Extended Dark Sectors, Neutrino Masses and the Baryon Asymmetry

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CSIC Consejo Superior de Investigaciones Científicas

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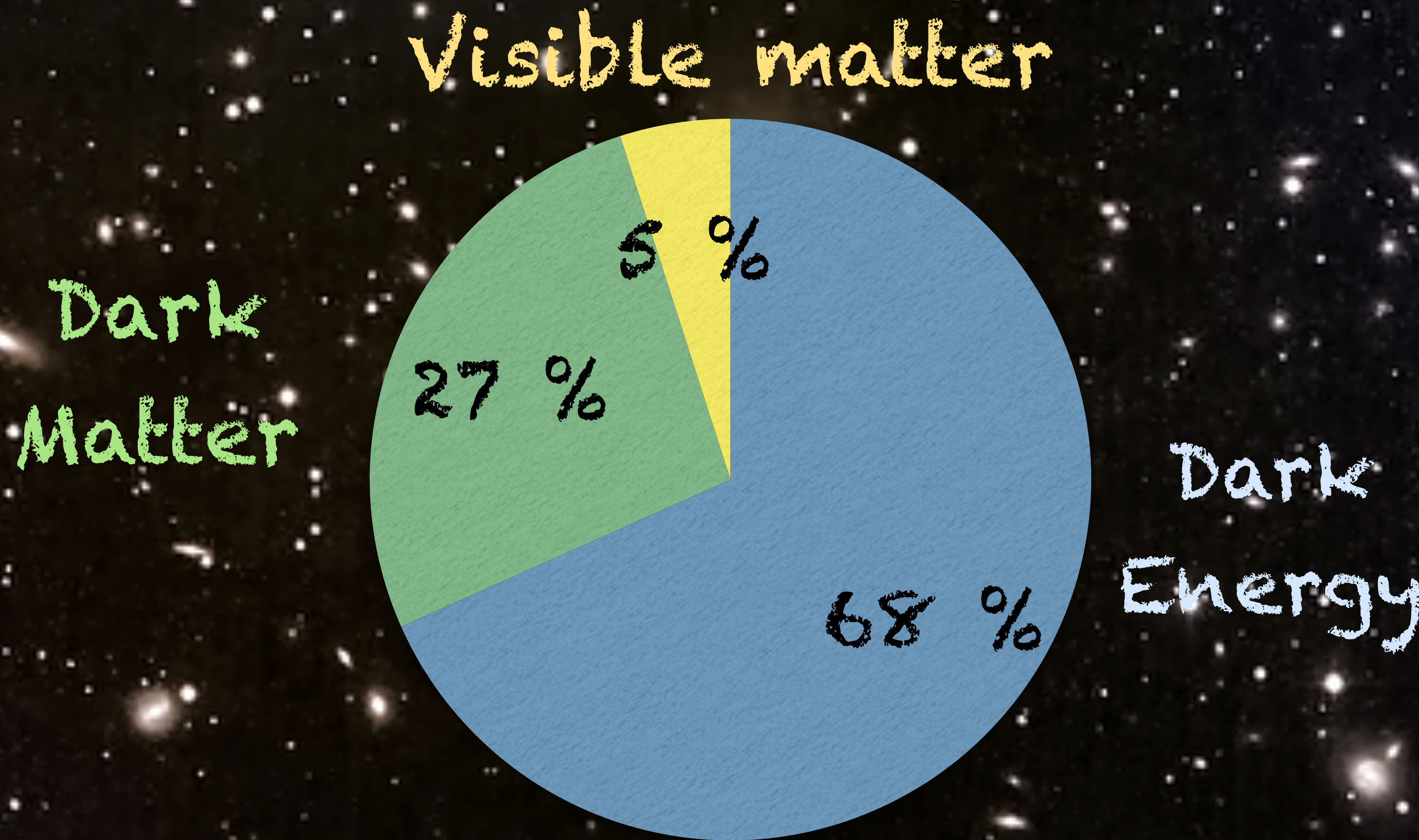
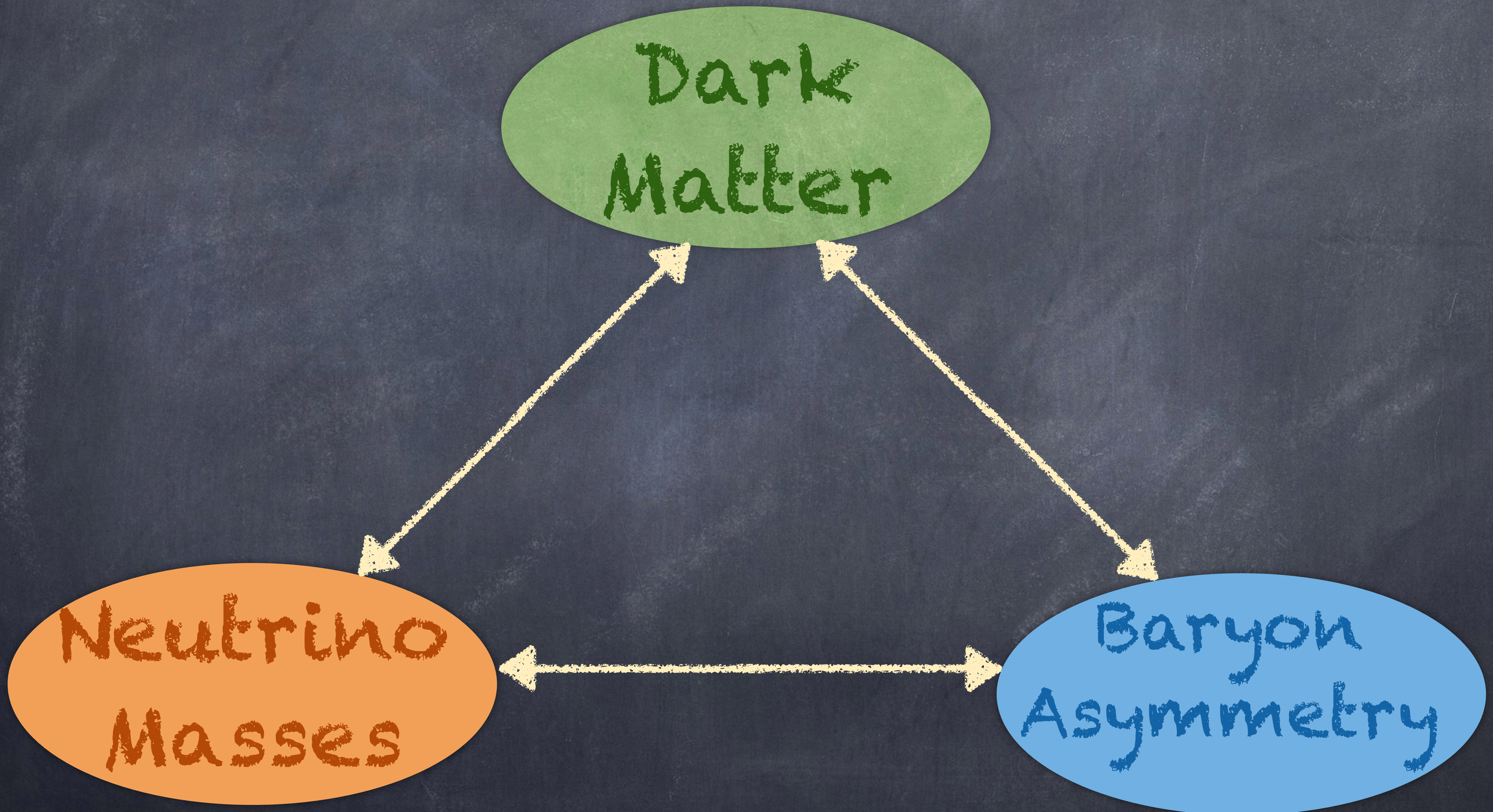
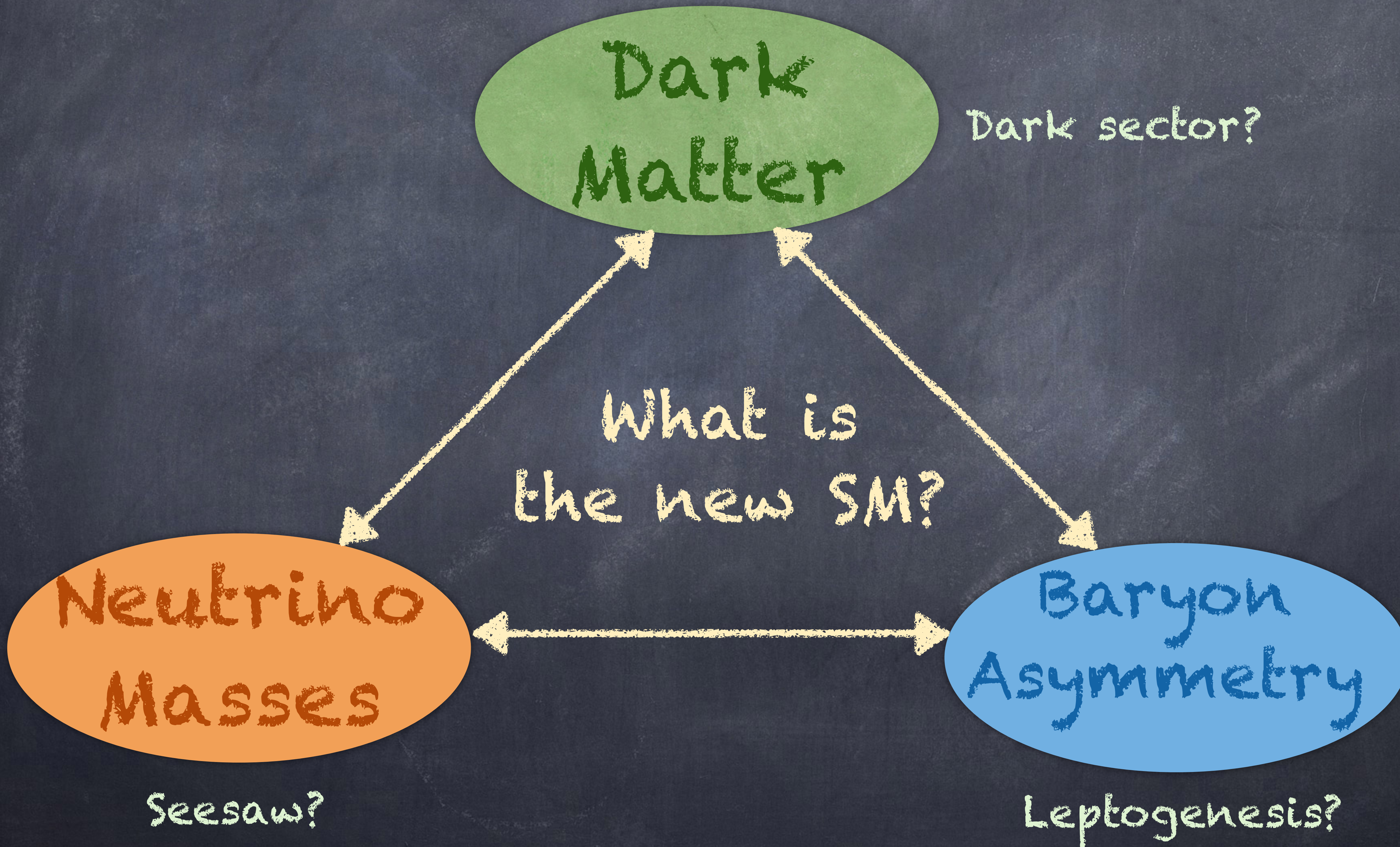


Coma cluster

SM problems with strongest experimental evidence



SM problems with strongest experimental evidence



Questions

i. What makes dark matter (DM)?
How is DM produced in the early Universe?
How can we detect in the lab?

ii. How is $n_B/n_\gamma \simeq 6 \cdot 10^{-10}$ dynamically generated?

iii. By which mechanism do neutrinos obtain their tiny masses and large mixings?

iv. Are these problems related?

Possible energy scales

$10^{>15}$ GeV — Proton Decay, GUTs, SO(10)?

10^{14} GeV — m_ν (seesaw)? BAU (leptogenesis)?

ν, BAU at high scales?

GAP?

1000 GeV — WIMPs?

100 GeV — SM

1 GeV — Asymmetric DM?

Partially - Asymmetric?

Dark Sector at low scales?

II - Extended dark sectors

"Asymmetries in extended dark sectors: a cogenesis scenario", JHEP05 (2023) 049

Giacomo Landini, JHG, Drona Vatsyayan

Bullet cluster

Visible Sector:

Multi-component: $\gamma, \nu, e, p\,(\mathrm{H}, \mathrm{He}\ldots)\ldots$

Asymmetric: $n_B/n_\gamma \simeq 6 \cdot 10^{-10}$

Dark Sector:

Several components?

Partially-asymmetric?

"Multi-component dark sectors: symmetries, asymmetries and conversions",

A. Bas, JHG, D. Vatsyayan, JHEP10 (2022) 075

$$\eta_i \equiv Y_i^+ - Y_i^-$$
$$r_i \equiv \frac{Y_i^-}{Y_i^+}$$

DM production and nature

Mechanism \ Nature	Symmetric	Partially - Asymmetric	Asymmetric
	$r_i > 0.9$	$0.01 < r_i < 0.9$	$r_i < 0.01$
Freeze-out	$\Omega_{\rm DM} \propto 1/\langle\sigma v\rangle$	$\Omega_{\rm DM} = f(\eta, m_\chi, \sigma v)$	$\Omega_{\rm DM} \propto \eta\, m_\chi$
Freeze-in	$\Omega_{\rm DM} \propto \langle\sigma v\rangle, \Gamma$	?	?

[See Hall 2010, Hook 2011, Unwin 2014]

"Asymmetries in extended dark sectors: a cogenesis scenario"

G. Landini, JHG, D. Vatsyayan; JHEP05 (2023) 049

- Late decays of an asymmetric particle
- Multicomponent DM naturally emerges
- Embedded in a cogenesis scenario (m_ν & BAU)

Cogenesis: connects m_ν, BAU and DM

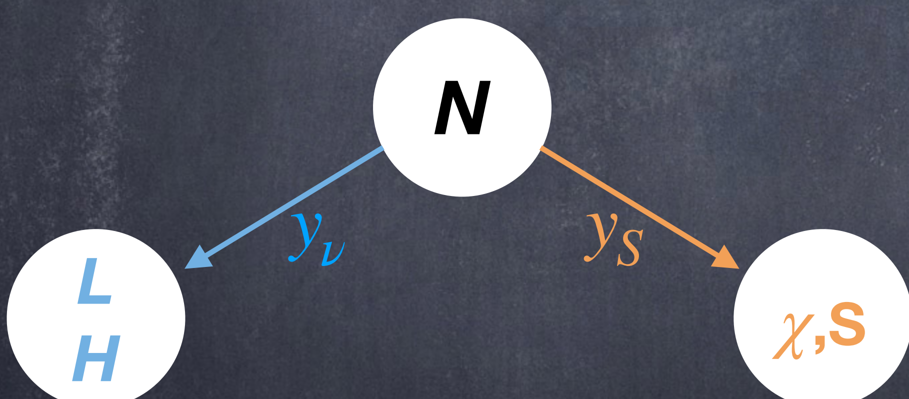
[Falkowski et al *JHEP* 05 (2011) 106]

[See also Hall et al 1010.0245, Cui et al 2020]

$$\mathscr{L}_{\rm int} = -\, y_\nu^{\alpha i}\, \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij}\, \sigma \overline{N_R^{ic}} N_R^j - y_S^i\, S \bar{N}_R^i \chi + \mathrm{H.c.}$$

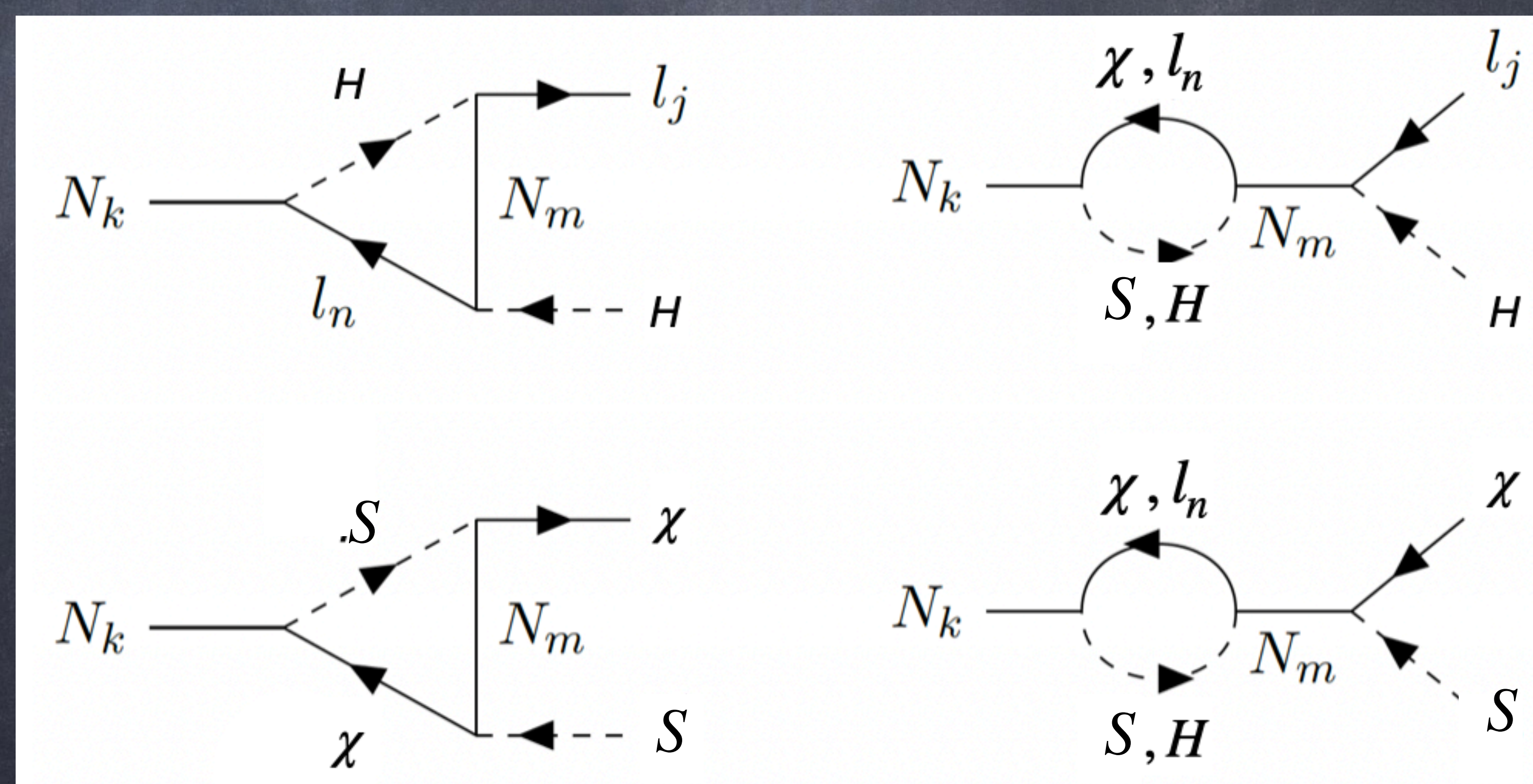
At $T < M_N$, CPV decays of RHNs: 2-sector leptogenesis

$\Delta L \neq 0, \Delta\chi = \Delta S \neq 0$ for $\mathcal{O}(1)$ complex y_ν, y_S



$$m_\nu \simeq -\, y_\nu \frac{v^2}{M_N} y_\nu^T$$

$\Delta L \to \Delta B$: sphalerons



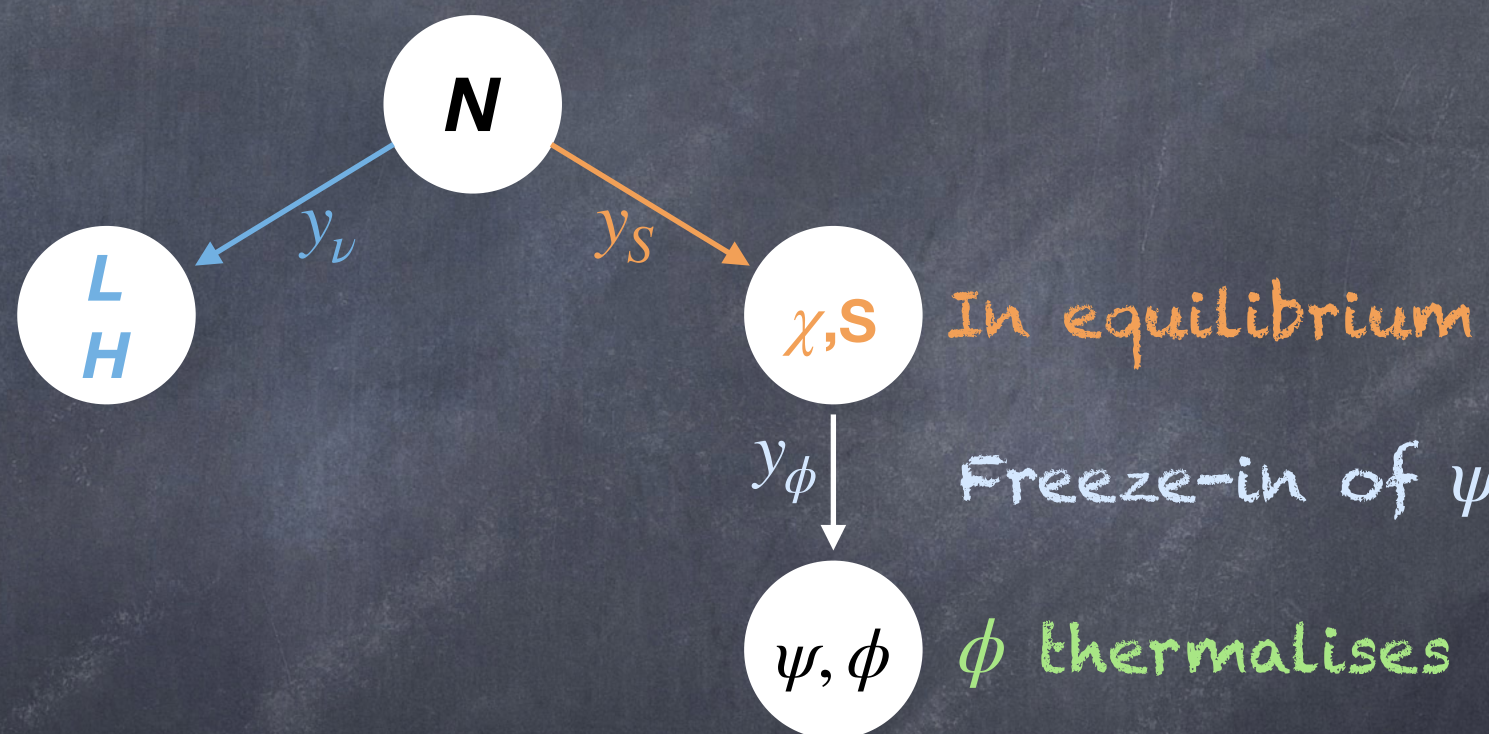
Extended cogenesis framework

[G. Landini, JHG, D. Vatsyayan, JHEP05 (2023) 049]

$$\mathscr{L}_{\rm int} = -\, y_\nu^{\alpha i}\, \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij}\, \sigma \overline{N_R^{ic}} N_R^j - y_S^i\, S \bar{N}_R^i \chi - y_\phi\, \phi \bar{\psi} \chi + \mathrm{H.c.}$$

$$m_\nu \simeq -\, y_\nu \frac{v^2}{M_N} y_\nu^T$$

$\Delta L \to \Delta B$ (sphalerons)



Idea: Dark asymmetry transferred via late decays $\chi \to \psi + \phi$ after χ symmetric population has been erased

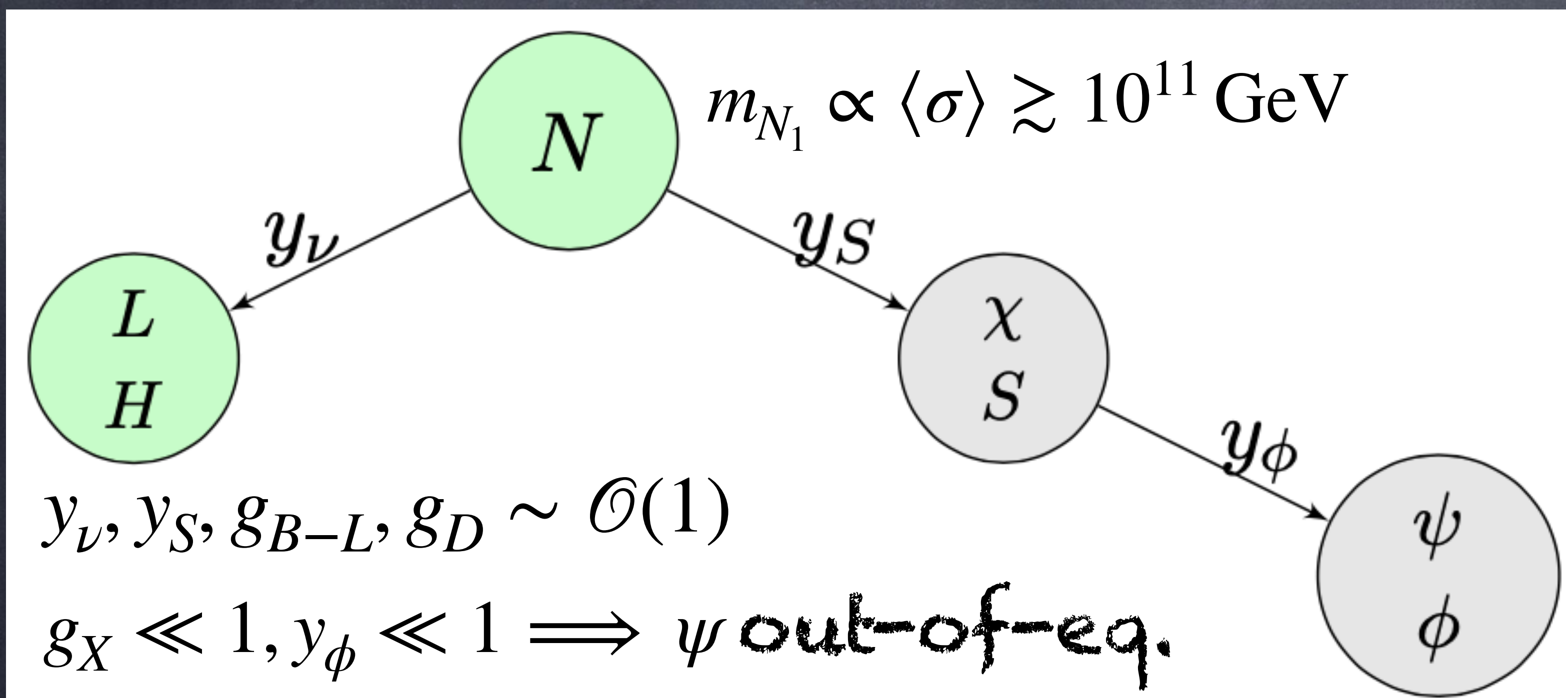
We consider $\eta_\chi \equiv \eta_D \simeq \eta_B$

2DM asymmetric model: $\psi + S$

$$\mathscr{L}_{\rm int} = -\, y_\nu^{\alpha i}\, \bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij}\, \sigma \overline{N_R^{ic}} N_R^j - y_S^i\, S \bar{N}_R^i \chi - y_\phi\, \phi \bar{\psi} \chi + \mathrm{H.c.}$$

$3\,N_i$ $\downarrow$ $U(1)_{B-L}$

DM stability & Dirac fermions $\rightarrow$ $U(1)_D$, $U(1)_X$



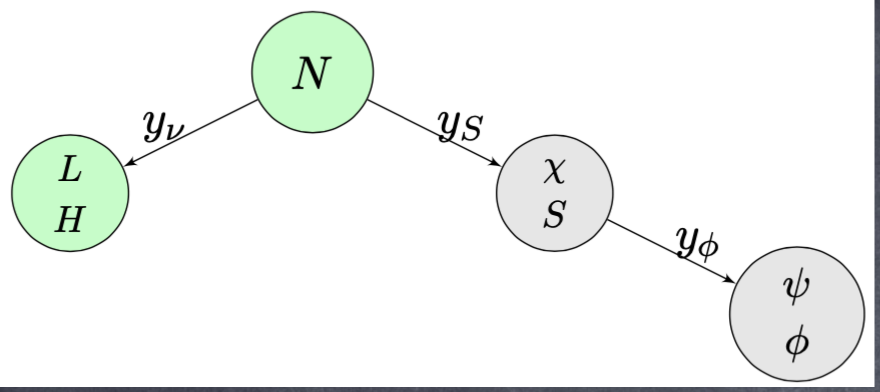
$$M_{N_1} \gg m_\chi \gg m_S \gtrsim m_\psi > m_\phi$$

Field	Spin	$U(1)_{B-L}$	$U(1)_D$	$U(1)_X$
N_R^i	1/2	-1	0	0
σ	0	+2	0	0
χ_0	1/2	-1	+1	0
ψ_0	1/2	0	0	+1
S	0	0	-1	0
ϕ	0	+1	-1	+1
		Z_{B-L}	Z_D	A_X

Gauge SSB: $U(1)_{B-L} \otimes U(1)_D \otimes U(1)_X \xrightarrow{\langle \sigma \rangle} U(1)_D \otimes U(1)_X \xrightarrow{\langle \phi \rangle} U(1)_{X+D}$

Remnant $U(1)_{X+D}$: +1 χ +1 ψ -1 S

DM candidates



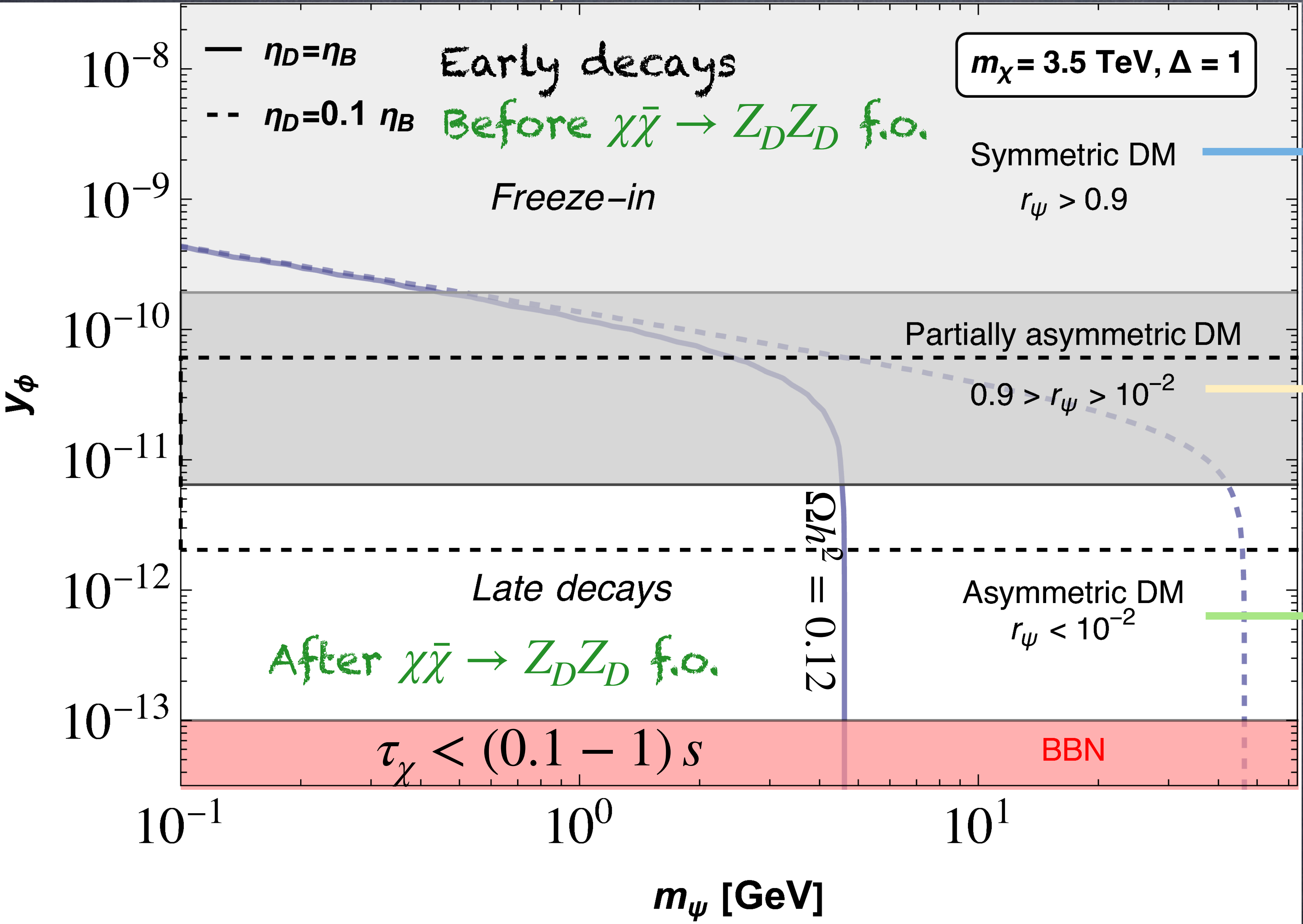
1DM: ψ

$Y_\psi^+ \simeq Y_{\rm FI}/2 + \eta_D$

$Y_\psi^- \simeq Y_{\rm FI}/2 + \eta_D r_\chi$

$\chi \xrightarrow{y_\phi} \psi + \phi \implies y_\phi$ controls ψ nature

No ψ thermalisation: $y_\phi < 5 \cdot 10^{-7}$



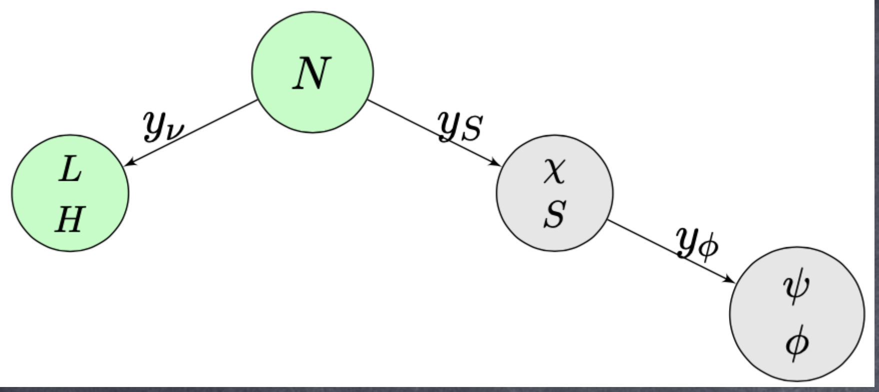
$T \simeq m_\chi \gg T_{fo} \simeq m_\chi/20$

$Y_{FI} \gg \eta_D$

$\eta_D r_\chi \ll Y_{FI} \ll \eta_D$

$T \ll m_\chi/20$

$\eta_D r_\chi \gg Y_{FI}$



2DM: $\psi + S$

- S from $N \to \chi + S$
- S from $\chi \to S^\dagger + \nu$: at $E \ll M_{N_1}$, $\mathcal{O}_5 = y_\nu \, y_S \dfrac{\bar{L}\tilde{H} S \chi}{M_{N_1}}$ mediates it
- $R \equiv \dfrac{\mathrm{BR}(\chi \to \mathrm{S}^\dagger \nu)}{\mathrm{BR}(\chi \to \psi\phi)} \simeq \dfrac{|y_S|^2 \, m_\nu}{y_\phi^2 \, M_{N_1}}$ [and $T_D^{(S)}/T_*^{(S)}$] control nature of S

S

$R > \mathcal{O}(10)$:	$R \ll 1$:
Symmetric	Asymmetric
$Y_S + Y_S^\dagger \sim 2\eta_D$	$Y_S^+ = \eta_D$
$m_S = 2.5\,\mathrm{GeV}\left(\dfrac{\eta_B}{\eta_D}\right)$	

$\Longrightarrow$ Scenario 6: see later

2DM scenarios

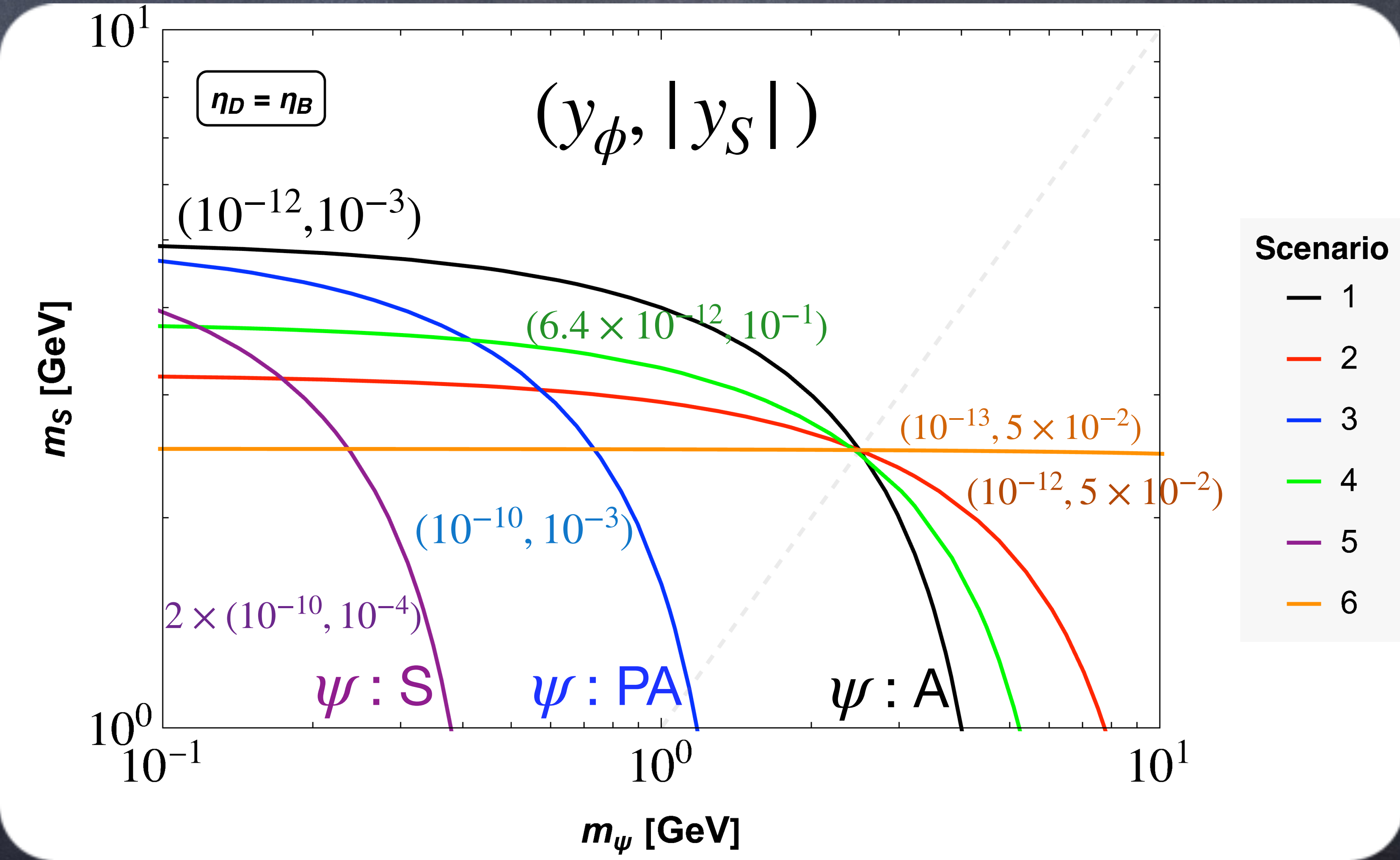
$$R \equiv \frac{\mathrm{BR}(\chi \to S^\dagger \nu)}{\mathrm{BR}(\chi \to \psi\phi)}$$

Sc.	ψ population	S population	$10^{-10} y_\phi / \sqrt{\eta_D/\eta_B}$	R	$T_D^{(S)}/T_*^{(S)}$
1	Asymmetric	Asymmetric	≤ 0.06	$\ll 1$	Any
2	Asymmetric	Partially Asymmetric	≤ 0.06	$\mathcal{O}(1)$	< 1
1-2	Asymmetric	Asymmetric	≤ 0.06	$\mathcal{O}(1)$	> 1
3	Partially Asymmetric	Asymmetric	$0.06 - 2$	$\ll 1$	Any
4	Partially Asymmetric	Partially Asymmetric	$0.06 - 2$	$\mathcal{O}(1)$	< 1
3-4	Partially Asymmetric	Asymmetric	$0.06 - 2$	$\mathcal{O}(1)$	> 1
5	Symmetric	Asymmetric	$\gtrsim 2$	$\ll 1$	Any
6	Negligible	1DM: S Symmetric	$y_\phi \lesssim 5 \times 10^{-7}$	$\gtrsim \mathcal{O}(10)$	< 1

$g_D = 0.5, M_{N_1} = 10^{11}$ GeV

$m_\chi = 3.5$ TeV, $m_{Z_D} = 500$ GeV

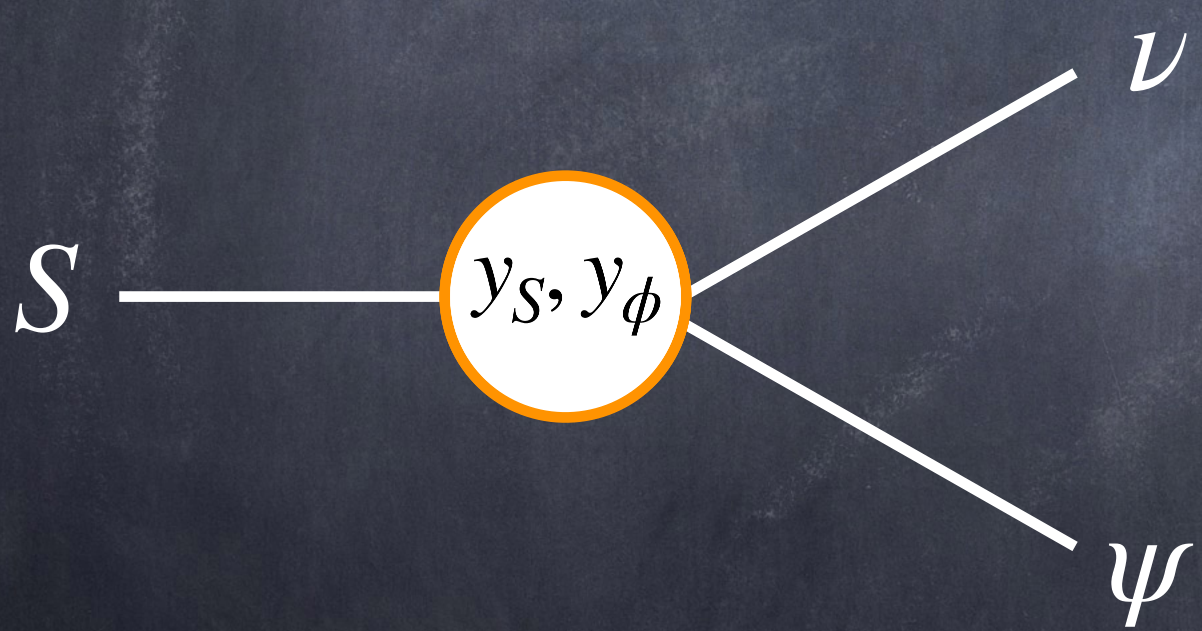
$$\frac{\Omega_\psi}{\Omega_S} \simeq \frac{m_\psi(\eta_D + Y_{\rm FI})}{\eta_D m_S}$$



Smoking gun:
ν line from S decays

At $E \ll m_\chi \ll M_{N_1}$, $\mathcal{O}_6 = \bar{L}\tilde{H}S\phi^\dagger\psi$ generates (for $m_S > m_\psi$):

$$\Gamma(S \to \bar{\psi} + \nu_L) \simeq \frac{|y_S|^2 y_\phi^2 m_S}{32\pi}\left(\frac{v_\phi}{m_\chi}\right)^2\left(\frac{m_\nu}{M_{N_1}}\right)\left(1 - \frac{m_\psi^2}{m_S^2}\right)$$



- S cosmologically stable:

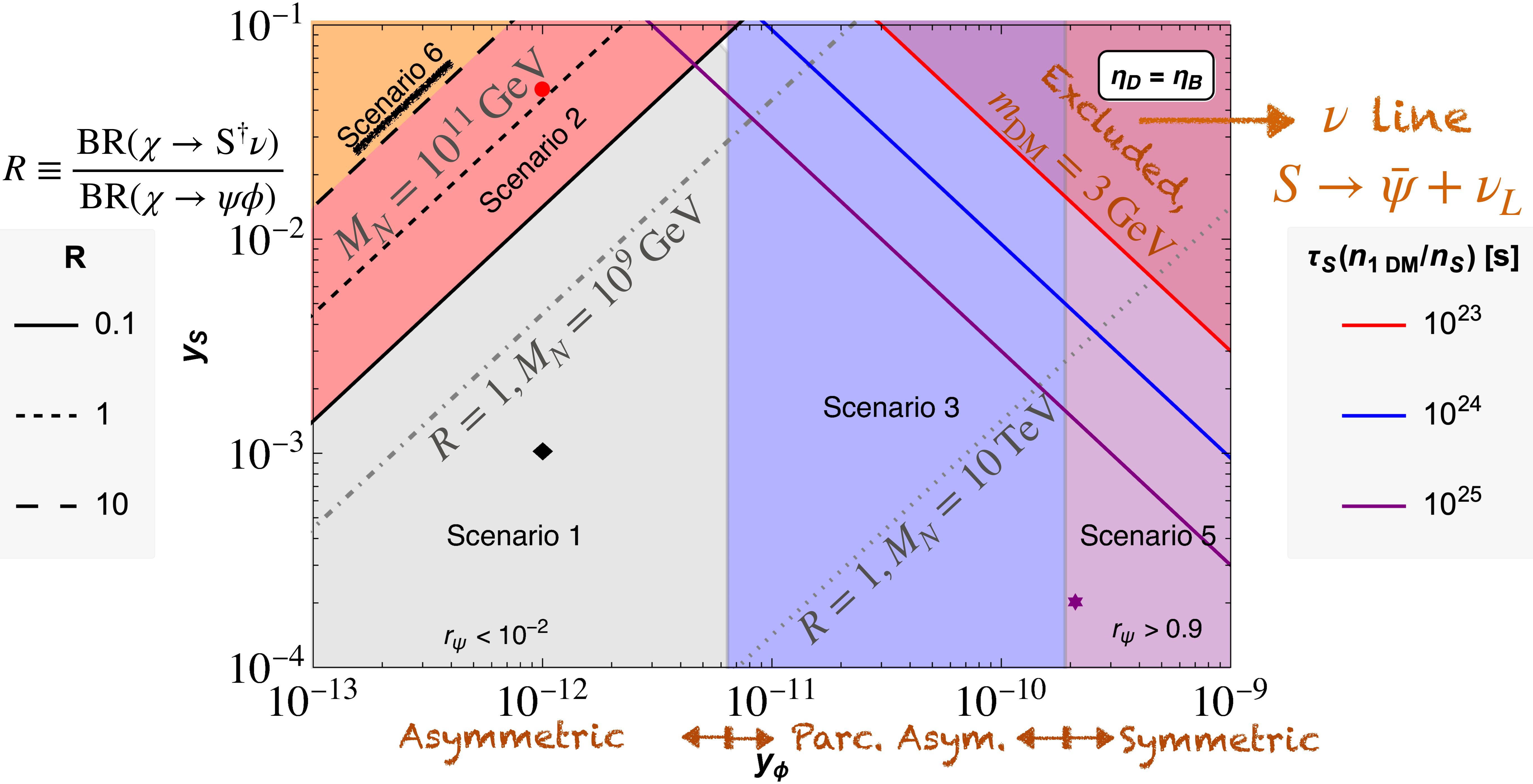
$\tau_S > t_U > 4 \times 10^{17}\, s$

- ID with ν: $\tau_S > 10^{23}\, s$

[Palomares-Ruiz 2008
Garcia-Cely et al 2017,
Coy et al 2021]

Prediction: ν line at $E_\nu = \dfrac{m_s}{2} \sim \mathcal{O}\,(\mathrm{GeV})$

Results



[DM masses such that abundance reproduced at every point]

Scenario 6: 1 DM, S

- $y_S \sim \mathcal{O}(1)$, y_ϕ tiny: $R \equiv \dfrac{\mathrm{BR}(\chi \to \mathrm{S}^\dagger \nu)}{\mathrm{BR}(\chi \to \psi\phi)} \gtrsim \mathcal{O}(10)$

- Asymmetric production of S and $S^\dagger$ from decays:

1) $N \xrightarrow{y_\phi} S + \chi$: S thermalises and is cold

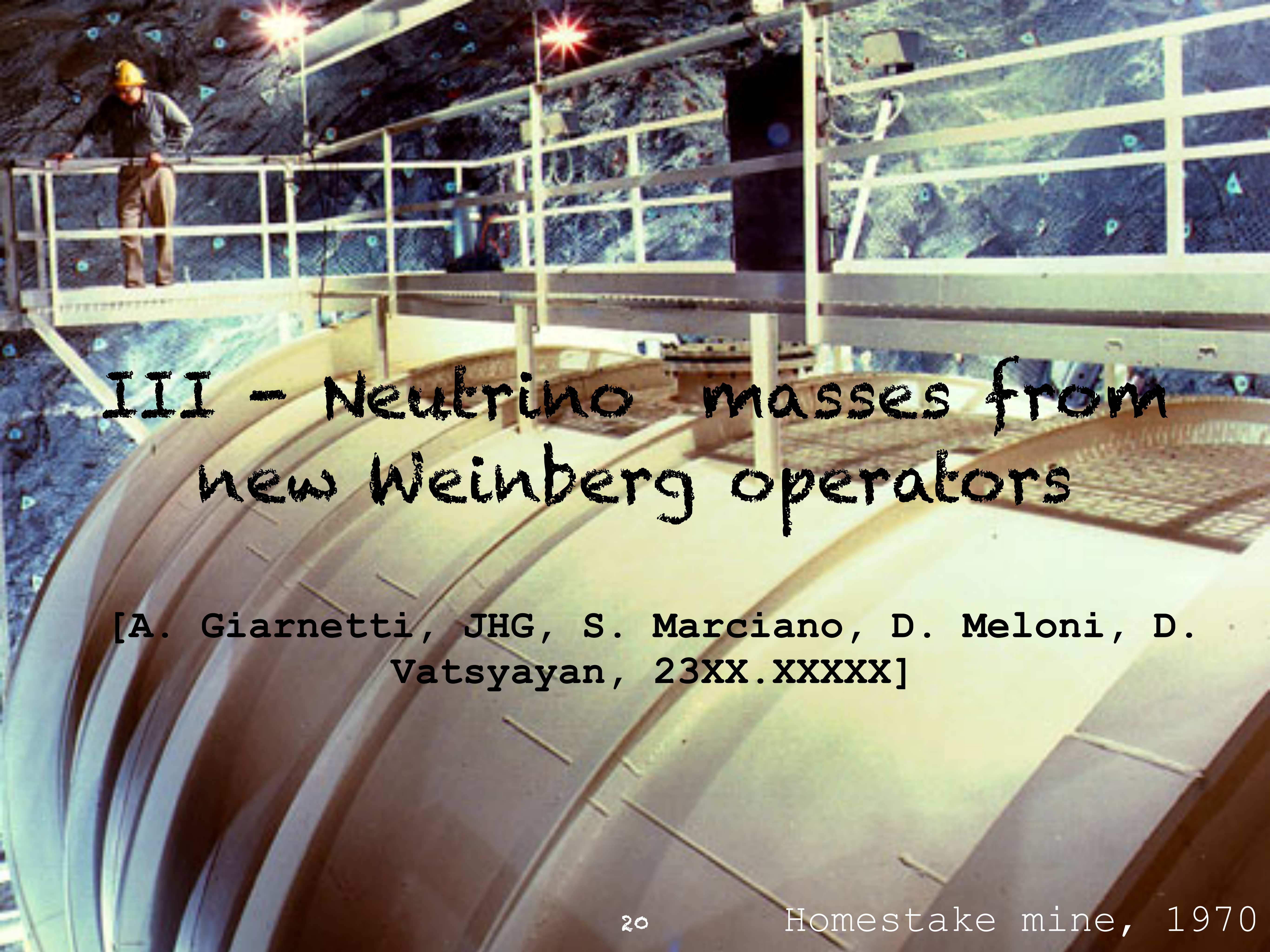
2) $\chi \xrightarrow{\mathcal{O}_5} S^\dagger + \nu$ ($m_\chi \gg m_S$), after S f.o. ($T_D^{(S)} < T_*^S$): S warm

- $S + S^\dagger$: mix cold + warm, with abundance $\propto$ asymmetry:

$$Y_S \simeq Y_S^\dagger \simeq \eta_D \quad \Longrightarrow \quad m_S \simeq 2.5\,\mathrm{GeV}\left(\eta_B/\eta_D\right)$$

- Enhanced ID, from Higgs portal $\lambda_{HS}(H^\dagger H)(S^\dagger S)$

Further studies may be interesting



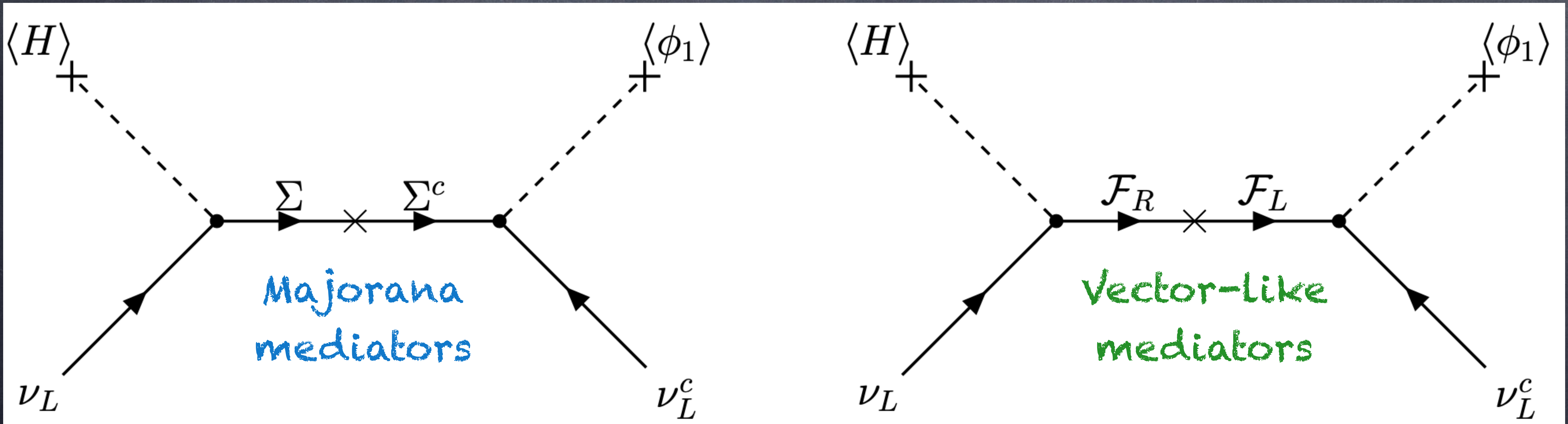
III - Neutrino masses from new Weinberg operators

[A. Giarnetti, JHG, S. Marciano, D. Meloni, D. Vatsyayan, 23XX.XXXXX]

Homestake mine, 1970

Extra scalars ϕ_i at EW scale

$$\mathscr{L}_{\text{EFT}} \supset \frac{c_5^{(0)}}{\Lambda} LLHH + \frac{c_5^{(1)}}{\Lambda} LLH\phi_i + \frac{c_5^{(2)}}{\Lambda} LL\phi_i\phi_i + \frac{c_5^{(3)}}{\Lambda} LL\phi_i\phi_j + \text{H.c.}$$



- Standard seesaws from $c_5^{(0)}$: difficult to test
- New genuine models: no $c_5^{(0)}$ generated

List of genuine models

[See also McDonald *JHEP* 07 (2013) 020]

$$\frac{c_5^{(1)}}{\Lambda} LLH\phi_i + \frac{c_5^{(2)}}{\Lambda} LL\phi_i\phi_i + \frac{c_5^{(3)}}{\Lambda} LL\phi_i\phi_j + \mathrm{H.c.}$$

$(SU(2), Y)$

Model	New Scalar Multiplets	Fermion Mediator	Operator
$\mathbf{A_1}$	$\phi_1 = (4, -1/2)$	$\Sigma = (5, 0)$ ≥ 2	$\mathcal{O}_5^{(2)}$
$\mathbf{A_2}$	$\phi_1 = (4, -3/2)$	$\mathcal{F} = (3, -1)$	$\mathcal{O}_5^{(1)}$
$\mathbf{B_1}$	$\phi_1 = (4, 1/2)$, $\phi_2 = (4, -3/2)$	$\mathcal{F} = (5, -1)$	$\mathcal{O}_5^{(3)}$
$\mathbf{B_2}$	$\phi_1 = (3, 0)$, $\phi_2 = (5, -1)$	$\mathcal{F} = (4, -1/2)$	$\mathcal{O}_5^{(3)}$
$\mathbf{B_3}$	$\phi_1 = (5, -2)$, $\phi_2 = (5, 1)$	$\mathcal{F} = (4, 3/2)$	$\mathcal{O}_5^{(3)}$
$\mathbf{B_4}$	$\phi_1 = (5, -1)$, $\phi_2 = (5, 0)$	$\mathcal{F} = (4, 1/2)$	$\mathcal{O}_5^{(3)}$

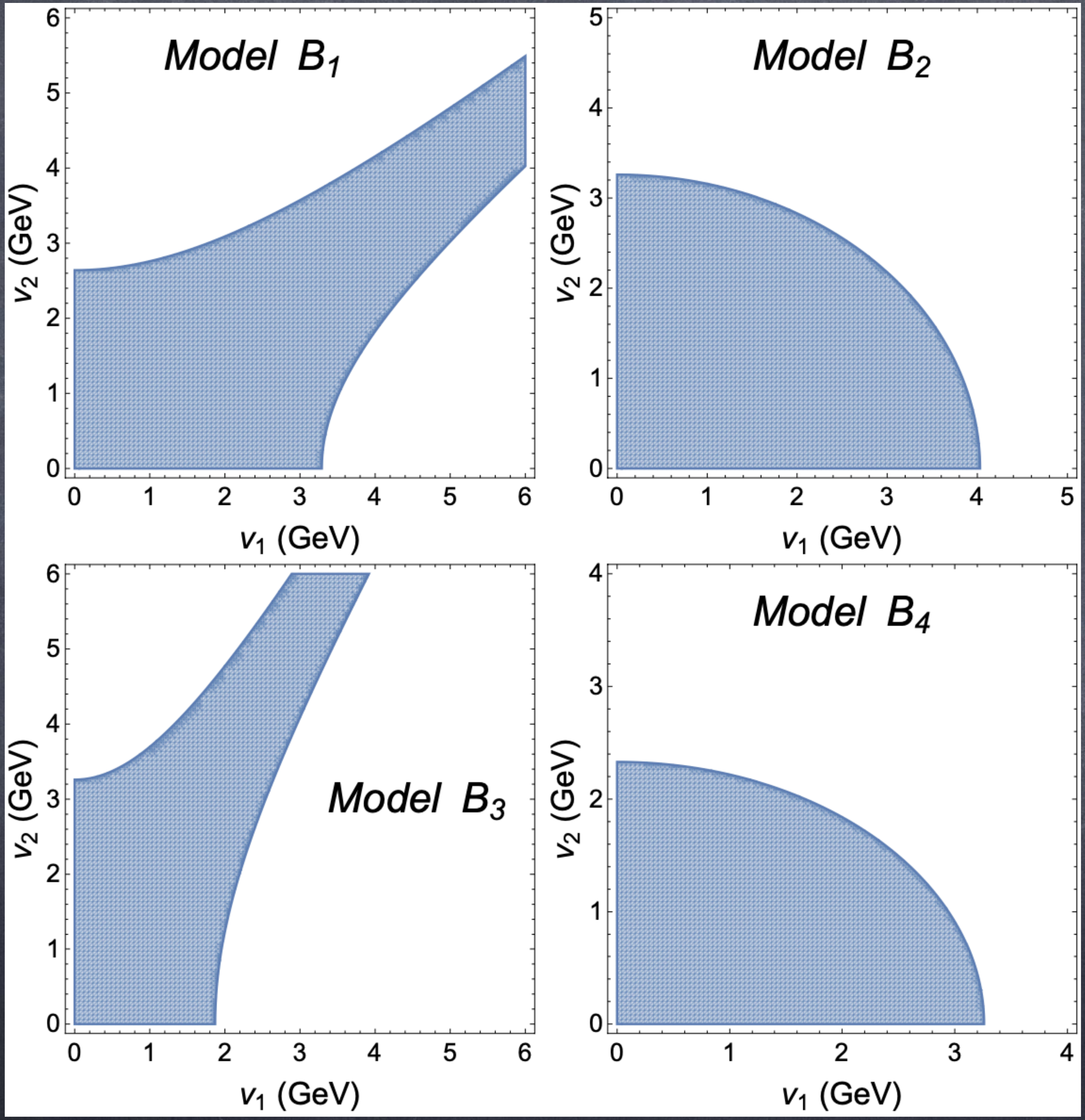
Tree-level neutrino masses:

$$(m_\nu)_{\alpha\beta} = \epsilon_2 v_1^2 \left(y_1 M_\Sigma^{-1} y_1^T\right)_{\alpha\beta} \quad \text{for } \mathbf{A1},$$

$$(m_\nu)_{\alpha\beta} = \epsilon_1 v_1 v \left(y_H M_\mathcal{F}^{-1} y_1^T + y_1 M_\mathcal{F}^{-1} y_H^T\right)_{\alpha\beta} \quad \text{for } \mathbf{A2},$$

$$(m_\nu)_{\alpha\beta} = \epsilon_3 v_1 v_2 \left(y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T\right)_{\alpha\beta} \quad \text{for } \mathbf{B_i},$$

The ρ parameter at tree level



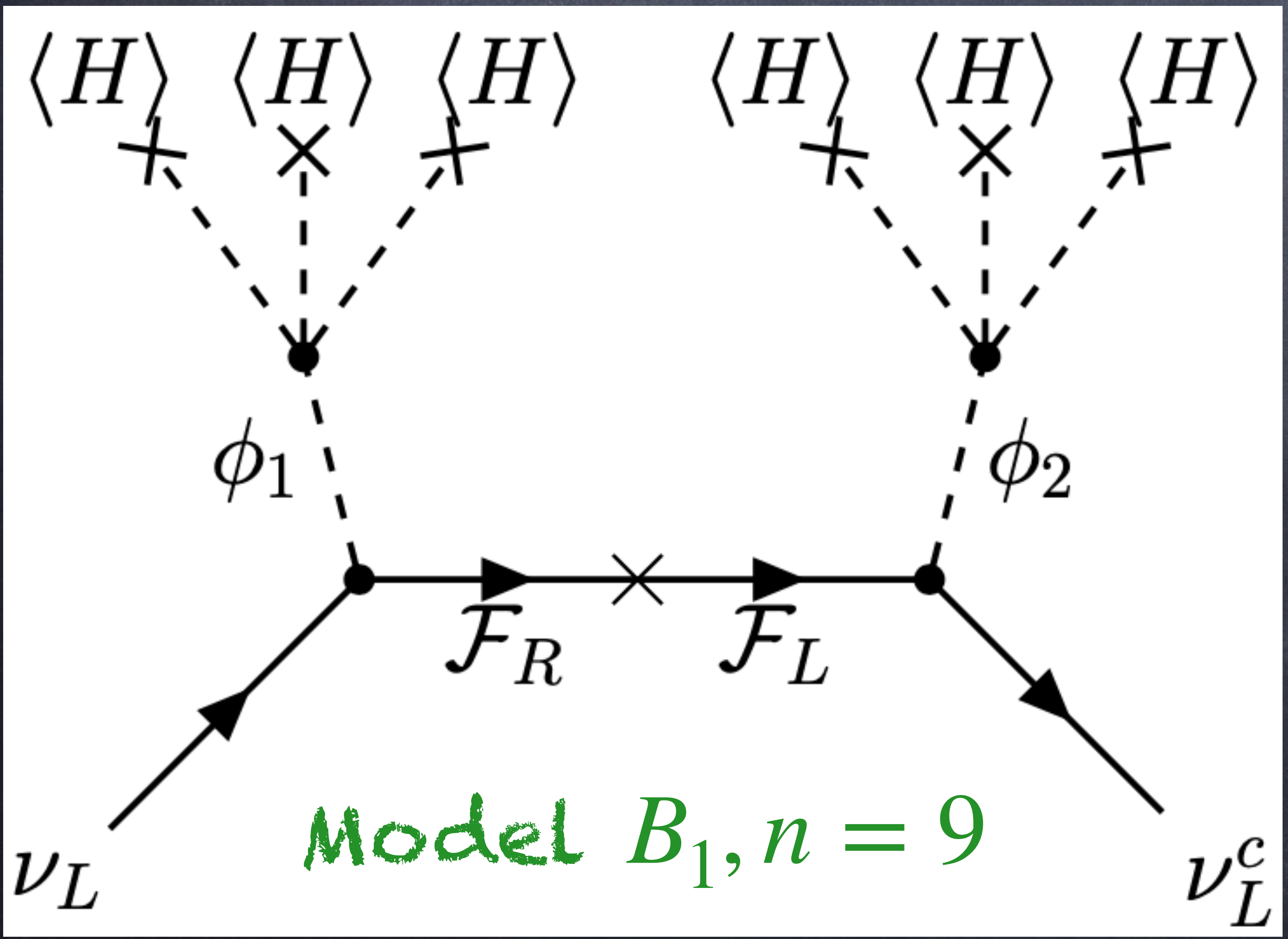
$\Longrightarrow$ New VEVs always small, $v_i < \mathcal{O}(\text{GeV}) \ll v$, so $\Lambda \Downarrow$

Naturally-small induced VEVs v_i

For example, for A_1, $\phi_1 = (4, -1/2)$:

$$V \supset \lambda_{\text{mix},1}\,(\phi_1 H)(H^\dagger H) + \text{H.c.} \Longrightarrow v_i \simeq \lambda_{\text{mix,i}} \frac{v^3}{m_{\phi_i}^2}$$

$\Longrightarrow v_i \ll v$ for $v \ll m_{\phi_i}$ and/or $\lambda_{\text{mix,i}} \ll 1$

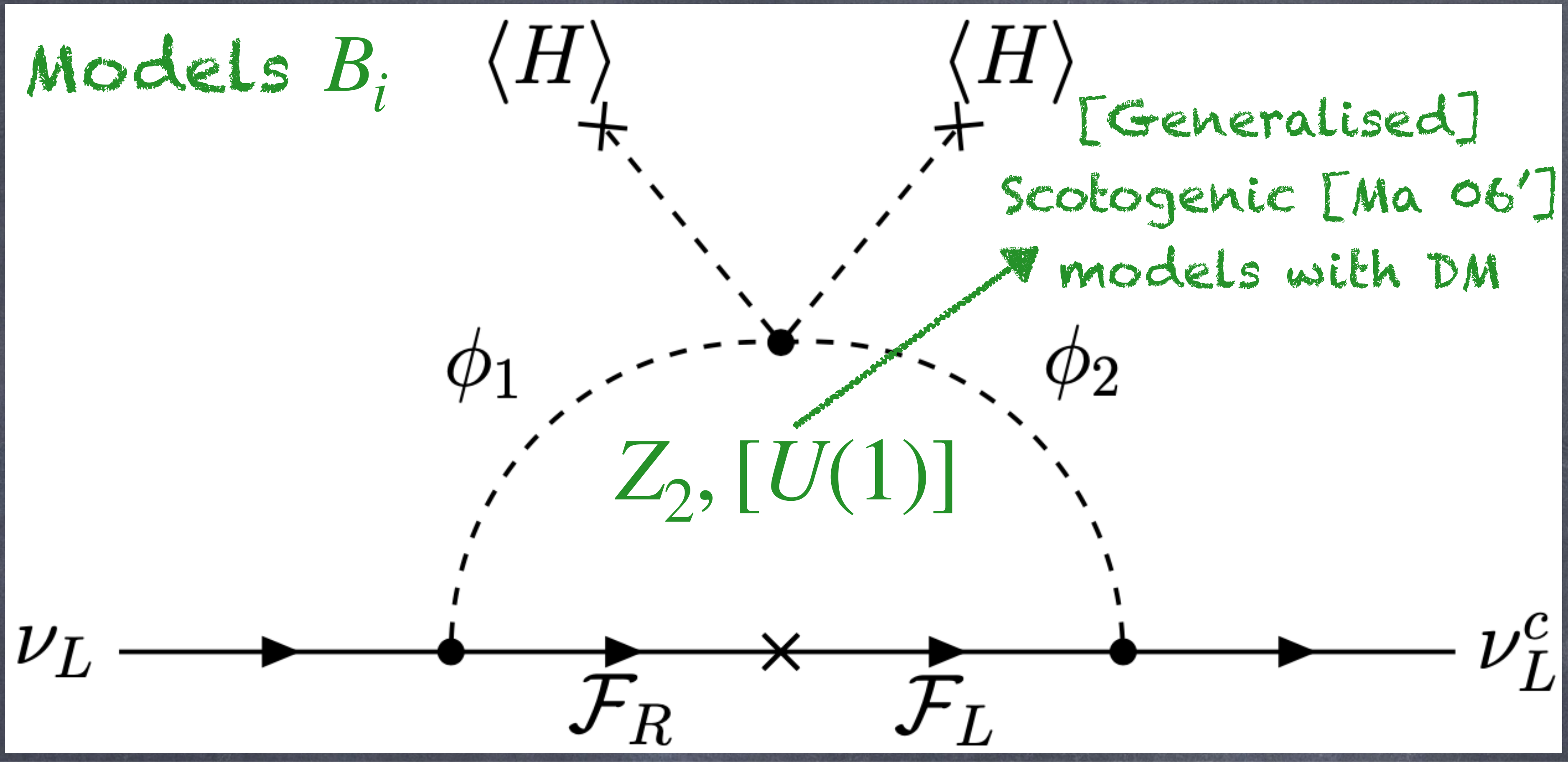


$D > 5$ Weinberg operators with the Higgs doublet:

$$\frac{c_n^{(0)}}{\Lambda^{n-4}} LLHH(H^\dagger H)^{\frac{n-5}{2}}$$

[Anamiati et al 2018]

Neutrino masses at one loop



$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \delta_1 \, \lambda_{\text{mix},1} \, \frac{v^2}{8\pi^2} \sum_{k=1}^{2} y_{1,\alpha k} \, y_{1,\beta k} \, m_k \;\; F_2(m_{(\phi_1)^R_0}, m_{(\phi_1)^I_0}, m_k) \quad \text{for } \mathbf{A_1} \,,$$

$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \delta_2 \, \lambda_{\text{mix},1} \, \frac{v^2}{8\pi^2} \left(y_H y_1^T + y_1 y_H^T\right)_{\alpha\beta} \, M_{\mathcal{F}} \, F_2(m_{\phi_1}, m_H, M_{\mathcal{F}}) \quad \text{for } \mathbf{A_2} \,,$$

$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \kappa_i \, \lambda_{\text{mix},12} \, \frac{v^2}{8\pi^2} \left(y_1 y_2^T + y_2 y_1^T\right)_{\alpha\beta} \, M_{\mathcal{F}} \, F_2(m_{\phi_1}, m_{\phi_2}, M_{\mathcal{F}}) \quad \text{for } \mathbf{B_i} \,,$$

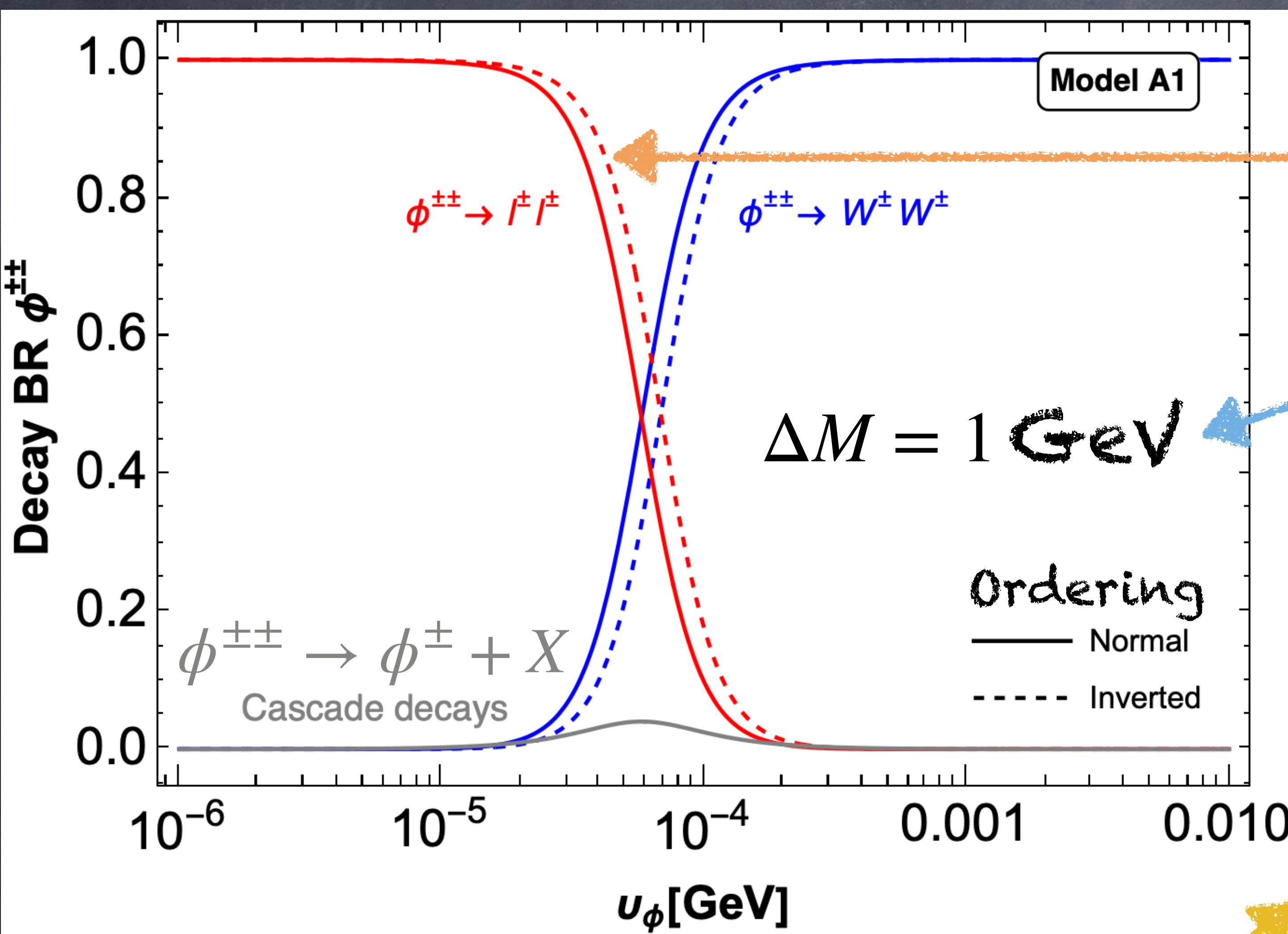
In some cases, loop contribution may dominate

Rich phenomenology

- Direct searches of new scalars at colliders
- Lepton flavour violation ($\mu \to e\gamma$, etc.)
- EWPTs
- Modified gauge boson couplings to leptons and non-unitary PMNS from $D = 6$ operators like

$$\mathcal{O}_6 = \left(\overline{L}_\alpha \tilde{\phi}_1\right) i\gamma_\mu D^\mu \left(\tilde{\phi}_1^\dagger L_\beta\right)$$

Doubly-charged scalars at colliders

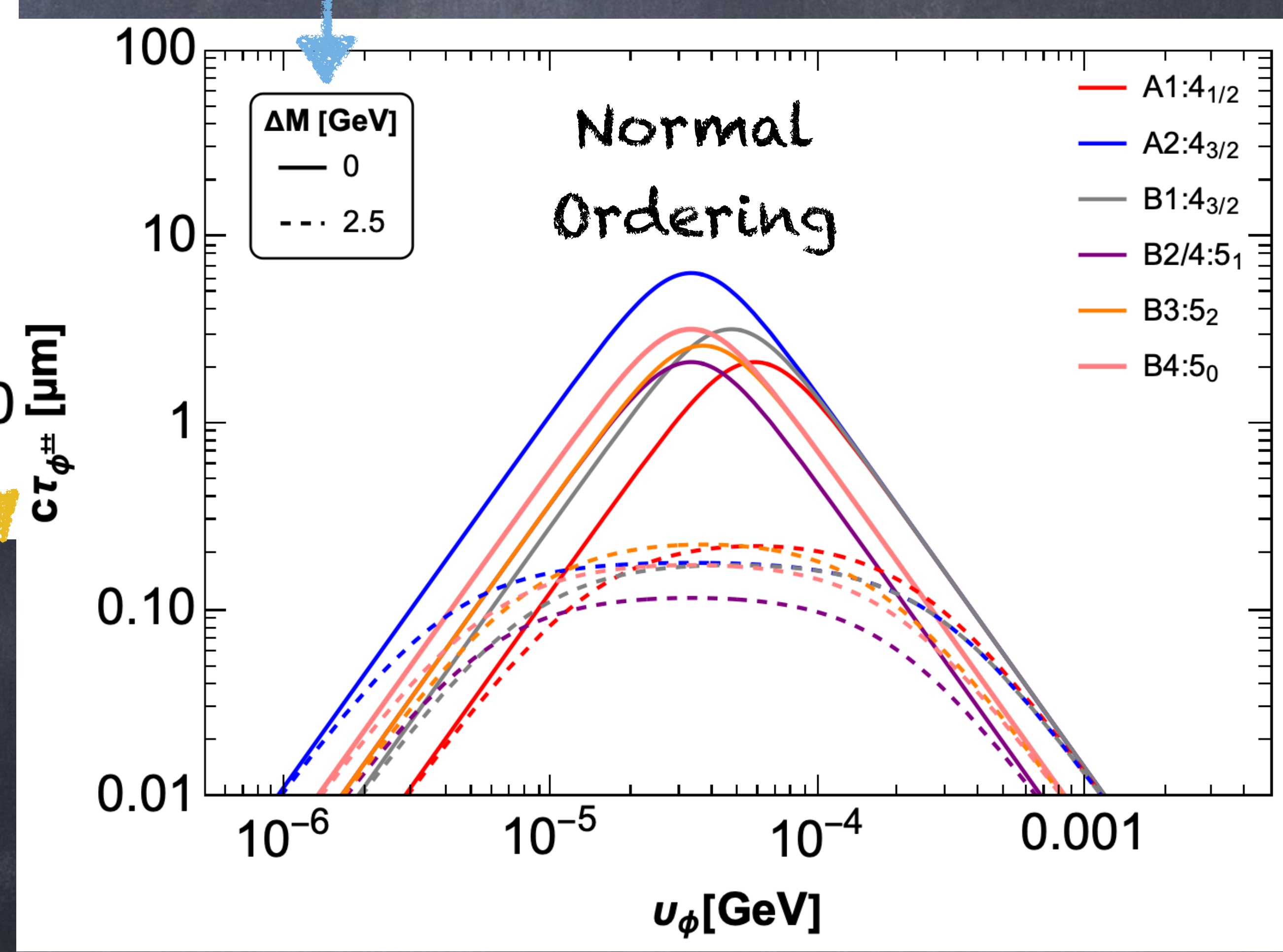


Same-sign leptons, $\propto \frac{m_\nu^2}{v_i^2}$

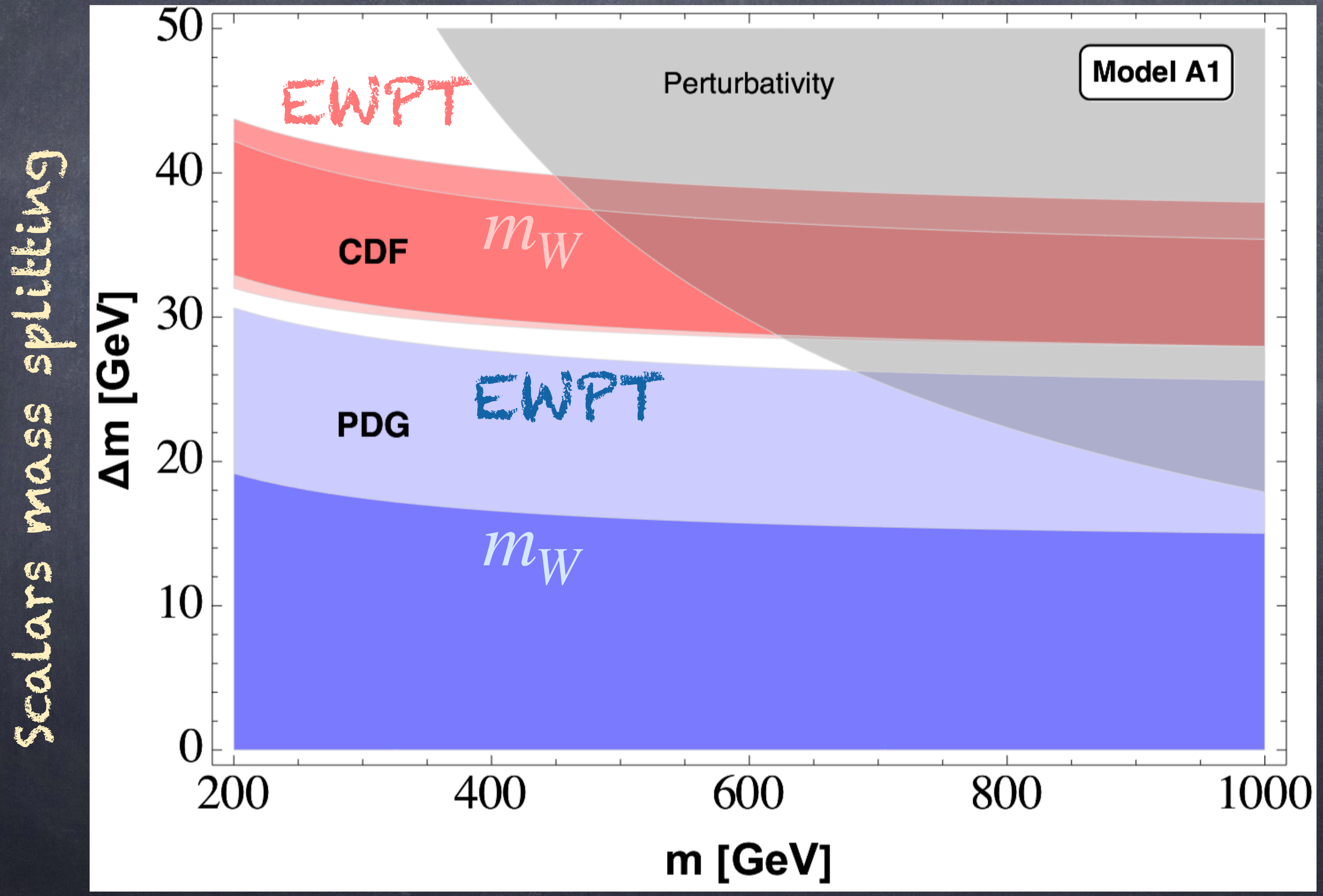
Scalars mass splitting

$M_\phi = 500$ GeV

Decay length



m_W and EWPT at one loop



IV - EFT approach to proton decay

[J. Gargalionis, JHG, M. Schmidt, 23XX.XXXXX]

[A. Bas, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]

Super-Kamiokande

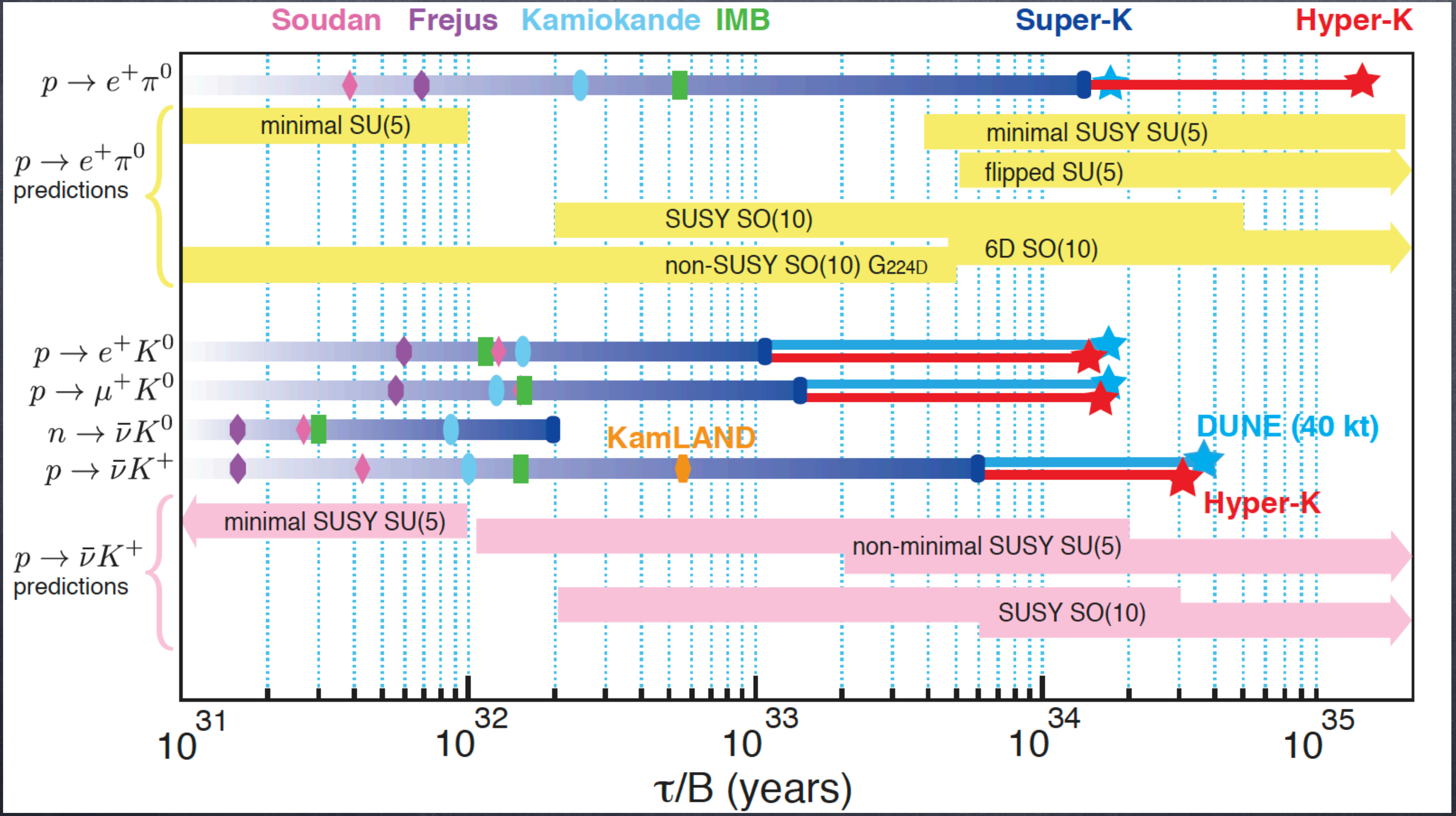
$\not{B}$: Proton Decay

- B expected to be violated at large energies ($\leq M_p$)
- BNV: necessary to generate the BAU [Shakarov 1967]
- Anomaly cancellation and GUTs: quarks - leptons unify
- At $D = 6,\ \Delta(B-L) = 0$ operators $\longrightarrow$ $\begin{array}{ccc} QQ & - & QL \\ | & & | \\ ue & - & ud \end{array}$
- Ej. $uued$, SK $\tau(p \to e^+\pi^0) > 2.4 \cdot 10^{34} y \implies \Lambda_{\rm BNV} > 10^{15}\,\mathrm{GeV}$

Highest energies probed

Experimental perspectives

[HK Design Report, 1805.04163]



BNV could be the next big discovery

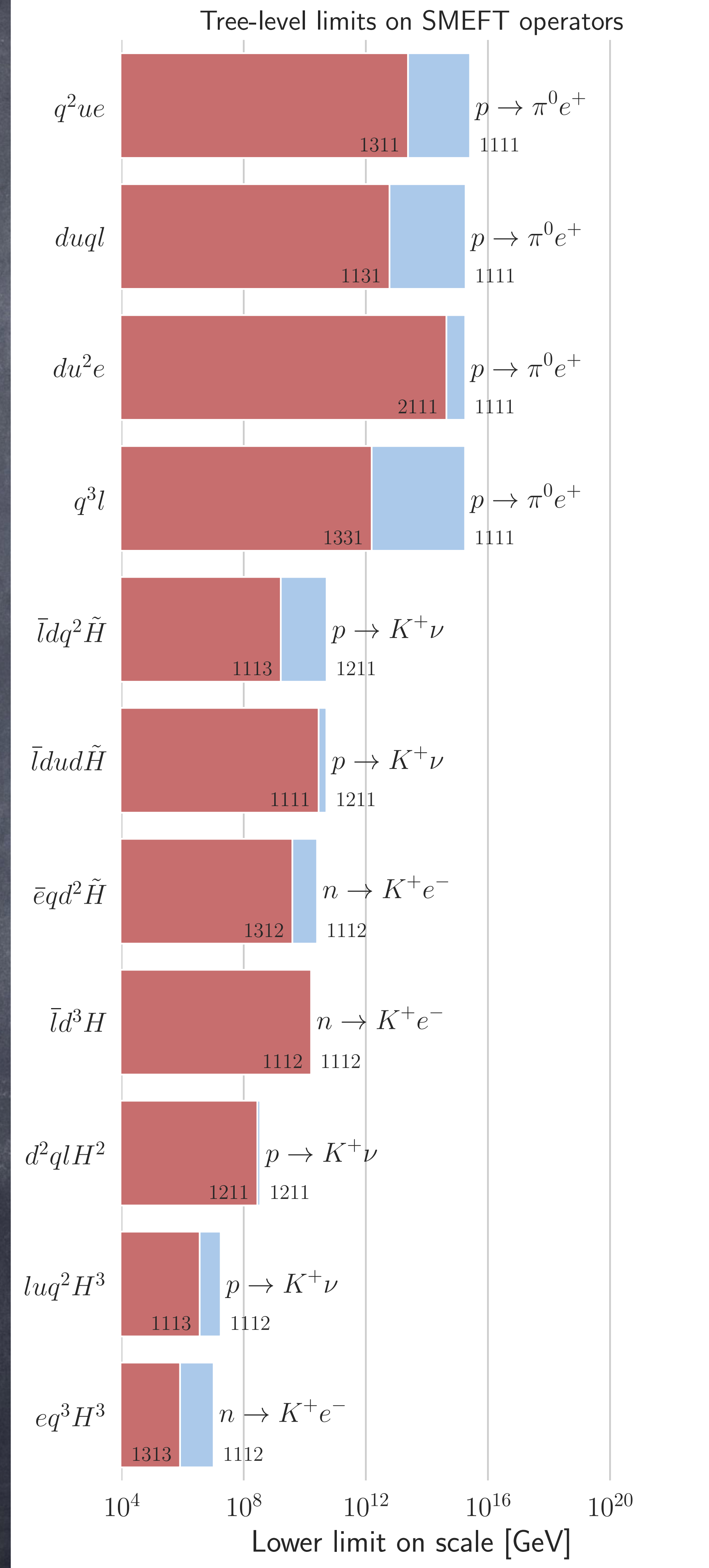
EFT Proton decay at tree level, $D \leq 7$

[J. Gargalionis, JHG, M. Schmidt, 23XX.XXXXX]

Label	Operator	D	B	L
1	$L_p Q_q Q_r Q_s$	6	1	1
2	$\bar{e}_p^\dagger Q_{\{q} Q_{r\}} \bar{u}_s^\dagger$	6	1	1
3	$\bar{e}_p^\dagger \bar{u}_q^\dagger \bar{u}_r^\dagger \bar{d}_s^\dagger$	6	1	1
4	$L_p Q_q \bar{u}_r^\dagger \bar{d}_s^\dagger$	6	1	1
5	$L_p \bar{d}_q \bar{d}_{[r} \bar{d}_{s]} H^\dagger$	7	-1	1
6	$D L_p Q_q^\dagger \bar{d}_{\{r} \bar{d}_{s\}}$	7	-1	1
7	$D \bar{e}_p^\dagger \bar{d}_{\{q} \bar{d}_r \bar{d}_{s\}}$	7	-1	1
8	$L_p Q_q^\dagger Q_r^\dagger \bar{d}_s H$	7	-1	1
9	$\bar{e}_p^\dagger Q_q^\dagger \bar{d}_{[r} \bar{d}_{s]} H$	7	-1	1
10	$L_p \bar{u}_q \bar{d}_r \bar{d}_s H$	7	-1	1

Study of RGE and correlations

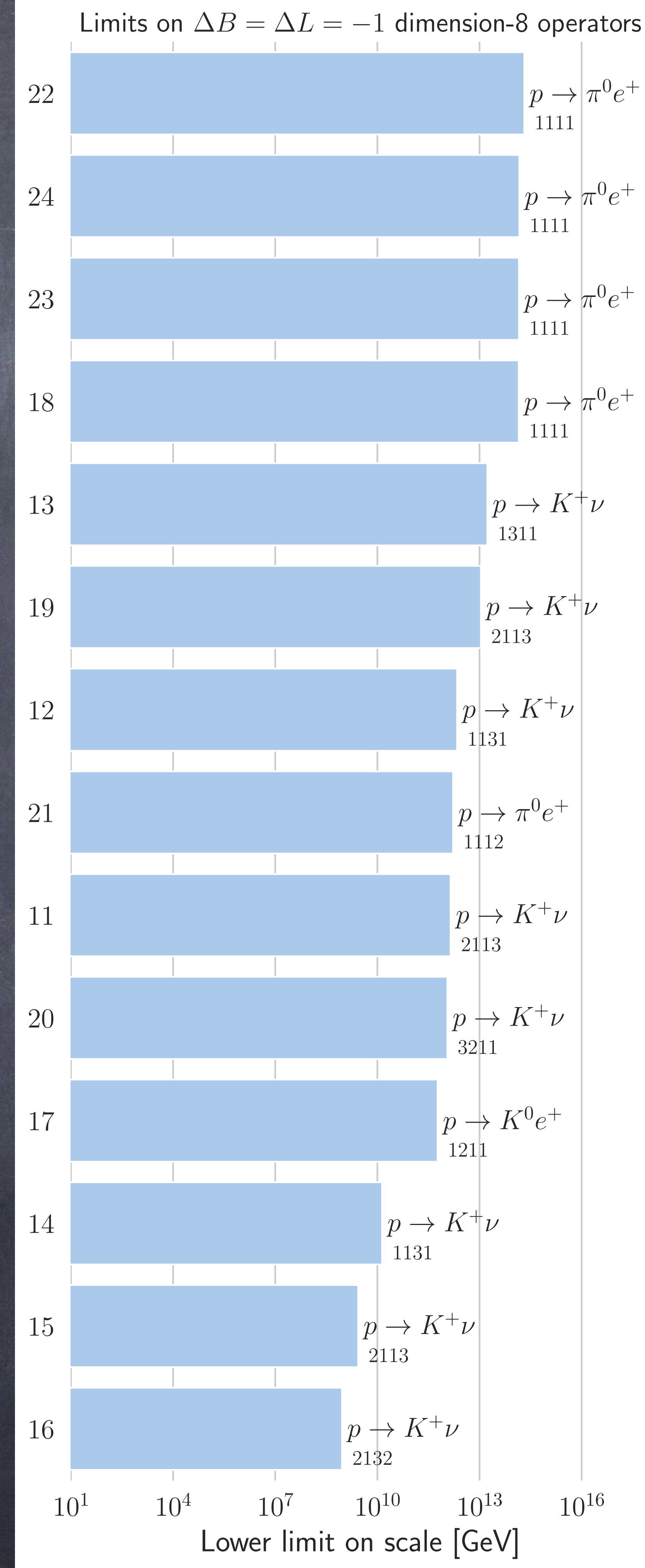
[A. Bas, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]



EFT Proton decay at loop level, $D \leq 9$

[J. Gargalionis, JHG, M. Schmidt, 23XX.XXXXX]

11	$DL_pQ_qQ_r\bar{d}^\dagger_s H$	8	1	1
12	$DL_p\bar{u}^\dagger_q\bar{d}^\dagger_r\bar{d}^\dagger_s H$	8	1	1
13	$DL_p\bar{u}^\dagger_q\bar{u}^\dagger_r\bar{d}^\dagger_s H^\dagger$	8	1	1
14	$L_pQ_q\bar{u}^\dagger_{[r}\bar{u}^\dagger_{s]}H^\dagger H^\dagger$	8	1	1
15	$\bar{e}^\dagger_p Q_{[q}Q_{r]}\bar{d}^\dagger_s HH$	8	1	1
16	$L_pQ_q\bar{d}^\dagger_{[r}\bar{d}^\dagger_{s]}HH$	8	1	1
17	$D\bar{e}^\dagger_pQ_q\bar{u}^\dagger_r\bar{u}^\dagger_sH^\dagger$	8	1	1
18	$L_pQ_qQ_rQ_sHH^\dagger$	8	1	1
19	$DL_pQ_qQ_r\bar{u}^\dagger_sH^\dagger$	8	1	1
20	$D\bar{e}^\dagger_pQ_qQ_rQ_sH$	8	1	1
21	$D\bar{e}^\dagger_pQ_q\bar{u}^\dagger_r\bar{d}^\dagger_sH$	8	1	1
22	$\bar{e}^\dagger_pQ_qQ_r\bar{u}^\dagger_sHH^\dagger$	8	1	1
23	$\bar{e}^\dagger_p\bar{u}^\dagger_q\bar{u}^\dagger_r\bar{d}^\dagger_sHH^\dagger$	8	1	1




V - Conclusions

Conclusions

- Over-simplified dark sector? SM as "guide": multi-component and asymmetric.
- Cogenesis: interesting connection of DM, m_ν and BAU.
- Asymmetric freeze-in model with 2DM and a ν line.
- New testable Weinberg operators and seesaws for m_ν.
- EFT useful for tree/loop estimates of proton decay.

Thanks!

James Webb
Pillars of creation

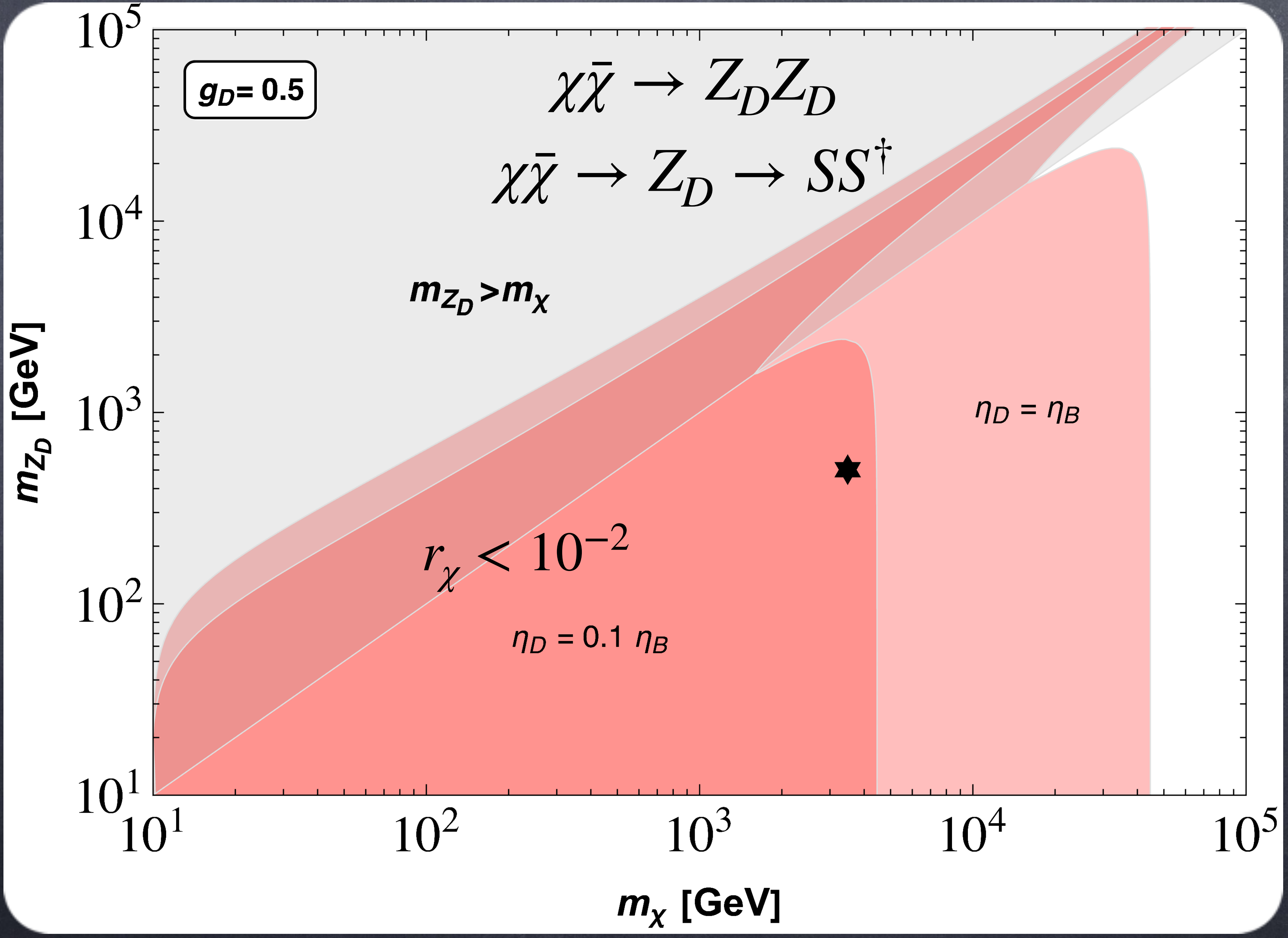

Back-up
James Webb
Carina Nebula

Partially-asymmetric DM

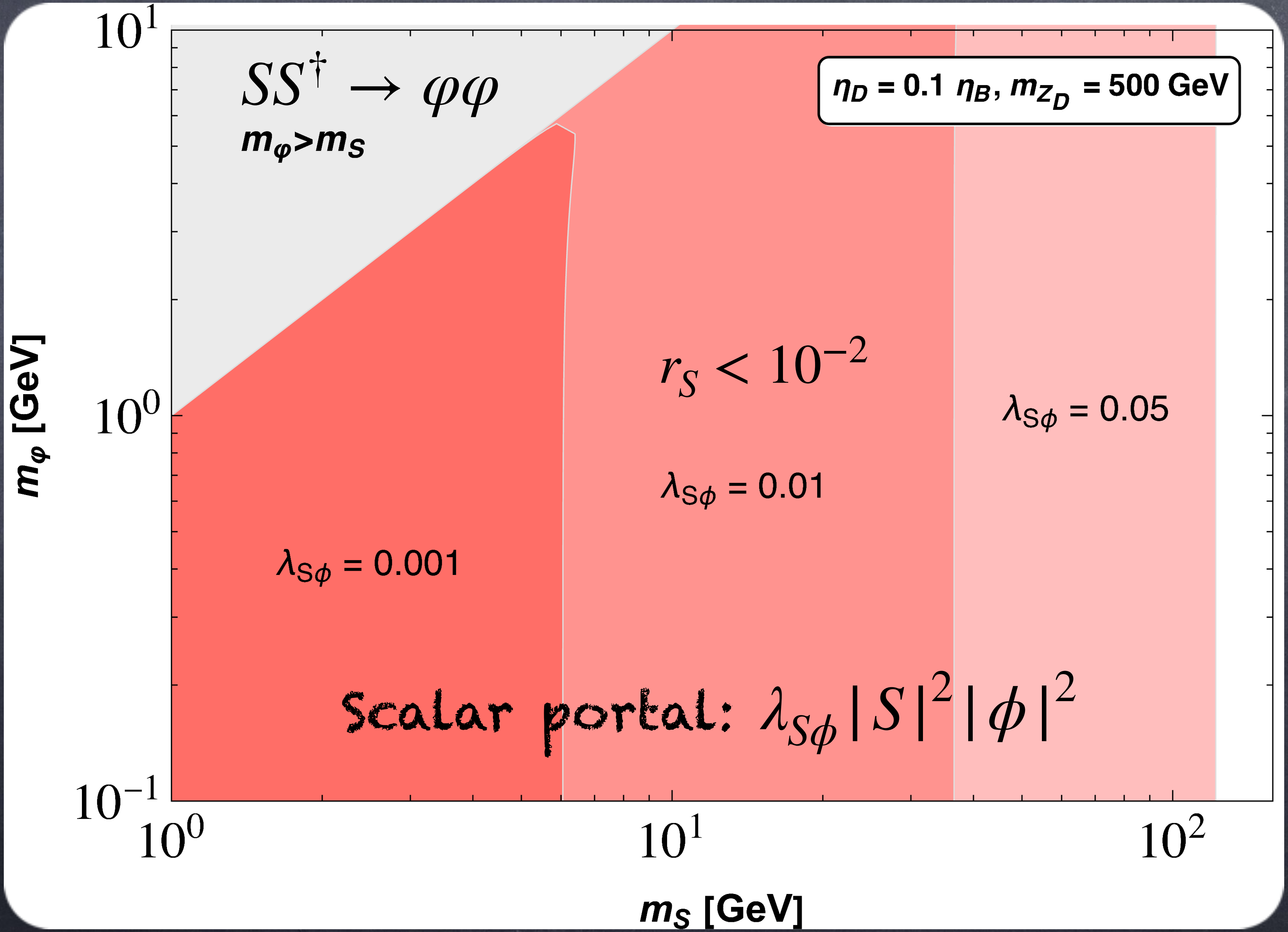
[Graesser et al 2011]

$$\rho_{\mathrm{DM}} = s \sum_i m_i \eta_i \left(\underbrace{1}_{\text{asymmetric}} + 2 \underbrace{\frac{r_{\infty,i}}{1 - r_{\infty,i}}}_{\text{symmetric}} \right)$$

Erasing χ symmetric population



Erasing S symmetric population



Decays $\chi \to S^\dagger + \nu$

After freeze-out of S, $T_D^{(S)} < T_*^{(S)}$ $\Longrightarrow$ Populate symmetric component, no active annihilations:

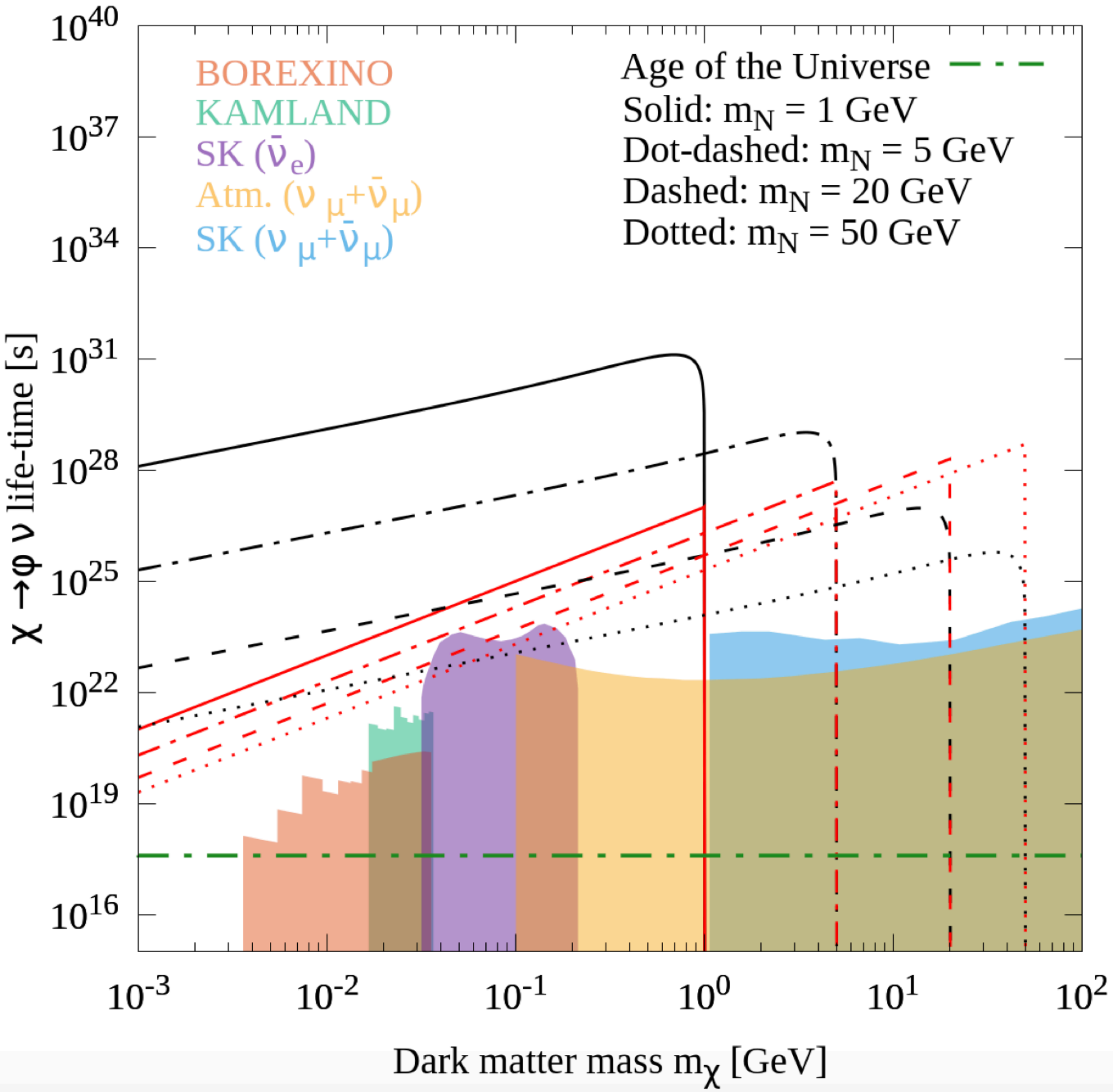
$$Y_S^+ = \eta_D, \quad Y_S^- = \frac{R}{1+R}\eta_D$$

Before freeze-out of S, $T_D^{(S)} > T_*^{(S)}$ $\Longrightarrow$ Annihilations active, partial washout, asymmetric:

$$Y_S^+ = \frac{1}{1+R}\eta_D, \quad Y_S^- \ll Y_S^+$$

Monochromatic ν Line Limits

[Coy et al, *Phys.Rev.D* 104 (2021) 8, 083024]



Scenarios

$$\frac{\Omega_\psi}{\Omega_S} = \frac{m_\psi(\eta_D + Y_{\rm FI})}{\eta_D m_S f(R)}$$

$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_\psi(\eta_D + Y_{\rm FI}) + \eta_D m_S f(R)}{\eta_B(1+R)m_p}$$

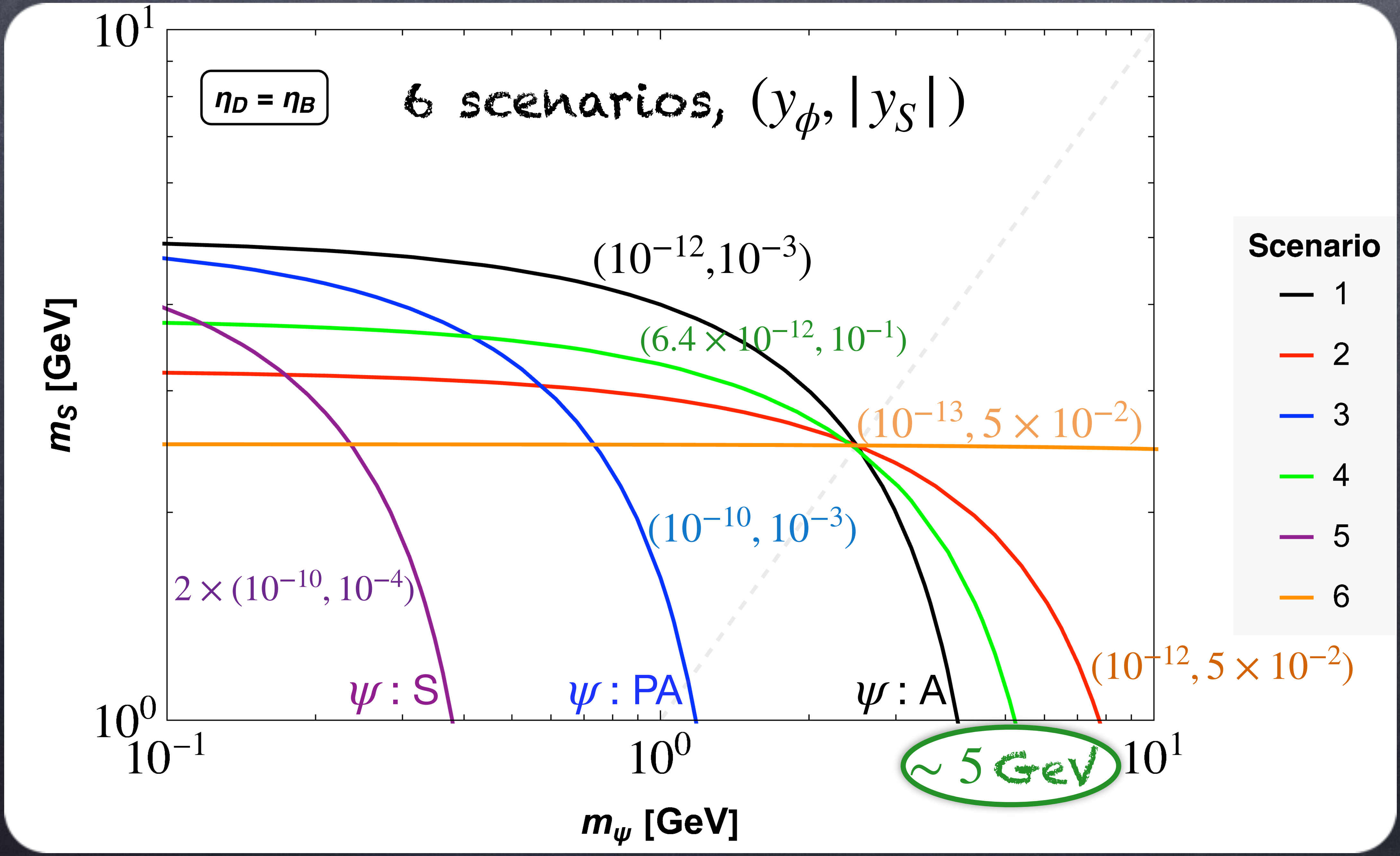
$$f(R) \begin{cases} 1+2R & \text{If } T_D^{(S)} < T_*^{(S)} \\ 1 & \text{If } T_D^{(S)} > T_*^{(S)} \end{cases}$$

Sc.	ψ	S	$\Omega_{\rm DM}/\Omega_B$	Ω_S/Ω_ψ
1	Asymmetric LD $\chi \to \psi\varphi$ $Y_\psi^+ = \eta_D$ $Y_\psi^- \ll Y_\psi^+$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ $Y_S^+ = \eta_D$ $Y_S^- \ll Y_S^+$	$\frac{\eta_D}{\eta_B}\frac{m_\psi+m_S}{m_p}$	$\frac{m_\psi}{m_S}$
2	Asymmetric LD $\chi \to \psi\varphi$ $Y_\psi^+ = \eta_D/(1+R)$ $Y_\psi^- \ll Y_\psi^+$	Partially asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D$ $Y_S^- = \eta_D R/(1+R)$	$\frac{\eta_D}{\eta_B}\frac{m_\psi+(1+2R)m_S}{(1+R)m_p}$	$\frac{m_\psi}{m_S(1+2R)}$
1-2	Asymmetric LD $\chi \to \psi\varphi$ $Y_\psi^+ = \eta_D/(1+R)$ $Y_\psi^- \ll Y_\psi^+$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D/(1+R)$ $Y_S^- \ll Y_S^+$	$\frac{\eta_D}{\eta_B}\frac{m_\psi+m_S}{(1+R)m_p}$	$\frac{m_\psi}{m_S}$
3	Partially asymmetric FI + LD $\chi \to \psi\varphi$ $Y_\psi^+ = Y_{\rm FI}/2 + \eta_D$ $Y_\psi^- = Y_{\rm FI}/2$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ $Y_S^+ = \eta_D$ $Y_S^- \ll Y_S^+$	$\frac{m_\psi(\eta_D+Y_{\rm FI})+\eta_D m_S}{\eta_B m_p}$	$\frac{m_\psi(\eta_D+Y_{\rm FI})}{m_S\eta_D}$
4	Partially Asymmetric FI +LD $\chi \to \psi\varphi$ $Y_\psi^+ = (Y_{\rm FI}/2+\eta_D)/(1+R)$ $Y_\psi^- = Y_{\rm FI}/(2(1+R))$	Partially Asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D$ $Y_S^- = \eta_D R/(1+R)$	$\frac{m_\psi(\eta_D+Y_{\rm FI})+\eta_D(1+2R)m_S}{\eta_B(1+R)m_p}$	$\frac{m_\psi(\eta_D+Y_{\rm FI})}{m_S\eta_D(1+2R)}$
3-4	Partially Asymmetric FI +LD $\chi \to \psi\varphi$ $Y_\psi^+ = (Y_{\rm FI}/2+\eta_D)/(1+R)$ $Y_\psi^- = Y_{\rm FI}/(2(1+R))$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D/(1+R)$ $Y_S^- \ll Y_S^+$	$\frac{m_\psi(\eta_D+Y_{\rm FI})+\eta_D m_S}{\eta_B(1+R)m_p}$	$\frac{m_\psi(\eta_D+Y_{\rm FI})}{m_S\eta_D}$
5	Symmetric FI $\chi \to \psi\varphi$ $Y_\psi^+ = Y_{\rm FI}/2+\eta_D \simeq Y_{\rm FI}/2$ $Y_\psi^- = Y_{\rm FI}/2$	Asymmetric FO $S^\dagger S \to \varphi\varphi$ $Y_S^+ = \eta_D$ $Y_S^- \ll Y_S^+$	$\frac{\eta_D}{\eta_B}\frac{m_\psi(Y_{\rm FI}/\eta_D)+m_S}{m_p}$	$\frac{m_\psi Y_{\rm FI}}{m_S\eta_D}$
6	Negligible production	Symmetric FO $S^\dagger S \to \varphi\varphi$ + LD $\chi \to S^\dagger \nu_L$ $Y_S^+ = \eta_D$ $Y_S^- = \eta_D$	< 1	$\frac{\eta_D}{\eta_B}\frac{2m_S}{m_p}$

2DM parameter space

$$\frac{\Omega_\psi}{\Omega_S} = \frac{m_\psi(\eta_D + Y_{\rm FI})}{\eta_D m_S f(R)} \qquad \frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_\psi(\eta_D + Y_{\rm FI}) + \eta_D m_S f(R)}{\eta_B(1+R)m_p}$$

$$f(R) \begin{cases} 1+2R & \text{If } T_D^{(S)} < T_*^{(S)} \\ 1 & \text{If } T_D^{(S)} > T_*^{(S)} \end{cases}$$

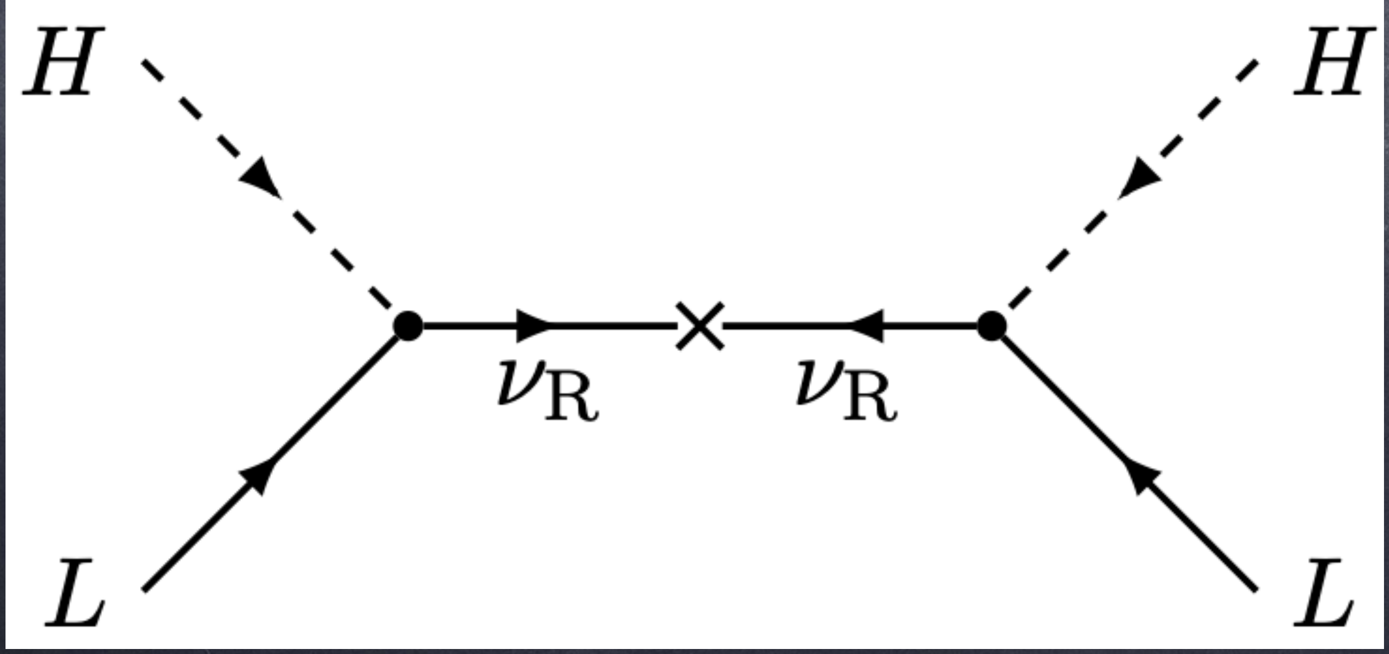


Seesaw Type I

- At $D = 5$ $LLHH$ [Weinberg], $\Delta L = 2 \Longrightarrow$

$$m_\nu \simeq c\,\frac{v^2}{\Lambda} \gtrsim 0.05\,\mathrm{eV} \Longrightarrow \Lambda \lesssim 10^{14}\,\mathrm{GeV}$$

- UV model: heavy ν_R, seesaw Type I



Leptogenesis?

Proton decay modes

[JUNO, 1507.05613]