Durham University

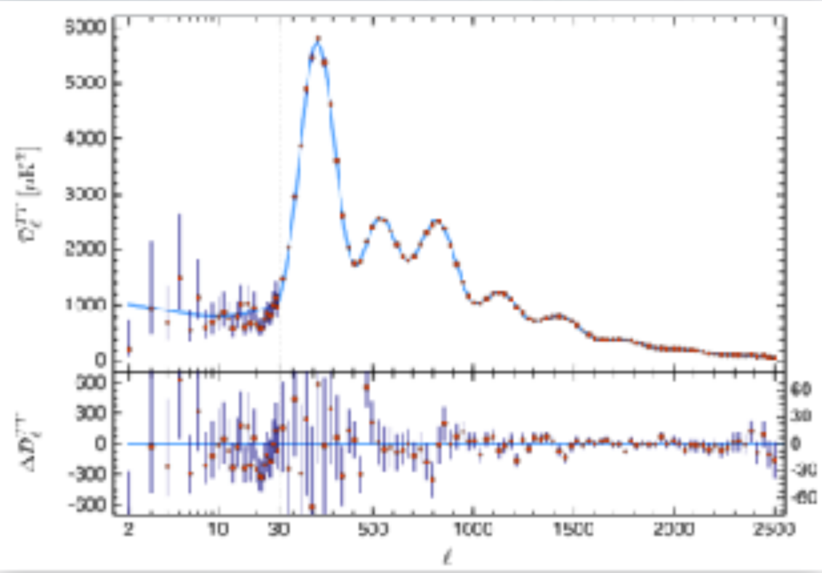
SEARCHING FOR LIGHT PHYSICS AT THE LHC

Patrick Foldenauer

NuTs extended workshop – Jun 1, 2022

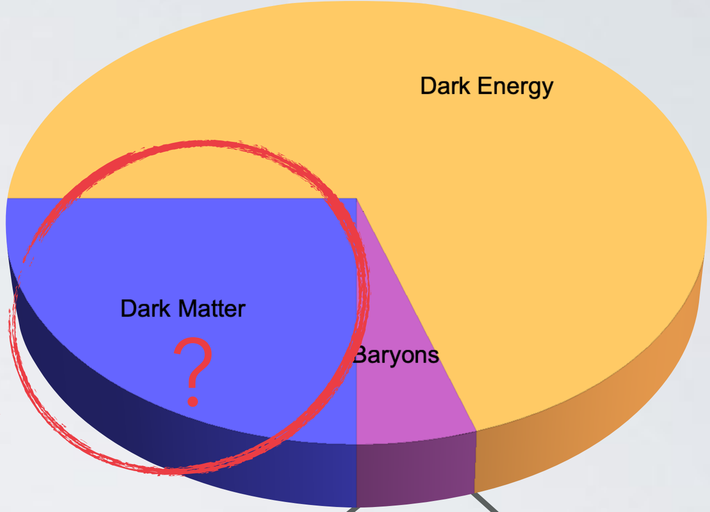
WHERE TO LOOK BEYOND SM?

Two obvious targets:

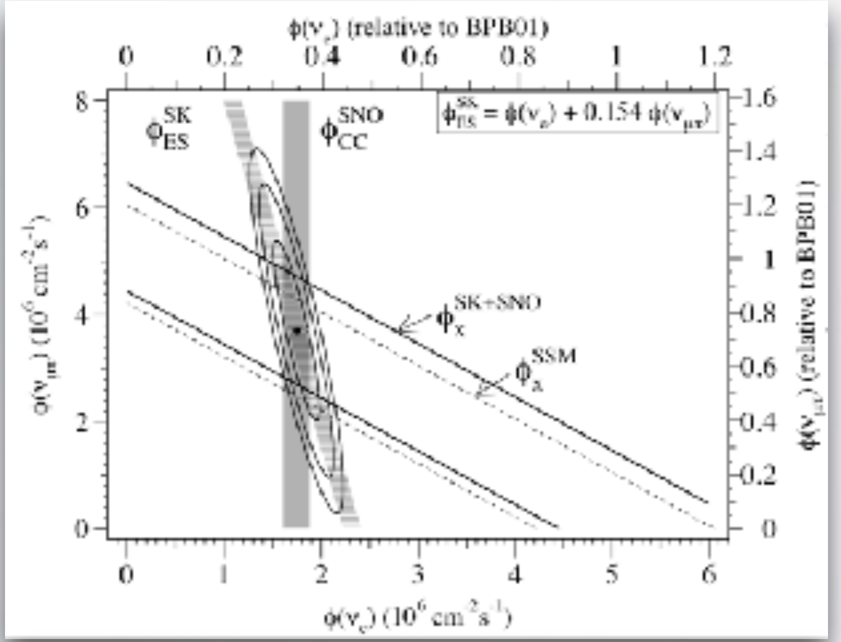


[Planck Collaboration; 1807.06209]

CMB informs
us
about energy
budget

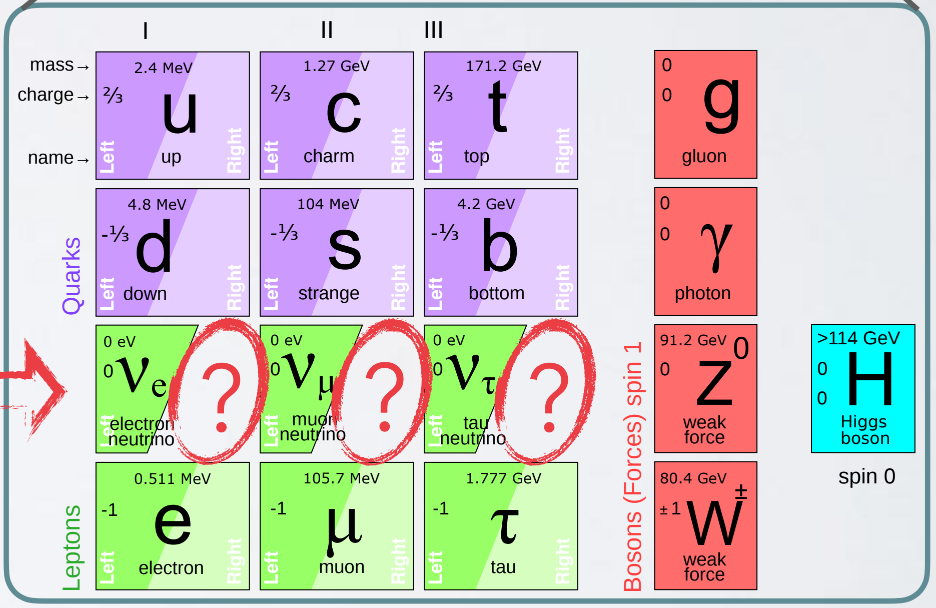


Part I



[SNO Collaboration PRL 87:071301]

Oscillations
require
massive
neutrinos



	I	II	III		
mass → charge → name →	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom	0 0 γ photon	
	0 eV 0 ν_e electron neutrino ?	0 eV 0 ν_μ muon neutrino ?	0 eV 0 ν_τ tau neutrino ?	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson spin 0
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	80.4 GeV ±1 $W^\pm$ weak force	

Part II

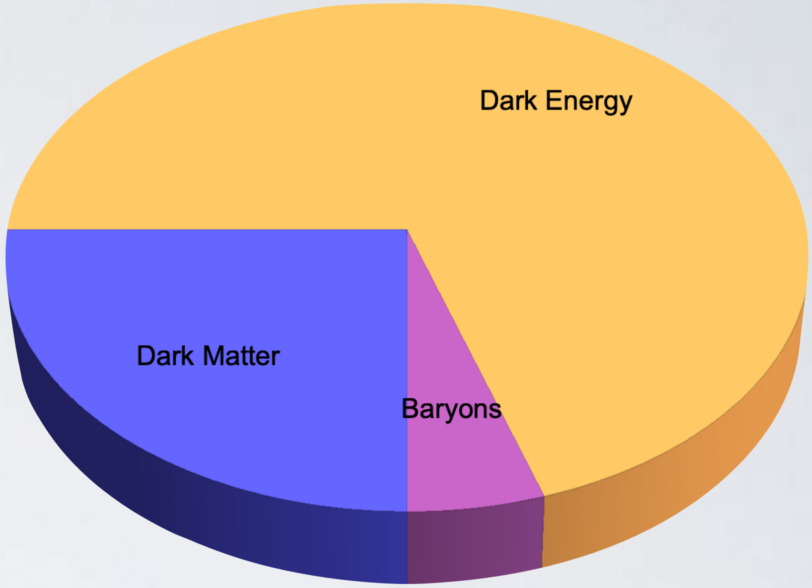
[Gninenko et al., 1301.5516]

What can we learn about these @ **LHC**?

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 ???



Galaxy formation

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

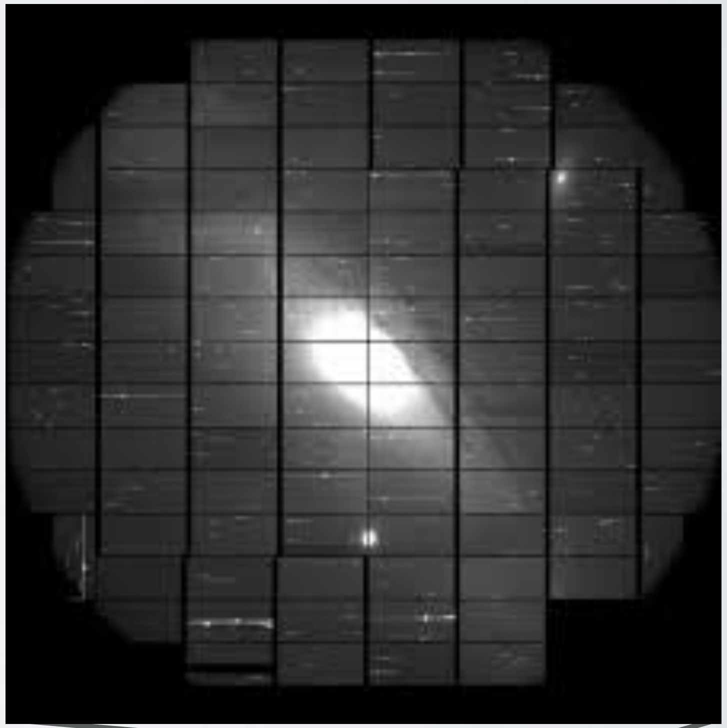
$$m \gtrsim 10^{-24}\,\mathrm{eV}$$

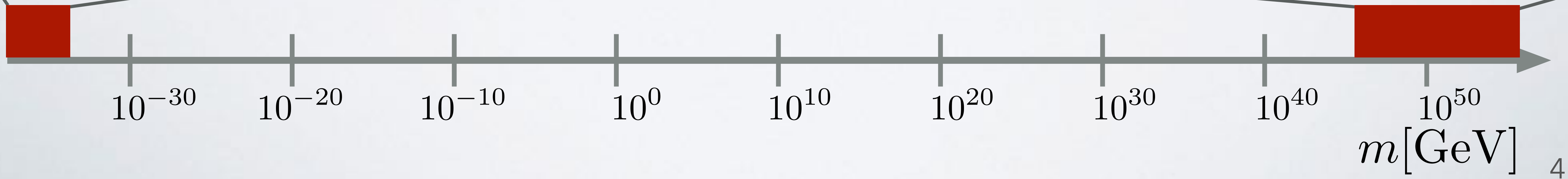
[Hlozek et al., PRD **91** (2015)]

microlensing searches of PBHs

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

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





THE FUZZY DM PARADIGM

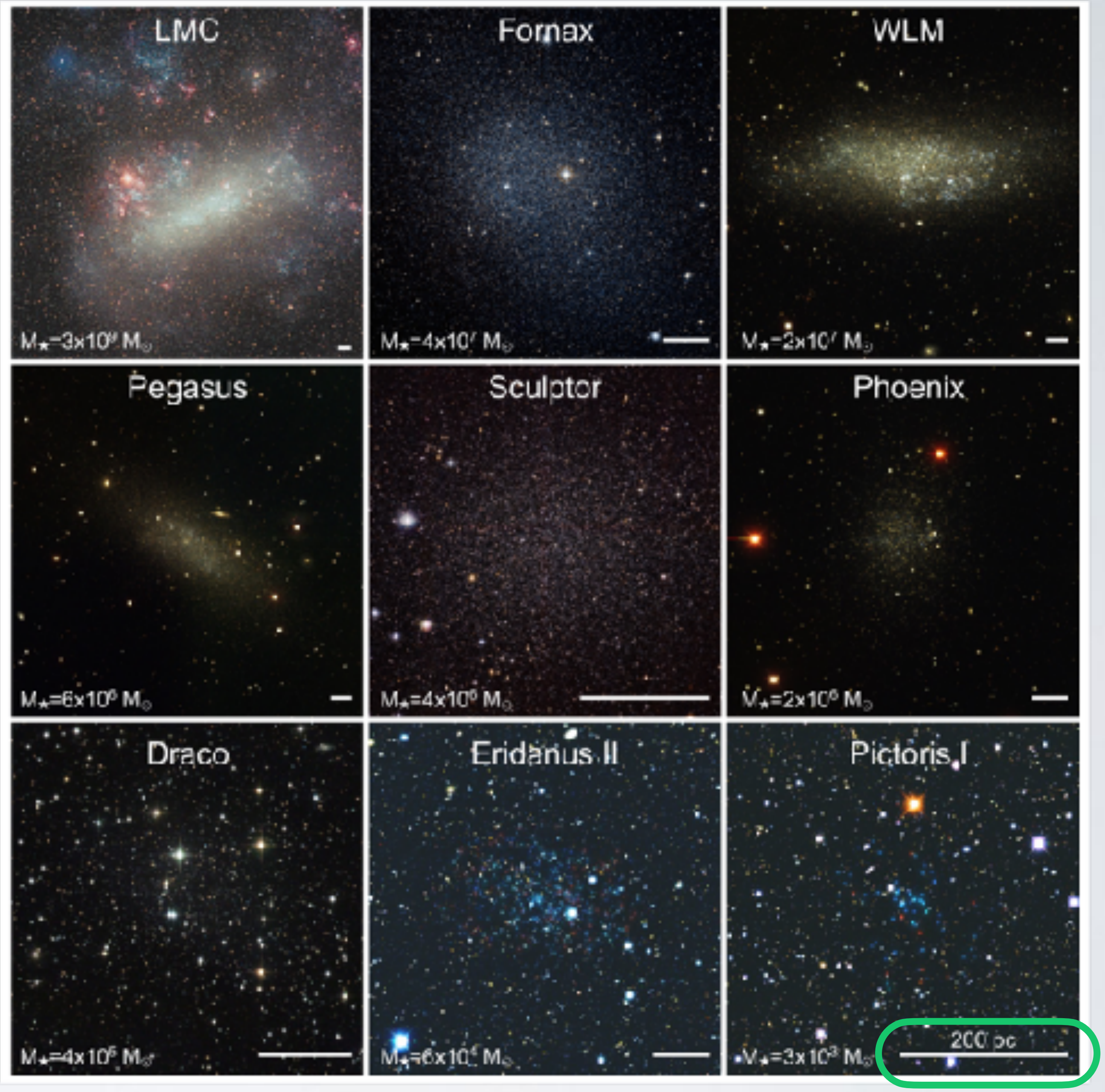
- Standard CDM typically produces too much small scale structure
- Can be suppressed if DM de Broglie wavelength prohibits small scale structures:

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

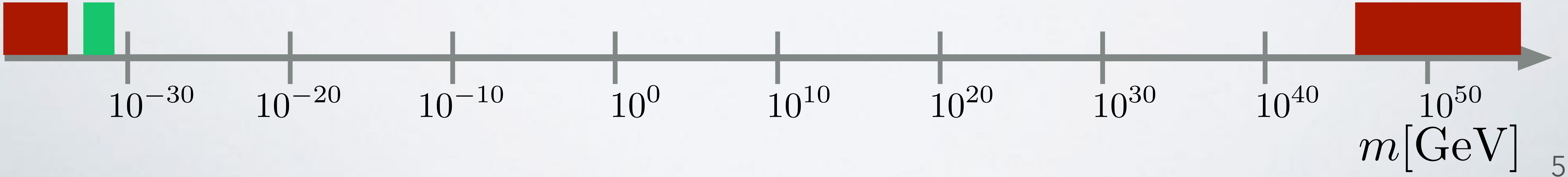
[Hu, Barkana, Gruzinov, PRL 85 (2000)]

Better fit to small scale structure!

Dwarf galaxies



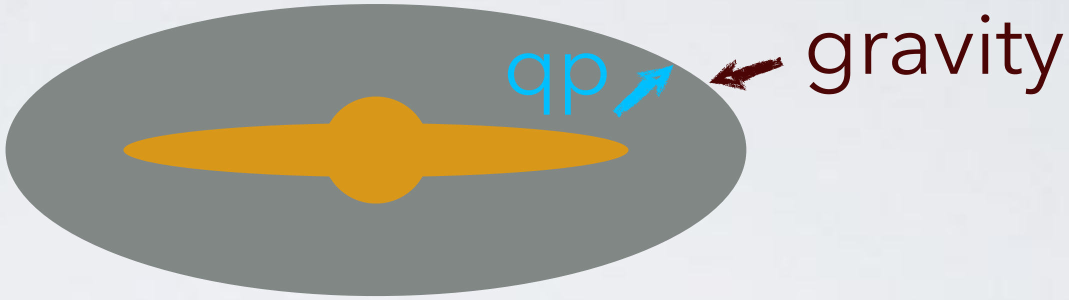
[Bullock et al., Ann.Rev.Astron.Astrophys. 55 (2017)]



THE FUZZY DM PARADIGM

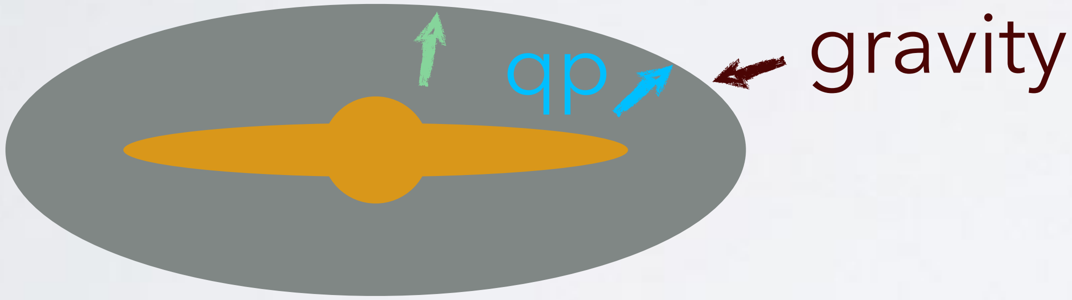
- Small scale is set by a balance of gravity and quantum pressure:

No self-interactions!



- Self-interactions may drastically alter situation:

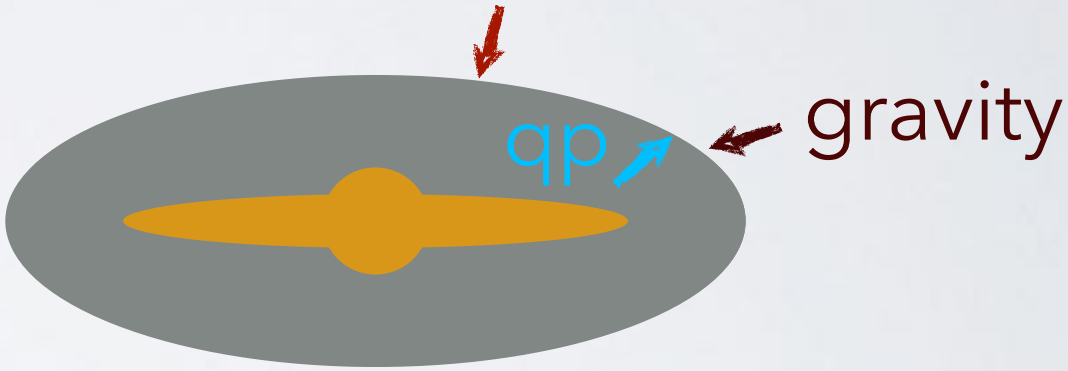
repulsive $\lambda > 0$



Relaxed mass range: [Ferreira, 2005.03254]

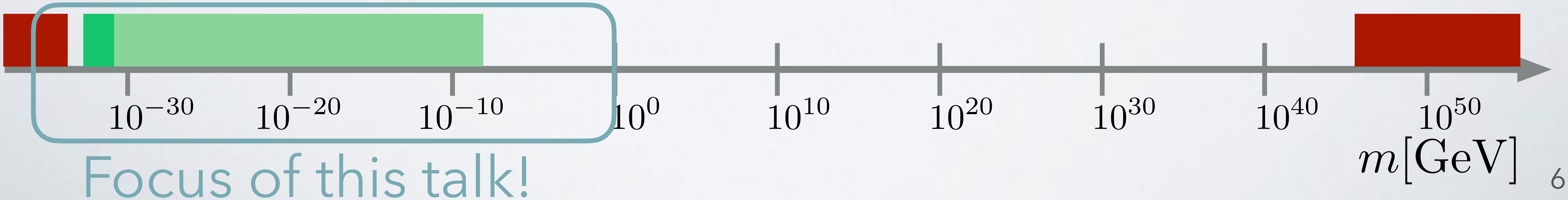
$m_{\mathrm{DM}} \approx 10^{-22} - 1\,\mathrm{eV}$

attractive $\lambda < 0$



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 toy 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:

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

  ii) **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

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

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

How do we search for wave DM?

VARIATION OF CONSTANTS

- Fundamental constants like m_f, $\alpha_{\rm em}$ 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 are modified, e.g. in the *Higgs portal*

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

where the DM field is described by the **classical wave**

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

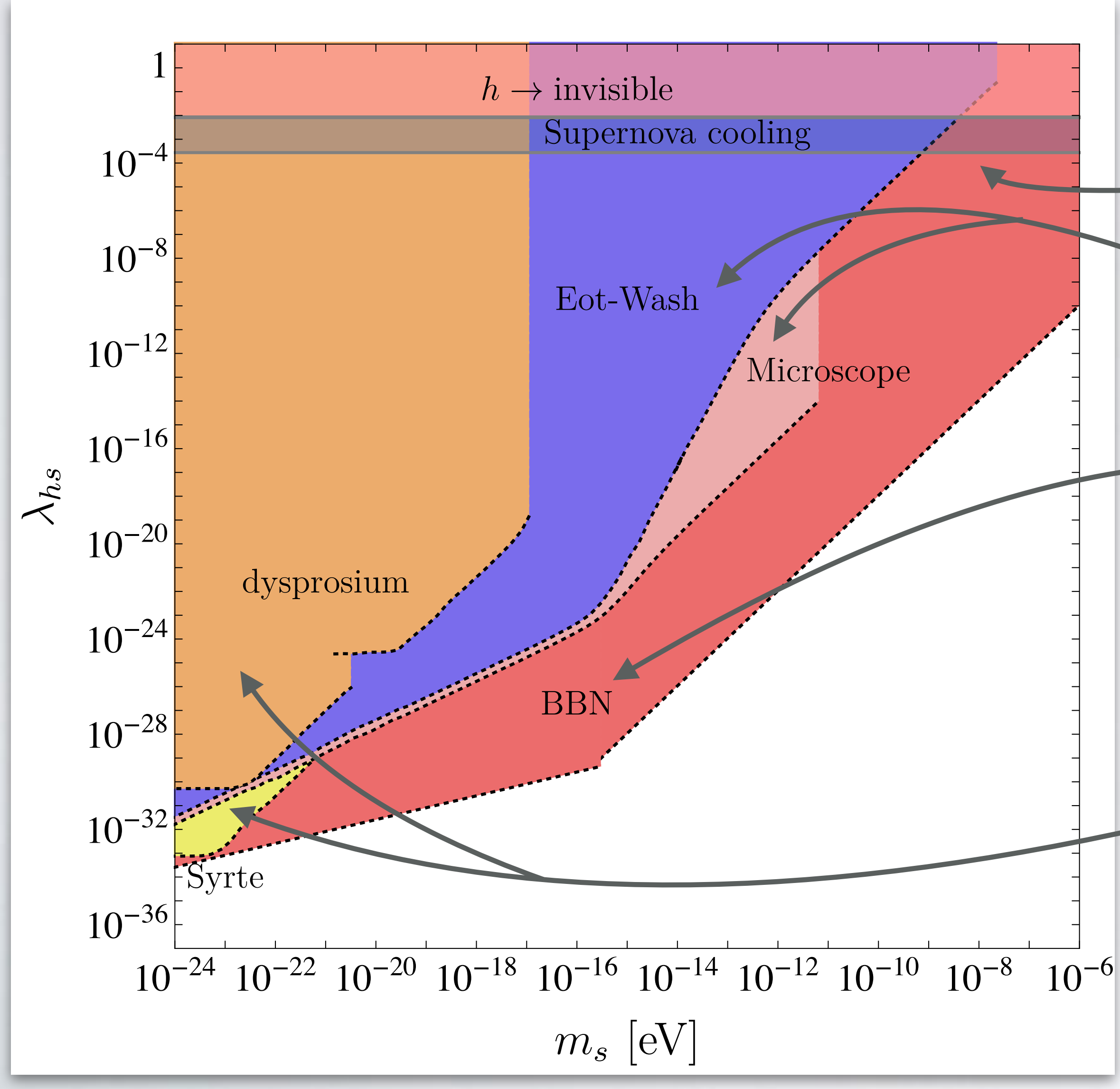
1. SCALAR DM — HIGGS PORTAL

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

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

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

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



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]

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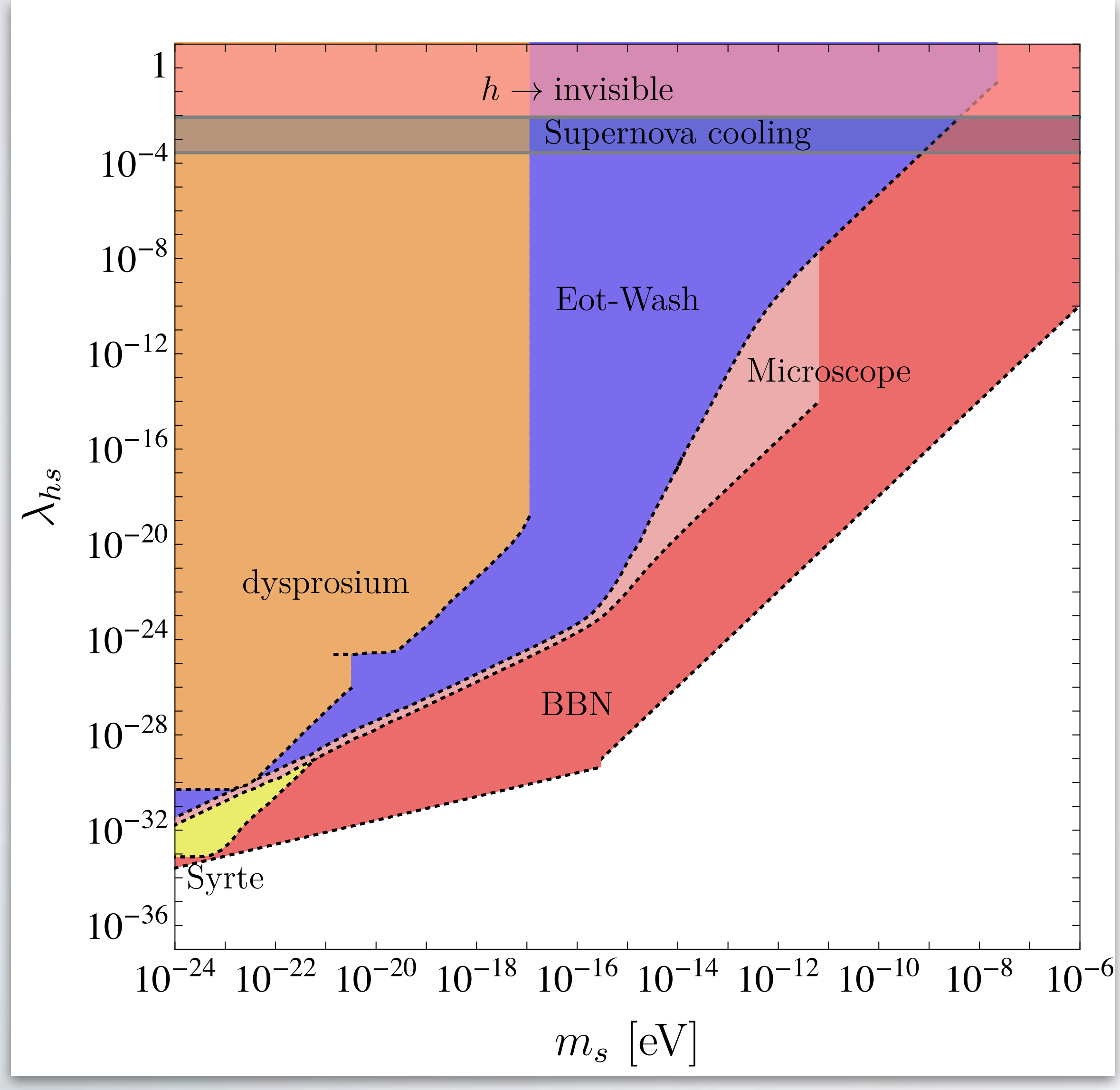
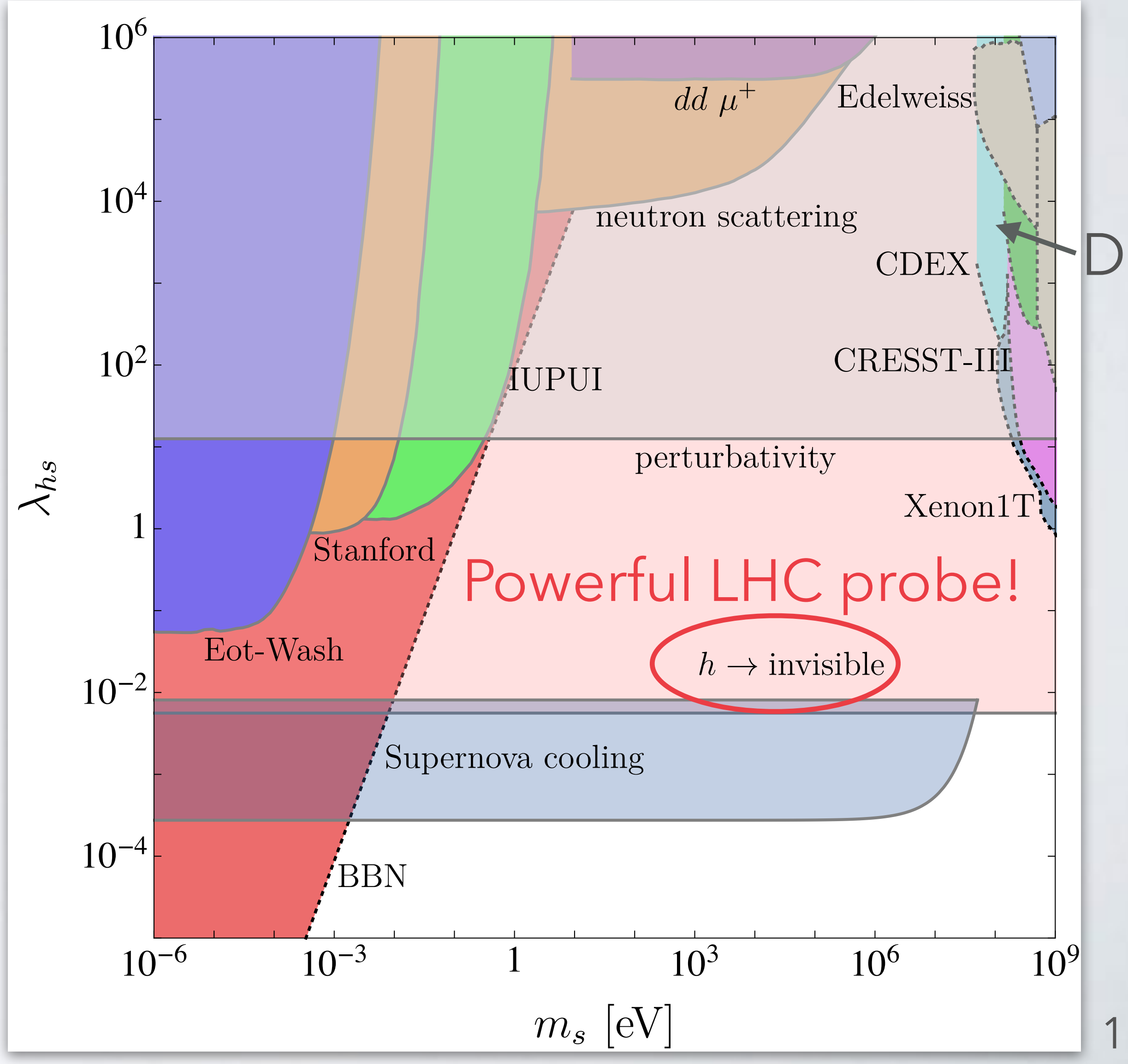
[Bauer, PF, Reimitz, Plehn, 2005.13551]





Powerful LHC probe!

DD

2. SCALAR DM — NEW MEDIATOR

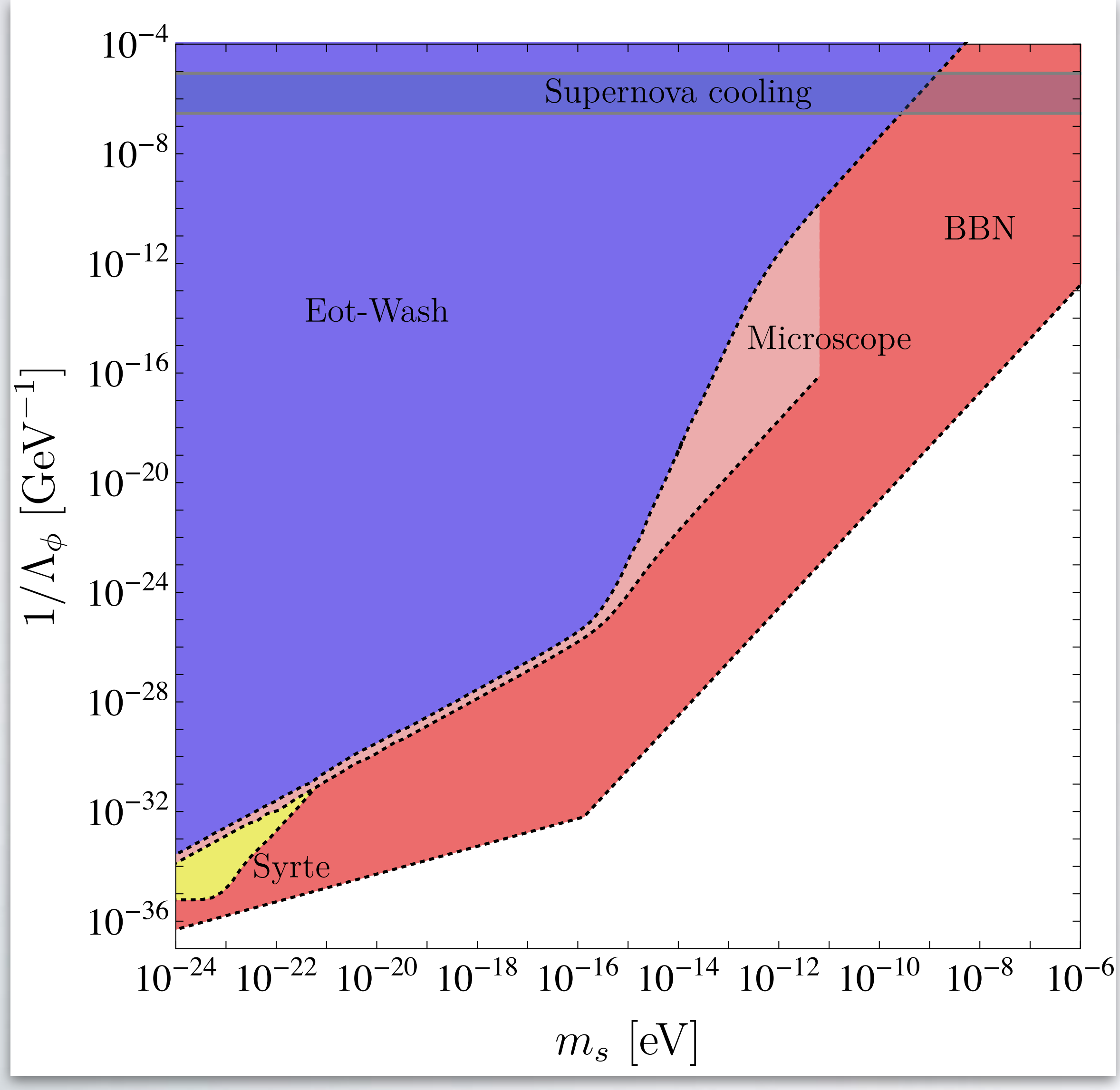
- Consider model with new weak scale mediator ϕ

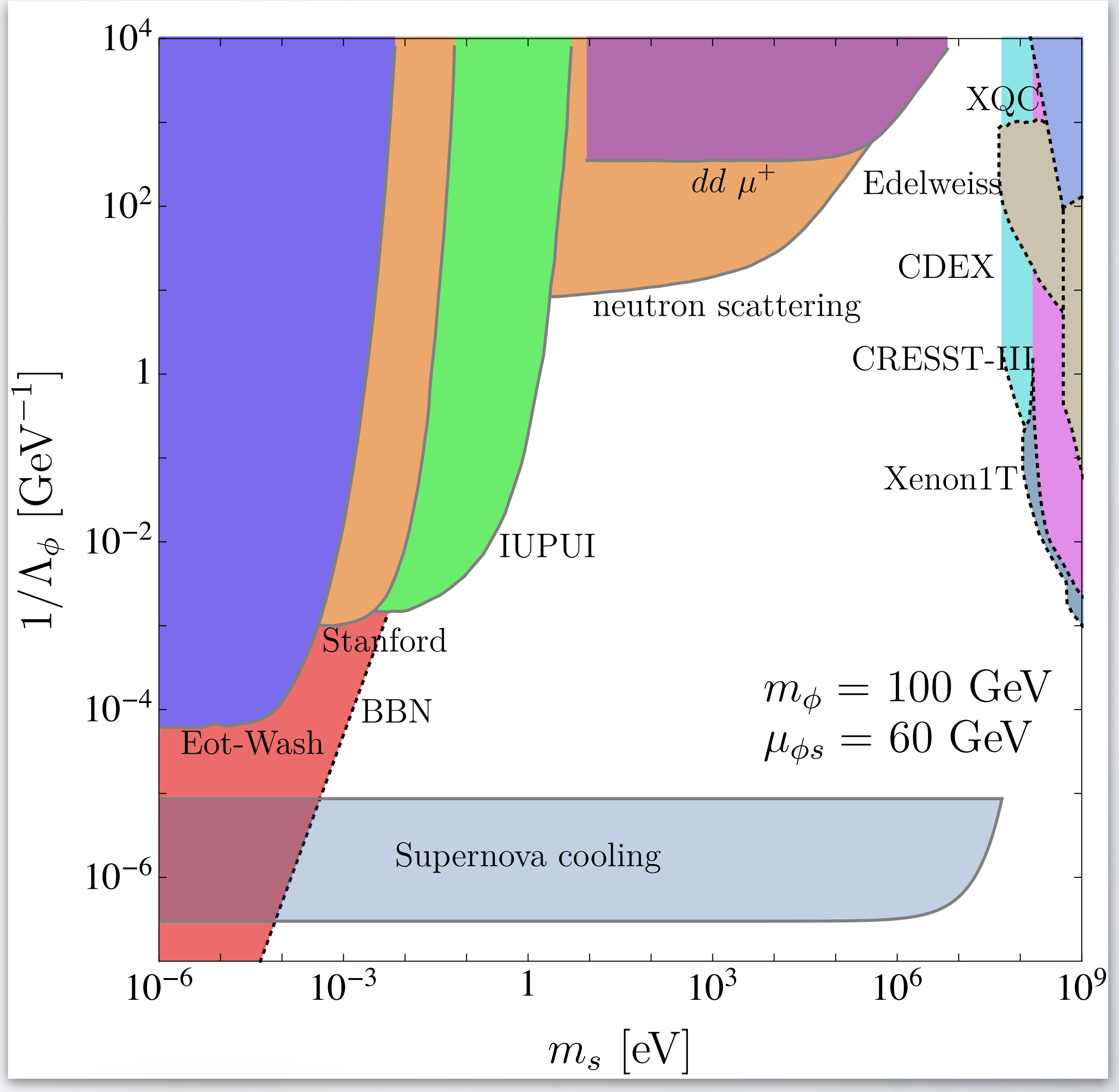
$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{\mu_{\phi s}}{2}\phi s^2 - \frac{\alpha_S}{\Lambda_\phi}\phi\,\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}] \longrightarrow c_{sNN}\, s^2\, \bar{N}N$$

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

- High mass window rather unconstrained!

[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:

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

Suppressed by heavy axion scale $f = \mathcal{O}(f_{\mathrm{GUT}})$

3. ALP DM — HIGGS MEDIATOR

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

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

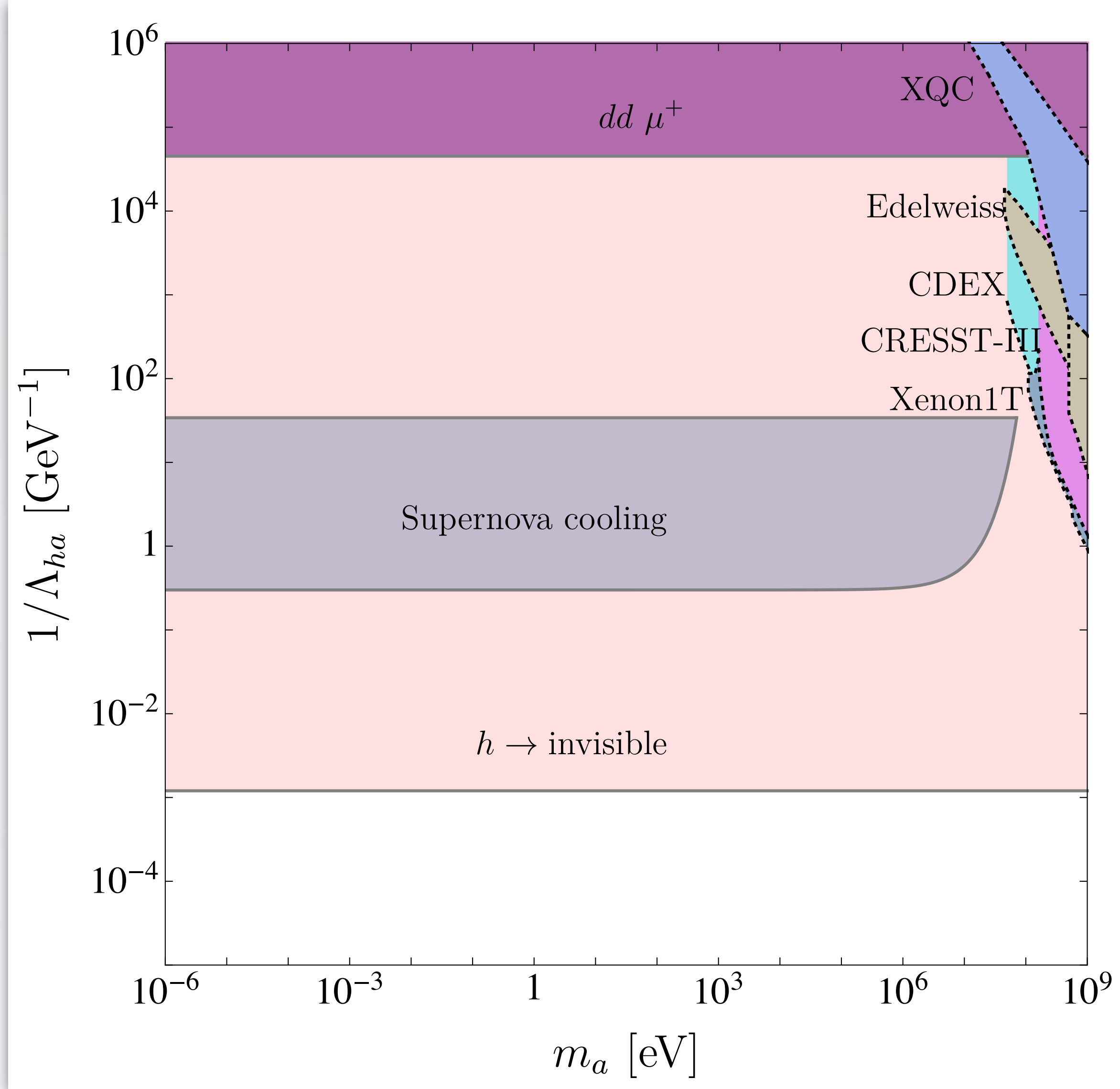
with $$c_{aNN} = \frac{1}{\Lambda_{ha}^2} \frac{m_N}{m_h^2} \frac{2n_H}{3(11 - \frac{2}{3} n_L)}$$

- **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]



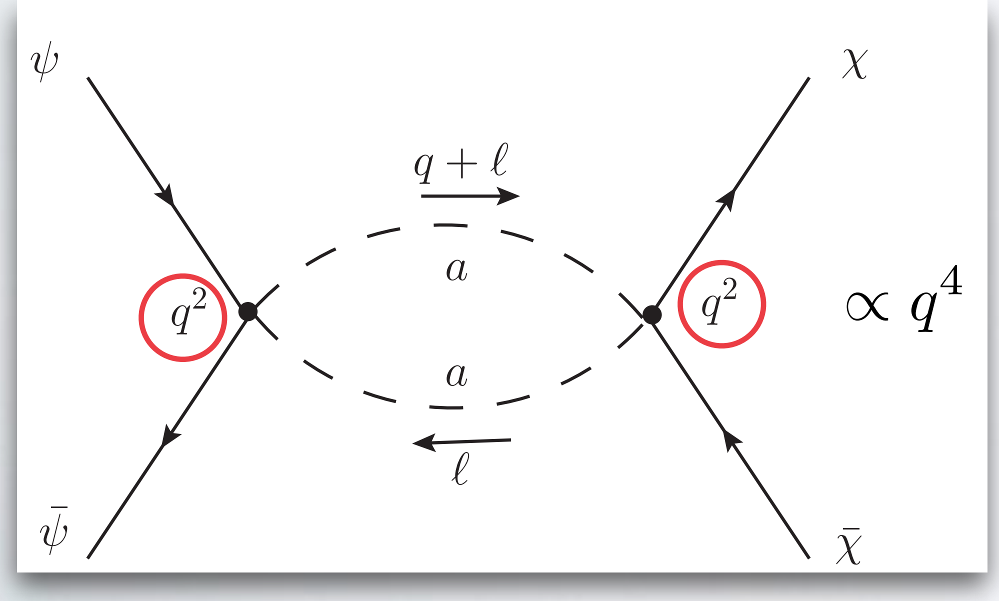
4. ALP DM — NEW MEDIATOR

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

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

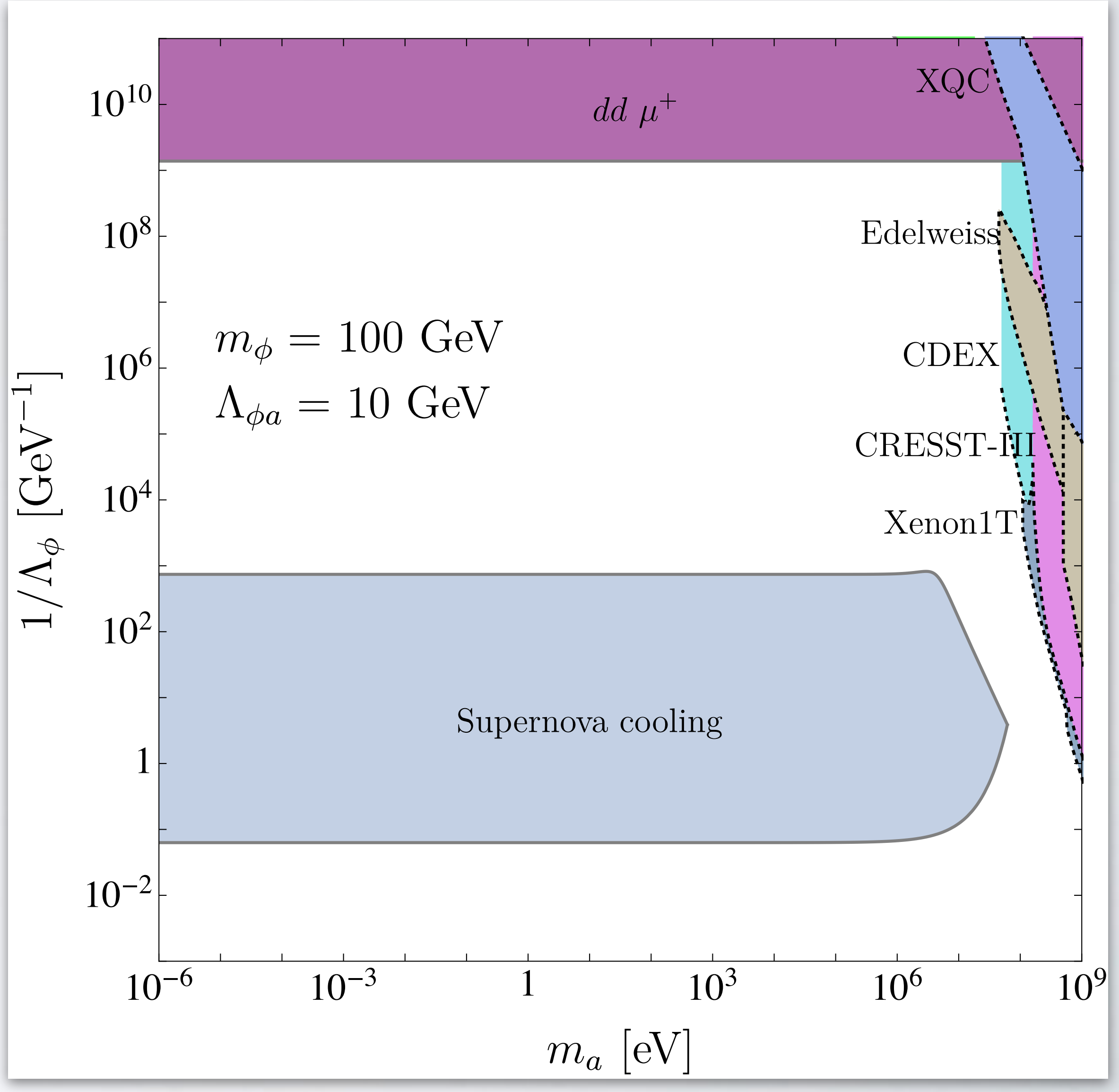
with $c_{aNN} = \dfrac{m_N}{\Lambda_{\phi a}\Lambda_\phi m_\phi^2}\dfrac{8\pi}{11-\frac{2}{3}n_L}$

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



$\propto q^4$

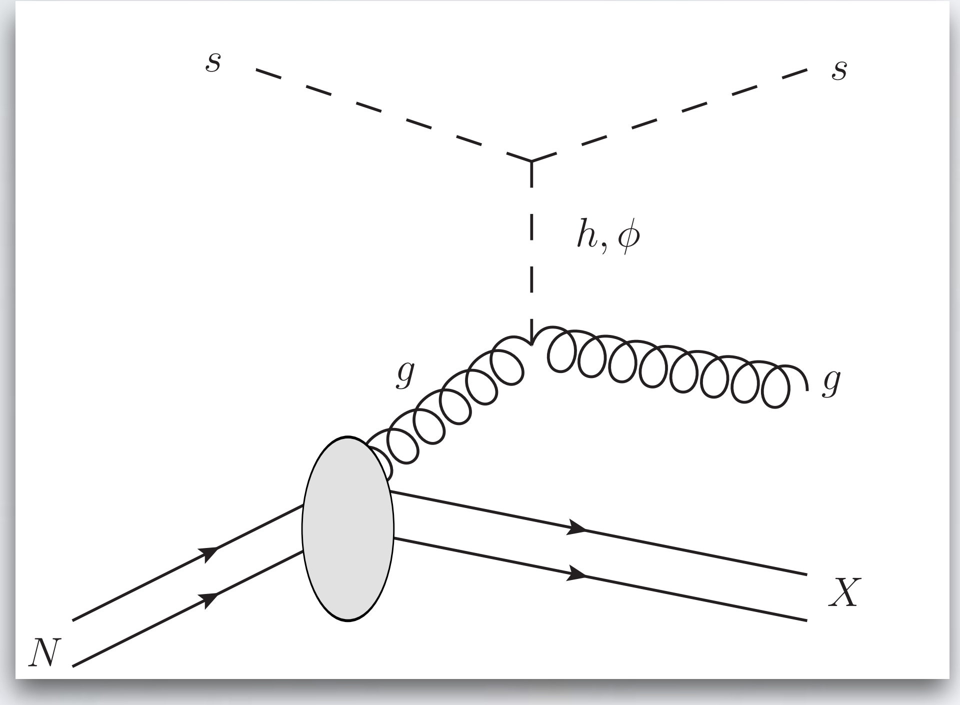
[Bauer, PF, Reimitz, Plehn, 2005.13551]



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:

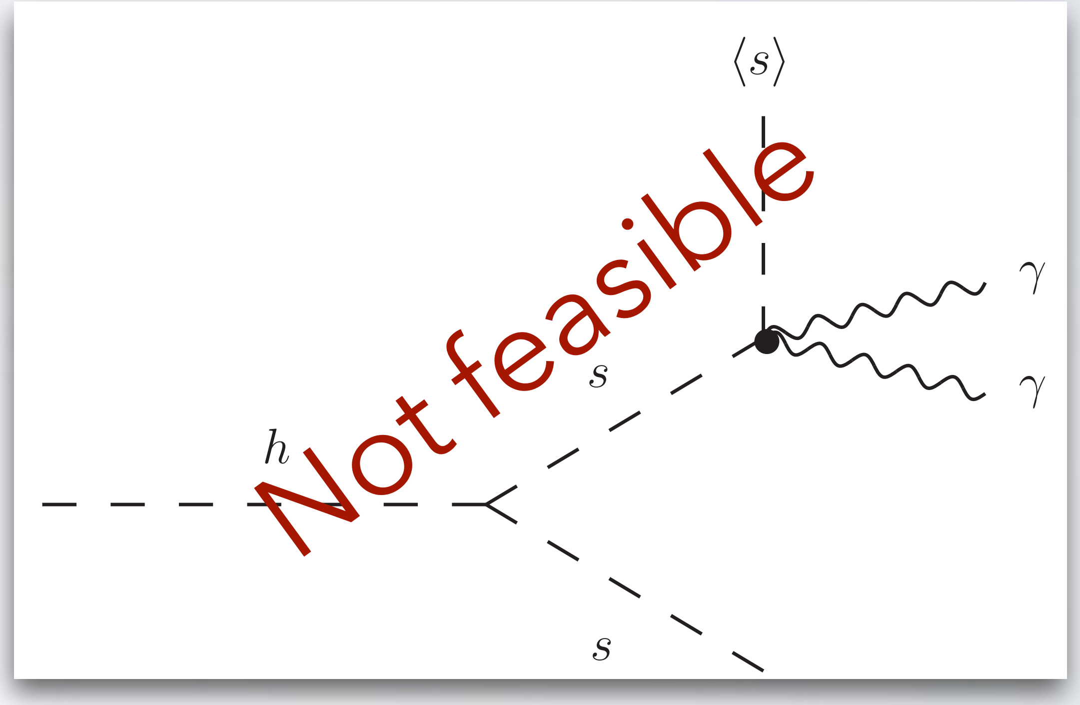
Direct detection @ LHC



(Deep inelastic scattering)

[Bauer, PF, Reimitz, Plehn, 2005.13551]

Indirect detection @ LHC

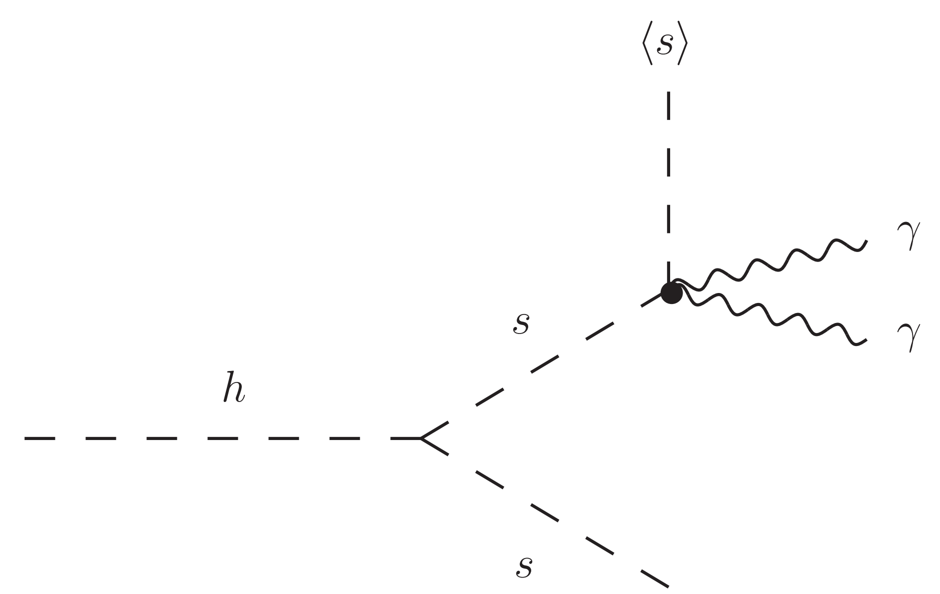


(Background annihilation)

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**

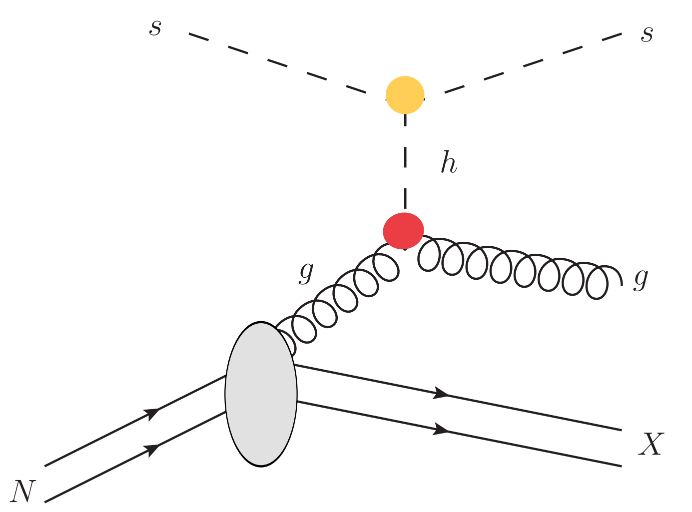
$$\lambda = \frac{1}{n_{\rm DM}\,\sigma_{\langle s\rangle s\to\gamma\gamma}} = \frac{4\pi}{\lambda_{hs}^2 g_{h\gamma\gamma}^2}\frac{m_h^3}{\rho_{\rm DM}} \gtrsim 10^{43}\ {\rm m}$$

⚡

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

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

DIRECT DETECTION



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

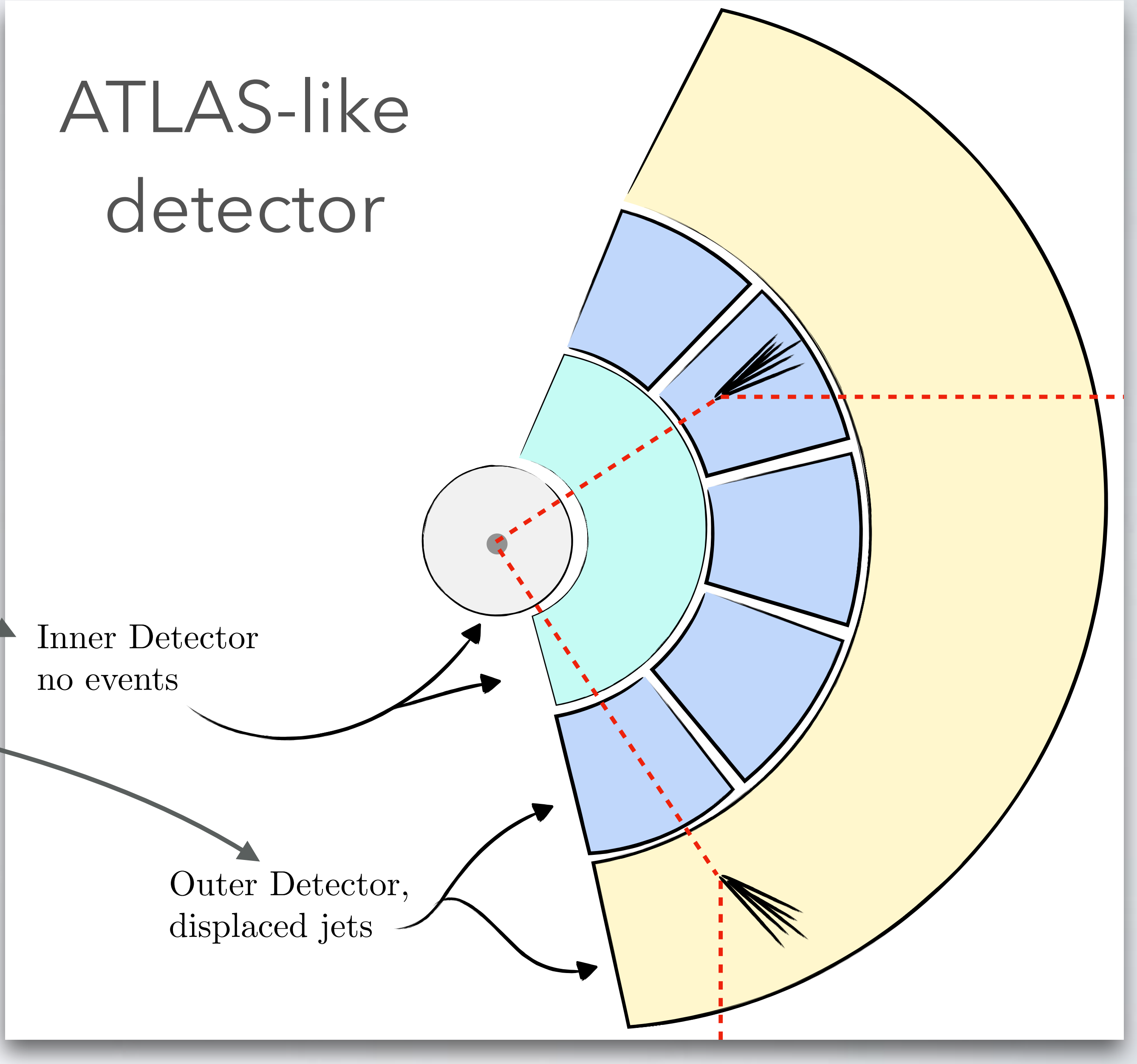
1. E.g. Higgs Portal:

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

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

Distinguishable from LLPs by location of interaction:

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



ATLAS-like detector

Inner Detector
no events

Outer Detector,
displaced jets

But unfortunately for HP:

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

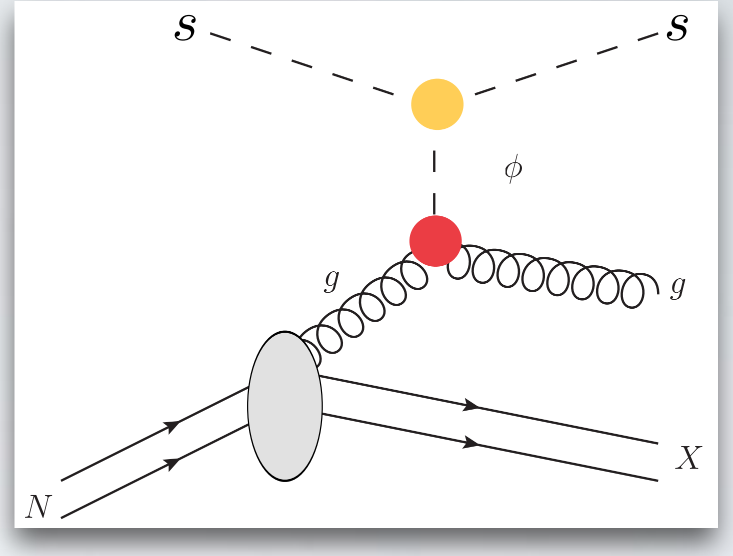
$$P_{\mathrm{DIS}} = 1 - e^{L_E\, n_{Pb}\, \sigma_{Pb}} e^{L_H\, n_{Fe}\, \sigma_{Fe}} \approx 7.5 \cdot 10^{-21}$$ ↯

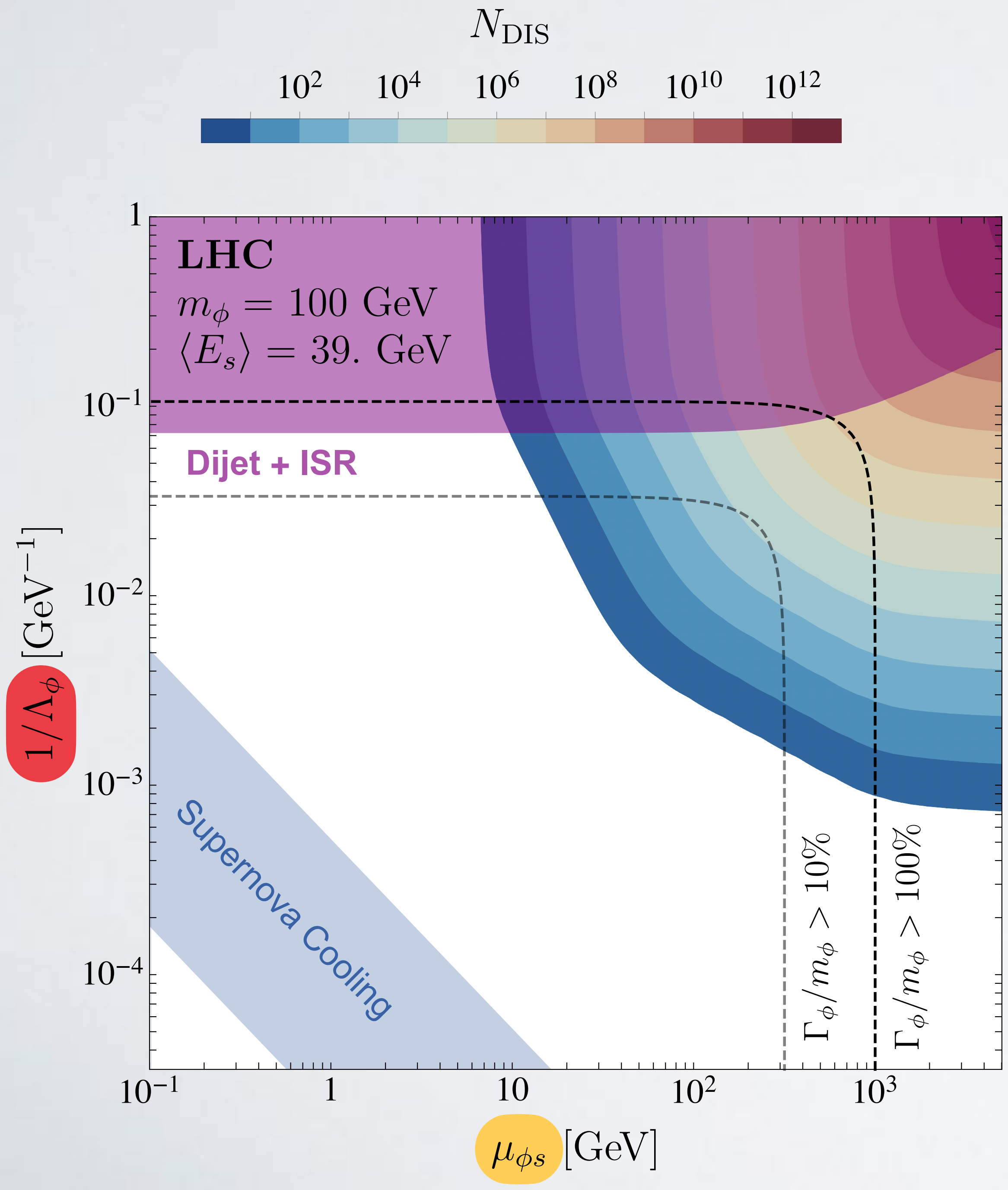
[Bauer, PF, Reimitz, Plehn, 2005.13551]

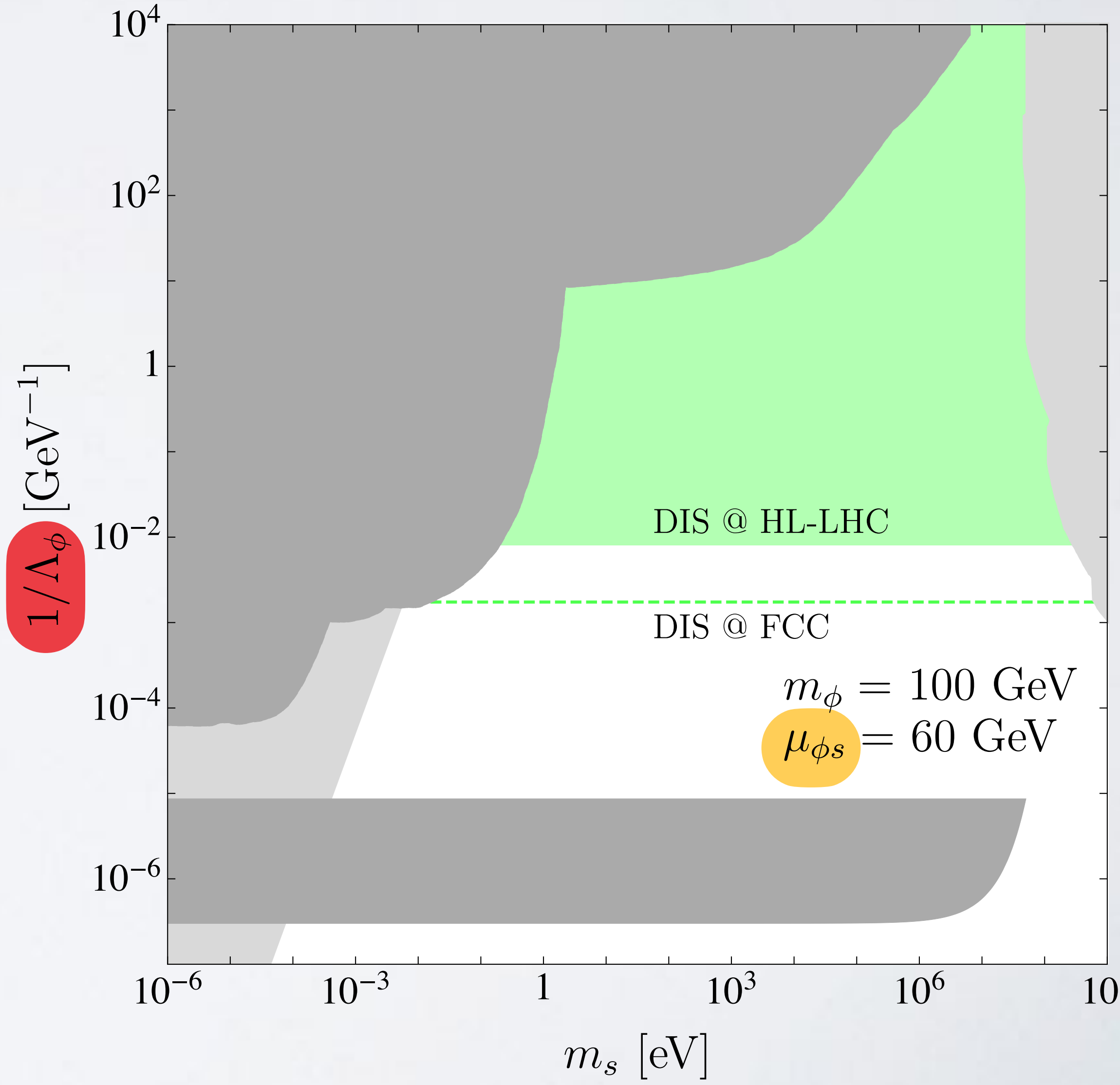
DIRECT DETECTION AT THE LHC

2. Scalar DM with new scalar mediator

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





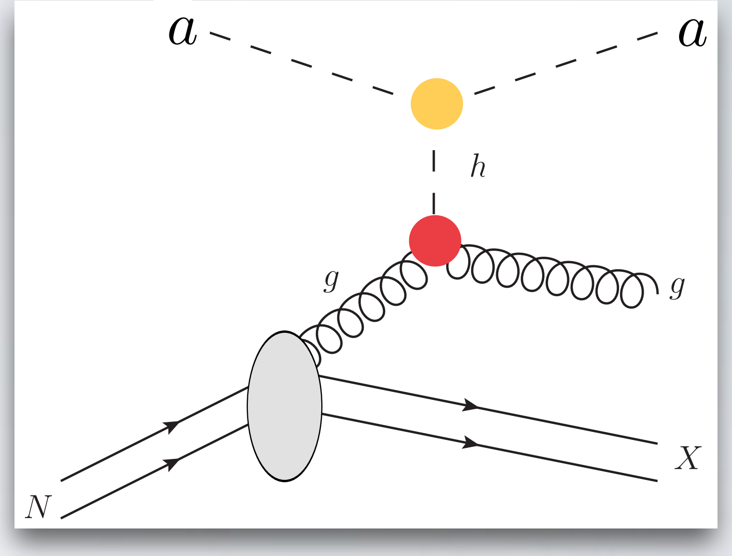


[Bauer, PF, Reimitz, Plehn, 2005.13551]

DIRECT DETECTION AT THE LHC

3. ALP DM with Higgs mediator

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



- With Higgs coupling

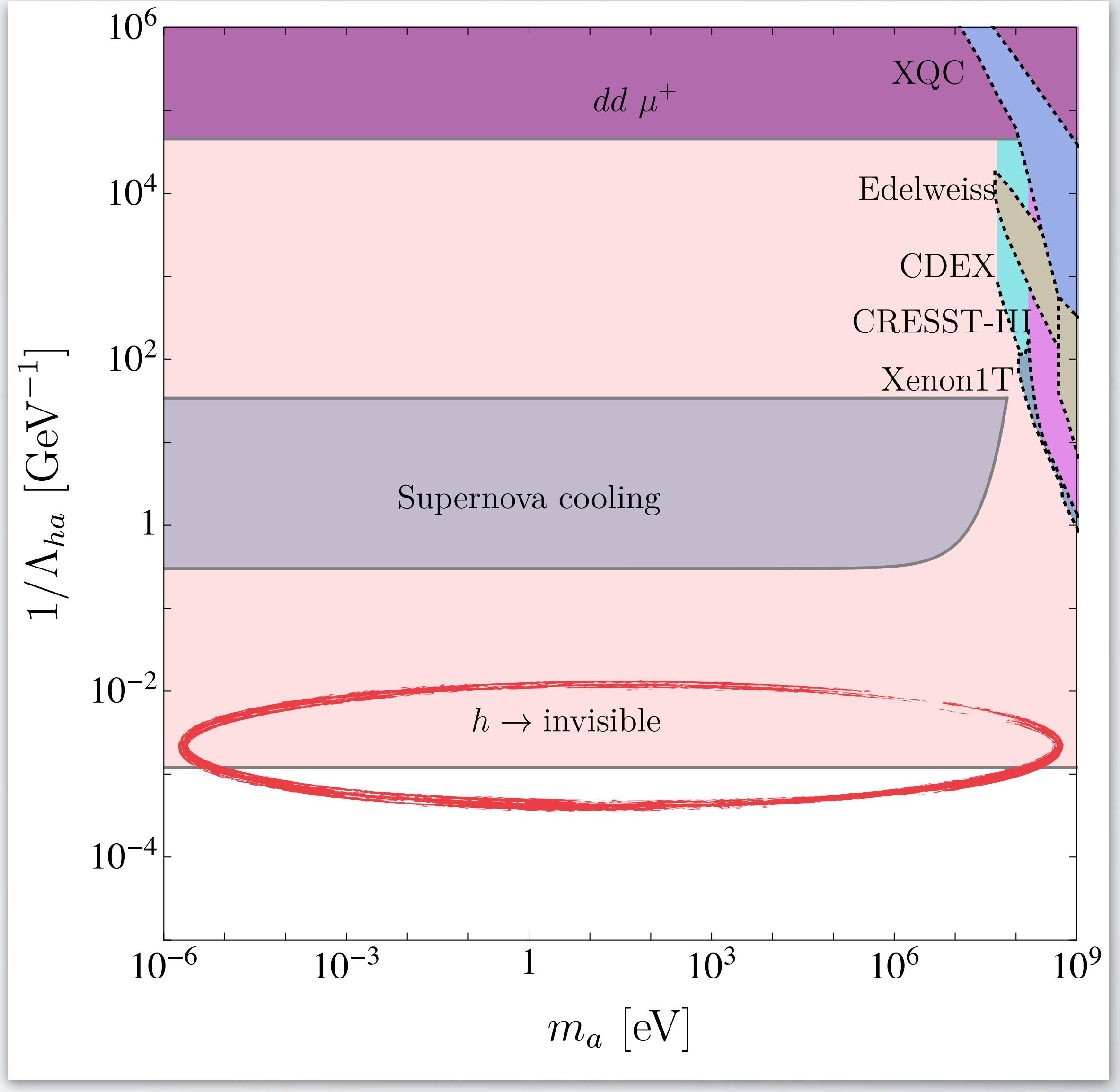
$$g_{hgg} = \alpha_s/(12\pi)$$

and the Higgs invisible constraint

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

we can estimate

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

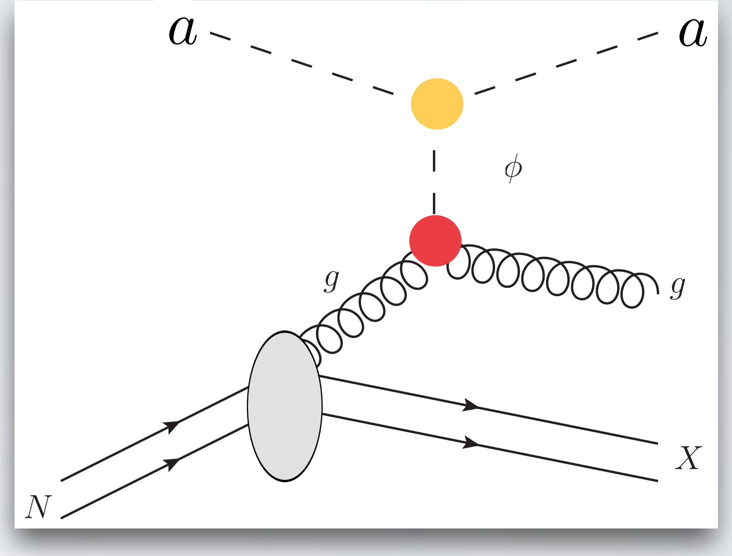


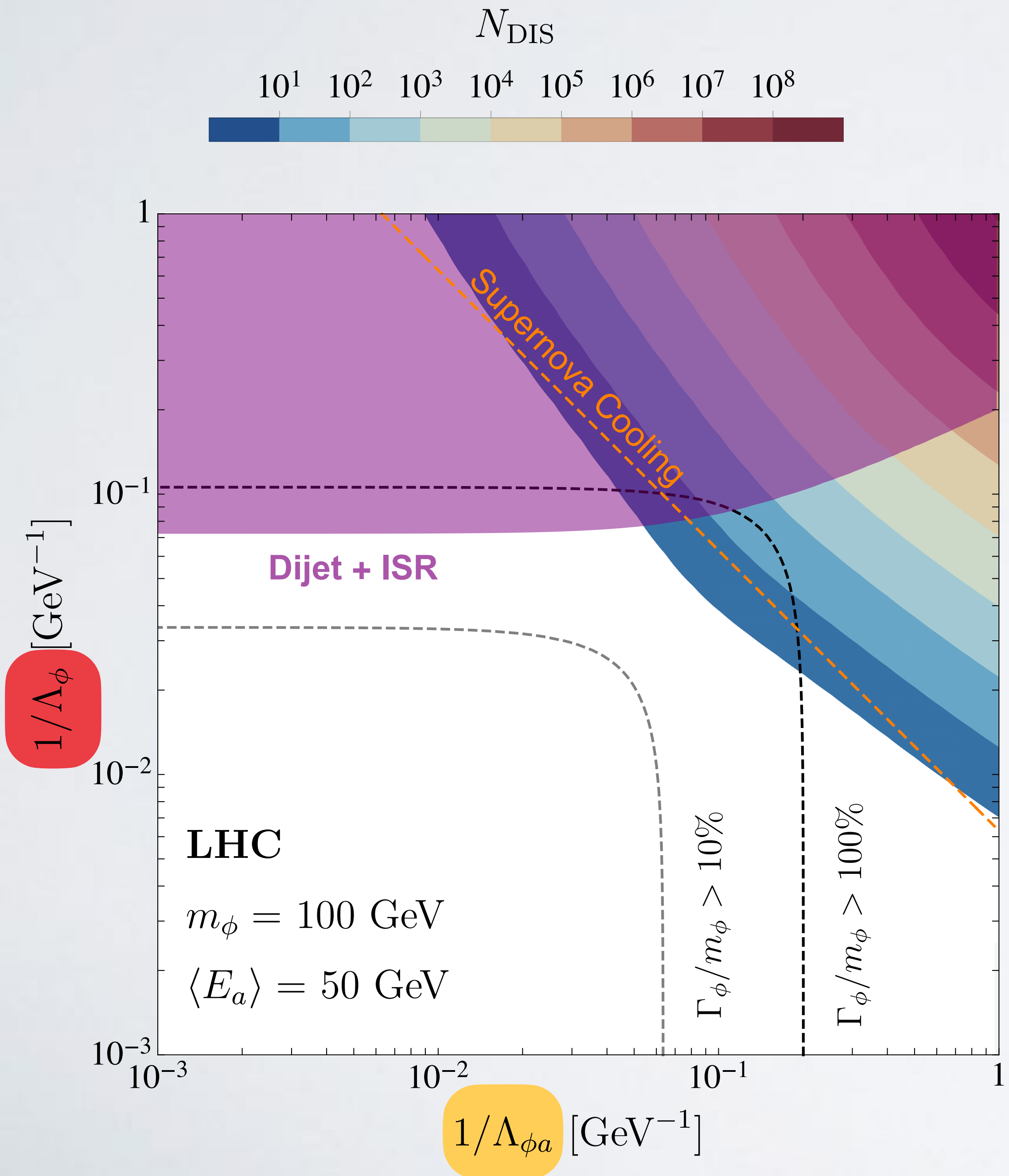
[Bauer, PF, Reimitz, Plehn, 2005.13551]

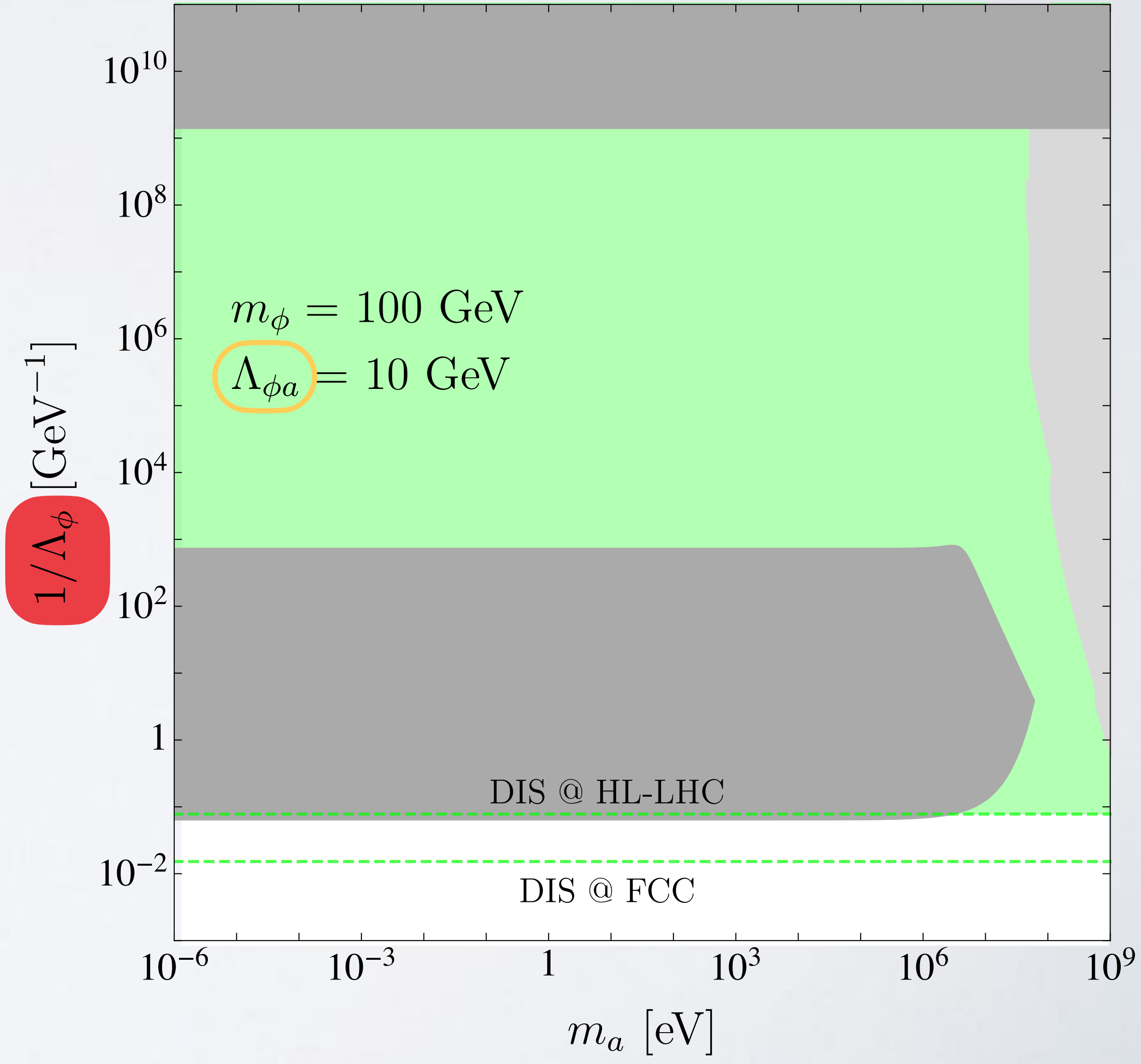
DIRECT DETECTION AT THE LHC

4. ALP DM with scalar mediator

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





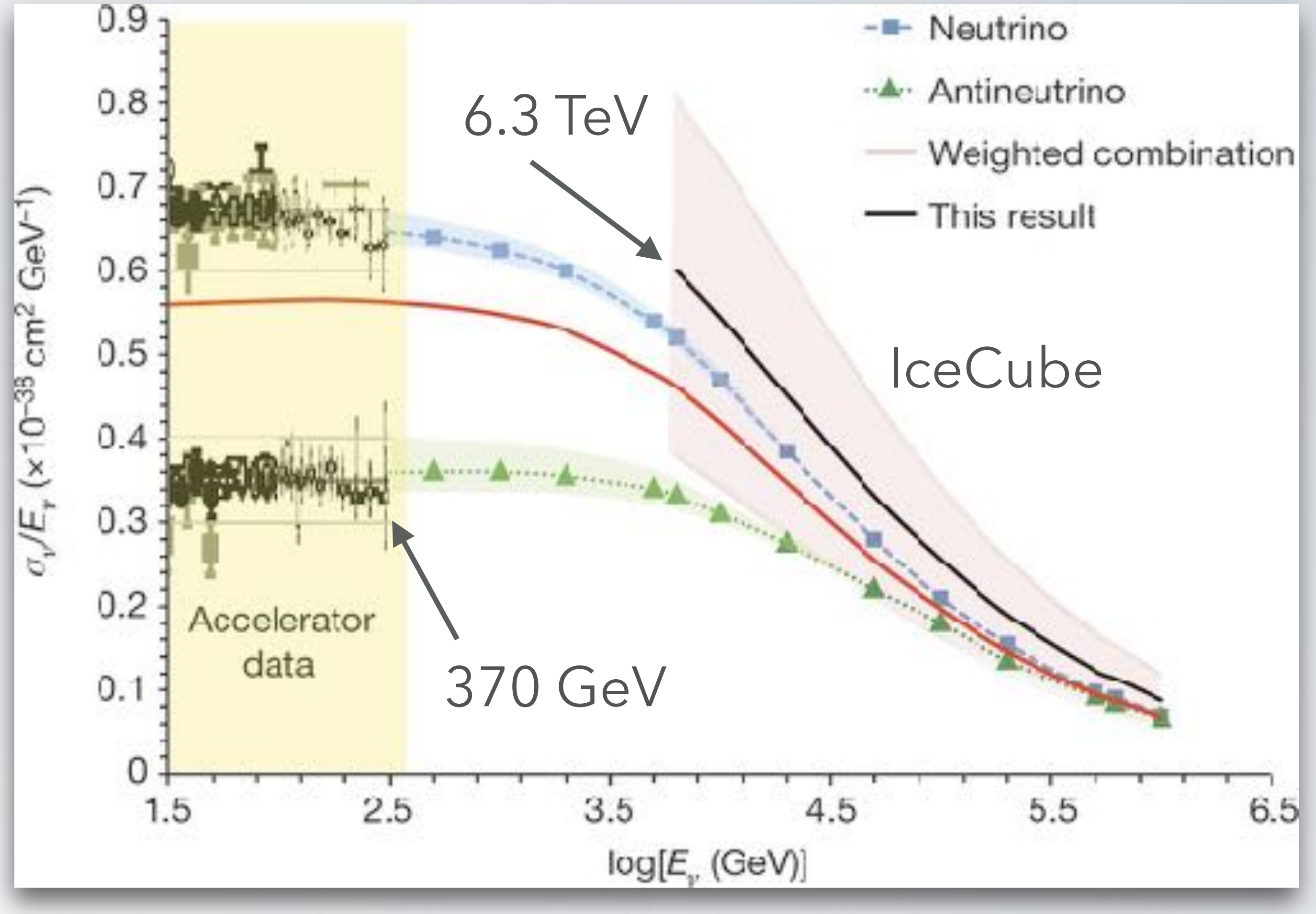


[Bauer, PF, Reimitz, Plehn, 2005.13551]

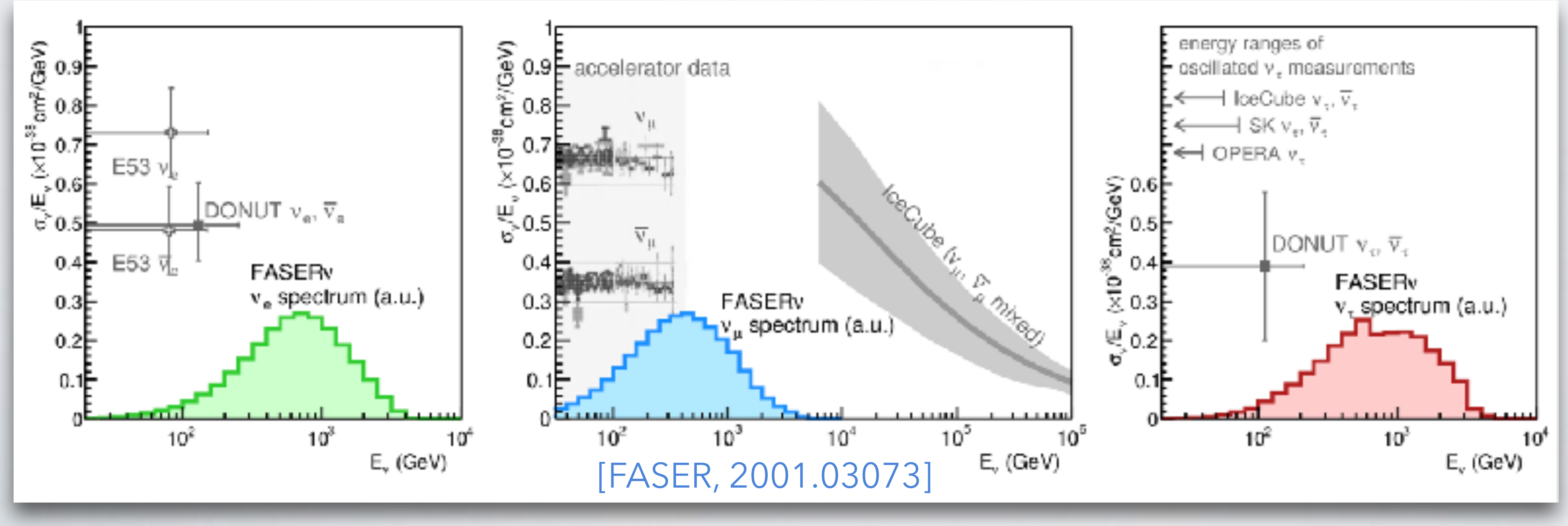
NEUTRINOS

NEUTRINO CROSS SECTIONS

- Neutrinos still least understood particles of SM: CP violation, masses, Majorana vs. Dirac
- Gap in knowledge of neutrino cross section between 370 GeV and 6.3 TeV!
- New LHC forward experiments (FASER, SND)!



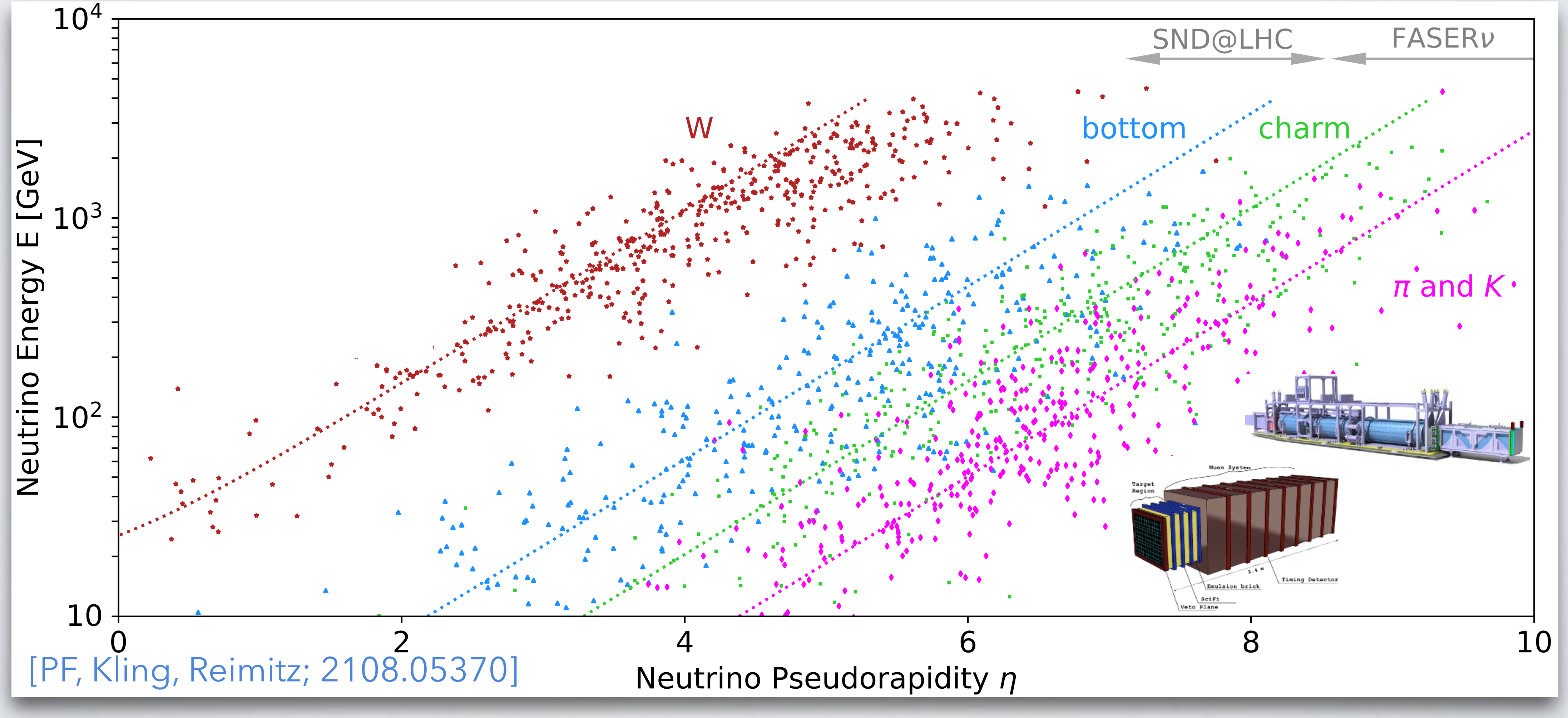
[IceCube, *Nature* 551 (2017) 596-600]



[FASER, 2001.03073]

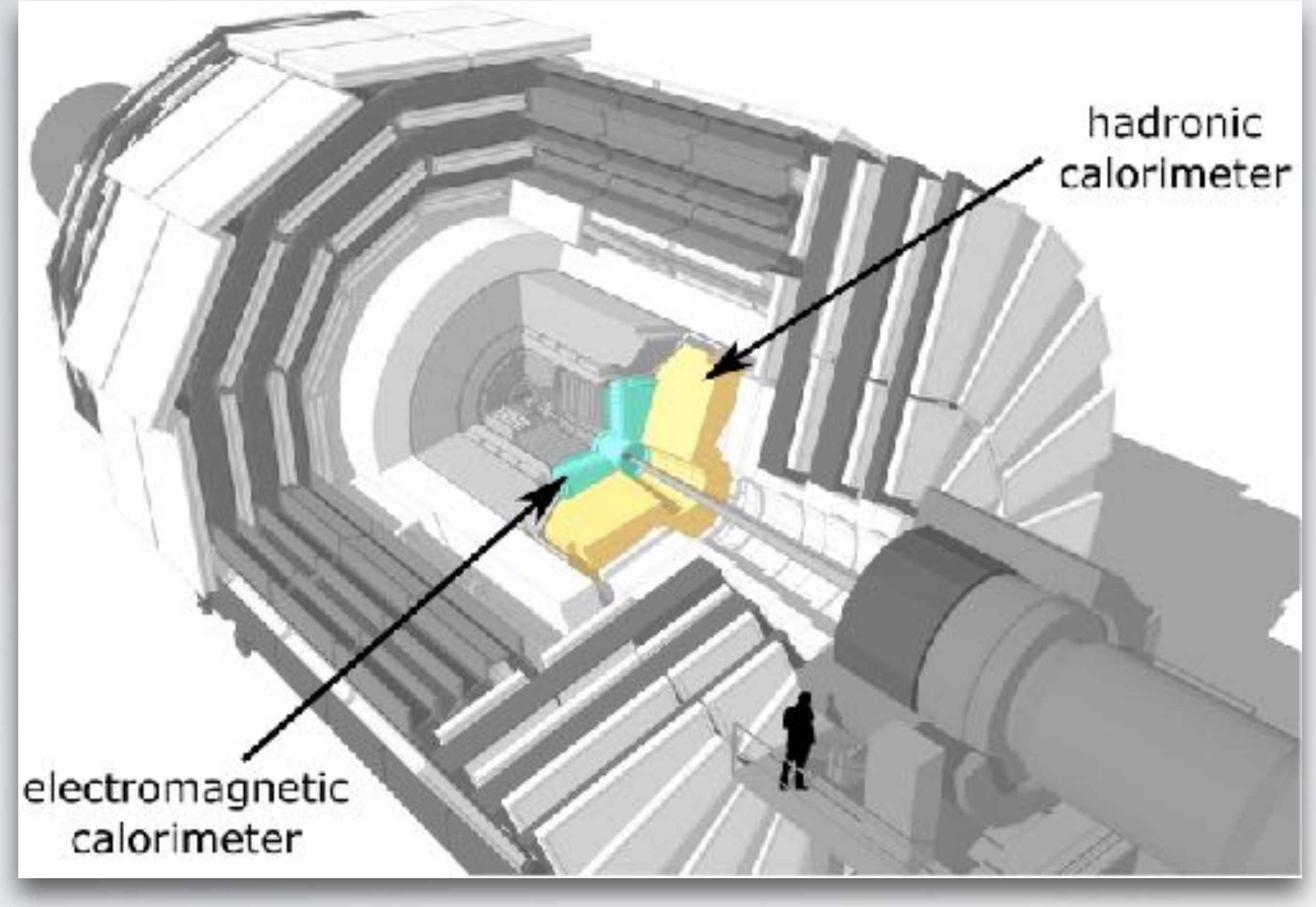
APPLICATION TO NEUTRINOS

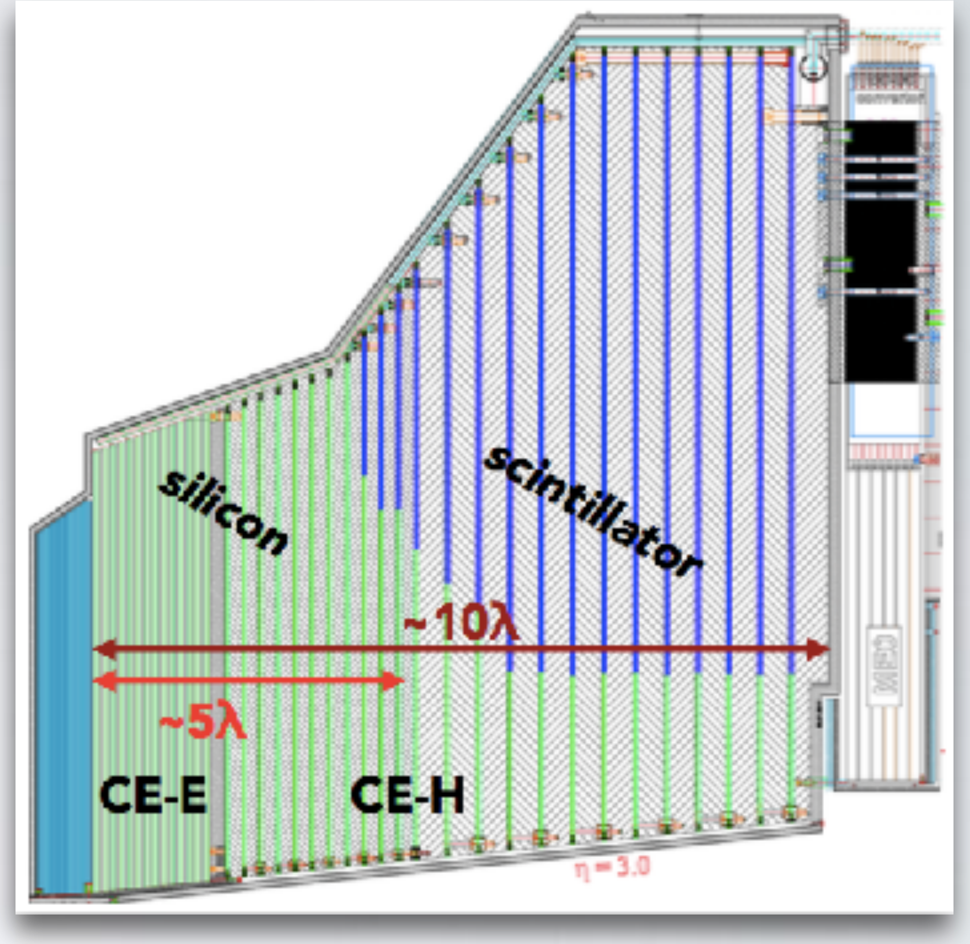
- Displaced jet signature interesting for **light particles** coupled to **weak scale mediator** ⟹ highly energetic **neutrinos @ LHC**
- Neutrino production typically peaks in very forward direction ⟹ dedicated forward experiments have excellent sensitivity to neutrinos from meson decays
- Large **unused potential** of high energy **W-produced neutrinos**!



[PF, Kling, Reimitz; 2108.05370]

CMS ENDCAP CALORIMETER





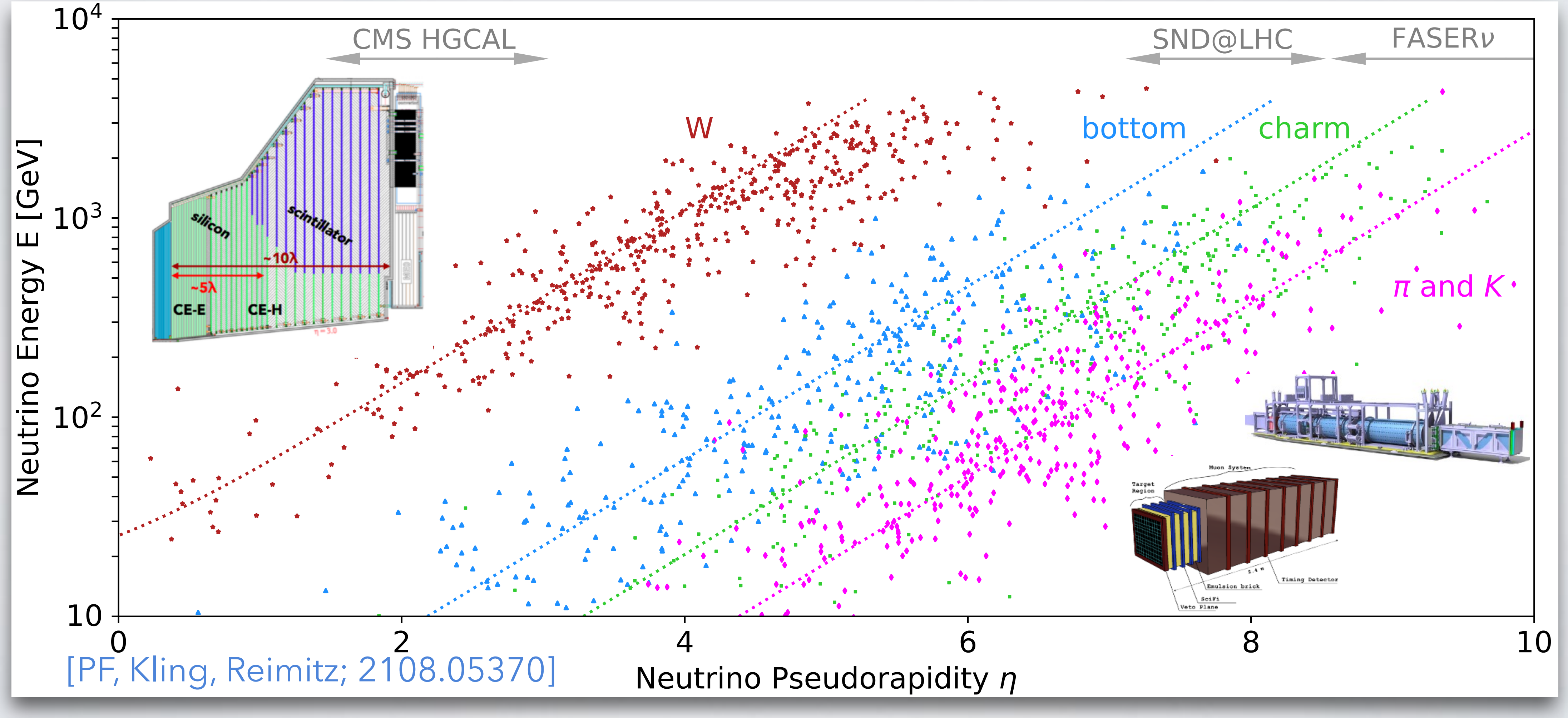
[CMS; Nucl.Instrum.Meth.A 978 (2020) 164428]

- Upgraded CMS high-granularity endcap calorimeter ideally suited to search for forward neutrino scattering
- Angular coverage in the forward region between $1.5 \leq |\eta| \leq 3.0$
- High cell granularity (0.5-1) cm^2 allows for high resolution measurement of lateral shower development and good two-shower separation!

APPLICATION TO NEUTRINOS

- Displaced jet signature interesting for **light particles** coupled to **weak scale mediator** ⟹ highly energetic **neutrinos @ LHC**
- CMS high-granularity endcap calorimeter upgrade (HGCAL) can access high-energy neutrinos $(E_\nu \gtrsim \mathcal{O}(100)\ \mathrm{GeV})$ from W production!

⟹ How do we search for those neutrinos at CMS?



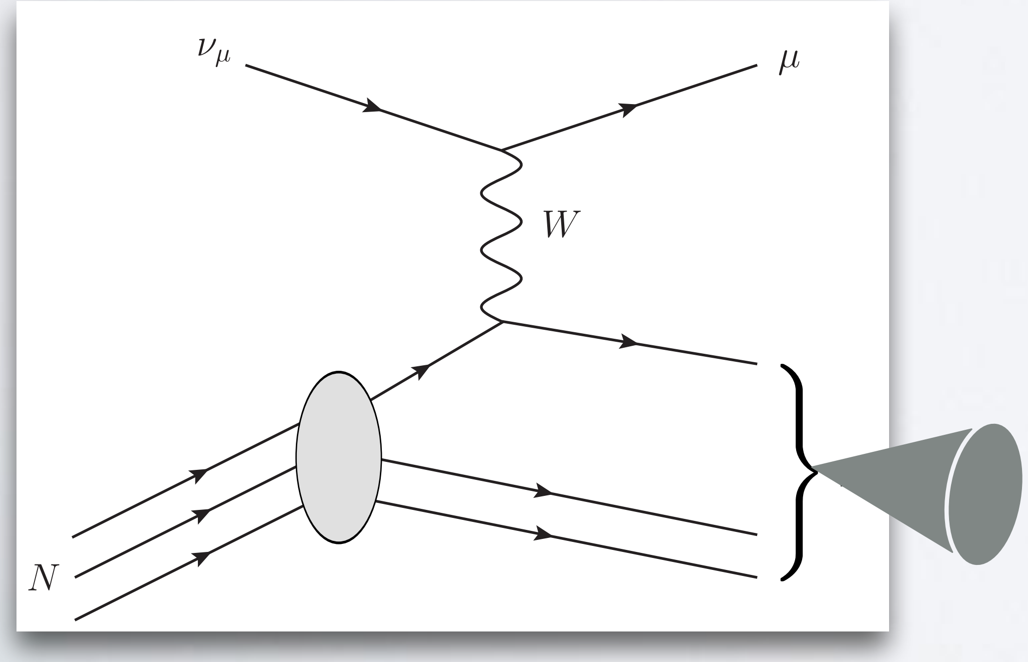
[PF, Kling, Reimitz; 2108.05370]

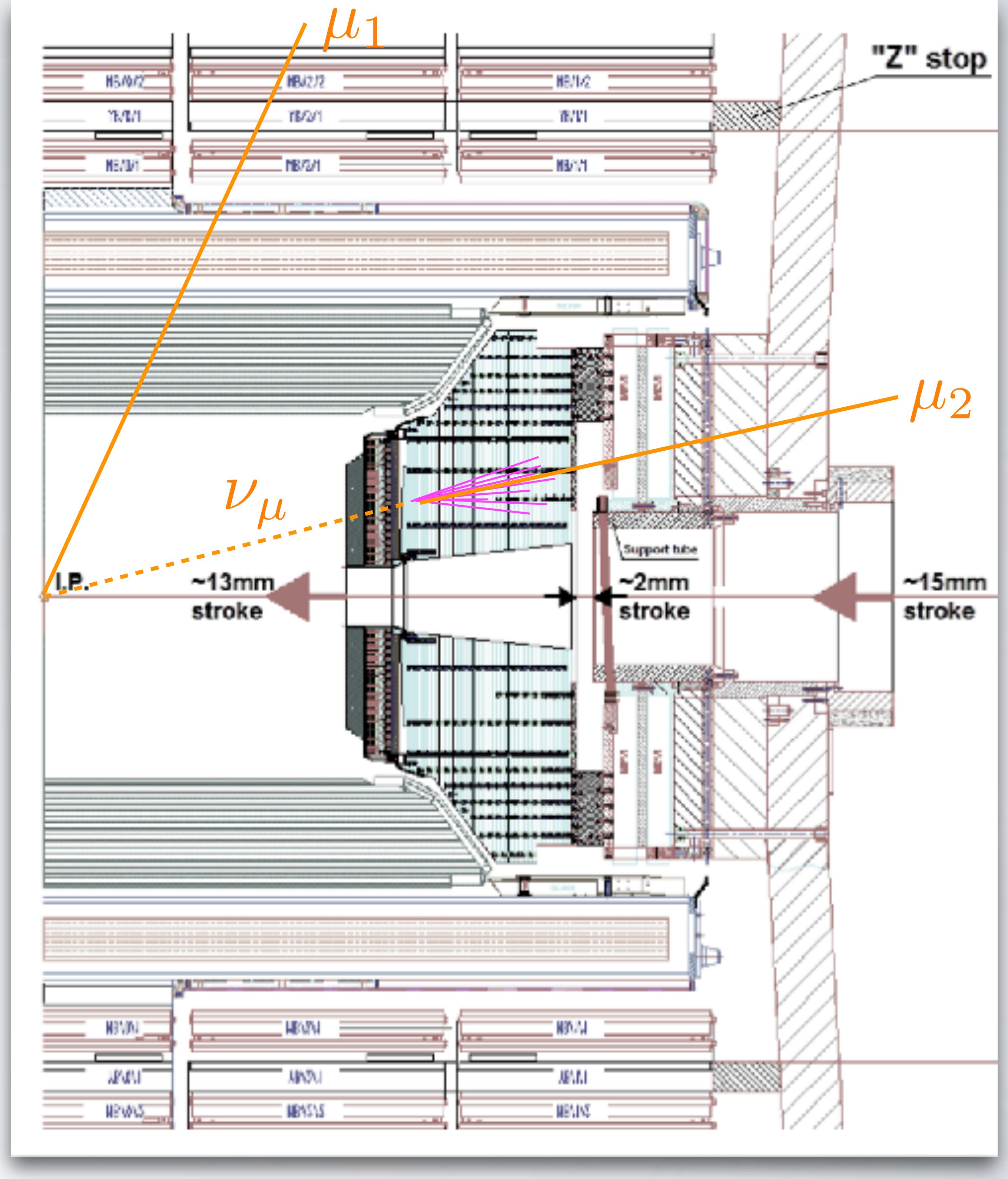
NEUTRINOS FROM W DECAY

- Promising candidate is W production with decay $qq' \to W \to \nu_\mu + \mu_1$

- Search for neutrino in CMS HGCAL via the process

$$\nu_\mu + N \to \text{jet} + \mu_2$$





NEUTRINOS FROM W DECAY

- PROBLEM:
  Huge background of neutral hadron due to pile-up!

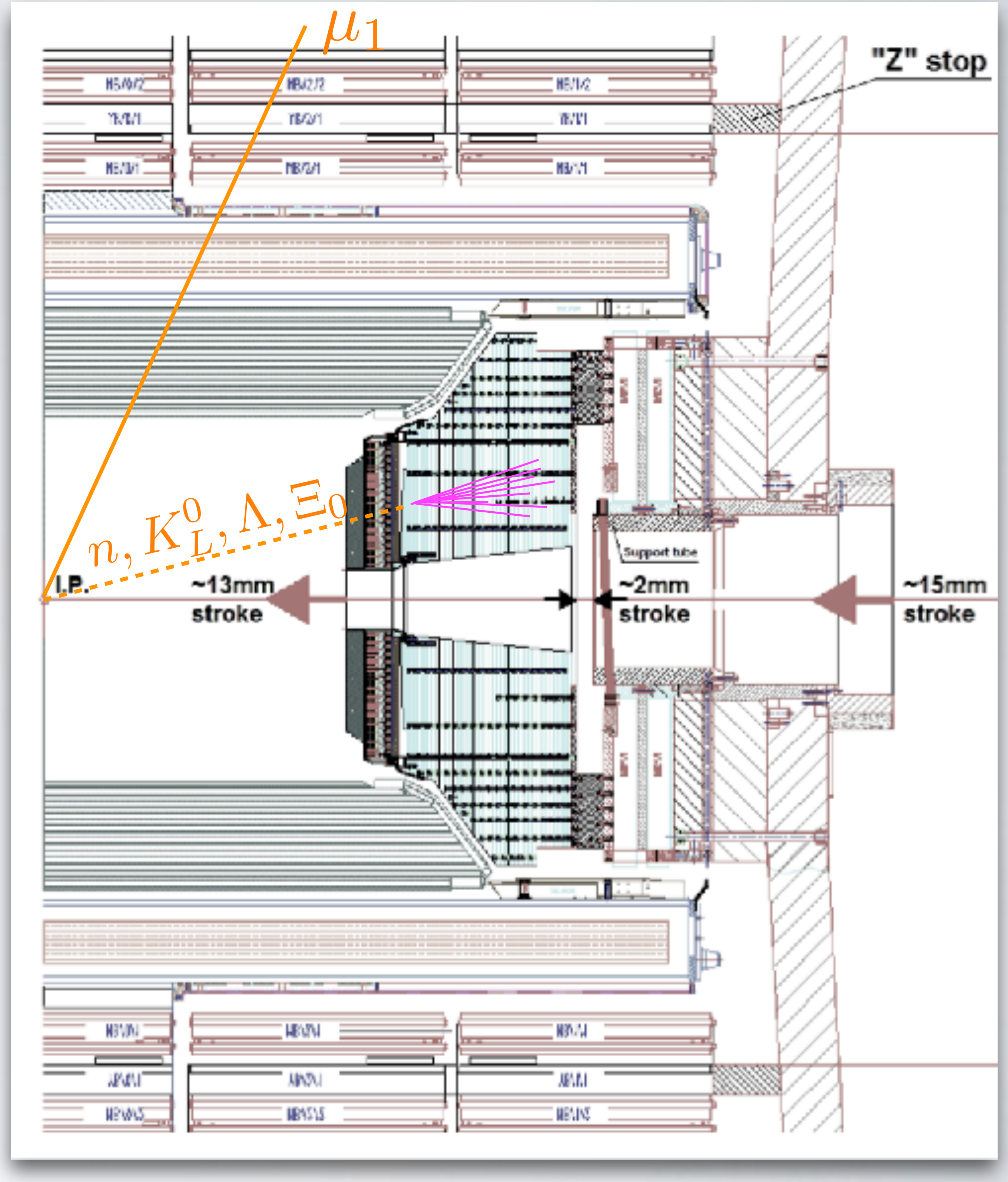
  $$qq' \to W + \mathrm{QCD} \to \mu_1 + \mathrm{QCD}$$

  and heavy hadron decays

  $$qq' \to b/c + \mathrm{QCD} \to \mu_1 + \mathrm{QCD}$$

- Scattering of neutral hadron can fake neutrino jet:

  $$\text{neutral hadron} + N \to \text{jet}$$



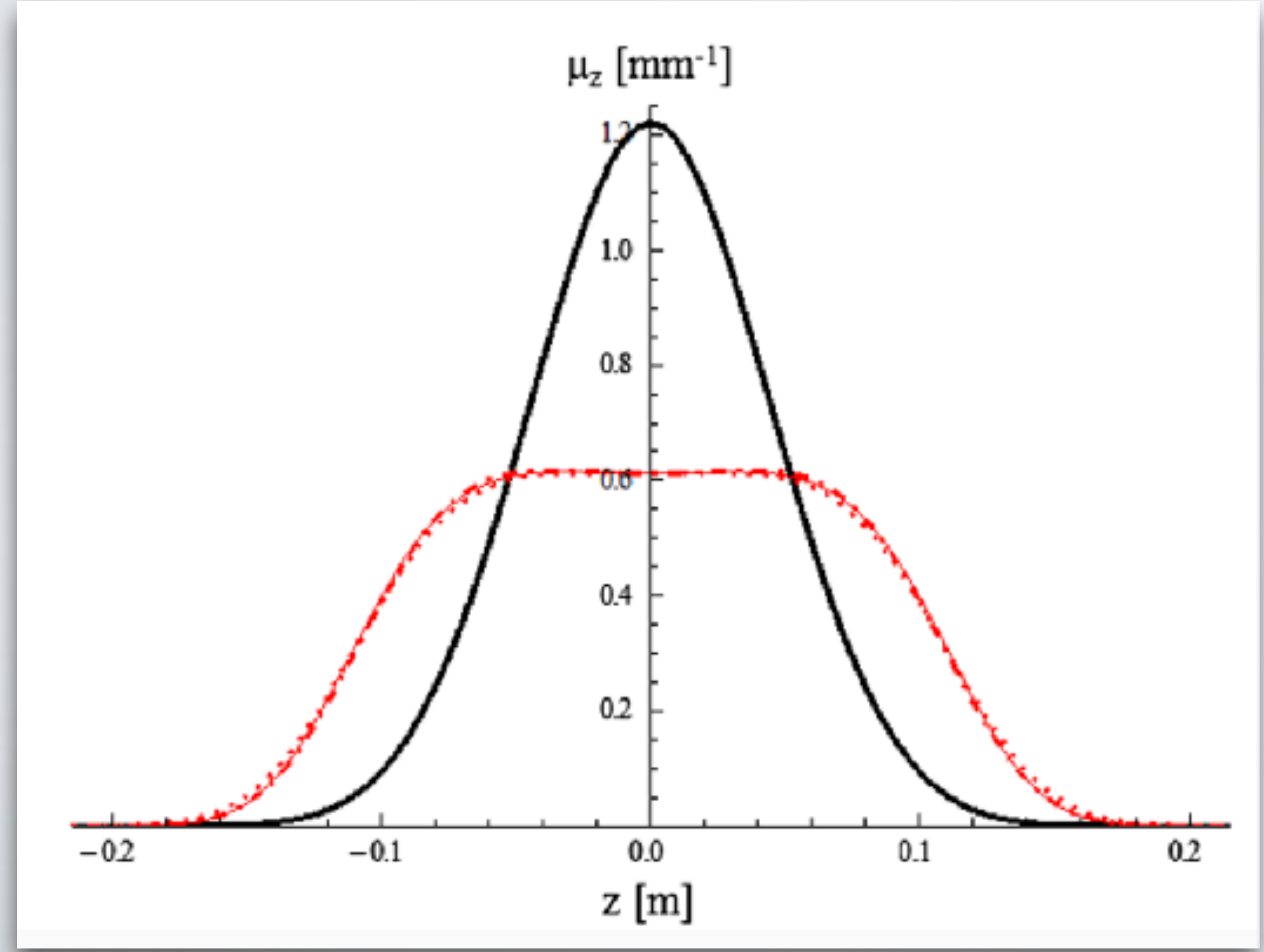
PILE-UP MITIGATION

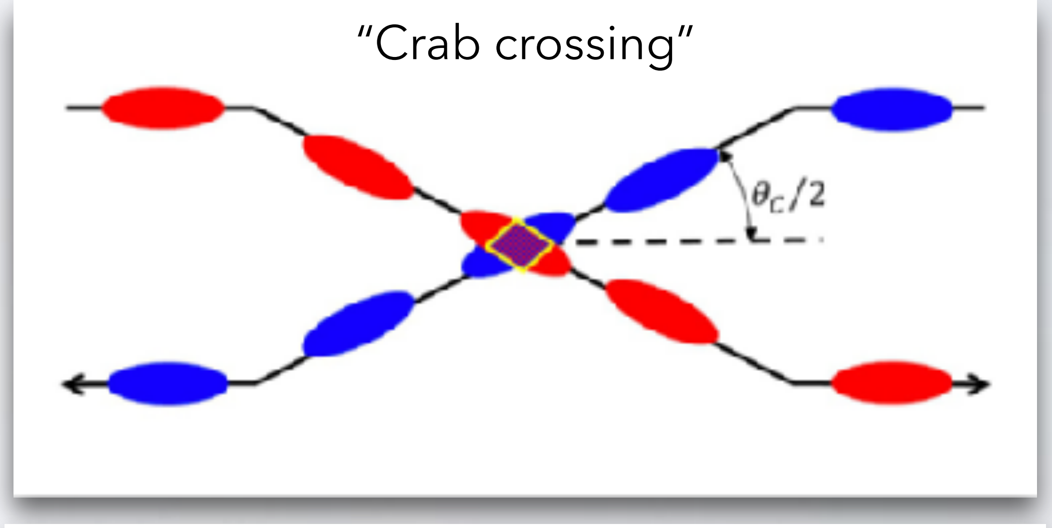
- HL-LHC: average of 130-200 pile-up events per bunch crossing (~40 now)
- *Crab kissing:* Novel collision technique stretches pile-up over ~31.4 cm
- **HGCAL has excellent timing** window of ~90 ps/$\Delta_l \sim 2.7$ cm

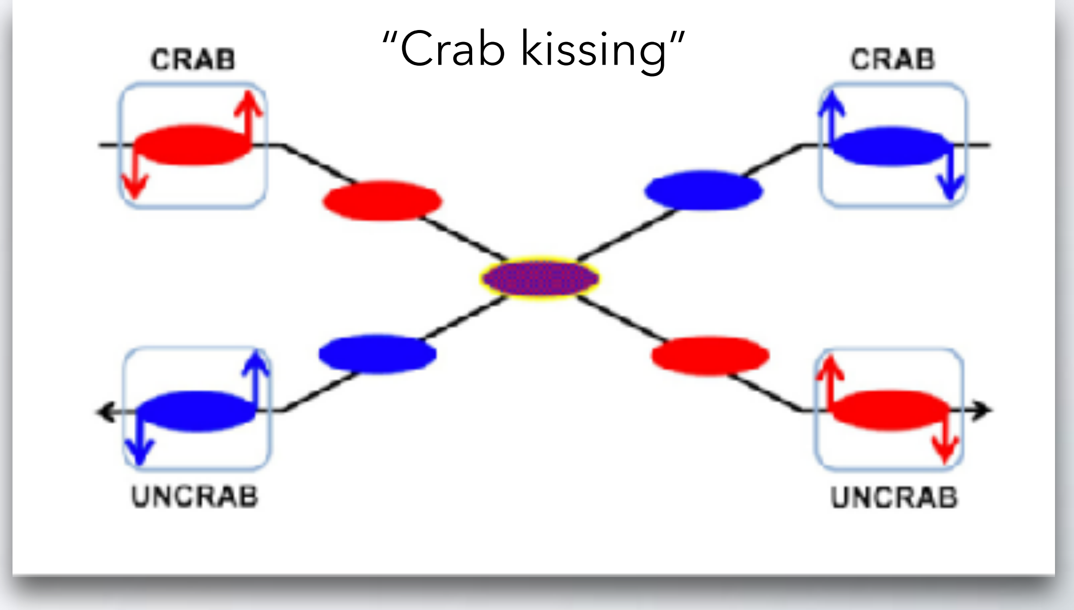
⟹ Can **reduce pile-up to ~11** per bunch crossing

[Verdu-Andres et al.; *Nucl.Part.Phys.Proc.* 273-275 (2016) 193-197]

[Fartoukh; Phys. Rev. ST Accel. Beams **17**, 111001]




"Crab crossing"


"Crab kissing"

NEUTRINOS FROM W DECAY

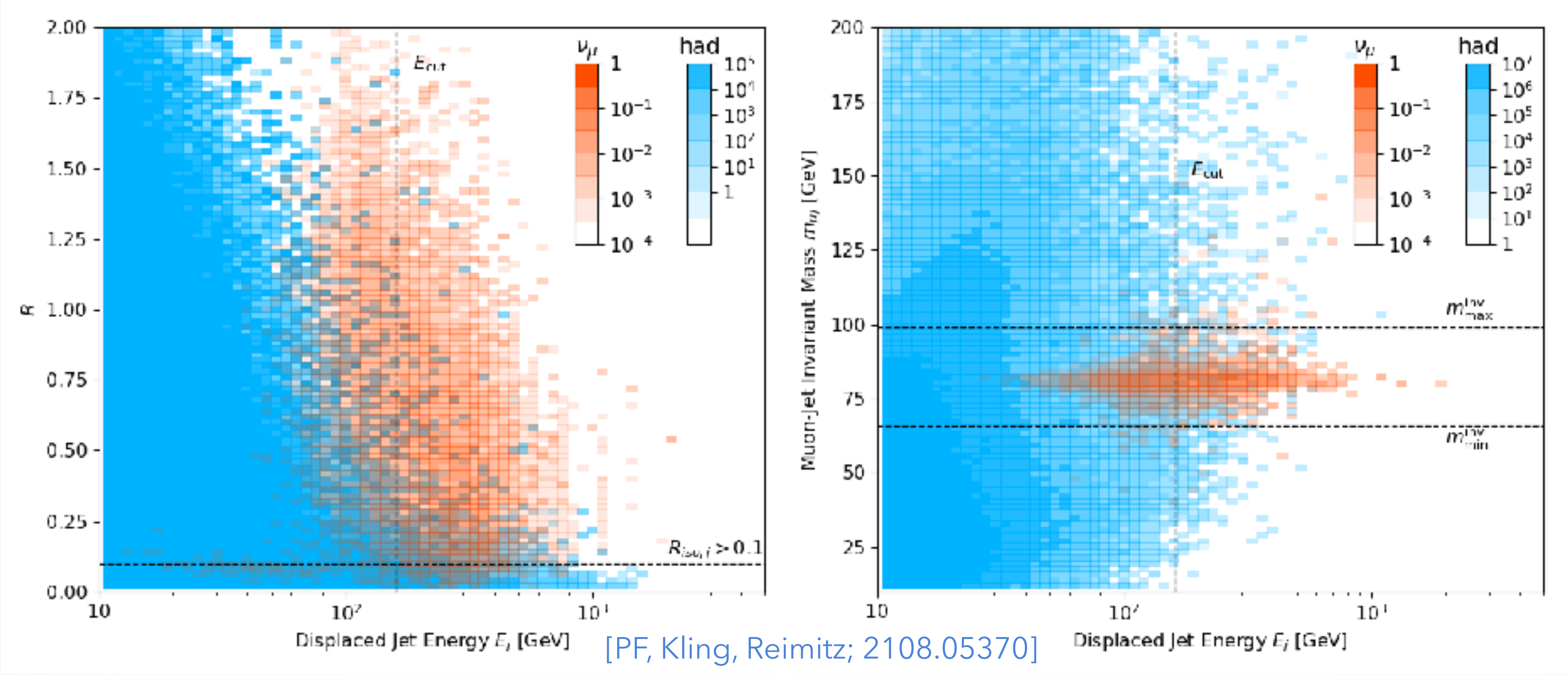
A. Isolated primary muon: $R_{\text{iso},\mu_1} > 0.1, \quad p_{T,\mu_1} > 20 \text{ GeV}, \quad |\eta_{\mu_1}| < 2.4$

B. Isolated jet: $R_{\text{iso},j} > 0.1$

C. W mass cut on invariant mass: $66 \text{ GeV} < m_{\mu\nu} < 99 \text{ GeV}$

D. Displaced jet energy cut: $E_{\text{cut}} > 160 \text{ GeV}$

background
still
dominates!



[PF, Kling, Reimitz; 2108.05370]

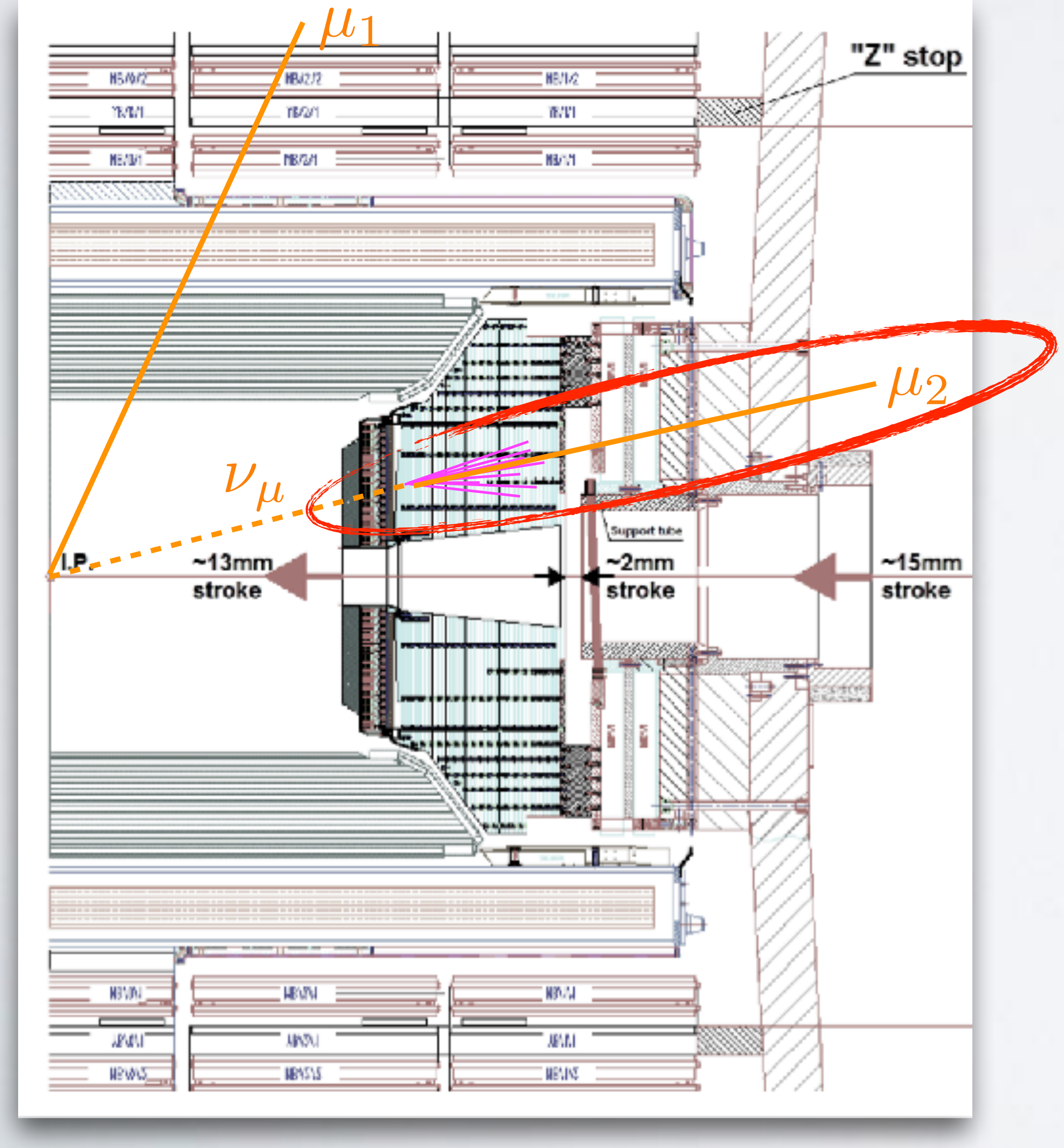
NEUTRINOS FROM W DECAY

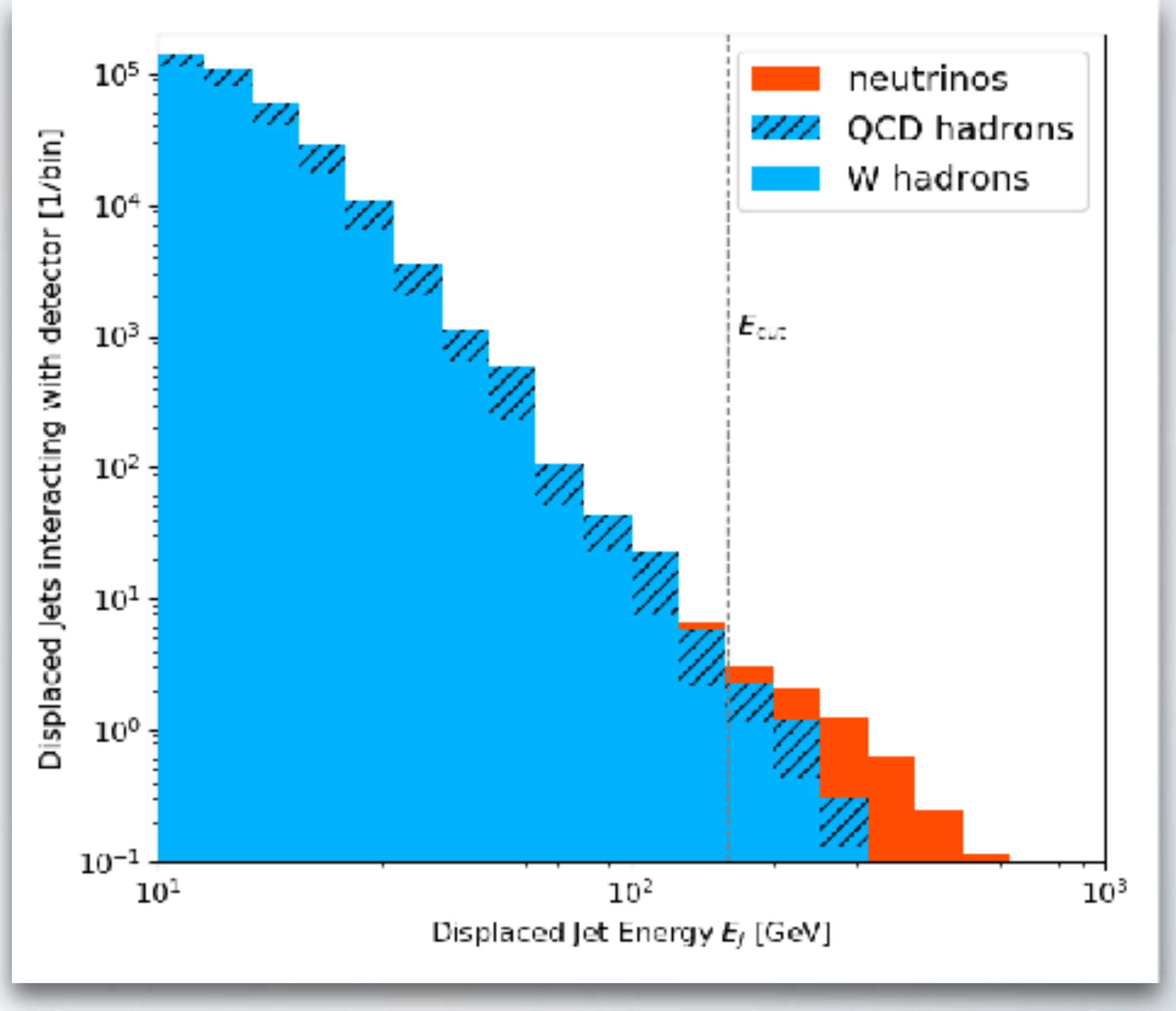
[PF, Kling, Reimitz; 2108.05370]

- Require highly energetic secondary muon:

$$E_{\mu_2}/E_{\rm j} > 0.33$$

Cuts	Hadrons	Neutrinos
isolated muon	$1.02 \cdot 10^{11}$	7.59
isolated jet	$8.63 \cdot 10^{10}$	7.05
W mass	$1.92 \cdot 10^{9}$	6.55
secondary muon	$3.49 \cdot 10^{5}$	5.48
$E_{\rm j} > 160$ GeV	3.52	3.60





CONCLUSIONS

- **Displaced recoil jets** are promising signature to search for **light physics at the LHC**

- Complementary to existing direct detection or ULDM probes! **Promising for momentum-suppressed interactions!**

- Promising signature to detect **neutrino** scattering at the LHC in **CMS HGCAL**

- Hadronic background suppression via **highly energetic secondary muon**

- More improvements and generalisations:
  - central muon station events
  - sterile neutrino
  - meson decays
  - shower development/jet variables
  - b/c neutrinos