LOOKING FOR THE WIMP NEXT DOOR

Jessie Shelton

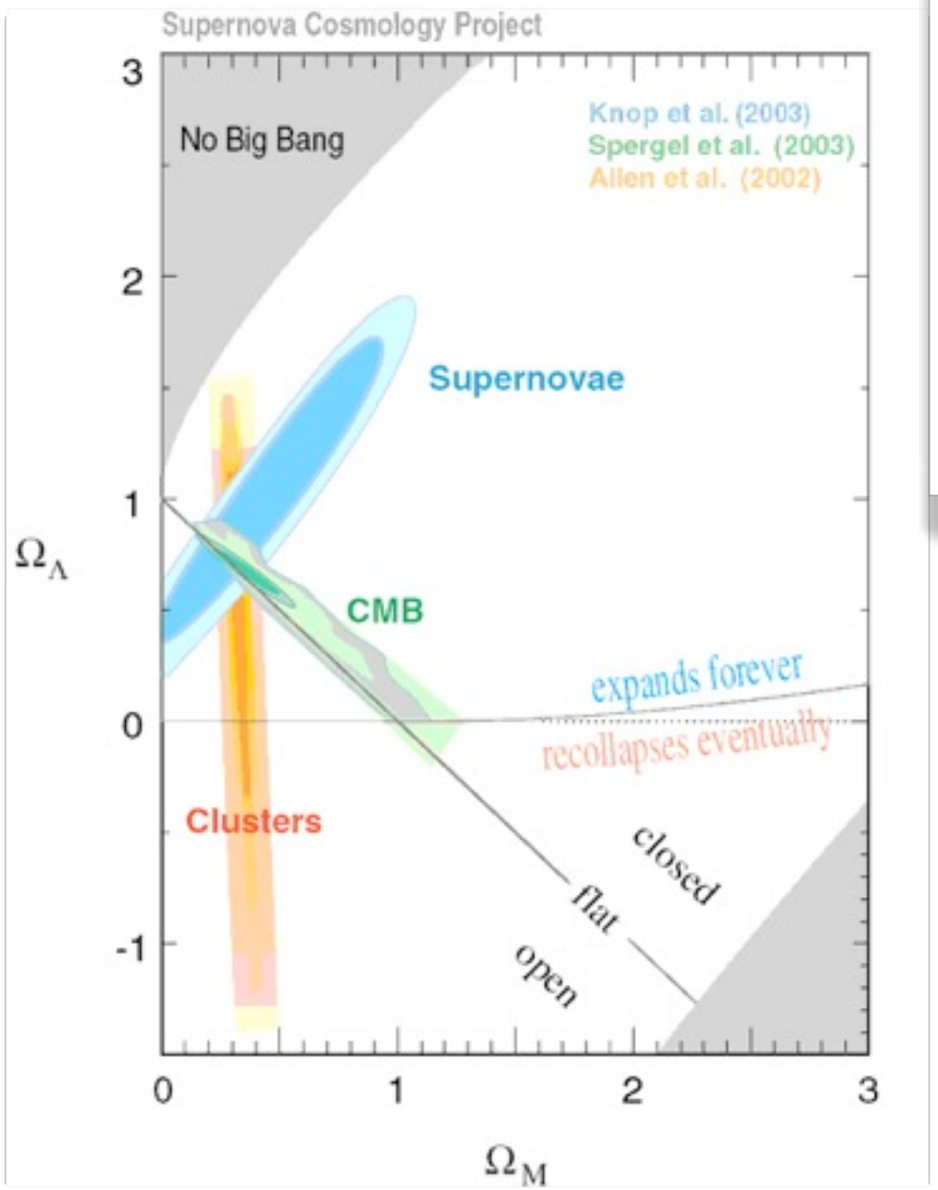
U. Illinois at Urbana-Champaign

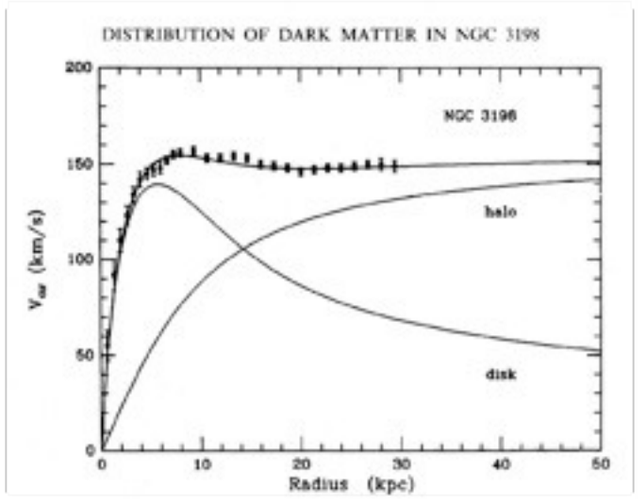
Aachen

"Future of the Search for Invisible Particles"

December 14, 2017

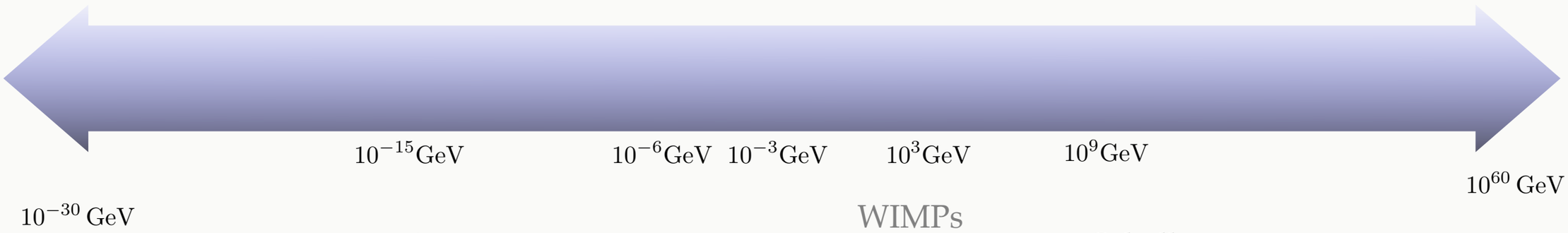
Dark matter in the universe





- ample gravitational evidence for dark matter
  - know present-day abundance
  - needs to be sufficiently cold
  - with limited self-interactions

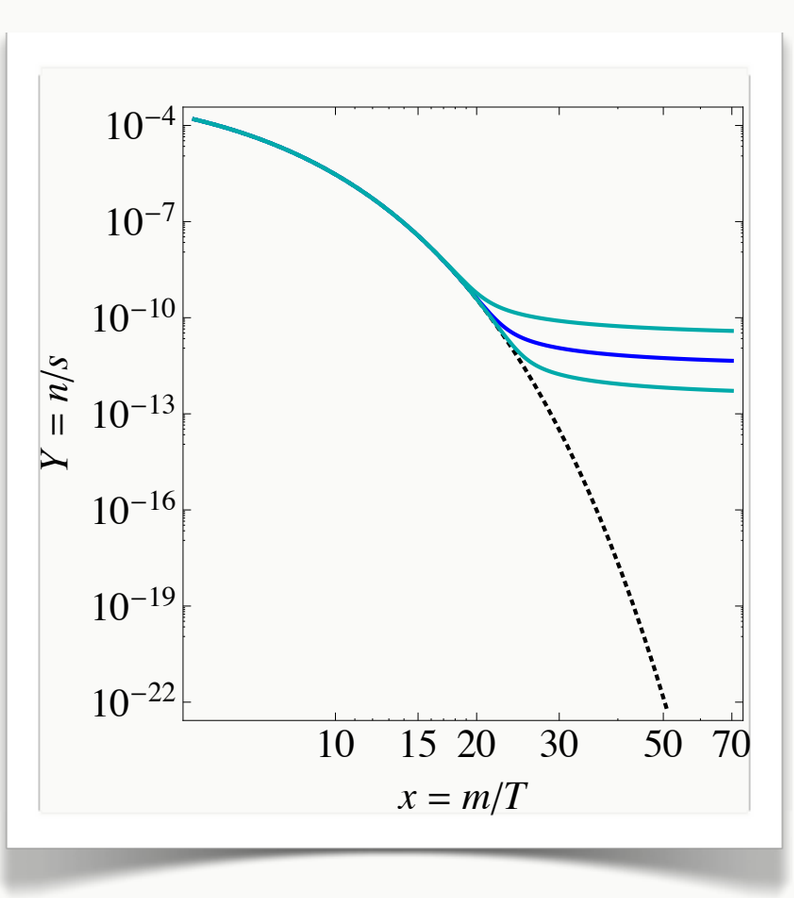
Dark matter bestiary

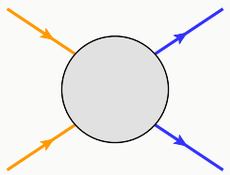


The hunt for WIMP dark matter

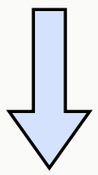
Thermal freezeout: WIMP miracle

- DM usually needs non-gravitational interactions to be populated in the early universe
- "WIMP miracle": thermal freezeout

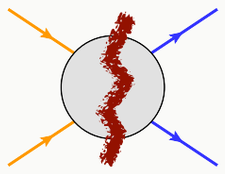




$n\langle\sigma v\rangle > H$



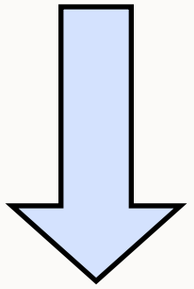
$$\Omega_{DM} \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m^2}{g^4}$$

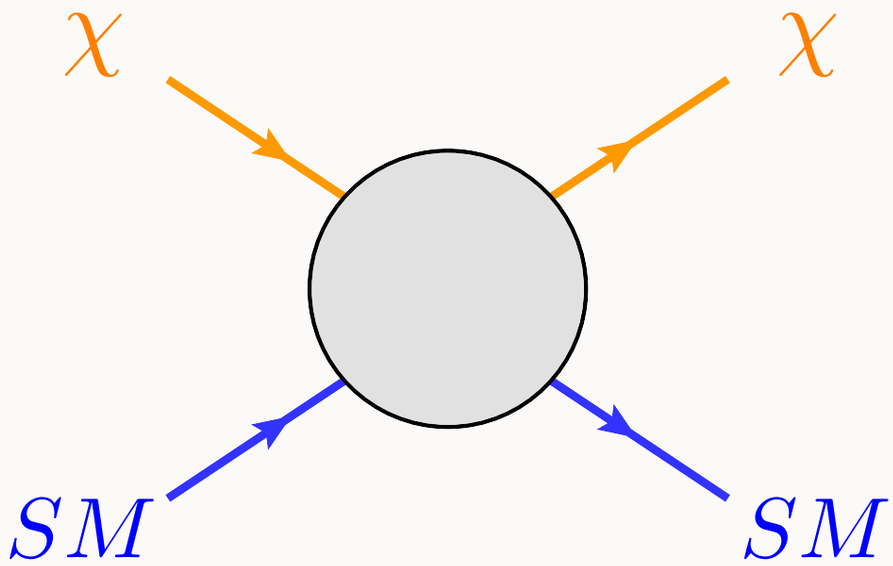


$n\langle\sigma v\rangle \ll H$

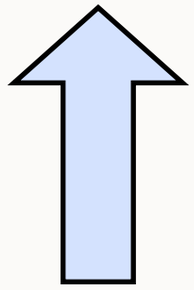
The hunt for **WIMP** dark matter

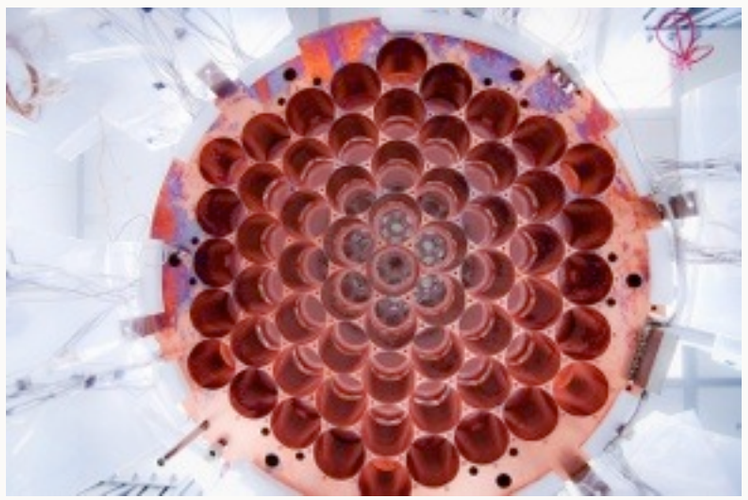
indirect detection



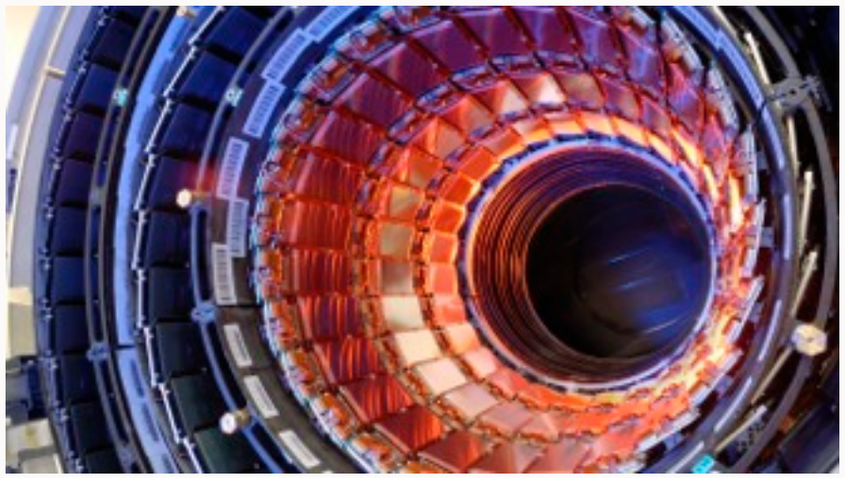


colliders



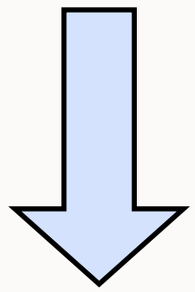


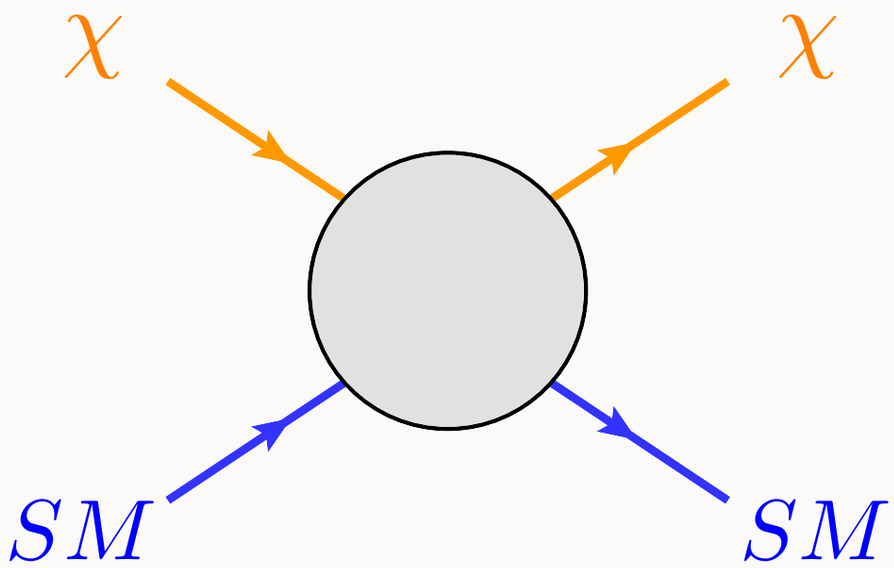
direct detection



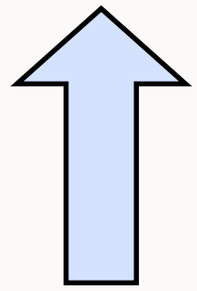
The hunt for **WIMP** dark matter

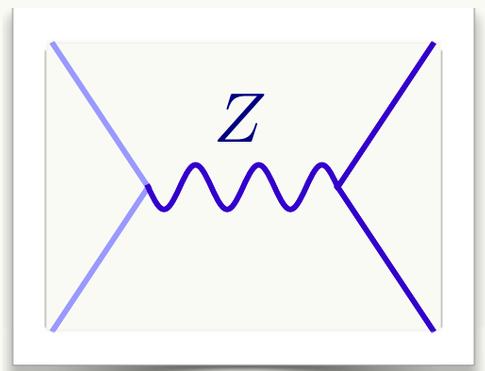
indirect detection

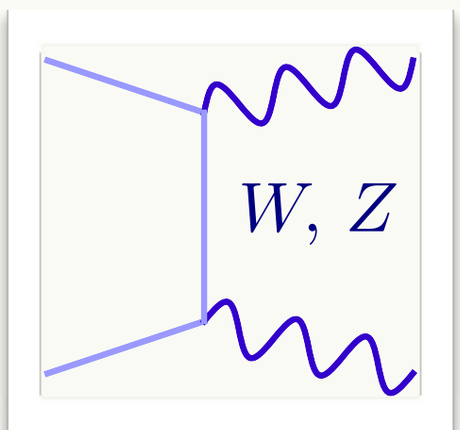


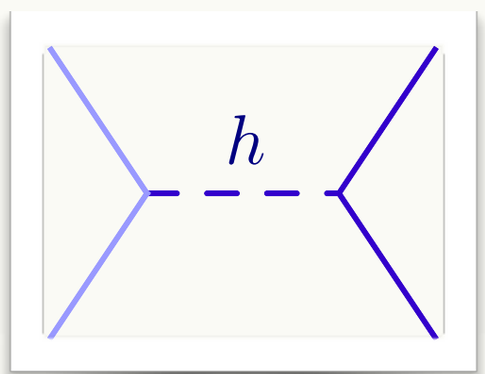


colliders



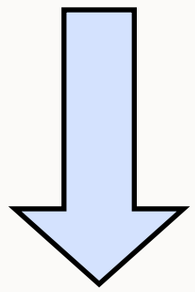


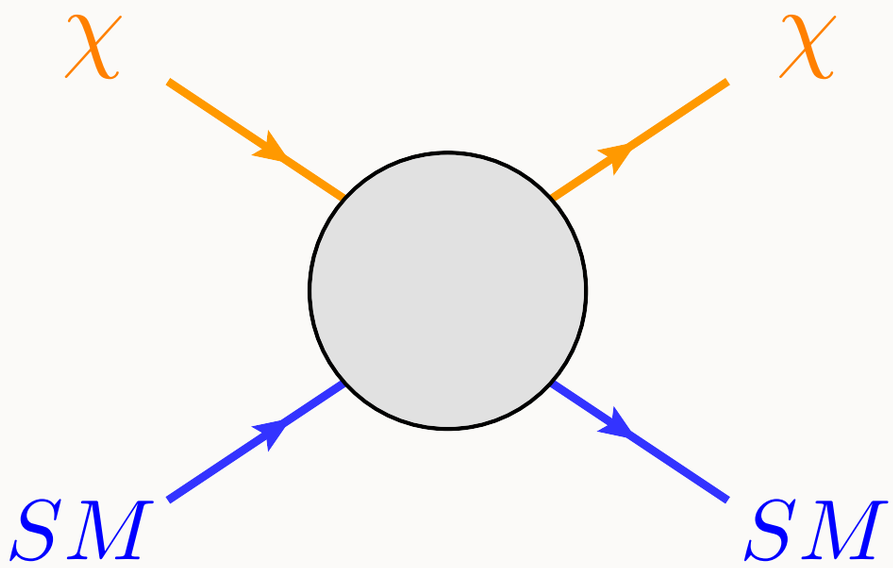




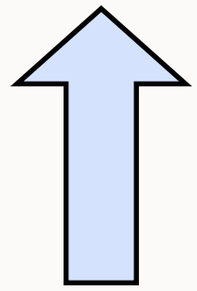
The hunt for **WIMP** dark matter

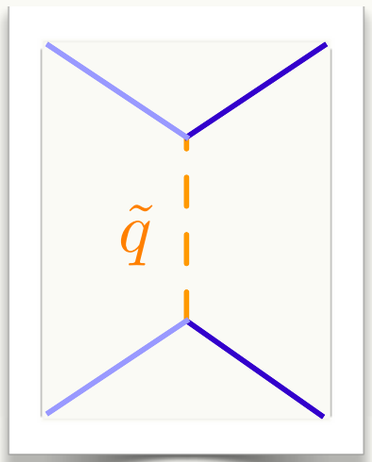
indirect detection

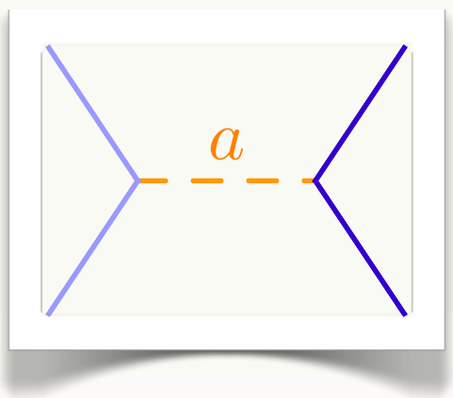


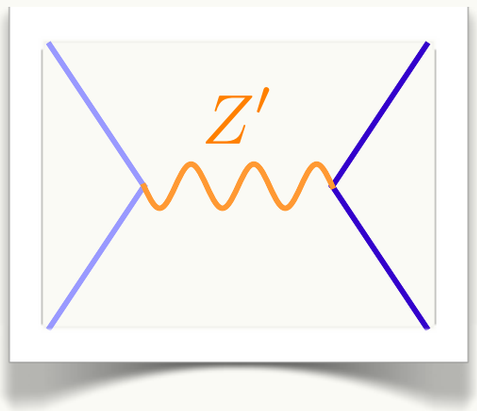


colliders

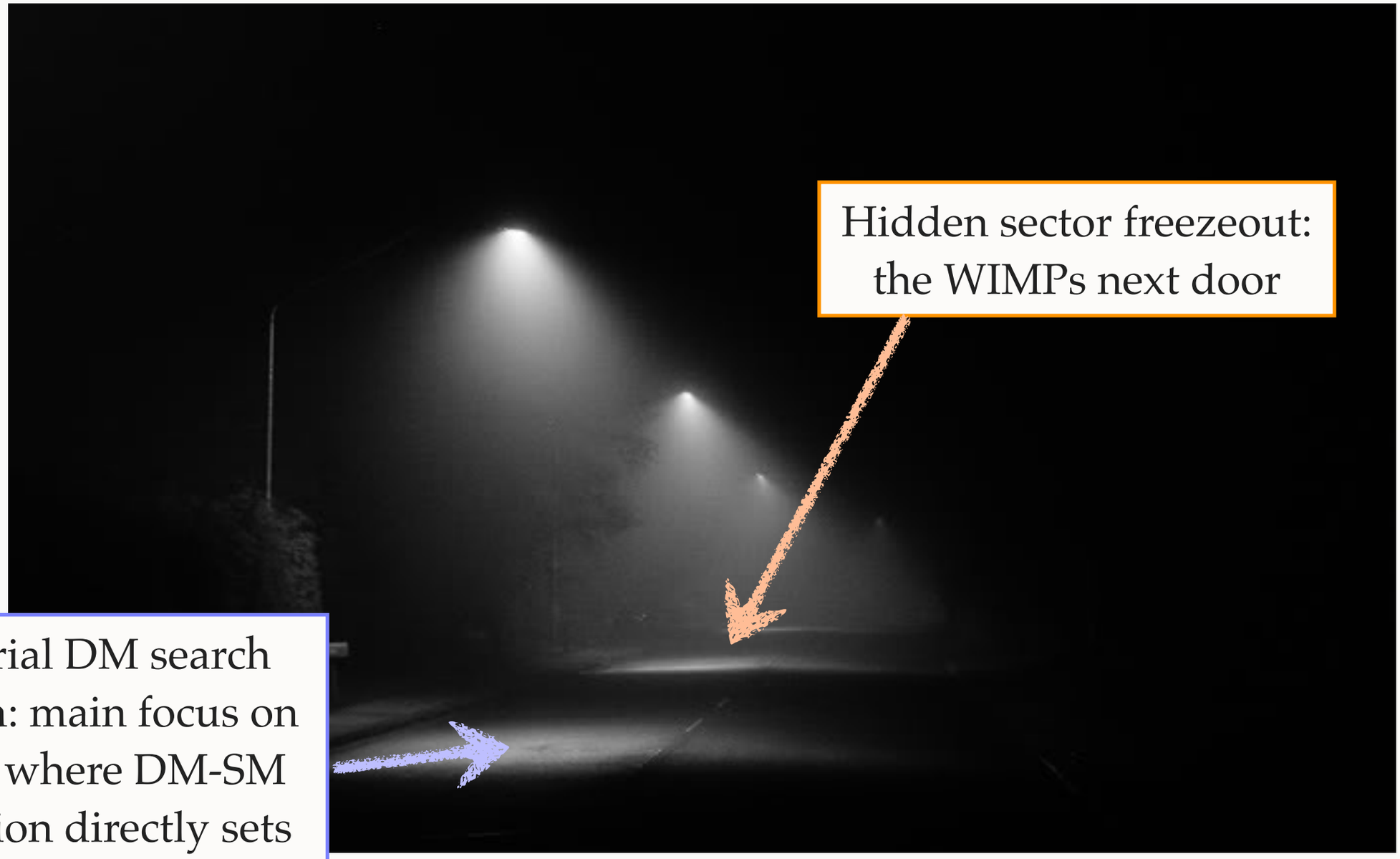








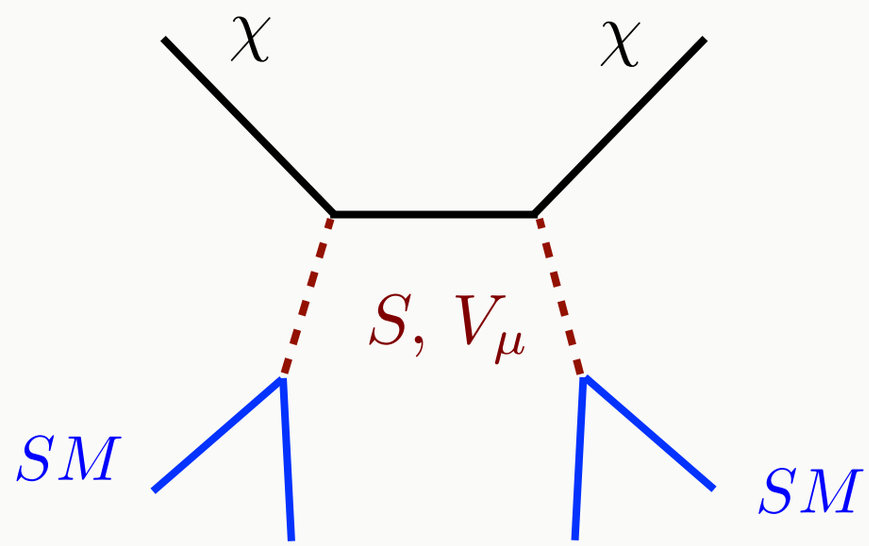
The hunt for WIMP dark matter



terrestrial DM search program: main focus on models where DM-SM interaction directly sets relic abundance

Hidden sector freezeout

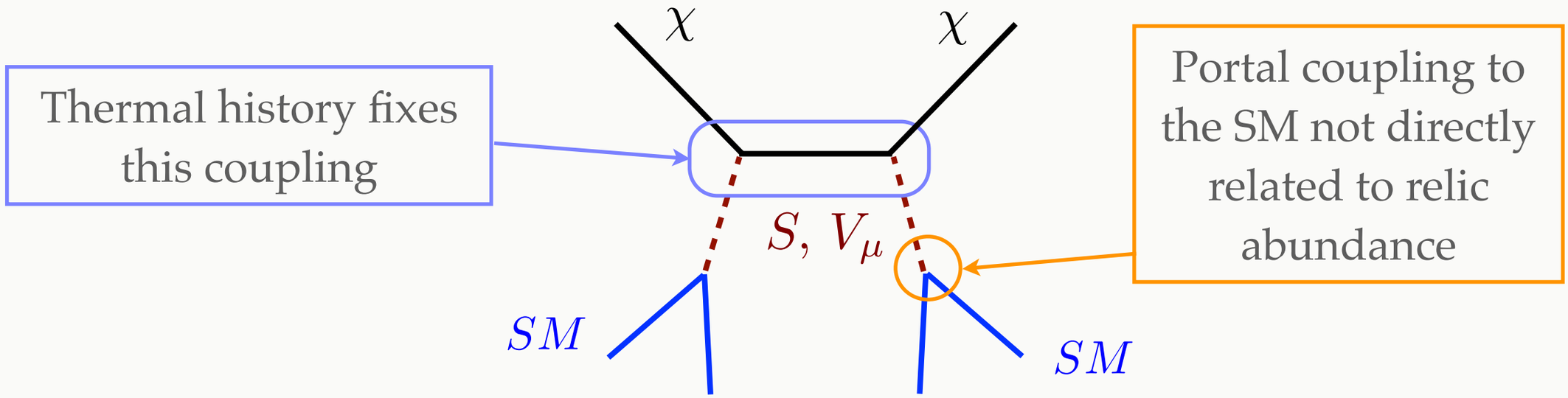
- Freezeout without the SM:



[Pospelov, Ritz, Voloshin; Feng, Kumar; Feng, Tu, Yu; ...]

Hidden sector freezeout

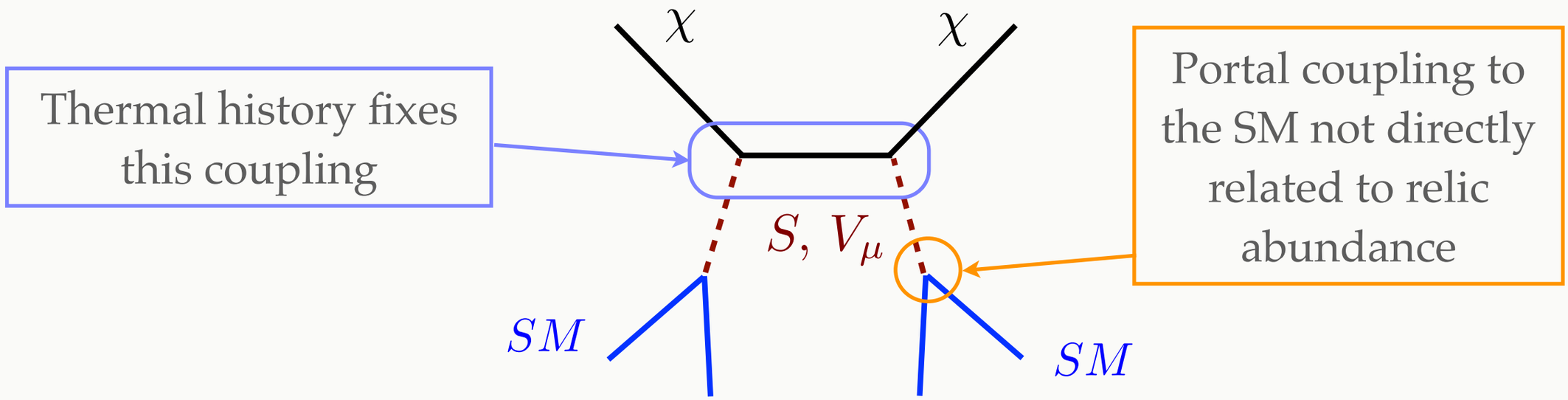
- Freezeout without the SM:



[Pospelov, Ritz, Voloshin; Feng, Kumar; Feng, Tu, Yu; ...]

Hidden sector freezeout

- Freezeout without the SM:



- Minimal models described by four parameters:

$$m_\chi,\ m_{med}, \epsilon, \alpha_D$$

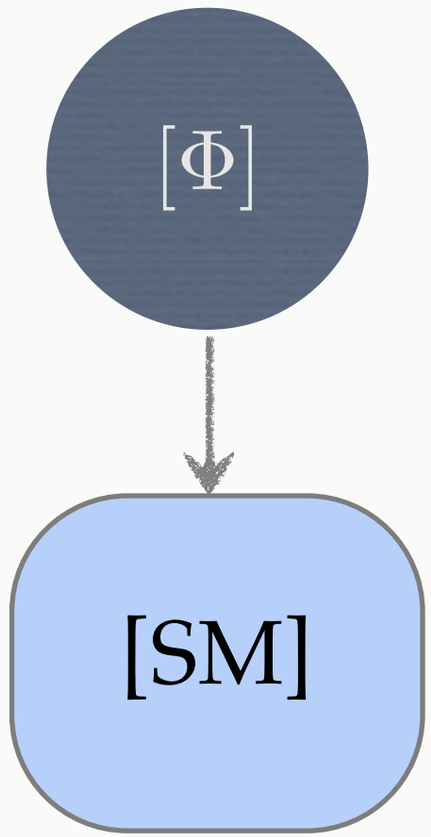
  - ϵ is a priori free and can be parametrically tiny
  - cosmic constraints (e.g. BBN) on ϵ mostly terrestrially irrelevant

[Pospelov, Ritz, Voloshin; Feng, Kumar; Feng, Tu, Yu; ...]

Where did we get dark matter?

- But how did this dark sector get populated?
- Thermal WIMP cosmology is simple:

New physics responsible for reheating populated SM in early universe

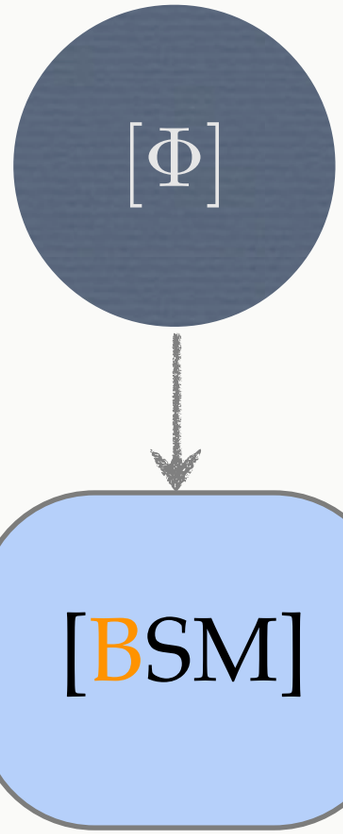


Thermal SM radiation bath: BBN (T~MeV)

Where did we get dark matter?

- But how did this dark sector get populated?
- Thermal WIMP cosmology is simple:

New physics responsible for reheating populated SM in early universe

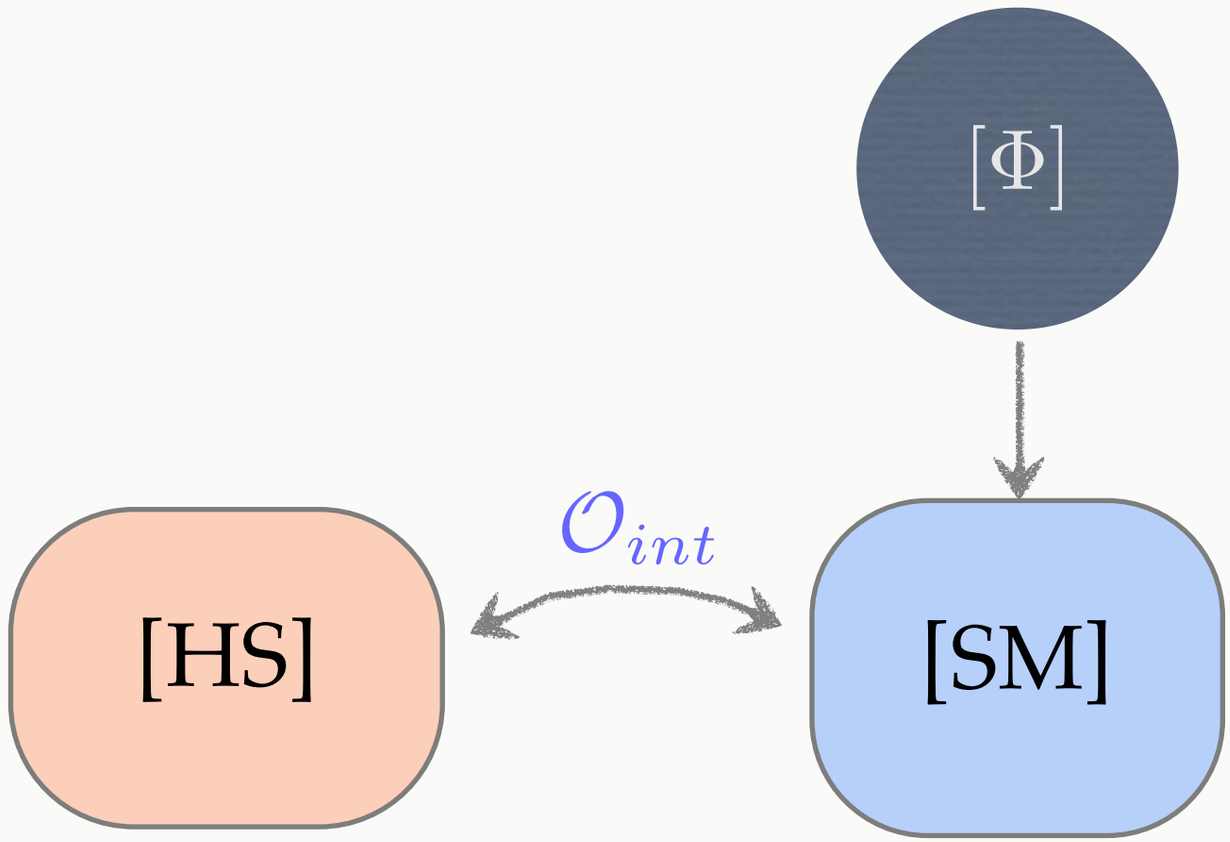


Additional species in radiation bath undergo interactions that yield right Ω_{DM} : freezeout

Thermal SM radiation bath: BBN (T~MeV)

Where did we get dark matter?

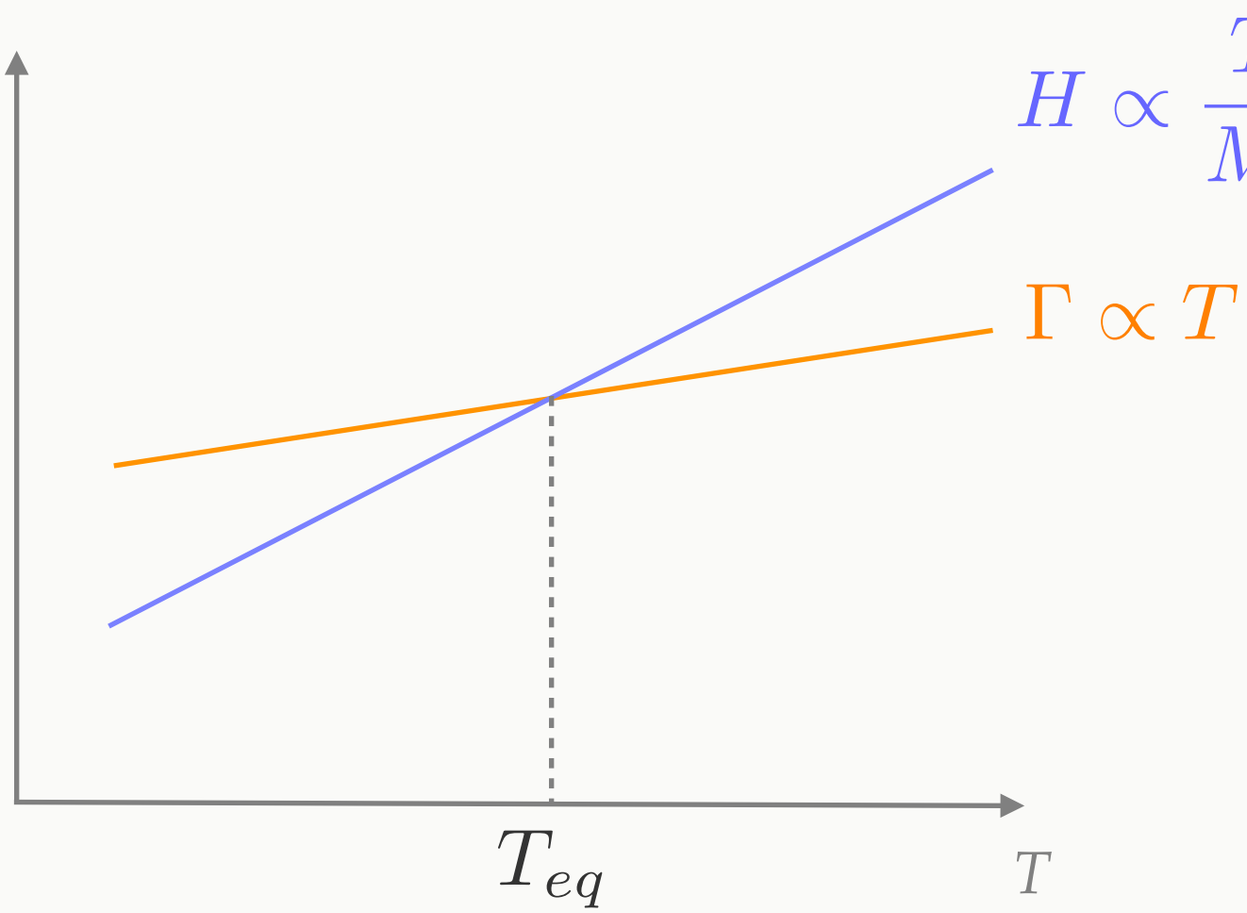
- Minimal scenario: HS thermally populated from SM

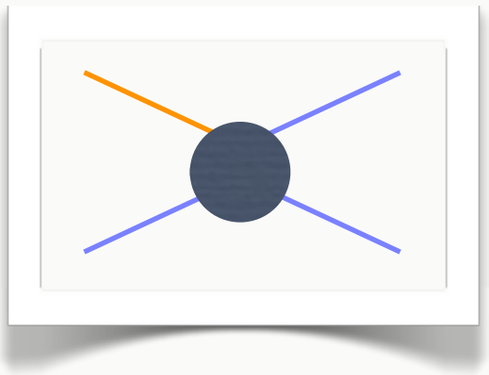


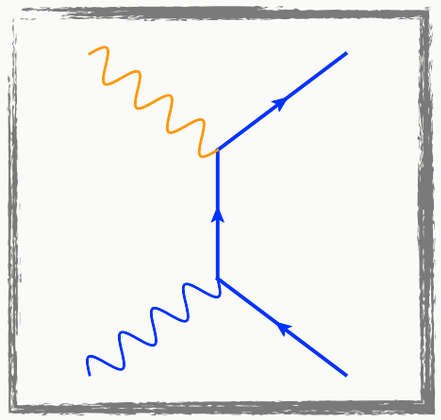
- Simple cosmology with several appealing features

Thermally coupled dark sector

- Advantage 1: insensitive to details of UV physics for natural choice of leading vector, Higgs portal interactions

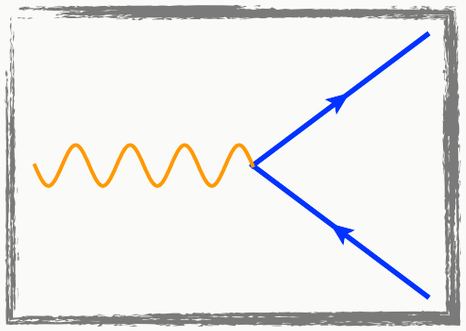


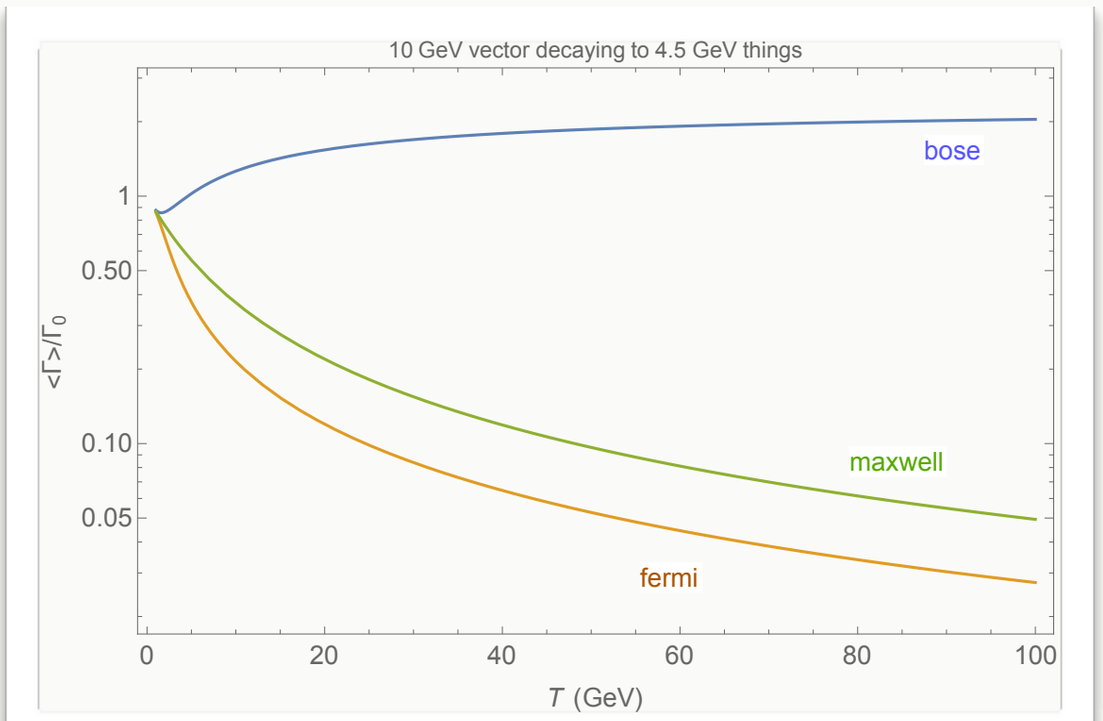




Thermally coupled dark sector

- Some fine print: this assumes T is only relevant scale
  - at $m_{med} \sim T_{fo}$ decays and inverse decays can be important compared to $2 \to 2$ scattering

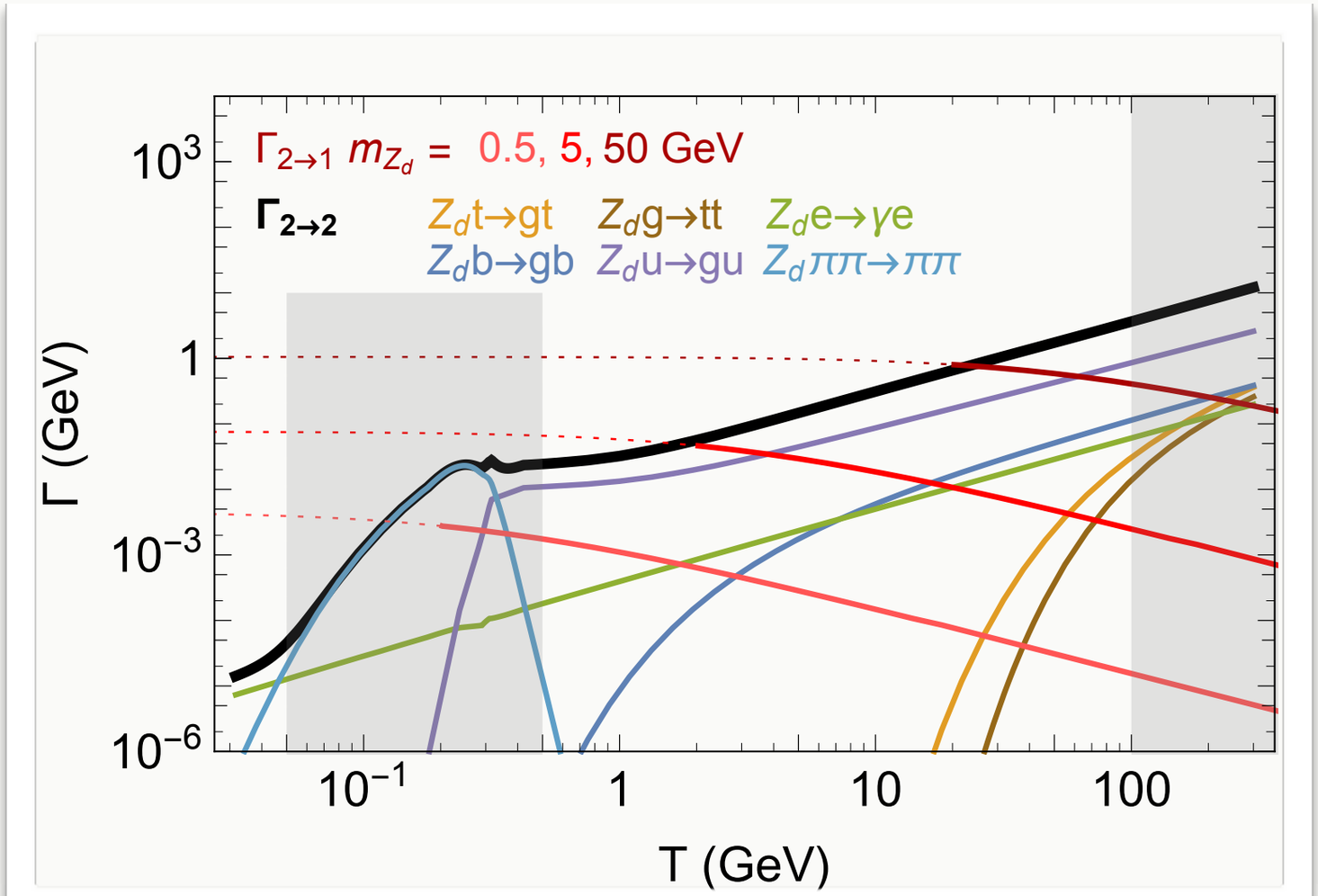




- Processes are comparable in rate for $m_{med} \sim T_{fo}$: $O(1)$ shifts in necessary ϵ

Thermally coupled dark sector

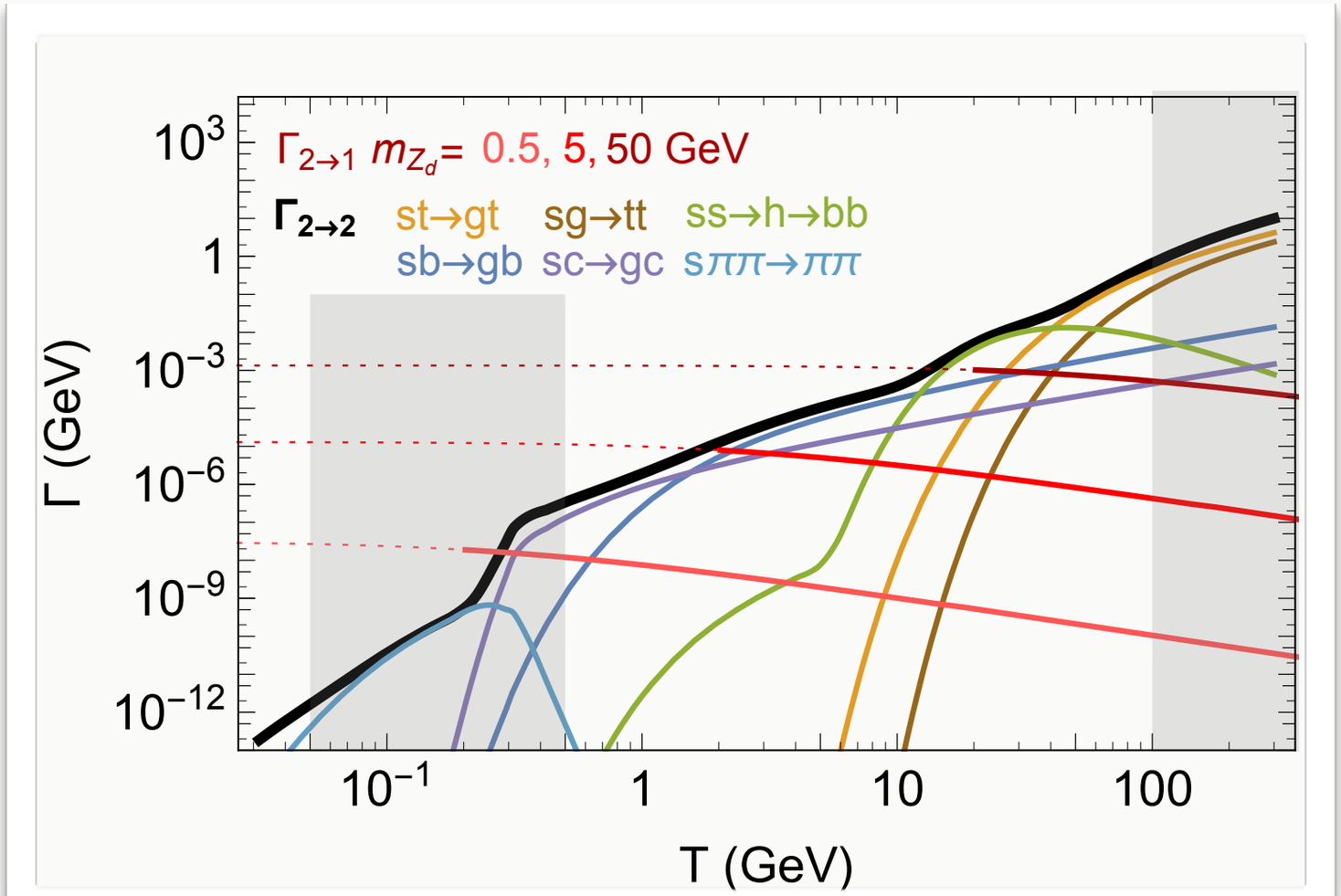
- Some of the many scattering processes contributing to equilibration:



[Evans, Gori, JS]

Thermally coupled dark sector

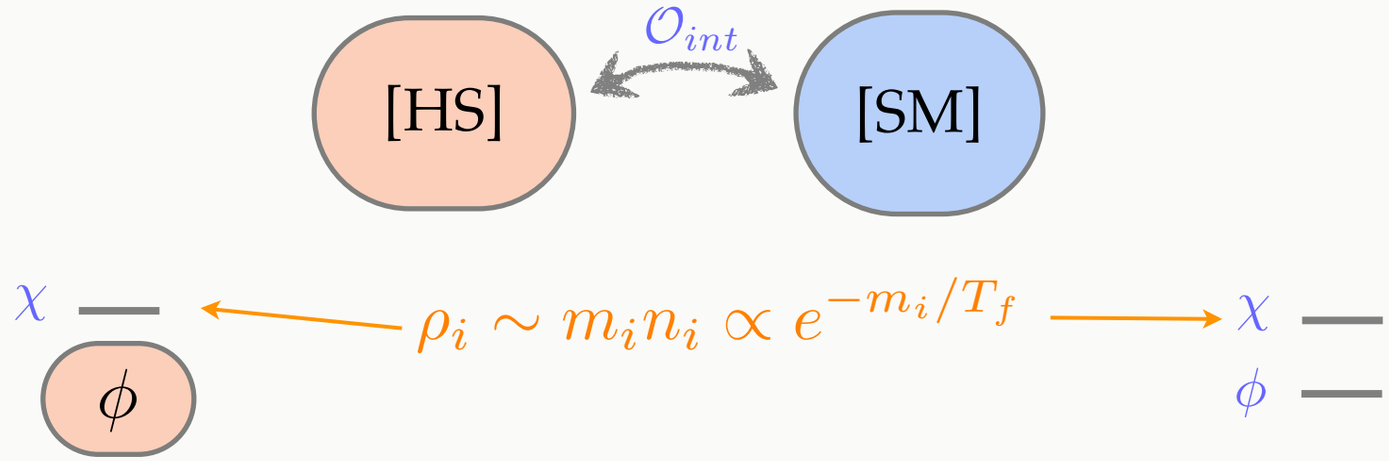
- Some of the many scattering processes contributing to equilibration:



[Evans, Gori, JS]

Thermally coupled dark sector

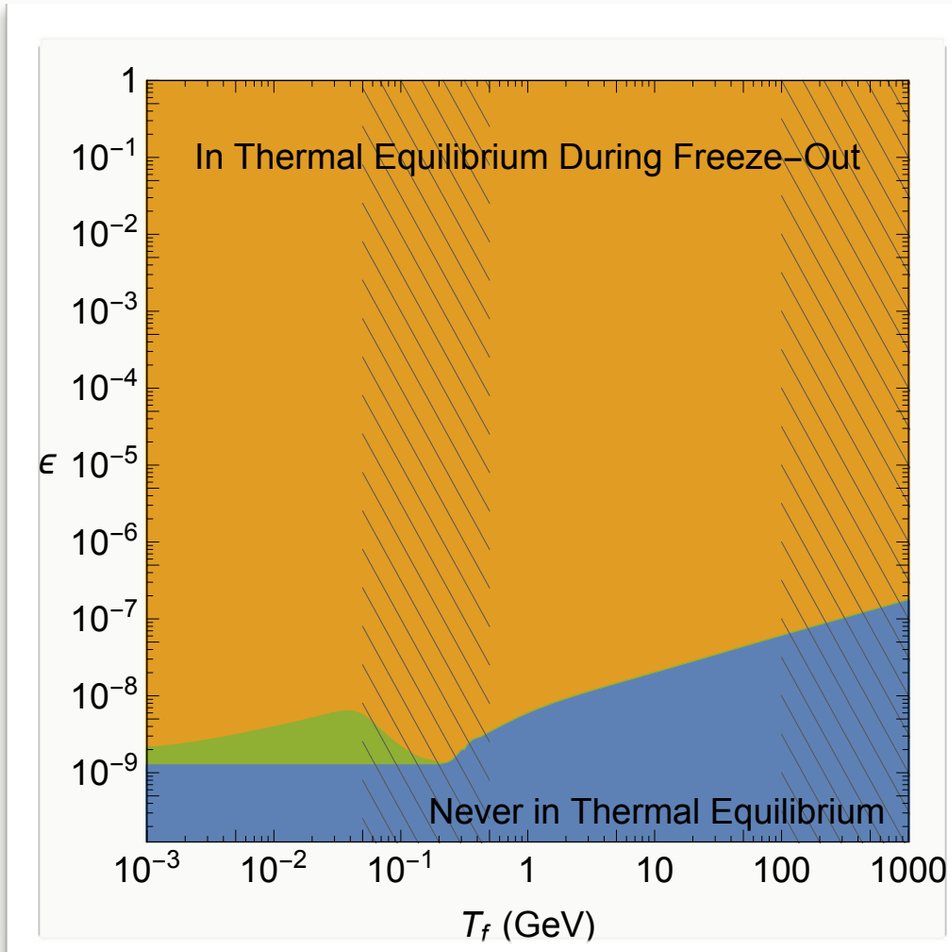
- Importance of a dark radiation bath:



- Minimality: ask mediator state to be relativistic at freezeout
  - less minimal dark sectors could make this requirement unnecessary; small quantitative shifts in thermalization floor

Thermally coupled dark sector

- Requirement of thermalization imposes a cosmological lower bound on strength of coupling to SM



- Comparing sum of scattering rates involving (mostly) SM fermions to Hubble

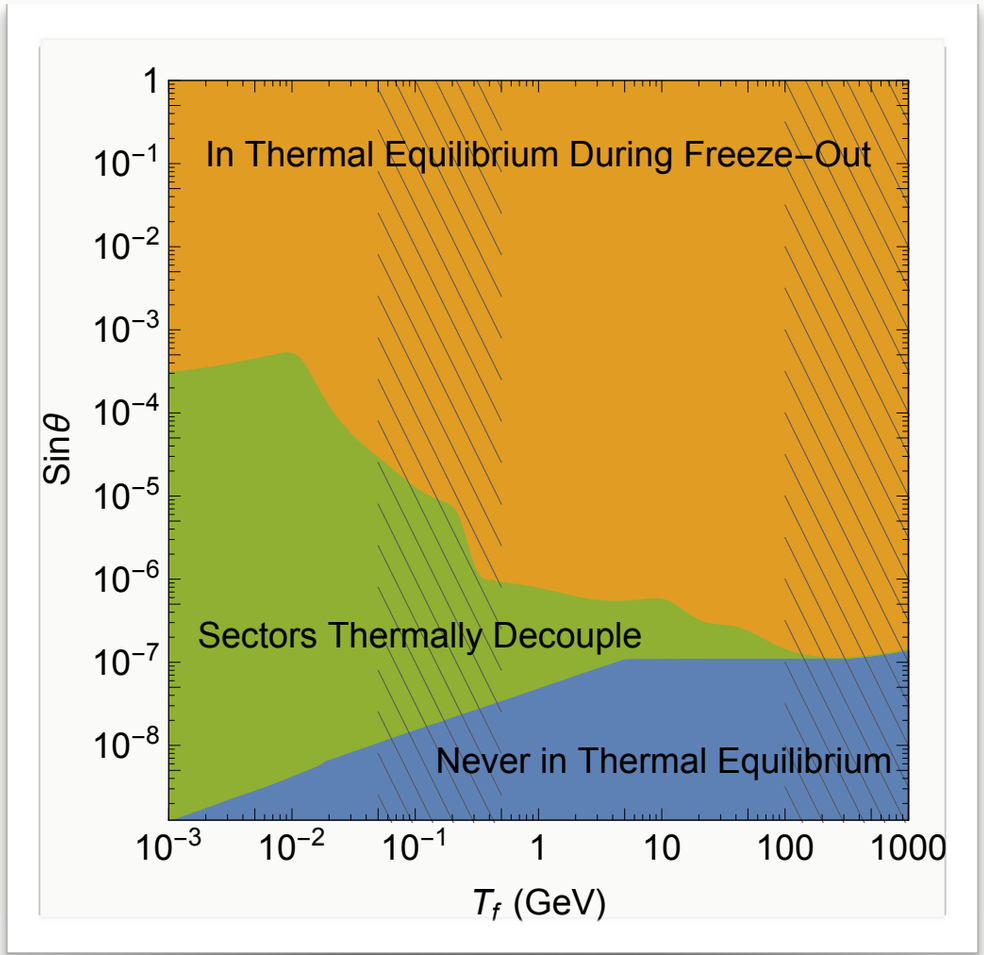
- thermally averaged using Maxwellian statistics

Illustration of coupling strengths giving thermally coupled DM through the vector portal

[Evans, Gori, JS]

Thermally coupled dark sector

- Requirement of thermalization imposes a cosmological lower bound on strength of coupling to SM



- Again, comparing sum of Maxwellian scattering rates involving SM fermions to Hubble
- Strong dependence on mass threshholds allows larger relative temperature drift

Illustration of coupling strengths giving thermally coupled DM through the Higgs portal

[Evans, Gori, JS]

Thermally coupled dark sector

- Advantage 2: limited sensitivity to details of hidden sector spectrum
- Thermal contact with SM radiation bath keeps freezeout story boring:
  - prevents runaway evolution of HS temperature (cannibalism)
  - also prevents large temperature ratios
  - Thus: either no* dark radiation (vector portal), or dark radiation that will be observable with CMB S4 (Higgs portal)

Thermally coupled dark sector

- Advantage 2: limited sensitivity to details of hidden sector spectrum
  - Cosmically short-lived states are mostly important through their impact on total expansion rate

$$H \propto \sqrt{g_{*SM} + g_{*HS}} \frac{T^2}{M_{pl}}$$

  - for minimal models, $g_{*SM} \gg g_{*HS}$, a small effect, but even for $g_{*SM} \sim g_{*HS}$, important at $O(1)$
  - of course, states in the UV with shared interactions could thermalize the two sectors: this is interesting and nonminimal

Thermally coupled dark sector

- Bottom line: parameter space for freezeout next door is bounded:
  - m_χ: from above by perturbativity
  - from below by BBN
  - m_{med}: from above by m_χ, from below by BBN
  - ϵ: from below by thermalization floor: terrestrially interesting
- Simple reference models a good guide to broader class of WIMPs next door in less minimal sectors

Simple vector portal model

- A simple reference model:

$$\mathcal{L}_{int} = \bar{\chi}\gamma_\mu Z_D^\mu \chi - m_D \bar{\chi}\chi + \frac{1}{2} m_{Z_D}^2 Z_{D\mu} Z_D^\mu + \frac{\epsilon}{2\cos\theta_W} Z_{\mu\nu} B^{\mu\nu}$$

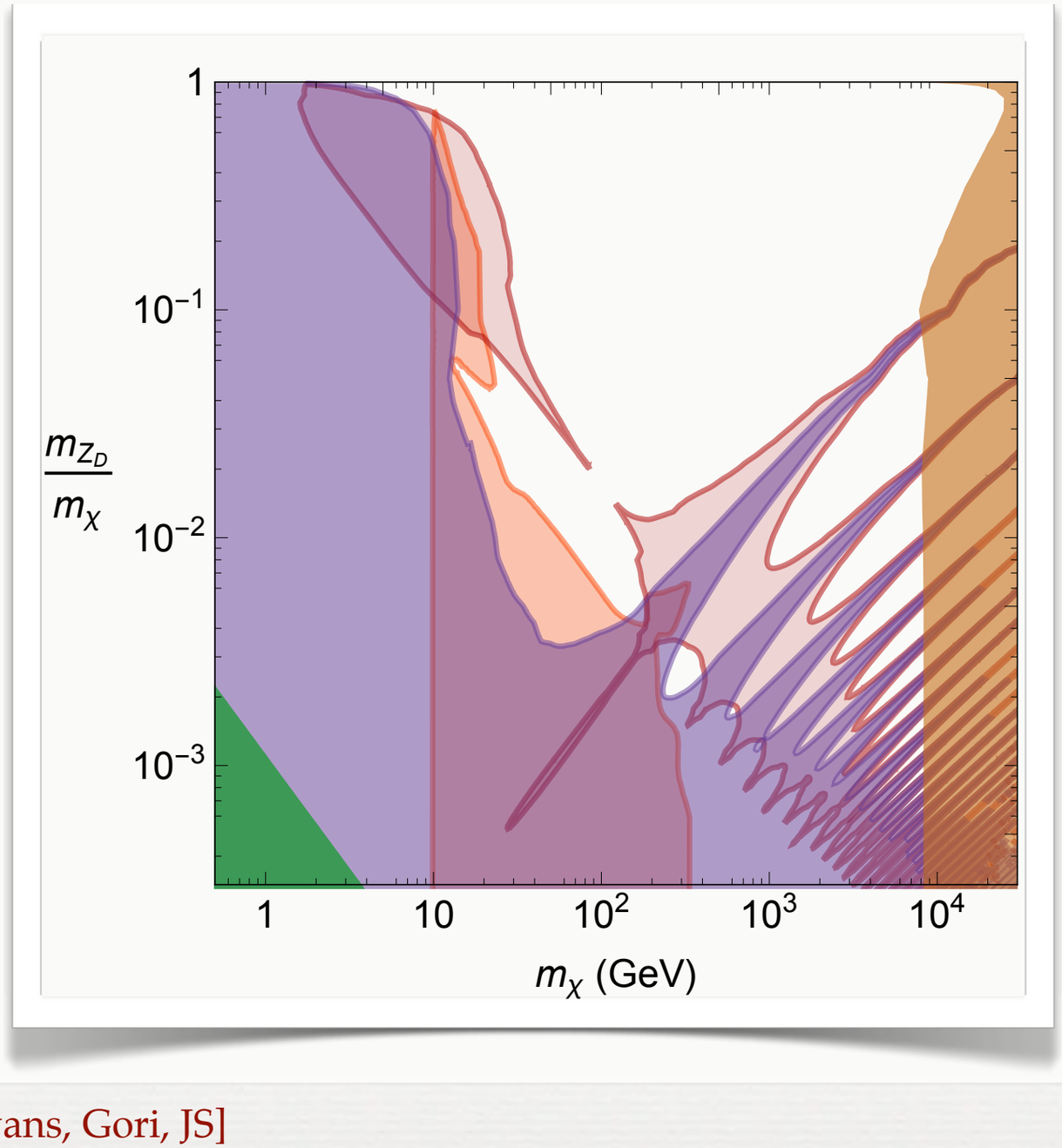
  - Dirac fermion dark matter χ
  - annihilating to a massive kinetically mixed vector boson Z_D
  - in the name of minimality, predictivity: Stueckelberg rather than dark Higgs. UV-complete

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Hooper, Weiner, Xue; Martin, JS, Unwin; Cline, Dupuis, Liu, Xue; Berlin, Gratia, Hooper, McDermott; ...]

Simple vector portal model

- Indirect detection:

- *s*-wave annihilation cross-section $\Rightarrow$ astrophysical constraints from cosmic rays, CMB



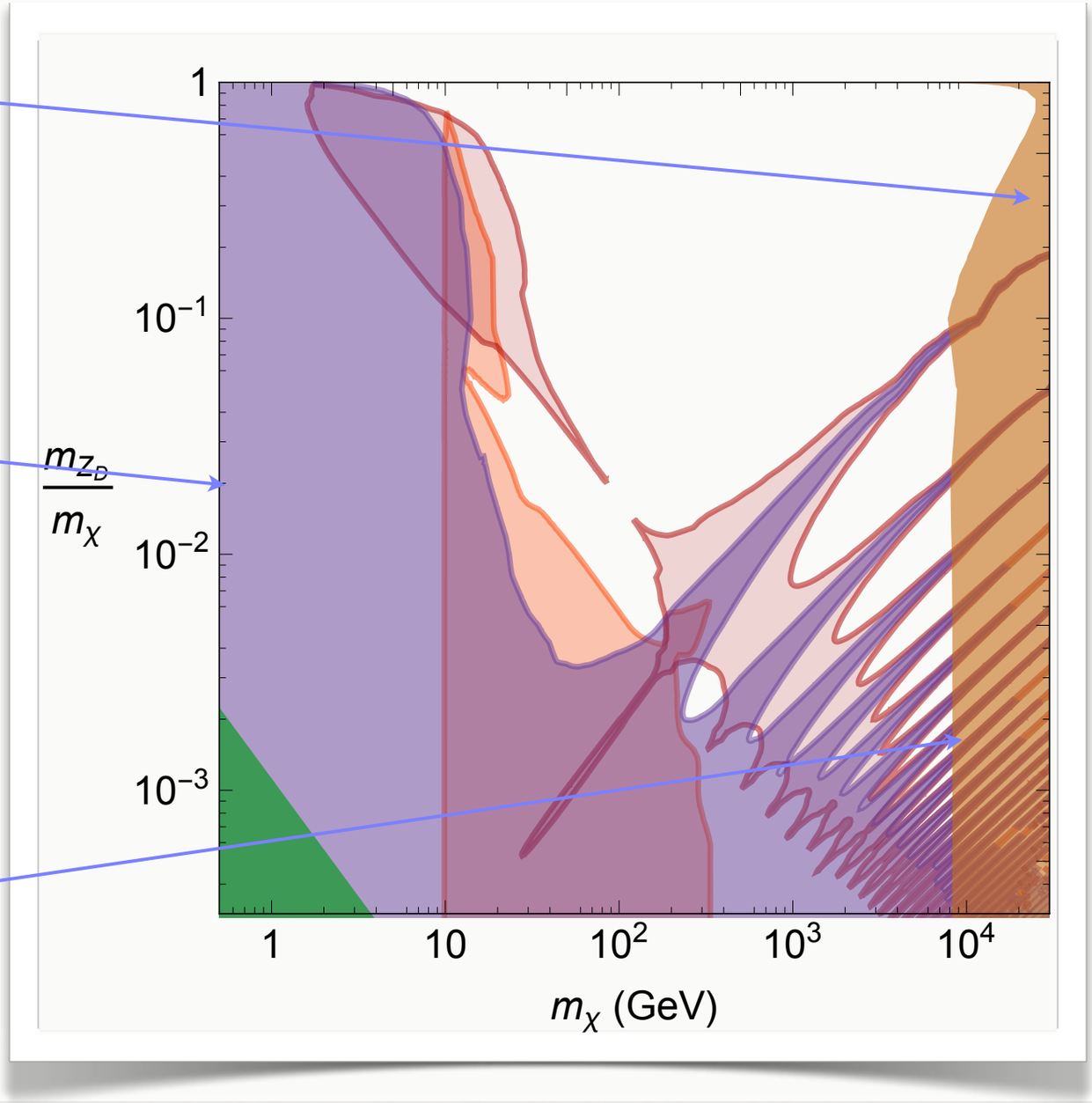
[Evans, Gori, JS]

Simple vector portal model

Upper end of mass range limited by perturbativity

Lower end of mass range limited by BBN

Sommerfeld enhancement during freezeout can be important for sufficiently heavy DM



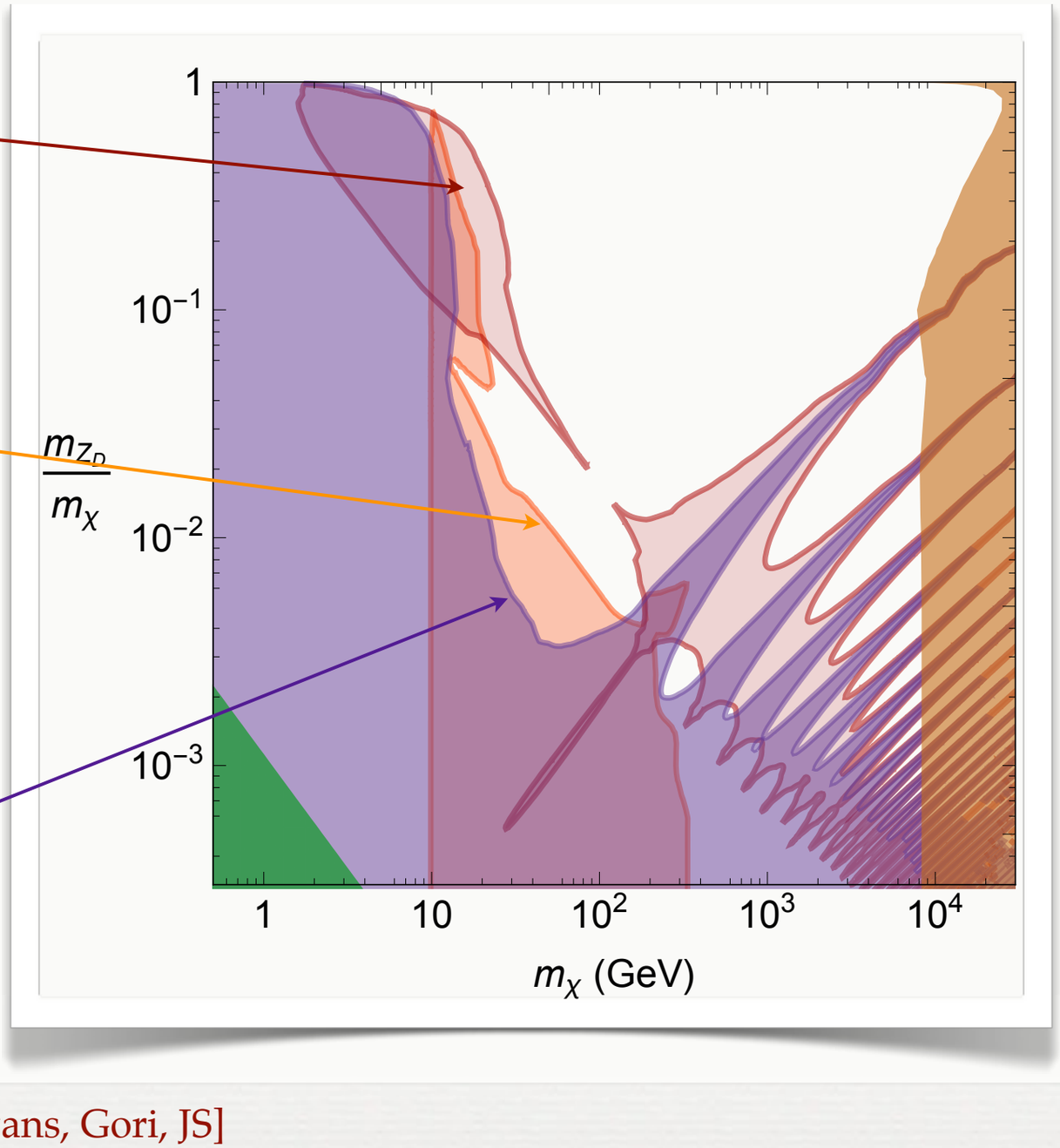
[Evans, Gori, JS]

Simple vector portal model

Excluded by Fermi dwarfs

Excluded by AMS-02 positrons

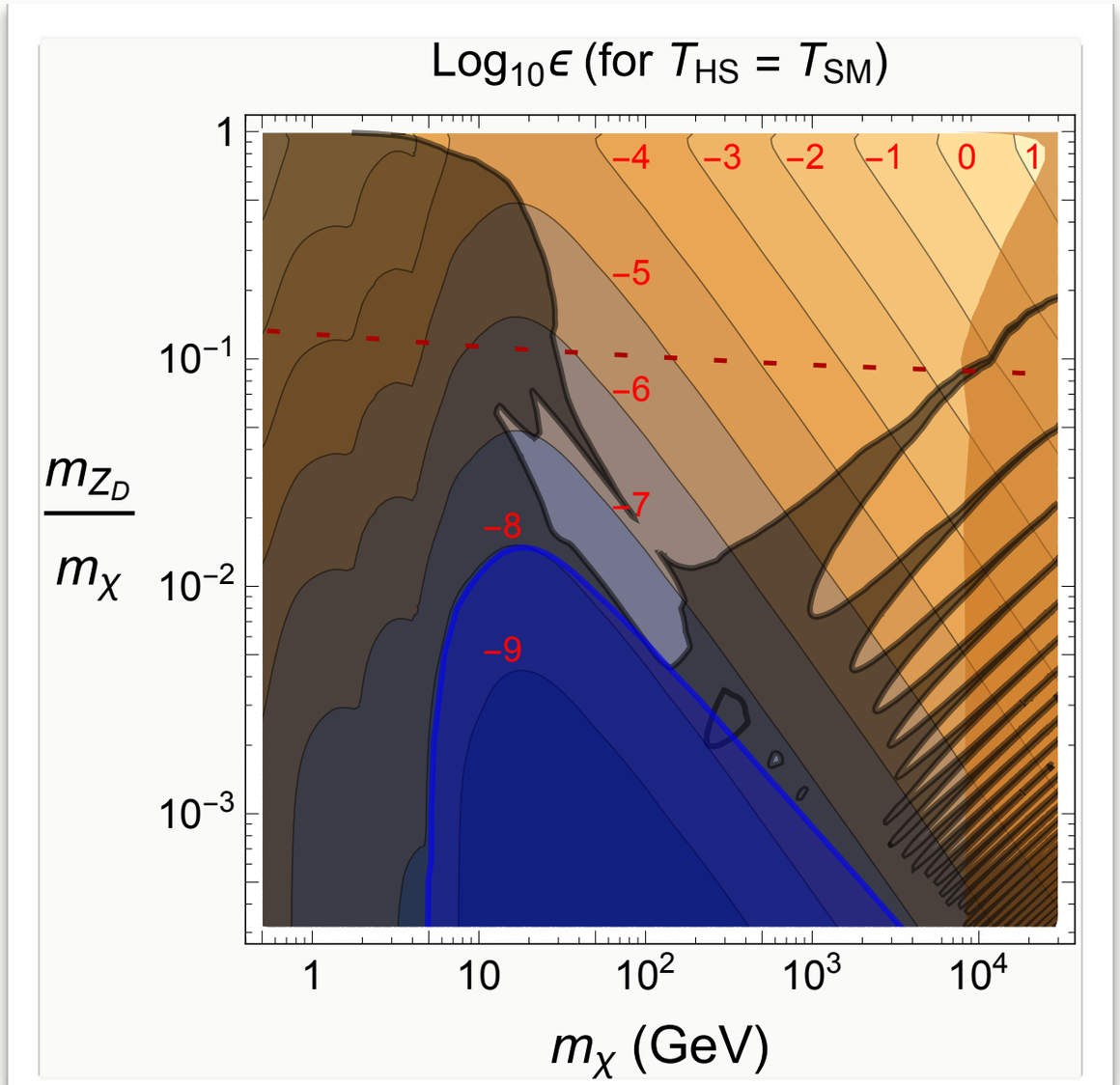
Excluded by Planck



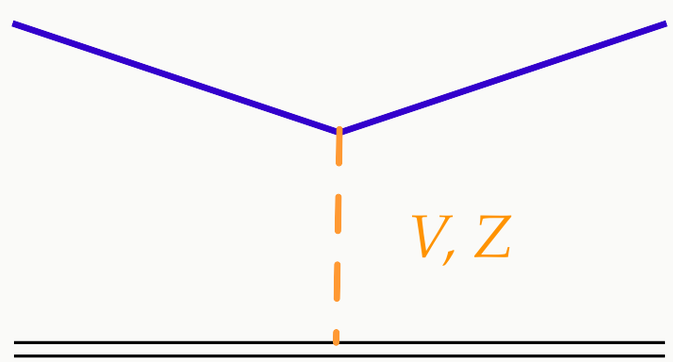
[Evans, Gori, JS]

Simple vector portal model

- Direct detection: cross-sections $\propto \epsilon^2$



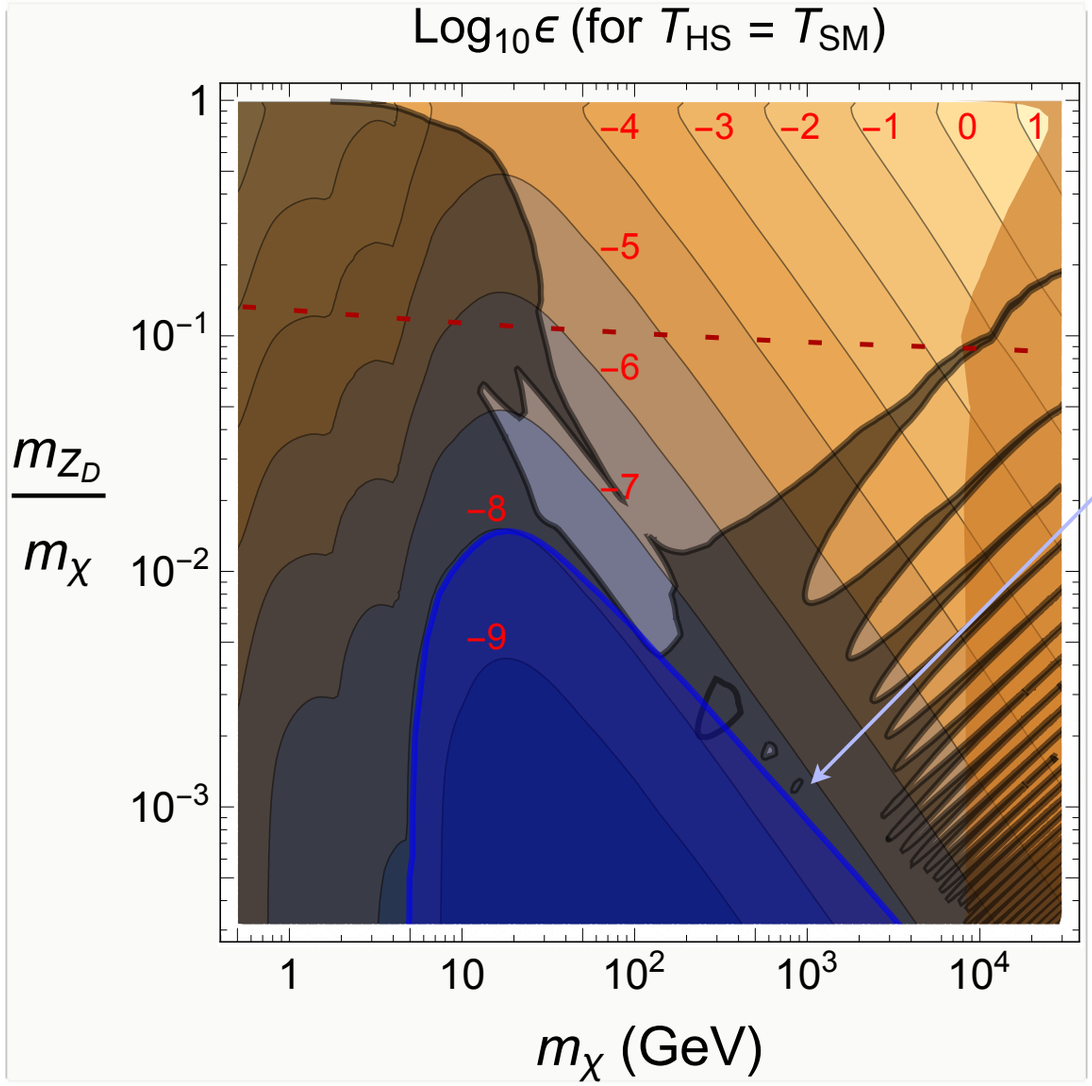
For Dirac fermion DM, leading spin-independent nuclear cross-section is unsuppressed



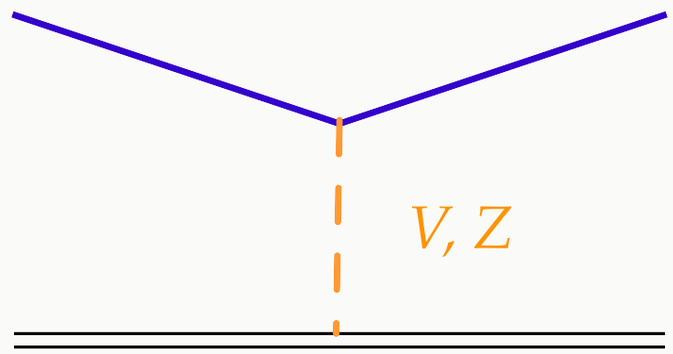
[Evans, Gori, JS]

Simple vector portal model

- Direct detection: cross-sections $\propto \epsilon^2$



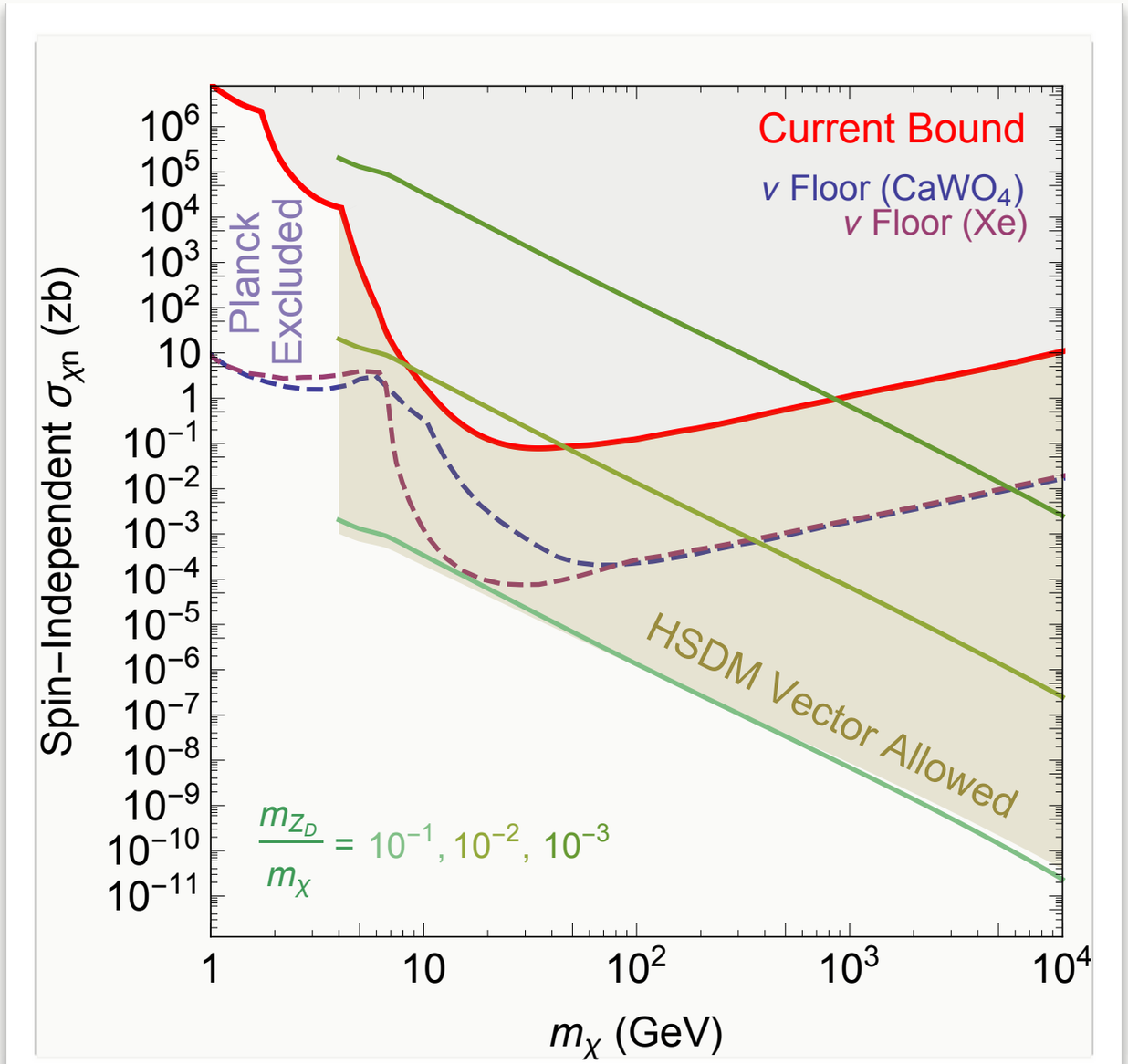
Direct detection can probe down to cosmological lower bound in favorable parts of parameter space



[Evans, Gori, JS]

Simple vector portal model

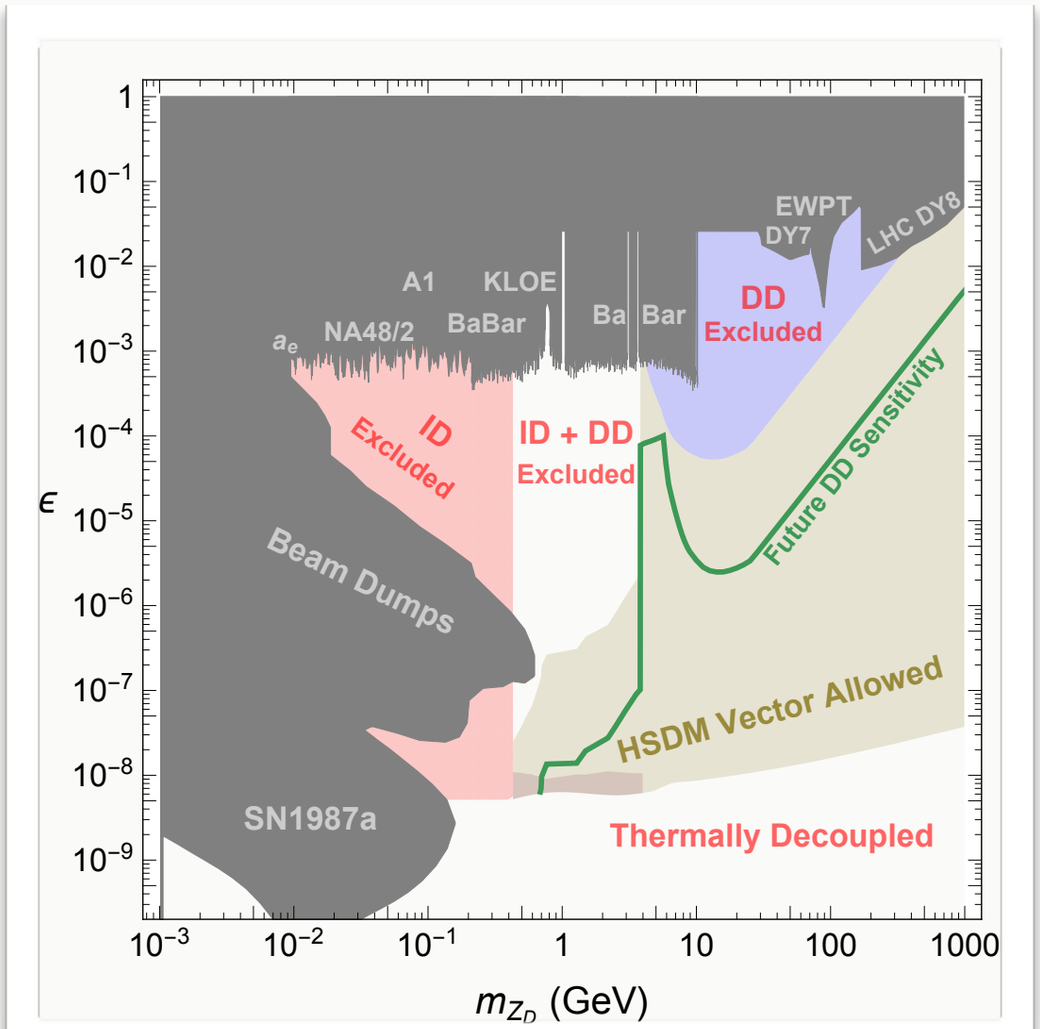
- Direct detection regions of interest below neutrino floor



[Evans, Gori, JS]

Simple vector portal model

- Leading accelerator signal: dark photon production
  - dark photon is lightest dark state, only SM decays



[Evans, Gori, JS]

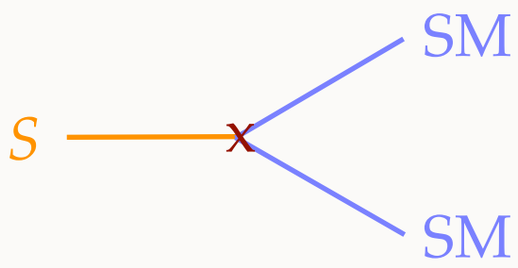
Simple Higgs portal model

- Another simple reference model:

$$\mathcal{L}_{int} = -yS\bar{\chi}\chi + \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4!}S^4 + \frac{\epsilon}{2}S^2|H|^2$$

  - Majorana dark matter χ
  - real scalar mediator s

- S gets a vev: Higgs portal mixing

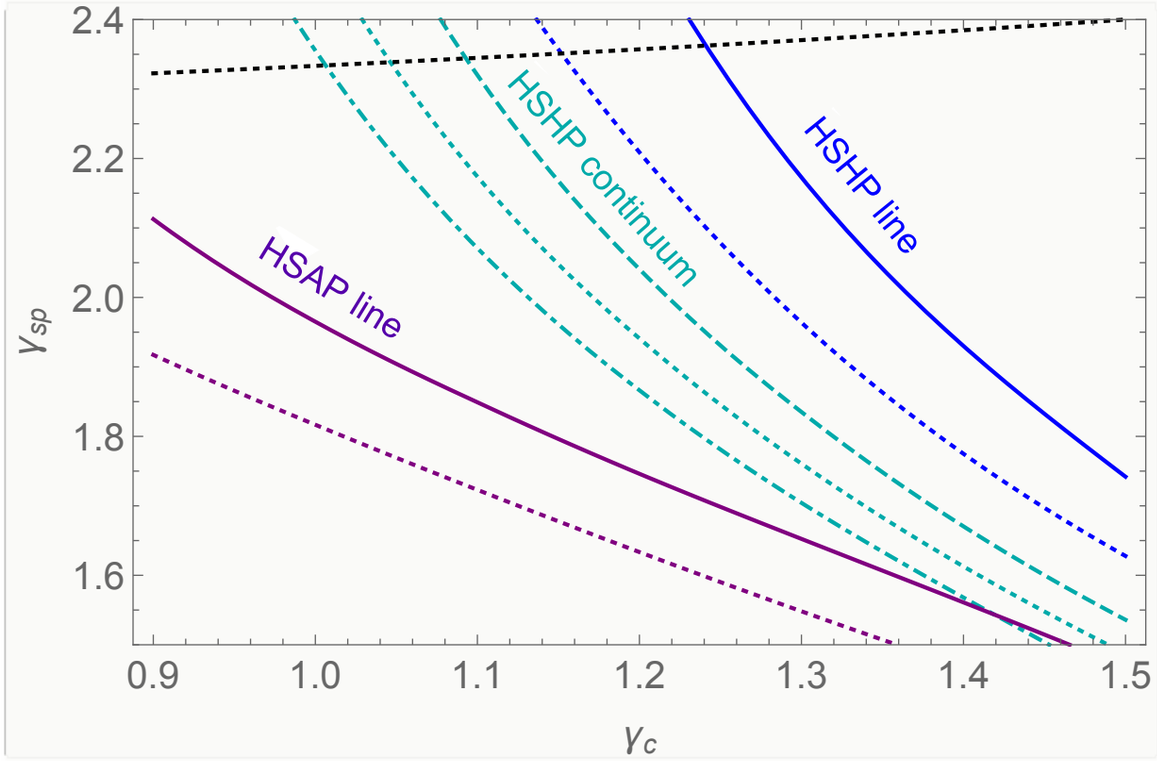


$$\theta_h = \frac{\epsilon\langle S\rangle v_h}{m_h^2 - m_s^2}$$

[JS, Shapiro, Fields]

Simple Higgs portal model

- Indirect detection:
  - our reference model has a *p*-wave annihilation cross-section $\Longrightarrow$ standard ID searches have no reach
  - astrophysical DM accelerators like BHs?
  - with $m_s \lll m_\chi$ bound state formation can give *s*-wave CMB signals

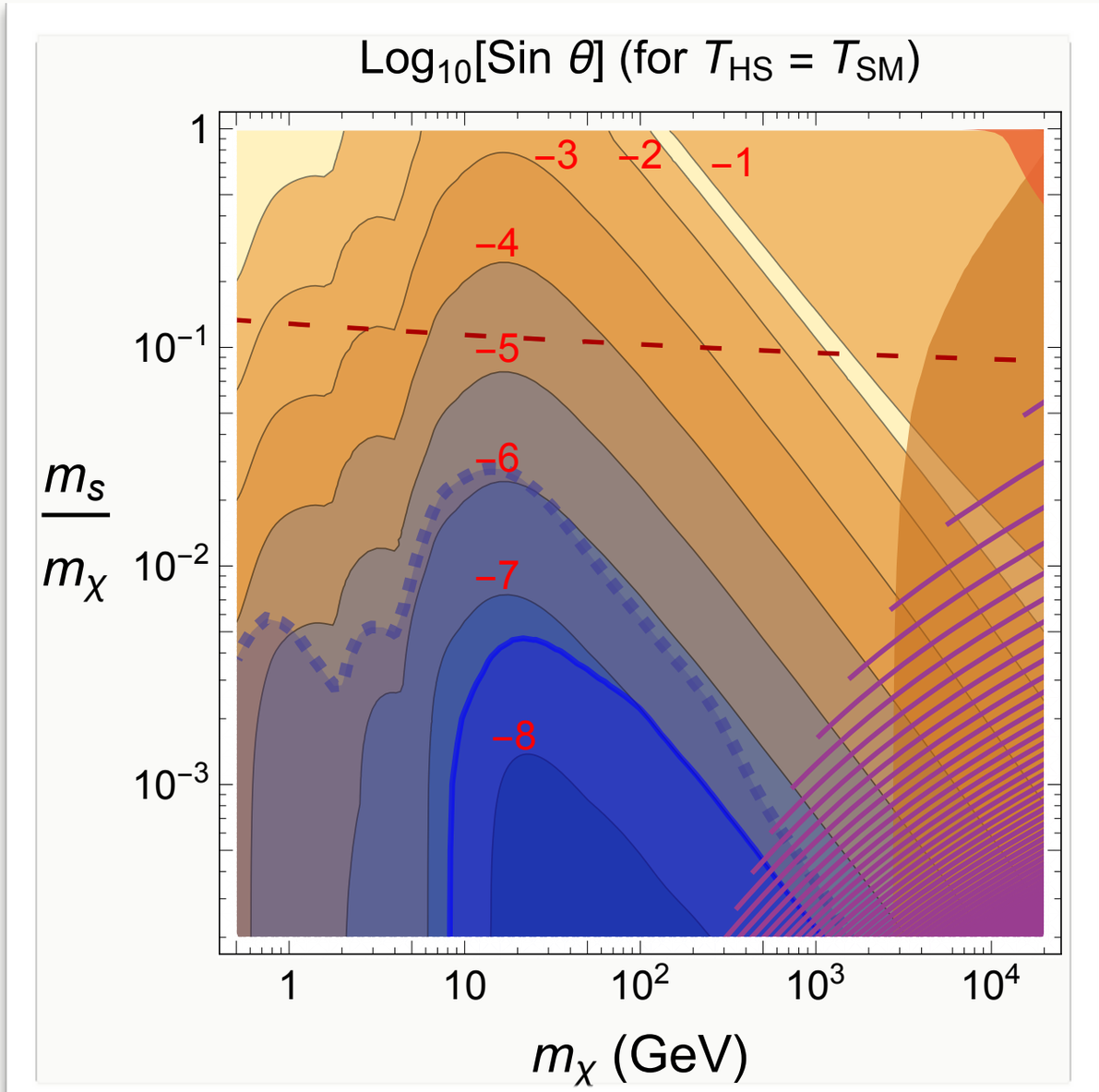


Sensitivity from annihilation in a potential density spike around the Milky Way's super-massive black hole

[JS, Shapiro, Fields; An, Wise, Zhang]

Simple Higgs portal model

- Direct detection: cross-sections $\propto \epsilon^2$

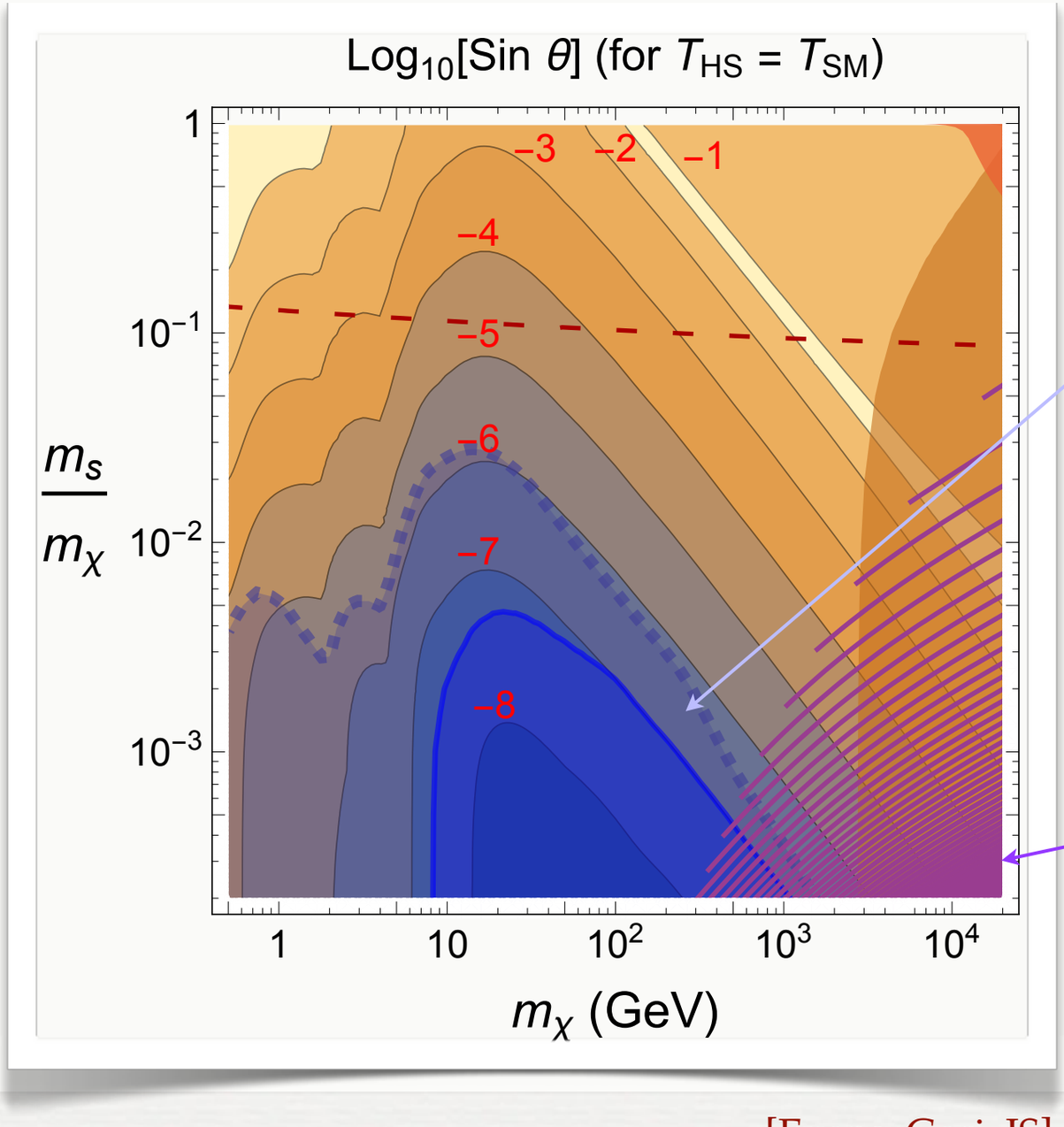


- Leading spin-independent interaction
- Yukawa-suppressed nucleon couplings lead to relatively smaller cross-sections
- Can again see down to cosmologically interesting values of portal coupling

[Evans, Gori, JS]

Simple Higgs portal model

- Direct detection: cross-sections $\propto \epsilon^2$



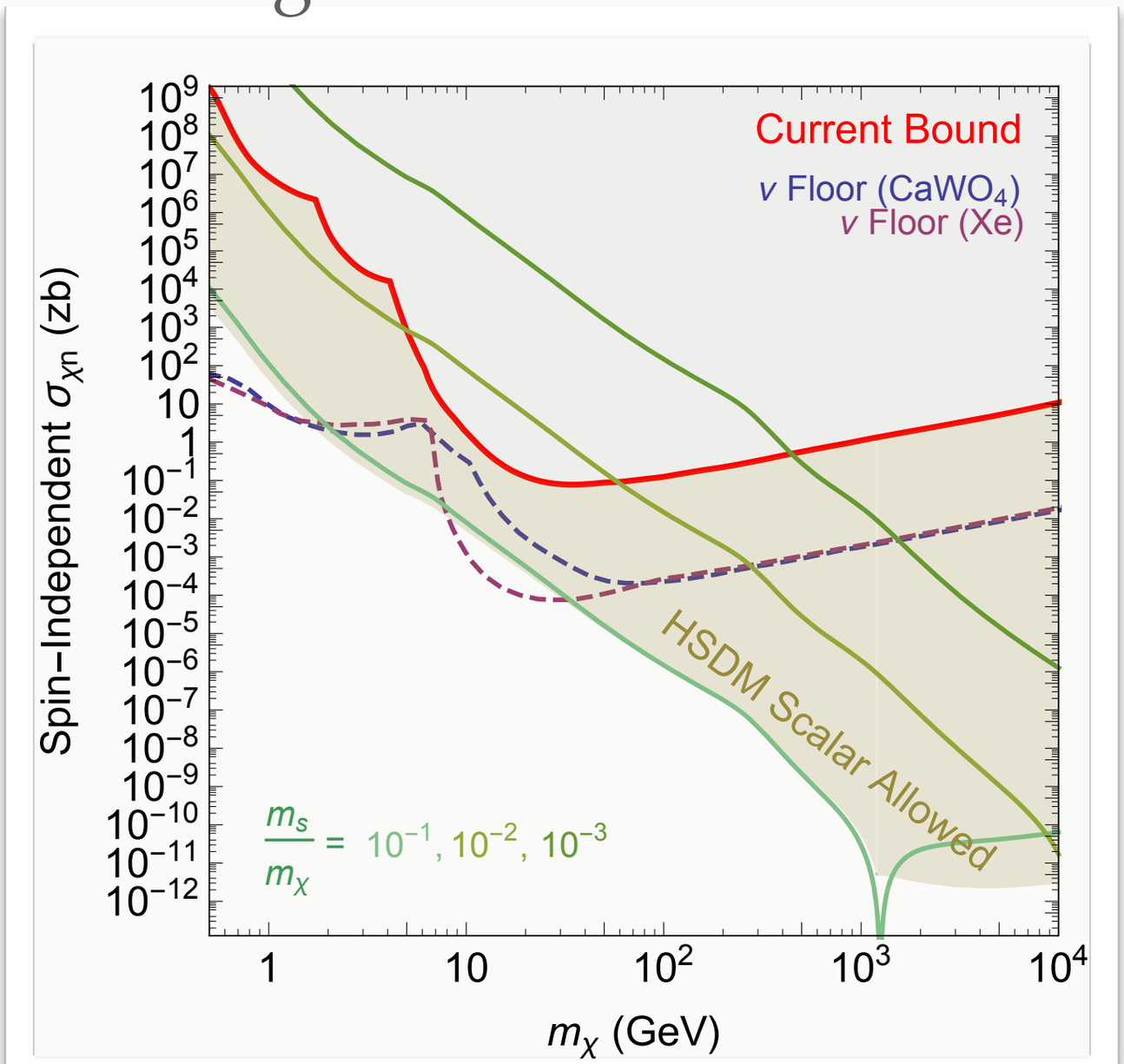
Direct detection can still probe down to cosmological lower bound in favorable parts of parameter space!

Planck constraints from bound state formation

[Evans, Gori, JS]

Simple Higgs portal model

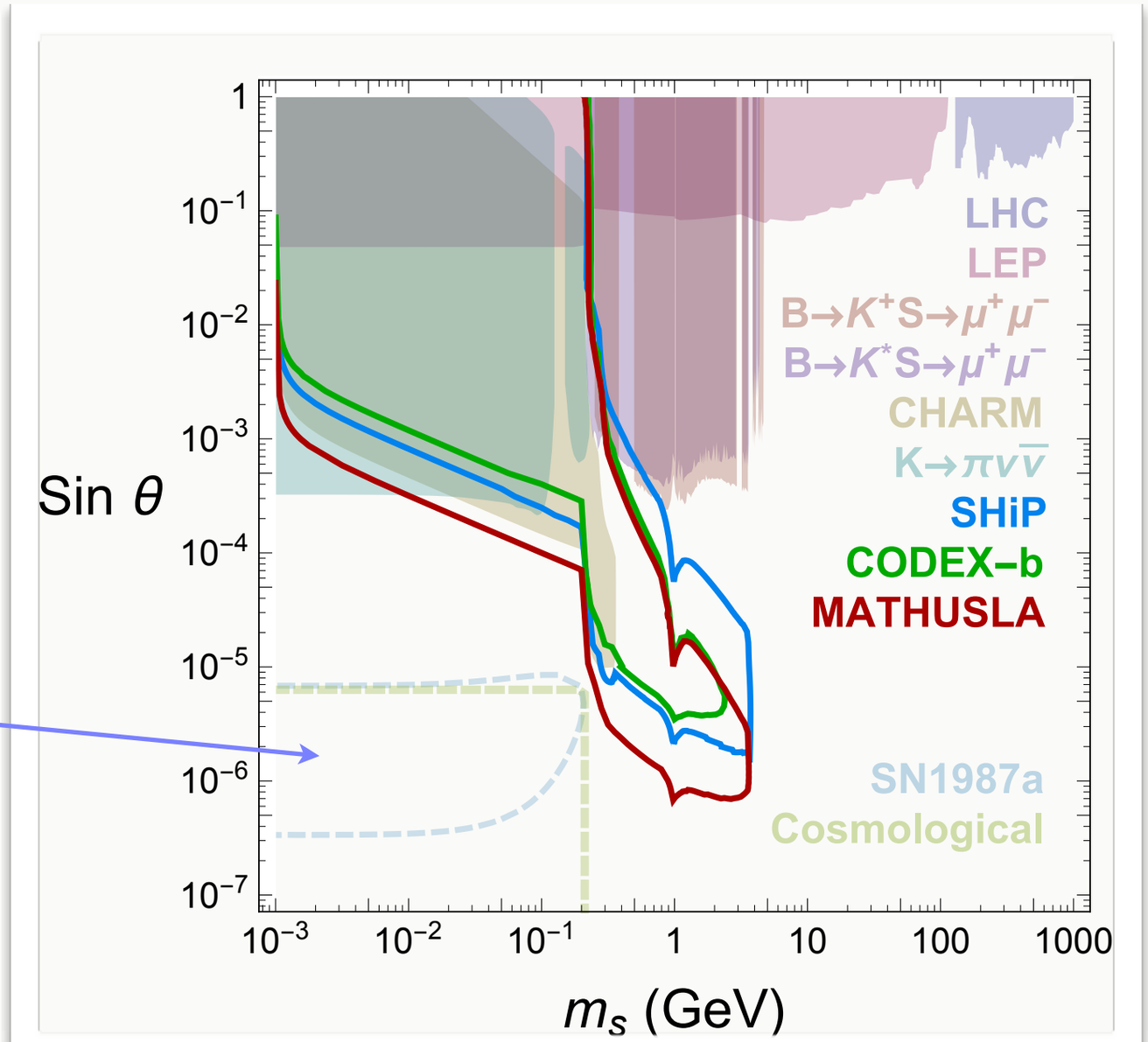
- Direct detection regions of interest below neutrino floor



[Evans, Gori, JS]

Simple Higgs portal model

- Leading accelerator searches again for mediator:

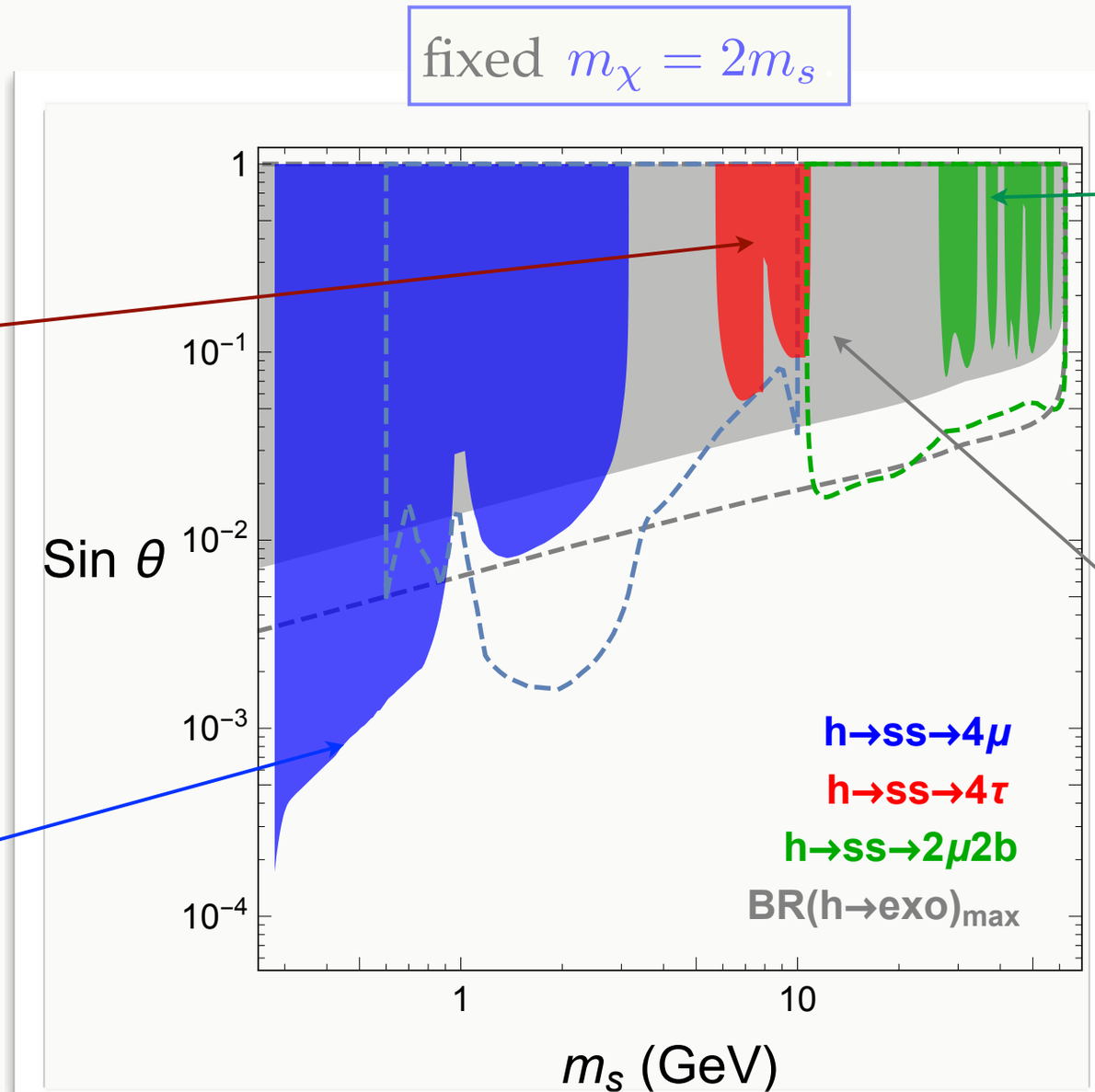


Below muon threshhold, astro/cosmo bounds

[Evans, Gori, JS]

Simple Higgs portal model

- Exotic Higgs decays additionally depend on S vev



$h \to ss \to 4\tau$

$h \to ss \to 2b2\mu$

$h \to ss \to 4\mu$

$Br(h \to \text{inv})$

[Evans, Gori, JS; Curtin, Essig, Zhong; Curtin, Essig, Gori, JS]

Conclusions

- Hidden sector freezeout: the WIMP next door
  - simple, minimal models, simple, minimal cosmology
  - well-defined and bounded parameter space: new evaluation of thermalization floor
  - minimal models a good guide to essential physics: “simplified models”
- Dark matter complementarity:
  - indirect detection: cannot parametrically suppress, typically most constraining if present
  - accelerator searches: for mediator states
  - direct detection often powerful test of thermalization floor