Implications of results of non-SM searches at the LHC and low energy colliders

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Interplay of Particle and Astroparticle Physics
August 22, 2014

DARK MEDIATORS

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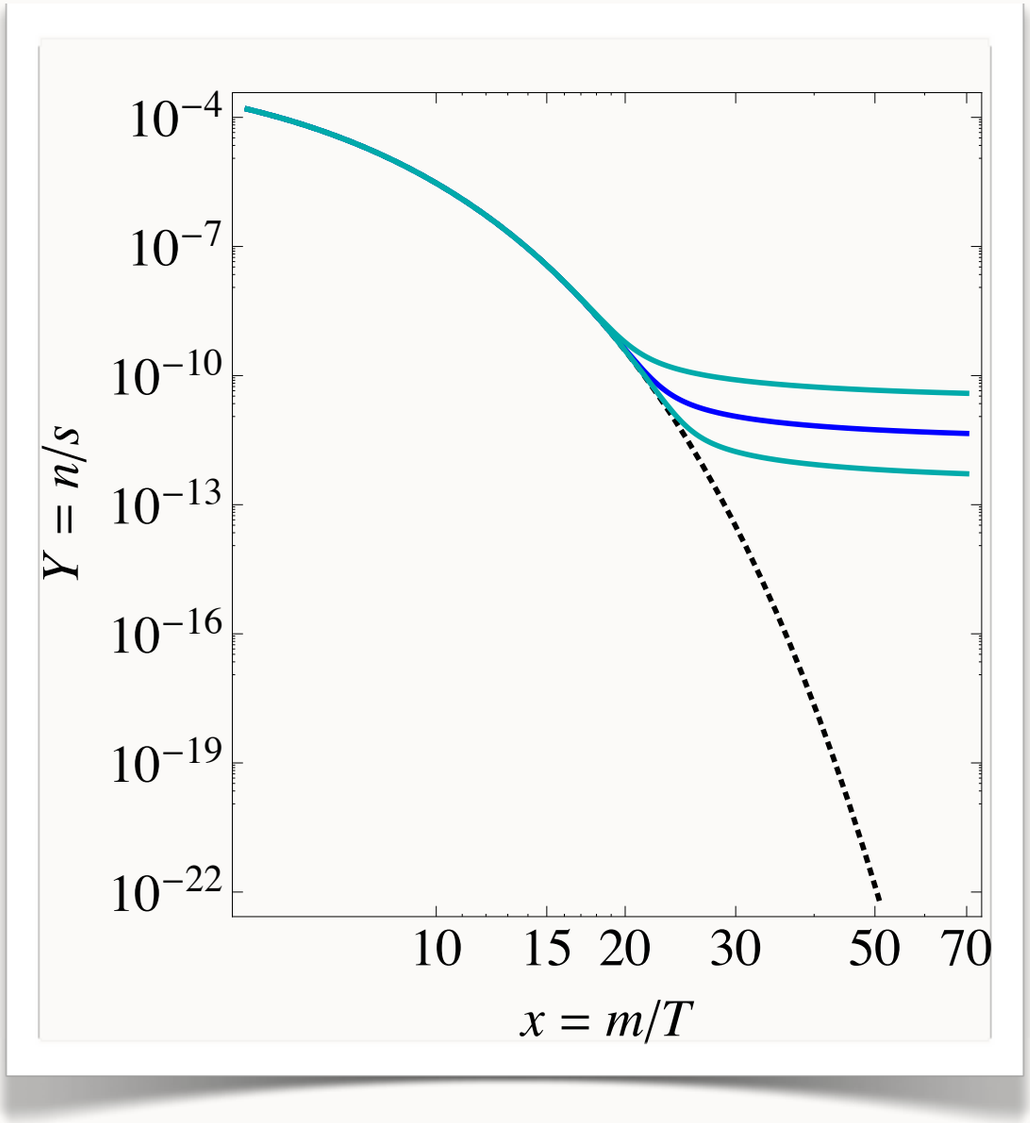
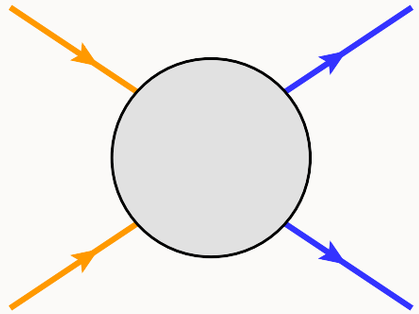
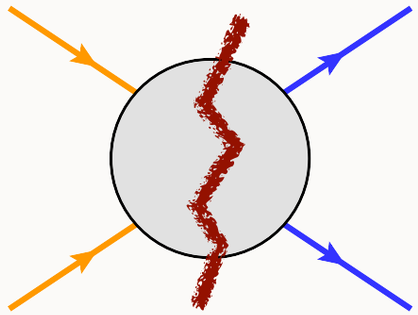
THE WIMP MIRACLE

- Thermal freezeout:





$$n\langle\sigma v\rangle > H$$



$$n\langle\sigma v\rangle \ll H$$

THE WIMP MIRACLE

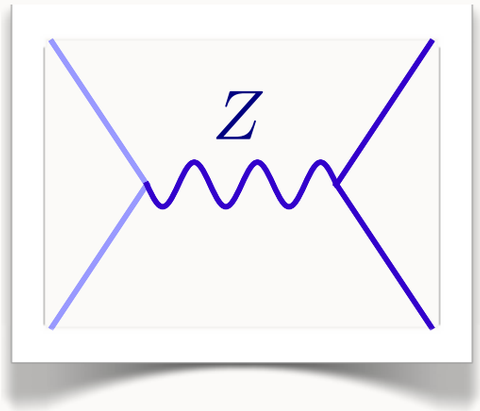
- WIMP miracle is really a statement about perturbative thermal relics:
  - upper bound on m: $g^2 < 4\pi$

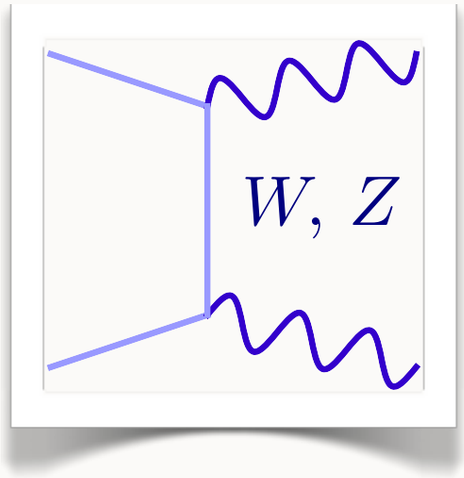
    $\Rightarrow\ m \lesssim 40\,\mathrm{TeV}$
  - lower bound on m: freezeout must happen when DM is relativistic

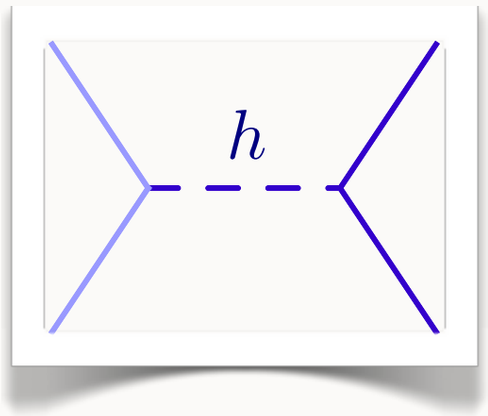
    $\Rightarrow\ m \gtrsim 10\,\mathrm{eV}$

THERMAL FREEZEOUT

- Three possibilities:
  - DM annihilates to SM via SM mediators
    - sharply predictive

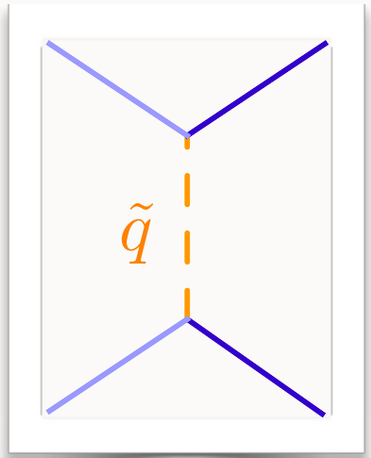


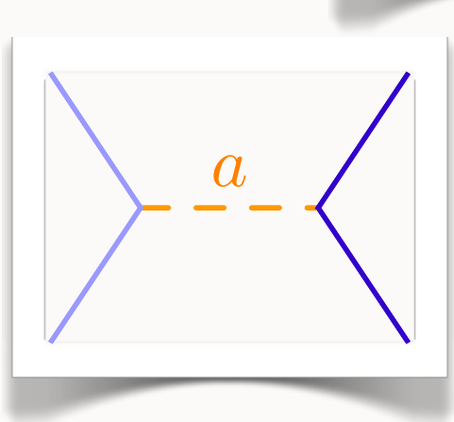


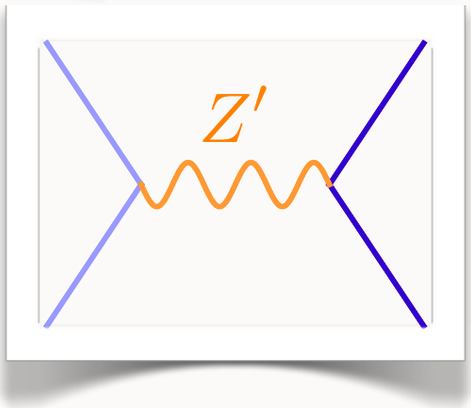


THERMAL FREEZEOUT

- Three possibilities:
  - DM annihilates to SM via SM mediators
    - sharply predictive
  - DM annihilates to SM via new mediators
    - lower bound on couplings from freezeout

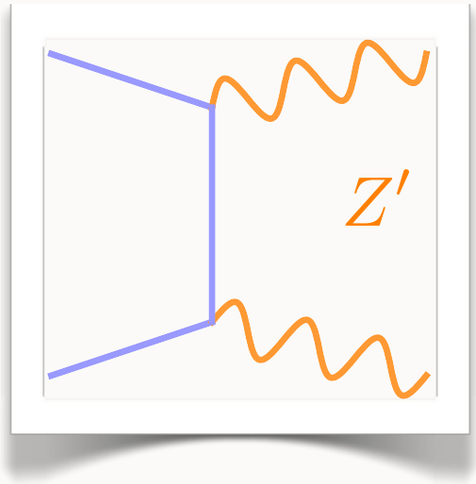


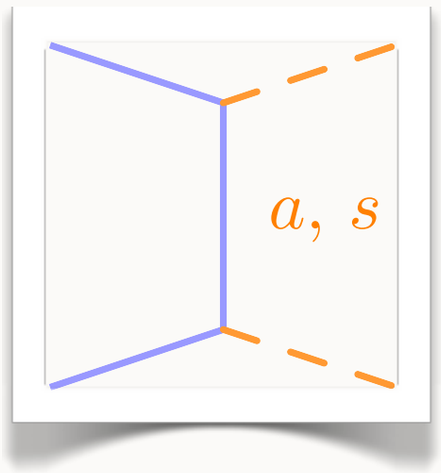




THERMAL FREEZEOUT

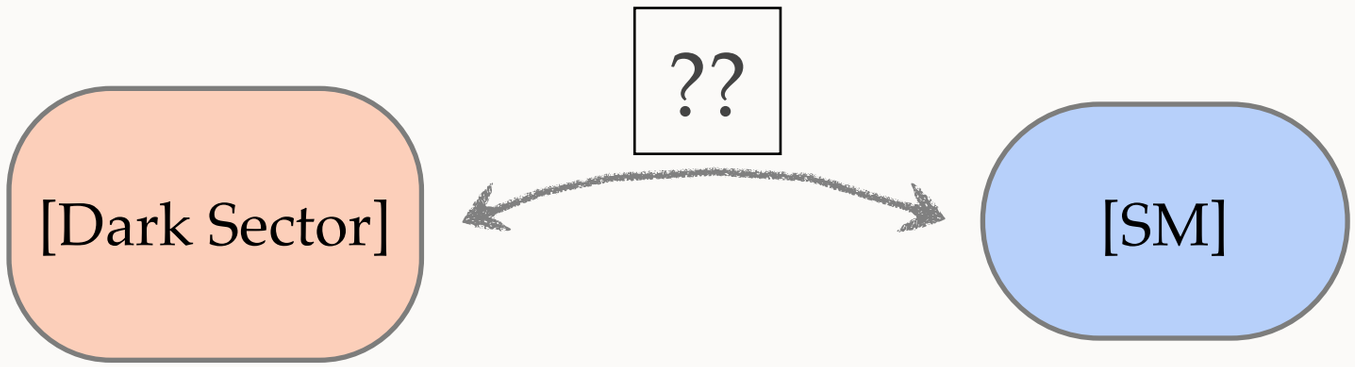
- Three possibilities:
  - DM annihilates to SM via SM mediators
    - sharply predictive
  - DM annihilates to SM via new mediators
    - lower bound on couplings from freezeout
  - DM annihilates to additional hidden sector states





DARK FREEZEOUT

- Mediator couplings to SM can be parametrically small

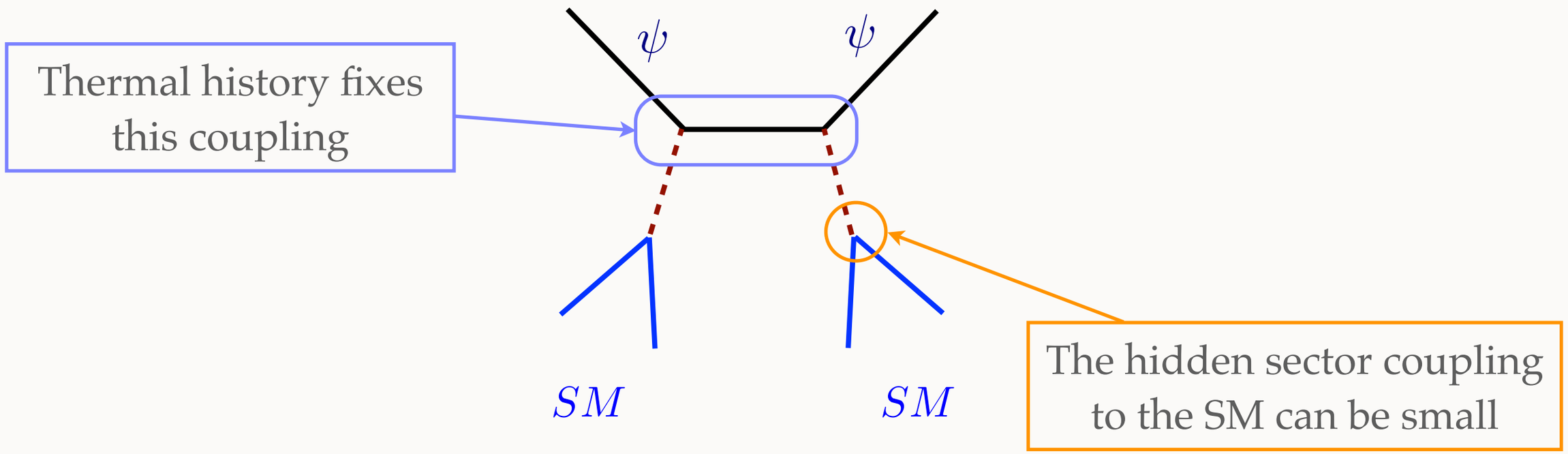


- Leading couplings at low energy:
  - Higgs portal $\mathcal{L}_{int} = \lambda s^2 |H|^2$
  - Vector portal $\mathcal{L}_{int} = \epsilon B_{\mu\nu} V^{\mu\nu}$

[Pospelov and Ritz]

DARK FREEZEOUT

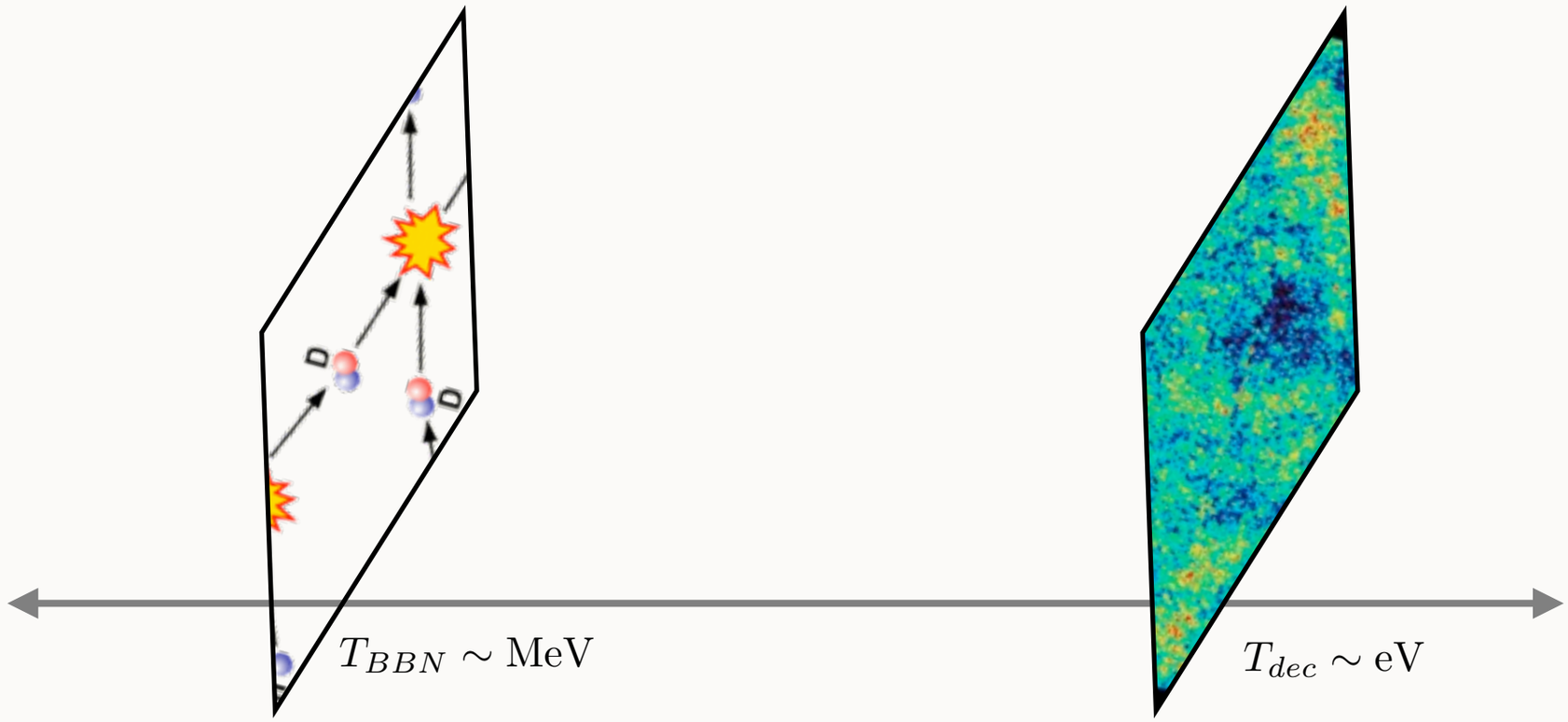
- Dark matter freezeout proceeds more or less independently of SM until mediator ultimately decays



[Pospelov and Ritz]

DARK MEDIATORS

- Bad news: dark mediator might be cosmologically stable



$$N_\nu|_{Planck+D/H} = 3.28 \pm 0.28$$

$$N_\nu|_{SPT} = 3.85 \pm 0.62$$

$$N_\nu|_{Planck} = 3.36 \pm 0.33$$

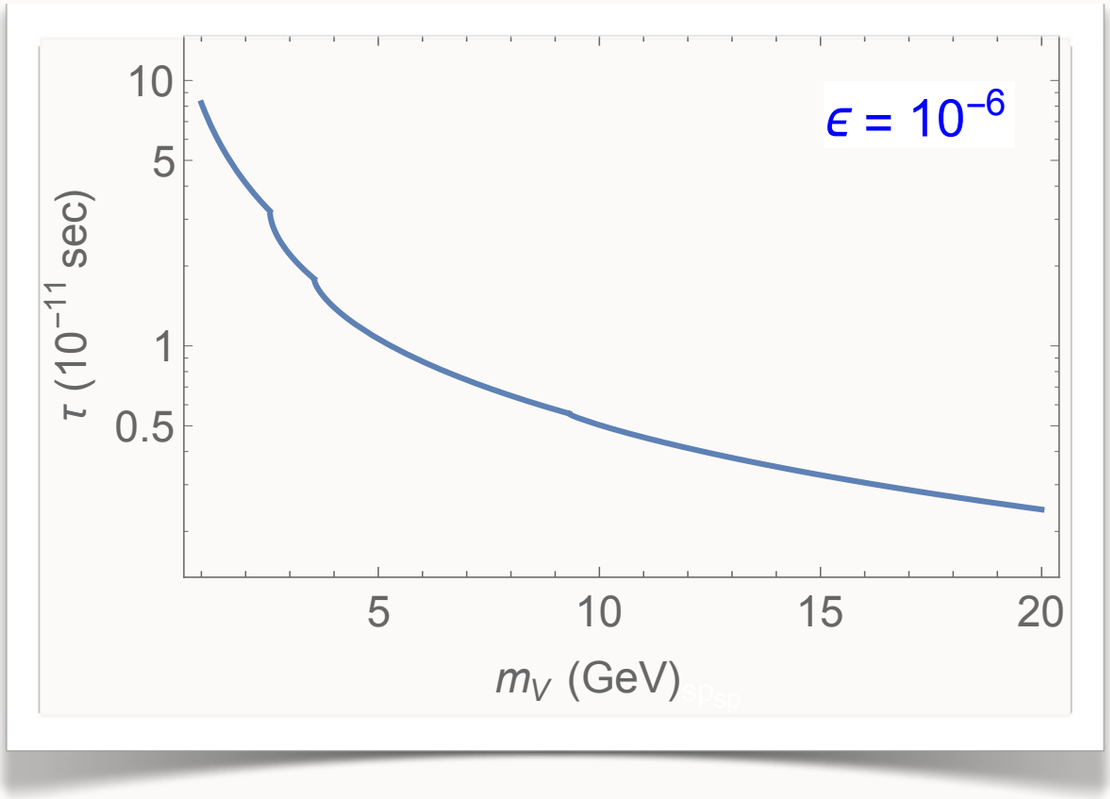
DARK MEDIATORS

- Good news: even very small couplings to the SM can allow the mediator to decay

$$\mathcal{L}_{int} = \epsilon V_{\mu\nu} B^{\mu\nu}$$

  - BBN: $\tau \lesssim 1$ sec
  - so for $m \gtrsim$ GeV,

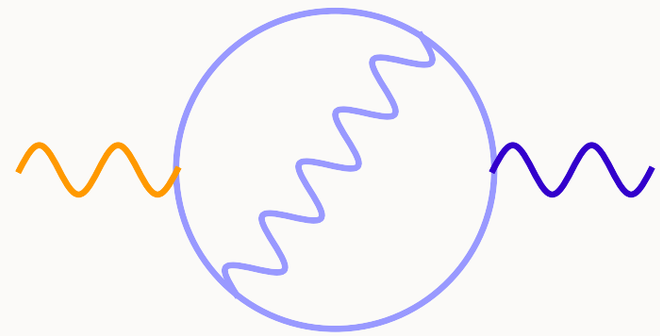
$$\epsilon \gtrsim 10^{-12}$$



- Bad news: lower end of allowed range still well out of reach for terrestrial experiments

DARK MEDIATORS

- Good news: generic GUT-scale origin gives an accessible range of ϵ



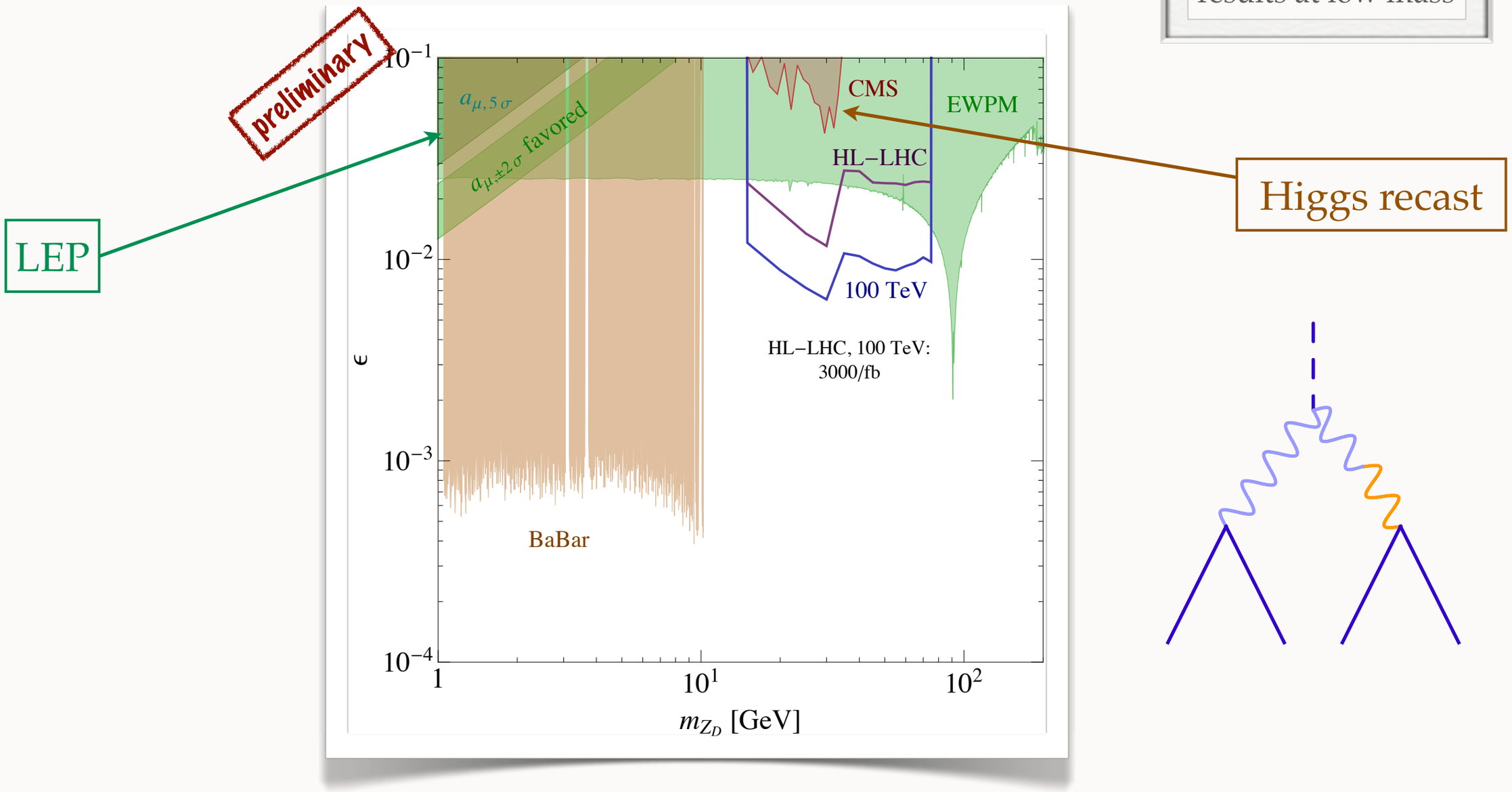
$$\propto \frac{g_Y g_D}{16\pi^2} \ln\left(\delta_{GUT}\right) \sim 10^{-6}\text{—}10^{-3}$$

- Bad news: other scenarios can motivate smaller values

KINETIC MIXING

- Limits from high energy colliders

see talks by Patel and Soffer for results at low mass



[Exotic Higgs Working Group (Curtin, JS, et al.); Curtin, Essig, Gori, JS; Falkowski, Vega-Morales]

KINETIC MIXING

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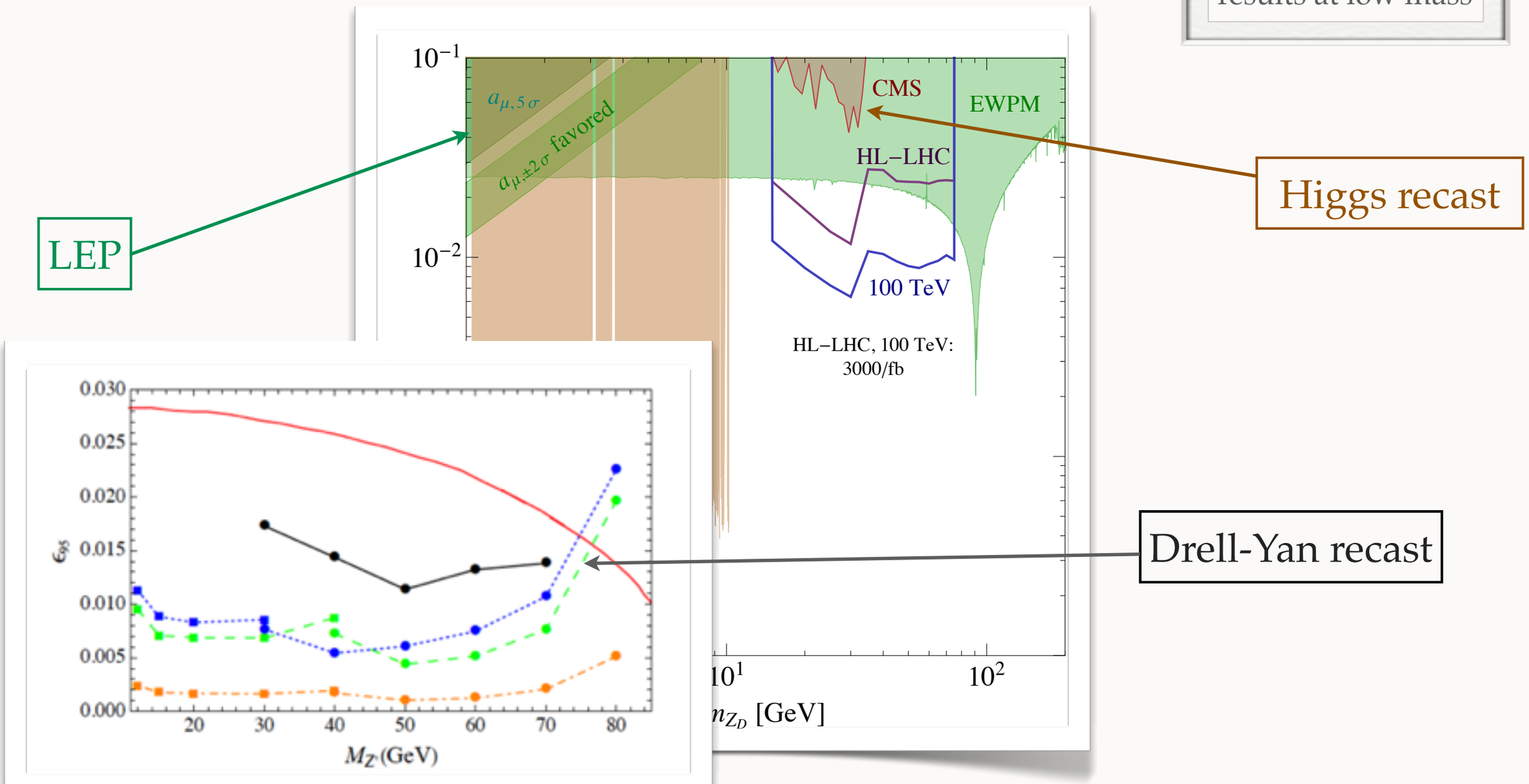
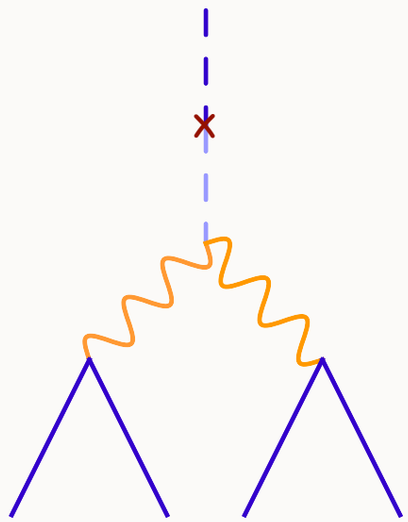


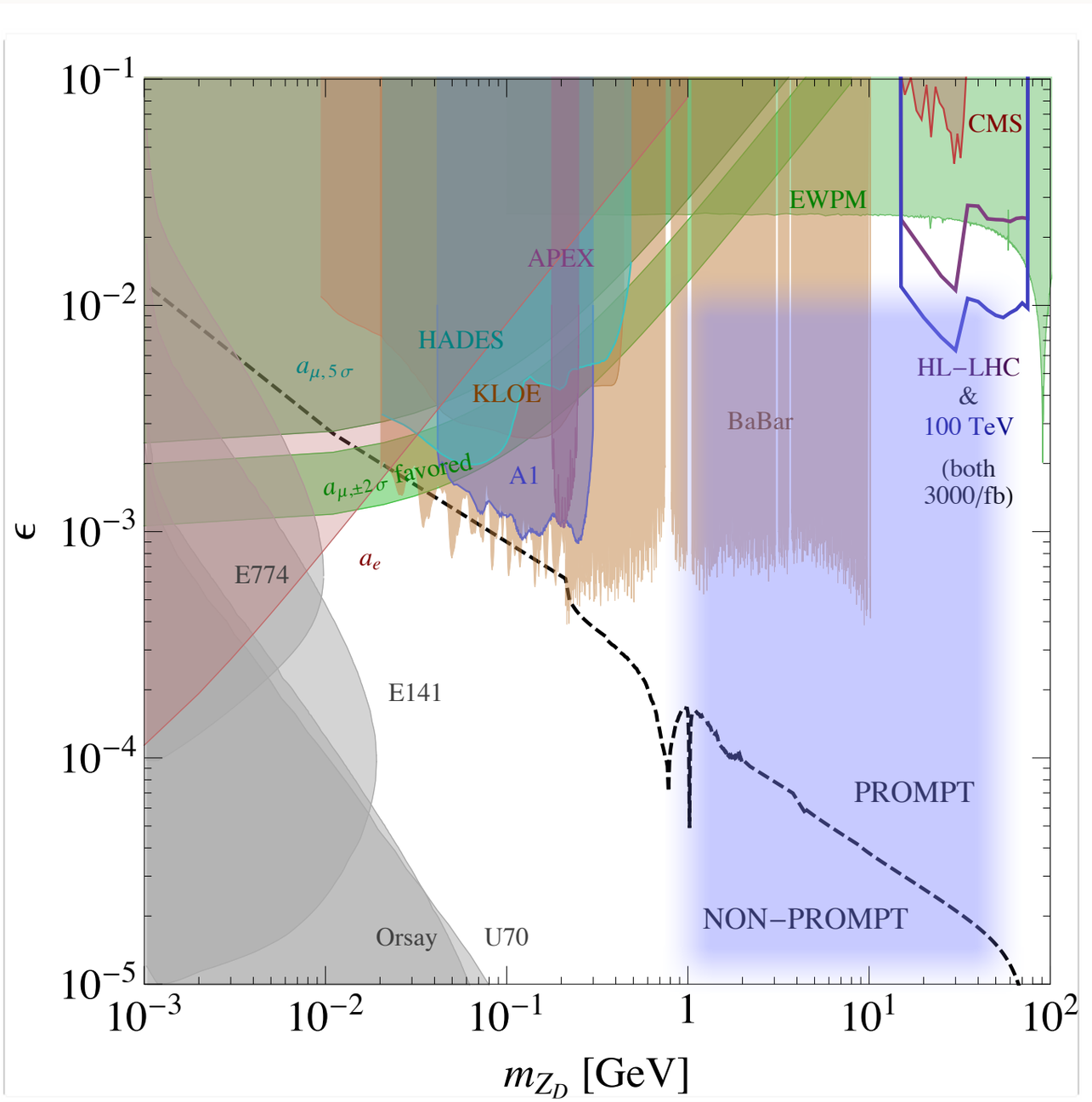
[Hoenig, Samach, Tucker-Smith]

KINETIC MIXING

- Another window

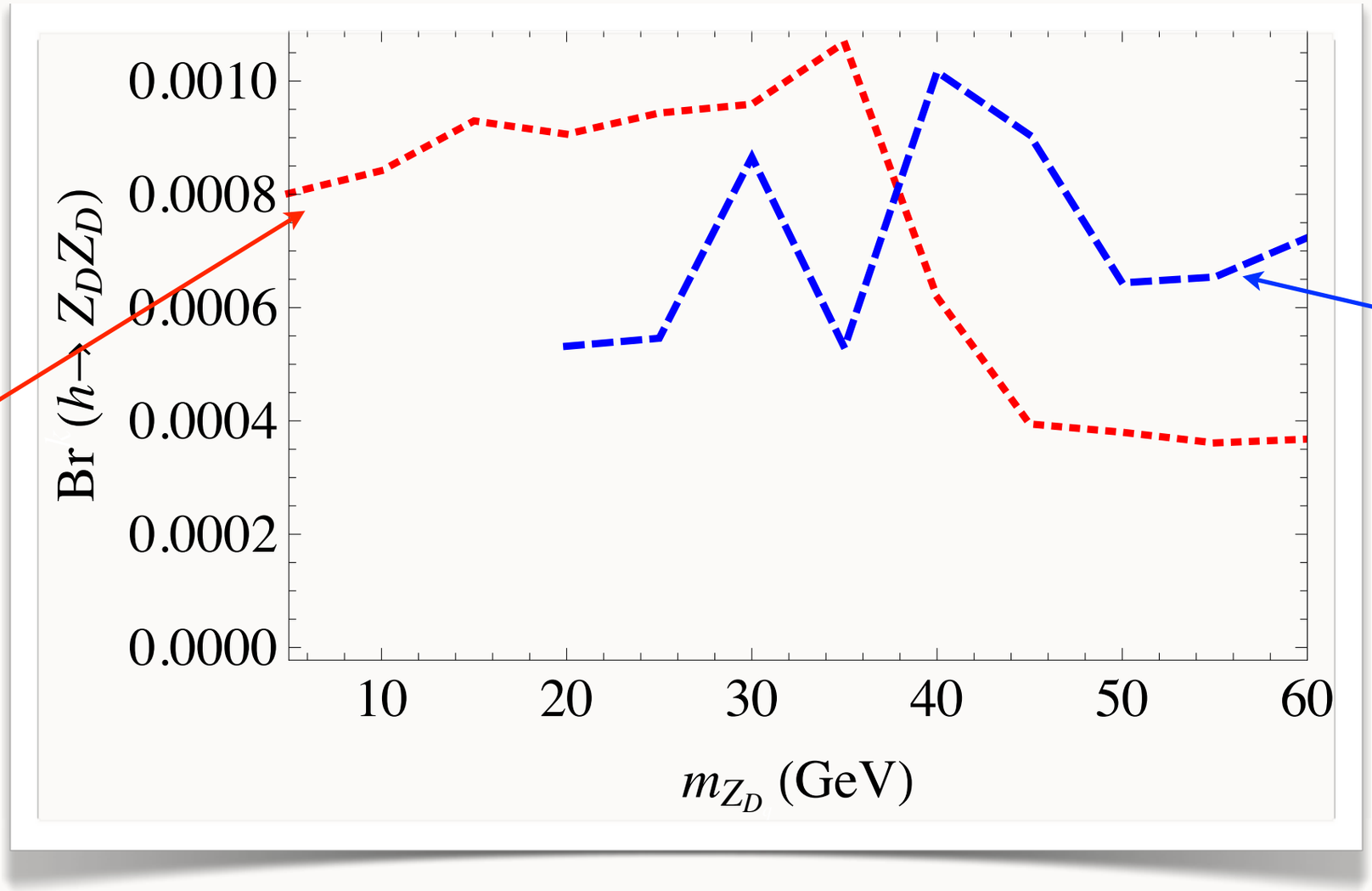
Higgs portal coupling: separate window into dark sector





HIGGS MIXING

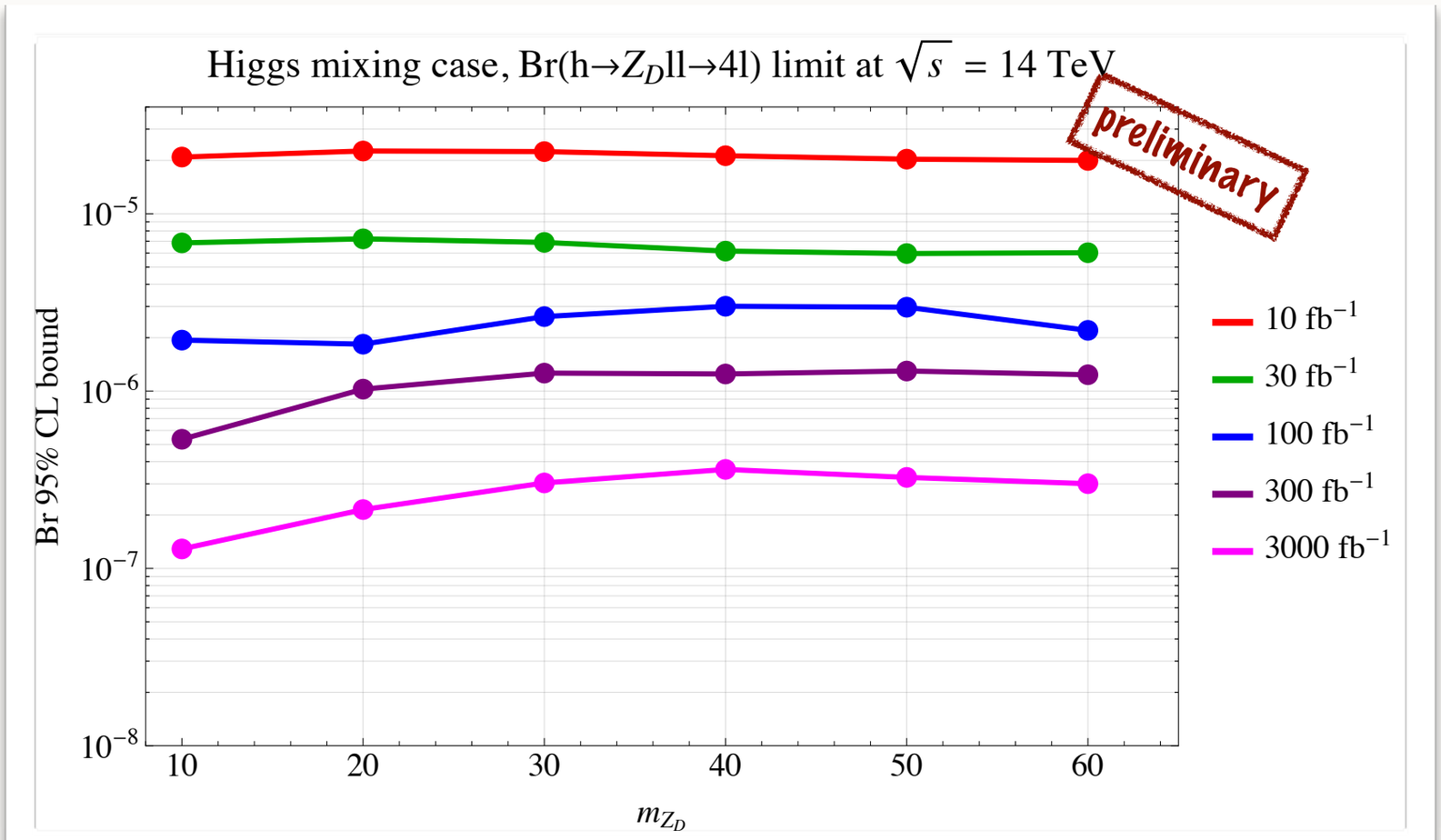
- Current limits on $h \to Z_D Z_D$ from recasting 8 TeV data



[Exotic Higgs Working Group (Curtin, JS, et al.)]

HIGGS MIXING

- Extremely clean signal: good estimator of best-case Higgs portal reach at hadron machines



[Curtin, Essig, Gori, JS]

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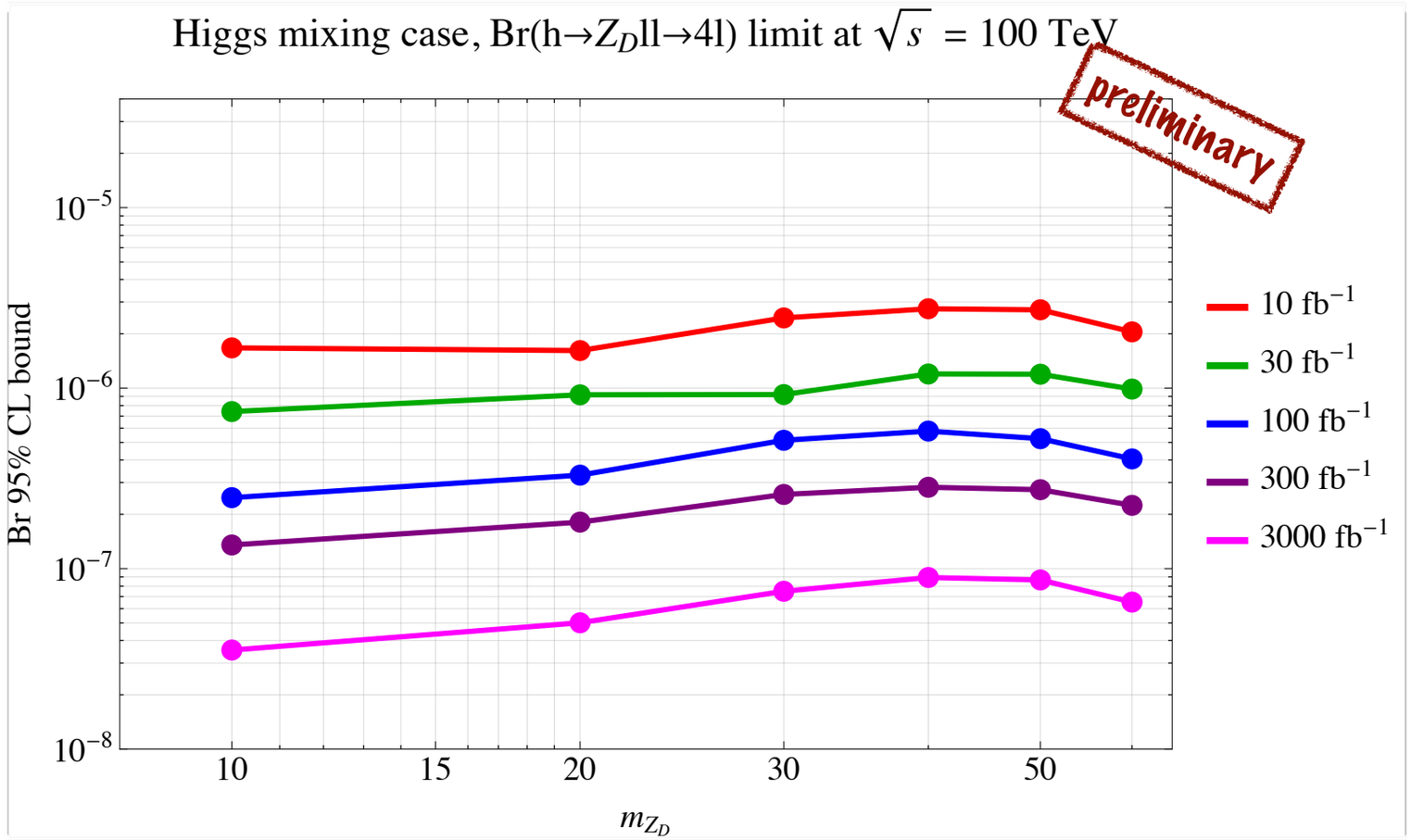
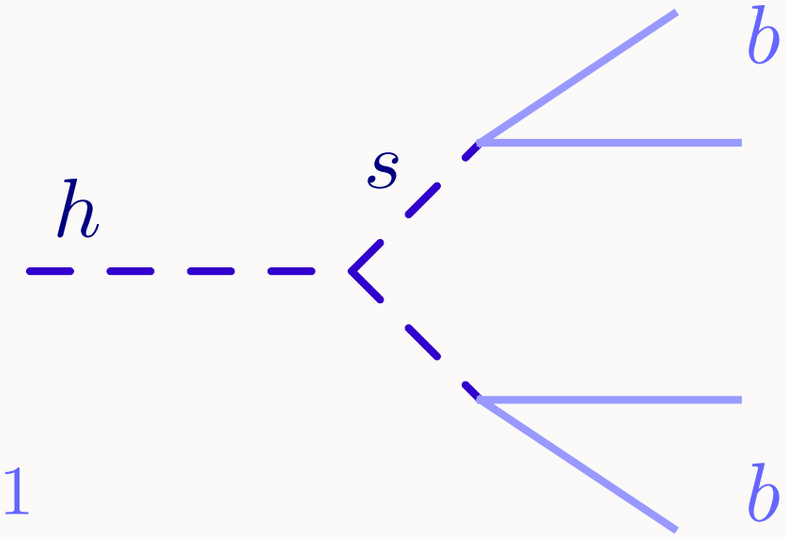


[Curtin, Essig, Gori, JS]

BOUNDS ON HIGGS MIXING

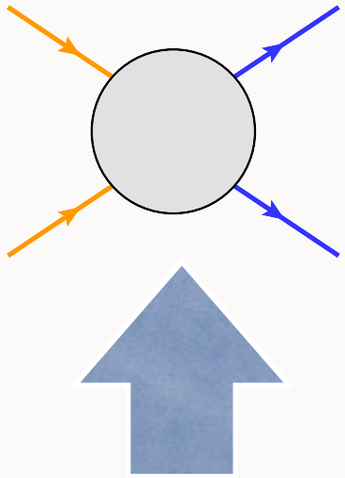
- Unfortunately most exotic Higgs decays are a much more difficult target, especially all-hadronic
  - E.g.: $h \to ss \to 4b$
  - low-p_T jets: Wh associated production, boosts, b-tagging
  - 95% CL sensitivity: $\mathrm{Br}(h \to 4b) = 0.1$ with 300 fb^{-1} at 14 TeV

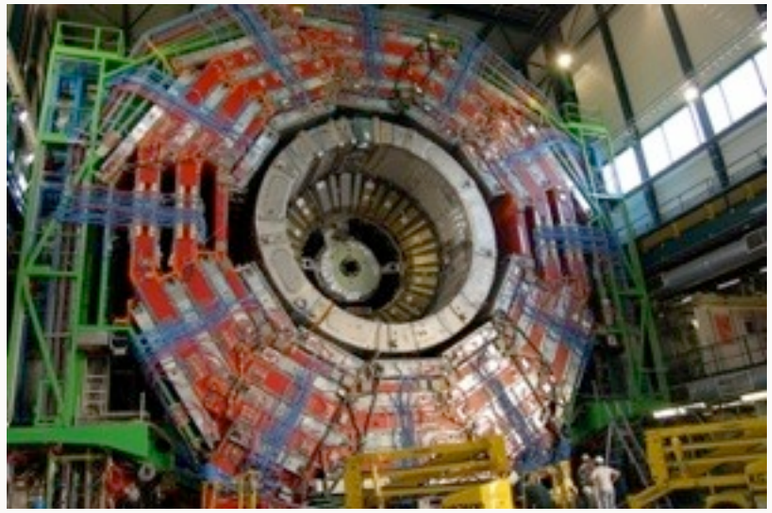


[Cao, Ding, Han, Yang, Zhu; Kaplan, MacAvoy; ...]

INTERPLAY

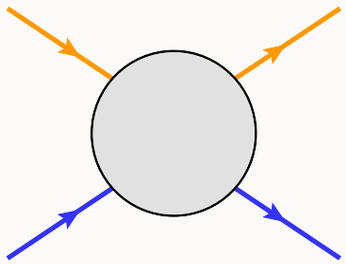
indirect detection



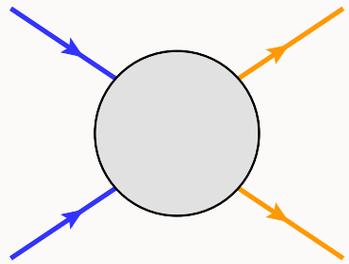


$\Omega_{DM}h^2$

direct detection

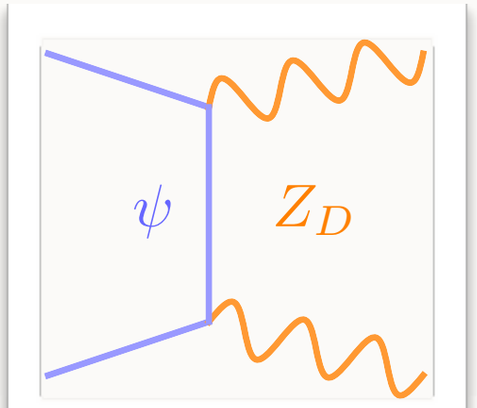


colliders



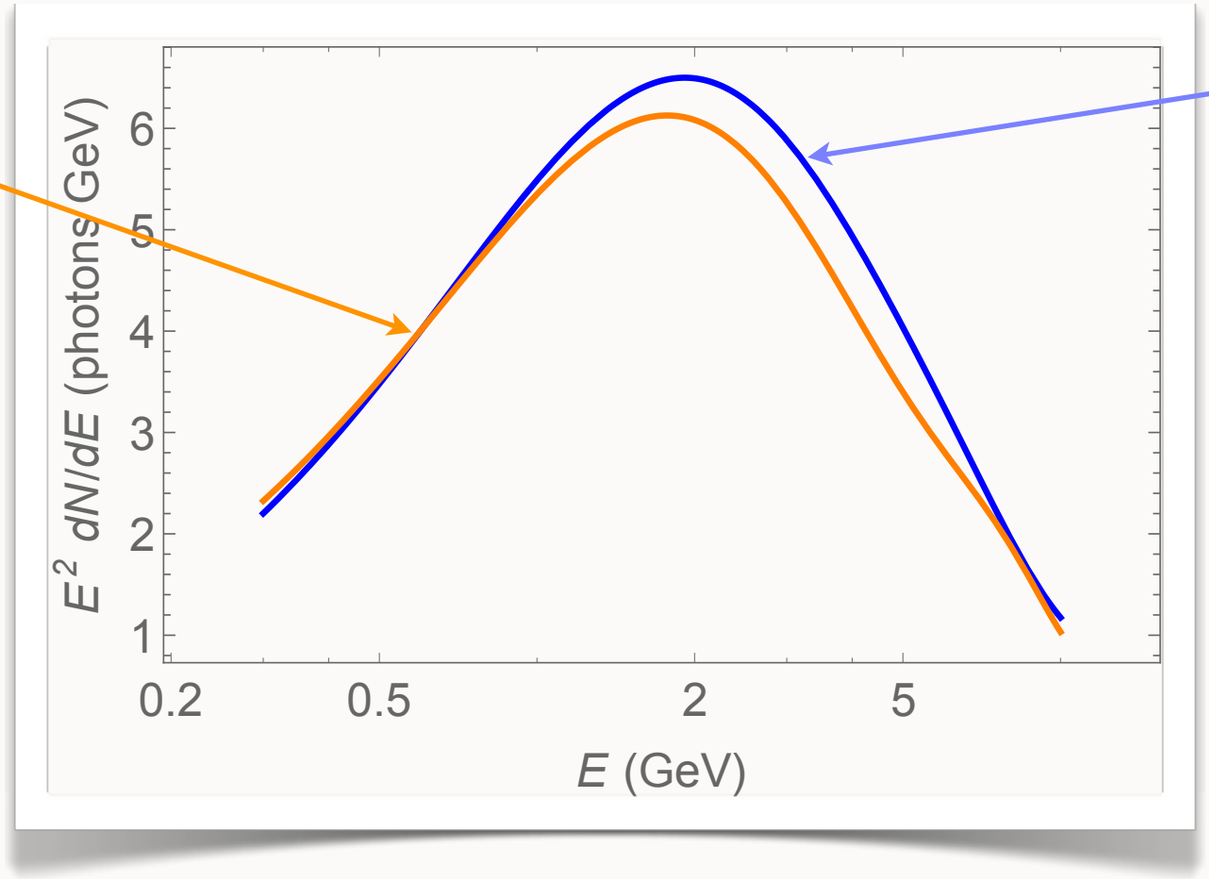
DARK FREEZEOUT (I)

- A simple model of dark freezeout:
  - two state hidden sector: ψ , Z_D
  - (HS Higgs mechanism)
  - s-wave thermal freezeout sets α_D
  - kinetic mixing allows Z_D to decay promptly on cosmological times



DARK FREEZEOUT (I)

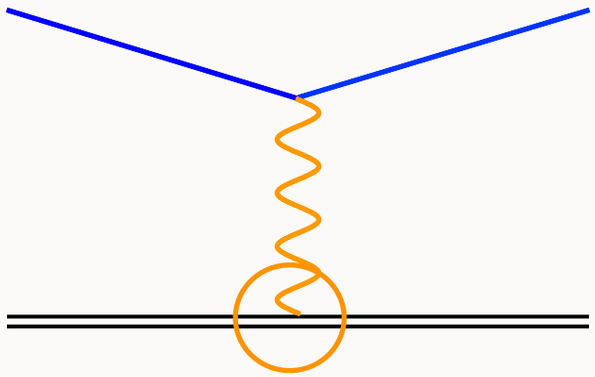
- Indirect detection
  - thermal cross-section (*bb*, *WW*) now becoming observable in gamma rays for DM masses ~10s of GeV

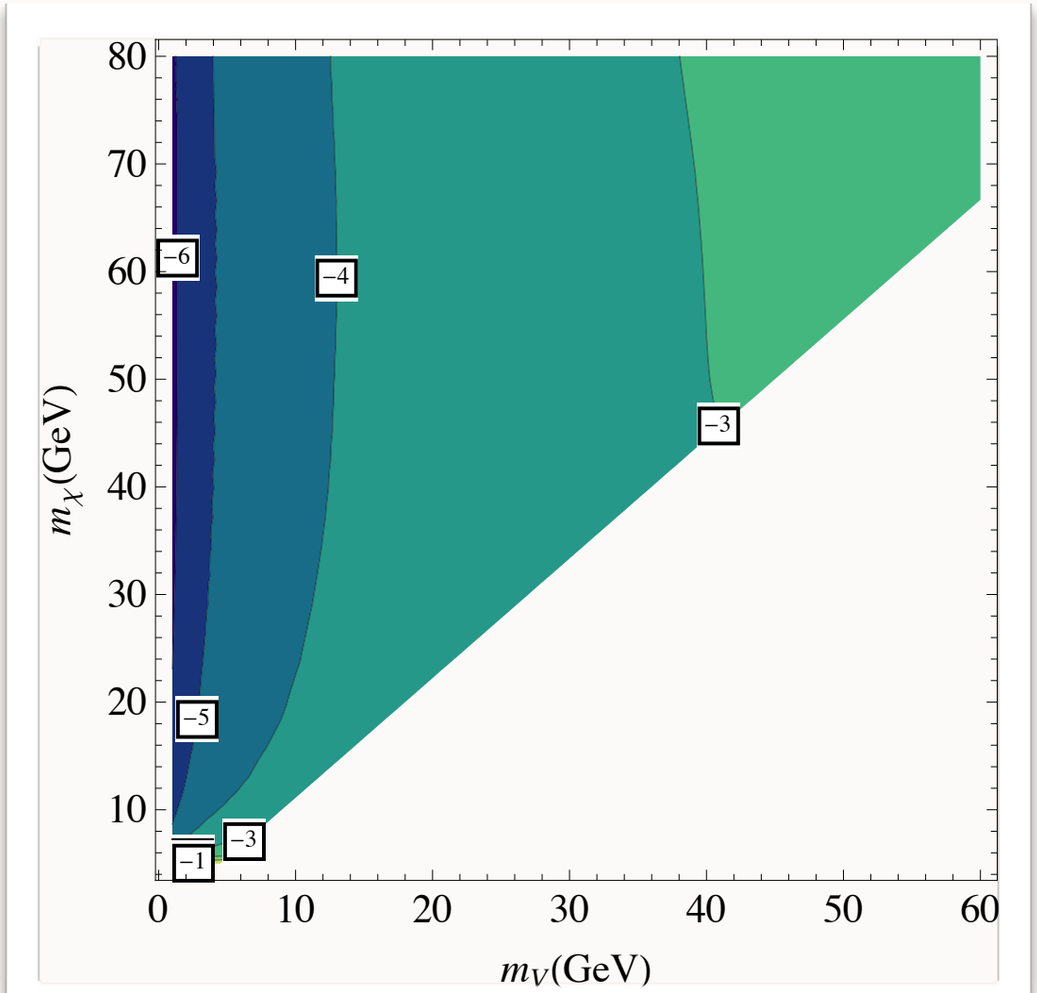


[Martin, JS, Unwin]

DARK FREEZEOUT (I)

- Direct detection
  - given α_D , LUX constrains kinetic mixing



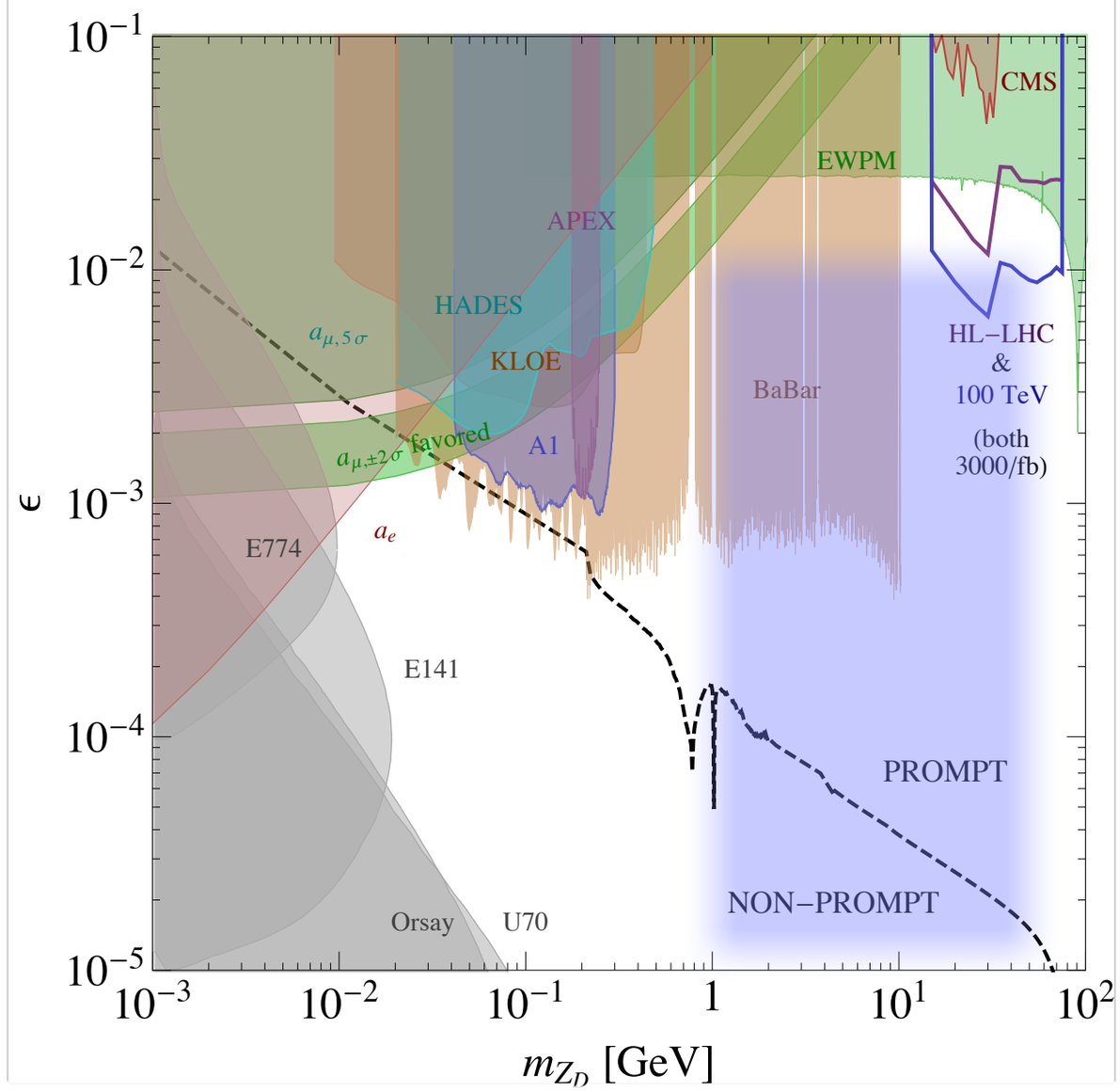


$\log_{10} \epsilon$

[Martin, JS, Unwin]

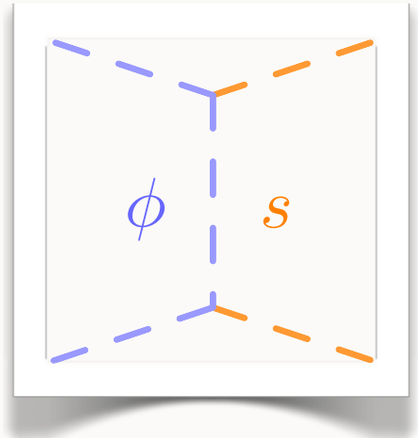
DARK FREEZEOUT (I)

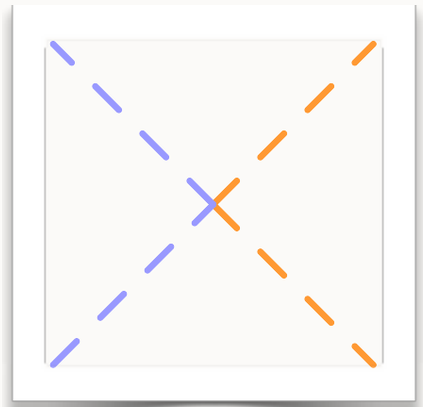
- Collider searches
  - Recall: LHC searches less sensitive than LUX in this mass range



DARK FREEZEOUT (II)

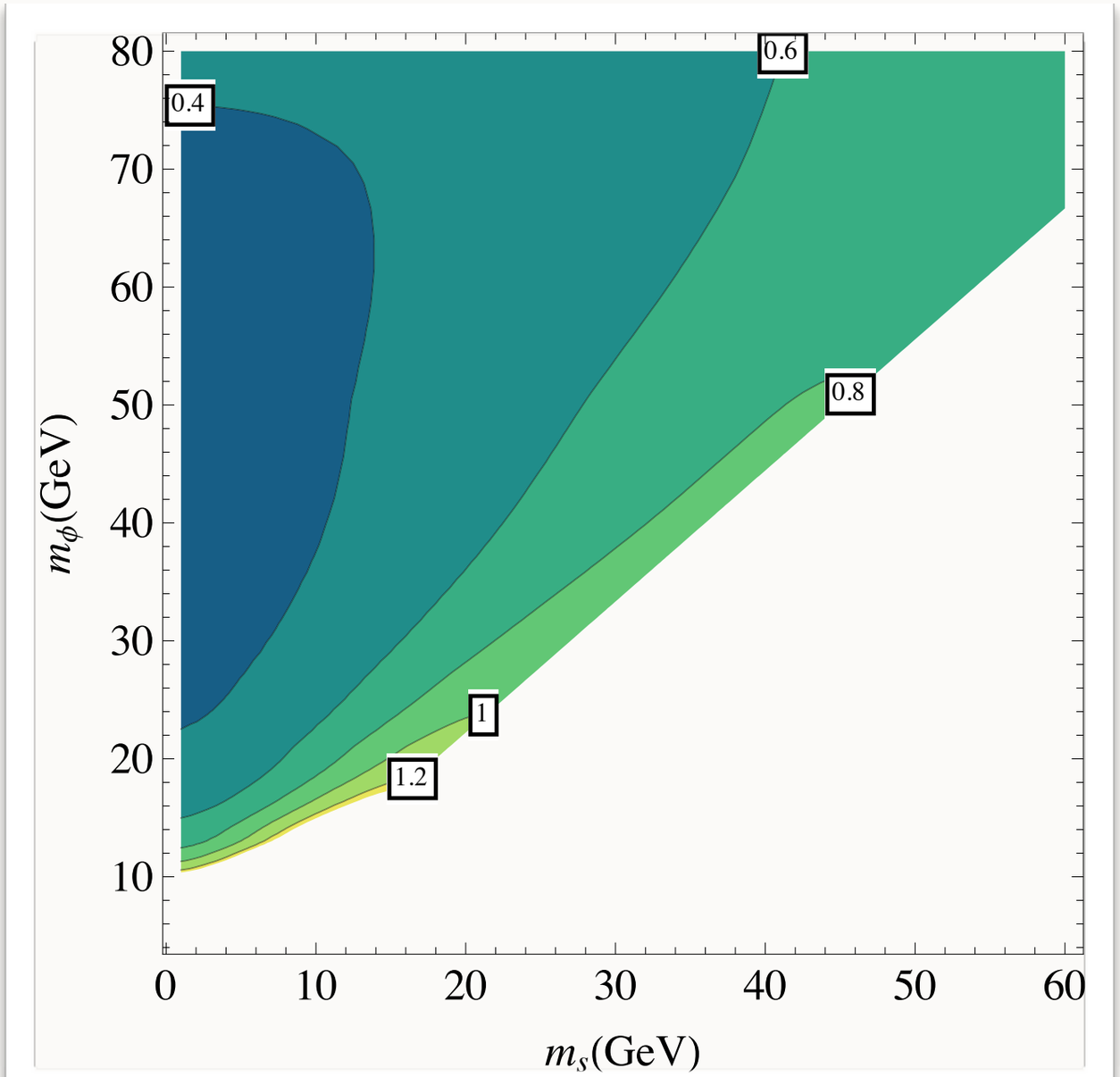
- Higgs portal mediators are a different story
  - again, simple two-state hidden sector: ϕ, s
  - (HS Higgs mechanism)
  - s-wave thermal freezeout requires scalar dark matter
  - scalar mediator decays via Higgs portal





DARK FREEZEOUT (II)

- Direct detection
  - DM-nucleon scattering suppressed by small SM Yukawas
  - $\mathcal{L}_{mix} = \epsilon s^2 |H|^2$

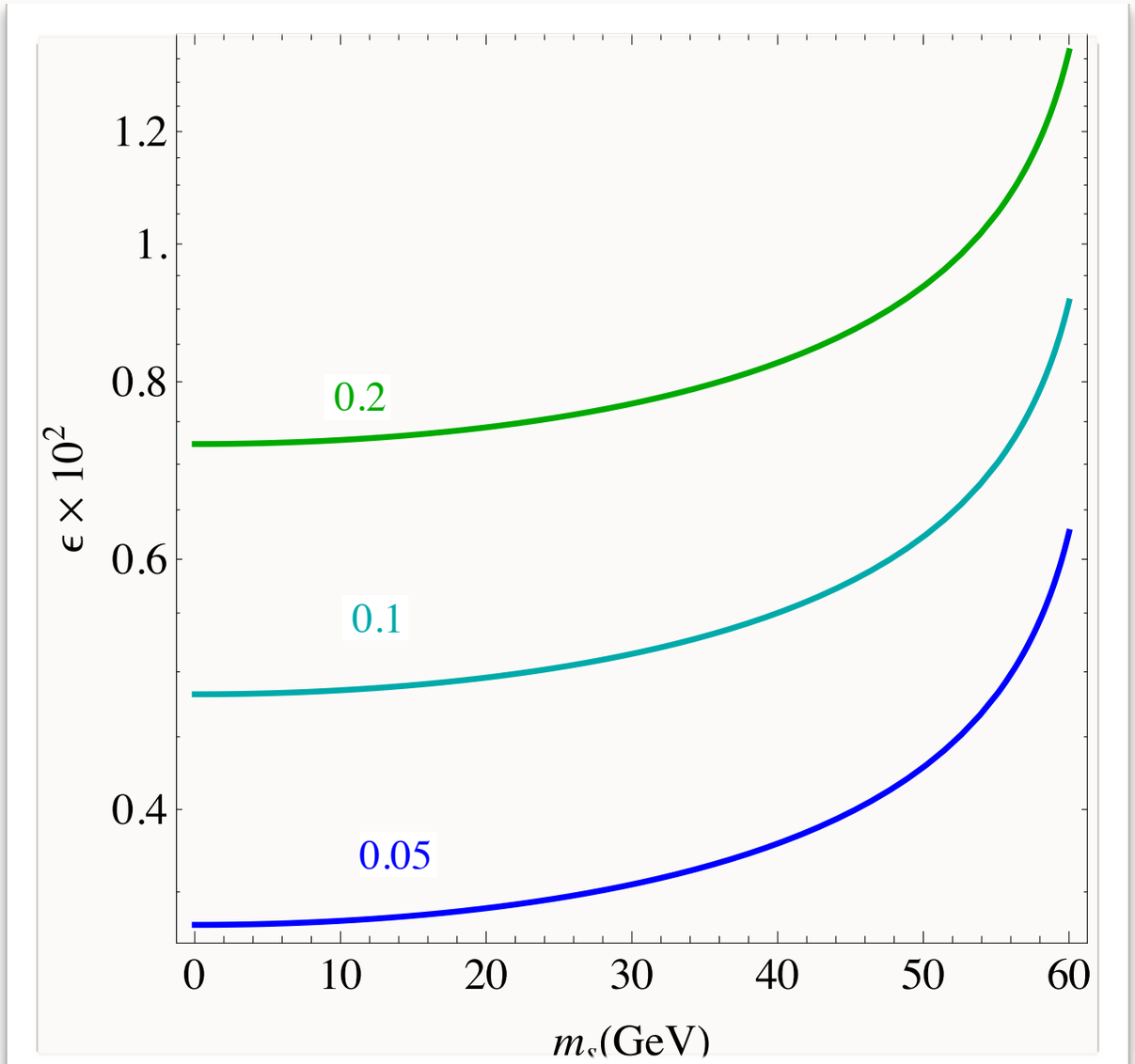


ϵ

[Martin, JS, Unwin]

DARK FREEZEOUT (II)

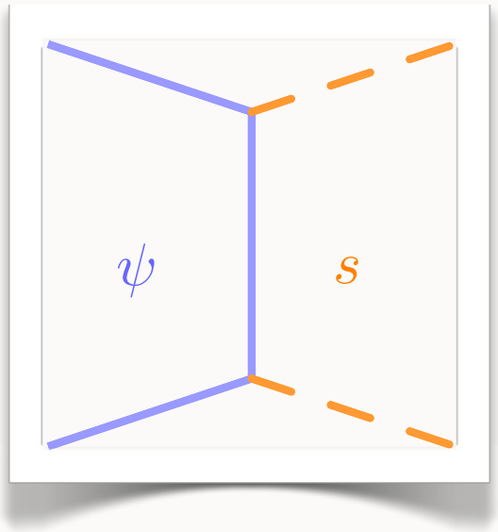
- Colliders
  - Best limits from exotic Higgs decays
  - Constraint on total exotic branching fraction assuming SM production
  - (direct observation will be hard: hadronic)
  - for $m_{DM} > m_h/2$, much harder



[Martin, JS, Unwin]

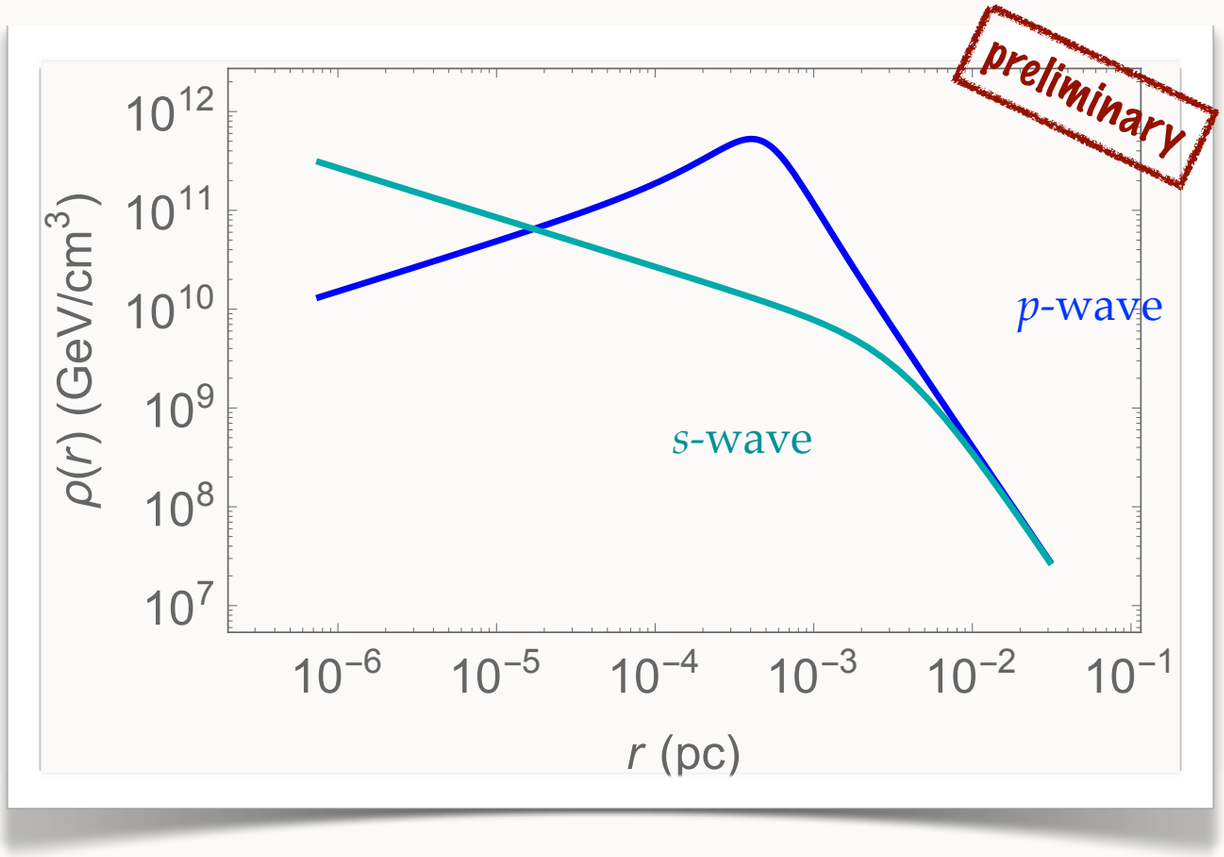
DARK FREEZEOUT (III)

- A harder set of signals:
  - consider fermionic dark matter annihilating to scalars
  - p-wave freezeout: annihilation signal from halo is gone
  - scalar mediator still via Higgs portal
  - relative sensitivities of direct detection, Higgs decays are similar



DARK FREEZEOUT (III)

- Need to think about additional signals!



adiabatic DM spikes
(Milky Way super-massive black hole)

- astrophysical uncertainties very large: galactic center environment, formation history
- velocity dispersion in spike approaches freezeout values
- potentially observable annihilation signals: point source

[Fields, Shapiro, JS]

CONCLUSIONS

- Dark freezeout is a simple scenario
  - that predicts new particles and interactions at accessible mass scales
  - but with parametrically small couplings
- Discovery reach at LHC, future hadron colliders from luminosity as well as energy
- Interplay of astrophysical and terrestrial signals
  - signals depend on: portal to SM, mass scale