Durham University

Lucien HEURTIER

IP3

Heavy Dark-Matter Particles

Based on :

LH and F. Huang. Phys.Rev. D100 (2019) no.4, 043507 [arXiv:1905.05191]

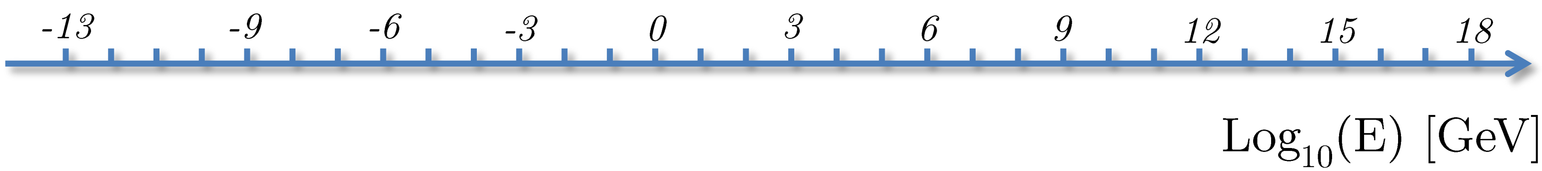
LH, Y. Mambrini and M. Pierre. Phys. Rev. D 99, no. 9, 095014 (2019) [arXiv:1902.04584]

LH, D. Kim, J. C. Park and S. Shin. Phys.Rev. D100 (2019) no.5, 055004 [arXiv:1905.13223]

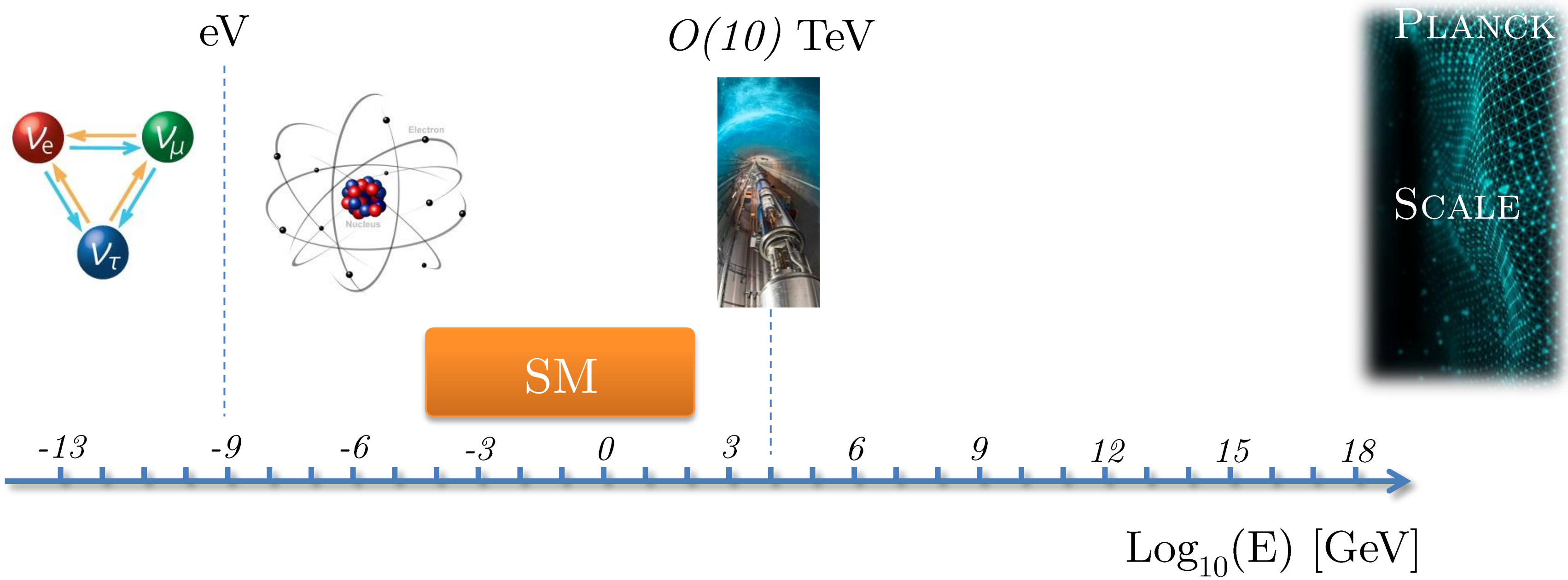
E. Dudas, L. Heurtier, K. Olive, M. Pierre, and Y. Mambrini. Phys.Rev.D 101 (2020) 11, 115029 [arXiv:2003.02846].

IAP, March 2021

« *Heavy* » ?

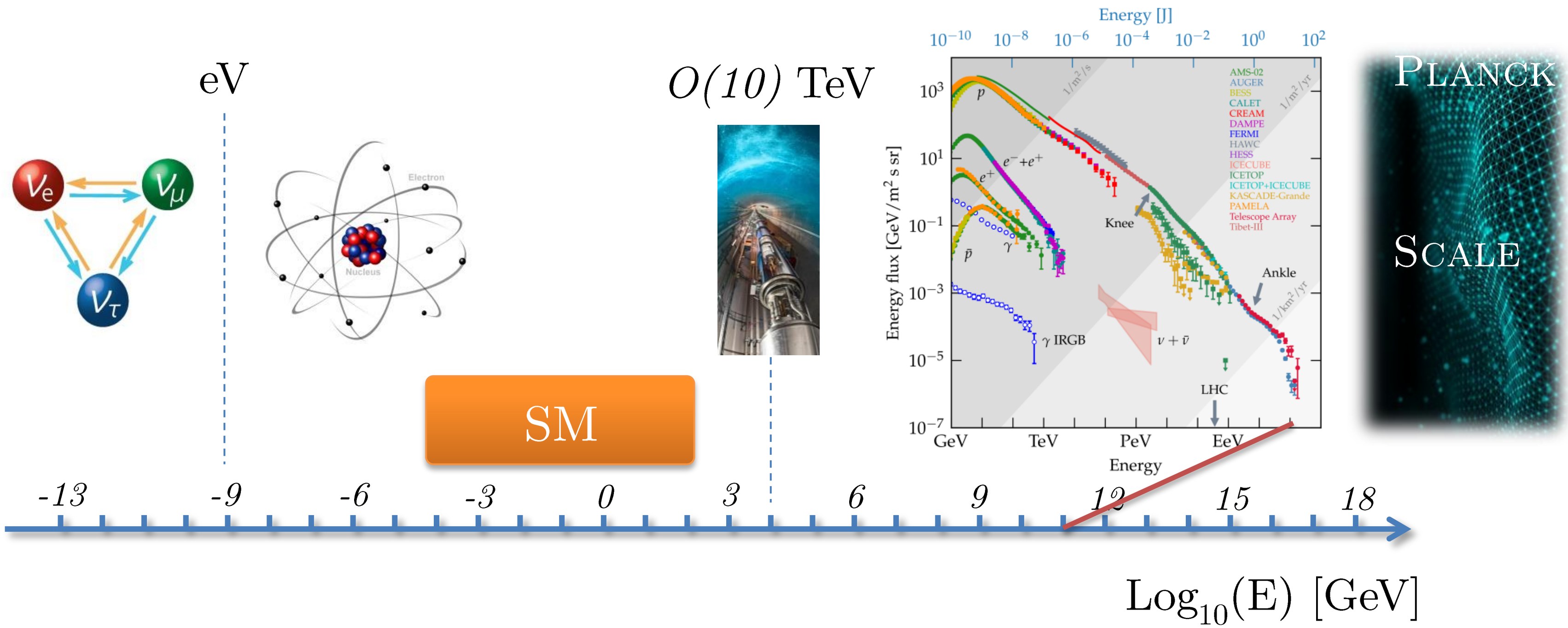


« Heavy » ?



eV
O(10) TeV
Planck
Scale
Electron
Nucleus
SM
-13
-9
-6
-3
0
3
6
9
12
15
18
Log$_{10}$(E) [GeV]

« *Heavy* » ?


eV
Electron
Nucleus
O(10) TeV
SM
Energy [J]
Energy flux [GeV/m² s sr]
Knee
Ankle
LHC
γ IRGB
ν + ν̄
GeV
TeV
PeV
EeV
Energy
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP
ICETOP+ICECUBE
KASCADE-Grande
PAMELA
Telescope Array
Tibet-III
PLANCK
SCALE
-13
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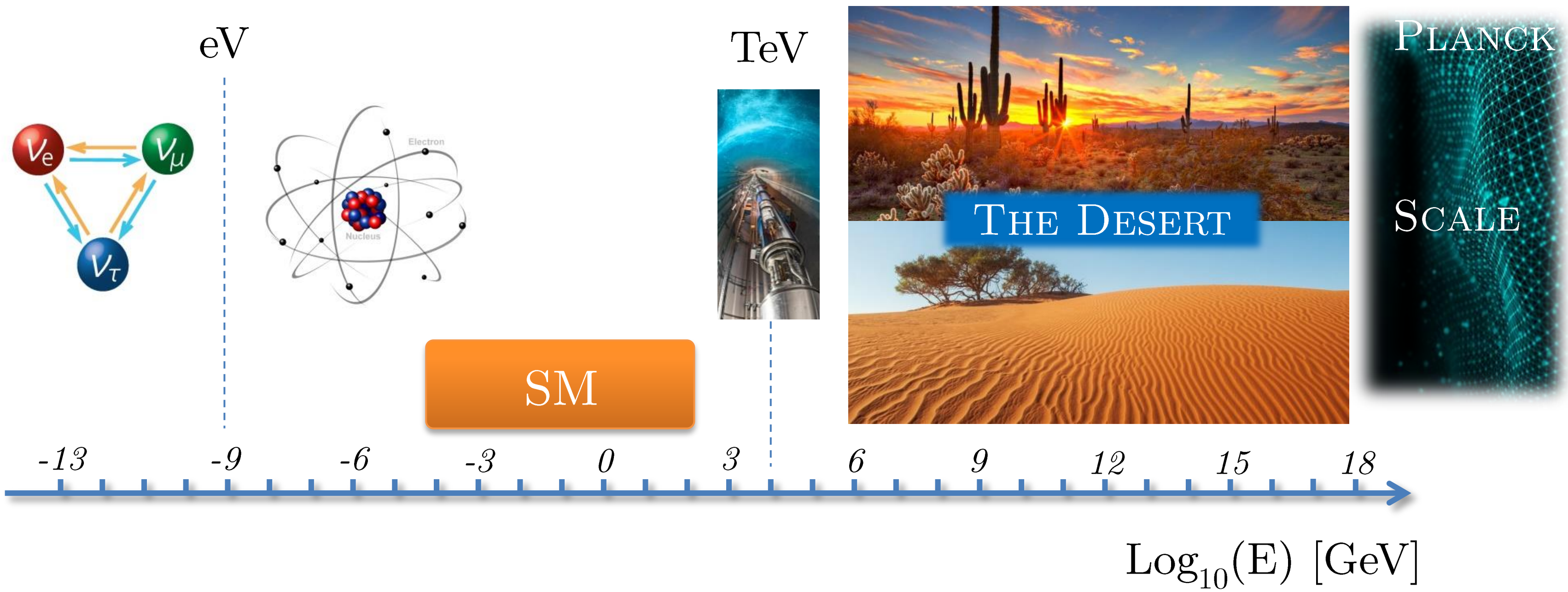
Log10(E) [GeV]

« *Heavy* » ?



eV
TeV
Electron
Nucleus
SM
THE DESERT
PLANCK
SCALE
-13
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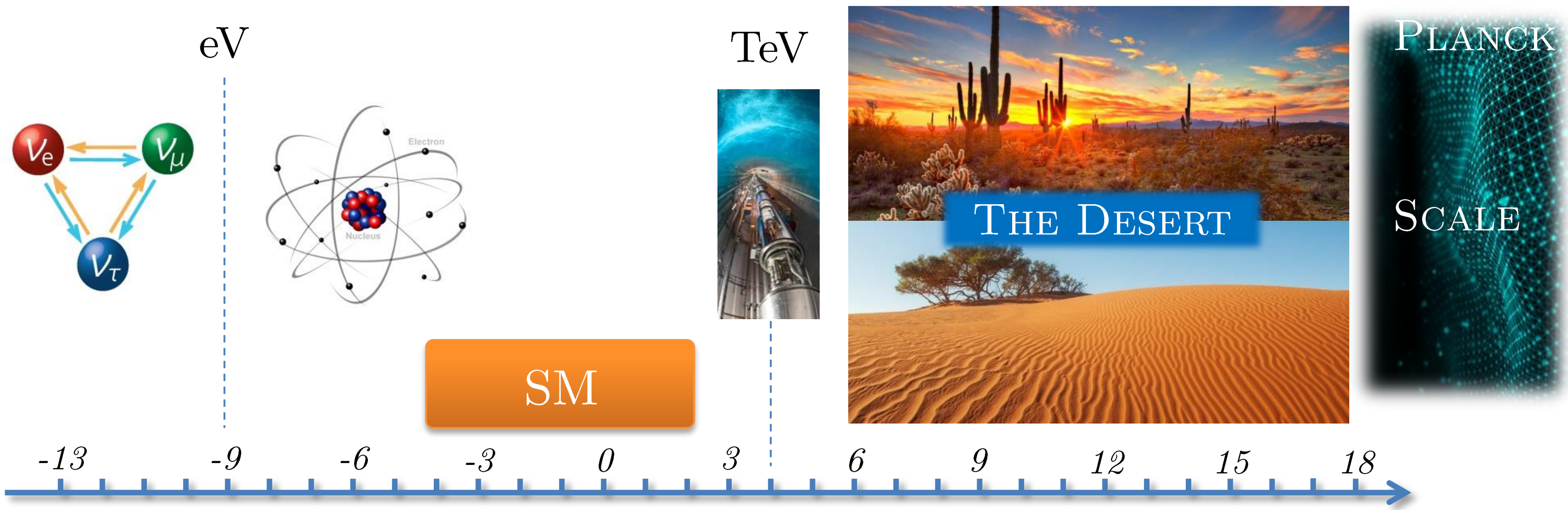
15
18
$\mathrm{Log}_{10}(\mathrm{E})$ [GeV]

« Heavy » ?


eV
TeV
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Electron
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The Desert
Planck
Scale
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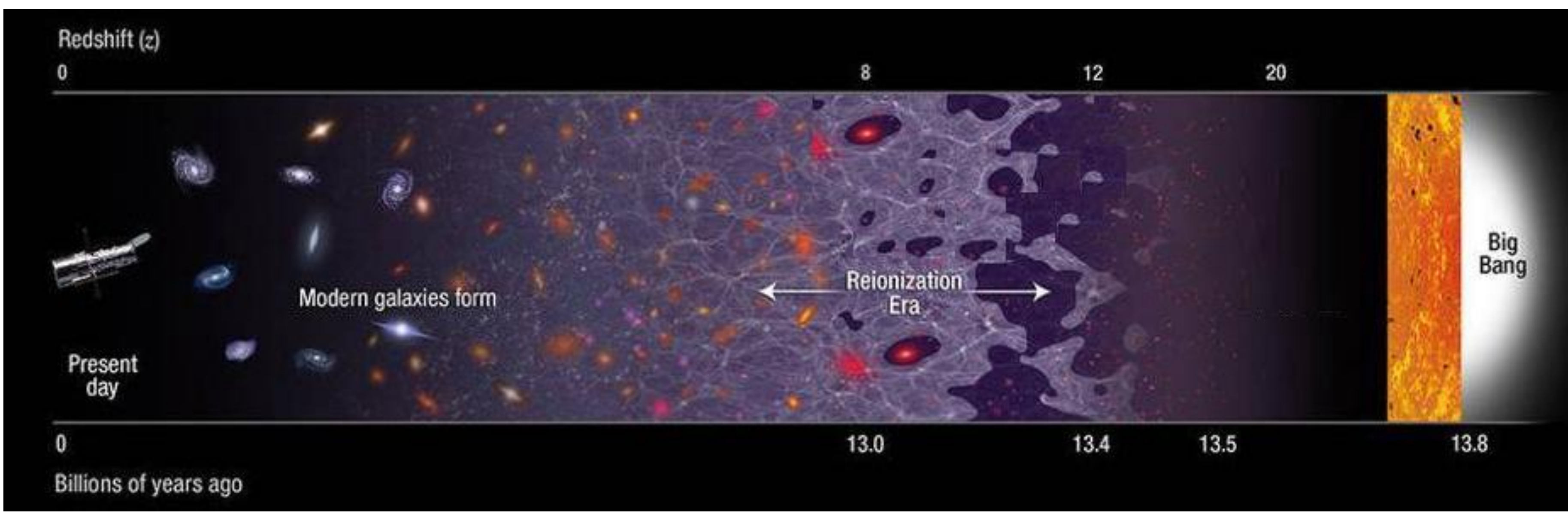
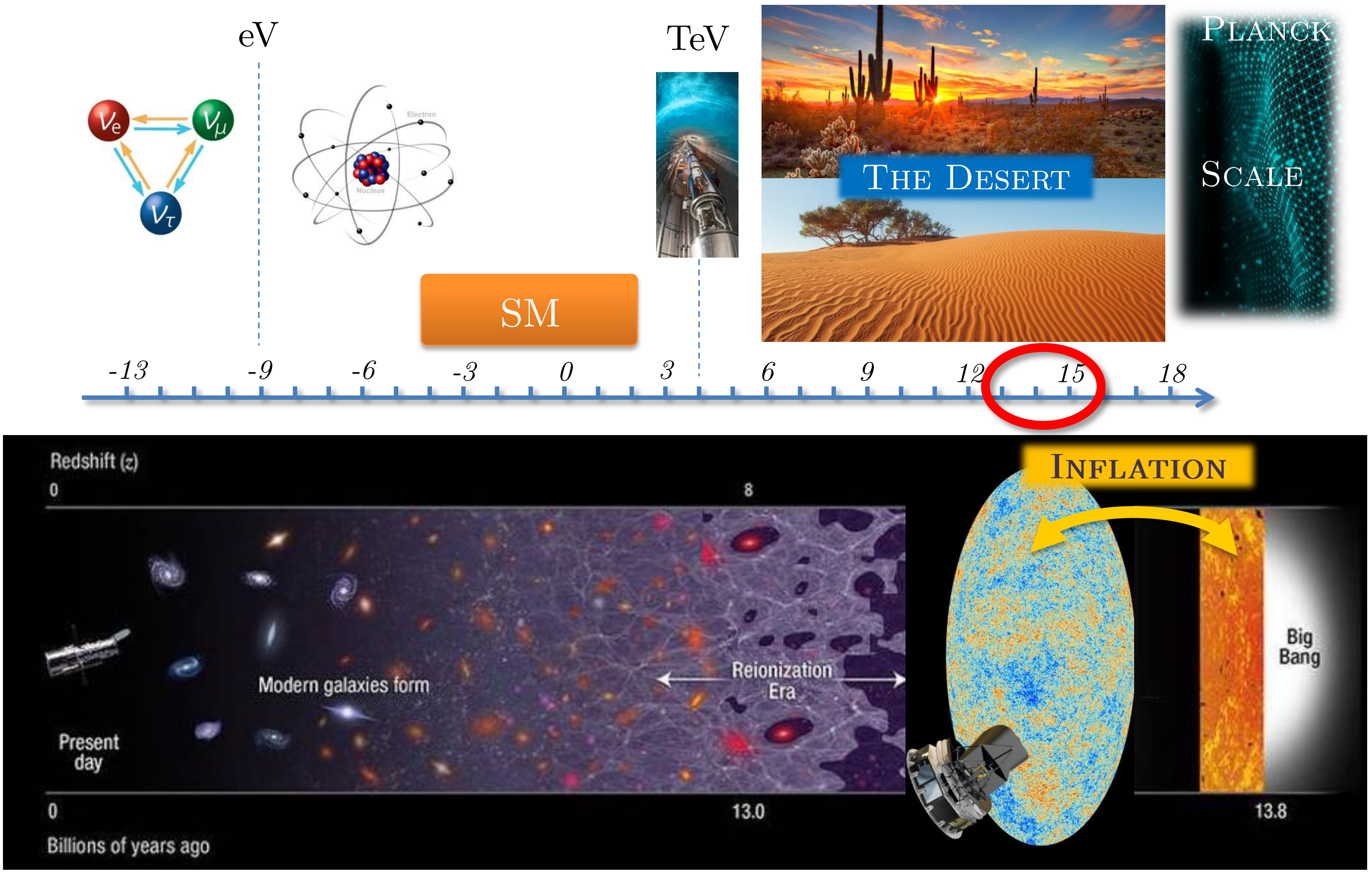

Redshift (z)
0
8
12
20
Modern galaxies form
Reionization
Era
Present
day
Big
Bang
0
13.0
13.4
13.5
13.8
Billions of years ago

« *Heavy* » ?



eV
TeV
PLANCK
SCALE
THE DESERT
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-6
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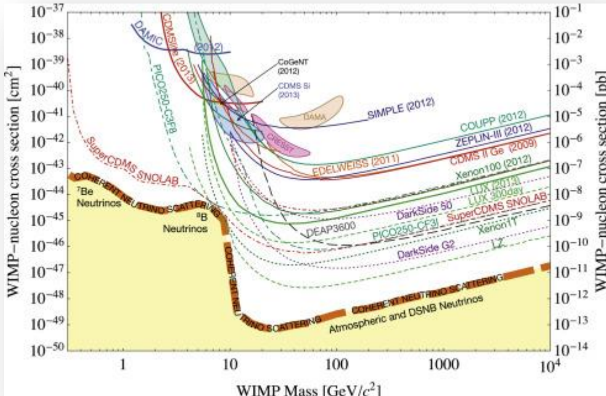
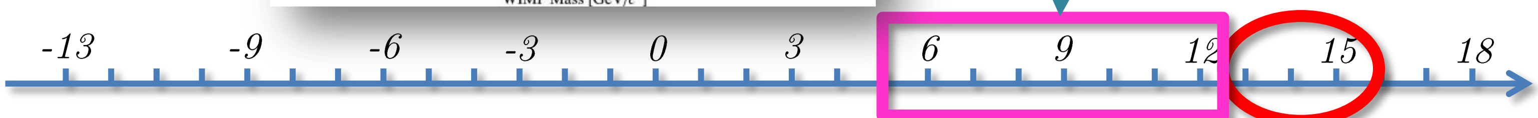
18
INFLATION
Redshift (z)
0
8
Modern galaxies form
Reionization
Era
Present
day
Big
Bang
0
13.0
13.8
Billions of years ago

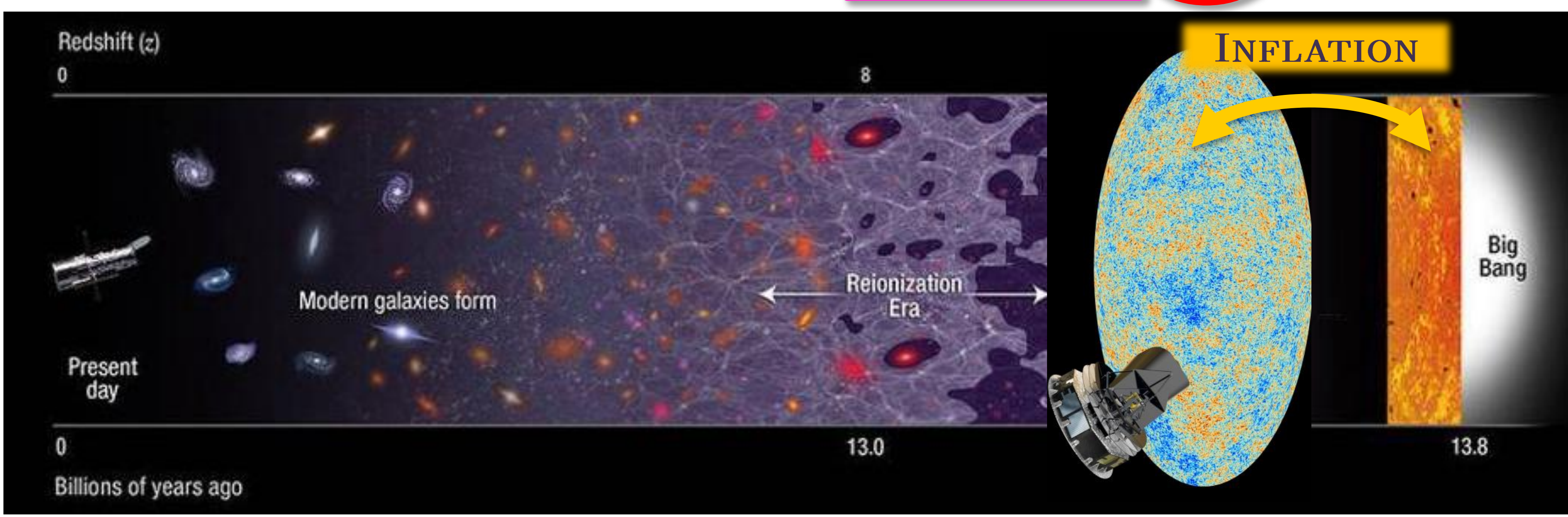
« Heavy » ?

WIMP



This talk





Heavy Dark Matter: *Main Features*

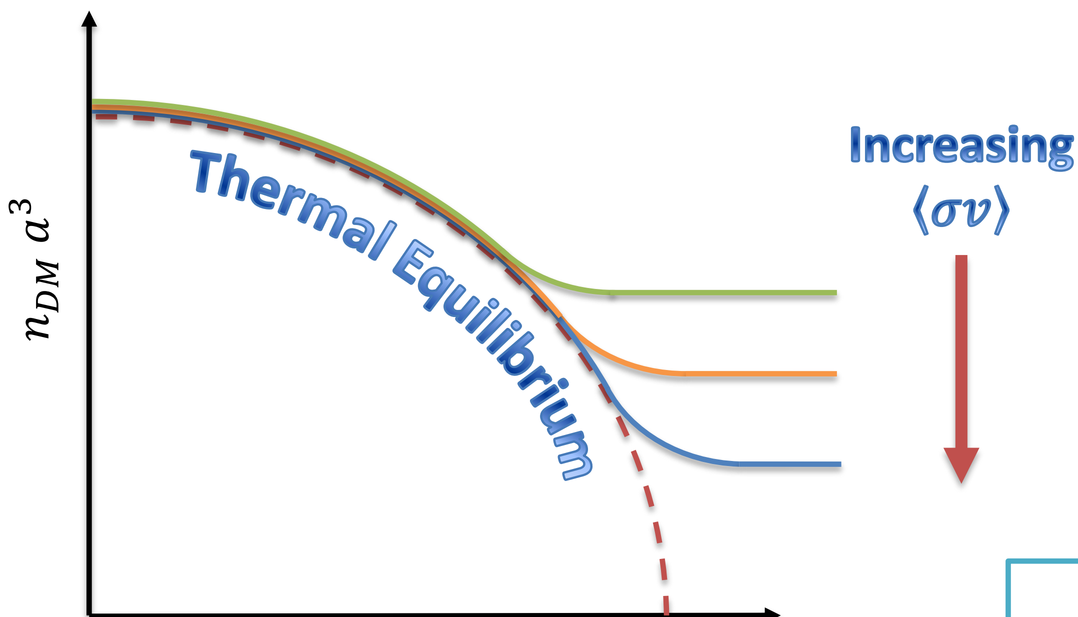
Large mass → Low density

$$n_{\mathrm{DM}} \simeq 3 \times 10^{-3} \left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{DM}}} \right)\ \mathrm{cm}^{-3}$$

Heavy Dark Matter: *Main Features*

✓ Very low density

Thermal Eq. → Over-dense universe



Boltzmann Equation

$$\frac{dn_{DM}}{dt} = -\langle \sigma v \rangle \left(n_{DM}^2 - n_{eq}^2 \right)$$

Unitarity: $m_{DM} \lesssim O(100)$ TeV

HEAVY DARK MATTER: *Main Features*

- ✓ Very low density
- ✓ Very feebly interacting

Stability?

Heavy Dark Matter: *Main Features*

- ✓ Very low density
- ✓ Very feebly interacting

Stability?

→ $\tau_{DM} > \tau_{universe}$ hard to achieve

Heavy Dark Matter: *Main Features*

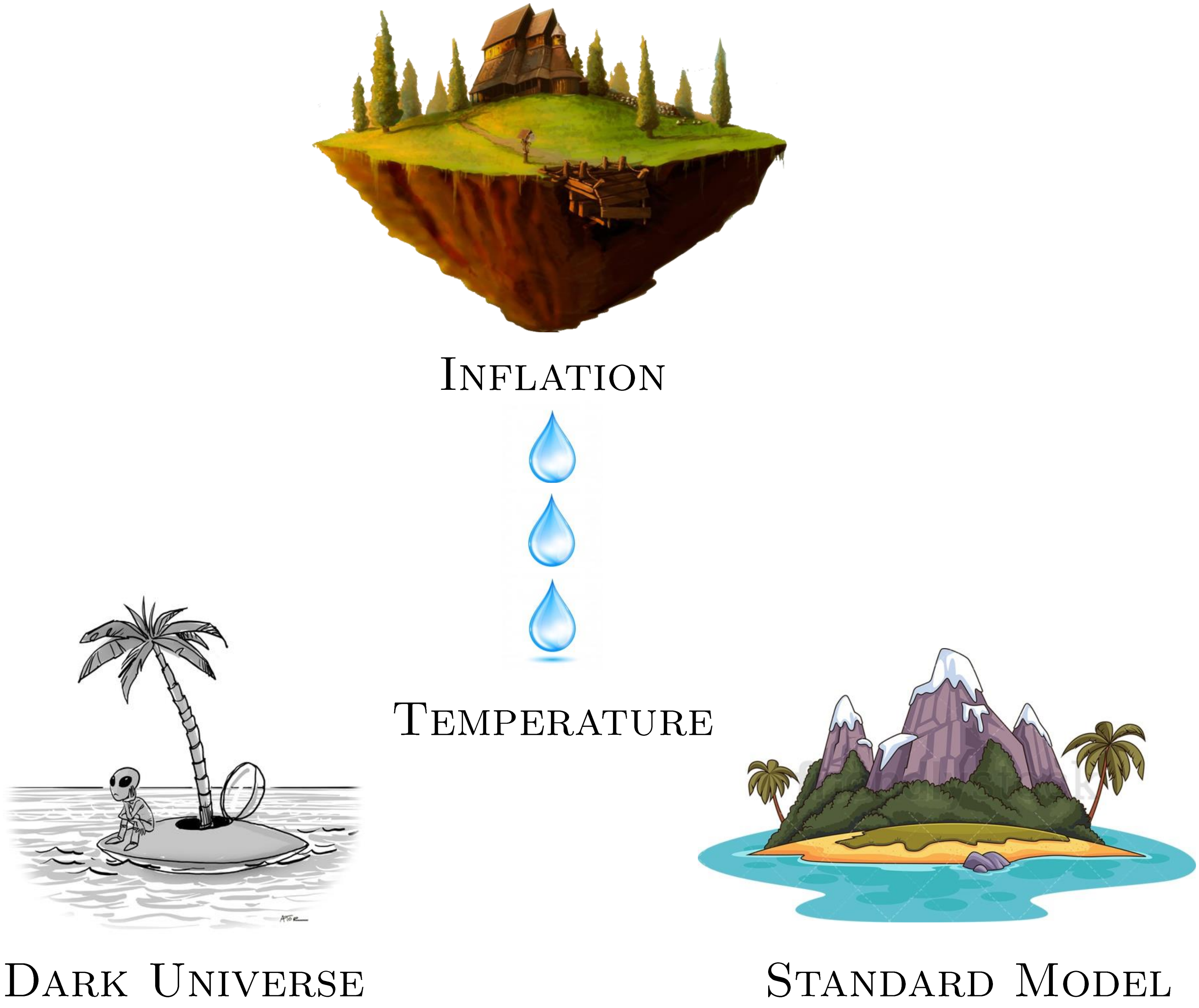
- ✓ Very low density
- ✓ **Very** feebly interacting
- ✓ Stability challenging to achieve

Outline

1. Heavy Dark Matter and Cosmology
   [**LH & F. Huang.** Phys.Rev. D100 (2019) no.4, 043507] and work in progress

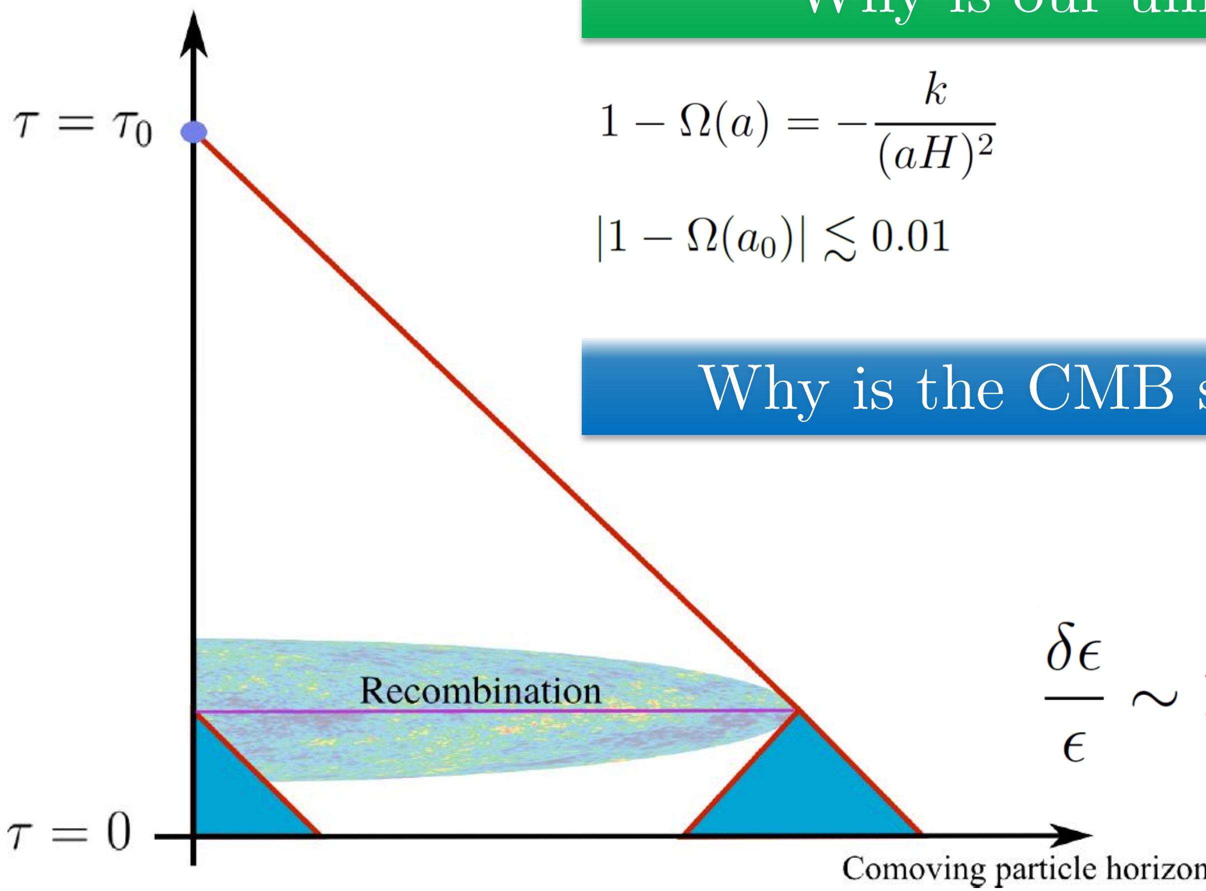
2. Metastable Heavy Dark Matter
   E. Dudas, LH, K. Olive, M. Pierre, & Y. Mambrini. Phys.Rev.D 101 (2020) 11, 115029

3. Heavy Dark Matter and UHECR searches
   [**LH, Y. Mambrini & M. Pierre.** Phys. Rev. D 99, no. 9, 095014 (2019)
   LH, D. Kim, J. C. Park & S. Shin. Phys.Rev. D100 (2019) no.5, 055004] and work in progress



Inflation
Temperature
Dark Universe
Standard Model

Why Cosmic Inflation?



Why is our universe so flat?

$$1 - \Omega(a) = -\frac{k}{(aH)^2}$$

$$|1 - \Omega(a_0)| \lesssim 0.01$$

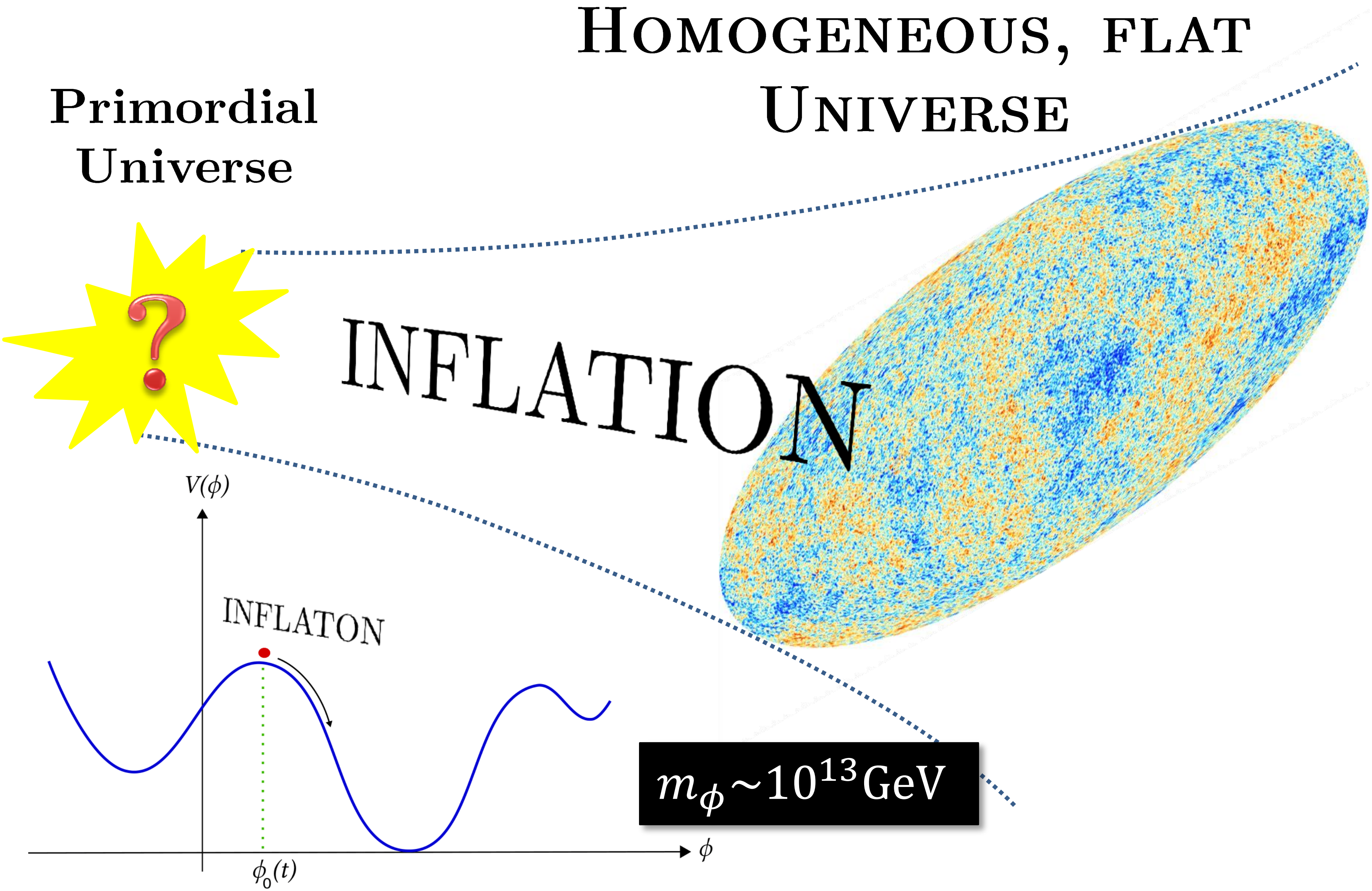
$$|1 - \Omega(a_{BBN})| \lesssim \mathcal{O}\left(10^{-16}\right)$$
$$|1 - \Omega(a_{GUT})| \lesssim \mathcal{O}\left(10^{-55}\right)$$
$$|1 - \Omega(a_P)| \lesssim \mathcal{O}\left(10^{-61}\right)$$

Why is the CMB so homogeneous?

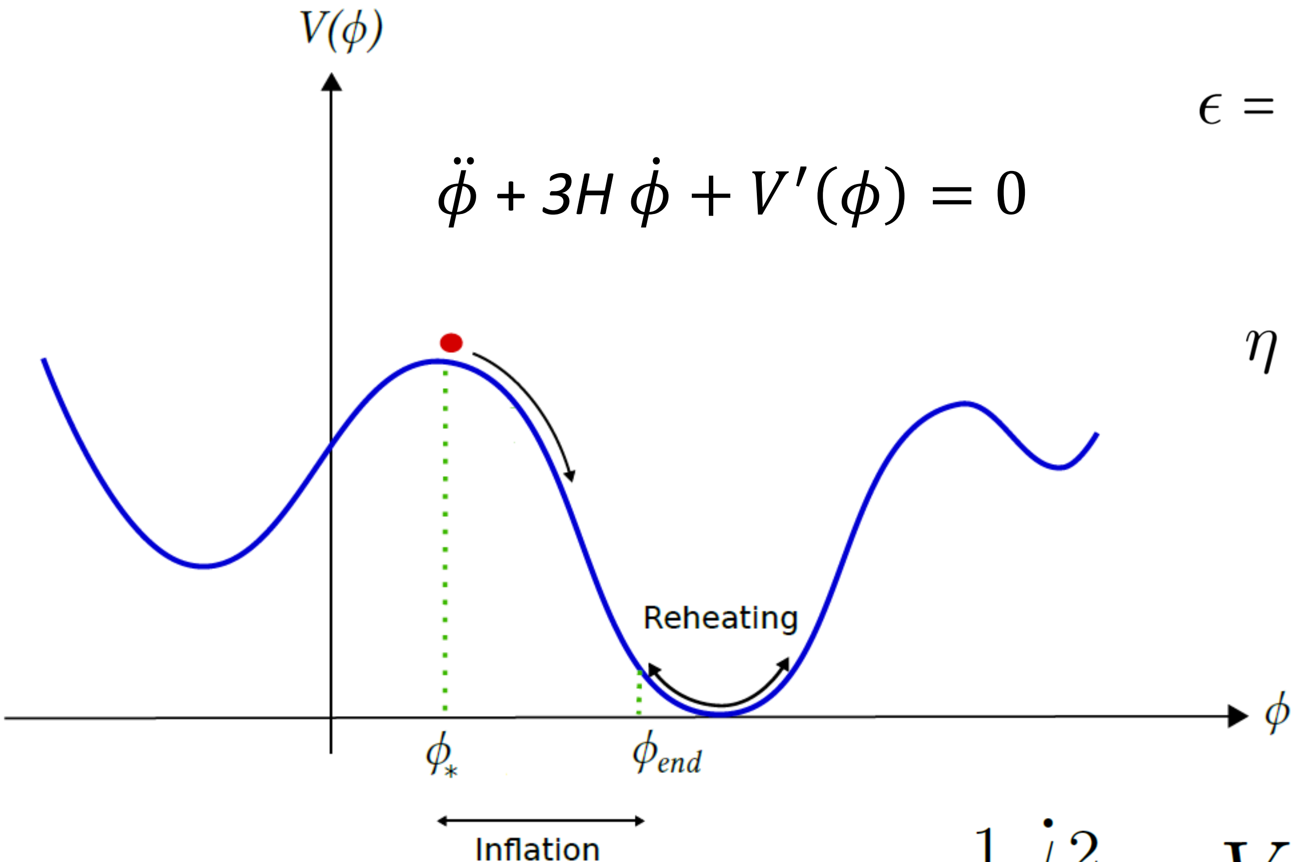
$$\frac{\delta\epsilon}{\epsilon} \sim 10^{-4}$$

What about magnetic monopoles?

The Cosmic Inflation Paradigm



Single Field Inflation



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

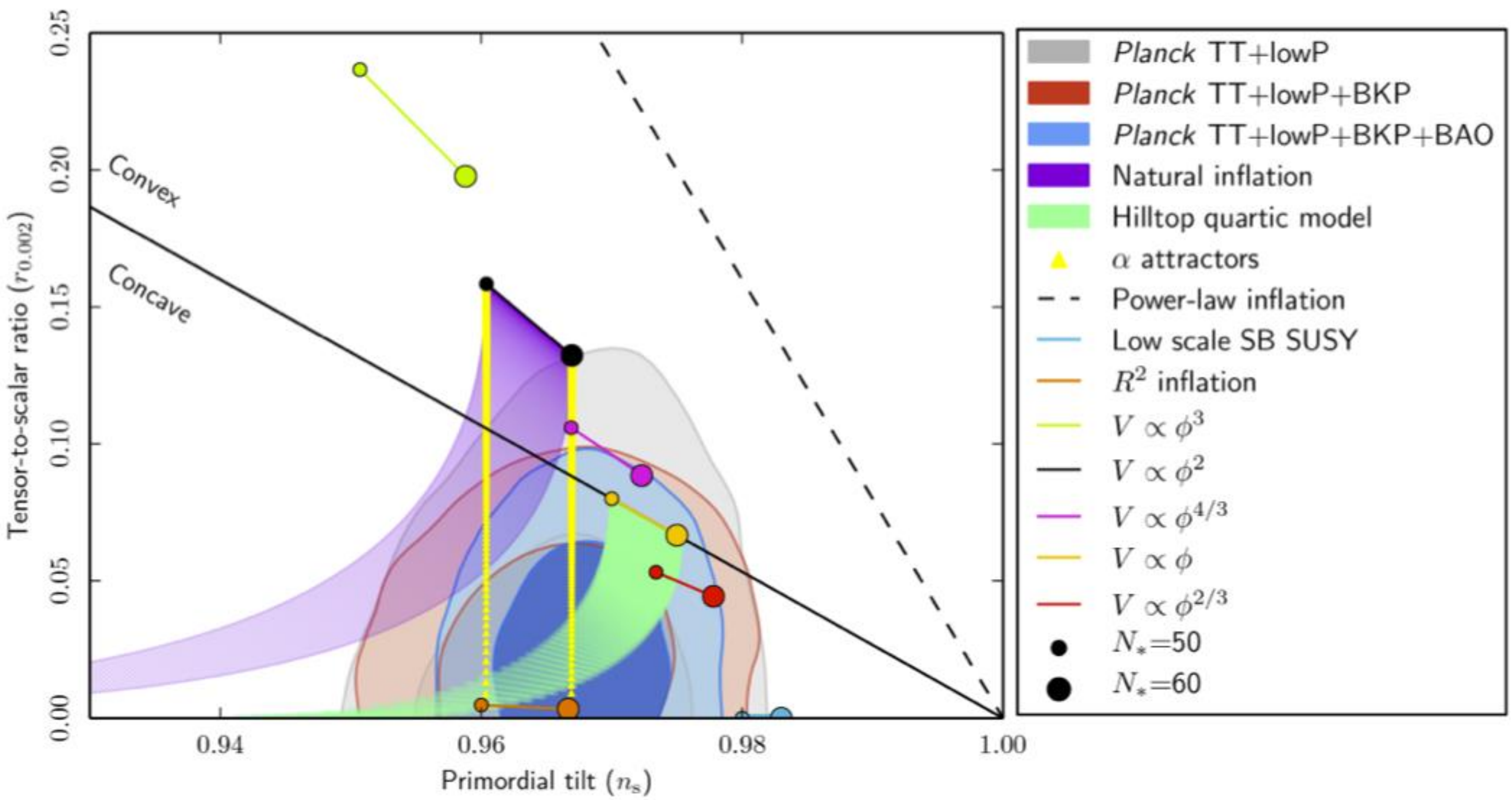
$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

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

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

Observational constraints?

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



From Inflation to Low energy physics

Inflation

[Buchmüller, Dudas, LH, Wieck, ‘14]
[Buchmüller, Dudas, LH, Westphal, Wieck, Winkler ‘15]
[Argurio, Dries, LH, Mariotti ‘16], [Linde ‘16], [Linde, Kallosh ‘04]
[J. Ellis, D. V. Nanopoulos, K. A. Olive, S. Verner ’19]...

SUSY breaking ?

String Theory ?
[So many ...]

Baryonic Asymetry ?
[D. Borah, B. Dev, A. Kumar, ‘19]

Grand Unification?
[T. Gonzalo, LH, A. Moursy, ‘17]
[J. Ellis, T. E. Gonzalo, J. Harz, W.-C. Huang, ‘15]
[J. Ellis, M. A.G. Garcia, N. Nagata, D. V. Nanopoulos, K. A. Olive]

Dark matter production
[D. Hooper, G. Krnjaic, A. J. Long, S. Mcdermott, ‘18], [LH, ‘17], ...

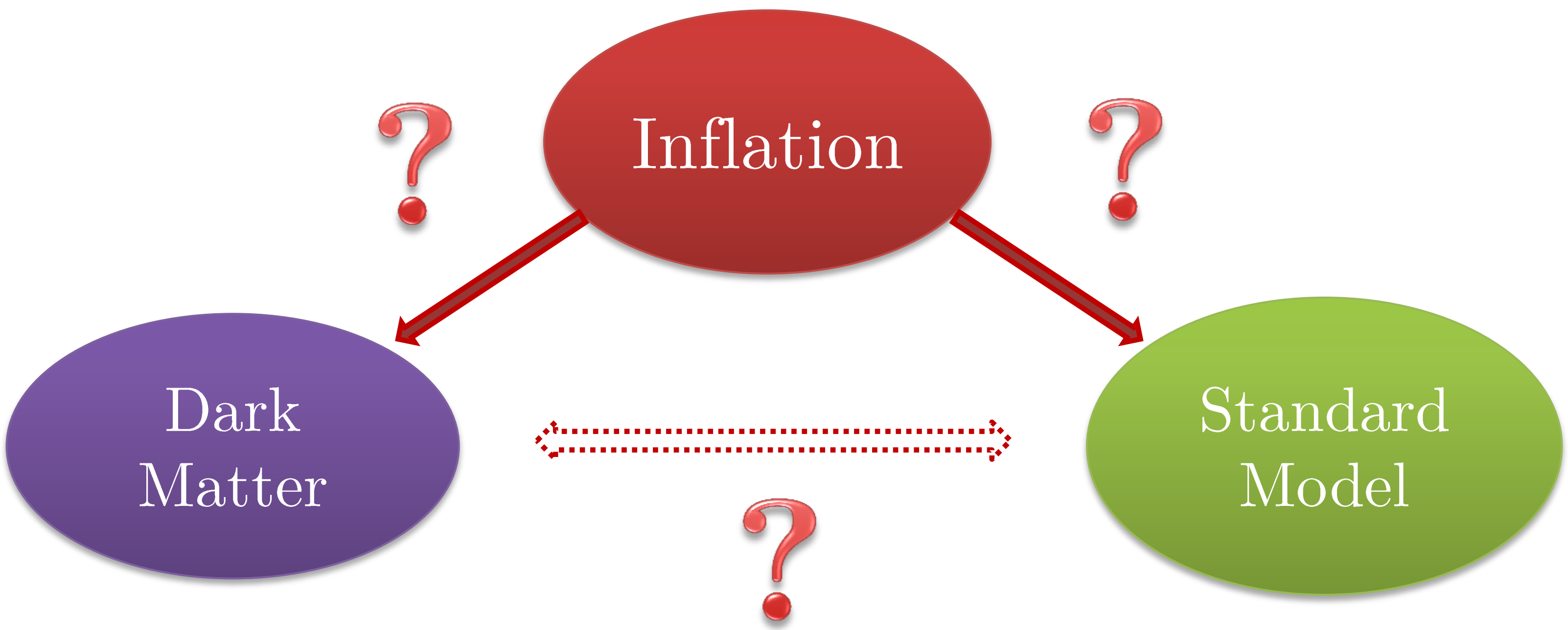
Strong CP problem
[G. Ballesteros, J. Redondo, A. Ringwald, C. Tamarit, ‘17]

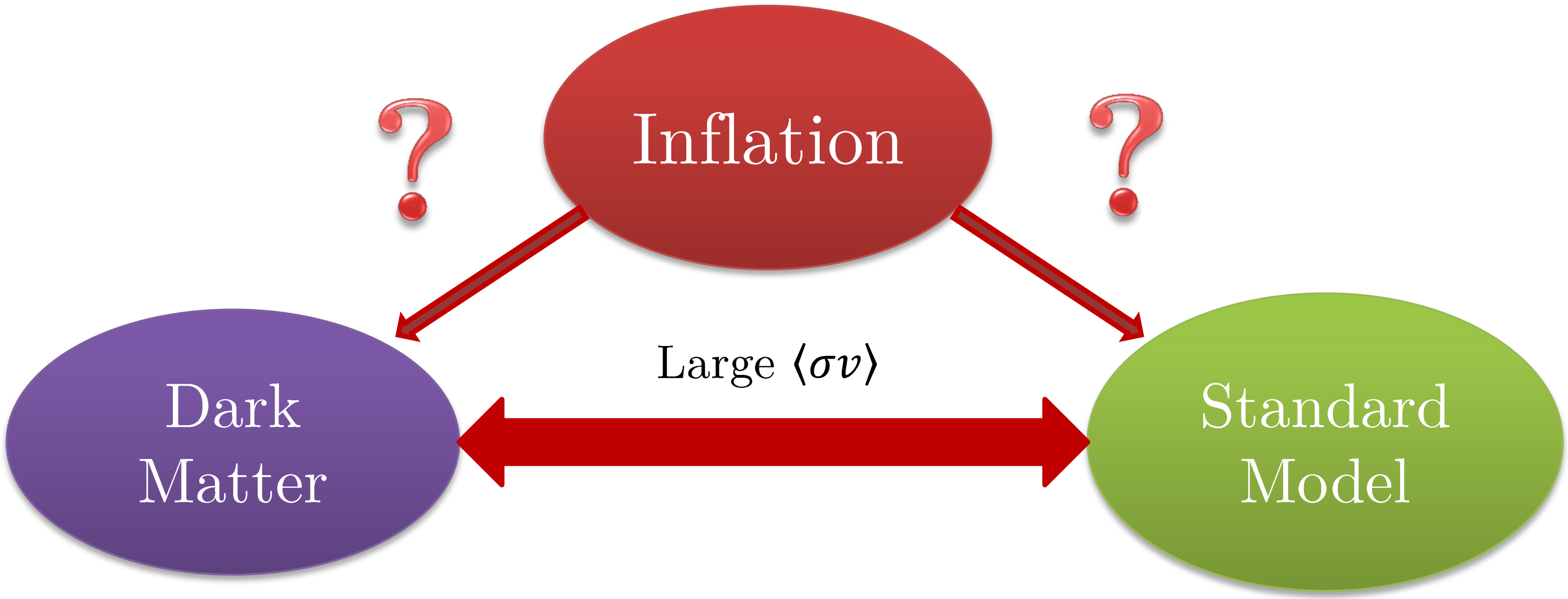
Standard Model

[Non exhaustive list ...]

The importance of the inflaton couplings

Inflaton Decay : Reheating





WIMP miracle:

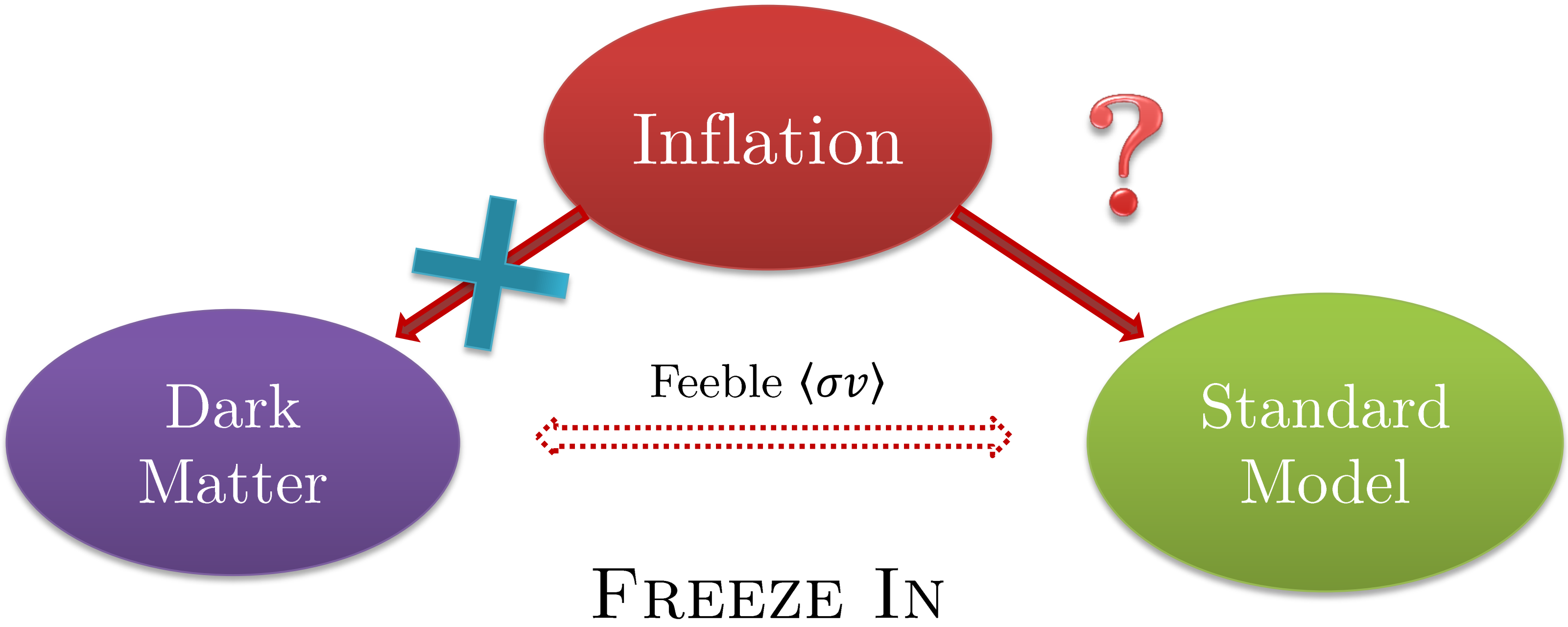
$\langle \sigma v \rangle \sim \langle \sigma v \rangle_{EW}$ and $m_{DM} \sim \mathcal{O}(100)$ GeV

$$\Downarrow$$

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

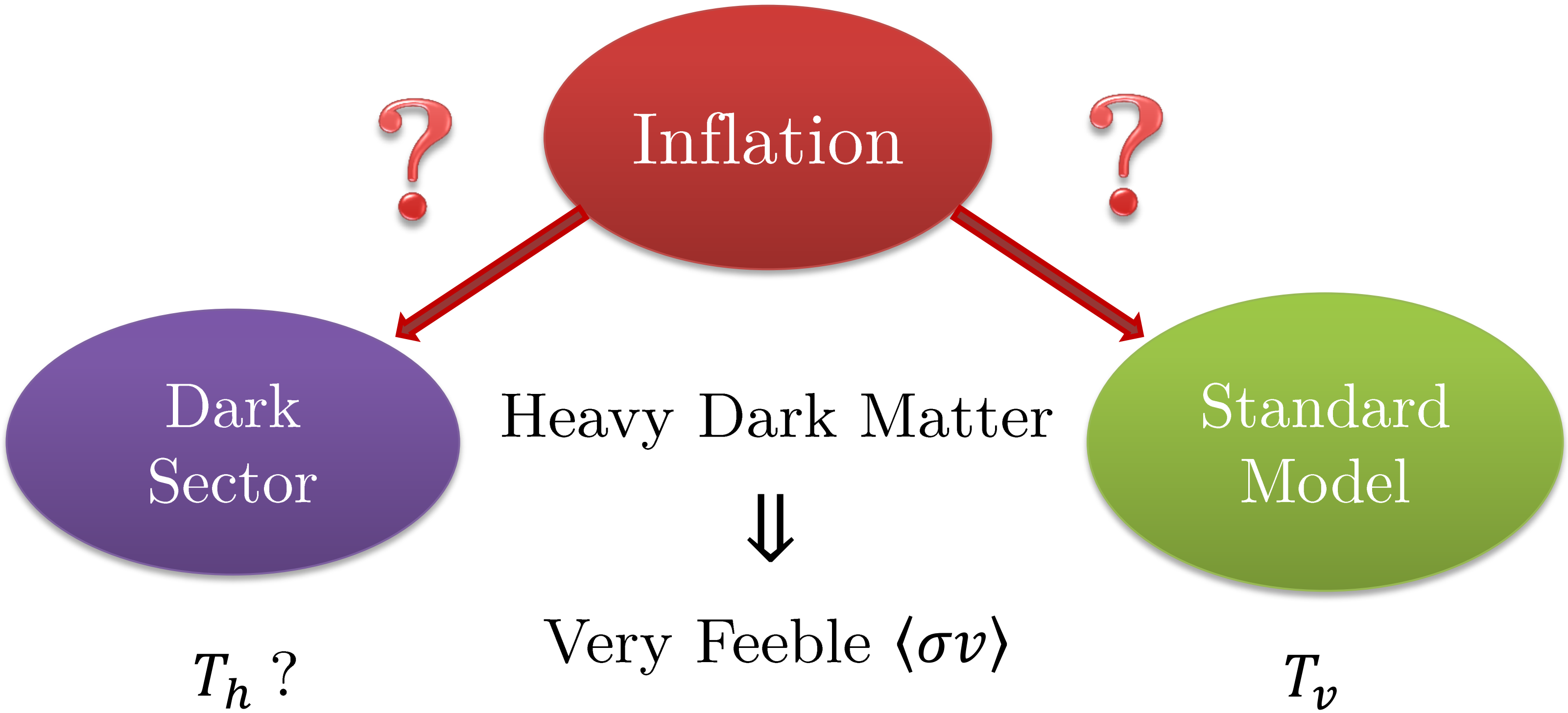
Unitarity bound :

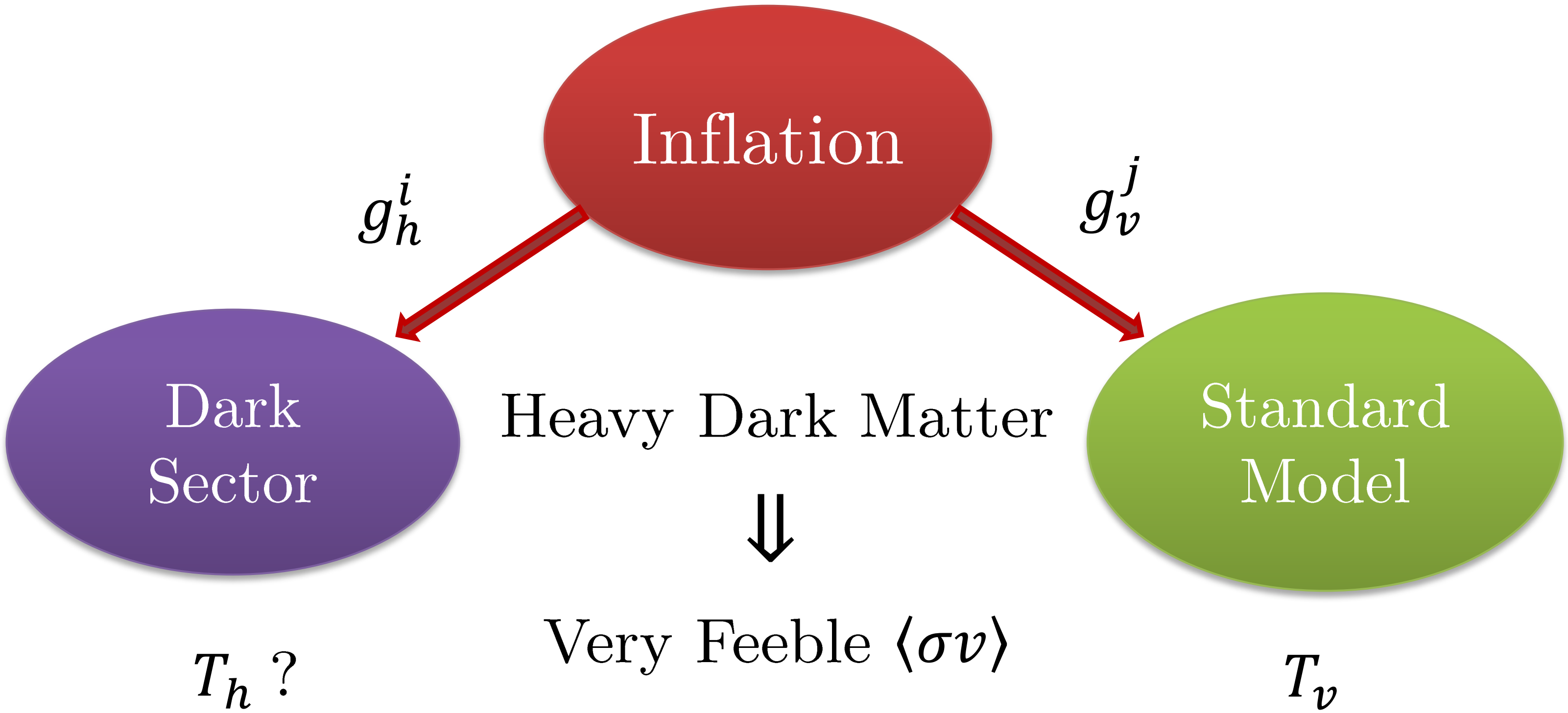
$m_{DM} \lesssim \mathcal{O}(100)$ TeV



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

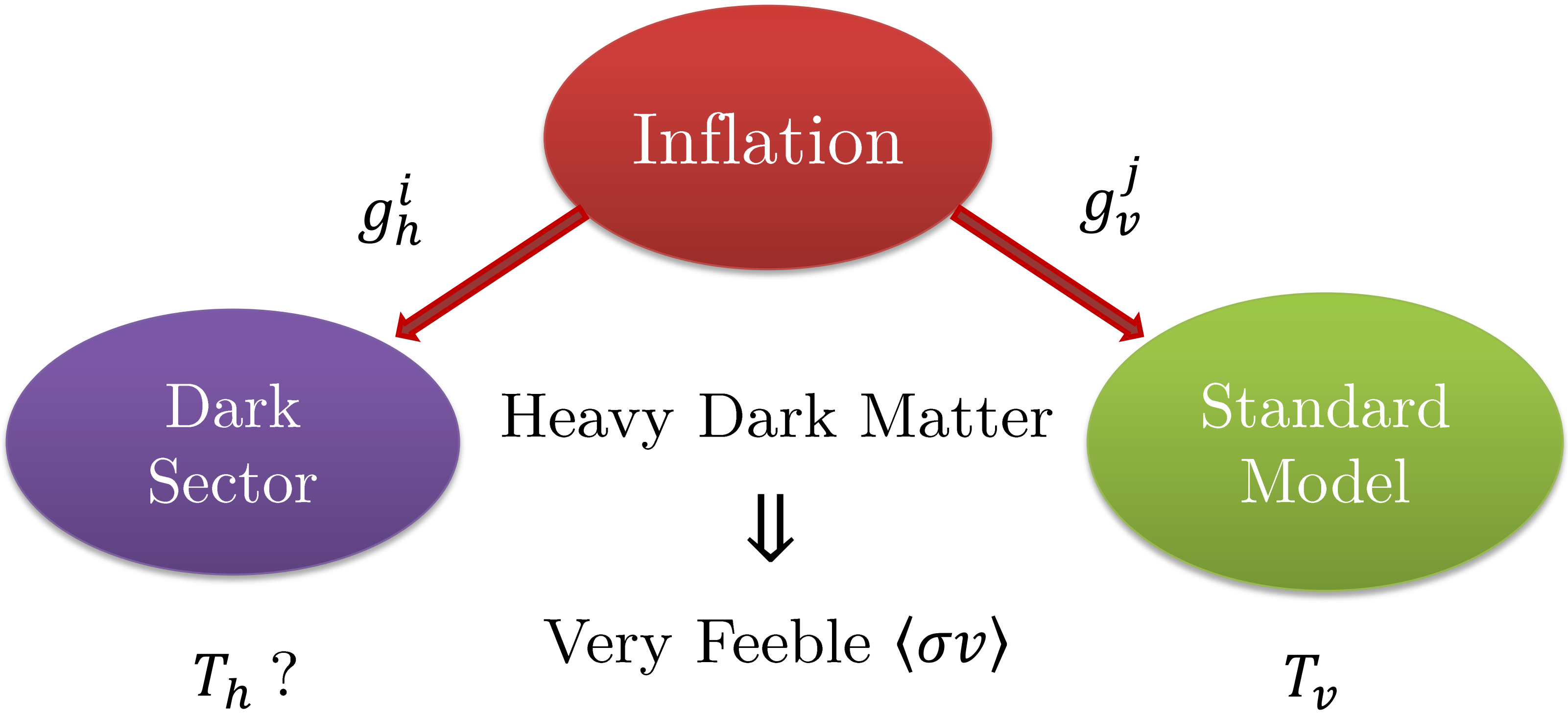
Such coupling HAS to be there at the loop level and could play an important role...
[Kaneta, Mambrini, Olive '19]


Inflation
Dark Sector
Heavy Dark Matter
⇓
Very Feeble $\langle \sigma v \rangle$
Standard Model
T_h ?
T_v



$g_h^i, g_v^j \rightarrow \rho_h \,/\, \rho_v$ after inflation

Sets initial conditions for a given HDM scenario...



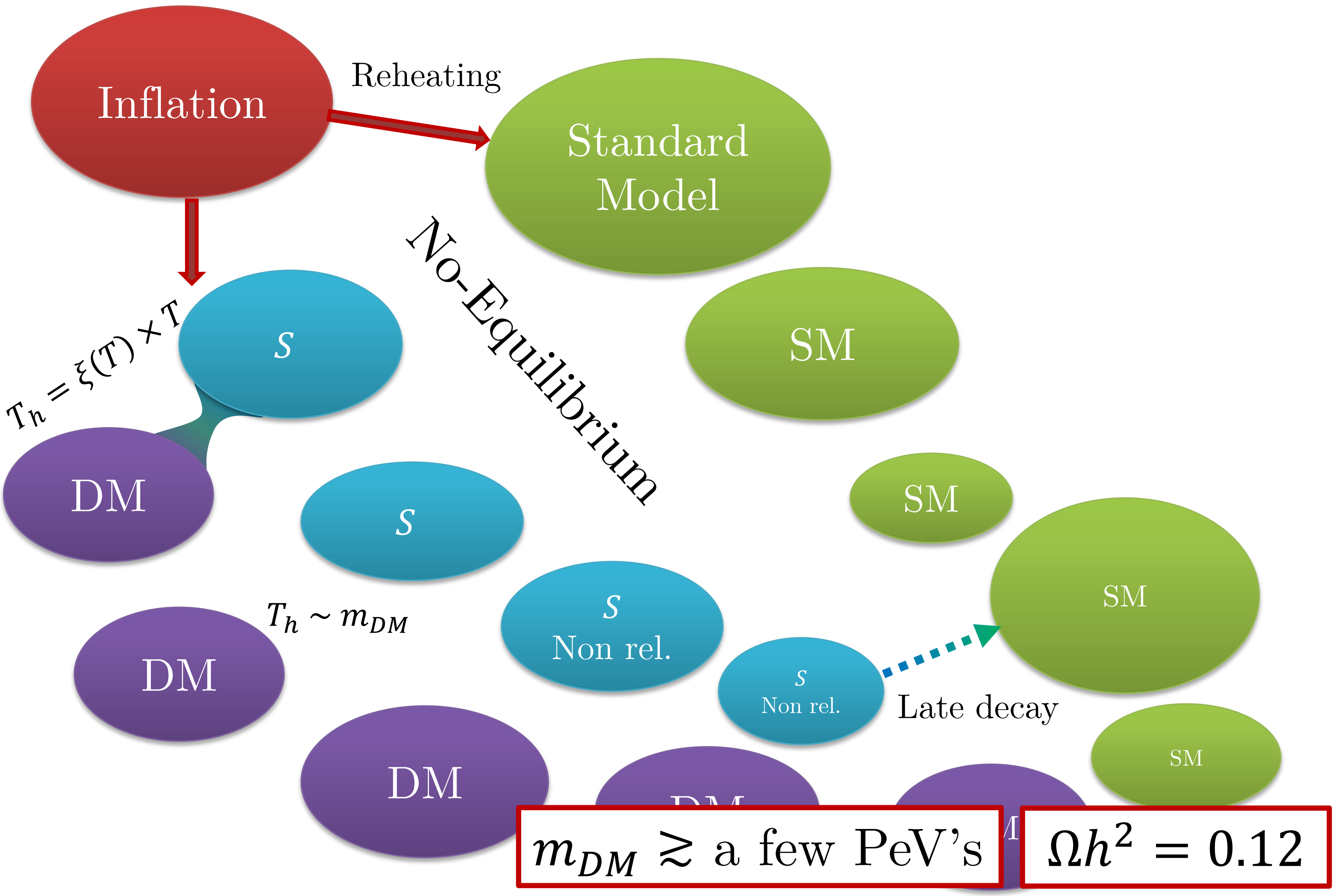
$g_h^i, g_v^j \rightarrow \rho_h \,/\, \rho_v$ after inflation

Sets initial conditions for a given HDM sce

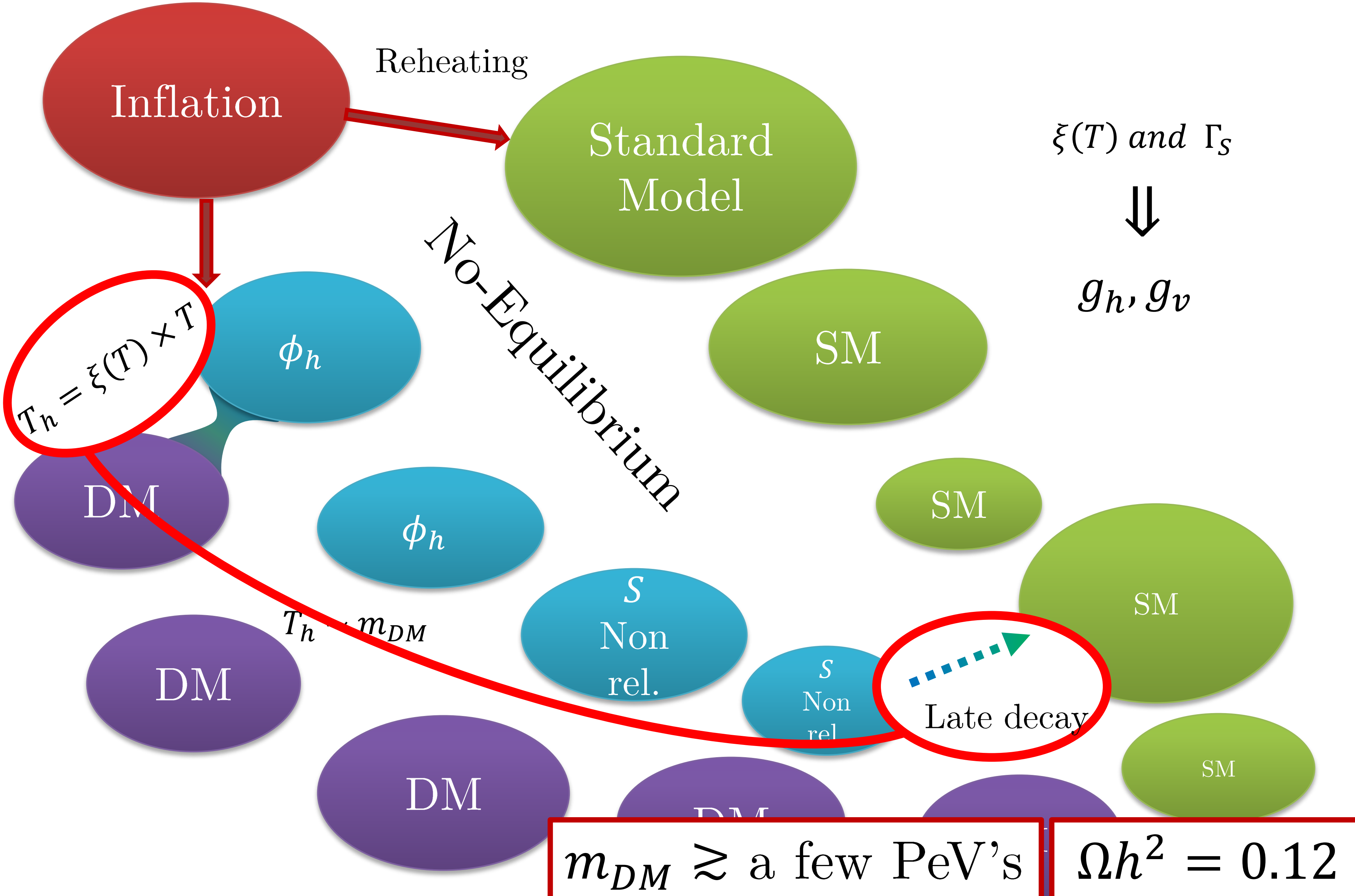
Inflaton Portal to DM

$g_h^i, g_v^j \rightarrow$ Interactions DS $\leftrightarrow$ SM

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



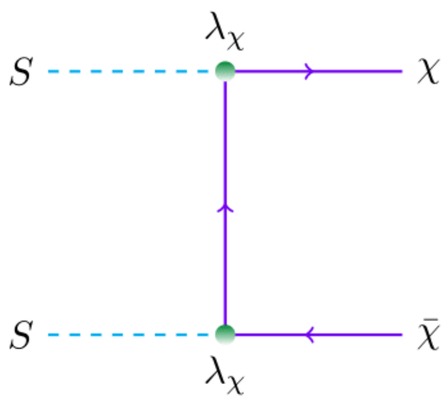
Decoupled Hidden sector [Hooper et al., '16]

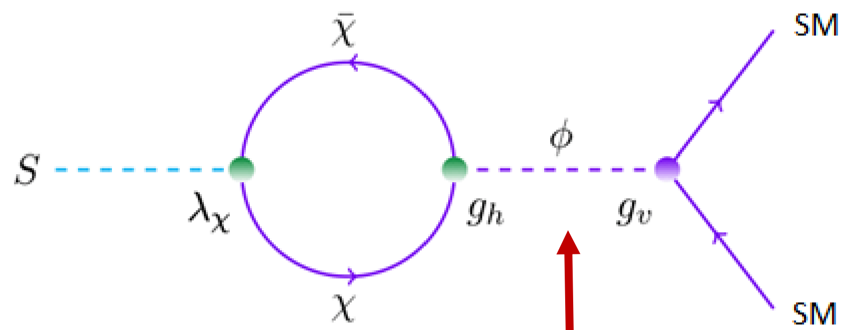


$m_{DM} \gtrsim$ a few PeV's

$\Omega h^2 = 0.12$

The Model





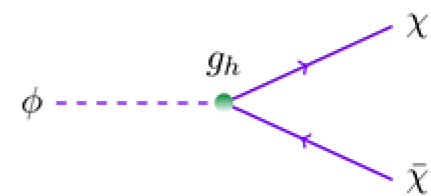
$m_\phi = 10^{13} GeV$

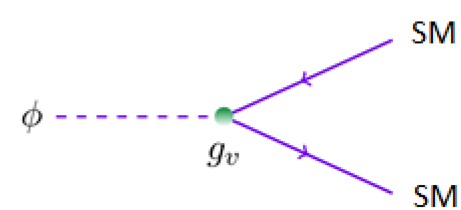
Thermal decoupling of dark matter in the dark sector

Natural suppression of the hidden scalar decay width...

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

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





Inflaton mass vs. inflation parameters

Inflaton mass: curvature of the potential

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

Inflaton mass vs. inflation parameters

Alpha-attractor : T- model

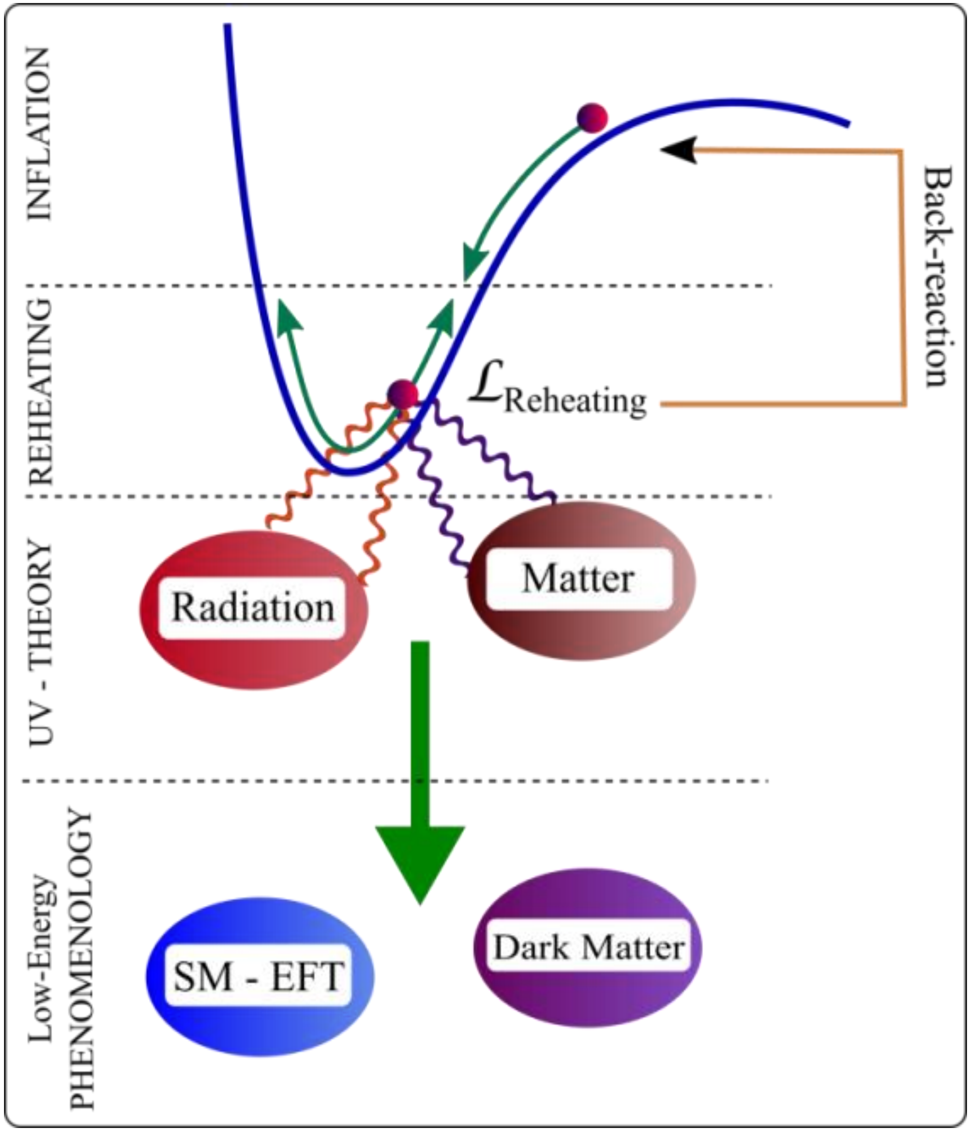
$$V(\phi) = V_0 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_p}}\right)^2$$

$$m_\phi^2 = \frac{4V_0}{3\alpha M_p^2}$$

$$V_{\rm inf}^{\alpha\gg 1}(\phi) \approx \frac{m_\phi^2}{2}\phi^2 \qquad \text{(Chaotic)}$$

$$V_{\rm inf}^{\alpha=1}(\phi) \approx V_0 \left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_p}}\right)^2 \qquad \text{(Starobinsky)}$$

What's on the inflation side?



Loop corrections backreact on the inflationary trajectory

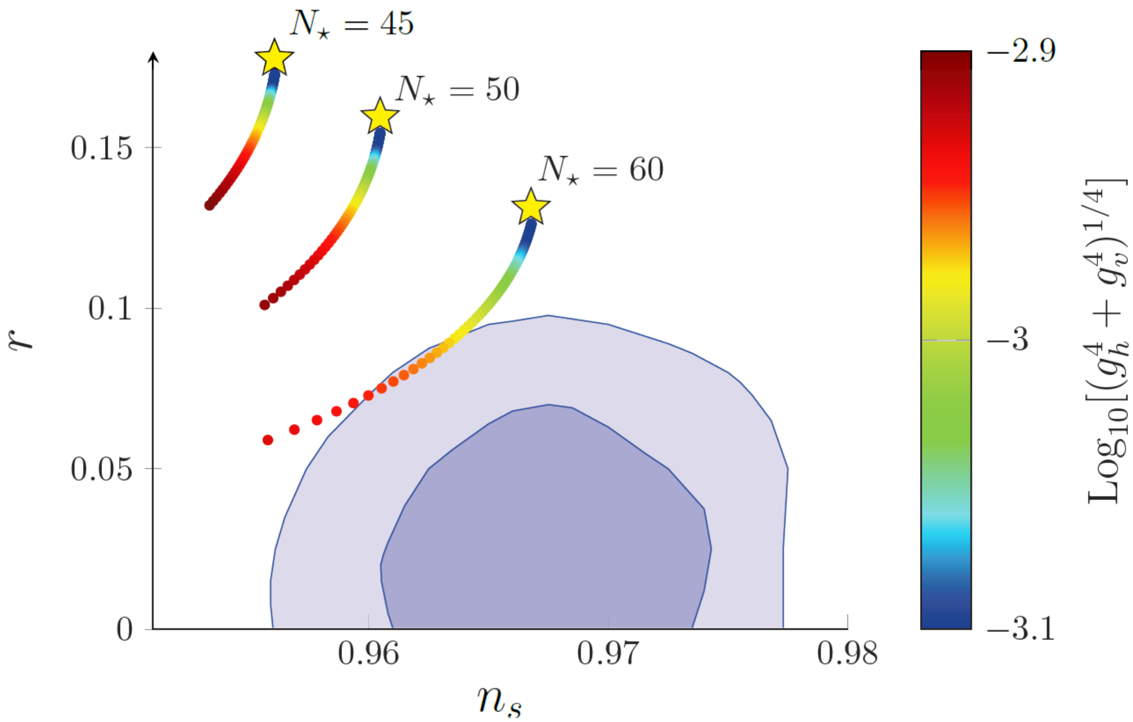
↓

Destabilizes the inflaton at large field values

↓

Modifies the predictions for inflation observables (r, n_s)

What's on the inflation side?



Loop corrections backreact on the inflationary trajectory

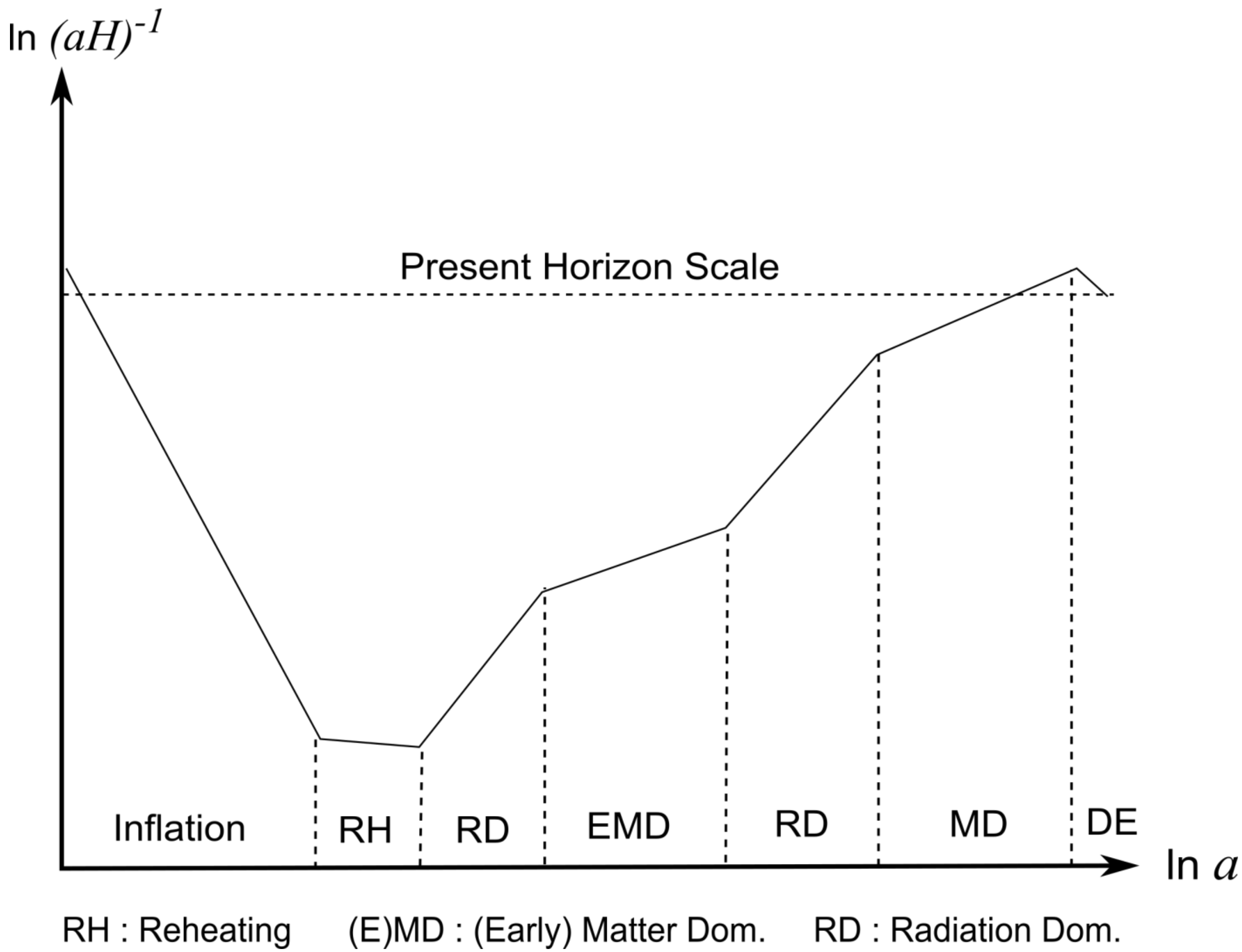
↓

Destabilizes the inflaton at large field values

↓

Modifies the predictions for inflation observables $(r,\ n_s)$

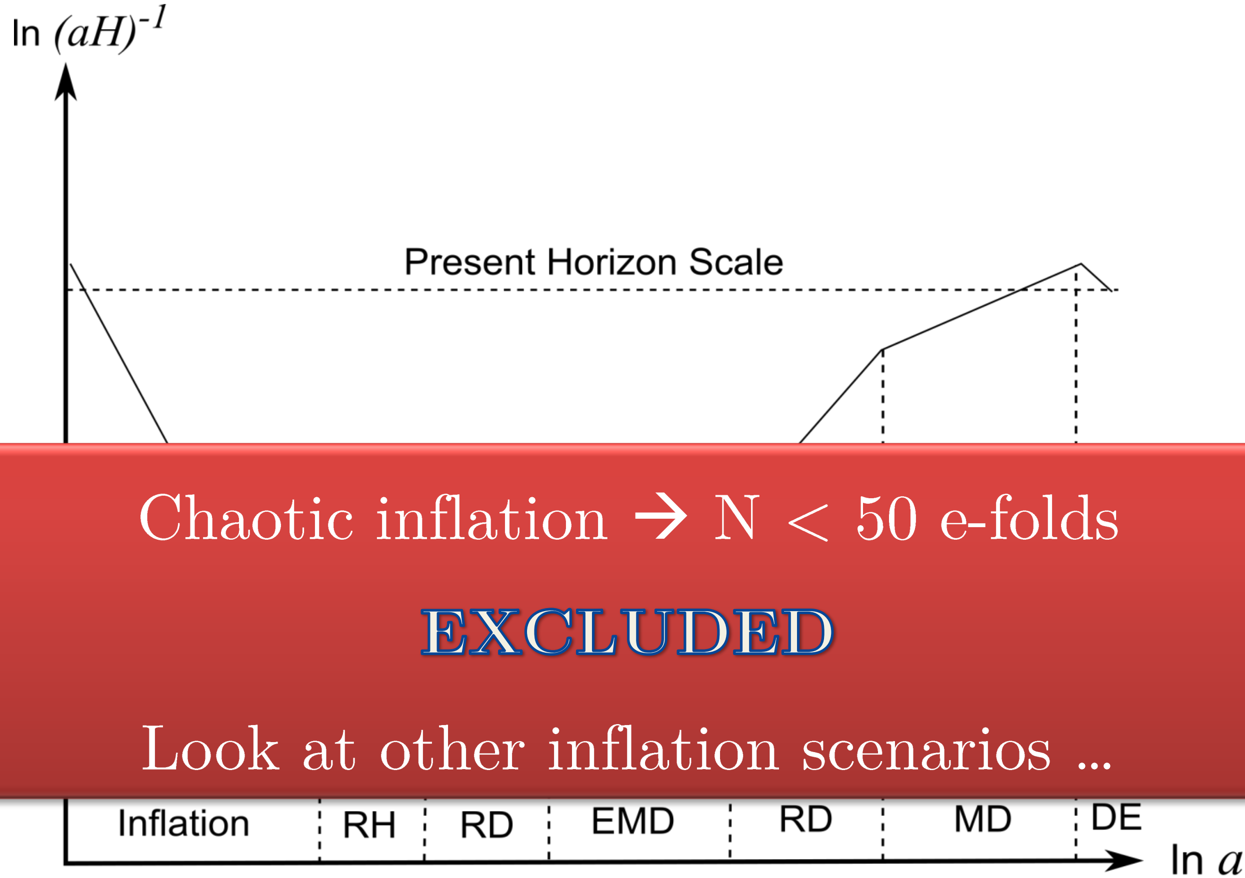
What about the primordial universe?



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

[Liddle, Leach '03]

What about the primordial universe?



Chaotic inflation → N < 50 e-folds

EXCLUDED

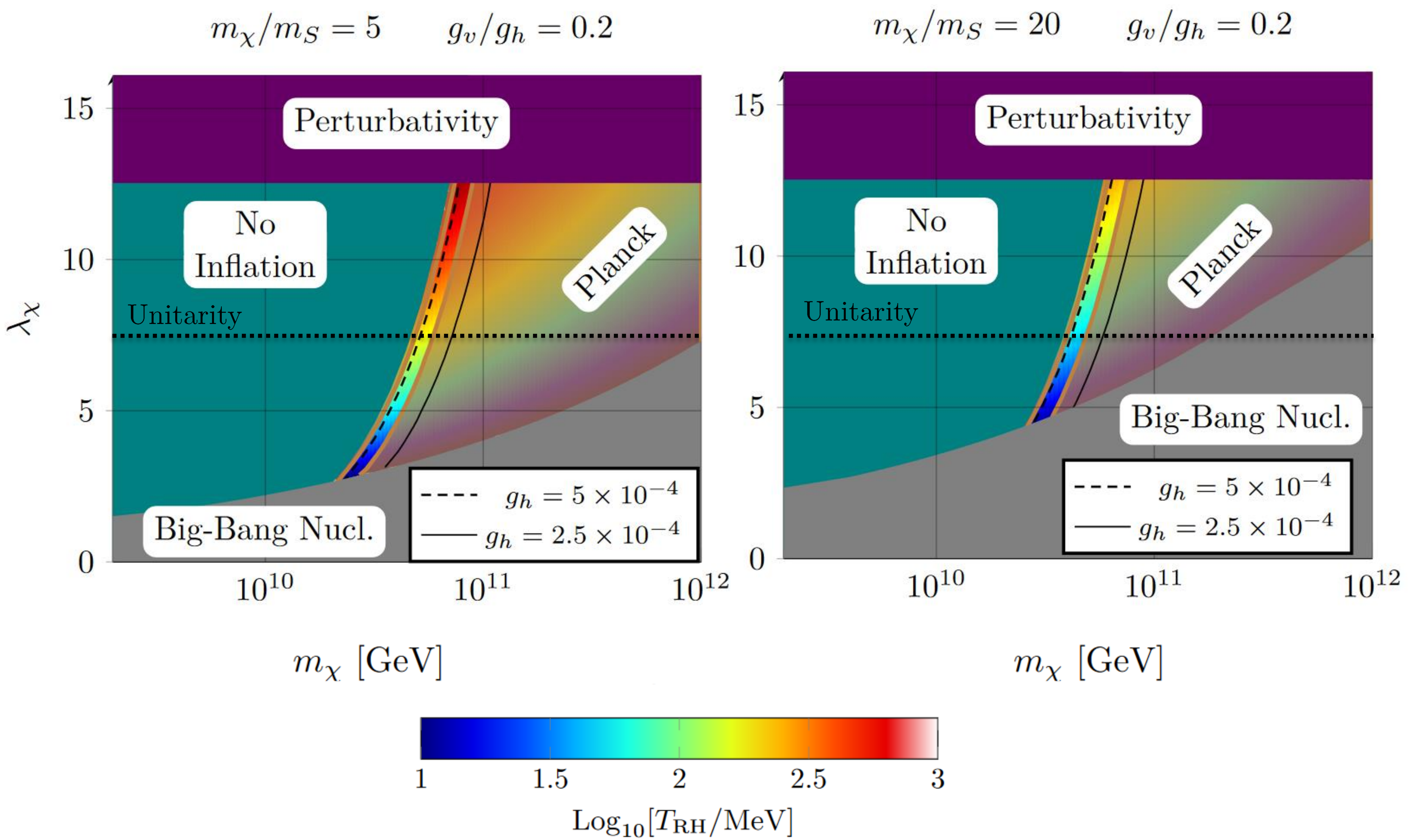
Look at other inflation scenarios ...

RH : Reheating (E)MD : (Early) Matter Dom. RD : Radiation Dom.

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

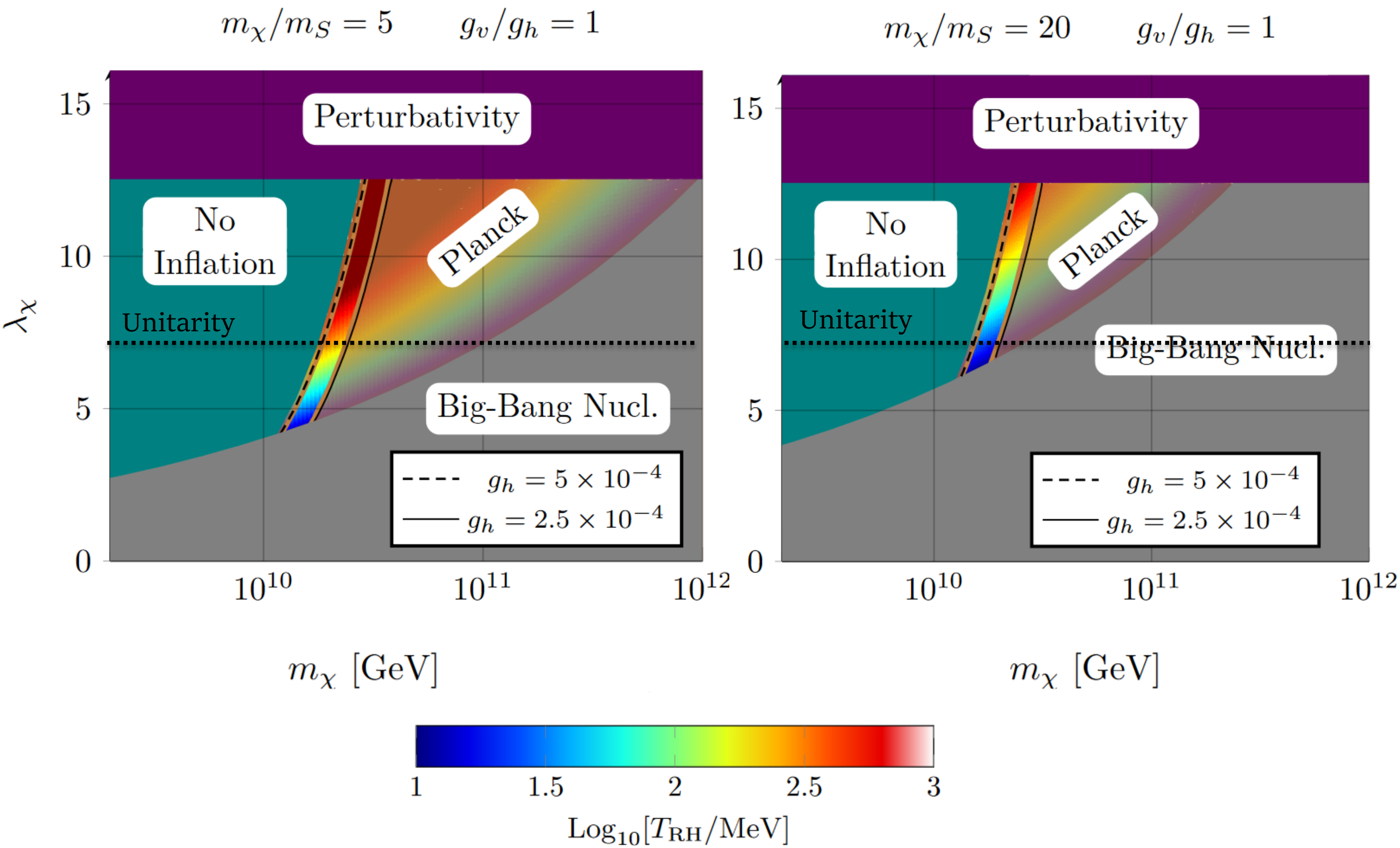
[Liddle, Leach '03]

Results



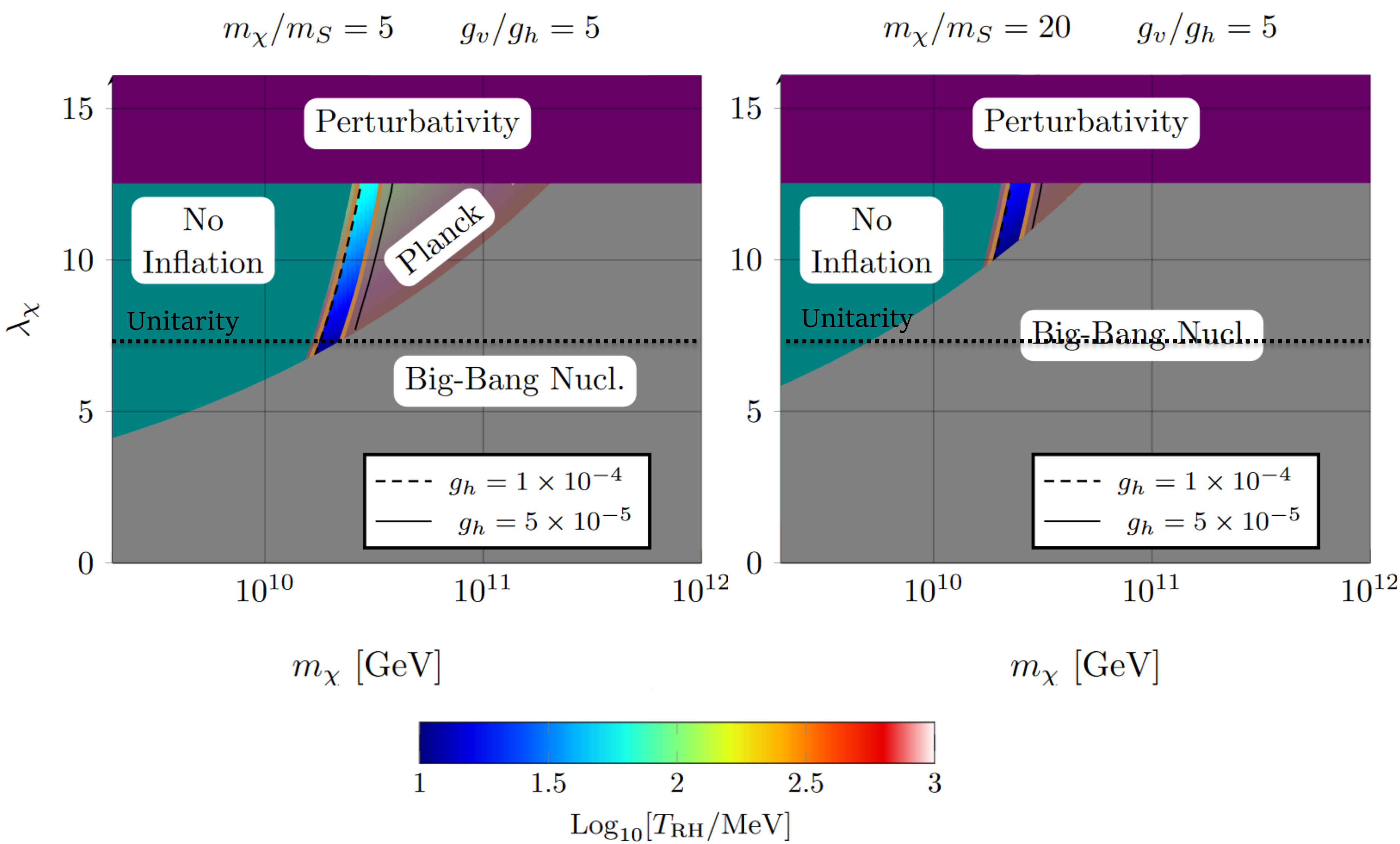
$m_\chi/m_S = 5$ $g_v/g_h = 0.2$
$m_\chi/m_S = 20$ $g_v/g_h = 0.2$
Perturbativity
No Inflation
Planck
Unitarity
Big-Bang Nucl.
$g_h = 5 \times 10^{-4}$
$g_h = 2.5 \times 10^{-4}$
λ_χ
m_χ [GeV]
$\mathrm{Log}_{10}[T_{\mathrm{RH}}/\mathrm{MeV}]$

Results



$m_\chi/m_S = 5$ $g_v/g_h = 1$
$m_\chi/m_S = 20$ $g_v/g_h = 1$
Perturbativity
No Inflation
Planck
Unitarity
Big-Bang Nucl.
$g_h = 5 \times 10^{-4}$
$g_h = 2.5 \times 10^{-4}$
λ_χ
m_χ [GeV]
15
10
5
0
10^{10}
10^{11}
10^{12}
1
1.5
2
2.5
3
$\mathrm{Log}_{10}[T_{\mathrm{RH}}/\mathrm{MeV}]$

Results



$m_\chi/m_S = 5$ $g_v/g_h = 5$
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10^{10}
10^{11}
10^{12}
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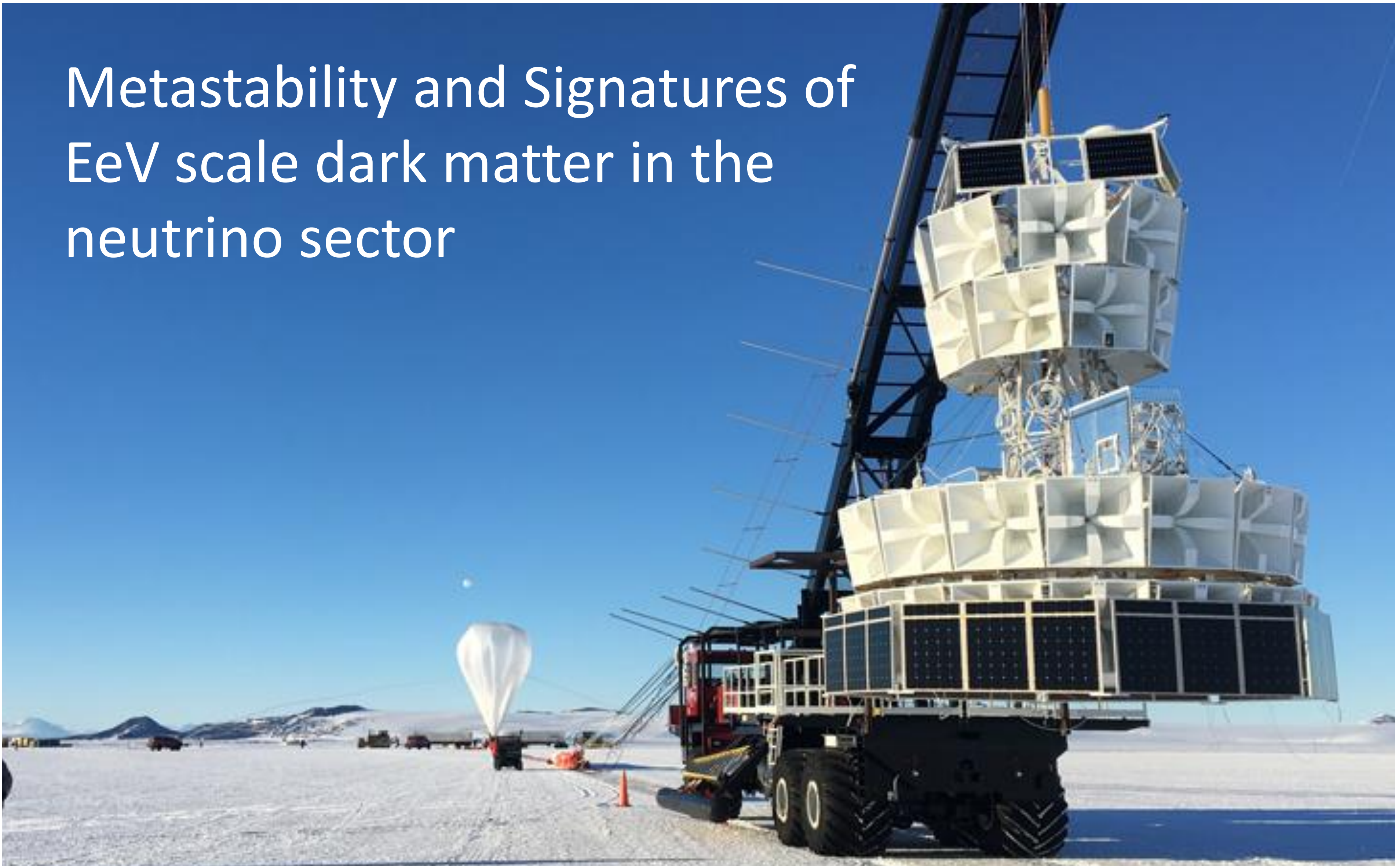
1.5
2
2.5
3
$\mathrm{Log}_{10}[T_{\mathrm{RH}}/\mathrm{MeV}]$

Part II & III

Metastability and Signatures of EeV scale dark matter in the neutrino sector



EeV Dark Matter

Models of (very) heavy dark matter are hard to probe observationally if they don't decay...

$$\Gamma = \frac{g^2}{16\,\pi}\, m \longrightarrow g \lesssim 10^{-25} \left(\frac{\text{EeV}}{m}\right)^{\frac{1}{2}} \left(\frac{\tau}{10^{17}\text{s}}\right)^{\frac{1}{2}}$$

$\Gamma \simeq \frac{m^3}{M_P^2}$ with a mass of 1EeV is too short-lived...

EeV Dark Matter

[E. Dudas, L. Heurtier, Y. Mambrini, K. A. Olive and M. Pierre, Phys. Rev. D 101 (2020) no.11, 115029]

$$\mathcal{L} \supset \frac{\alpha_s}{2M_P}(\partial_\mu a)\bar{\nu}_s\gamma^\mu\gamma^5\nu_s$$

$$\mathcal{L} \supset \frac{i}{2}[\bar{\nu}_s\gamma^\mu \mathcal{Z}_s\partial_\mu\nu_s - (\partial_\mu\bar{\nu}_s)\gamma^\mu \mathcal{Z}_s^*\nu_s]$$

with $\mathcal{Z}_s = 1+\frac{\beta_s}{M_P}t+i\frac{\alpha_s}{M_P}\gamma_5 a$

[D. Chowdhury, E. Dudas, M. Dutra and Y. Mambrini]

Majoron models

$$\mathcal{L}_\phi = \phi\nu_s\nu_s + \text{h.c.},$$

$$\phi = \chi e^{\frac{ia}{M_P}} \qquad \nu_s \to e^{-\frac{ia}{2M_P}}\nu_s$$

[I. Z. Rothstein, K. S. Babu and D. Seckel]

EeV Dark Matter

[E. Dudas, L. Heurtier, Y. Mambrini, K. A. Olive and M. Pierre, Phys. Rev. D 101 (2020) no.11, 115029]

$$\mathcal{L} \supset \frac{\alpha_s}{2M_P}(\partial_\mu a)\bar{\nu}_s\gamma^\mu\gamma^5\nu_s$$

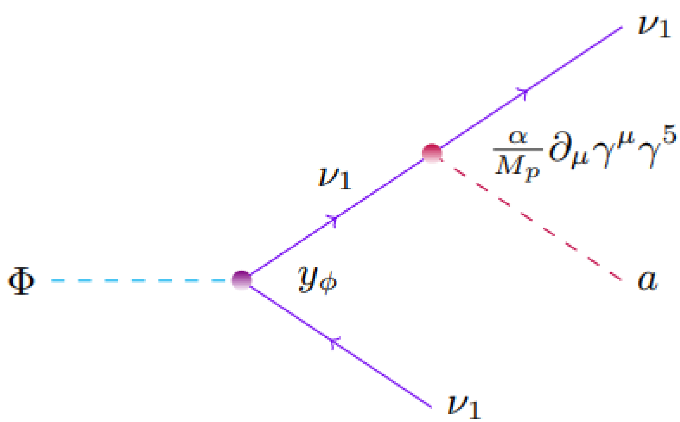
$$\tau \propto \left(\frac{M_P}{m_\nu}\right)^2 \frac{1}{m}$$

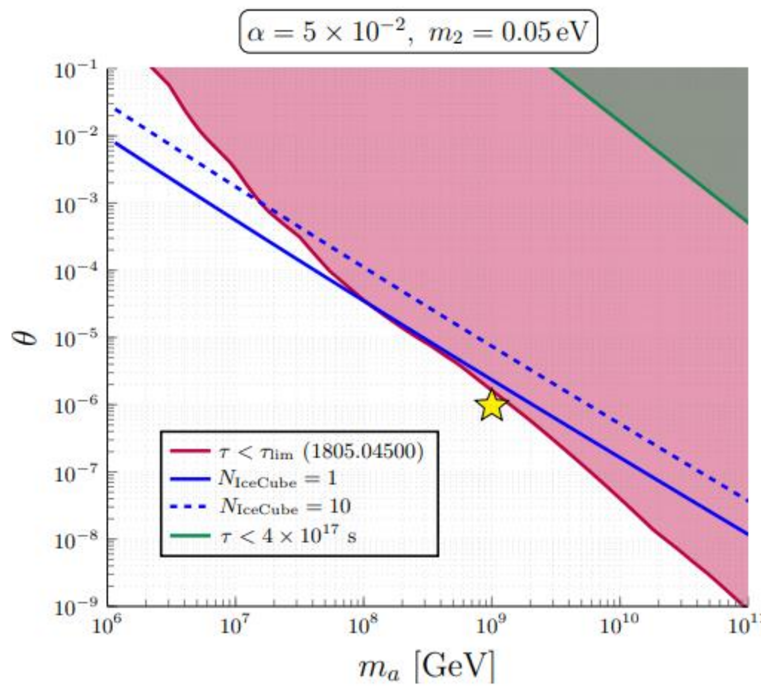
$$\simeq 10^{33}\ \mathrm{s} \left(\frac{0.05\ \mathrm{eV}}{m_\nu}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m}\right)$$

EeV Dark Matter

[E. Dudas, L. Heurtier, Y. Mambrini, K. A. Olive and M. Pierre, Phys. Rev. D 101 (2020) no.11, 115029]

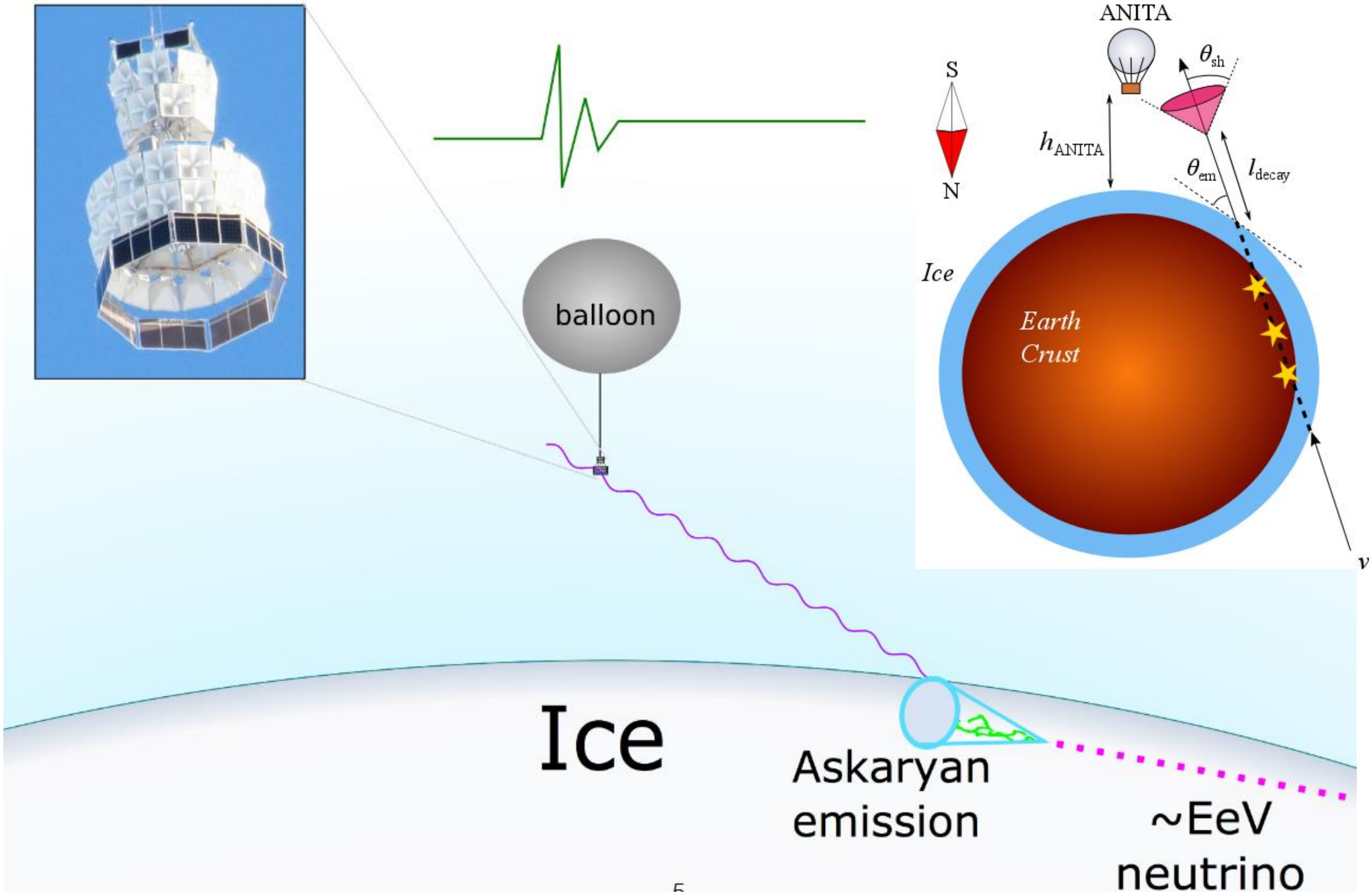
$$\mathcal{L} \supset \frac{\alpha_s}{2M_P}(\partial_\mu a)\bar{\nu}_s\gamma^\mu\gamma^5\nu_s$$





$$\tau_a \gtrsim 5.5\times10^{28}\mathrm{s}\left(\frac{10^{-2}}{\alpha}\right)^2\left(\frac{10^{-5}}{\theta}\right)^2\left(\frac{10^9\ \mathrm{GeV}}{m_a}\right)^3$$

ANtarctic **I**mpulsive **T**ransient **A**ntenna

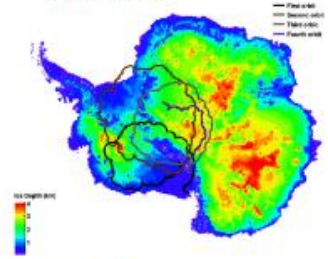


ANITA

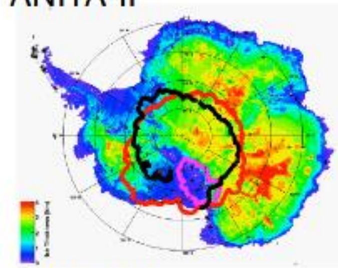
- **ANtarctic Impulsive Transient Antenna**
  - NASA ultralong duration balloon experiment
- Seeking radio signals from earth-skimming UHE neutrinos
- To this date, 4 flights

ANITA-Lite	ANITA-I	ANITA-II	**ANITA-III**	ANITA-IV
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger
Analyzed	Analyzed	Analyzed	**Recently analyzed**	Analysis Ongoing

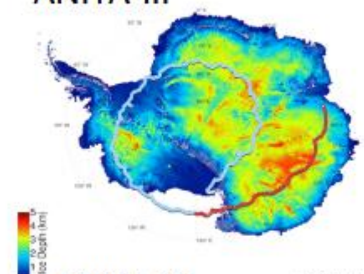
ANITA-I



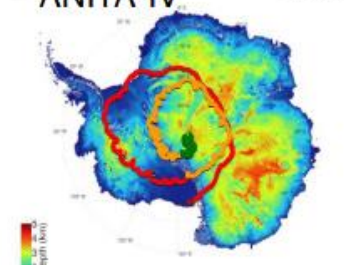
ANITA-II



ANITA-III



ANITA-IV



Slide from Carsten Rott ©

Events Features

ANITA

	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 $\varepsilon_{\rm cr}$	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
$p_{\rm SM}(\varepsilon_\tau > 0.1\,{\rm EeV})$ for $\varepsilon_\nu = 1$ EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{\rm SM}(z > z_{\rm obs})$ for $\varepsilon_\nu = 1$ EeV, $\varepsilon_\tau > 0.1$ EeV	6.7×10^{-5}	3.8×10^{-6}
$n_\tau(1\text{–}10\,{\rm PeV}) : n_\tau(10\text{–}100\,{\rm PeV}) : n_\tau(>0.1\,{\rm EeV})$	34 : 35 : 1	270 : 120 : 1

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

Possible Interpretations

SM-origin upward-going Extensive Air Showers (EAS) excluded...

Pure SM, downward going

- Downward-going events, interacting with the geomagnetic field [de Vries, Prohira]
- Downward-going events, reflected by sub-layers of the ice sheet [Shoemaker, Kusenko, Munneke, Romero-Wolf, Schroeder, Siegert]

BSM, downward going

- Axionic UHECR reflecting on the ice [Esteban, Lopez-Pavon, Martinez-Soler, Salvado]
- Askaryan emission in the Ice, induced by heavy dark matter [Hooper, Wegsman, Deaconu, Vieregg]

BSM, upward going

- SUSY interpretations [Fox, Sigurdson, Murase *et al.*] [Collins, P. S. Bhupal Dev, and Y. Su]
- Sterile neutrino converting in the Earth [Cherry, Shoemaker][Huang]

DM -> SM scattering, upward going

- Dark Matter decaying into leptons [Cline, Gross, Xue]
- Dark Matter decaying into RH neutrinos [**LH**, Mambrini, Pierre]

DM -> BSM scattering, upward going

- Inelastic Boosted Dark Matter [**LH**, Kim, Park, Shin]

Events Features

ANITA

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

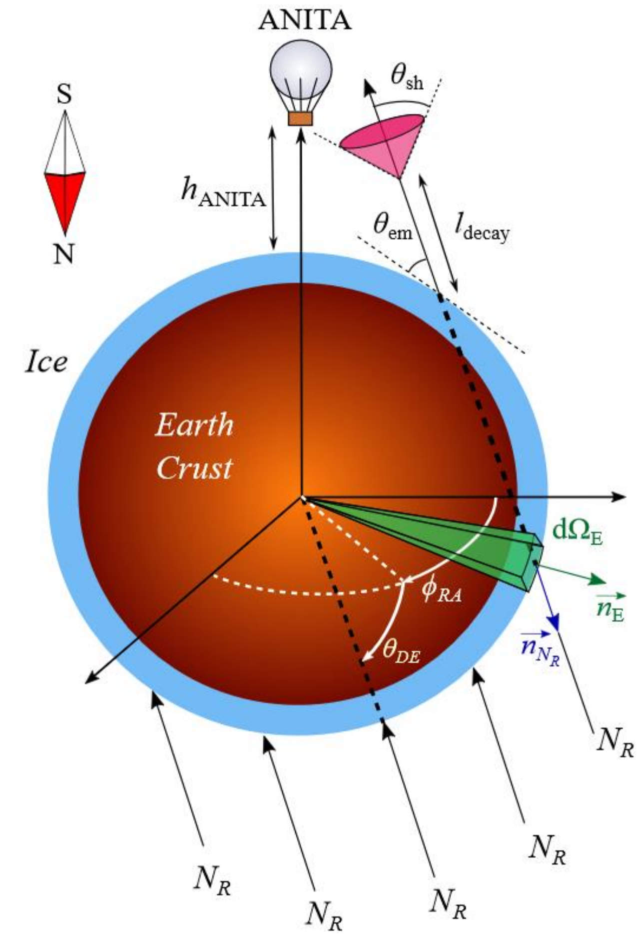
IceCube

		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°.34 ± 0°.22, Dec. +11°.42 ± 0°.08	R.A. 293°.29, Dec. +32°.82	R.A. 169°.61, Dec. +28°.04
Zenith angle z		101°.42	122°.82	118°.04
Earth chord length ℓ		2535 km	6910 km	5990 km
As tau:	$\varepsilon_{\tau,obs}$ (median)	70 PeV	13 PeV	12 PeV
	Mean interaction length for $\varepsilon_\nu = 1$ EeV	340 km	270 km	285 km
	$p_{SM}(\varepsilon_\tau > \varepsilon_{\tau,obs})$ for $\varepsilon_\nu = 1$ EeV	2.2×10^{-4}	3.8×10^{-6}	1.0×10^{-5}
	$p_{SM}(z > z_{obs})$ for $\varepsilon_\nu = 1$ EeV, $\varepsilon_\tau > \varepsilon_{\tau,obs}$	5.0×10^{-3}	4.5×10^{-5}	1.8×10^{-4}

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

Challenges for BSM interpretations

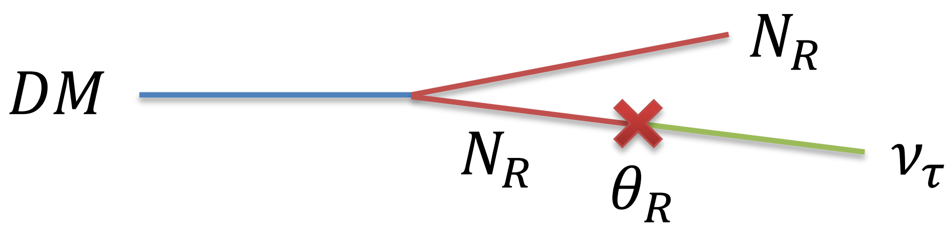
- Understand the total number of events
    1. Incoming Flux
    2. Probability of scattering
    3. Probability that the scattering products escape the Earth
    4. Probability that they decay in the low atmosphere
- Understand the angular distribution of the events
    1. Integrate over incoming particle directions
    2. Integrate over points of impact on the Earth surface
    3. Analyse the results emergence angle per emergence angle



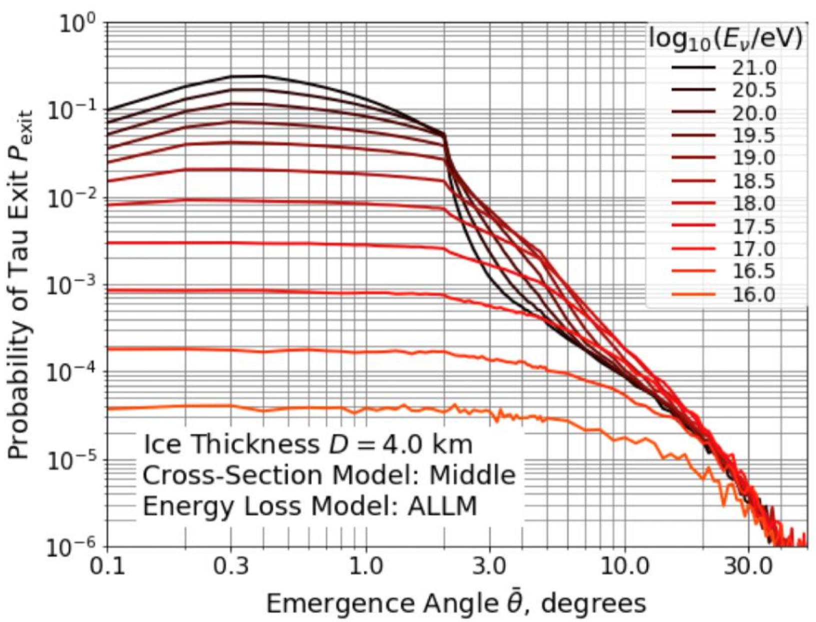
$$\frac{d^2 A_{\rm eff}}{dE_{\rm exit} d\theta_{\rm em}}(E_{\rm exit}, \theta_{\rm em} \mid E_{\rm N}, \theta_{\rm N}, \phi_{\rm N}) = R_{\rm E}^2 \int d\Omega_{\rm E} \vec{n}_{\rm N} \cdot \vec{n}_E$$

$$\times \frac{dP_{\rm exit}}{dE_{\rm exit}}(E_{\rm exit}, \theta_{\rm em} \mid E_{\rm N}, \theta_{\rm N}, \phi_{\rm N}, \theta_{\rm E}, \phi_{\rm E}) \times \int \frac{dP_{\rm decay}}{dl}(l \mid E_{\rm exit}) \times P_{\rm det}(\theta_{\rm sh} | l, \theta_{\rm N}, \phi_{\rm N}, \theta_{\rm E}, \phi_{\rm E}) dl$$

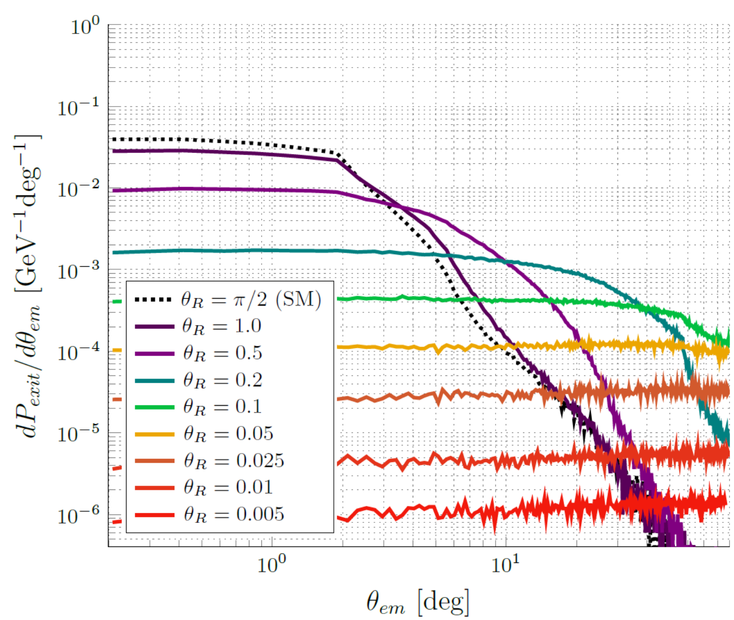
A right-handed neutrino interpretation



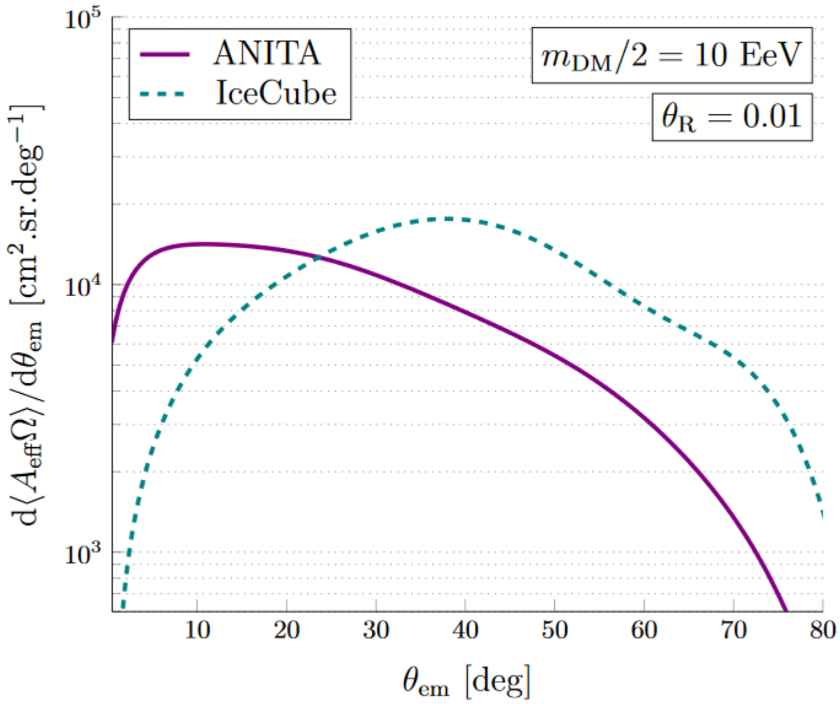
Propagation and conversion into tau's

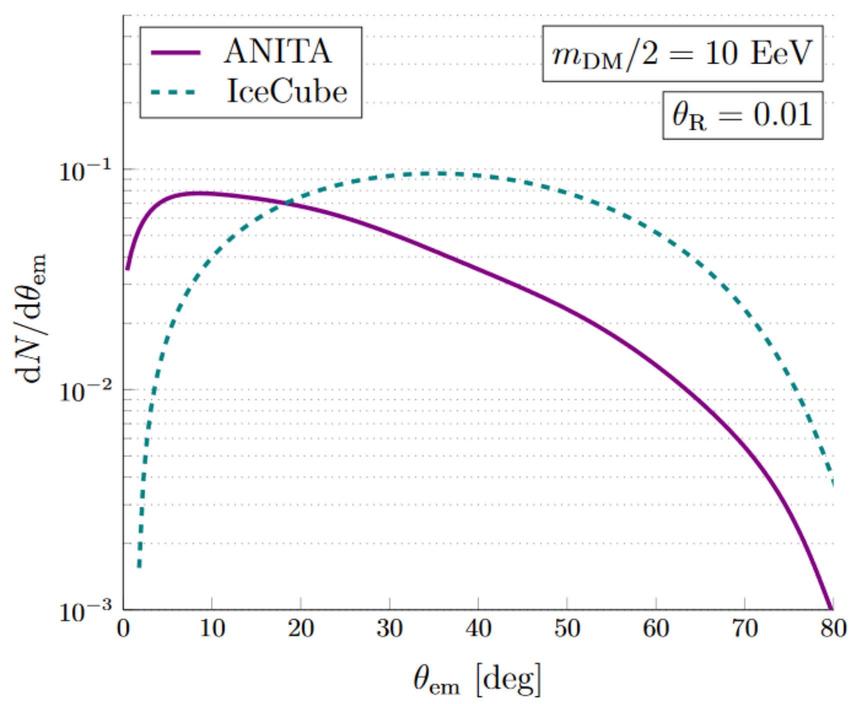


SM



ANITA and IceCube detection

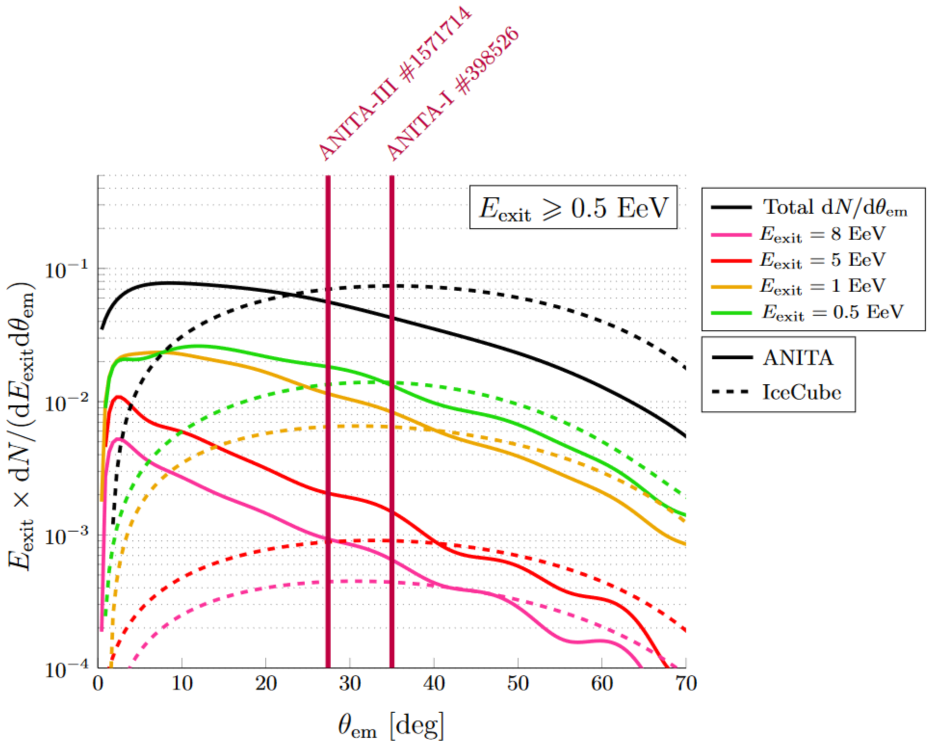


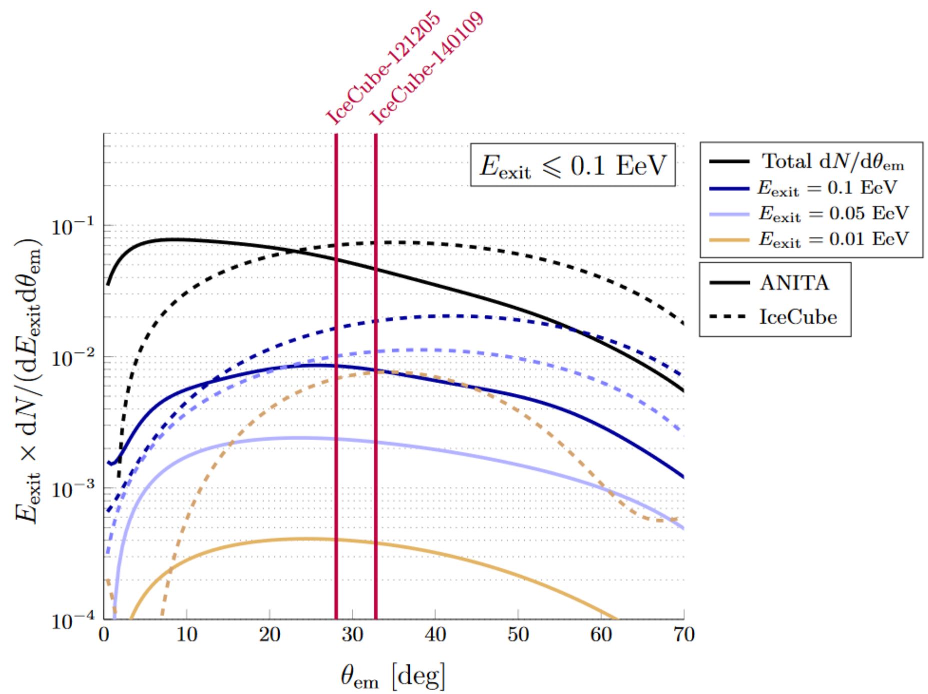


$$N_{\rm tot}^{\rm ANITA} \simeq 3.03 \left(\frac{\theta_R}{0.01}\right)^2 \left(\frac{10^{23}{\rm s}}{\tau_{\rm DM}}\right) \left(\frac{T_{\rm exp}}{85.5\ {\rm days}}\right) \left(\frac{20\ {\rm EeV}}{m_{\rm DM}}\right)^{0.67} \quad [\ \theta_R \lesssim 0.025\,;\ m_{\rm DM} > 2\ {\rm EeV}\ ]$$

$$N_{\rm tot}^{\rm IceCube} \simeq 3.65 \left(\frac{\theta_R}{0.01}\right)^2 \left(\frac{10^{23}{\rm s}}{\tau_{\rm DM}}\right) \left(\frac{T_{\rm exp}}{3142.5\ {\rm days}}\right) \left(\frac{20\ {\rm EeV}}{m_{\rm DM}}\right)^{0.70} \quad [\ \theta_R \lesssim 0.025\,;\ m_{\rm DM} > 2\ {\rm EeV}\ ]$$

ANITA/IceCube detection





Energies > 0.5 EeV : Favour an ANITA detection at angles $\sim 30°$

Energies < 0.5 EeV : Favour an IceCube detection at angles $\sim 30°$

Perfect complementarity between the two collaborations detection !

Conclusion

- Heavy Dark-Matter models induce very feeble number density and interactions DM - SM
- HDM models might be observed through the prism of primordial cosmology
- Connecting low energy phenomenology to inflation cosmology might lead to constrain both sectors at once
- Heavy Dark matter can be rendered metastable through the use of derivative couplings
- Decaying heavy dark matter can be observed by UHECR detectors in the near future

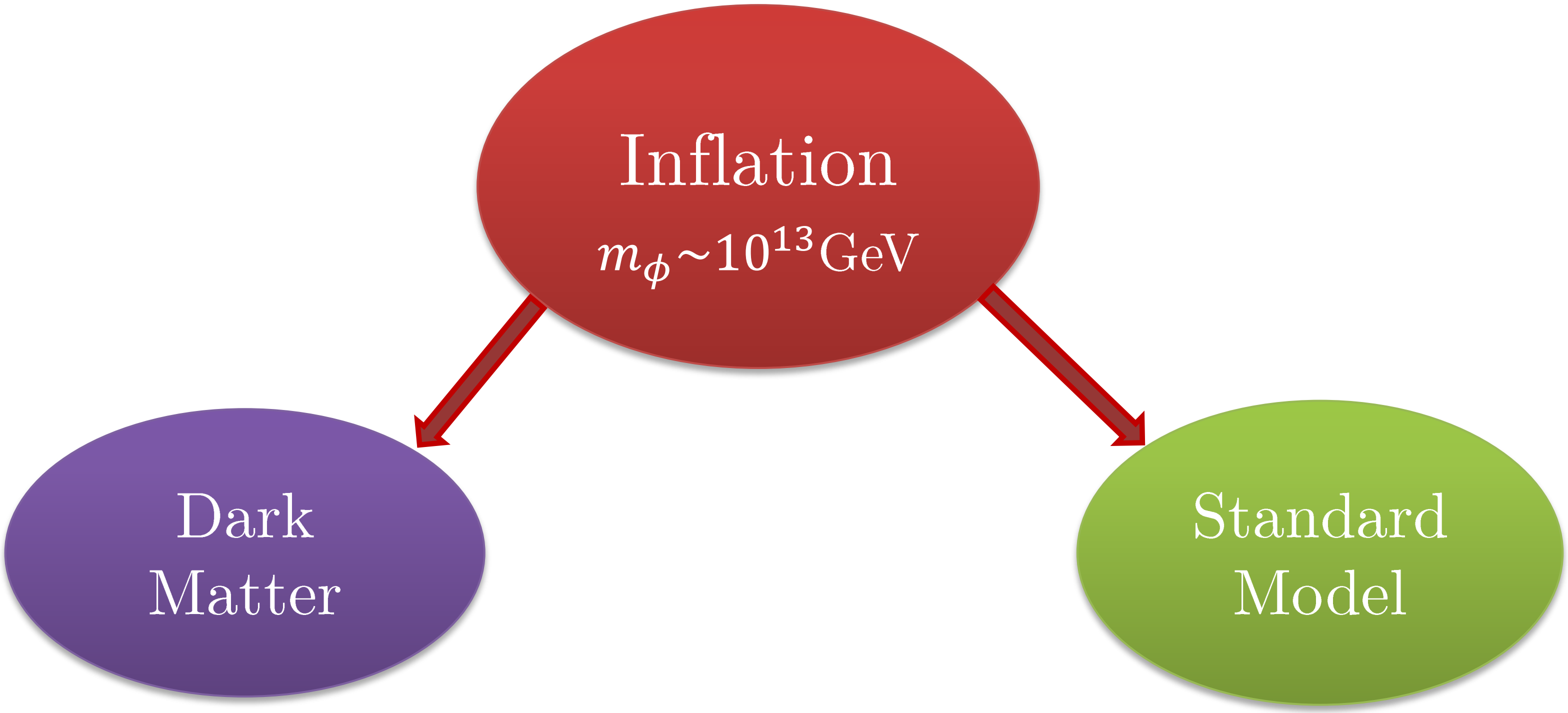
Future Directions

- The use of **the Earth as a Beam Dump target** can reveal to be successful for the search of any kind of heavy new physics..
- Taking into account the energy loss during propagation might help to provide complementary signals at low energy
- Search for heavy resonances in the propagation of UHECR through the Earth with GRAND, POEMMA, etc.
- Cosmological scenarios involving heavy DM can be constrained further through a **thorough study of the reheating phase** (effective inflaton mass, parametric resonances, EoS parameter before and during the reheating..)

Thank you very much !

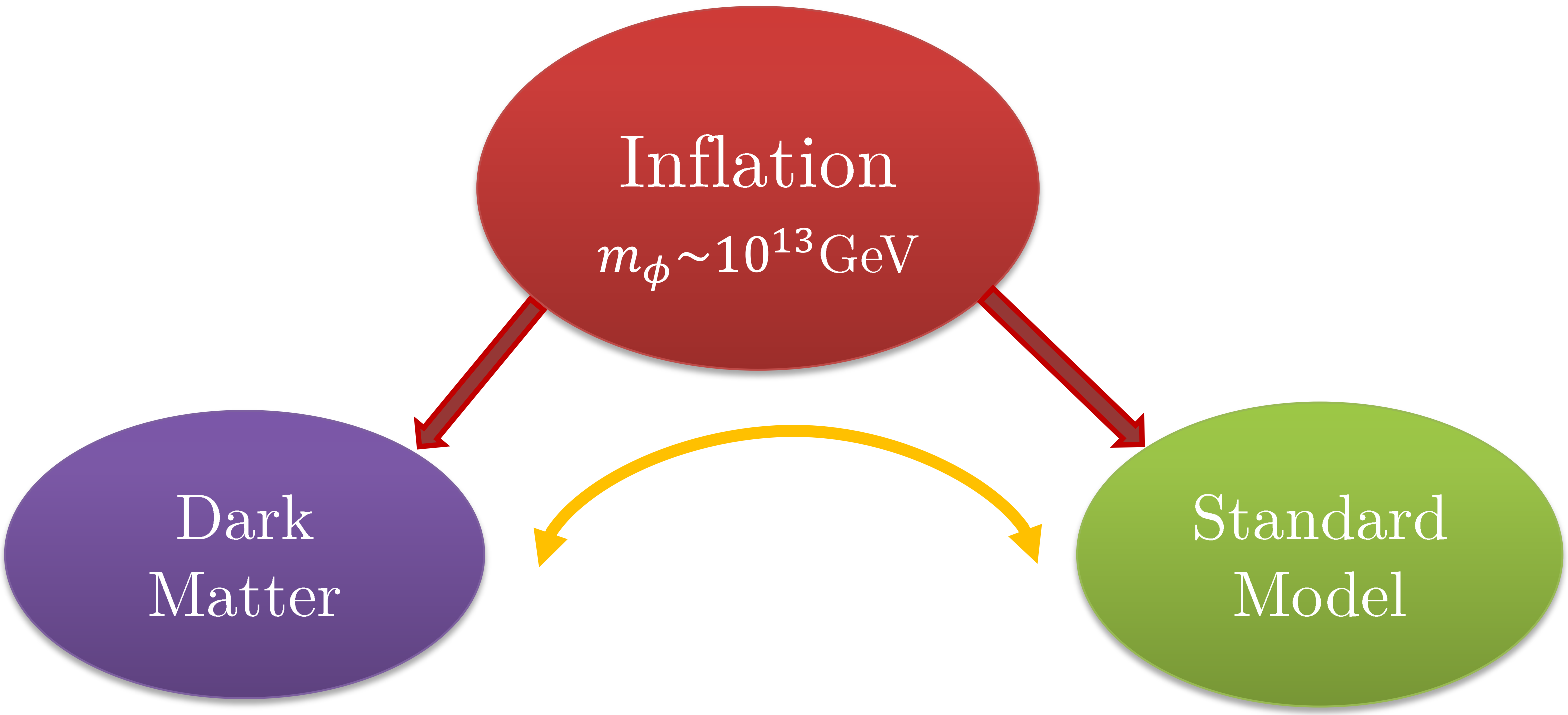
Back Up Slides

The inflaton portal to DM



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

The inflaton portal to DM



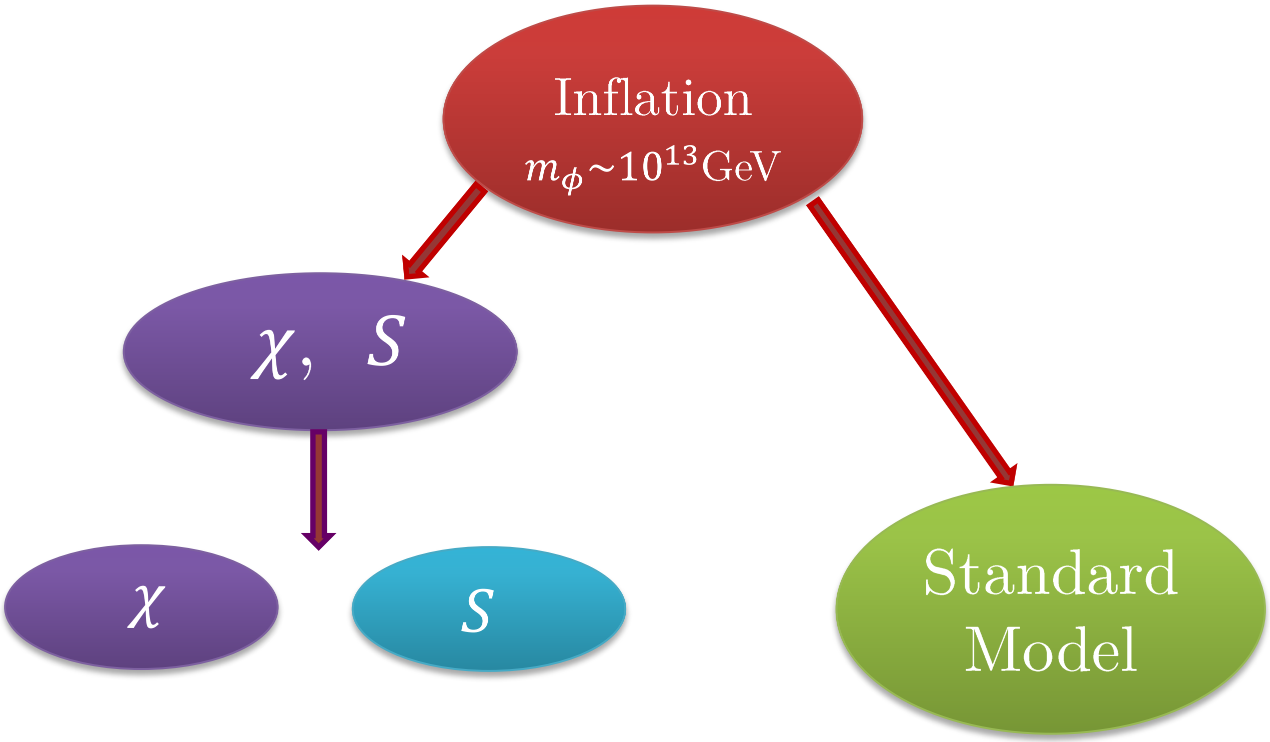
$m_\phi \sim 10^{13}$GeV $\rightarrow$ Annihilation cross section feeble

$\rightarrow$ No possible thermal scenario

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

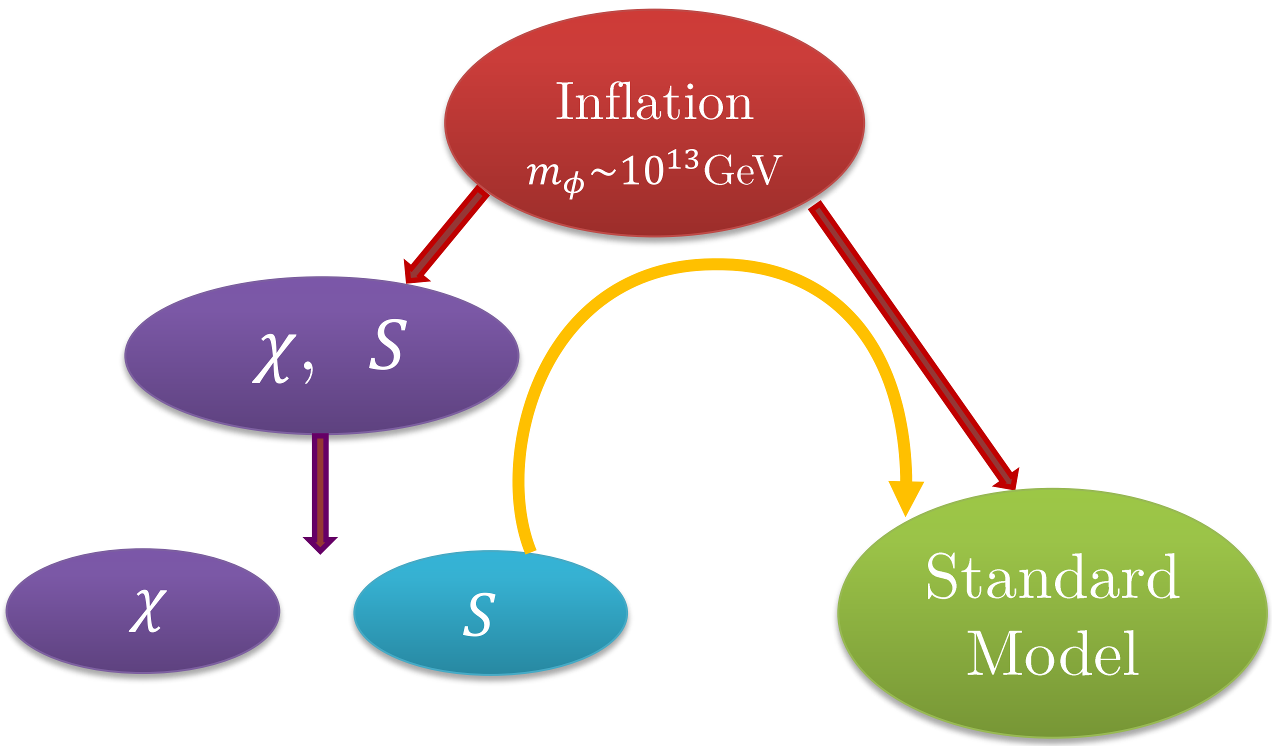
The inflaton portal to DM

Highly decoupled sectors?



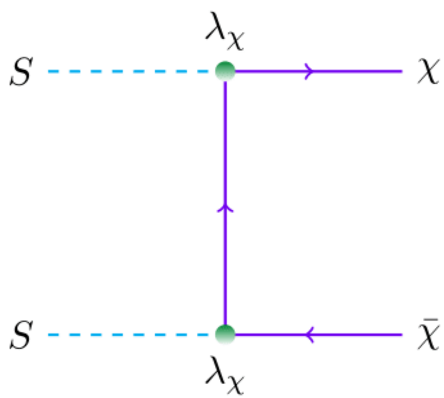
The inflaton portal to DM

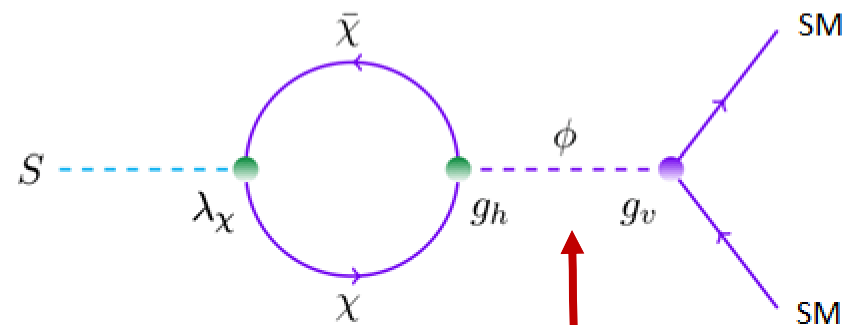
Highly decoupled sectors?



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

The Model





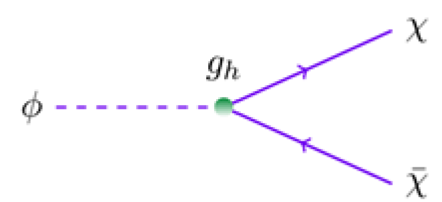
$m_\phi = 10^{13}\,GeV$

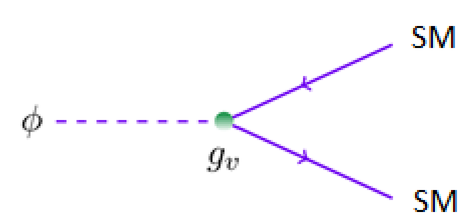
Thermal decoupling of dark matter in the dark sector

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

Generic range of masses

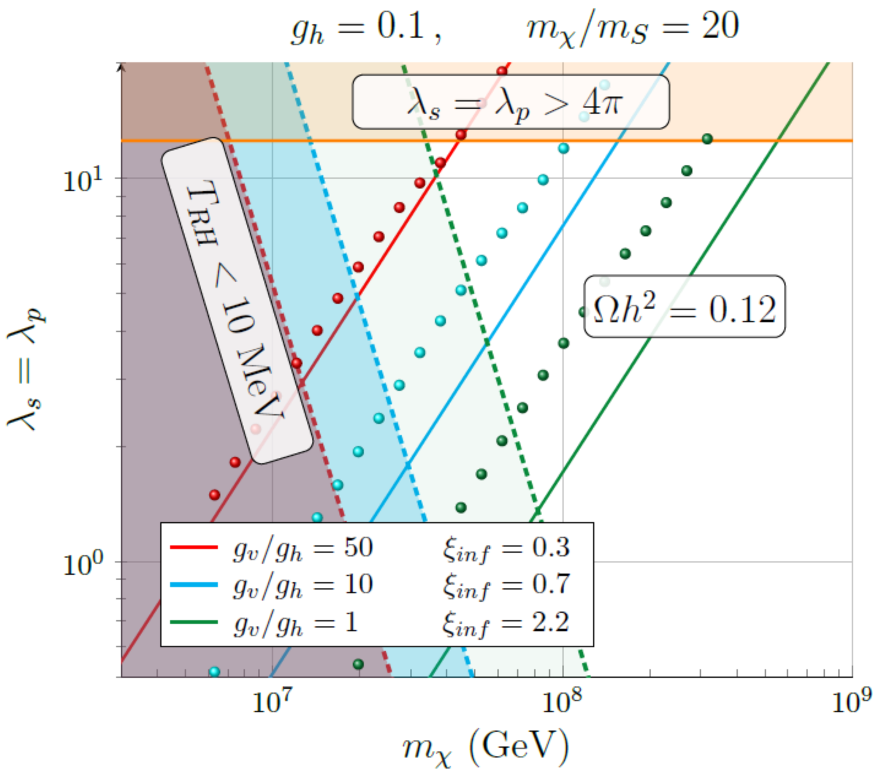
$$\frac{\Omega_\chi h^2}{S_f/S_i} \approx 0.16\ \xi_{\rm FO}^{-2} \left(\frac{T_{\rm RH}}{10{\rm MeV}}\right)\left(\frac{m_\chi}{50{\rm PeV}}\right)\left(\frac{m_\chi/m_S}{20}\right)\left(\frac{0.8}{\alpha_\chi}\right)^2$$

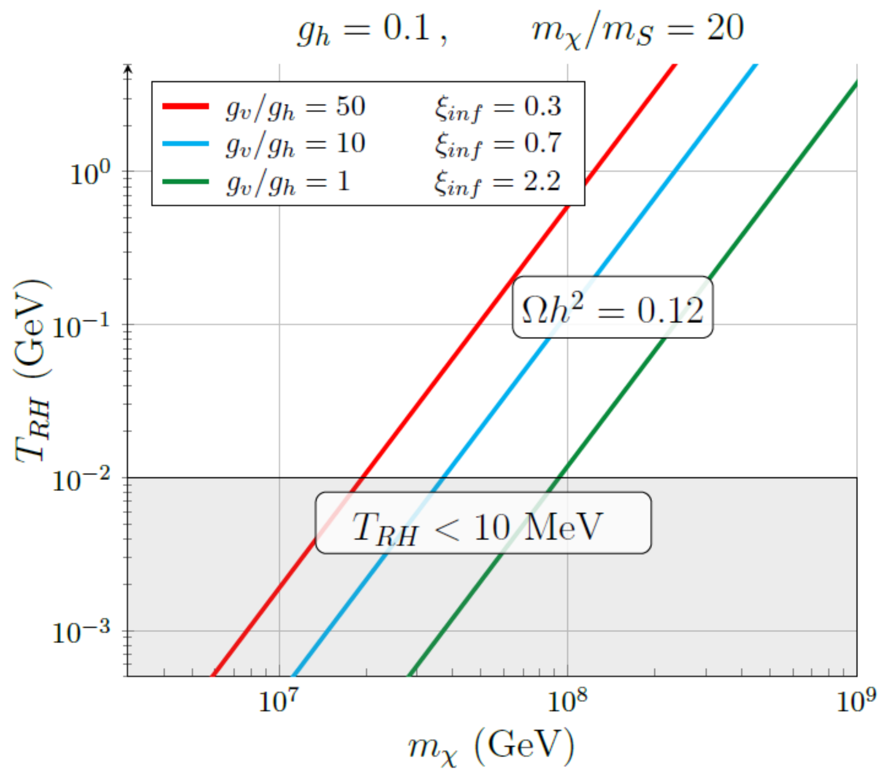
$\mathcal{O}(0.1)$ **Relic density**

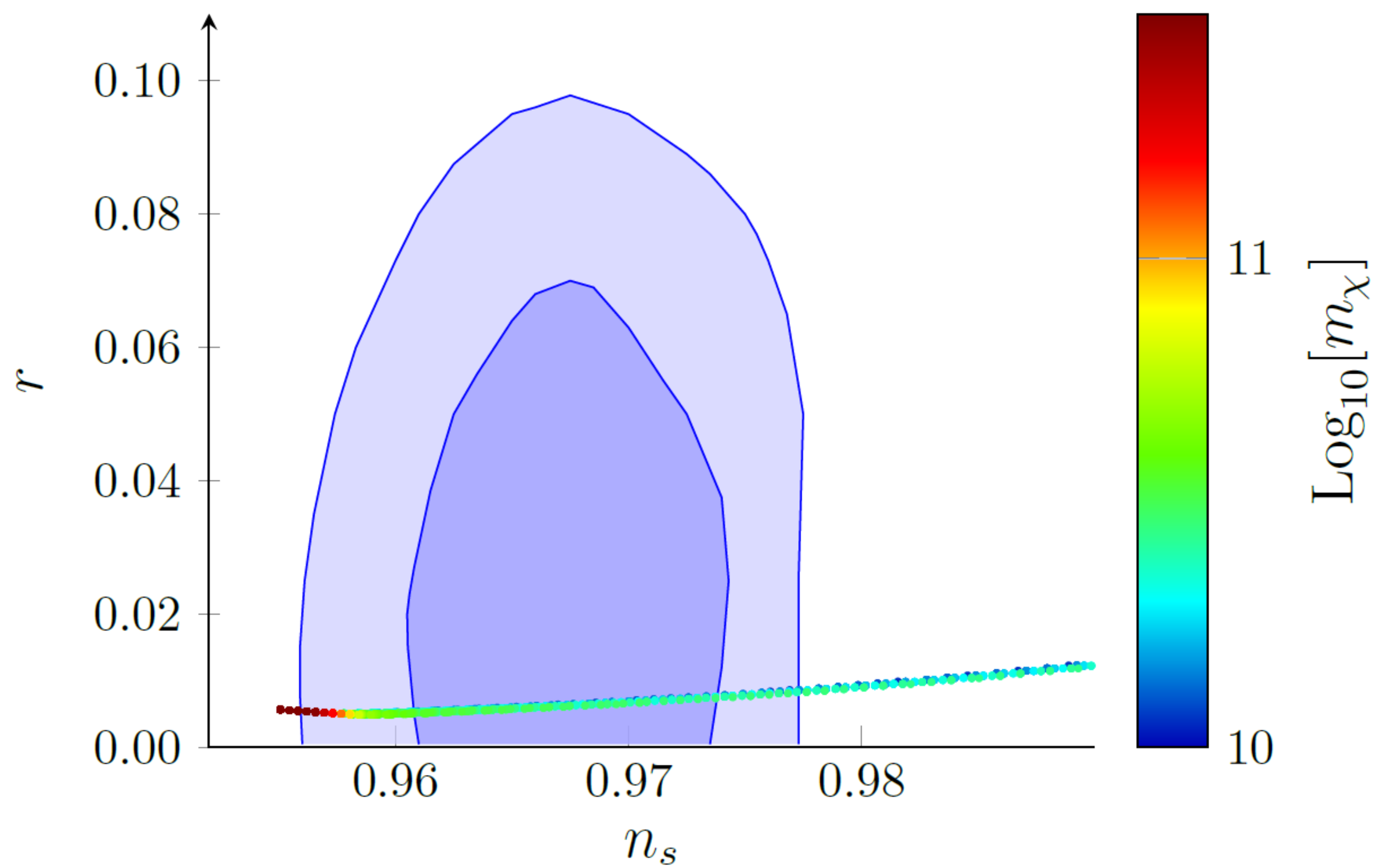
with « natural » choices for the inflaton mass and couplings

$$T_{\rm RH} \approx 119\ {\rm MeV}\left(\frac{10^{13}{\rm GeV}}{m_\phi}\right)^2\left(\frac{m_\chi}{50{\rm PeV}}\right)^{5/2}\left(\frac{m_\chi/m_S}{20}\right)^{-1/2} g_h g_v\sqrt{\frac{\lambda_s^2+\lambda_p^2}{2}}$$

Relic Density





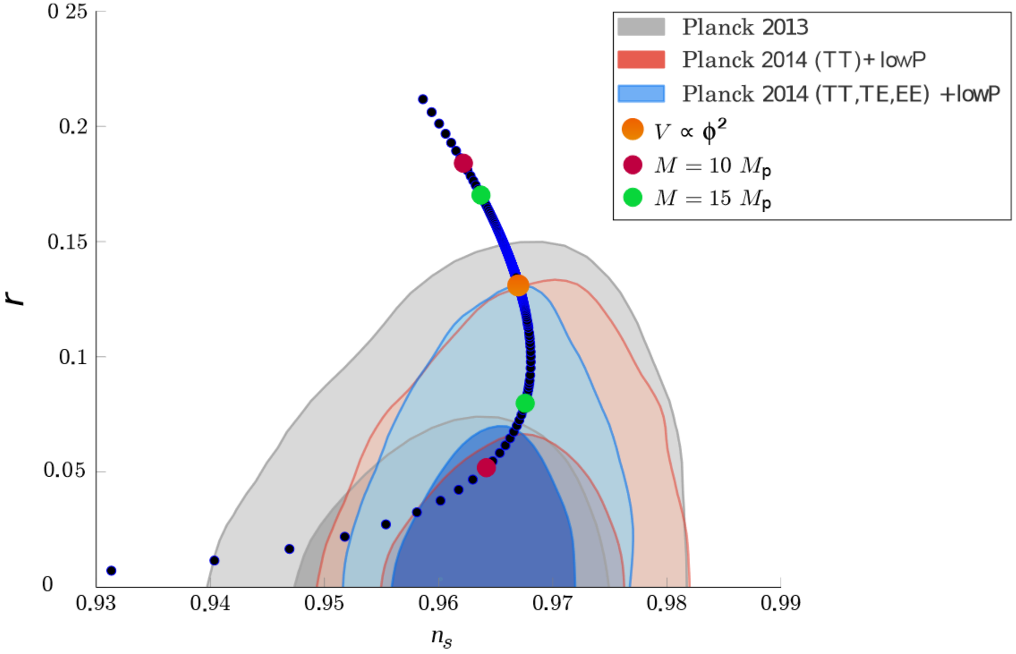


0.10
0.08
0.06
0.04
0.02
0.00
r
0.96
0.97
0.98
n_s
11
10
$\mathrm{Log}_{10}[m_\chi]$

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

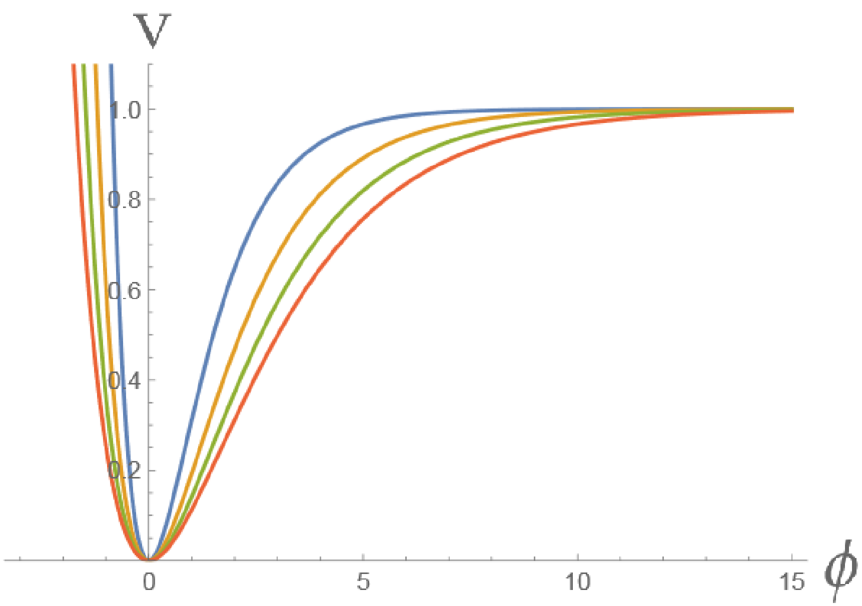
- α-attractors (E-model)

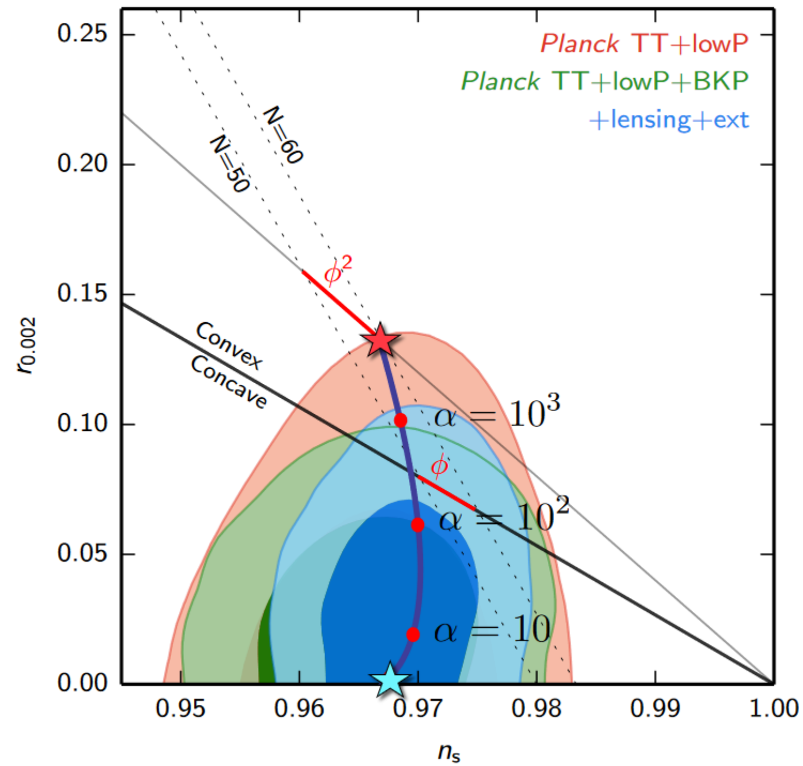
$$V(\phi) = V_0 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{Pl}}}\right)^2$$

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

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

[Carrasco, Kallosh, Linde '15]

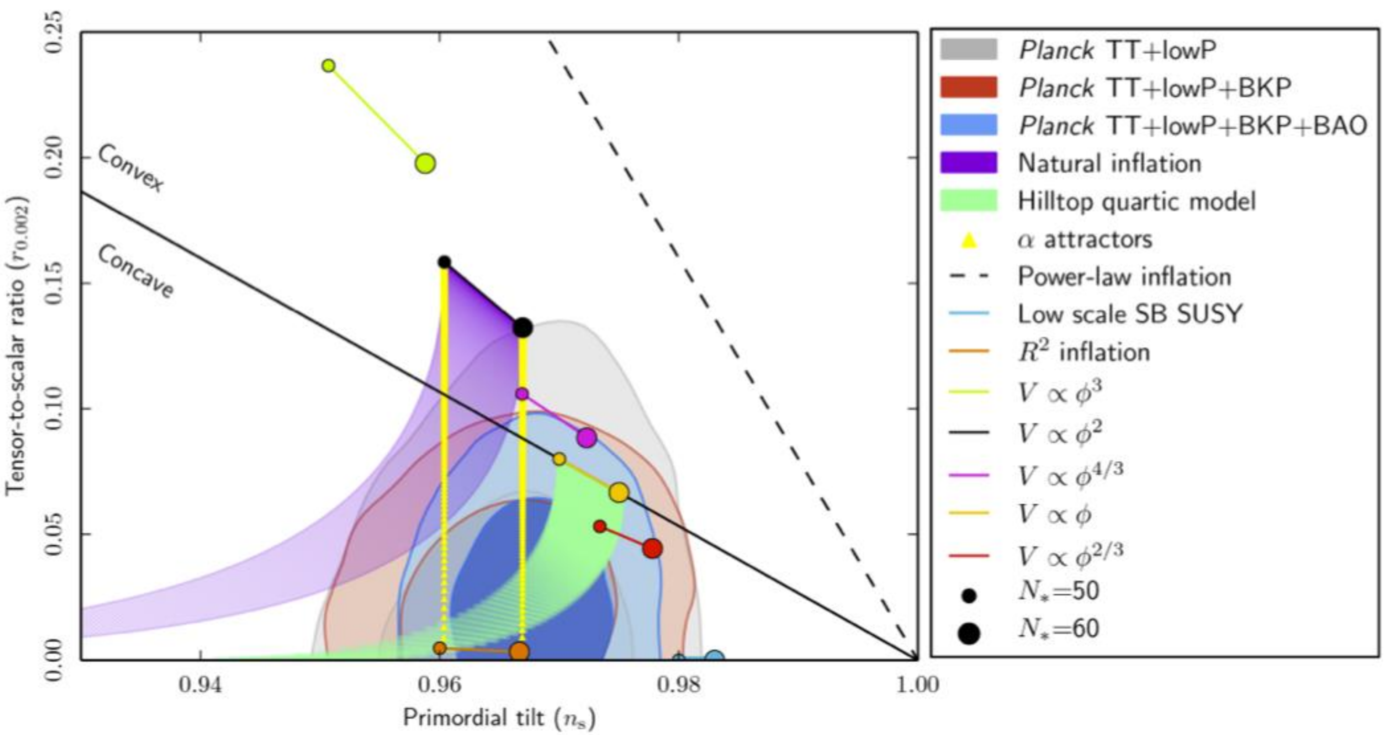




Vacuum mass versus inflation parameters

- Natural inflation

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



Smoking-gun 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 <u>from DM annihilation</u>?**

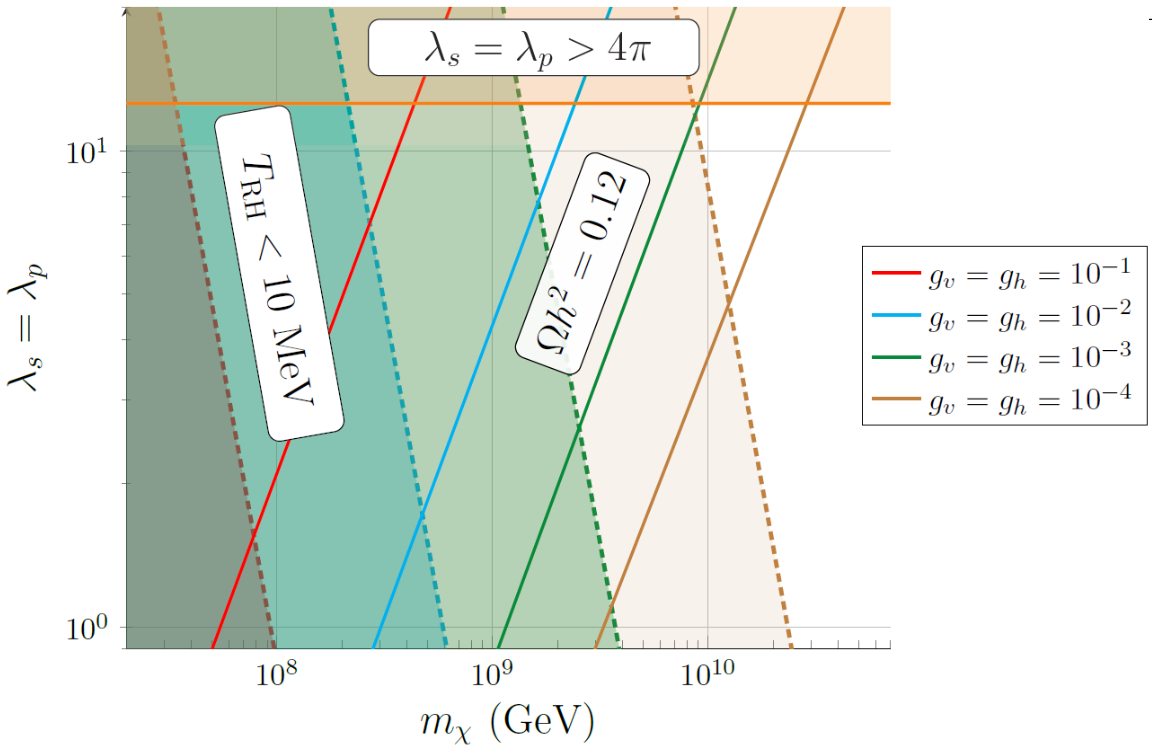
Same problem: Low DM number density, low flux of decay products, extremely hard to detect.

→ **Indirect Detection <u>from DM decay</u>?**

Possible through ultra-high-energy cosmic ray searches [LH, Y. Mambrini, M. Pierre '19][D. Hooper, S. Wegsman, C. Deaconu, A. Vieregg '19]...

... See second part of the talk!

What's on the inflation side?



Loop corrections backreact on the inflationary trajectory

↓

Destabilizes the inflaton at large field values

↓

Modifies the predictions for inflation observables (r, n_s)

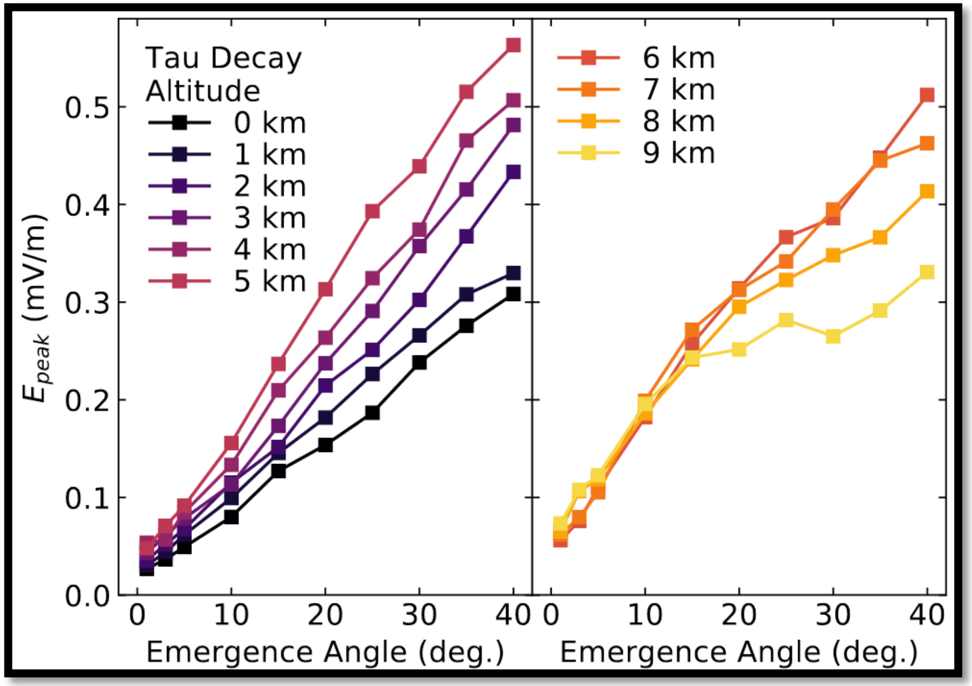
$$\frac{1}{2}\left(\bar{\nu}_L \;\; \bar{\nu}^c_s \;\; \bar{\nu}^c_R\right)\begin{pmatrix} 0 & m^s_D & m^R_D \\ m^s_D & m_s & 0 \\ m^R_D & 0 & M_R \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_s \\ \nu^c_R \end{pmatrix} + \text{h.c.}\;, \qquad m_s < m^R_D \ll M_R$$

$$\begin{aligned} \nu_1 &= \cos\theta\;(\nu_s + \nu^c_s) + \sin\theta\;(\nu_L + \nu^c_L) \\ \nu_2 &= \cos\theta\;(\nu_L + \nu^c_L) - \sin\theta\;(\nu_s + \nu^c_s) \\ \nu_3 &\sim \nu_R\;, \end{aligned}$$

$$\begin{aligned} \mathcal{L} = \alpha\frac{\partial_\mu a}{M_P}\,&(\bar{\nu}_1\gamma^\mu\gamma_5\nu_1 \\ &- \theta(\bar{\nu}_2\gamma^\mu\gamma_5\nu_1 + \bar{\nu}_1\gamma^\mu\gamma_5\nu_2) + \mathcal{O}(\theta^2)) \end{aligned}$$

$$\Gamma_{a\to\nu_1\nu_2 h} = \frac{\alpha^2\theta^2 m_a^3}{192\pi^3 v^2 M_P^2}(m_1 + m_2)^2$$

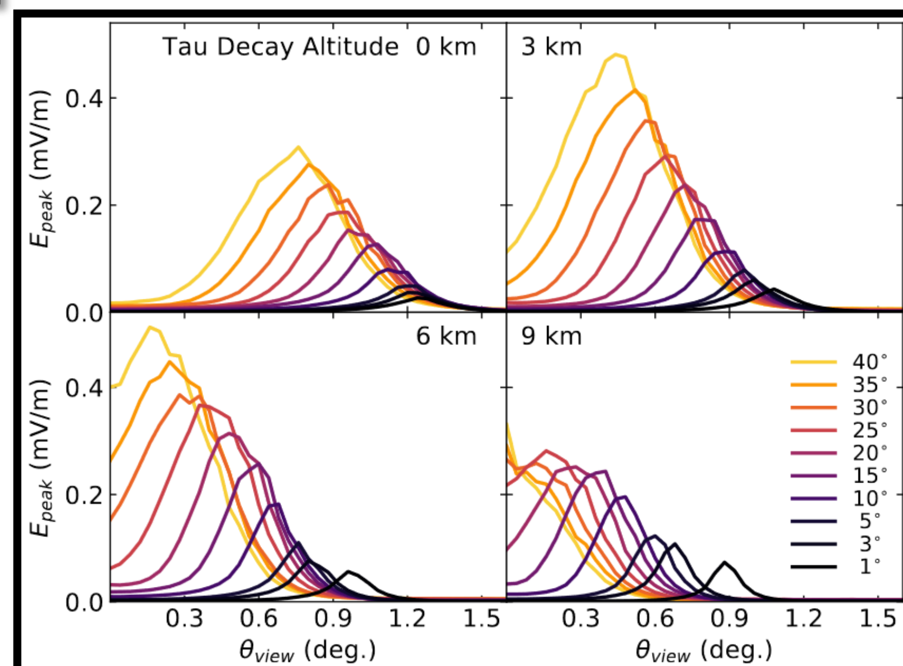
$$\tau_a \gtrsim 5.5\times 10^{28}\text{s}\left(\frac{10^{-2}}{\alpha}\right)^2\left(\frac{10^{-5}}{\theta}\right)^2\left(\frac{10^9\ \text{GeV}}{m_a}\right)^3 \qquad \text{for } m_1 \ll m_2 \lesssim 0.05\ \text{eV}$$



[ANITA collaboration, 1811.07261]

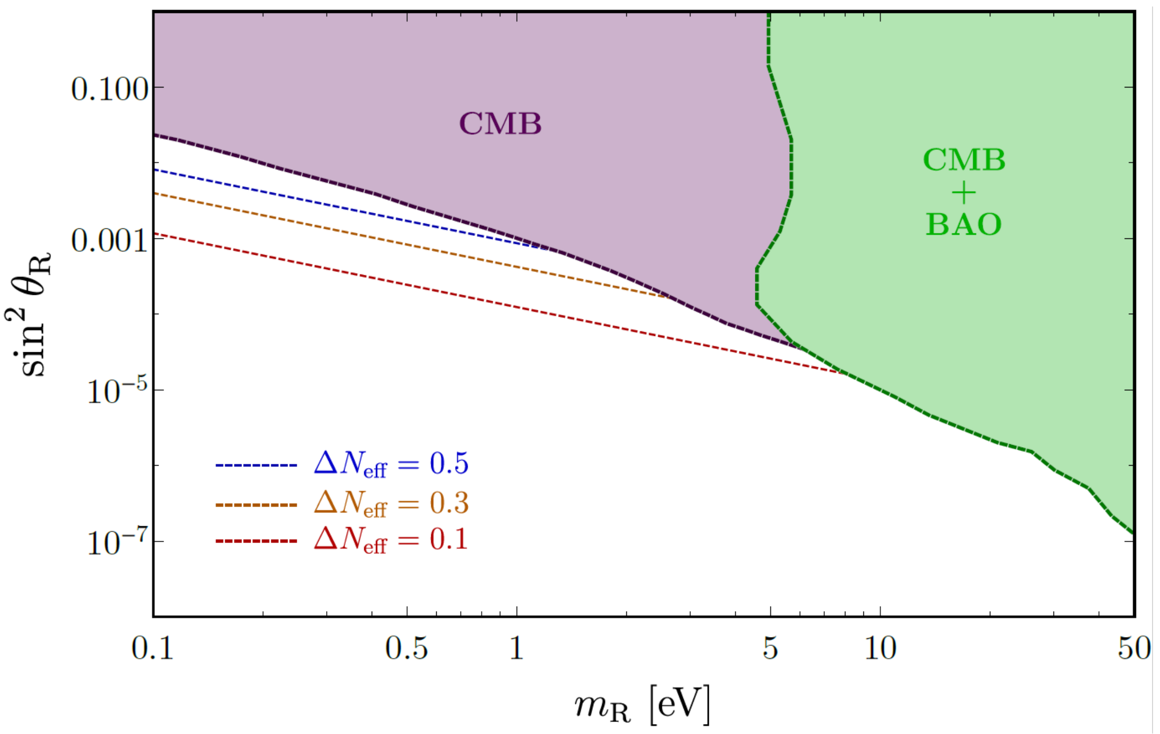
Full development of an EAS depends on the altitude

Angular opening of the shower ~ 1.5°



A right-handed neutrino interpretation

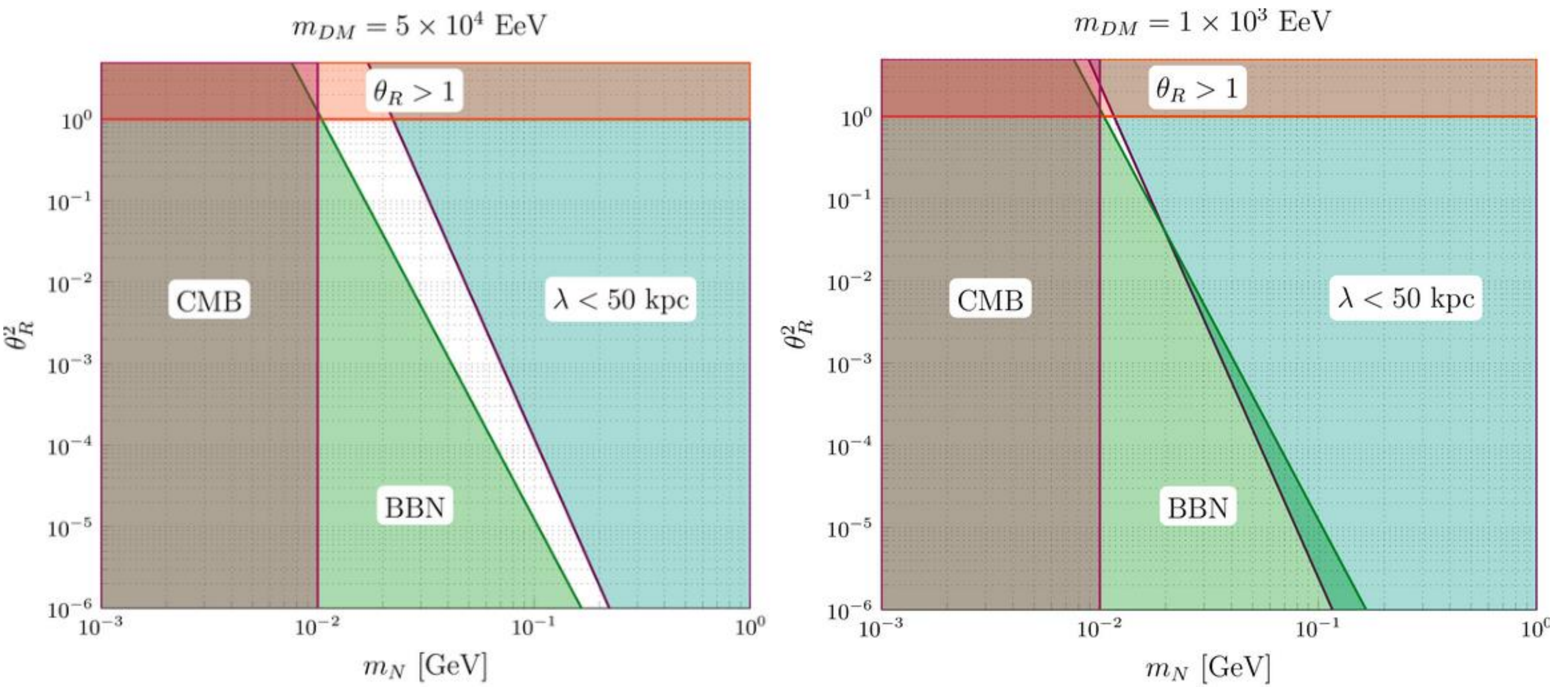
$m_R < 10$ eV or $m_R \sim 0.1$ GeV



$m_R < 10$ eV → $m_{DM} \sim 10$ EeV

A right-handed neutrino interpretation

$$\lambda \simeq \frac{c\gamma}{\Gamma_{N_R \to 3\nu}} \simeq 40\ \text{kpc} \left(\frac{10^{-2}}{\theta_R}\right)^2 \left(\frac{22\ \text{MeV}}{m_R}\right)^6 \left(\frac{m_{\text{DM}}}{20\ \text{EeV}}\right)$$

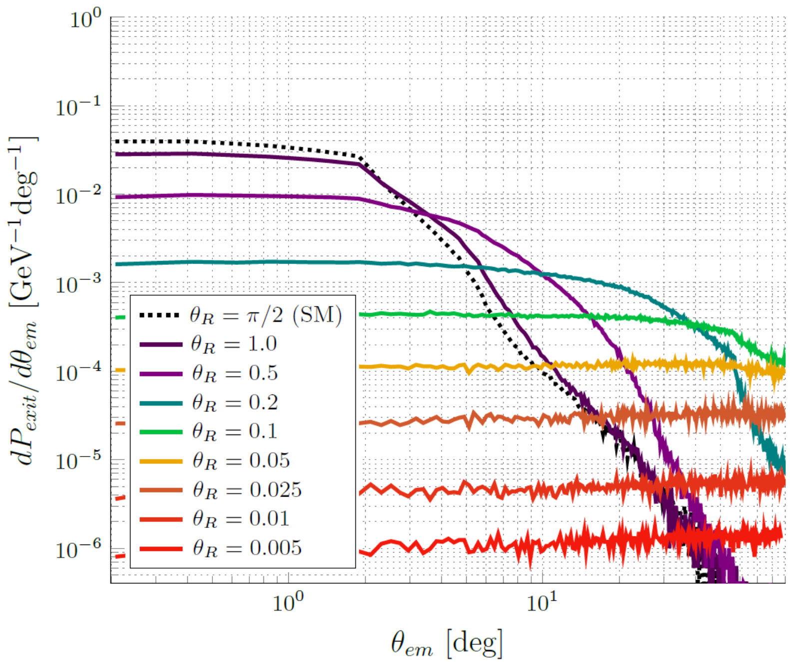


$m_R \sim 0.1$ GeV → $m_{DM} \gtrsim 10^3$ EeV $= 10^{12}$ GeV

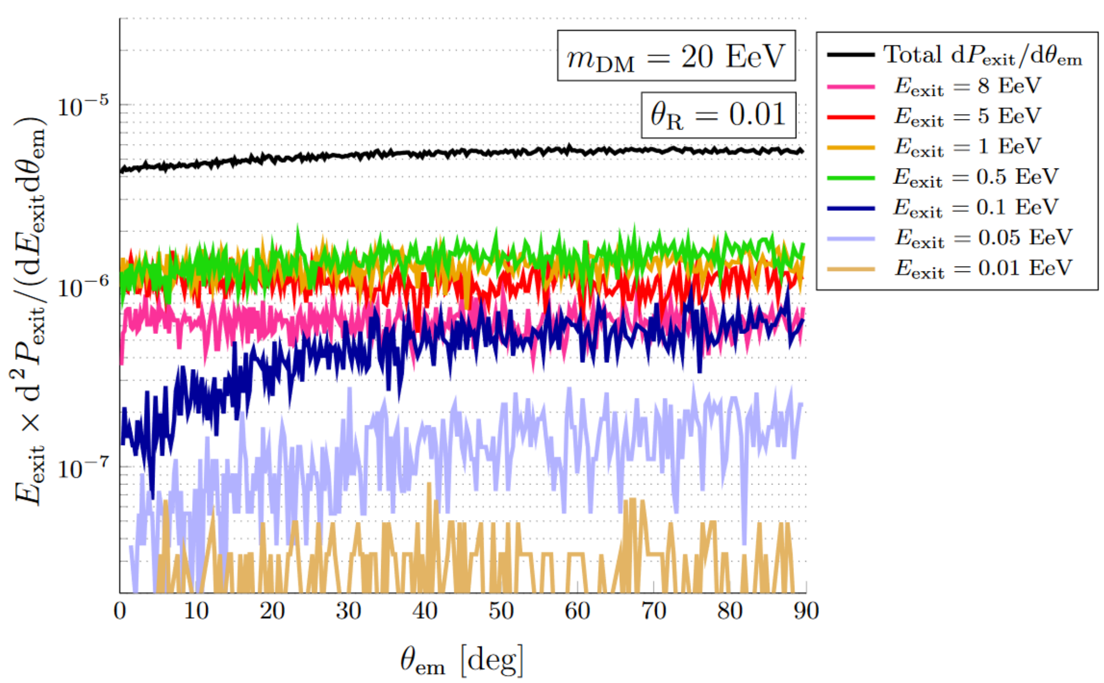
Approaches the inflaton mass…

Differential Exit Probability

Total Exit Probability

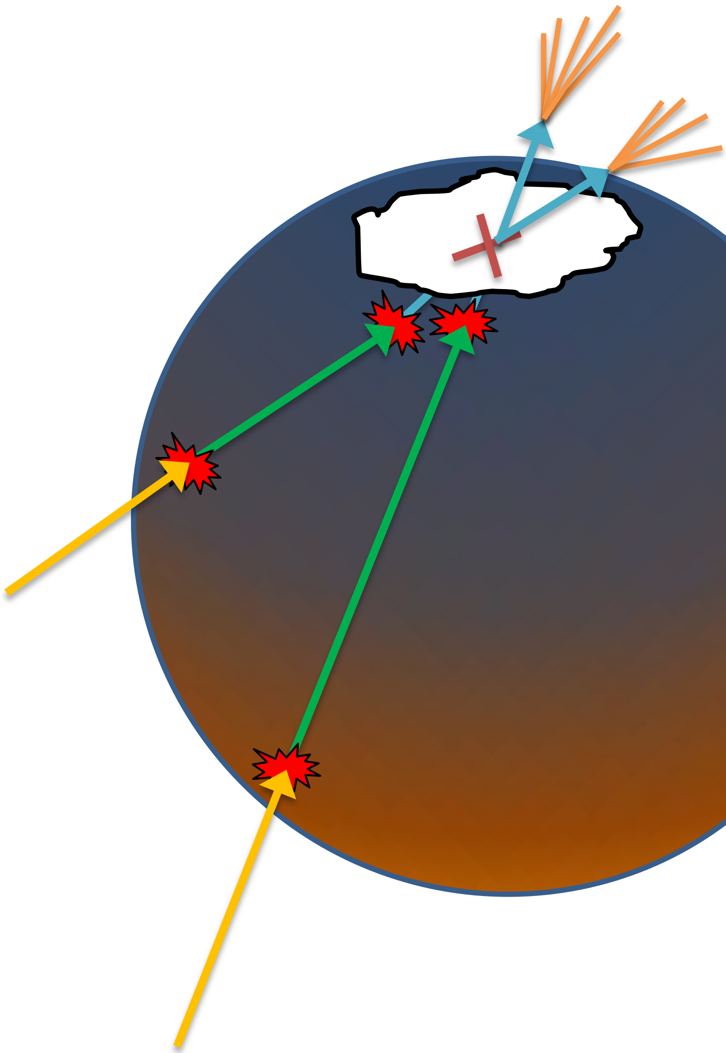


Diff. Exit Probability



→ Access to the energy distribution per emergence angle of the predicted events

How to get a better angular distribution?



Assuming a tau escapes the Earth and produces the EAS

↓

Need to produce it (very) close to the surface in order to let it escape

↓

Relatively small volume in which scattering (or decay) should take place

↓

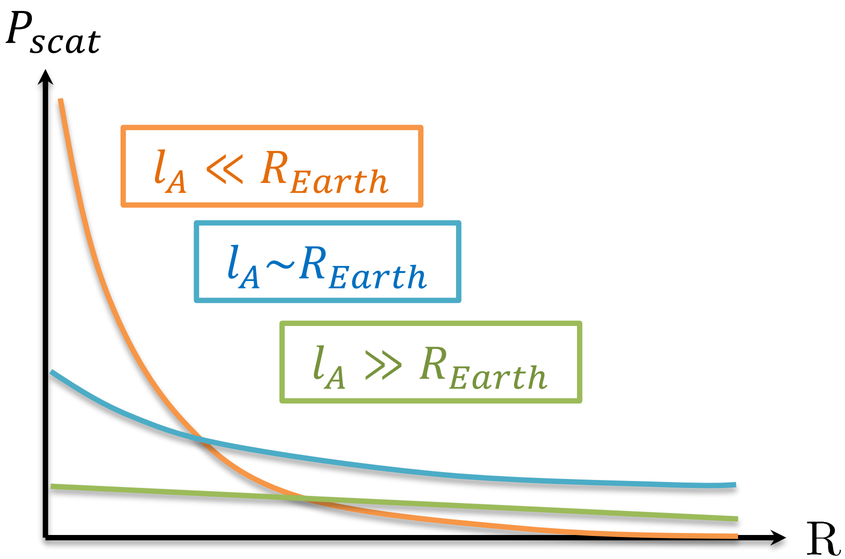
Need to push up the scattering cross section

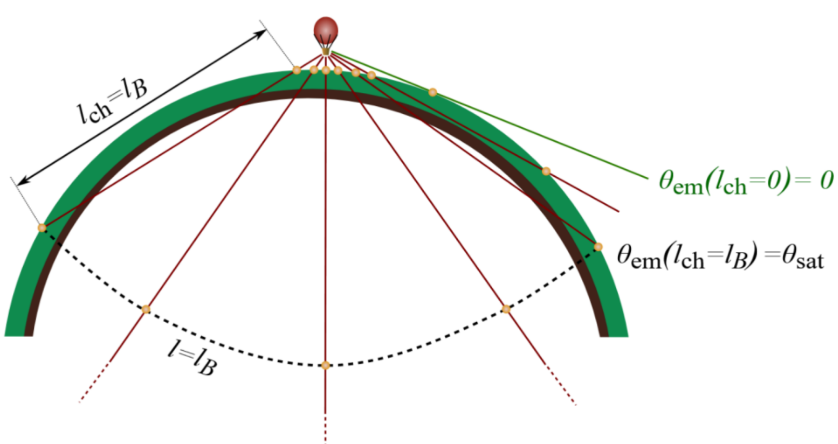
↓

Earth relatively opaque at large angles...

A translucent Earth makes it better!

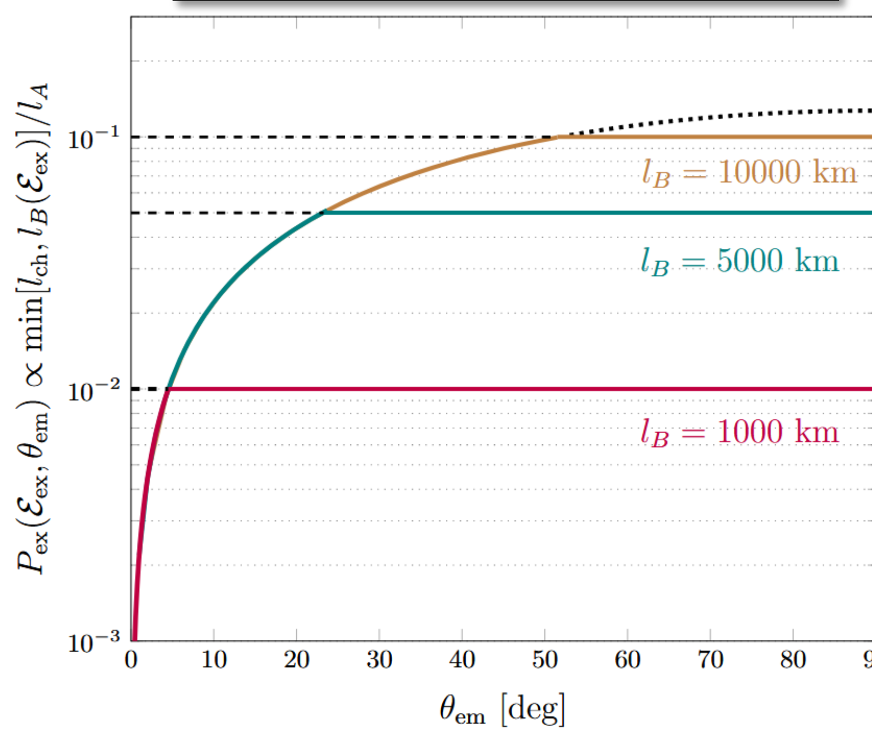
If some dark particle decays into hadrons → No need for propagating EW particles through the Earth !

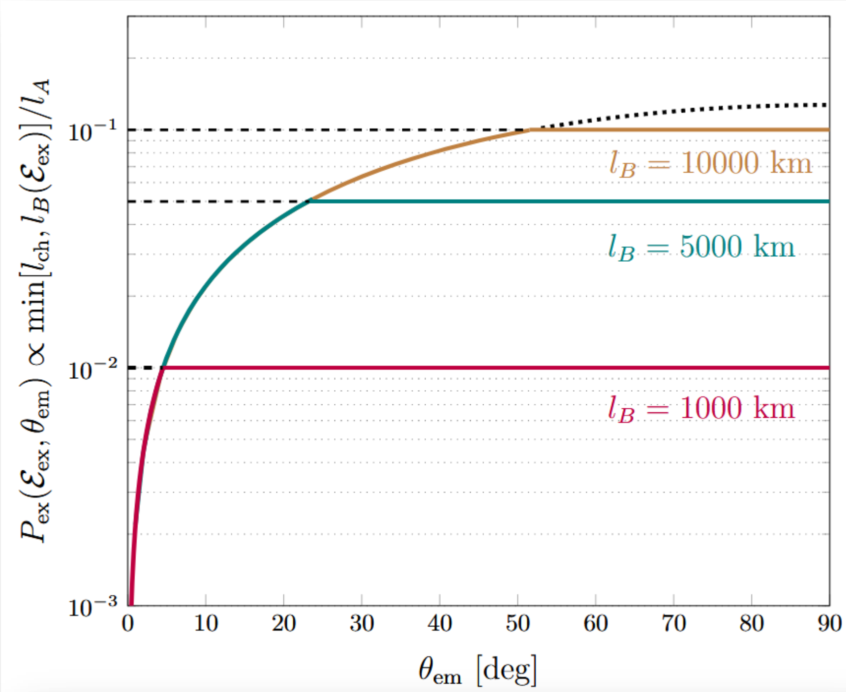




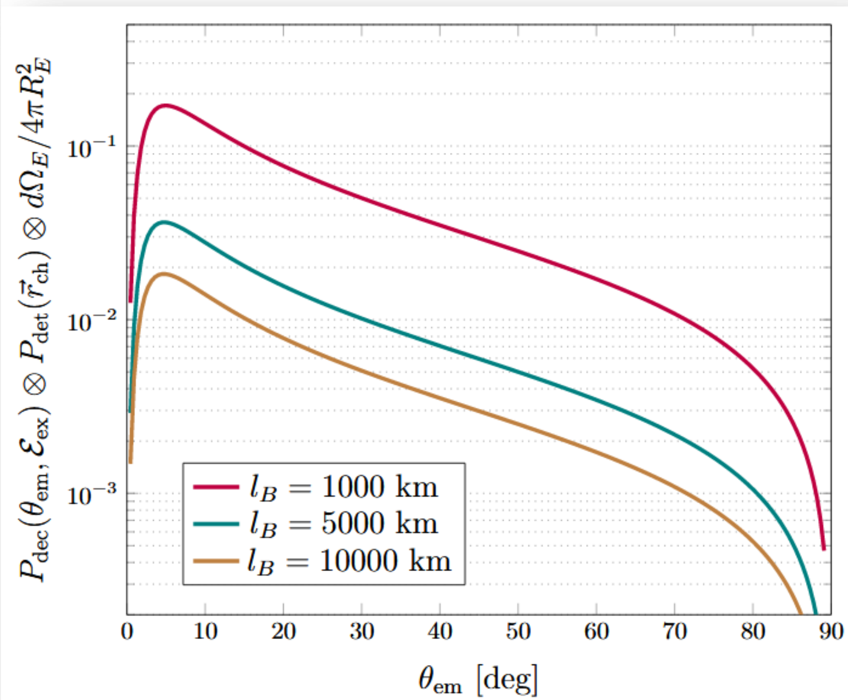
$$A \xrightarrow{\sigma_{AN}} B \xrightarrow{\Gamma_B} \bar{q}q$$

$$P_{\rm ex}(\theta_{\rm em}, \mathcal{E}_{\rm ex}) \propto \frac{\min[l_{\rm ch}, l_B(\mathcal{E}_{\rm ex})]}{l_A}$$

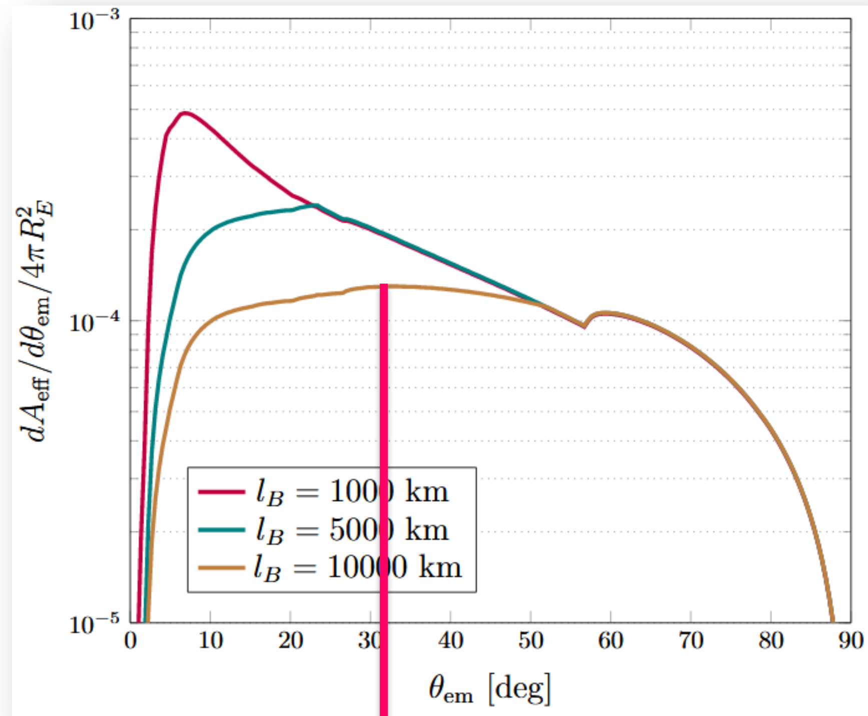




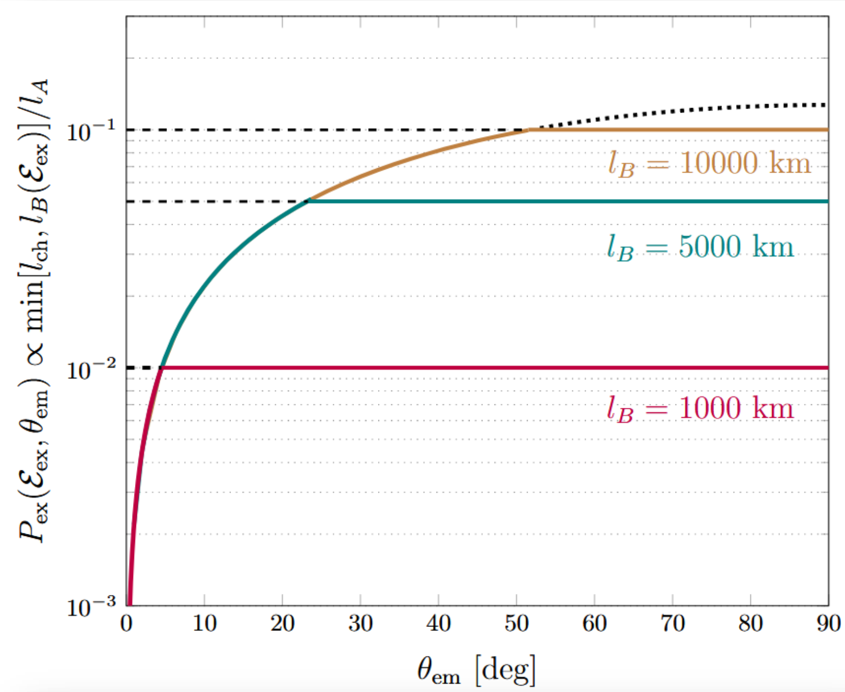
$P_{ex}(\mathcal{E}_{ex}, \theta_{em}) \propto \min[l_{ch}, l_B(\mathcal{E}_{ex})]/l_A$
10^{-1}
10^{-2}
10^{-3}
$l_B = 10000$ km
$l_B = 5000$ km
$l_B = 1000$ km
0
10
20
30
40
50
60
70
80
90
θ_{em} [deg]

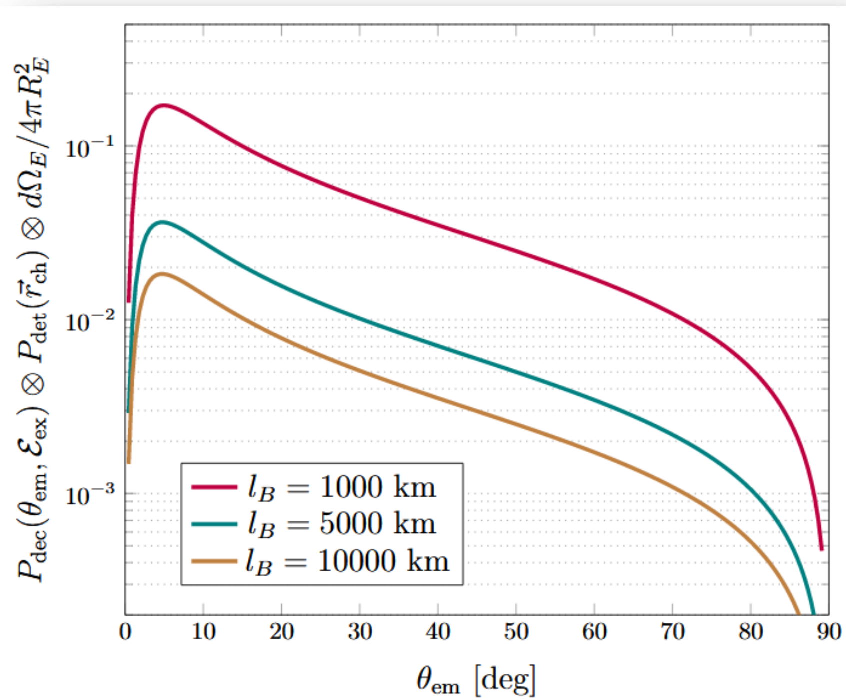


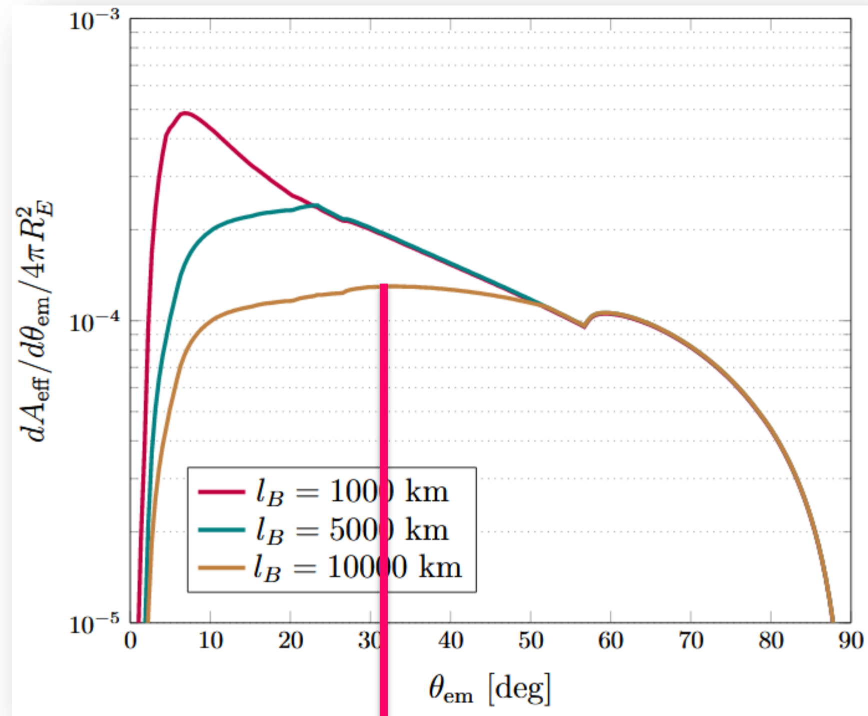
$P_{dec}(\theta_{em}, \mathcal{E}_{ex}) \otimes P_{det}(\vec{r}_{ch}) \otimes d\Omega_E/4\pi R_E^2$
10^{-1}
10^{-2}
10^{-3}
$l_B = 1000$ km
$l_B = 5000$ km
$l_B = 10000$ km
0
10
20
30
40
50
60
70
80
90
θ_{em} [deg]



$dA_{eff}/d\theta_{em}/4\pi R_E^2$
10^{-3}
10^{-4}
10^{-5}
$l_B = 1000$ km
$l_B = 5000$ km
$l_B = 10000$ km
0
10
20
30
40
50
60
70
80
90
θ_{em} [deg]







$\theta_{max} \sim 30°$

Inelastic Boosted Dark Matter

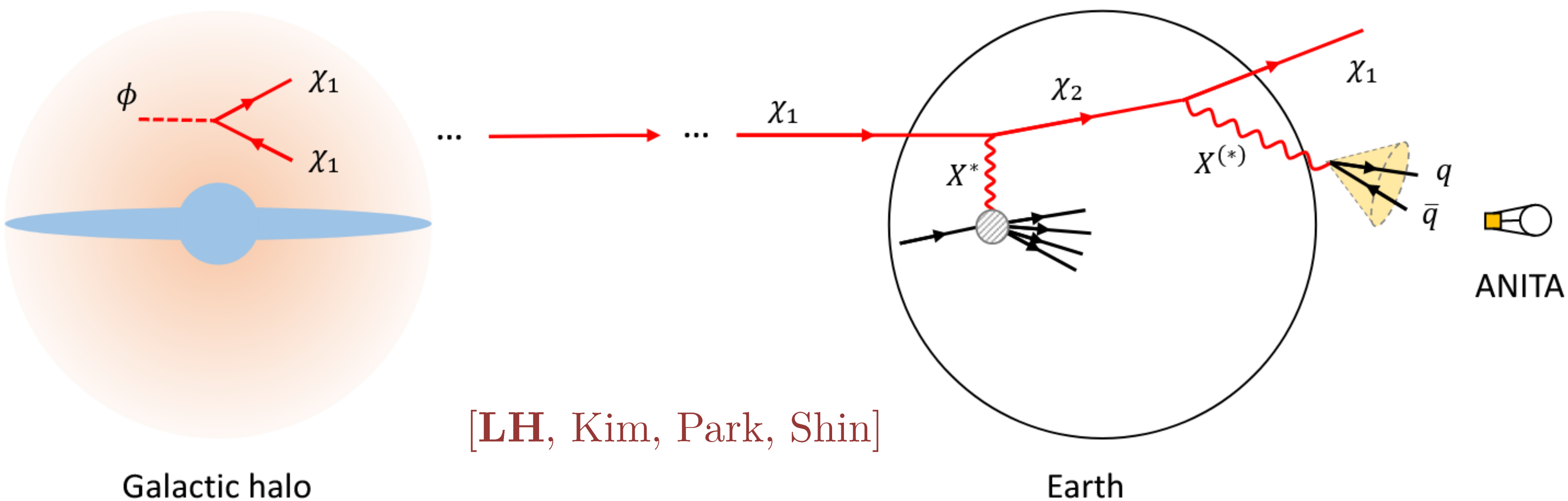
$$\mathcal{L}_{\rm int} \supset y_\phi \phi \bar{\chi}_1 \chi_1 - \frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + (g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + \text{h.c.})$$

[Kim, Park, Shin 1702.02944][Kim, Park, Shin 1612.06867][Giudice, Kim, Park, Shin, 1712.0712]

Super-heavy DM

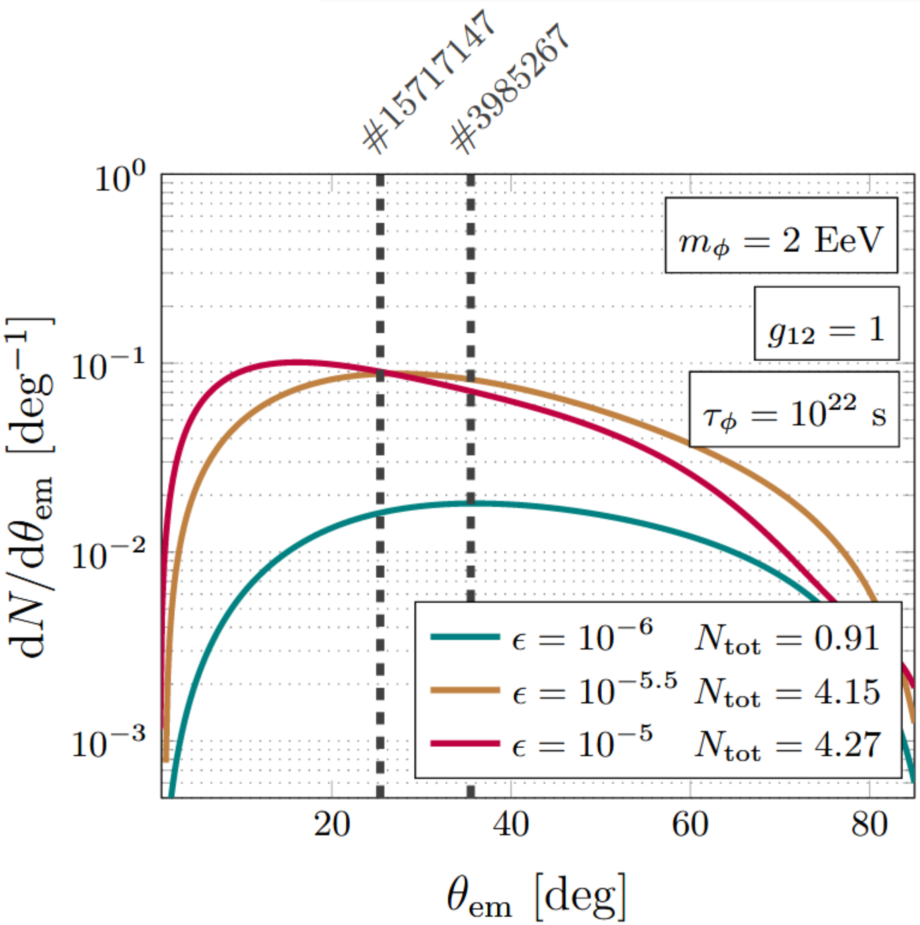
Light, boosted DM

$U(1)_X$ −charged dark sector

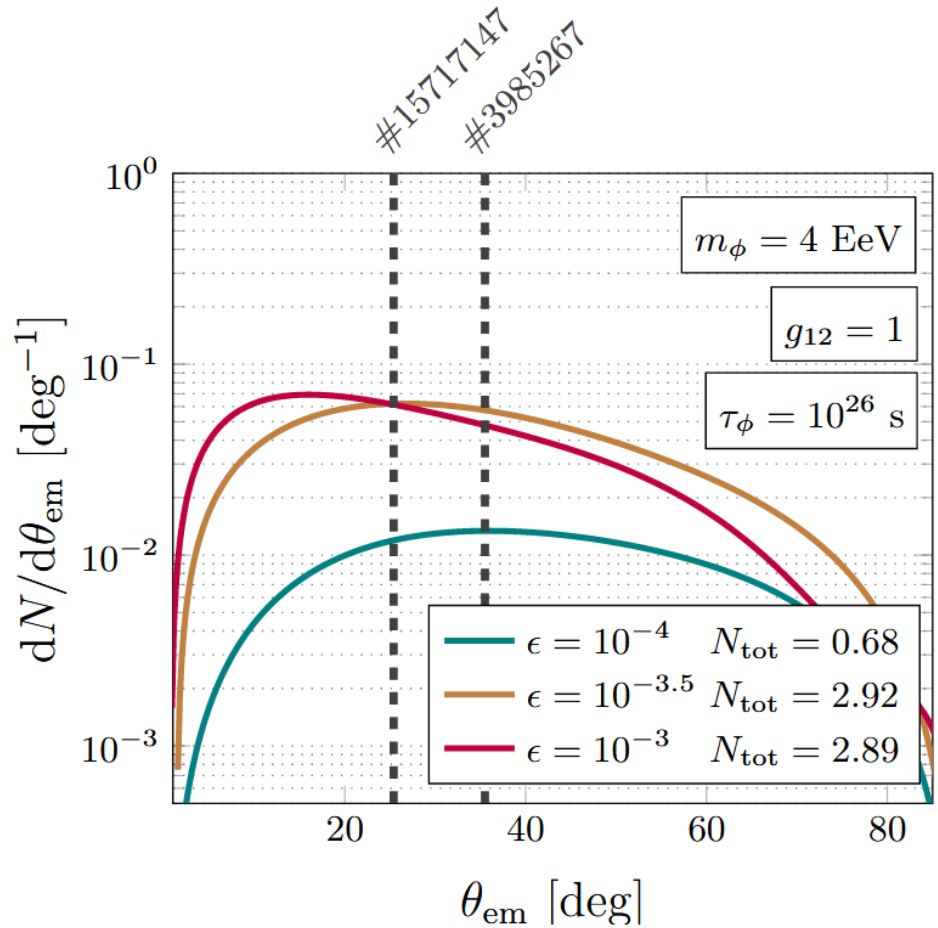


[**LH**, Kim, Park, Shin]

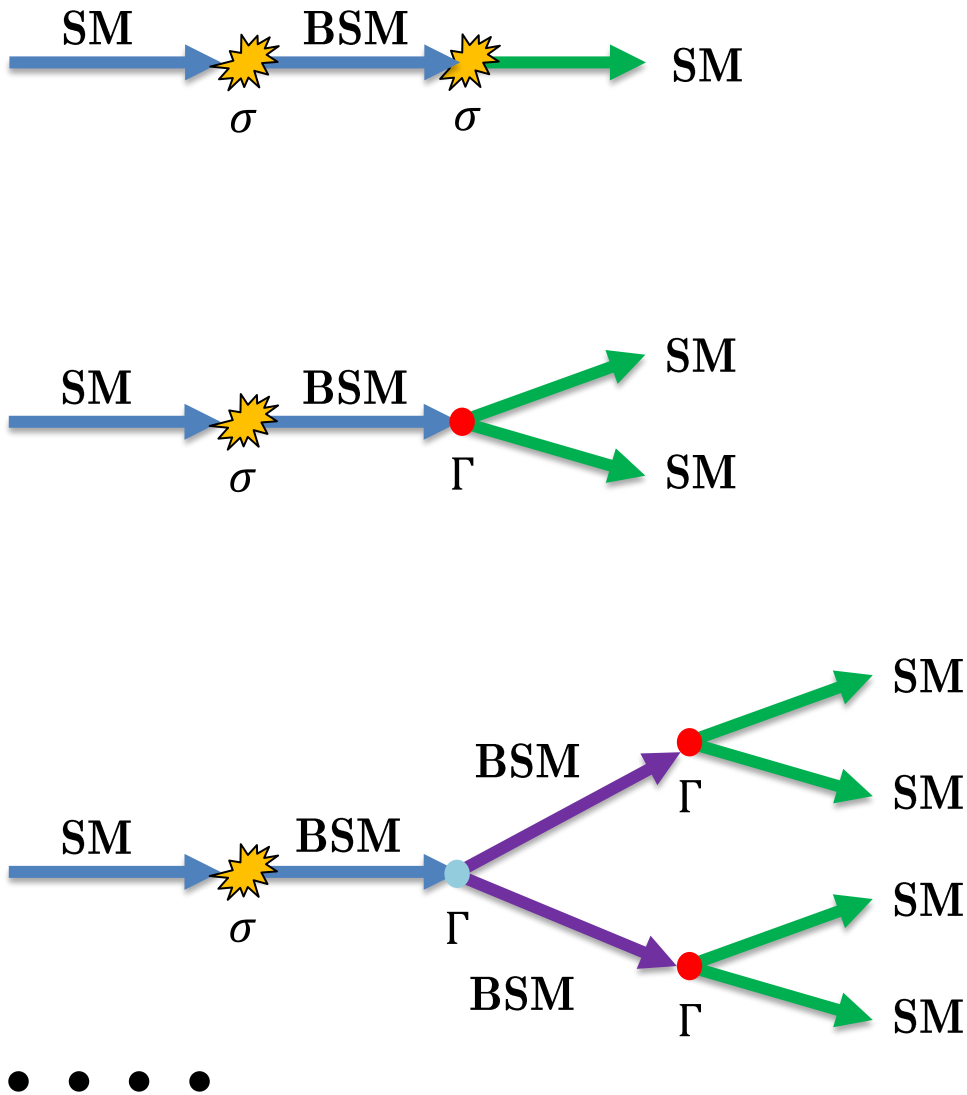
On-shell: $m_2 > m_1 + m_X,\ m_X = 0.5$ GeV,
$m_\phi = 2$ EeV,
Off-shell: $m_2 = 2.5$ GeV, $m_1 = 2$ GeV, $m_X = 2$ GeV,
$m_\phi = 4$ EeV.



On-shell scenario



Off-shell scenario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