Dark pion DM, Dark Higgs, Inflation and GW

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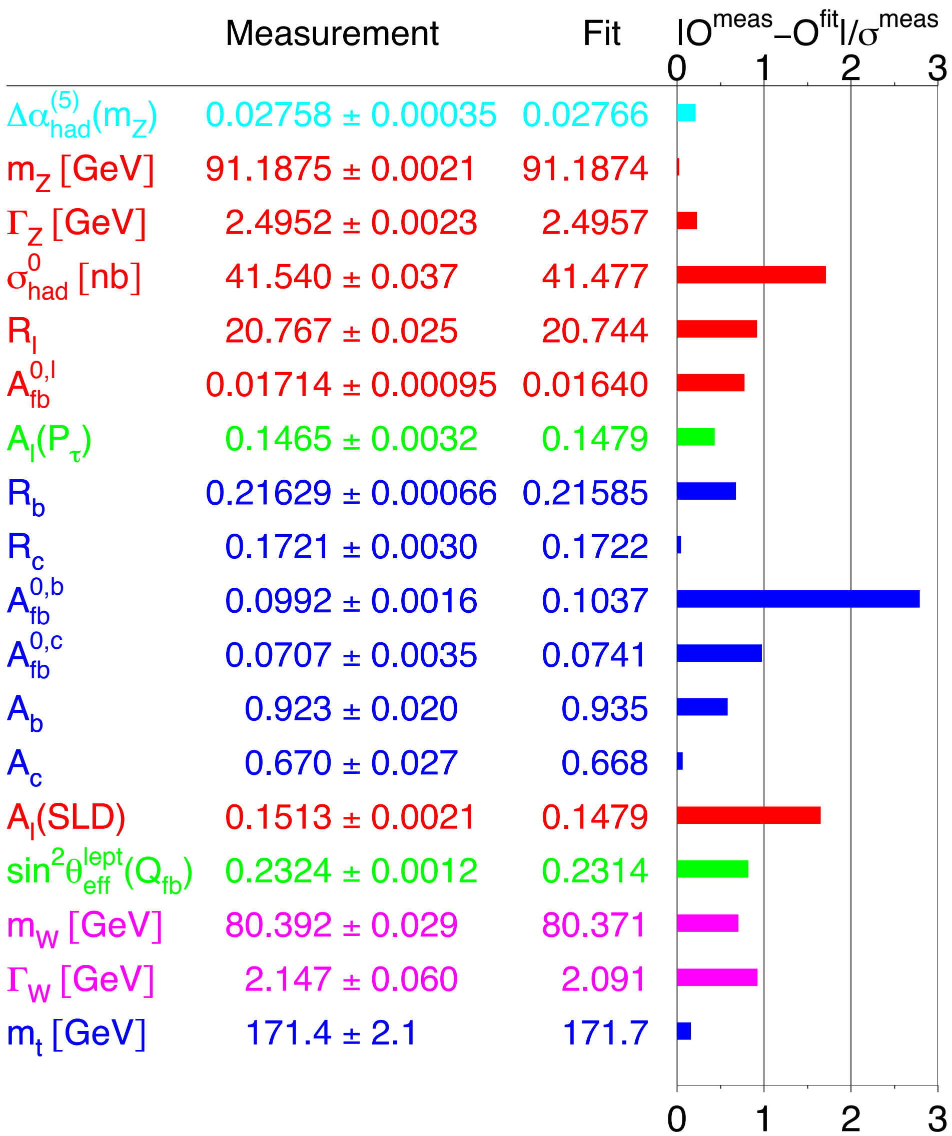
Contents

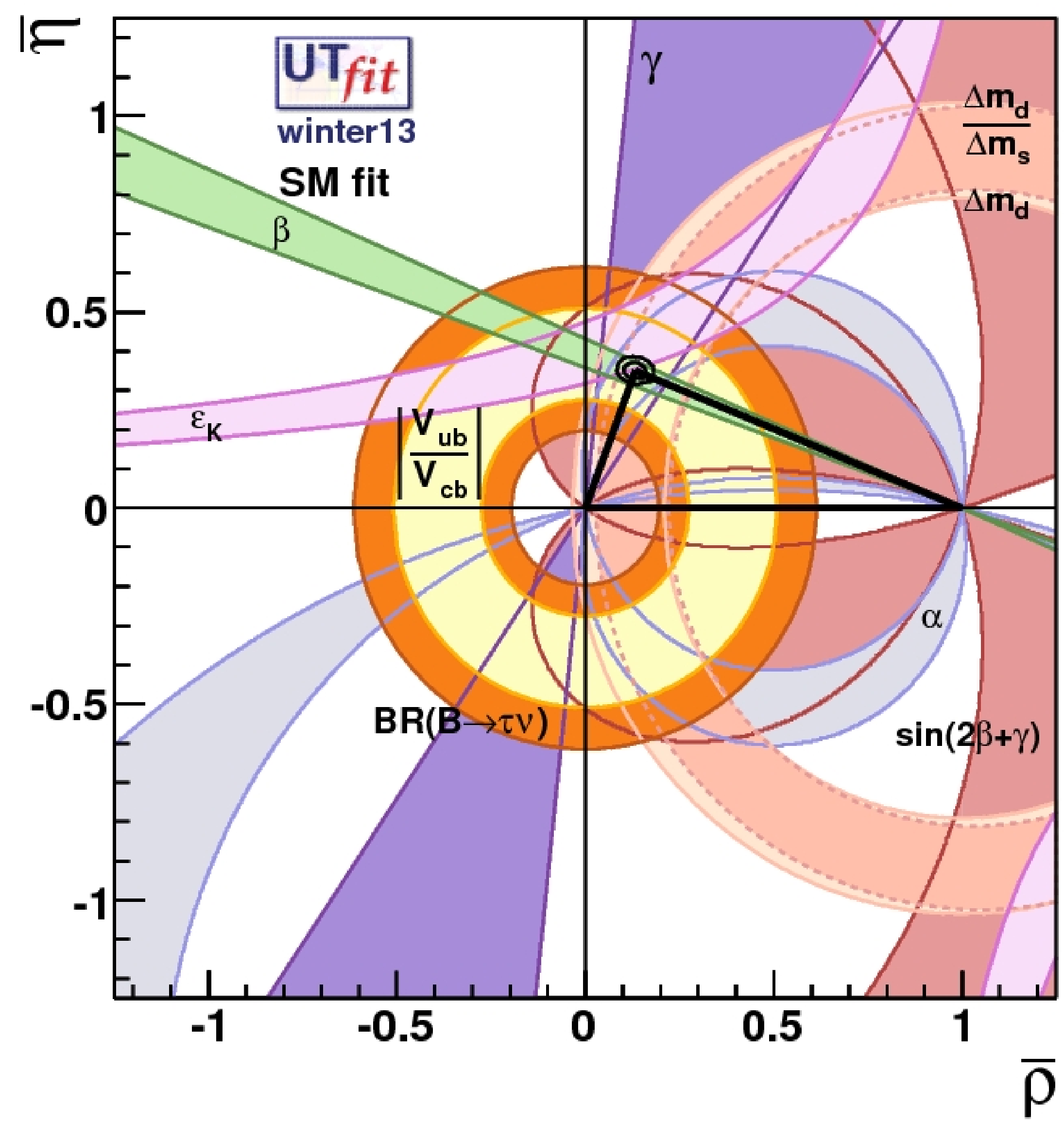
Introduction

SM Chapter almost closed

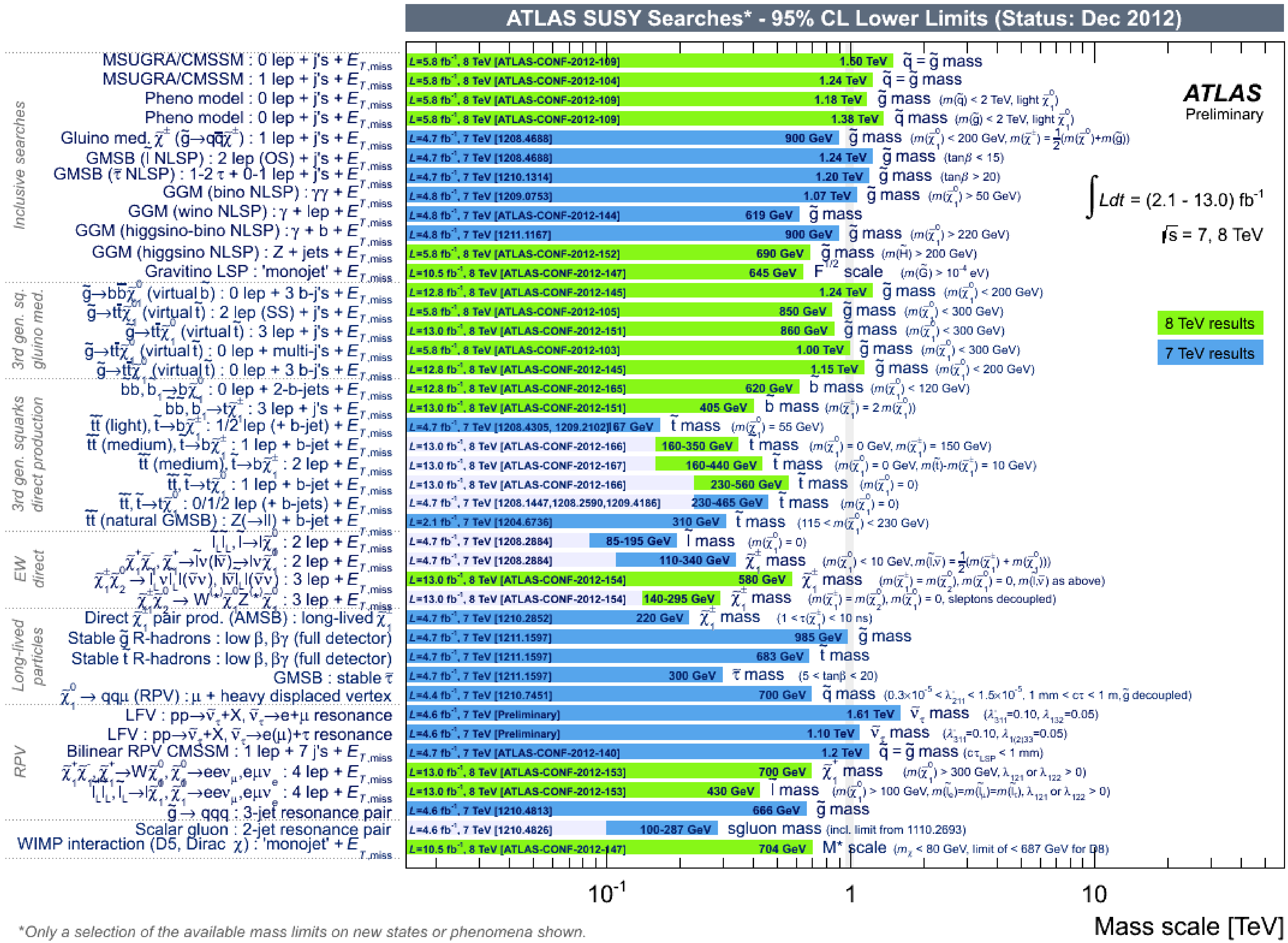
- SM has been tested at quantum level
  - EWPT favors light Higgs boson
  - CKM paradigm is working very well so far
  - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC

EWPT & CKM

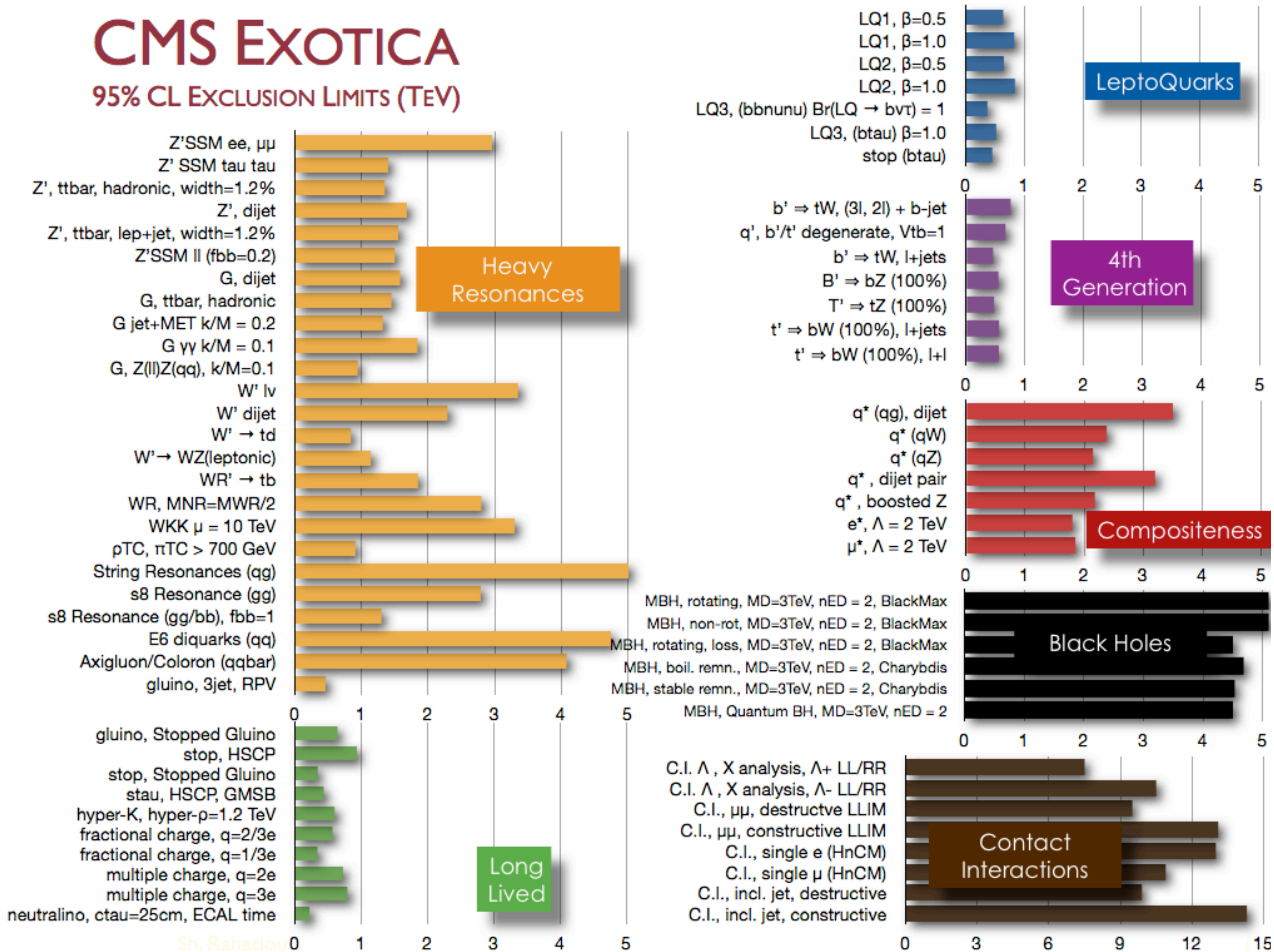




Almost Perfect !



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


CMS Exotica
95% CL Exclusion Limits (TeV)
Heavy Resonances
Z'SSM ee, μμ
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lv
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 5
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
0 1 2 3 4 5
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
0 1 2 3 4 5
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5
Black Holes
MBH, rotating, MD=3TeV, nED = 2, BlackMax
MBH, non-rot, MD=3TeV, nED = 2, BlackMax
MBH, rotating, loss, MD=3TeV, nED = 2, BlackMax
MBH, boil. remn., MD=3TeV, nED = 2, Charybdis
MBH, stable remn., MD=3TeV, nED = 2, Charybdis
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
0 3 6 9 12 15

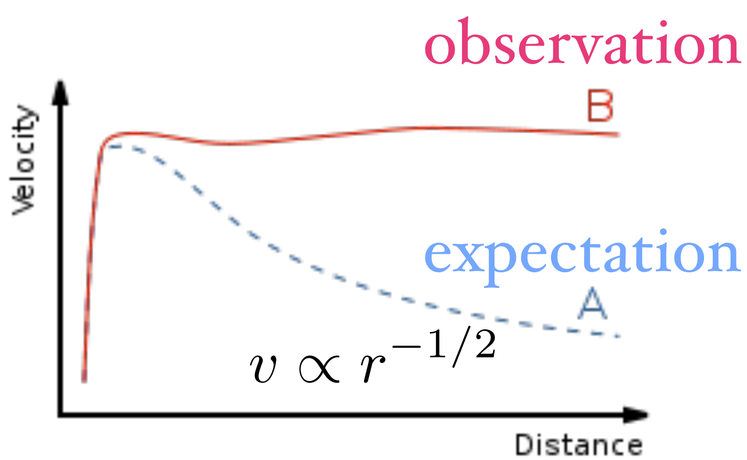
SM Lagrangian

$$
\begin{aligned}
\mathcal{L}_{MSM} = & -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
& +|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\
& +\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
& -\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) .(1)
\end{aligned}
$$

Based on local gauge principle

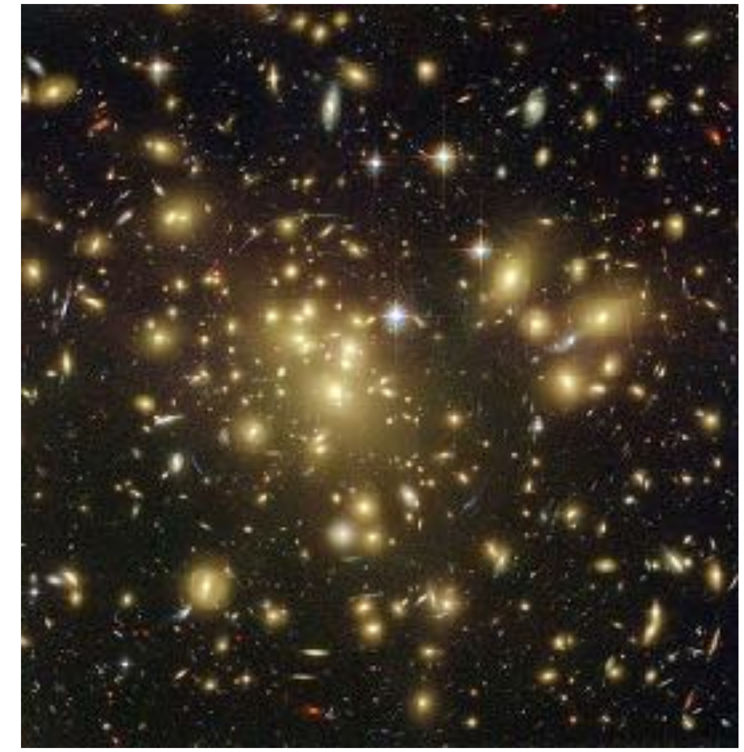
- Only Higgs (~SM) and Nothing Else So Far at the LHC
- Nature is described by Local Gauge Theories
- All the observed particles carry some gauge charges (no gauge singlets observed so far)

- Dark & visible matter and dark energy, neutrinos

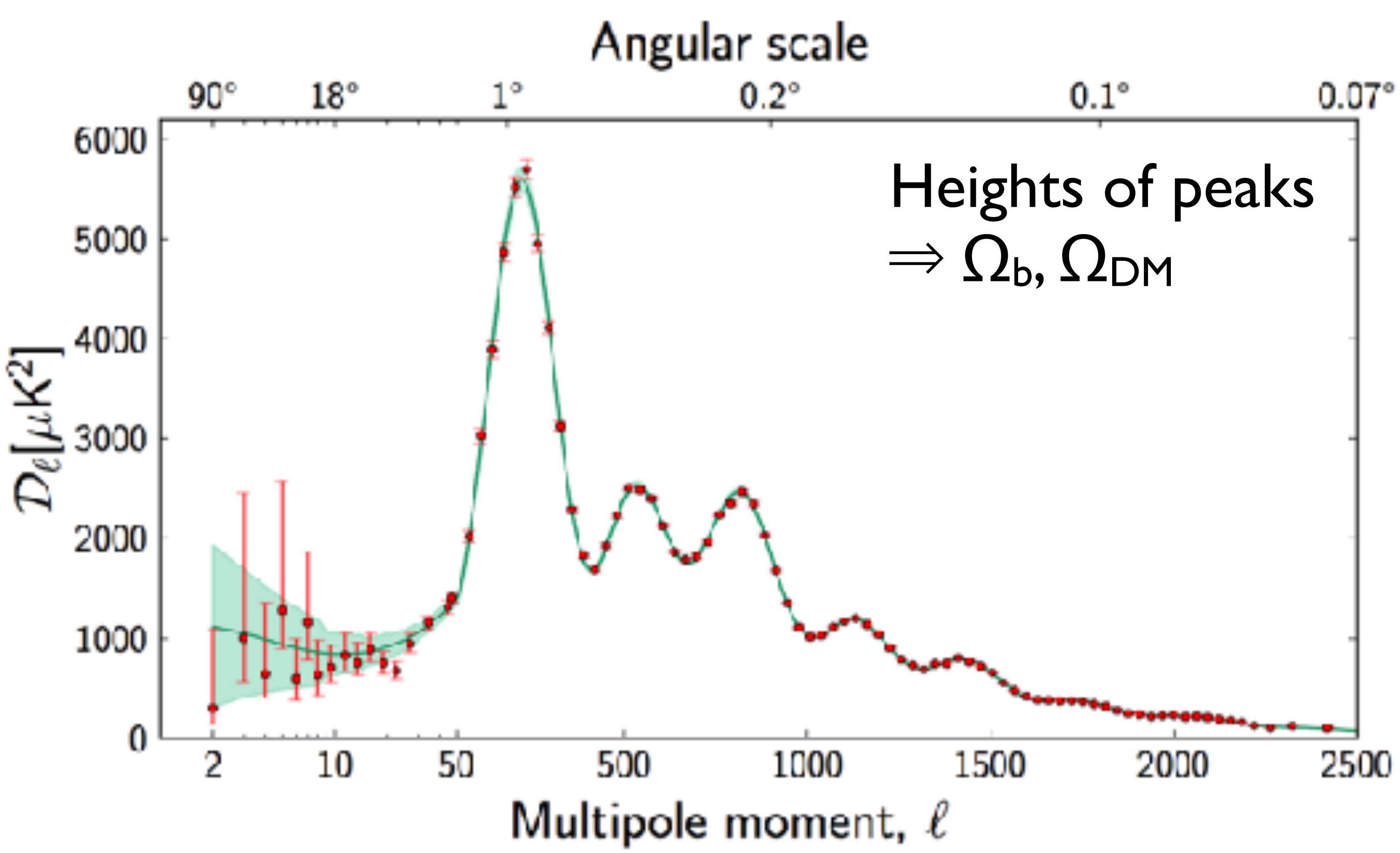


Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster



Strong gravitational lensing in Abell 1689

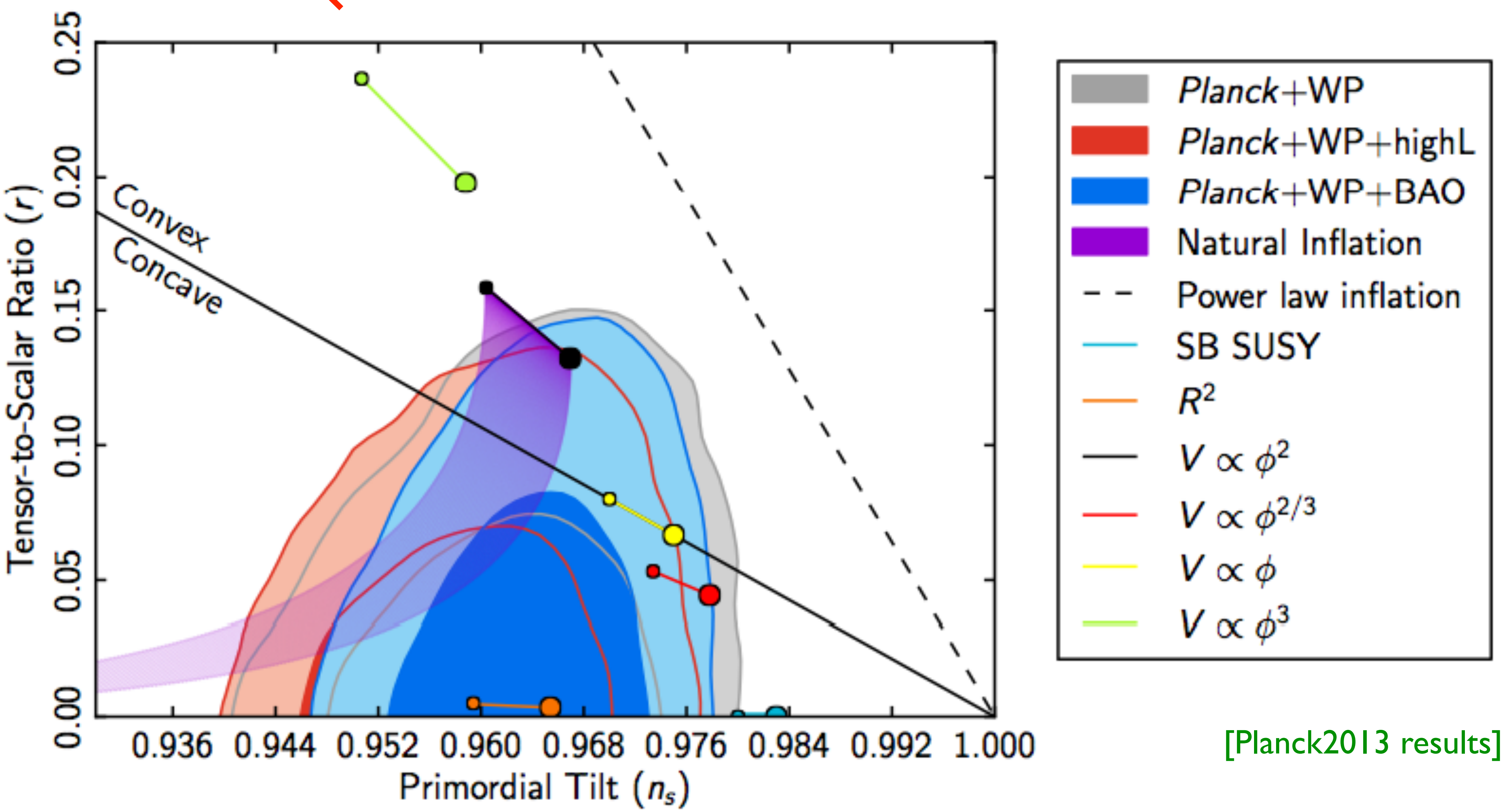


$$\Omega_b \simeq 0.048$$
$$\Omega_{DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

Inflation models in light of Planck2013 data

$V \propto \phi^4$



[Planck2013 results]

Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky ? Higgs Inflations

Many candidates

Can we attack these problems ?

Maybe it is right time to think about what LHC and Planck data tell us about New Physics@EW scale

Origin of EWSB ?

- LHC discovered a scalar ~ SM Higgs boson
- This answers the origin of EWSB within the SM in terms of the Higgs VEV, v
- Still we can ask the origin of the scale “v”
- Can we understand its origin by some strong dynamics similar to QCD or TC ?

Origin of Mass

- Massive SM particles get their masses from Higgs mechanism or confinement in QCD
- How about DM particles ? Where do their masses come from ?
- SM Higgs ? SUSY Breaking ? Extra Dim ?
- Can we generate all the masses as in proton mass from dim transmutation in QCD ? (proton mass in massless QCD)

Questions about DM

- Electric Charge/Color neutral
- How many DM species are there ?
- Their masses and spins ?
- Are they absolutely stable or very long lived ?
- How do they interact with themselves and with the SM particles ?
- Where do their masses come from ? Another (Dark) Higgs mechanism ? Dynamical SB ?
- How to observe them ?

- Most studies on DM were driven by some anomalies: 511 keV gamma ray, PAMELA/AMS02 positron excess, DAMA/CoGeNT, Fermi/LAT 135 GeV gamma ray, 3.5 keV Xray, Gamma ray excess from GC etc
- On the other hand, not so much attention given to DM stability/longevity in nonSUSY DM models
- Important to implement this properly in QFT which is supposed to a framework to describe DM properties (including its interactions)

- Also, often extra particles (the so-called mediators, scalar, vector etc) are introduced to solve three puzzles in CDM paradigm in terms of DM self-interaction
- DR and its interaction with DM may help to relax the tension between H0 and σ_8
- Phenomenologically nice, but theoretically rather ad hoc
- Any good organizing principle ?

- Note that extra particles (the so-called mediators, scalar, vector etc) are introduced to solve three puzzles in CDM paradigm in terms of DM self-interaction
- DR and its interaction with DM may help to relax the tension between H0 and σ_8
- Phenomenologically nice, but theoretically rather ad hoc
- Any good organizing principle ?
- YES ! >> Dark Gauge Symmetry

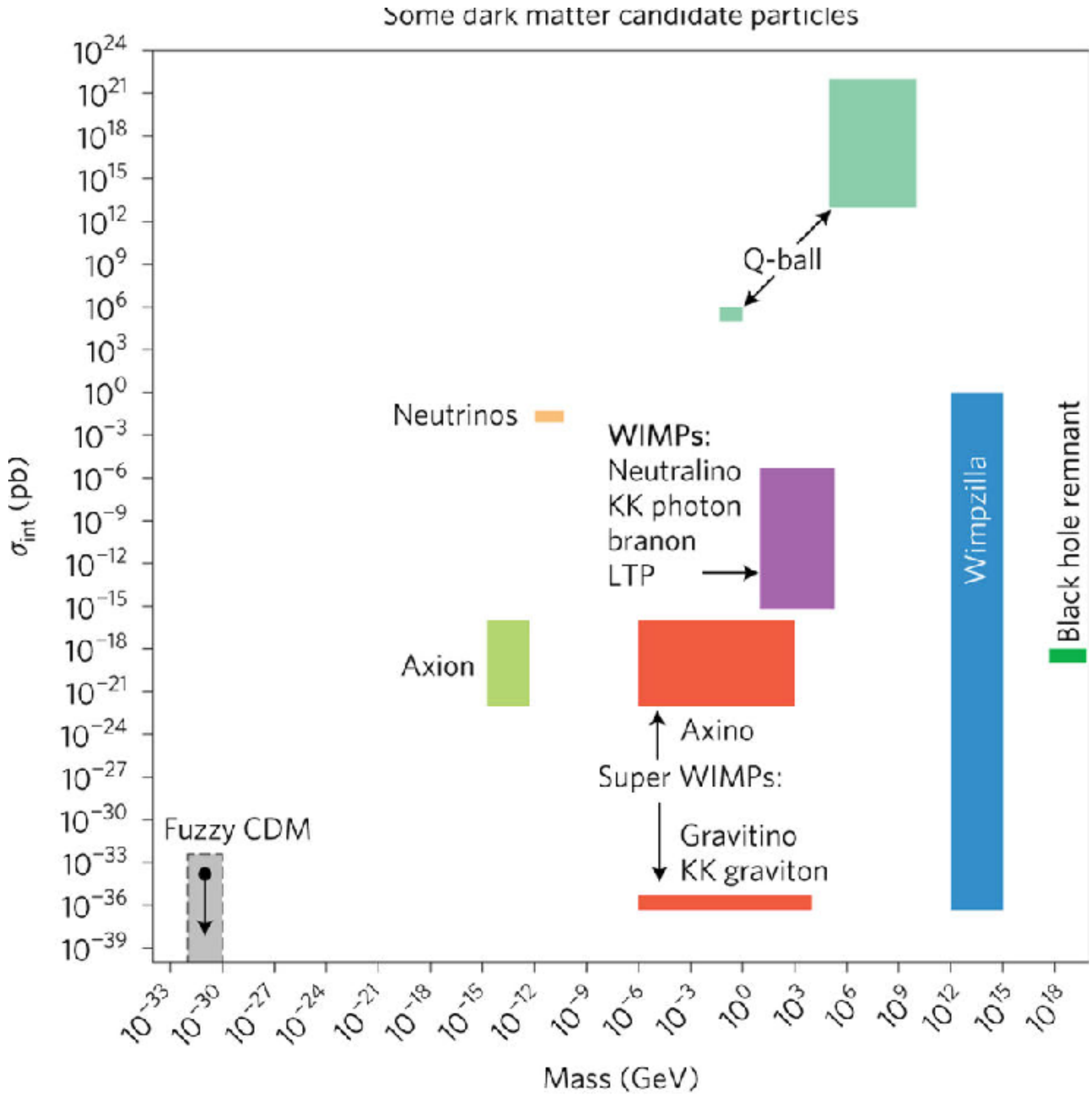
Local Dark Gauge Sym

- Well tested principle in the SM
- Completely fix the dynamics of DM, SM
- Guarantees stability/longevity of DM
- Force mediators already present in a gauge invariant way (Only issue is the mass scales)
- Predictable amount of dark radiation

NB: The first 3 points are also true in the minimal DM scenarios
(No new gauge sym, just SM gauge symmetries)

Basic assumptions

- DM, DR, Mediators : particles that can be described by conventional QFT
- DM stability/longevity is due to unbroken dark gauge symmetry/accidental symmetry of dark gauge theory (similarly to the SM: electron stability / proton longevity)
- Very conservative approach to DM models



Some dark matter candidate particles
σ_int (pb)
Mass (GeV)
Q-ball
Neutrinos
WIMPs:
Neutralino
KK photon
branon
LTP
Axion
Axino
Super WIMPs:
Gravitino
KK graviton
Fuzzy CDM
Wimpzilla
Black hole remnant

SM vs. DM Physics

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- electron stability : U(1)em gauge invariance, electric charge conservation
- proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

SM vs. DM Physics

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- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “Chiral dark gauge theories without any global sym”
- Origin of DM stability/ longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

Hidden (Dark) QCD Scenario

hQCD (Dark QCD)

- Strassler + Zurek (2006) : hQCD + U(1)' , new collider signatures but no discussion on DM from hQCD. hep-ph/0604261. PLB (2007)
- B. Patt and F. Wilczek, hep-ph/0605188. "Higgs portal"
- Hur, Ko, Jung, Lee (2007): EWSB and CDM from h-QCD, arXiv:0709.1218 [hep-ph], PLB (2011)
- Hur, Ko (2007) : scale inv. extension of SM+hQCD. All the mass scales (including DM mass) from hQCD. PRL(2011)
- Proceedings: Int.J.Mod.Phys. A23 (2008) 3348-3351, AIP Conf.Proc. 1178 (2009) 37-43, arXiv:1012.0103 (ICHEP), etc
- Hochberg et al. : SIMP in Dark QCD (2014, 2015)
- Hatanaka, Jung, Ko : AdS/QCD approach, arXiv:1606.02969, JHEP (2016)

Hidden Sector

- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could make CDM
- Hidden gauge sym can stabilize CDM
- Generic in many BSM's including SUSY models
- Can address "QM generation of all the mass scales from strong dynamics in the hidden sector" (orthogonal to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

Nicety of QCD

- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction, ignoring dim-5 operators; proton is stable or very long lived)

$$\frac{1}{M_{\rm Planck}} H^\dagger H \overline{q_h} \gamma_5 q_h$$

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

WIMP scenario with the S-H portal

- Hur, Jung, Ko, Lee, arXiv:0709.1218
- Hur, Ko, 1103.2571, PRL (2011)
- Hatanaka, Jung, Ko, 1606.02969, JHEP (2016)

And proceedings:

- Int. J. Mod. Phys. A23 (2008) 3348-3351
- AIP Conf. Proc. 1178 (2009) 37-43
- ICHEP 2010 Proceeding, hep-ph/1012.0103

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

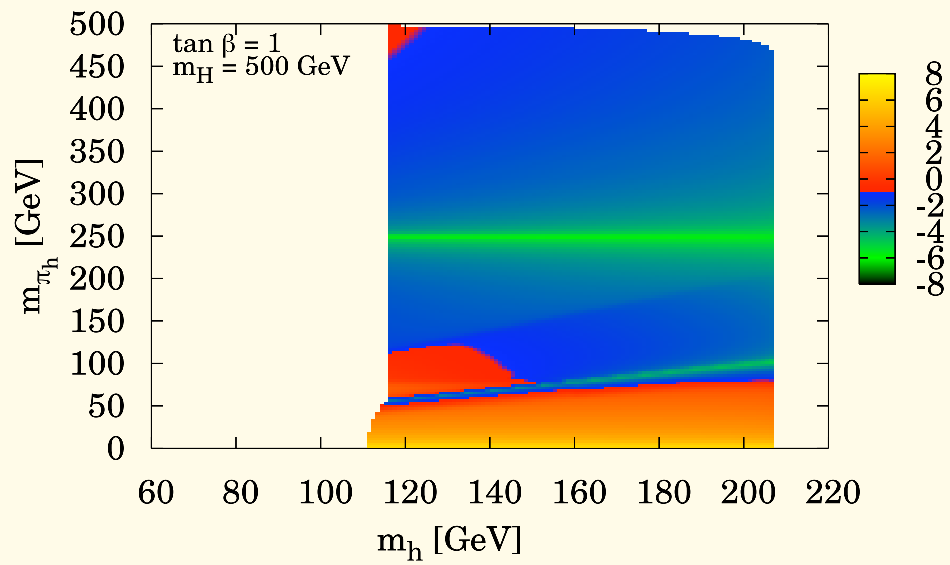
Not present in the two-Higgs Doublet model

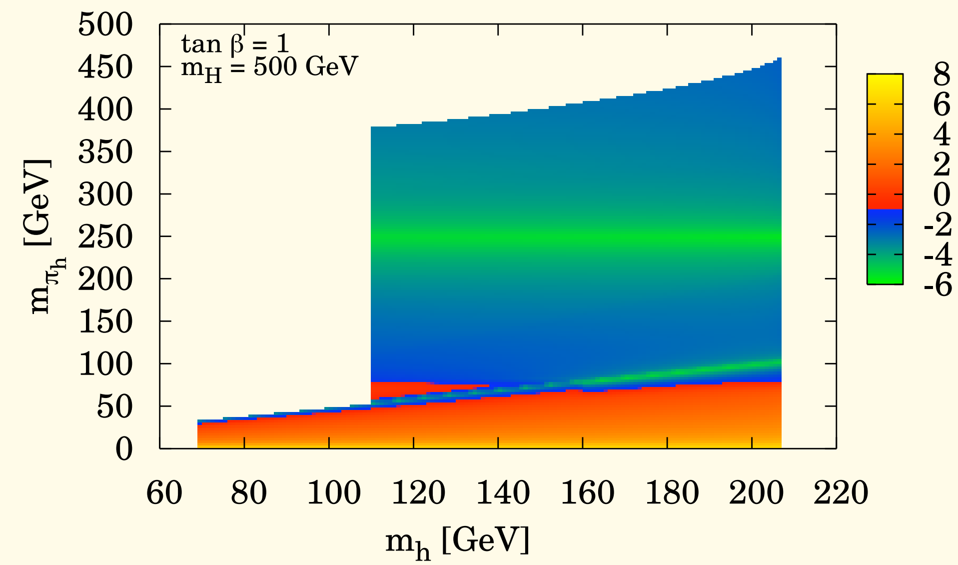
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

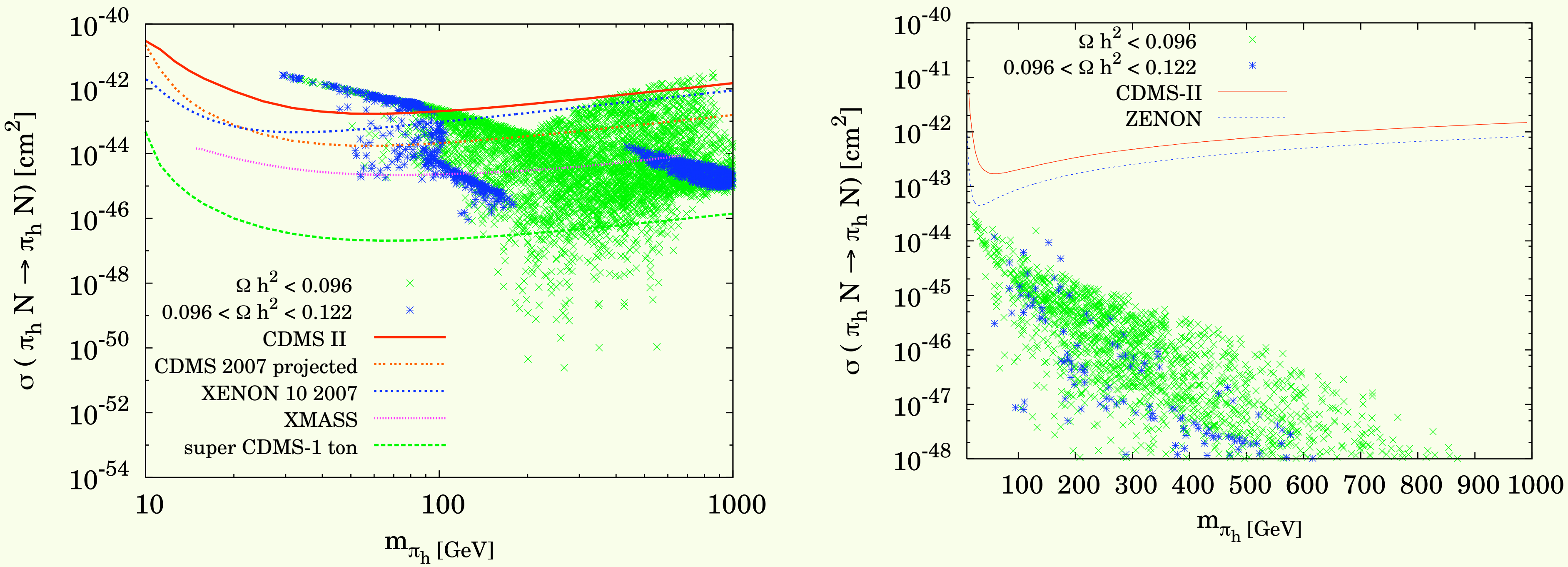
Relic Density





- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate



- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Classical Scale Sym Model

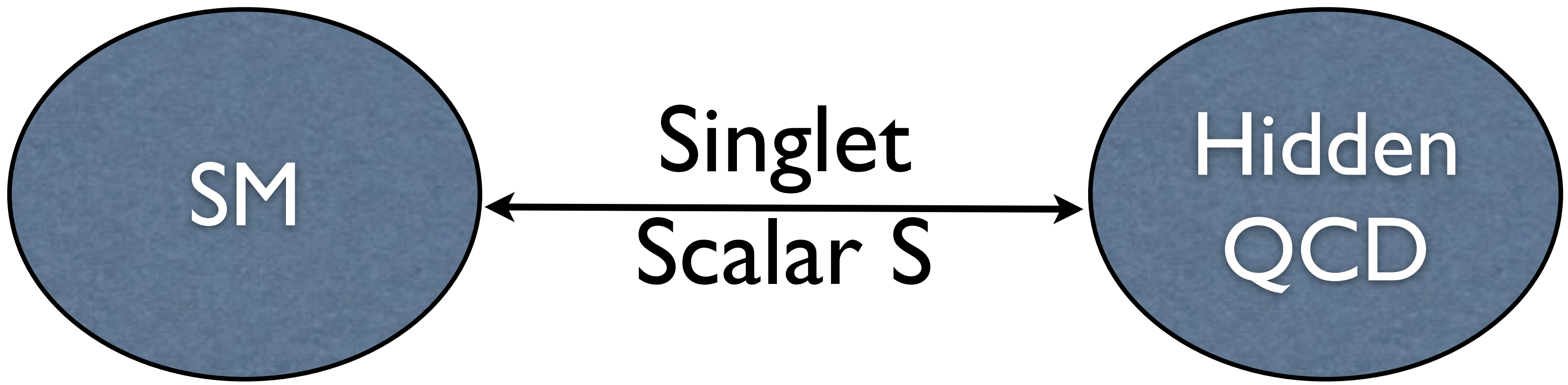
- Scale invariant extension of the SM + hQCD
- Mass scale is generated by nonperturbative strong dynamics in the hidden sector
- EWSB and CDM from hQCD sector

All the masses (including CDM mass) from hidden sector strong dynamics

Appraisal of Scale Invariance

- May be the only way to understand the origin of mass dynamically (including spontaneous sym breaking)
- Without it, we can always write scalar mass terms for any scalar fields, and Dirac mass terms for Dirac fermions, the origin of which is completely unknown
- Probably only way to control higher dimensional op's suppressed by Planck scale

Model I (Scalar Messenger)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by "S"

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$
\begin{aligned}
\mathcal{L}_{\rm SM} \;=\; & \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\
+ \; & \Big(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \\
+ \; & \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c.\Big)
\end{aligned}
$$

Hidden sector lagrangian with new strong interaction

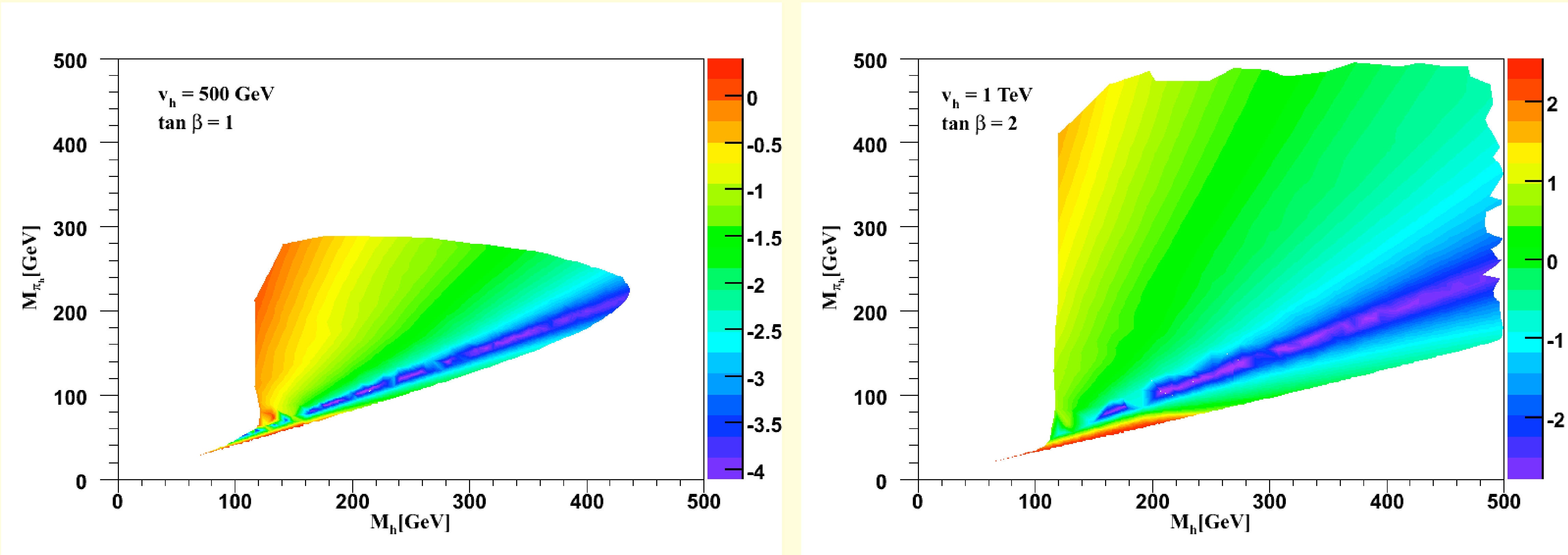
$$
\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k
$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

Relic density

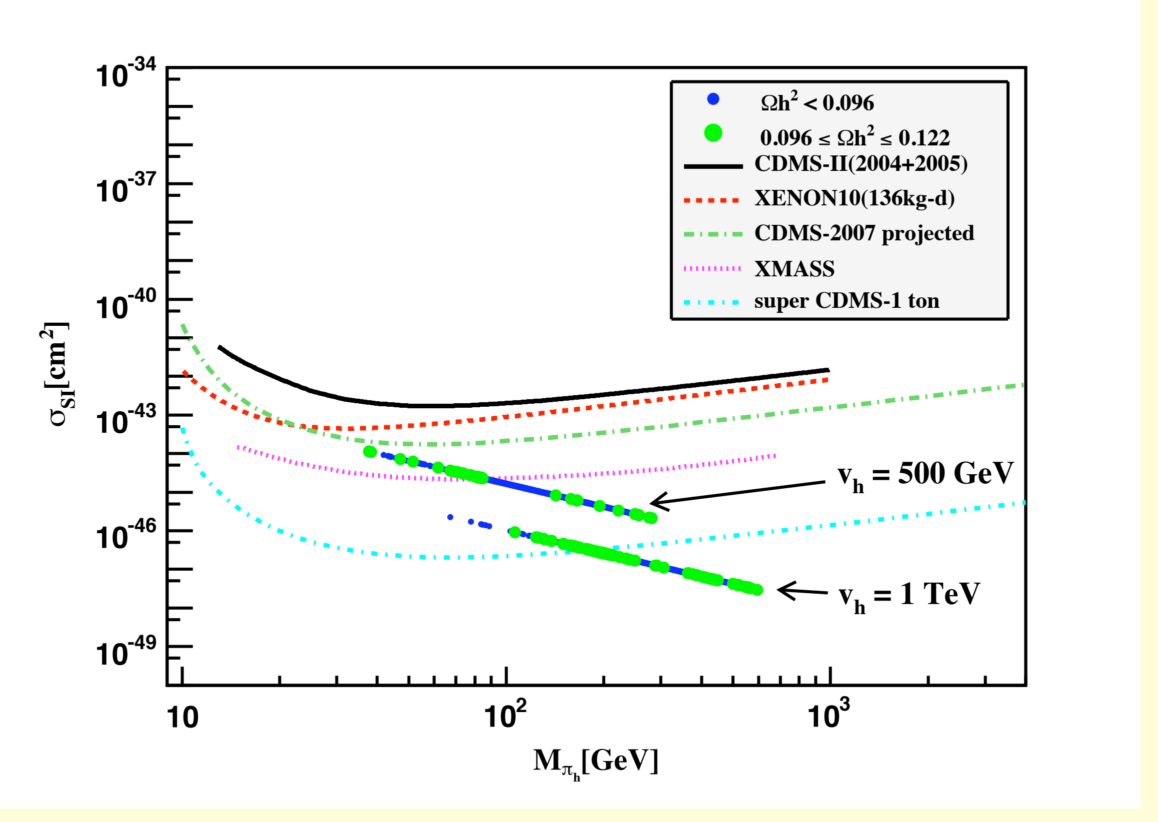


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Comparison with the previous models

- Dark gauge symmetry is unbroken (DM could be absolutely stable if they appeared in the asymptotic states), but confining like QCD (No long range dark force, DM becomes composite)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Additional singlet scalar improves the vacuum stability up to Planck scale
- Can modify Higgs inflation scenario (Higgs-portal assisted Higgs inflation [arXiv:1405.1635, JCAP (2017) with Jinsu Kim, WIPark]
- The 2nd scalar could be very very elusive
- Can we find the 2nd scalar at LHC ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

EFT vs. UV completion with a singlet scalar-Higgs portal

Seungwon Baek, Pyungwon Ko, Wan-Il Park,

arXiv:1112.1847, JHEP (2012);
arXiv:1405.3530, PRD (2014)

Higgs portal DM as examples

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

$$\mathcal{L}_{\text{fermion}} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \,\overline{\psi}\psi$$

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

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

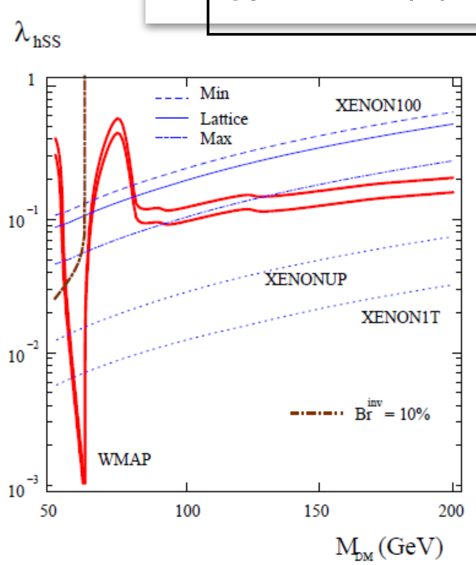


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

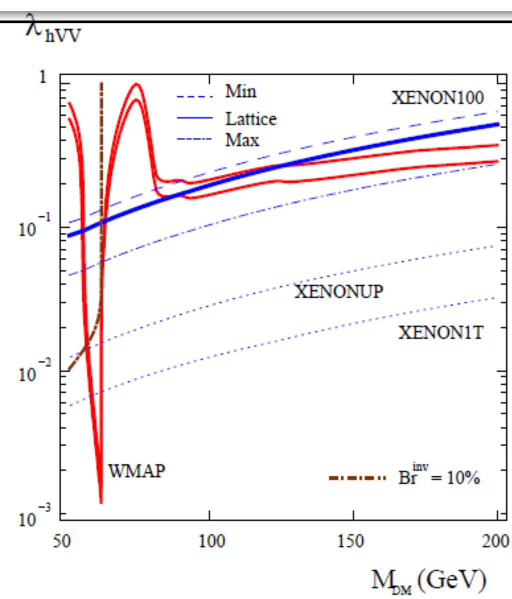


FIG. 2. Same as Fig. 1 for vector DM particles.

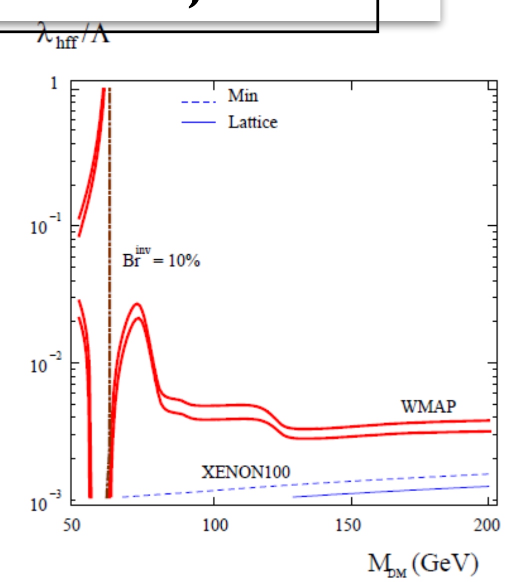


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \ \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

- Scalar CDM : looks OK, renorm. .. BUT .....
- Fermion CDM : nonrenormalizable
- Vector CDM : looks OK, but it has a number of problems (in fact, it is not renormalizable)

Usual story within EFT

- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in the full theories (renormalizable) however

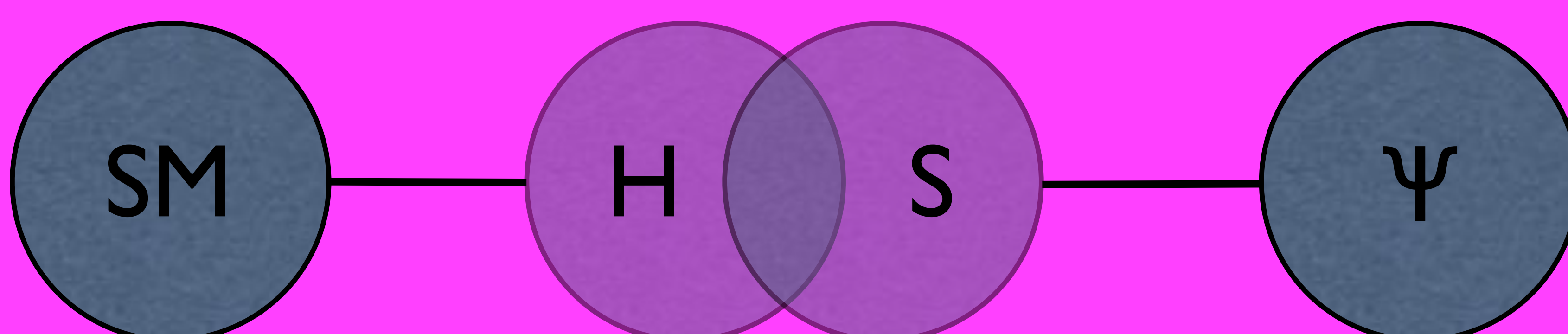
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\
&\quad + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4 \\
&\quad + \overline{\psi}(i \not\partial - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi
\end{aligned}
$$

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Ratiocination

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2}\lambda_{HS} v_S^2,$$
$$m_S^2 = -\frac{\mu_S^3}{v_S} - \mu_S' v_S - \lambda_S v_S^2 - \frac{\mu_{HS} v_H^2}{2 v_S} - \frac{1}{2}\lambda_{HS} v_H^2,$$

at vacuum

$$M_{\rm Higgs}^2 \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$
$$H_2 = h\sin\alpha + s\cos\alpha.$$

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \, \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \, \mathrm{Br}(h \to \mathrm{SM})}$$

$$r_1 = \frac{\cos^4\alpha \, \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \, \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \, \Gamma^{\mathrm{hid}}_{H_1}}$$

$$r_2 = \frac{\sin^4\alpha \, \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \, \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \, \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$

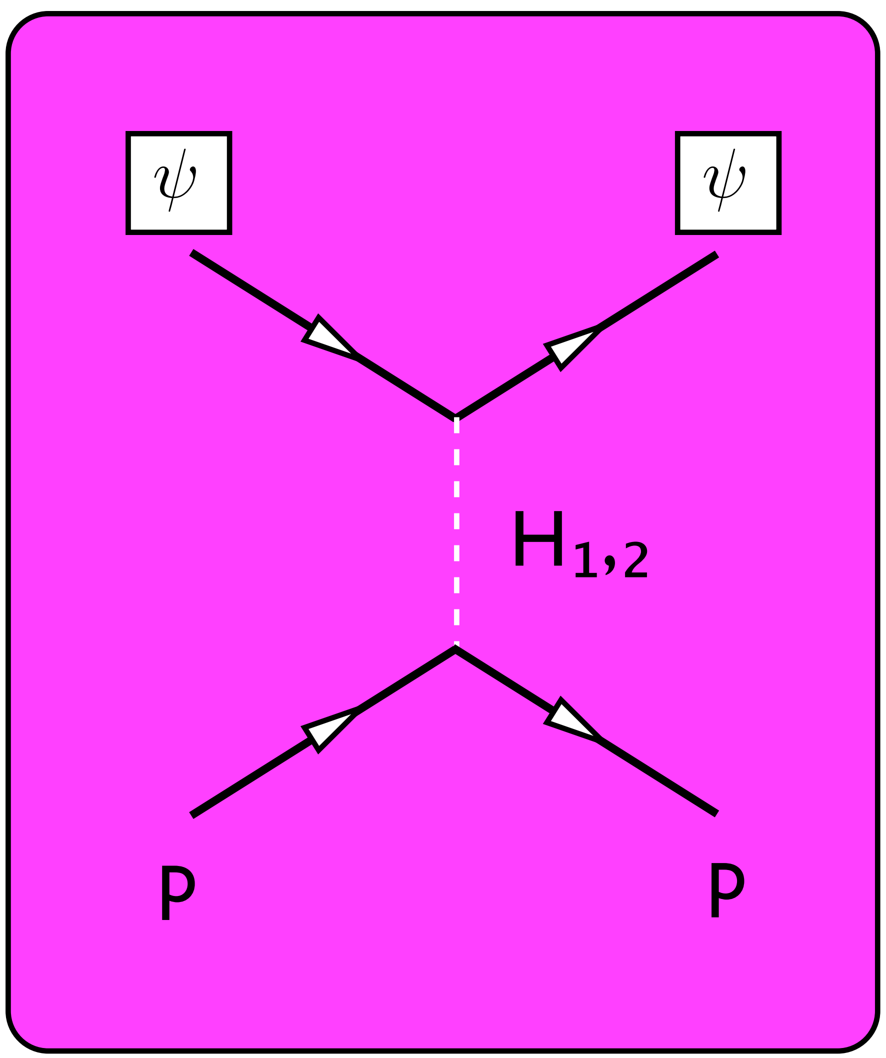
Invisible decay mode is not necessary!

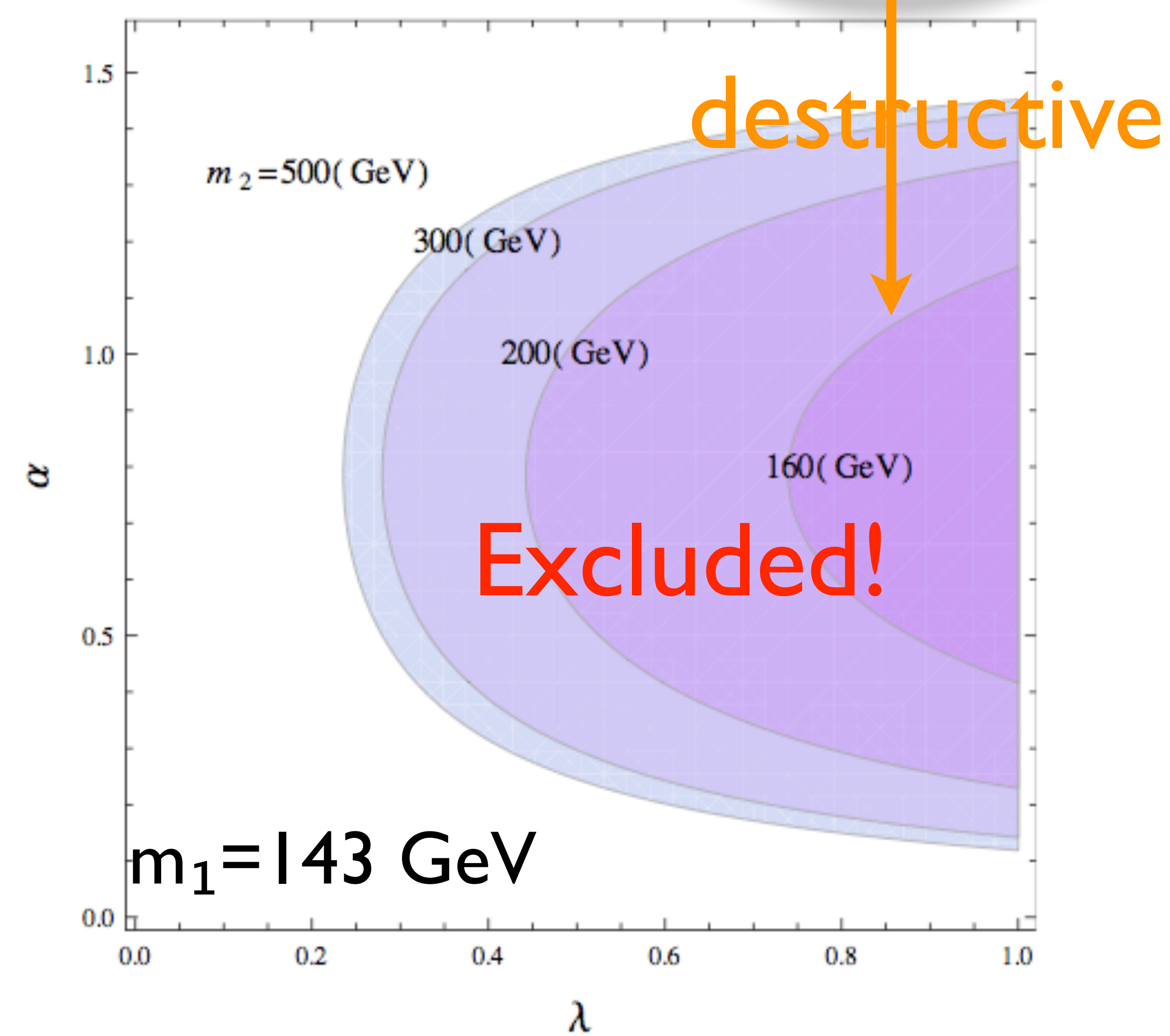
If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda\sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$





- We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

$$\mathcal{L}_{\rm eff} = \overline{\psi} \left(m_0 + \frac{H^\dagger H}{\Lambda} \right) \psi. \qquad \text{or} \qquad \lambda h \overline{\psi} \psi$$

Breaks SM gauge sym

- Only one Higgs boson (alpha = 0)

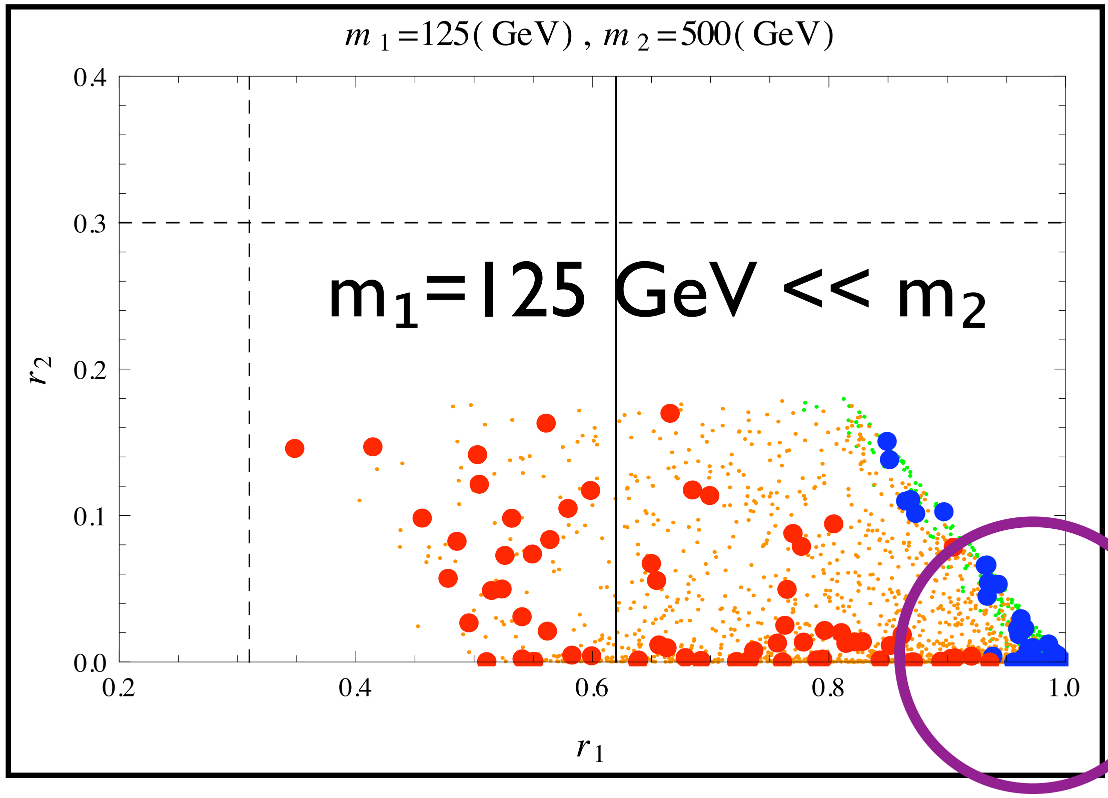
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

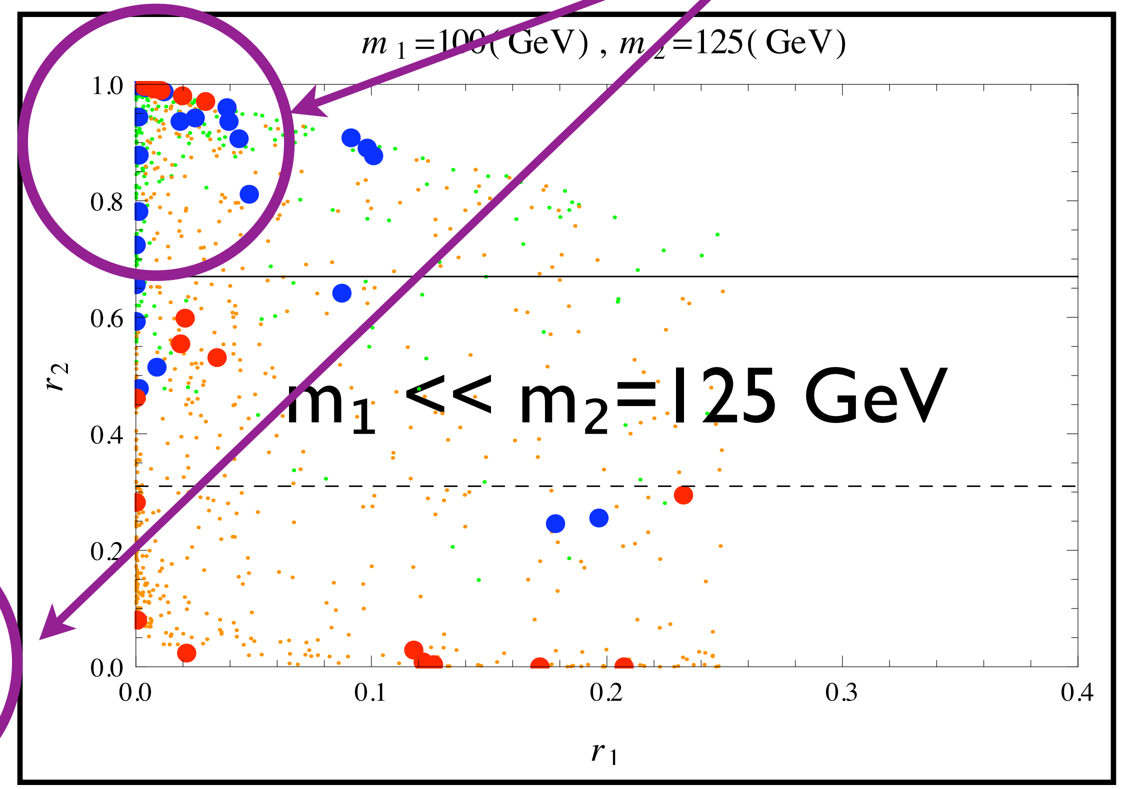
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

- Signal strength (r_2 vs r_1)

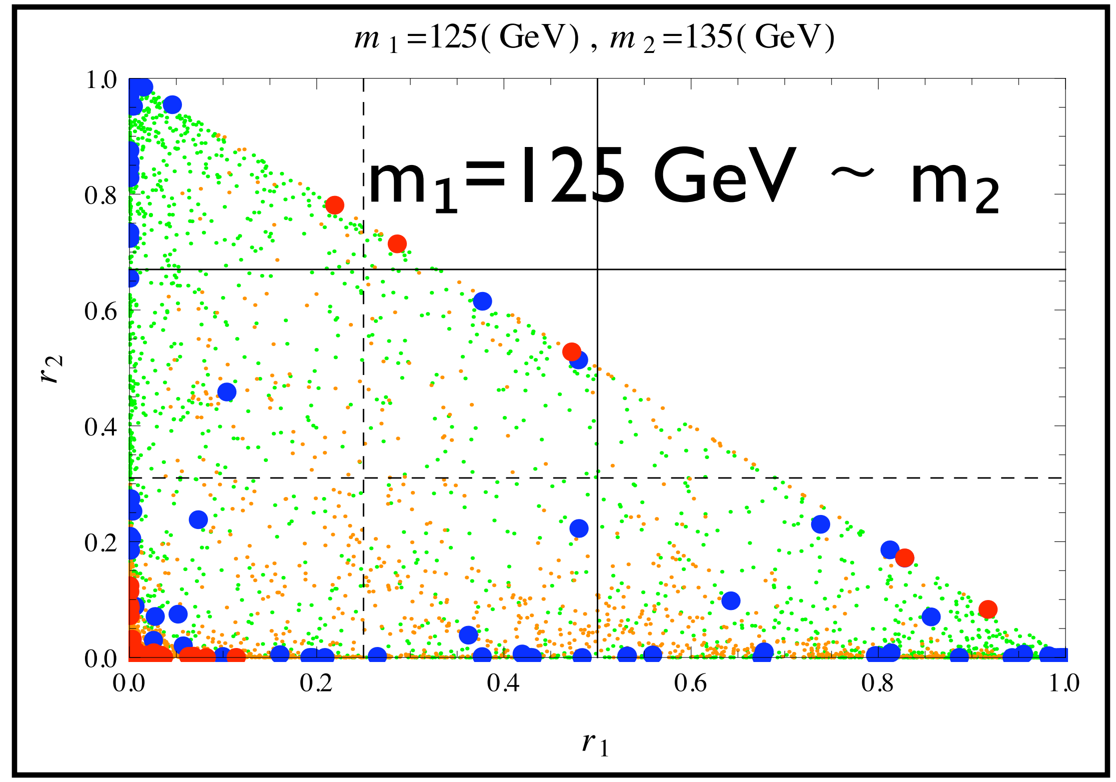
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.



- (green): Ω(x),σ_p(x)
- (orange): Ω(x),σ_p(o)
- (blue): Ω(o),σ_p(x)
- (red): Ω(o),σ_p(o)

Low energy pheno.

- Universal suppression of collider SM signals

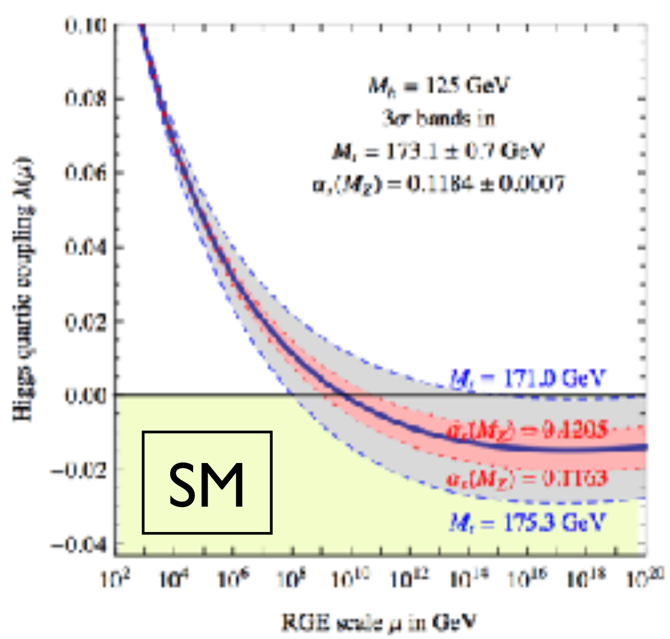
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!

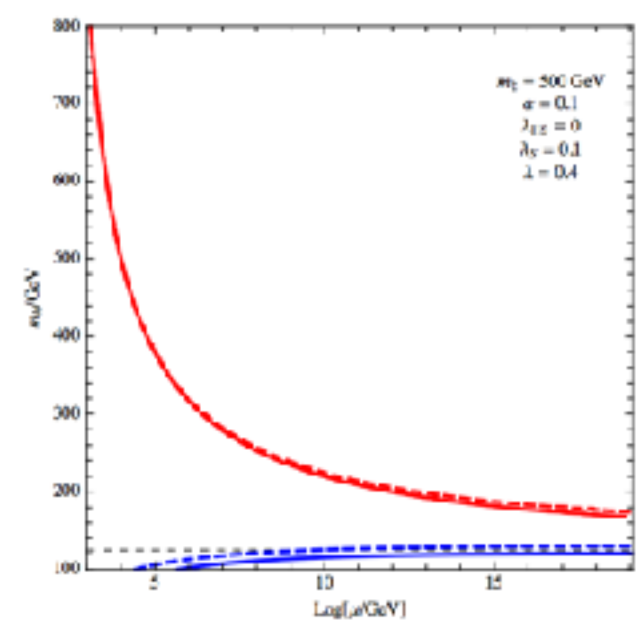
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

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

If "$m_\phi > m_h$", vacuum instability can be cured.

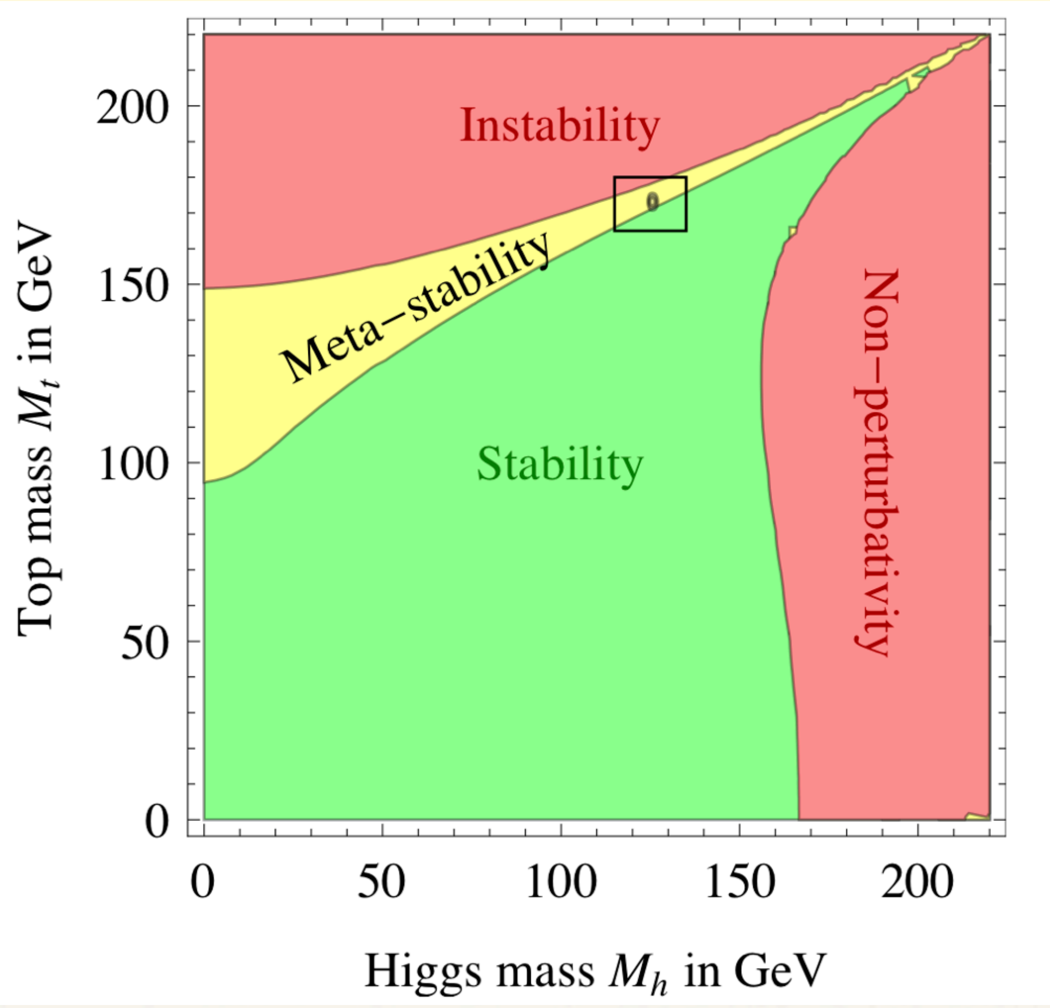


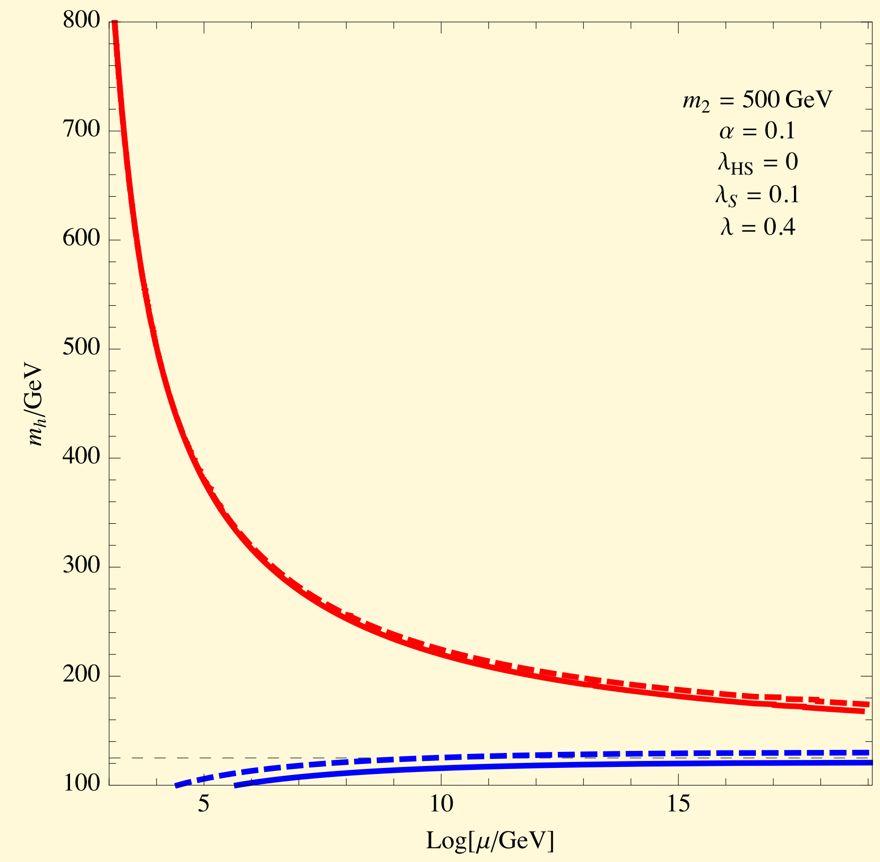
[G. Degrassi et al., 1205.6497]



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

Vacuum Stability Improved by the singlet scalar S





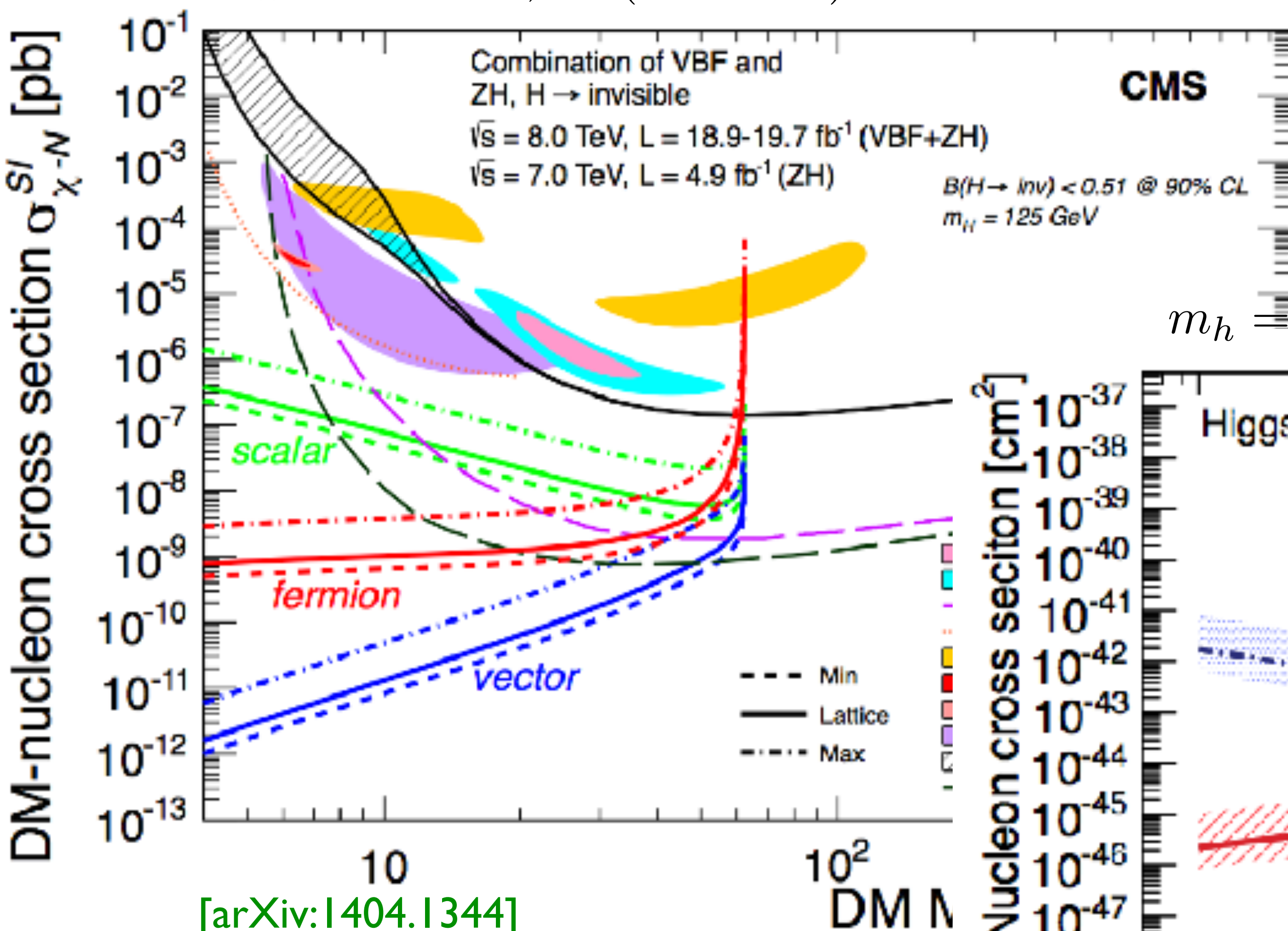
A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Collider Implications

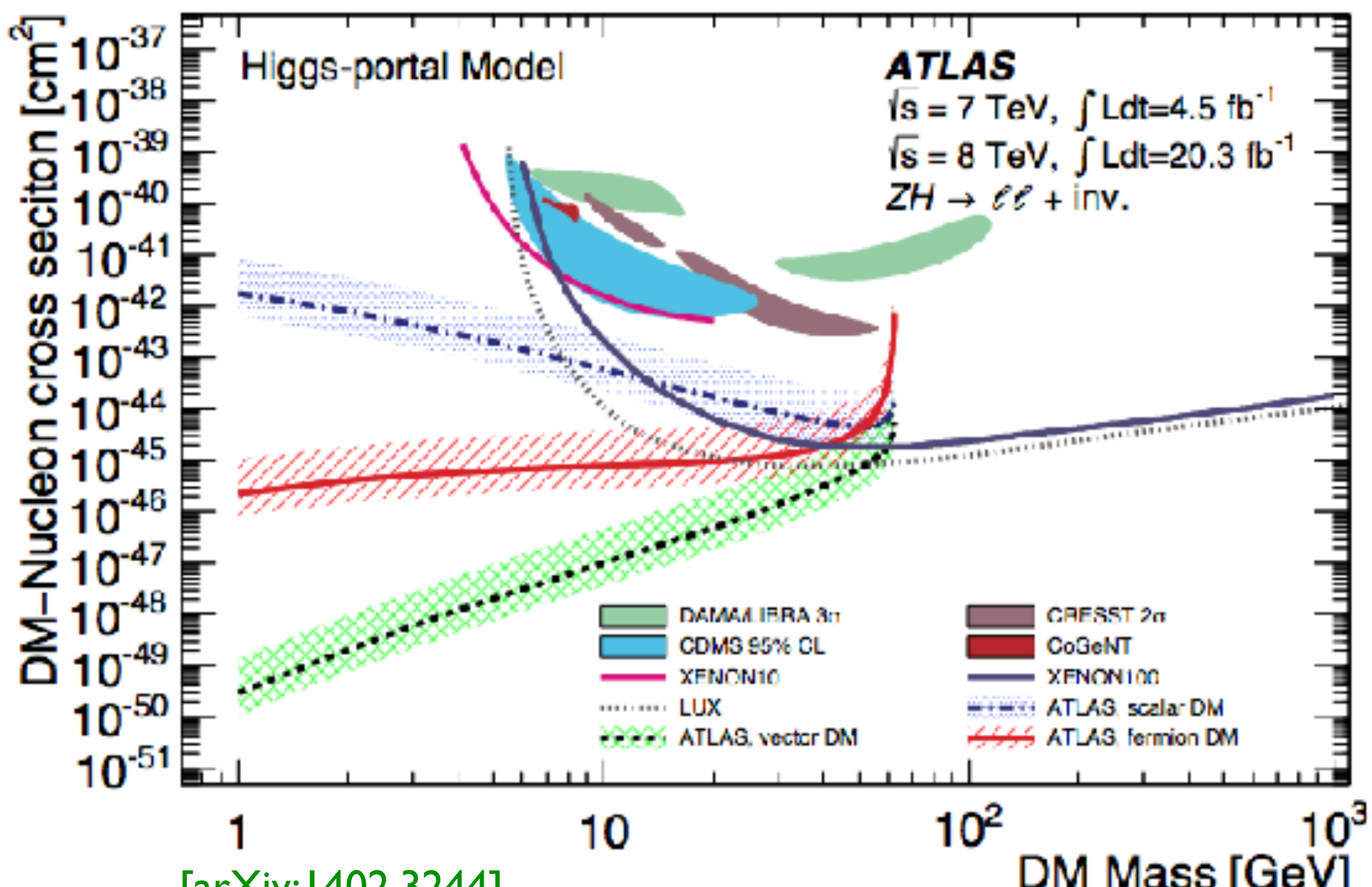
Based on EFTs

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



[arXiv:1404.1344]

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



[arXiv:1402.3244]

- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

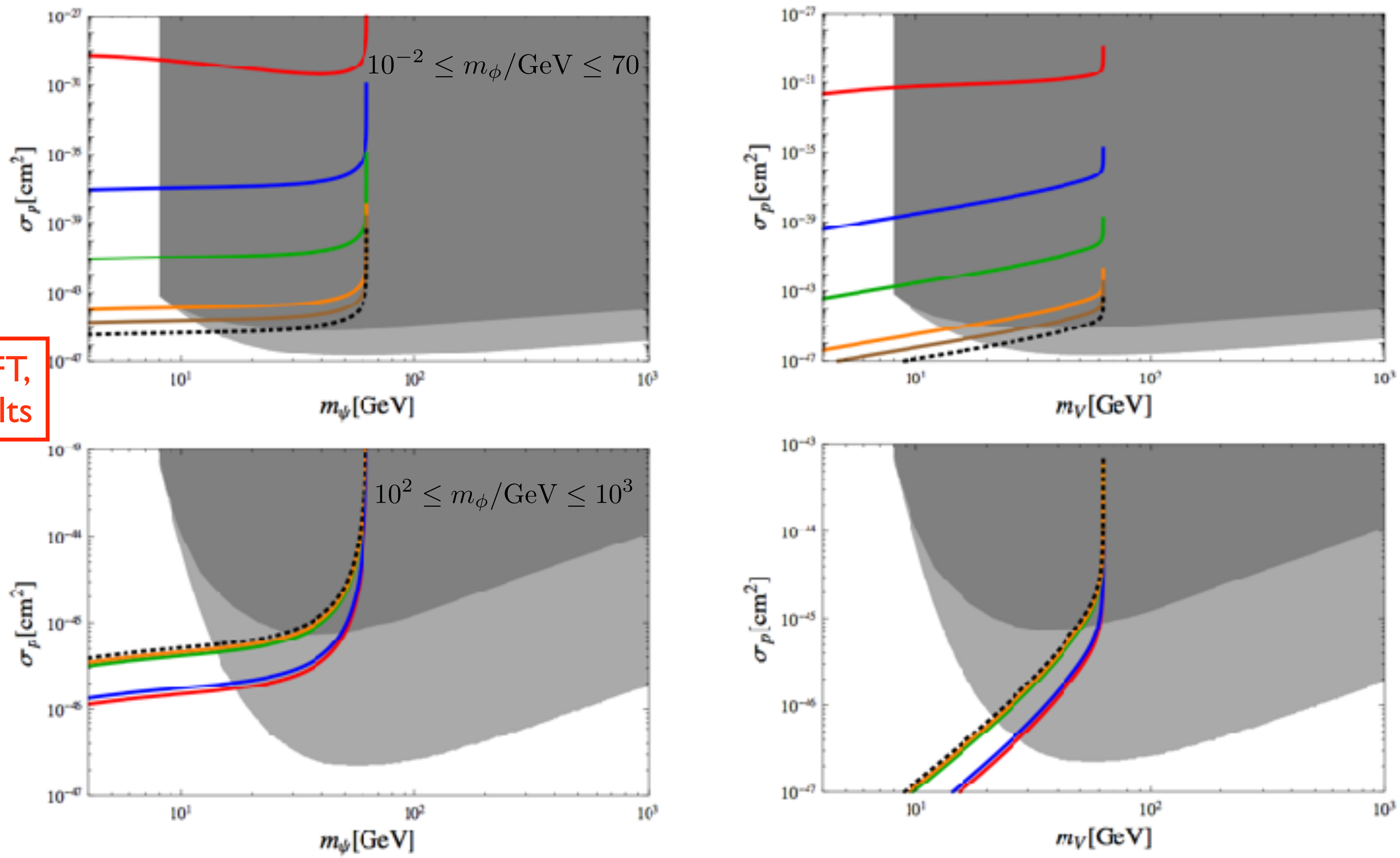
[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

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

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

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

Dashed curves:EFT, ATLAS,CMS results

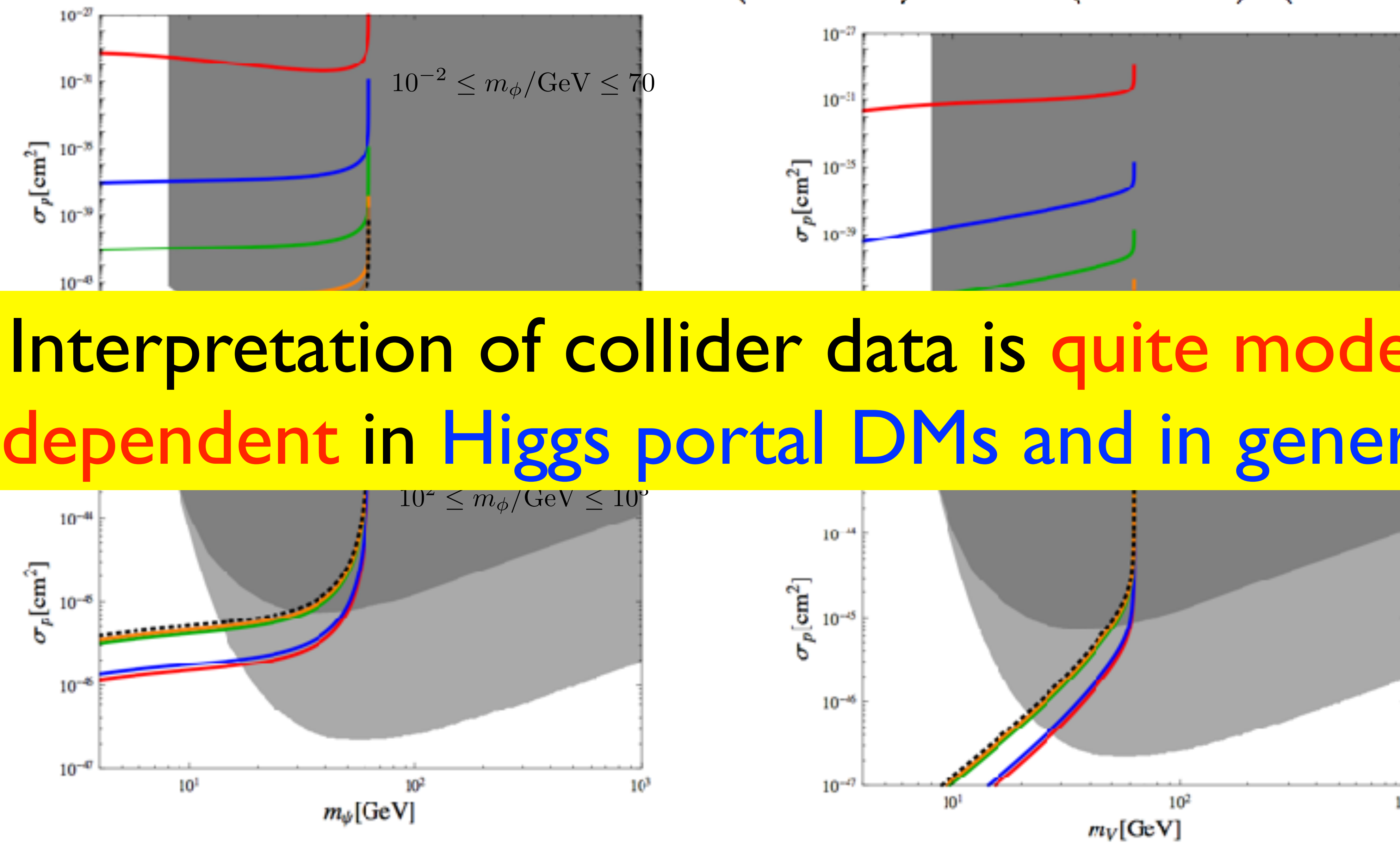


- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\ c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\ c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

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



Interpretation of collider data is quite model-dependent in Higgs portal DMs and in general

Role of Dark Higgs at Colliders

DD vs. Monojet :
Why complementarity
breaks down in EFT ?

- S. Baek, P. Ko, M. Park, WIPark, C. Yu, arXiv:1506.06556 Phys. Lett. B756 (2016)289
- P. Ko and Jinmian Li, arXiv:1610.03997, PLB (2017)
- P. Kamon, P. Ko, Jinmian Li, arXiv:1705.02149, EPJC(2017)

NOT COVERED HERE

Impact of dark higgs -Cosmo.

(Higgs-portal assisted Higgs inflation)

- Jinsu Kim, P. Ko, WIPark, arXiv: 1405.1635, JCAP (2017)

Higgs Inflation

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm P}^2}{2}\left(1 + \xi_h \frac{h^2}{M_{\rm P}^2}\right) R + \mathcal{L}_h$$

Bezrukov and Shaposhnikov,
hep-ph/0710.3755, PLB(2018)

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \ , \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2} \ .$$

$$S_E = \int d^4x \sqrt{-\hat{g}} \Bigg\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi) \Bigg\}$$

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$

Potential & Predictions

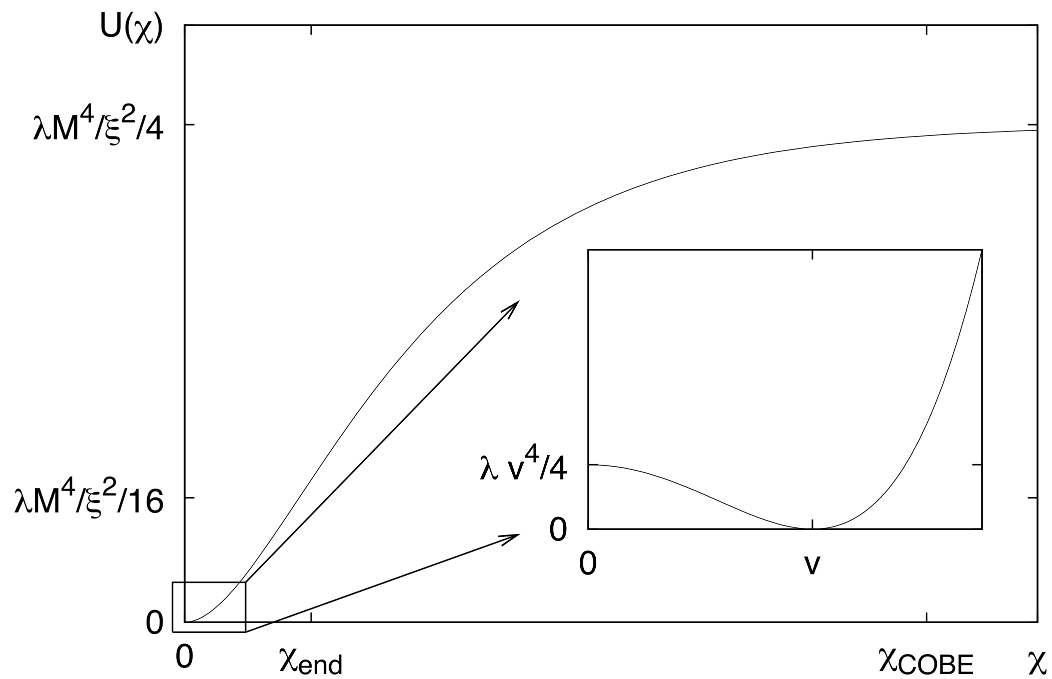


Fig. 1. Effective potential in the Einstein frame.

Analysis of the inflation in the Einstein frame [3] can be performed in standard way using the slow-roll approximation. The slow roll parameters (in notations of

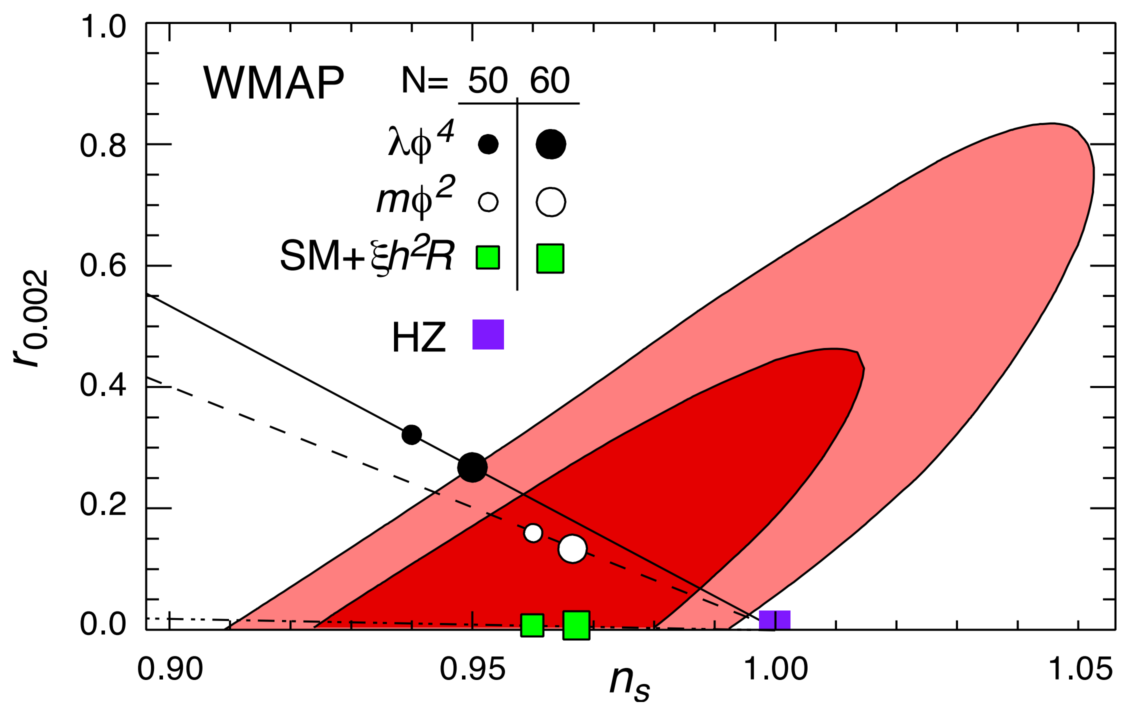
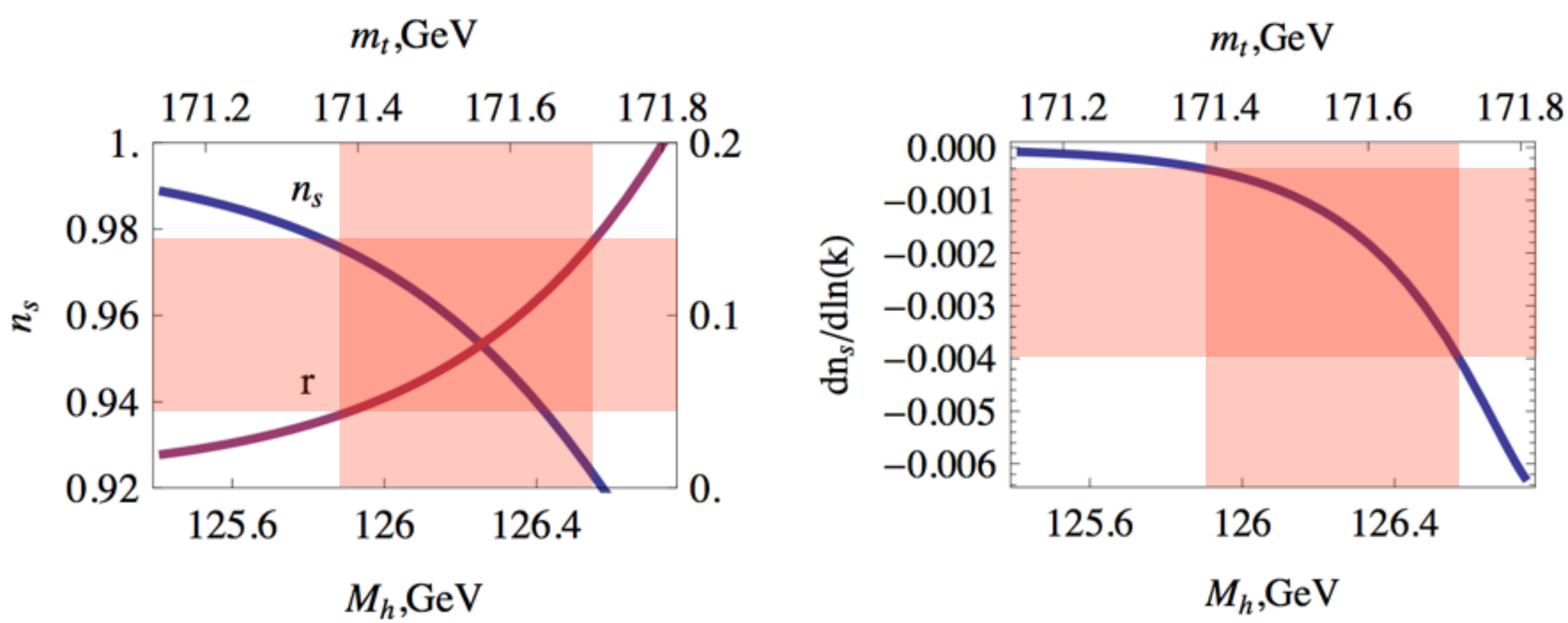


Fig. 2. The allowed WMAP region for inflationary parameters (r, n). The green boxes are our predictions supposing 50 and 60 e–foldings of inflation. Black and white dots are predictions of usual chaotic inflation with $\lambda\phi^4$ and $m^2\phi^2$ potentials, HZ is the Harrison-Zeldovich spectrum.

$$\xi \simeq \sqrt{\frac{\lambda}{3}} \frac{N_{\rm COBE}}{0.027^2} \simeq 49000\sqrt{\lambda} = 49000\frac{m_H}{\sqrt{2}v}$$

RG Improvement

- Prediction of SM Higgs inflation



$$\frac{dn_s}{d\ln k} \sim 10^{-3}$$

- Y. Hamada, H. Kawai, K.Y. Oda, S.C.Park, arXiv:1403.5043
- F. Bezrukov, M. Shaposhnikov, arXiv:1403.6078

Higgs portal interaction with Dark Higgs can change the whole story

$$\lambda_H = \left[1 - \left(1 - \frac{m_\phi^2}{m_h^2}\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$

And by RG running of Higgs self coupling

No strong dependence on the top quark mass

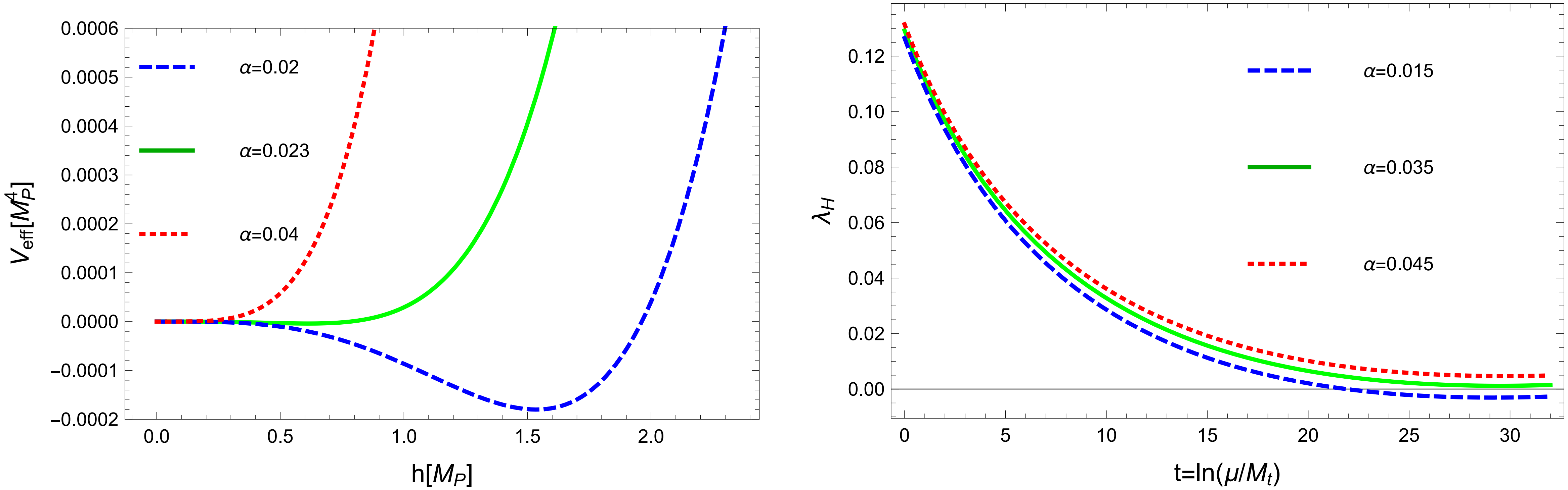


Figure 3. Jordan-frame Higgs potential V_{eff} (left panel) and the running of λ_H (right panel) in SFDM for $\xi_h = 440$, $\xi_s = 0$, $m_s = 600\,\text{GeV}$, $\lambda_{SH} = 0.1$, $\lambda_S = 0.2$, and $\lambda_\psi = 0.3$ chosen at M_t scale.

α	m_s	λ_{SH}	λ_S	λ_ψ	ξ_h	N_e	$10^9 P_S$	n_s	r	α_s
0.036	500	0.1	0.2	0.3	433	57.3	2.2	0.9758	0.0926	−0.0003
0.03885	500	0.1	0.1	0.1	396	57.3	2.2	0.9775	0.0878	−0.0003

Table 1. Cosmological observables in SFDM. Two parameter sets which result in a sizeable value of the tensor-to-scalar ratio r are presented. Here the pivot scale $k_* = 0.05\,\text{Mpc}^{-1}$ is chosen. For the upper (lower) case, we obtained $x \approx 0.25$ (0.26) and $y \approx 0.11$ (0.11), where x and y are defined as eq. (3.15).

Predictions

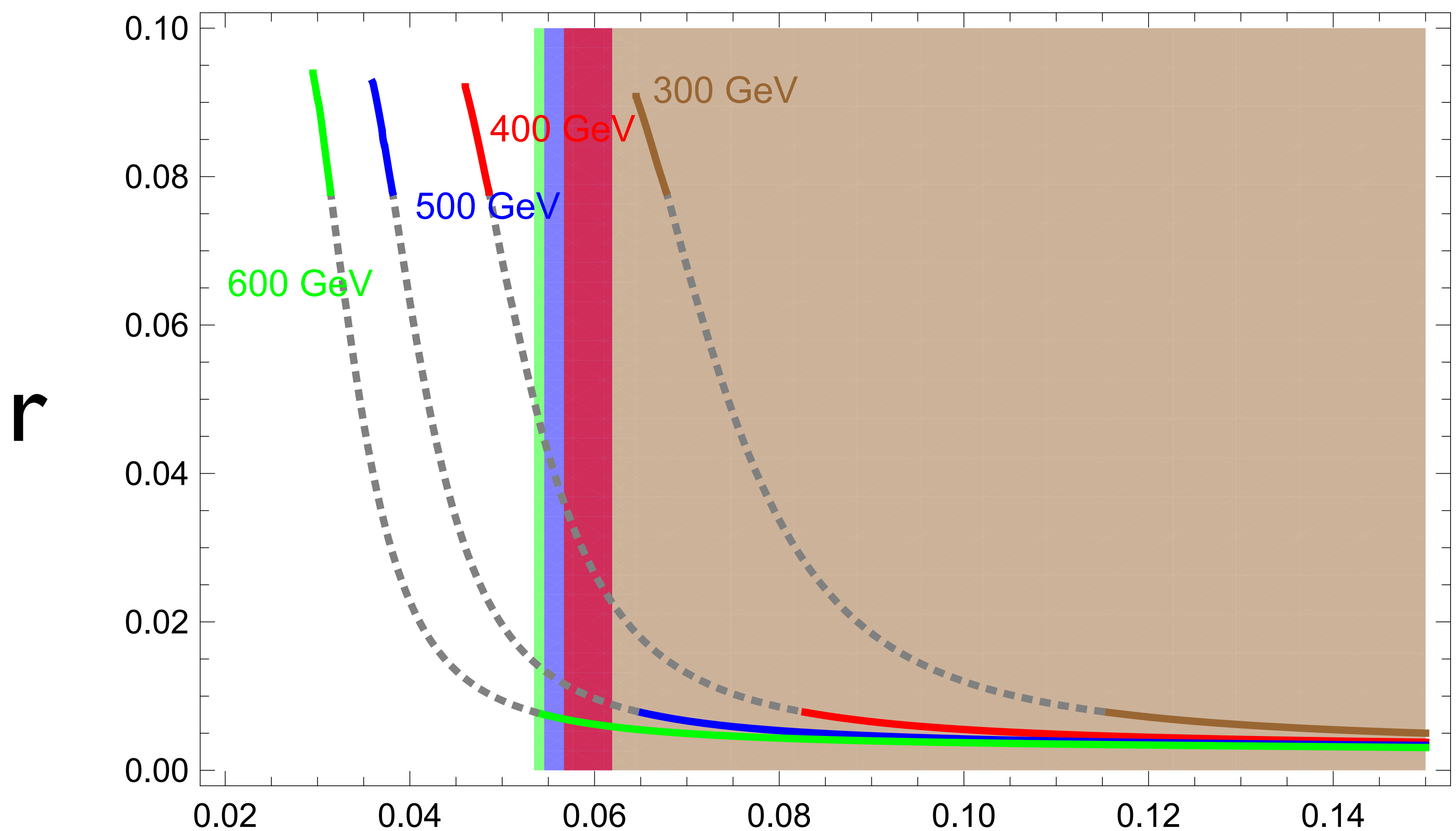


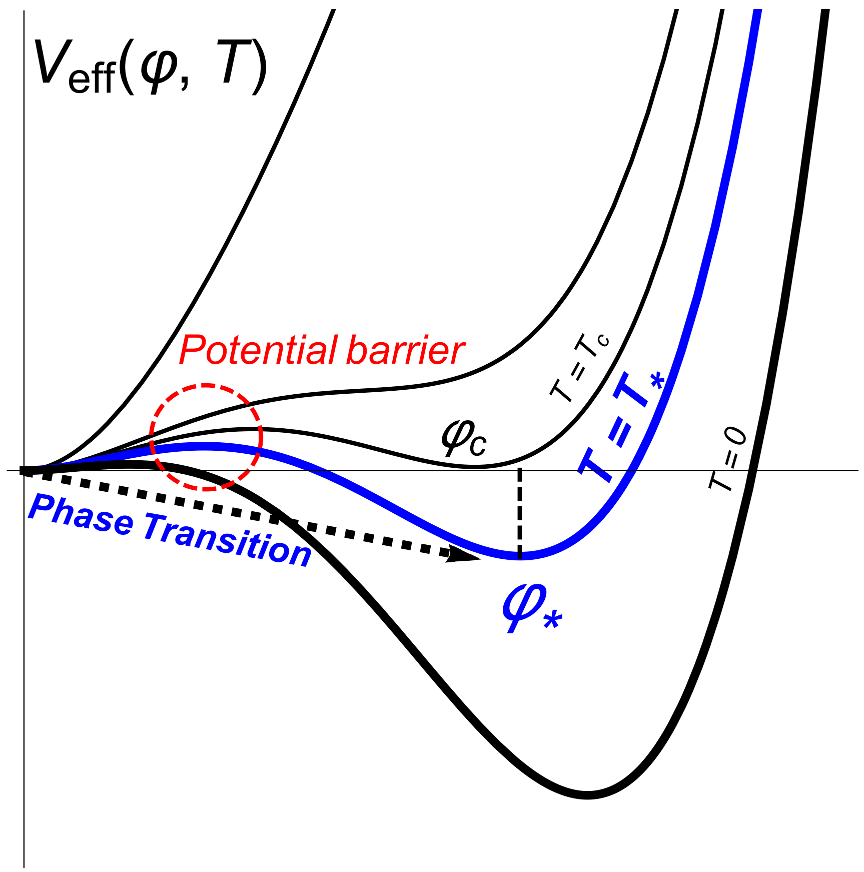
Figure 6. Tensor-to-scalar ratio as a function of the mixing angle α for $m_s = 300\,\text{GeV}$, $400\,\text{GeV}$, $500\,\text{GeV}$ and $600\,\text{GeV}$, with the constraints discussed in the main text. The stringent upper bounds for a given m_s comes from the DM physics. The values of the other parameters are the same as in figure 4. Color-shaded regions (following the scheme of colored lines) are the excluded regions from the latest LUX experiment, corresponding to different dark Higgs masses.

Gravitation wave vs. Higgs self couplings

Katsuya Hishino, Shinya Kanemura, Mitsuru Kakizaki,
Pyungwon Ko, Toshinori Matsui,
arXiv:1609.00297, Phys. Lett. B766 (2017) 49

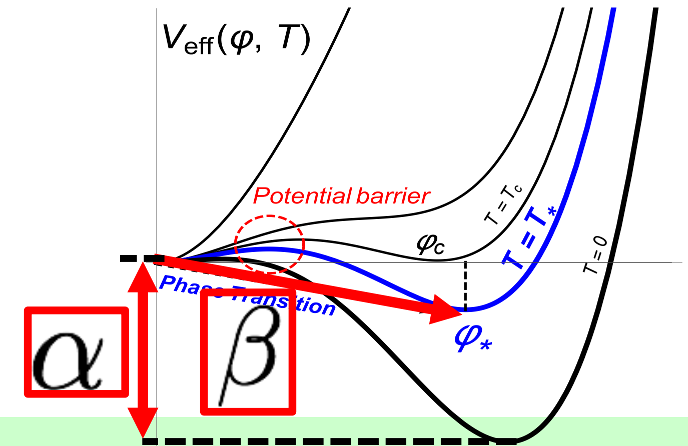
EWBGEN ?

- Baryon # asymmetry of the universe : $n_B/s \simeq \mathcal{O}(10^{-10})$
- Sakharov's 23 conditions : (i) B violation, (ii) C, CP violation, (iii) Departure from equilibrium



- Strongly 1st OPT $\varphi_*/T_* \gtrsim 1$
- EWBG maybe possible
- SM with m_h=125 GeV cannot satisfy this condition
- Extended Higgs sector may work

GW from 1st OPT



Characteristic parameters of 1stOPT

- α is defined as $\alpha \equiv \left.\dfrac{\epsilon}{\rho_{\rm rad}}\right|_{T=T_t}$. ($\rho_{\rm rad}$ is energy density of rad.)
  - Latent heat: $\epsilon(T) \equiv -\Delta V_{\rm eff}(\varphi_B(T),T) + T\dfrac{\partial \Delta V_{\rm eff}(\varphi_B(T))}{\partial T}$

  α ~ "Normalized difference of the potential minima"

- β is defined as $\beta \equiv \left.\dfrac{1}{\Gamma}\dfrac{d\Gamma}{dt}\right|_{t=t_t}$. $\rightarrow \tilde{\beta}\left(\equiv \dfrac{\beta}{H_t}\right) = T_t \left.\dfrac{d(S_3(T)/T)}{dT}\right|_{T=T_t}$
  - Bubble nucleation rate: $\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$
  - 3-dim. Euclidean action: $S_3(T) = \int dr^3 \left\{\frac{1}{2}\left(\vec{\nabla}\varphi\right)^2 + V_{\rm eff}(\varphi,T)\right\}$

  β^{-1} ~ "Transition time"

$V_{\rm eff}(\varphi, T)$ (Model)

↓

$\alpha,\ \tilde{\beta}$ @T=T_t

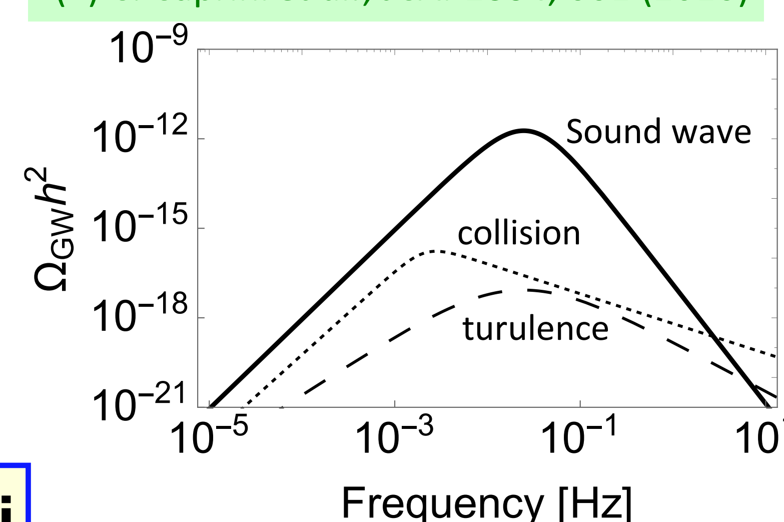
↓ Prediction*

$\Omega_{\rm GW}(f)h^2$ (Observable)

(*) C. Caprini *et al.*, JCAP**1604**, 001 (2016)

Three sources of GWs (relic abundance @ peak frequency)

"Sound waves" (Compressional plasma)
"Bubble collision" (Envelope approximation)
"Magnetohydrodynamic turbulence in the plasma"



Slide : courtesy of T. Matsui

Higgs-singlet model

Fuyuto, Senaha, PRD90, 015015 (2014),
Hashino, Kakizaki, Kanemura, Ko, Matsui, PLB766, 49 (2017)

- Higgs potential (8 parameters)

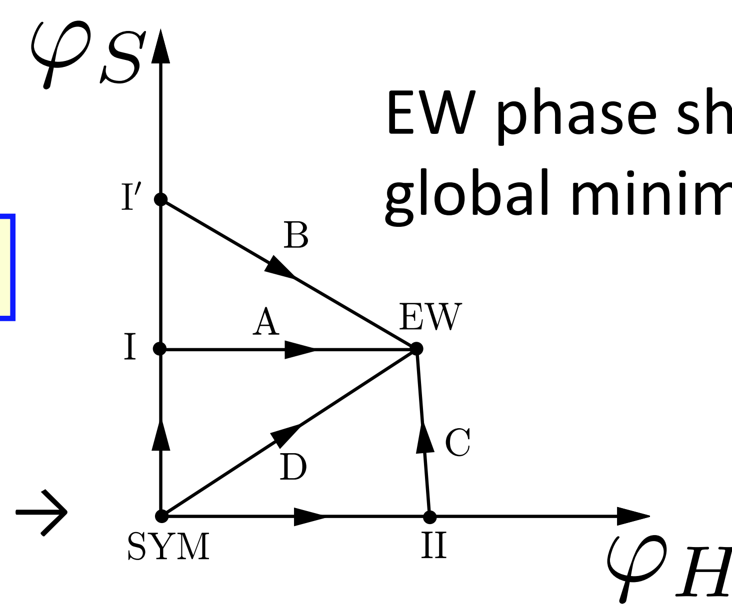
$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4,$$

  - Vanishing tadpole conditions ; (v_Φ, v_S)
  - Diabonalization of 2 scalar mass matrix : $(\phi_1, \phi_2) \to (m_h, m_H)$ and θ

- Two field analysis @ finite T

Diverse patterns possible

- EW vac: global min @ T=0 →



EW phase should be global minimum at T=0.

Theoretical Constraints

- Perturbative Unitarity : $|a_0(W_L^+ W_L^- \to W_L^+ W_L^-)| \leq 1$

$$m_h^2 \cos^2\theta + m_H^2 \sin^2\theta \leq \frac{4\pi\sqrt{2}}{3G_F} \approx (700\text{GeV})^2$$

- Vacuum stability

$$\lambda_\Phi(\mu) > 0, \qquad \lambda_S(\mu) > 0, \qquad 4\lambda_\Phi(\mu)\lambda_S(\mu) > \lambda_{\Phi S}^2(\mu)$$

- Landau pole

$$|\lambda_{\Phi,S,\Phi S}(\Lambda_{\text{LP}})| = 4\pi$$

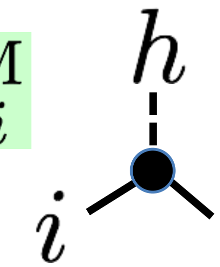
- Oblique parameters (S,T,U)

$$\cos\theta \gtrsim 0.92 \quad \text{when } m_H \gtrsim 400\text{GeV} \ (m_h \approx 125\text{GeV})$$

S. Baek, P. Ko, W. I. Park and E. Senaha, JHEP 1211, 116 (2012)

Collider data on Higgs

- Deviation of Higgs couplings from SM: $\kappa_i \equiv g_{hii}/g_{hii}^{\rm SM}$



  - Recent LHC data: $\kappa_Z = 1.03^{+0.11}_{-0.11}, \kappa_W = 0.91^{+0.10}_{-0.10}$

    (1σ; combination of ATLAS and CMS) [ATLAS-CONF-2015-044]
  - Expected accuracy: κ_V : 2%@HL-LHC 14TeV 3000fb^{-1} [CMS collaboration, 1307.7135],

    κ_V : 0.6% @ILC 250GeV 2000fb^{-1} [Durieux et al. (2017)]

    κ_Z (κ_W) : 0.37% (0.51%) @ILC 500GeV 500fb^{-1} [Fujii et al, 1506.05992]

- Deviation of *hhh* coupling from SM: $\Delta\lambda_{hhh} \equiv \dfrac{\lambda_{hhh}^{\rm HSM} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}}$
  - Expected accuracy: 54%@HL-LHC 14TeV 3000fb^{-1} [CMS-PAS-FTR-15-002],

    27%@ILC 500GeV 4000fb^{-1} [Fujii et al, 1506.05992],

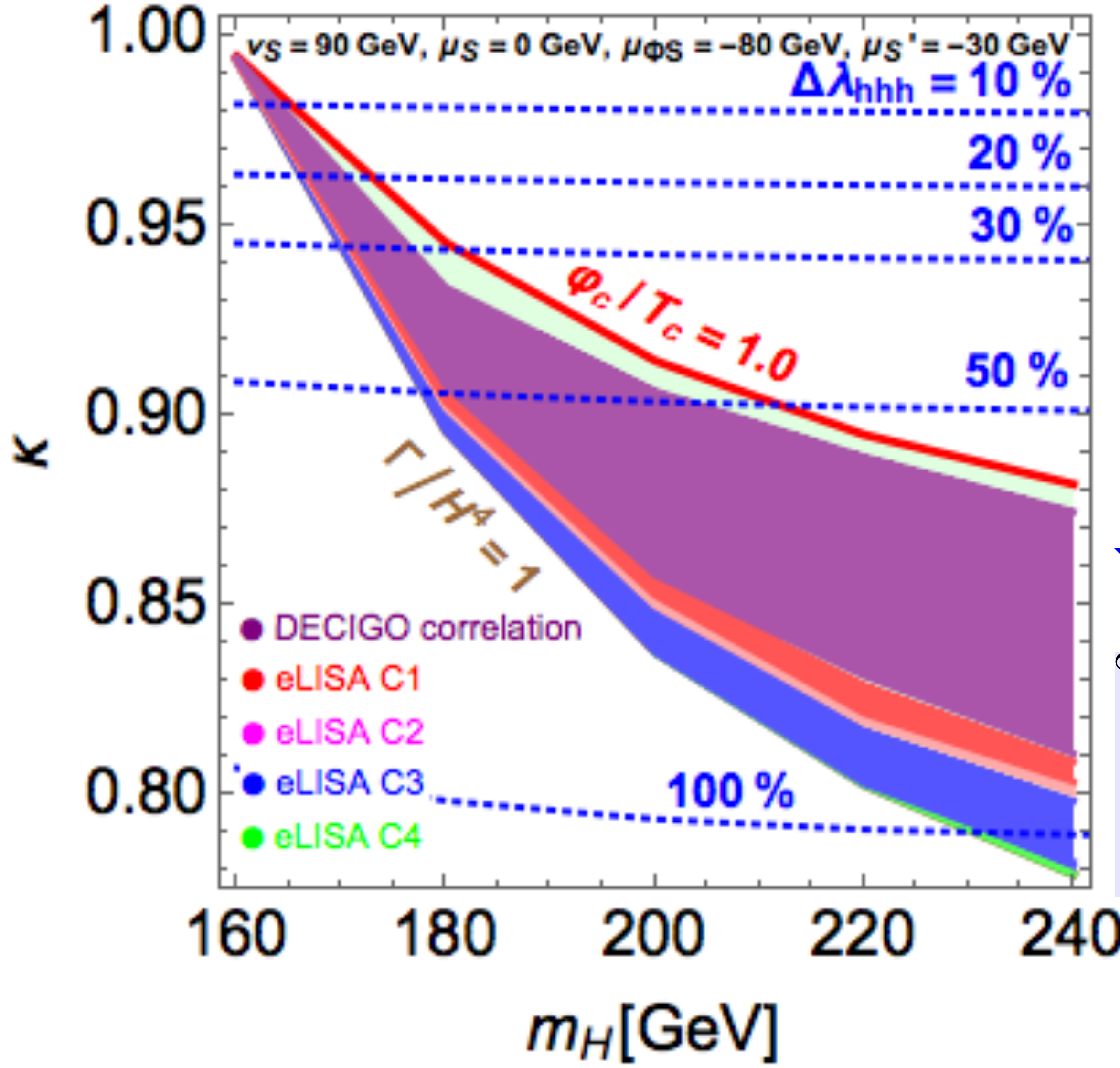
    16% (10%)@ILC 1TeV 2000fb^{-1} (5000fb^{-1}) [Fujii et al, 1506.05992]

Slide : by courtesy of Toshinori Matsui

Numerial Results

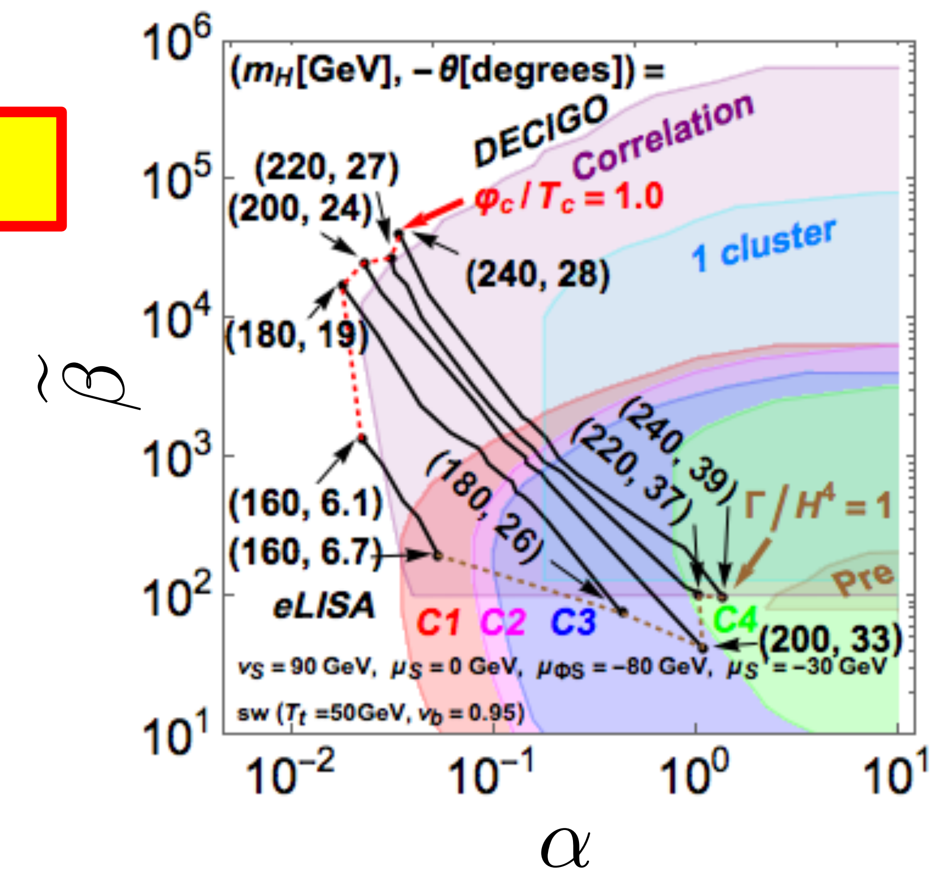
- Benchmark point:

v_Φ [GeV]	v_S [GeV]	m_h [GeV]	$\mu_{\Phi S}$ [GeV]	μ'_S [GeV]	μ_S [GeV]	m_H [GeV]	θ [degrees]
246.2	90	125.5	−80	−30	0	[160, 240]	[−15, −35]



$\Omega_{\mathrm{GW}}(f)h^2$

$\varphi_c/T_c \gtrsim 1$

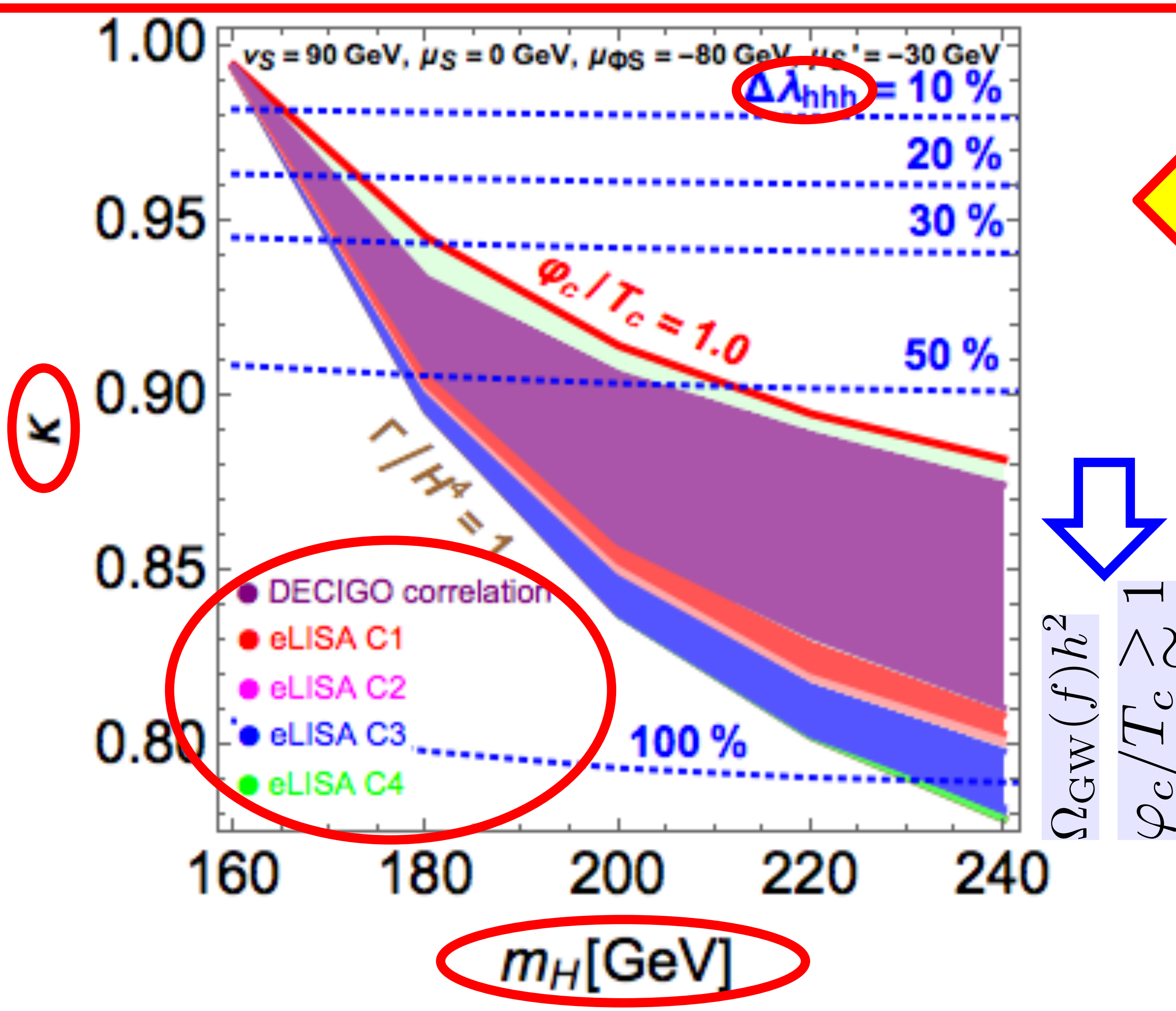


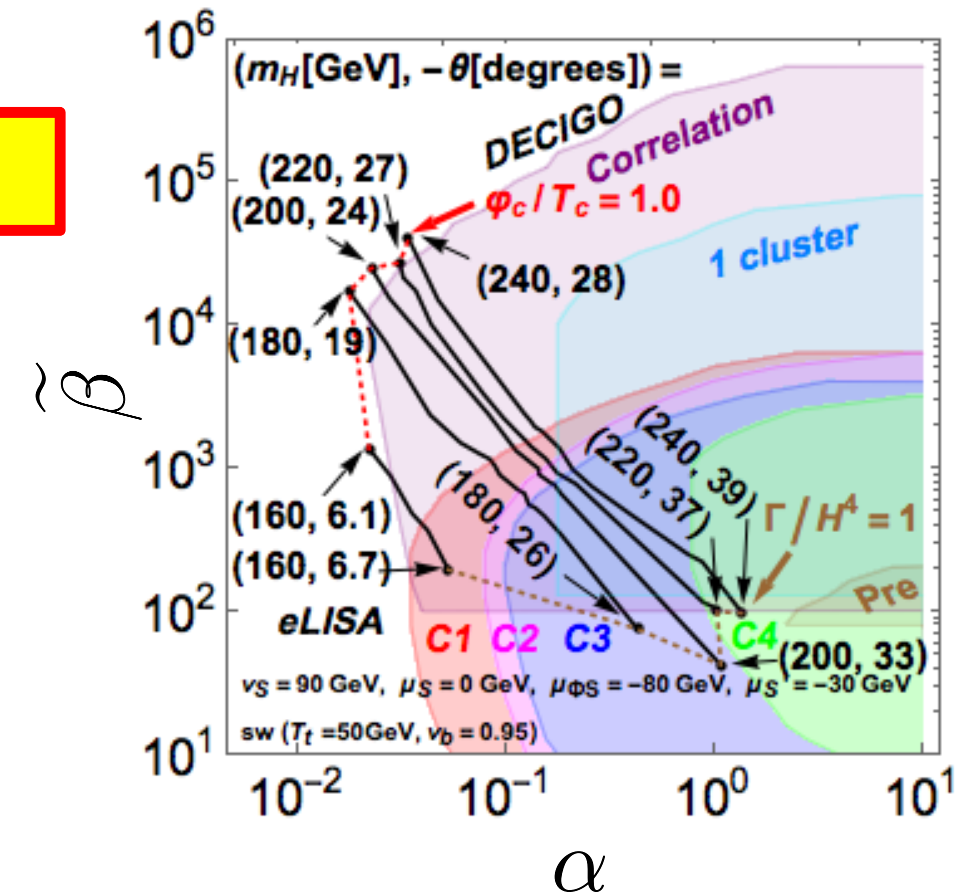
DECIGO [Class. Quant. Grav. 28, 094011 (2011)], eLISA [arXiv:1512.06239]

Hashino, Kakizaki, Kanemura, TM, Ko, PLB **766**, 49 (2017)

Numerical results

The synergy between the precision measurements of the Higgs boson couplings and GWs at future experiments is important!





DECIGO [Class. Quant. Grav. 28, 094011 (2011)], eLISA [arXiv:1512.06239]

Hashino, Kakizaki, Kanemura, TM, Ko, PLB **766**, 49 (2017)

See also Nightmare scenario with Z3 symnmetry: Z. Kang, P.Ko, T. Matsui, arXiv:1706.09721

Conclusion

- Dark pion DM and Singlet fermion DM model with Higgs-singlet portal are still viable option for DM, consistent with all the data so far

- Unlikely to see this DM @ LHC soon, if this makes the only component of DM in our universe

- Singlet scalar (dark Higgs) is generic in many DM models in the hidden sector (dark gauge symmetries)

    - Improves EW vacuum stability up to Planck scale, and disconnect the strong dependence on top/Higgs mass in the original Higgs inflation

    - Leave its footprints in collider signatures, EW PhaseTrasition, and GW, etc.

Backup:
DM-DR Interaction

*P.Ko,Y.Tang: arXiv:***1608.01083(PLB)**
*P.Ko,Y.Tang: arXiv:***1609.02307(PLB)**
*P.Ko,N.Nagata,Y.Tang;***arXiv:1706.05605(PLB))**

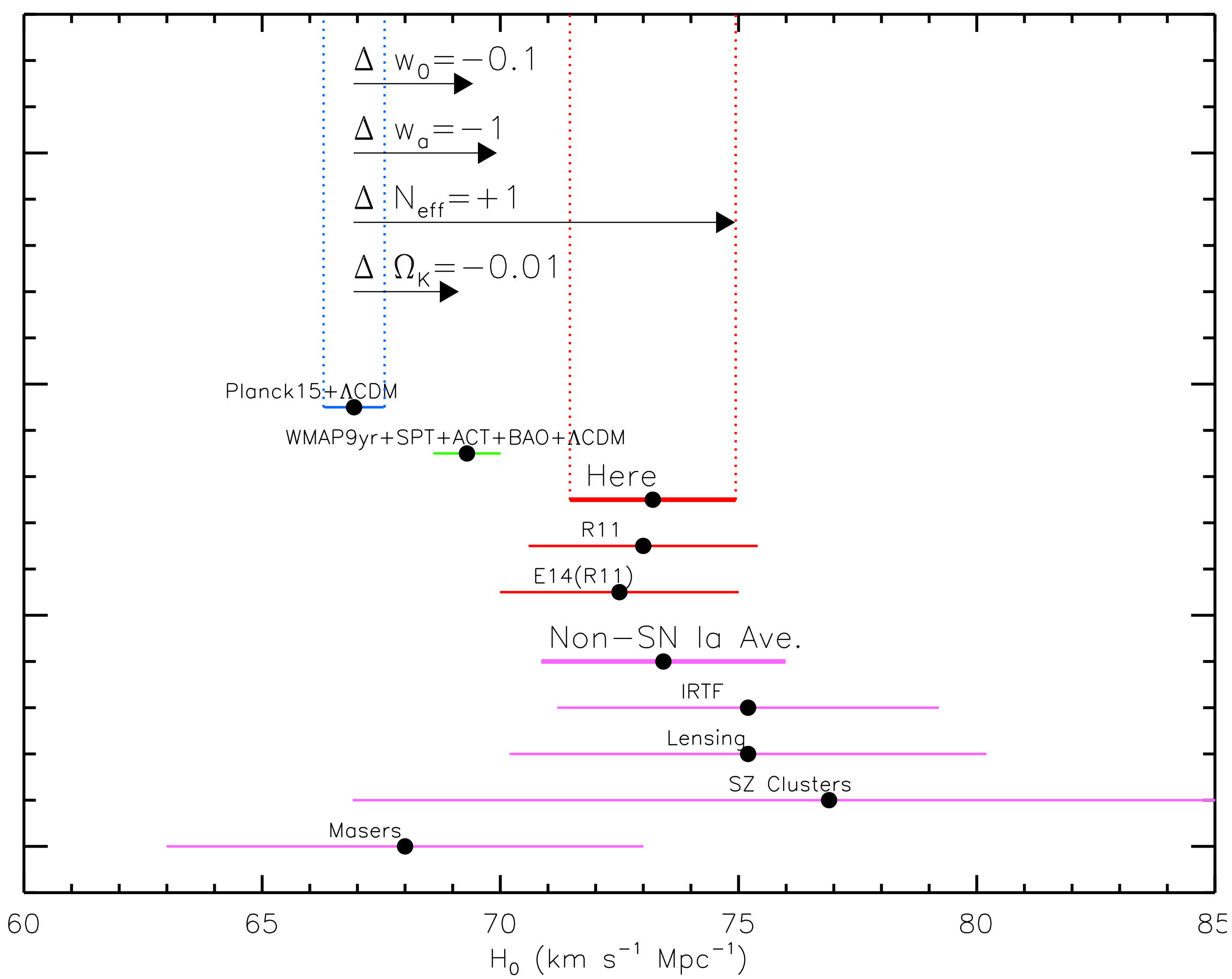
Tension in Hubble Constant?

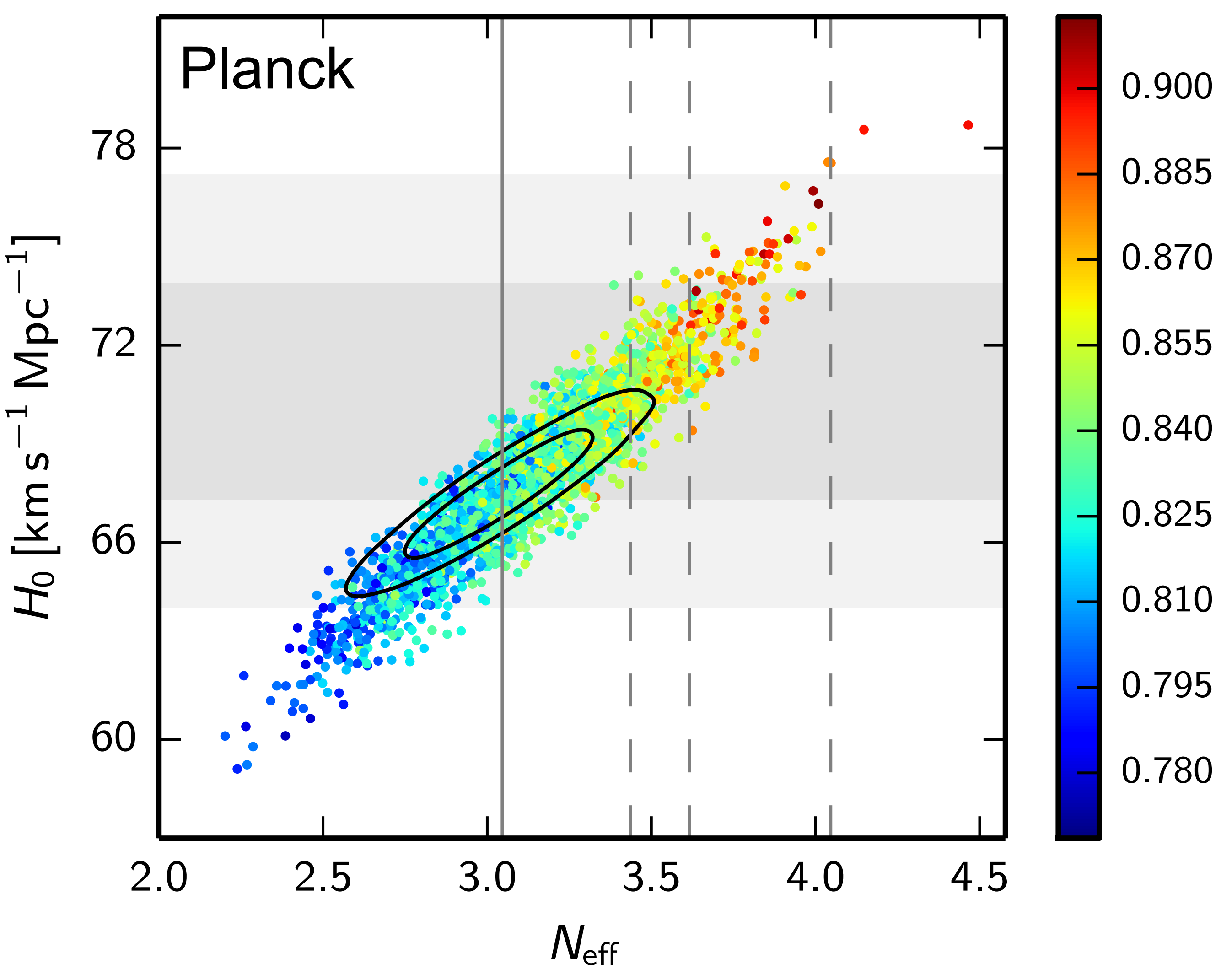
- Hubble Constant H_0 defined as the present value of

$$H \equiv \frac{1}{a}\frac{da}{dt} = \frac{\sqrt{\rho_r + \rho_m + \rho_\Lambda}}{M_p}$$

- Planck(2015) gives $67.8 \pm 0.9\ \mathrm{km\ s^{-1}Mpc^{-1}}$
- HST(2016) gives $73.24 \pm 1.74\ \mathrm{km\ s^{-1}Mpc^{-1}}$

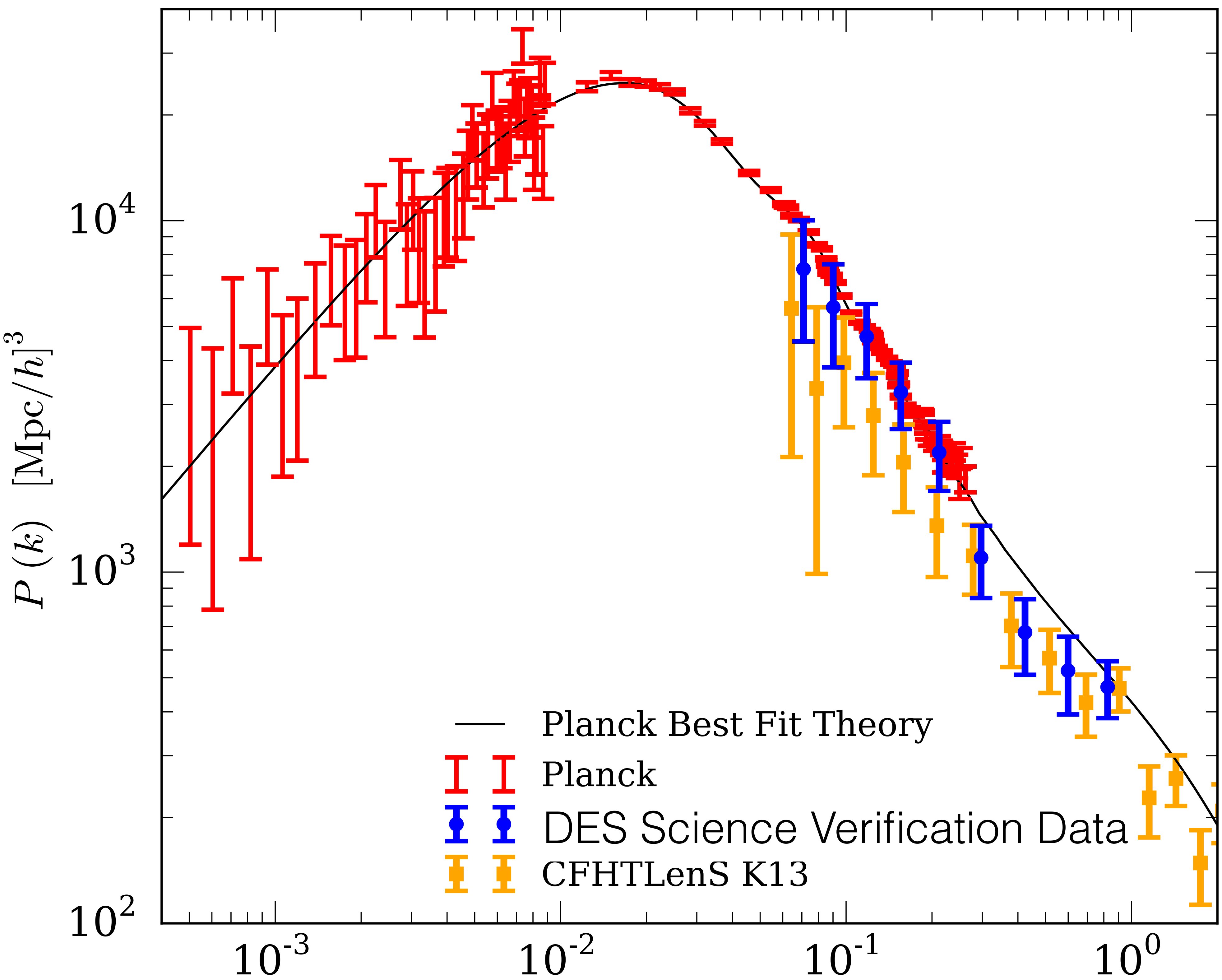
RIESS ET AL.





Matter Power Spectrum

DES astroph/150705552

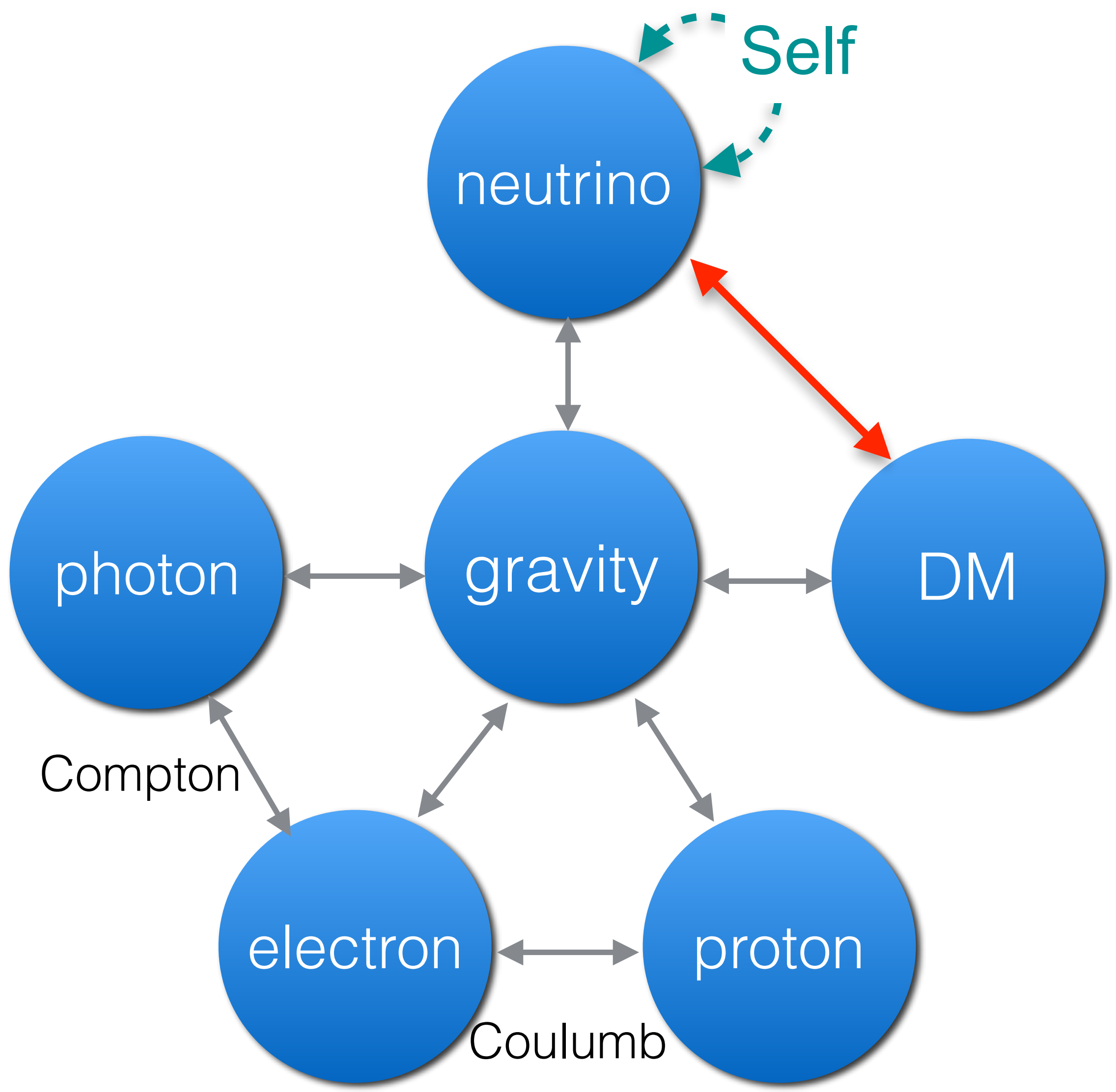


Interacting DM-DR

- Since all components are connected by Einstein's equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- first-order perturbation of Boltzmann equation
  - anisotropy in CMB
  - matter power spectrum for LSS
- (Self-)Interaction sometimes also matters



Diffusion Damping

- Dark Matter scatters with radiation, which induces new contributions in the cosmological perturbation equations,

$$\dot{\delta}_\chi = -\theta_\chi + 3\dot{\Phi},$$
$$\dot{\theta}_\chi = k^2\Psi - \mathcal{H}\theta_\chi + S^{-1}\dot{\mu}\,(\theta_\psi - \theta_\chi),$$
$$\dot{\theta}_\psi = k^2\Psi + k^2\left(\frac{1}{4}\delta_\psi - \sigma_\psi\right) - \dot{\mu}\,(\theta_\psi - \theta_\chi),$$

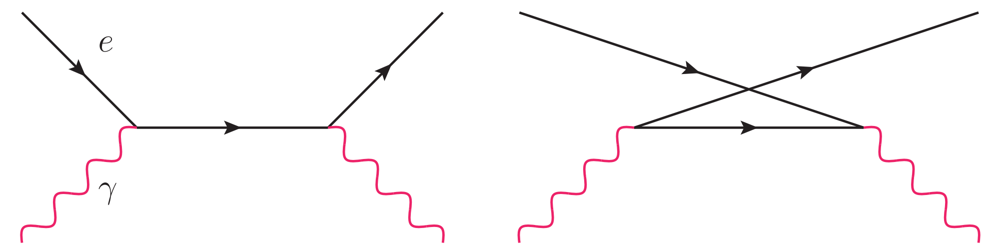
where dot means derivative over conformal time $d\tau \equiv dt/a$ (a is the scale factor), θ_ψ and θ_χ are velocity divergences of radiation ψ and DM χ's, k is the comoving wave number, Ψ is the gravitational potential, δ_ψ and σ_ψ are the density perturbation and the anisotropic stress potential of ψ, and $\mathcal{H} \equiv \dot{a}/a$ is the conformal Hubble parameter. Finally, the scattering rate and the density ratio are defined by $\dot{\mu} = a n_\chi \langle \sigma_{\chi\psi} c \rangle$ and $S = 3\rho_\chi/4\rho_\psi$, respectively.

Relation to Particle Physics

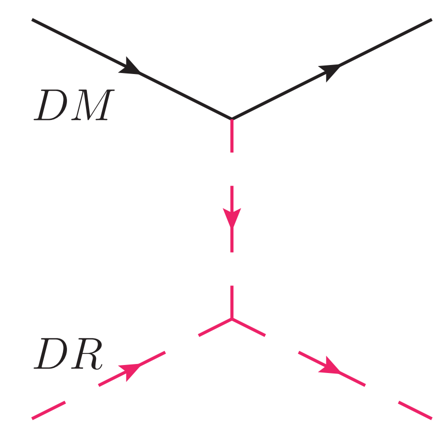
- The precise form of the scattering term, $\langle \sigma c \rangle$, is fully determined by the underlying microscopic or particle physics model, for example

IR behaviour

  - electron-photon, $\langle \sigma c \rangle \sim 1/m^2$
    Thomson scattering -> CMB, BAO



  - DM-radiation with massive mediator, $\langle \sigma c \rangle \sim T^2/m^4$
    Boehm *et al*(astro-ph/0410591,1309.7588)



  - non-Abelian radiation, $\langle \sigma c \rangle \sim 1/T^2$
    Schmaltz et al(2015), 1507.04351,1505.03542
  - (pseudo-)scalar radiation, $\langle \sigma c \rangle \sim 1/T^2$, μ^2/T^4, T^2/μ^4
    Y.Tang,1603.00165(PLB)

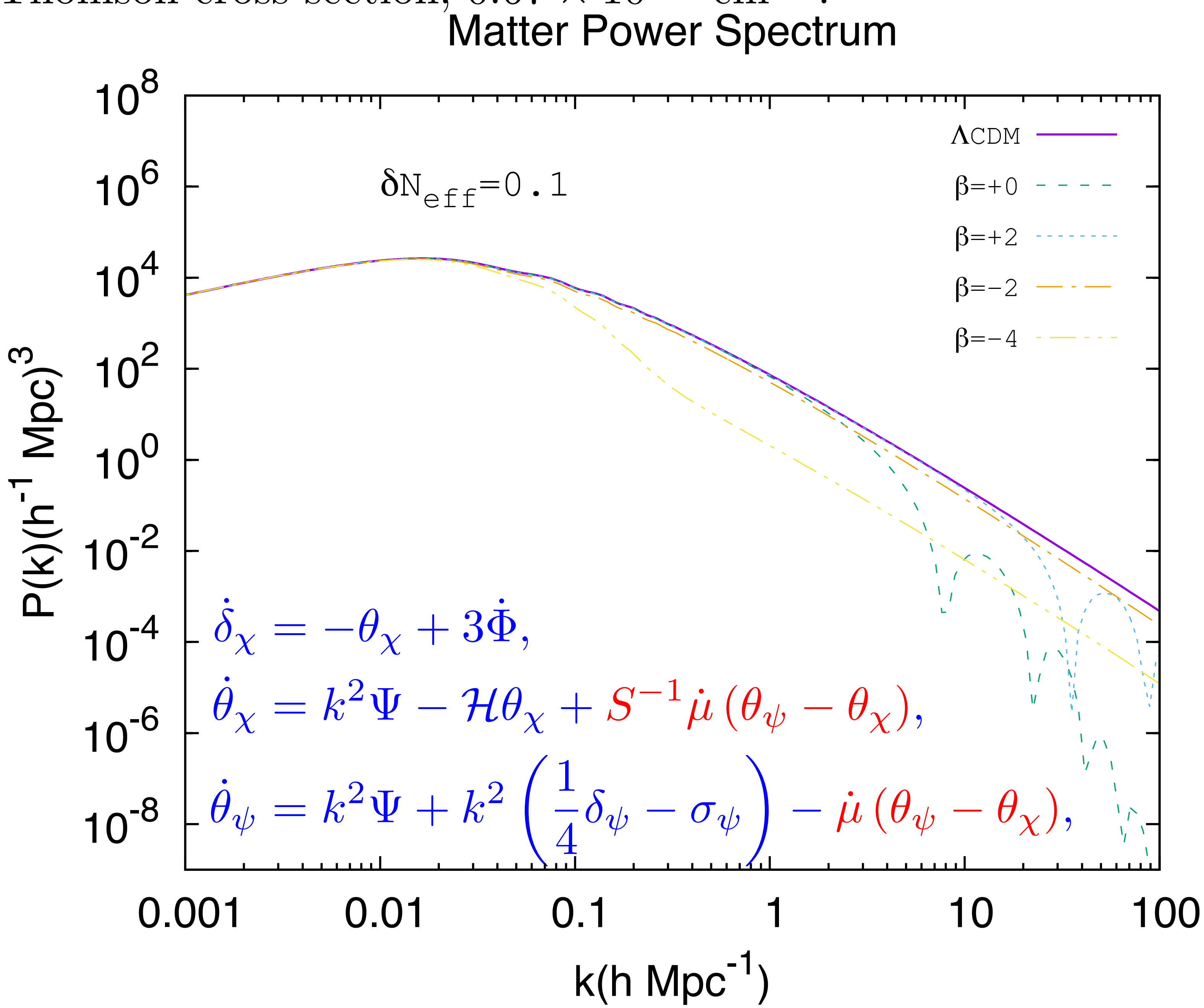
Effects on LSS

Parametrize the cross section ratio

Y.Tang,1603.00165(PLB)

$$u_0 \equiv \left[\frac{\sigma_{\chi\psi}}{\sigma_{\rm Th}}\right]\left[\frac{100\mathrm{GeV}}{m_\chi}\right], u_\beta(T) = u_0\left(\frac{T}{T_0}\right)^\beta,$$

where $\sigma_{\rm Th}$ is the Thomson cross section, $0.67\times10^{-24}\mathrm{cm}^{-2}$.



$$\dot{\delta}_\chi = -\theta_\chi + 3\dot{\Phi},$$

$$\dot{\theta}_\chi = k^2\Psi - \mathcal{H}\theta_\chi + S^{-1}\dot{\mu}\left(\theta_\psi - \theta_\chi\right),$$

$$\dot{\theta}_\psi = k^2\Psi + k^2\left(\frac{1}{4}\delta_\psi - \sigma_\psi\right) - \dot{\mu}\left(\theta_\psi - \theta_\chi\right),$$

Residual Non-Abelian DM&DR

P.Ko&YT, 1609.02307

- Consider *SU(N)* Yang-Mills gauge fields and a Dark Higgs field Φ

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - \lambda_\phi \left(|\Phi|^2 - v_\phi^2/2\right)^2 ,$$

- Take *SU(3)* as an example,

$$A^a_\mu t^a = \frac{1}{2} \begin{pmatrix} A^3_\mu + \frac{1}{\sqrt{3}} A^8_\mu & A^1_\mu - i A^2_\mu & A^4_\mu - i A^5_\mu \\ A^1_\mu + i A^2_\mu & -A^3_\mu + \frac{1}{\sqrt{3}} A^8_\mu & A^6_\mu - i A^7_\mu \\ A^4_\mu + i A^5_\mu & A^6_\mu + i A^7_\mu & -\frac{2}{\sqrt{3}} A^8_\mu \end{pmatrix} .$$

- *SU(3)* $\rightarrow$ *SU(2)*

$$\langle \Phi \rangle = \begin{pmatrix} 0 & 0 & \frac{v_\phi}{\sqrt{2}} \end{pmatrix}^T , \Phi = \begin{pmatrix} 0 & 0 & \frac{v_\phi + \phi(x)}{\sqrt{2}} \end{pmatrix}^T ,$$

The massive gauge bosons $A^{4,\cdots,8}$ as dark matter obtain masses,

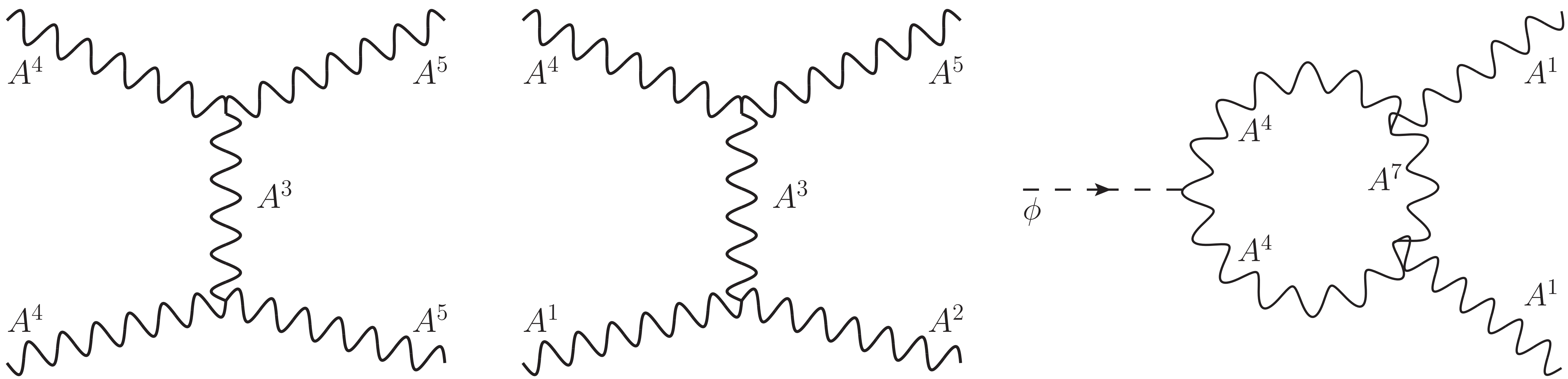
$$m_{A^{4,5,6,7}} = \frac{1}{2} g v_\phi, \; m_{A^8} = \frac{1}{\sqrt{3}} g v_\phi,$$

and massless gauge bosons $A^{1,2,3}_\mu$. The physical scalar ϕ can couple to $A^{4,\cdots,8}_\mu$ at tree level and to $A^{1,2,3}$ at loop level.

Phenomenology

- Scattering and decay processes

P.Ko&**YT**, 1609.02307



- Constraints

$$\delta N_{\rm eff} = \frac{8}{7}\left[(N-1)^2 - 1\right] \times 0.055,$$

$$g^2 \lesssim \frac{T_\gamma}{T_A}\left(\frac{m_A}{M_P}\right)^{1/2} \sim 10^{-7},$$

$$\frac{m_A}{T_{\rm reh}} \sim \ln\left[\frac{\Omega_b M_P g^4}{\Omega_X m_p \eta}\right] \sim \mathcal{O}(30).$$

- ***N<6 if thermal***
- ***small coupling,***
- ***non-thermal production,***
- ***low reheating temperature***

Schmaltz et al(2015) EW charged DM

Matter Power Spectrum

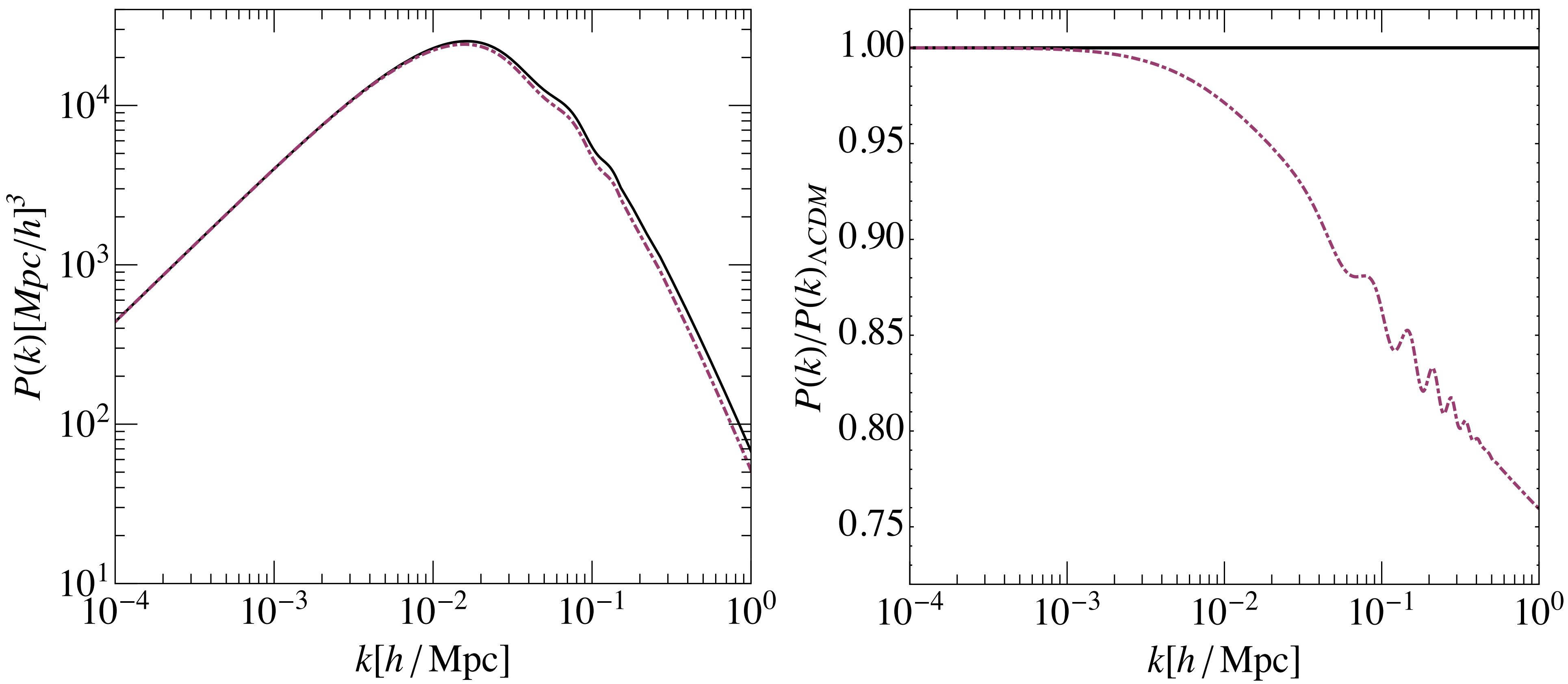


FIG. 3. Matter power spectrum $P(k)$ (left) and ratio (right) with $m_\chi \simeq 10$TeV and $g_X^2 \simeq 10^{-7}$, in comparison with ΛCDM. The black solid lines are for ΛCDM and the purple dot-dashed lines for interacting DM-DR case, with input parameters in Eq. 21. We can easily see that $P(k)$ is suppressed for modes that enter horizon at radiation-dominant era. Those little wiggles are due to the well-known baryon acoustic oscillation.

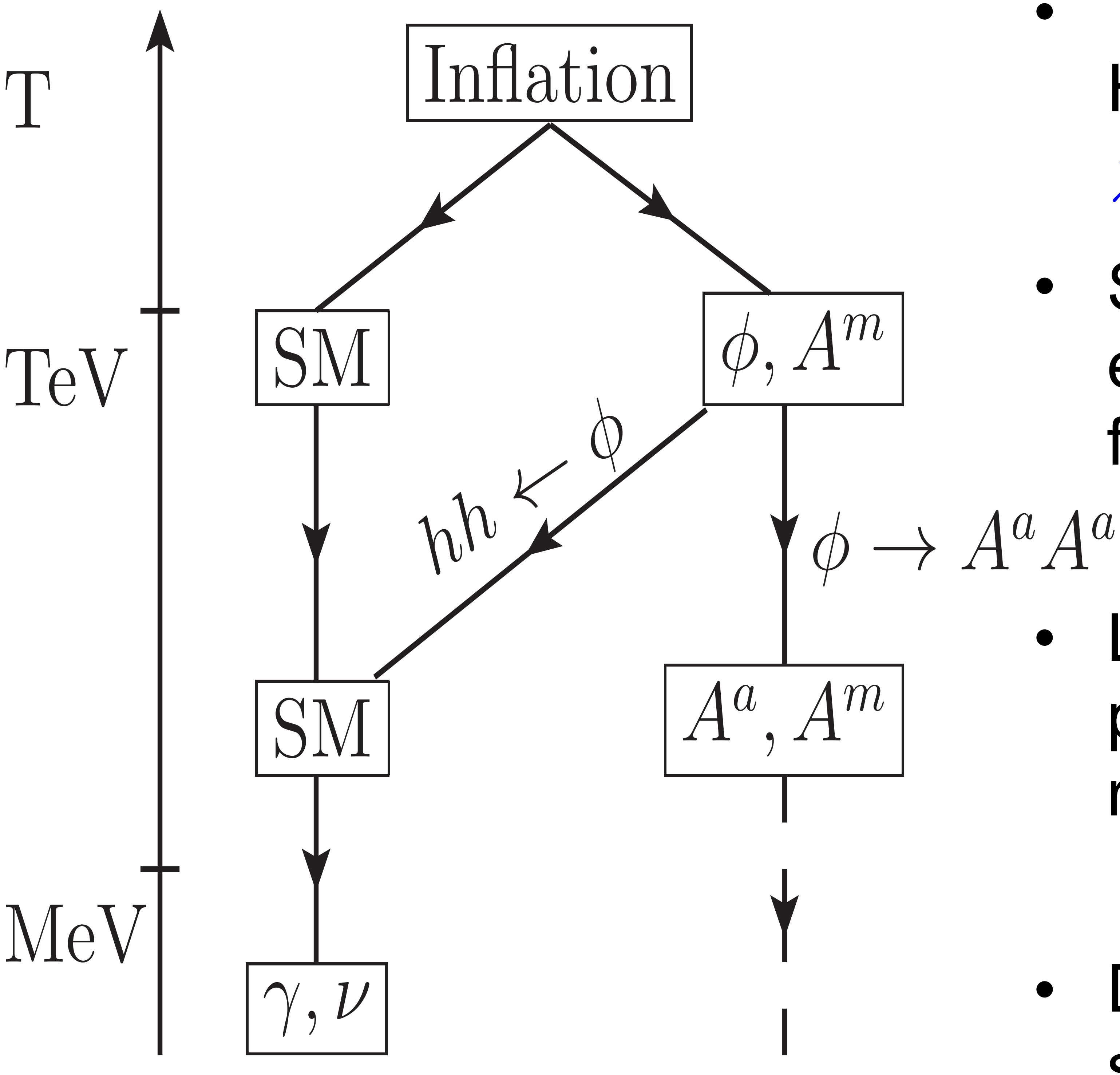
Results

$$\Omega_b h^2 = 0.02227, \Omega_c h^2 = 0.1184, 100\theta_{\rm MC} = 1.04106,$$
$$\tau = 0.067, \ln\left(10^{10} A_s\right) = 3.064, n_s = 0.9681, \quad (21)$$

and treat neutrino mass the same way as `Planck` did with $\sum m_\nu = 0.06\text{eV}$, which gives $\sigma_8 = 0.815$ in vanilla ΛCDM cosmology. Together with the same inputs as above, we take $\delta N_{\rm eff} \simeq 0.5$, $m_\chi \simeq 10\text{TeV}$ and $g_X^2 \simeq 10^{-7}$ in the interacting DM-DR case, we have $\sigma_8 \simeq 0.746$ which is much closer to the value $\sigma_8 \simeq 0.730$ given by weak lensing survey CFHTLenS [12].

- Within DM models with local dark SU(3) broken into SU(2), DM, DR and their interactions have common origin!
- And we could increase Neff, H_0 whereas making σ_8 decrease, thereby relaxing the tension between H_0 and σ_8

Thermal History



- The minimal setup with Higgs portal interaction $\lambda_{\phi H} \Phi^\dagger \Phi H^\dagger H$
- SM and DS are decoupled early, DM is produced by freeze-in mechanism
- Late time decay, entropy production due to non-relativistic decay, DR($\delta N_{\rm eff}$)
- DM and DS scattering suppress the matter power spectrum