How To Search For Light New Physics

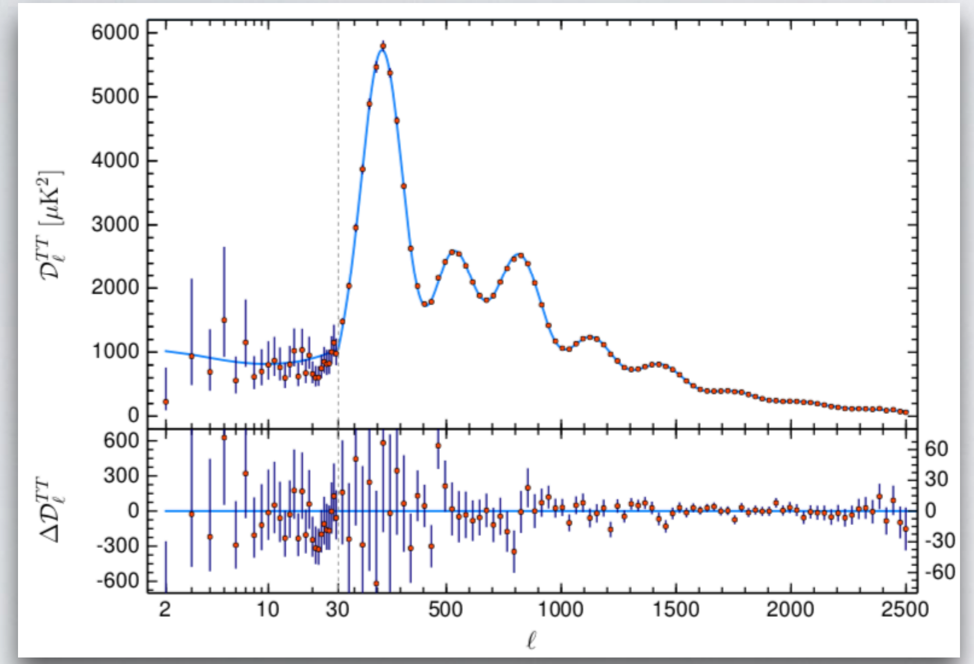
Patrick Foldenauer

Based on
[Bauer, PF, Reimitz, Plehn, 2005.13551]
[Amaral, Cerdeno, PF, Reid; 2006.11225]
[Bauer, PF, Mosny; 2011.12973]

IPPP Internal Seminar/virtual – Feb 19, 2021

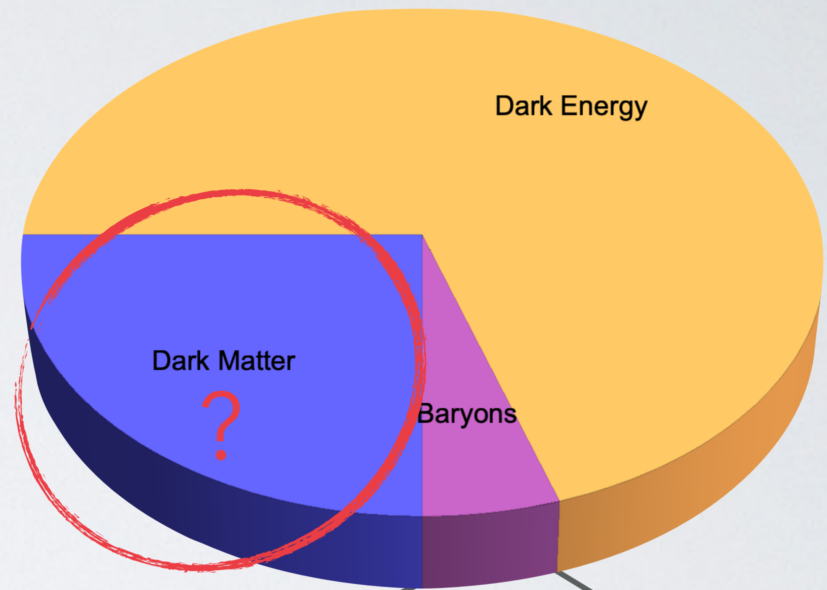
WHY GO BEYOND THE SM?

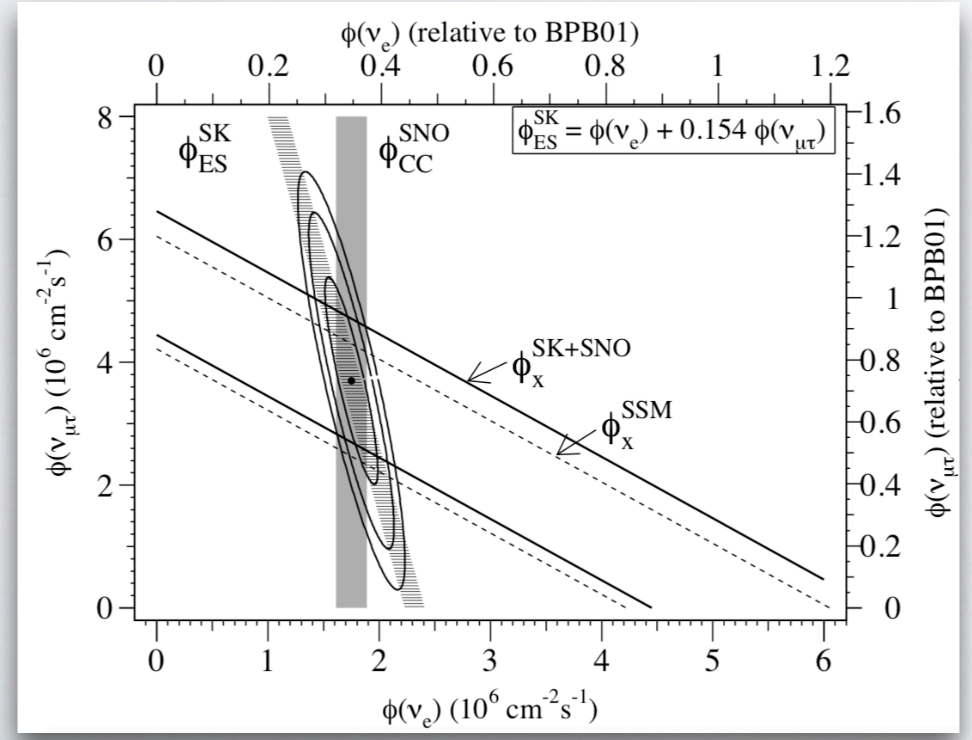
Two obvious reasons:



[Planck Collaboration; 1807.06209]

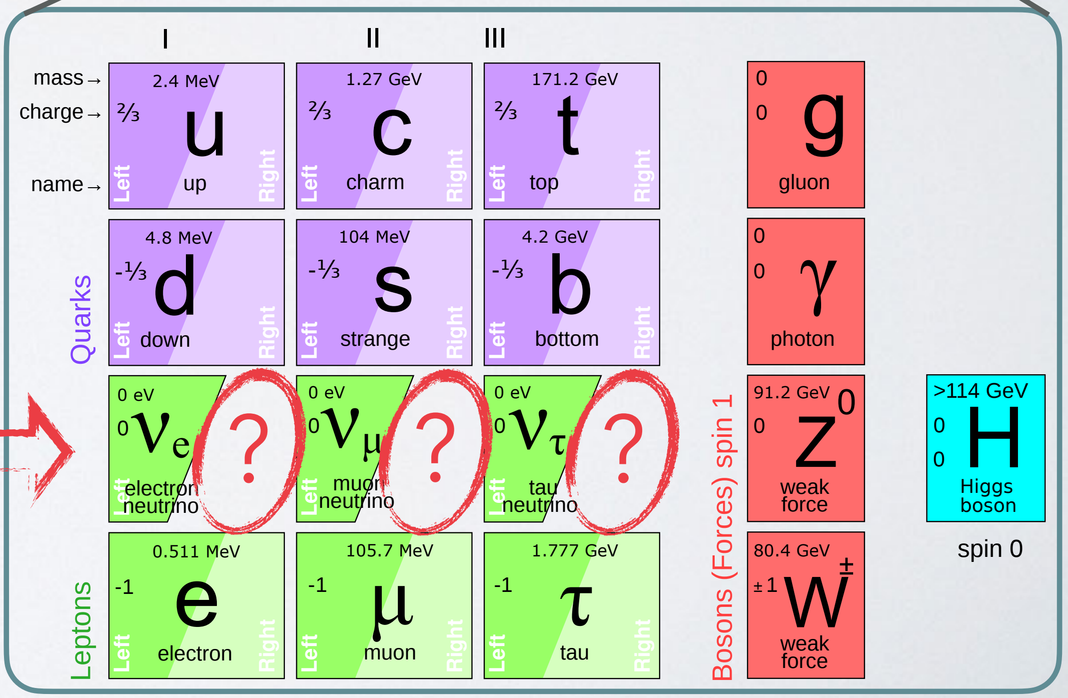
CMB informs us about energy budget





[SNO Collaboration PRL 87:071301]

Oscillations require massive neutrinos

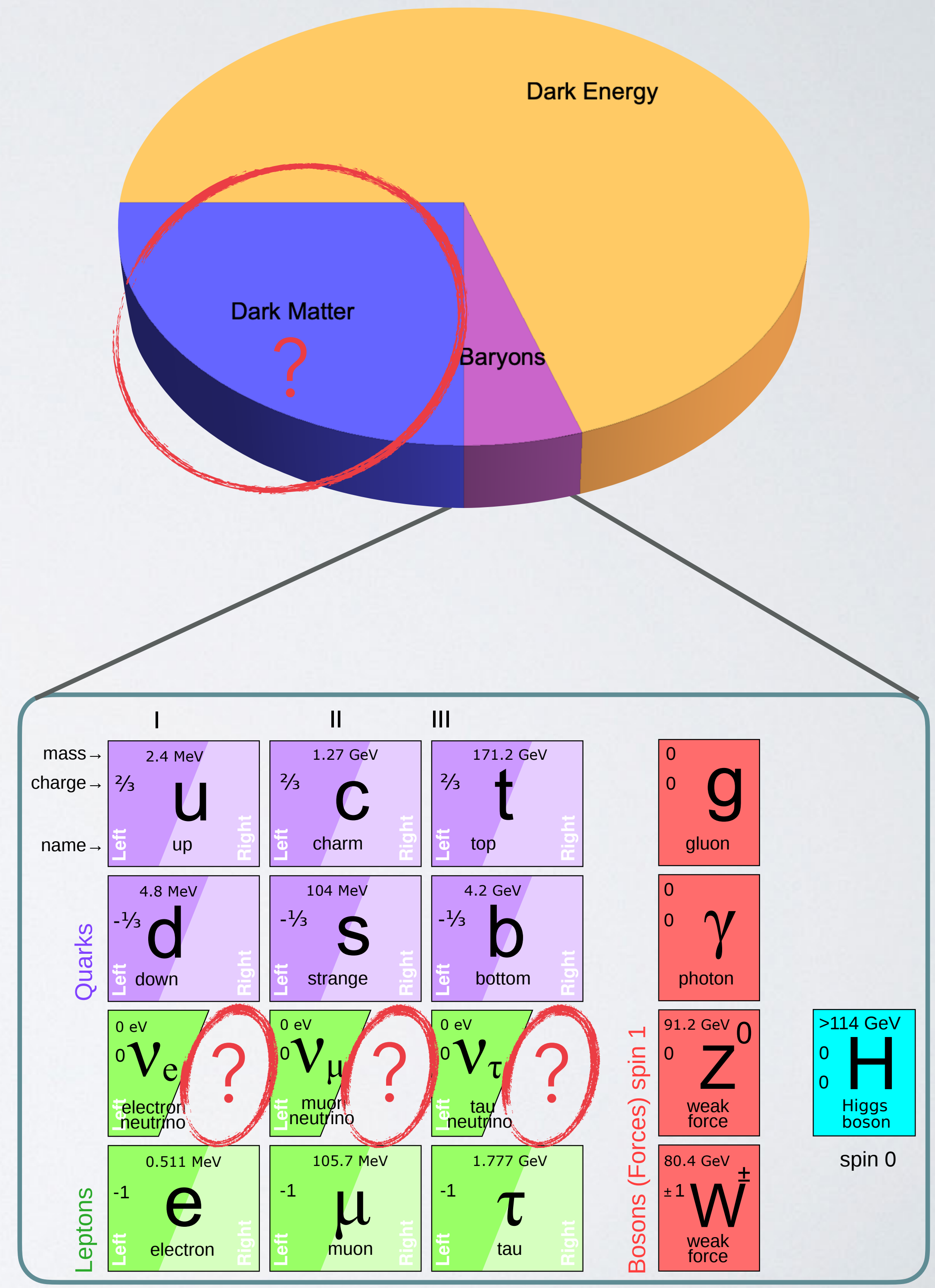


[Gninenko et al., 1301.5516]

WHY GO BEYOND THE SM?

Possible hints for New Physics:

- $(g-2)_\mu$ **anomaly**
- **Flavour anomalies** $R_{K^{(*)}}$ and $R_{D^{(*)}}$ (BaBar, Belle, LHCb)
- H_0 **tension**
- Cosmic ray **positron excess** (PAMELA, FermiLAT, AMS-02)
- **XENON1T** excess



[Gninenko et al., 1301.5516]

PORTALS TO NEW PHYSICS

- Can build three renormalisable dim 4 portal interactions from the SM singlets $H^\dagger H$, $\bar{L}\tilde{H}$ and $B_{\mu\nu}$ by combining them with Dark Sector singlets

Higgs Portal $\lambda_{HS} S^\dagger S H^\dagger H$ — Second part of talk!

Neutrino Portal $-Y^N \bar{L}\tilde{H} N$

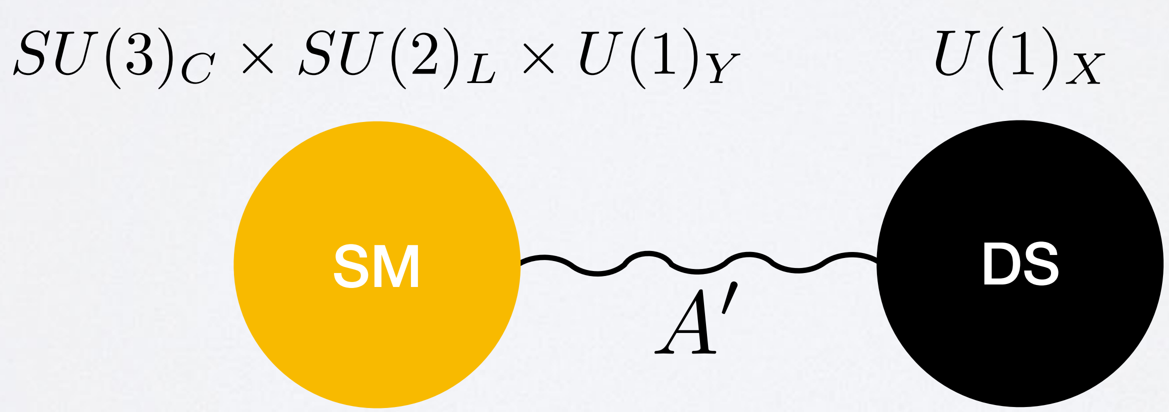
Vector Portal $-\frac{\epsilon_Y}{2} B_{\mu\nu} X^{\mu\nu}$ ← Requires new $U(1)_X$ symmetry

First part of talk!

- Plus non-renormalisable dim-5 portal interaction:

Axion portal $\frac{G_{agg}}{4} a \, \mathrm{Tr}[G_{\mu\nu}\tilde{G}^{\mu\nu}]$

A NEW DARK SYMMETRY



SECLUDED HIDDEN PHOTONS

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_X^2}{2} X_\mu \, X^\mu - g_x \, J_\mu^X X^\mu$$

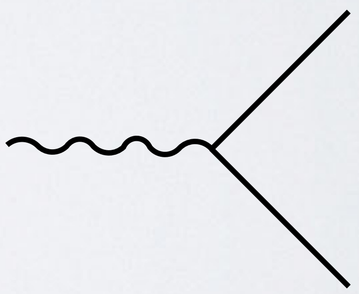
[Holdom; PLB 166, 196]

- Minimal choice is pure secluded U(1) symmetry with

$$J_X^\mu = 0$$

- For light mediators $M_{A'} \ll M_W \sim \mathcal{O}(v)$ the kinetic mixing term in the mass basis can be diagonalised by the field redefinition:

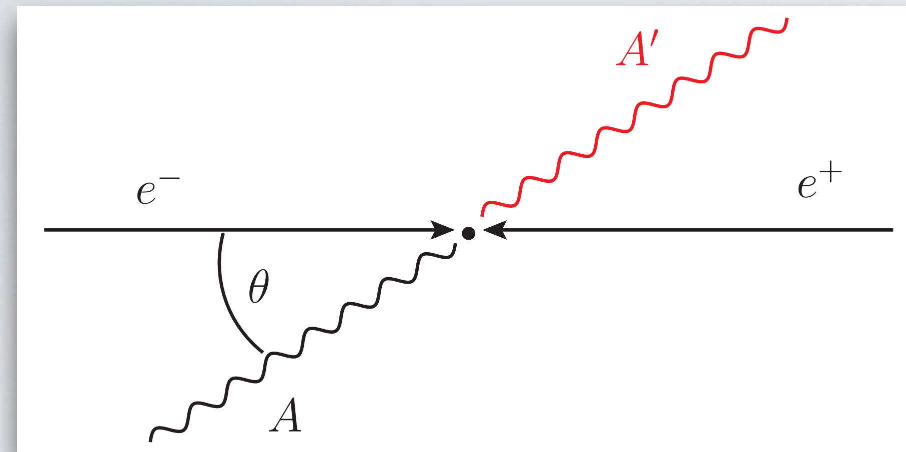
$$A^\mu \to A^\mu - \epsilon A'^\mu \quad \longrightarrow \quad e A_\mu J^\mu_{\rm EM} - \epsilon \, e A'_\mu J^\mu_{\rm EM}$$



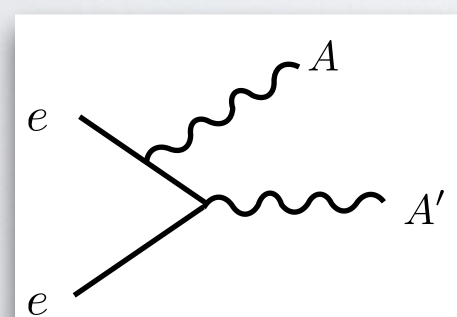
Hidden Photon couples to EM current suppressed by ϵ !

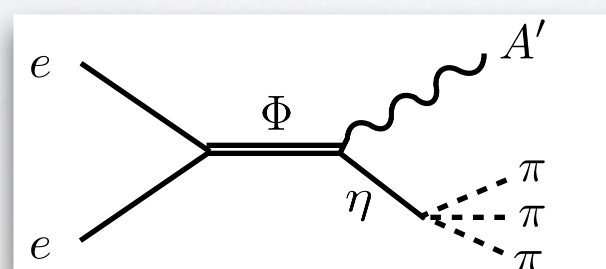
HIDDEN PHOTON SEARCHES

Colliders:



- Production:

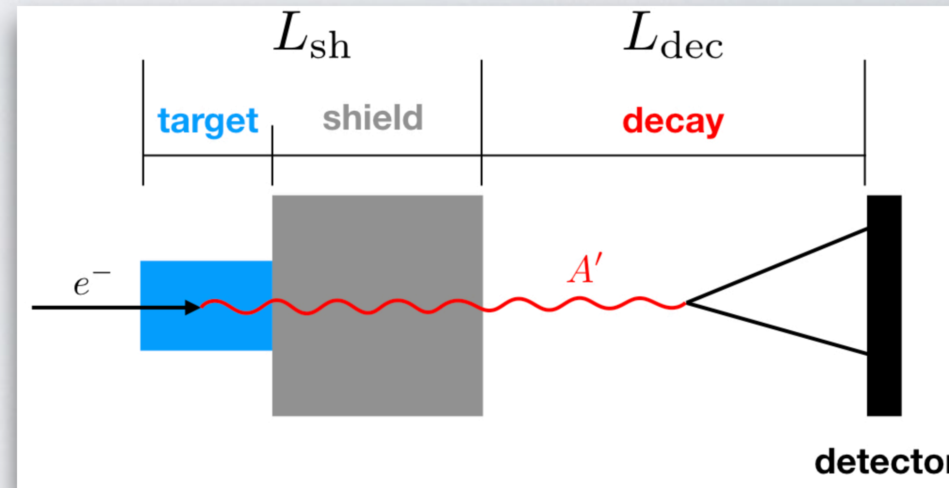




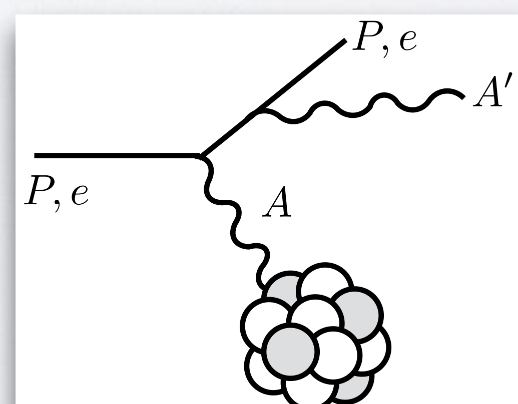
$$\mathscr{L}^{\text{coll}} \approx \mathcal{O}(10^{-1})\ \text{ab}^{-1}\text{yr}^{-1}$$

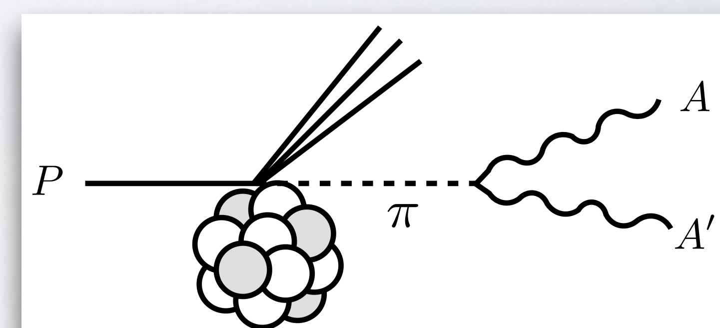
$$\sigma_{A'}^{\text{coll}} \propto \frac{\alpha^2\,\epsilon^2}{E_{\text{CM}}^2}$$

Beam dumps:



$$P_{\text{dec}} = e^{-\frac{L_{\text{sh}}}{\ell_{A'}}}\left(1 - e^{-\frac{L_{\text{dec}}}{\ell_{A'}}}\right)$$

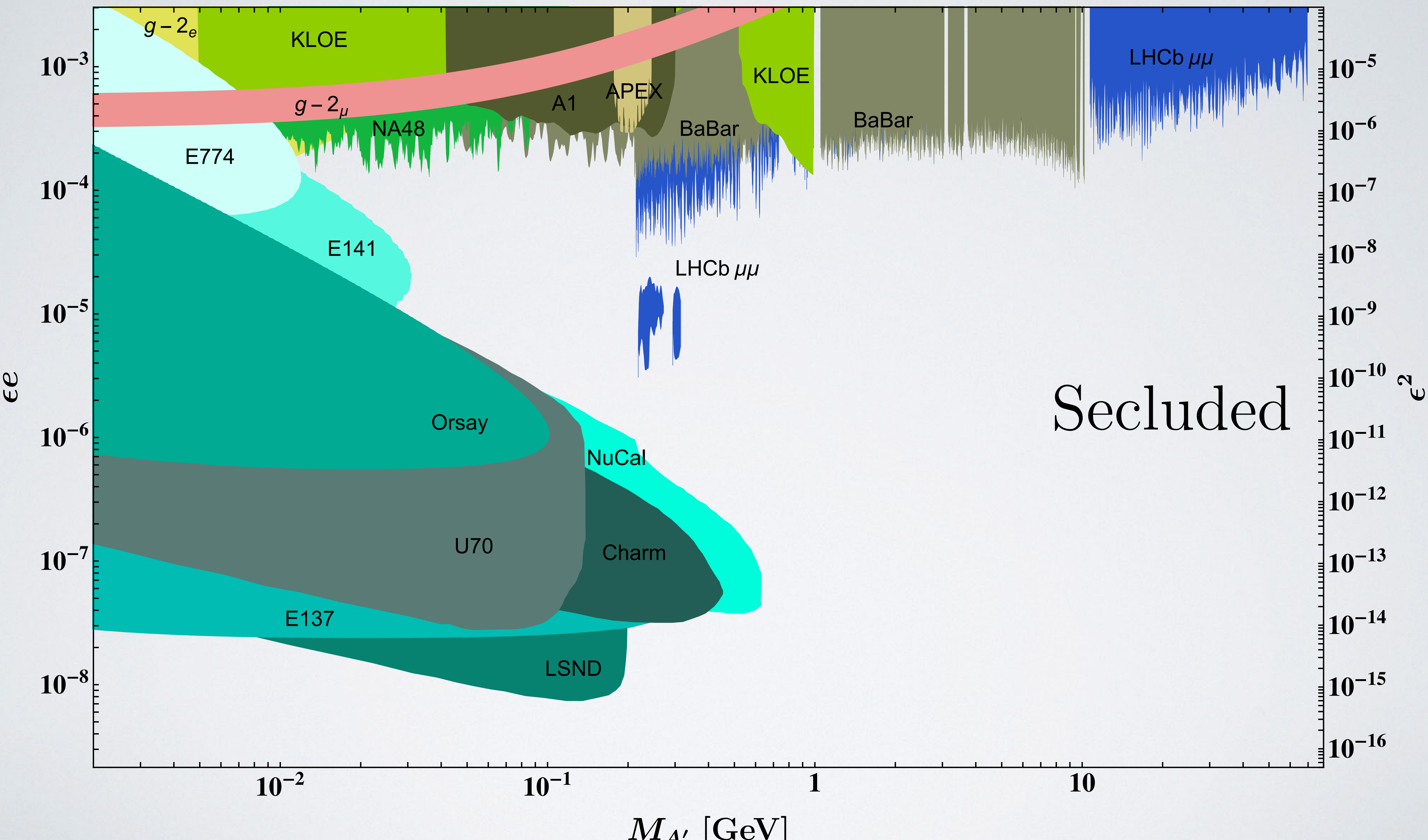




$$\mathscr{L}^{\text{bd}} \approx \mathcal{O}(1)\ \text{ab}^{-1}\text{d}^{-1}$$

$$\sigma_{A'}^{\text{bd}} \propto \frac{\alpha^3\,Z^2\,\epsilon^2}{M_{A'}^2}$$

SECLUDED $U(1)_X$



adapt.[Bauer, PF, Jaeckel; 1803.05466]

ANOMALY FREE GAUGE EXTENSIONS

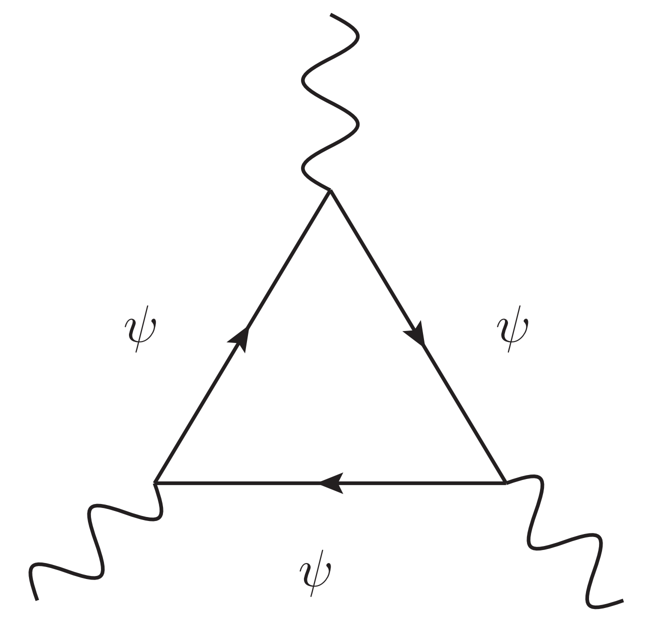
$$J^{\mu}_{X} \neq 0$$

ANOMALY FREE MODELS

- Constraints on possible charge assignments of SM fields plus 3 RH neutrinos from **anomaly cancellation:**

$$J^\mu_X = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Define sum of family charges $\quad X^n_\psi = \sum_i^3 (Q_{\psi_i})^n$



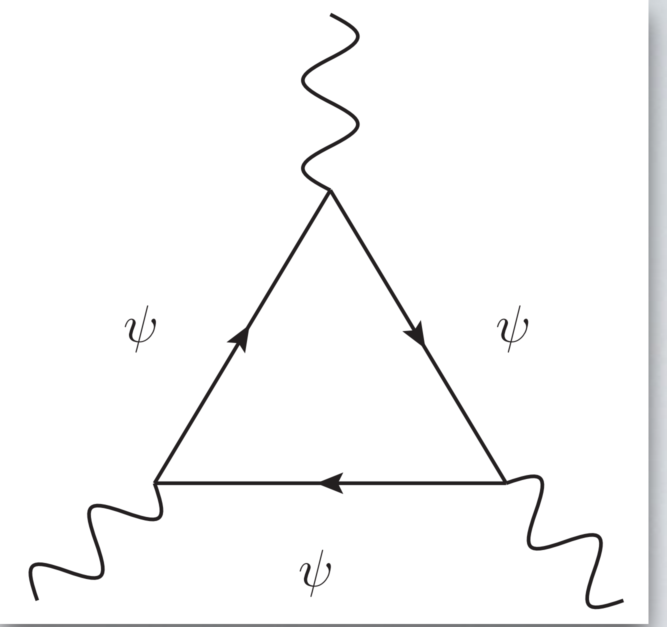
Anomaly	Charge combinations
$U(1)^3_X$	$2X^3_L + 6X^3_Q - X^3_\ell - X^3_\nu - 3(X^3_u + X^3_d)$
$U(1)^2_X U(1)_Y$	$2Y_L X^2_L + 6Y_Q X^2_Q - Y_\ell X^2_\ell - Y_\nu X^2_\nu - 3(Y_u X^2_u + Y_d X^2_d)$
$U(1)_X U(1)^2_Y$	$2Y^2_L X_L + 6Y^2_Q X_Q - Y^2_\ell X_\ell - Y^2_\nu X_\nu - 3(Y^2_u X_u + Y^2_d X_d)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$

ANOMALY FREE MODELS

- Constraints on possible charge assignments of SM fields plus 3 RH neutrinos from **anomaly cancellation:**

$$J_X^\mu = \sum_\psi \bar\psi\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Define sum of family charges $\quad X_\psi^n = \sum_i^3 (Q_{\psi_i})^n$



- Additional constraints from **Yukawa terms:**

$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} \sum_\psi \bar\psi y_\psi \psi$$

Anomaly	Charge combinations	with Yukawa constraints
$U(1)_X^3$	$2X_L^3 + 6X_Q^3 - X_\ell^3 - X_\nu^3 - 3(X_u^3 + X_d^3)$	$X_L^3 - X_\nu^3$
$U(1)_X^2 U(1)_Y$	$2Y_L X_L^2 + 6Y_Q X_Q^2 - Y_\ell X_\ell^2 - Y_\nu X_\nu^2 - 3(Y_u X_u^2 + Y_d X_d^2)$	0
$U(1)_X U(1)_Y^2$	$2Y_L^2 X_L + 6Y_Q^2 X_Q - Y_\ell^2 X_\ell - Y_\nu^2 X_\nu - 3(Y_u^2 X_u + Y_d^2 X_d)$	$-\frac{1}{2}(X_L + 3X_Q)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$	0
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$	$X_L - X_\nu$

DIRAC NEUTRINOS

- Structural invariance of Yukawa terms allows for **three different classes** of family charges

$$Q_\psi = (a,a,a) \quad (a,a,b) \quad (a,b,c)$$

and hence w.l.o.g. $Q_Q = Q_u = Qd$ and $Q_L = Q_\ell = Q_\nu$

- After diagonalising the mass terms $\bar{\psi}_L \, U_\psi \, M_\psi \, W_\psi^\dagger \, \psi_R$ final set of **constraints** from

$$V_{\mathrm{CKM}} = U_u U_d^\dagger \qquad\qquad V_{\mathrm{PMNS}} = U_\ell U_\nu^\dagger$$

- In **absence** of **Majorana masses** (Dirac neutrinos) only a^3lepton charges can reproduce viable PMNS matrix! Thus:

$$X_{\mathrm{leptons}} + 3X_{\mathrm{quarks}} = 0 \quad \Longrightarrow \quad U(1)_{B-L}$$

[Bauer, PF, Mosny; 2011.12973]

MAJORANA NEUTRINOS

- All other anomaly free groups **must have Majorana neutrinos!**

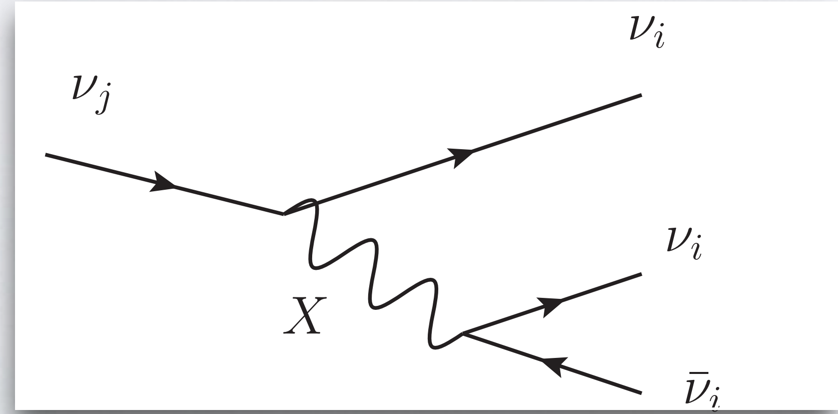
  e.g. $U(1)_{L_i - L_j}$, $U(1)_{B-3L_i}$, $\cdots$

- Majorana mass terms induce **neutrino flavour changing couplings** of neutrino mass eigenstates

$$[Q_\ell, U_\nu^M] = [Q_\nu, U_\nu^M] \neq 0$$

$$\bar{\nu}_\alpha \, Q_{\alpha\alpha} \gamma^\mu \, \nu_\alpha \; X_\mu \quad \rightarrow \quad \bar{\nu}_i \; \underbrace{U^\dagger_{i\alpha} Q_{\alpha\alpha} U_{\alpha j}}_{Q_{ij}} \; \gamma^\mu \, \nu_j \; X_\mu$$

- This could in principle induce neutrino decays. Potentially interesting for astrophysical neutrinos



but $\Gamma \propto \dfrac{g^2 m_\nu^5}{M_X^4}$ ϟ

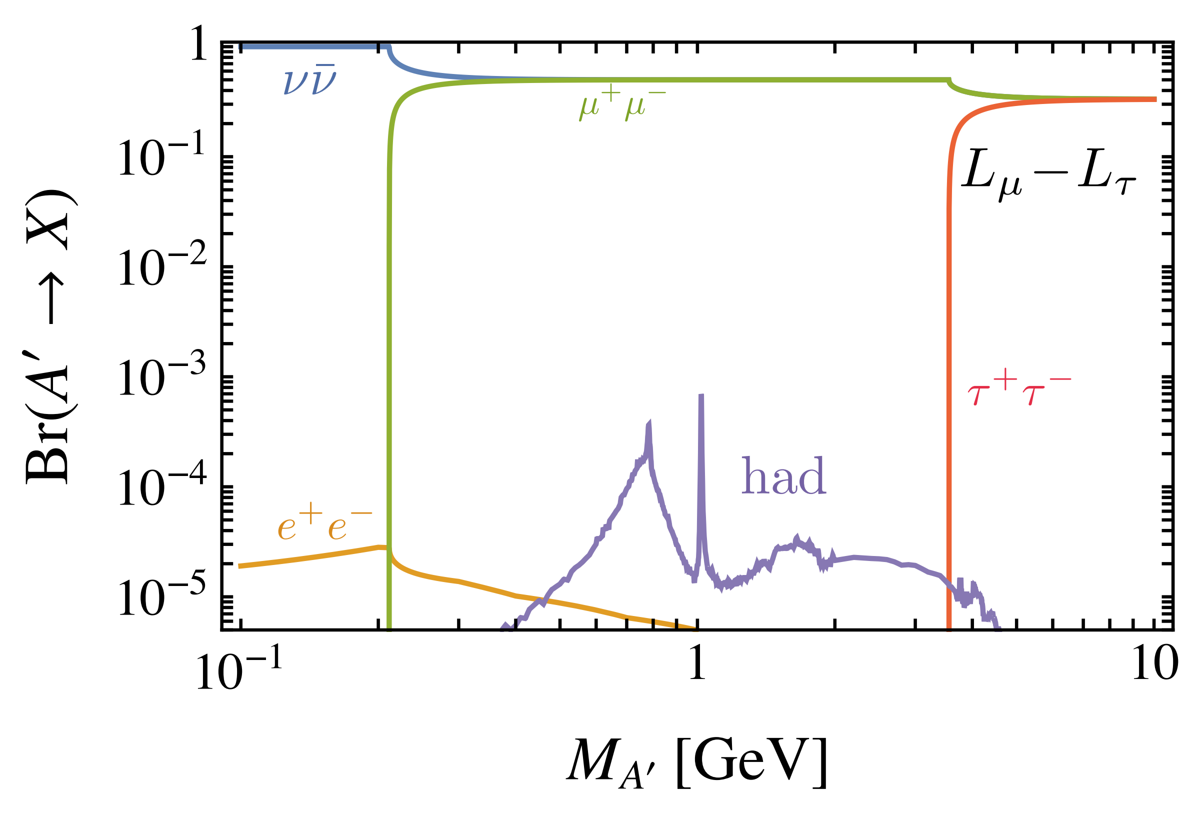
[Bauer, PF, Mosny; 2011.12973]

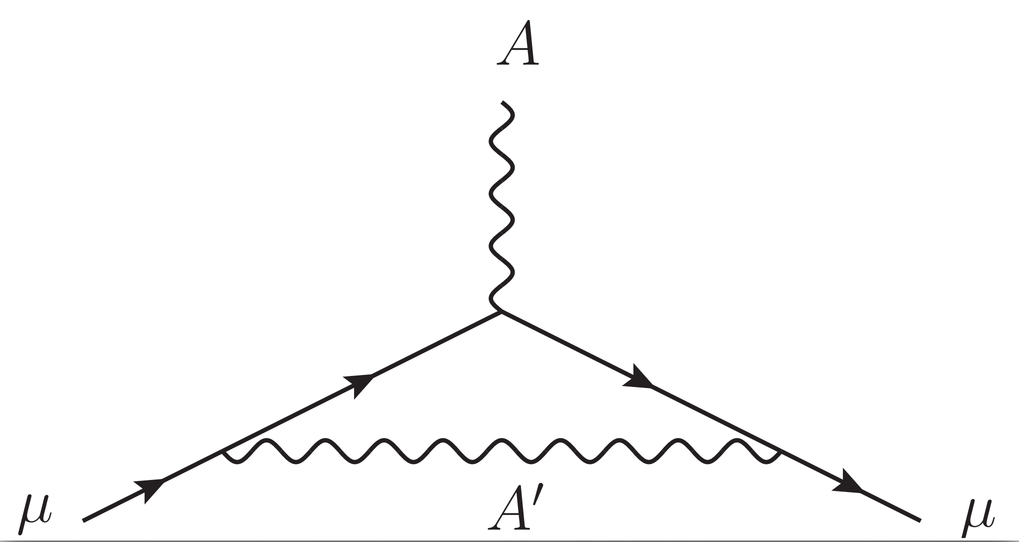
POPULAR EXAMPLE — $U(1)_{L_\mu - L_\tau}$

Why is this interesting?

- **No gauge interactions with ordinary matter!**
- Below dimuon threshold **only decays to neutrinos** (almost)
- Only minimal U(1) extension with viable $(g-2)_\mu$ **solution**

$$\Delta a_\mu = Q_\mu'^2 \frac{\alpha'}{\pi} \int_0^1 du \frac{u^2(1-u)}{u^2 + \frac{(1-u)}{x_\mu^2}}$$





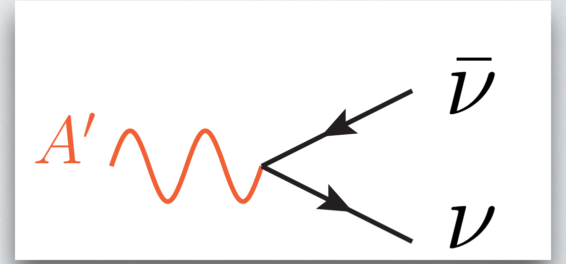
GAUGING LEPTON SYMMETRIES

- Four extra anomaly-free groups within the SM (and combinations):

$L_\mu - L_e$ charging 1st & 2nd generation leptons

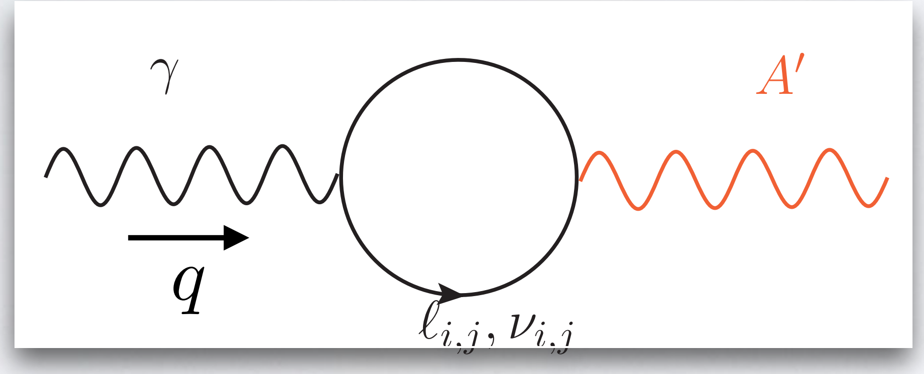
$L_e - L_\tau$ charging 1st & 3rd generation leptons

$L_\mu - L_\tau$ charging 2nd & 3rd generation leptons



$$g_X \, Q_\nu \, \bar{\nu}\gamma^\mu \nu \, A'_\mu$$

- Loop-induced mixing is unavoidable!
  However, it is finite and calculable for $L_i - L_j$:



$$\Rightarrow \quad \frac{\epsilon_{ij}(q^2)}{2} \, F^{\mu\nu} F'_{\mu\nu}$$

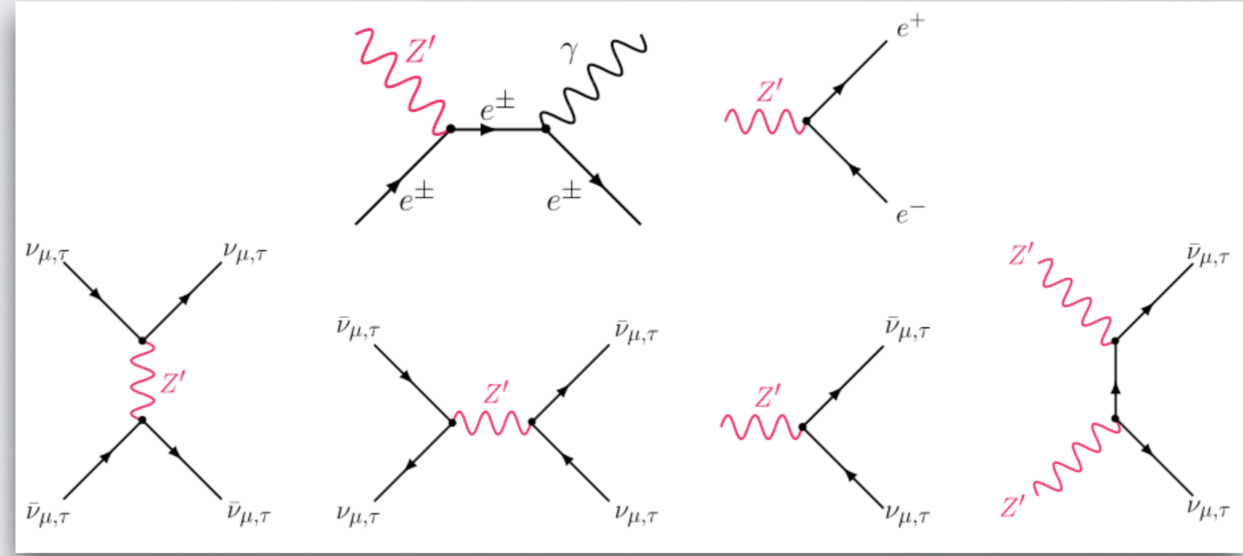
$$\epsilon_{ij}(q^2) = \frac{e\, g_{ij}}{2\pi^2} \int_0^1 dx \, x(1-x) \left[\log \left(\frac{m_i^2 - x(1-x)q^2}{m_j^2 - x(1-x)q^2} \right) \right]$$

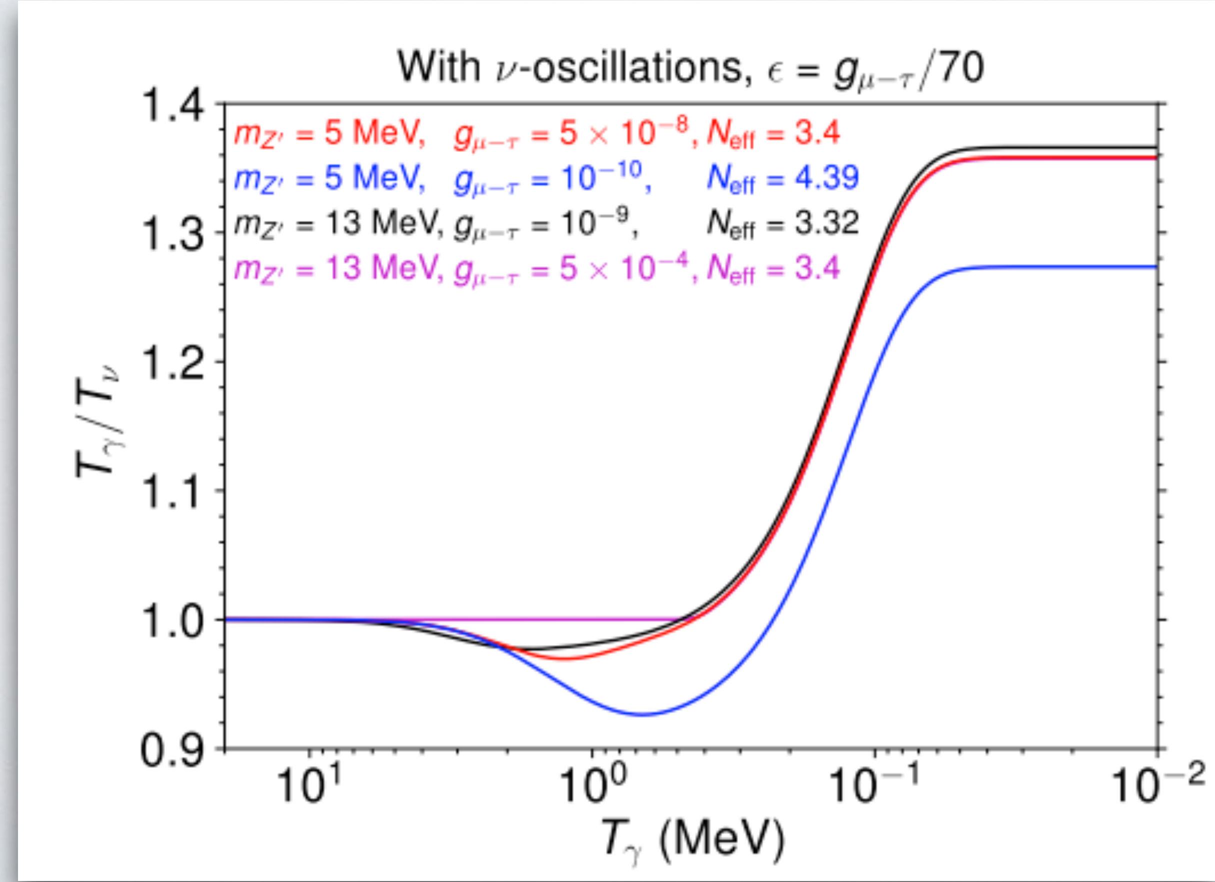
NEUTRINOS AND HUBBLE

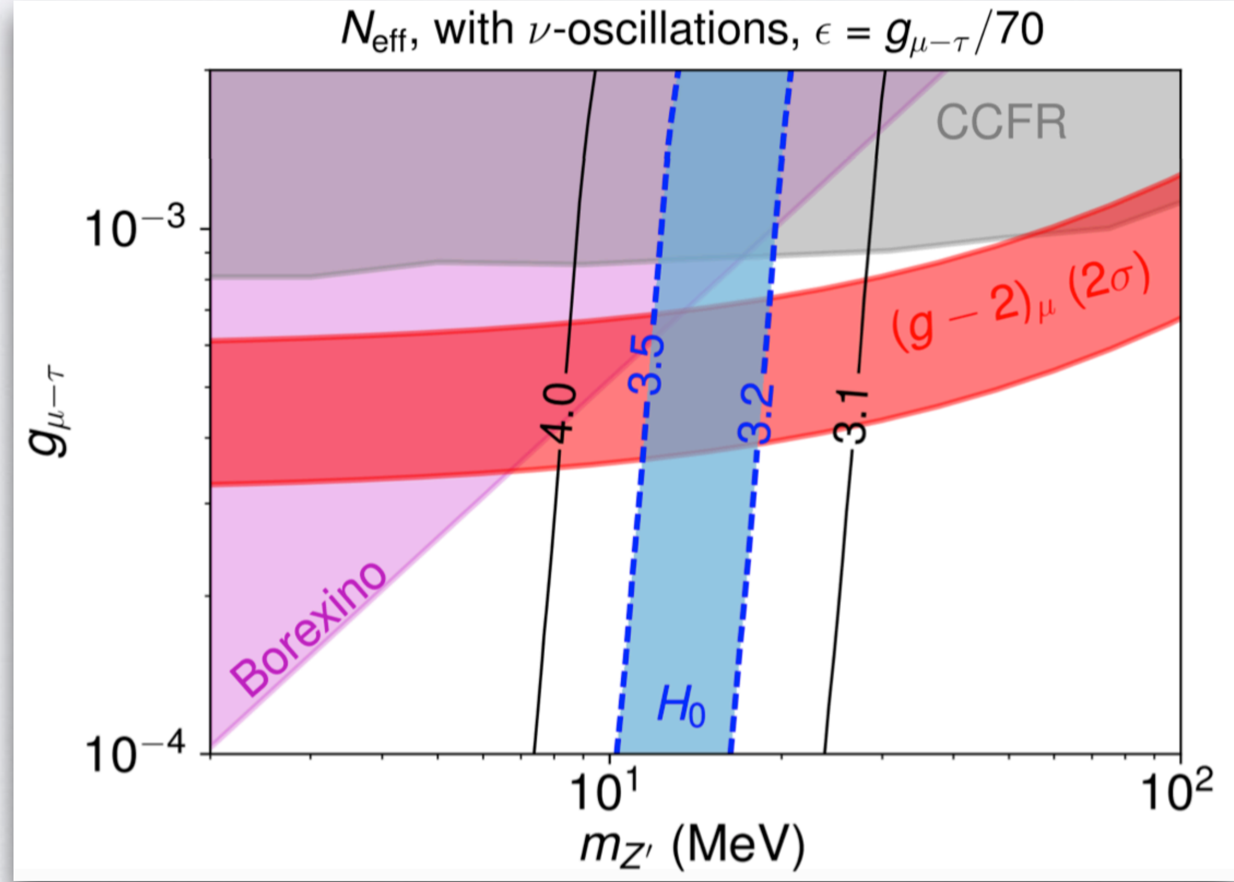
- Decay of A' heats neutrino gas and delays the decoupling

  $\Rightarrow$ increase of $N_{\rm eff}$ at early times

- Leads to larger H_0







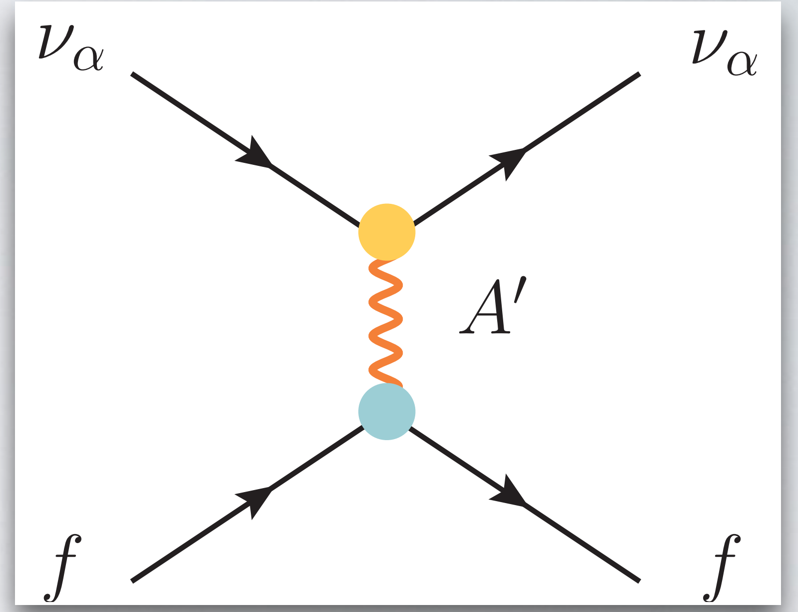
[Escudero, Hooper, Krnjaic, Pierre; JHEP 1903 (2019) 071]

NEUTRINO INTERACTIONS

- QUESTION: Can we utilise gauge-neutrino interactions to test this interesting parameter space?

- IDEA: A' contributes to **neutrino-electron and -nucleus scattering** via kinetic mixing.

- Can be effectively treated as NSI interaction:

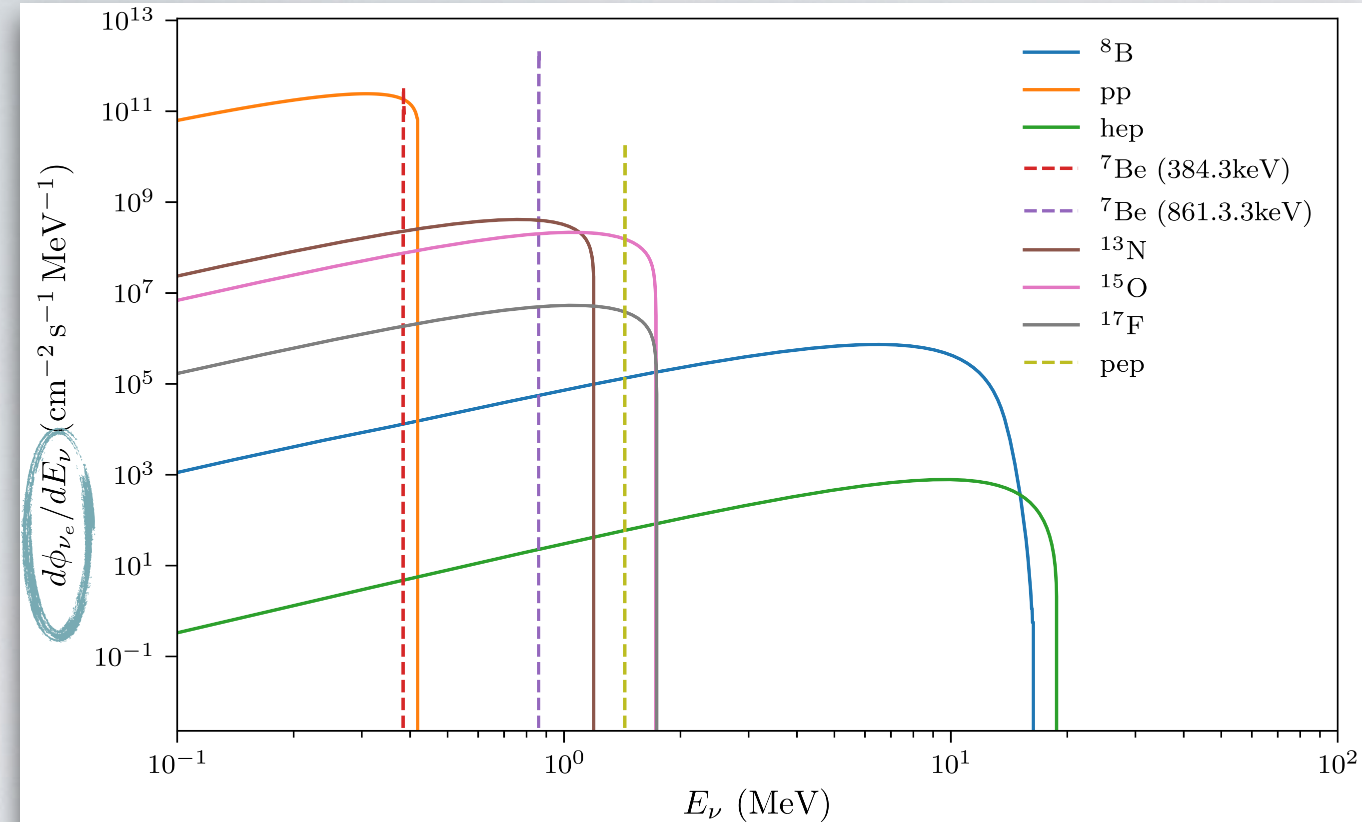


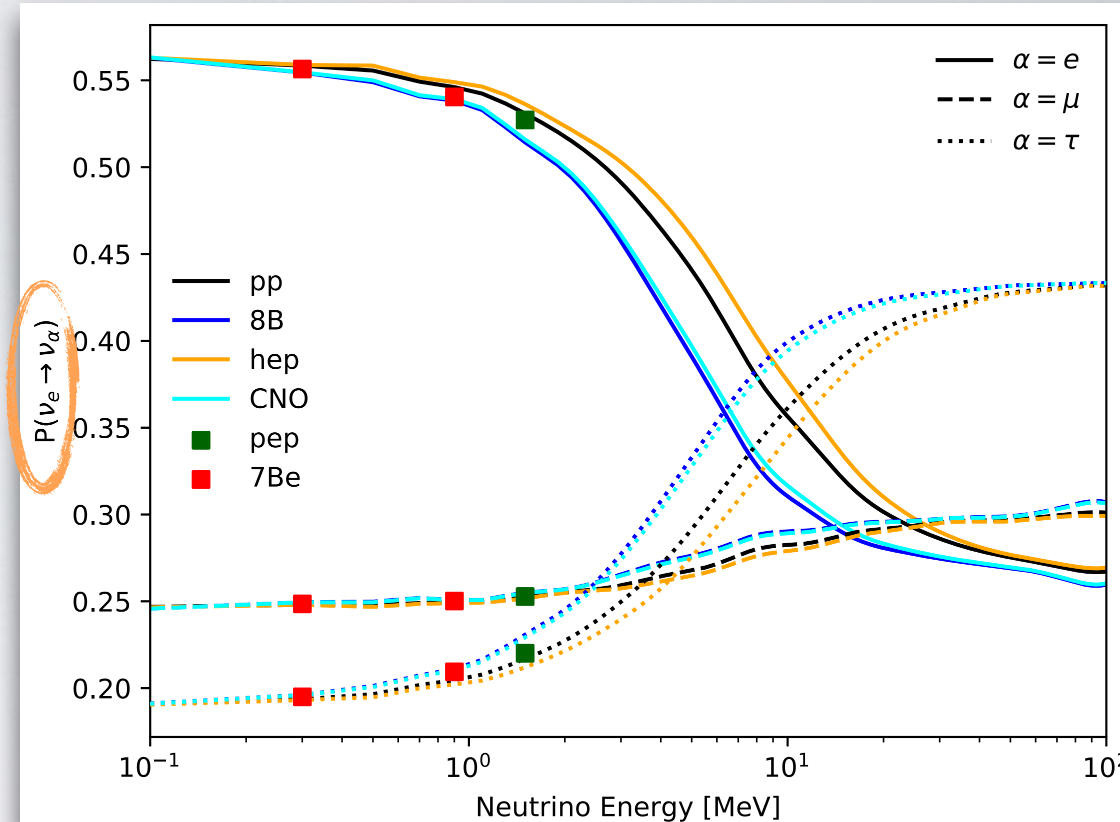
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F \sum_{\substack{f=u,d,e \\ \alpha=e,\mu,\tau}} \varepsilon_{\alpha\alpha}^{fP} \,[\bar{\nu}_\alpha \gamma_\rho P_L \nu_\alpha]\,[\bar{f}\gamma^\rho P f]$$

with

$$\varepsilon_{\alpha\alpha}^{fP}(E_R) = -\frac{g_{\mu\tau}\, Q'_{\nu_\alpha}\; e\,\epsilon_{\mu\tau}\, Q_f^{\rm EM}}{2\sqrt{2}\,G_F\,(2m_f E_R + M_{A'}^2)}$$

SOLAR NEUTRINO SCATTERING





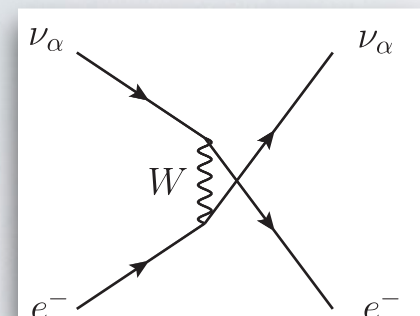
[Amaral, Cerdeno, PF, Reid; 2006.11225]

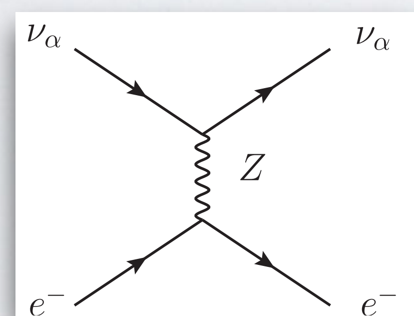
- Solar neutrinos produced in various processes, but initially always in electron flavour.
- In-medium oscillation within solar matter dominantes flavour composition reaching earth
- Total counts in scattering experiment given by

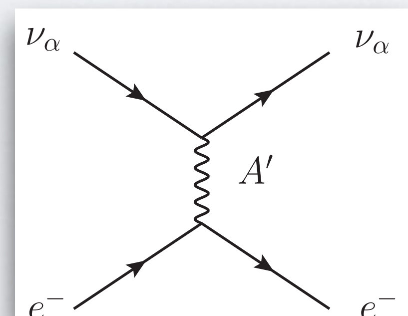
$$N = \varepsilon\, n_T \int_{E_{\rm th}}^{E_{\rm max}} \sum_{\nu_\alpha} \int_{E_\nu^{\rm min}} \frac{d\phi_{\nu_e}}{dE_\nu} P(\nu_e \to \nu_\alpha) \frac{d\sigma_{\nu_\alpha T}}{dE_R}\, dE_\nu dE_R$$

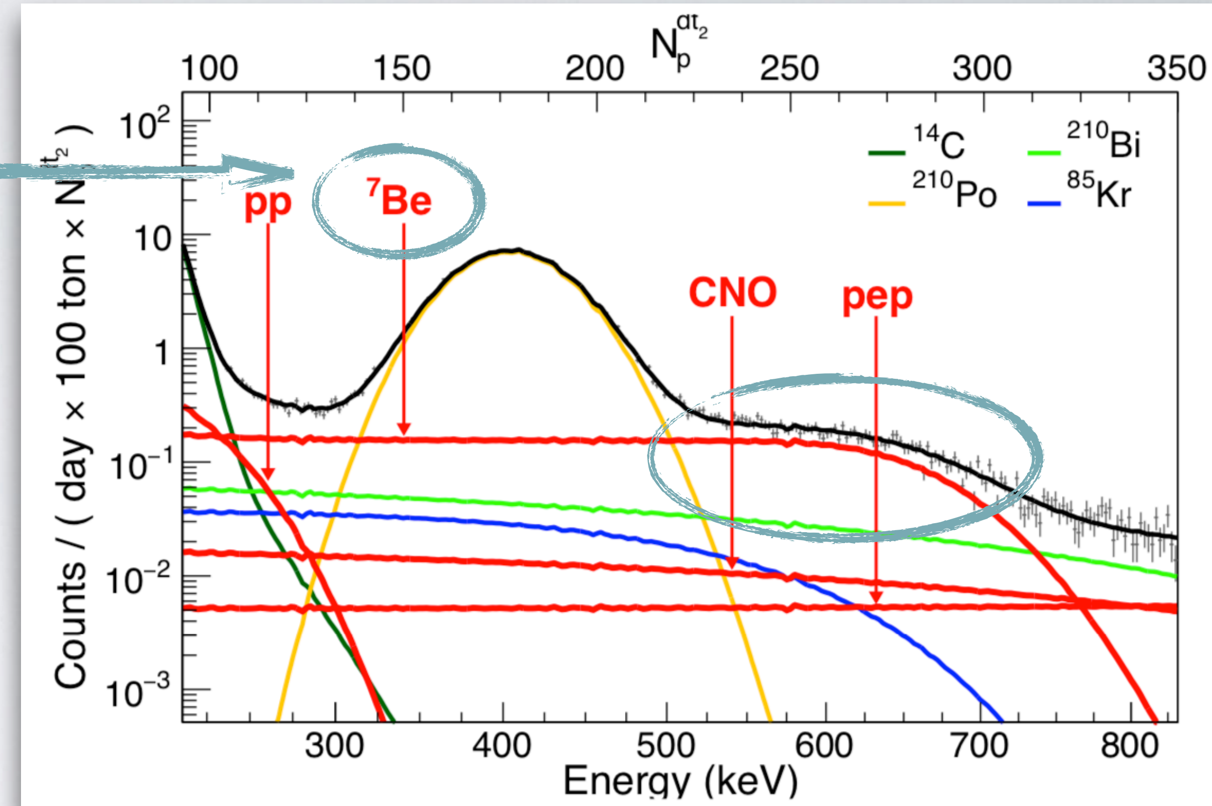
BOREXINO

- Borexino measured the $^7\mathrm{Be}$ flux very precisely in its Phase I and II runs.









Phase II [Borexino; PRD 100, 082004]

Phase I [Borexino; PRL 107, 141302]

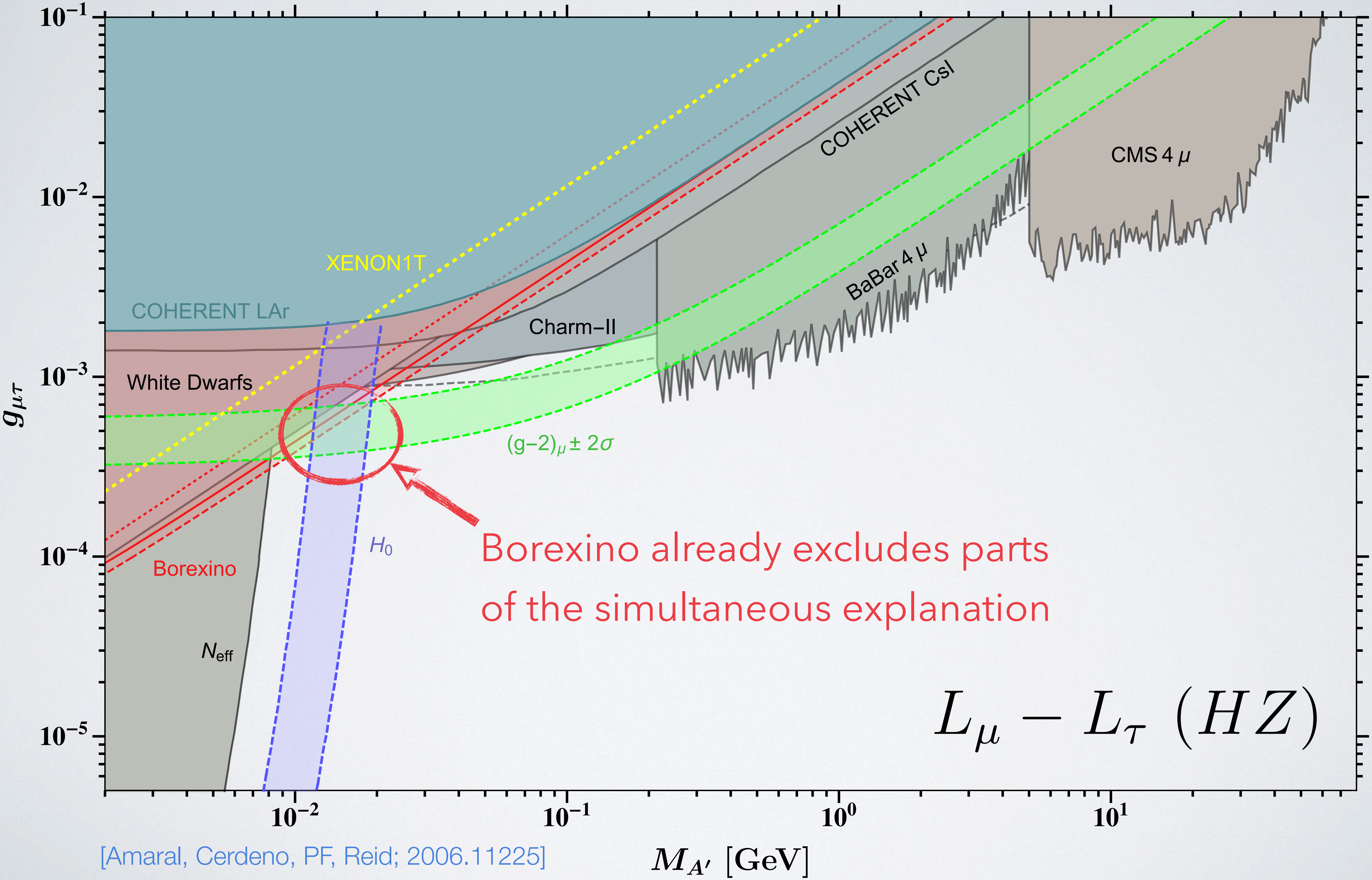
- In the NSI formulation we have:

$$\frac{d\sigma_{\nu_\alpha e}}{dE_R} = \frac{2G_F^2\, m_e}{\pi}\left[(g_1^\alpha)^2 + (g_2^\alpha)^2\left(1 - \frac{E_R}{E_\nu}\right)^2 - g_1^\alpha\, g_2^\alpha\, \frac{m_e E_R}{E_\nu^2}\right]$$

with

$$g_1^\alpha = \begin{cases} 1 + g_L^e + \varepsilon_{\alpha\alpha}^{eL}\,, & \text{for } \alpha = e \\ g_L^e + \varepsilon_{\alpha\alpha}^{eL}\,, & \text{for } \alpha = \mu, \tau \end{cases} \qquad g_2^\alpha = g_R^e + \varepsilon_{\alpha\alpha}^{eR}$$

$U(1)_{L_\mu - L_\tau}$ — CURRENT

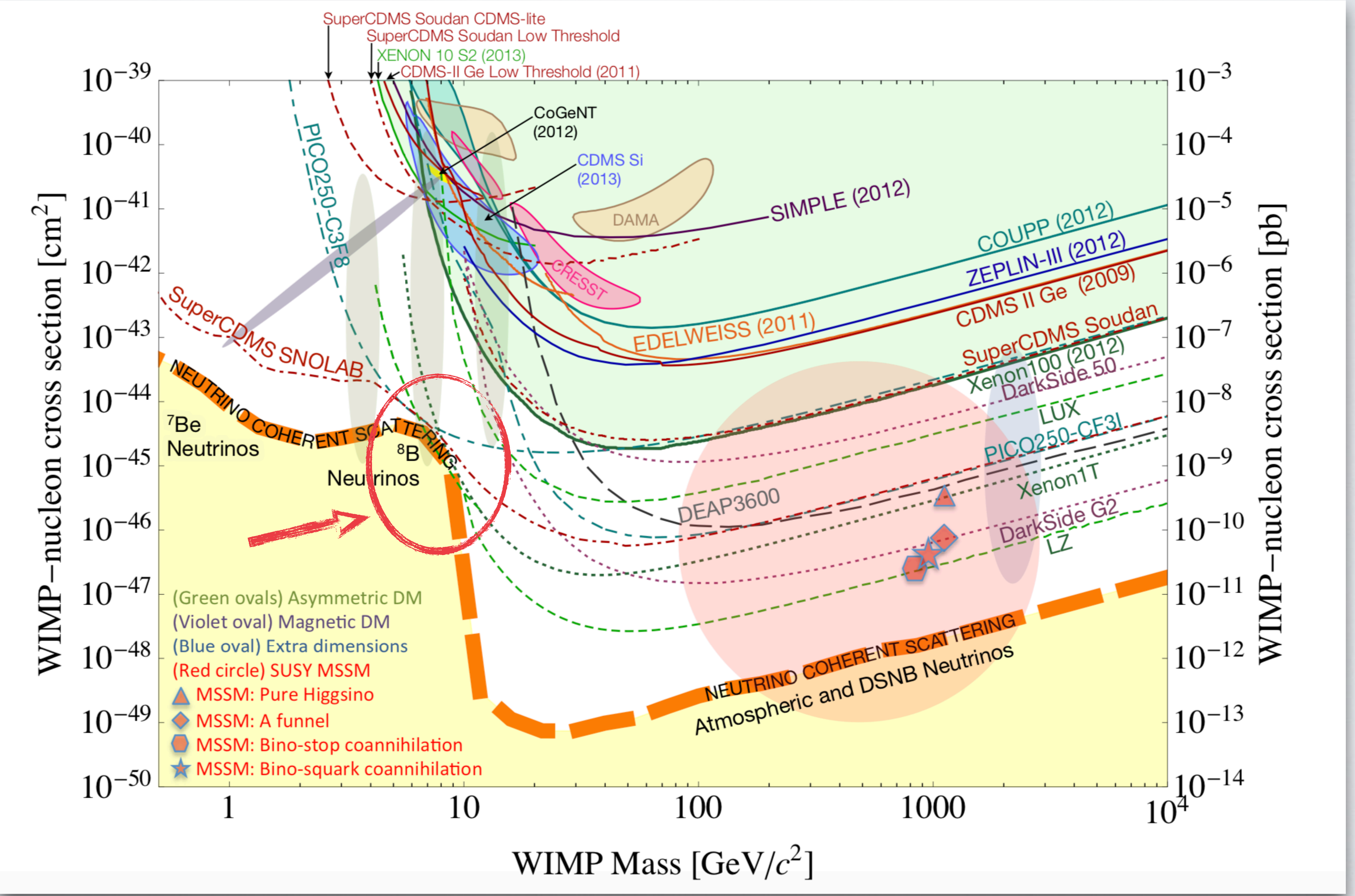


Borexino already excludes parts of the simultaneous explanation

[Amaral, Cerdeno, PF, Reid; 2006.11225]

NEUTRINO FLOOR

- Direct detection experiments will become sensitive to solar neutrino scattering (in particular coherent scattering)



[Snowmass CF1 Summary; 1310.8327]

DIRECT DETECTION

- Future low-threshold DD experiments will be sensitive to NR and ER of solar neutrino scattering

Experiment		ε (t·yr)	NR ($\mathrm{keV_{nr}}$)	ER ($\mathrm{keV_{ee}}$)	NR + ER ($\mathrm{keV_{nr}}$)
G2-Ge	(SuperCDMS iZIP)	0.056	[0.272, 10.4]	[0.120, 50]	-
	(SuperCDMS HV)	0.044	-	-	[0.040, 2]
G2-Xe	(LZ)	15	[3, 5.8]	[2, 30]	[0.7, 100]
G3-Xe	(DARWIN)	200	[3, 5.8]	[2, 30]	[0.6, 100]
G3-Ar	(DarkSide-20k)	100	-	[7, 50]	[0.6, 15]

cannot discriminate NR only

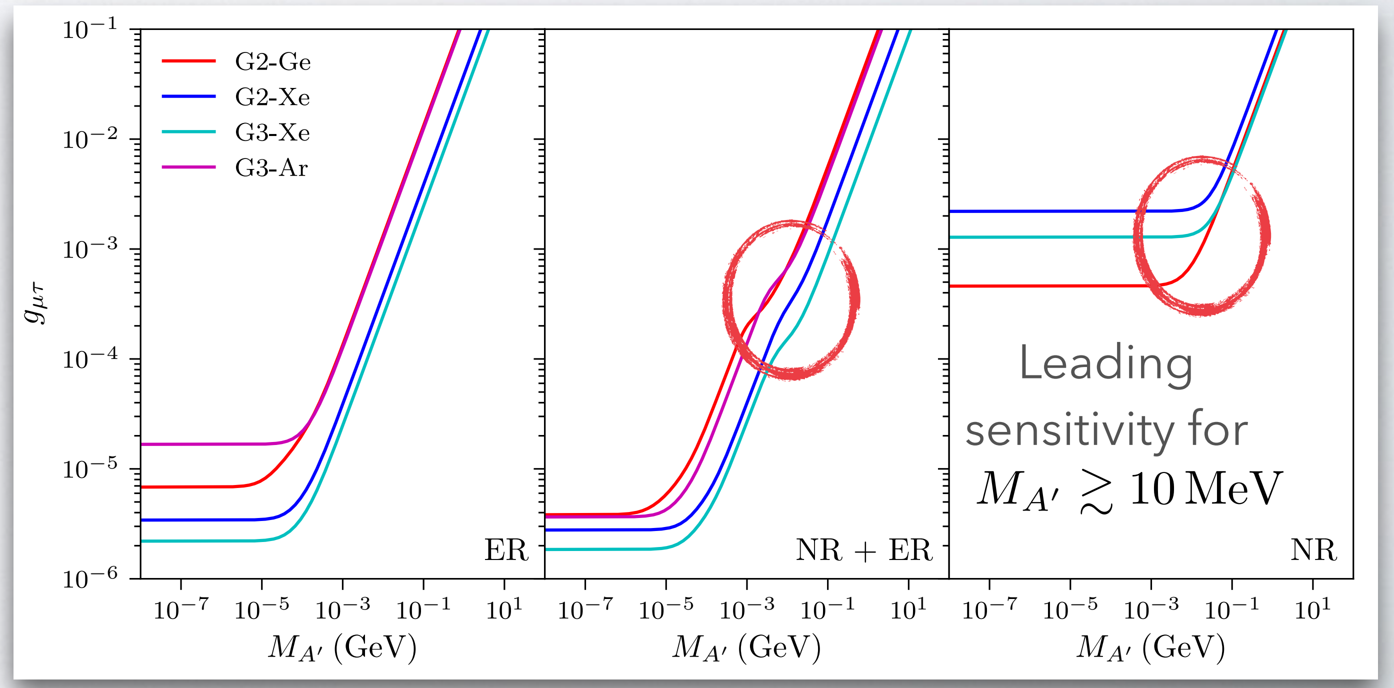
- Coherent neutrino-nucleus scattering:

$$\frac{d\sigma_{\nu_\alpha N}}{dE_R} = \frac{G_F^2 M_N}{\pi}\left(1 - \frac{M_N E_R}{2E_\nu^2}\right)\left\{ {G_{\nu N}^{\mathrm{SM}}}^2 + 2\, G_{\nu N}^{\mathrm{SM}}\, G_{\nu_\alpha N}^{\mathrm{NSI}} + {G_{\nu_\alpha N}^{\mathrm{NSI}}}^2 \right\} F^2(E_R)$$

with

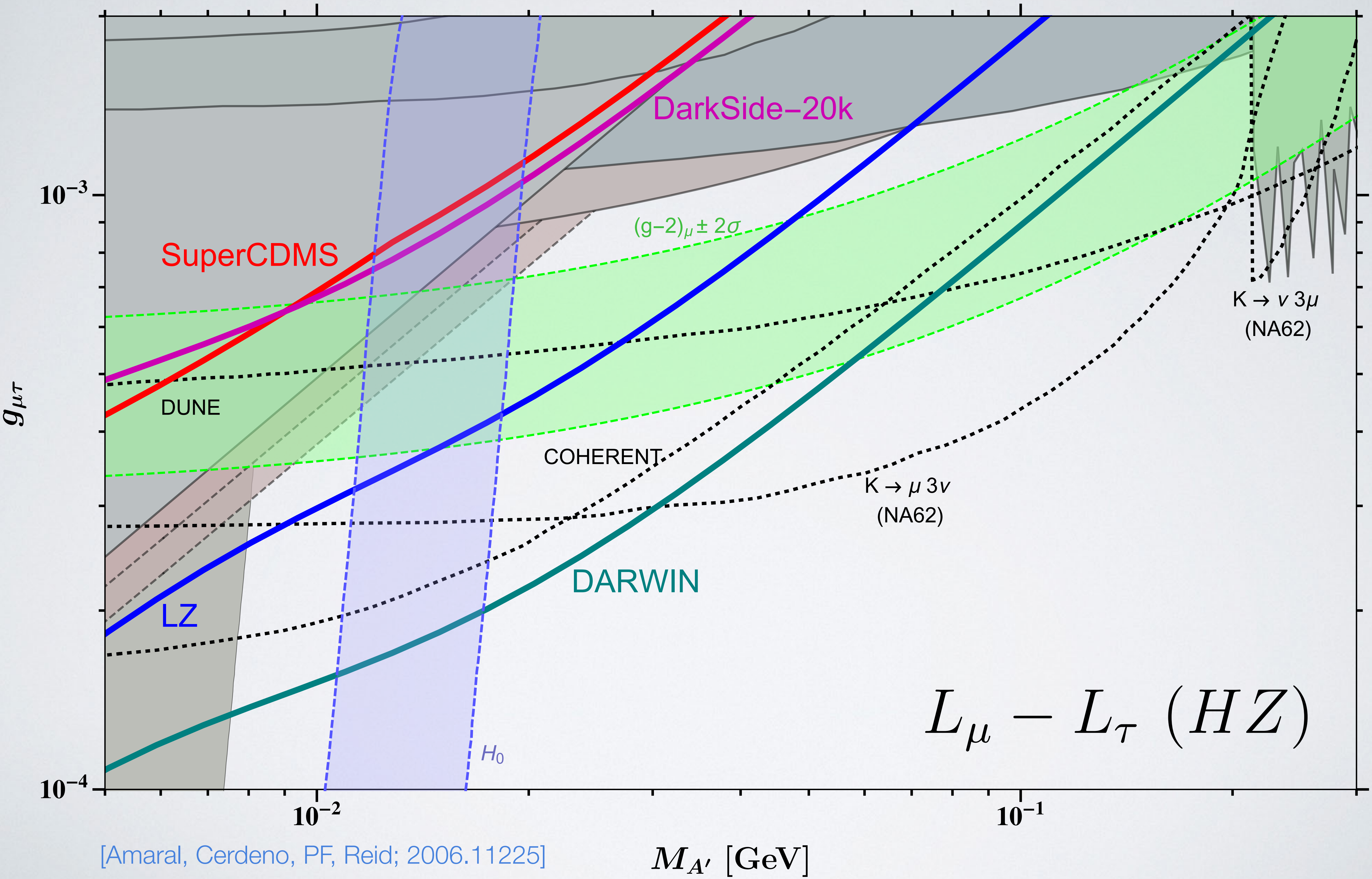
$$G_{\nu N}^{\mathrm{SM}} = -\frac{1}{2}\left[N - (1 - 4\, s_w^2)Z\right]$$

$$G_{\nu_\alpha N}^{\mathrm{NSI}} = -\frac{e\,\epsilon\, g_{\mu\tau}\, Q'_{\nu_\alpha}}{\sqrt{2}G_F(2\,E_R\, M_T + M_{A'}^2)}\, Z$$



[Amaral, Cerdeno, PF, Reid; 2006.11225]

$U(1)_{L_\mu - L_\tau}$ — FUTURE



[Amaral, Cerdeno, PF, Reid; 2006.11225]

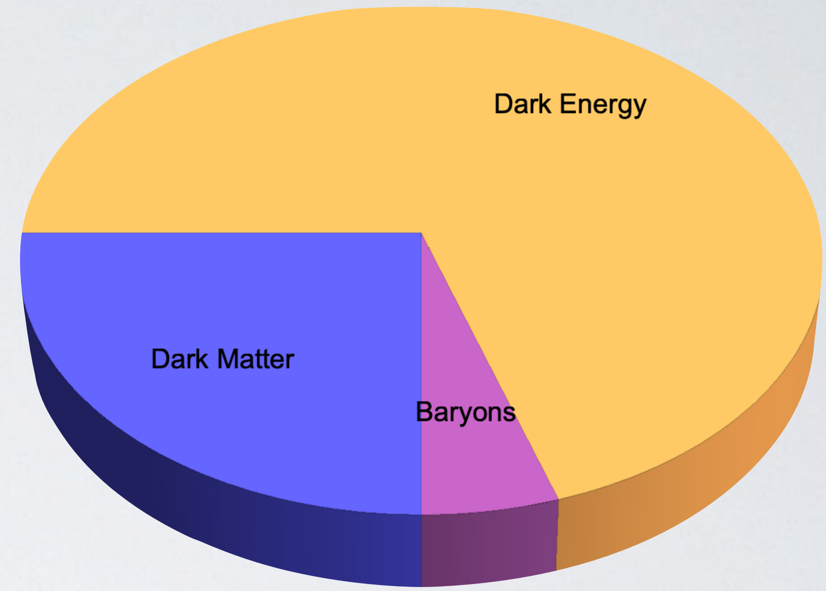
SUMMARY PART I

- General minimal **phenomenologically viable U(1)** models require **Majorana neutrinos**
- **Neutrinos** will play a special role to **test flavour structure** of these models (in particular FCNCs)
- **Solar neutrino scattering** at Borexino excludes part of joint H_0 and $(g-2)_\mu$ explanation within $U(1)_{L_\mu - L_\tau}$
- In the **future direct detection experiments** become sensitive to this explanation, in particular in NR. **Increasing exposure** is more favourable than lowering the threshold to gain sensitivity.

ULTRALIGHT DM

QUICK REMINDER ABOUT DM

1. Stable, cold, (almost) collisionless, dissipationless substance
2. Interacts (only?) gravitationally
3. Makes up ~25 % of the energy density of the universe
4. Mass ?



[Niikura et al., Nat. Astr. 3 (2019) 6]

Galaxy formation

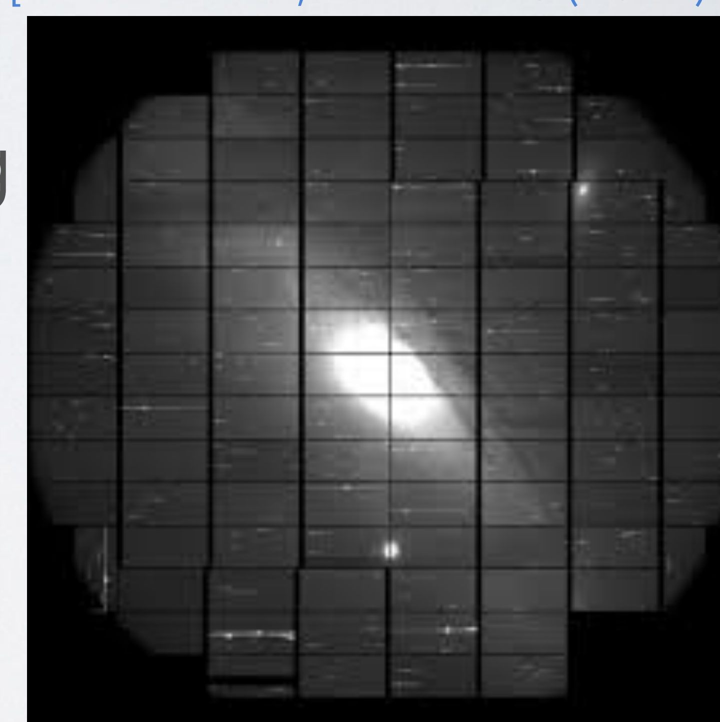
$$\lambda_{dB} = \frac{2\pi}{mv} \lesssim 100 \text{ kpc}$$

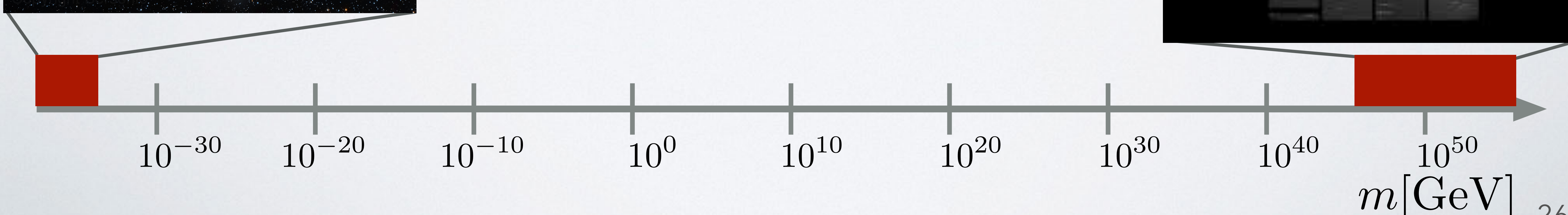
$$m \gtrsim 10^{-24}\,\text{eV}$$

[Hlozek et al., PRD **91** (2015)]

microlensing searches of PBHs

$$m \lesssim 10^{46}\,\text{GeV}$$





THE FUZZY DM PARADIGM

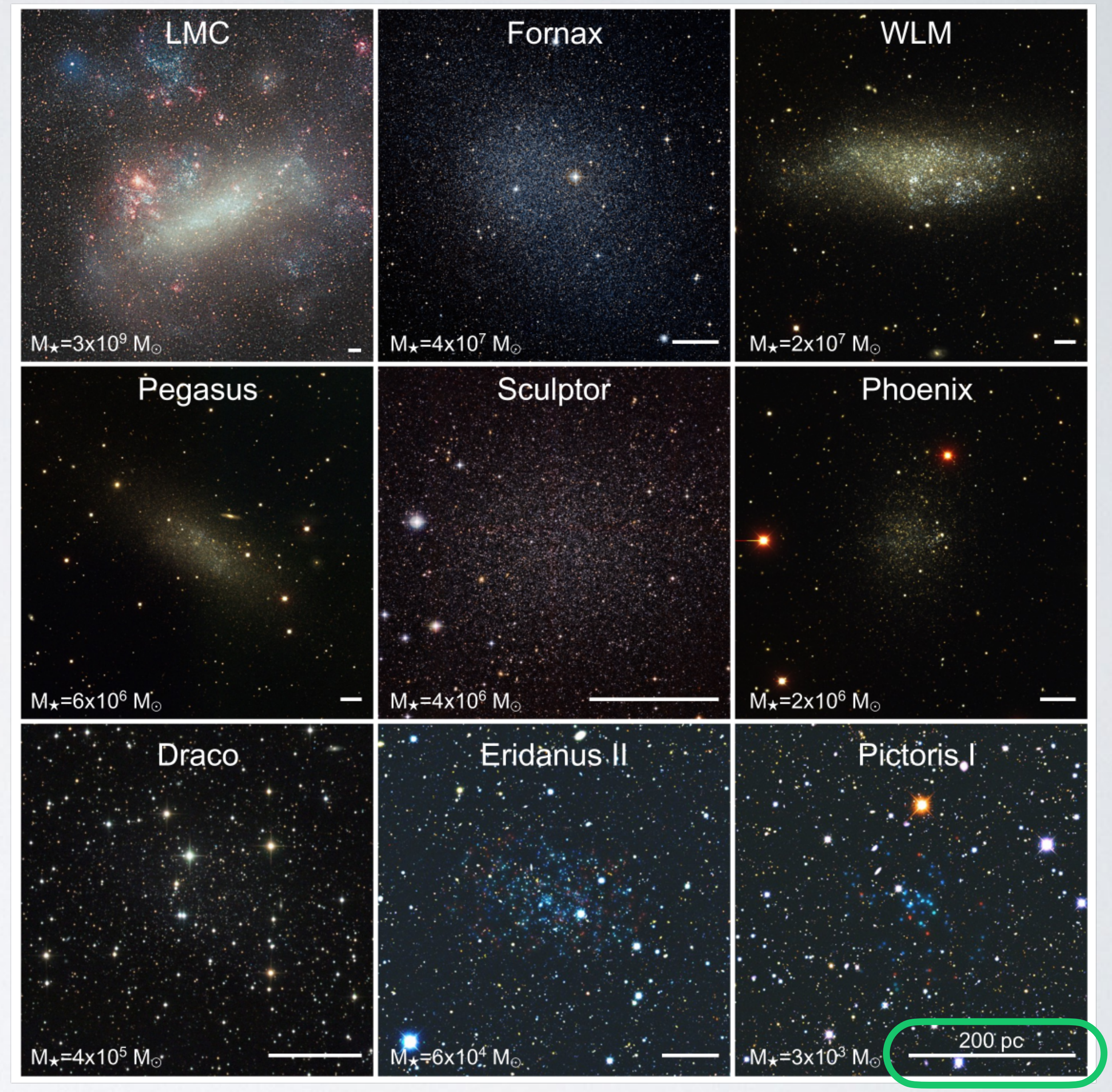
Dwarf galaxies

- Standard CDM typically produces too much small scale structure
- Can be suppressed if DM de Broglie wavelength prohibits small scale structures:

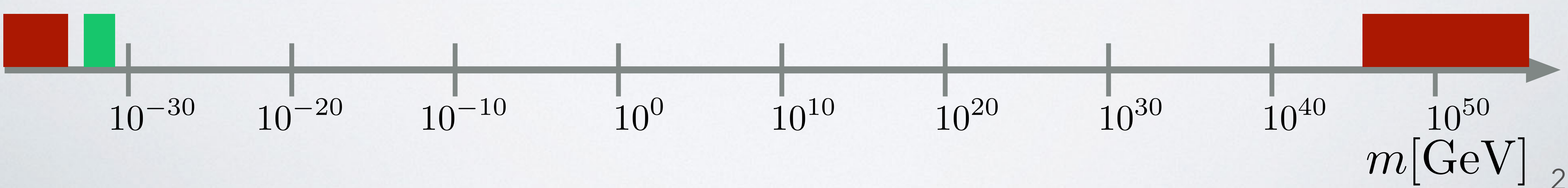
$$m_{\rm DM} \approx 10^{-22}\,{\rm eV} \quad \Rightarrow \lambda_{\rm dB} \gtrsim 1\,{\rm kpc}$$

[Hu, Barkana, Gruzinov, PRL 85 (2000)]

Better fit to small scale structure!



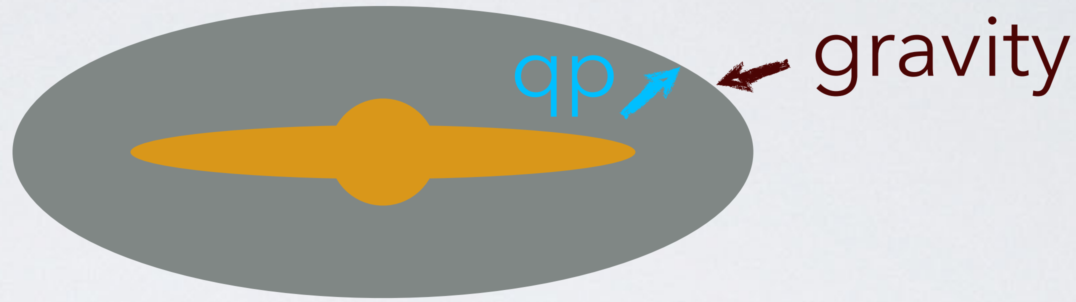
[Bullock et al., Ann.Rev.Astron.Astrophys. 55 (2017)]



THE FUZZY DM PARADIGM

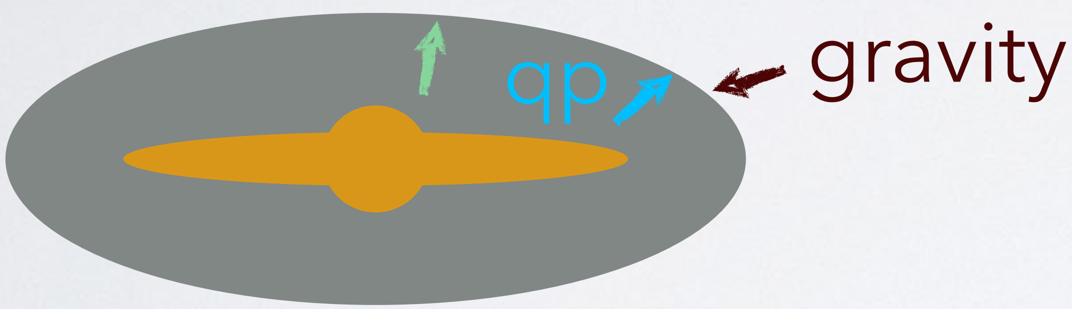
- Small scale is set by a balance of gravity and quantum pressure:

No self-interactions!

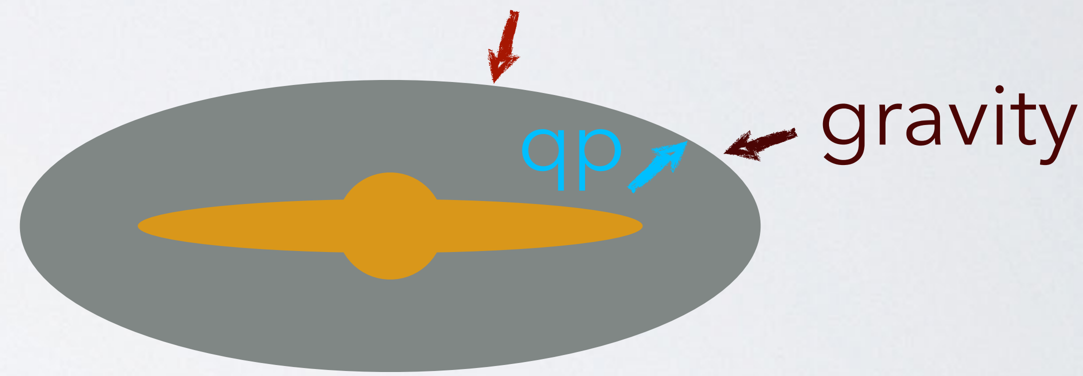


- Self-interactions may drastically alter situation:

repulsive $\lambda > 0$



attractive $\lambda < 0$

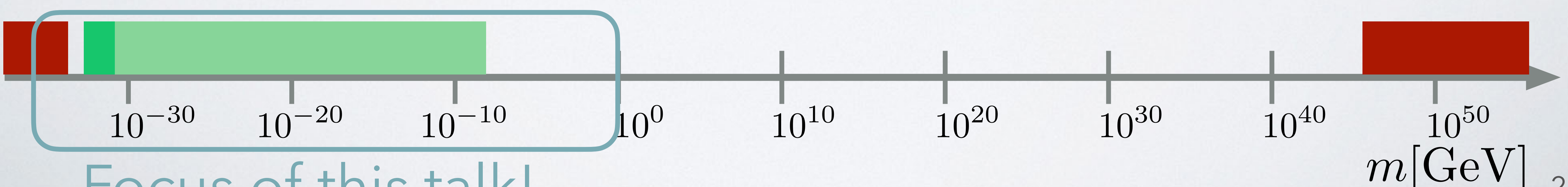


Relaxed mass range: [Ferreira, 2005.03254]

$$m_{\rm DM} \approx 10^{-22} - 1\,\mathrm{eV}$$

Instabilities!

[Guth et al. PRD **92**, 2015]



Focus of this talk!

QFT TOY MODELS FOR FUZZY DM

- Typical searches for Fuzzy DM (FDM) employ their properties of a classical background field.

- **QUESTION**: Can we write down QFT models for this kind of DM and learn something about the microscopic properties?

- **STRATEGY**: Explore complementary search strategies using the particle properties of QFT toy models:

  - FDM can be **scalar** s or **pseudo-scalar** a

  - **Coupled** to SM via **Higgs** H or **new heavy singlet mediator** ϕ

1. SCALAR DM — HIGGS PORTAL

- Most economic way to couple fuzzy DM to SM via Higgs Portal:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu s \partial^\mu s - \frac{1}{2}m_s^2 s^2 - \frac{1}{4!}\lambda_s s^4 - \frac{1}{2}\lambda_{hs} s^2 H^\dagger H$$

- DM is protected by a Z_2 symmetry and has positively bounded potential $\lambda_s > 0$

$\Rightarrow$ FDM can have wide mass range (but for no good reason) due to repulsive self-interactions

- In the FDM regime momenta are small and the occupation numbers are huge

$$n\,\lambda_{\rm dB}^3 \approx 6.35 \cdot 10^5 \left(\frac{\rm eV}{m}\right)^4$$

$\Rightarrow$ can be treated as a classical wave!

How do we search for wave DM?

1. SCALAR DM — HIGGS PORTAL

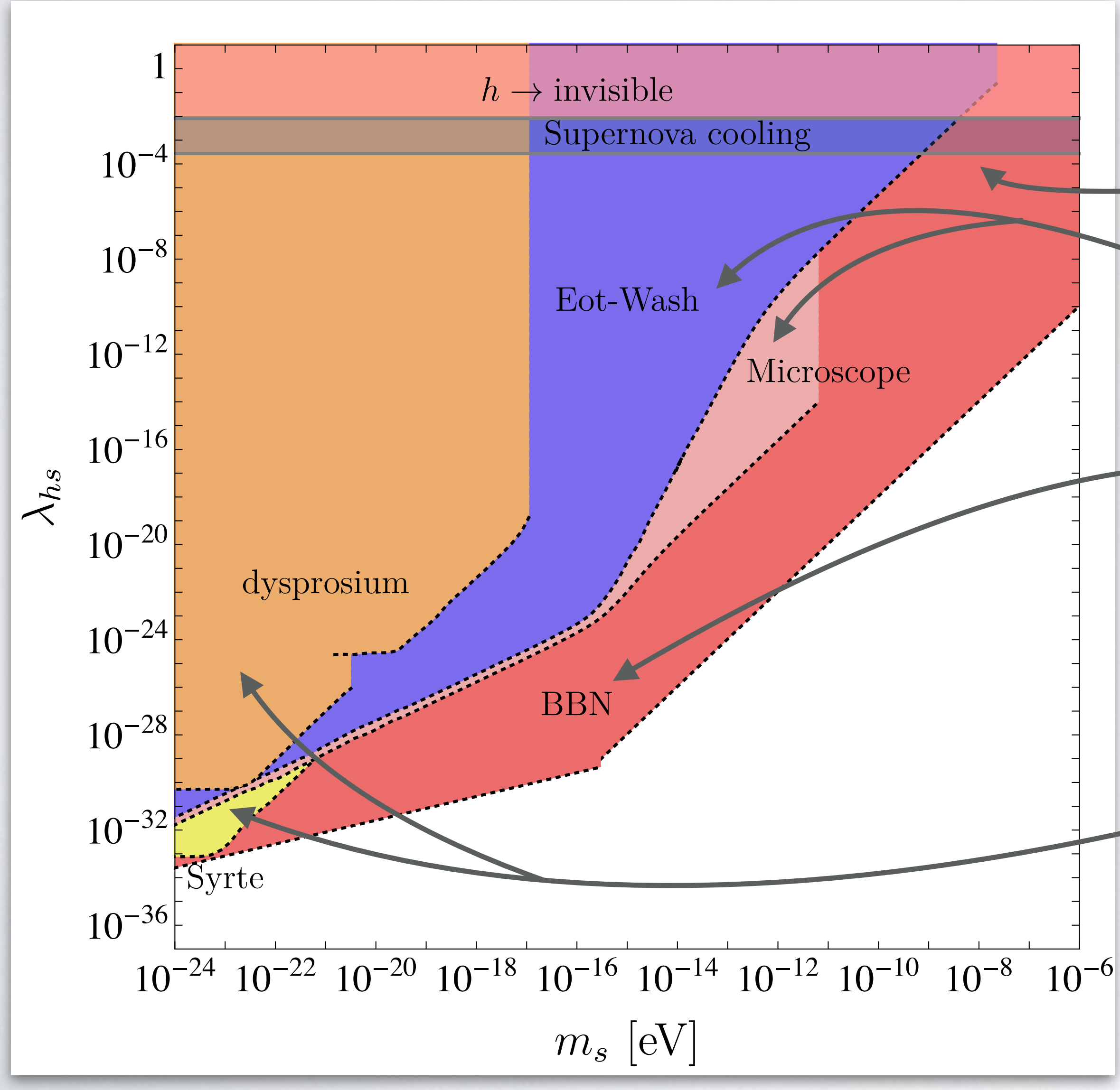
- At low momenta Higgs portal mediates an effective DM-nucleon coupling

$$\mathcal{L} \supset -\frac{1}{2}\lambda_{hs}\, s^2\, H^\dagger H \longrightarrow c_{sNN}\, s^2\, \bar{N} N$$

$$c_{sNN} = \lambda_{hs} \frac{m_N}{m_h^2} \frac{2 n_H}{3(11 - \frac{2}{3} n_L)}$$

where now

$$s^2 = s_0^2 \cos^2(m_s t) \to \frac{s_0^2}{2}(1 + \cos(2 m_s t))$$



Supernova

fifth force

primordial helium abundance

$$m_N - m_P \propto c_{sNN}\, s_0^2$$

oscillating energy levels

[Brax et al.,PRD**97**, 2018]
[Hees et al., PRD **98**, 2018]
[Bauer, PF, Reimitz, Plehn, 2005.13551]

1. SCALAR DM — HIGGS PORTAL

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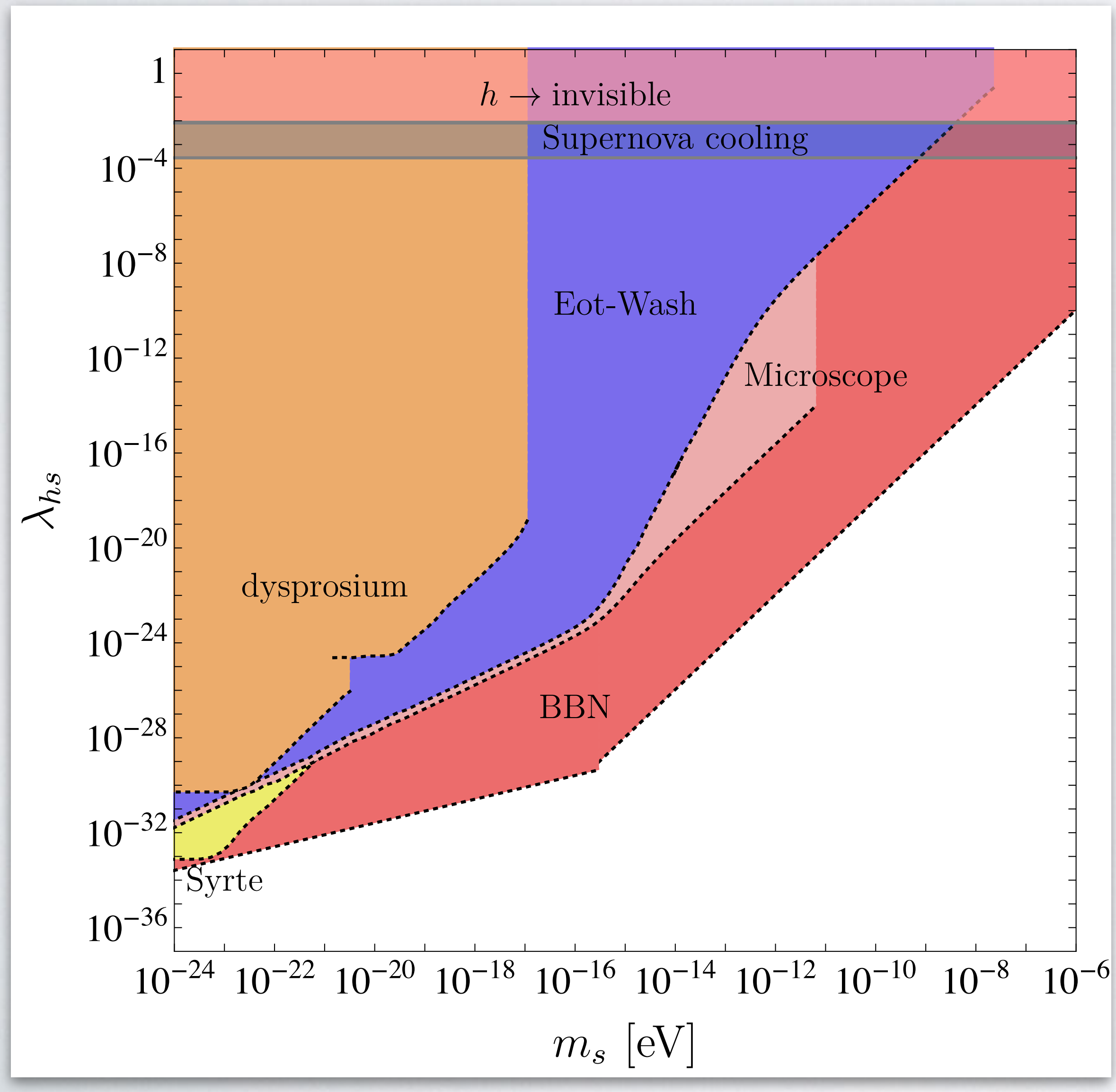
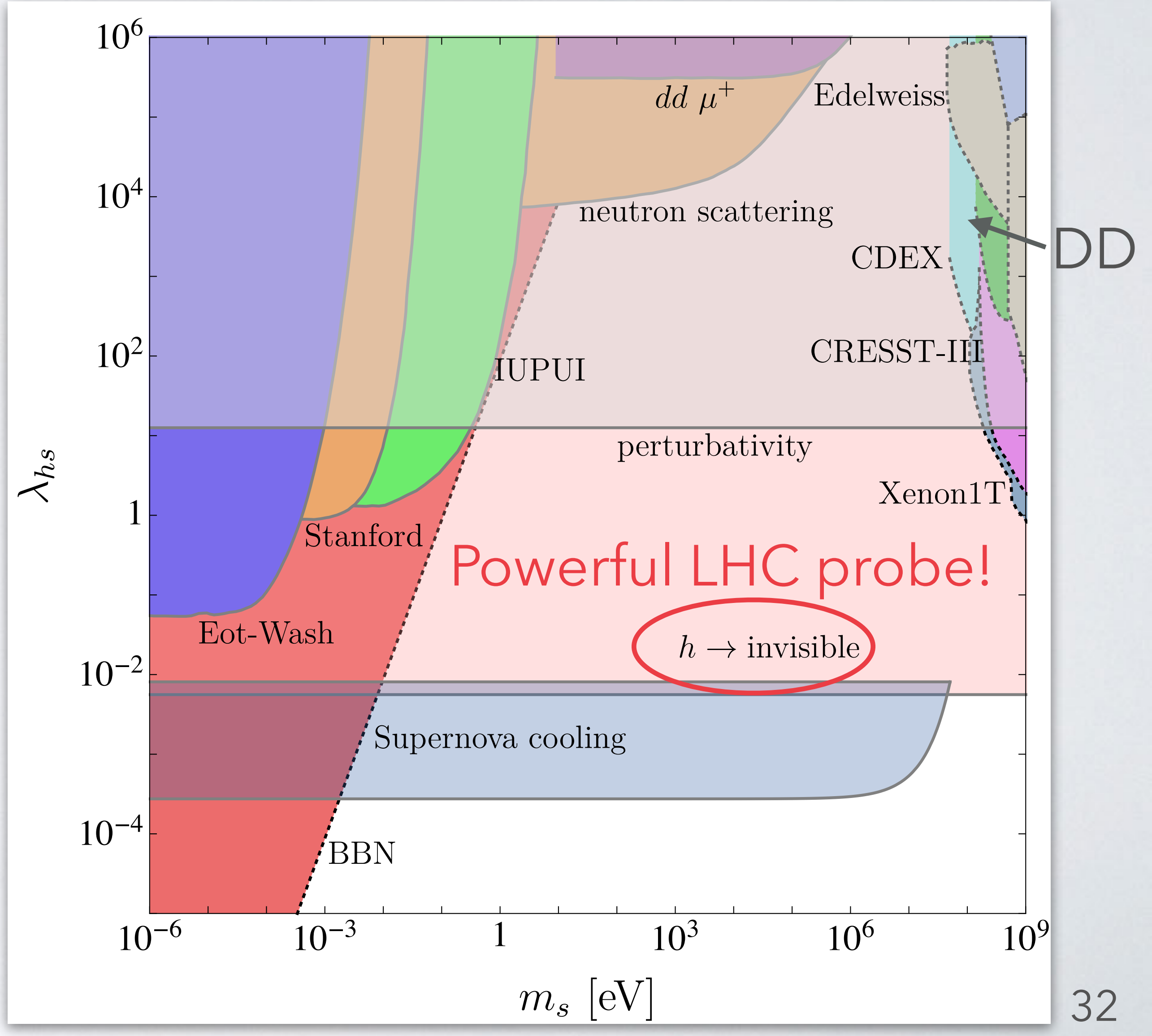
[Bauer, PF, Reimitz, Plehn, 2005.13551]





2. SCALAR DM — NEW MEDIATOR

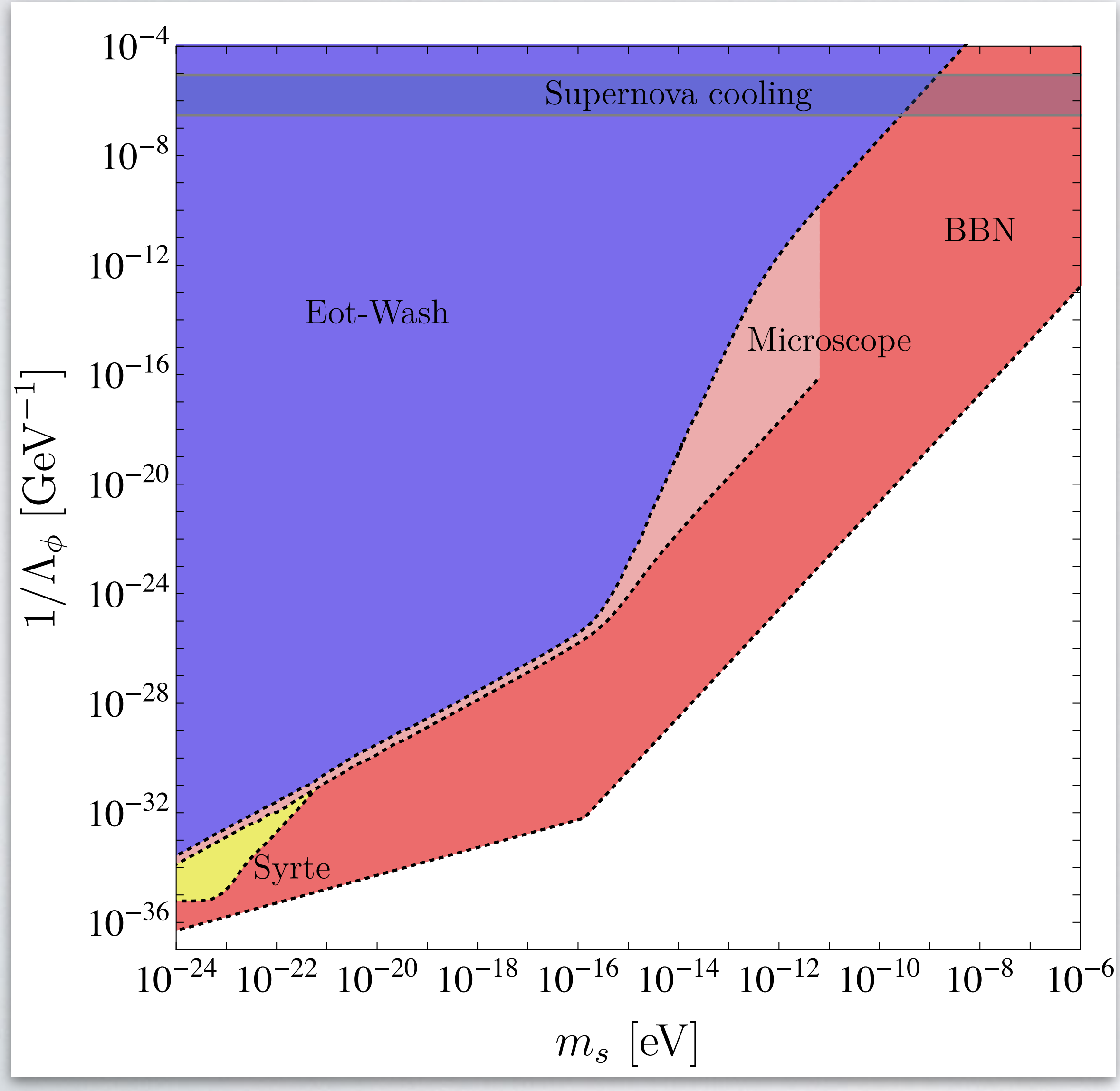
- Consider model with new weak scale mediator ϕ

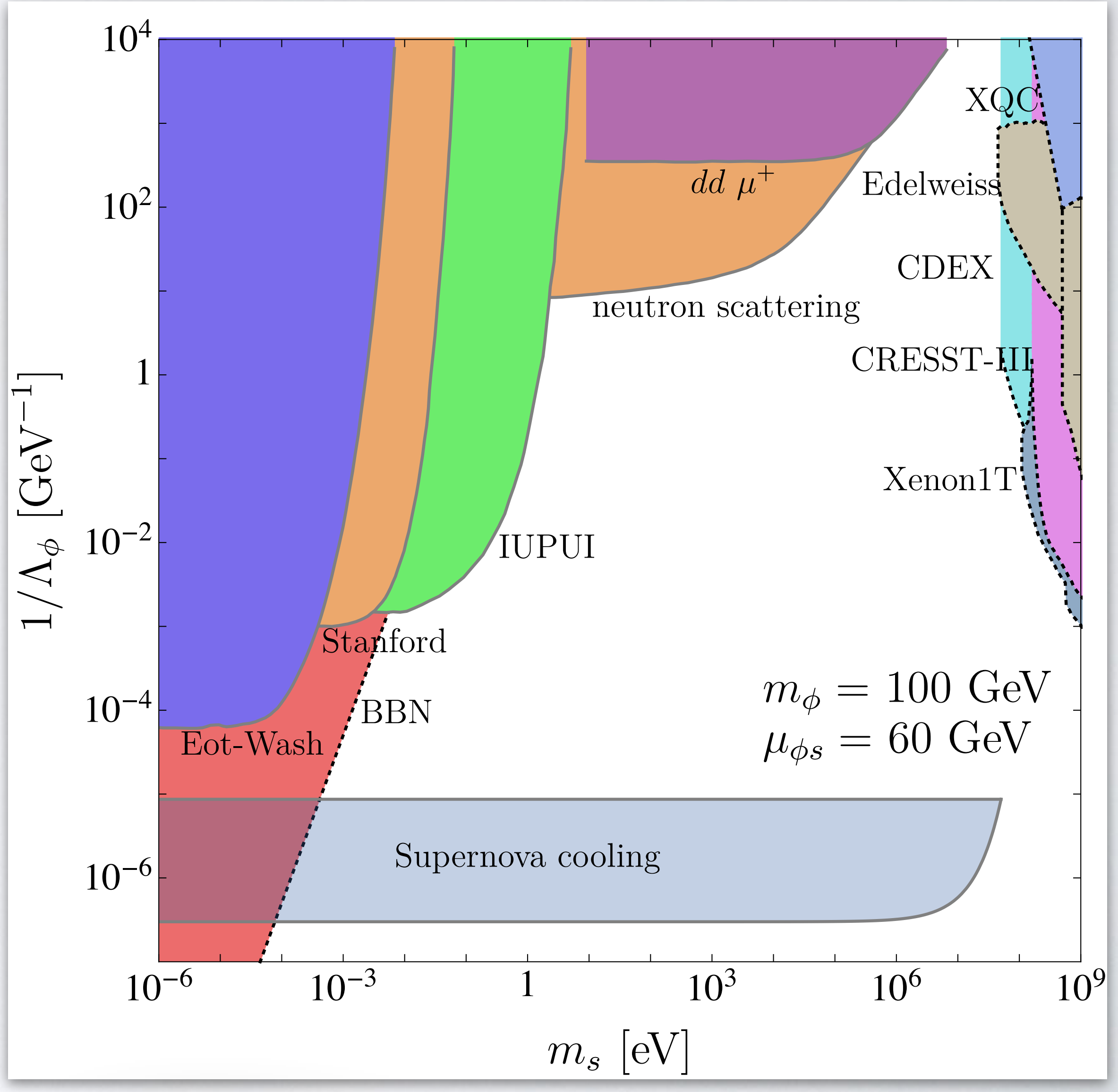
$$\mathcal{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - \frac{\mu_{\phi s}}{2} \phi s^2 - \frac{\alpha_S}{\Lambda_\phi} \phi \, \mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}] \longrightarrow c_{sNN} \, s^2 \, \bar{N} N$$

- High mass window rather unconstrained!

$$c_{sNN} = \frac{\mu_{\phi s}}{\Lambda_\phi} \frac{m_N}{m_\phi^2} \frac{8\pi}{11 - \frac{2}{3} n_L}$$

[Bauer, PF, Reimitz, Plehn, 2005.13551]





LIGHT DM — ALPS

- Maybe best motivated candidate for FDM is an axion-like particle. It has a reason to be very light

- Axions are Nambu-Goldstone particles, protected by shift symmetry:

$$S = \frac{s+f}{\sqrt{2}}\, e^{ia/f} \qquad\qquad e^{i\,a/f} \to e^{i\,(a+c)/f} = e^{i\,a/f} e^{i\,c/f}$$

- Mass is generated by small explicit breaking:

$$V(a) = \Lambda^4 \left[1 - cos\left(\frac{a}{f}\right)\right] = \frac{\Lambda^4}{2f^2} a^2 + \dots$$

with the heavy axion scale

$$f = \mathcal{O}(f_{\rm GUT})$$

3. ALP DM — HIGGS MEDIATOR

- Can couple the Goldstone mode a of complex scalar S to the Higgs via Dim-6 operator

$$\mathcal{L} = \frac{(\partial_\mu S)(\partial^\mu S)^\dagger}{\Lambda_{ha}^2} H^\dagger H \supset \frac{\partial_\mu a\, \partial^\mu a}{2\Lambda_{ha}^2} H^\dagger H \longrightarrow c_{aNN}\, \partial_\mu a \partial^\mu a\, \bar{N} N$$

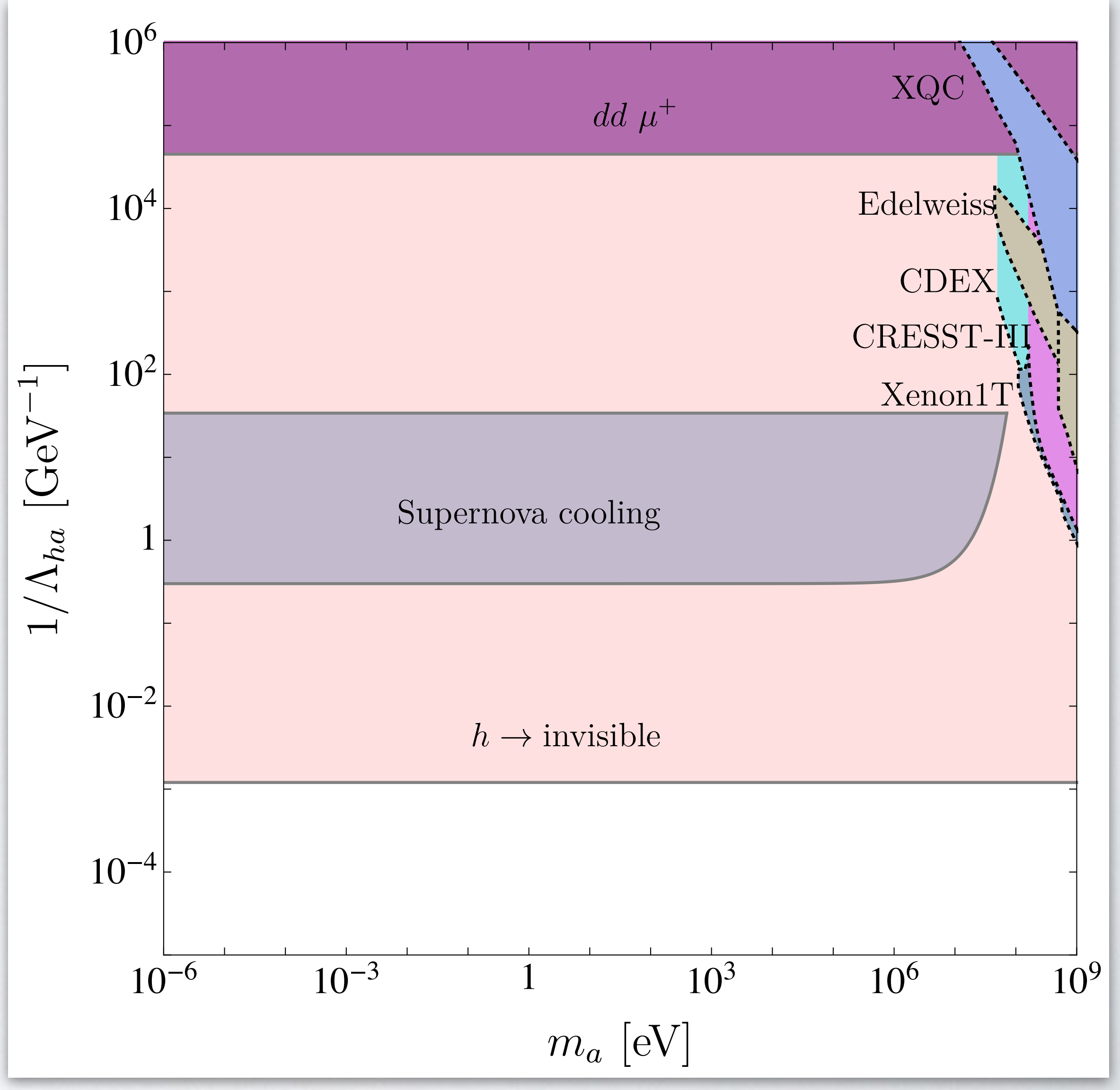
with $$c_{aNN} = \frac{1}{\Lambda_{ha}^2} \frac{m_N}{m_h^2} \frac{2n_H}{3(11 - \frac{2}{3}n_L)}$$

- Strong model independent Higgs to invisible bound:

$$\Gamma(h \to aa) \approx \frac{v^2 m_h^3}{128\pi \Lambda_{ha}^4}$$

$$\Lambda_{ha} \gtrsim 832 \text{ GeV}$$

[Bauer, PF, Reimitz, Plehn, 2005.13551]



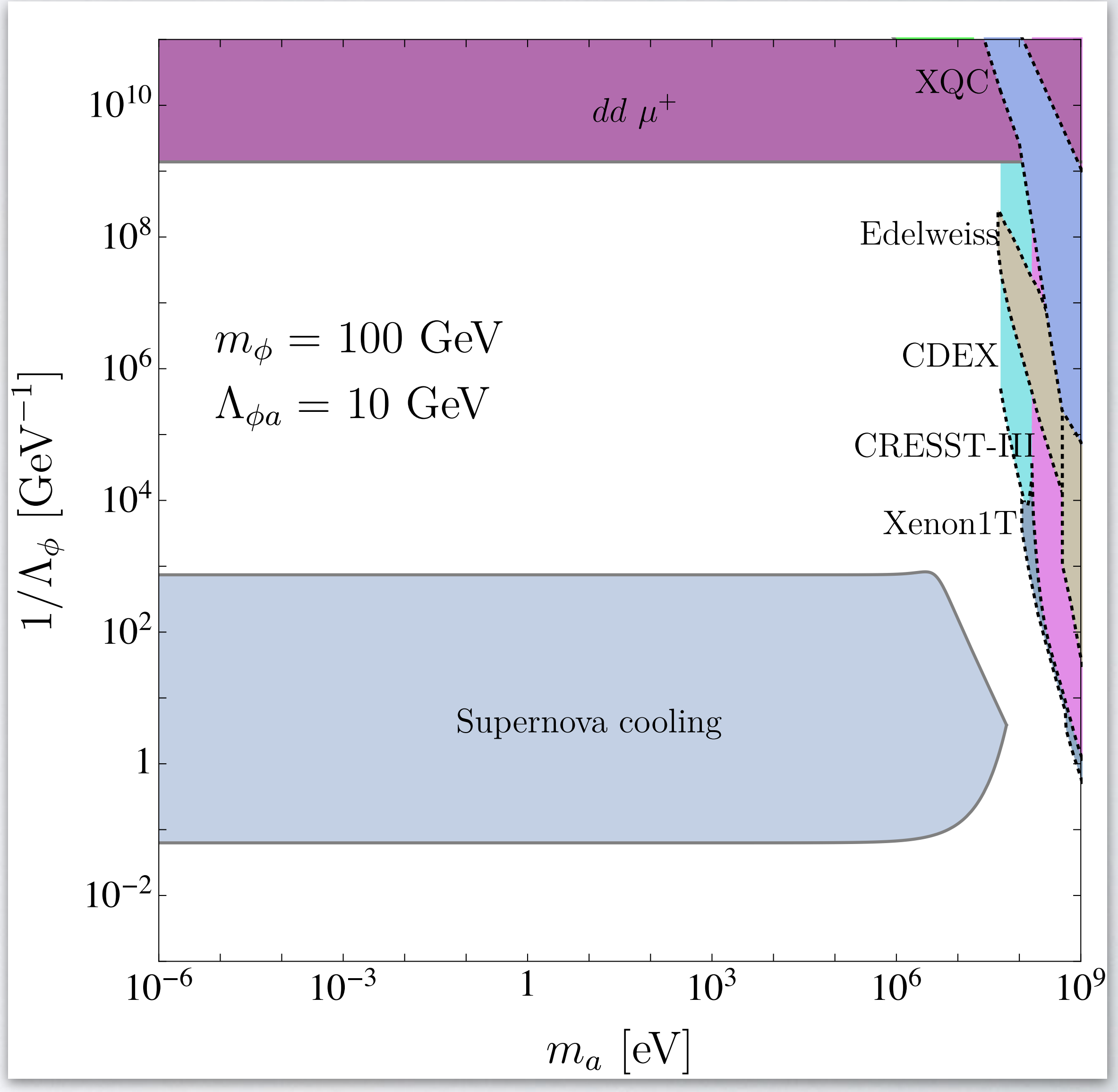
4. ALP DM — NEW MEDIATOR

- Consider model with new weak scale mediator ϕ and ALP DM candidate a. Only shift-symmetric couplings allowed:

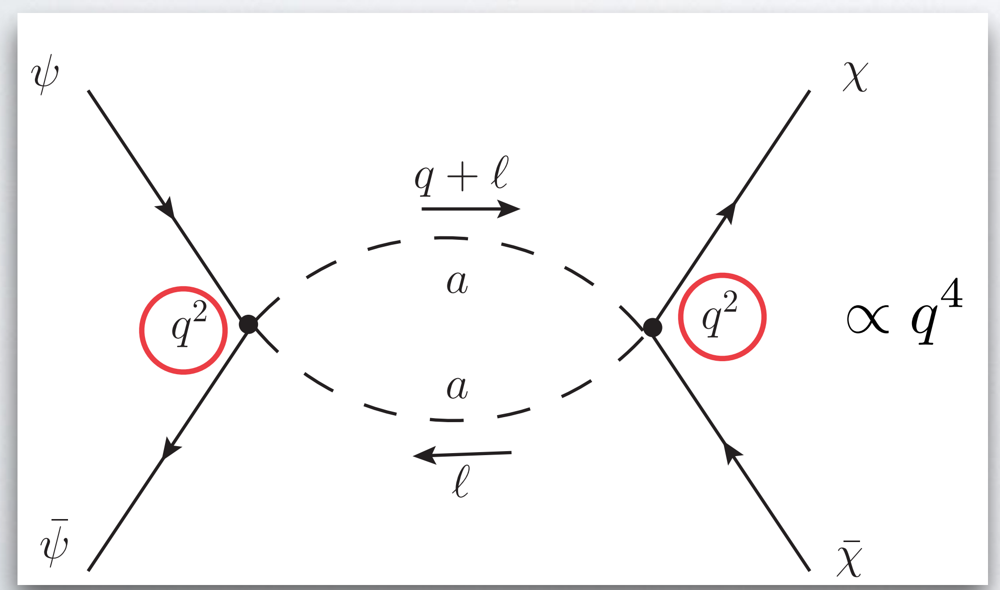
$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{\partial_\mu a \partial^\mu a}{2\,\Lambda_{\phi a}}\phi - \frac{\alpha_S}{\Lambda_\phi}\,\phi\;\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}] \longrightarrow c_{aNN}\,\partial_\mu a \partial^\mu a\,\bar{N}N$$

with $c_{aNN} = \frac{m_N}{\Lambda_{\phi a}\Lambda_\phi m_\phi^2}\frac{8\pi}{11-\frac{2}{3}n_L}$

[Bauer, PF, Reimitz, Plehn, 2005.13551]



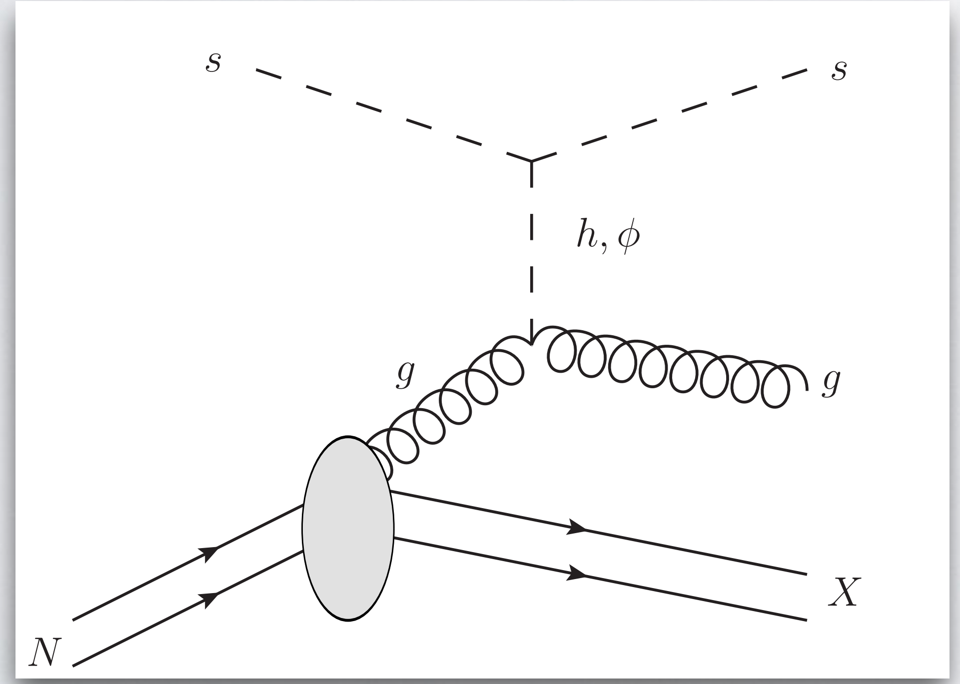
- Almost unconstrained at low masses (momenta) because of momentum suppression:



NEW SEARCH STRATEGIES AT LHC

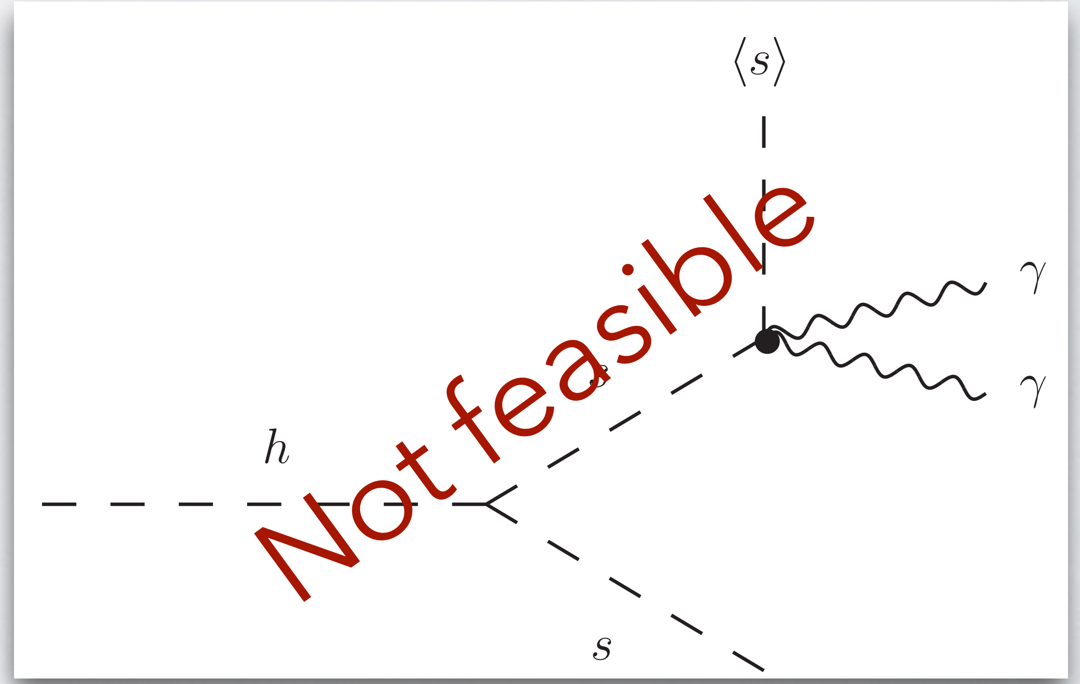
- Conventional direct and indirect DM search strategies hopeless due to low momenta of (U)LDM
- But production at LHC enhances momenta:

Direct detection @ LHC



(Deep inelastic scattering)

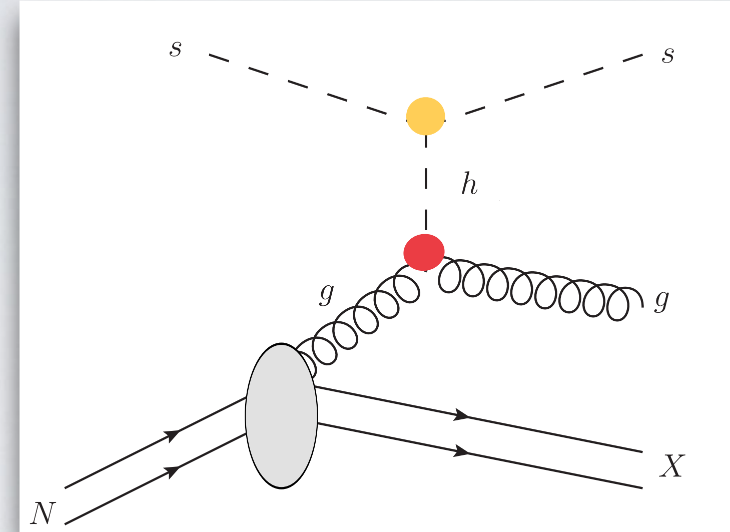
Indirect detection @ LHC



(Background annihilation)

[Bauer, PF, Reimitz, Plehn, 2005.13551]

DIRECT DETECTION



- Boosted DM can undergo DIS in detector material and produce jets.

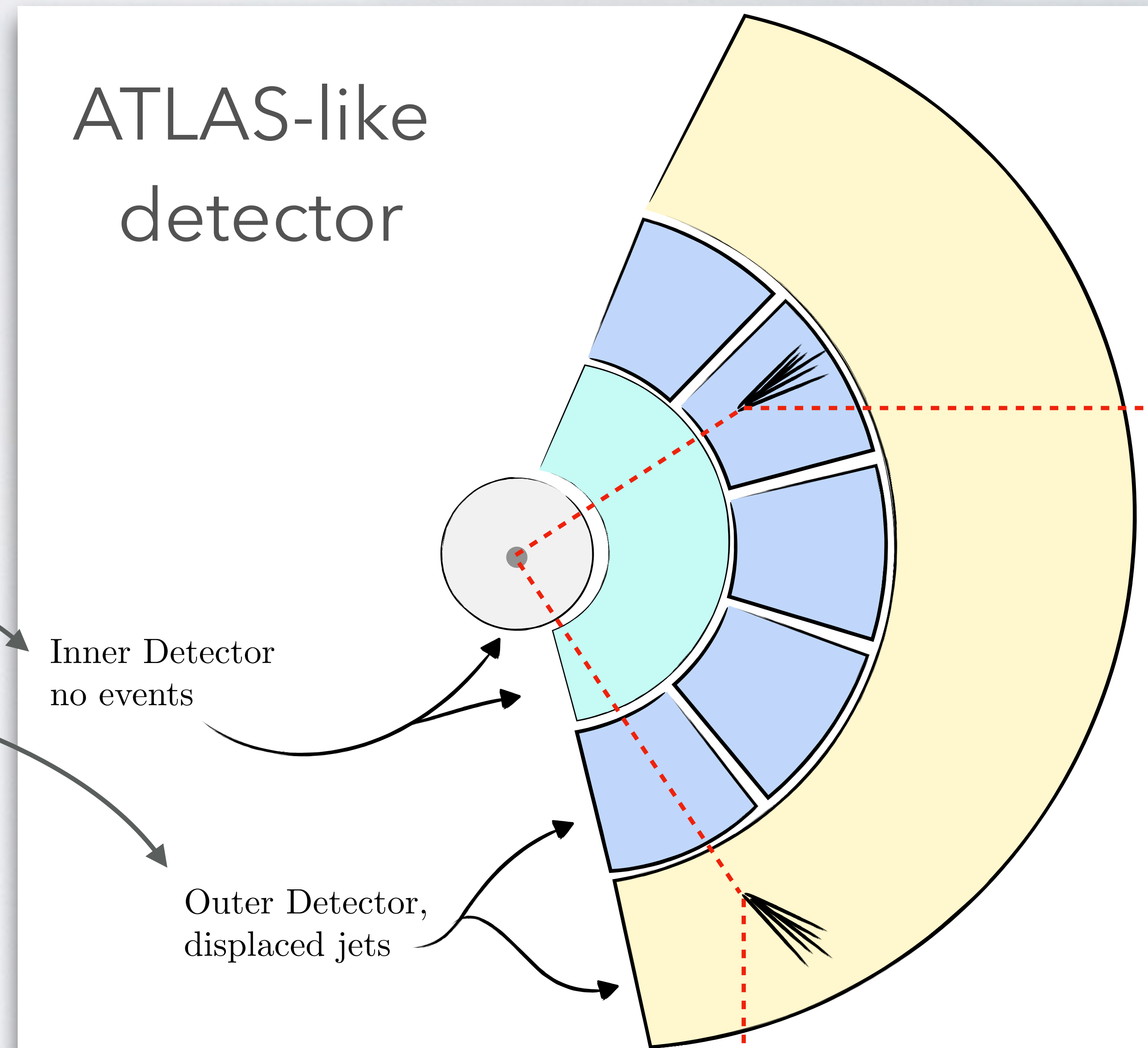
1. E.g. Higgs Portal:

$$N_{\rm DIS} = \mathcal{L}_{\rm HL}\,\sigma_h\,{\rm BR}_{h\to ss}\,P_{\rm DIS}$$

with $P_{\rm DIS} = 1 - e^{L_{det}\,n_X\,\sigma_X}$

Distinguishable from LLPs:

$$n_{Pb} \gg n_{Xe}$$



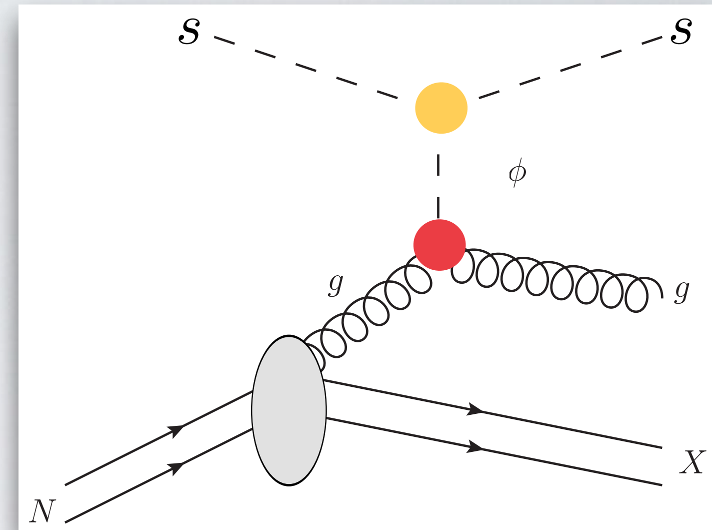
But unfortunately for HP:

$$\frac{d^2\hat{\sigma}_{\rm DIS}}{dx\,dy} = \frac{\lambda_{hs}^2 g_{hgg}^2}{4\pi\,\hat{s}}\,\frac{Q^4}{(Q^2+m_h^2)^2}$$

$$P_{\rm DIS} = 1 - e^{L_E\,n_{Pb}\,\sigma_{Pb}}\,e^{L_H\,n_{Fe}\,\sigma_{Fe}} \approx 7.5\cdot 10^{-21}$$

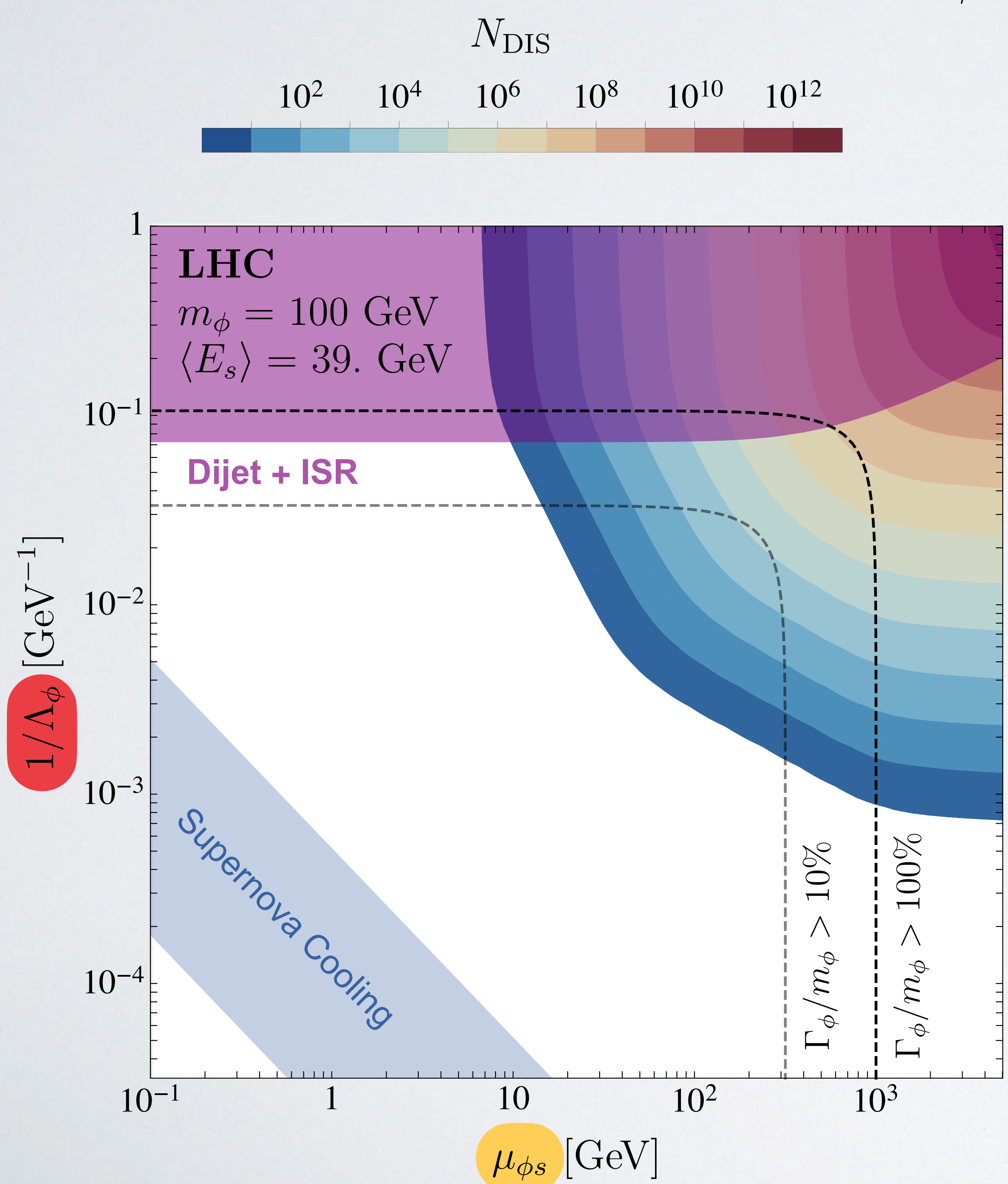
[Bauer, PF, Reimitz, Plehn, 2005.13551]

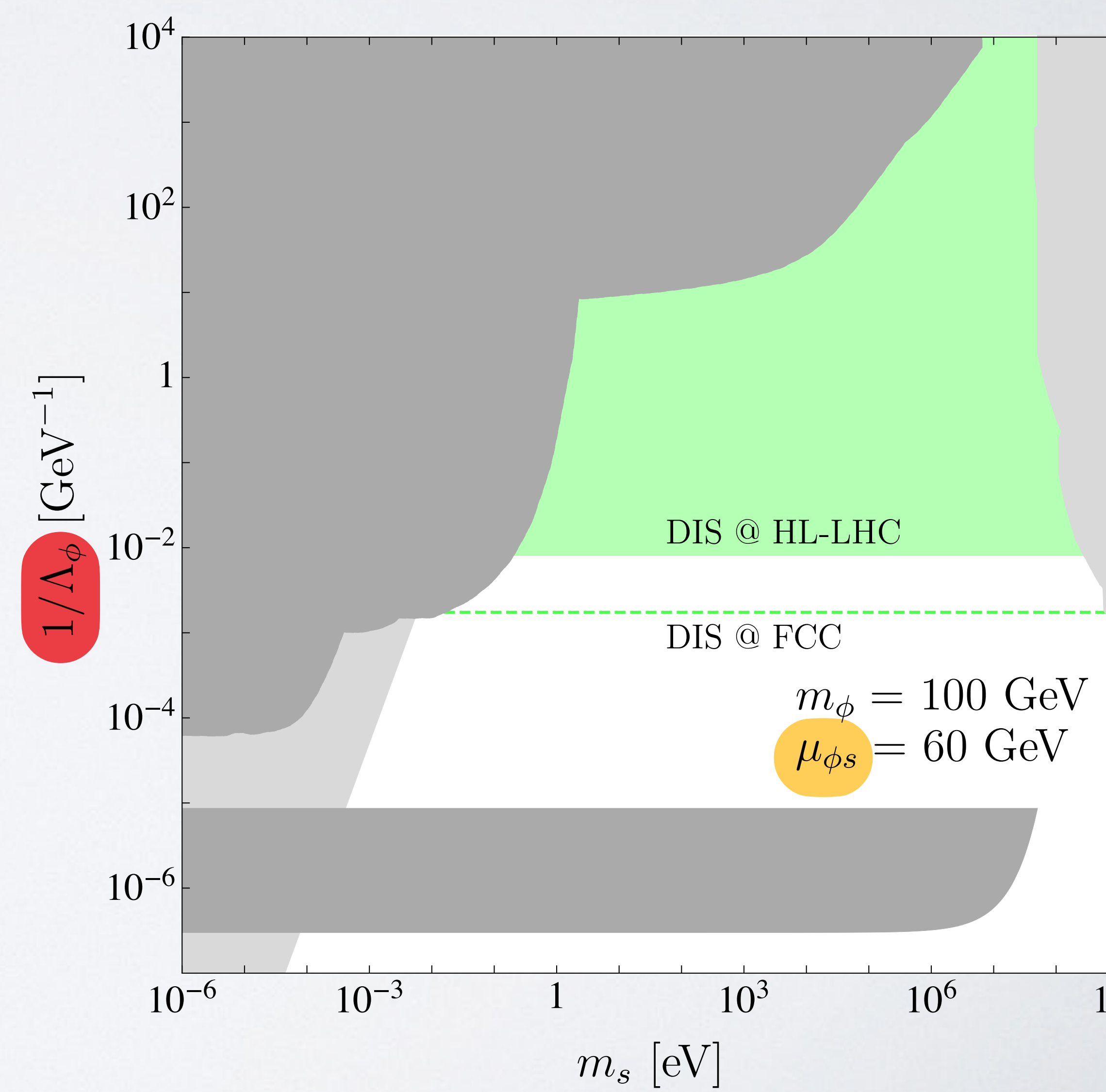
DIRECT DETECTION AT THE LHC



2. Scalar DM with new scalar mediator

$$\frac{d^2\hat{\sigma}_{\mathrm{DIS}}}{dx\,dy} = \frac{\alpha_s^2}{4\pi\,\hat{s}}\left(\frac{\mu_{\phi s}}{\Lambda_\phi}\right)^2 \frac{Q^4}{(Q^2+m_\phi^2)^2}$$



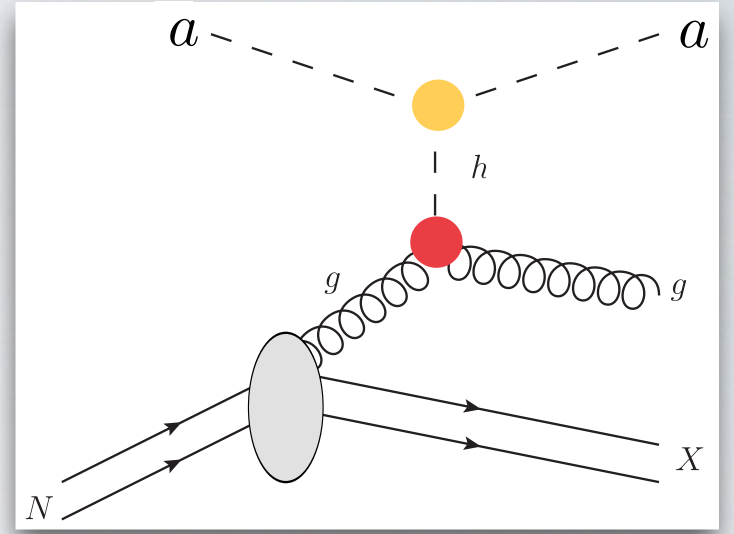


[Bauer, PF, Reimitz, Plehn, 2005.13551]

DIRECT DETECTION AT THE LHC

3. ALP DM with Higgs mediator

$$\frac{d^2\hat{\sigma}_{\rm DIS}}{dx\,dy} = \frac{g_{hgg}^2}{16\pi\,\hat{s}}\,\frac{Q^4}{\Lambda_{ha}^4}\left(\frac{Q^2+2m_a^2}{Q^2+m_h^2}\right)^2$$



- With Higgs coupling

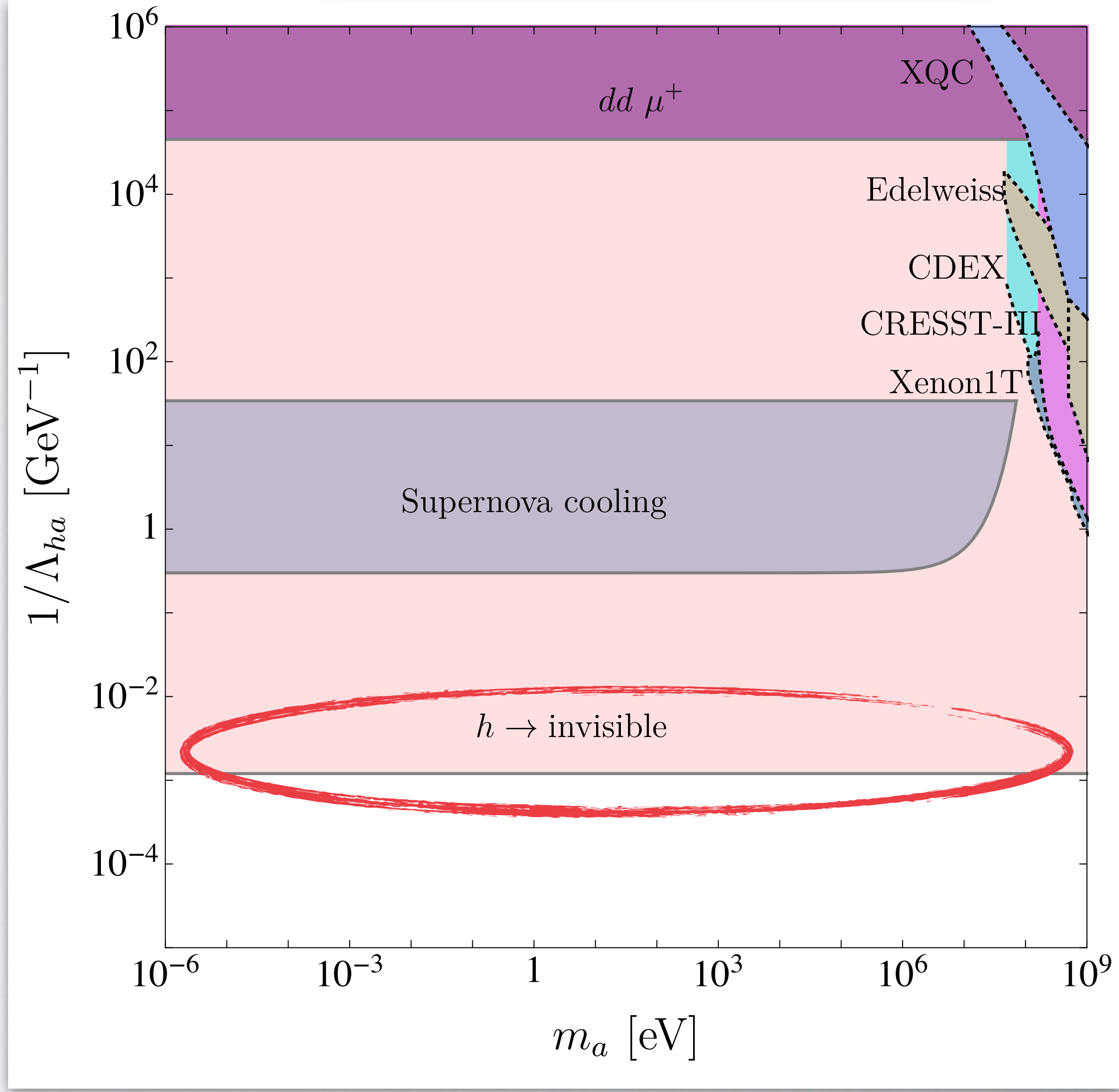
$$g_{hgg} = \alpha_s/(12\pi)$$

and the Higgs invisible constraint

$$\Lambda_{ha} \gtrsim 832 \text{ GeV}$$

we can estimate

$$P_{\rm DIS} = 1 - e^{-L_{\rm E}\, n_{\rm Pb}\, \sigma_{\rm Pb}} e^{-L_{\rm H}\, n_{\rm Fe}\, \sigma_{\rm Fe}} \approx 10^{-23}$$

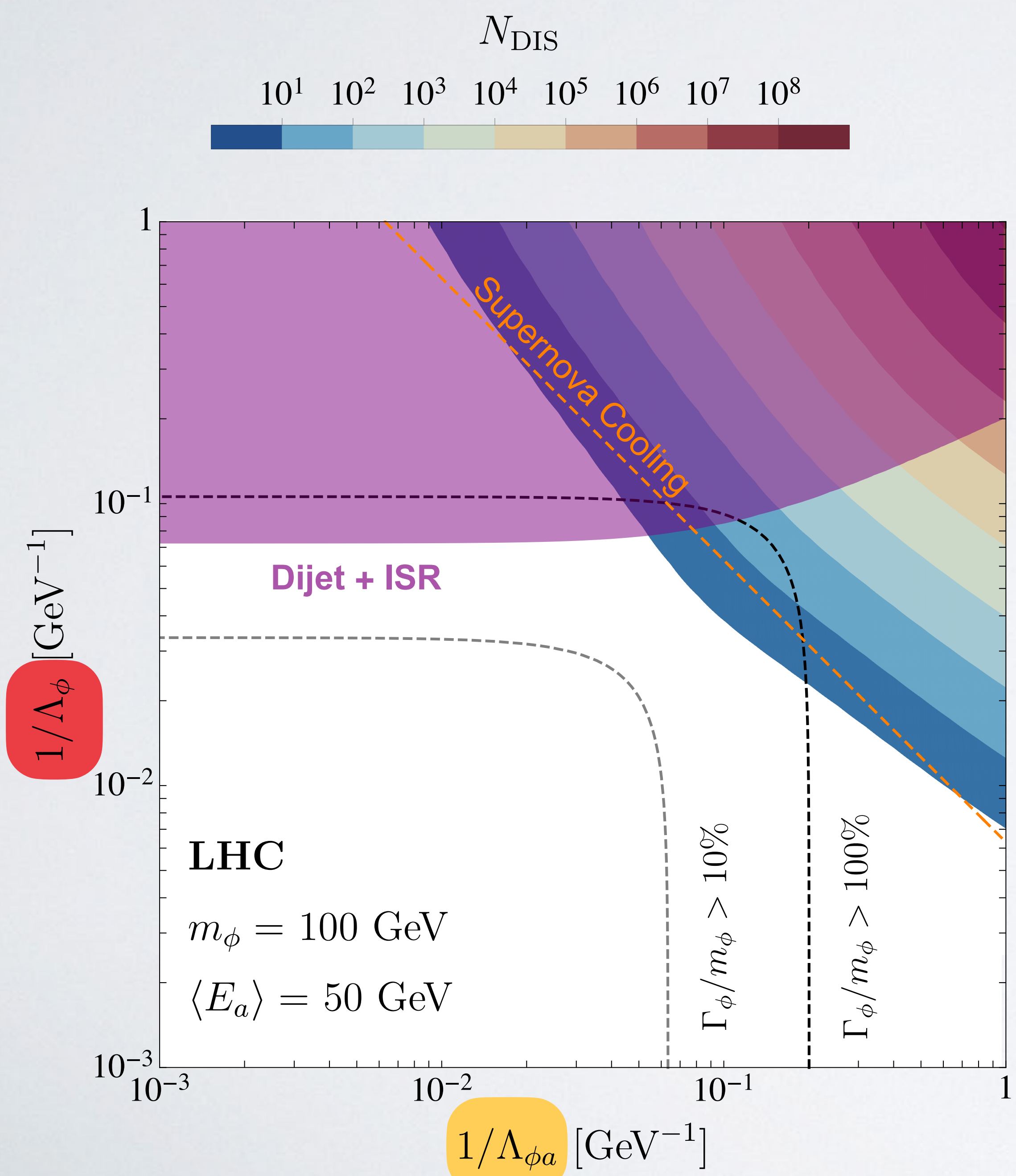


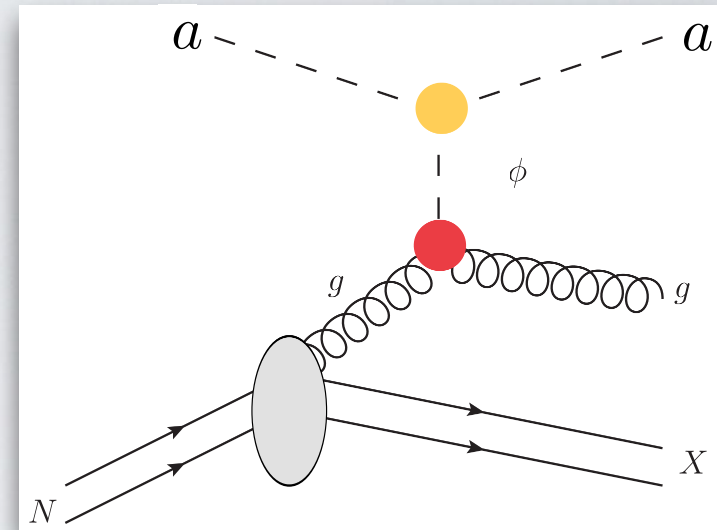
[Bauer, PF, Reimitz, Plehn, 2005.13551]

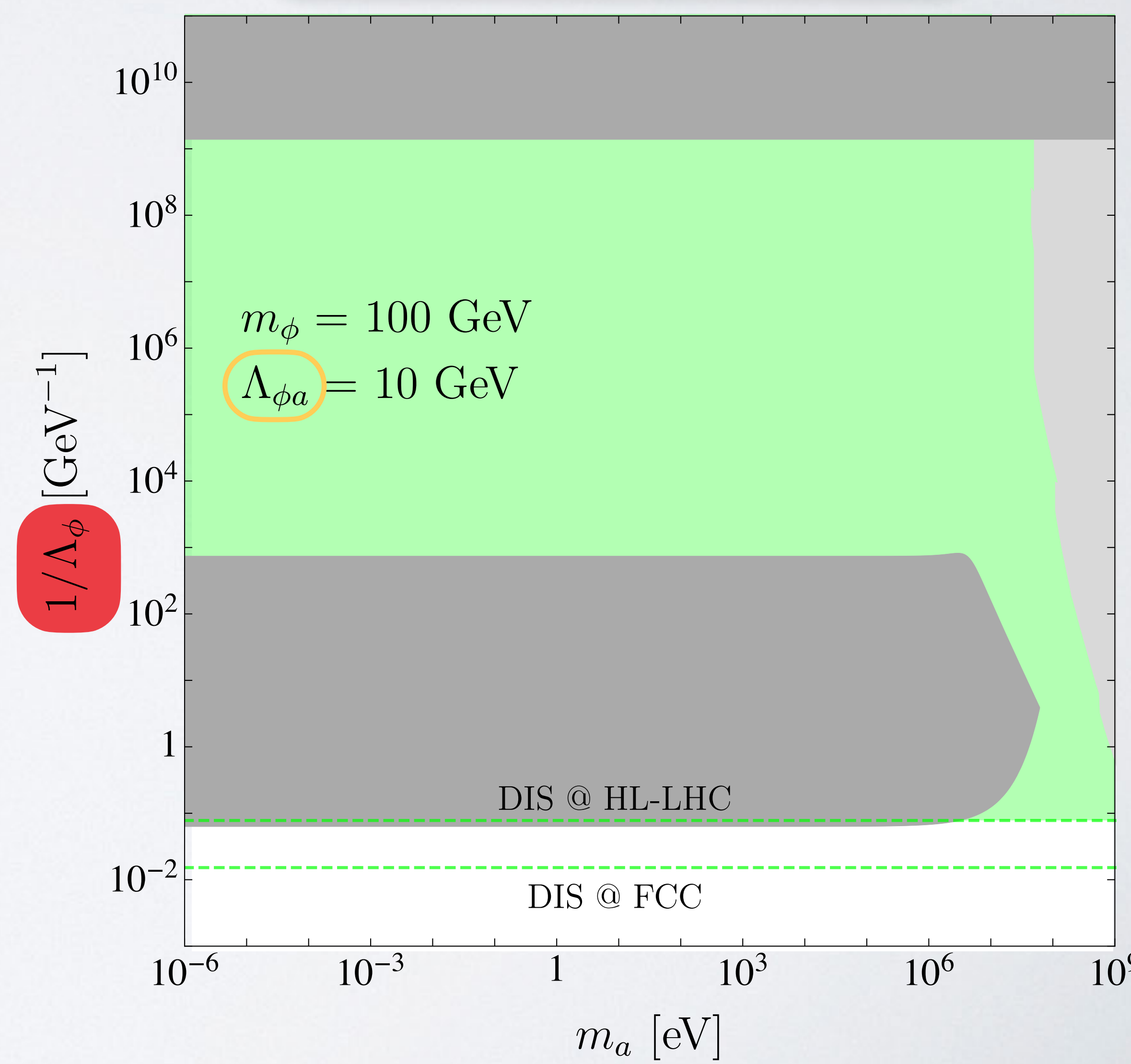
DIRECT DETECTION AT THE LHC

4. ALP DM with scalar mediator

$$\frac{d^2\hat{\sigma}_{\text{DIS}}}{dx\,dy} = \frac{\alpha_s^2}{16\pi\,\hat{s}}\,\frac{Q^4}{\Lambda_{\phi a}^2\,\Lambda_\phi^2}\left(\frac{Q^2+2m_a^2}{Q^2+m_\phi^2}\right)^2$$





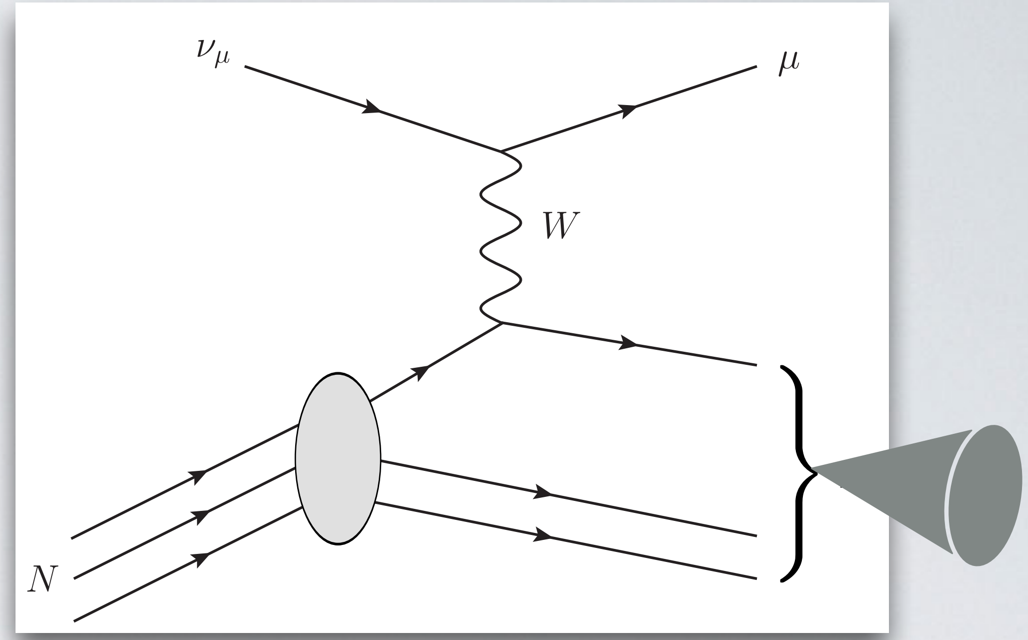


[Bauer, PF, Reimitz, Plehn, 2005.13551]

APPLICATION TO NEUTRINOS

- Highly-energetic **neutrinos** are copiously produced at **HL-LHC**.

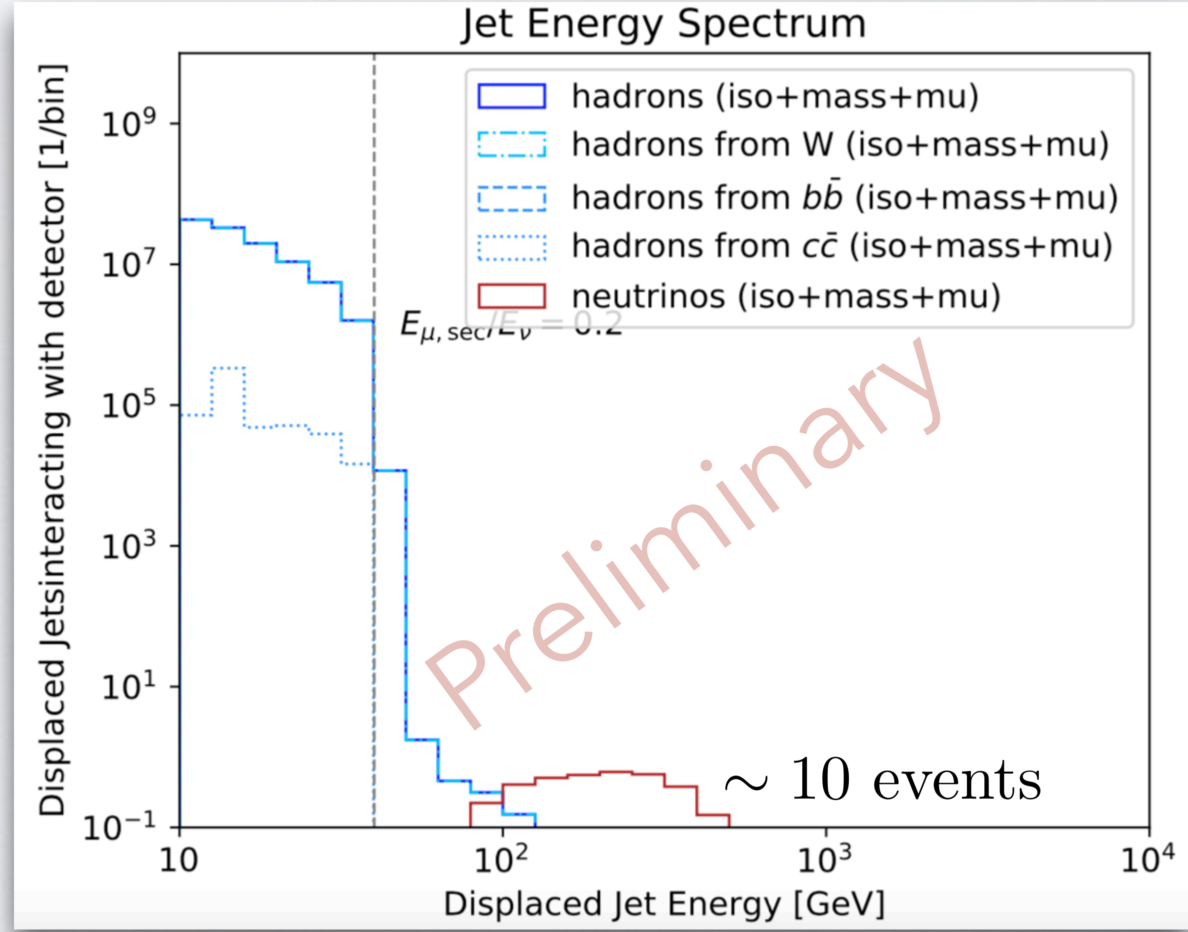
  Look for them in neutrino-nucleus scattering



- Promising candidate is $W \to \mu\,\nu_\mu$ decay with subsequent

$$\nu_\mu + N \to \mu + \text{jet}$$

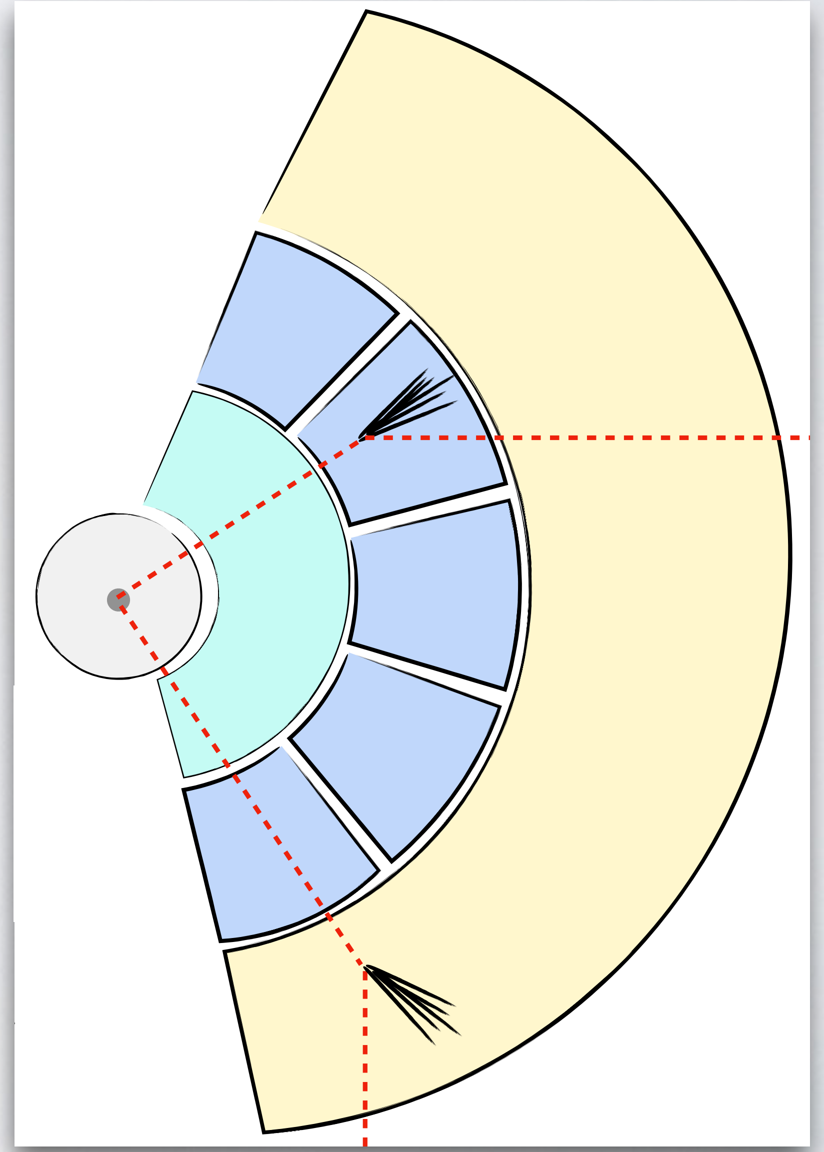
- Proposed cut selection:
  - isolated muon and jet
  - reconstructed W-mass
  - secondary muon tag



[Bauer, PF, Kling, Plehn, Reimitz; in progress]

SUMMARY PART II

- **(U)LDM** can be produced at the LHC with large boost and then be **detected by recoil jets** produced in DIS
- Complementary to existing direct detection or ULDM probes! **Promising for momentum-suppressed interactions!**
- Potentially interesting signature for flavour in LHCb, Belle-II, …
- Promising signature to detect **neutrino** scattering **at the LHC in CMS**
- More improvements and generalisations:
  - quark couplings
  - sterile neutrino
  - meson decays
  - new detectors
  - …



THANK YOU!

BACKUP

VARIATION OF CONSTANTS

- Fundamental constants like m_f, α or m_V are described by SM operators

$$\mathcal{L}_{\rm SM} \supset -\sum_f m_f \bar{f} f - \frac{F_{\mu\nu}F^{\mu\nu}}{4} + \sum_V \delta_V m_V^2 V_\mu V^\mu$$

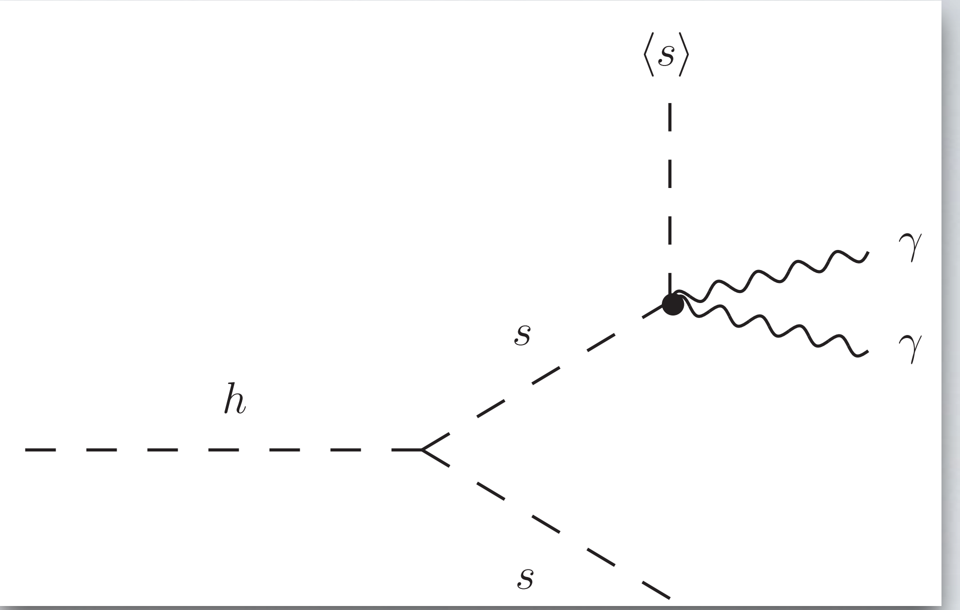
- In the presence of ULDM these operators modified, e.g. in the Higgs portal

$$\mathcal{L} \supset \frac{\lambda_{hs}}{2}\frac{m_f}{m_h^2}\, s^2 \bar{f} f - \frac{\lambda_{hs} g_{h\gamma\gamma}}{2}\frac{1}{m_h^2}\, s^2 F_{\mu\nu}F^{\mu\nu} - \lambda_{hs}\delta_V \frac{m_V^2}{m_h^2}\, s^2 V_\mu V^\mu$$

where the DM field is described by the classical wave

$$s^2 = s_0^2 \cos^2(m_s t) \to \frac{s_0^2}{2}(1 + \cos(2 m_s t))$$

INDIRECT DETECTION @ LHC



- ULDM has huge occupation numbers. Can it annihilate with the halo background field if produced at LHC?

$$n_{\rm DM} = \frac{\rho_{\rm DM}}{m_s} \approx \frac{3\times 10^{30}}{\rm cm^3}\left(\frac{10^{-22}\,{\rm eV}}{m_s}\right)$$

- But cross section scales with mass

$$\sigma_{\langle s\rangle s\to\gamma\gamma} \approx \frac{\lambda_{hs}^2 g_{h\gamma\gamma}^2}{4\pi}\frac{m_s}{m_h^3}$$

- Mean free path independent of mass and very large

$$\lambda = \frac{1}{n_{\rm DM}\,\sigma_{\langle s\rangle s\to\gamma\gamma}} = \frac{4\pi}{\lambda_{hs}^2 g_{h\gamma\gamma}^2}\frac{m_h^3}{\rho_{\rm DM}} \gtrsim 10^{43}\ {\rm m}$$

- Larger cross section above electron threshold, but also lower densities!

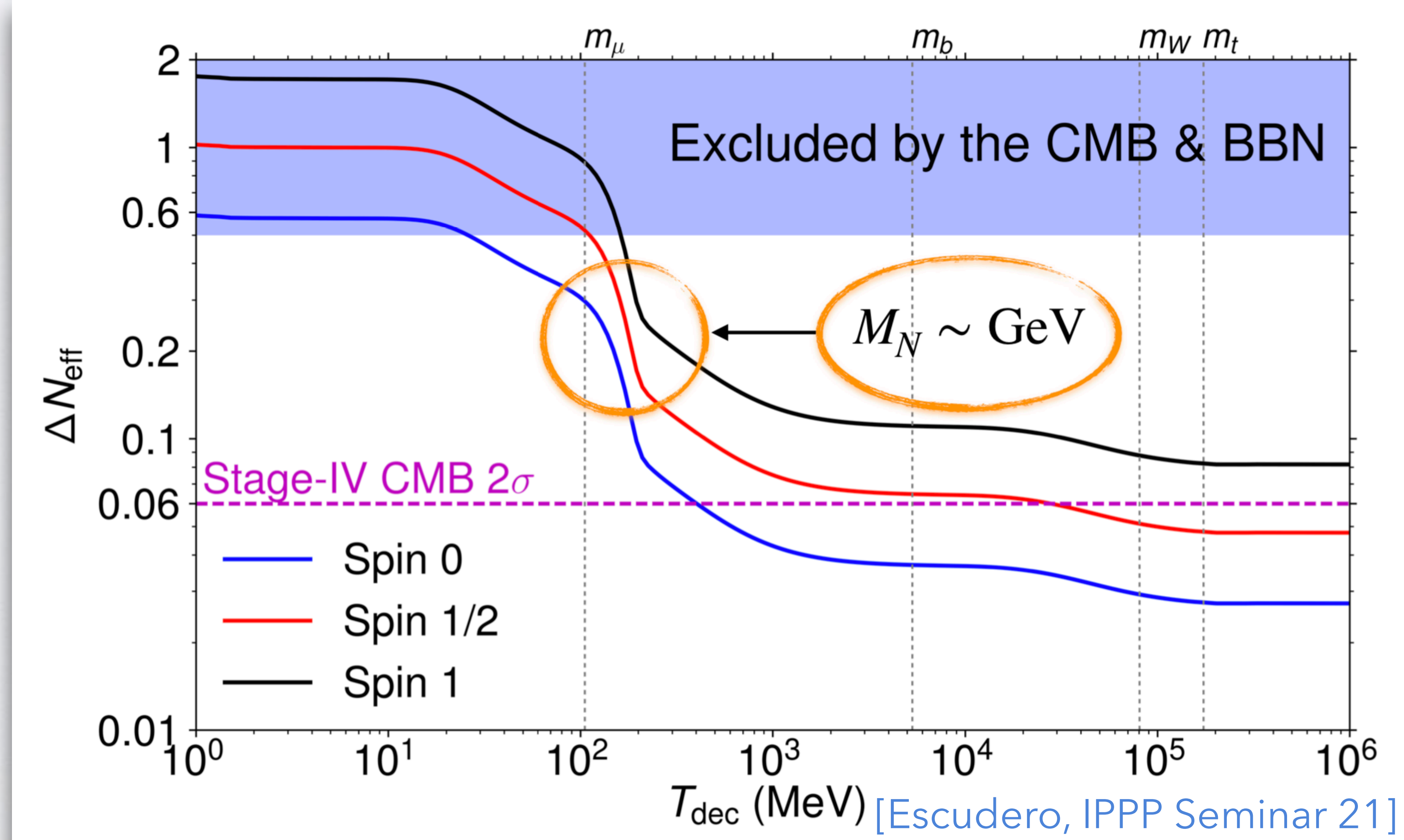
$$\sigma_{\langle s\rangle s\to\bar{f}f} = \frac{\lambda_{hs}^2}{8\pi}\frac{m_f^2}{m_h^4}\left(1-\frac{4m_f^2}{m_s m_h}\right)$$

CONTRIBUTION TO $N_{\rm eff}$

- DM has large coupling to gluon. Will keep DM in thermal equilibrium until after QCD phase transition

$$\frac{\alpha_S}{\Lambda_\phi}\,\phi\ \mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}] \to \frac{\alpha_S}{\Lambda'}\partial_\mu\pi\partial^\mu\pi$$

- (Pseudo-)scalar particle contributes $\Delta N_{\rm eff} \lesssim 0.5$ for decoupling of $1\ \mathrm{MeV} \lesssim T_{\rm dec} < T_{\rm QCD}$



[Escudero, IPPP Seminar 21]