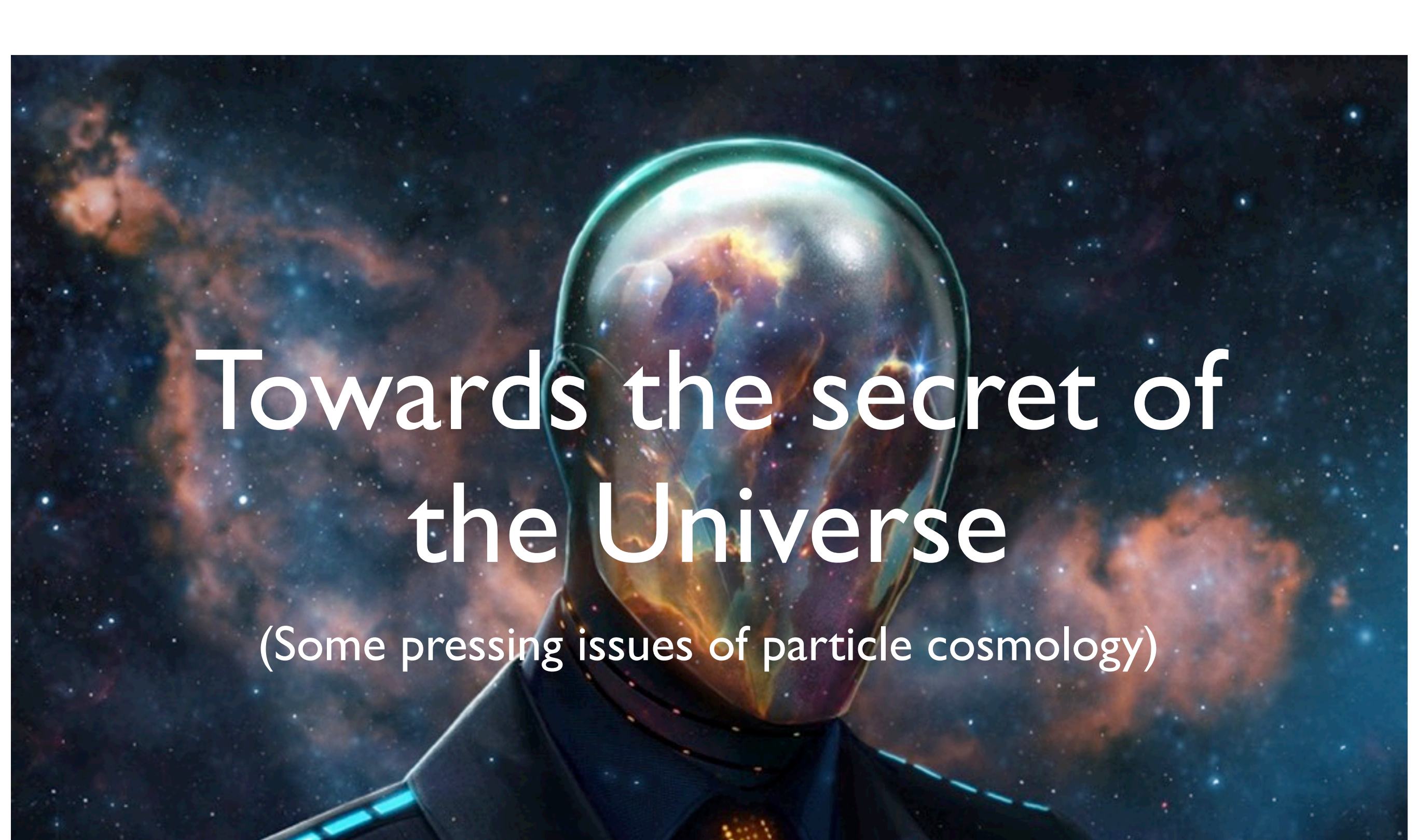




Towards the secret of the Universe

(Some pressing issues of particle cosmology)

Wan-il Park (FTUV & IFIC)

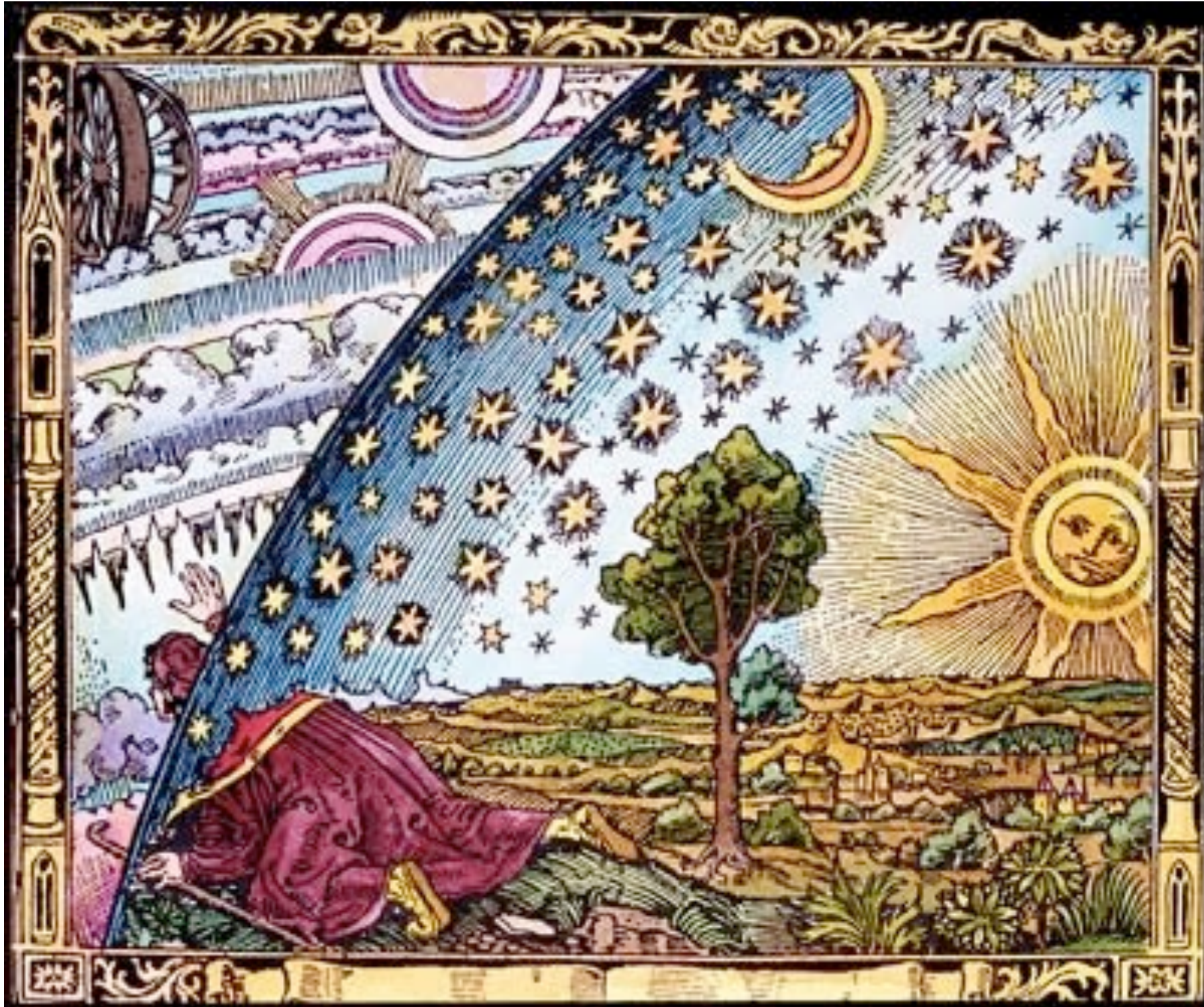
[www.rantlifestyle.com]

FTUV, Feb. 12 (2015)

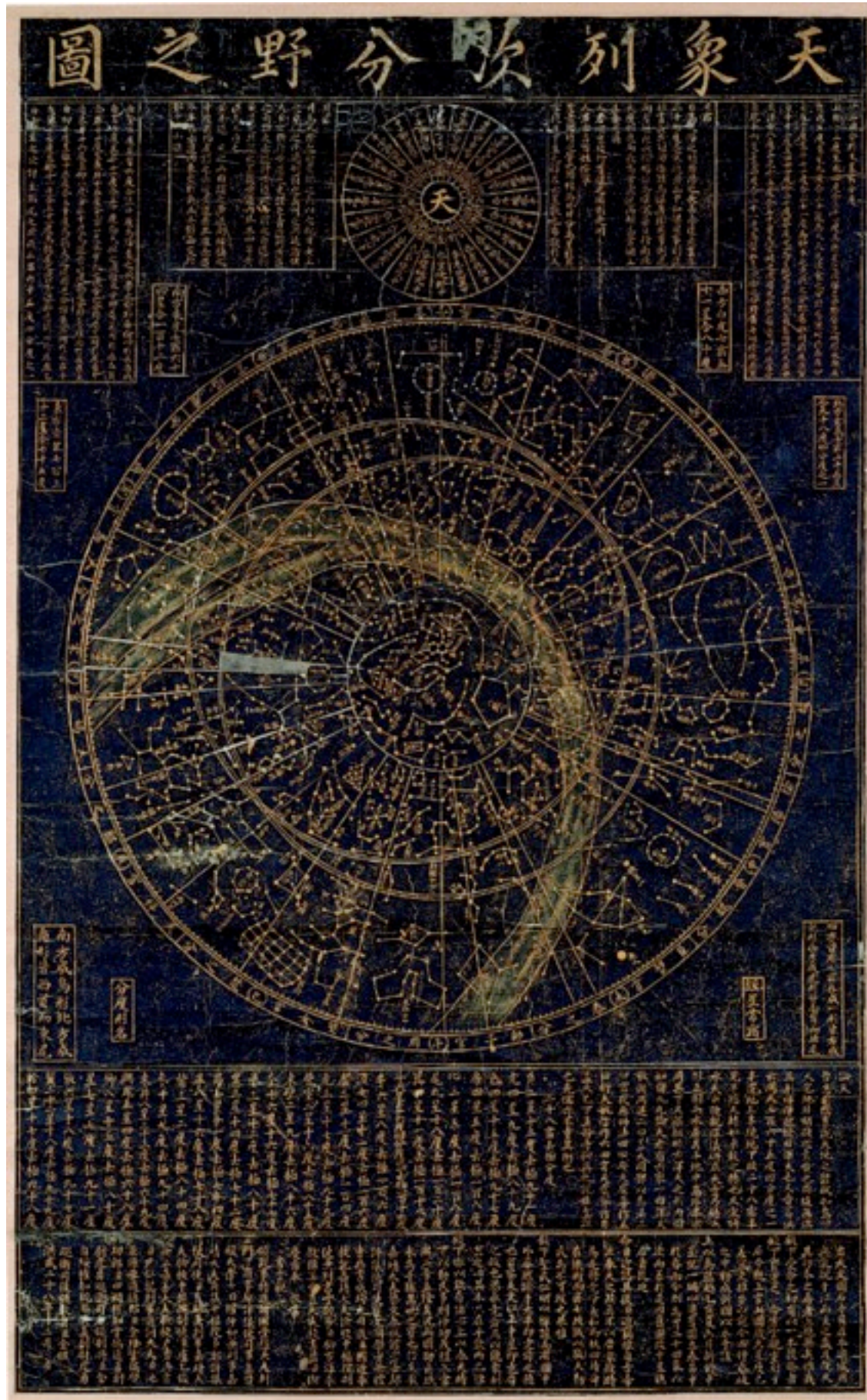


We are living on earth
in the vast Universe

For millennia, we have thought about our universe,
looking at the sky



[The Universe and Man: Image courtesy of Photodisc, Inc.]



... and even at the ancient times we could draw a map of stars in the universe. ...

Chun-sang-yeol-cha-bun-ya-gi-do

(The ancient Korean full sky map)

- * Original: ~AD 1st(?) century
- * Revision: AD 1395 (Joseon dynasty)
- * # of stars: 1467
- * Feature: Sizes depending on luminosity



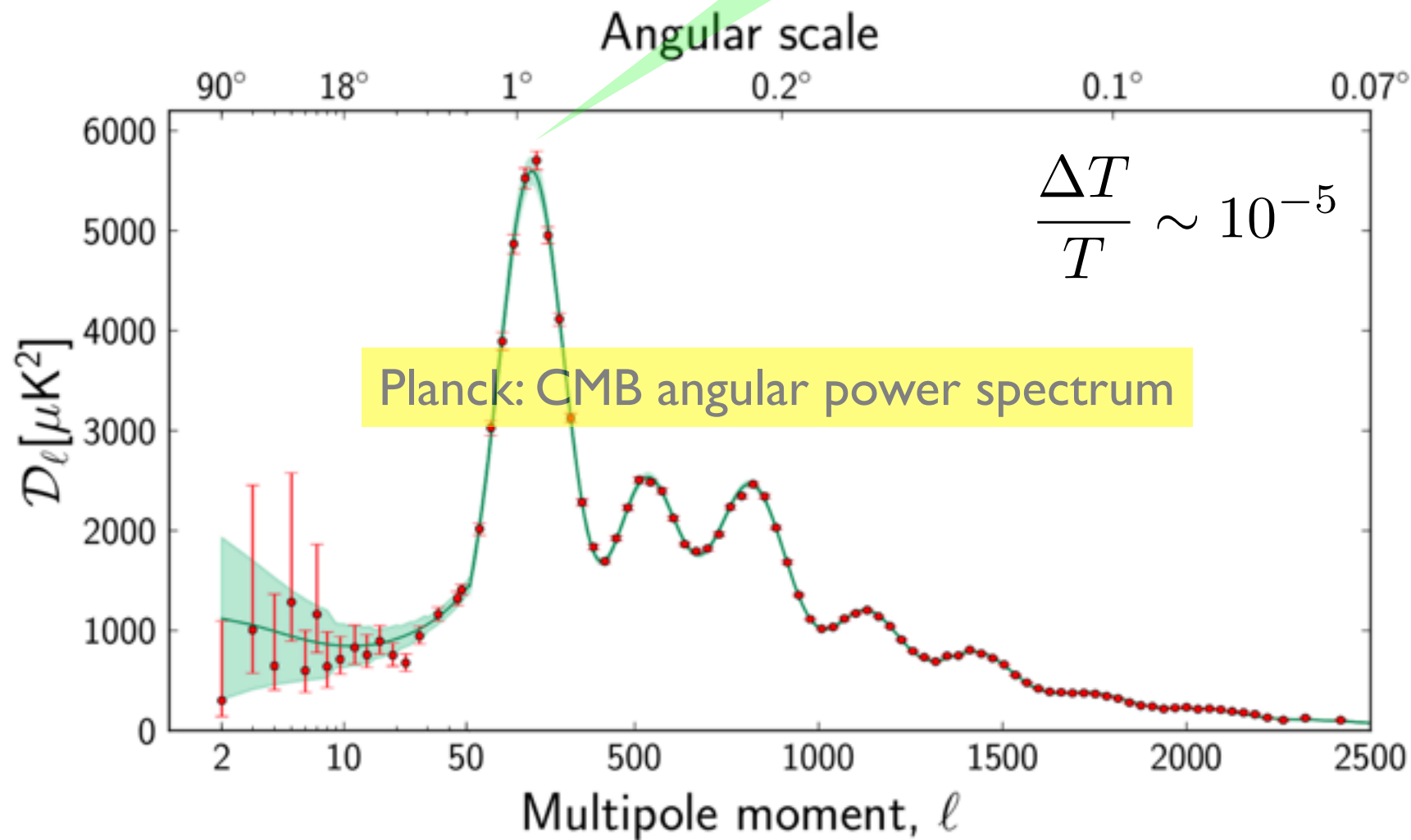
The ^{observable} Universe looks ...

- transparent
- lots of matter
- very old
- very big
- spatially flat
- expanding

- * More precise quantitative information is from various observations, e.g.,
 - Supernovae
 - large scale structure
 - cosmic microwave background (CMB)
 - ...
- * In particular, CMB provides a great deal of information.
- * CMB is nearly homogeneous and isotropic,
but there is tiny perturbation of order of 10^{-5}

Planck: Constraints on the basic six-parameter LCDM model

Parameter	Planck		Planck+WP	
	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314		
σ_8	0.8344	0.834		
z_{re}	11.35	11.4		
H_0	67.11	67.4		
$10^9 A_s$	2.215	2.23		
$\Omega_m h^2$	0.14300	0.14		
Age/Gyr	13.819	13.8		
z_*	1090.43	1090		
$100\theta_*$	1.04139	1.04		
z_{eq}	3402	3386		



Puzzles from observations

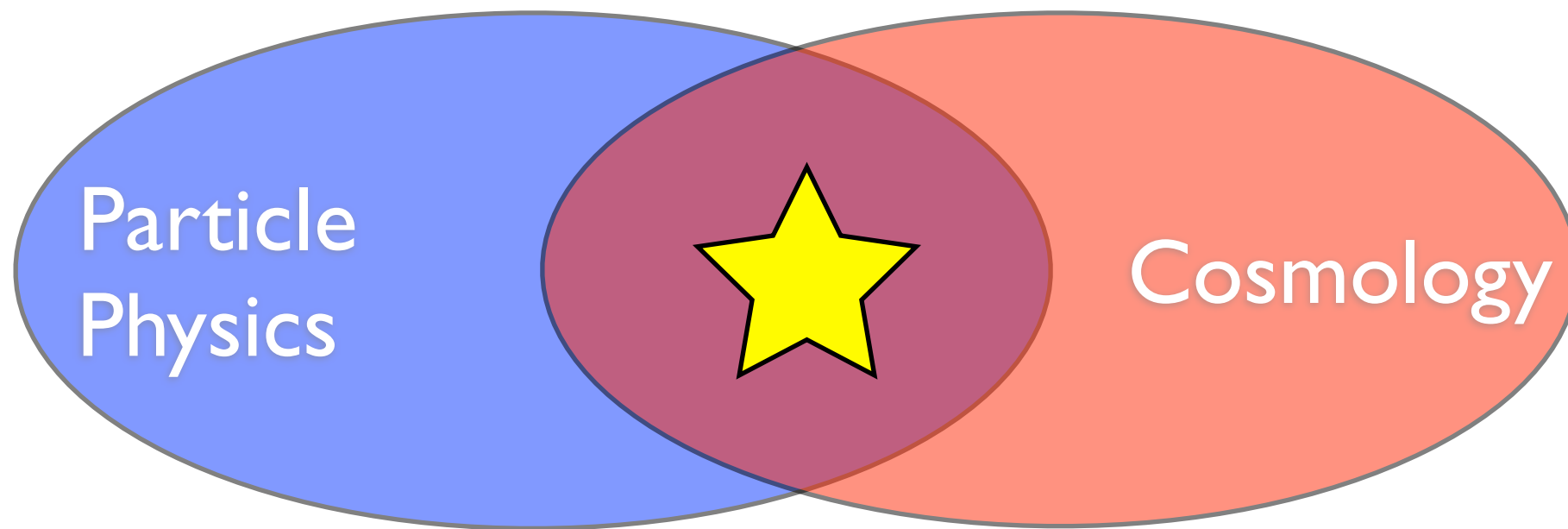
- Why is CMB homogeneous and isotropic?
- Why is the observable universe so flat?
- What is the seed of the density perturbation?
- Why is there only matter without antimatter?
- What is dark matter?
- What is dark energy?
- What is dark radiation?
- ...



- * How can we explain the present properties of the Universe?
- * What is the early history of the Universe?
- * What would the future of the Universe?

Particle cosmology

(Interplay between particle physics and cosmology (mainly) during the early history of the Universe)



- ☑ Early universe cosmology →
 - ☑ Dark energy
 - ☑ Astroparticle physics
- [
- ◆ Inflation
 - ◆ Density perturbation
 - ◆ Baryogenesis
 - ◆ Dark matter/radiation
 - Cosmological implications of high energy theories (e.g., String theories, SUGRA)

I. Cosmic Inflation

(An expansion of the universe with an accelerated rate)

Inflation-basics

- Definition

$$\text{scale factor} \rightarrow \frac{\ddot{a}}{a} = -\frac{2}{3} \frac{\overset{\text{energy density}}{\rho} + \overset{\text{pressure}}{3p}}{M_{\text{P}}^2} > 0 \Rightarrow w \equiv \frac{p}{\rho} < -\frac{1}{3}$$

- Purpose

1. Solution to monopole-problem
2. Solution to horizon- and flatness-problem

- Additional crucial role

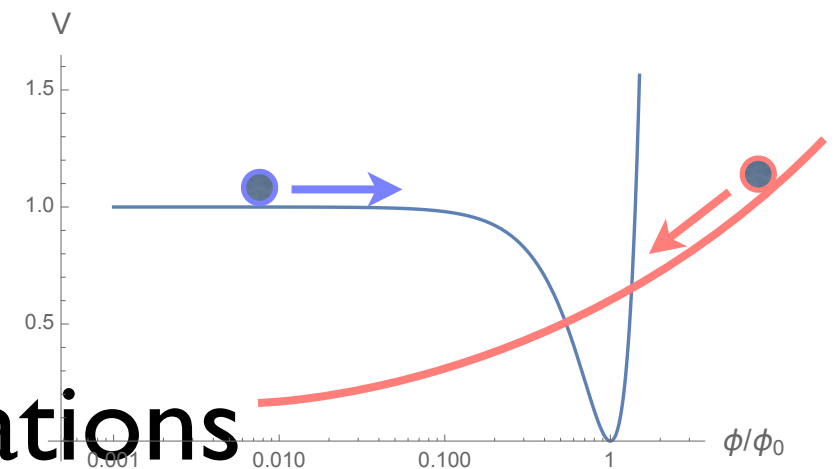
The most compelling source of the present density perturbation

- Simple realization

A slow-rolling scalar field

- Requirements from observations

1. At least about 60 e-foldings
2. Nearly flat red-tilted density power spectrum



Inflation-issues

- Flatness of inflaton potential

Observations require slow-roll parameters to satisfy

$$\epsilon \equiv \frac{1}{2} \left| \frac{M_{\text{P}} V'}{V} \right|^2 \lesssim 10^{-2}, \quad \eta \equiv \frac{M_{\text{P}}^2 V''}{V} \lesssim 10^{-2}$$

(slope) (curvature)

However, in many simple UV-realization of inflation, the slow-roll parameter associated with **inflaton curvature is of order unity** due to **gravitational effects**.

$$\Delta V \sim cV \frac{\phi^2}{M_{\text{P}}^2} \sim cH^2 \phi^2 \quad \Rightarrow \quad \eta \sim \pm \mathcal{O}(c) \sim \pm \mathcal{O}(1)$$

($\langle \phi \rangle \lesssim M_{\text{P}}$ is assumed)

This is called “ **η -problem**”.

- **Trans-Planckian excursion**

Even if η -problem is assumed to be cured somehow, generically the observed power spectrum requires a trans-Planckian excursion of inflaton field.

E.g.,
$$V = \begin{cases} V_0 - \frac{1}{2}m^2\phi^2 + \dots & \text{for } \phi \ll \phi_0 \\ \frac{1}{2}m^2\phi^2 & \text{for } \phi \gg M_P \end{cases}$$


$$\epsilon \equiv \frac{1}{2} \left| \frac{M_P V'}{V} \right|^2 \sim \begin{cases} (M_P \phi / \phi_0^2)^2 & \text{for } \phi \ll \phi_0 \\ (M_P / \phi)^2 & \text{for } \phi \gg M_P \end{cases}$$

$$\eta \equiv \frac{M_P^2 V''}{V} \sim \begin{cases} M_P^2 / \phi_0^2 & \text{for } \phi \ll \phi_0 \\ M_P^2 / \phi^2 & \text{for } \phi \gg M_P \end{cases}$$


$$\phi_* \text{ or } \phi_0 \sim \mathcal{O}(10)M_P$$

This raises a **question on the validity of inflaton potential in view of EFT.**

Solutions(?)

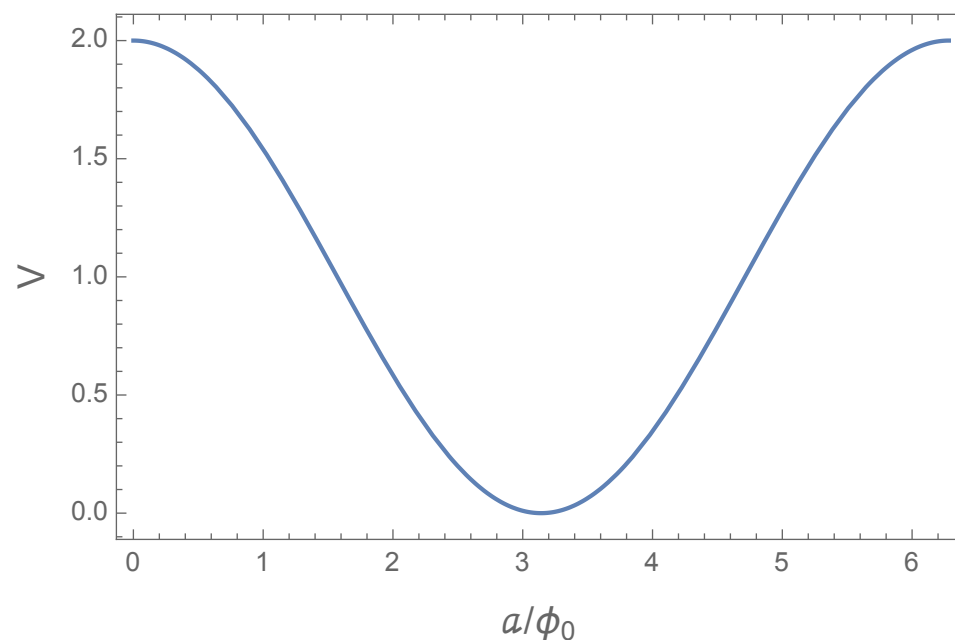
- To eta-problem

- * **Forbidding mass correction**

- ⇒ Shift symmetry, **pNGB**, Heisenberg symmetry, ...?

- $K = f(\phi - \phi^\dagger) + \dots$ $K = f(\rho); \rho = T + T^\dagger - |\Phi|^2 + \dots$

e.g.) Natural inflation (using a pNGB)



$$\text{For } \Phi = \frac{1}{\sqrt{2}} \phi e^{ia/\phi_0},$$

$$V = \Lambda^4 \left[1 + \cos \left(\frac{a}{\phi_0} \right) \right]$$

- ☞ However **a global symmetry** is expected to be broken by gravity.
- ☞ Hence there would be **dangerous Planck-suppressed symmetry breaking operators**.

- To trans-Planckian excursion

* **Conformal symmetry(?)**: Dangerous higher order operators are not allowed.

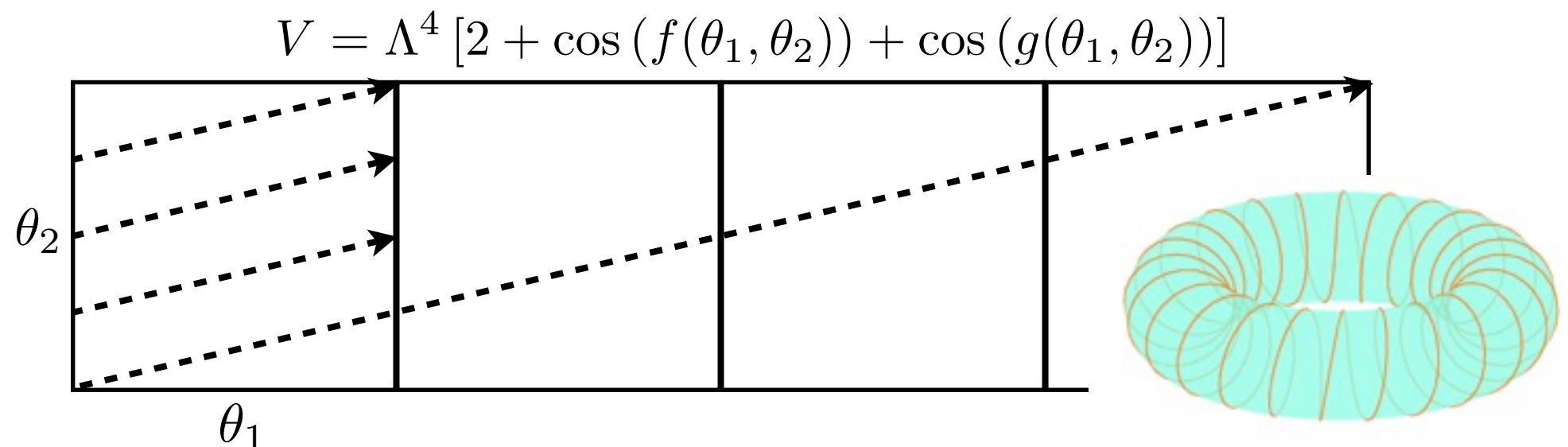
$$V = \frac{1}{4}\lambda\phi^4 \text{ where } \lambda \begin{cases} \sim \mathcal{O}(10^{-12}) & \text{in GR} \\ \lesssim \mathcal{O}(1) & \text{in modified gravity} \end{cases}$$

but (i) Conformal sym. is broken at loop-level.

(ii) Inconsistent with data or unitarity issue

* **Compactification of trajectory(?)**: Trans-Planckian excursion can be compactified in a sub-Planckian regime of multi-dimensional field space.

(e.g.) Aligned natural inflation, axion monodromy, etc.



Spiral inflation

[Gabriela Barenboim and WIP, Phys.Lett. B741, 252 [arXiv:1412.2724]]

- Potential

$$V = V_\phi + V_M ; \quad \Phi = \frac{1}{\sqrt{2}} \phi e^{i\theta}$$

$$V_\phi = \begin{cases} \frac{1}{4} \lambda (\phi^2 - \phi_0^2)^2 \\ \frac{1}{4} \lambda \phi_0^4 + \lambda \left[\ln \left(\frac{\phi}{\phi_0} \right) - \frac{1}{4} \right] \\ \dots \end{cases}$$

➡ Symmetry-breaking potential

$$V_M = \Lambda^4 [1 + \sin(\phi/M + \theta)]$$

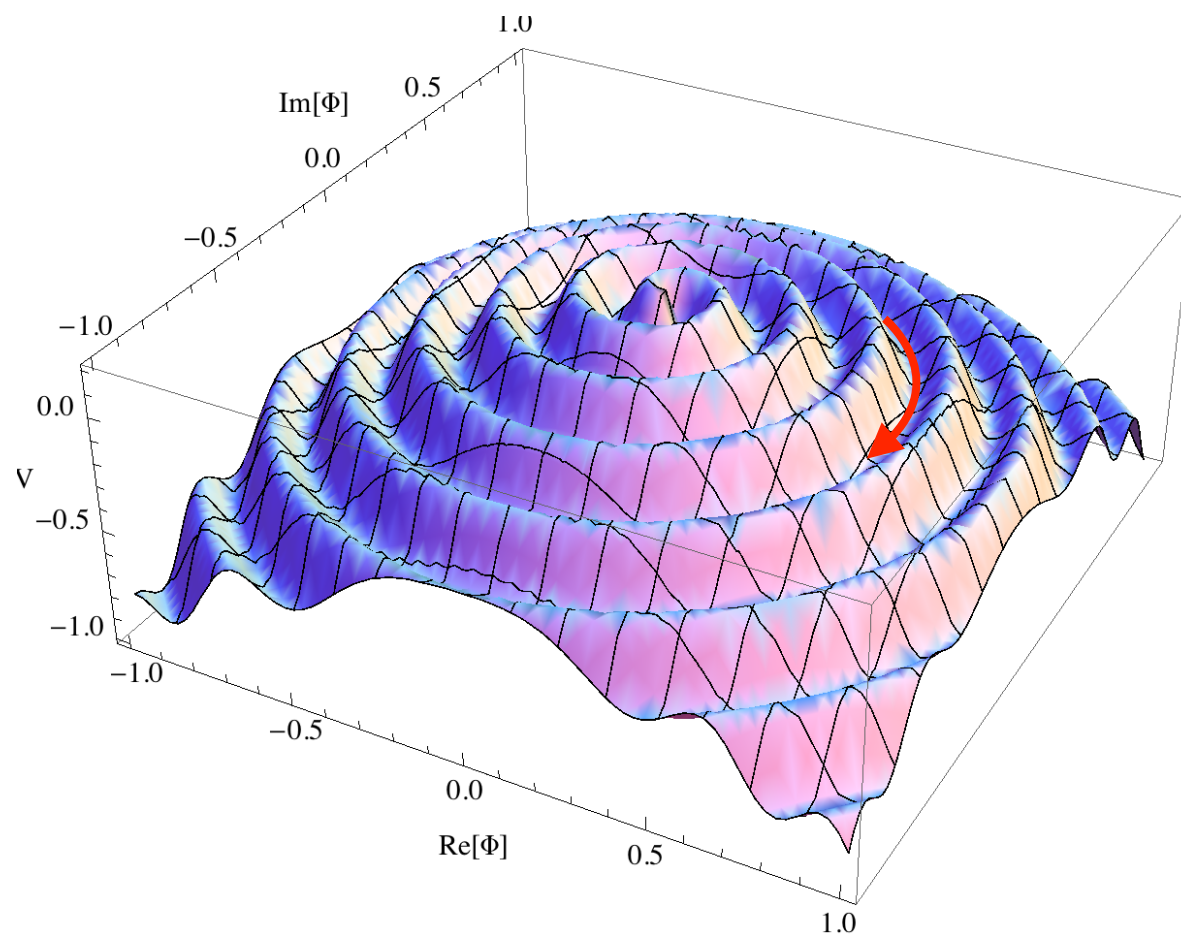
➡ Modulating potential

$$\mathcal{L} \supset \frac{g^2}{32\pi^2} \left(\frac{\phi}{M} + \theta \right) G\tilde{G}$$

Planck scale physics?

● Inflation

$$V = V_\phi + \Lambda^4 [1 - \sin(\phi/M + \theta)]$$



- * Inflation along spiraling-out valley
- * $M \ll \Phi_0 \Rightarrow$ Many turns $\Rightarrow$ Elongated trajectory
- * ϵ and η can be adjusted by “ M/Φ_0 ”



- * $\Phi_0 \ll M_P$ is possible
- * η -problem is absent.

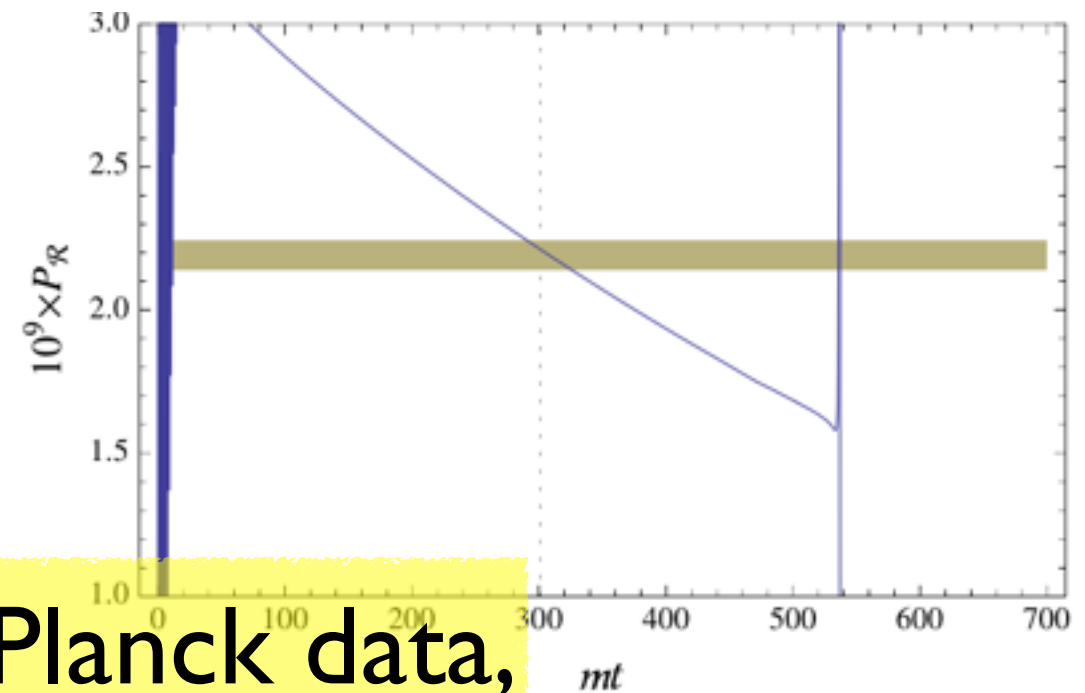
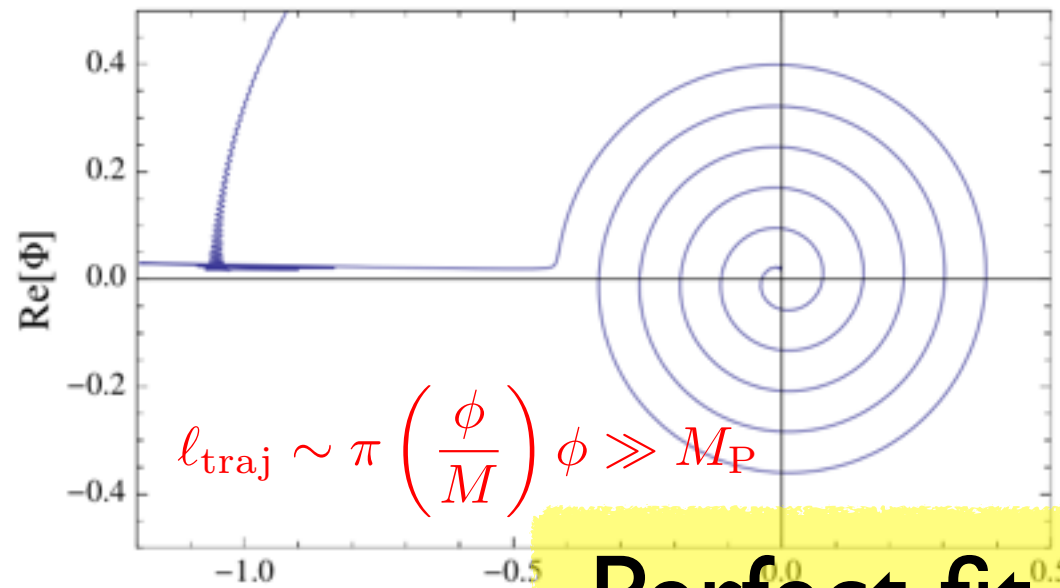
$$\epsilon \approx \epsilon_\phi / a^2, \quad \eta \approx \eta_\phi / a^2 \quad \text{with } a \equiv \phi/M \gg 1$$

- A numerical simulation

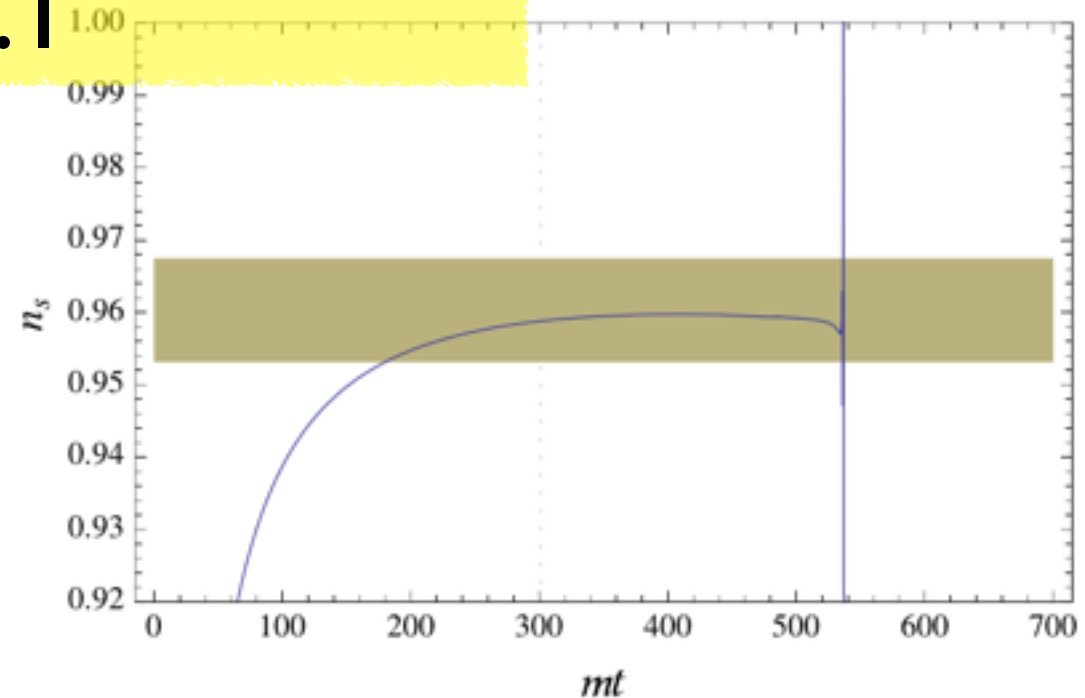
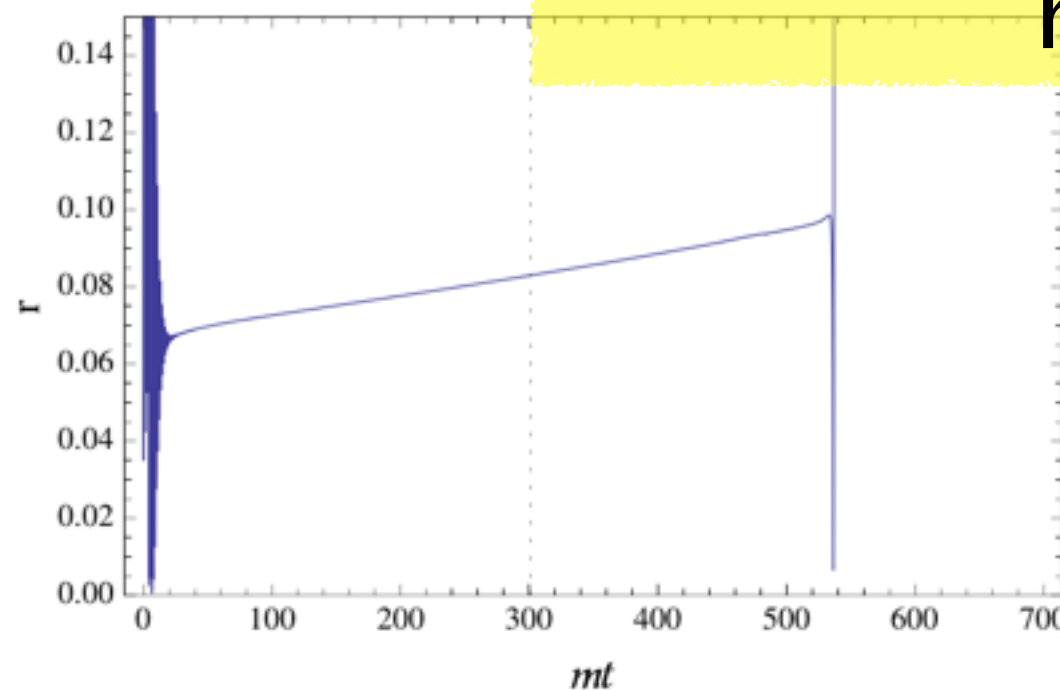
$$V_\phi = V_0 - \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4,$$

$$\frac{m}{10^{14}\text{GeV}} = 0.796 \times 2\sqrt{3}, \quad \frac{\Lambda^4}{m^2 M_{\text{P}}^2} = 4 \times 10^{-3}$$

$$\frac{M}{M_{\text{P}}} = 7.3 \times 10^{-2}, \quad \lambda = (m/M_{\text{P}})^2$$



Perfect fit to Planck data,
 $r \sim 0.1$

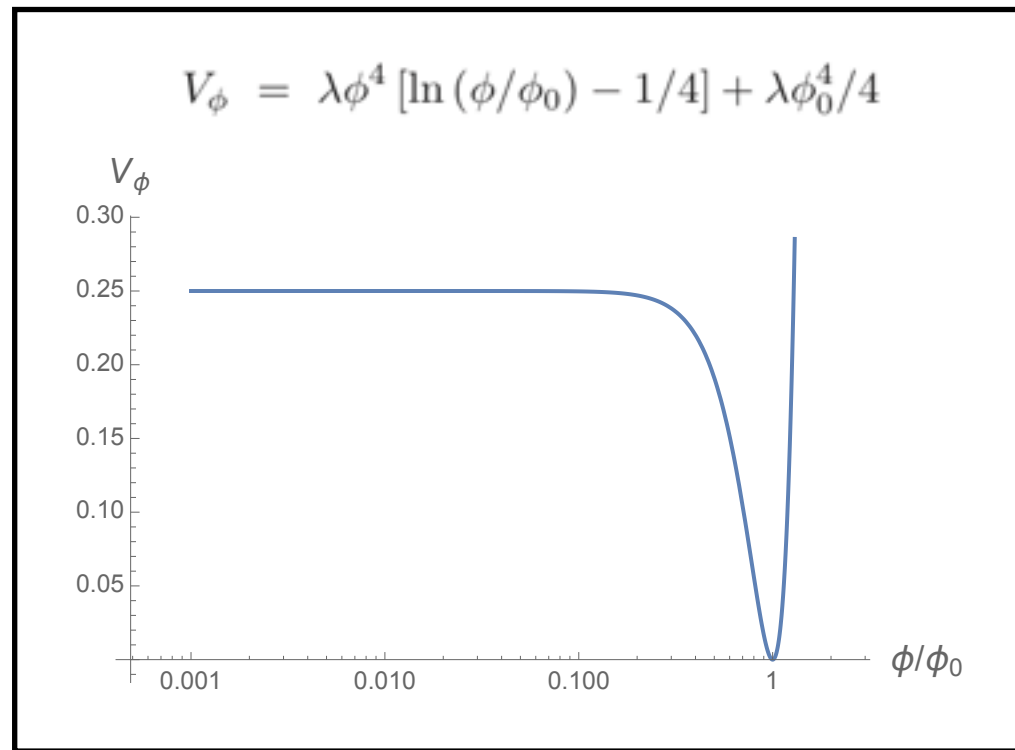


SI with CW potential

[Gabriela Barenboim and WVIP, PRDxx, xxxxxx [arXiv: 1501.00484]]

- Difficulty of Coleman-Weinberg inflation

[Gabriela Barenboim, Eung Jin Chun and Hyun Min Lee, PLB730, 81]



$$\epsilon = 8 \left(\frac{4M_P}{v_\phi} \right)^2 \left(\frac{\phi}{v_\phi} \right)^6 \ln^2 \left(\frac{\phi}{v_\phi} \right),$$

$$\eta = \left(\frac{4M_P}{v_\phi} \right)^2 \left(\frac{\phi}{v_\phi} \right)^2 \left(3 \ln \left(\frac{\phi}{v_\phi} \right) + 1 \right)$$

For $v_\phi \lesssim M_P$,

$$\epsilon^{\text{obs}}, \eta^{\text{obs}} \lesssim 10^{-2} \Rightarrow \frac{\phi}{\phi_0} \lesssim \mathcal{O}(10^{-2} - 0.1)$$

$$\Rightarrow \epsilon \lll \eta$$

$$P_{\mathcal{R}} = 2.2 \times 10^{-9} \Rightarrow \lambda \sim 10^{-14}$$

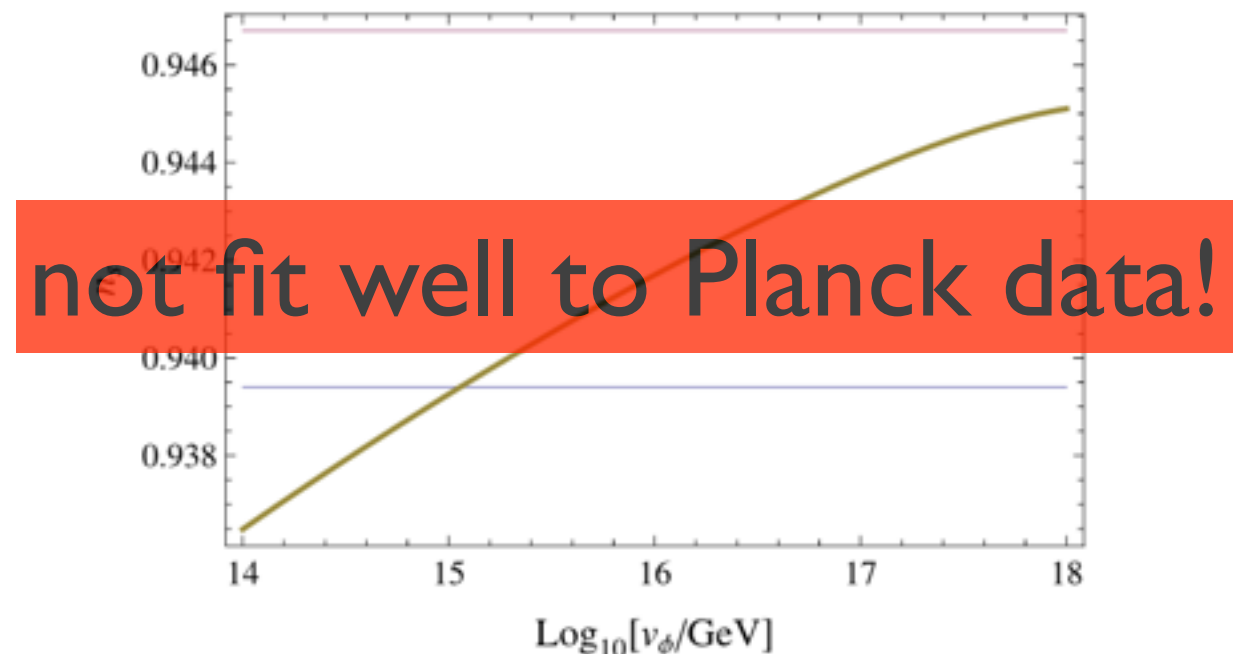
Also,

$$N \approx \frac{3}{1 - n_s} \cdot n_s \approx 0.96 \pm 0.007 \Rightarrow N \approx 75$$

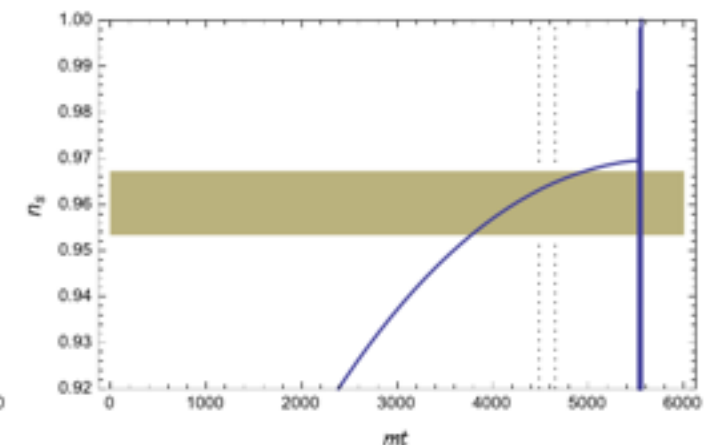
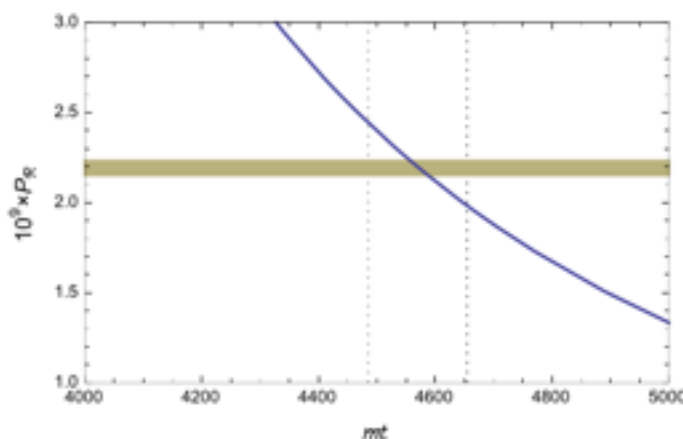
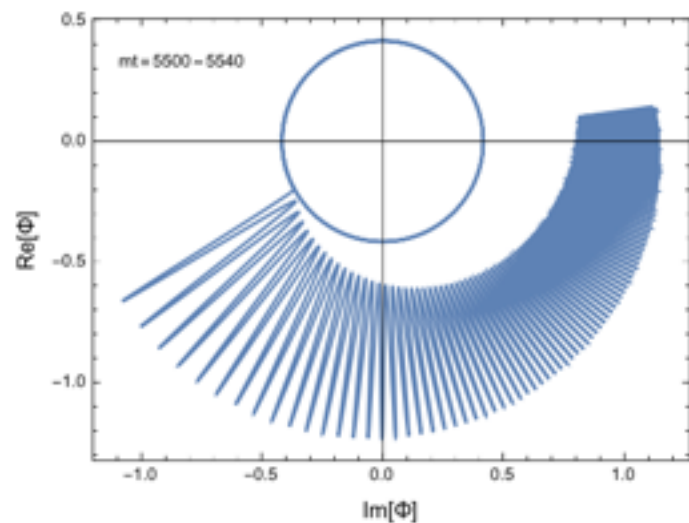
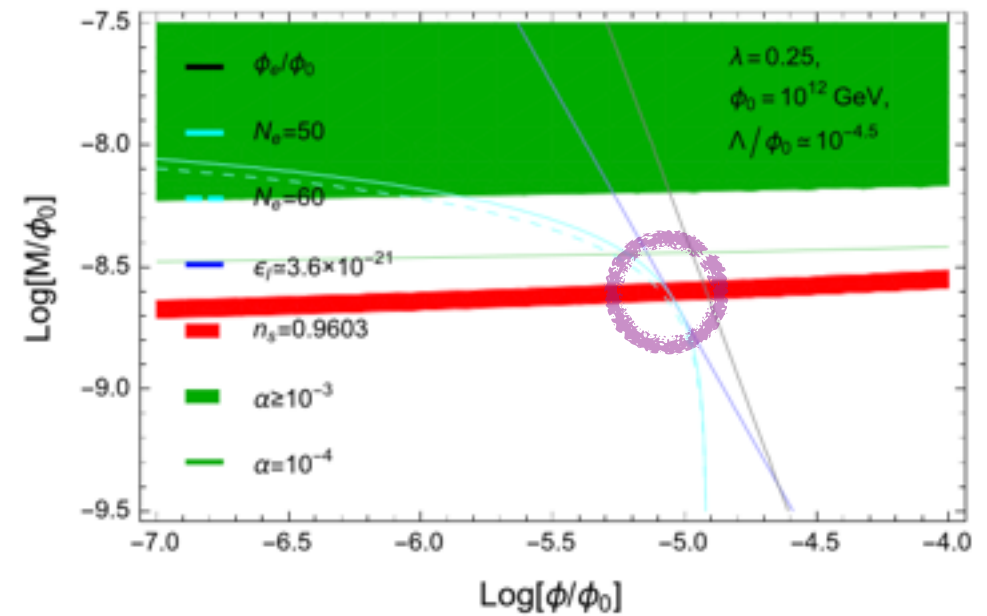
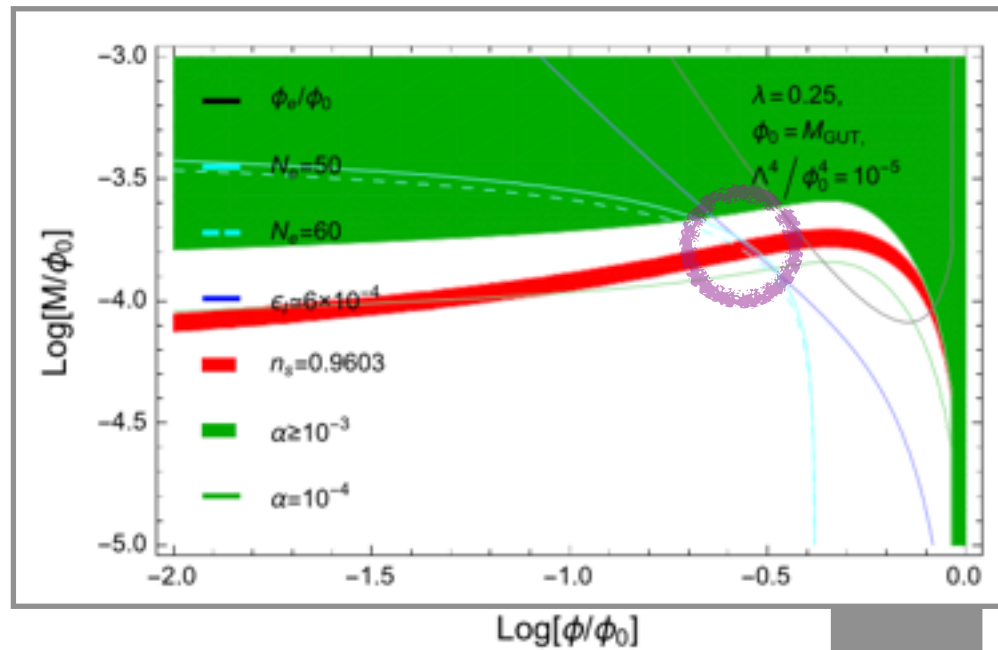
but

$$N_* = \frac{1}{3} \ln \left(\frac{\rho_{\text{reh}}}{\rho_{\text{end}}} \right) + \frac{1}{4} \ln \left(\frac{\rho_{0r}}{\rho_{\text{reh}}} \right) + \frac{1}{2} \ln \left(\frac{\rho_*}{\rho_0} \right)$$

$$\simeq 61 - \ln \left(\frac{10^{16} \text{ GeV}}{V_*^{1/4}} \right) + \ln \left(\frac{V_*^{1/4}}{V_{\text{end}}^{1/4}} \right) - \frac{1}{3} \ln \left(\frac{V_{\text{end}}^{1/4}}{\rho_{\text{reh}}^{1/4}} \right)$$



- Spiral inflation with CW potential

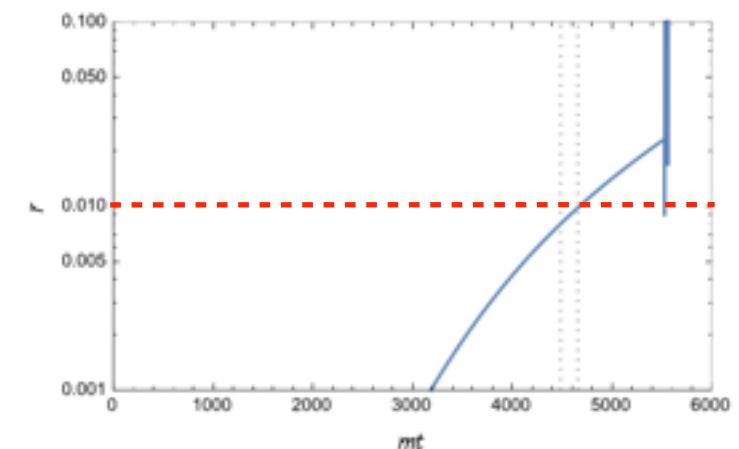


☞ Inflation works well for $\lambda \sim 0.1$ and

$$10^{12} \text{ GeV} \lesssim \phi_0 \lesssim M_{\text{GUT}}$$

$$10^{-9} \lesssim M/\phi_0 \lesssim 10^{-4}$$

☞ However UV-realization is not clear yet.



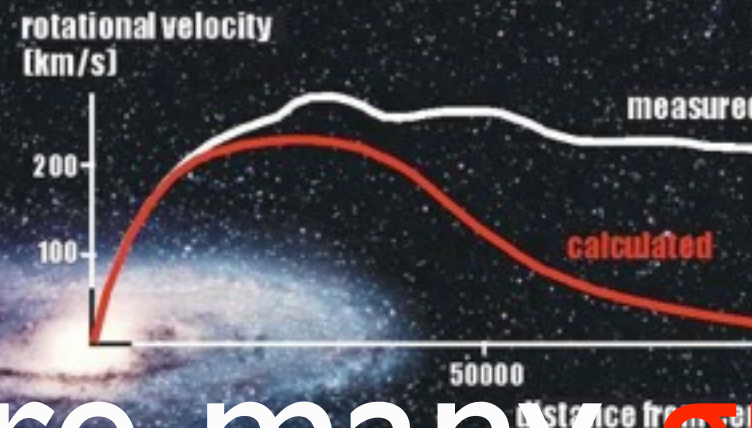
Part I -summary

- Generically, inflation models suffer from **eta-problem** and/or **trans-Planckian excursion of inflaton**
- Both problems can be solved if inflaton is a **elongated compactified trajectory** in a sub-Planckian multi-dimensional field space (e.g., aligned natural inflation, axion monodromy, spiral inflation)
- In particular, **spiral inflation** is an interesting possibility although its full UV-realization is not clear yet.

II. Dark matter

Coma Cluster

Coma Cluster
0.5-2.0 keV



There are many gravitational
evidences of dark matter

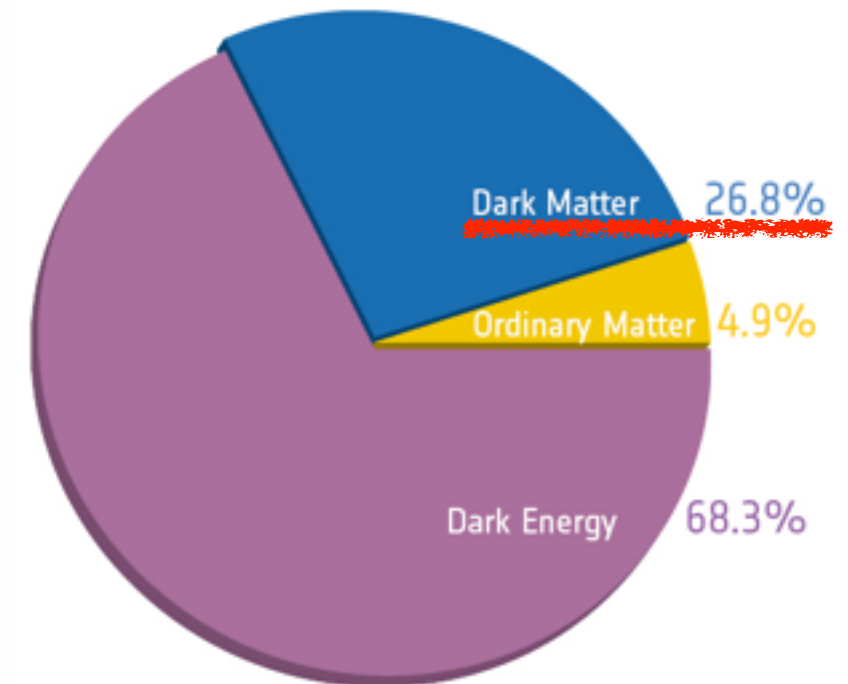
Bullet Cluster

Weak Lensing

Planck says ...

- Cosmological parameters (based on LCDM)

Parameter	Planck		Planck+lensing		Planck+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{dr}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_b h^2$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_p	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091



Energy budget

What we know about DM

(Observational requirements)

- Electromagnetically neutral

Invisible $\Rightarrow$ no interaction to EM field

- Matter-like

Clustered $\Rightarrow$ particle-like

- Non-baryonic

from BBN, gravitational microlensing and CMB observation

$$\Omega_b \simeq 0.049, \quad \Omega_{\text{CDM}} \simeq 0.268 \quad [\text{Planck data (2013)}]$$

- Mostly cold

Pattern of structure formation (from comparison to simulation)

- Long-living or absolute stable

It is present in the present universe.

What we don't know yet

(Unknown nature of dark matter)

- Why is it stable?
- What is its mass?
- How does it interact with visible particles?
 - ⇒ Implications on
 - (i) collider experiments
 - (ii) direct/indirect detections
 - (iii) CMB
- How is it produced?
- Is it single component?

DM is stable because...

- Symmetries

- (ad hoc) Z_2 symmetry
- R-parity
- Topology (from a spontaneously broken sym.)

- Very small mass and weak coupling

e.g: QCD-axion ($m_a \sim \Lambda_{\text{QCD}}^2/f_a$; $f_a \sim 10^9\text{-}10^{12}$ GeV)


$$\Gamma_a \sim \mathcal{O}(10^{-5}) \frac{m_a^3}{f_a^2} \ll H_0 \sim 10^{-42} \text{ GeV}$$

But for WIMP ...

- Global sym. is not enough since

$$-\mathcal{L}_{\text{int}} = \begin{cases} \lambda \frac{\phi}{M_{\text{P}}} F_{\mu\nu} F_{\mu\nu} & \text{for boson} \\ \lambda \frac{1}{M_{\text{P}}} \bar{\psi} \gamma^\mu D_\mu \ell_{Li} H^\dagger & \text{for fermion} \end{cases}$$

Observation requires [M.Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\text{DM}} \gtrsim 10^{26-30} \text{sec} \Rightarrow \begin{cases} m_\phi \lesssim \mathcal{O}(10) \text{keV} \\ m_\psi \lesssim \mathcal{O}(1) \text{GeV} \end{cases}$$

$\Rightarrow$ **WIMP is unlikely to be stable**

- SM is guided by gauge principle

It looks natural and may need to consider
a gauge symmetry in dark sector, too.

Hidden Sector (HS)

- Naturally appears in high energy UV theories.
- Gauge principle may govern the sector.
- DM might be a gauge-charged ptl. in HS

We assume this is the case.

➡ Contrary to a global sym., absolute stability of DM can be guaranteed.

Hidden Gauge Sym. of DM

- Abelian or non-abelian?
- Broken or unbroken?
- Interaction with SM fields?

* Decoupled hidden sector?

☞ The sym. have to be confined or broken for a consistent DM phenomenology.

If unbroken and not confined,

⇒ long range force

⇒ DM self-interaction by massless mediator

⇒ Structure formation requires $\alpha_X \ll \alpha_{ew}$

⇒ DM overproduction.

☞ No way of direct/indirect detection of DM.

Connecting HS to SM

(Portals)

- Kinetic mixing of U(1)s

$$\mathcal{L} \supset \frac{1}{2} \epsilon B_{\mu\nu} F'^{\mu\nu}$$

- Unbroken U(1): mini-charged DM
- Broken U(1): massive dark photon mixed with SM Z-boson

- Gauge singlet portals

$\mathcal{O}_{3/2}^{\text{SM}} = N_R$	$\times$	$\mathcal{O}_?^{\text{HS}} = ?$
$\mathcal{O}_2^{\text{SM}} = H^\dagger H, B_{\mu\nu}$		
$\mathcal{O}_{5/2}^{\text{SM}} = \bar{\ell} \tilde{H}$		

Higgs Portals

- Singlets (up to dim=5) in EFTs

Singlet Scalar : $S^n H^\dagger H$ ($n = 1 - 3$)

Singlet Fermion : $\frac{1}{\Lambda} \bar{\psi} (a + b\gamma_5) \psi H^\dagger H$

Singlet Vector : $V_\mu V^\mu H^\dagger H$

Non-renormalizable
or
not gauge-invariant,
not unitary!

* A global Z_2 sym. could be imposed for DM, but gravity is expected to break the sym.

[See I402.2115, Seungwon Baek, P. Ko, WIP and Yong Tang for example]

- Charged fields in renormalizable models

Scalar : $\Phi^\dagger \Phi H^\dagger H$ (Φ can be a dark higgs)

Fermion : $S \bar{\psi} (a + b\gamma_5) \psi + S^2 H^\dagger H$

Vector : $|D_\mu \Phi|^2 \rightarrow V_\mu V^\mu \Phi^\dagger \Phi$ gauge-invariant and unitary!

A scalar is necessary to connect to SM

Dark Higgs

- Why?

- To break G_{HS} . (except confined G_{HS})
- Unitarity (in case of vector DM)

- Basic effect

- Mixing between SM and dark Higgses.

$$V \supset \lambda_{\Phi H} \Phi^\dagger \Phi H^\dagger H \Rightarrow \begin{cases} h = H_1 \cos \alpha - H_2 \sin \alpha \\ \phi = H_1 \sin \alpha + H_2 \cos \alpha \end{cases}$$

➡ $H_{1,2}$ becomes mediator between SM and HS.

Low energy pheno.

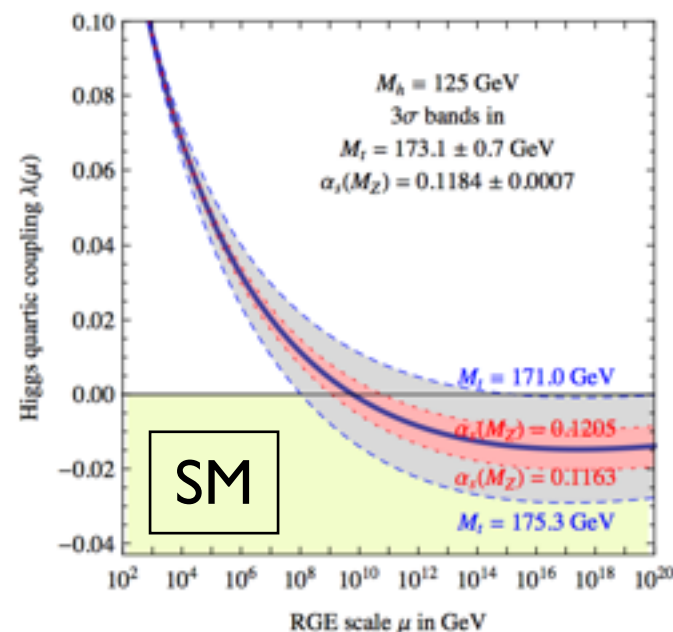
- Universal suppression of collider SM signals

[See I112.1847, Seungwon Baek, P. Ko & WIP]

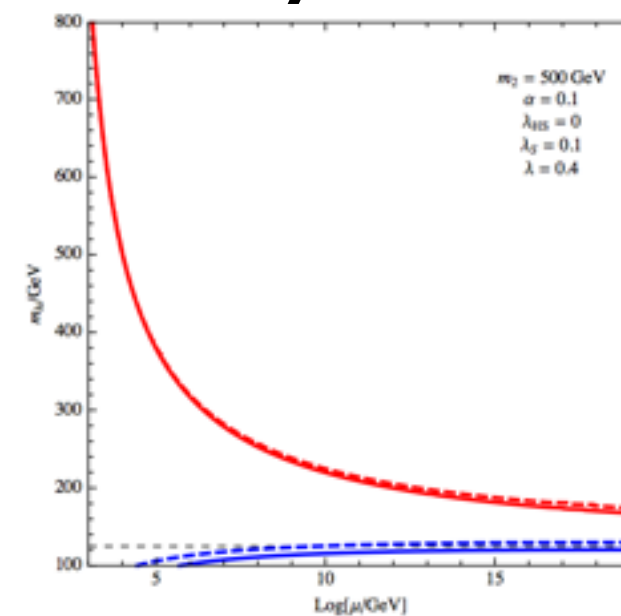
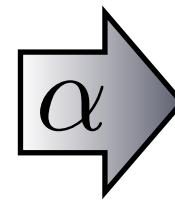
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1 \right) \sin^2 \alpha \right] \lambda_H^{SM}$$

➡ If “ $m_\phi \square \gtrsim m_h$ ”, vacuum instability can be cured.



[G. Degrandi et al., I205.6497]



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

- If “ $m_h > 2 m_\phi \square$ ”, non-SM Higgs decay!

DM Pheno.

- Thermalization of Hidden Sector
- Allowing parameter space excluded in EFTs at direct DM searches [1212.2131, Seungwon Baek, P. Ko, WVIP & Eibun Senaha]
- Saving (some) scenarios of unbroken dark gauge sym. [1311.1035, Seungwon Baek, P. Ko & WVIP]
- Explaining some astrophysical anomalies [1404.5257, P. Ko, WVIP & Yong Tang; 1407.6588, Seungwon Baek, P. Ko & WVIP]
- Breaking connection of collider data to DM direct searches [1405.3530, Seungwon Baek, P. Ko & WVIP]

Colliders connected to DM direct searches?

- Some scenarios of Higgs portal in EFT

$$\mathcal{L}_{\text{SSDM}} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{HS}}{2} S^2 H^\dagger H$$

$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi)\psi - \frac{\lambda_{\psi H}}{\Lambda} \bar{\psi}\psi H^\dagger H$$

$$\mathcal{L}_{\text{VDM}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{2} V_\mu V^\mu H^\dagger H - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

Non-renormalizable
or
not gauge-invariant,
not unitary!

m_H (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(H \rightarrow \text{inv}) / \sigma_{\text{SM}}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—

[arXiv:1404.1344]



$$\sigma_{\text{S-N}}^{\text{SI}} = \frac{4\Gamma_{\text{inv}}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2},$$

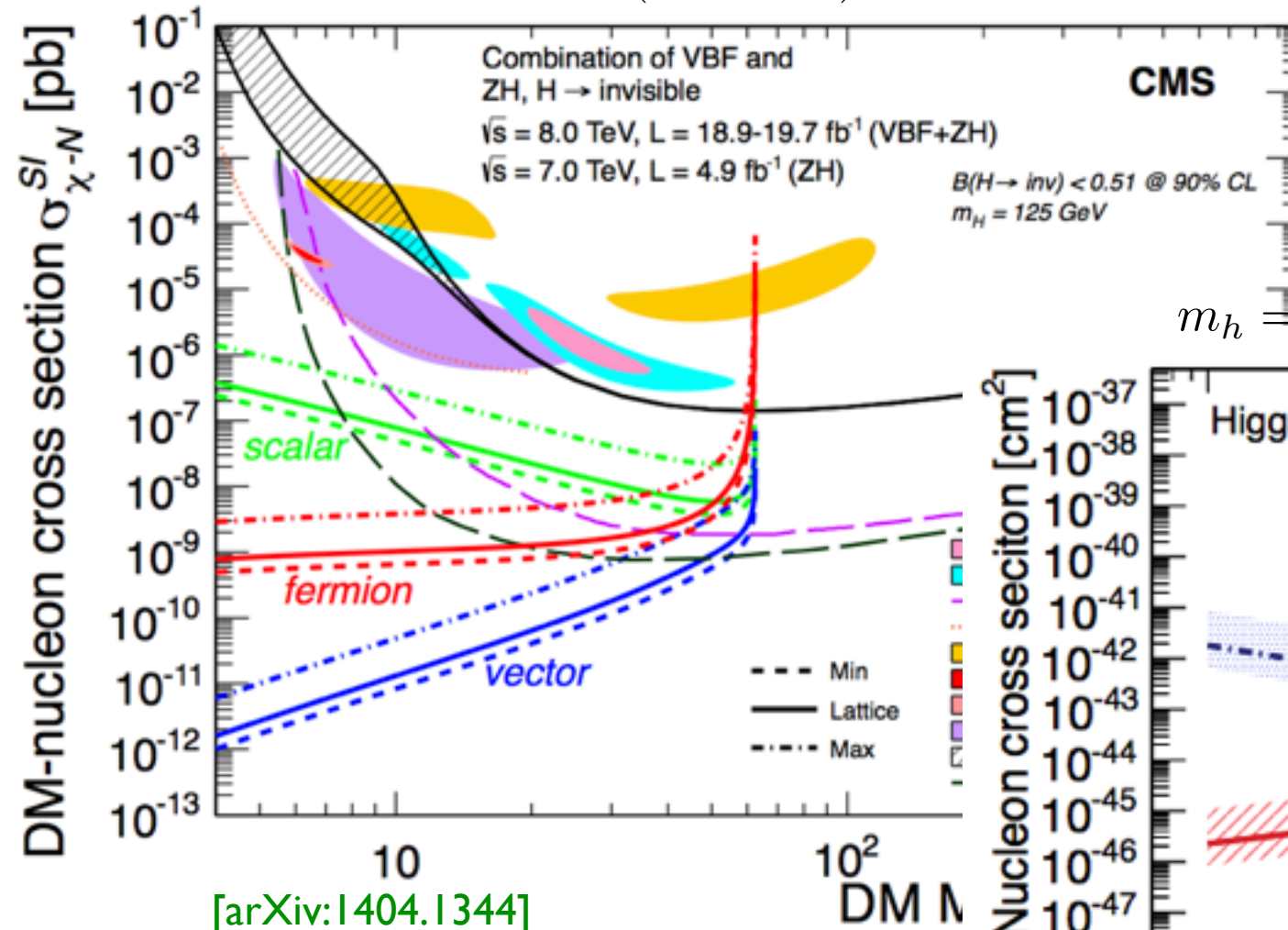
$$\sigma_{\text{V-N}}^{\text{SI}} = \frac{16\Gamma_{\text{inv}} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma_{\text{f-N}}^{\text{SI}} = \frac{8\Gamma_{\text{inv}} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}.$$

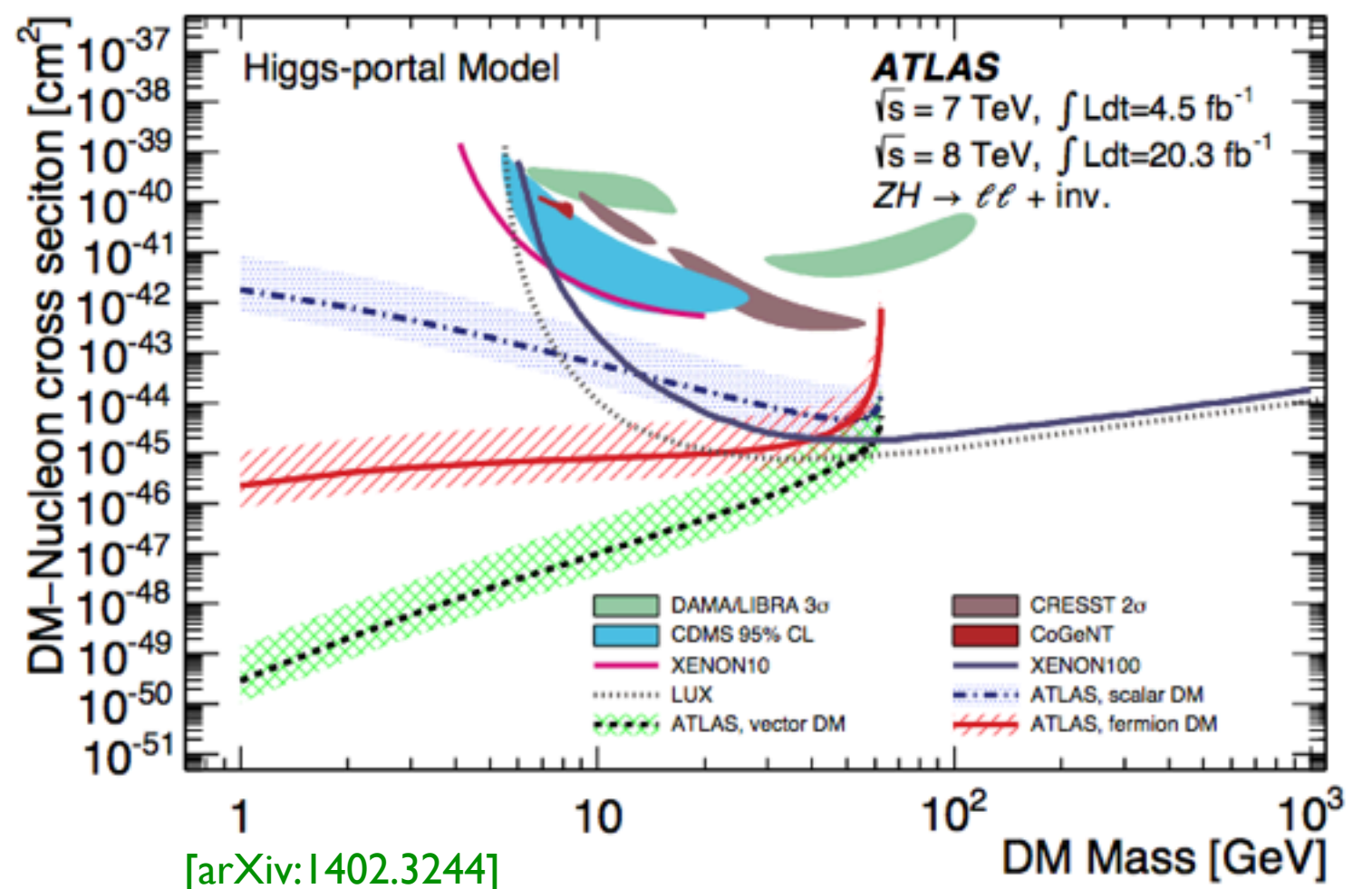
Γ_{inv} is constrained $\Rightarrow$ So is σ^{SI}

- DM-nucleon scattering in EFT Higgs portals

$m_h = 125\text{GeV}$, $\text{Br}(H \rightarrow \text{inv}) < 0.51$ at 90% CL



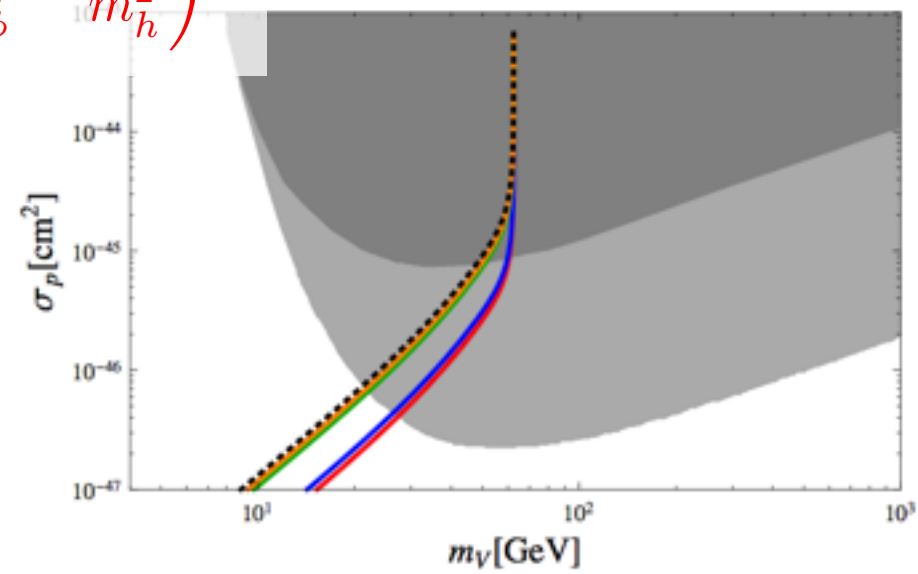
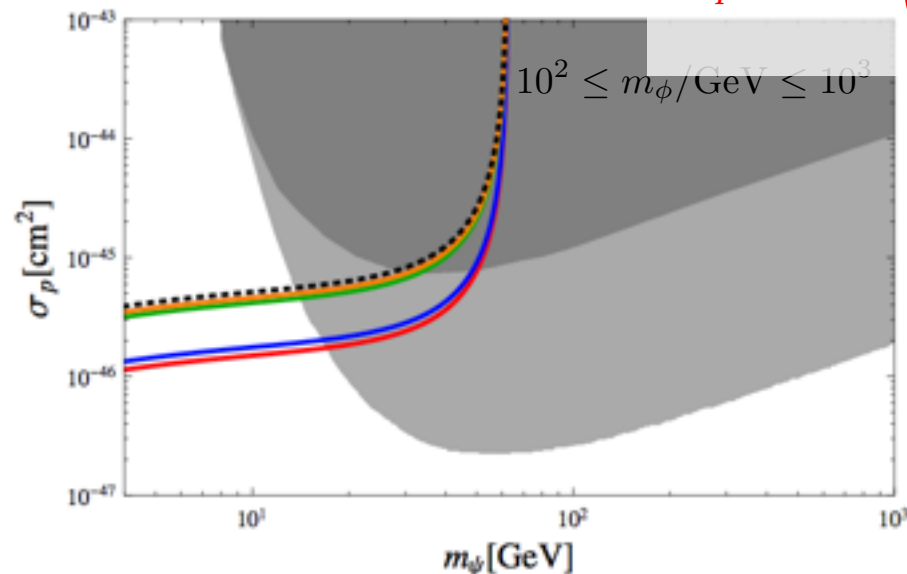
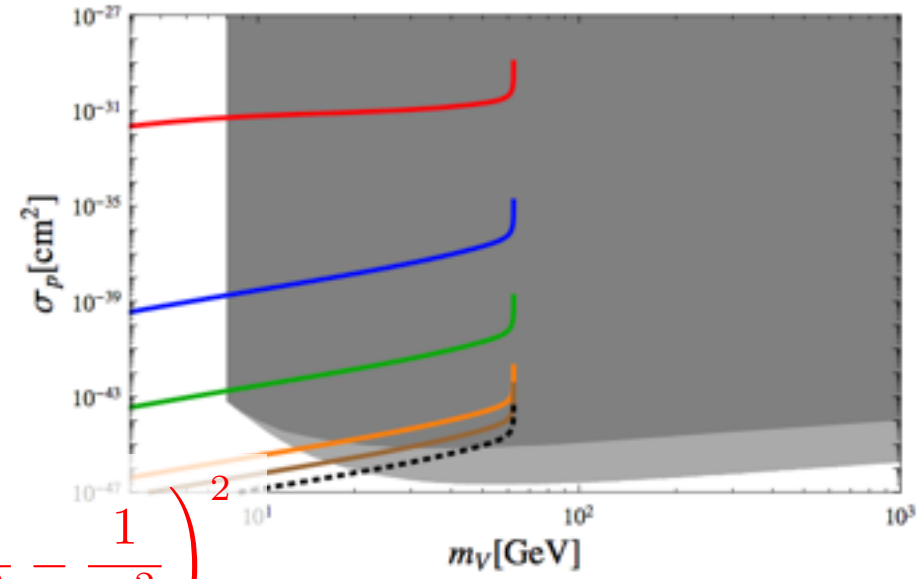
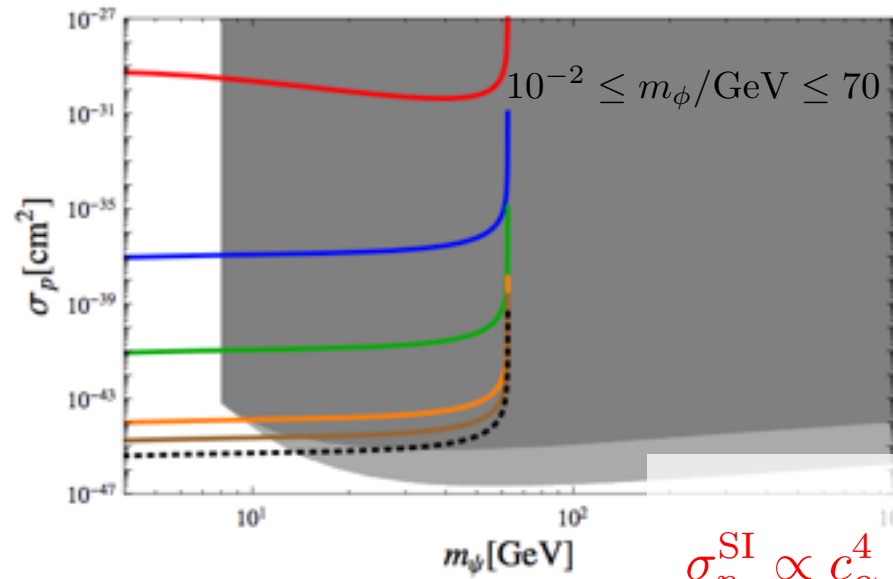
$m_h = 125.5\text{GeV}$, $\text{Br}(H \rightarrow \text{inv}) < 0.52$ at 90% CL



- However, in renormalizable unitary models of Higgs portals, [\[arXiv: 1405.3530, Seungwon Baek, P. Ko & VIP\]](#)

$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\mathcal{L}_{\text{VDM}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{\Phi H} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) \left(H^\dagger H - \frac{v_H^2}{2} \right)$$

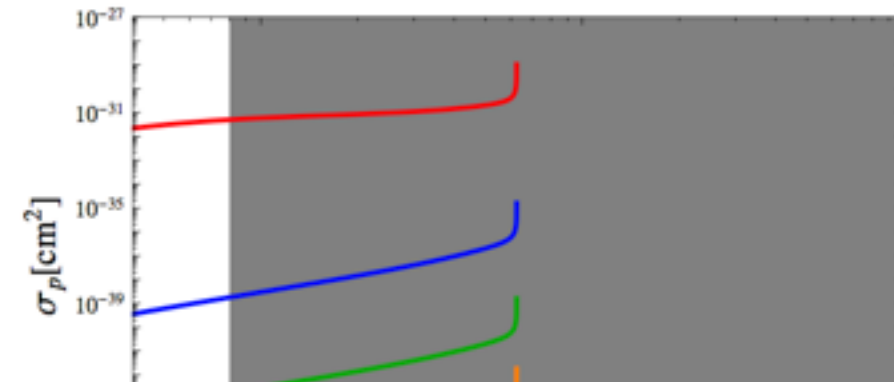
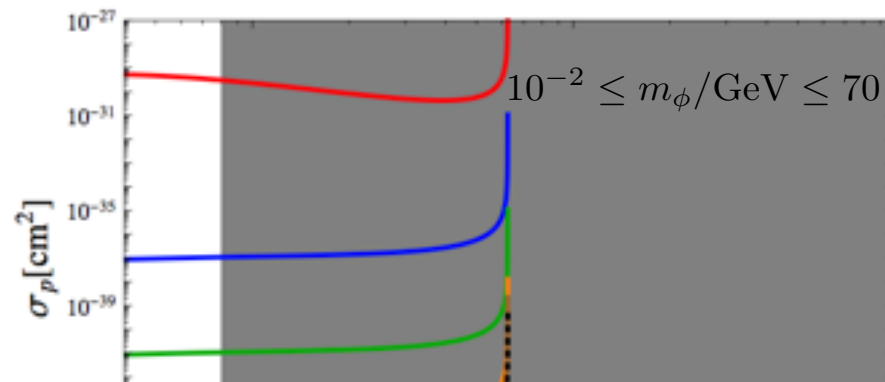


$$\sigma_p^{\text{SI}} \propto c_\alpha^4 \left(\frac{1}{m_\phi^2} - \frac{1}{m_h^2} \right)^2$$

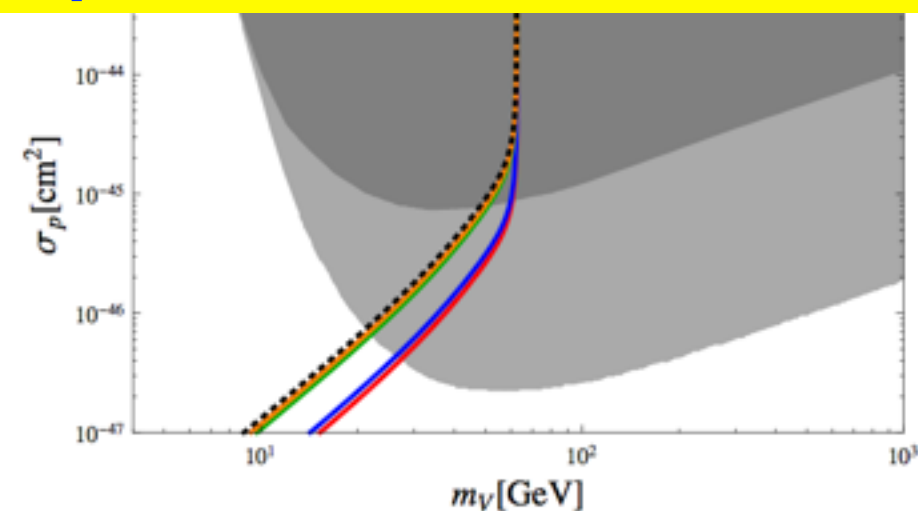
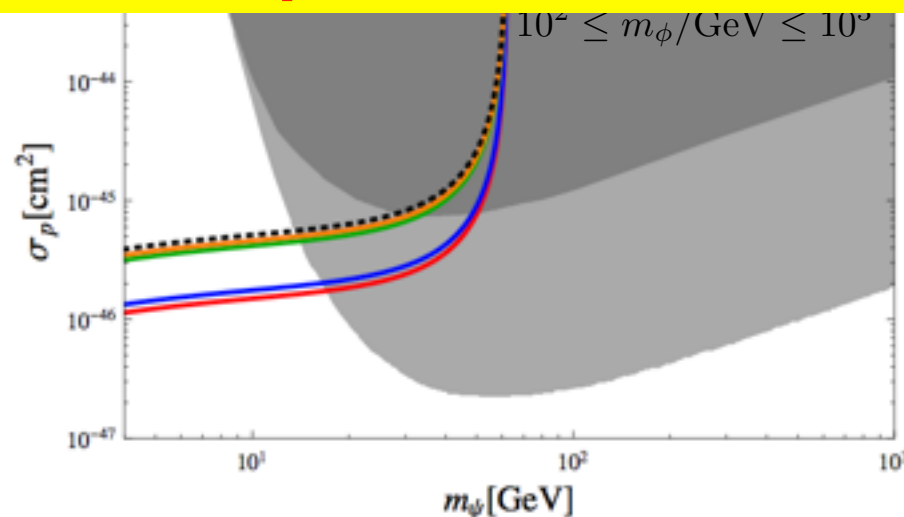
- However, in renormalizable unitary models of Higgs portals,

$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\mathcal{L}_{\text{VDM}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{\Phi H} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) \left(H^\dagger H - \frac{v_H^2}{2} \right)$$



Interpretation of collider data is quite model-dependent in Higgs portal scenarios.



Part II-summary

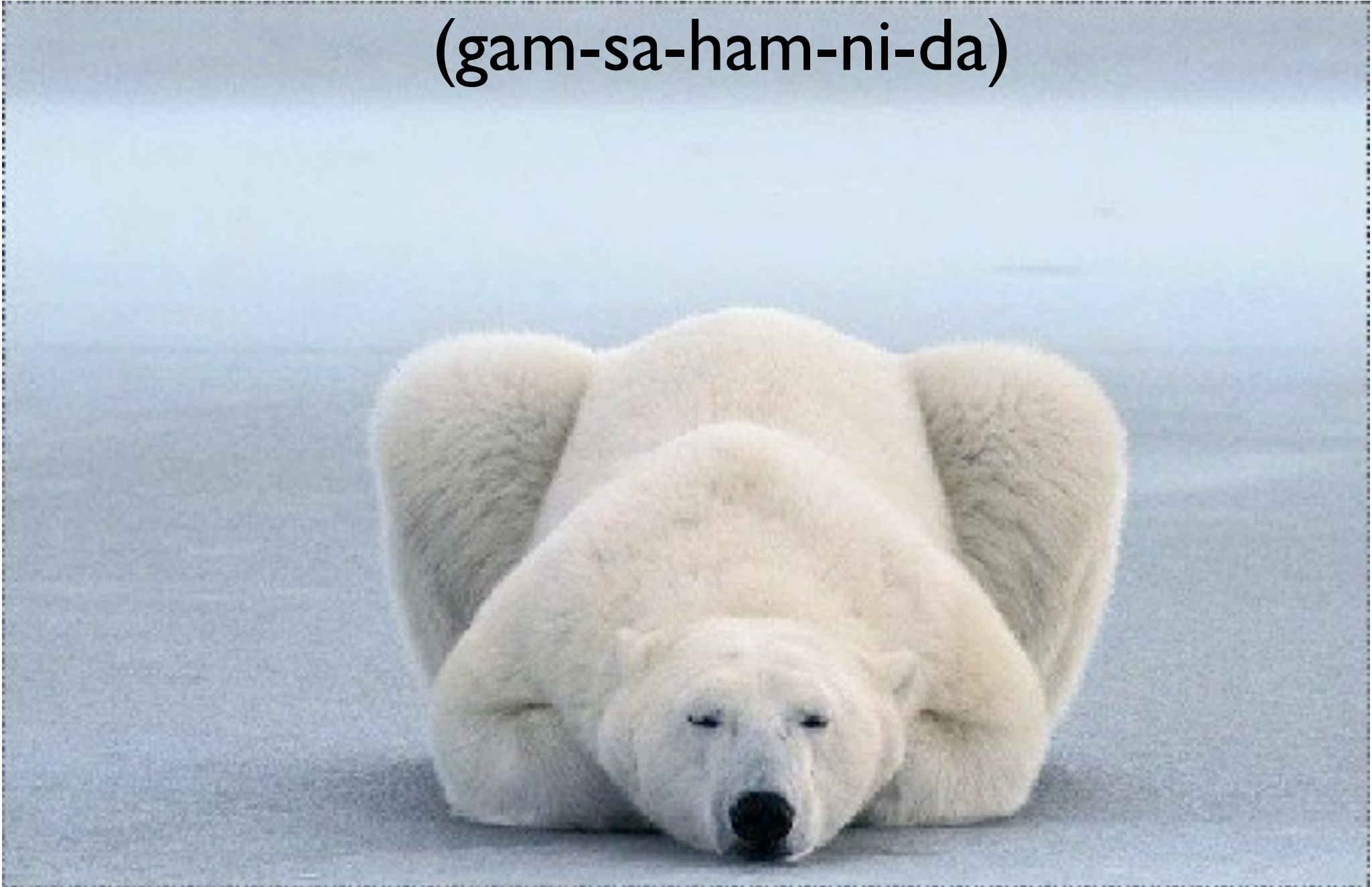
- The nature of dark matter is unknown except some properties associated with gravitational interaction
- The stability of dark matter may imply a local symmetry in the hidden sector.
- In the scenario of a gauged hidden sector, dark higgs seems necessary to break the hidden gauge sym.
- The presence of dark higgs and dark photon associated with a local dark $U(1)$ results in a variety of interesting phenomenology.

Summary/conclusions

- Particle cosmology is a playground you can enjoy theoretical and phenomenological physics of particles and the universe.
- There are many interesting issues waiting for your unlimited imaginations.

감사합니다.

(gam-sa-ham-ni-da)



Gracias!