Higgs inflation puts lower and upper bounds on tensor-to-scalar ratio and on Higgs-portal-DM mass

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with

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Yukari Nakanishi (Osaka)

1709.09350

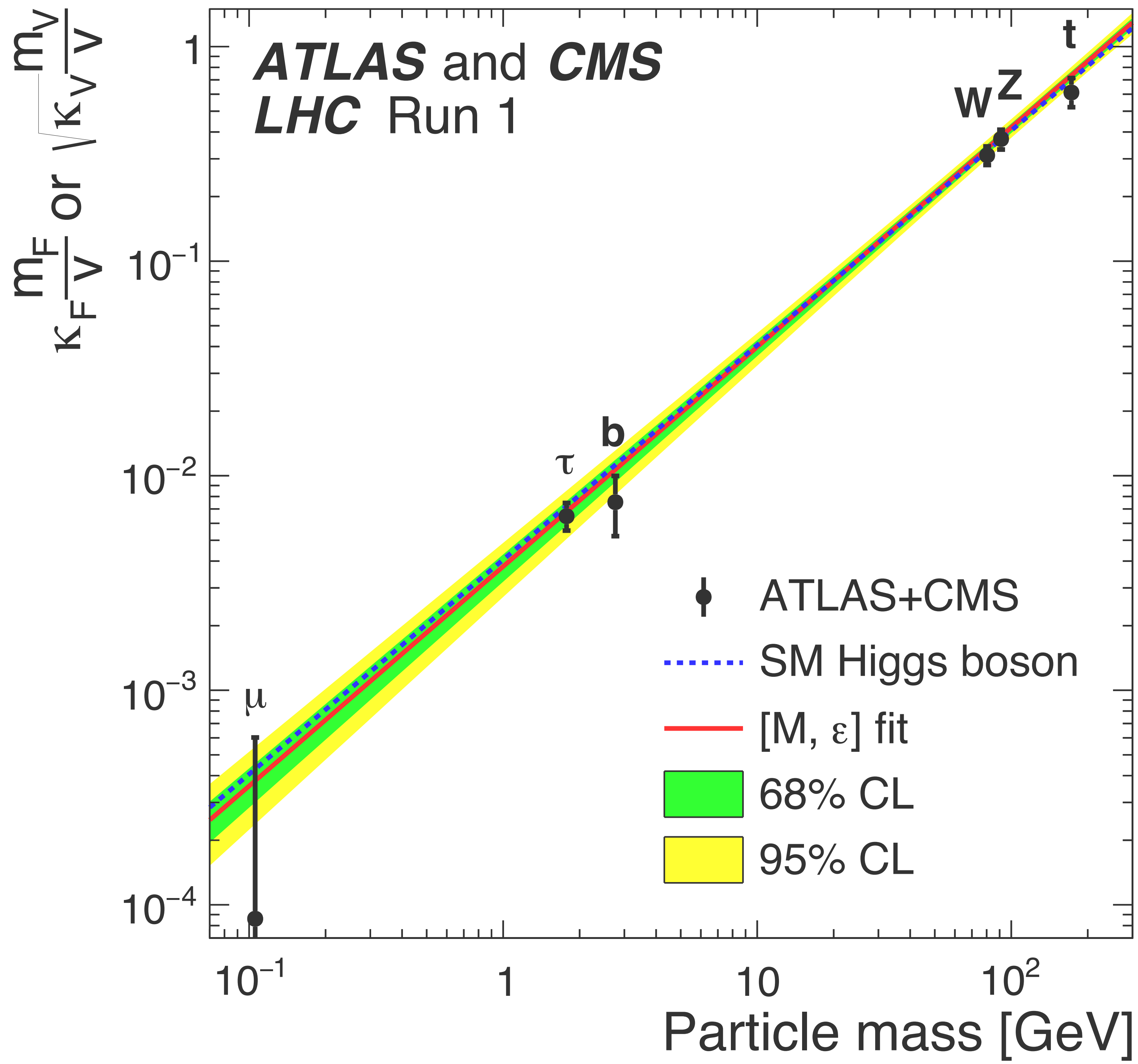
For those who have already listened to

- There’s something new:
  - Bounds got **tighter** than previous talks

So,

Picture from web

Coupling ∝ mass

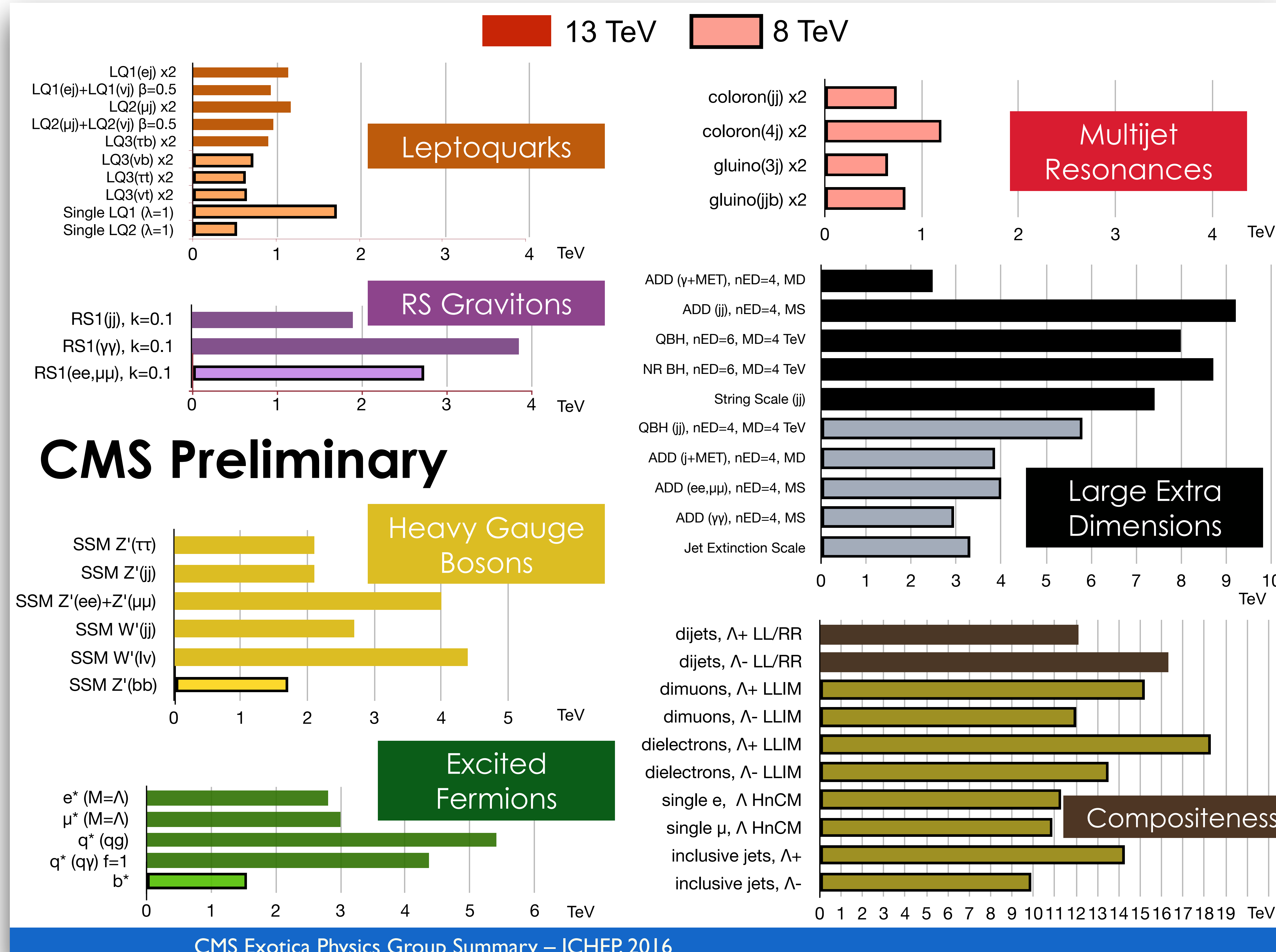


ATLAS & CMS (2016)

- ✦ Higgs ever more SM-like:
  - ★ All particles **massless** in SM
  - ★ Gets **mass** from **coupling** to Higgs VEV
- ✦ Not only with **gauge bosons**, but also with **quarks** and **leptons**.

On the other hand,

BSM total carnage



BSM total carnage

TeV SUSY / Extra dim's are dead too

Where we are

- SM may well valid up to very large scales.

- Where is new physics?

  - We know for sure that there **must** be **DM** and **neutrino masses**.

- Can we say something on them?

Plan

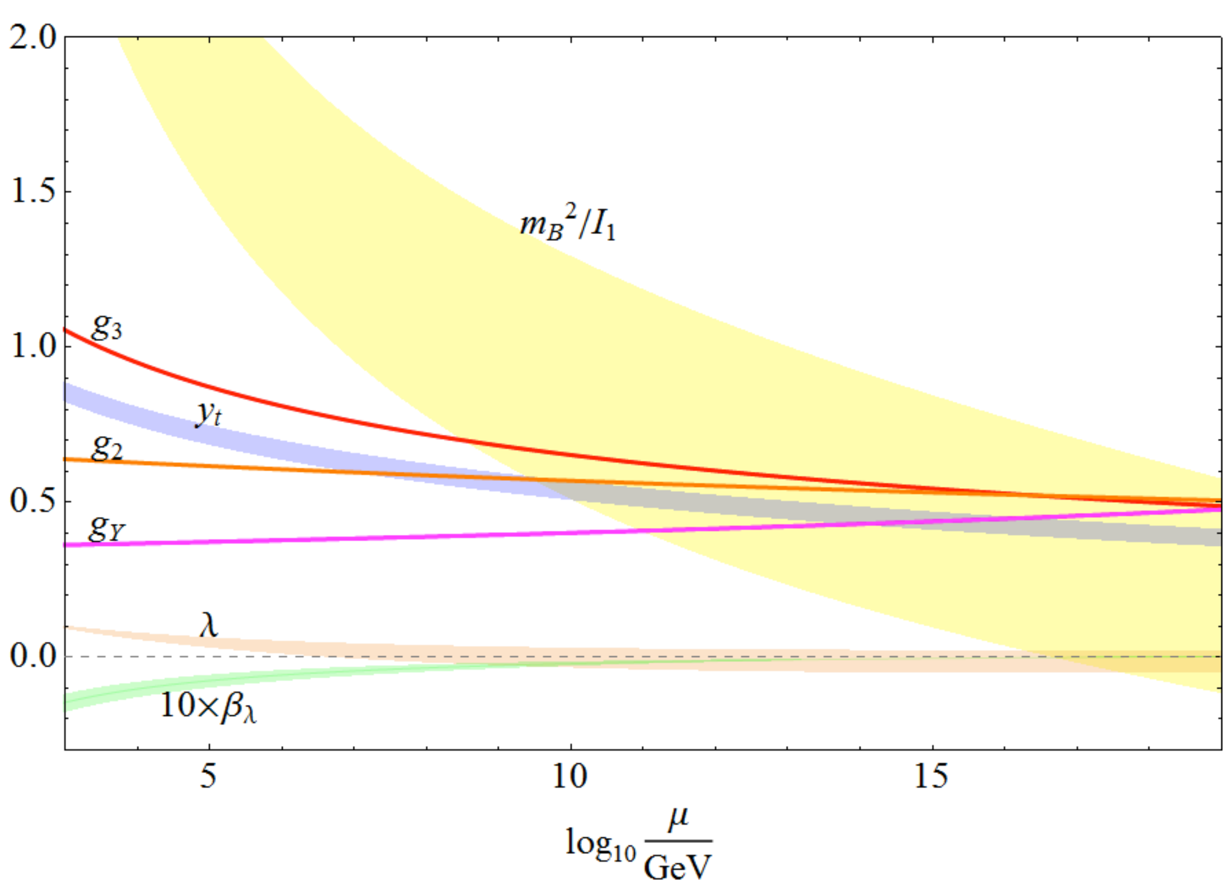
1. SM criticality

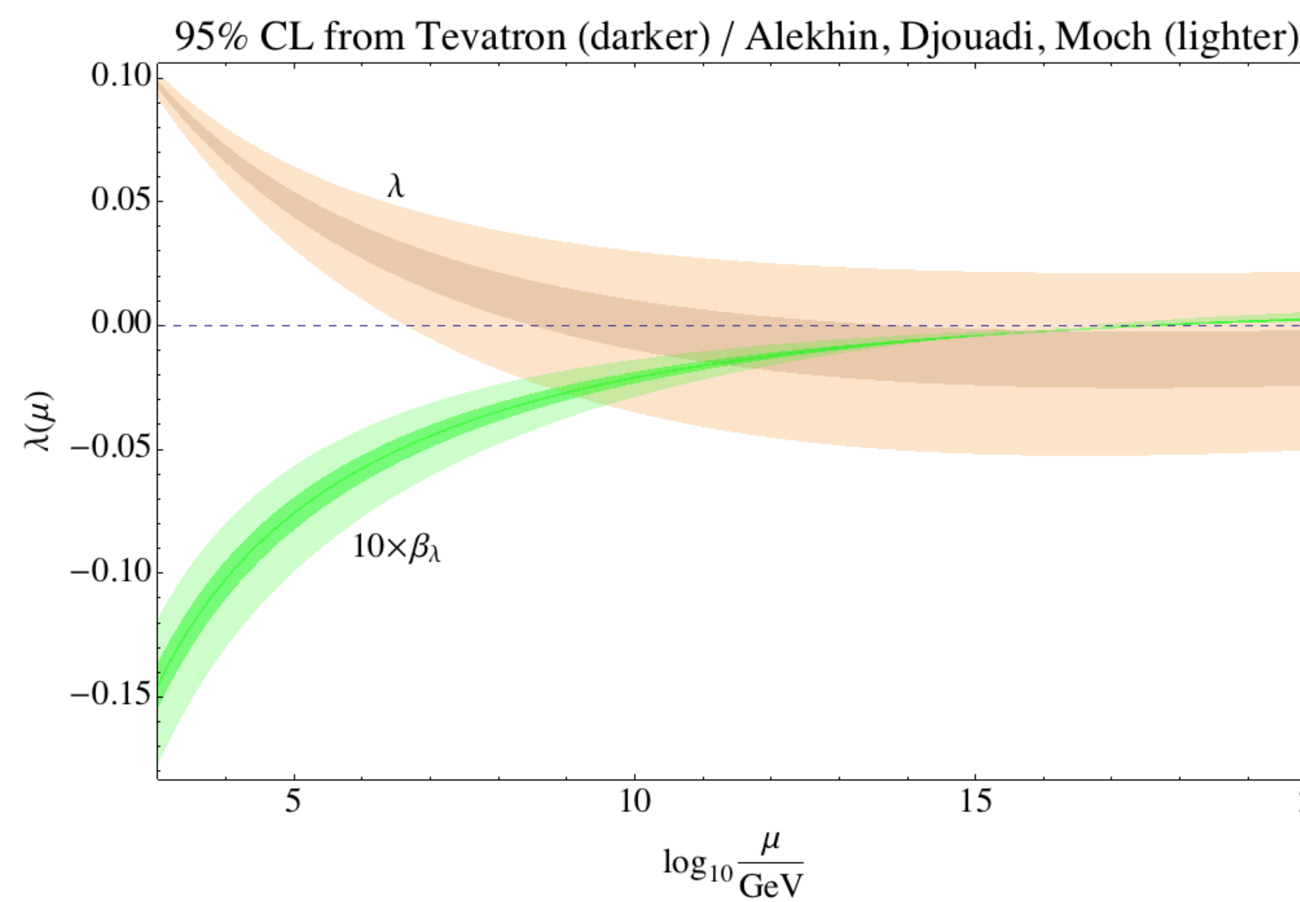
2. Higgs inflation

3. Constraints on DM and neutrino

SM criticality

- Triple criticality at Planck scale 10^{18} GeV:
  - ★ Higgs **coupling** · **scale dependence** · **bare mass** ∼0





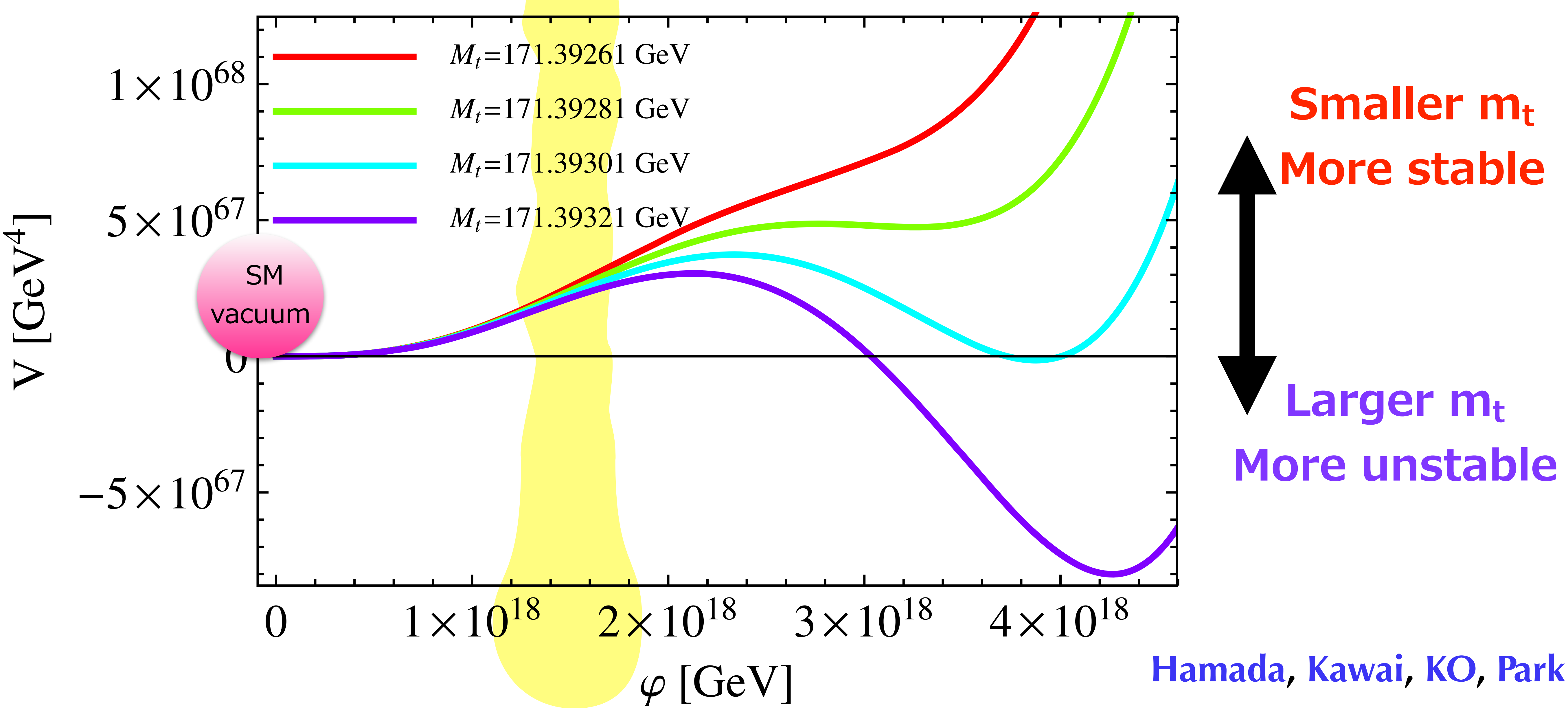
Hamada, Kawai, KO

Phys.Rev. **D87** (2013) 053009

PTEP **2014** (2014) 023B02

Higgs potential at Planck scale

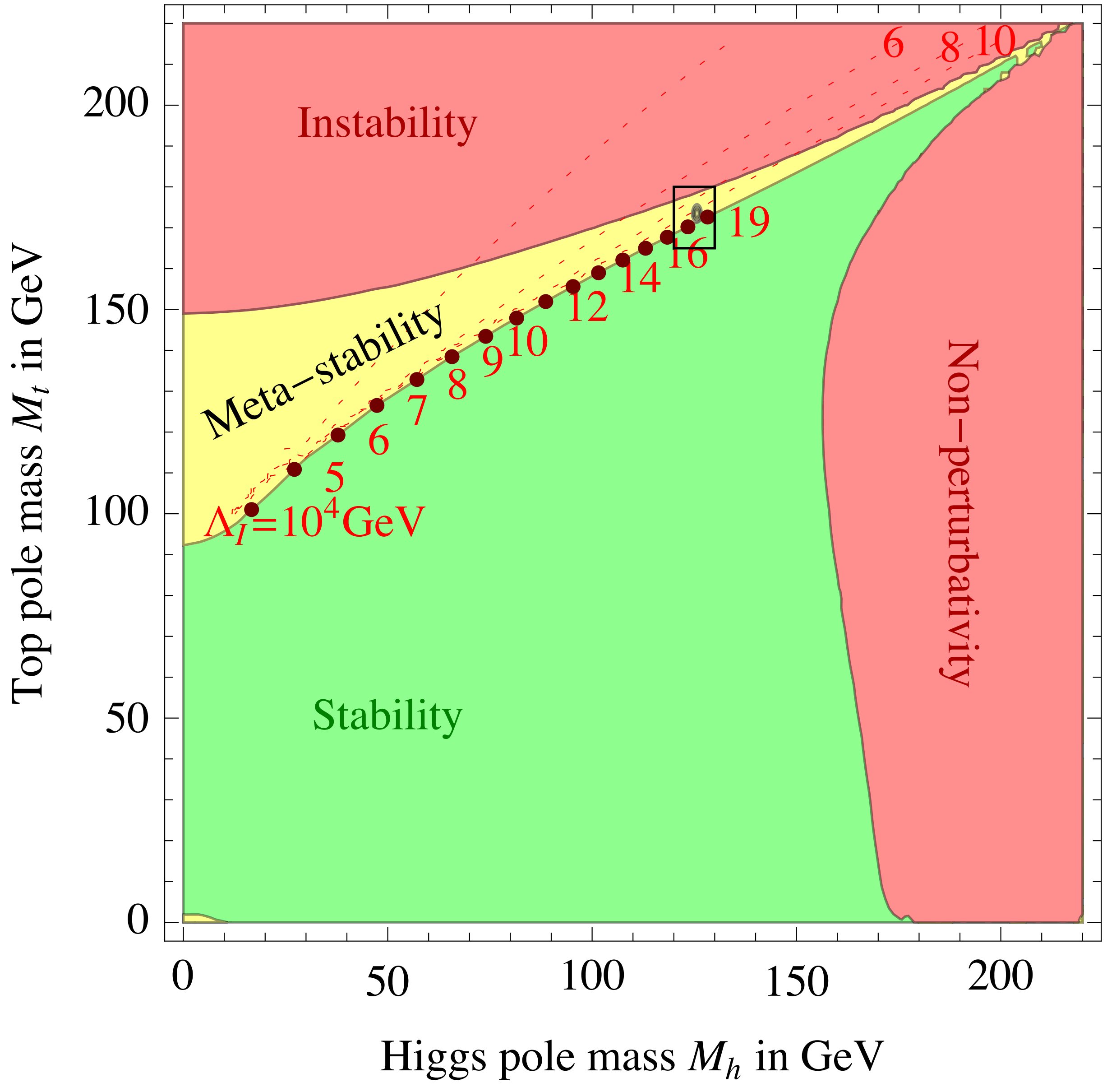
✦ **Flat** and **low** (compared to $\varphi^4 \sim 10^{72}\text{GeV}^4$)



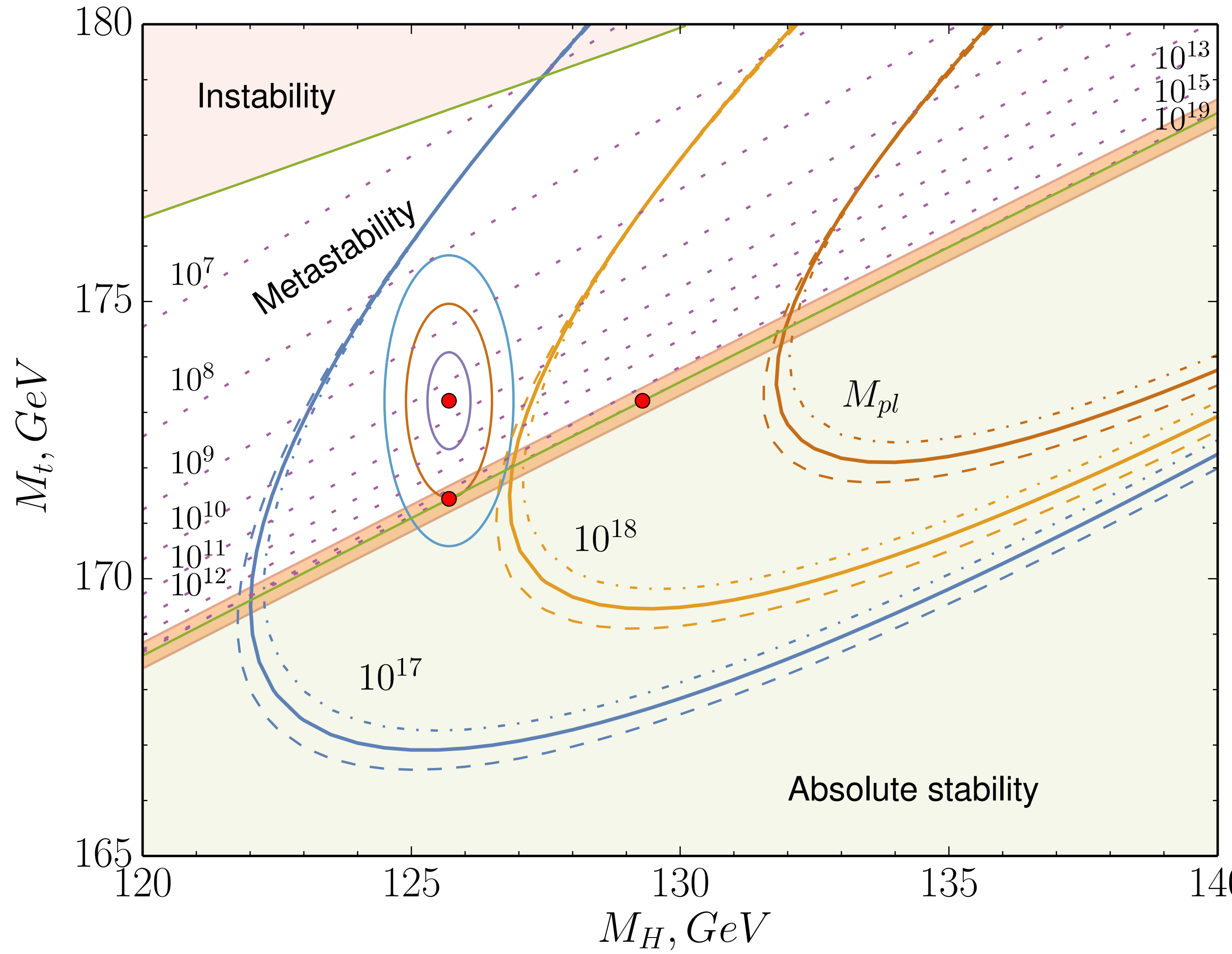
Hamada, Kawai, KO, Park
Phys.Rev. **D91** (2015) 053008

What it means

We are put on the edge



Buttazzo et al. (2013)



Bednyakov et al. (2015)

On the edge

picture from web

There is something at Planck scale

Suggesting Higgs mass related to quantum gravity

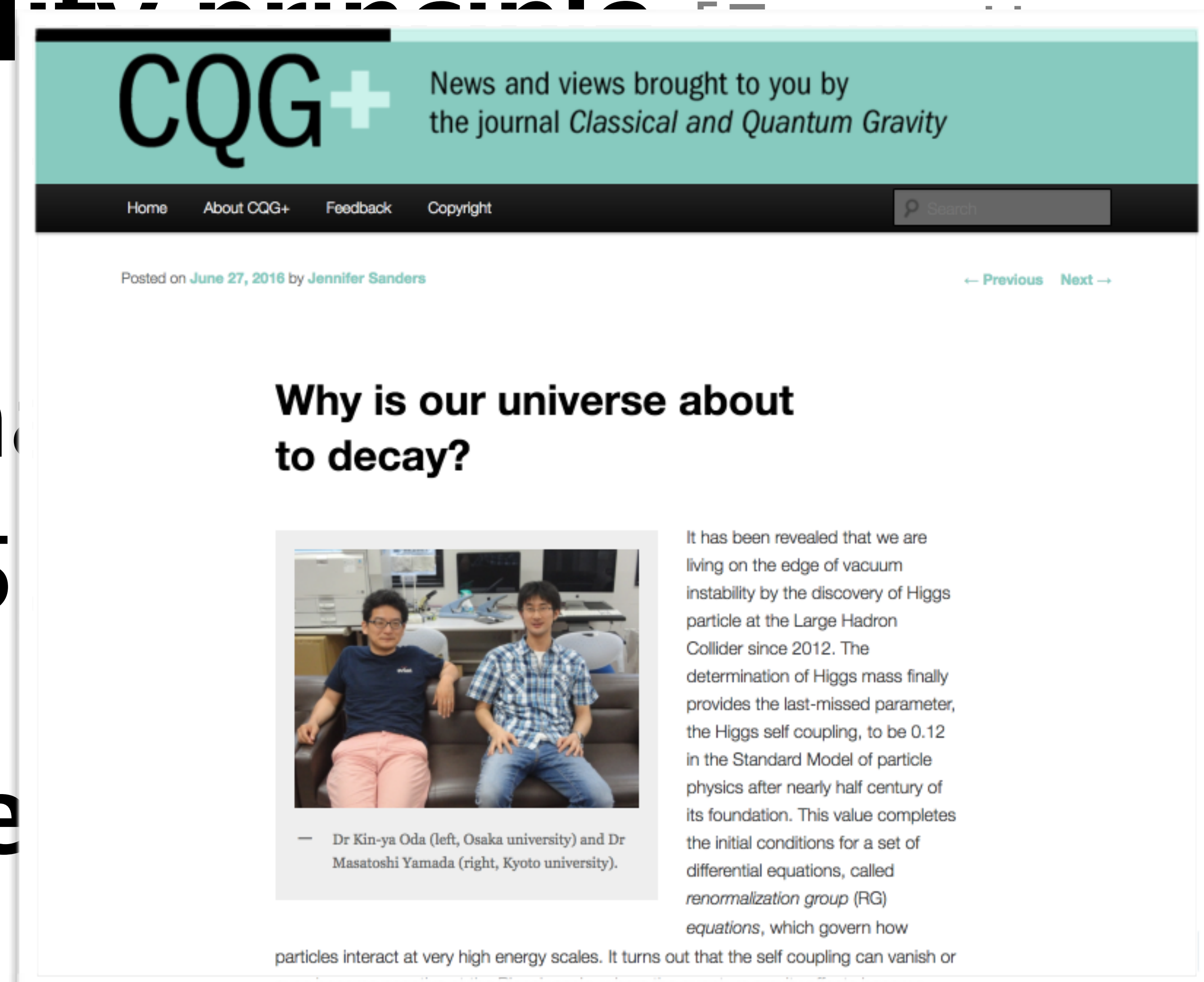
- **Multiple point criticality principle** [Froggatt, Nielsen] indeed requires this situation
  - ★ **PREdicted** Higgs mass in 1995: 135±9GeV (Cf. observed: 125.09±0.24GeV)
- Criticality in **string theory**

  Hamada, Kawai, KO
  PTEP **2014** (2014) 023B02
  Phys.Rev. **D92** (2015) 045009
- Higgs in **asymptotically safe gravity**

  KO, Yamada
  Class.Quant.Grav. **33** (2016) 125011

Suggesting Higgs mass related to quantum gravity

- **Multiple point critical**
  Nielsen] indeed requires
  - **PREdicted** Higgs m
    (Cf. observed: 125
- Criticality in **string the**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Posted on June 27, 2016 by Jennifer Sanders ← Previous Next →

Why is our universe about to decay?

— Dr Kin-ya Oda (left, Osaka university) and Dr Masatoshi Yamada (right, Kyoto university).

It has been revealed that we are living on the edge of vacuum instability by the discovery of Higgs particle at the Large Hadron Collider since 2012. The determination of Higgs mass finally provides the last-missed parameter, the Higgs self coupling, to be 0.12 in the Standard Model of particle physics after nearly half century of its foundation. This value completes the initial conditions for a set of differential equations, called *renormalization group* (RG) *equations*, which govern how particles interact at very high energy scales. It turns out that the self coupling can vanish or

- Higgs in **asymptotically safe gravity** KO, Yamada
  Class.Quant.Grav. **33** (2016) 125011

Mass parameter of theory

- Higgs mass only mass parameter in SM
- Planck mass only mass parameter in Einstein gravity
- No wonder if they are related in quantum gravity.

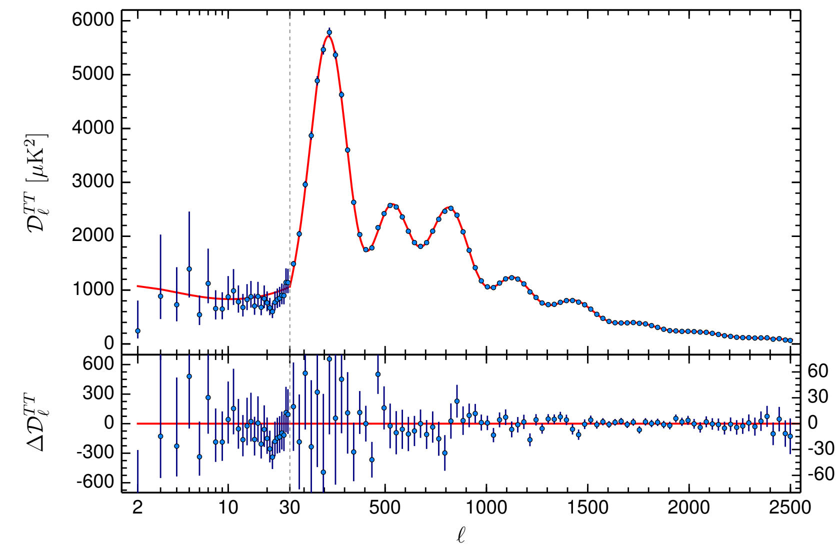
Plan

1. SM criticality
2. Higgs inflation
3. Constraints on DM and neutrino

Clear & present new physics BSM in the sky

- Hundreds of data points beautifully fit by just 6 parameters

- Today's topic:
  - ★ **Inflation**
  - ★ **DM** & neutrinos



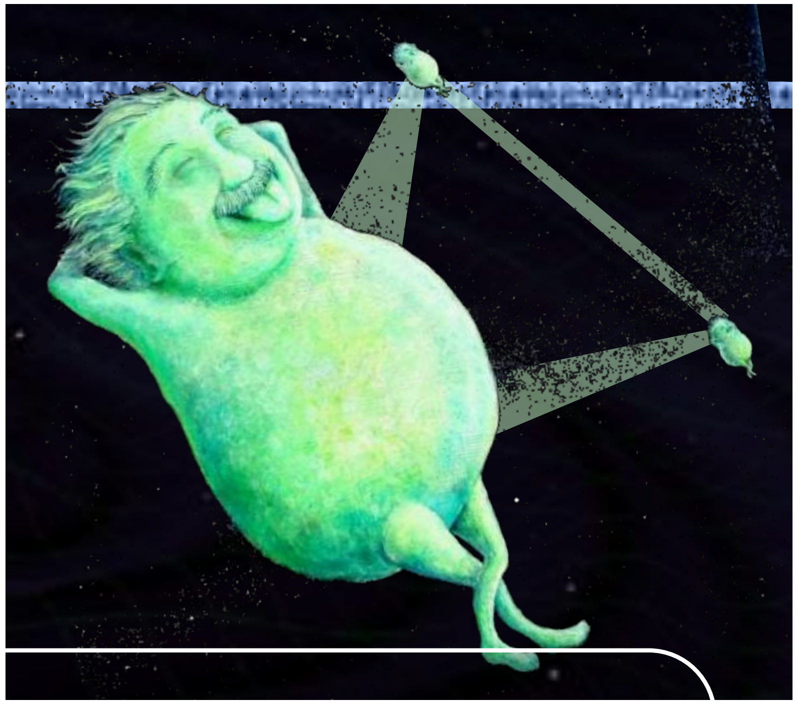
Parameter	TT+lowP 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_Λ	0.685 ± 0.013
Ω_m	0.315 ± 0.013

Planck (2016)

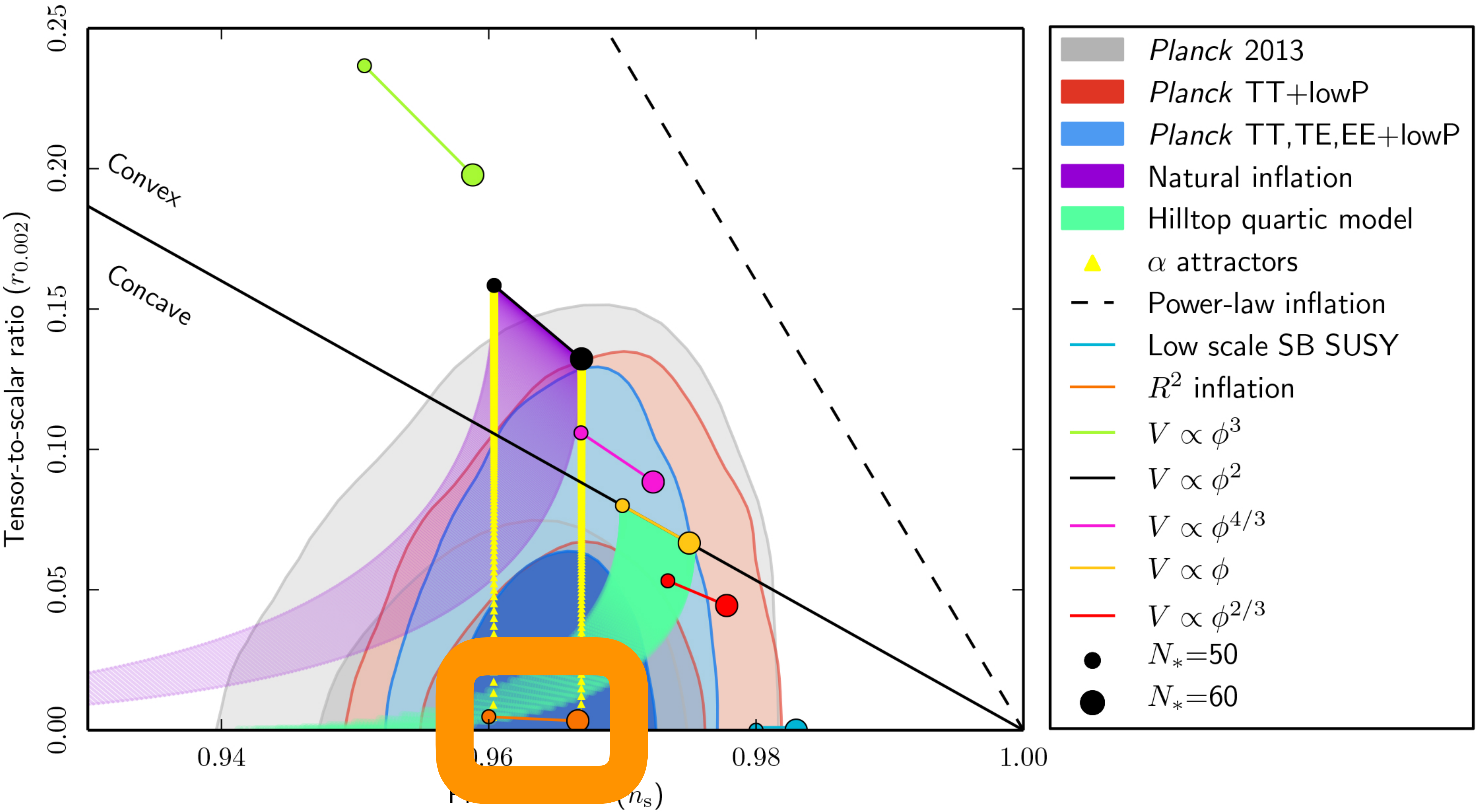
Furthermore,

Near future developments expected

- ✦ Cosmic **graviton** background:
  - ★ **Indirectly** from *r*
    - ✤ CMB B-mode immediately (Recall BICEP2 festival)
  - ★ Even **direct** observation
    - ✤ by (Ultimate) DECIGO
- ✦ Handle on **quantum gravity**


from DECIGO website

Higgs inflation



Planck (2016)

Model

Salopek, Bond, Bardeen (1989); Bezrukov, Shaposhnikov (2008)

$$S = \int d^4x \sqrt{-g} \left[\frac{M_\mathrm{P}^2}{2} \mathcal{R} + \xi \left| H \right|^2 \mathcal{R} + \mathcal{L}_\mathrm{SM} \right]$$

- **Non-minimal coupling ξ** between Higgs and gravity
- Effective Planck scale changed at $\langle H \rangle \sim M_\mathrm{P} / \sqrt{\xi}$:
  $M_\mathrm{P}{}^2 \to M_\mathrm{P}{}^2 + \xi \langle H \rangle^2$
- Flatter potential realized → inflation

Problem?

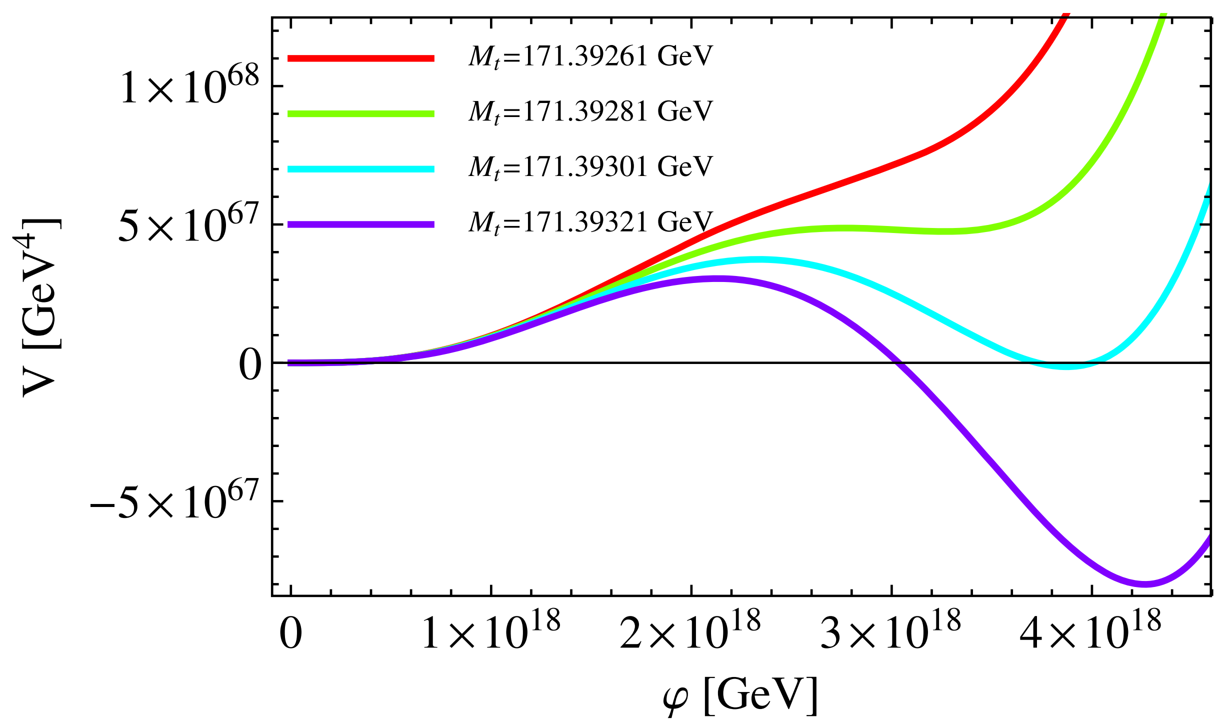
- Large **$\xi \sim 10^5$** required to yield small 10^{-5} CMB fluctuation
  - ★ Unnatural?
  - ★ Unitarity? (Though inflation itself OK)
- Implicitly assumes form of all higher dimensional $(\varphi/M_\mathrm{P})^n$ terms

Hamada, Kawai, Nakanishi, KO
Phys.Rev. **D95** (2017) 103524

Critical Higgs inflation

Hamada, **Kawai**, **KO**, **Park**
Phys.Rev.Lett. **112** (2014) 241301
Also, [Bezrukov, Shaposhnikov, 2014]

- ✦ Criticality seems requirement from quantum gravity
  - ★ **Flat** and **low** potential (compared to $\varphi^4 \sim 10^{72}\text{GeV}^4$)
  - ★ **ξ~10** suffices for viable inflation
  - ★ **Tensor-to scalar ratio *r*** observable!



Hamada, **Kawai**, **KO**, **Park**
Phys.Rev. **D91** (2015) 053008

Alternative

✦ **Hill-climbing Higgs inflation** [Jinno, Kaneta, **KO**, 2017]

$$S = \int d^4x \sqrt{-g}\, [F(\phi)\mathcal{R} + \mathcal{L}_{\rm SM}]$$

✦ Instead of $F(\varphi) \to \xi\varphi^2$, $\boldsymbol{F(\varphi) \to 0}$ can cause inflation.

⋆ $F(\varphi)=0$ at $V(\varphi) = 0$ point.

⋆ Better match with Nielsen's **MPP**?

Important point hereafter

- Both critical and Hill-climbing Higgs inflations are **almost SM** slightly below **Planck scale**.
- "Slightly below" here means roughly 10^{17}GeV
  - This is also good old **string scale**.
- "Almost"?
  - We put **Higgs-portal scalar DM** and **right-handed neutrinos**.

Plan

1. SM criticality
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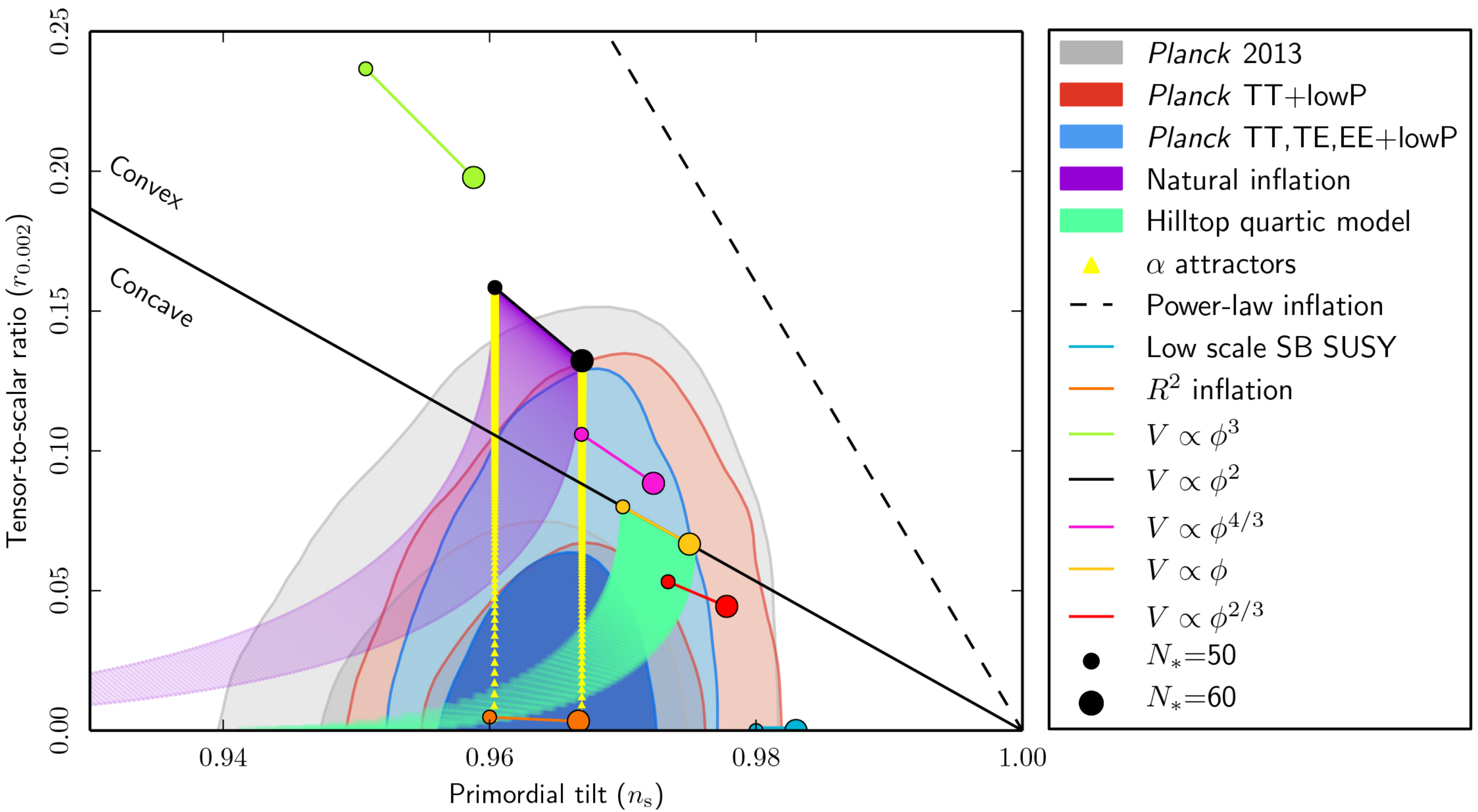
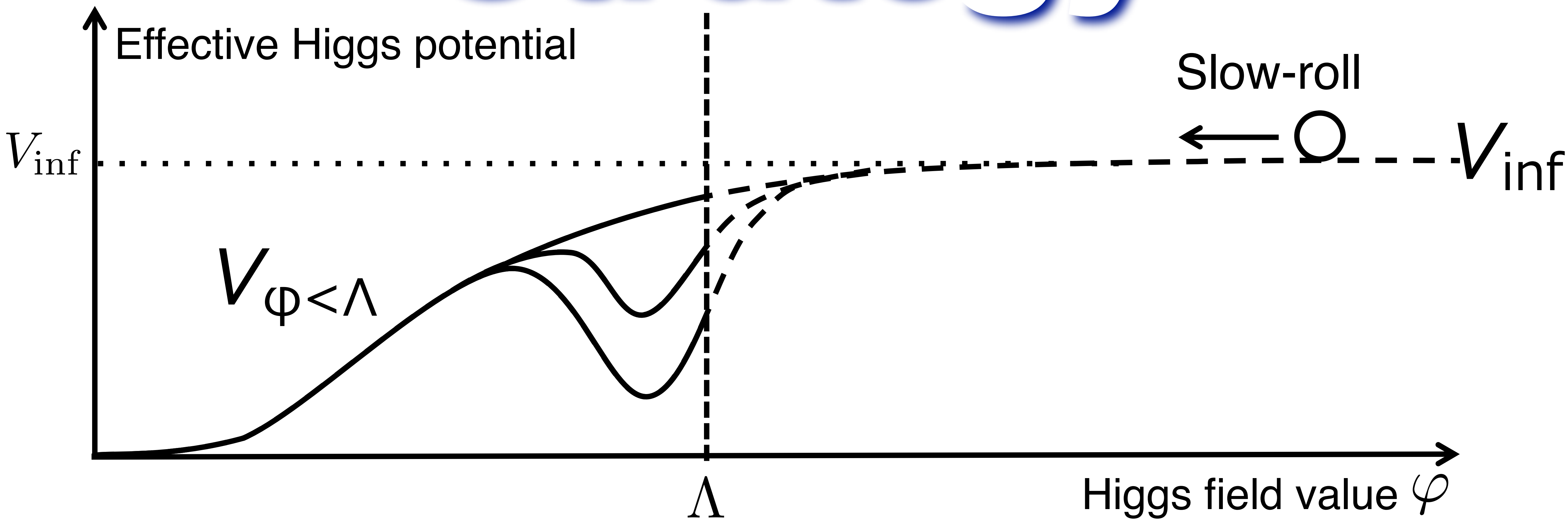
Recall



Planck (2016)

Strategy

Hamada, Kawai, **KO** (2014)



- From low energy potential $V_{\varphi<\Lambda}$, we get lower bound: $V_{\rm inf} > V_{\varphi<\Lambda}^{\rm max}$.
- In slow-roll, $A_s = 0.068\ V_{\rm inf}/r$ ($=2.2\times10^{-9}$, fixed)
- So we have lower bound: $r > V_{\varphi<\Lambda}^{\rm max}/(3.2\times10^{16}\,{\rm GeV})^4$.

Note: This analysis can be performed for ANY model that changes λ running

Do it for your model.

Inflation-model independence

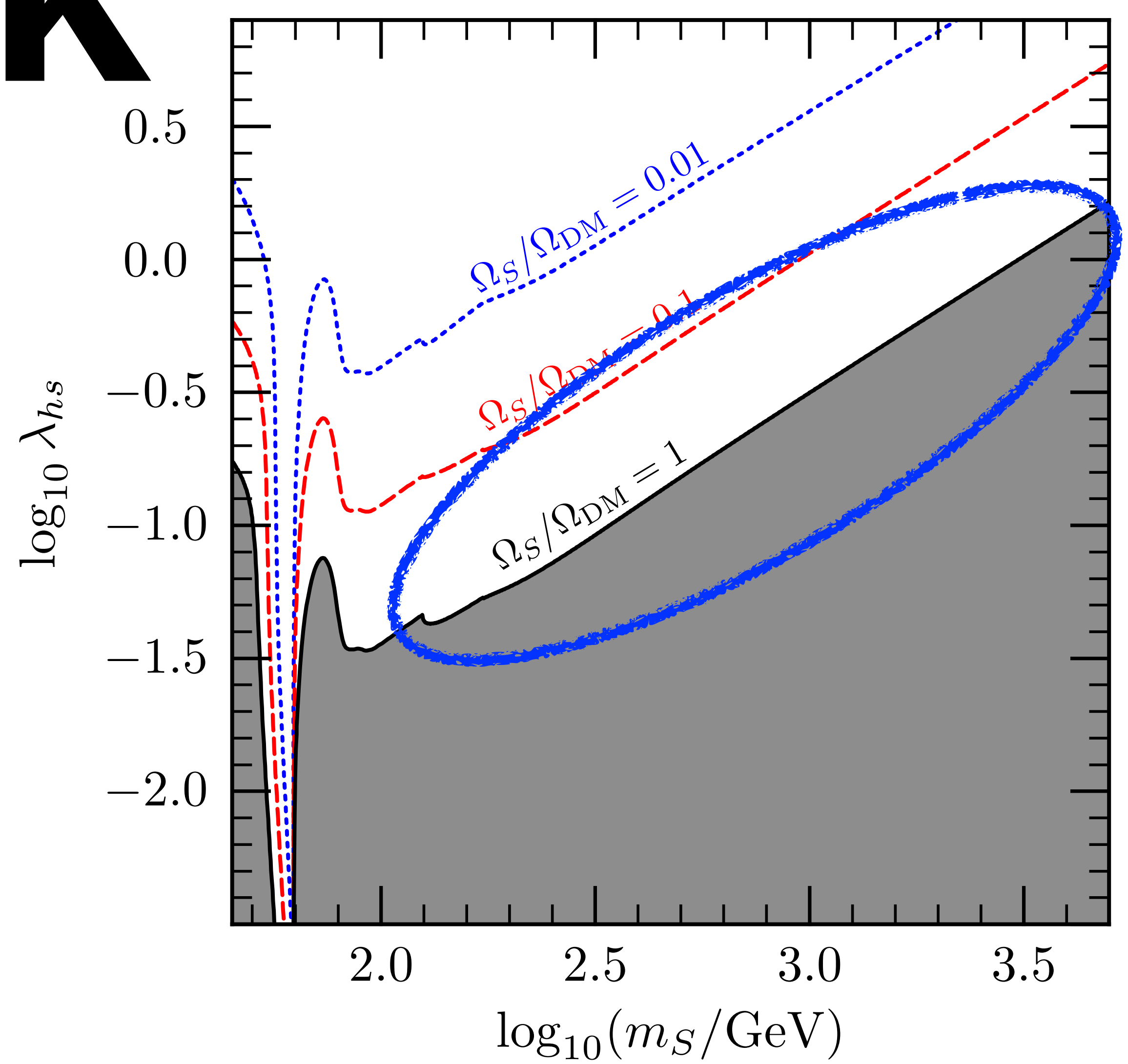
- This analysis does **not** assume the form of inflaton potential.
- Can be derived **only from low energy data**.
- Can be **critical Higgs inflation**; but even if not, **any deformation of Higgs potential** should obey our constraint, if **the modified Higgs potential at high scales** inflates universe.

Higgs-portal Z_2 scalar DM

Mass vs portal coupling

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4!}S^4 - \frac{\kappa}{2}S^2\Phi^\dagger\Phi$$

κ



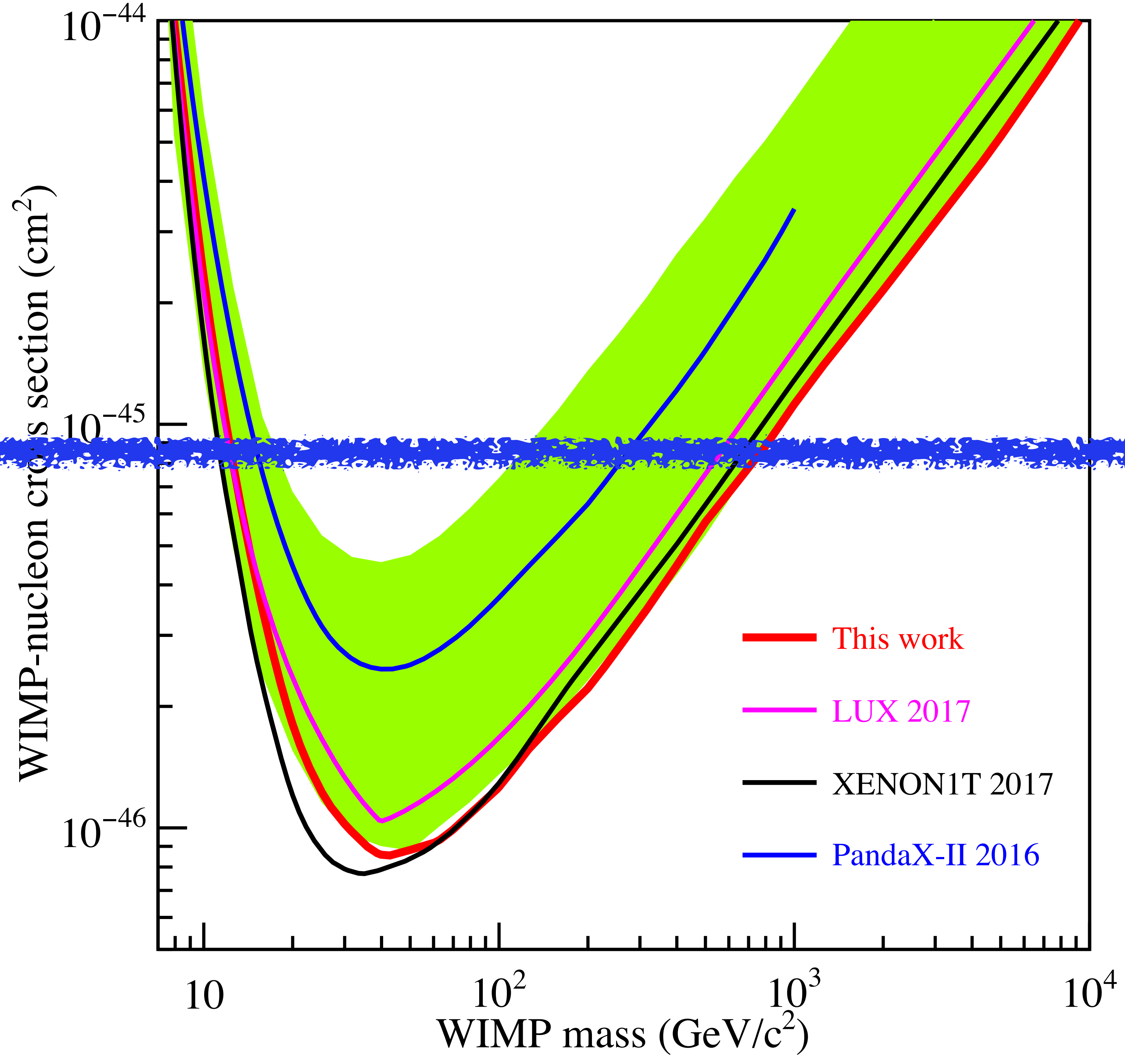
$$m_{\rm DM} \simeq \kappa \times 3.2\,\mathrm{TeV}$$

$\sigma_{\rm SI} \sim 10^{-45}\mathrm{cm}^2$, fixed

***m*DM**

Cline, Kainulainen, Scott, Weniger (2013)

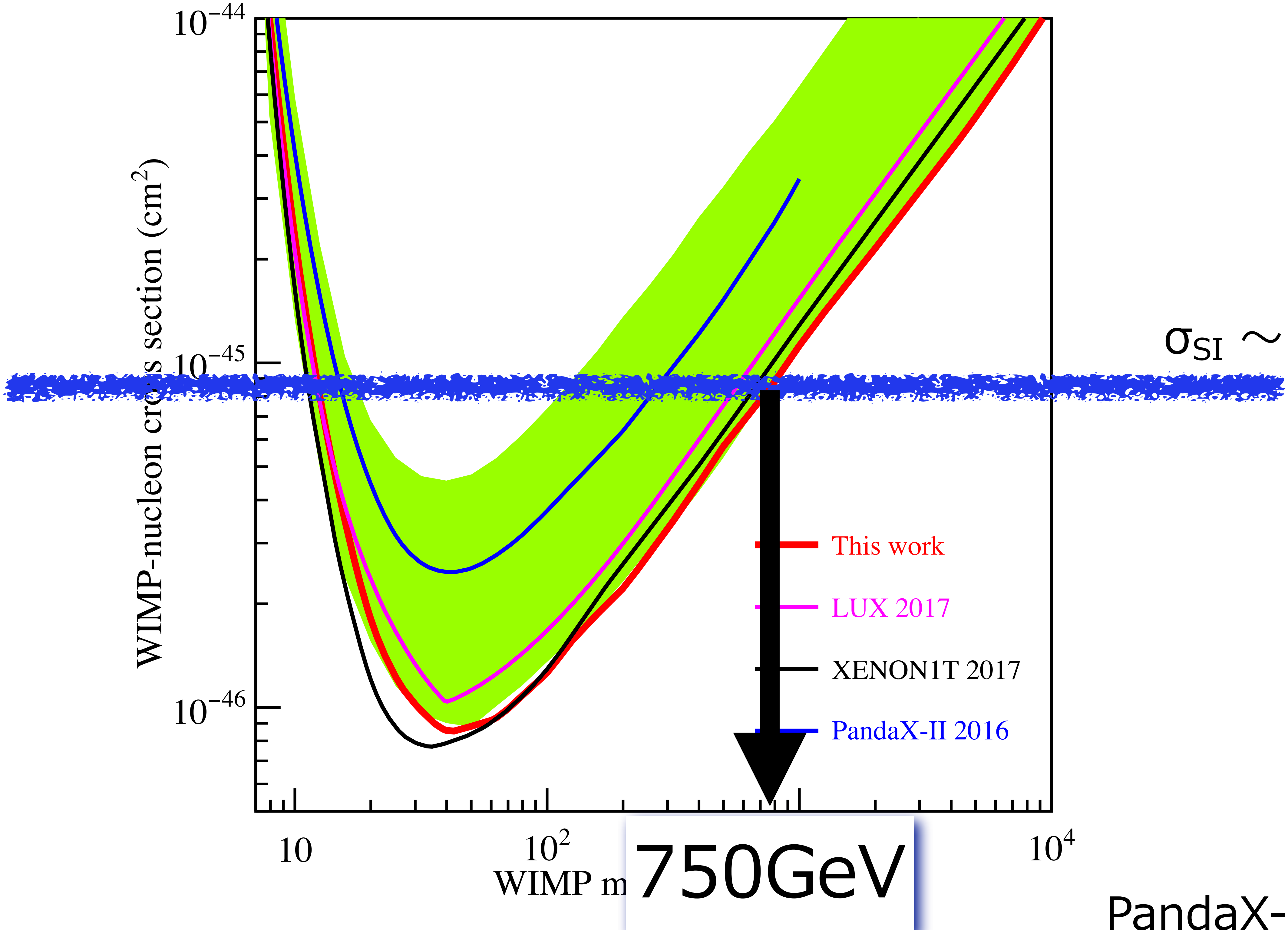
Lower bound on DM mass



$\sigma_{SI} \sim 10^{-45} cm^2$

PandaX-II (2017)

Lower bound on DM mass



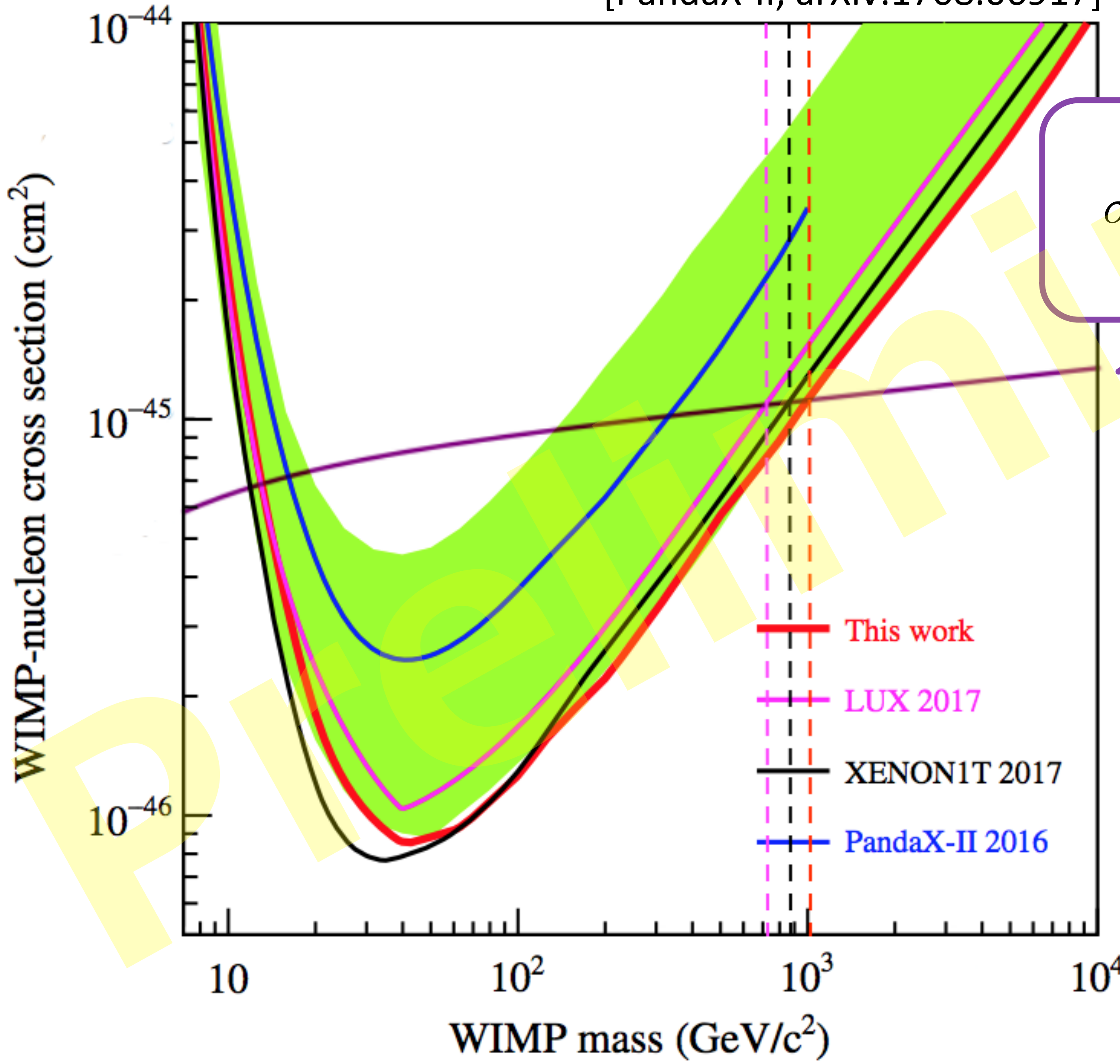
$\sigma_{SI} \sim 10^{-45}\mathrm{cm}^2$

PandaX-II (2017)

Lower bound on DM mass

Spin-independent cross section between DM and nucleon

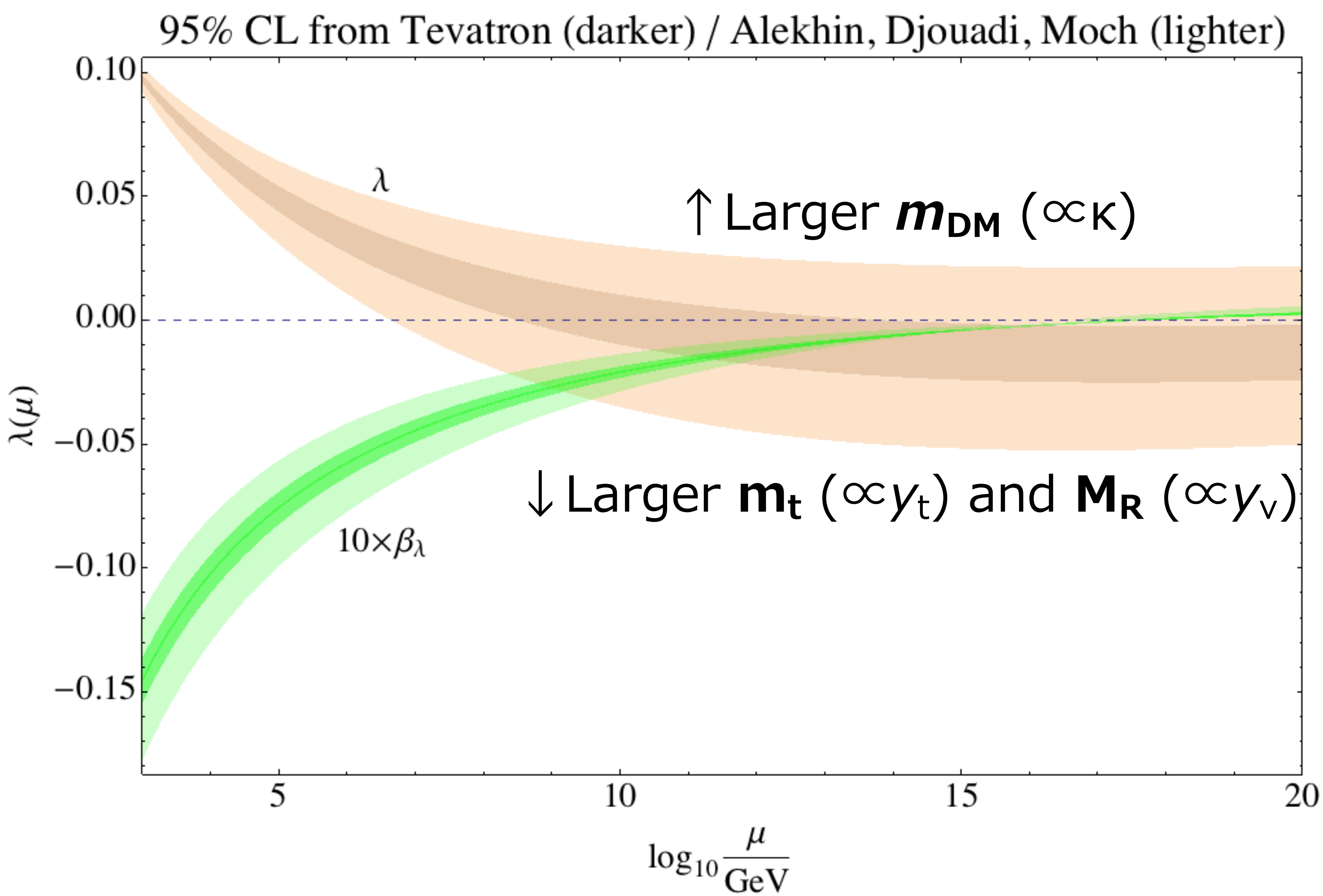
[PandaX-II, arXiv:1708.06917]



$$\sigma_{\rm SI} = \frac{\kappa^2 f_N^2}{4\pi}\left(\frac{m_n m_{\rm DM}}{m_n + m_{\rm DM}}\right)^2 \frac{m_n^2}{m_H^4 m_{\rm DM}^2}$$

現在の制限は $\gtrsim 1\,\mathrm{TeV}$

High scale potential



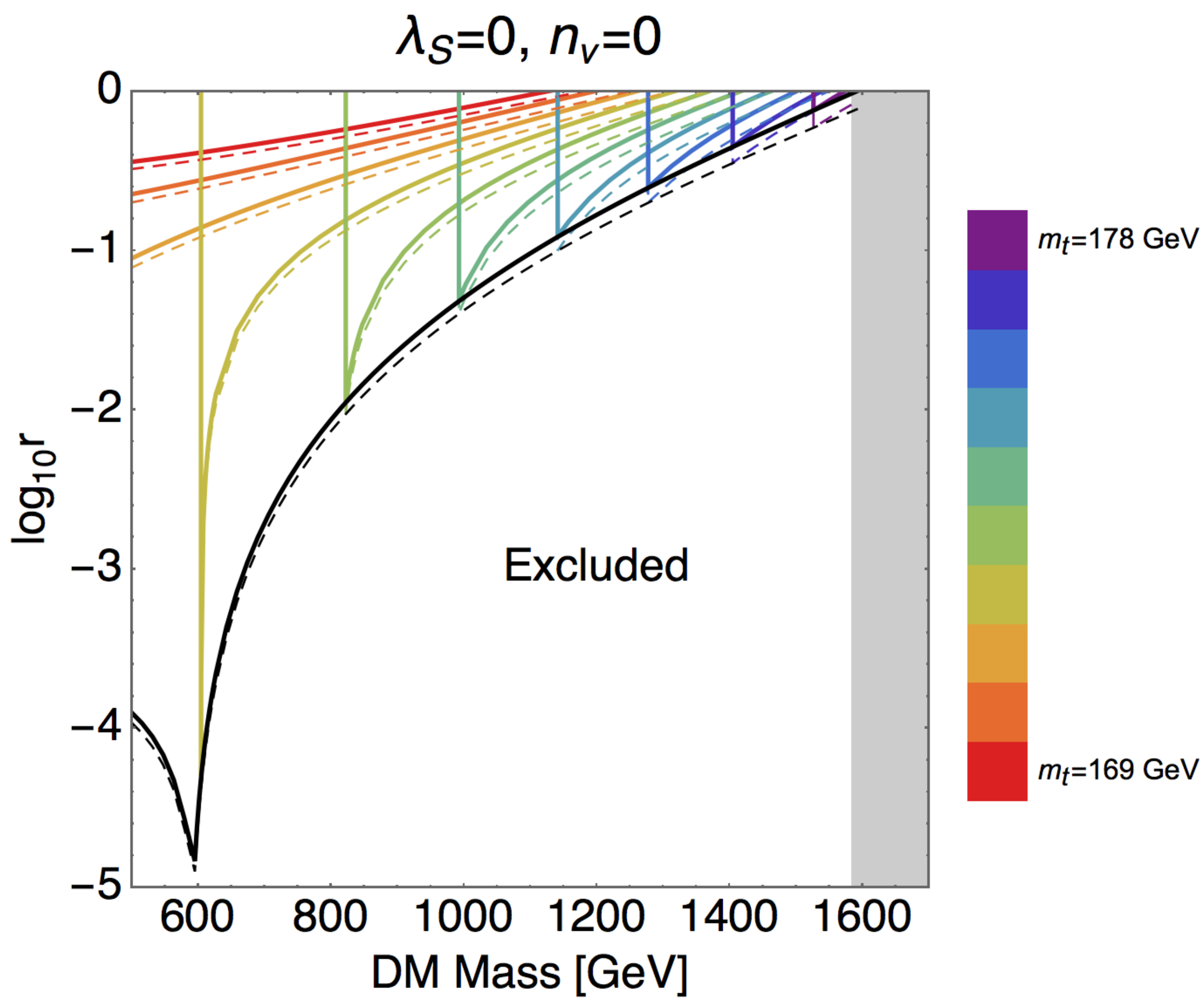
Hamada, Kawai, **KO** (2014)

Basics

- Larger κ ($\propto m_{DM}$) makes **Planck-scale potential *V*** higher.
  - Gives larger (severer) **lower bound on *r***.
- Larger **top mass $\mathbf{m_t}$** gives smaller *V*.
  - Potential gets **negative** without κ contribution.

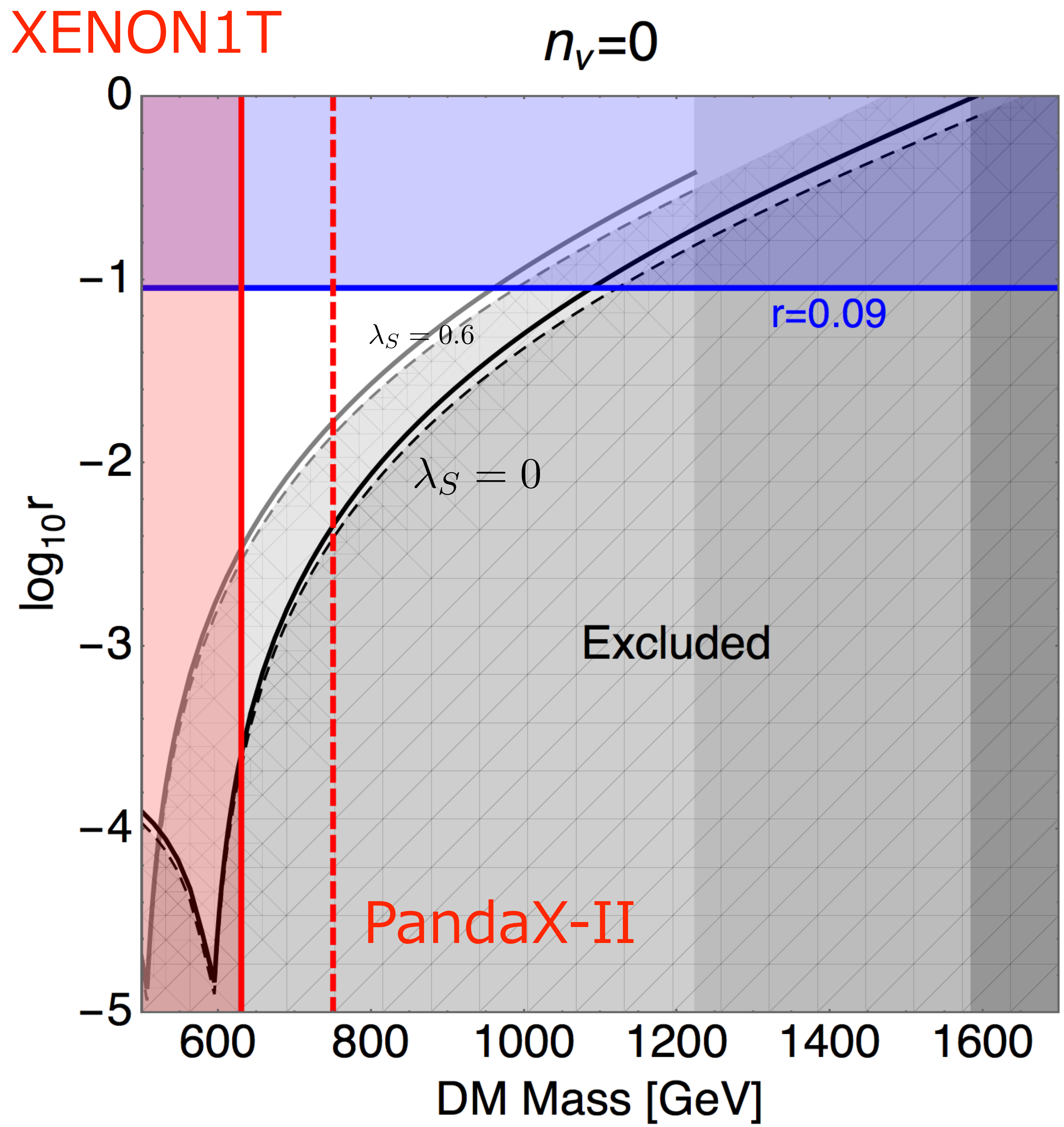
Result

Lower bound on r



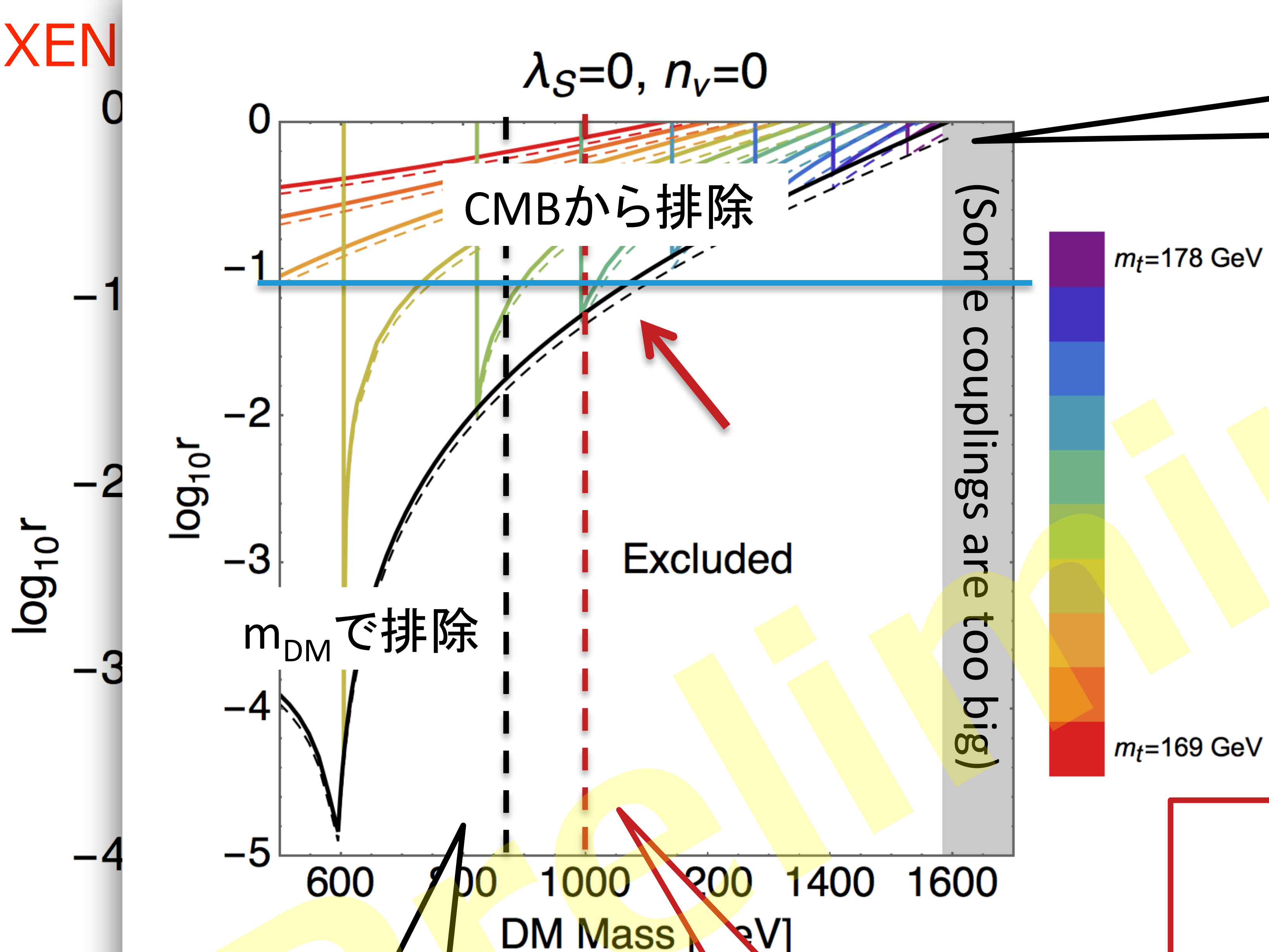
✦ Vertical line from potential positivity.

Varying m_t



- We get $\underline{m_{DM} < 1.1\text{TeV}}$, soon observable!
- Also PandaX-II bound reads $\underline{r > 4\times10^{-3}}$, detectable in near future

Varying m_t



- - - - : Wave function renormalization error

トップクォーク質量を固定した場合の制限

XENON1T
$\gtrsim 870\,\mathrm{GeV}$

PandaX-II
$\gtrsim 1\,\mathrm{TeV}$

$$r \gtrsim 4 \times 10^{-2}$$

$$m_{\mathrm{DM}} \lesssim 1.1\,\mathrm{TeV}$$

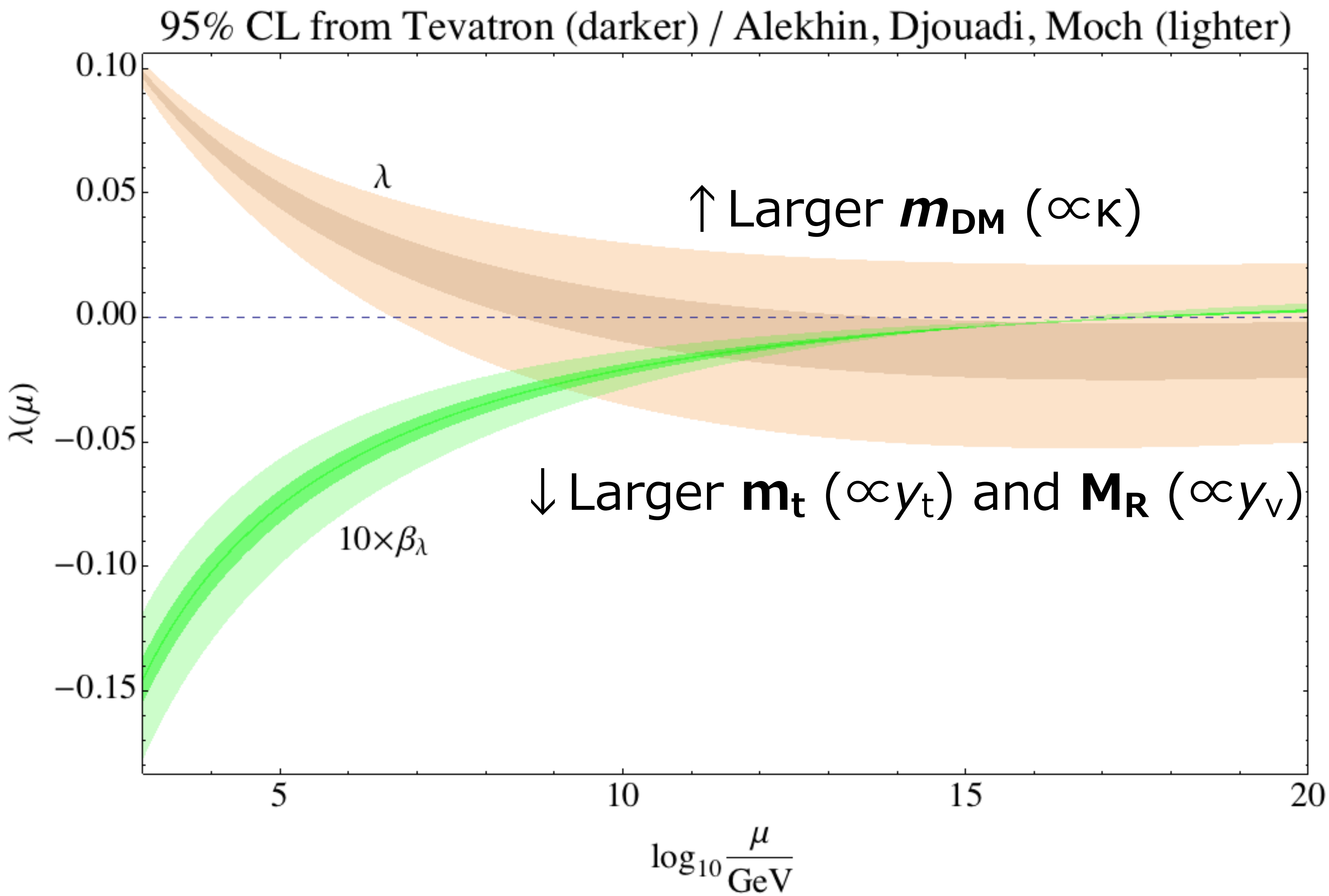
$$174\,\mathrm{GeV} \lesssim m_t < 175\,\mathrm{GeV}$$

Right-handed neutrinos

Basics

- **Right-handed neutrinos** reduces *V*.
  - Contributes like top-quark above M_R.
  - Makes **lower bound on *r*** smaller (milder).
  - *V* gets **negative** if κ ($\propto m_{DM}$) too small.

Recall



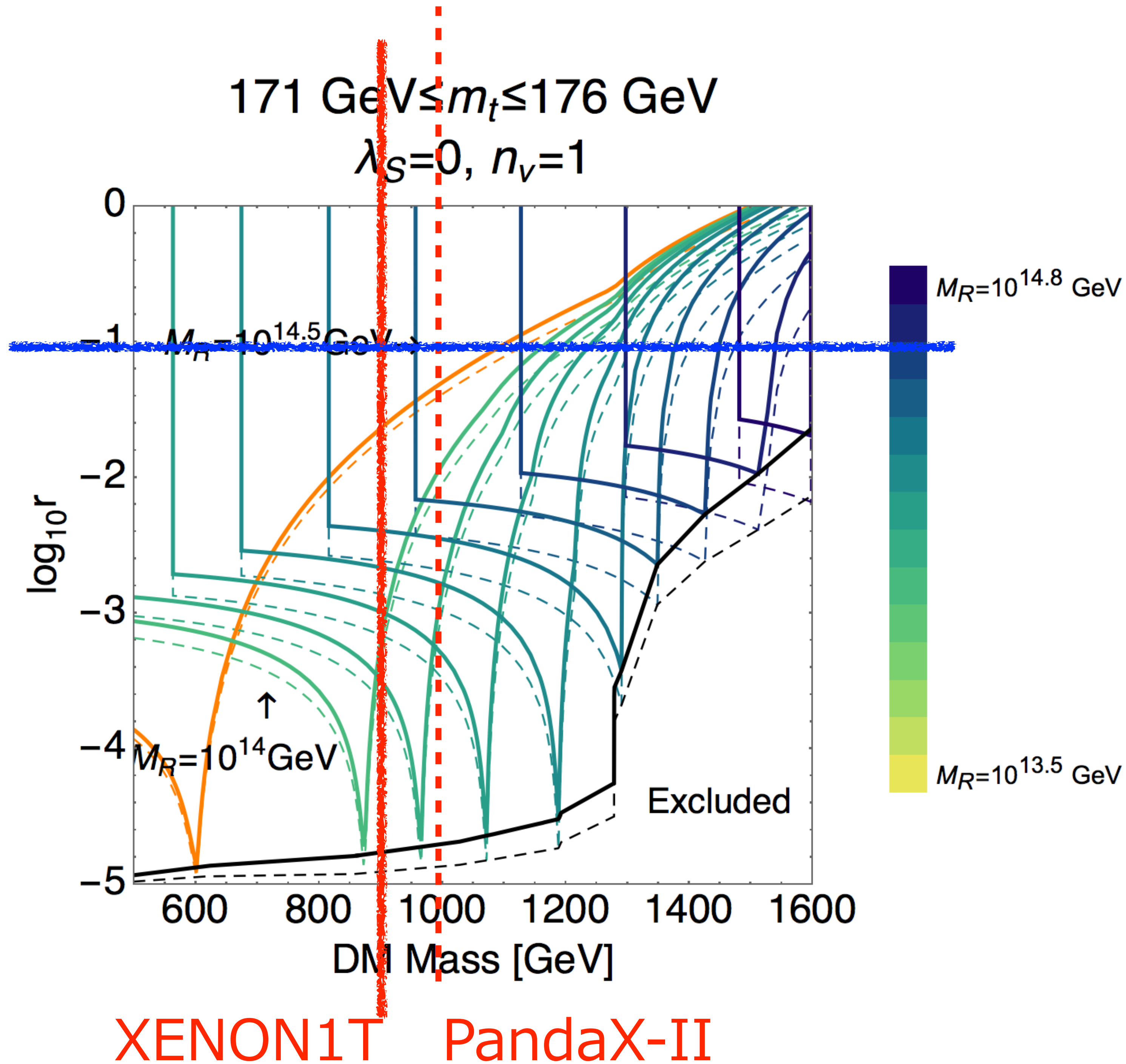
Hamada, Kawai, **KO** (2014)

Result

Inclusion of ν_R

Hamada, Kawai, Nakanishi, **KO** (2017)

- $M_R = 10^{14\text{-}15}$**GeV** widen allowed region.
- Still $r > \sim 10^{-3}$ without fine-tuning.
- Absolute bound $r > 10^{-5}$.
  - ★ Even when we allow maximum fine-tuning.



For fixed m_t (same)

Hamada, Kawai, Nakanishi, **KO** (2017)

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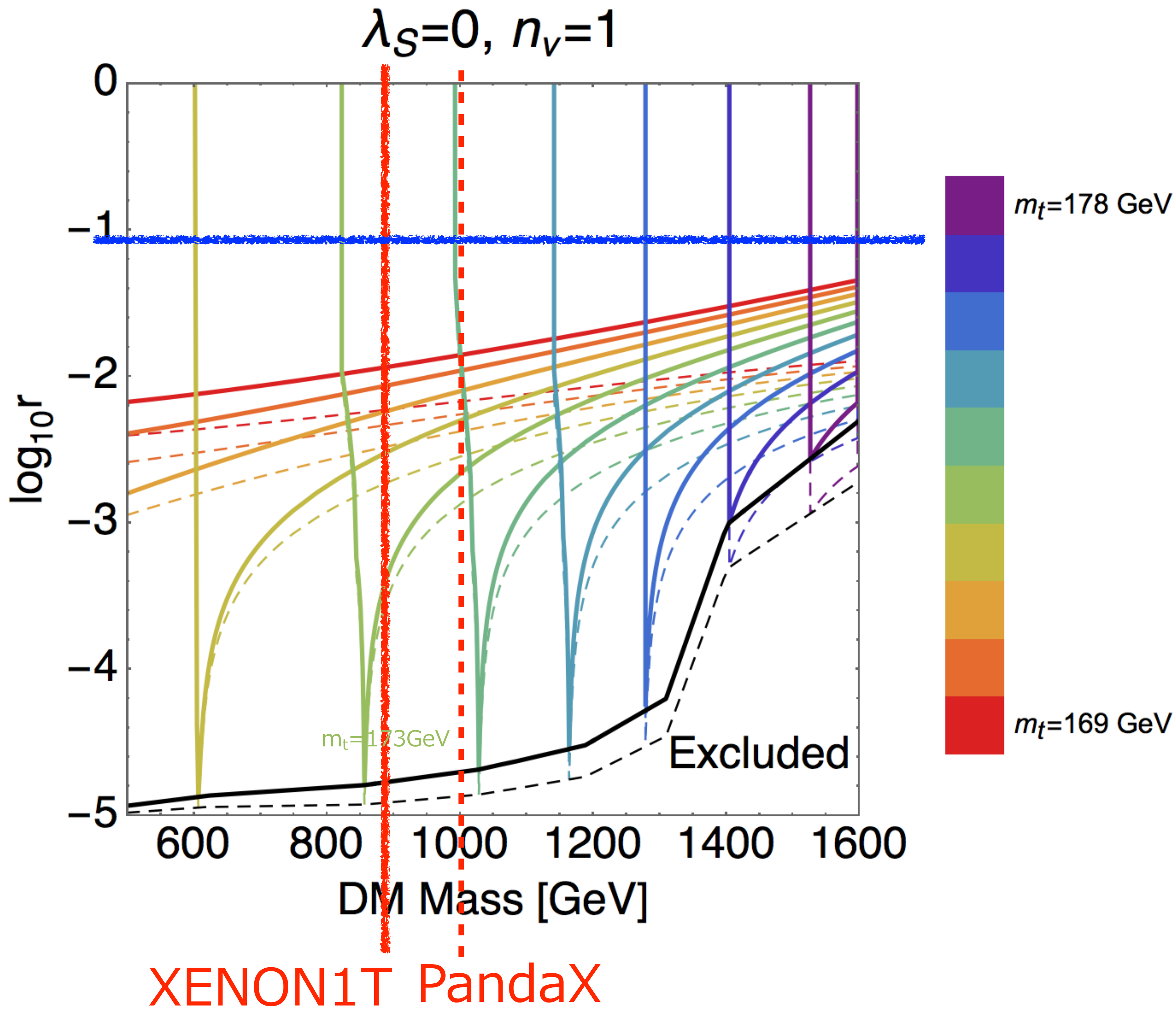


Backup for degenerate

- Possible mass patters.

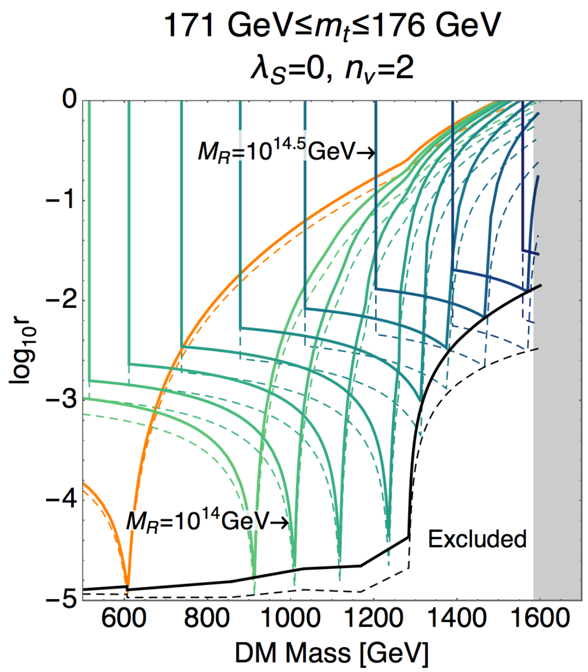
	m_1 [eV]	m_2 [eV]	m_3 [eV]	Pattern
1. Normal Hierarchy	0 (set)	8.6×10^{-3}	5.1×10^{-2}	$m_1 \ll m_2 < m_3$
2. Inverted Hierarchy	5.0×10^{-2}	5.0×10^{-2}	0 (set)	$m_1 \simeq m_2 \gg m_3$
3. Degenerate (NO)	0.1 (set)	1.0×10^{-1}	1.1×10^{-1}	$m_1 \simeq m_2 \simeq m_3$
3. Degenerate (IO)	1.1×10^{-1}	1.1×10^{-1}	0.1 (set)	$m_1 \simeq m_2 \simeq m_3$

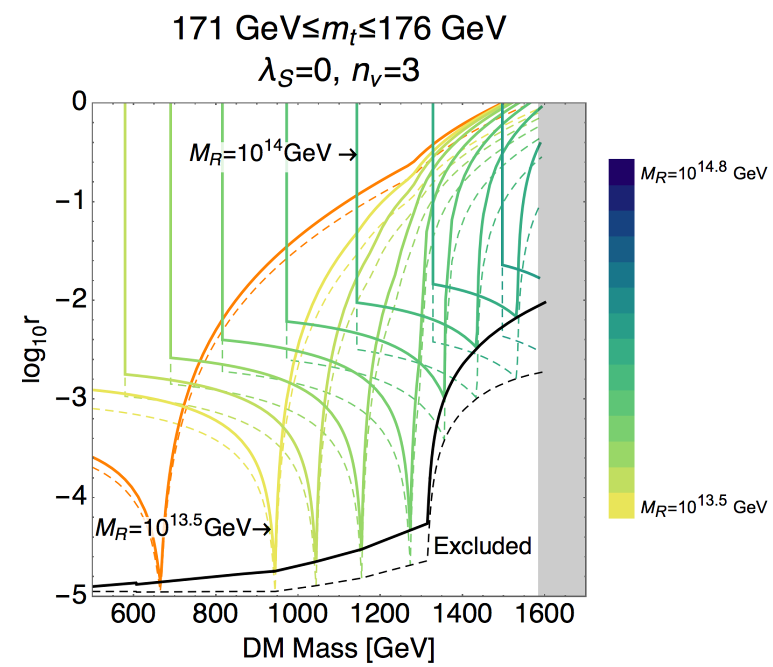
- Our assumption. ($M_R \propto$ unit matrix)

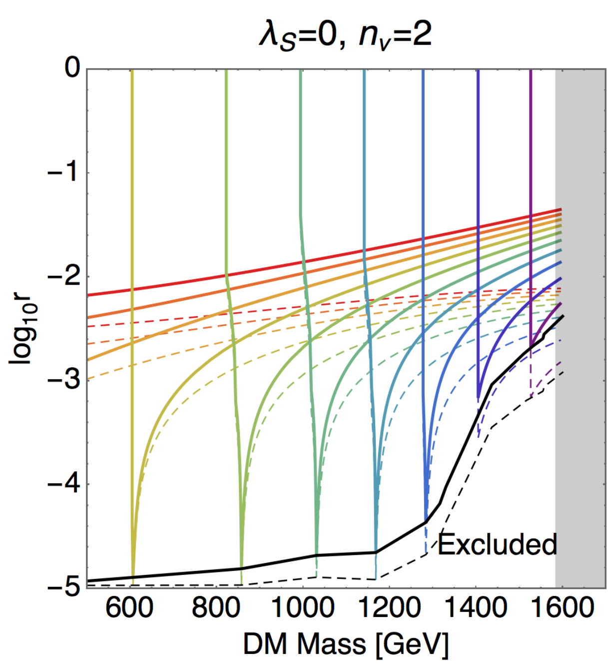
	Number of effective ν	Common mass m_ν [eV]
1. Normal Hierarchy	$n_\nu = 1$	5.1×10^{-2}
2. Inverted Hierarchy	$n_\nu = 2$	5.0×10^{-2}
3. Degenerate	$n_\nu = 3$	1.1×10^{-1}

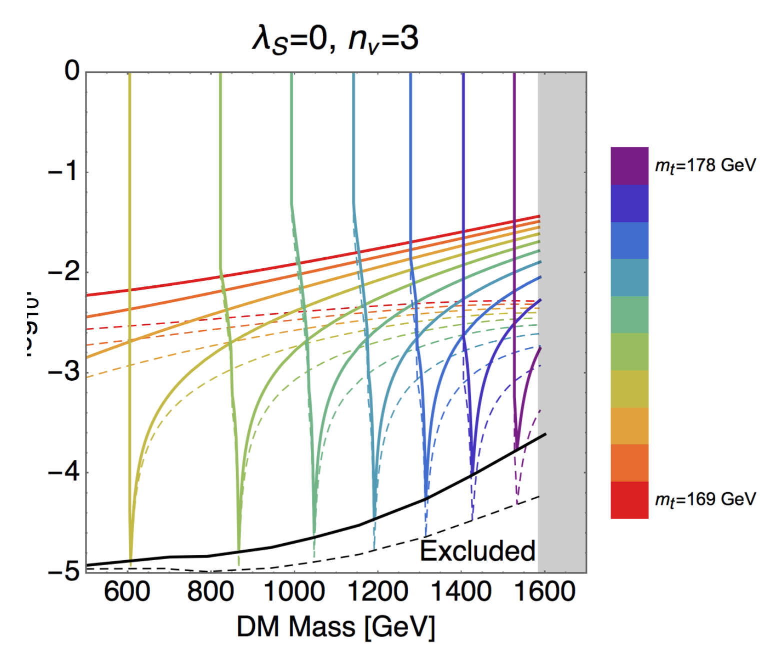
Backup result

- ✦ For 2 and 3 degenerate generations









Summary

1. SM criticality

2. Higgs inflation

3. Constraints on DM and neutrino


Thank you!