SEARCHING FOR LIGHT PHYSICS AT THE LHC

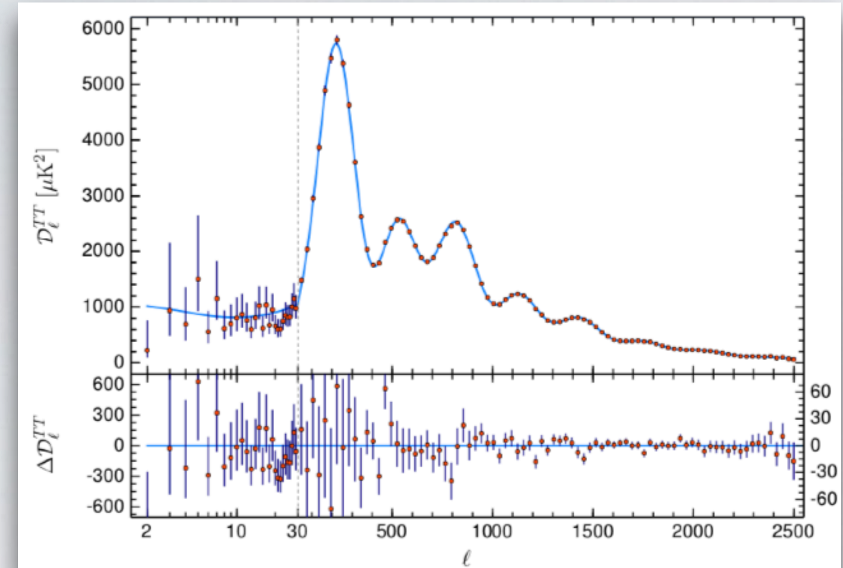
Patrick Foldenauer

Based on [2005.13551] in collaboration with M. Bauer, P. Reimitz and T. Plehn
and [2108.05370] in collaboration with F. Kling and P. Reimitz

FPCapri2022 – Jun 13, 2022

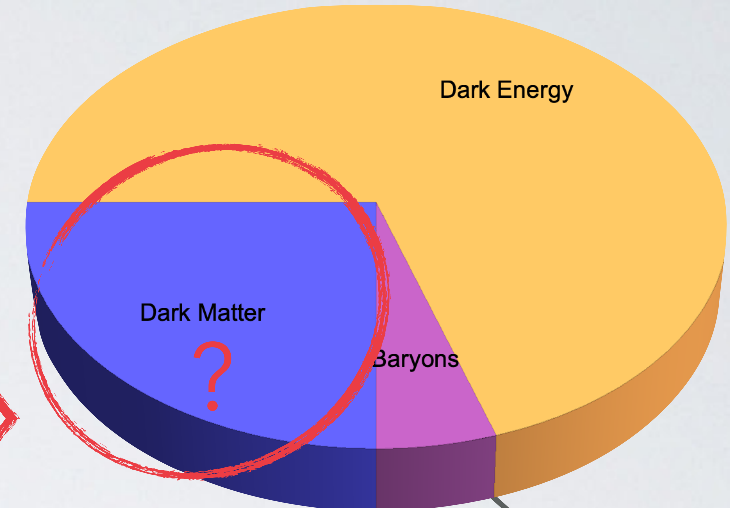
WHERE TO LOOK BEYOND SM?

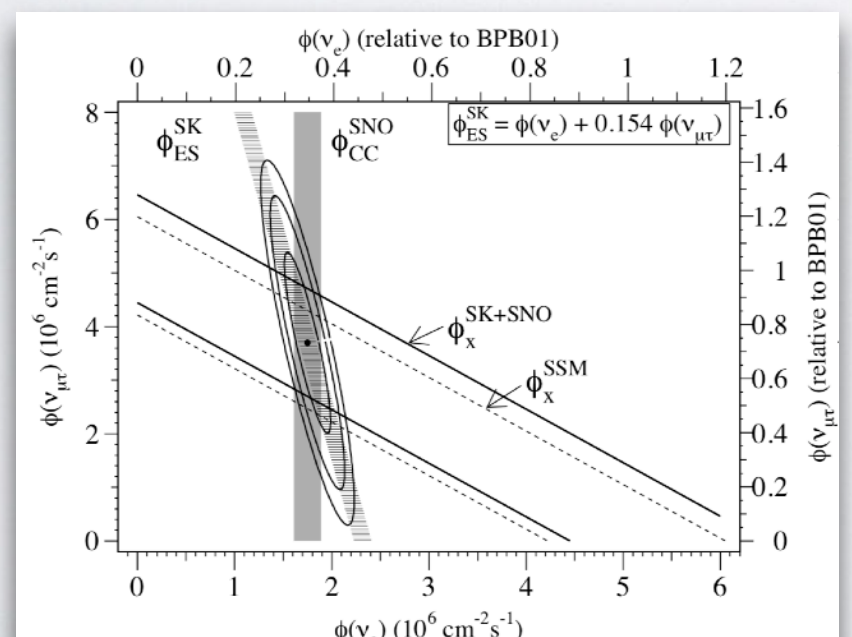
Two obvious targets:



[Planck Collaboration; 1807.06209]

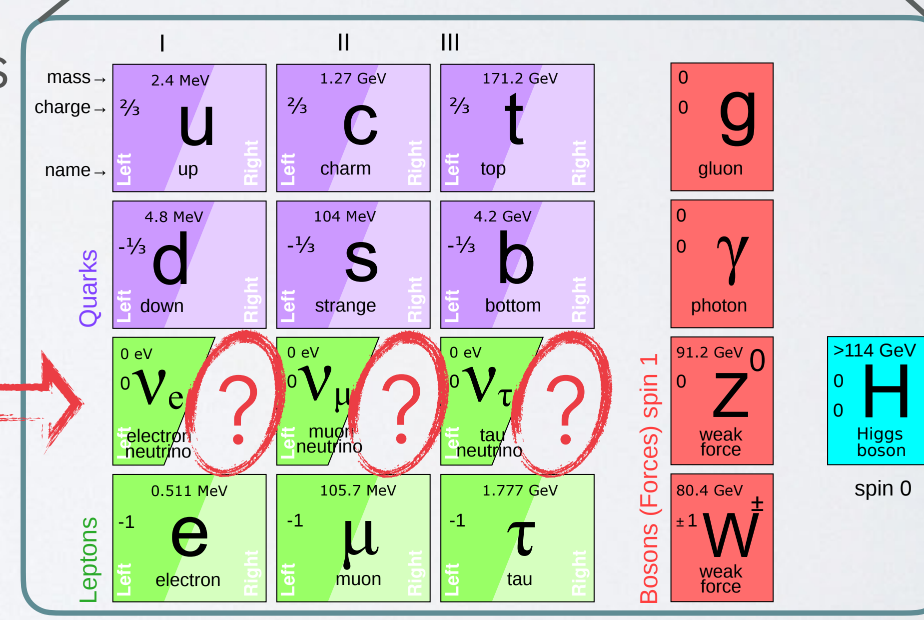
CMB informs us about energy budget





[SNO Collaboration PRL 87:071301]

Oscillations require massive neutrinos



[Gninenko et al., 1301.5516]

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

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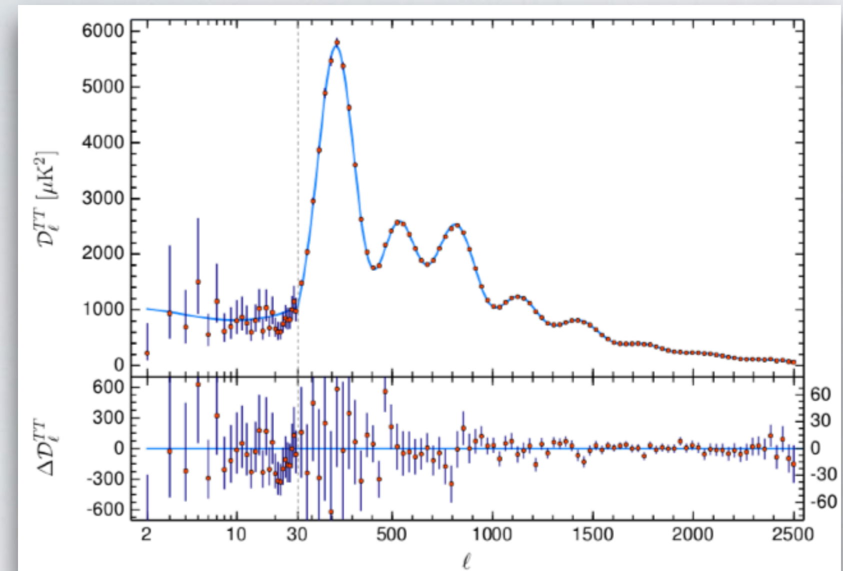

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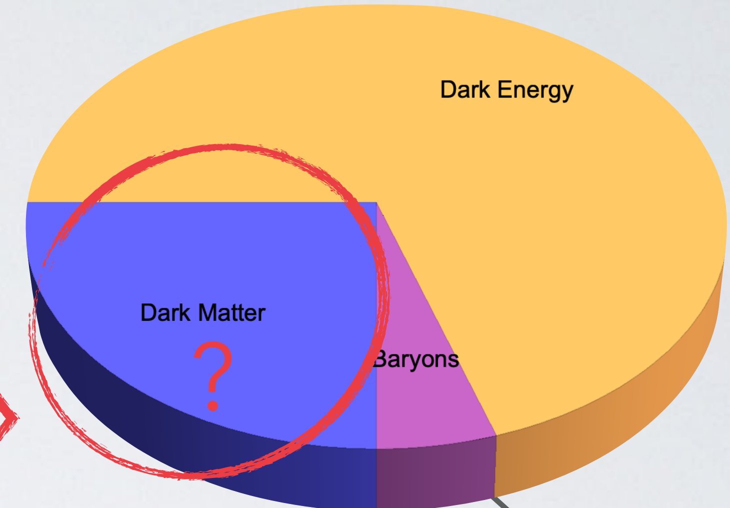
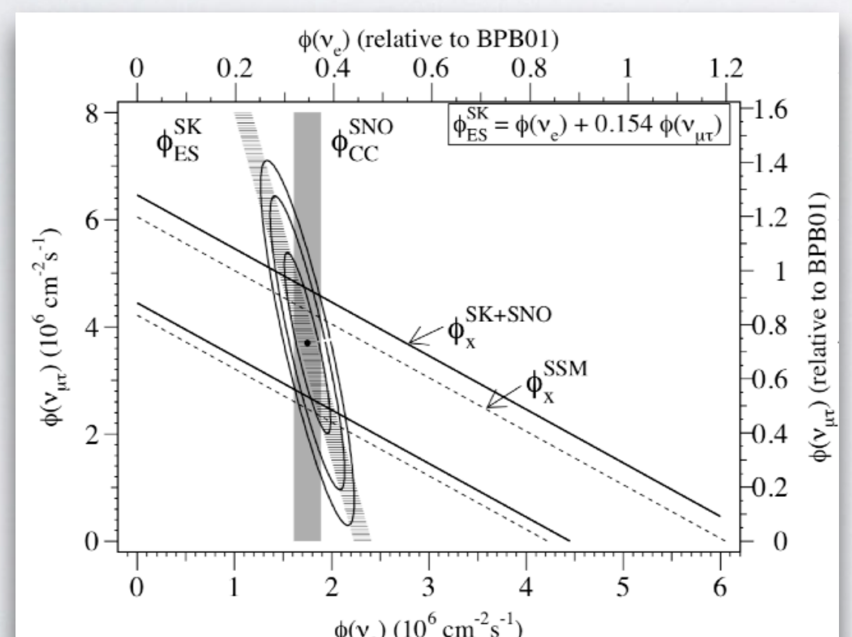


Part I



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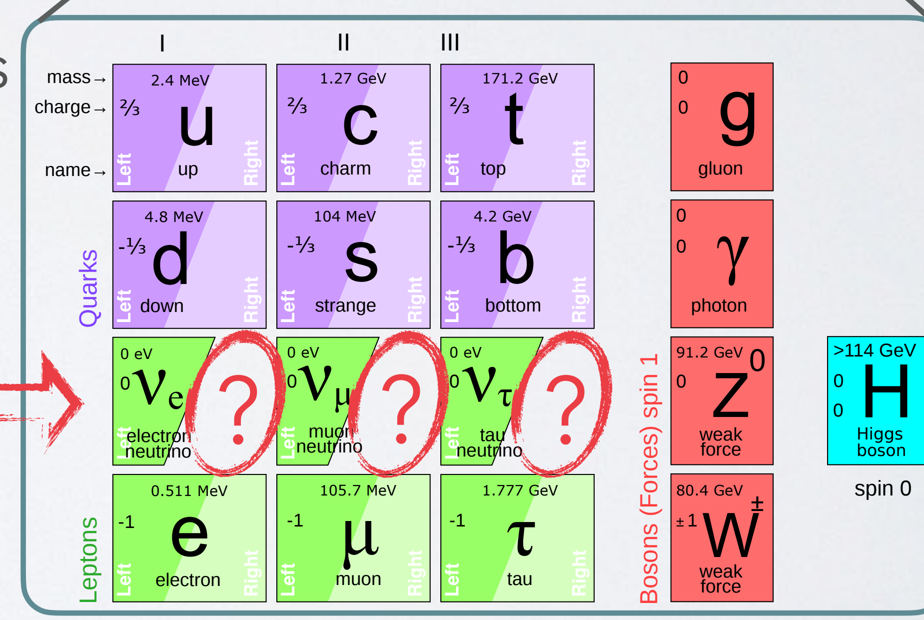


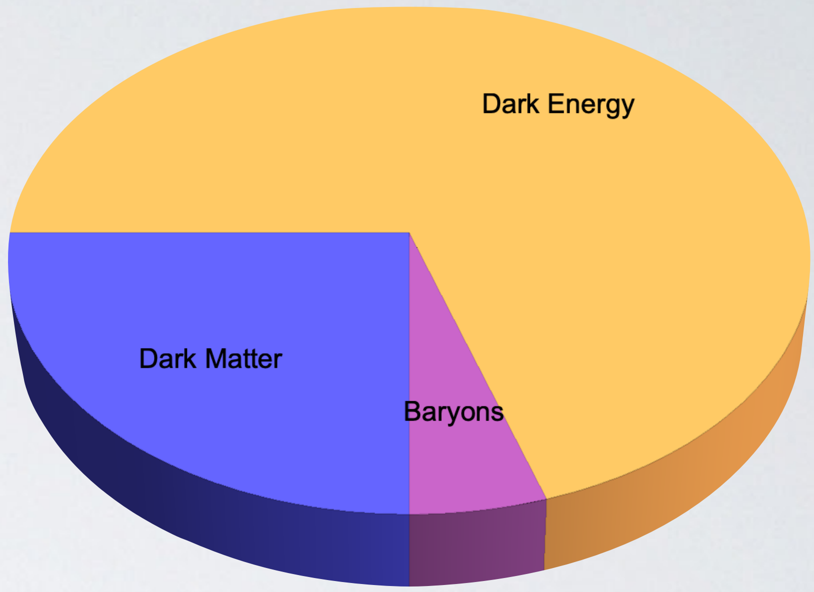
Part II

[Gninenko et al., 1301.5516]

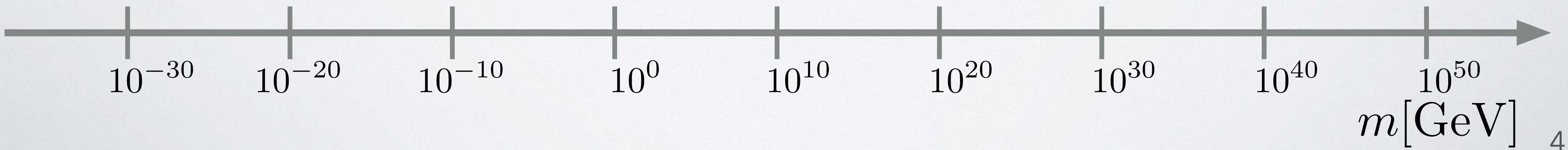
What can we learn about these @ **LHC**?

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 ?



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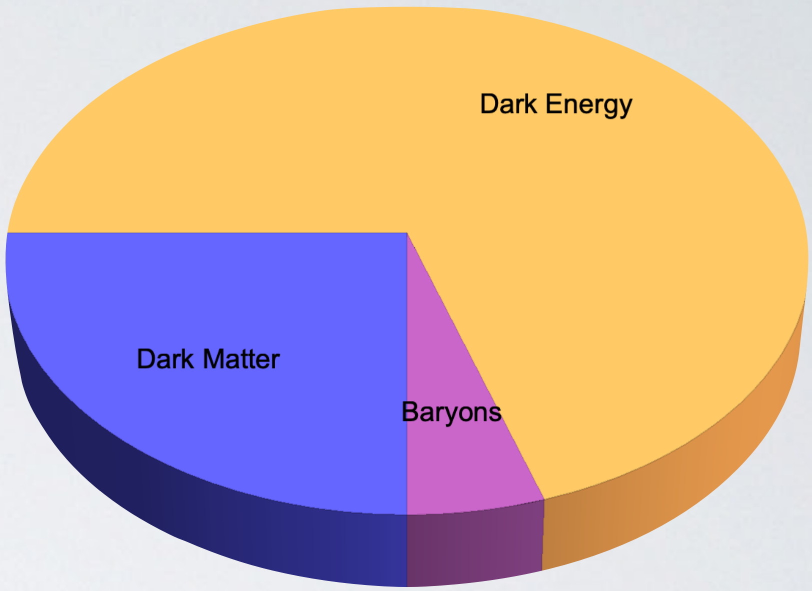


Galaxy formation

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

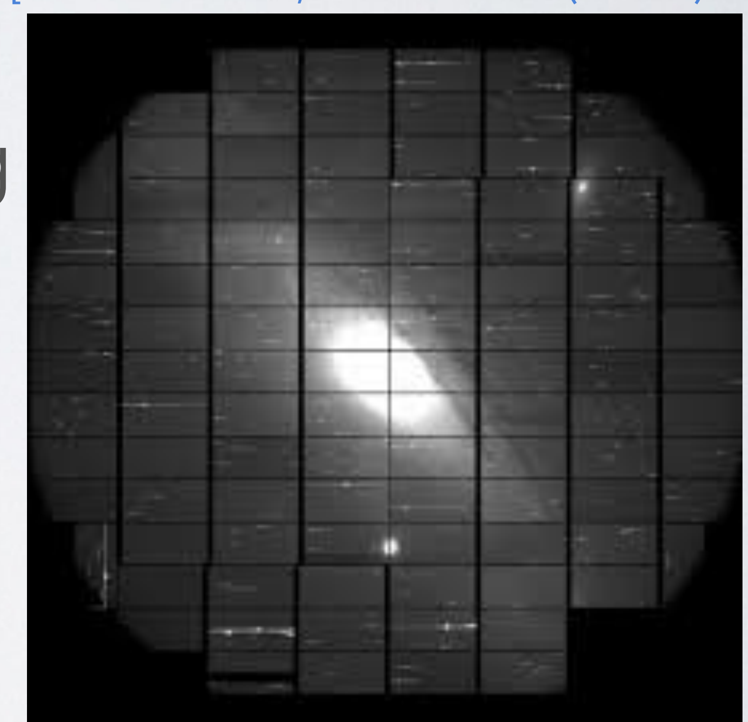
$$m \gtrsim 10^{-24}\,\text{eV}$$

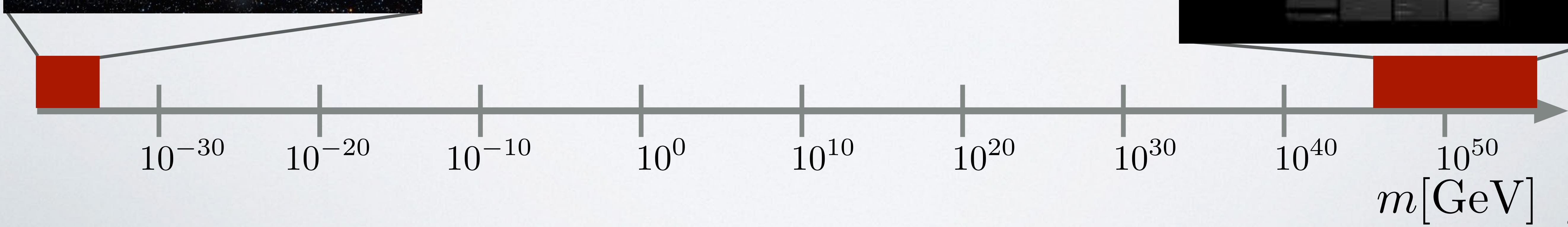
[Hlozek et al., PRD **91** (2015)]

microlensing searches of PBHs

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

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





THE FUZZY DM PARADIGM

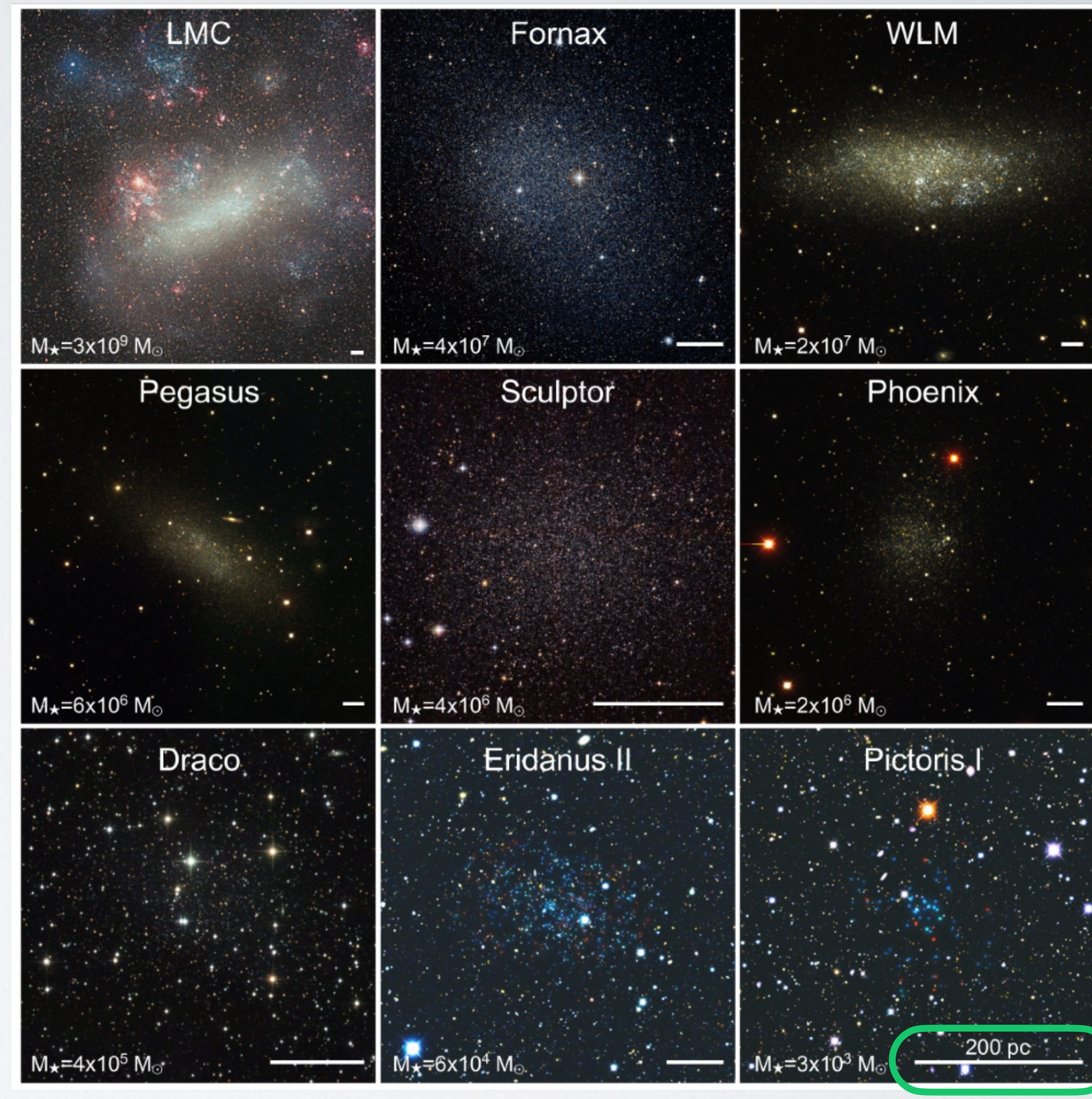
Dwarf galaxies

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

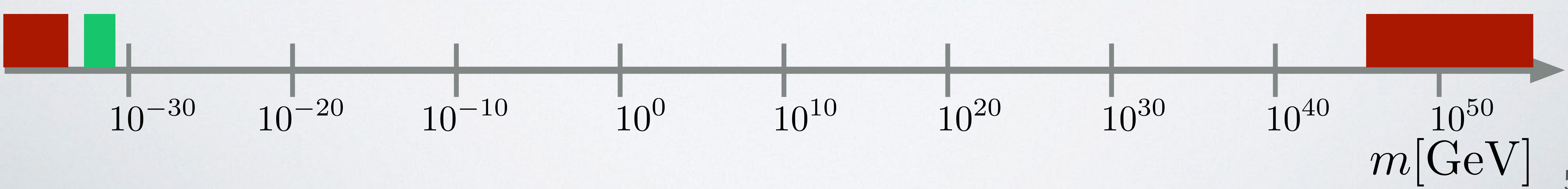
$$m_{\rm DM} \approx 10^{-22}\,{\rm eV} \quad \Rightarrow \lambda_{\rm dB} \gtrsim 1\,{\rm kpc}$$

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

Better fit to small scale structure!



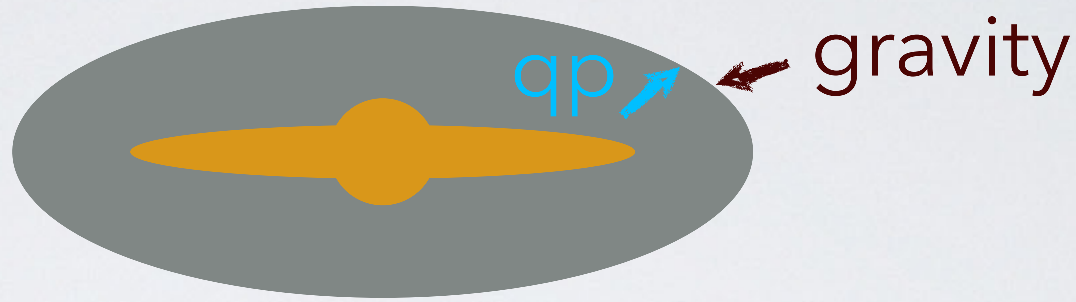
[Bullock et al., Ann.Rev.Astron.Astrophys. 55 (2017)]



THE FUZZY DM PARADIGM

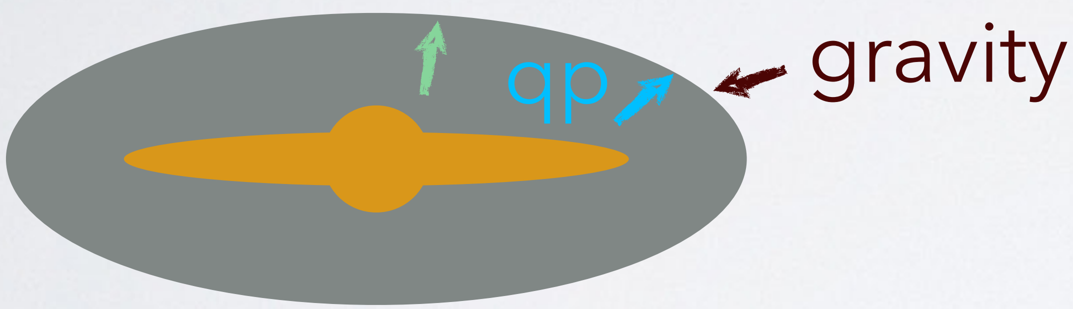
- Small scale is set by a balance of gravity and quantum pressure:

No self-interactions!

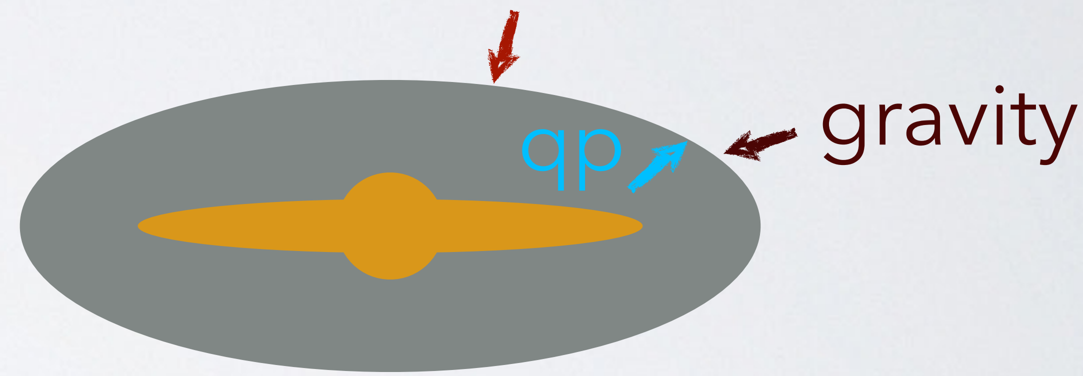


- Self-interactions may drastically alter situation:

repulsive $\lambda > 0$



attractive $\lambda < 0$

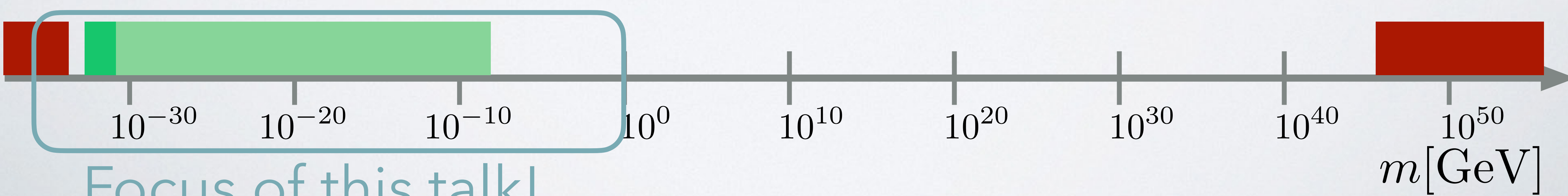


Relaxed mass range: [Ferreira, 2005.03254]

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

Instabilities!

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



SCALAR DM — HIGGS PORTAL

- At low momenta Higgs portal mediates an effective DM-nucleon coupling $\mathcal{L} \supset -\frac{1}{2}\lambda_{hs}\, s^2\, H^\dagger H \longrightarrow c_{sNN}\, s^2\, \bar{N} N$

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

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

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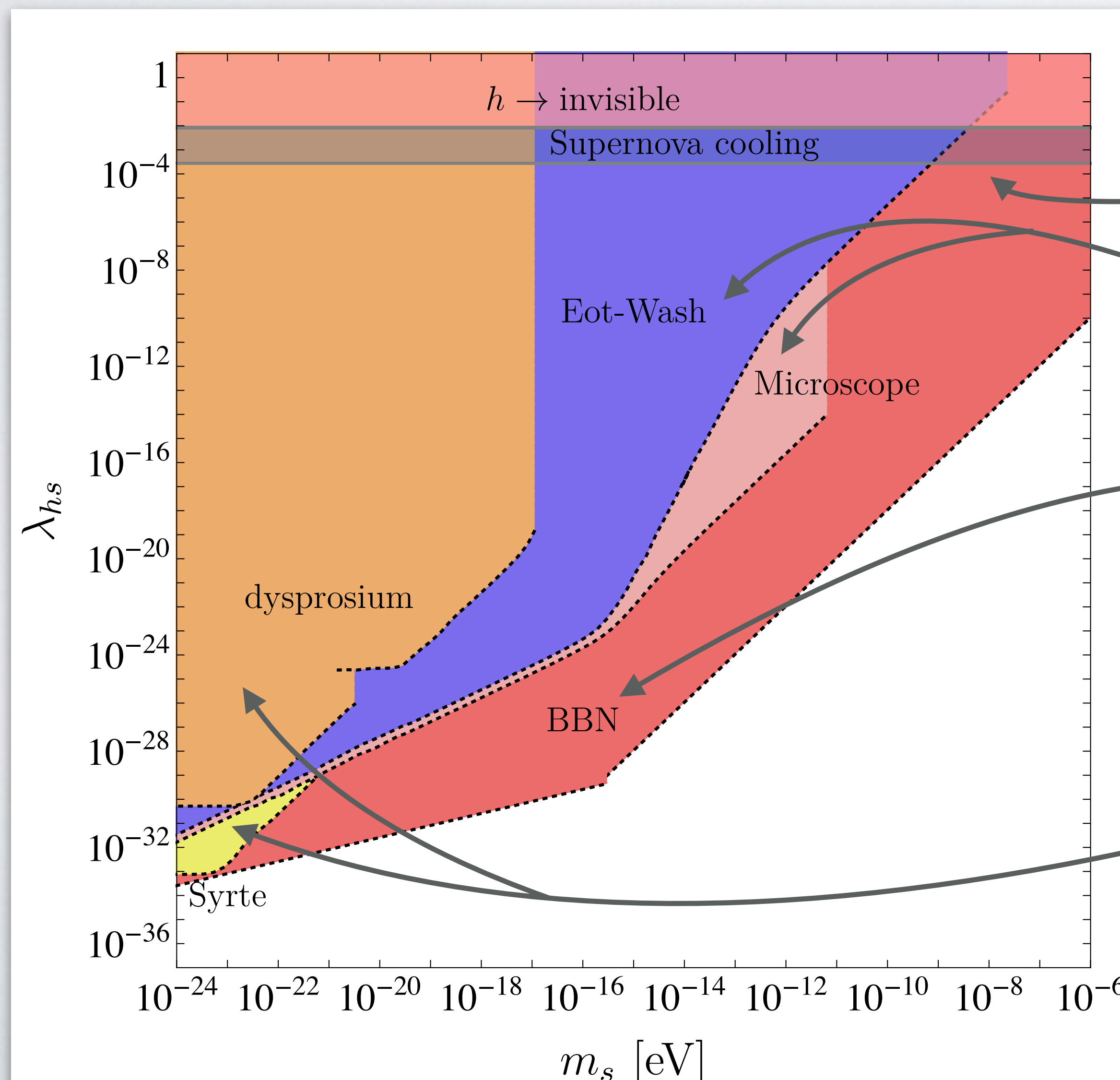

Supernova

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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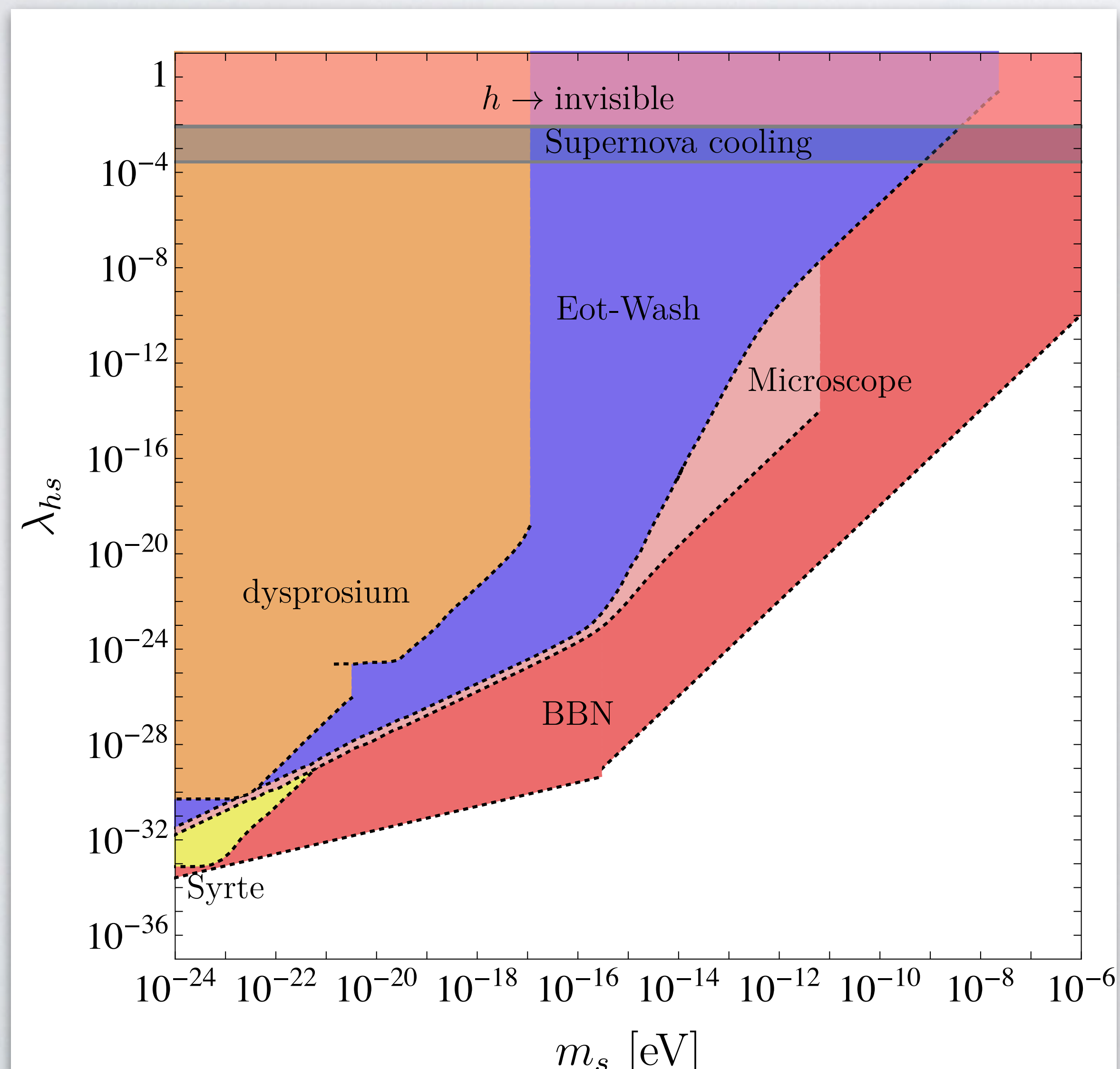
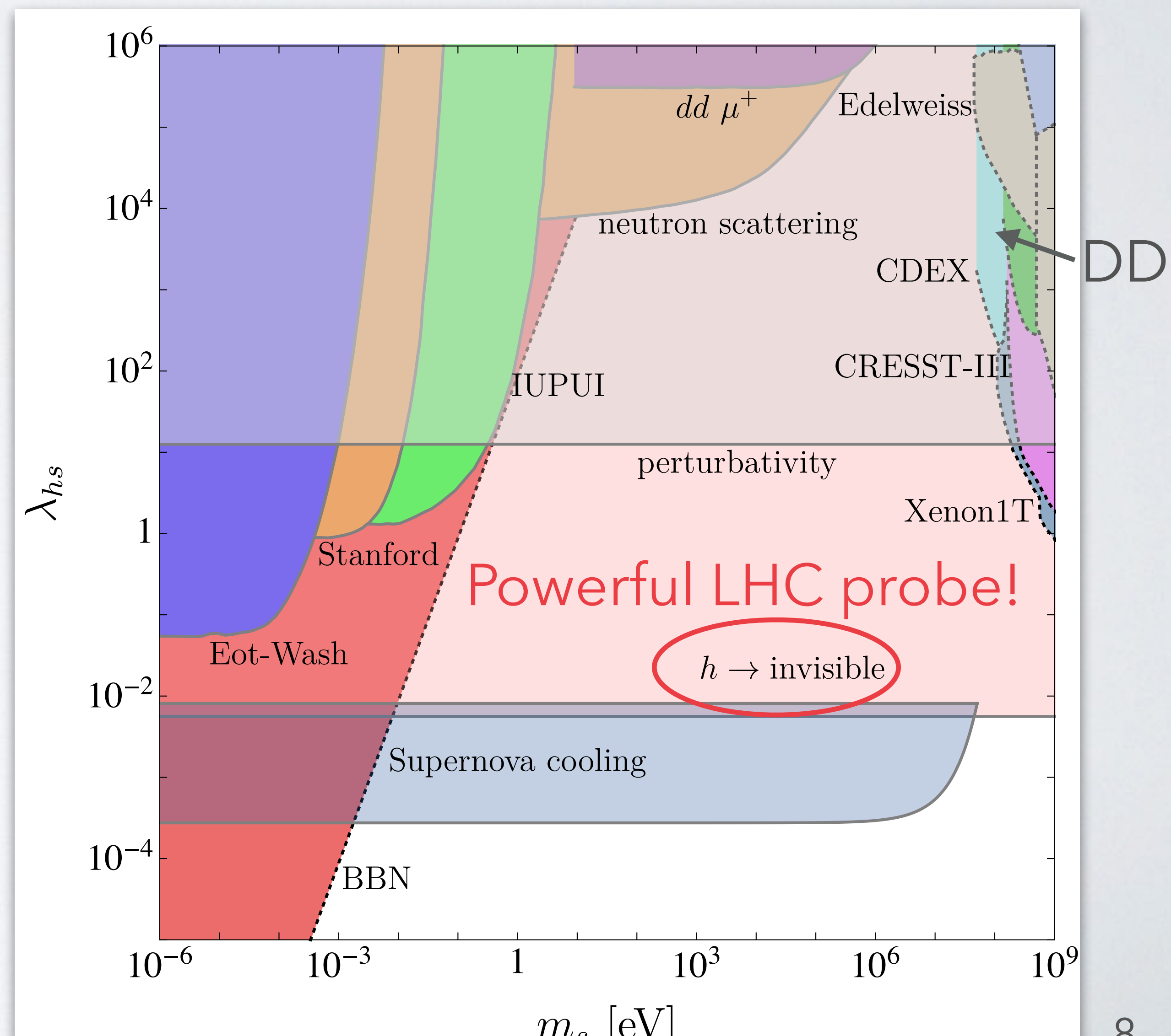
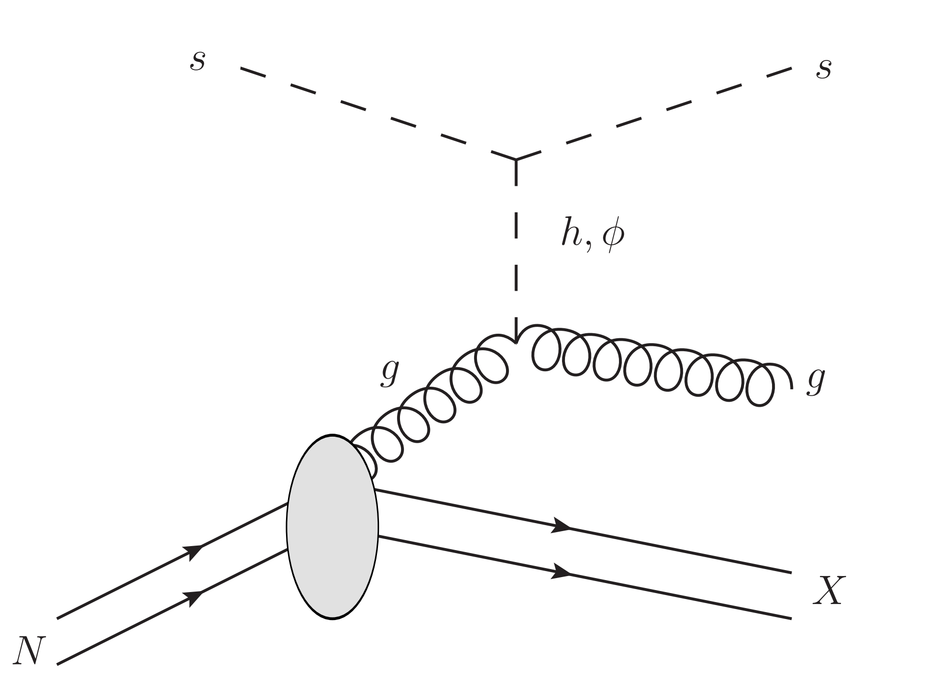




NEW SEARCH STRATEGIES AT LHC

- 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]

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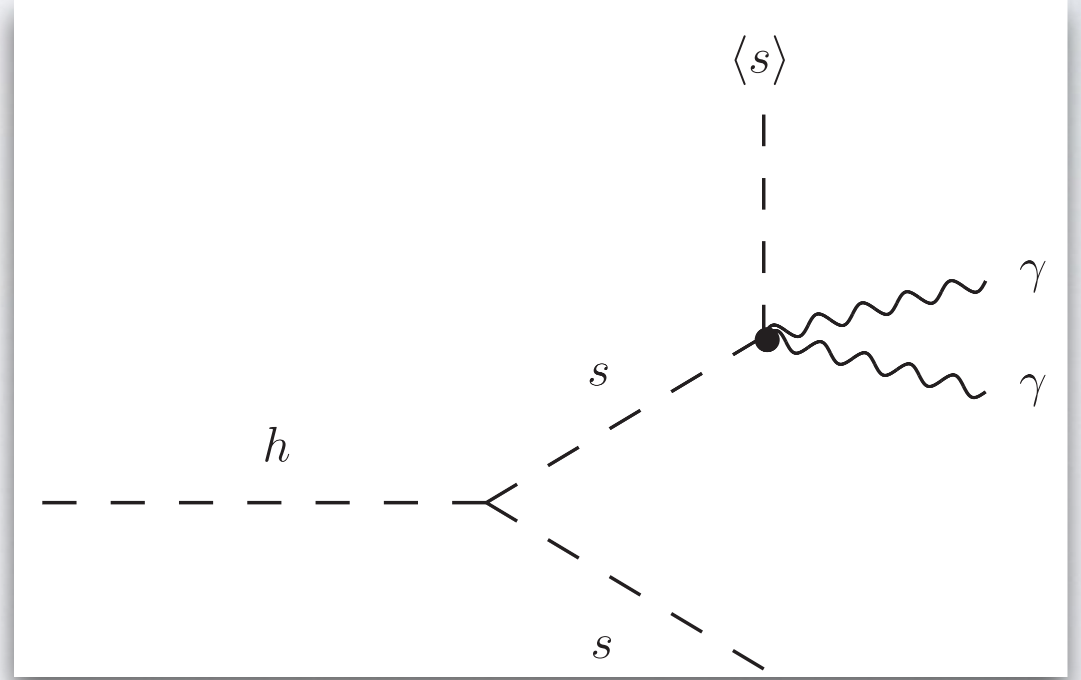

(Background annihilation)

Mean free path: $\lambda \gtrsim 10^{43}$ m

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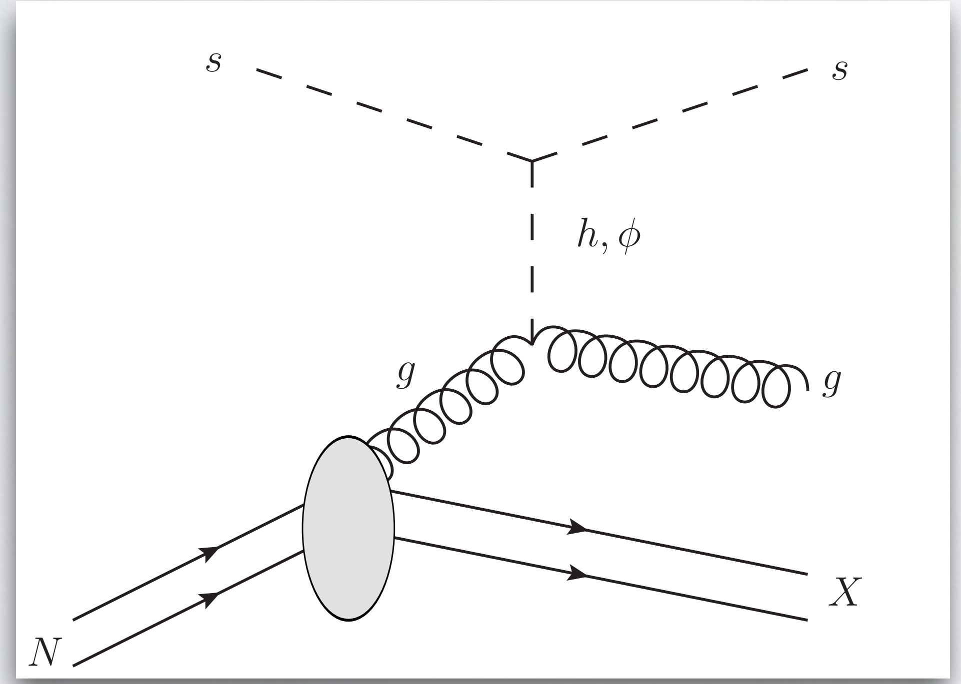

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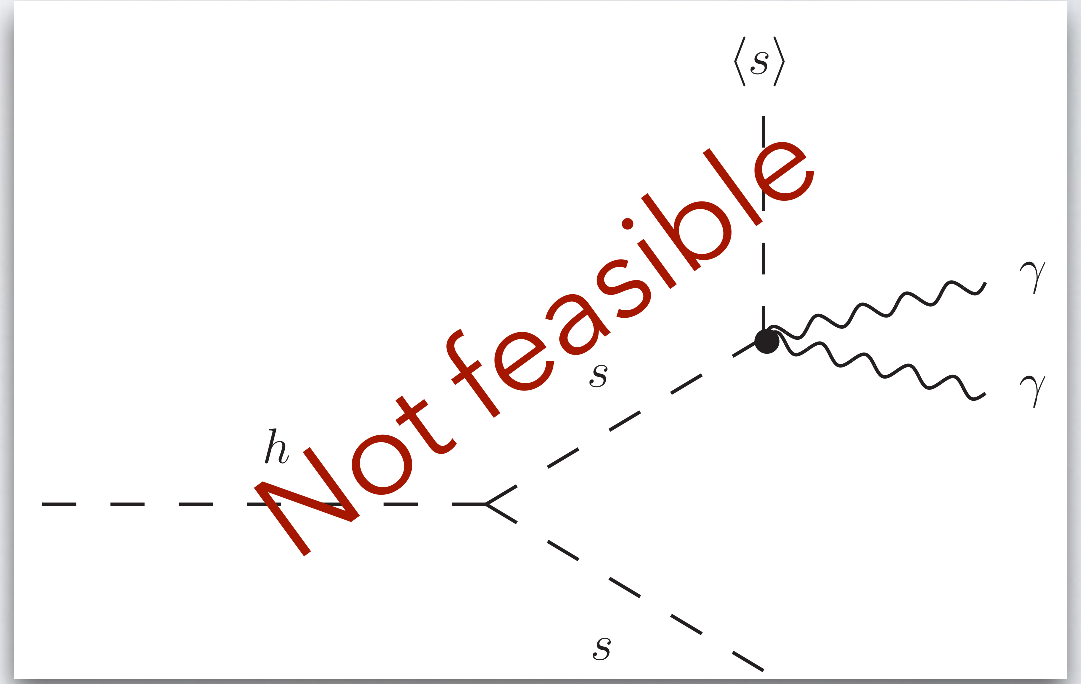

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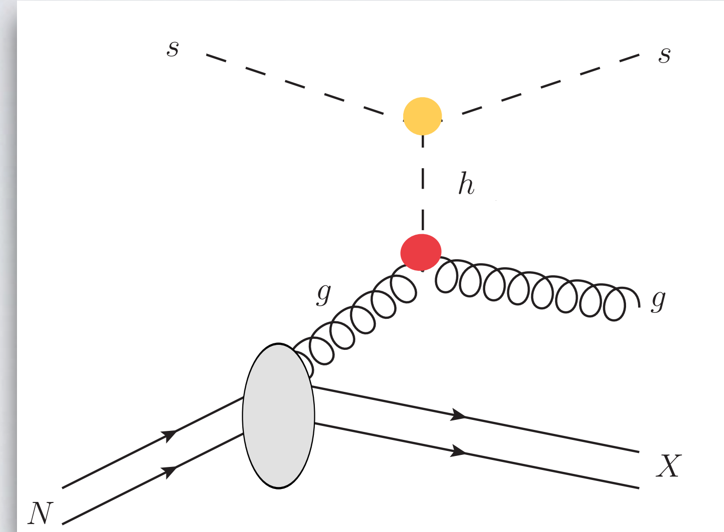
DIRECT DETECTION

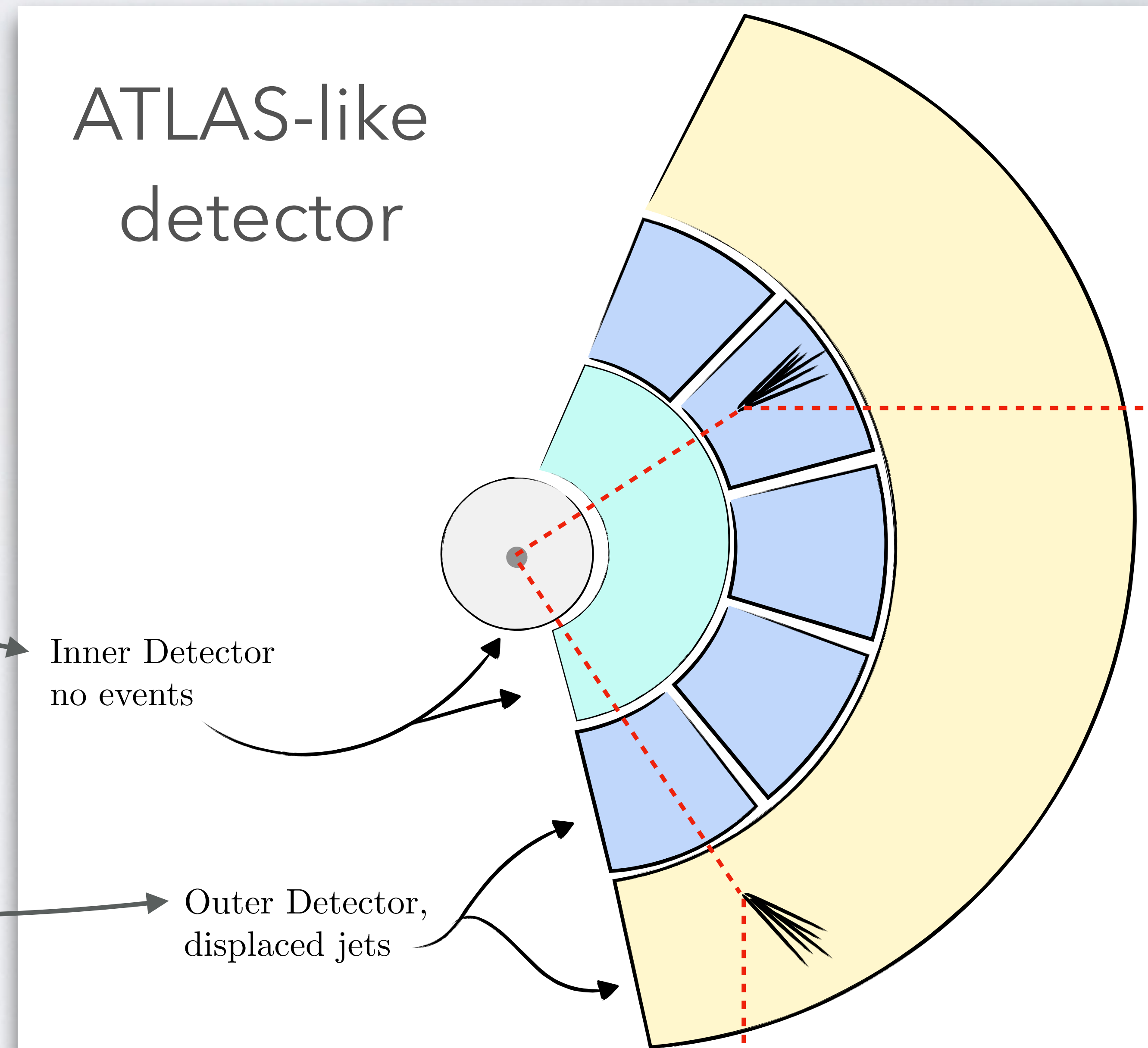


- Boosted DM can undergo DIS in detector material and produce jets.
- E.g. Higgs Portal:

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

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

Distinguishable from LLPs by location of interaction:



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

But unfortunately for HP:

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

[Bauer, PF, Reimitz, Plehn, 2005.13551]

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:

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

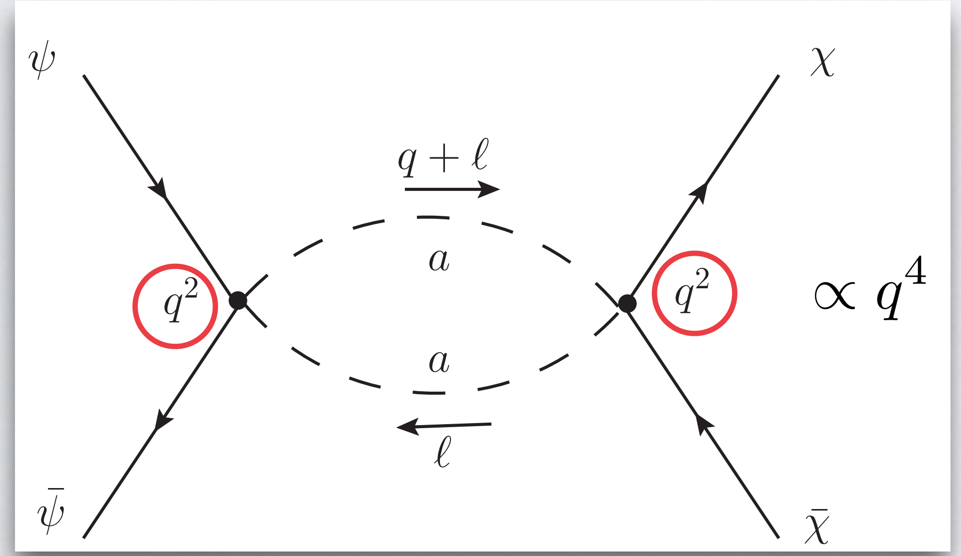
Suppressed by heavy axion scale $f = \mathcal{O}(f_{\rm GUT})$

HADROPHILIC ALP

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

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

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



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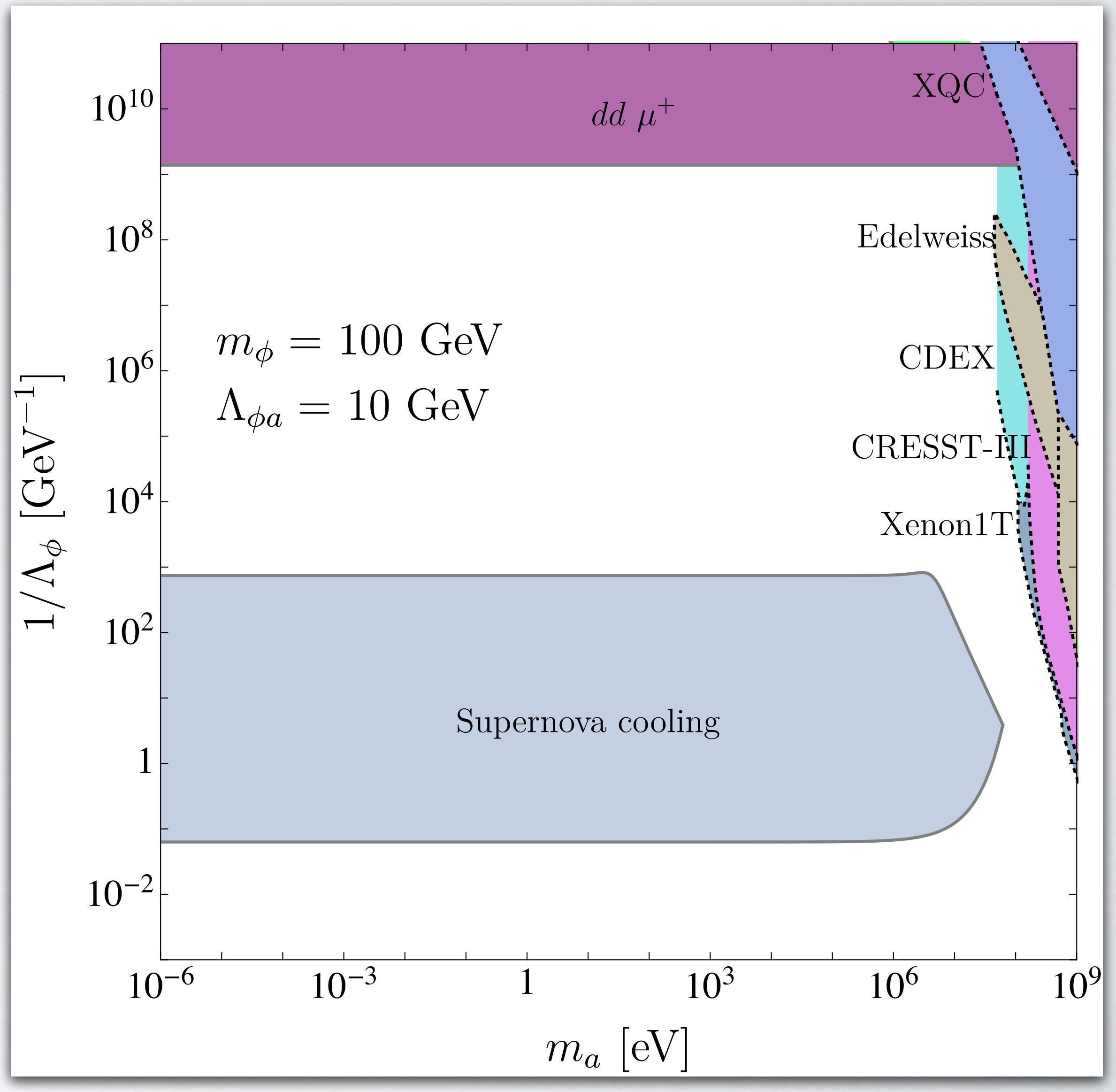

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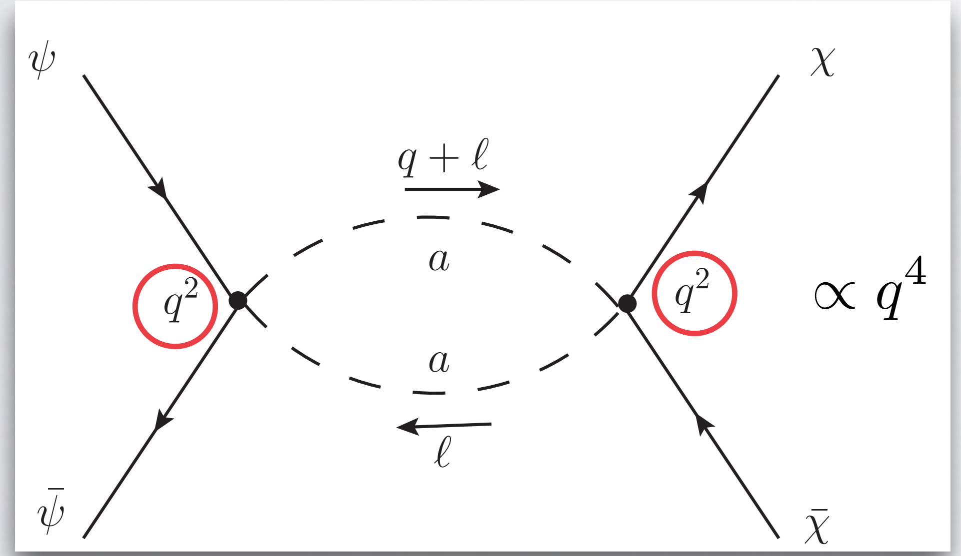
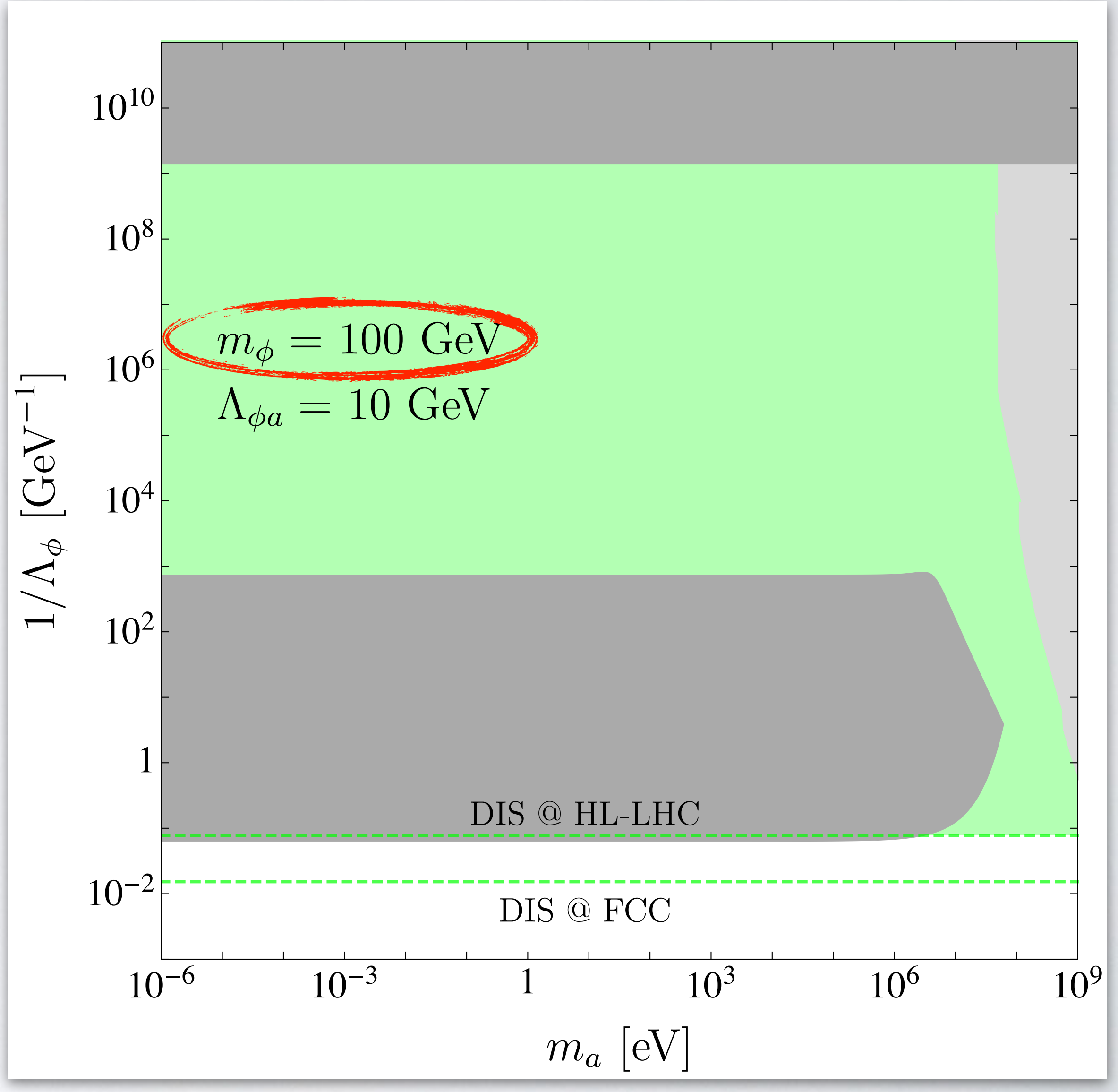


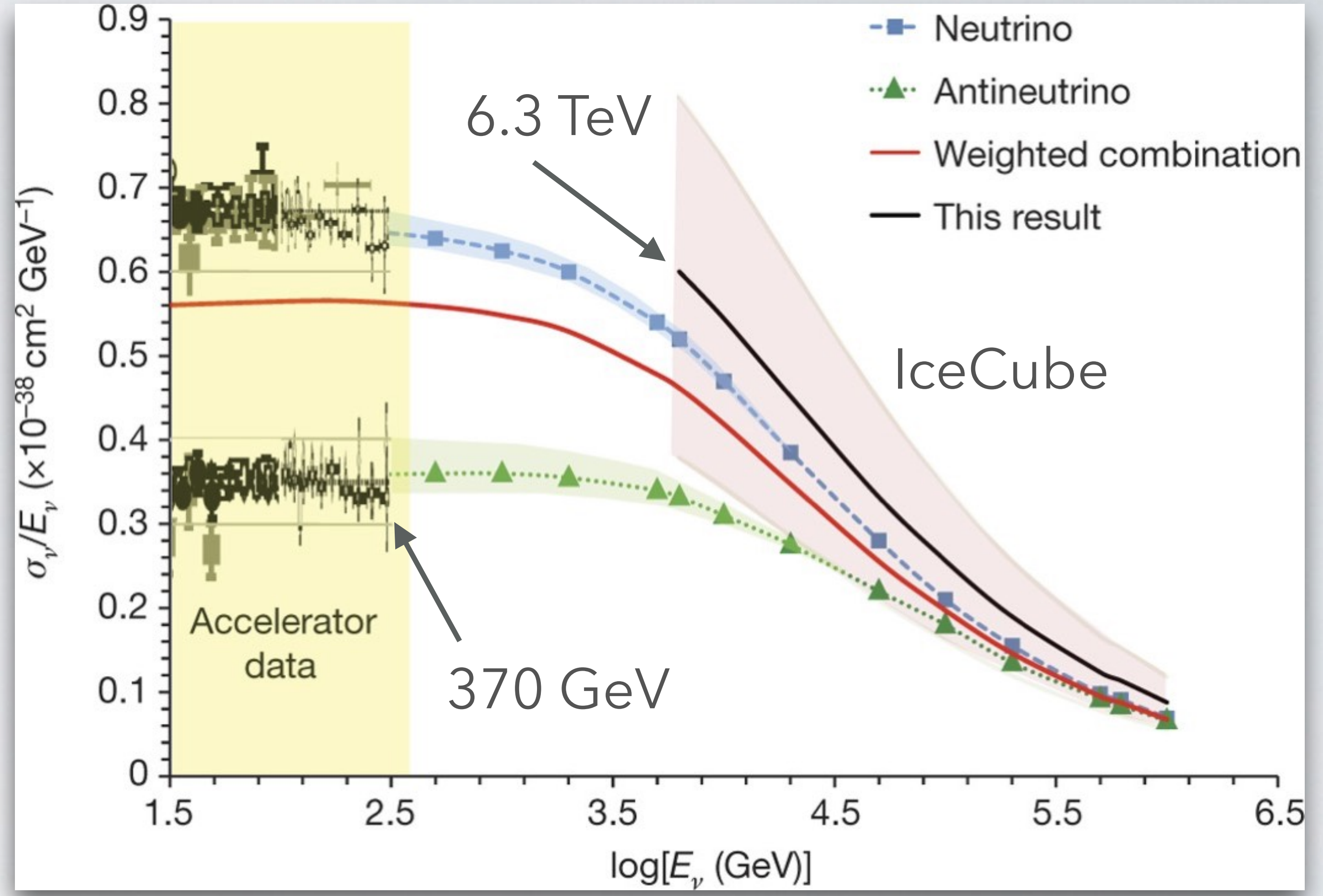


- Such ALPs can be abundantly produced at LHC and scatter in denser detectors $\Rightarrow$ **displaced jets**

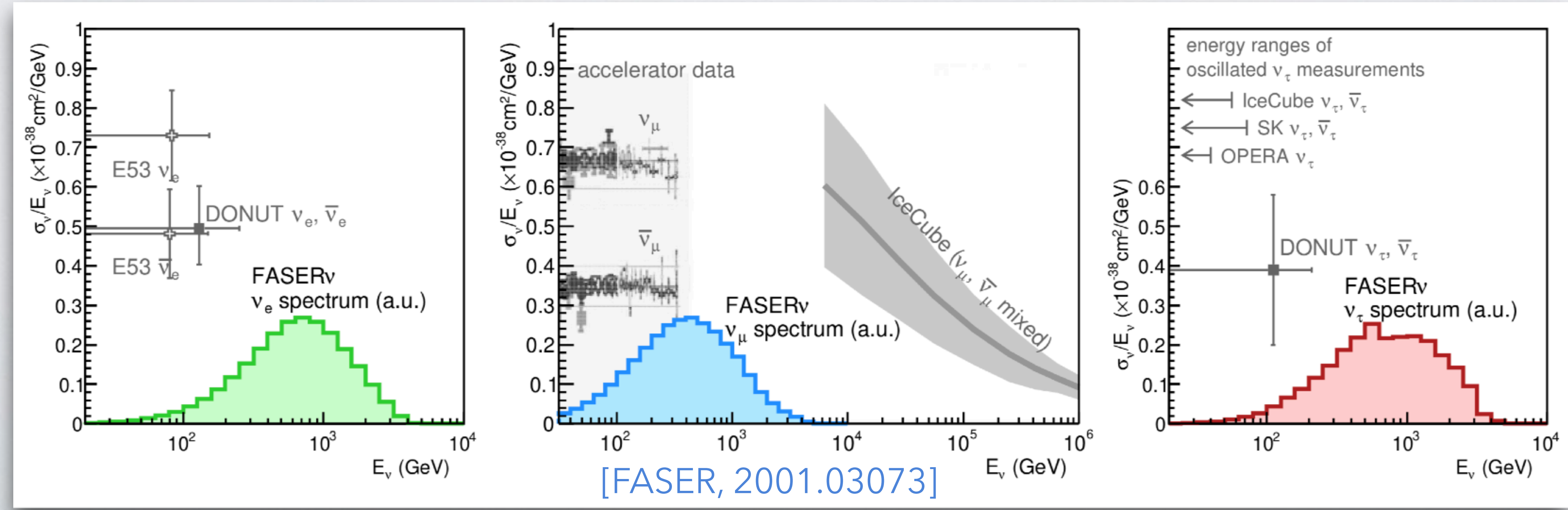
NEUTRINOS

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]



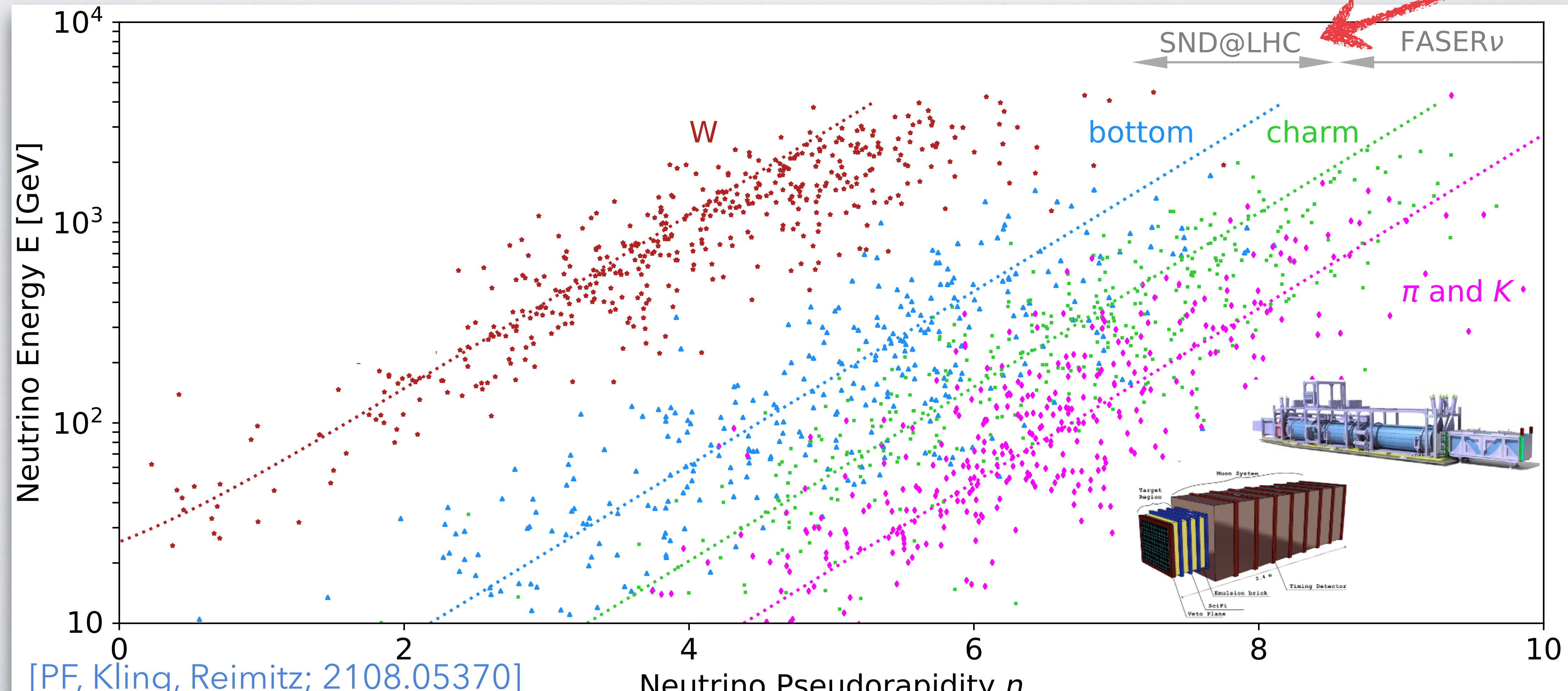
[FASER, 2001.03073]

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

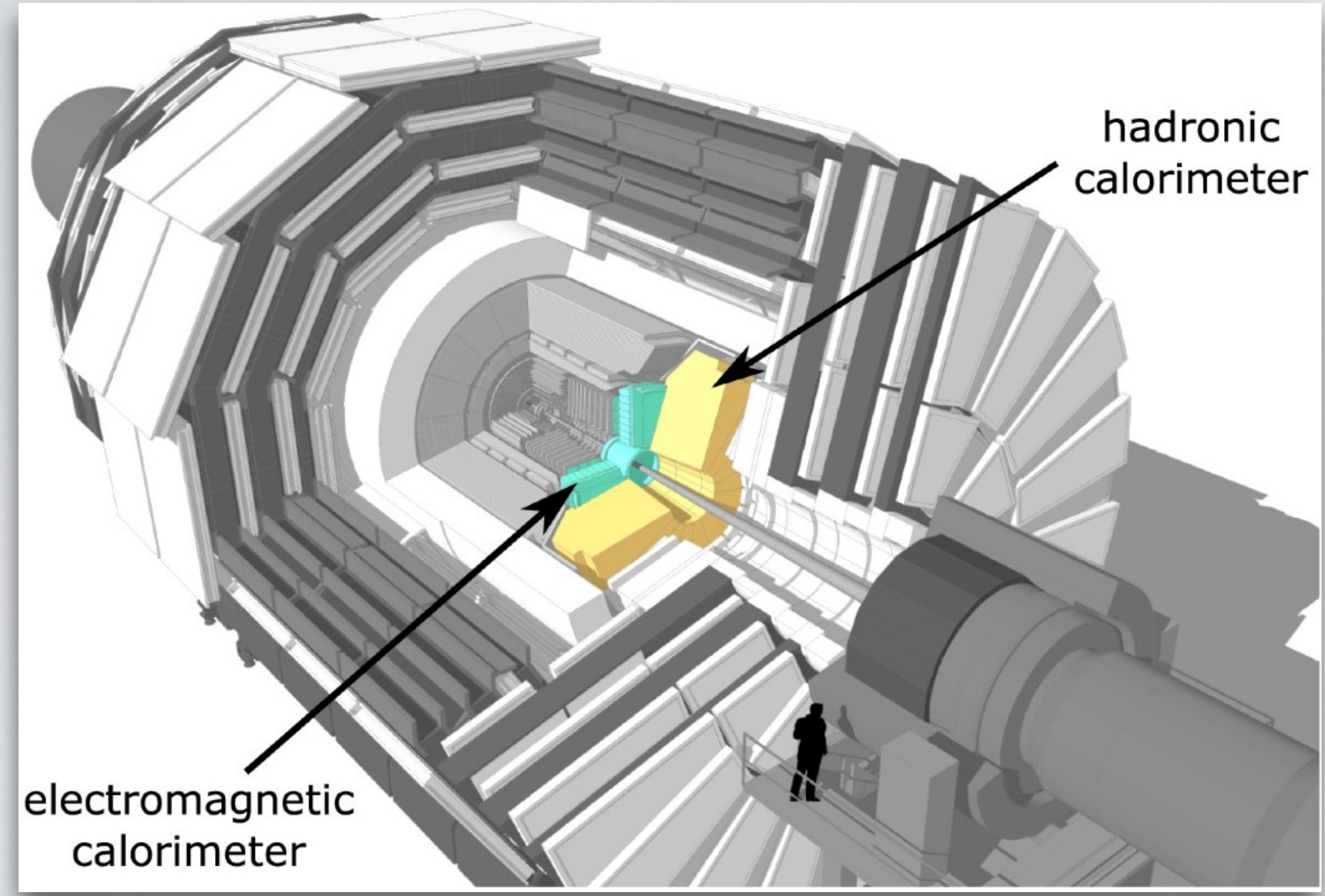
see talk Giovanni's talk

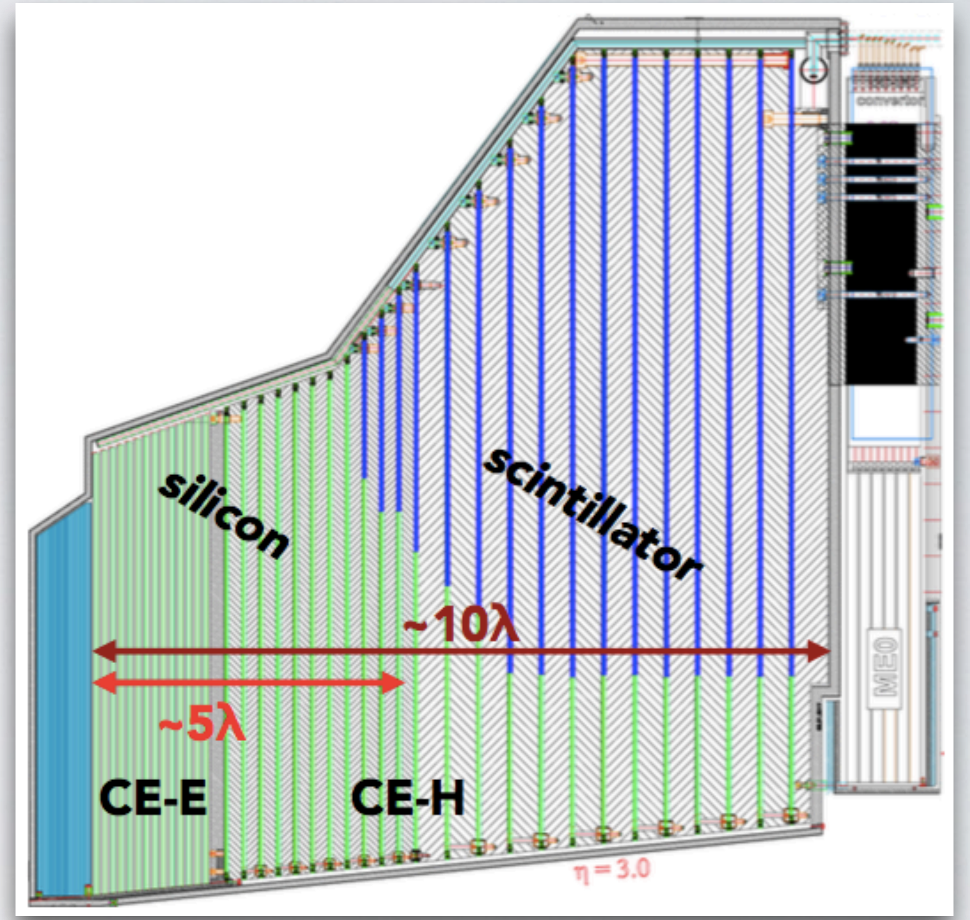
- Large **unused potential** of high energy **W-produced neutrinos**!



[PF, Kling, Reimitz; 2108.05370]

CMS ENDCAP CALORIMETER





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

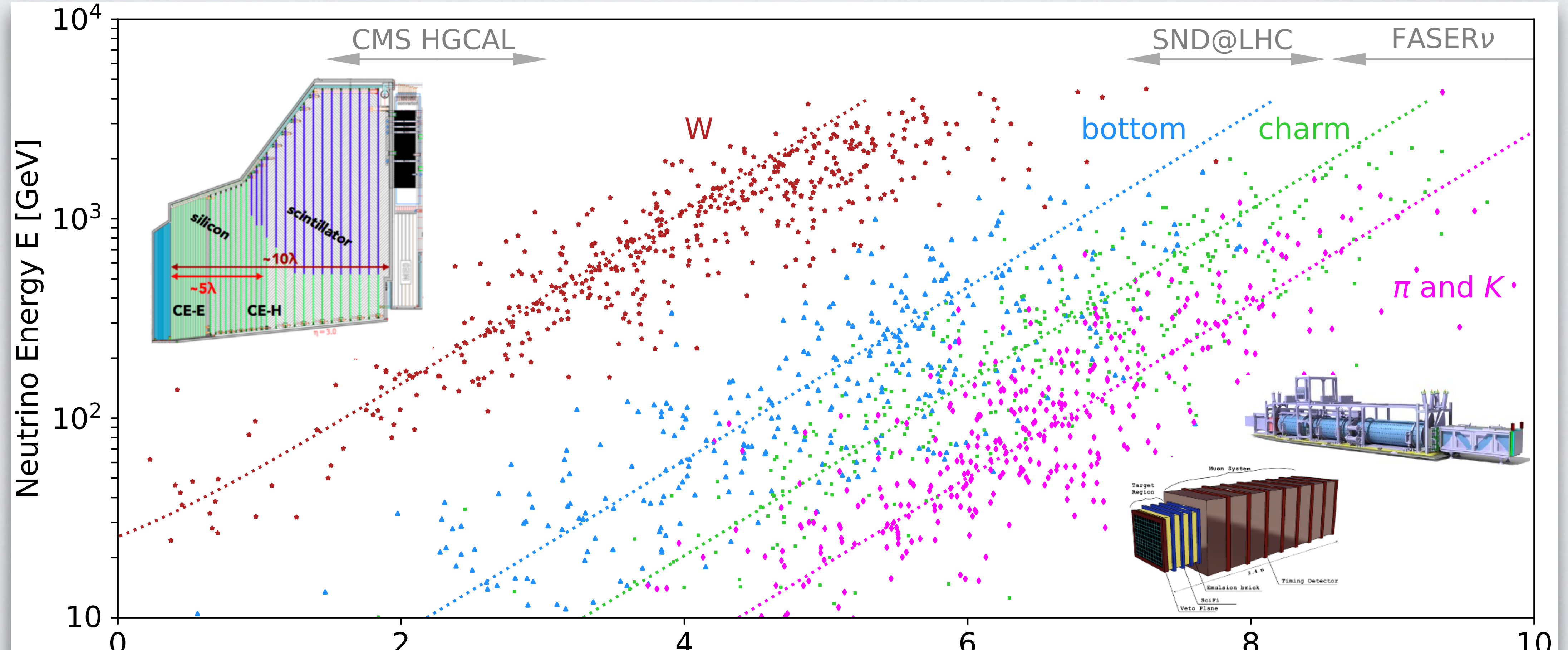
- Upgraded CMS high-granularity endcap calorimeter ideally suited to search for forward neutrino scattering
- Angular coverage in the forward region between $1.5 \leq |\eta| \leq 3.0$
- High cell granularity (0.5-1) cm^2 allows for high resolution measurement of lateral shower development and good two-shower 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 $(E_\nu \gtrsim \mathcal{O}(100)$ GeV$)$ from W production!

⟹ How do search for those neutrinos at CMS?



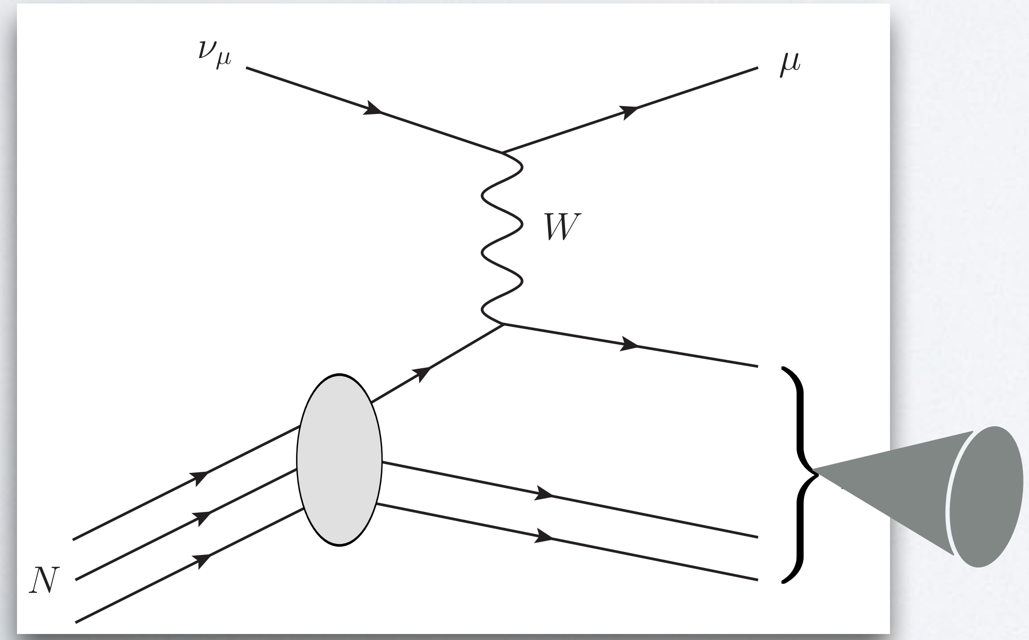
[PF, Kling, Reimitz; 2108.05370]

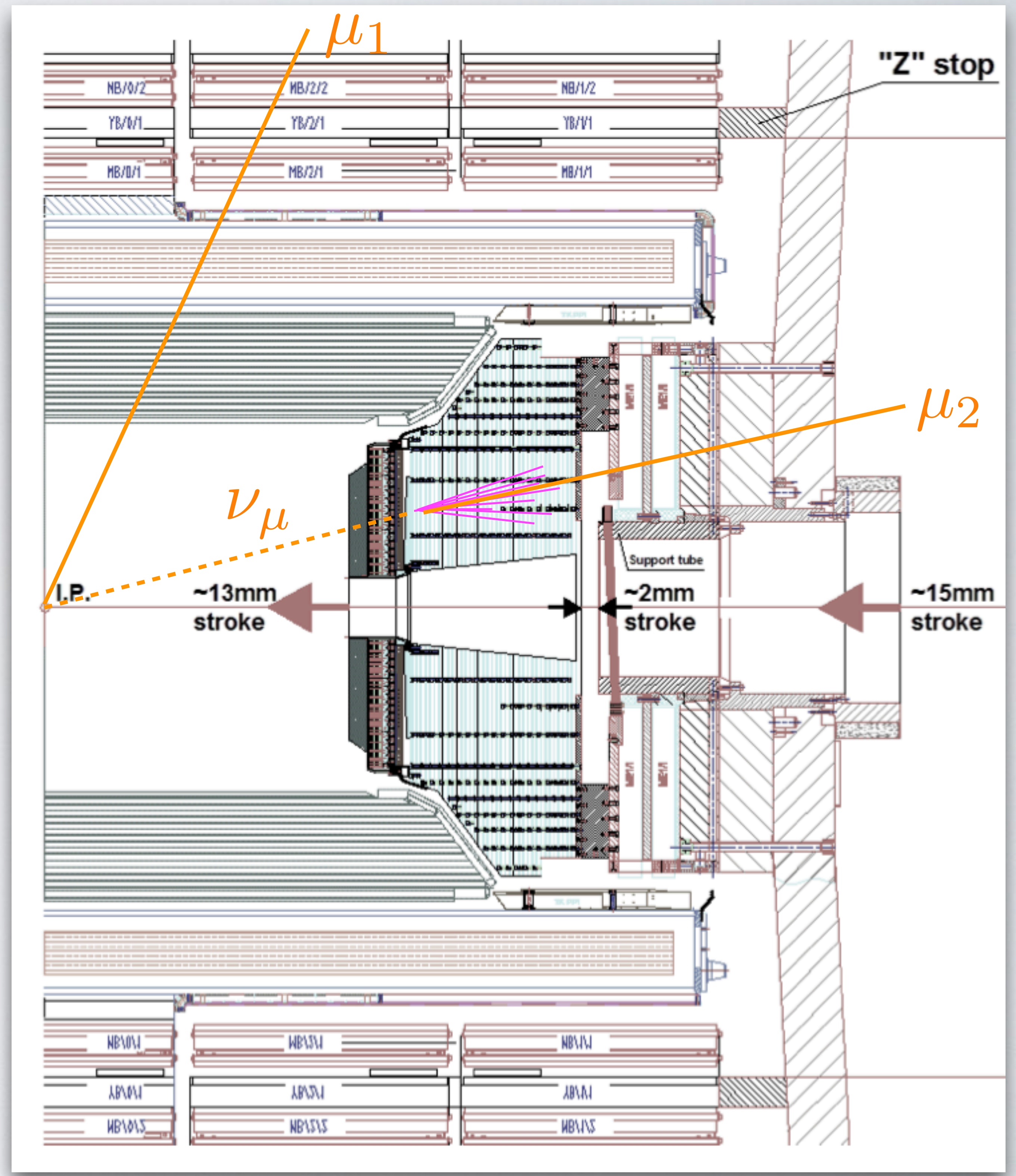
NEUTRINOS FROM W DECAY

- 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!

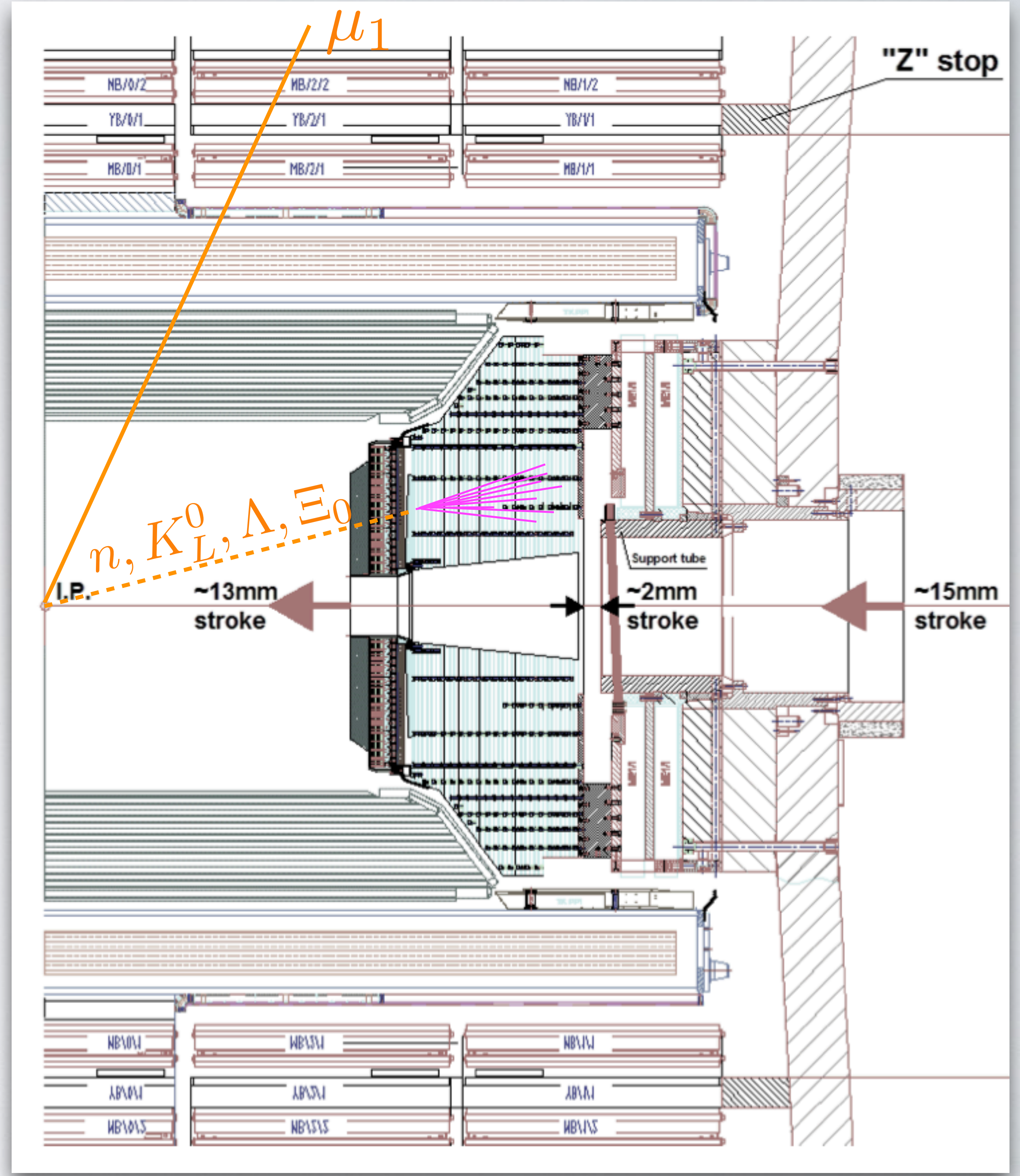
  $$qq' \to W + \text{QCD} \to \mu_1 + \text{QCD}$$

  and heavy hadron decays

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

- Scattering of neutral hadron can fake neutrino jet:

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



NEUTRINOS FROM W DECAY

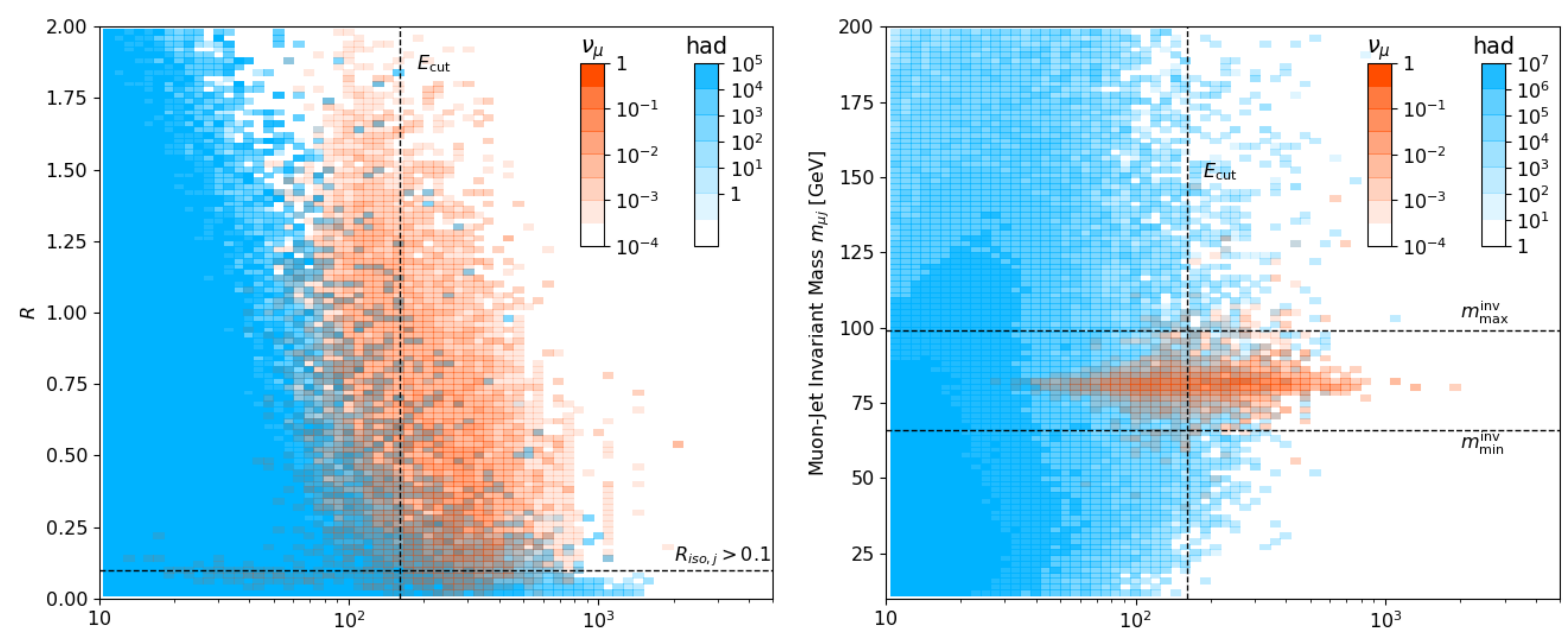
A. Isolated primary muon: $R_{\mathrm{iso},\mu_1} > 0.1, \quad p_{T,\mu_1} > 20 \text{ GeV}, \quad |\eta_{\mu_1}| < 2.4$

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

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

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

background still dominates!



[PF, Kling, Reimitz; 2108.05370]

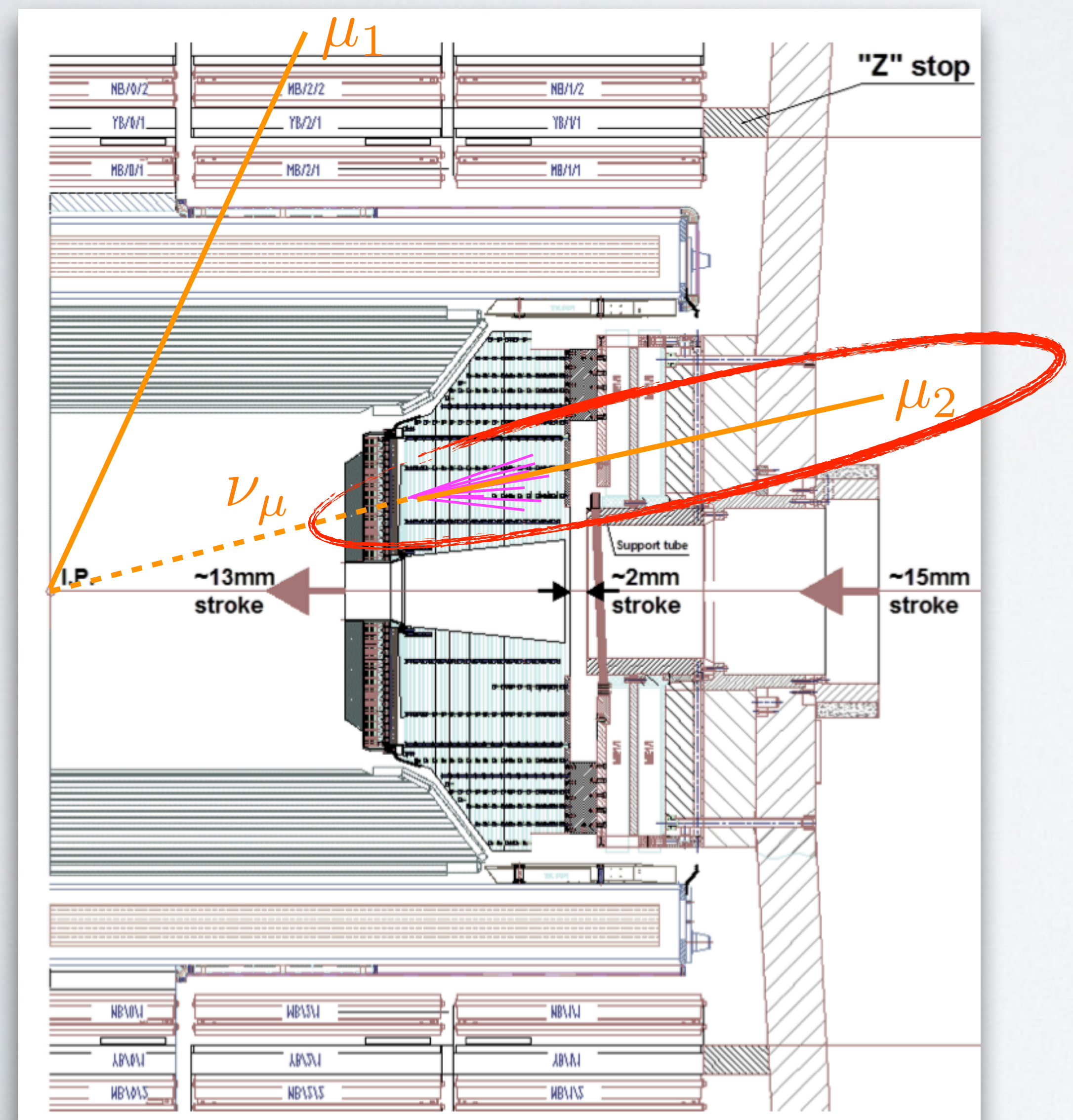
NEUTRINOS FROM W DECAY

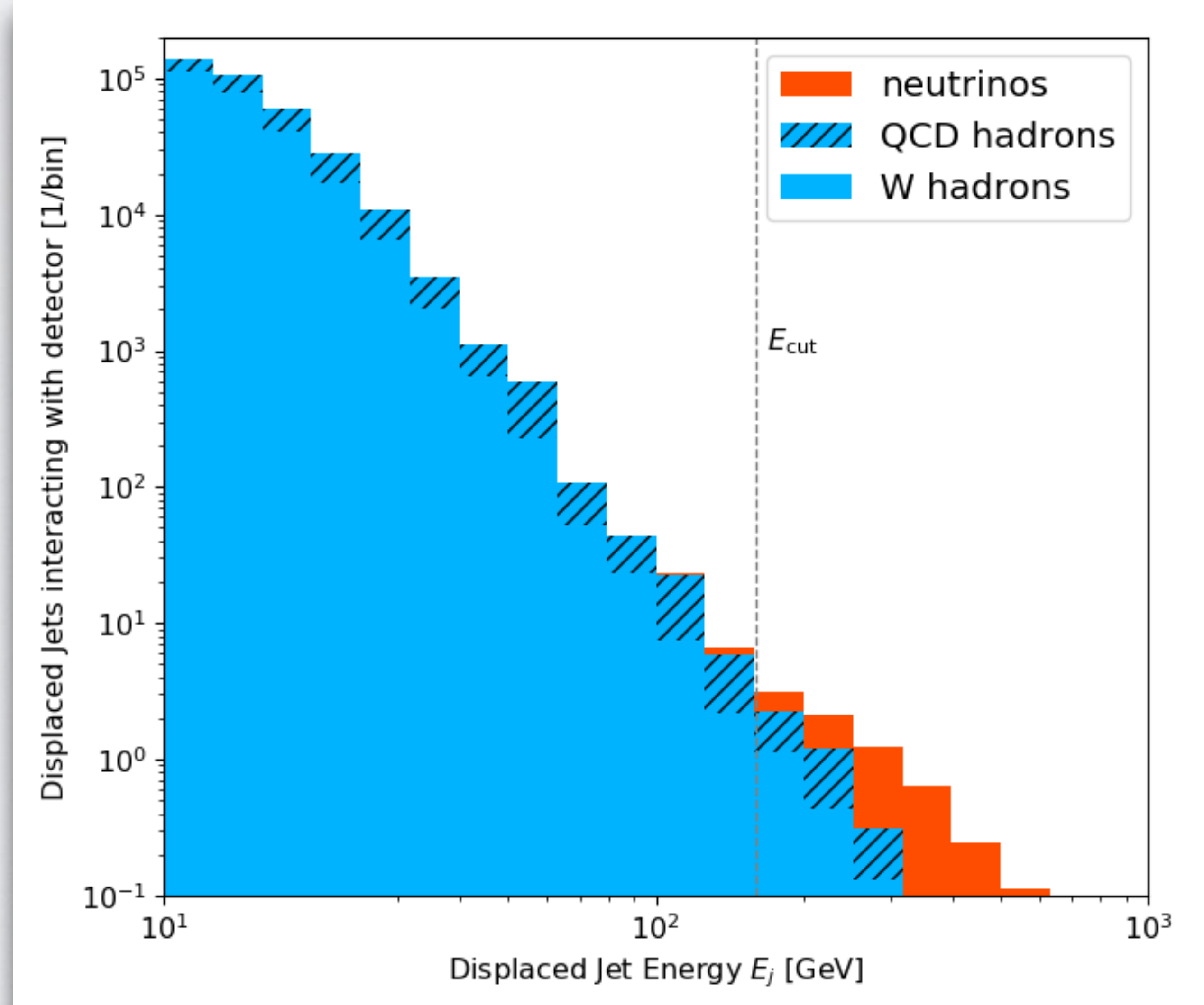
[PF, Kling, Reimitz; 2108.05370]

- Require highly energetic secondary muon:

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

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
$E_\text{j} > 160$ GeV	3.52	3.60





CONCLUSIONS

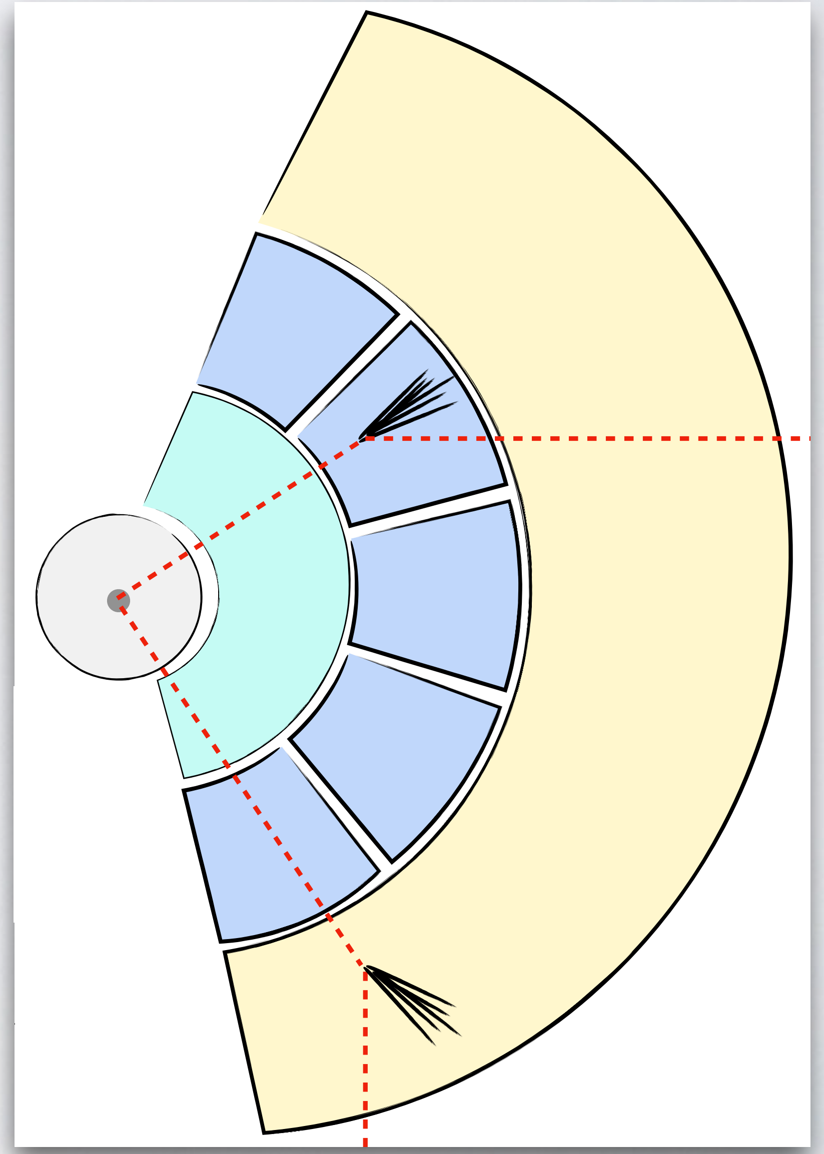
- **Displaced recoil jets** are promising signature to search for **light physics at the LHC**

- 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



BACKUP

VARIATION OF CONSTANTS

- Fundamental constants like $m_f, \alpha_{\rm em}$ or m_V are described by SM operators

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

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

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

δm_f $\delta\alpha_{\rm em}$ δm_V

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

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

PILE-UP MITIGATION

- HL-LHC: average of 130-200 pile-up events per bunch crossing (~40 now)
- *Crab kissing:* Novel collision technique stretches pileu-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]