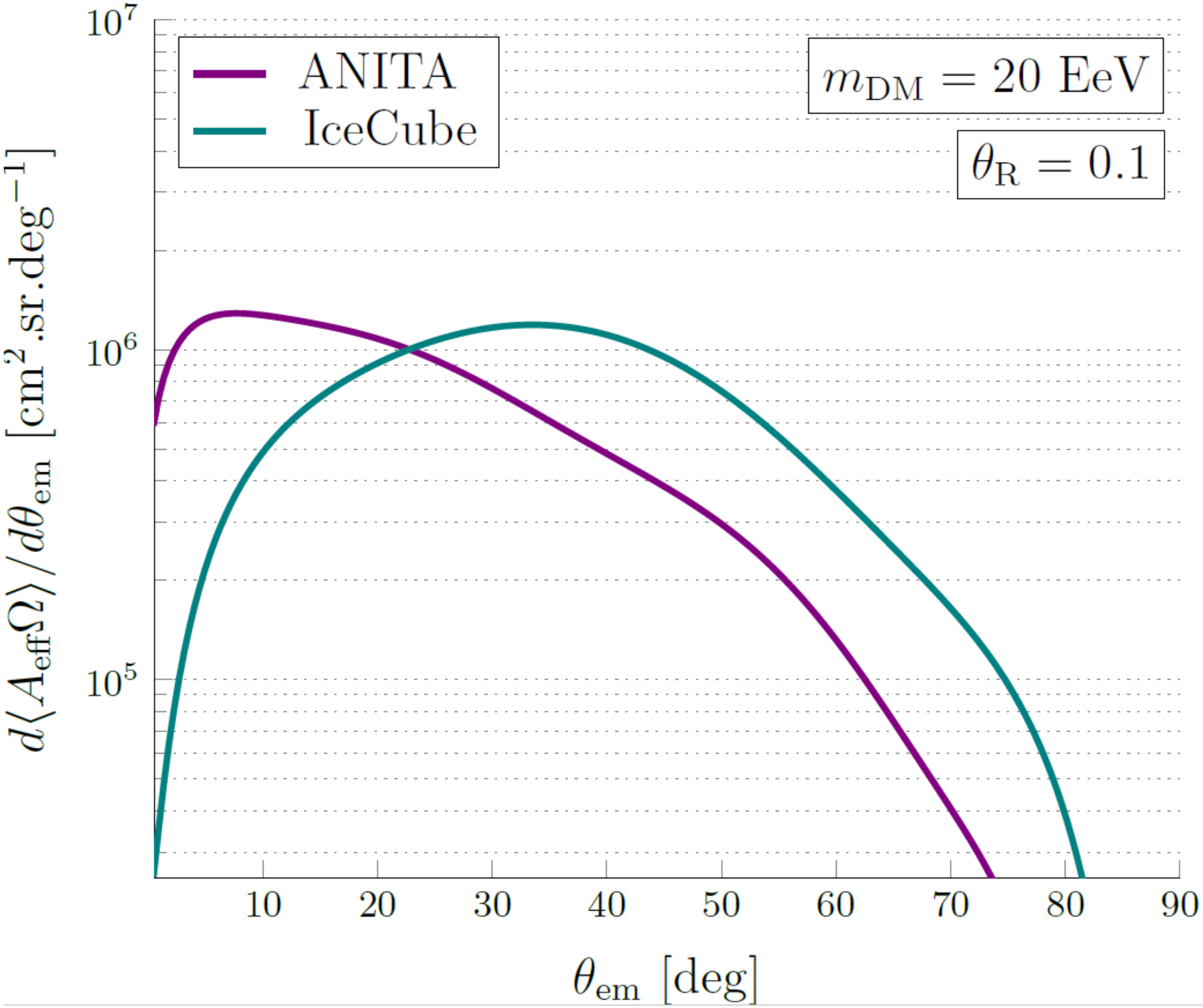
$$\times \int \frac{\mathrm{d}P_{\mathrm{decay}}}{\mathrm{d}l}(l \mid E_{\mathrm{exit}}) \times P_{\mathrm{det}}(\theta_{\mathrm{sh}}|l, \theta_{\mathrm{N}}, \phi_{\mathrm{N}}, \theta_{\mathrm{E}}, \phi_{\mathrm{E}})\mathrm{d}l$$

ANITA and IceCube detection

Simulate the detection probability of a shower for IceCube and ANITA

- IceCube : Fiducial volume of 1km under the Earth surface
- ANITA : shower must be produced in the low atmosphere, within a cone of around 1.5° away from the detector

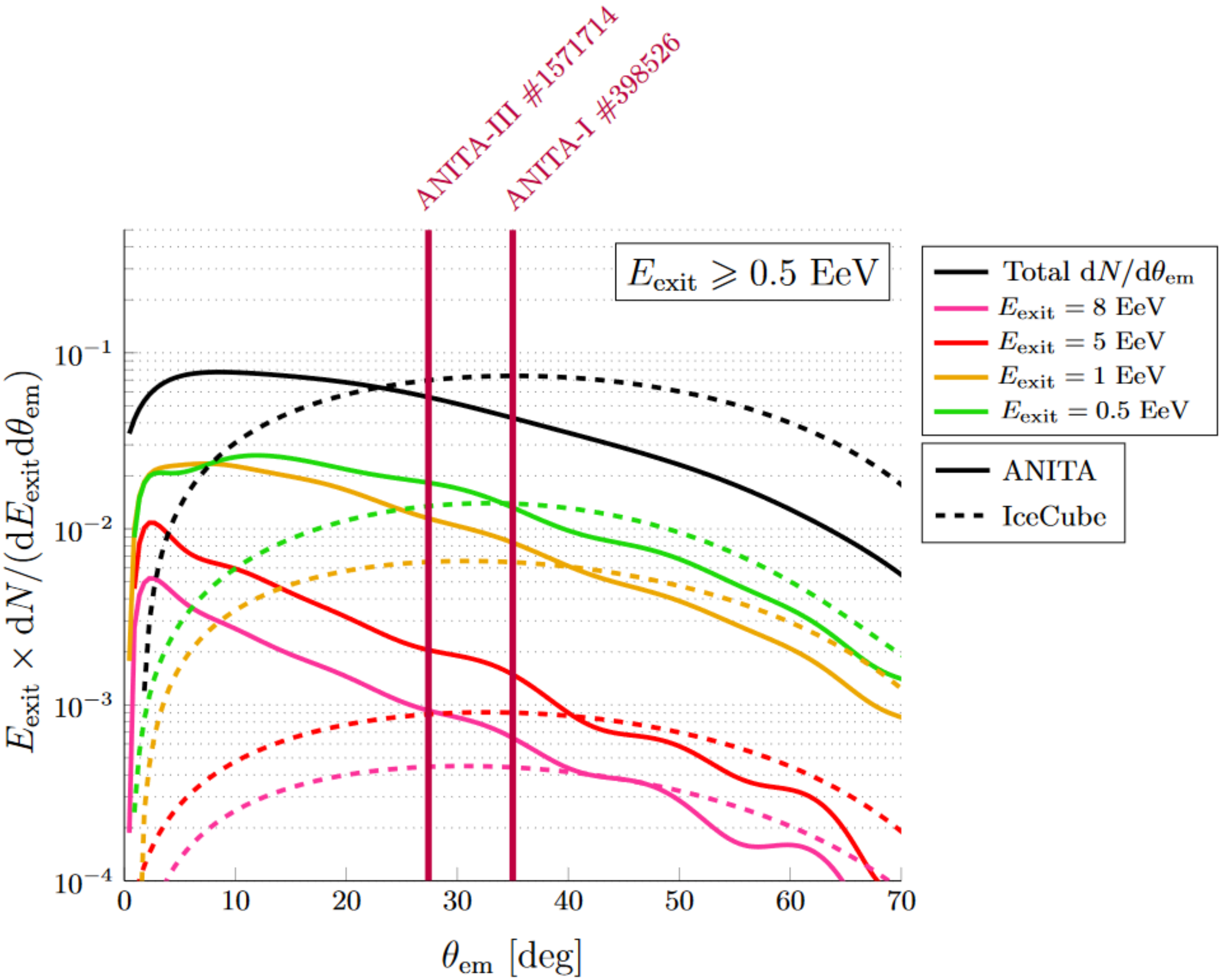
ANITA and IceCube detection



N_{IC} = 2.35 (2431 days)

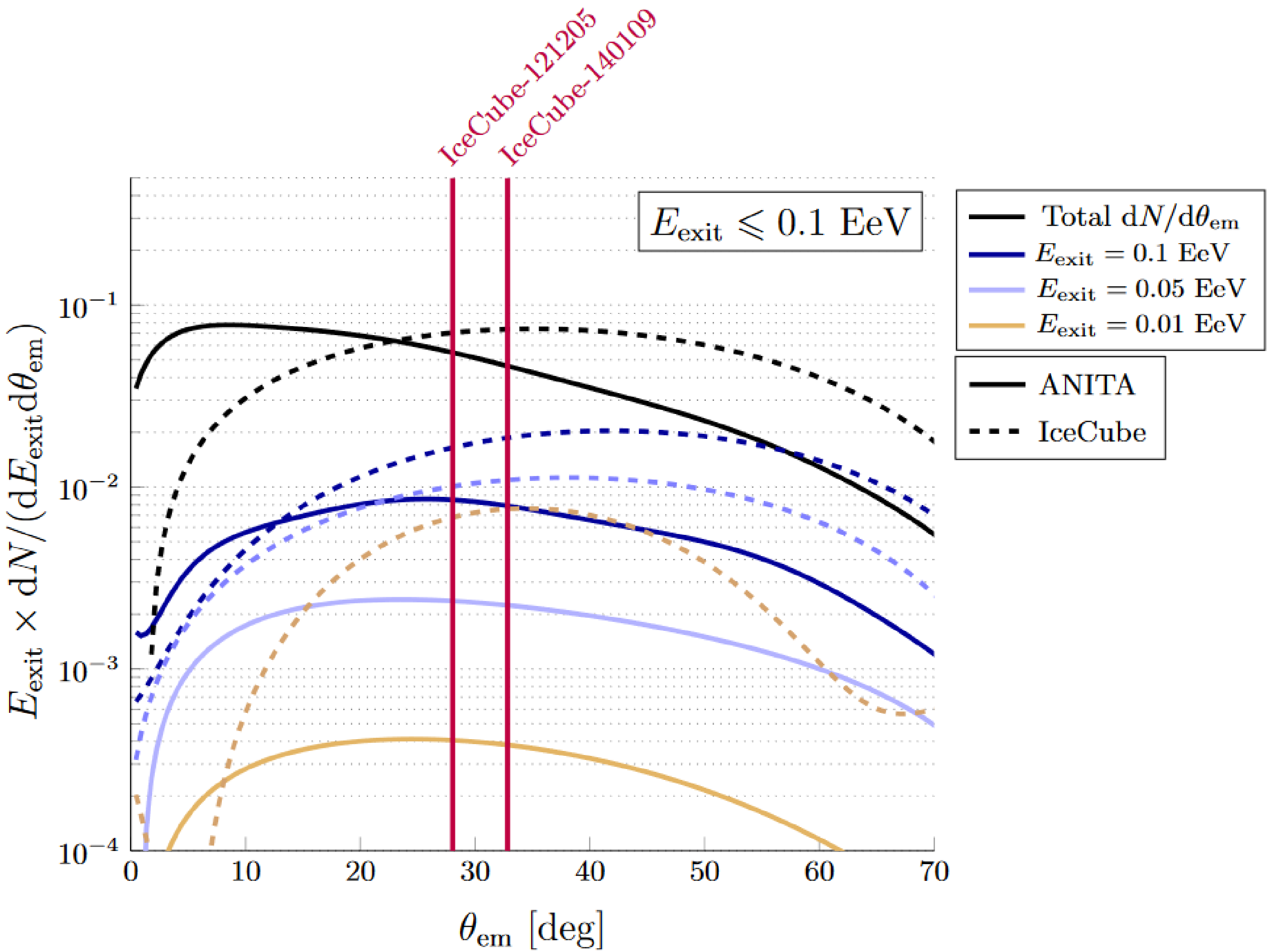
N_{ANITA} = 2.29 (85 days)

ANITA detection



[**LH**, Y. Mambrini, M. Pierre, 1901.XXXX]

IceCube detection



[**LH**, Y. Mambrini, M. Pierre, 1901.XXXX]

Conclusion (II)

- A dark matter of mass as large as $\gtrsim$ 10EeV decaying indirectly into neutrinos might lead to interesting signatures in the neutrino sector.

- The presence of a BSM sector modifies the way the neutrinos can propagate in the Earth

- A dark scalar decaying into right-handed neutrinos can explain the recent measurements of both IceCube and ANITA

- Given this model, a dark matter mass of mass >10 EeV predicts a perfect complementarity between the two collaborations.

Thank you very much