高スケール超対称性
における
シングリーノ暗黒物質

Teppei Kitahara
University of Tokyo

Progress in **P**article **P**hysics **2014**

July 30, 2014, YITP, Kyoto

Based on

K. Ishikawa, TK, M. Takimoto,

“Singlino Resonant Dark Matter and 125 GeV Higgs Boson in High-Scale Supersymmetry",

arXiv:1405.7371

Outlook

SM

Hierarchy problem.... Unstable vacuum... No dark matter candidate.... GUT....


Stable Vacuum
GUT
No Hierarchy problem
Dark Matter
LHC Run2
HL-LHC
SUSY
SUSY theorists and experimentalists

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Supersymmetry

NULL Result +
Higgs mass + FCNC/EDM constraint

μ Problem

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High-scale SUSY

SUGRA effect, [Giudice, Masiero '88]
Singlet extension

What is DM?

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What is DM?

Anomaly mediation

Wino DM → 市川君のトーク
[Giudice, Luty, Murayama, Rattazzi '98]

Gaugino coannihilation DM
[Harigaya, Kaneta, Matsumoto '14]

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Our proposal

Singlino DM
[Ishikawa, **TK**, Takimoto '14]

μ Problem and singlet extension

- After electroweak symmetry breaking takes place, μ has to be the order of the EW ~ SUSY breaking scale ➡ μ Problem [Kim, Nilles '84]

$$W_{\rm MSSM} = \mu \hat{H}_u \hat{H}_d + y_t \hat{Q} \hat{H}_u \hat{t}_R - y_b \hat{Q} \hat{H}_d \hat{b}_R - y_\tau \hat{L} \hat{H}_d \hat{\tau}_R$$

MGUT - MPlanck

$$\longleftrightarrow \quad \mu^2 = -\frac{1}{2} M_Z^2 + \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1 - \tan^2\beta}$$

$$\sim M_{\rm SUSY}$$

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- If a gauge singlet field S has a vev which is order SUSY breaking scale, an effective μ term is generated and μ problem is solved

$$W \supset \lambda \hat{S} \hat{H}_u \hat{H}_d$$

$$\longrightarrow \quad \mu_{\rm eff} = \lambda \langle S \rangle \sim M_{\rm SUSY}$$

The Next MSSM(NMSSM)

[Fayet '75]

- The Next MSSM (NMSSM) is one of the minimal models, which have MSSM + gauge singlet superfield $\hat{S} = (S,\ \tilde{S})$
- The discrete Z3 is imposed

$$W_{\rm NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + W_{\rm Yukawa}$$

- Domain wall problem vs Tadpole problem

UV theoryに難あり

- If the singlino is DM candidate, SUSY breaking scale should be low scale
- The General NMSSM (GNMSSM)

$$W_{\rm GNMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + f(\hat{S}) + W_{\rm Yukawa}$$

→ 庄司君のトーク

今回のstudyではこれらの模型は考えません

The Nearly MSSM(nMSSM)

[Panagiotakopoulos, Pilaftsis '00]

- **The Nearly (New) MSSM (nMSSM)** is also one of the minimal models, which have **MSSM** + gauge singlet superfield $\hat{S} = (S,\ \tilde{S})$
- **The discrete R-symmetry Z5 (or Z7)** is imposed. At the Planck scale, the superpotential and kahler potential are given by

$$W_{\rm nMSSM} = \lambda \hat{S}\hat{H}_u\hat{H}_d + W_{\rm Yukawa}$$

$$K_{\rm nMSSM} = K_{\rm MSSM} + |\hat{S}|^2 + \kappa_2 \frac{\hat{S}^2\hat{H}_d\hat{H}_u}{M_P^2} + \kappa_5 \frac{\hat{S}(\hat{H}_d\hat{H}_u)^3}{M_P^5}$$

$$+ \text{higher term} + \text{h.c.}$$

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$$+ \text{higher term} + \text{h.c.}$$

- In the case of soft supersymmetry breaking terms ~ M_{SUSY} induced by a hidden sector in supergravity, a tadpole term (divergence) is induced via six-loop level

$$W_{\rm tad} \sim \frac{\kappa_2\kappa_5\lambda^4}{(16\pi^2)^6} M_P M_{\rm SUSY}\hat{S} \sim \mathcal{O}(M_{\rm SUSY}^2)\hat{S}$$

The Nearly MSSM(nMSSM)

[Panagiotakopoulos, Pilaftsis '00]

- In the nMSSM, once supersymmetry is broken, the superpotential and SUSY breaking terms are given by

$$W_{\rm nMSSM} = \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{m_{12}^2}{\lambda}\hat{S} + W_{\rm Yukawa}$$

$$V_{\rm soft} = m_S^2|S|^2 + (\lambda A_\lambda H_u H_d S + t_S S + {\rm h.c.}) + V_{\rm soft}^{\rm MSSM}$$

where $m_{12}^2 \sim O(M_S^2), t_S \sim O(M_S^3)$

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- In this scalar potential, S obtains vacuum expectation value

$$\langle S \rangle \sim -t_S/m_S^2 \sim O(M_S)$$

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therefore $\mu_{\rm eff} \equiv \lambda \langle S \rangle \sim O(M_S)$

μ problem is solved

Neutralino masses in the nMSSM

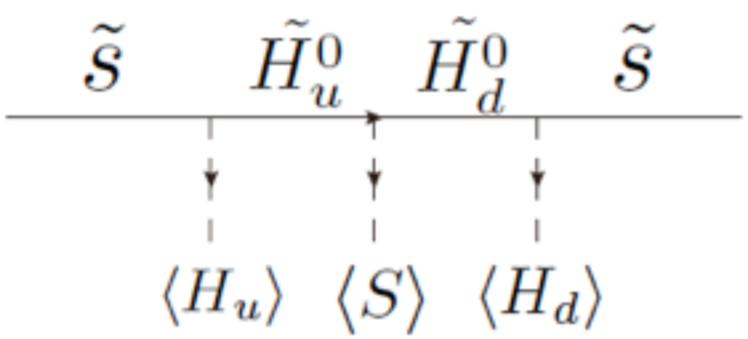
- **In the nMSSM,** tree-level singlino mass is obtained only via mixing with Higgsino

basis

$$(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}) \qquad \mathcal{M}_{\rm tree} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\rm eff} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix}$$

No mass term

$$m_{\tilde{s}} \sim \lambda^2 \frac{v^2}{M_{\rm SUSY}} \sin 2\beta$$



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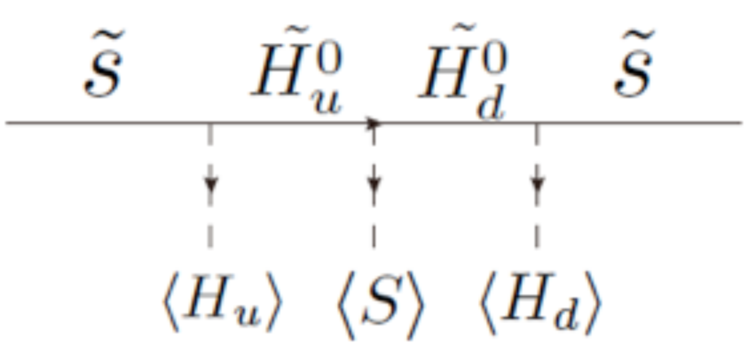
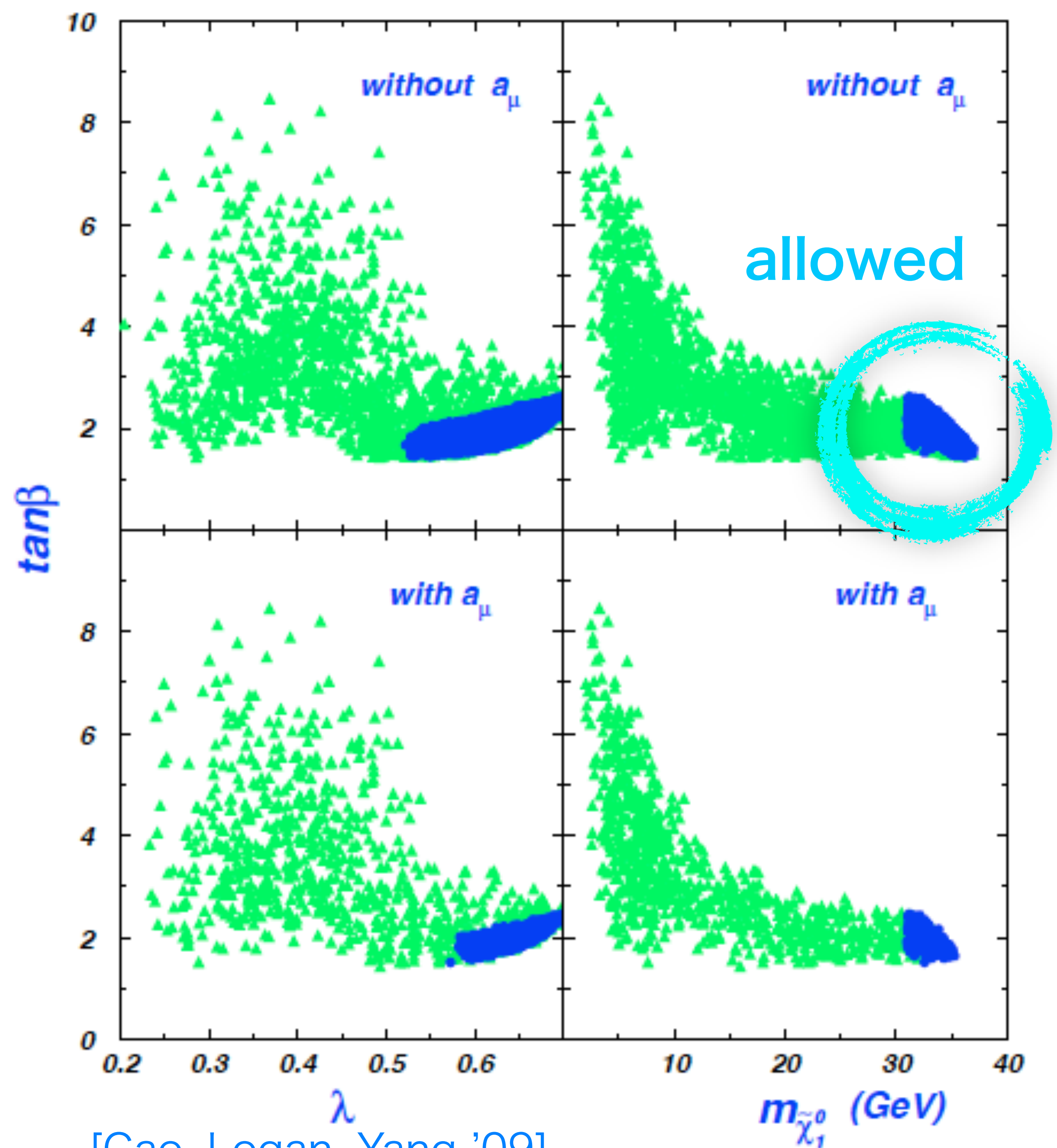


- Since singlino mass has suppression of SUSY breaking scale, singlino is always light and becomes LSP, and **can be a DM candidate**

Problems of the nMSSM

- Typically, the singlino DM overclose the universe.....



[Cao, Logan, Yang '09]

$m_{a_1} > M_Z$

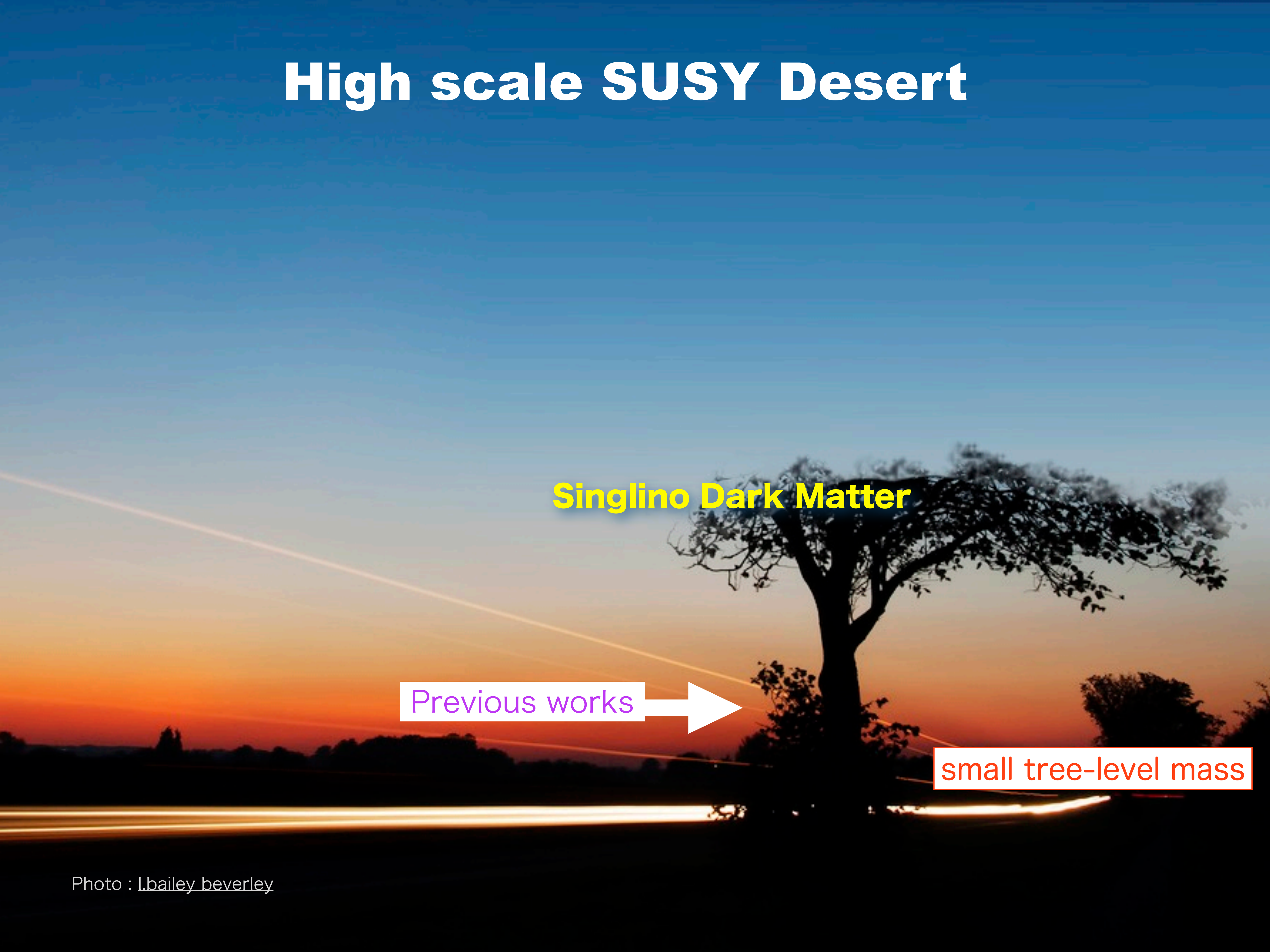
resonant DM via Z boson, allowed region

$m_{a_1} < M_Z$

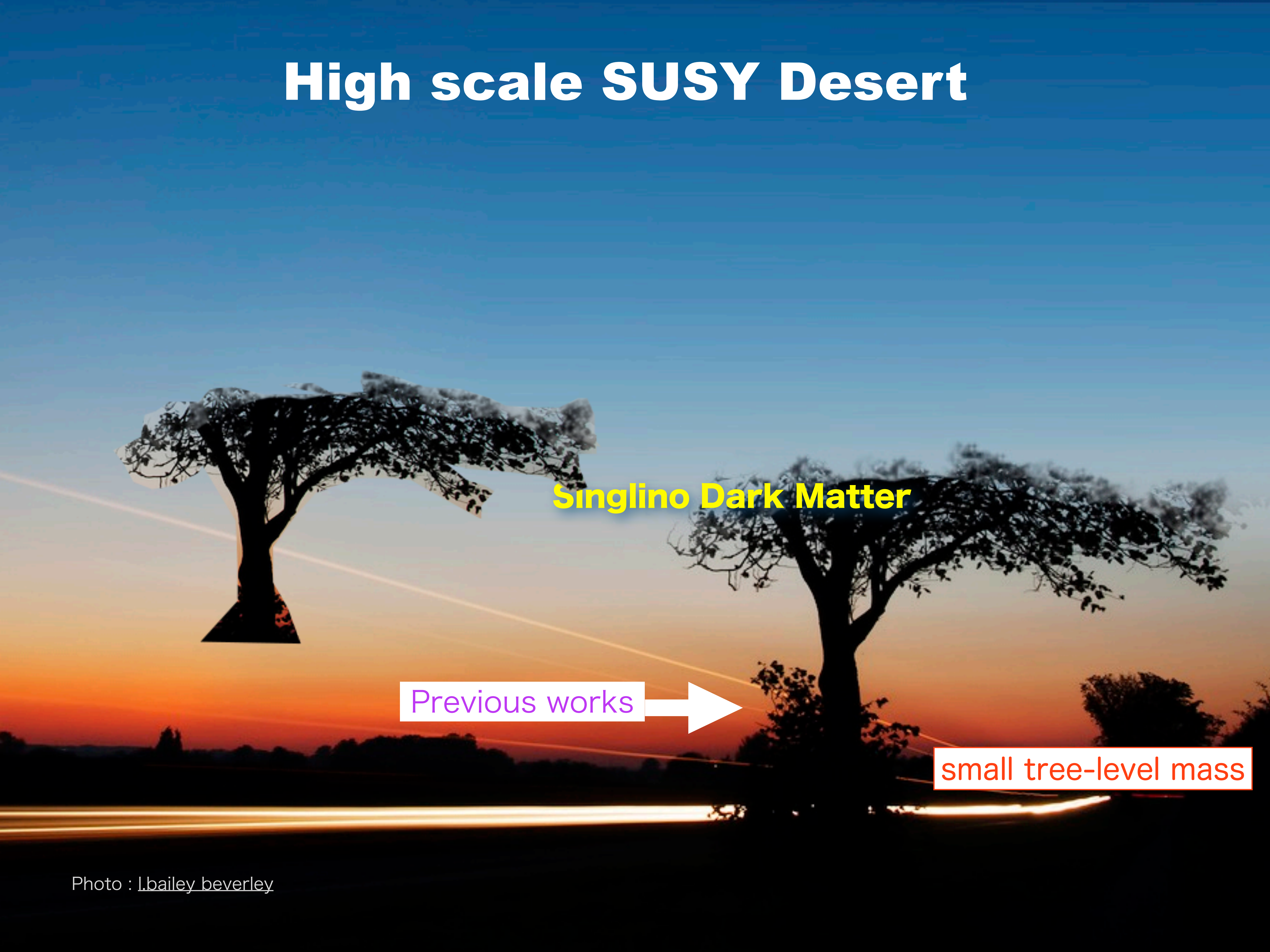
resonant DM via a1 Higgs, highly constraint region by h->a1a1

In order to obtain sizable singlino mass and sizable coupling to Z boson, SUSY breaking scale should be low scale

The singlino DM is incompatible with TeV SUSY?


High scale SUSY Desert
Singlino Dark Matter
Previous works
small tree-level mass
Photo : l.bailey beverley

High scale SUSY Desert



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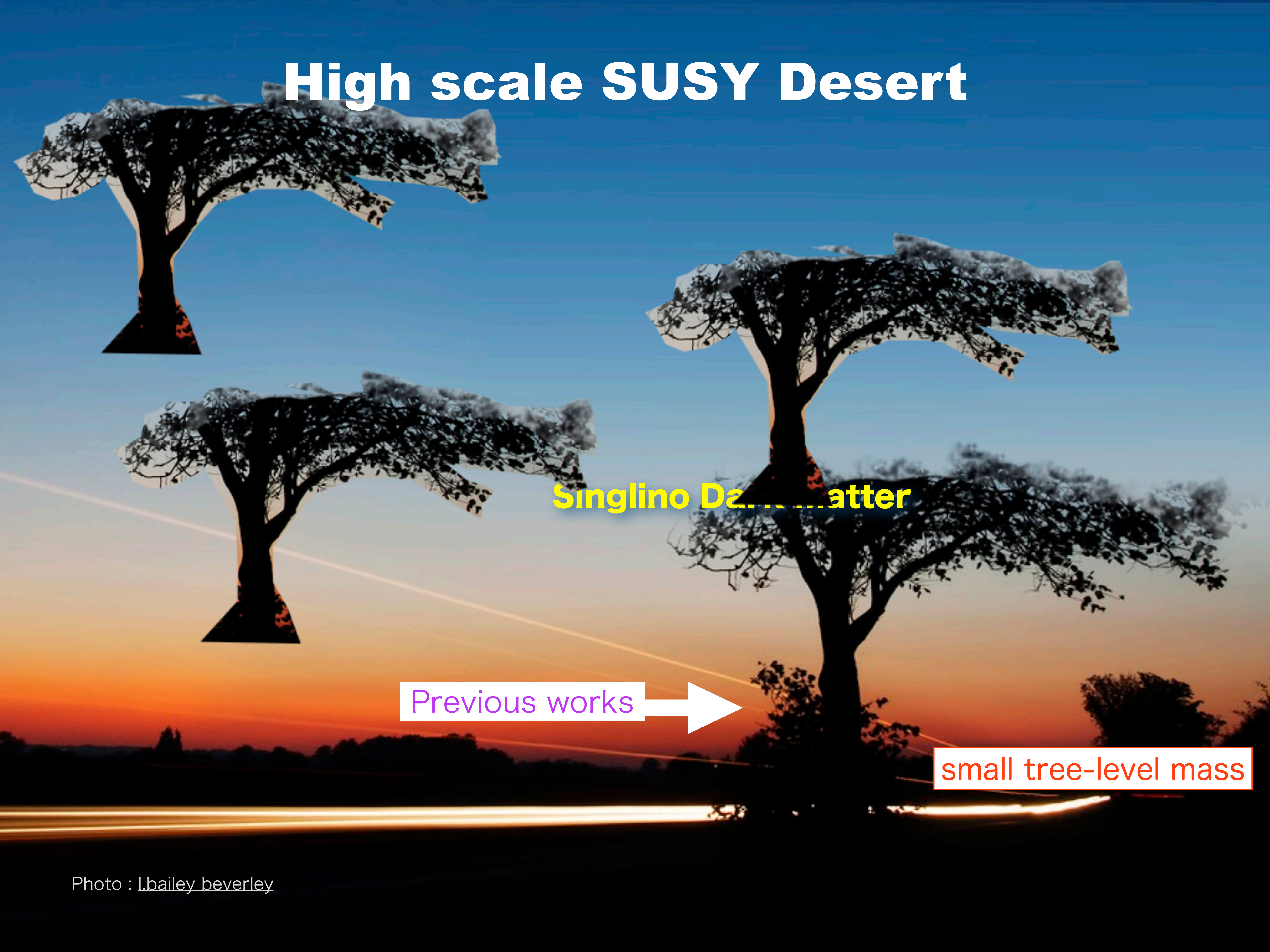

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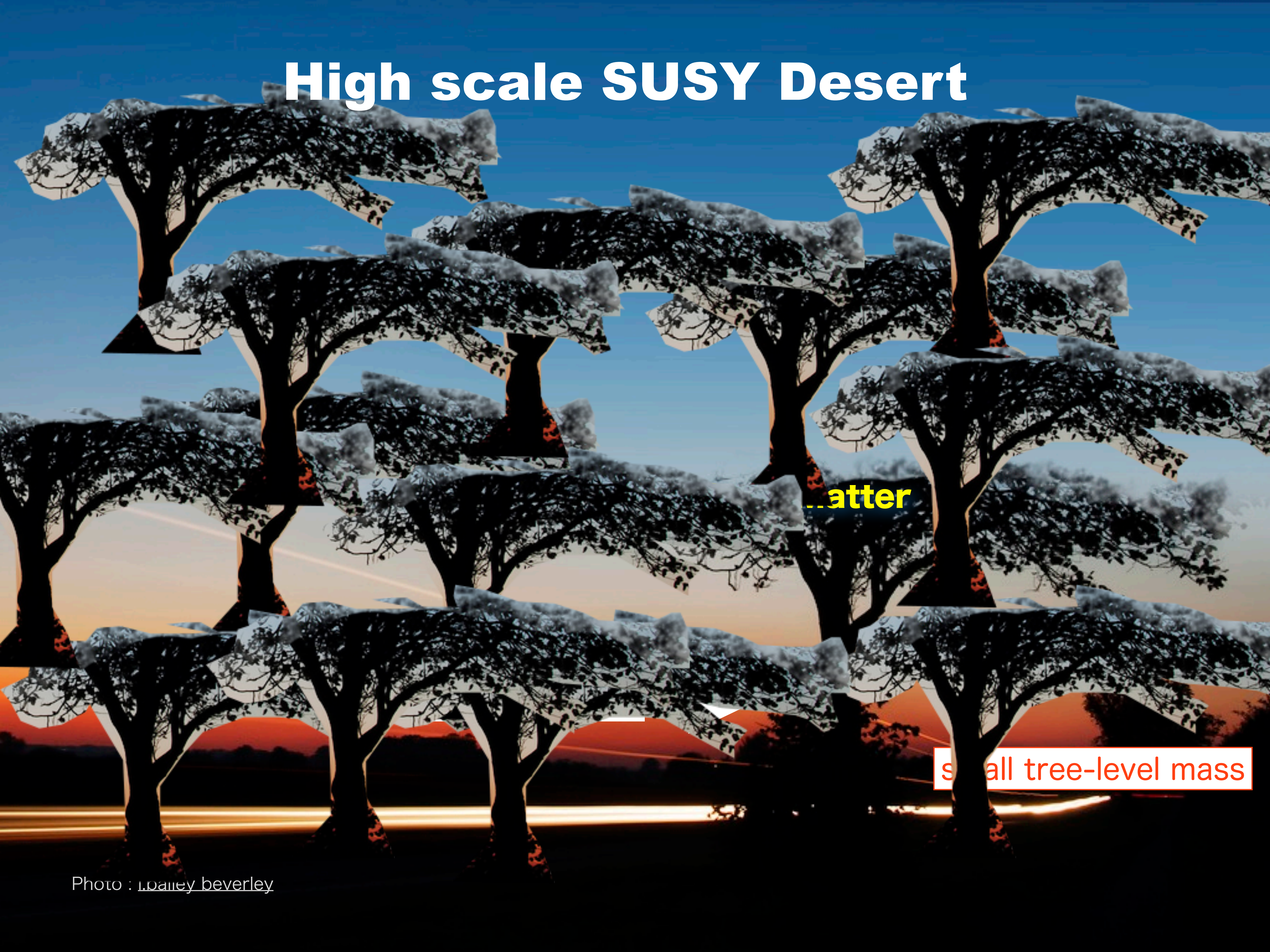


Photo : i.bailey beverley

High scale SUSY Desert

Singlino becomes overabundant....!

...Is this true?

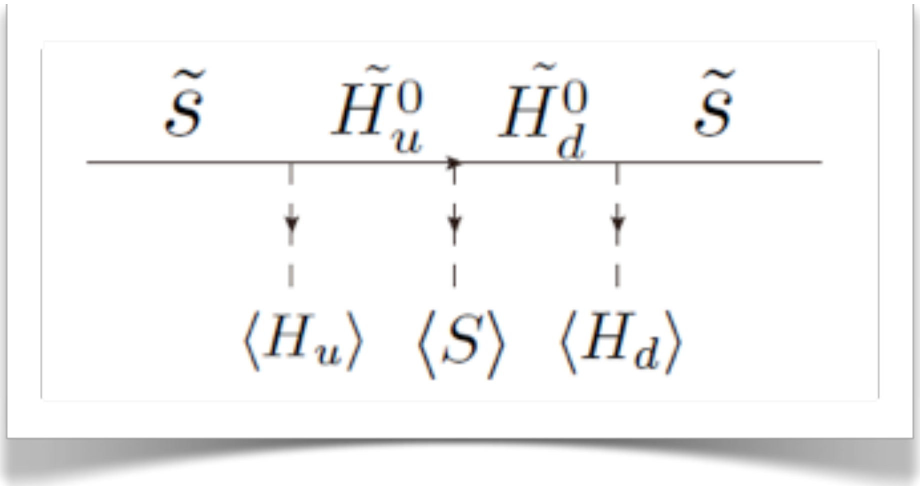
Photo : l.bailey beverley

One-loop corrections

Radiative singlino mass

- We consider **one loop corrections to the singlino mass** which are **not included in the literature.** In the our paper, we calculated the full one-loop corrections to the neutralino 5×5 mass matrix

tree mass



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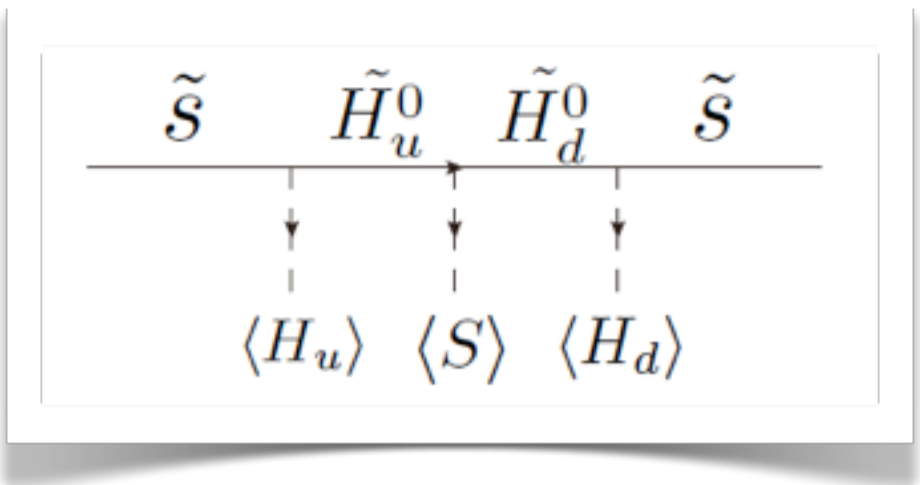

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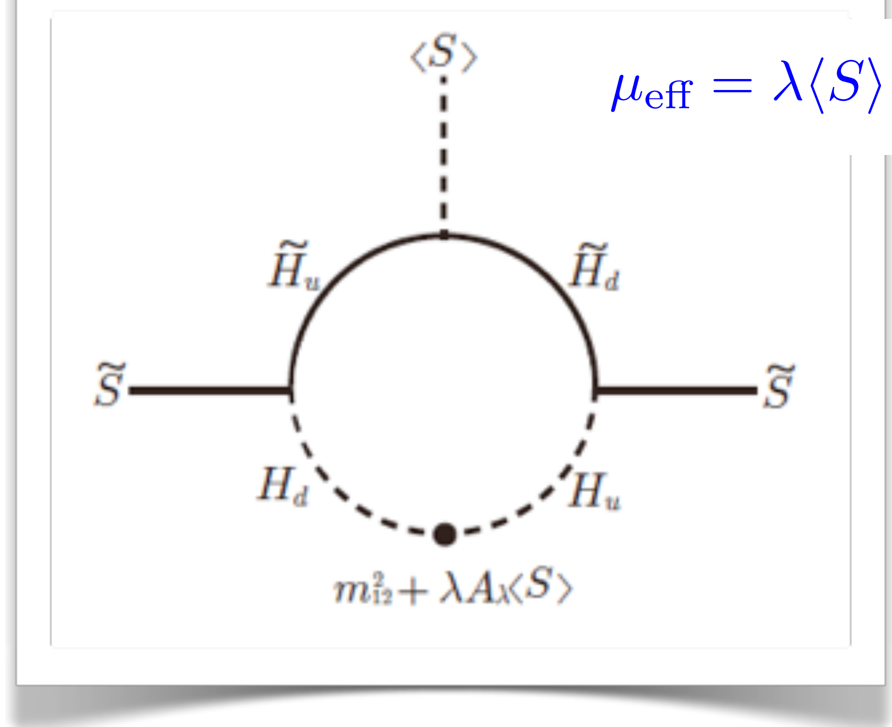

$$\mu_{\rm eff} = \lambda \langle S \rangle \sim M_{\rm SUSY}$$

$$m_{\tilde{s}}^{\text{1-loop}} \sim \frac{\lambda^2}{(4\pi)^2} M_{\rm SUSY} \sin 2\beta$$

[Ishikawa, **TK**, Takimoto '14]

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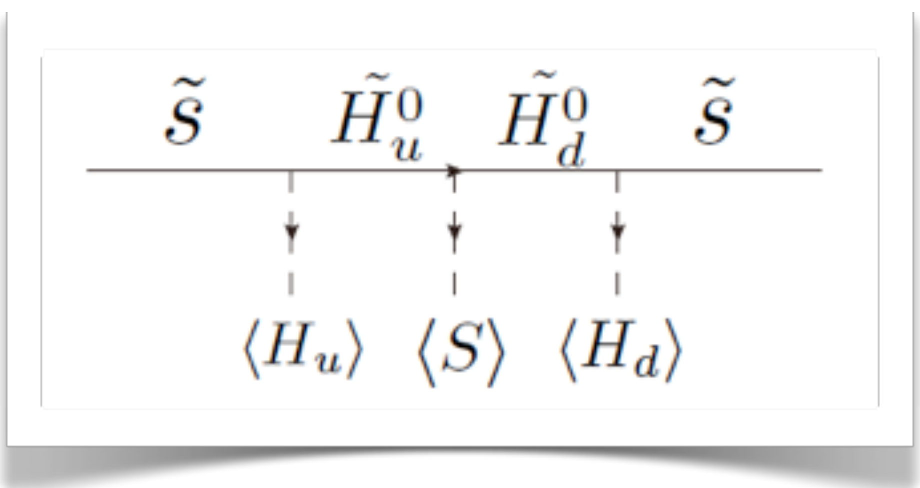

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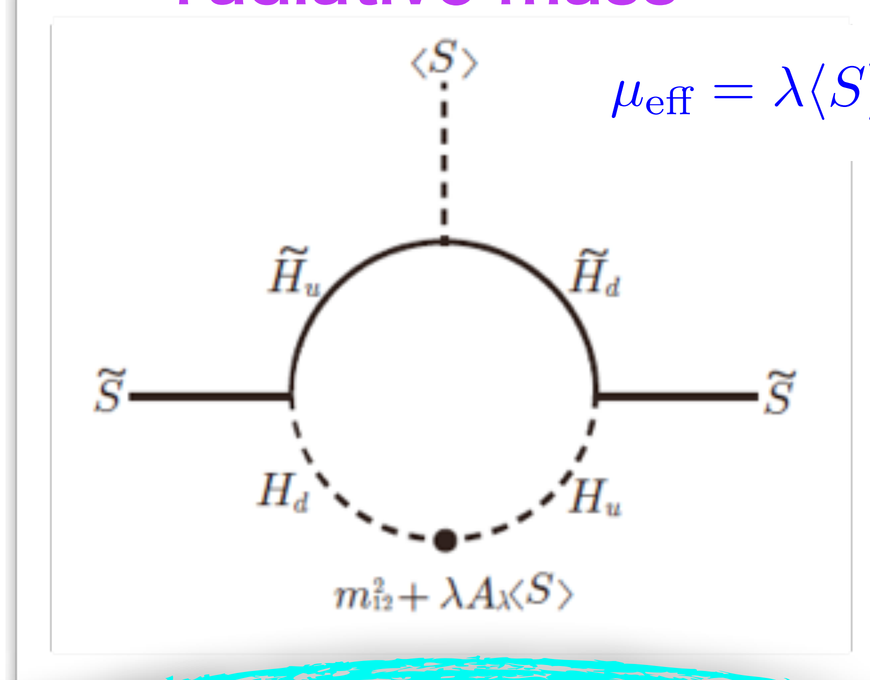

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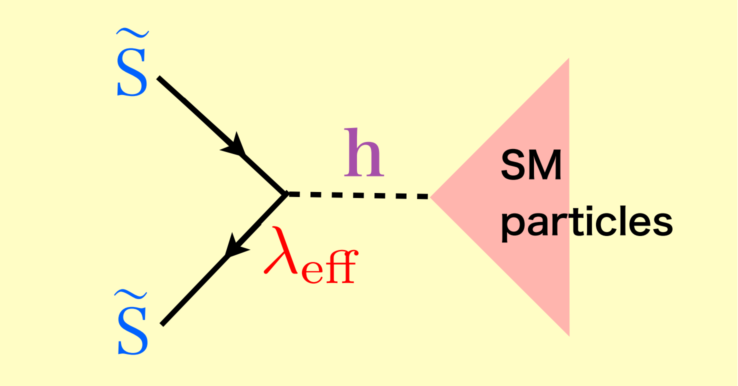
[Ishikawa, **TK**, Takimoto

Radiative singlino mass

- We find that the singino DM receives **a significant radiative corrections in the TeV scale SUSY model**

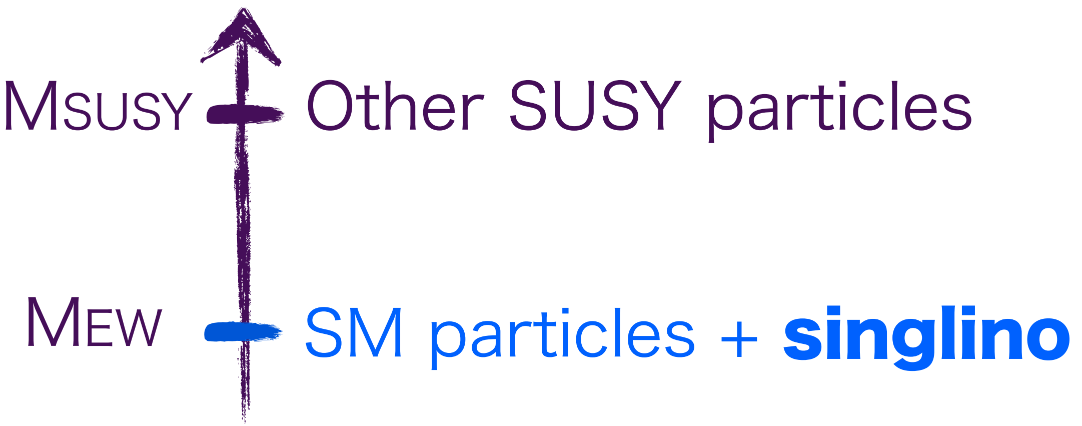
> These radiative corrections open a window for the singlino DM scenario **with resonant annihilation via exchange of SM Higgs boson**



- In order to estimate the capability of this scenario, let us consider the singlino + Higgs effective Lagrangian

$$-\mathcal{L}_{\rm eff} \supset +\frac{m_{\tilde{s}}}{2}\tilde{s}\tilde{s}+\frac{\lambda_{\rm eff}}{2}h\tilde{s}\tilde{s}$$

singlino mass   singlino-Higgs coupling



Singlino resonant DM

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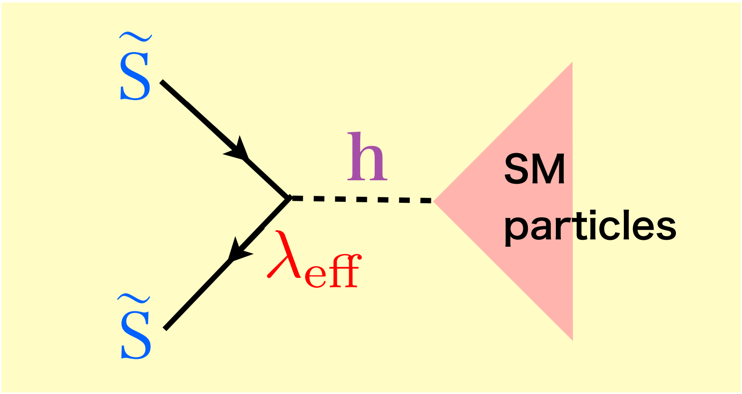
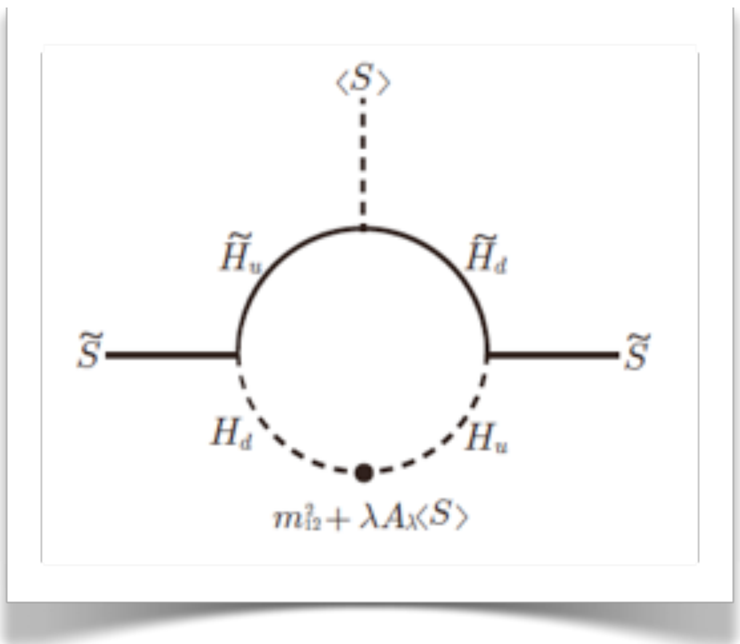
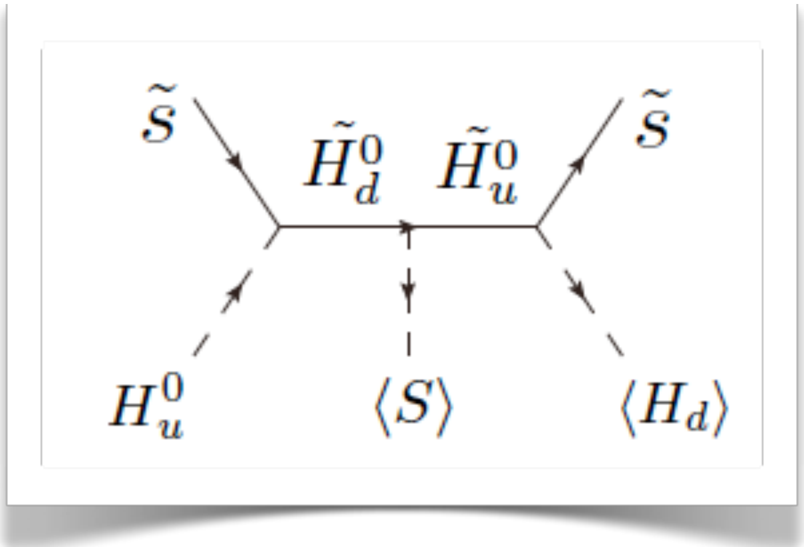


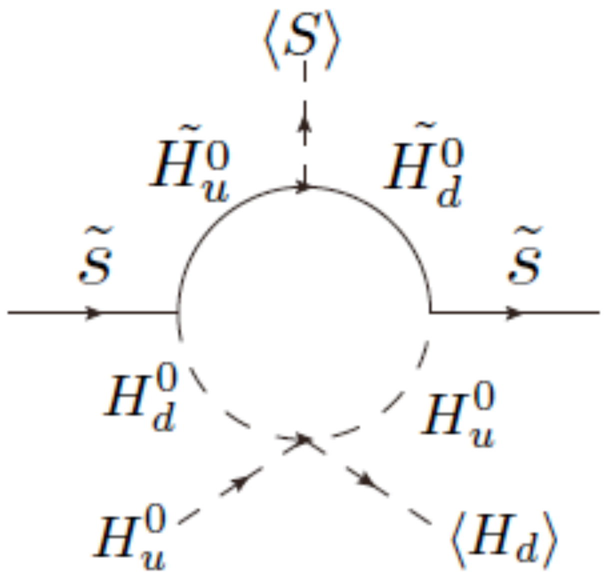
singlino mass



$$m_{\tilde{s}}^{\text{1-loop}} \sim \frac{\lambda^2}{(4\pi)^2} M_{\rm SUSY} \sin 2\beta$$

singlino-Higgs coupling





$$\lambda_{\rm eff}^{\rm tree} \sim \lambda^2 \frac{v}{M_{\rm SUSY}} \sin 2\beta \qquad \lambda_{\rm eff}^{\text{1-loop}} \sim \frac{\lambda^4}{(4\pi)^2}\frac{v}{M_{\rm SUSY}} \sin 2\beta$$

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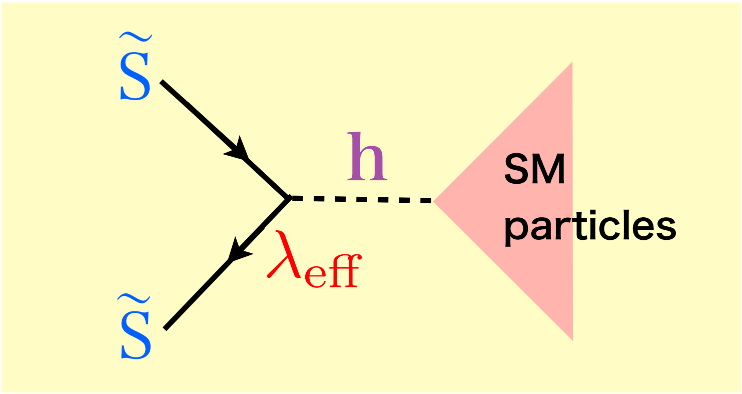

singlino mass

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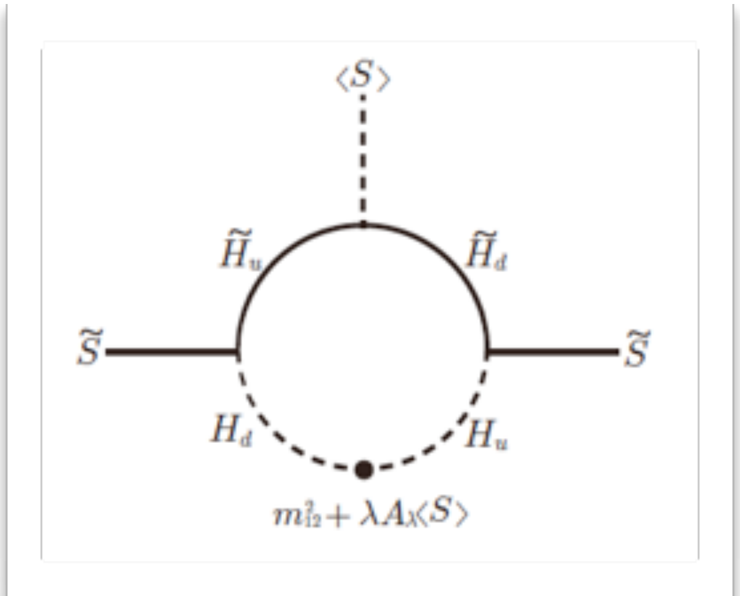

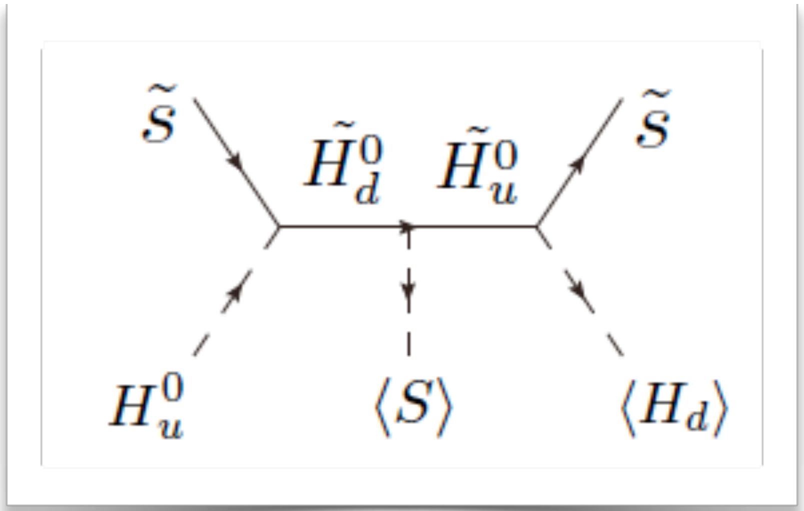

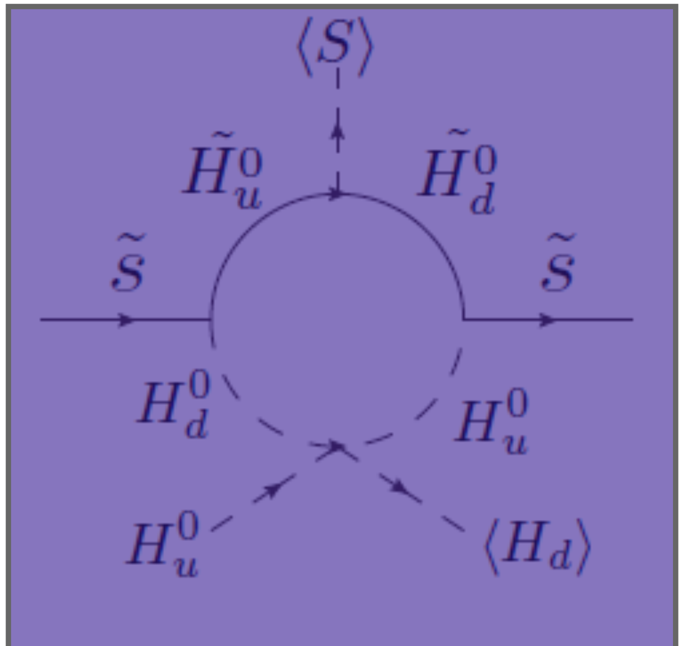

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negligible

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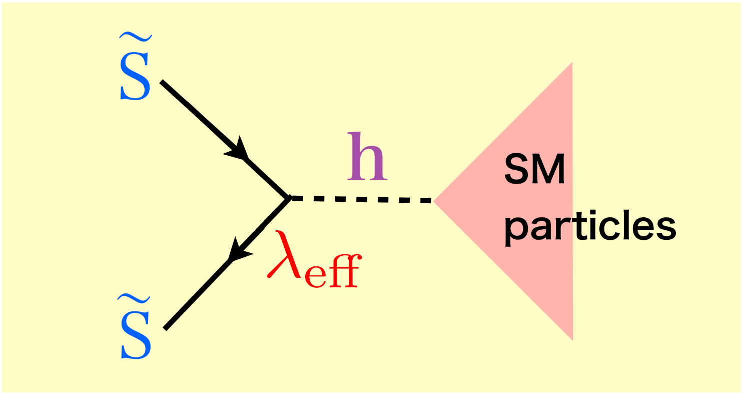

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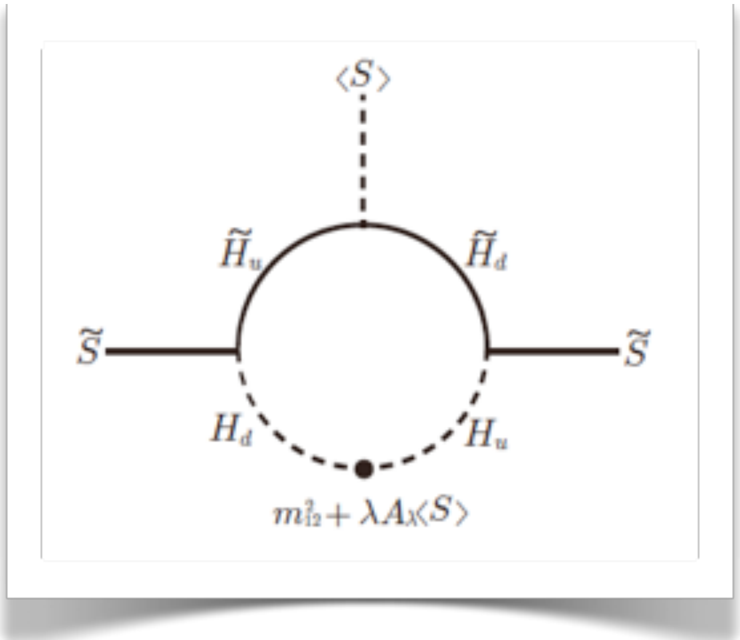

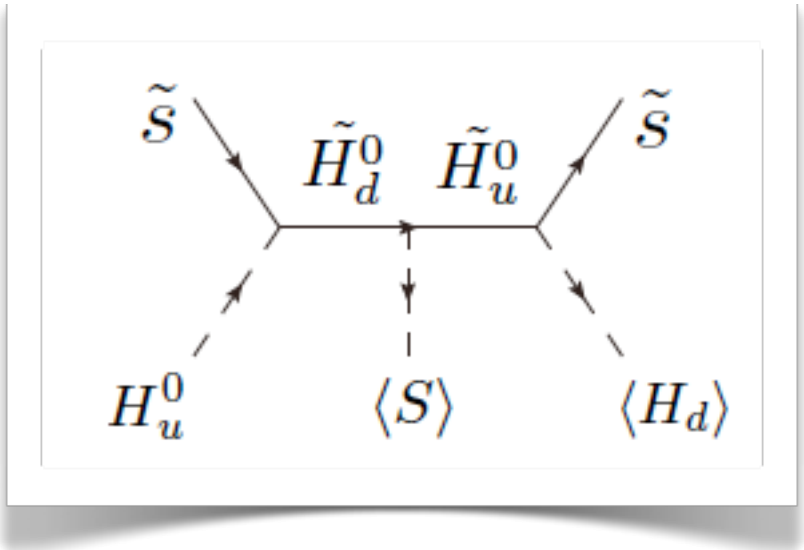

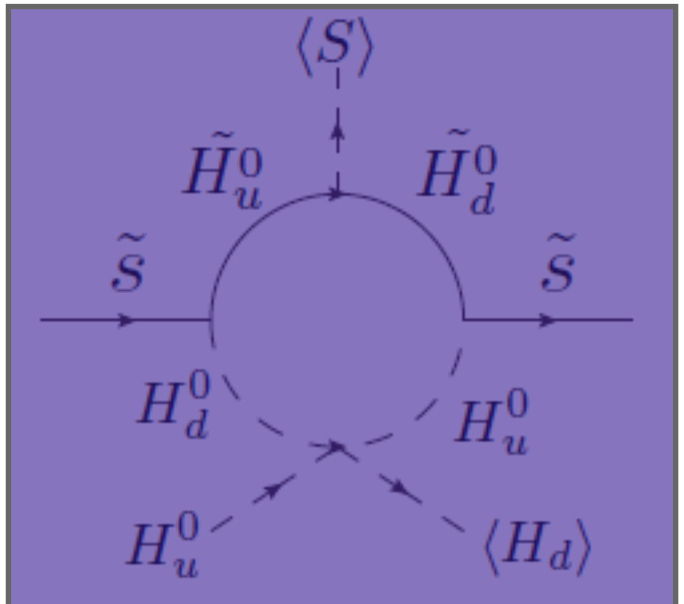

$$m_{\tilde{s}}^{\text{1-loop}} \sim \frac{\lambda^2}{(4\pi)^2} M_{\rm SUSY} \sin 2\beta$$

$$\sim 60 \text{ GeV}$$

$$\lambda_{\rm eff}^{\rm tree} \sim \lambda^2 \frac{v}{M_{\rm SUSY}} \sin 2\beta$$

$$\sim \mathcal{O}(0.01)$$

$$\lambda_{\rm eff}^{\text{1-loop}} \sim \frac{\lambda^4}{(4\pi)^2} \frac{v}{M_{\rm SUSY}} \sin 2\beta$$

negligible

$$M_{\rm SUSY} \sim \mathcal{O}(10) \text{ GeV}, \ \tan\beta \sim \mathcal{O}(1), \ \lambda \sim \mathcal{O}(1)$$

[Ishikawa, **TK**, Takimoto '14]

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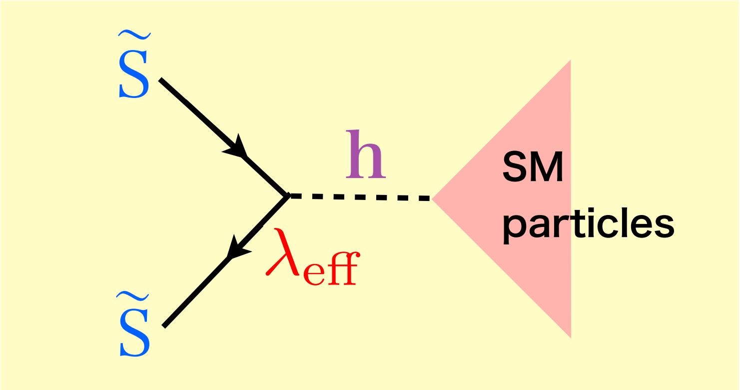
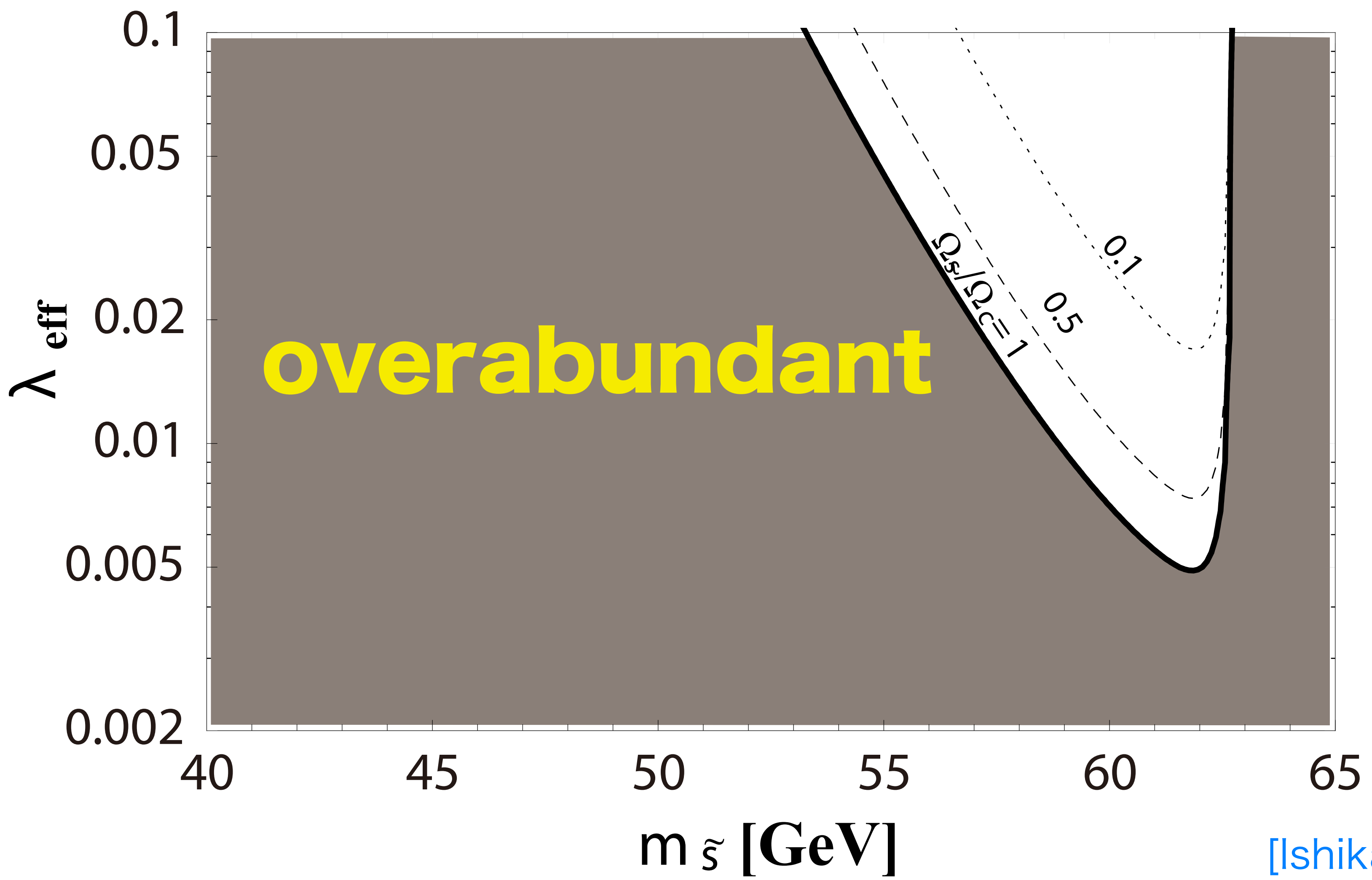


The thermal relic abundance of singlino with this effective Lagrangian by solving Bolzmann equation



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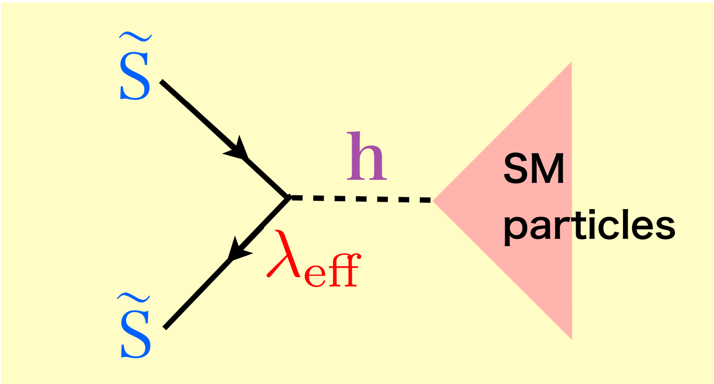

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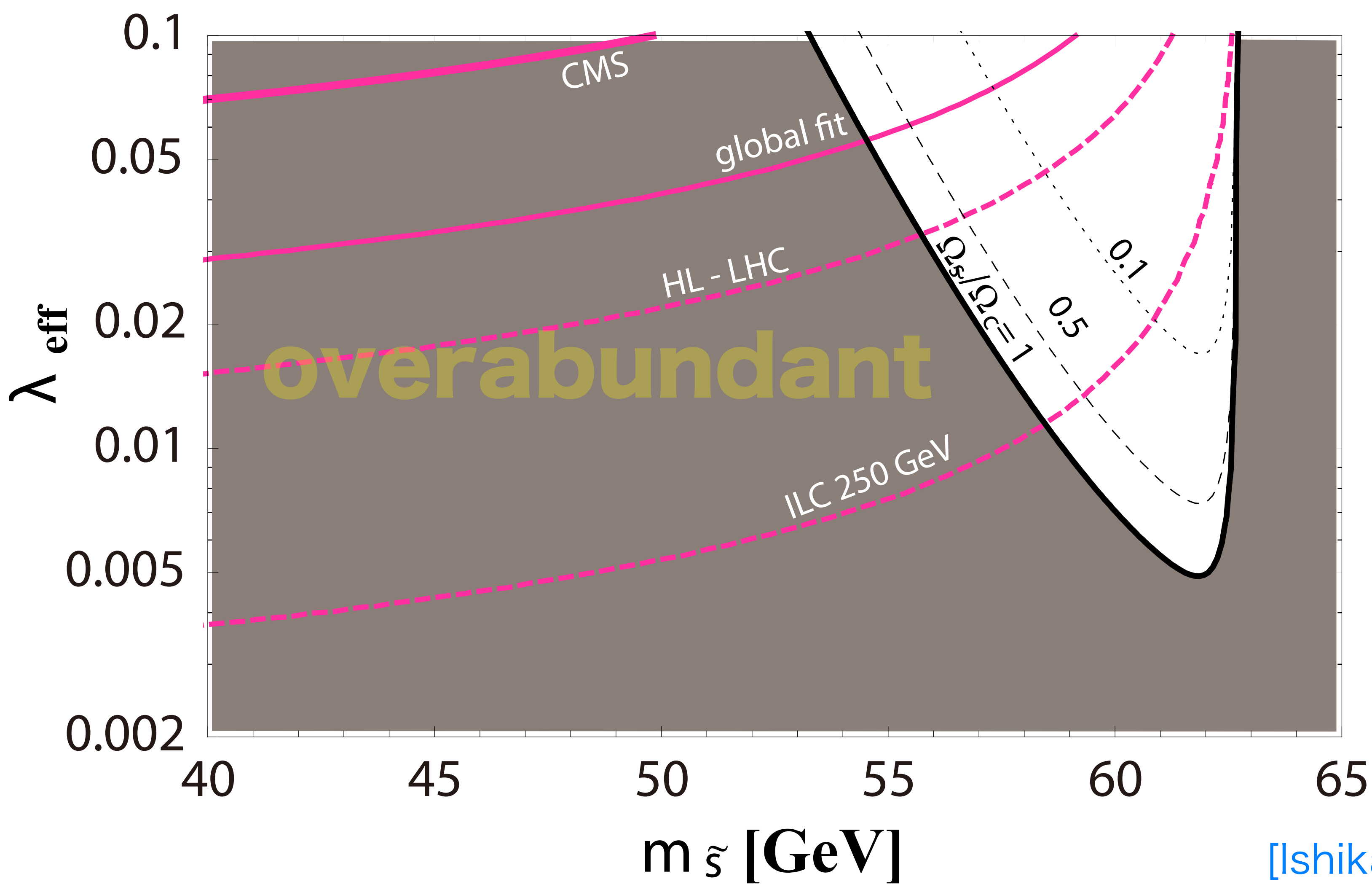
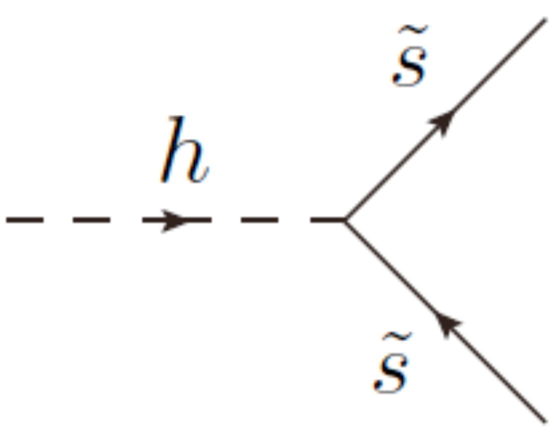


Pink Line

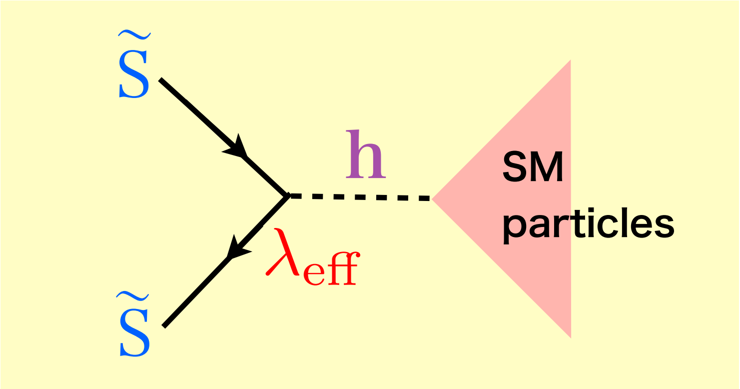
Indirect search



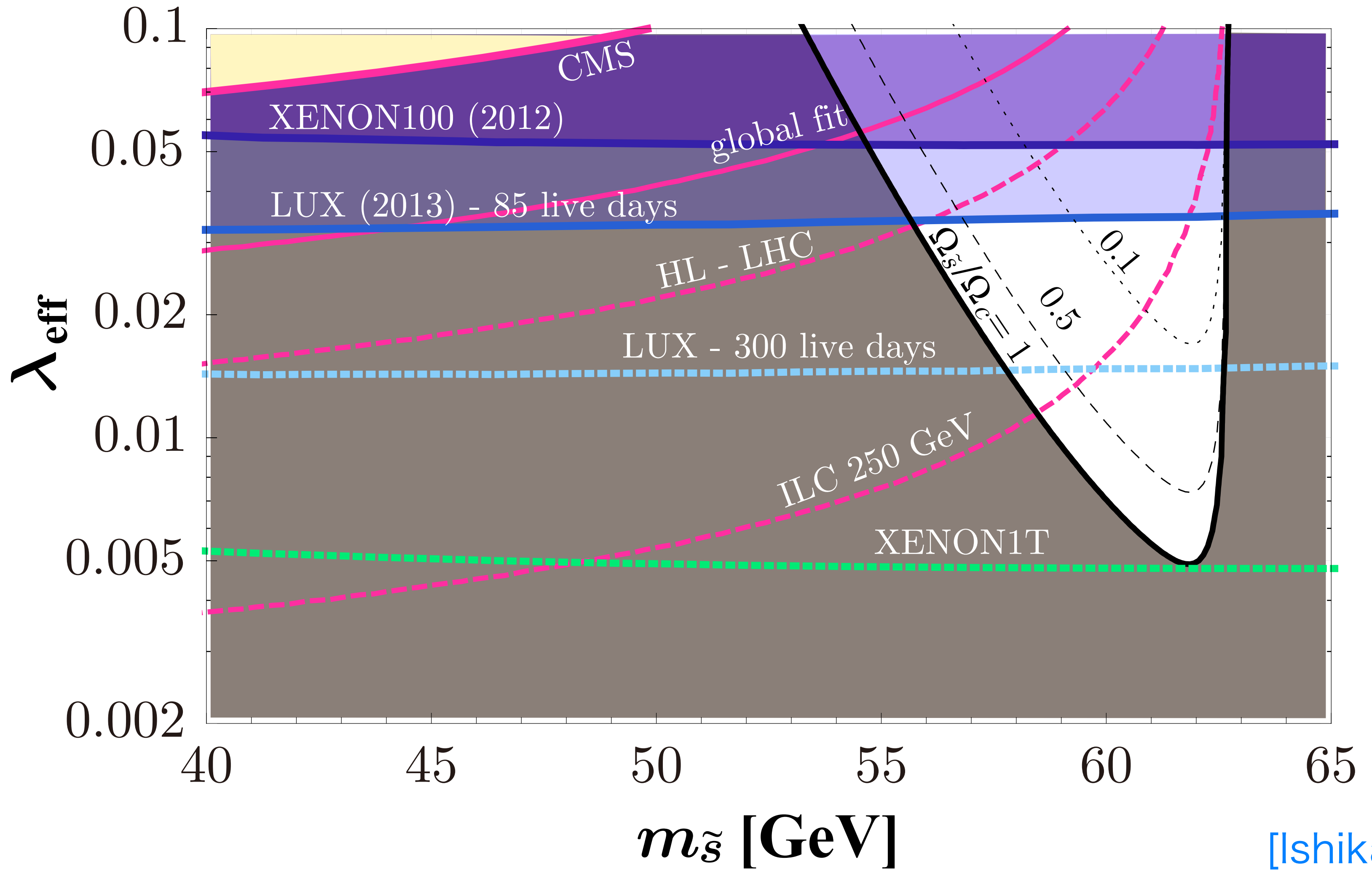
[Ishikawa, **TK**, Takimoto '14]

Singlino resonant DM

$$-\mathcal{L}_{\rm eff} \supset +\frac{m_{\tilde{s}}}{2}\tilde{s}\tilde{s}+\frac{\lambda_{\rm eff}}{2}h\tilde{s}\tilde{s}$$

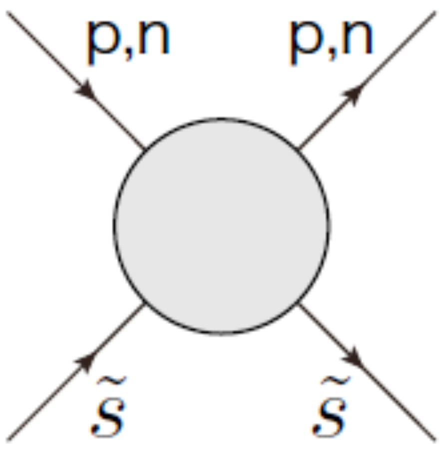


The thermal relic abundance of singlino with this effective Lagrangian by solving Bolzmann equation



Blue/Green Line

Direct search



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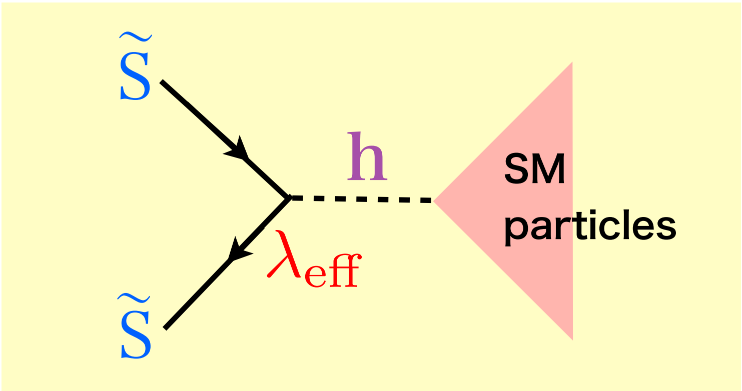

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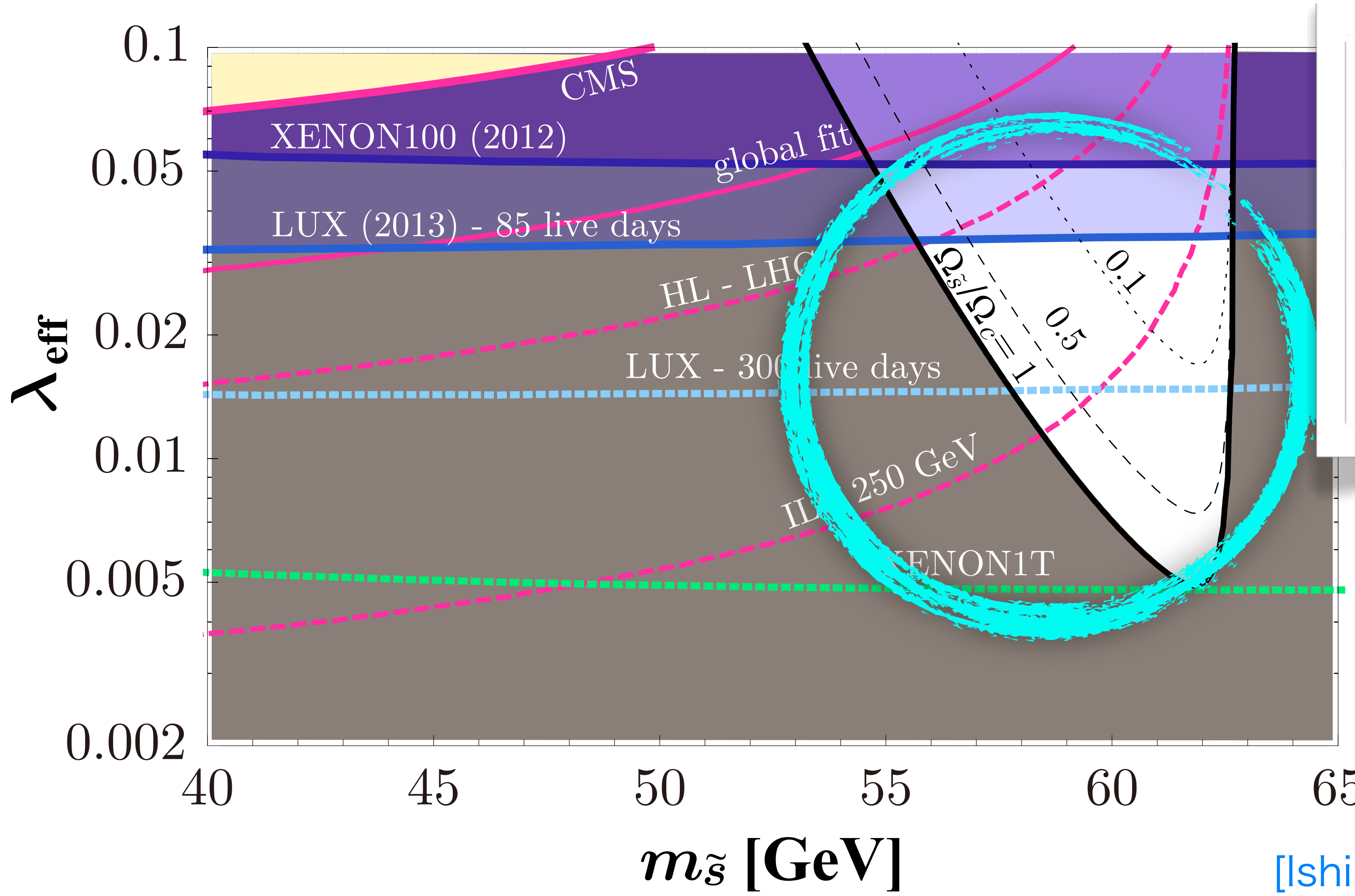
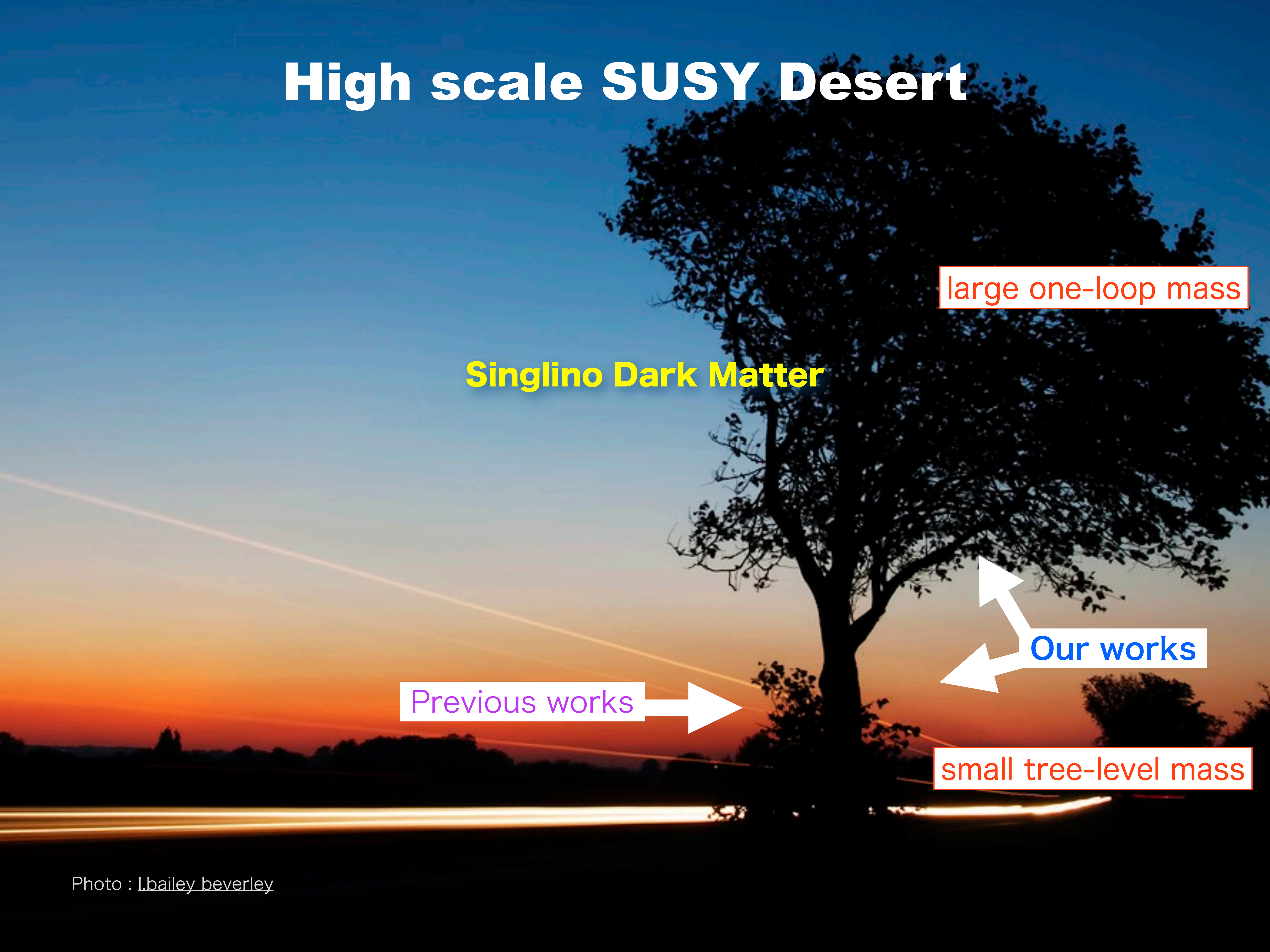


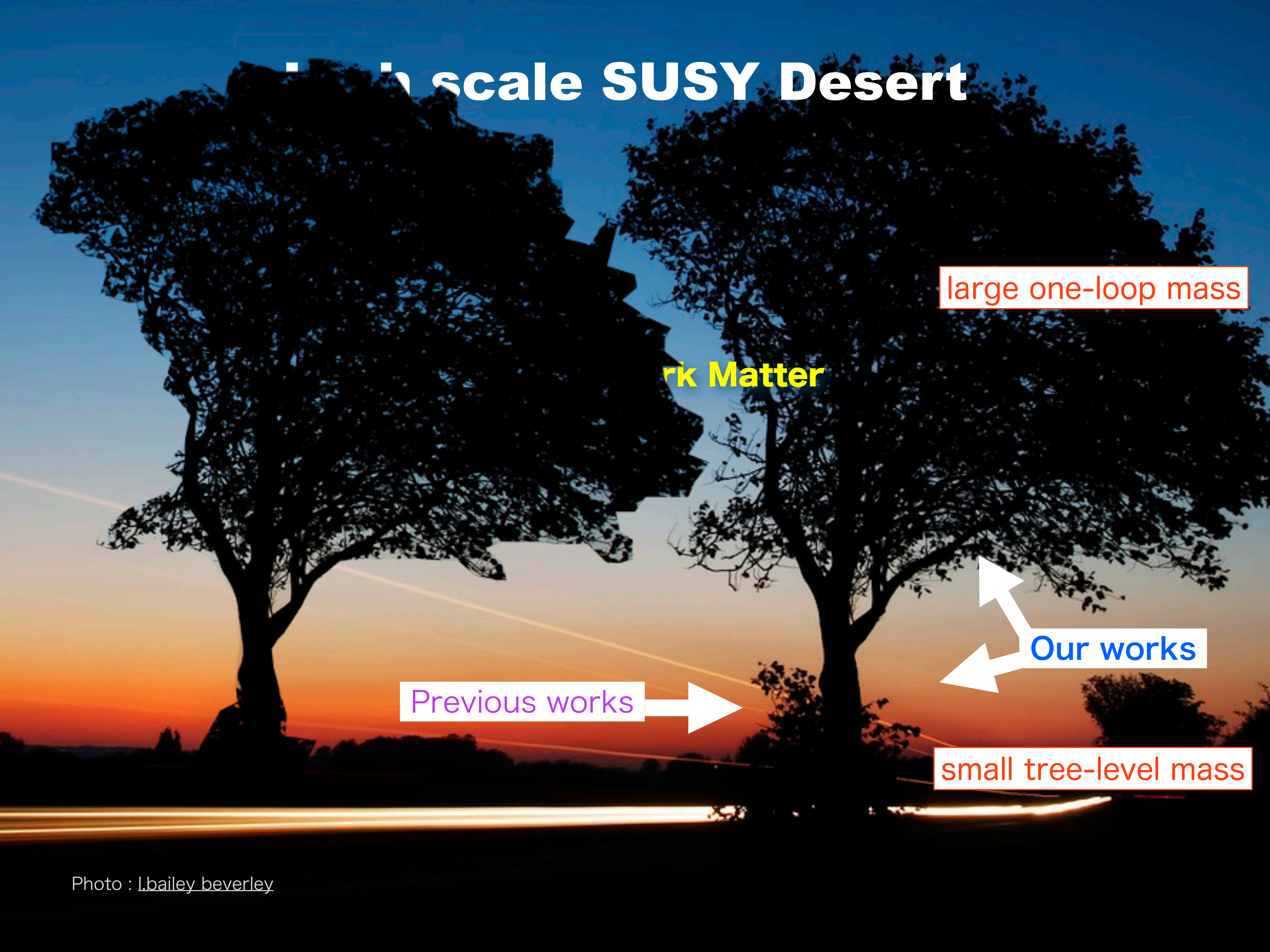
The allowed region is consistent with the rough estimation of singlino parameters

~ 60 GeV

$\sim \mathcal{O}(0.01)$

[Ishikawa, **TK**, Takimoto '14]


High scale SUSY Desert
large one-loop mass
Singlino Dark Matter
Our works
Previous works
small tree-level mass
Photo : I.bailey beverley



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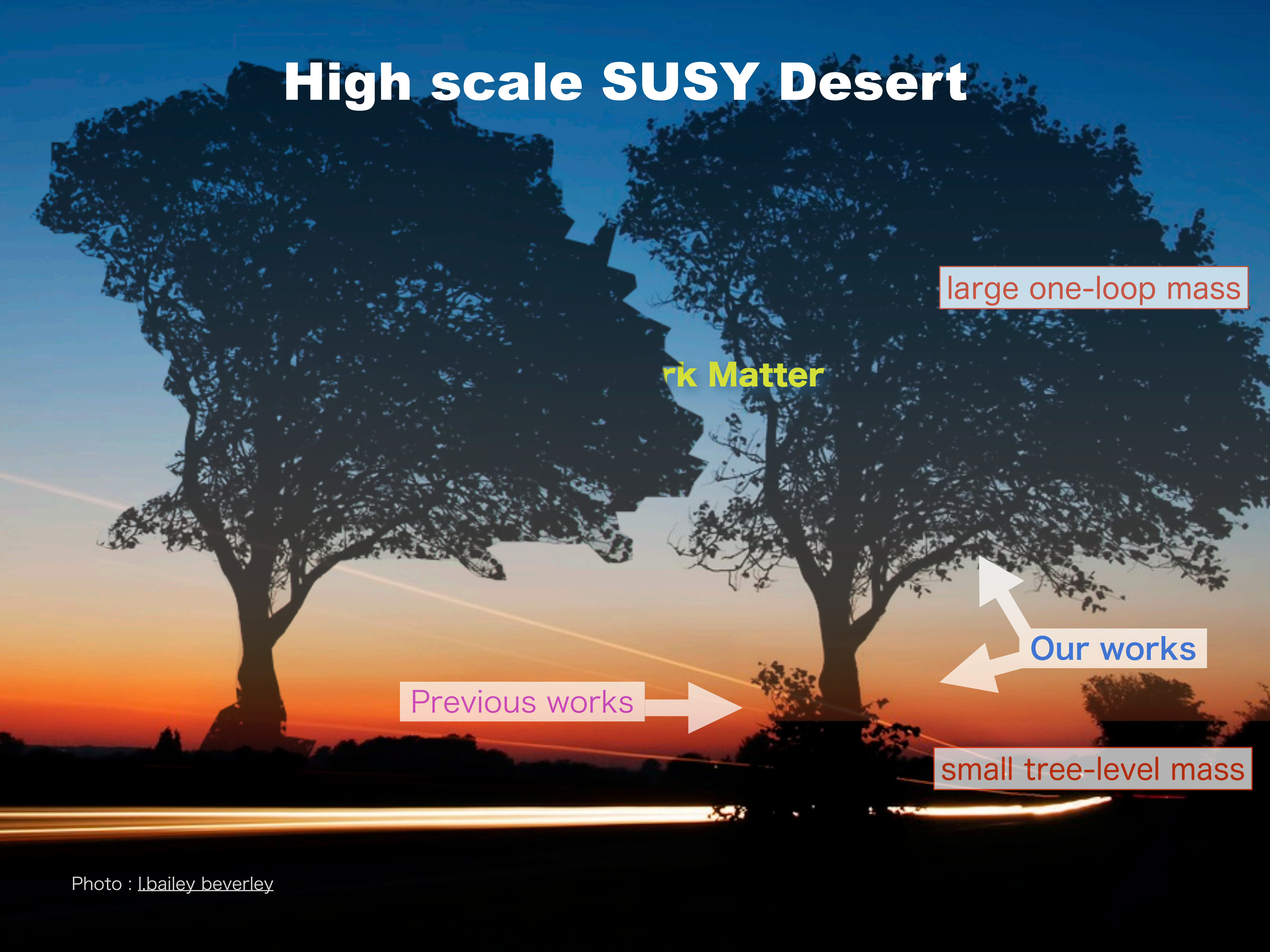
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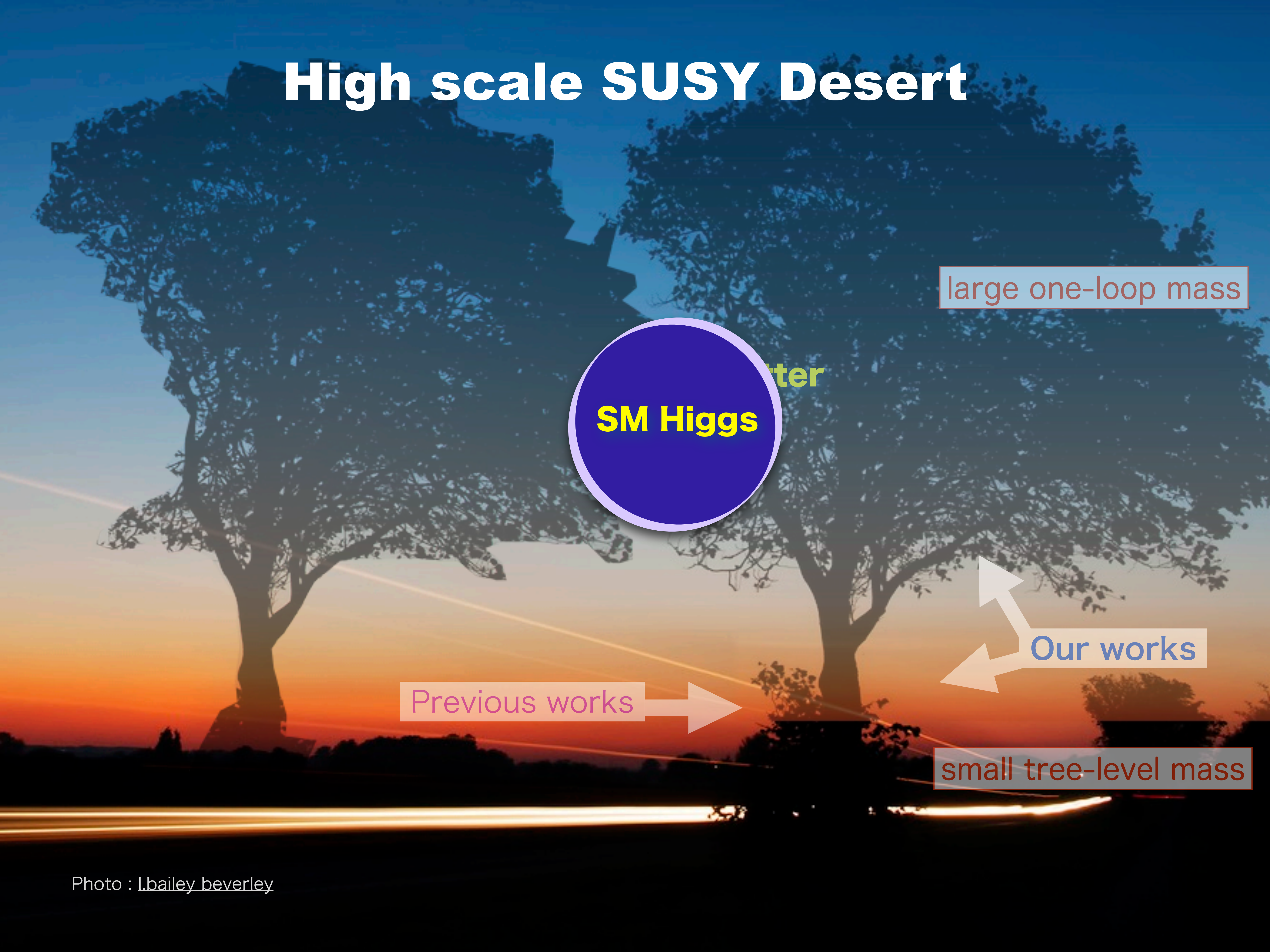
High scale SUSY Desert



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High scale SUSY Desert

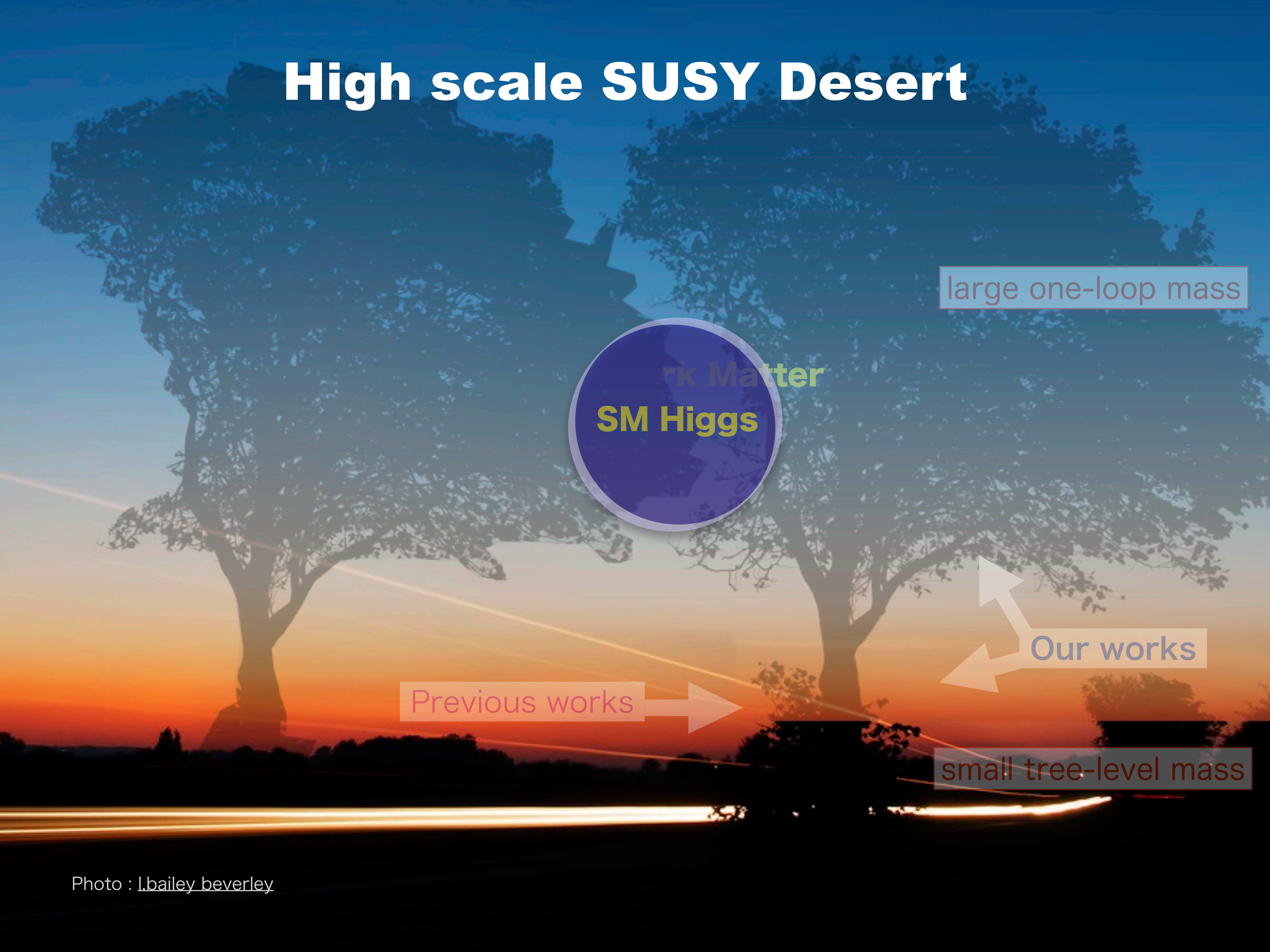


Photo : I.bailey beverley

High scale SUSY Desert

Photo : l.bailey beverley

High scale SUSY Desert

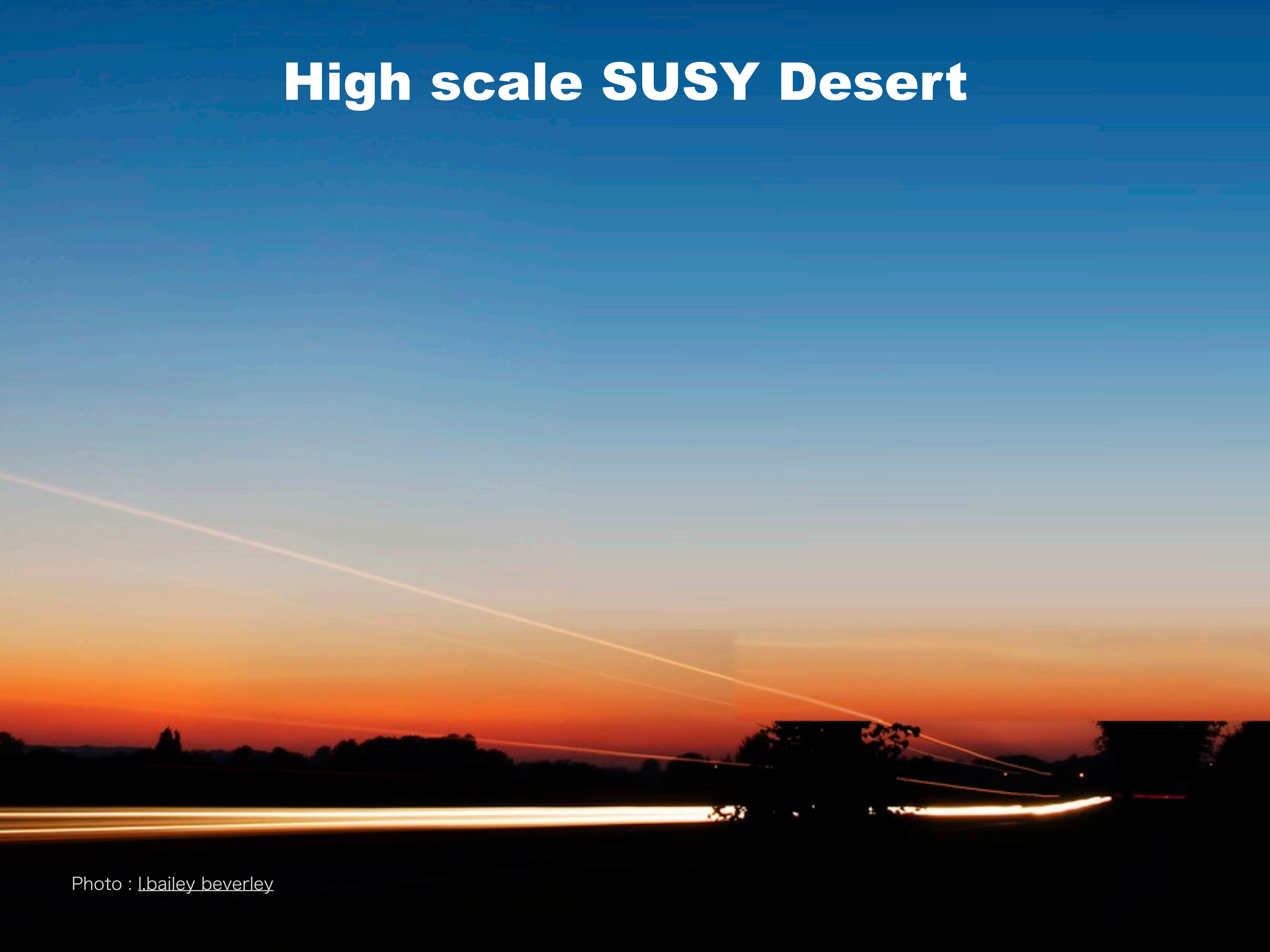


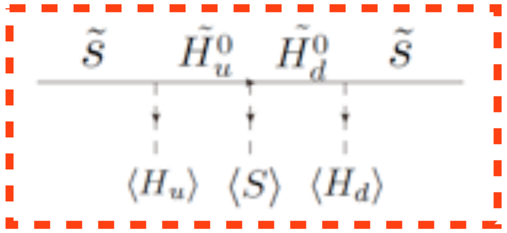
Photo : I.bailey beverley

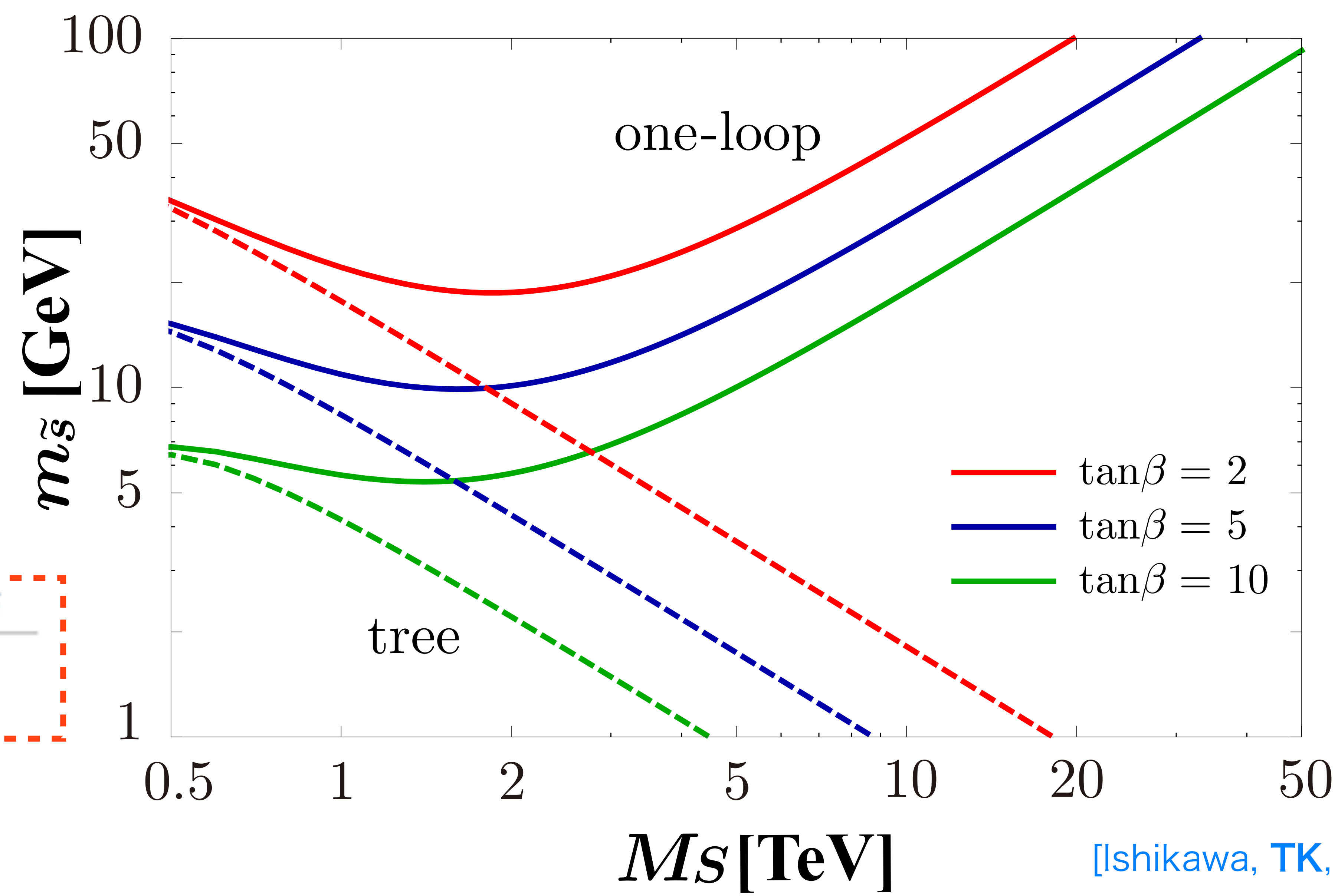
Numerical analysis in the nMSSM parameters

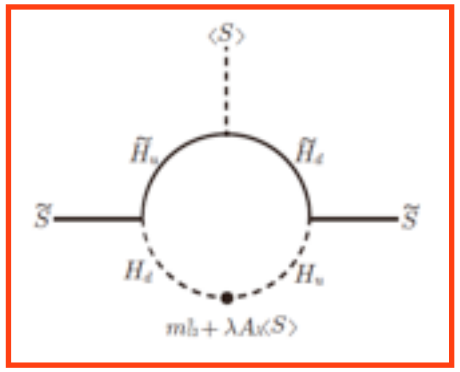
Radiative Singlino mass

- Full one-loop corrections to neutralino mass matrix are included

$\lambda = 0.75$ All dimensionful parameters $= M_S$



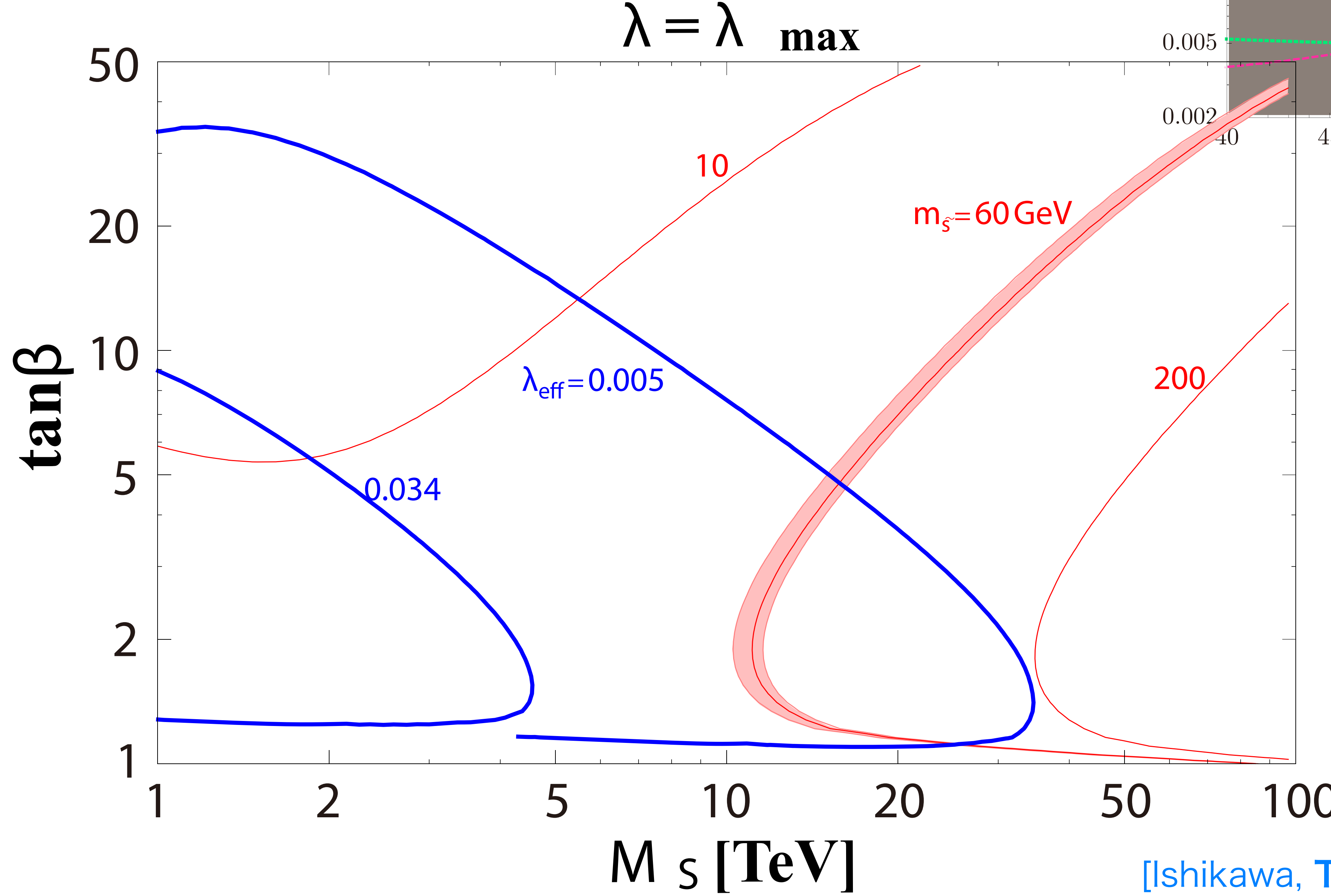


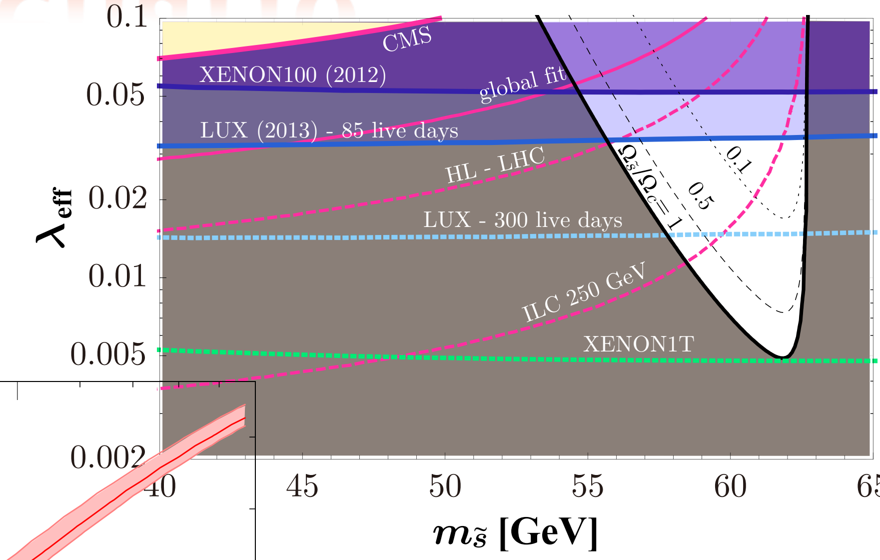


[Ishikawa, **TK**, Takimoto '14]

Singlino resonant DM scenario

$A_\lambda^2 = \frac{2}{5} M_S^2$ Other dimensionful parameters $= M_S$



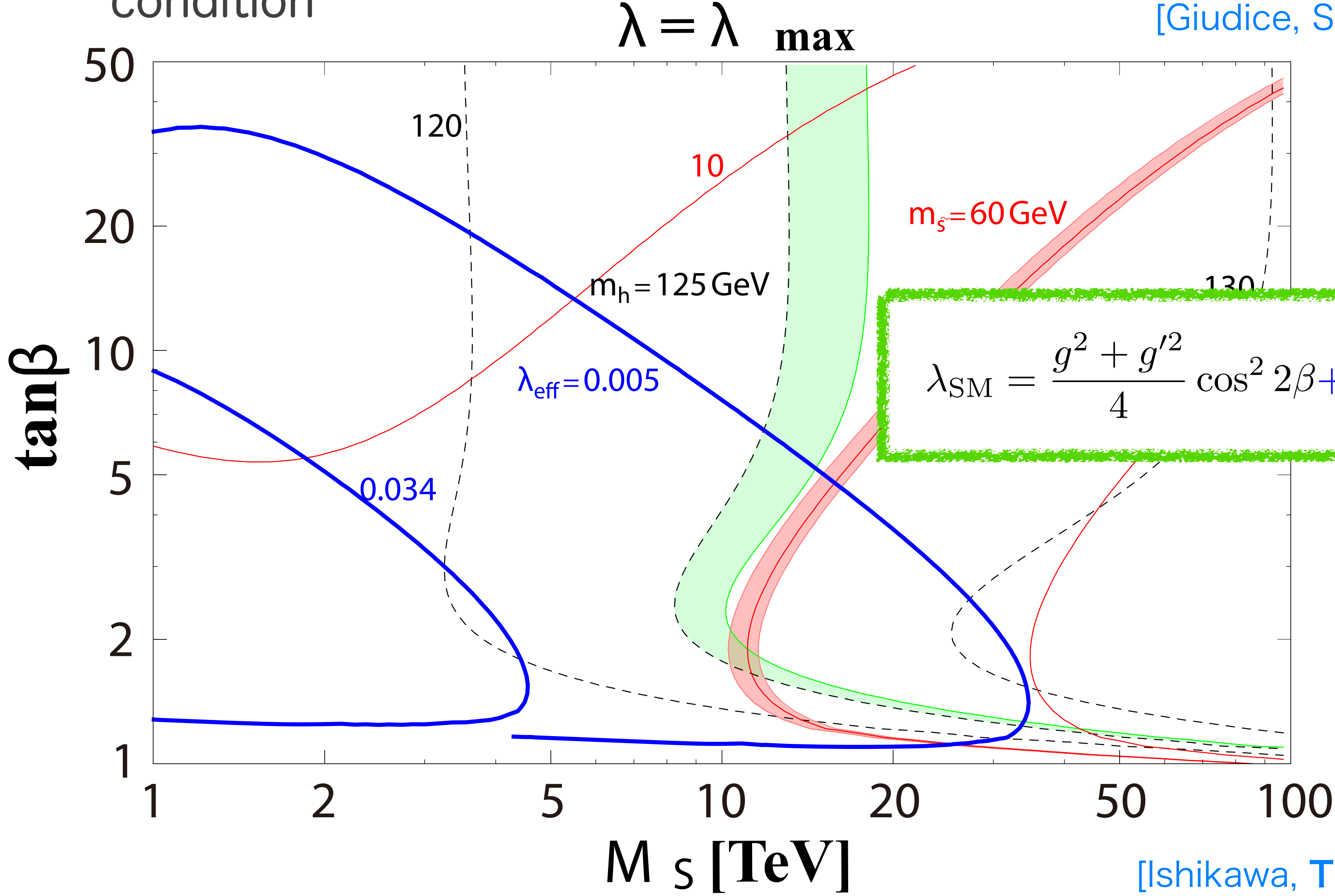


[Ishikawa, **TK**, Takimoto '14]

Singlino resonant DM scenario

- In this paper, we calculate the Higgs boson mass using **the two-loop renormalization group equation** including the matching condition

[Giudice, Strumia '12]



$$\lambda_{\rm SM} = \frac{g^2+g'^2}{4}\cos^2 2\beta + \frac{\lambda^2}{2}\frac{m_S^2 - A_\lambda^2}{m_S^2}\sin^2 2\beta$$

[Ishikawa, **TK**, Takimoto '14]

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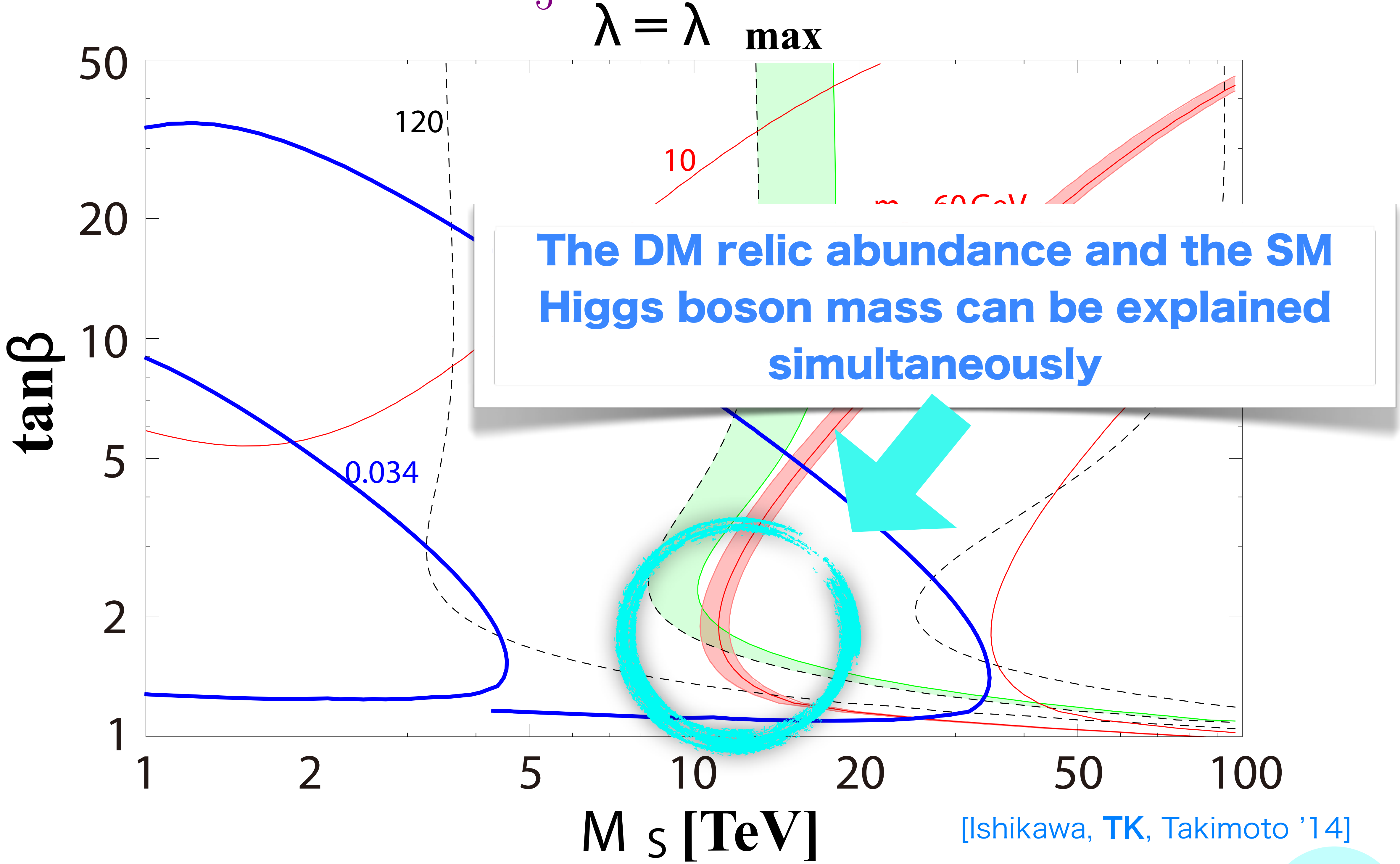
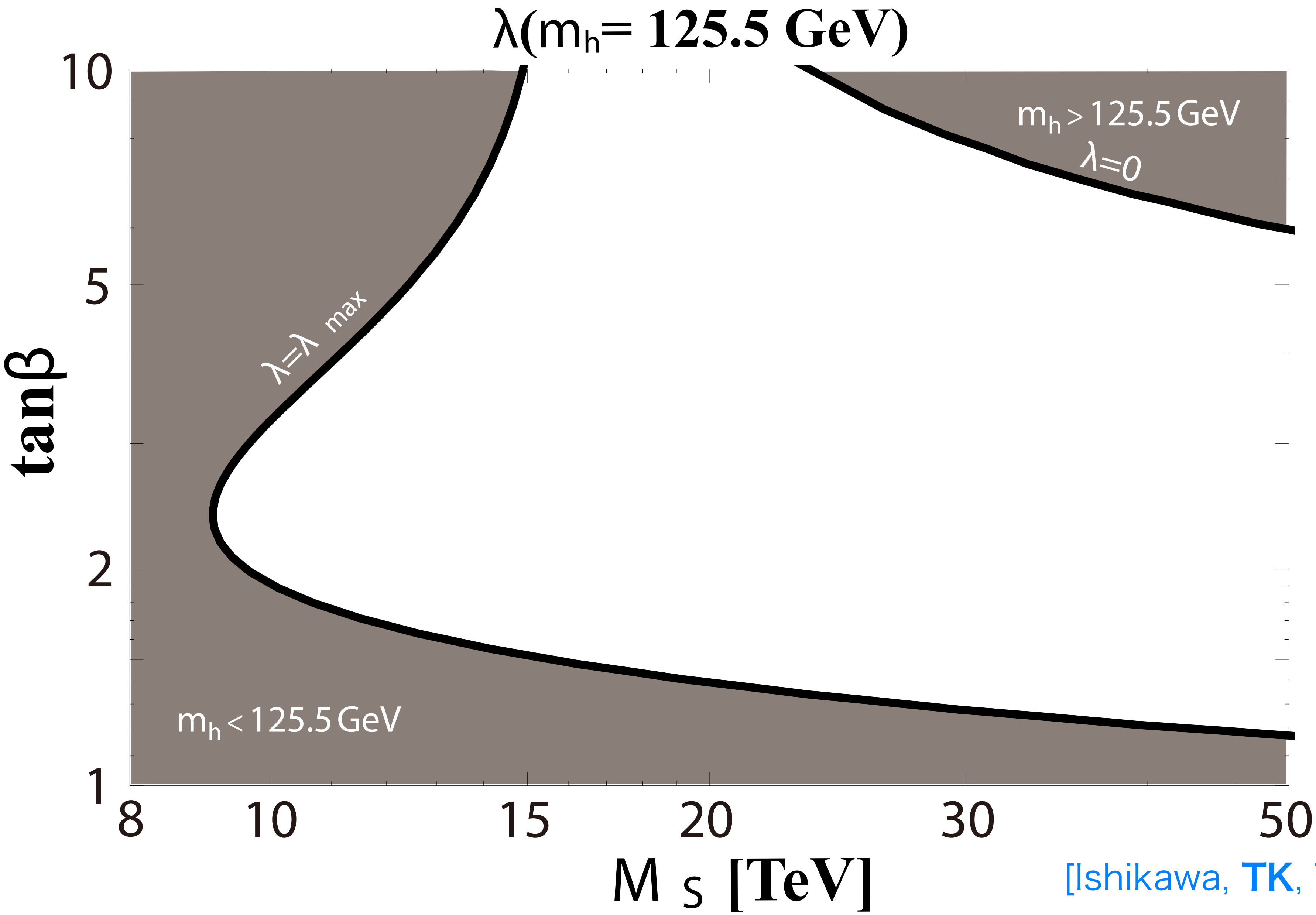


[Ishikawa, **TK**, Takimoto '14]

Results : vs Future experiments

- The Higgs boson mass is fixed to be 125.5 GeV by changing the parameter λ, $0 \leq \lambda \leq \lambda_{\max}$



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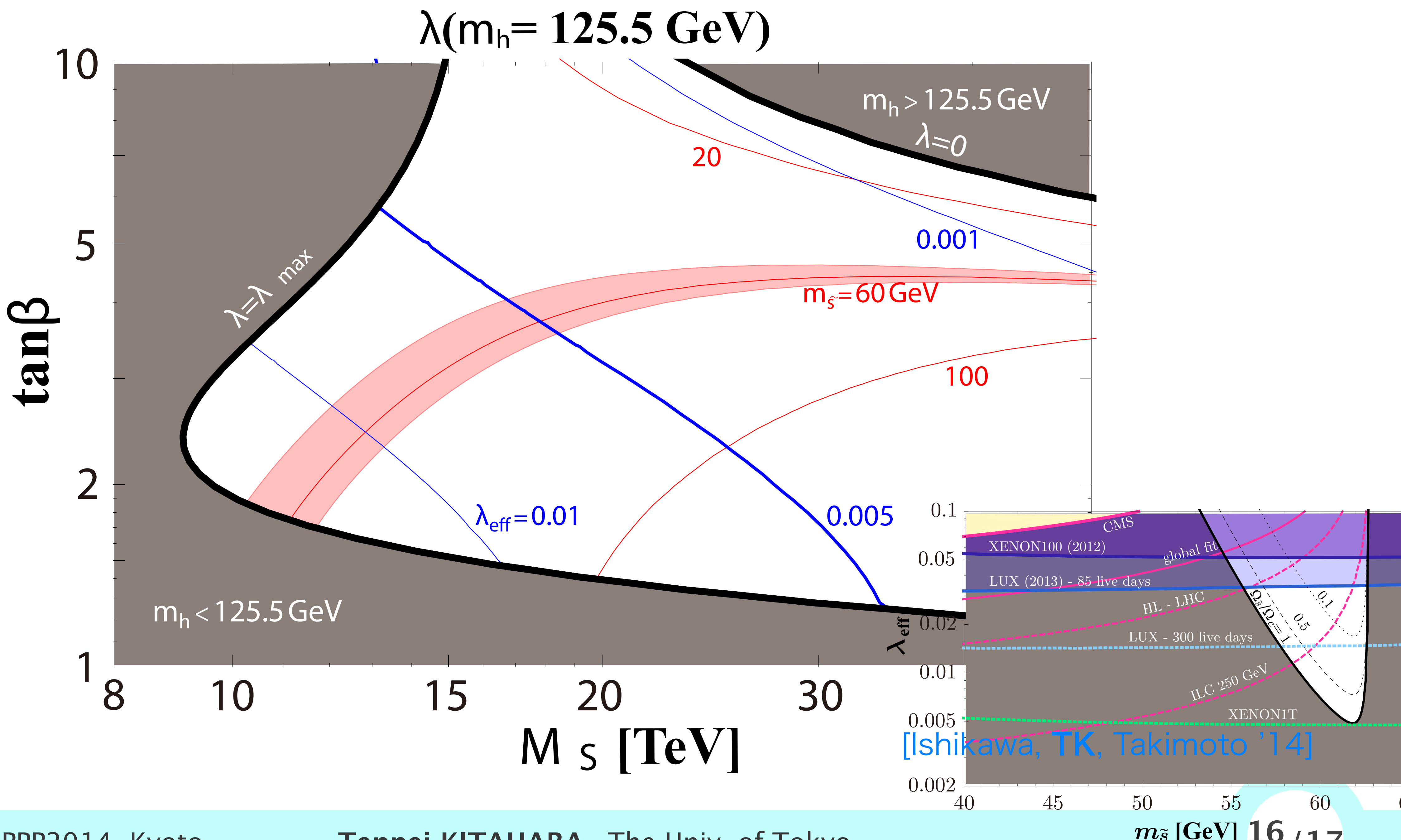

[Ishikawa, TK, Takimoto '14]

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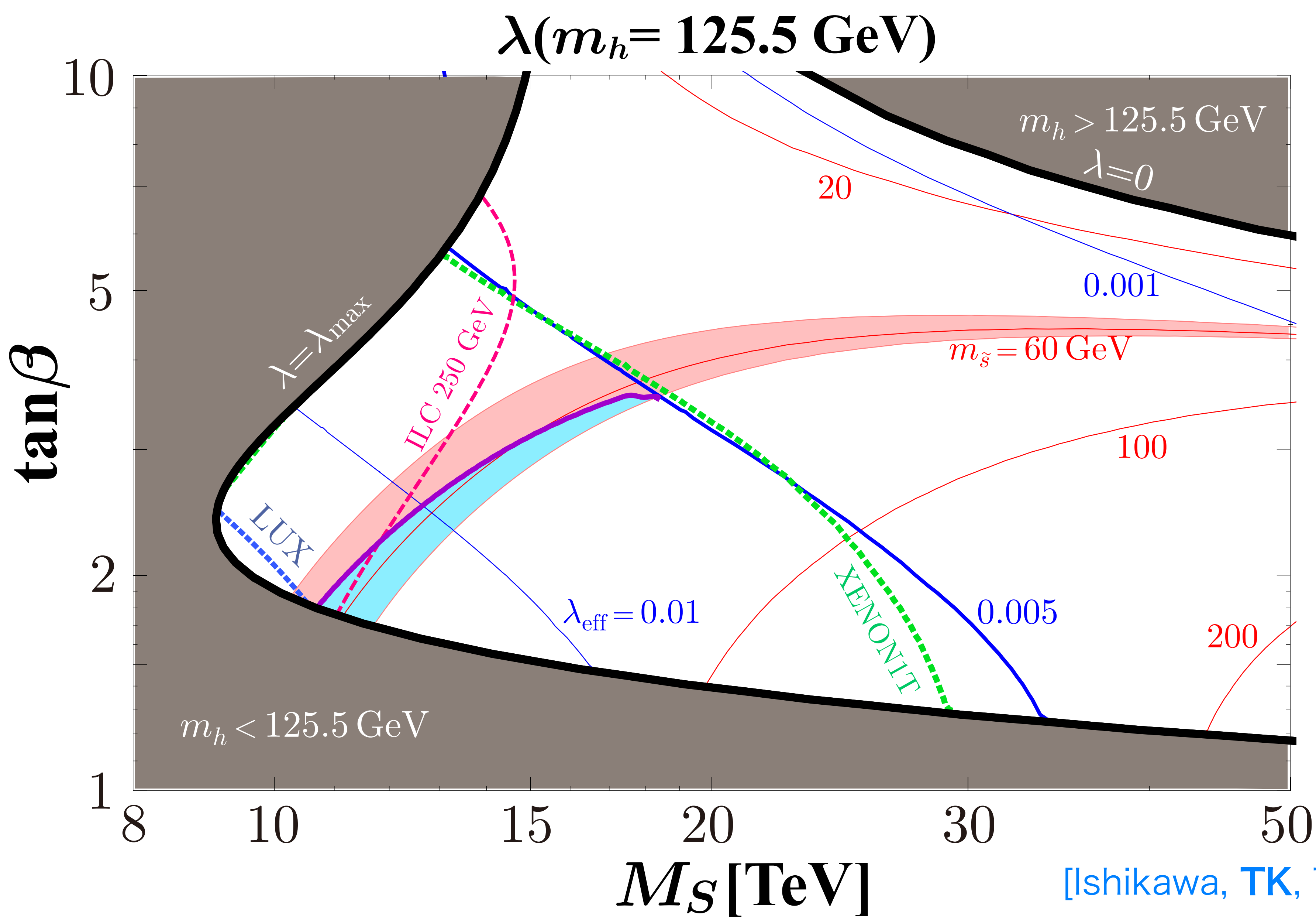

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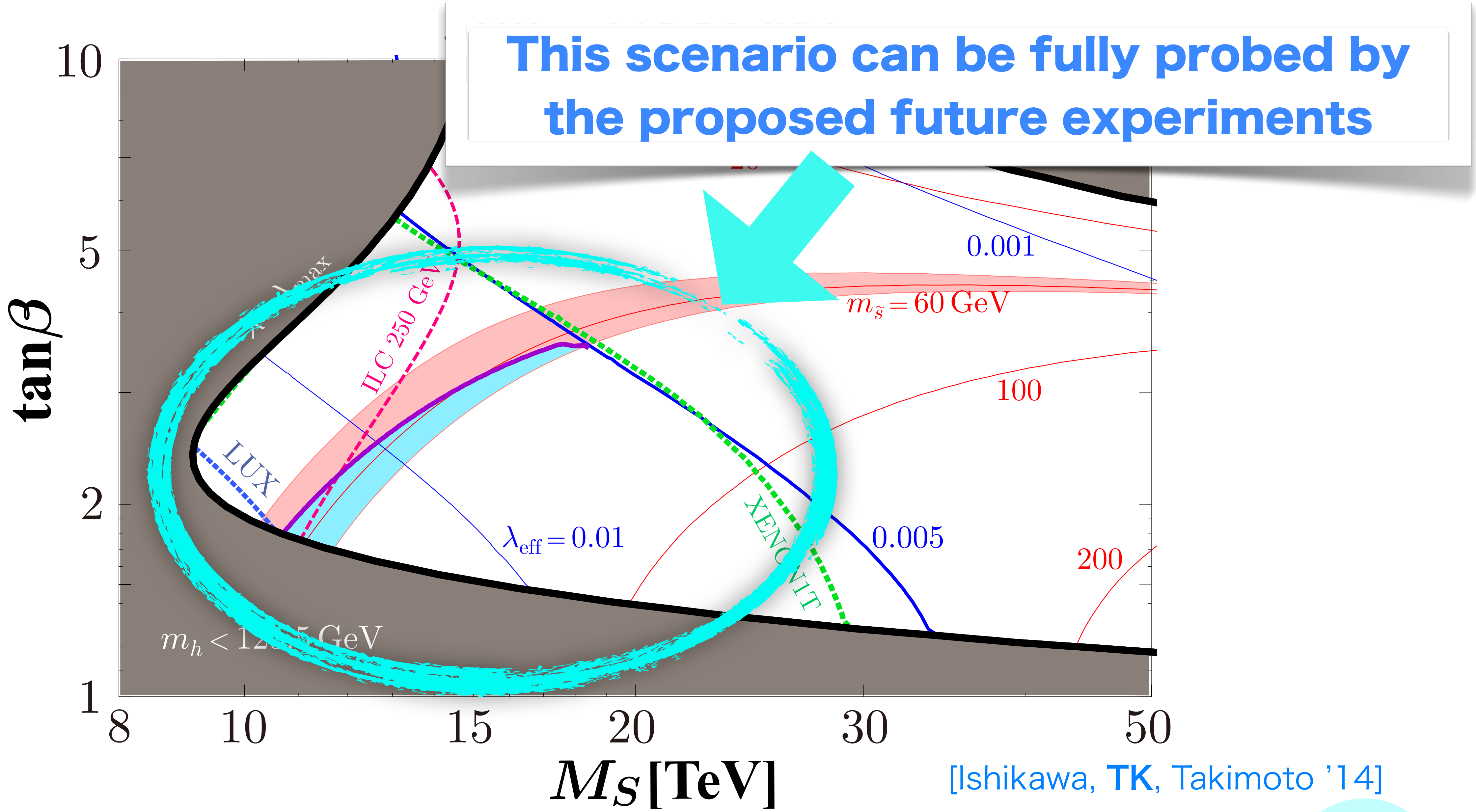

[Ishikawa, **TK**, Takimoto '14]

Conclusions

- With high-scale SUSY breaking (O(10) TeV), **the singlino can obtain a sizable radiative mass,** which **opens a window for the resonant DM scenario via the SM Higgs boson**
- In this scenario, **the current DM relic abundance** and **the observed Higgs boson mass** can be explained **simultaneously**
- This scenario **can be fully probed by the future experiments** (ILC Higgs invisible search + XENON direct DM search)

The singlino DM signal can be "a first sign" of the high-scale supersymmetry!

Teppei KITAHARA, arXiv:1405.7371
kitahara@hep-th.phys.s.u-tokyo.ac.jp


Thank you for your attention
Photo : l.bailey beverley

Backup slide

SM Higgs boson mass in the nMSSM

[Giudice, Strumia '12]

- In the nMSSM, there is a **sizable tree-level contribution** to the Higgs boson mass. When integrating out heavy SUSY particles and matching with the SM, the SM Higgs quartic coupling is

$$V(H) = \frac{\lambda_{\rm SM}}{2}(H^\dagger H - v^2)^2$$

$$\lambda_{\rm SM} = \frac{g^2 + g'^2}{4}\cos^2 2\beta + \frac{\lambda^2}{2}\frac{m_S^2 - A_\lambda^2}{m_S^2}\sin^2 2\beta$$

- **Large λ and small $\tan\beta$** can give a sizable contribution to the Higgs boson mass
- In this paper, we calculate the Higgs boson mass using **the two-loop renormalization group equation** including the above matching condition

Singlino resonant DM scenario

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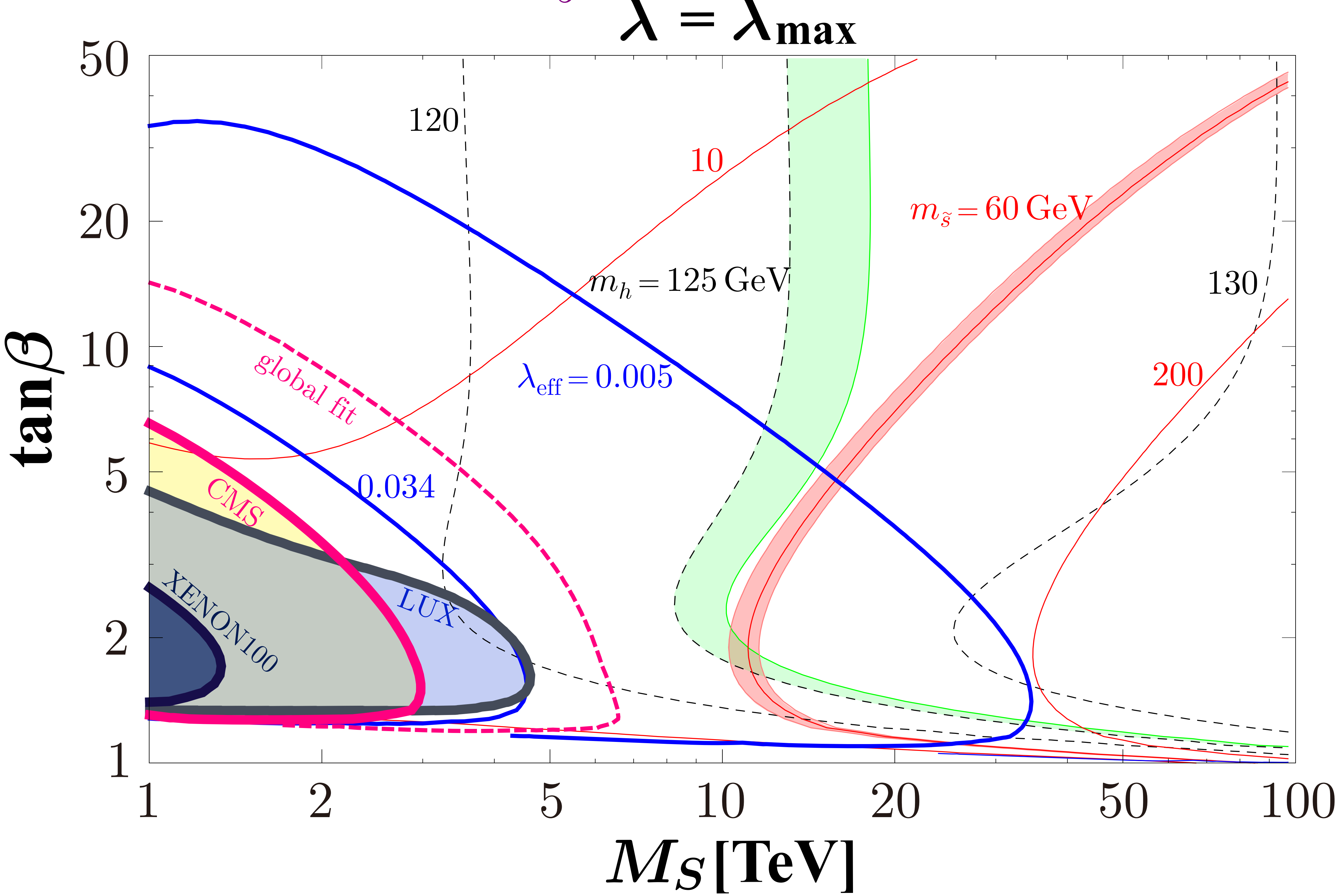


Discrete R-symmetry Z5

[Panagiotakopoulos, Pilaftsis '00]

	H_d	H_u	S	Q	U	D	L	e	θ
Z5 charge	1	1	4	2	3	3	2	3	1/2

where "1" means charge $\omega = \exp(2\pi i/5)$, and "5" means $\omega^5 = 1$

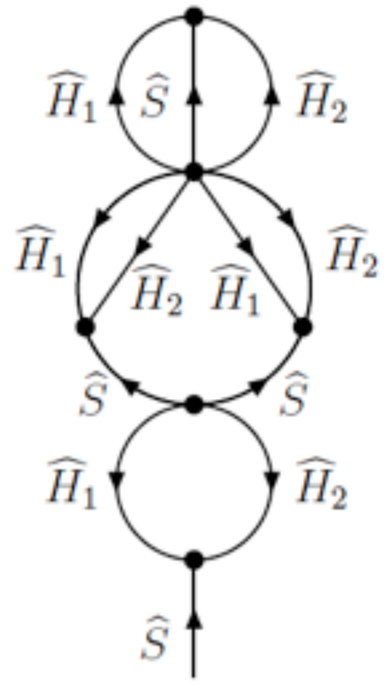
$$W_{\rm nMSSM} = \lambda \hat{S}\hat{H}_u\hat{H}_d + W_{\rm Yukawa}$$

$$K_{\rm nMSSM} = K_{\rm MSSM} + |\hat{S}|^2 + \kappa_2 \frac{\hat{S}^2\hat{H}_d\hat{H}_u}{M_P^2} + \kappa_5 \frac{\hat{S}(\hat{H}_d\hat{H}_u)^3}{M_P^5}$$

$$+ \text{higher term} + \text{h.c.}$$

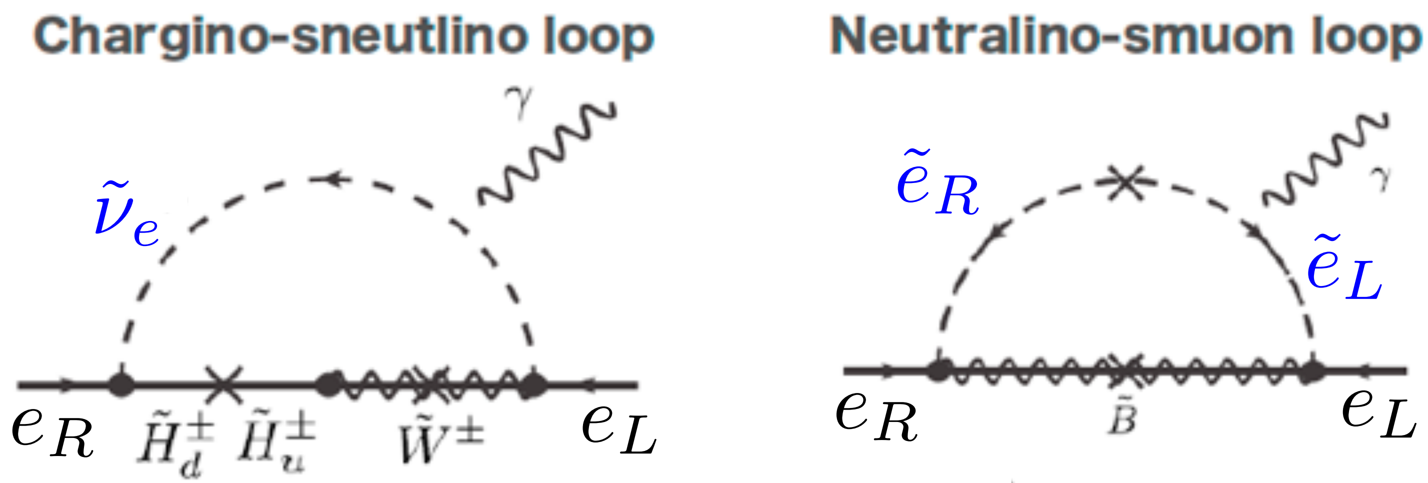
Once supersymmetry is broken, tadpole term is emerged

$$W_{\rm tad} \sim \frac{\kappa_2\kappa_5\lambda^4}{(16\pi^2)^6} M_P M_{\rm SUSY}\hat{S} \sim \mathcal{O}(M_{\rm SUSY}^2)\hat{S}$$



leading diagram of the tadpole

EDM in the high scale nMSSM



$$\left|\frac{d_e}{e}\right| \sim \frac{5g_2^2+g_1^2}{384\pi^2}\frac{m_e}{M_S^2}\sin\phi\tan\beta \quad [\mathrm{GeV}^{-1}]$$

$$\sim 6\times 10^{-29}\left(\frac{10\,\mathrm{TeV}}{M_S}\right)^2 \sin\phi\tan\beta \quad [\mathrm{cm}],$$

where $\phi = \arg(\mu_{\mathrm{eff}} M_{\mathrm{gaugino}})$.

therefore $|d_e| \sim \mathcal{O}(10^{-29})\ e\ \mathrm{cm}$

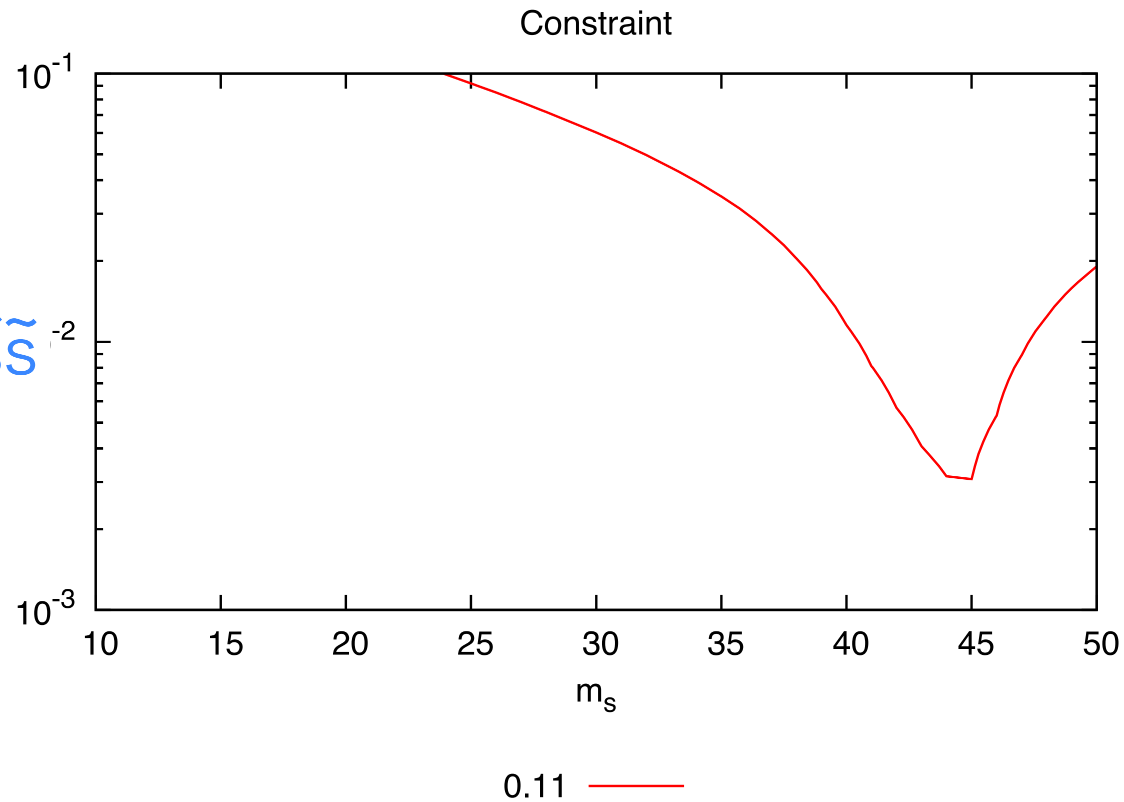
$|d_e| < 8.7\times 10^{-29} e$ cm (90% CL @ThO molecule

Table 2: Future prospects for EDM

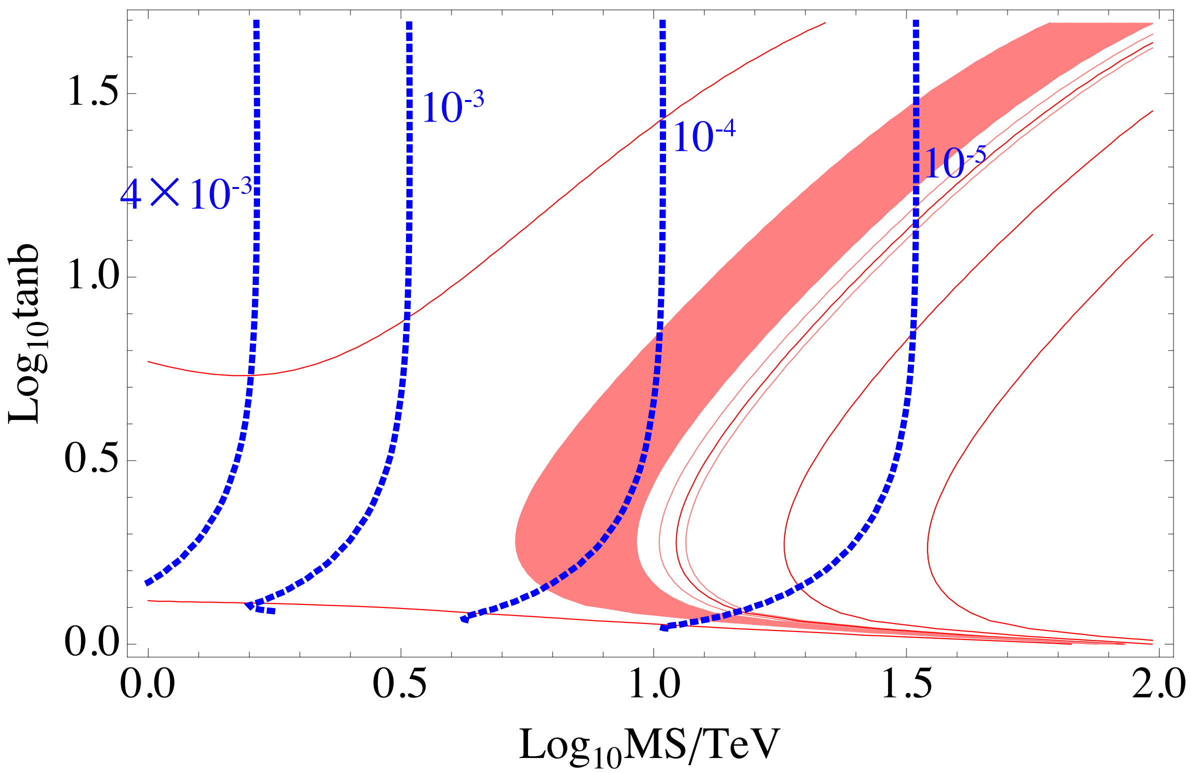
experiments	upper bound on $\lvert d_e\rvert$ cm
Fr [24]	$1\times 10^{-29}e$
YbF molecule [25]	$1\times 10^{-30}e$
WN ion [26]	$1\times 10^{-30}e$

Z resonance

$\lambda_{Z\tilde{s}\tilde{s}}$



$\lambda_{Z\tilde{s}\tilde{s}}$



High scale SUSY breakingでは
Z resonance singlino DMの解は無し

Verification

- Verification : One loop corrections become zero in the SUSY Limit