New Scientist
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Dark Radiation with Super heavy DM

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Unitarity bound for WIMP

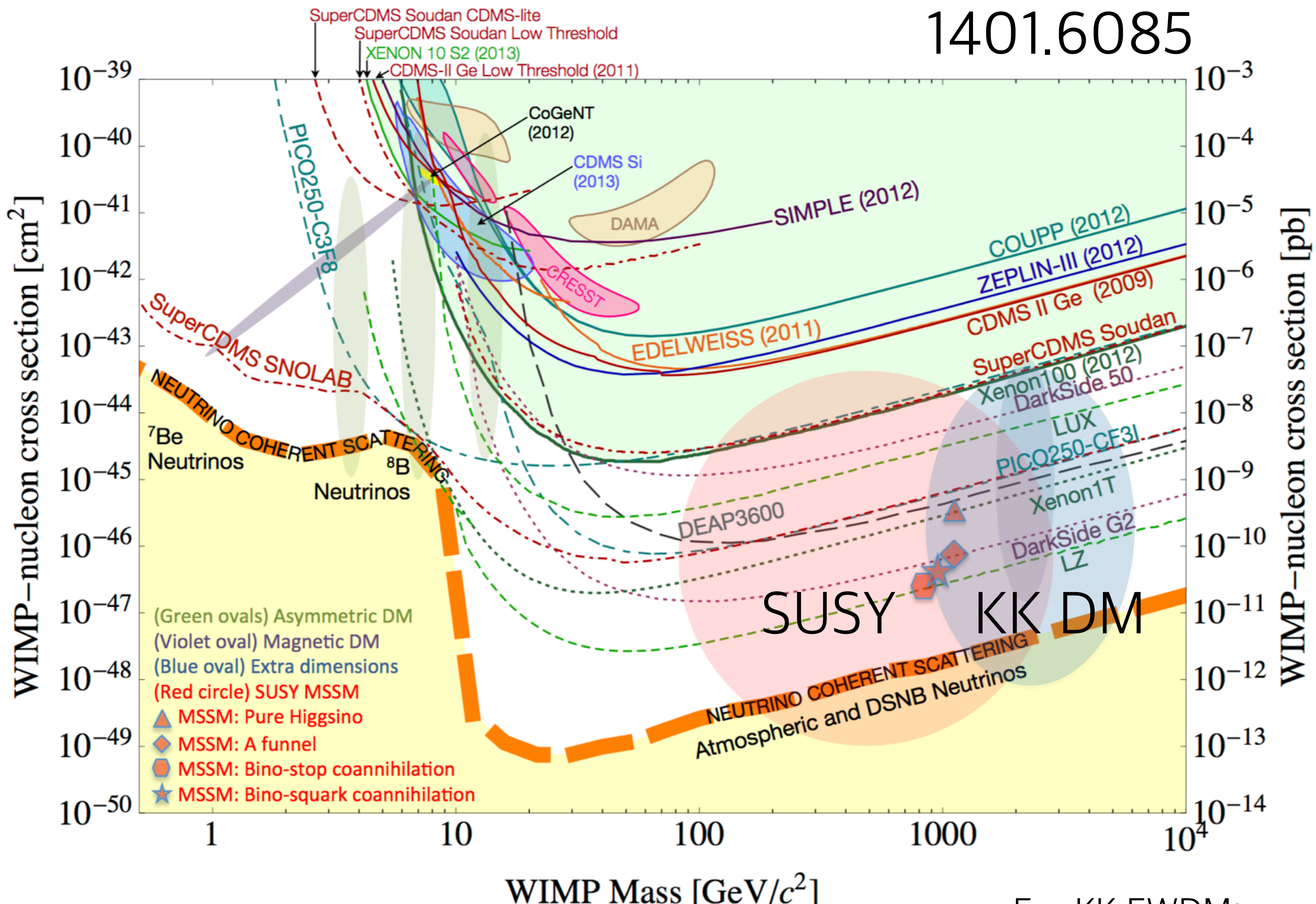
[Griest, Kamionkowski, PRL 1990]

Partial wave analysis: $\langle \sigma_J v \rangle \lesssim \frac{16\pi(2J+1)}{m_{\rm DM}^2}$

$$\Omega_\chi h^2 \simeq \frac{0.1\text{Pb}\cdot c}{\langle \sigma v \rangle} \lesssim 0.11 \quad \Rightarrow m_\chi \lesssim 120 \text{ TeV}$$

(cf) used to be 340 TeV in 1990s

The Window for WIMP is closing out fast…



For KK EWDM:
Flacke, Kong, Kang, SCP 1607.xxxx

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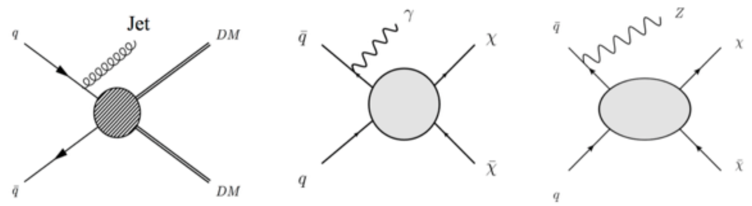

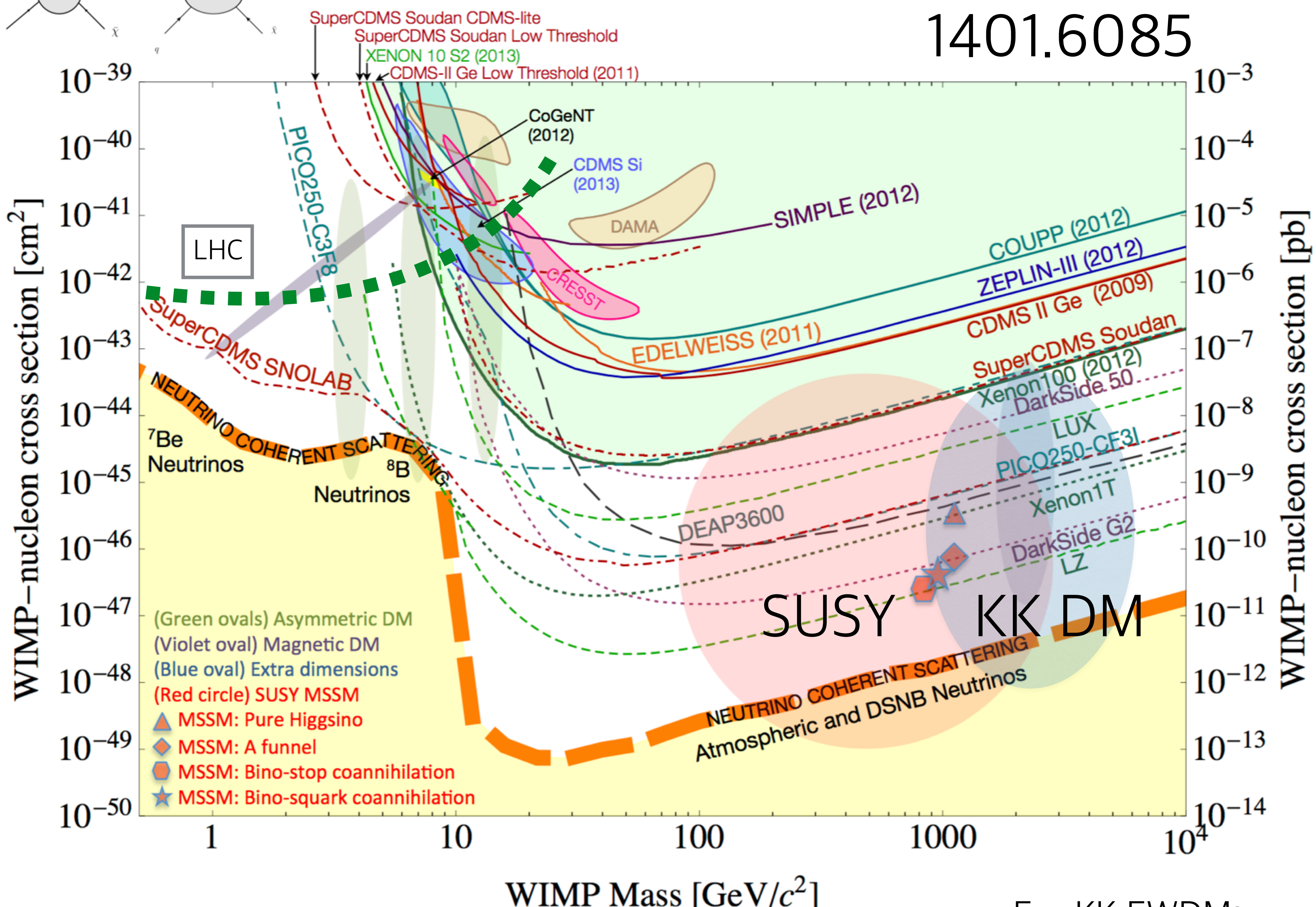

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Beyond WIMP?

- One potentially interesting domain for DM is >100 TeV beyond the unitarity bound.
- The superheavy dark matter is sometimes called as "WIMPZILLA: Monster particle from the dawn of time" (after an editor of "New Scientist")

Superheavy DM

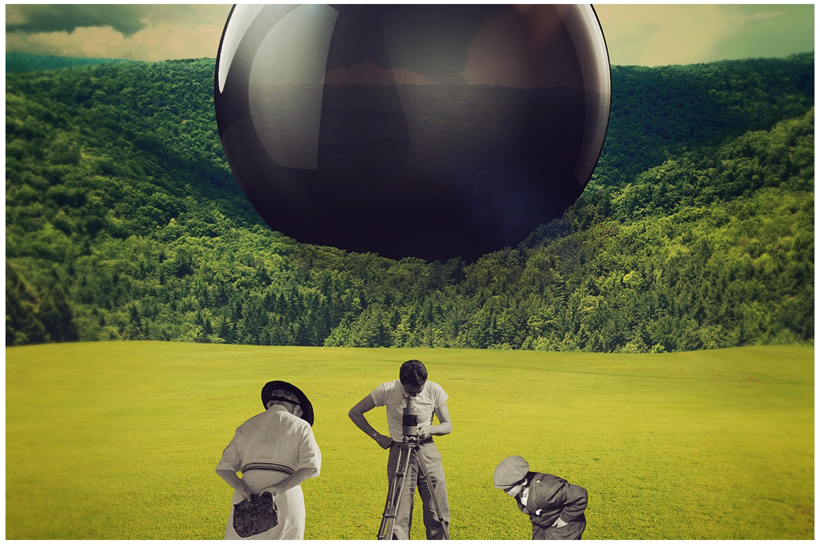
- stable or super-long lived
- M =(100 TeV, M_{inf}/2), this talk

unitarity → 100 TeV

production → M_{inf}/2

WIMP??

Production of superheavy DM



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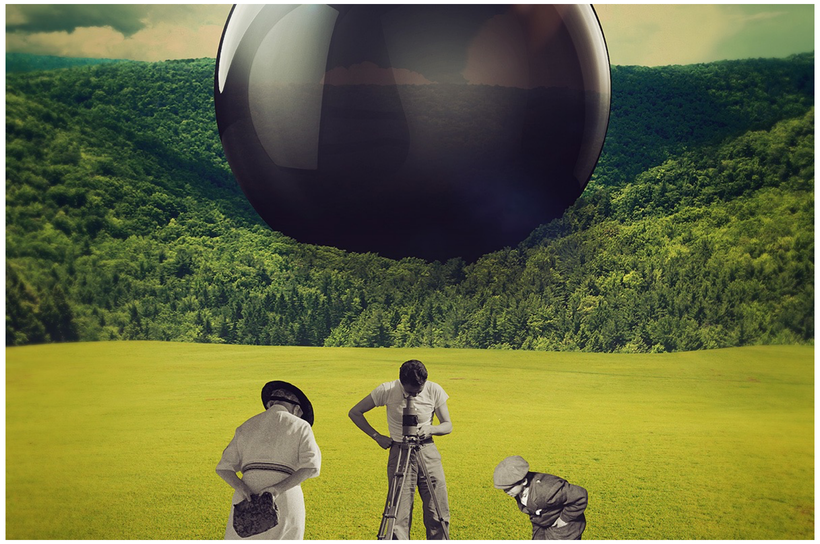

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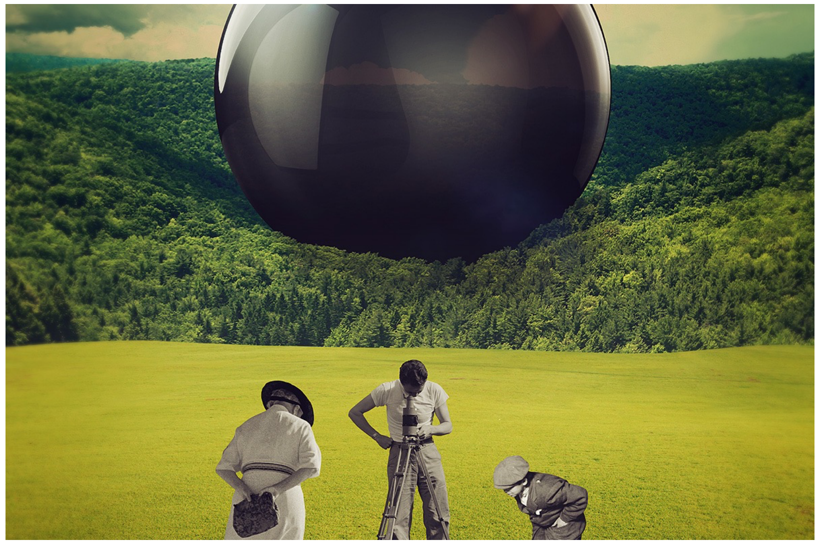

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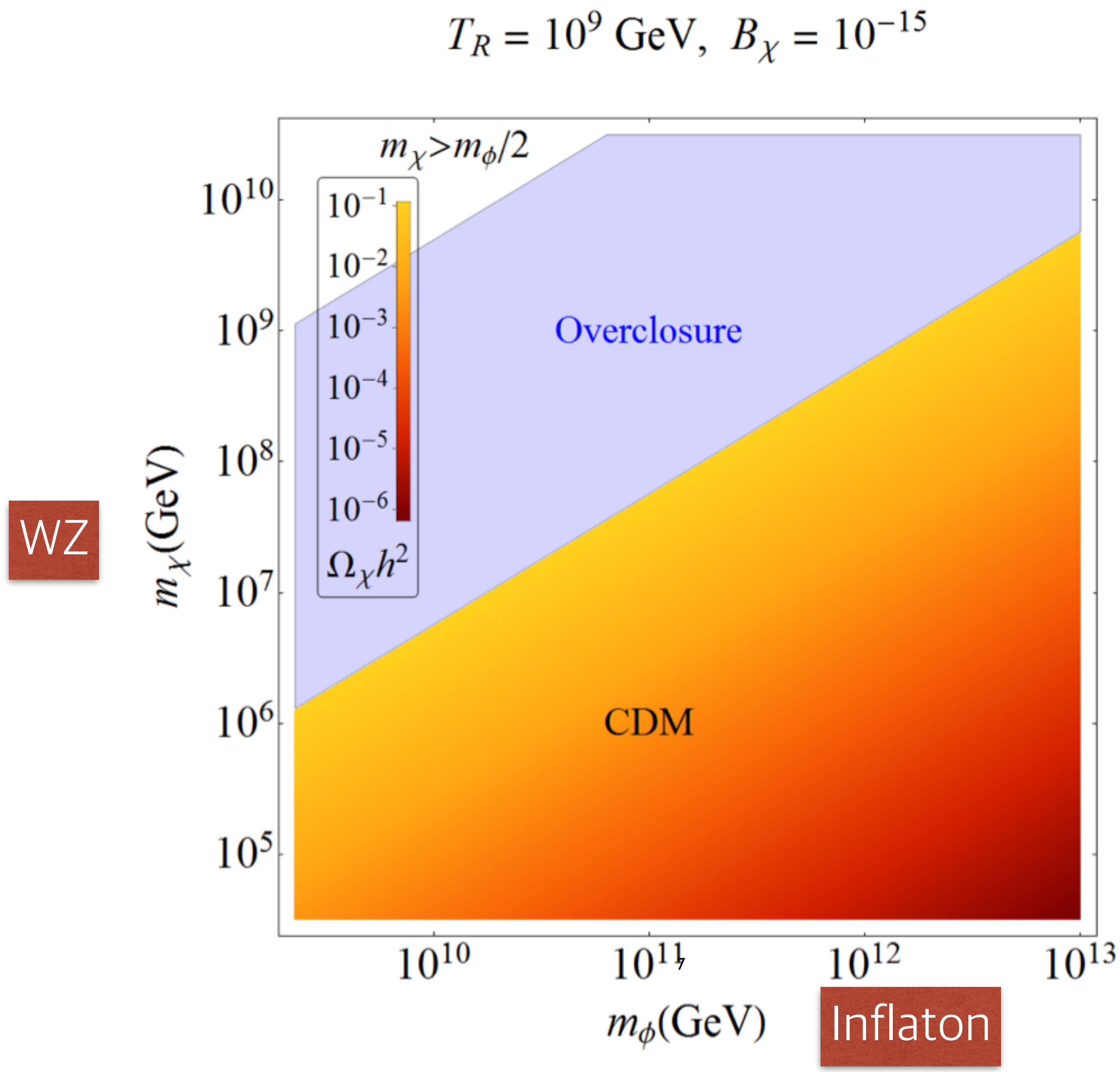
- An interesting window well above 200 TeV (could be $\sim M_{GUT}$) pops out of the calculation by Chung, Kolb, Riotto (1998), Hui, Stewart (1998) with $T \sim 10^9$ GeV or higher reheating temperature.

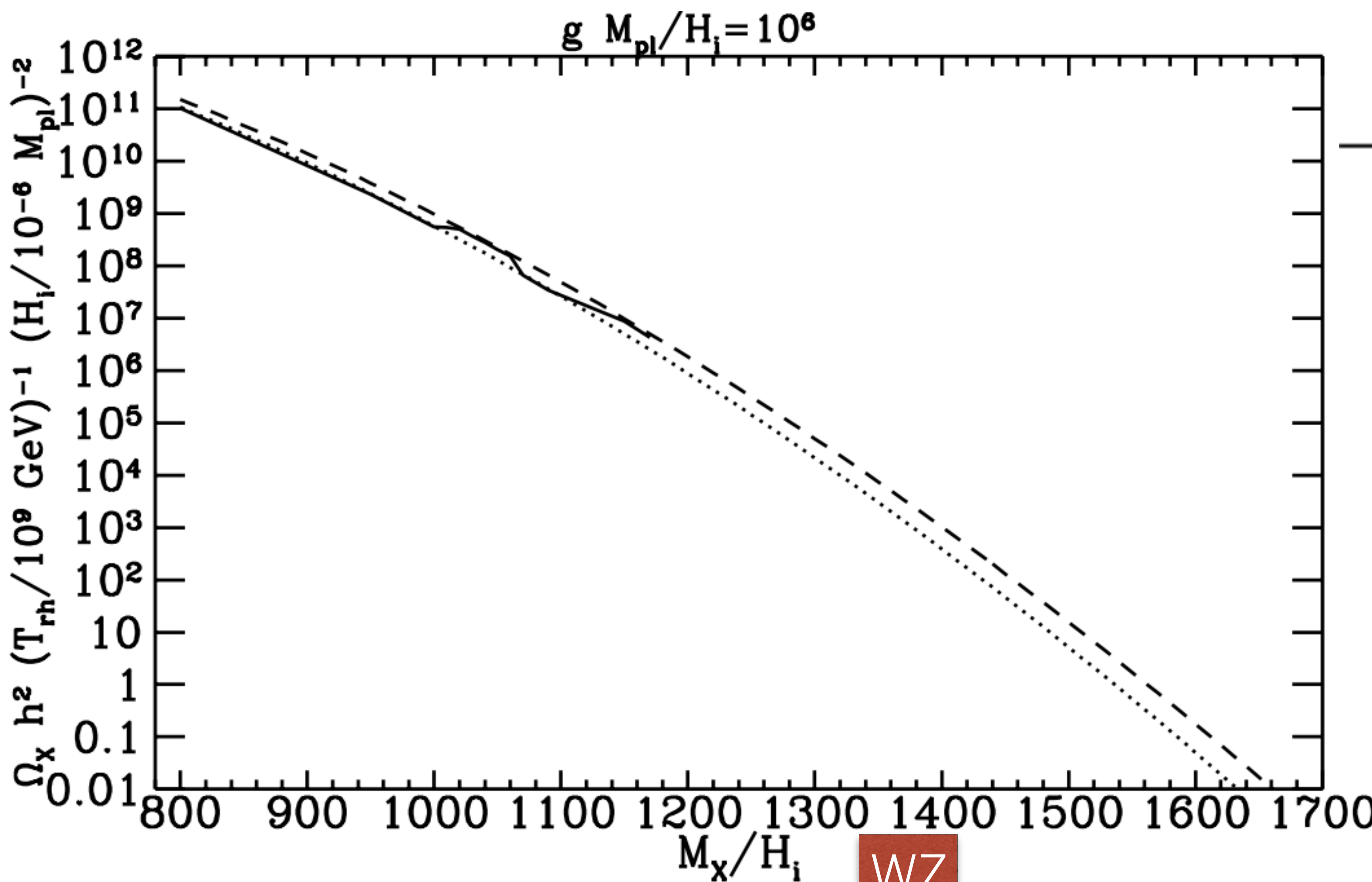
WZ abundance from inflaton decay



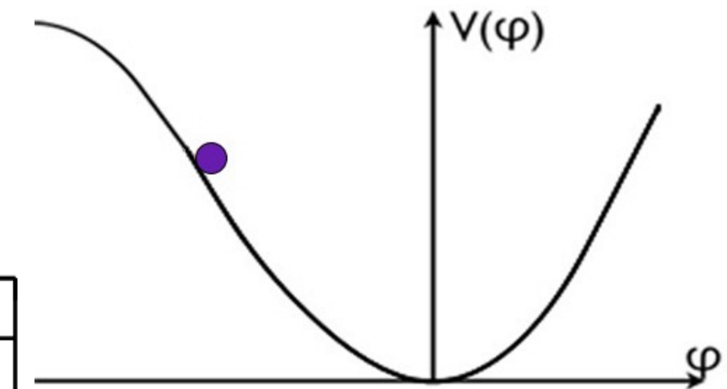
[Mazumdar et.al. 1311.5297]

WZ production from preheating

preheating via damped oscillation of Inflaton



WZ



$$\mathcal{L} = g^2\phi^2\chi^2$$

[Chung, Kolb, Riotto PRL1998]

How to detect WZ?

- High energy cosmic ray from WZ decay [Rott, Kohri, SCP, PRD(2015)]
- Dark radiation: this talk [J.C.Park, SCP, PLB(2014), 2015]

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- $1/\Gamma \sim \Delta t \sim 1/\Delta E \sim 1/M$

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- The new gauge boson associated with $U(1)_{WZ}$ is very light or even massless: this may provide observational consequences such as Dark Radiation

Is Dark Radiation dead?

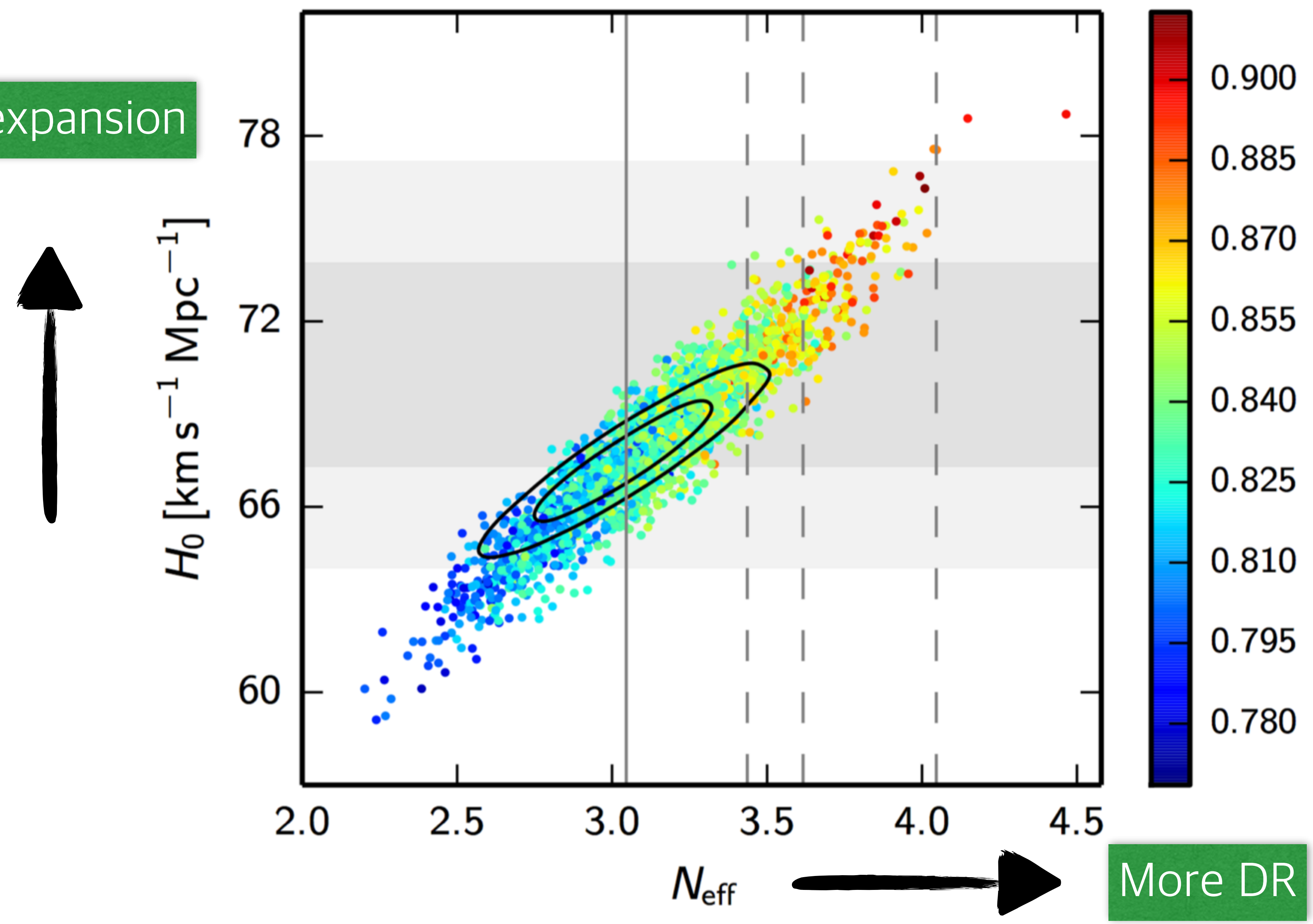
$$\rho = N_{\rm eff} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \rho_\gamma .$$

$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck} \text{ TT+lowP},$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck} \text{ TT+lowP+BAO},$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck} \text{ TT, TE, EE+lowP},$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

Planck collaboration, [arXiv:1502.01589]

H_0 vs N_{eff}

faster expansion



More DR

$$1 + z_{eq} = a_{eq}^{-1} = \frac{\rho_c + \rho_b}{\rho_\gamma + \rho_\nu} \simeq 40500 \frac{\Omega_c h^2 + \Omega_b h^2}{1 + 0.23 N_{eff}}.$$

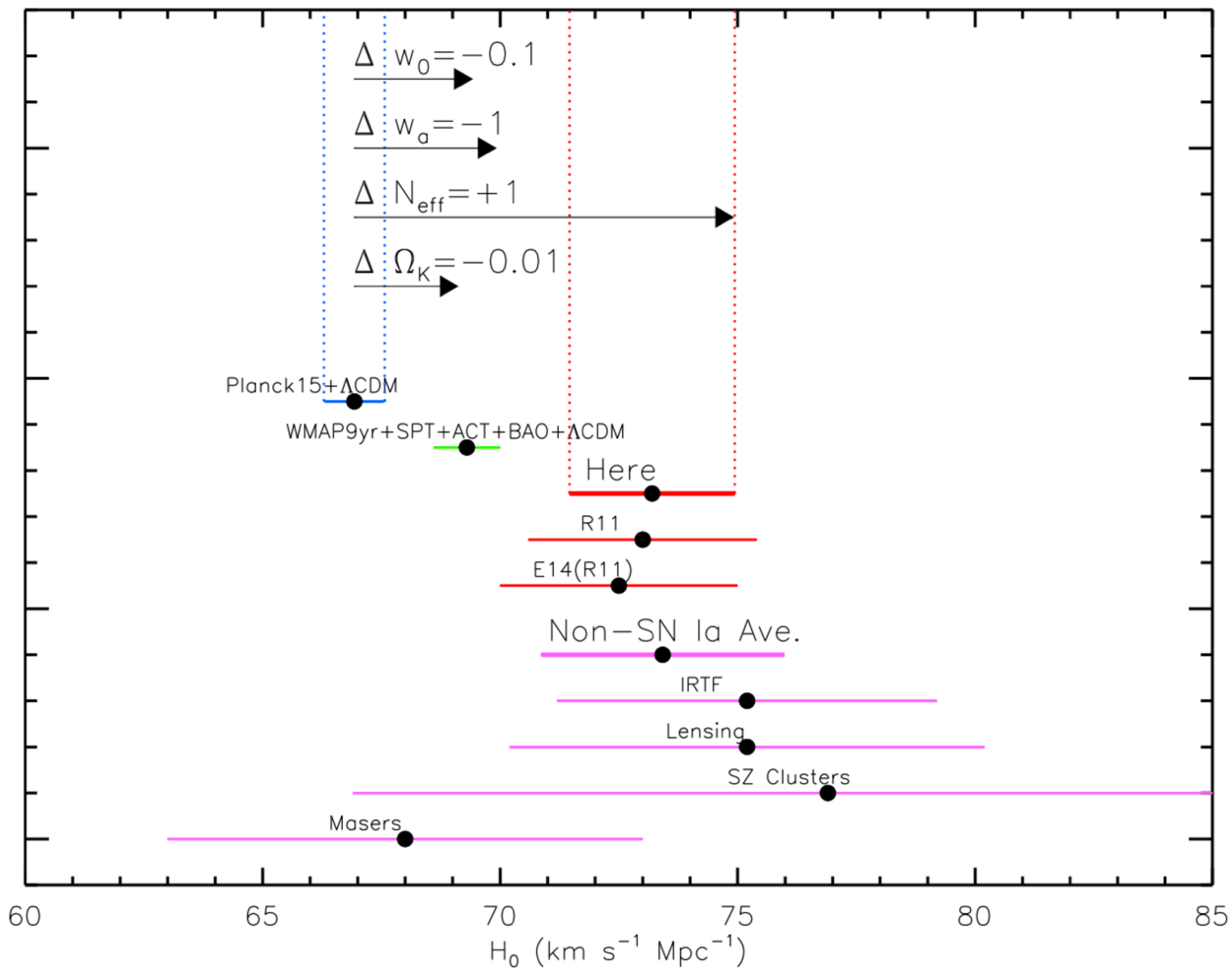
~ positively correlated

sigma 8 tension?

See Neelima Sehgal 's talk

Planck collaboration, [arXiv:1502.01589]

Tension in Hubble Constant



Adam G. Riess et. al. [arXiv:1604.01424]

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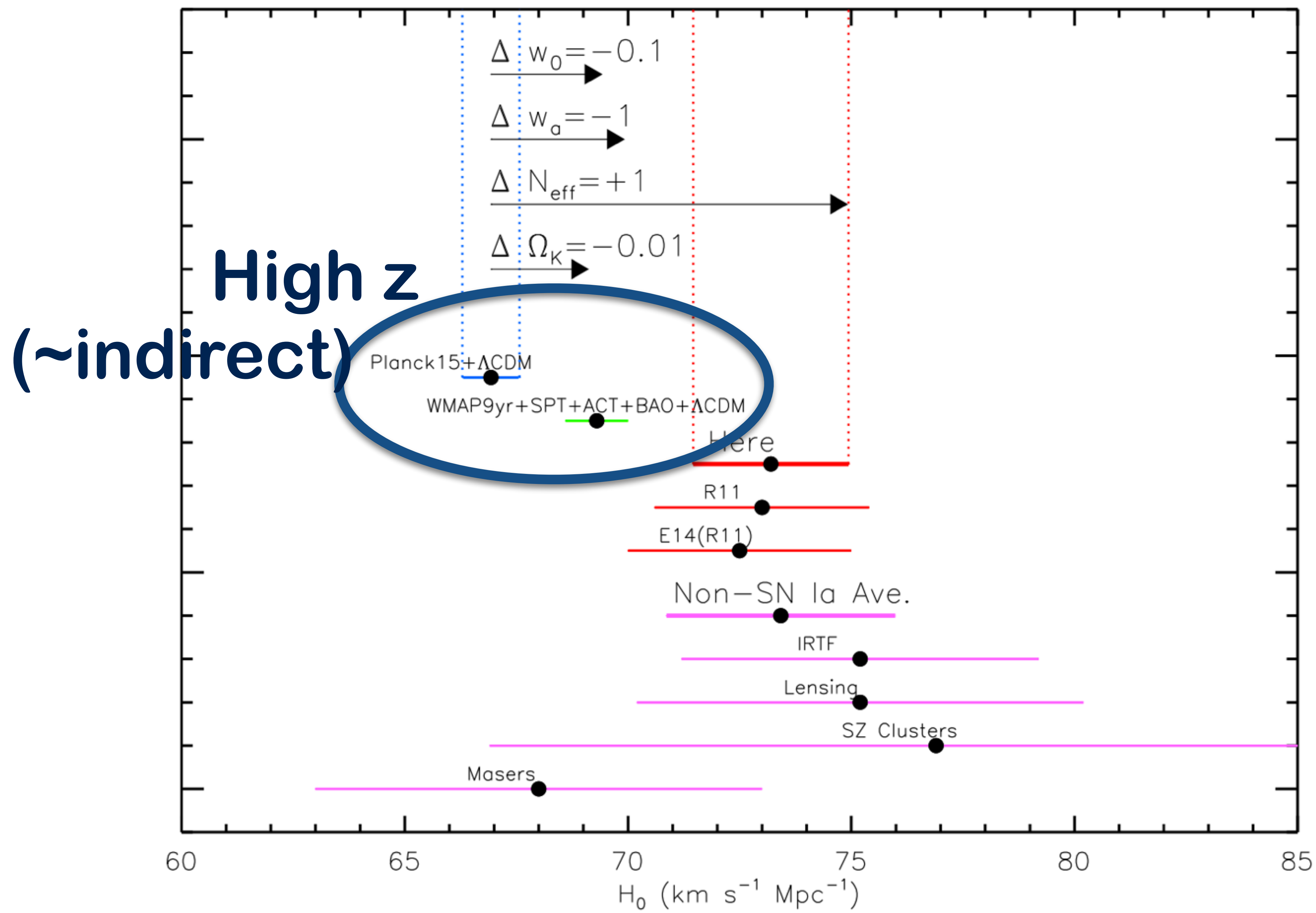

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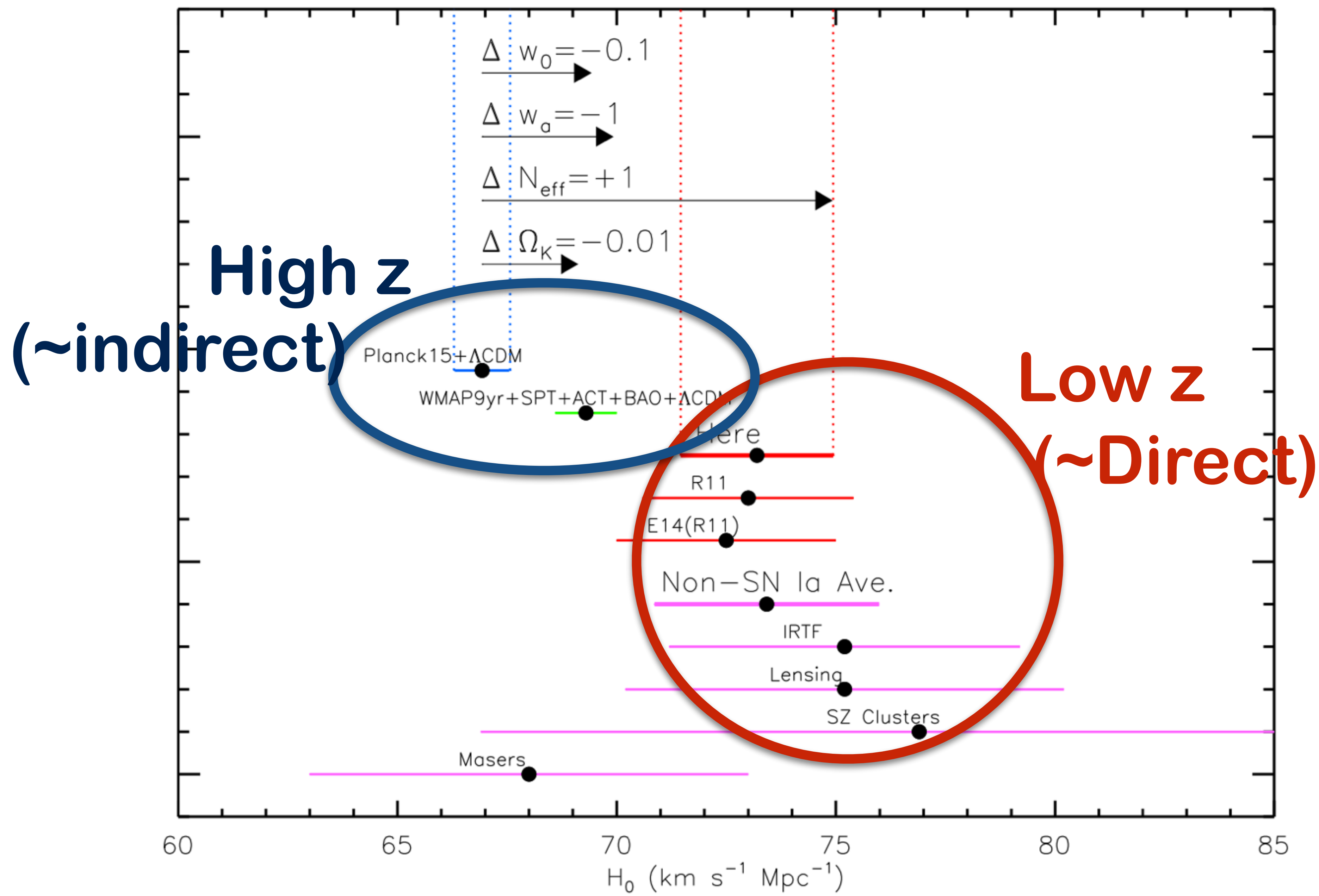

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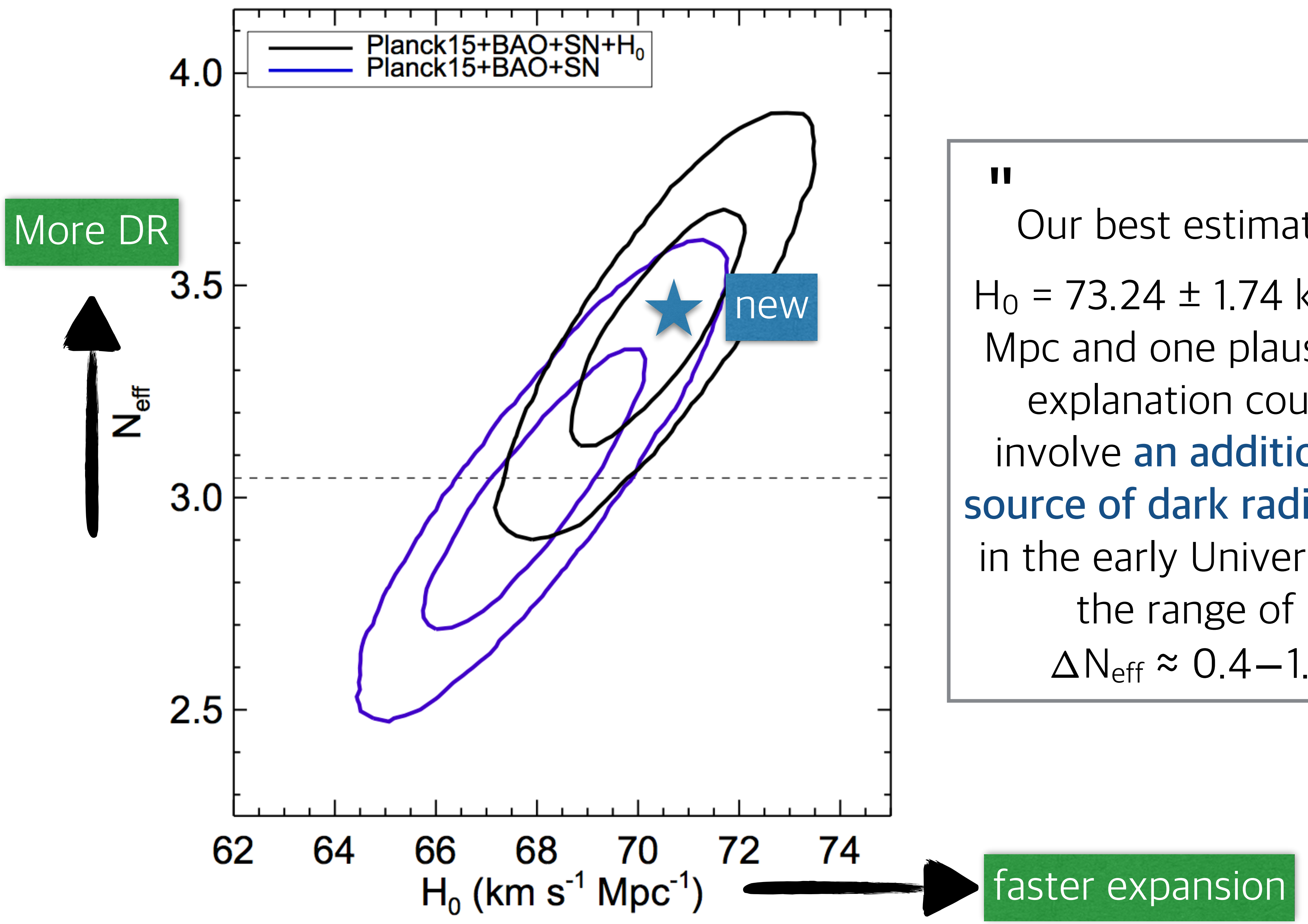

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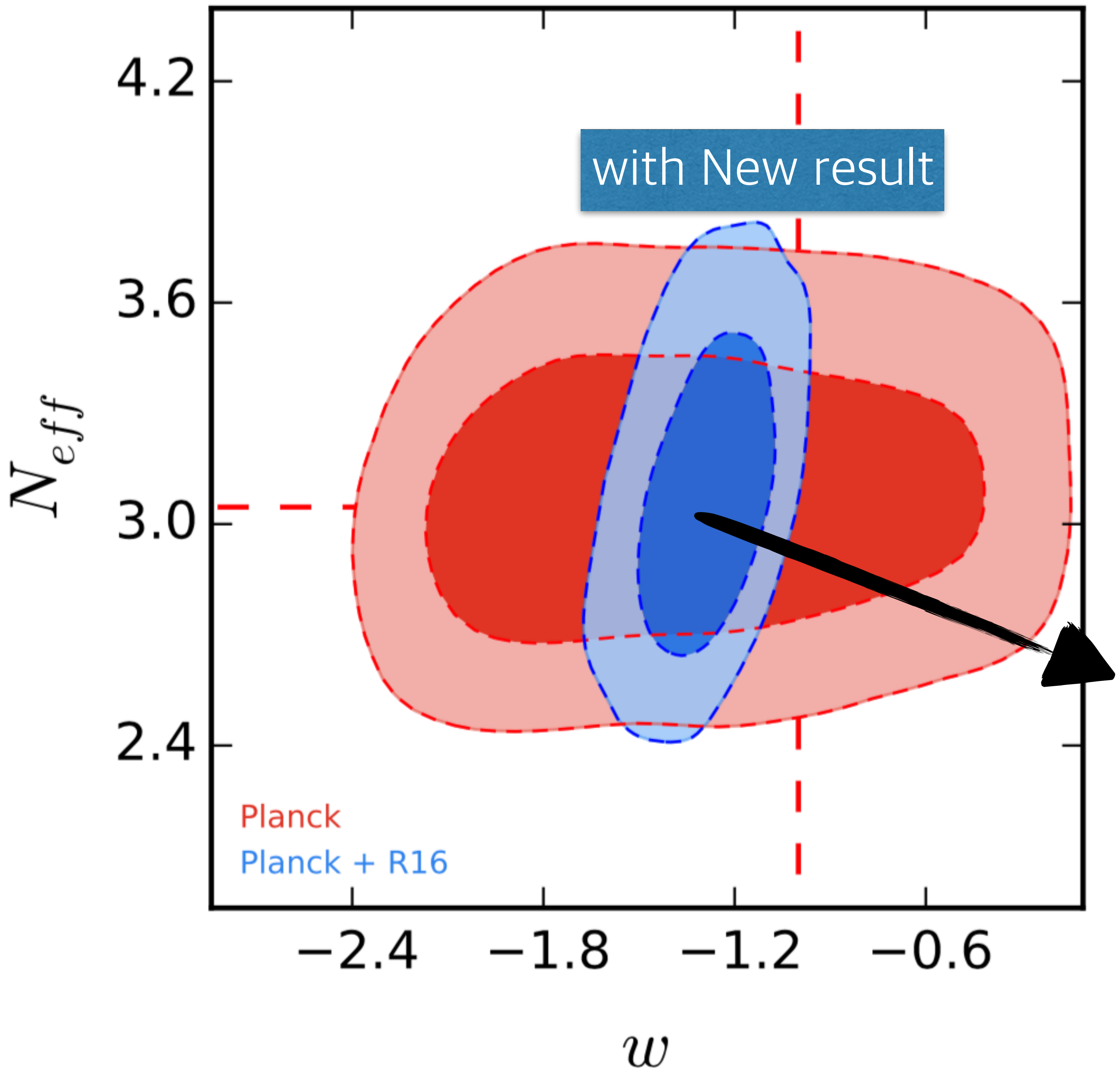
" Our best estimate of H_0 = 73.24 ± 1.74 km/s/Mpc and one plausible explanation could involve **an additional source of dark radiation** in the early Universe in the range of $\Delta N_{eff} \approx 0.4$–1."

Tension reconciled w/ Ghost?



12 parameters fit
to the cosmological data

A Ghost??

Eleonora Di Valentino, Alessandro Melchiorri, and Joseph Silk [arXiv:1606.00634]

The lesson

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- Dark Radiation is **NOT excluded**.

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- Even we may say that DR is needed to reconcile with the data from low-z Hubble expansion.

DR with WZ

- "DR= Dark gauge boson" associated with "Dark gauge symmetry
- Dark gauge symmetry is responsible for stability of superheavy dark matter >100 TeV

Local symmetry
vs
Global symmetry

Local symmetry
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Global symmetry

A global symmetry does not work in the presence of gravity, especially in the vicinity of black hole. All the stable particles (strings and branes) should be associated with gauge symmetries.

T. Banks and N. Seiberg, Phys. Rev. D 83, 084019 (2011)

Dark radiation observation

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$$
\begin{aligned}
N_{\rm eff}^{\rm CMB} &= 3.30 \pm 0.27 \quad \text{(Planck 2013)}, \\
N_{\rm eff}^{\rm CMB} &= 3.84 \pm 0.40 \quad \text{(WMAP9)}, \\
N_{\rm eff}^{\rm BBN} &= 3.71^{+0.47}_{-0.45} \quad \text{(BBN)}.
\end{aligned}
$$

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    - ★ t_{BBN}~O(0.1-1000) sec,
    - ★ t_{CMB}~$3.8X10^5$ yr=$1.2X10^{13}$ sec
- WIMZILLA :U(1) charged fermion, which never decays but contributes the late time decay of a light particle

A minimal model

J-C. Park, SCP (2014 & 2015)

X : WZ → stable, Dirac DM

ϕ : new scalar → long lived ~BBN,CMB

A_H : dark photon → DR

$$\mathcal{L} = i\bar{X}\gamma^\mu(\partial_\mu - ig_H A^H_\mu)X - m_X\bar{X}X - y_\psi\phi\bar{X}X$$
$$-\frac{1}{4}F^{\mu\nu}_H F_{H\mu\nu} + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2_\phi\phi^2$$
$$-\lambda_{\phi H}\phi^2|H|^2 \quad -\frac{\epsilon}{4}F^{\mu\nu}_{em}F_{H\mu\nu}$$

- The most general anomaly free, renormalizable Lagrangian of this type

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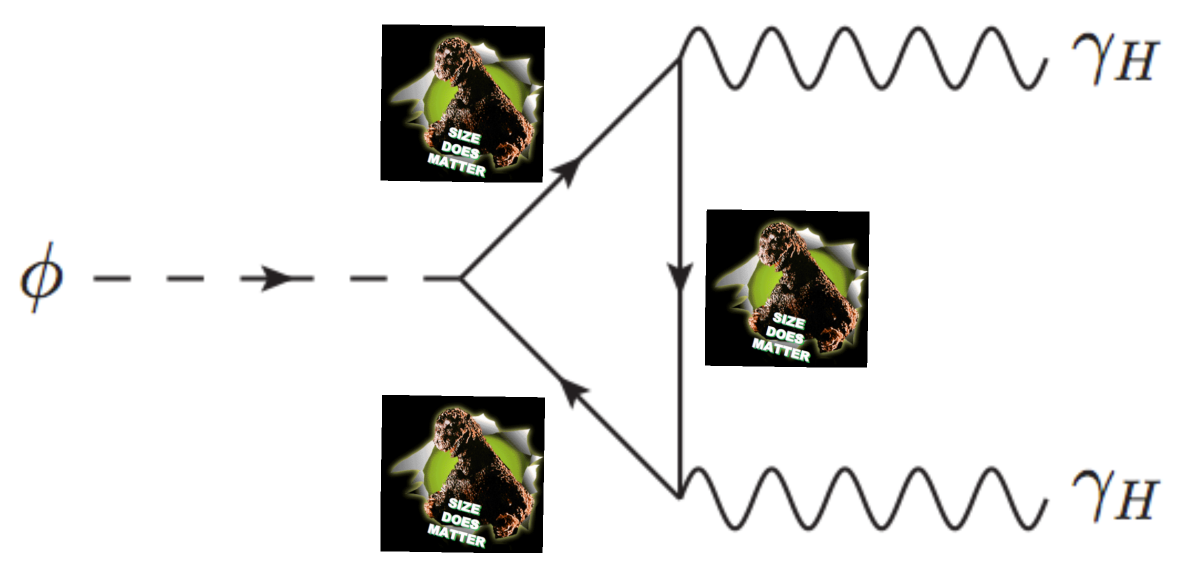
- Why not Scalar WZ? .. not good unless ‘Higgs portal’ interaction is forbidden, which introduces additional constraints from other experiments
- U(1) mixing may be neglected if there is no bi-charged particle in the spectrum, which is the case for us

Late time decay via WZ loop

hidden sector particle



dark radiation

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$$\frac{1}{\tau_{\phi \to \gamma_H \gamma_H}} \approx \frac{(\alpha_H y_\psi)^2}{144\pi^3} \frac{m_\phi^3}{m_\psi^2}$$

(taken the asymptotic value for Veltman-Passario 1-loop function)

Dark Radiation

$$N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\phi\text{-decay}} + \Delta N_{\gamma_H}$$

$$N_{\rm eff}^{\rm SM} = 3.046$$ (well known since Mangano et. al. 2005)

primordial

$$\Delta N_{{\rm eff},\gamma_H} = \frac{2}{(7/8)\cdot 2}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_{*S,0}}{g_{*S,\gamma_H{\rm dec}}}\right)^{4/3} \simeq 0.053\,,$$

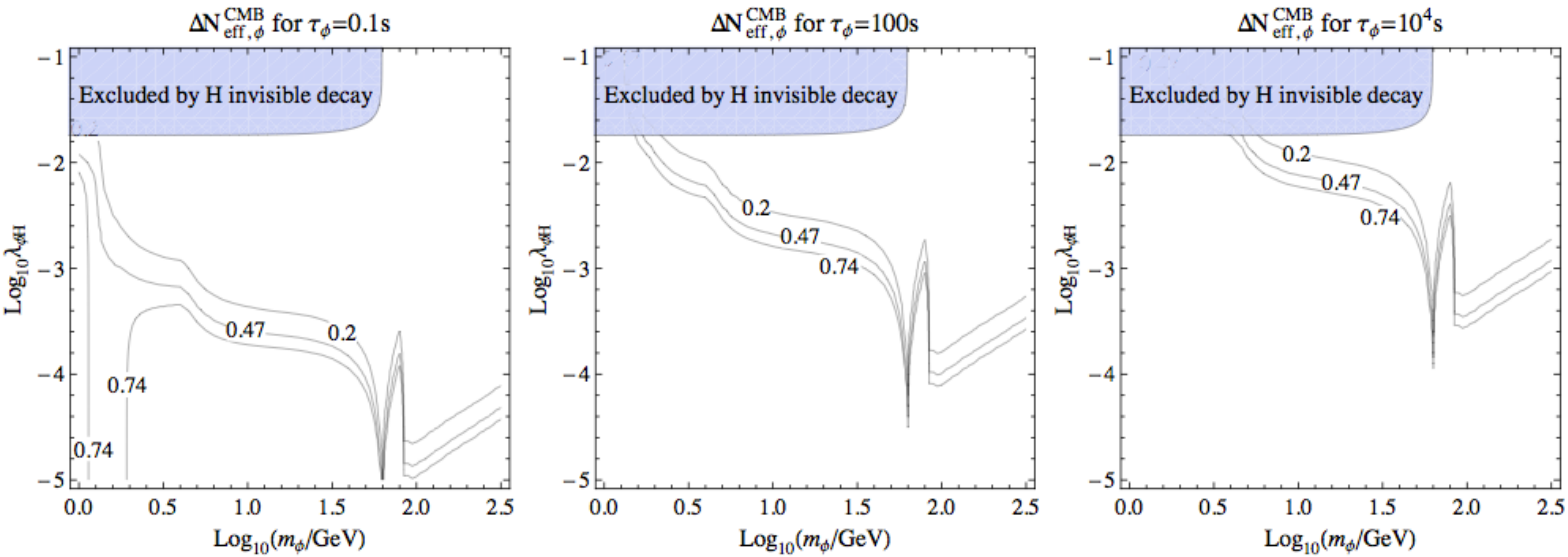
(our estimation /w 3.91, 107.75 at present and decoupling time)

late time decay

$$\Delta N_{{\rm eff},\phi} = 8.3(Y_\phi m_\phi/{\rm MeV})(\tau_\phi/{\rm s})^{1/2}$$

↑ from ϕ decay

The ball park range for DR from WZ



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- Obviously there are more.