LIGHT DM AT THE LHC

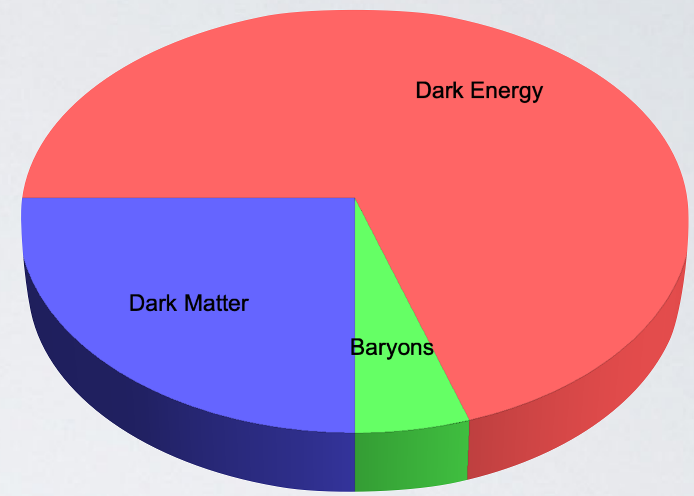
Patrick Foldenauer

IPPP Durham

FPCP 2020 – June 10, 2020

WHAT IS DM AGAIN?

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

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

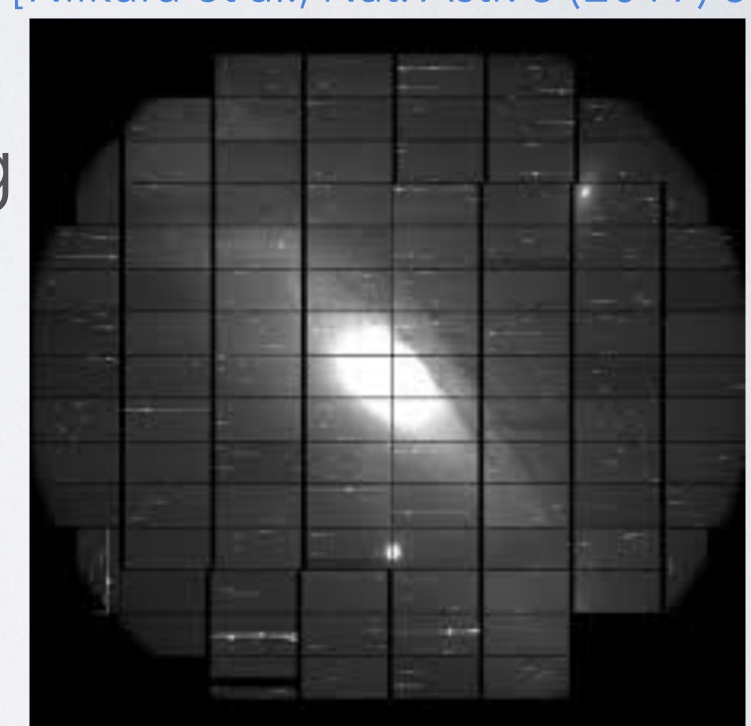
$$m \gtrsim 10^{-24}\,\mathrm{eV}$$

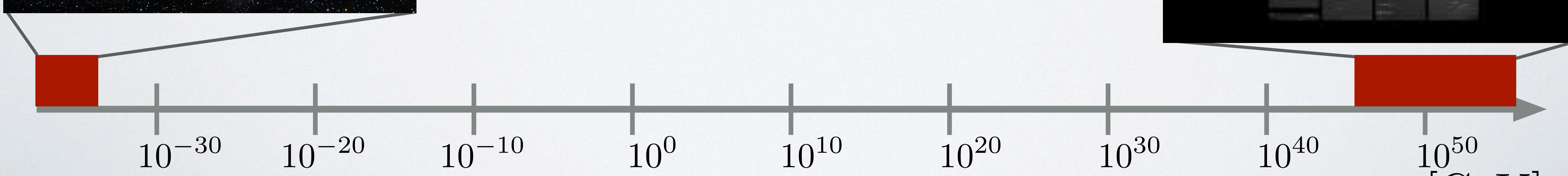
[Hlozek et al., PRD **91** (2015)]

microlensing searches of PBHs

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

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





THE FUZZY DM PARADIGM

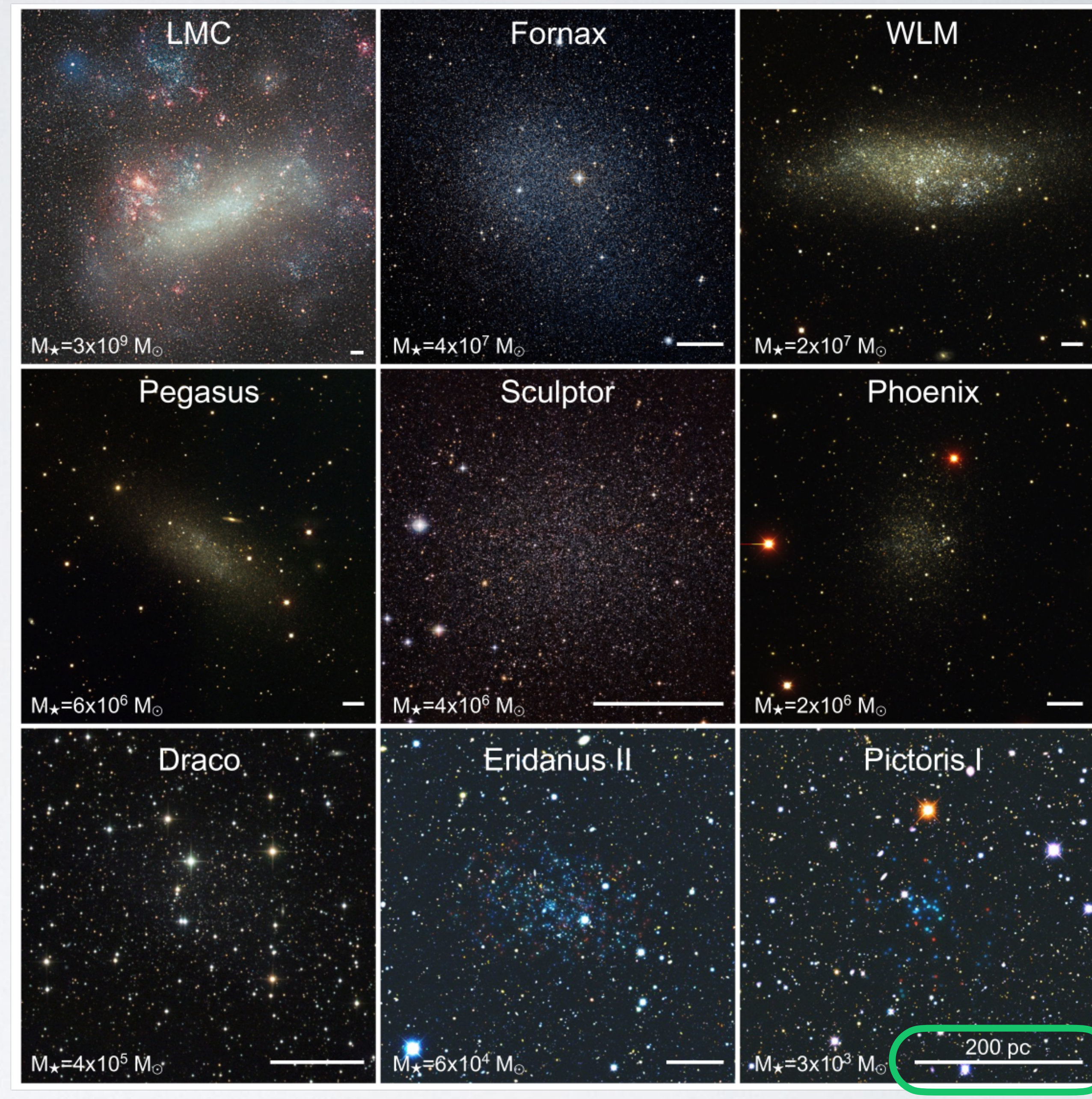
Dwarf galaxies

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

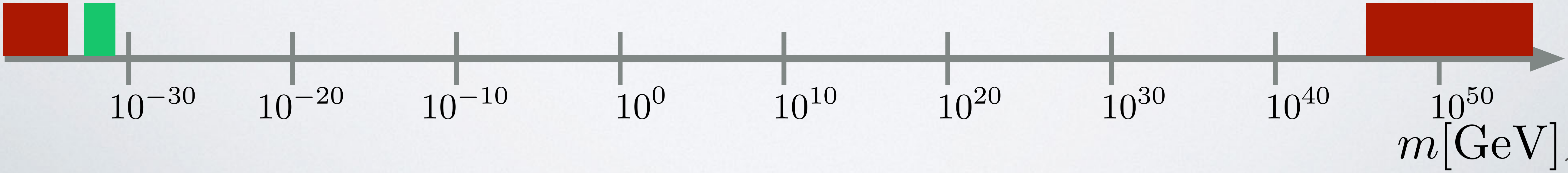
$$m_{\mathrm{DM}} \approx 10^{-22}\,\mathrm{eV} \quad \Rightarrow \lambda_{\mathrm{dB}} \gtrsim 1\,\mathrm{kpc}$$

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

Better fit to small scale structure!



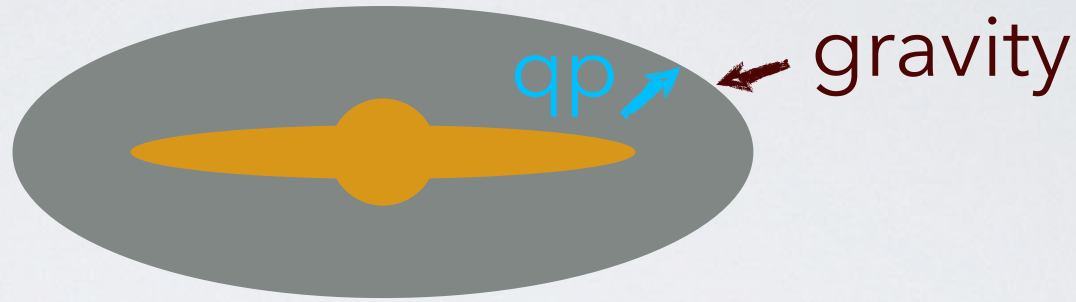
[Bullock et al., Ann.Rev.Astron.Astrophys. 55 (2017)]



THE FUZZY DM PARADIGM

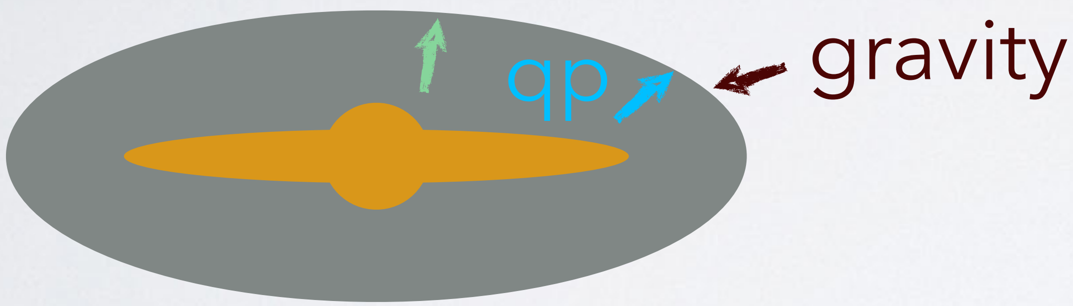
- Small scale is set by a balance of gravity and quantum pressure:

No self-interactions!

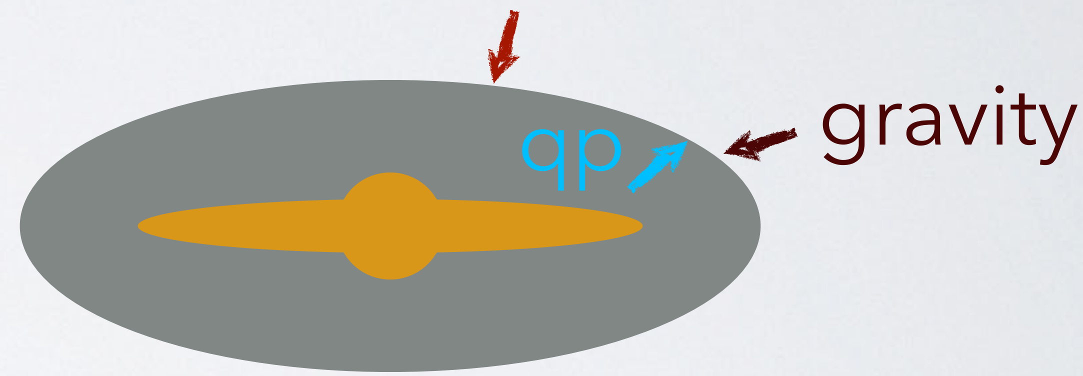


- Self-interactions may drastically alter situation:

repulsive $\lambda > 0$



attractive $\lambda < 0$

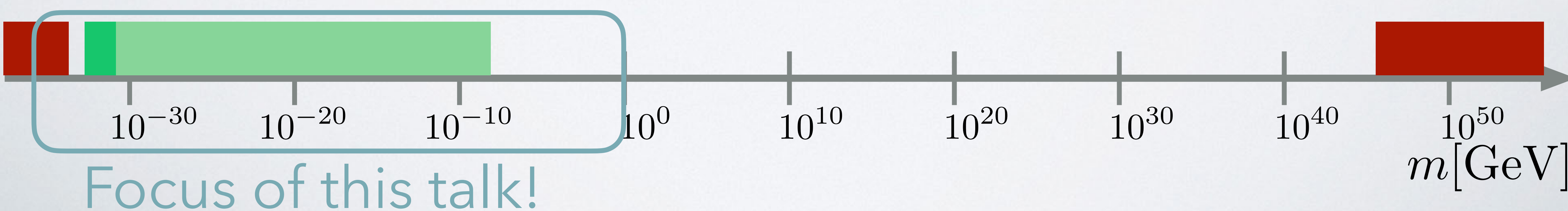


Relaxed mass range: [Ferreira, 2005.03254]

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

Instabilities!

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



LIGHT 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 $\lambda_s > 0 \Rightarrow$ a priori wide range of FDM masses allowed!

- In the FDM regime 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!

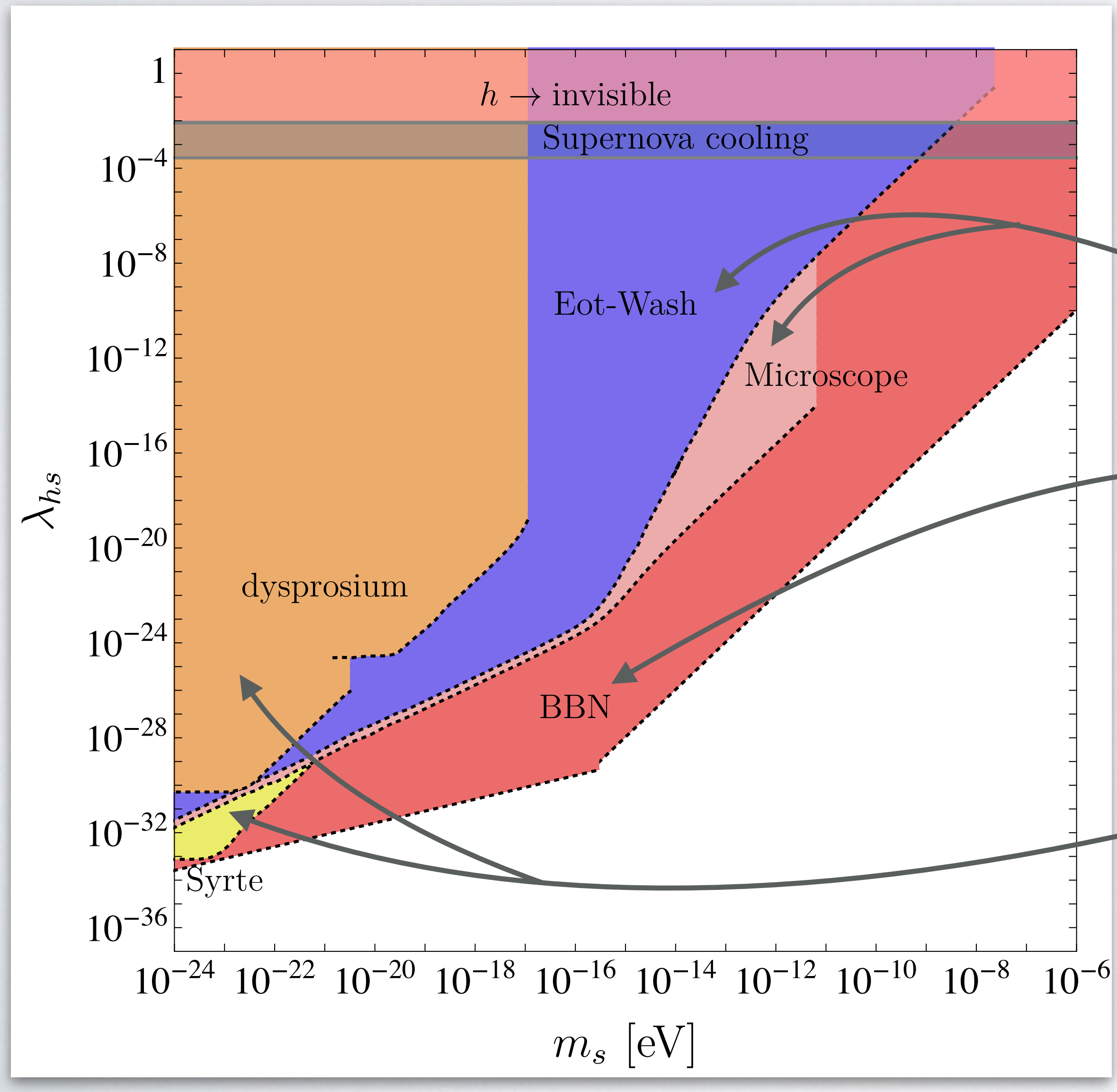
How do we search for wave DM?

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



fifth force

premordial 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]

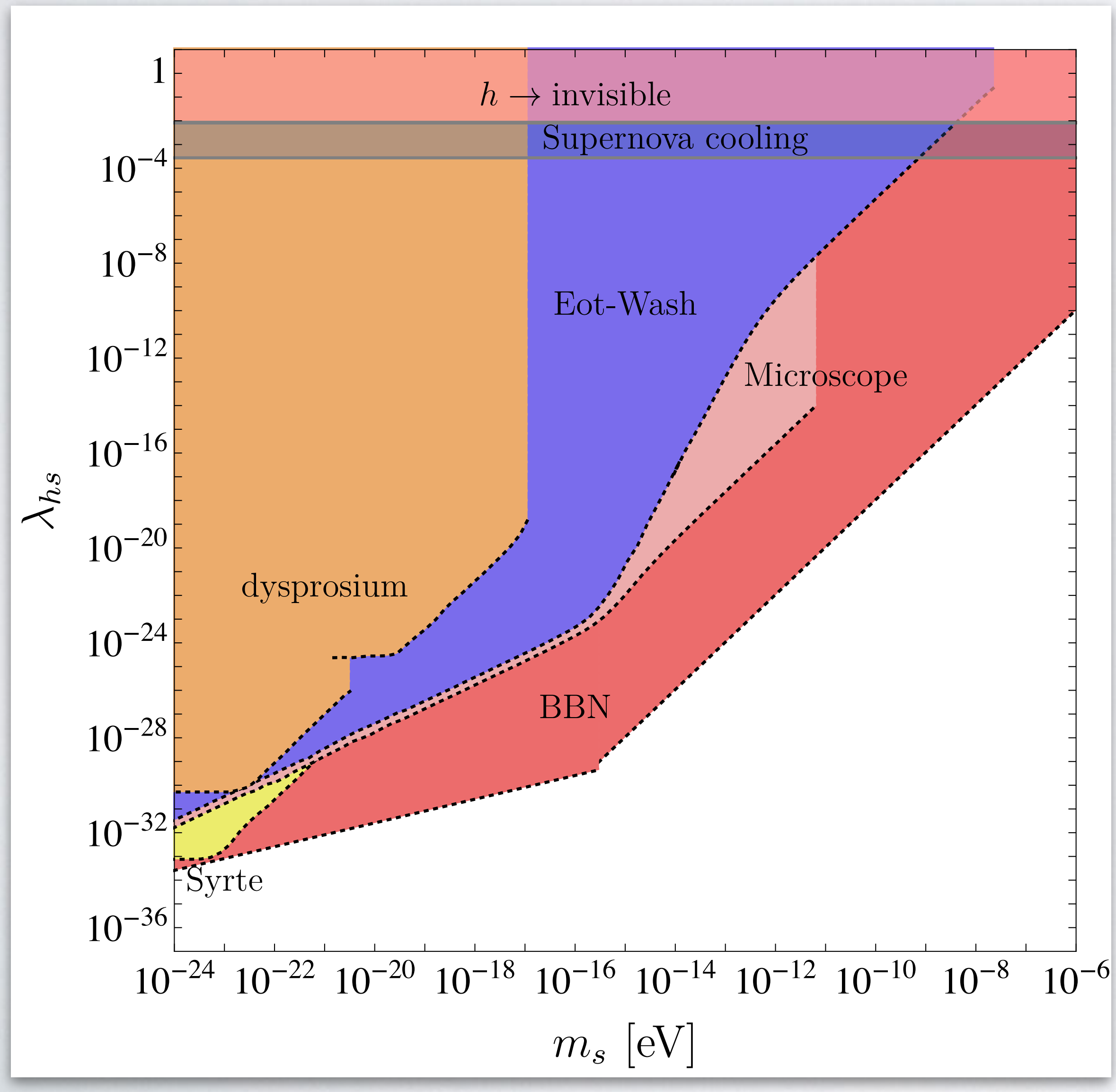
LIGHT DM – HIGGS PORTAL

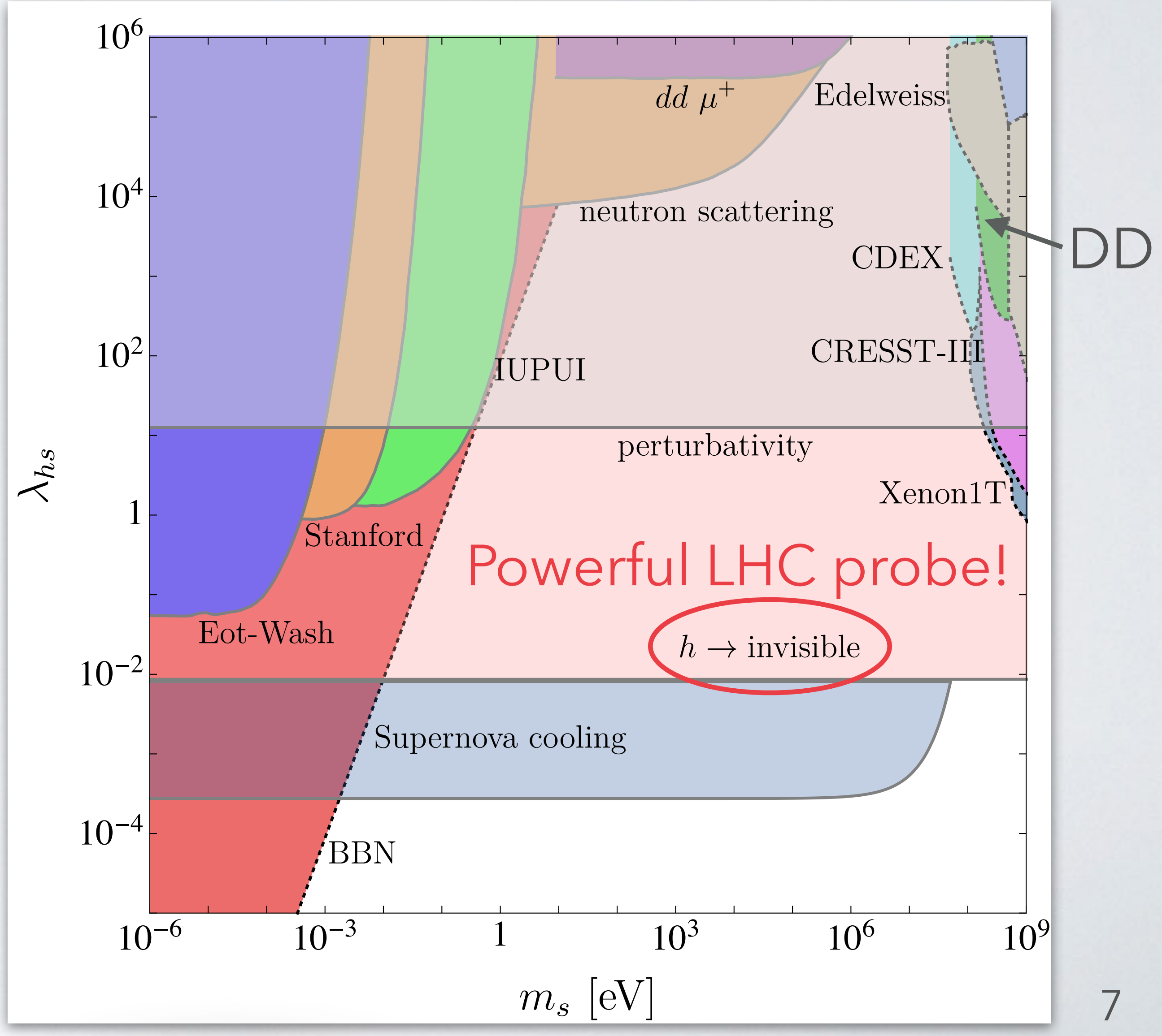
- At low momenta Higgs portal mediates an effective DM-nucleon coupling $\mathcal{L} \supset -\frac{1}{2}\lambda_{hs}\, s^2\, H^\dagger H \longrightarrow c_{sNN}\, s^2\, \bar{N}N$

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

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

[Bauer, PF, Reimitz, Plehn, 2005.13551]





LIGHT DM – NEW MEDIATOR

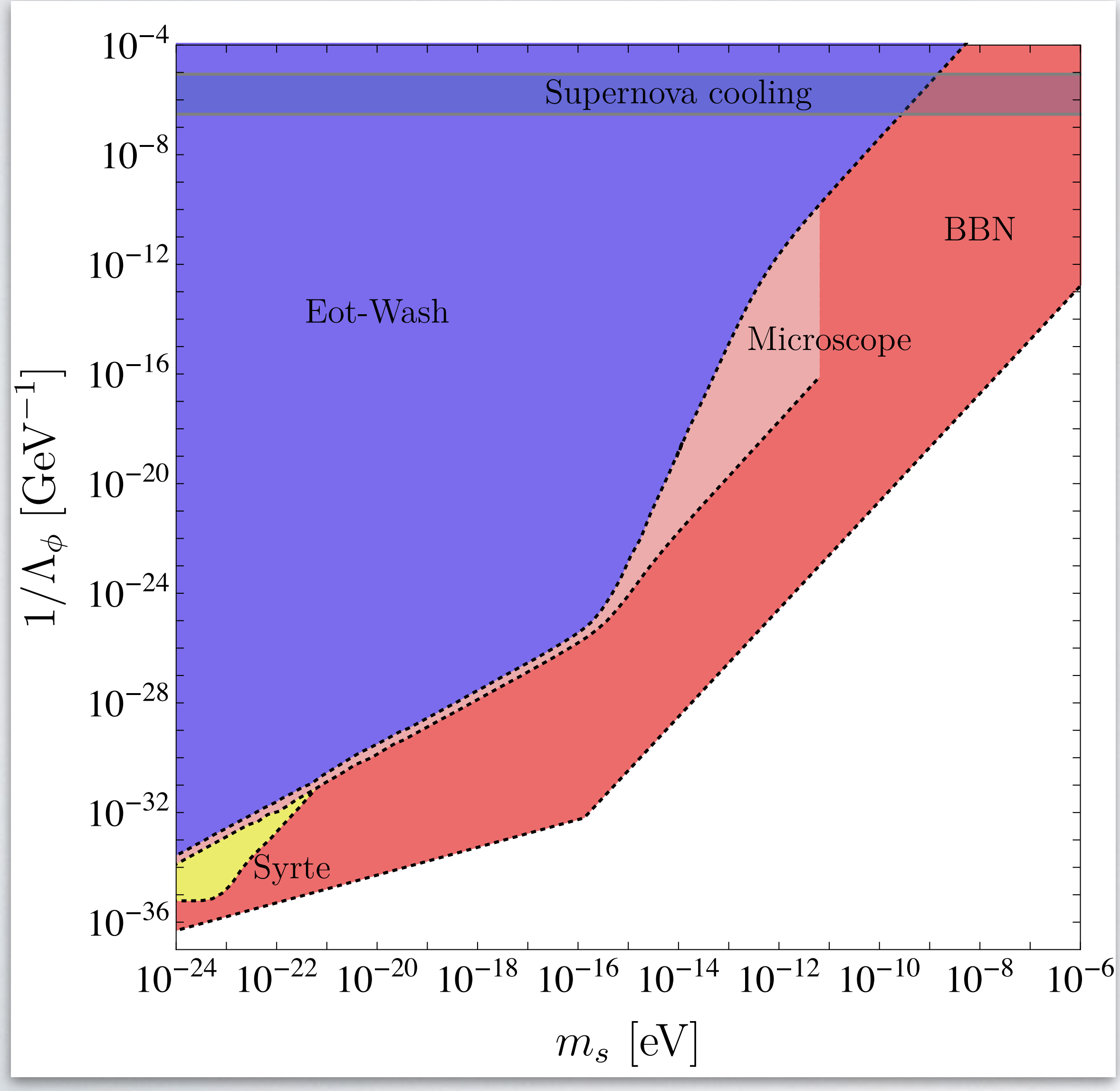
- Consider model with new weak scale mediator ϕ

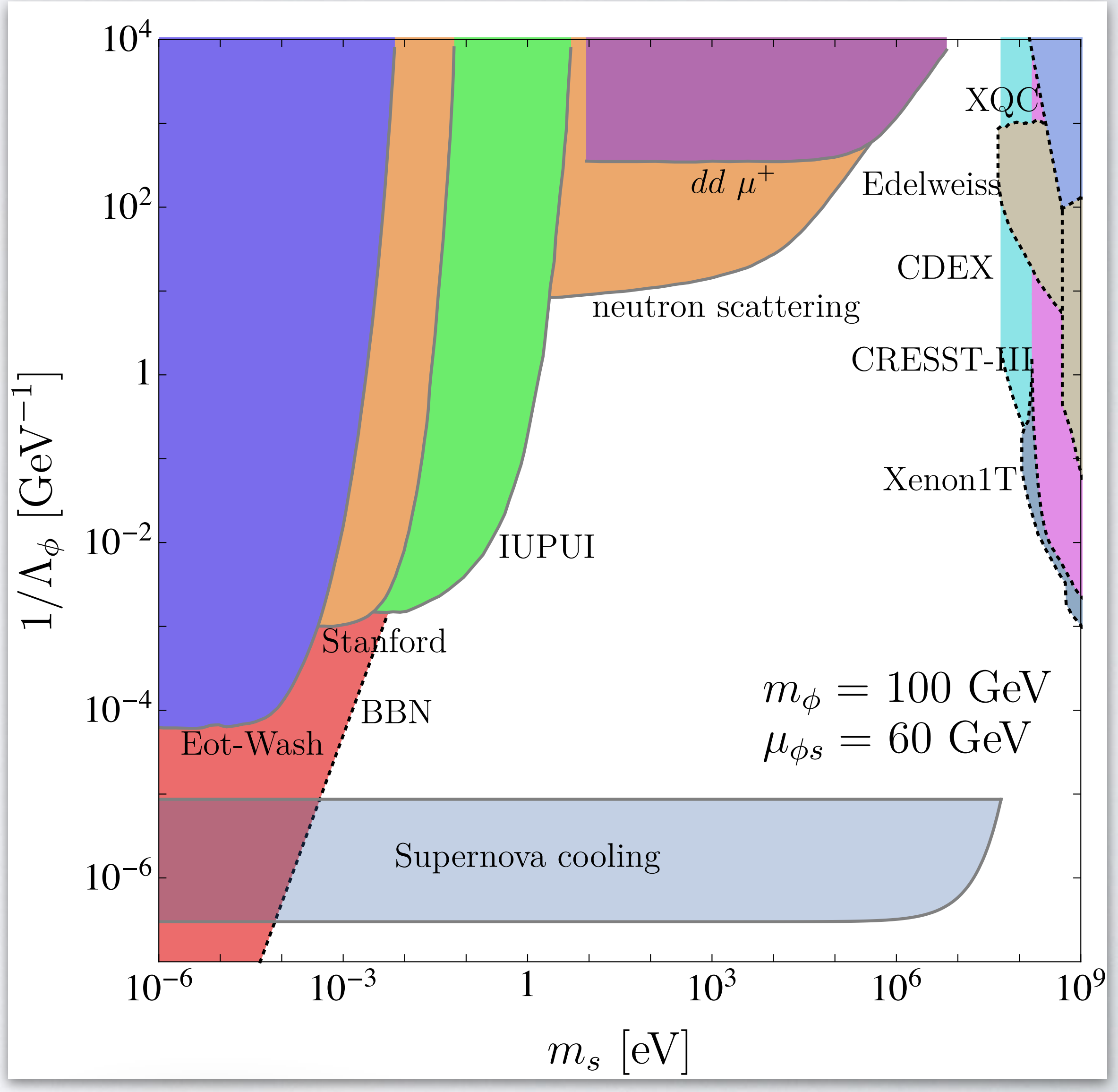
$$\mathcal{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - \frac{\mu_{\phi s}}{2} \phi s^2 - \frac{\alpha_S}{\Lambda_\phi} \phi \, \mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}] \longrightarrow c_{sNN} \, s^2 \, \bar{N} N$$

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

- 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:

$$\Phi = (f + s)e^{i\,a/f} \qquad\qquad e^{i\,a/f} \to e^{i\,(a+c)/f} = e^{i\,a/f}e^{i\,c/f}$$

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

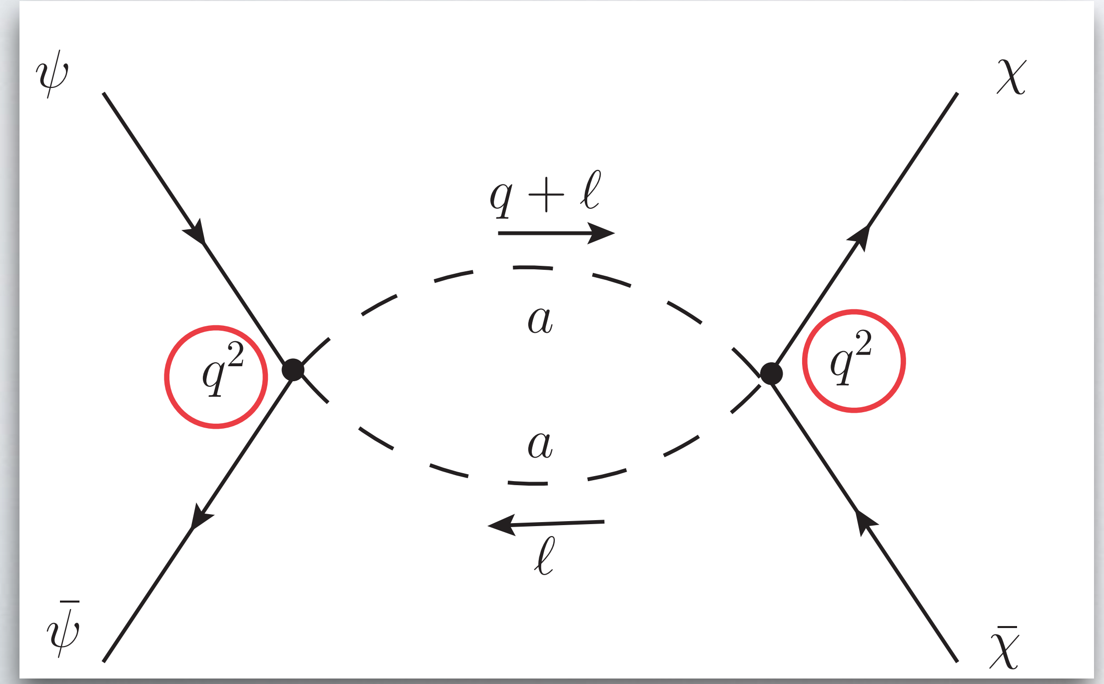
LIGHT DM – ALPS

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

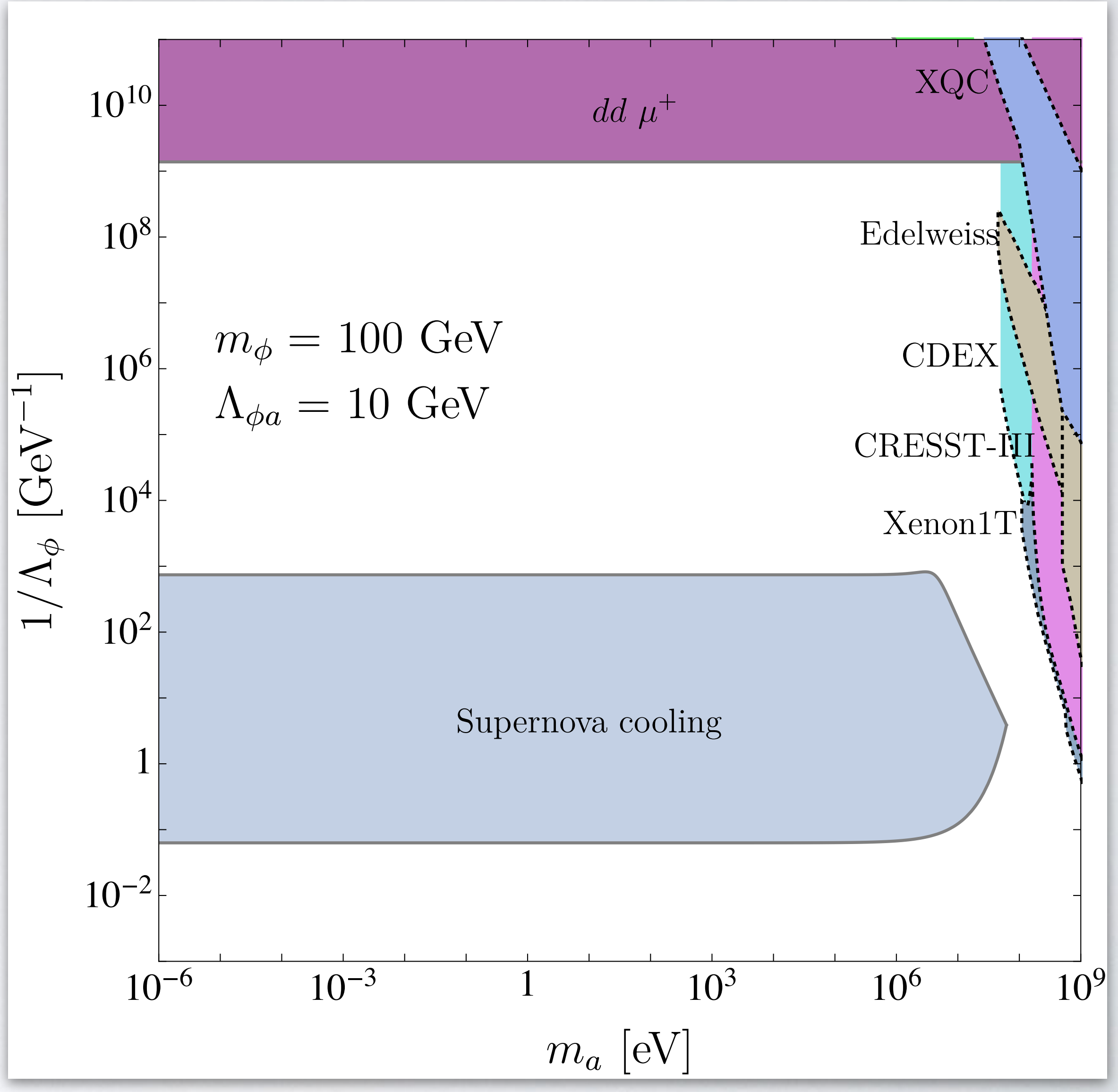
$$\mathcal{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - \frac{\partial_\mu a \partial^\mu a}{2\,\Lambda \phi a} \phi - \frac{\alpha_S}{\Lambda_\phi} \phi \,\mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}] \longrightarrow c_{aNN}\, \partial_\mu a \partial^\mu a\, \bar{N} N$$

[Bauer, PF, Reimitz, Plehn, 2005.13551]

- Almost unconstrained at low masses because of momentum suppression:



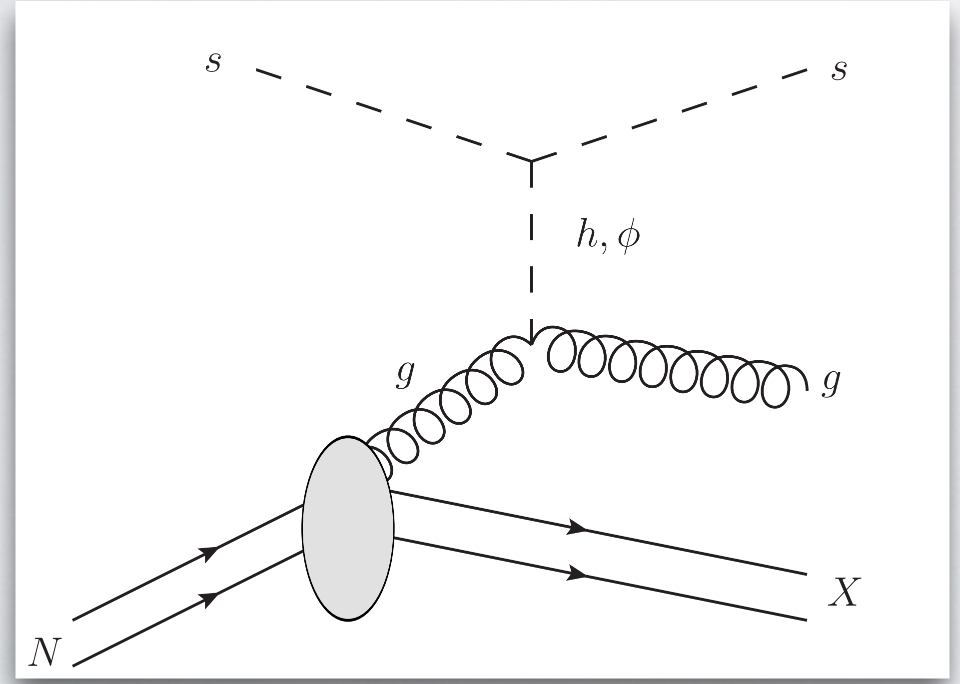
$\propto q^4$



NEW SEARCH STRATEGIES AT LHC

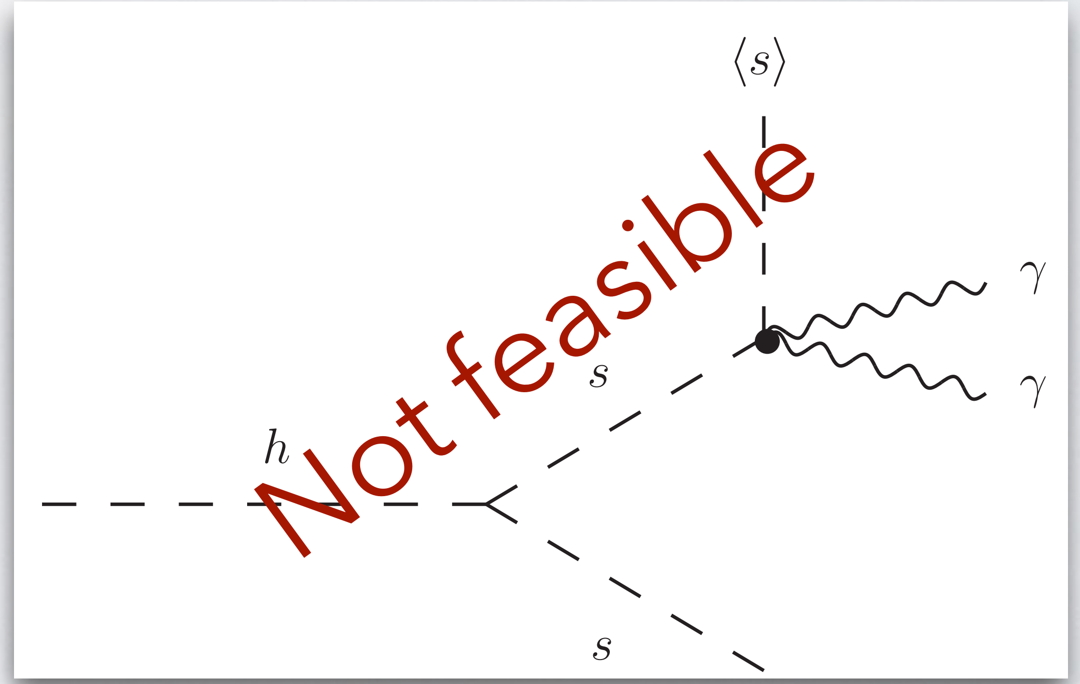
- Conventional direct and indirect DM search strategies hopeless due to low momenta of (U)LDM
- But production at LHC enhances momenta:

Direct detection @ LHC



(Deep inelastic scattering)

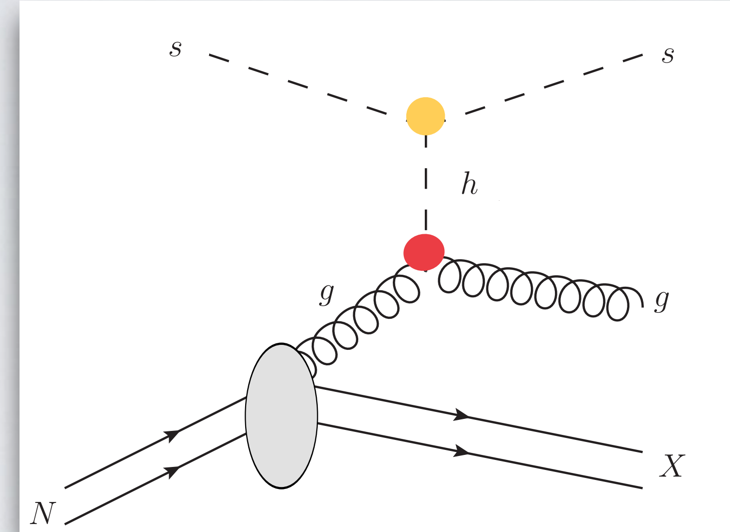
Indirect detection @ LHC



(Background annihilation)

[Bauer, PF, Reimitz, Plehn, 2005.13551]

DIRECT DETECTION



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

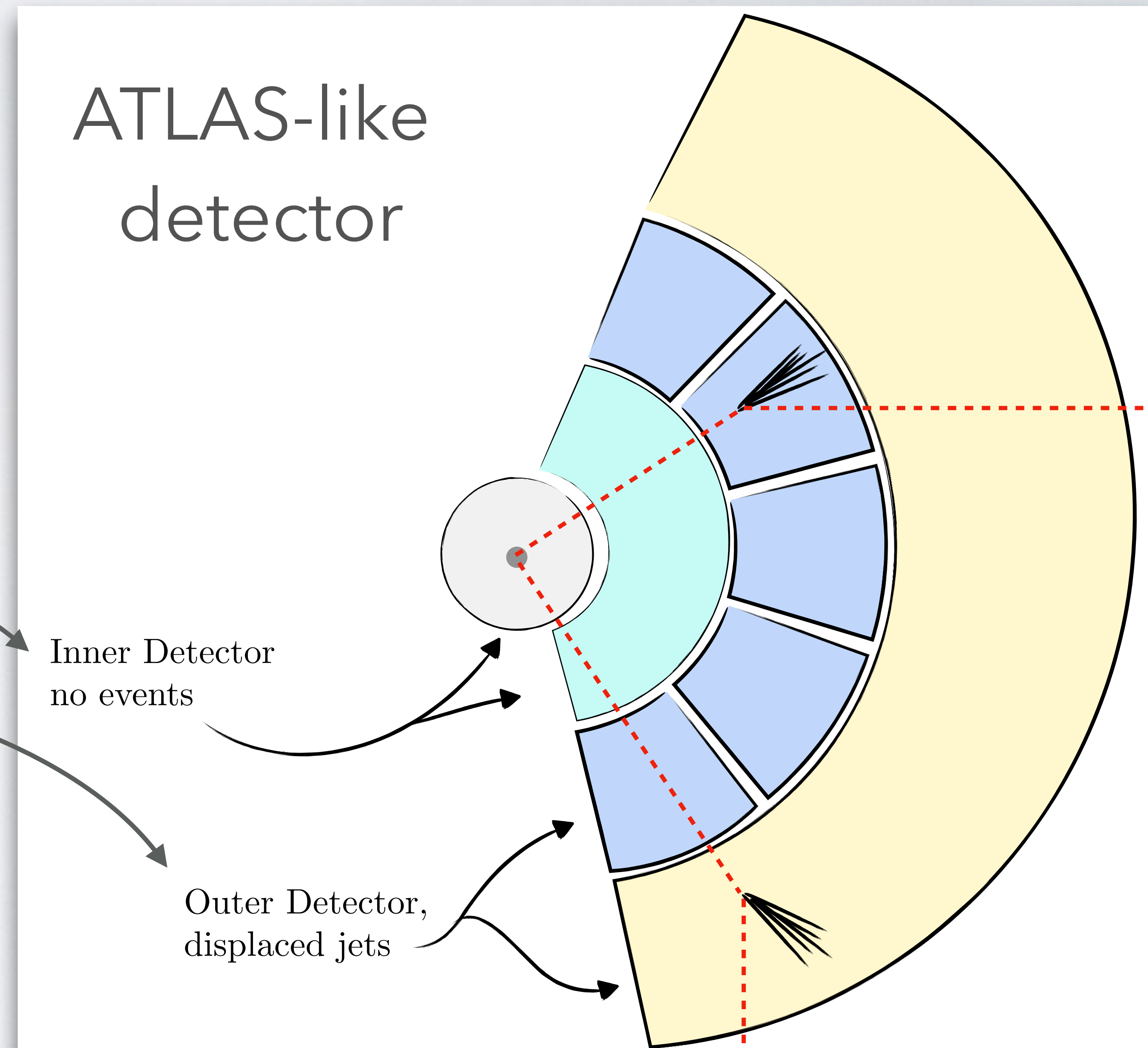
1. E.g. Higgs Portal:

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

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

Distinguishable from LLPs:

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



But unfortunately for HP:

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

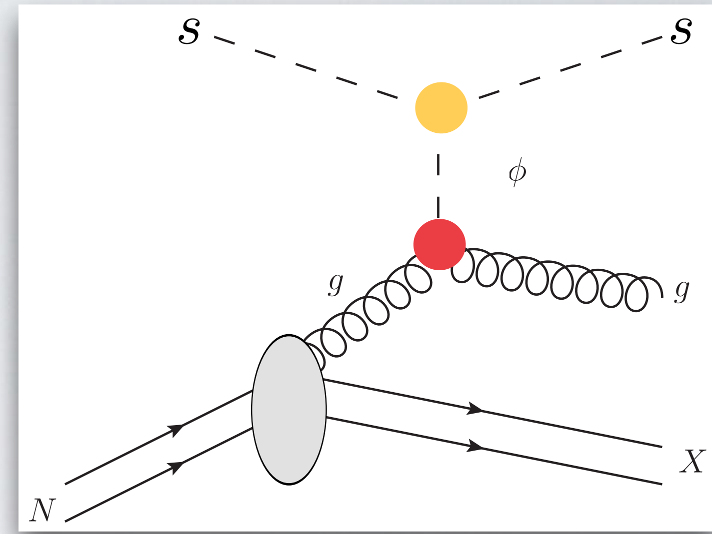
$$P_{\rm DIS} = 1 - e^{L_E\, n_{Pb}\, \sigma_{Pb}} e^{L_H\, n_{Fe}\, \sigma_{Fe}} \approx 7.5 \cdot 10^{-21}$$

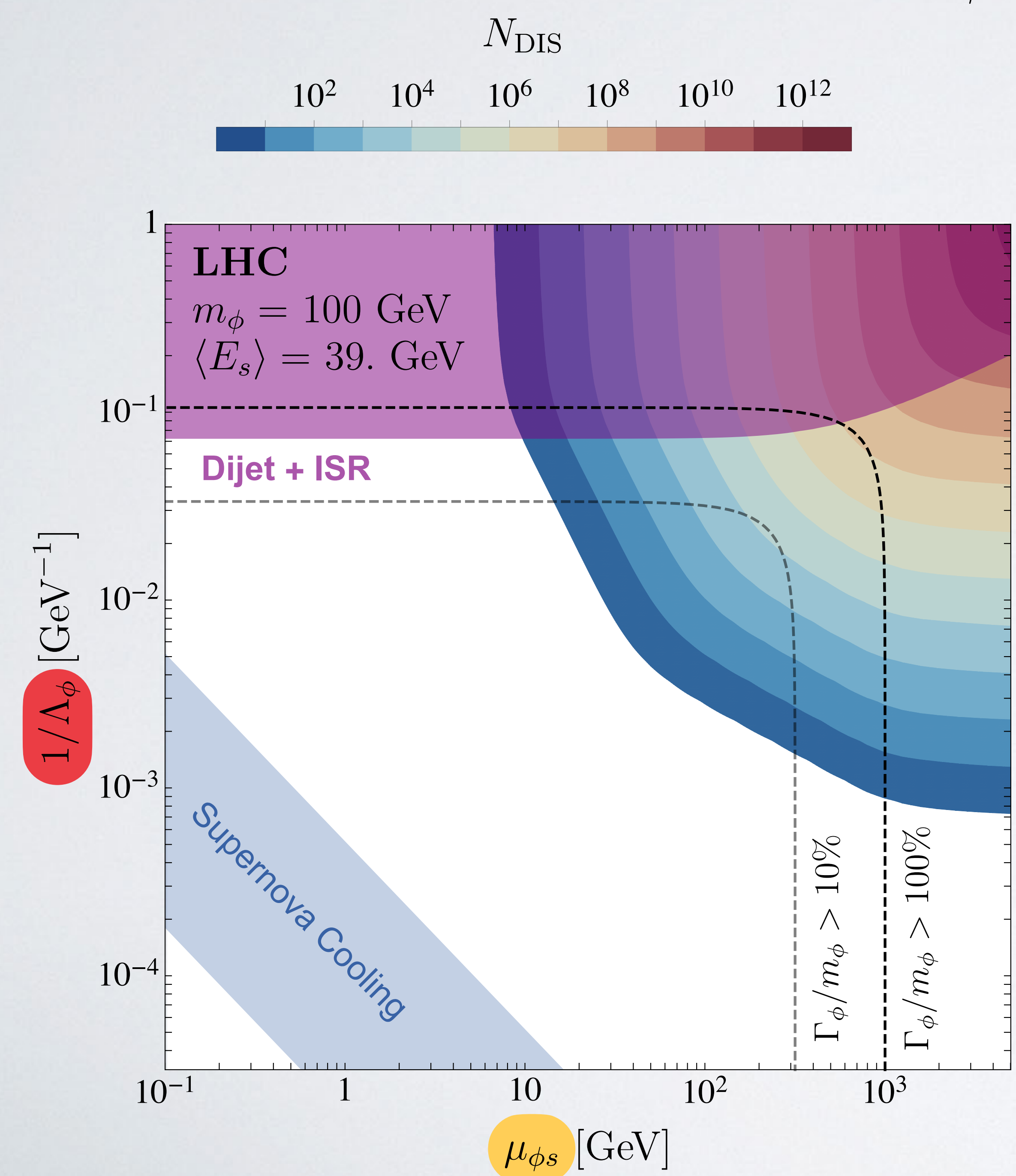
[Bauer, PF, Reimitz, Plehn, 2005.13551]

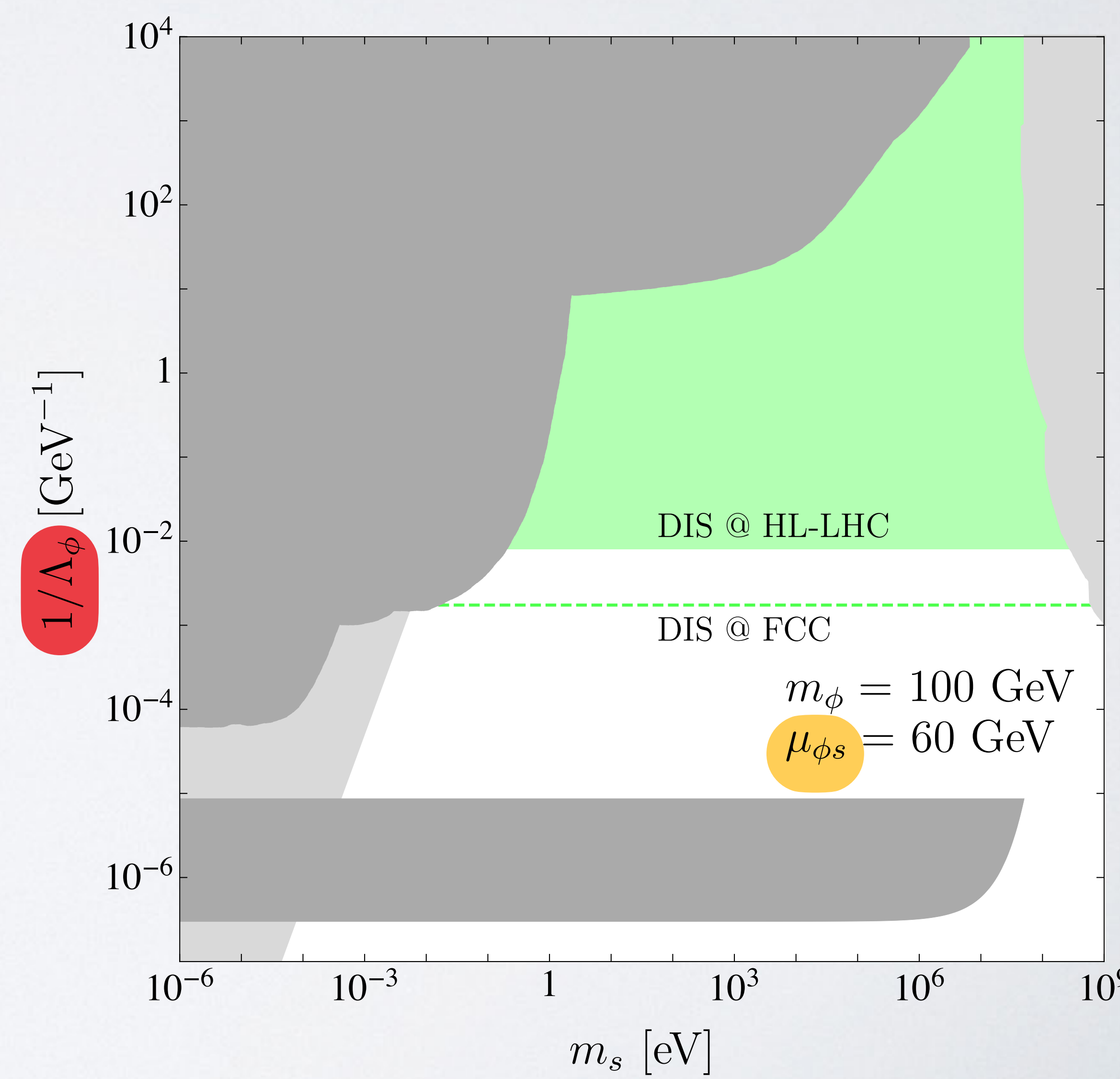
DIRECT DETECTION AT THE LHC

2. Scalar DM with scalar mediator

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





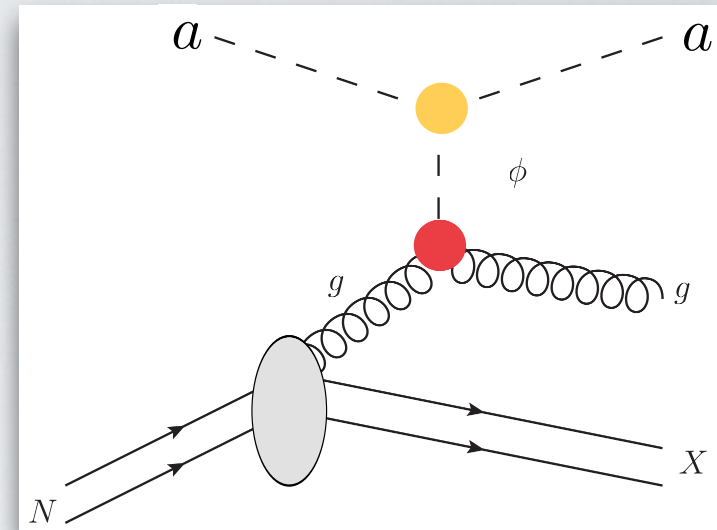


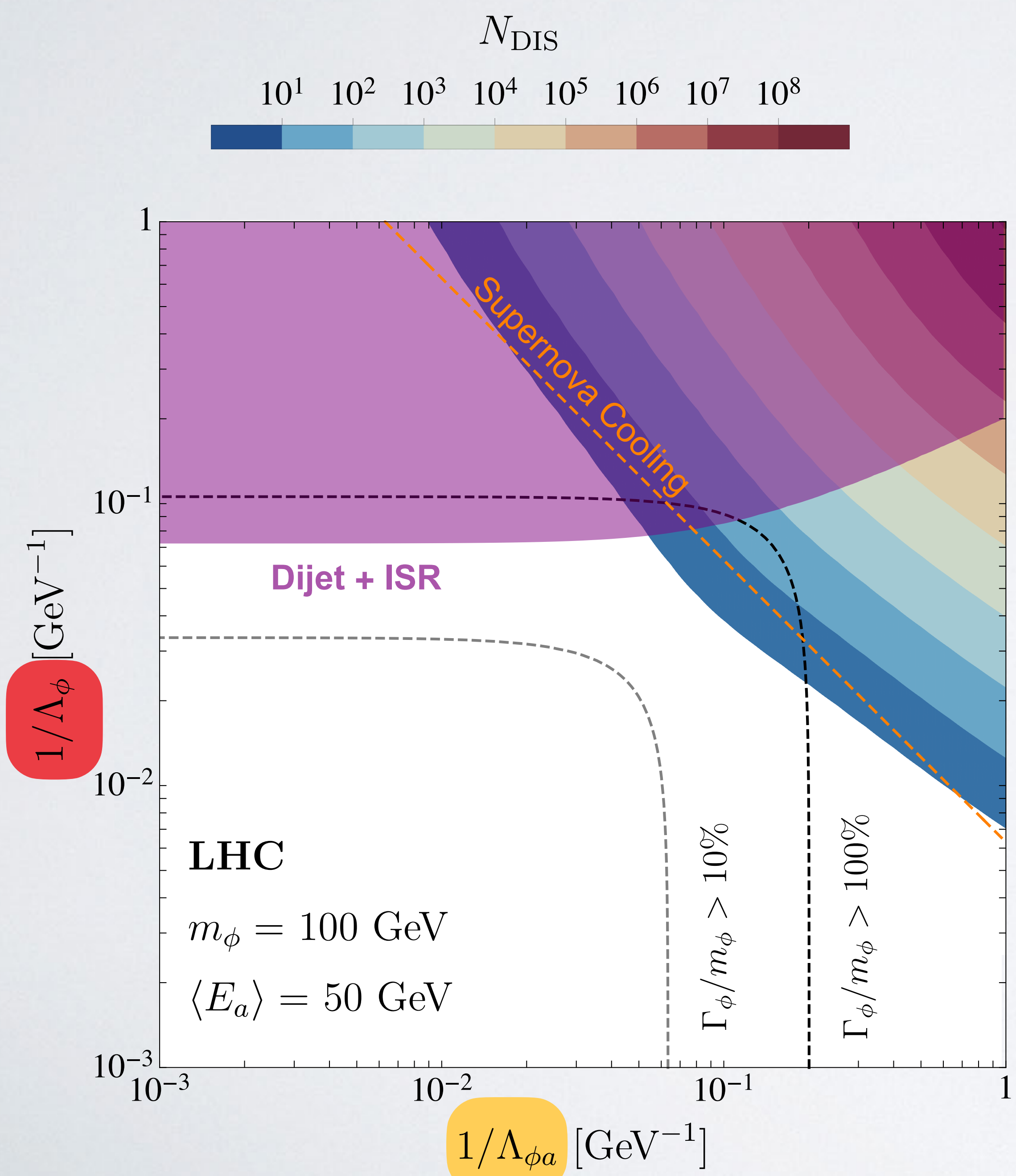
[Bauer, PF, Reimitz, Plehn, 2005.13551]

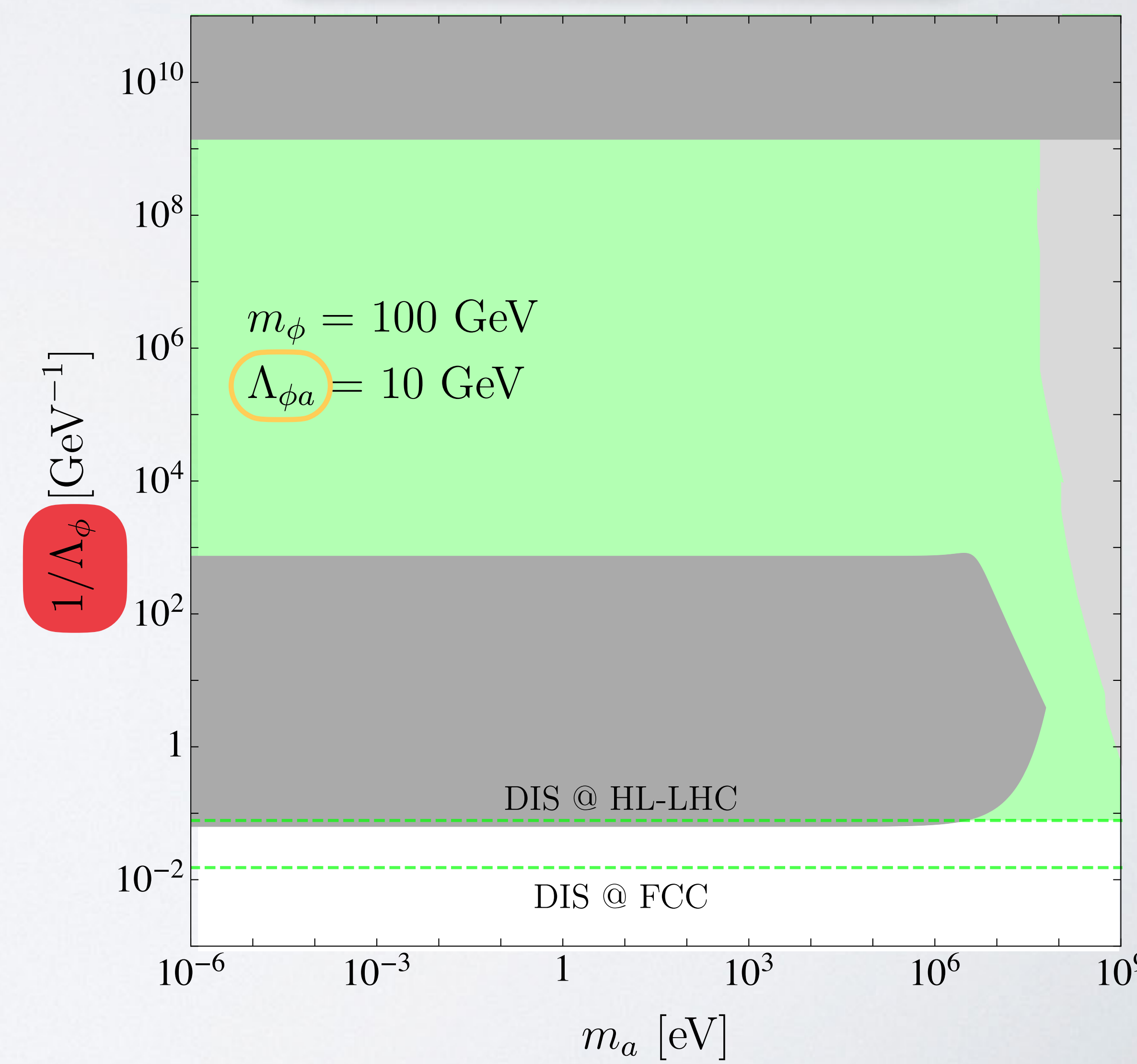
DIRECT DETECTION AT THE LHC

3. ALP DM with scalar mediator

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







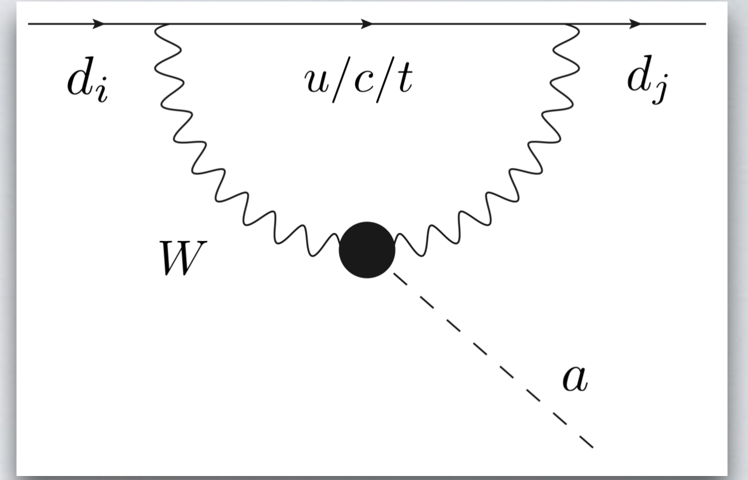
[Bauer, PF, Reimitz, Plehn, 2005.13551]

WHAT ABOUT BOOSTED FLAVOR

- Axion couplings to weak gauge bosons

$$\mathcal{L} \supset (\partial_\mu a)^2 - \frac{m_a^2}{2} a^2 - \frac{g_{aWW}}{4} \, a \, \mathrm{Tr}[W_{\mu\nu} \widetilde{W}^{\mu\nu}]$$

induces flavor decays $B \to K^{(*)} a$, $K \to \pi a$

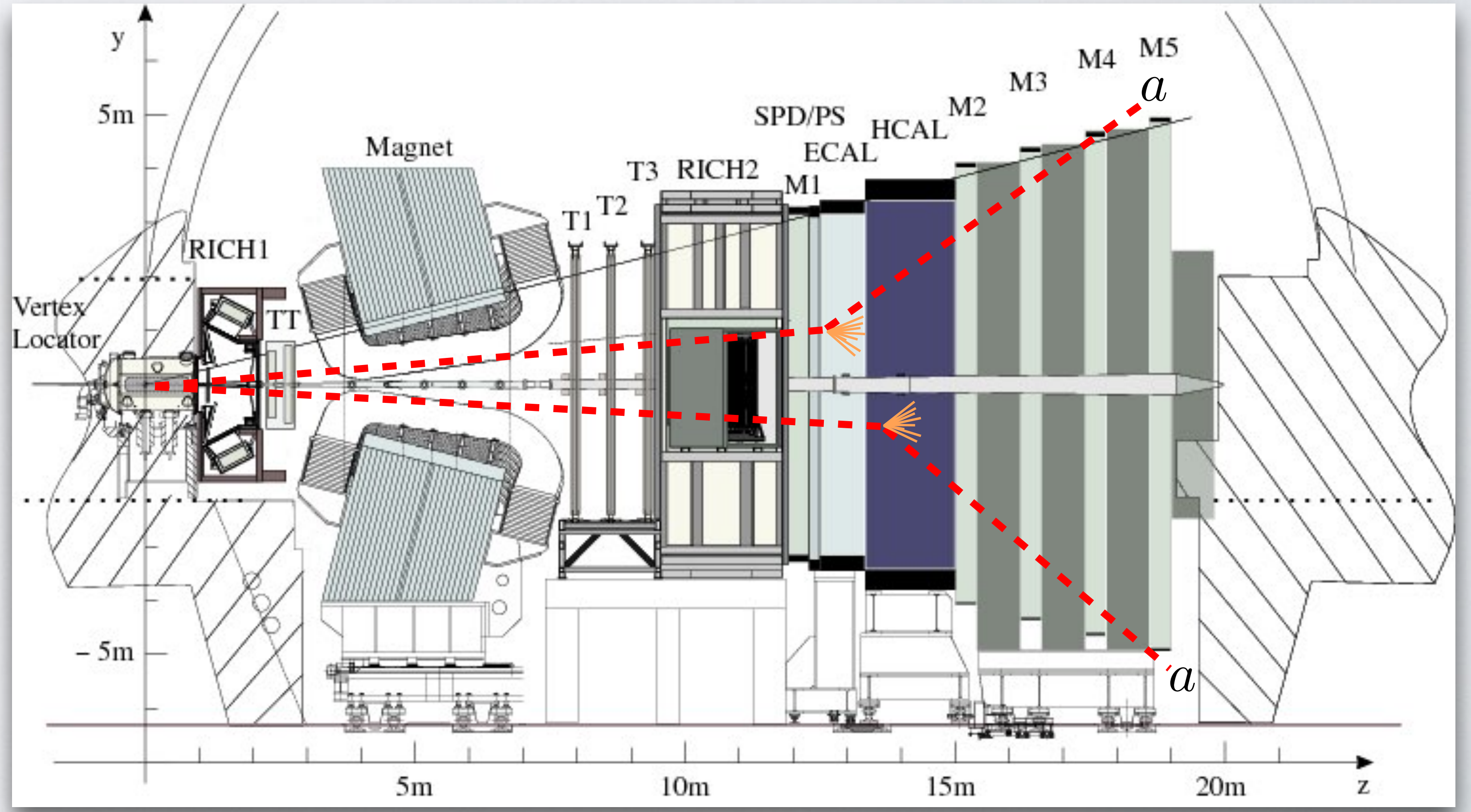


[Izaguirre, Lin, Shuve, PRL118 (2017)]

- Tagged flavor decay plus recoil jet as emerging signature for Belle-II or LHCb?

- E.g. LHCb produces large numbers of boosted B's:

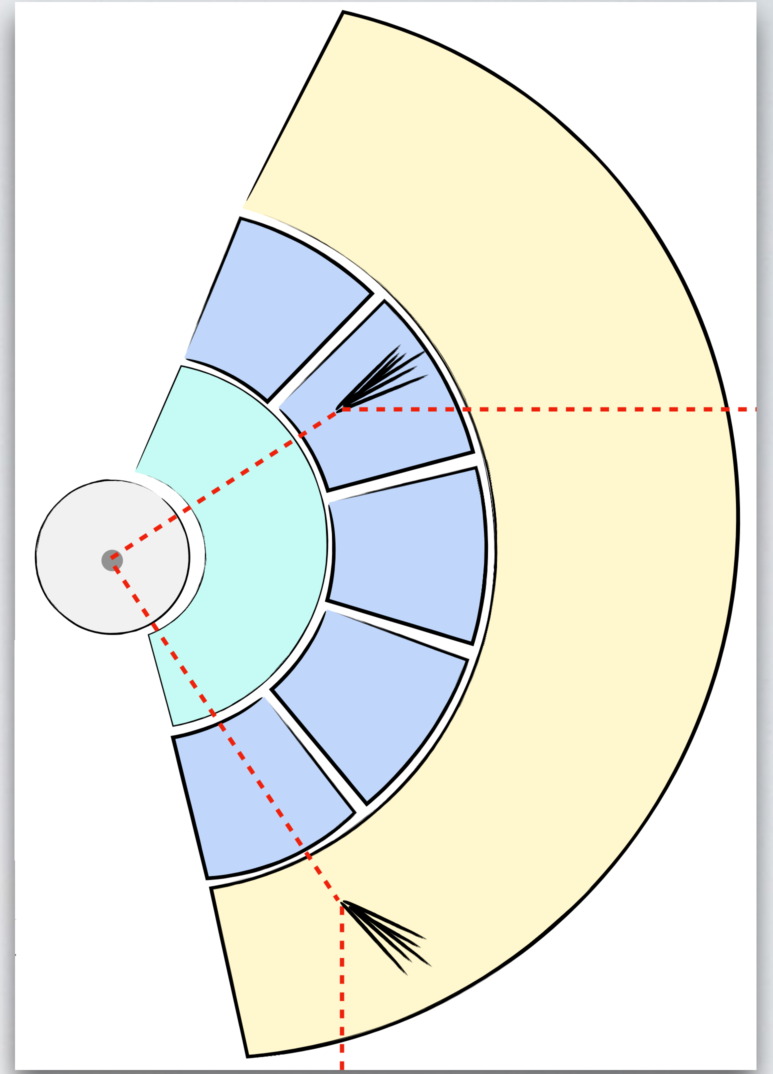
median $p_a \sim 40\,\mathrm{GeV}$
and 20% $p_a > 90\,\mathrm{GeV}$



[thanks to Martino Borsato for these numbers]

SUMMARY

- (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!

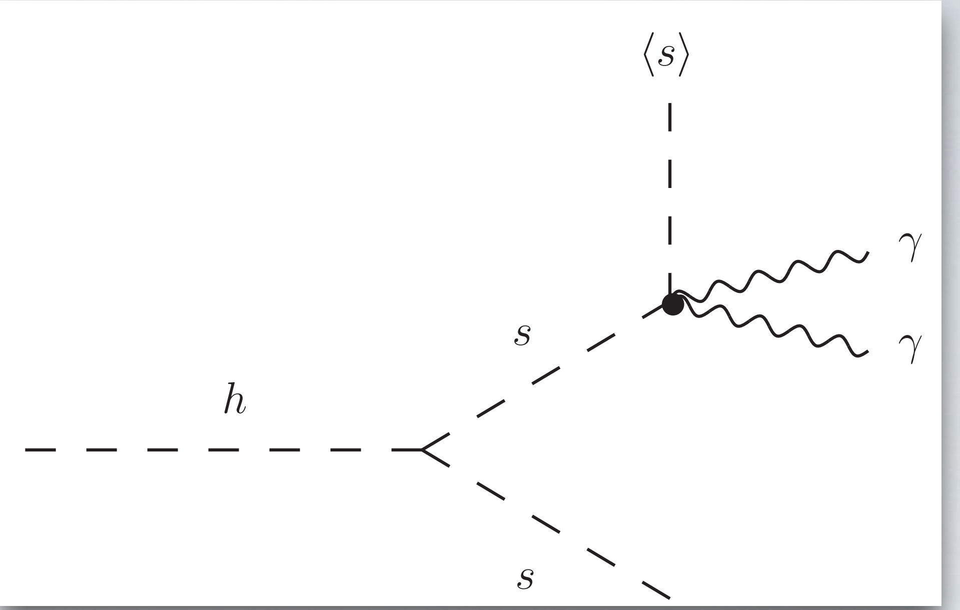
- Potentially interesting signature for flavor in LHCb, Belle-II, …

- Many more improvements and generalizations:
  - quark couplings
  - SM neutrinos, steriles
  - meson decays
  - new detectors
  - …

BACKUP

INDIRECT DETECTION @ LHC

- ULDM has huge occupation numbers, so can it annihilate with the halo background field if produced at LHC?



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

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

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

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