LOOKING FOR THE WIMP NEXT DOOR

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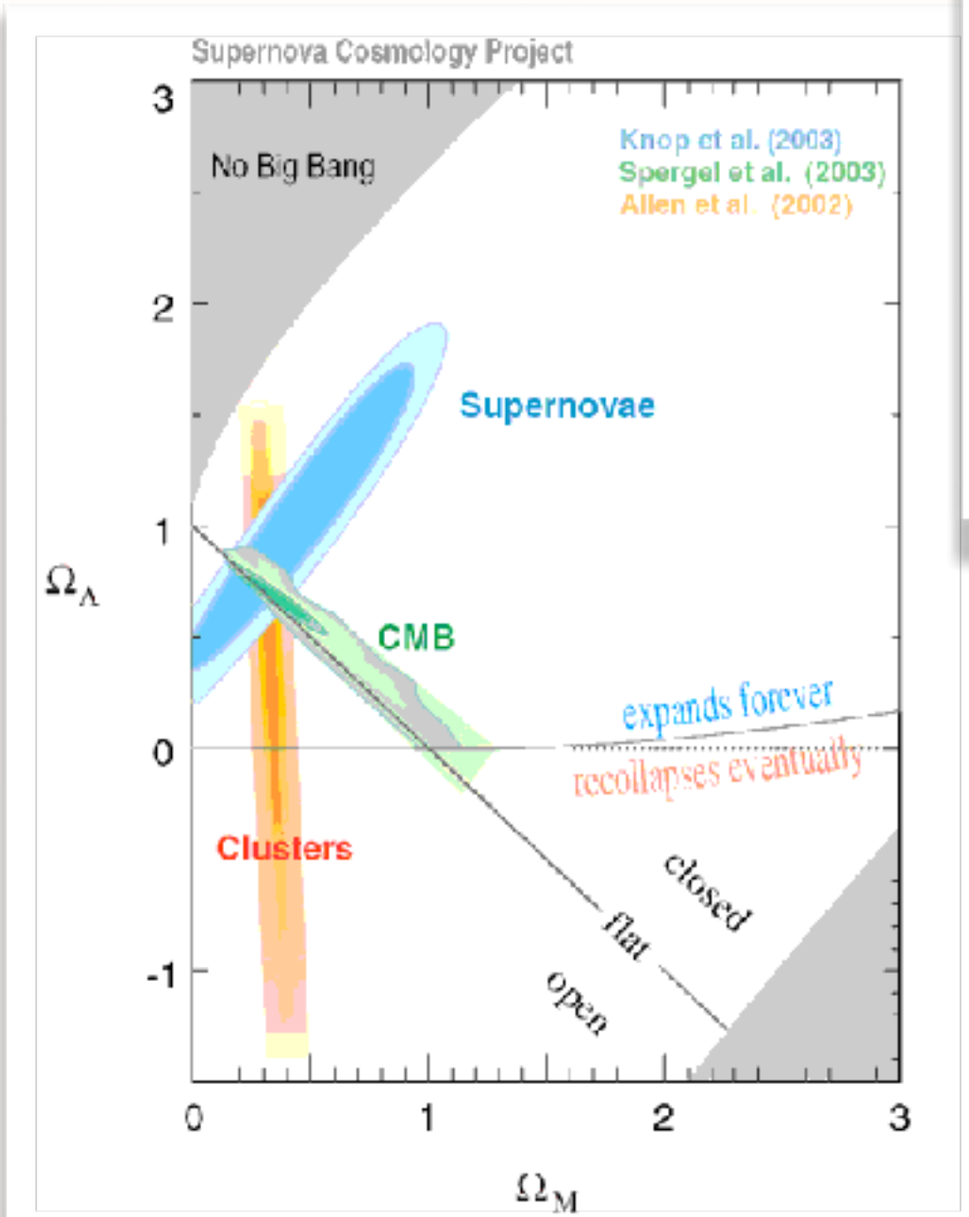
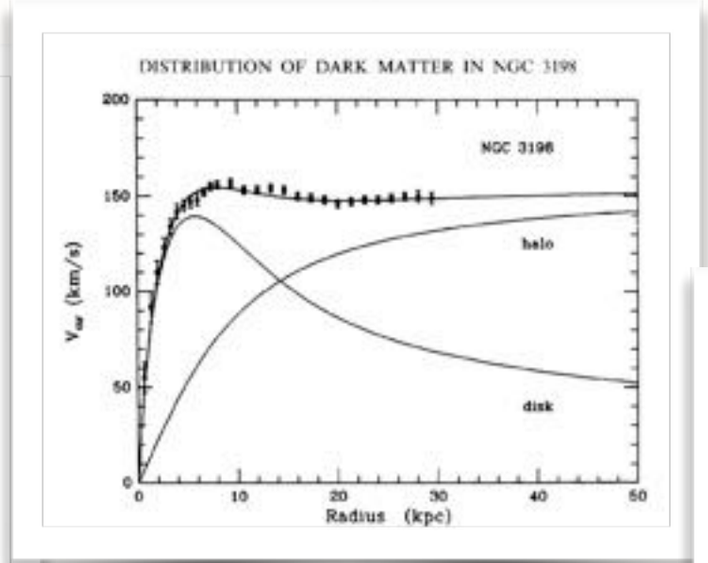
Dark matter in the universe





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

Dark matter bestiary

10^{-30} GeV

10^{-15}GeV

10^{-6}GeV

10^{-3}GeV

10^{3}GeV

10^{9}GeV

10^{60} GeV

fuzzy DM
ultra-light
axions

axions

sterile
neutrinos

super-WIMPs

WIMPs

hidden sector
thermal relics

Q-balls

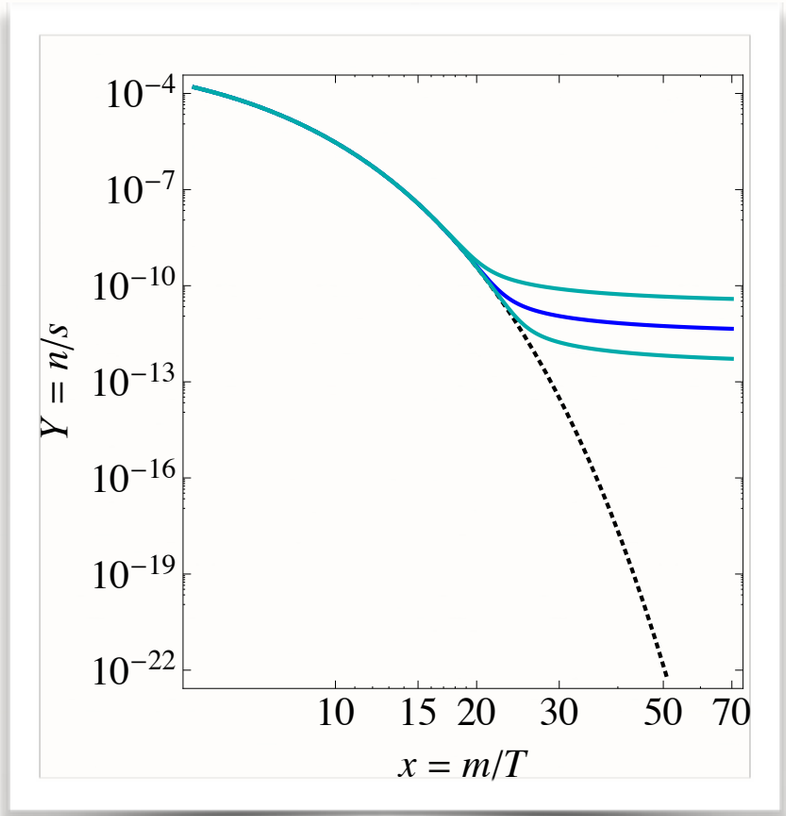
primordial
black holes

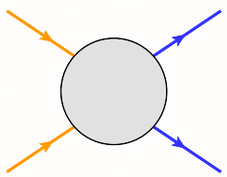
The hunt for dark matter

Thermal freezeout: WIMP m

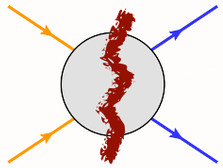
other reasons to like WIMPs! ie susy

- DM usually needs non-gravitational interac
  populated in the early universe
- exemplar: “WIMP miracle”: thermal freezeout





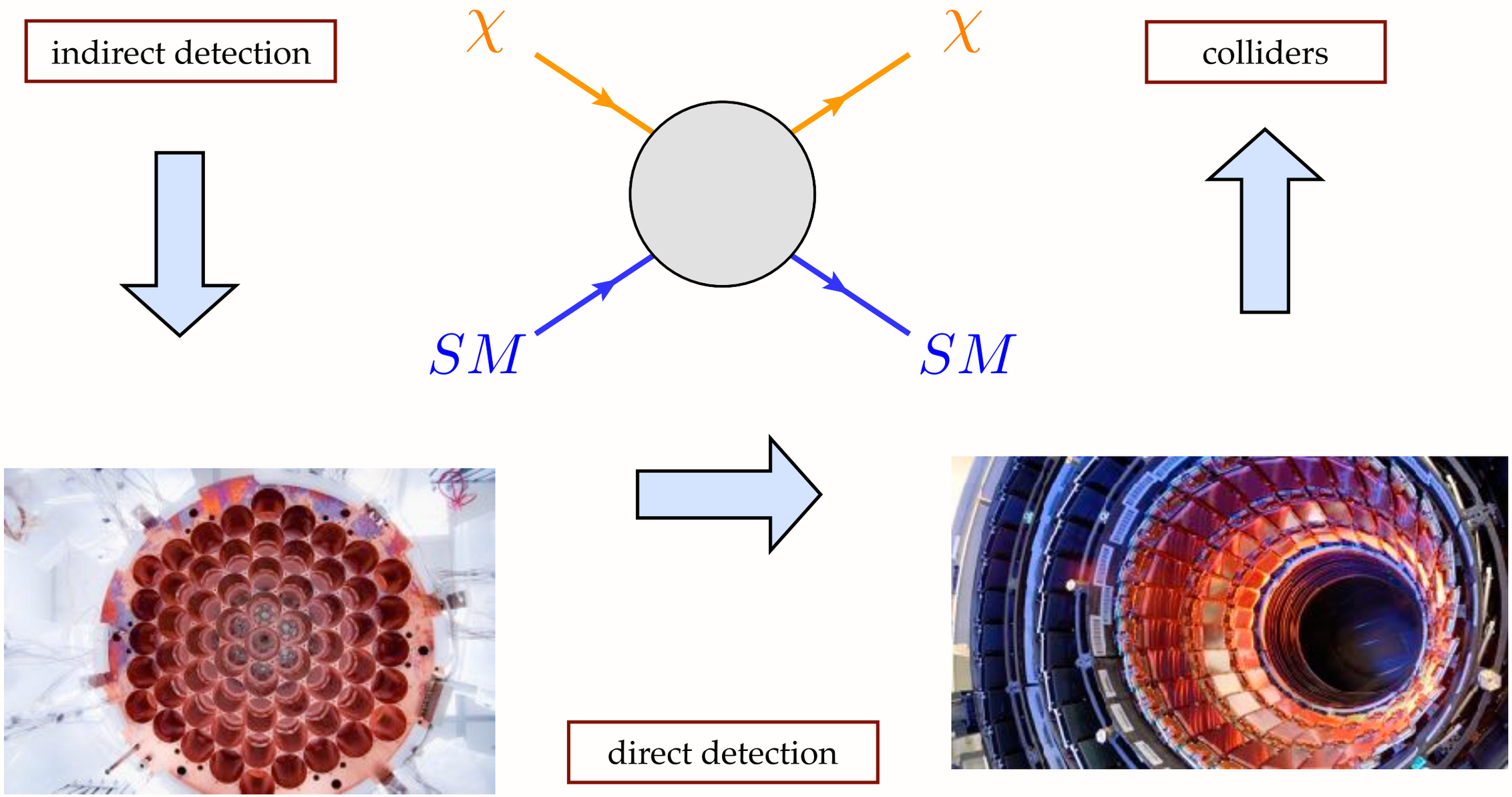
$n\langle\sigma v\rangle > H$



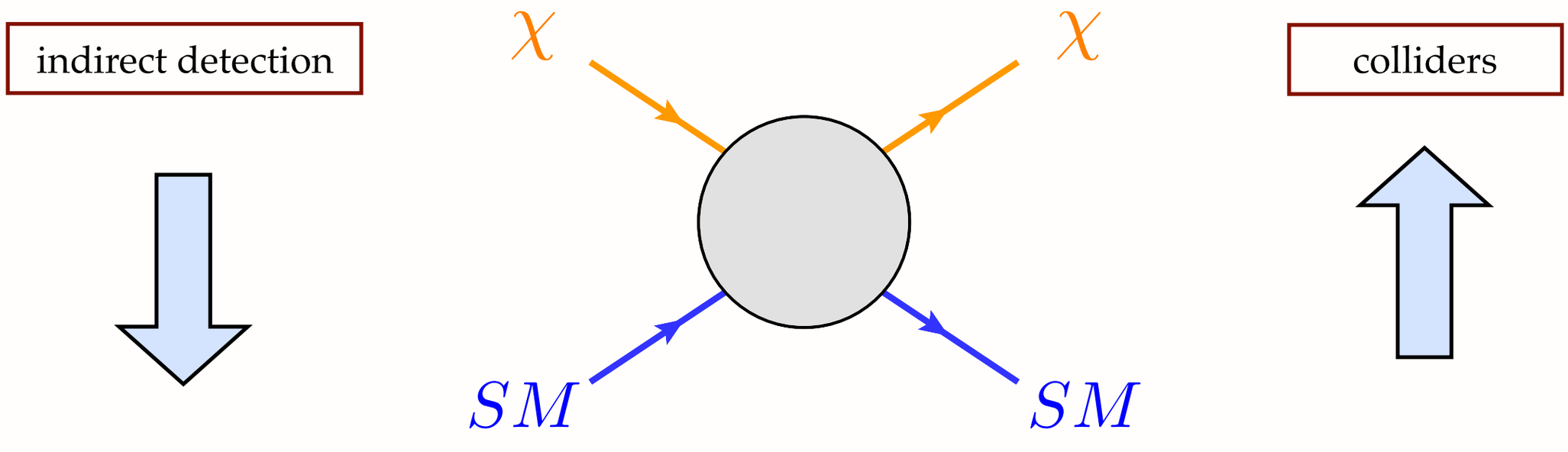
$n\langle\sigma v\rangle \ll H$

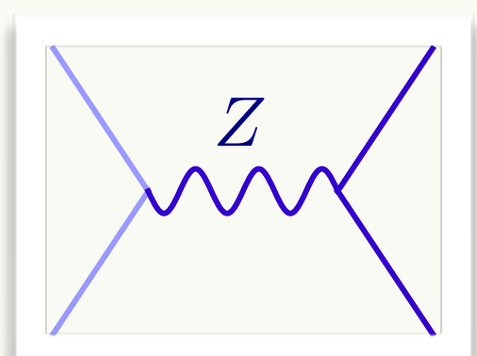
$$\Omega_{DM} \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m^2}{g^4}$$

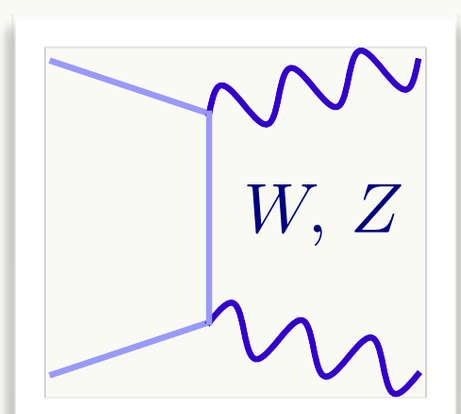
The hunt for **WIMP** dark matter

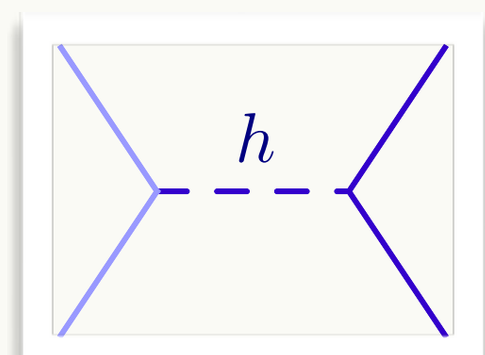


The hunt for **WIMP** dark matter

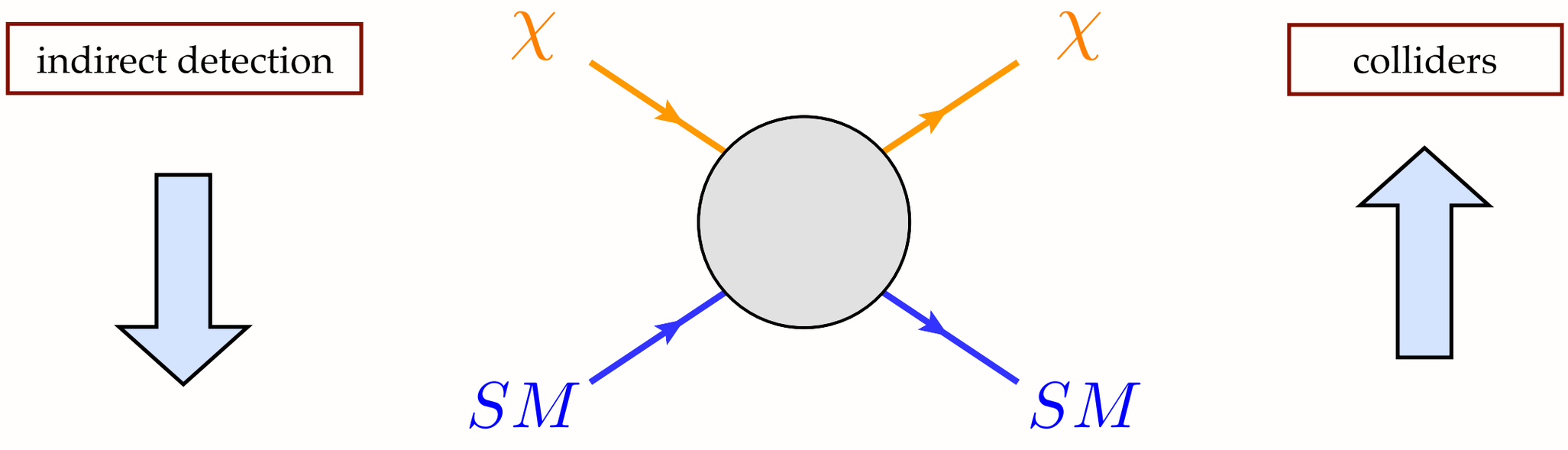


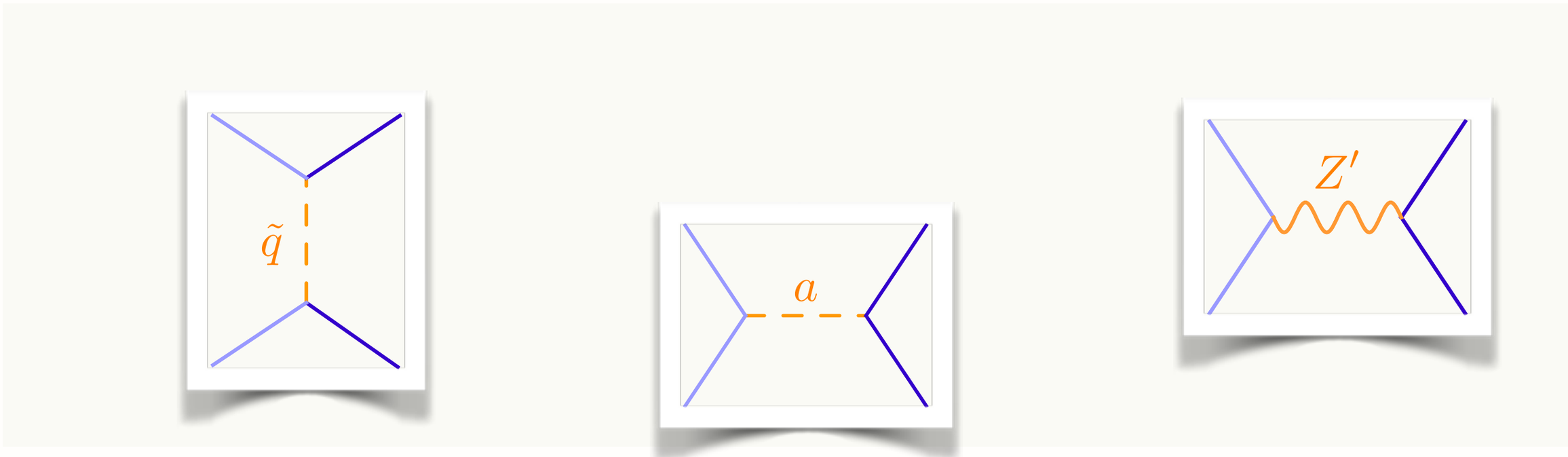




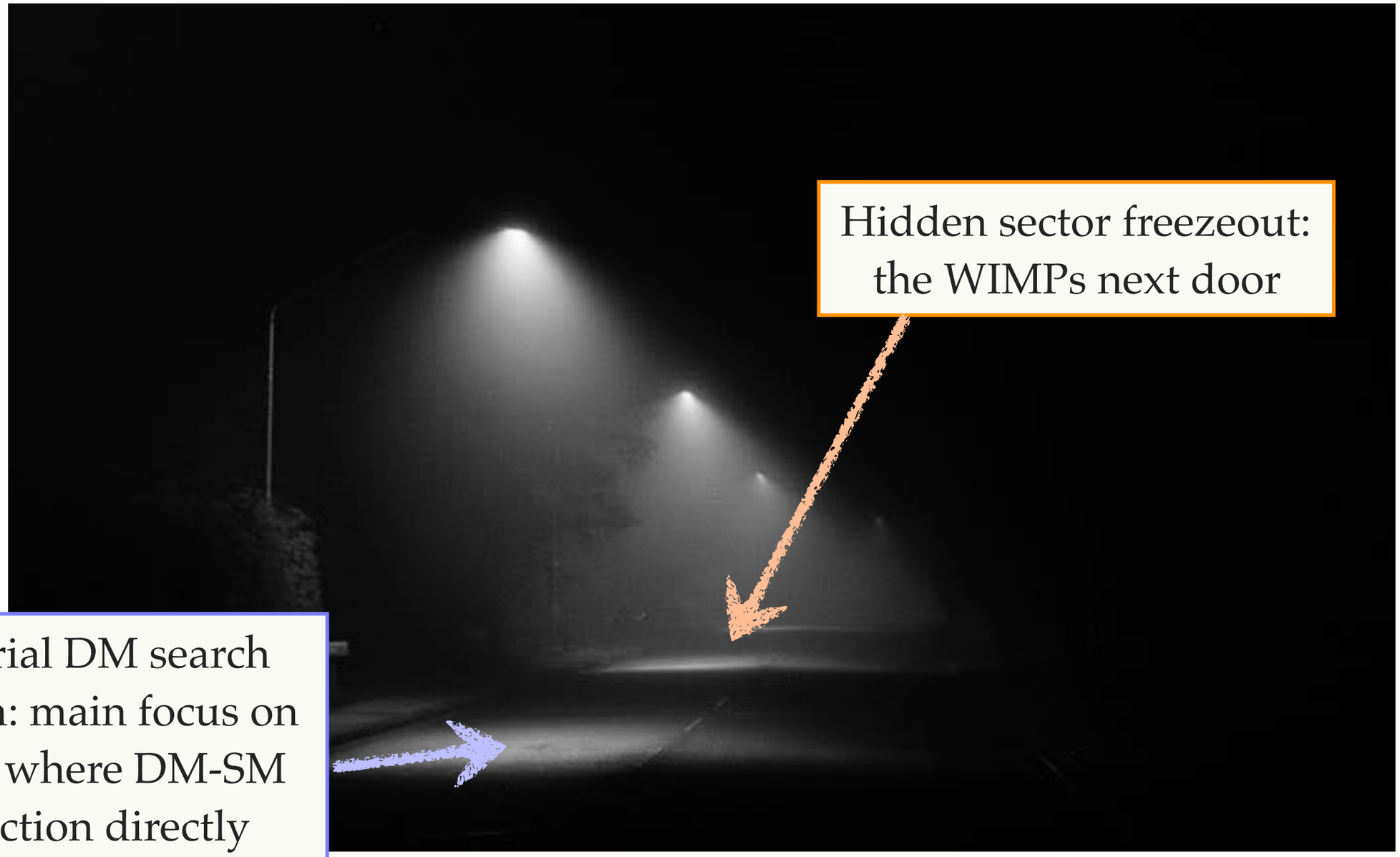


The hunt for **WIMP** dark matter





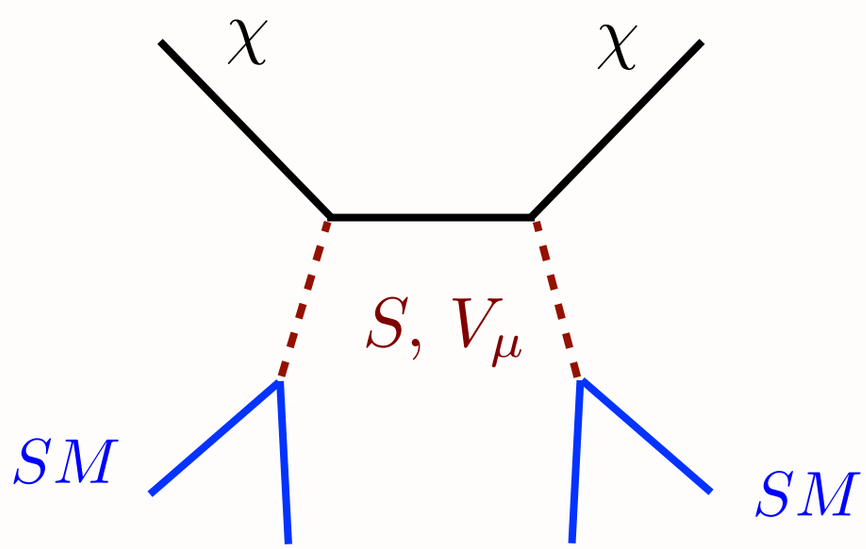
The hunt for dark matter



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

Hidden sector freezeout

- Freezeout without the SM:



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

Hidden sector freezeout

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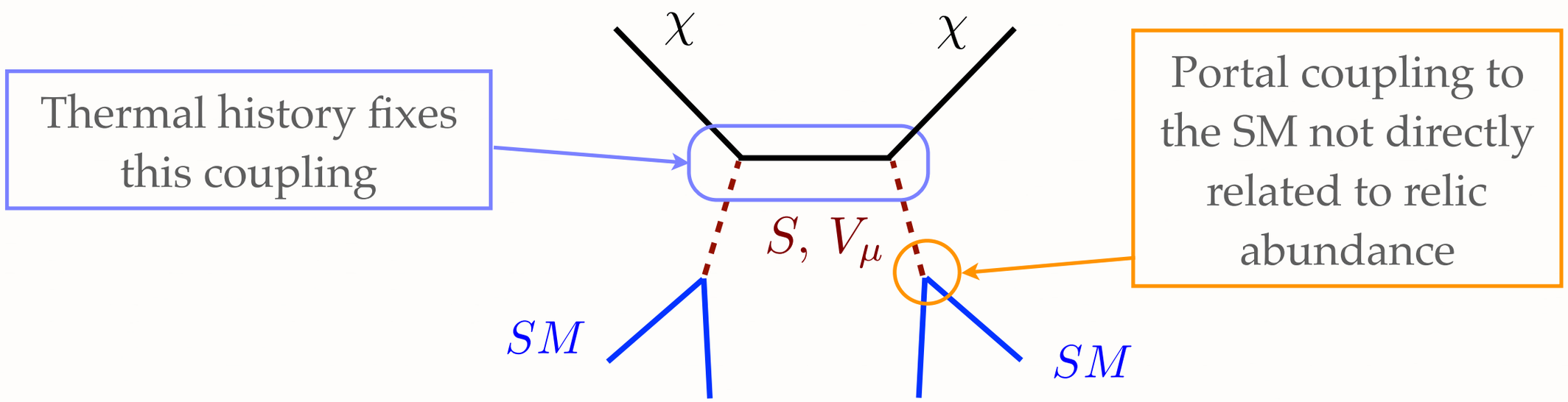

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Hidden sector freezeout

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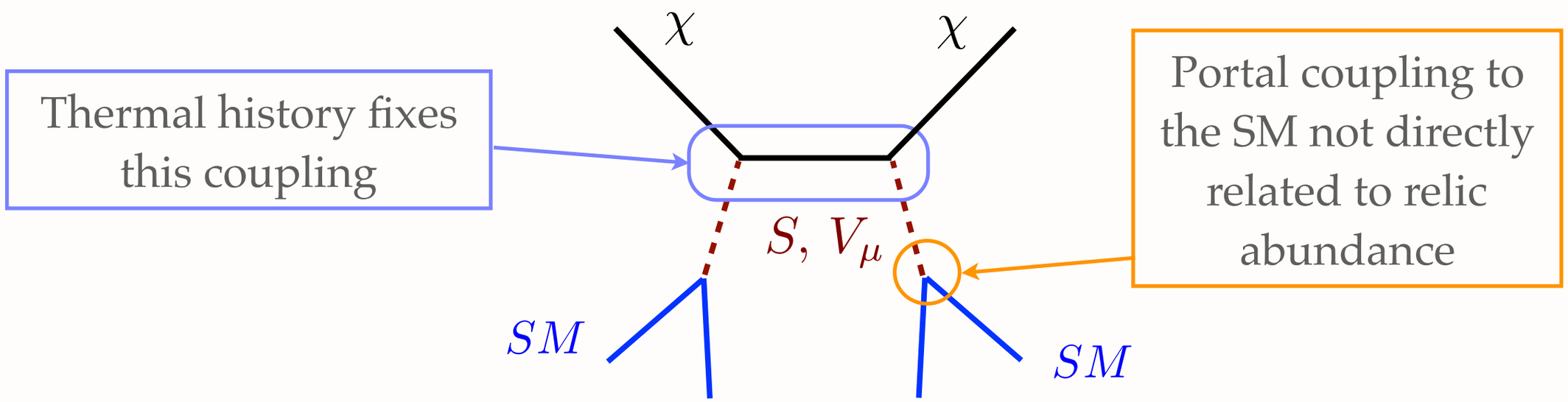


- Minimal models described by four parameters:

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

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

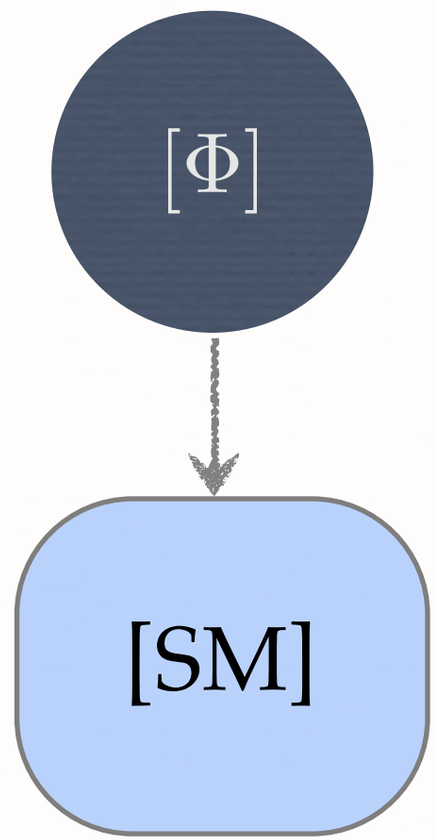
[Pospelov, Ritz, Voloshin; Feng, Kumar; Feng, Tu, Yu; ...]

Where did we get dark matter?

this is one of its very attractive features

- But how did this dark sector get populat
- Thermal WIMPy cosmology is simple:

New physics responsible for reheating populated SM in early universe



Thermal SM radiation bath: BBN (T~MeV)

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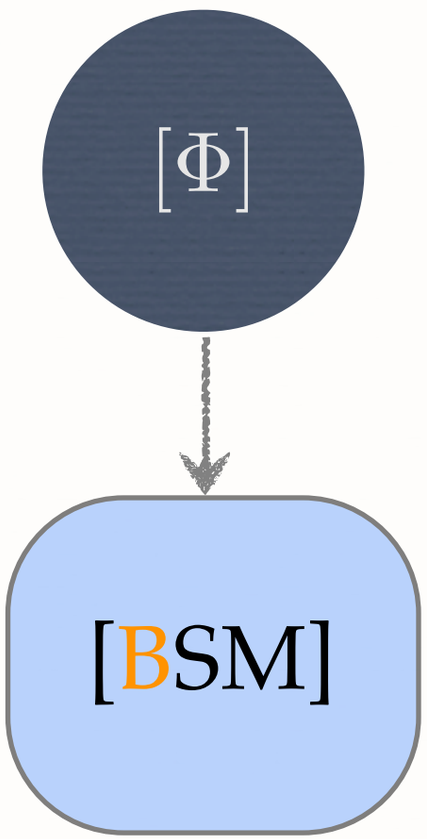
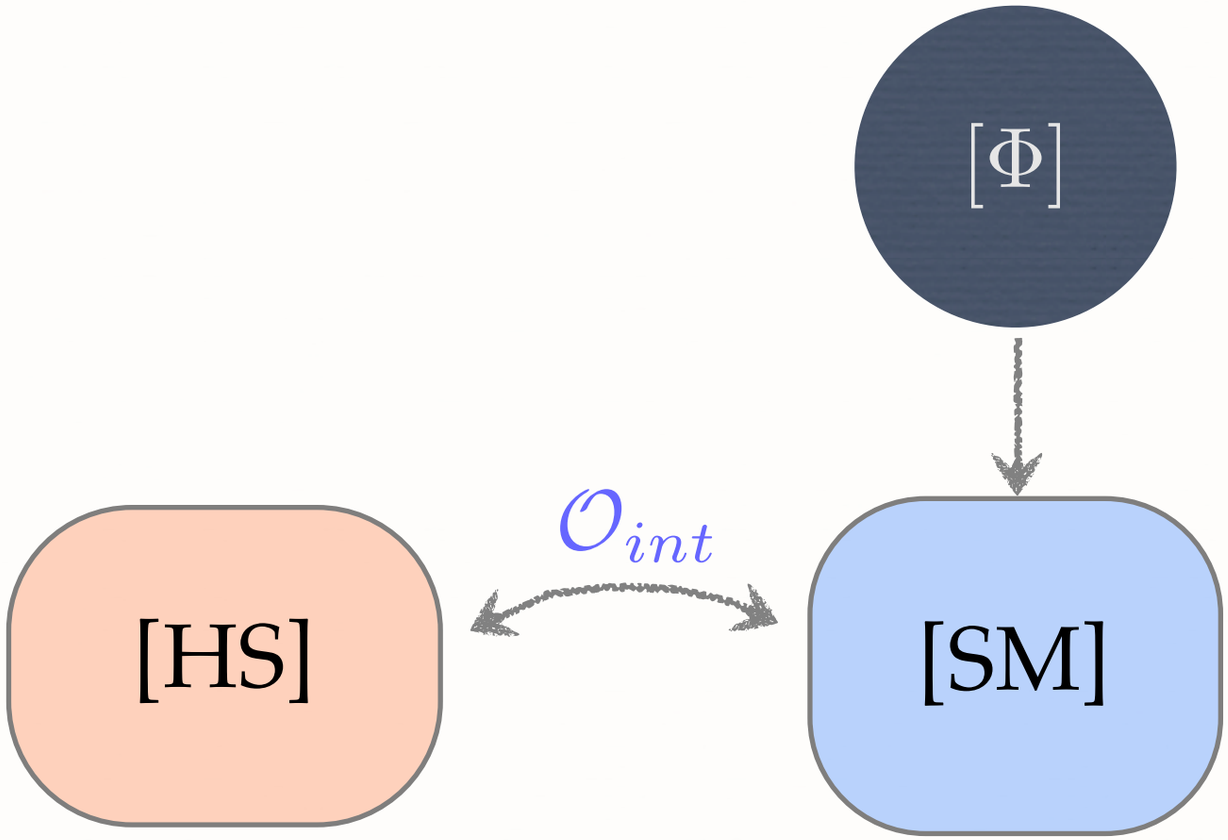


Additional species in radiation bath undergo interactions that yield right Ω_{DM} : freezeout

Thermal SM radiation bath: BBN (T~MeV)

Where did we get dark matter?

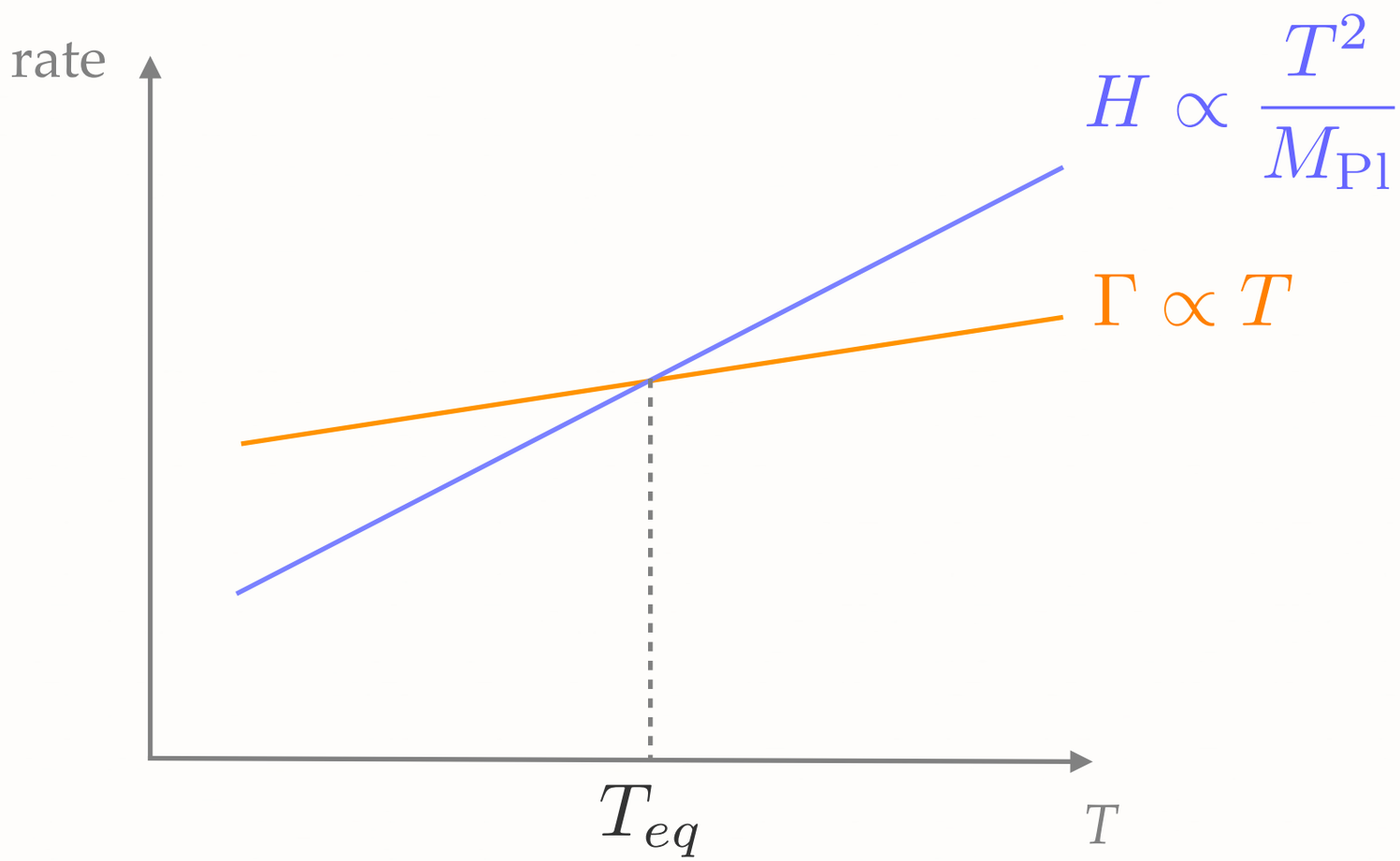
- Minimal scenario: HS thermally populated from SM

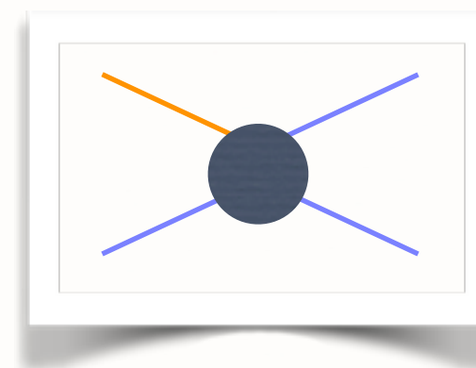


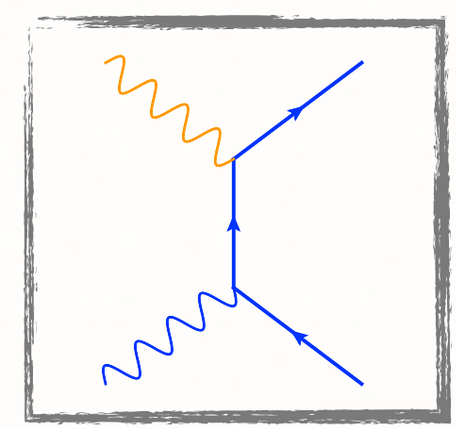
- Simple cosmology with several appealing features

Thermally coupled dark sector

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

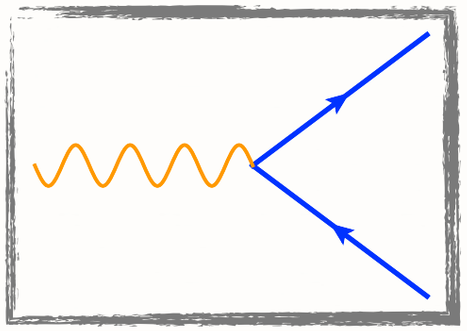


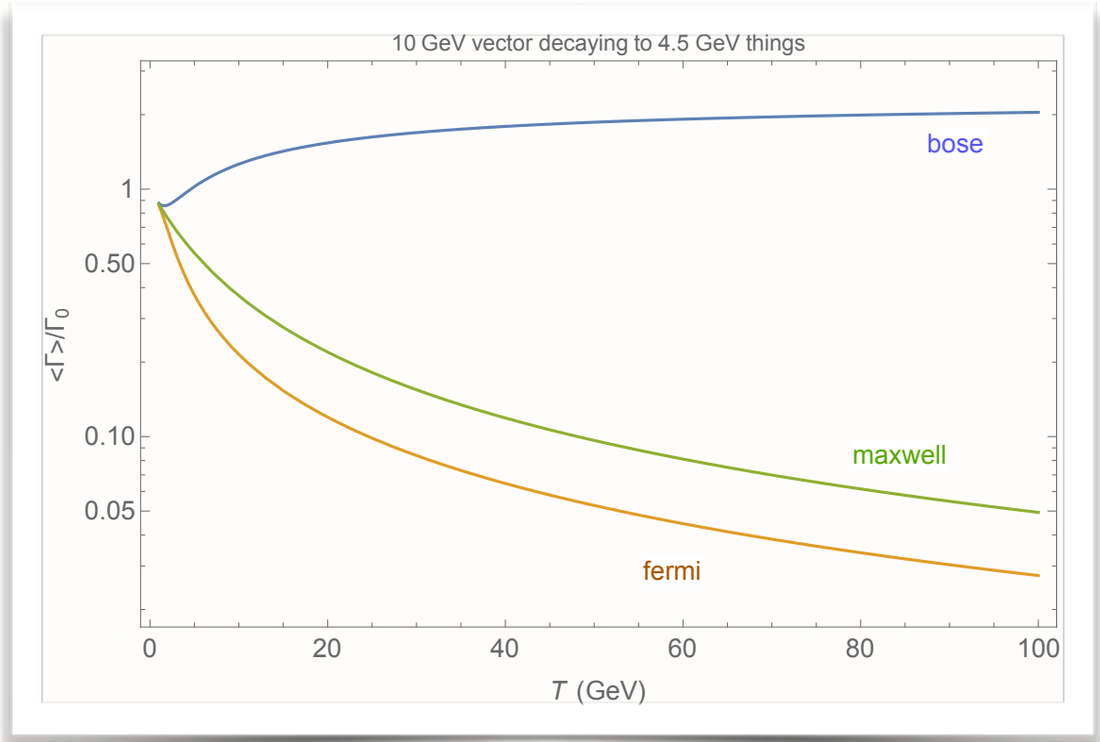




Thermally coupled dark sector

- 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

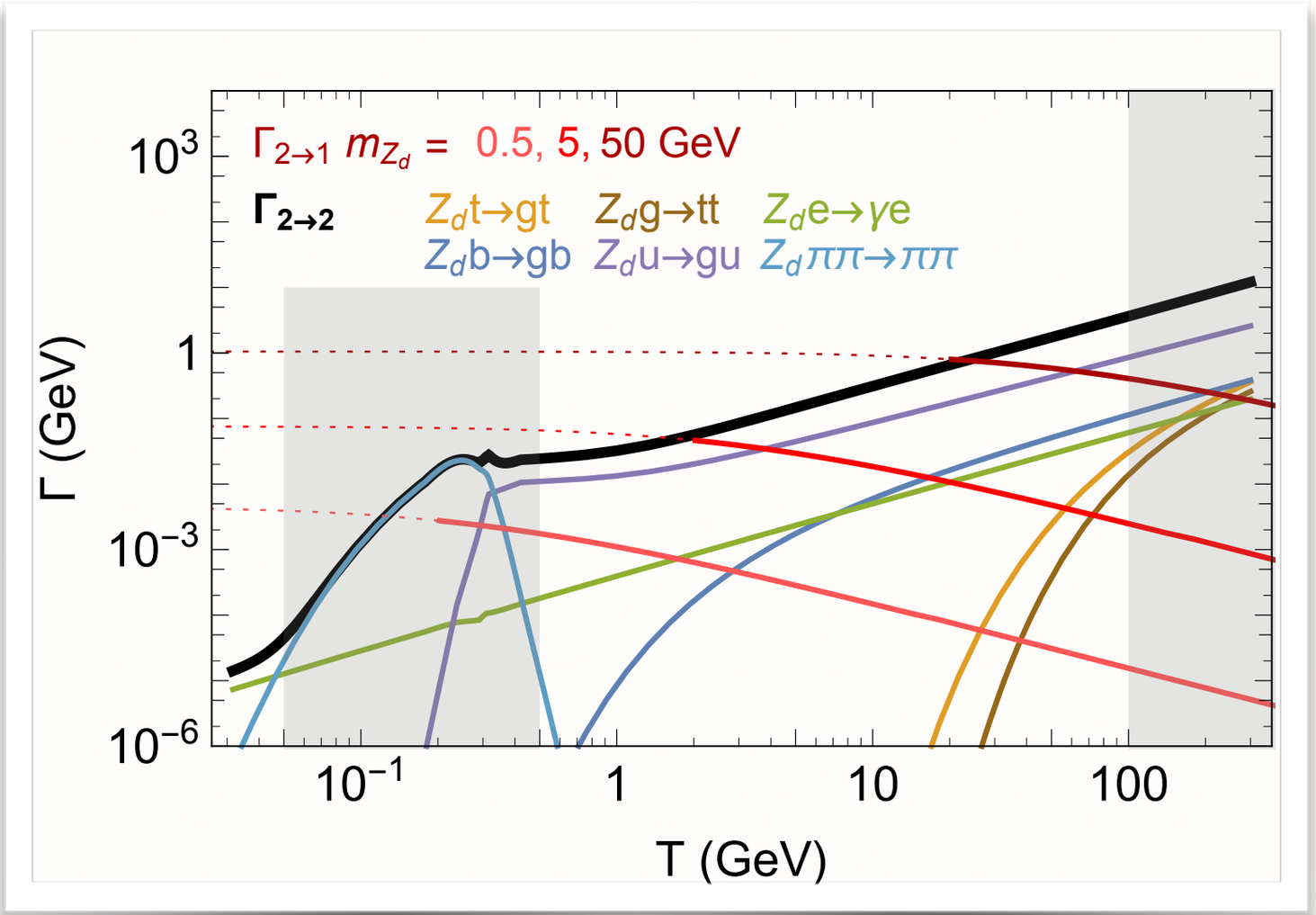




  - Processes are comparable in rate for $m_{med} \sim T_{fo}$: $O(1)$ shifts in necessary ϵ

Thermally coupled dark sector

- Some of the many scattering processes contributing to equilibration:



[Evans, Gori, JS]

Thermally coupled dark sector

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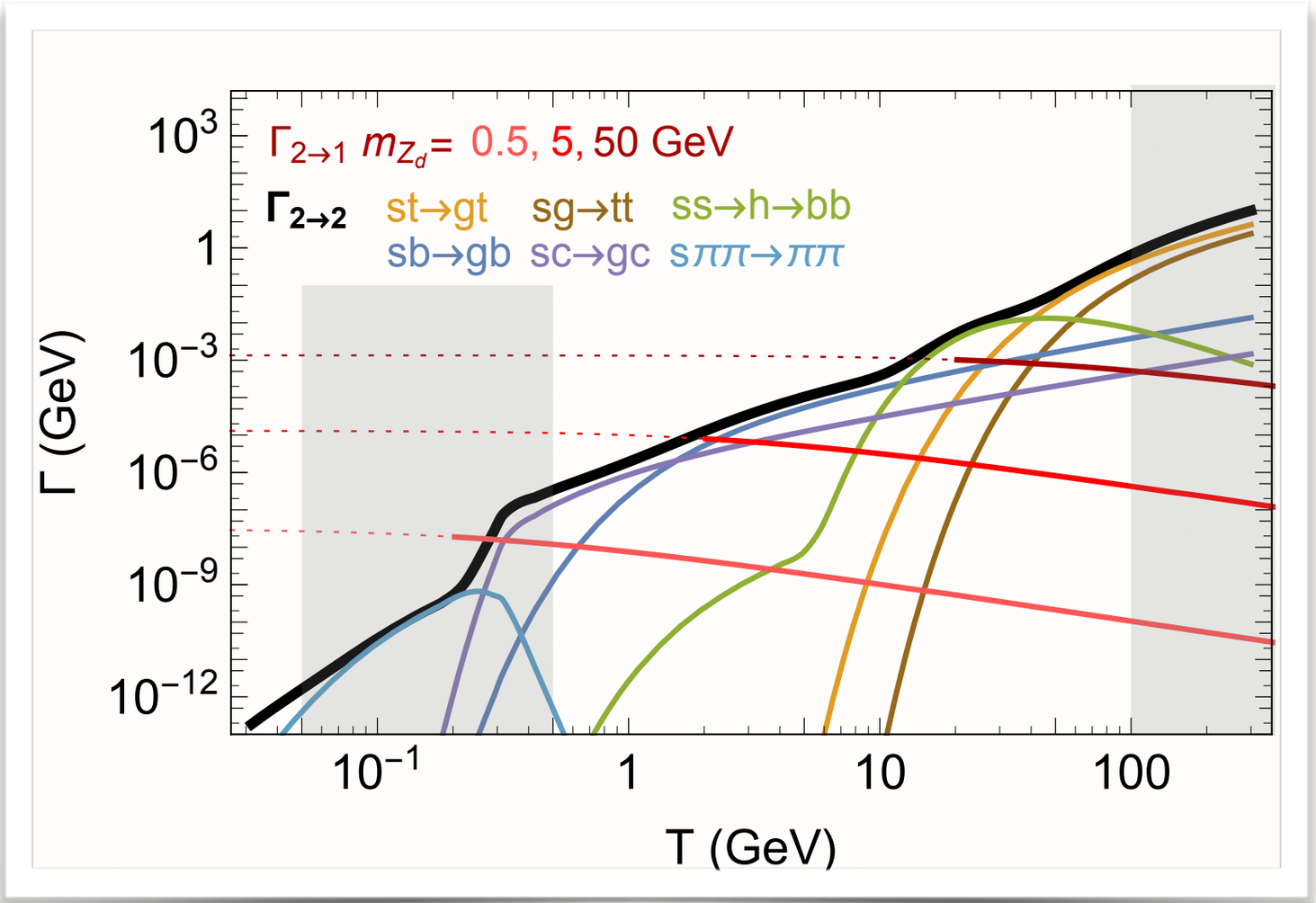

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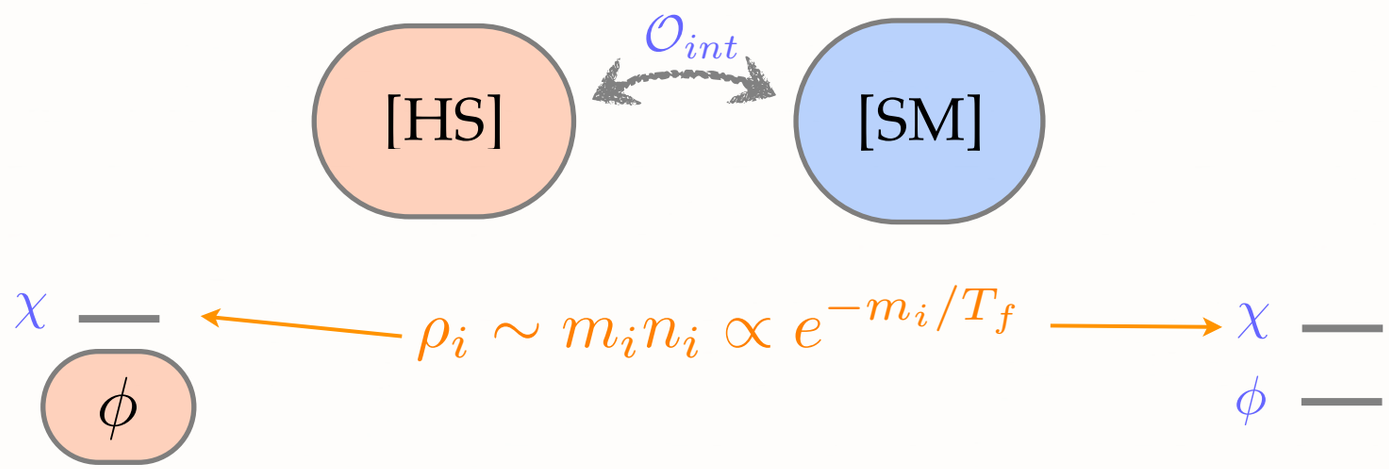
Thermally coupled dark sector

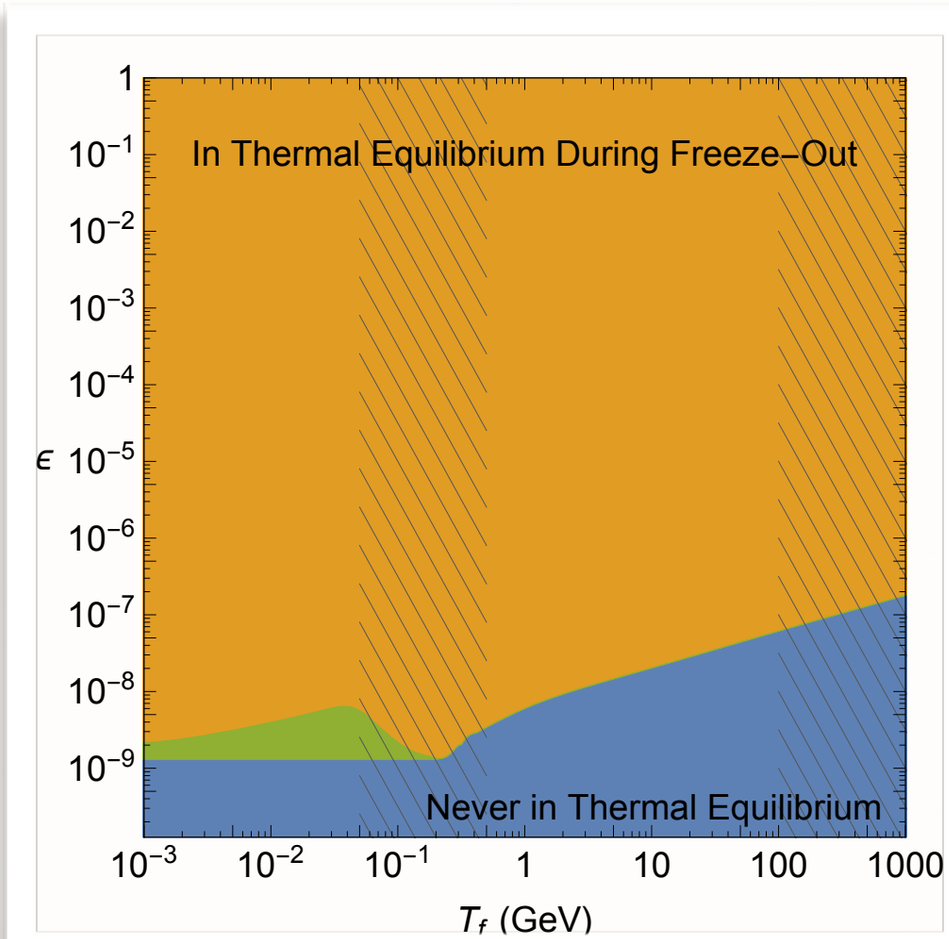
- Importance of a dark radiation bath:



- 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



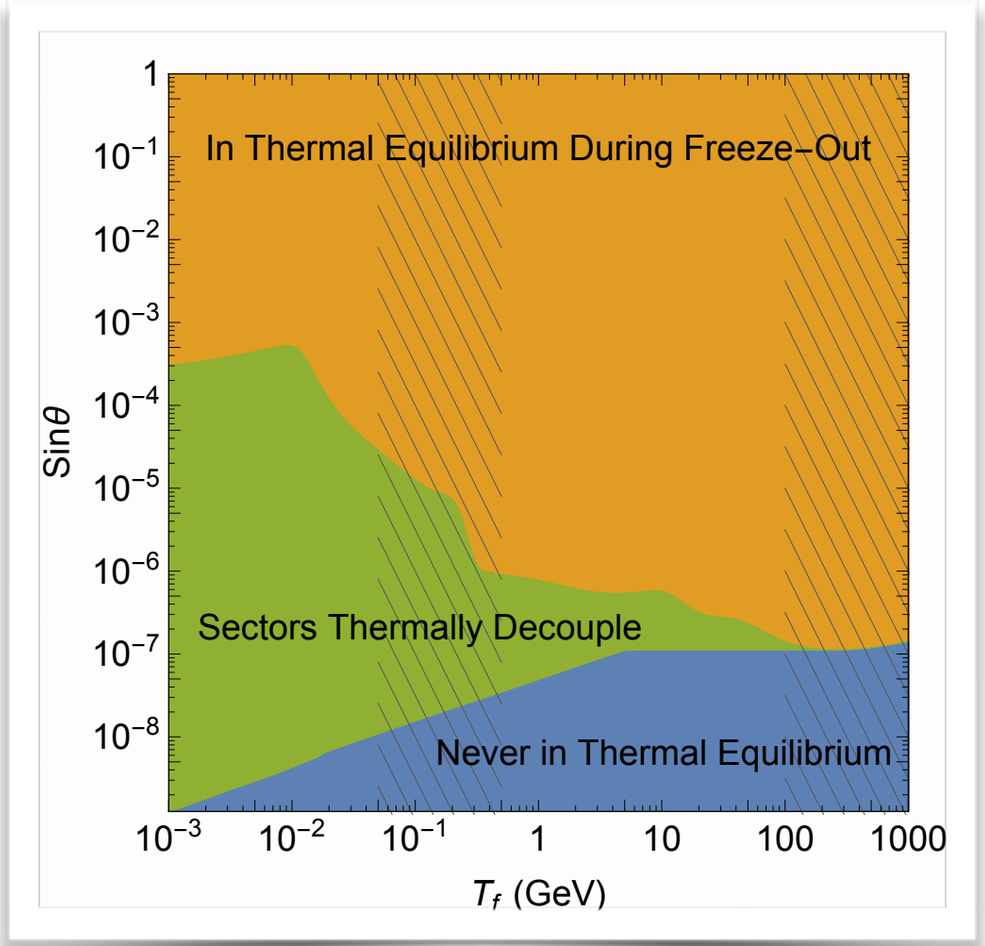
- Comparing sum of scattering rates involving (mostly) SM fermions to Hubble
- thermally averaged using Maxwellian statistics

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:

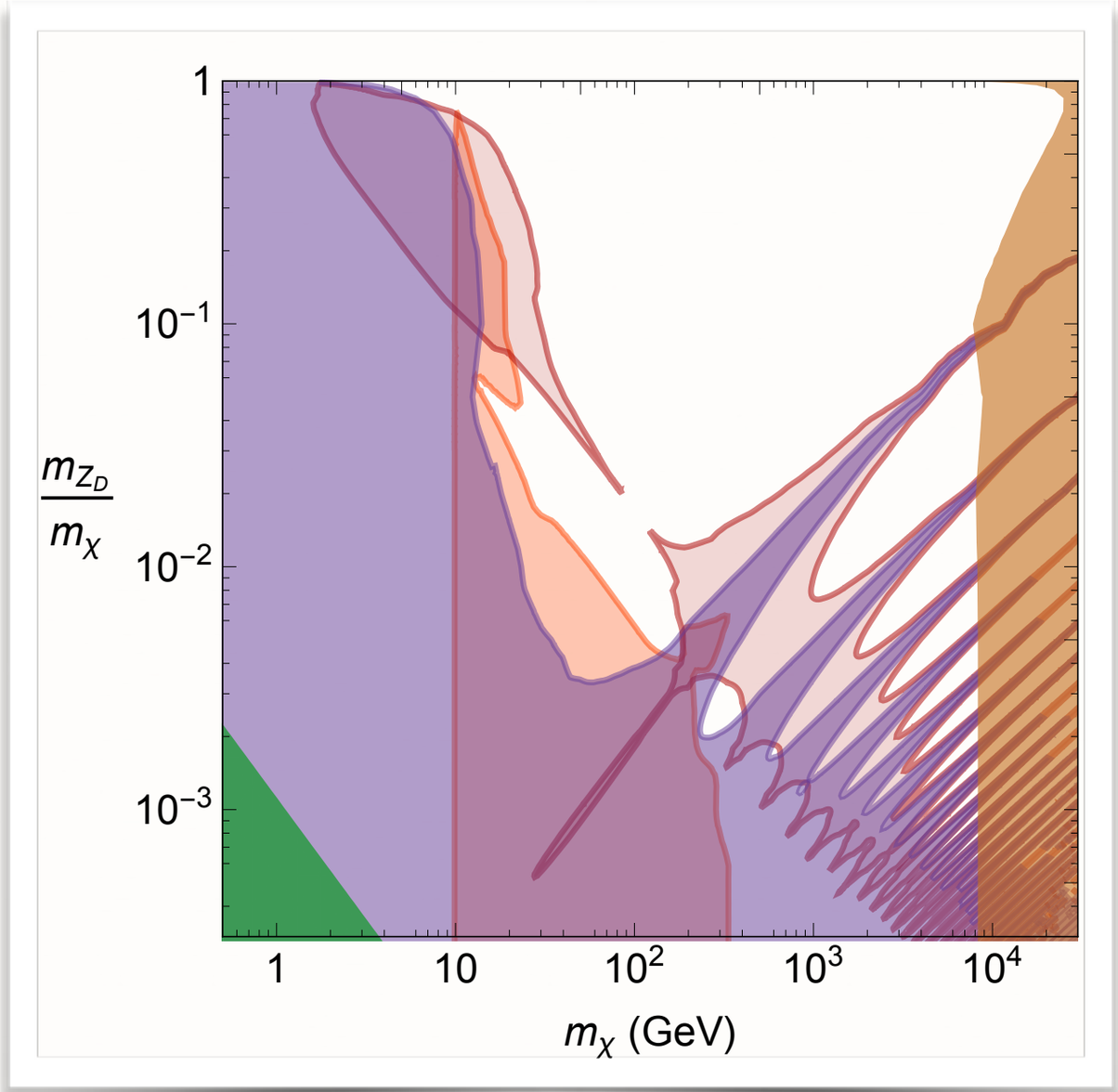
$$\mathcal{L}_{int} = \bar{\chi}\gamma_\mu Z_D^\mu \chi - m_D \bar{\chi}\chi + \frac{1}{2} m_{Z_D}^2 Z_{D\mu} Z_D^\mu + \frac{\epsilon}{2\cos\theta_W} Z_{\mu\nu} B^{\mu\nu}$$

  - 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 ⇒ astrophysical constraints from cosmic rays, CMB



[Evans, Gori, JS]

Simple vector portal model

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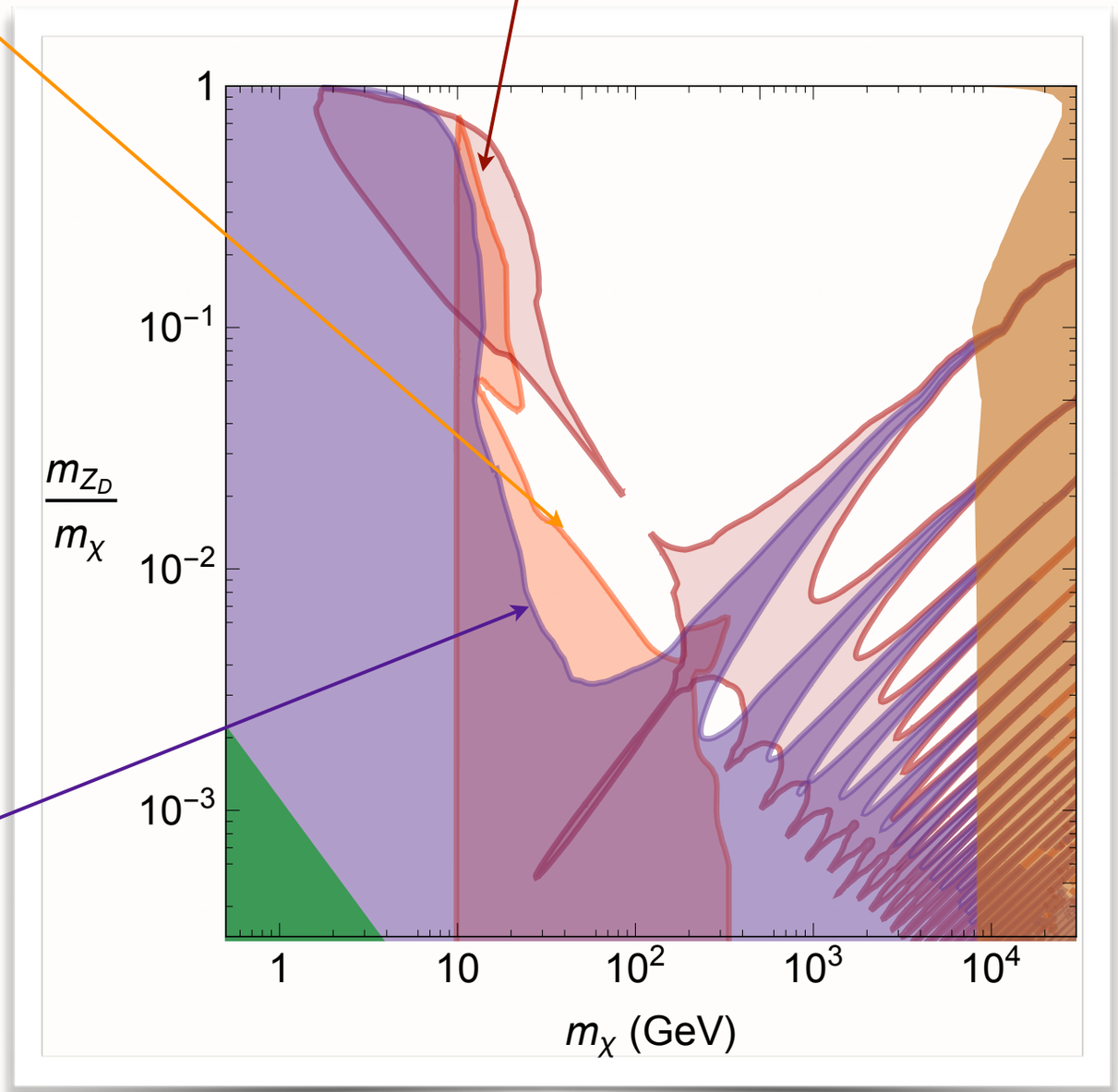
Excluded by Fermi dwarfs

Excluded by AMS-02 positrons

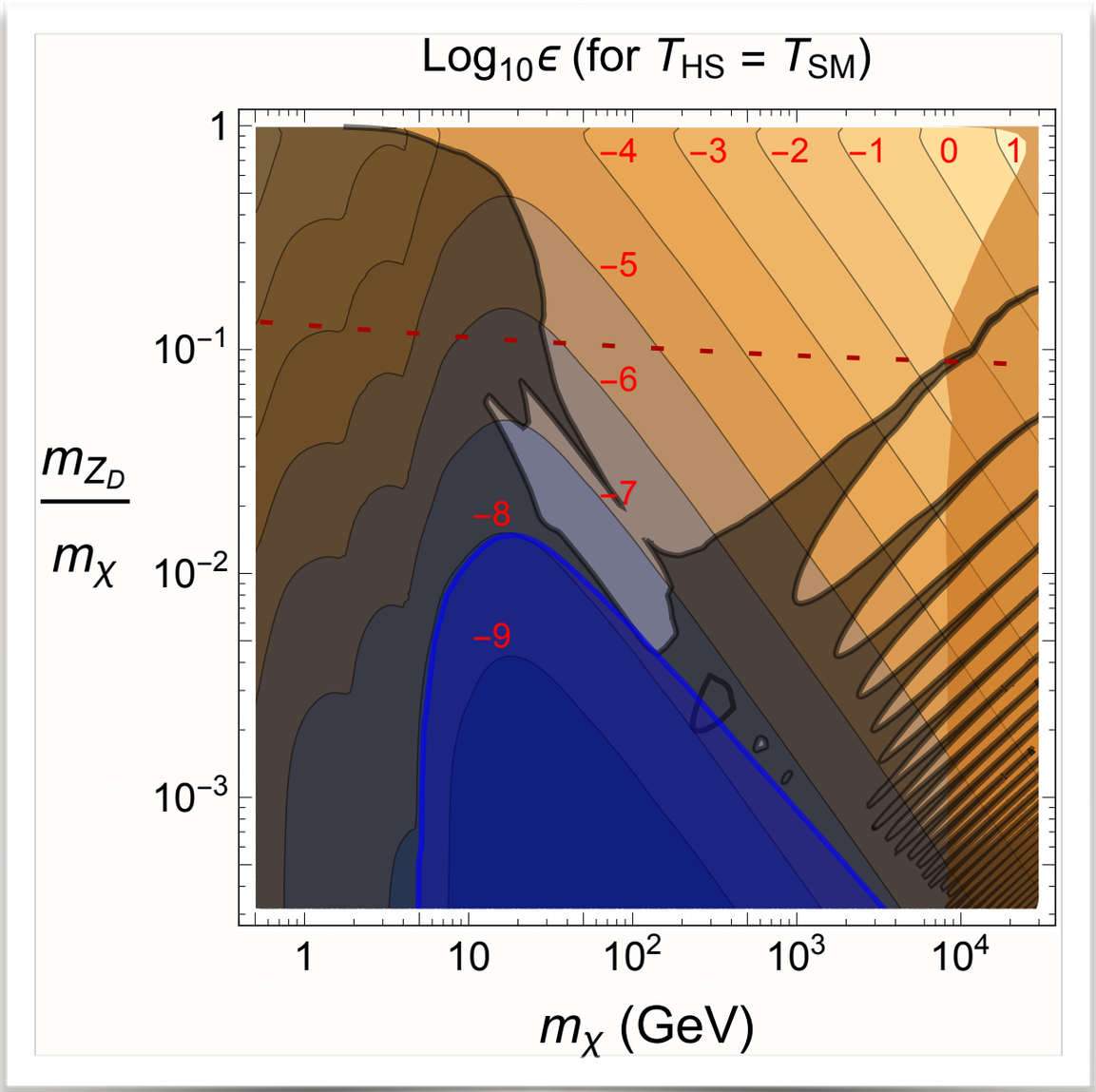


Excluded by Planck

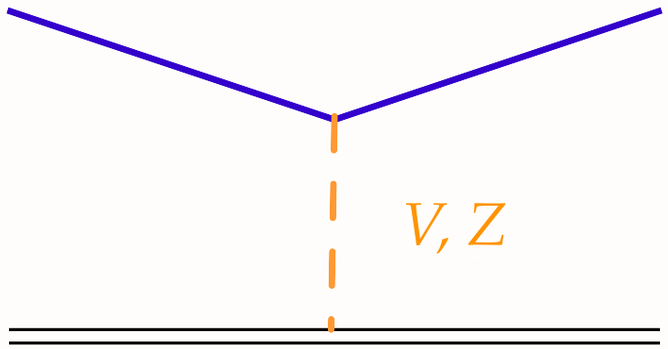
[Evans, Gori, JS]

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]

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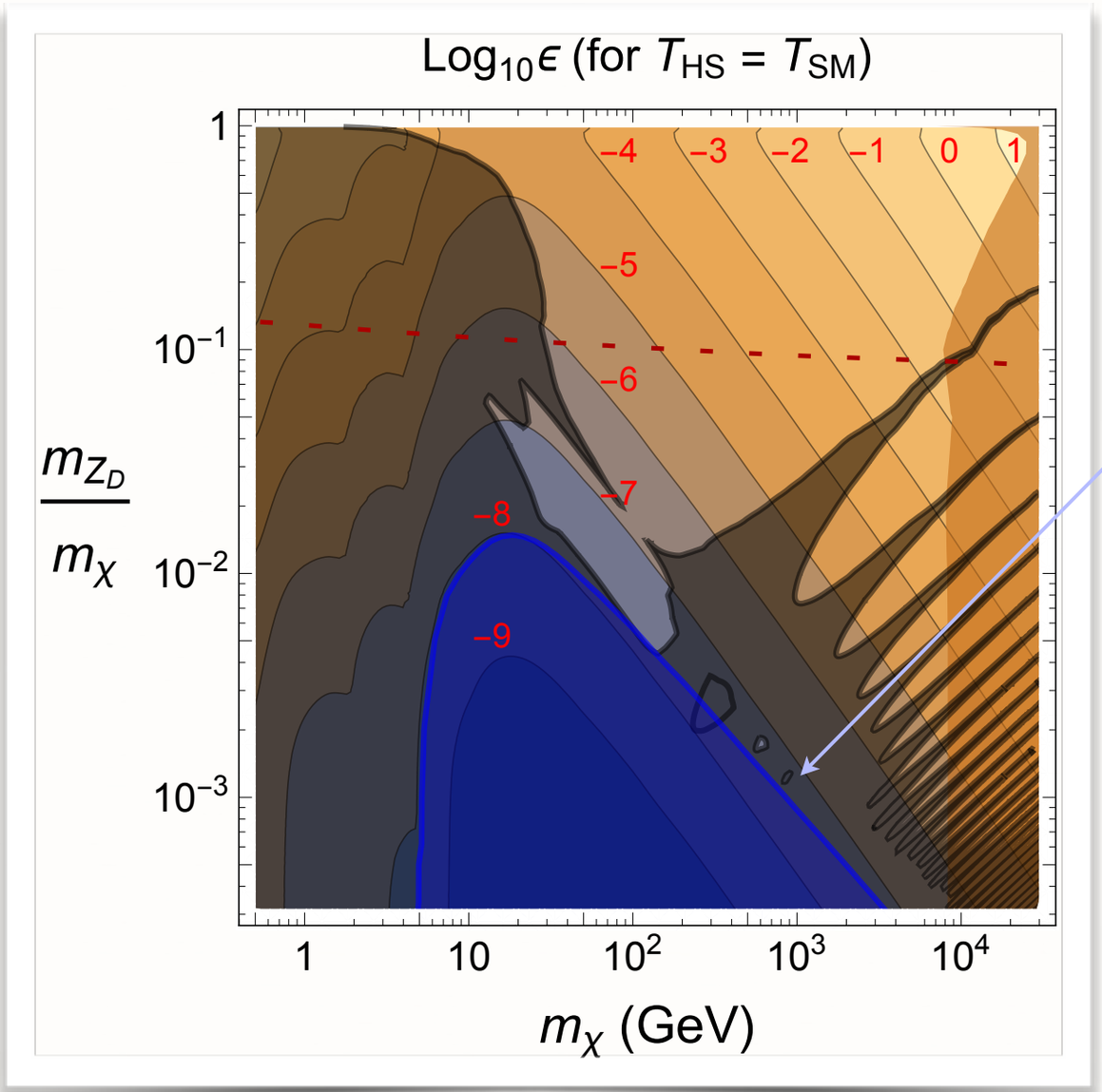
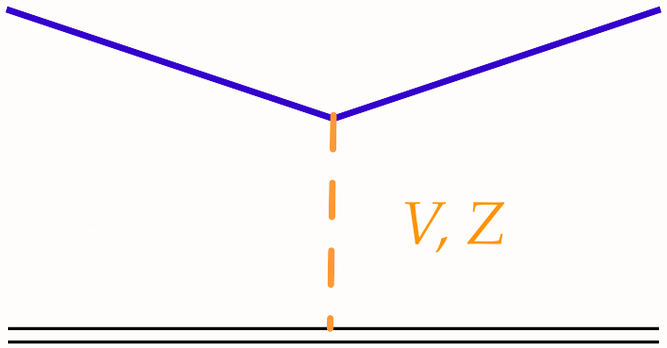


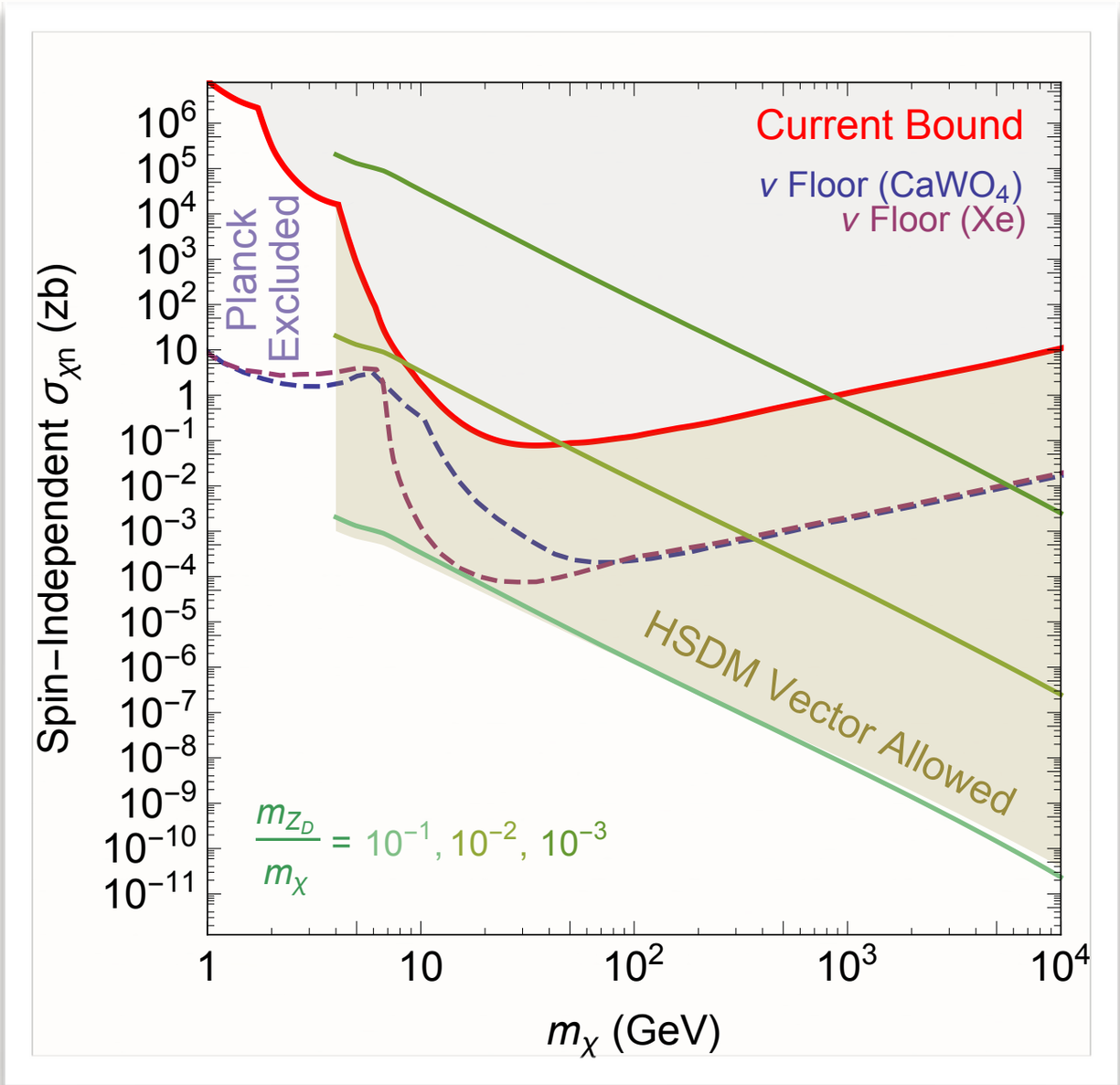
Direct detection can probe down to cosmological lower bound in favorable parts of parameter space



[Evans, Gori, JS]

Simple vector portal model

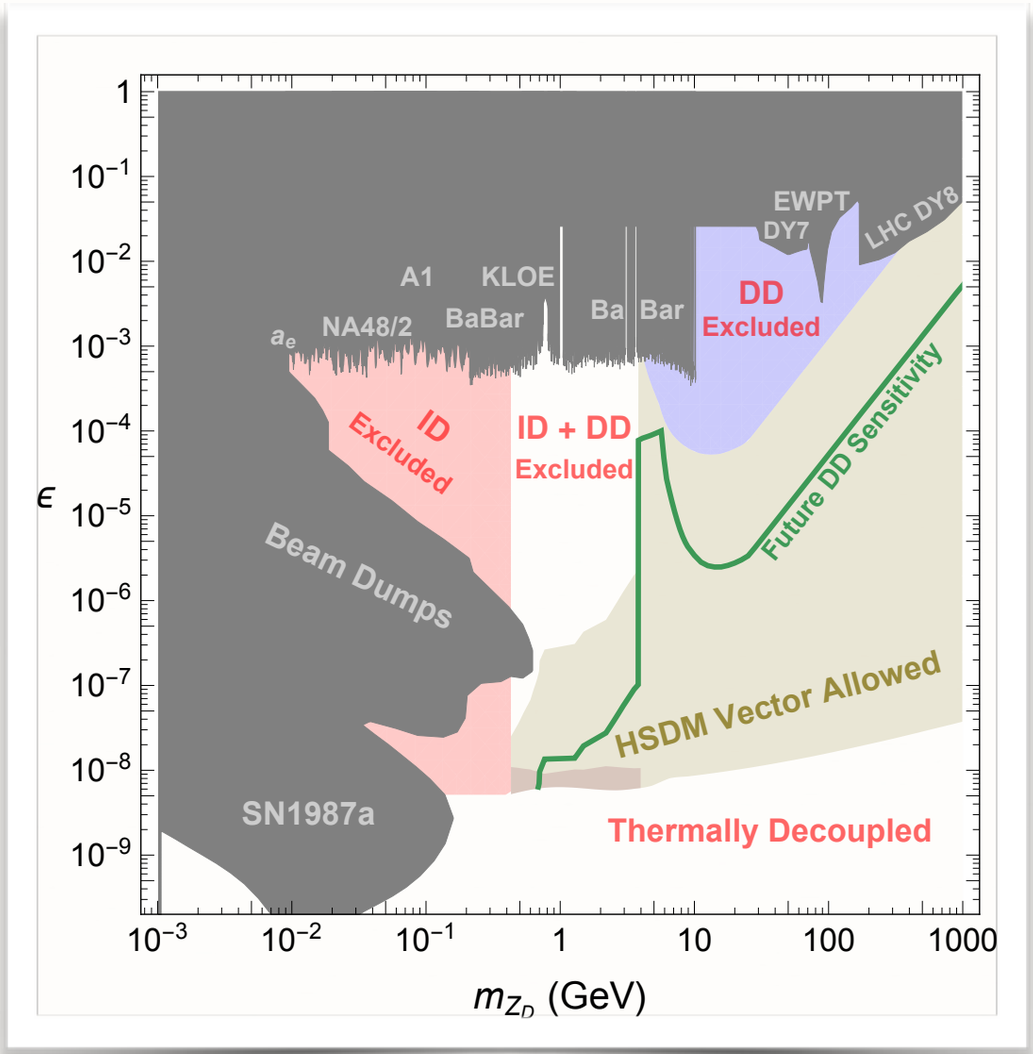
- Direct detection regions of interest below neutrino floor



[Evans, Gori, JS]

Simple vector portal model

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



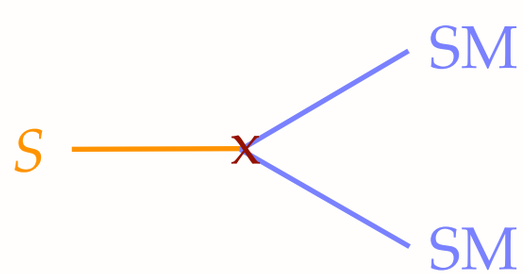
[Evans, Gori, JS]

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

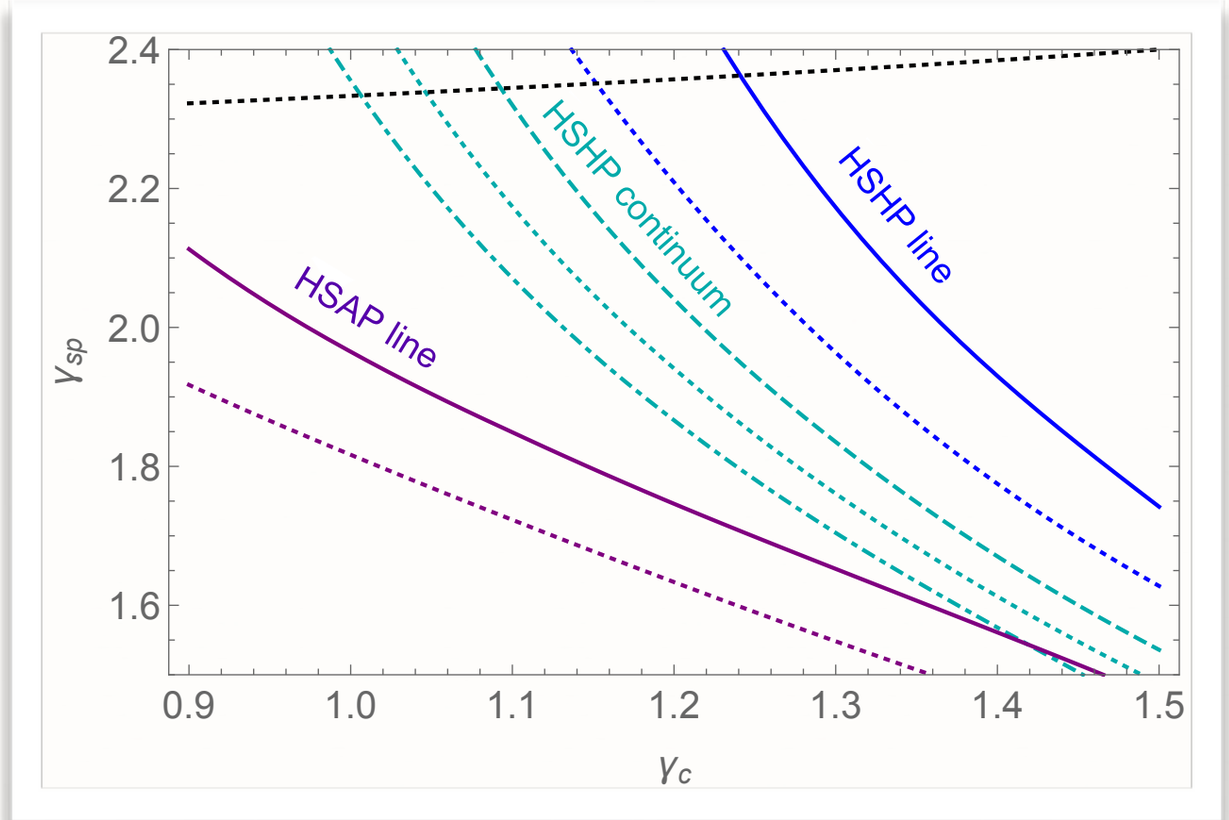


$$\theta_h = \frac{\epsilon\langle S\rangle v_h}{m_h^2 - m_s^2}$$

[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

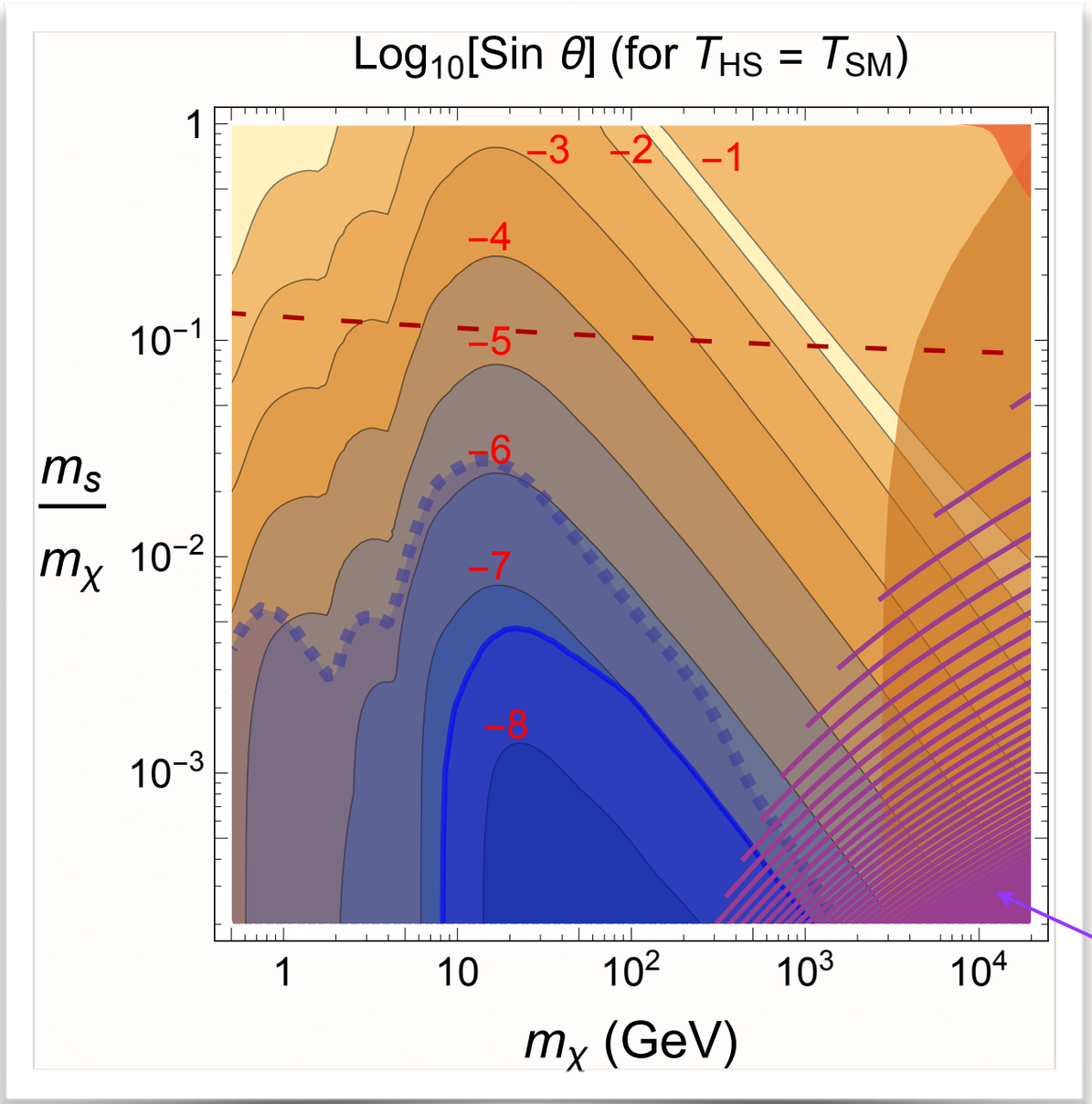


Sensitivity from annihilation in a potential density spike around the Milky Way's super-massive black hole

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

Simple Higgs portal model

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



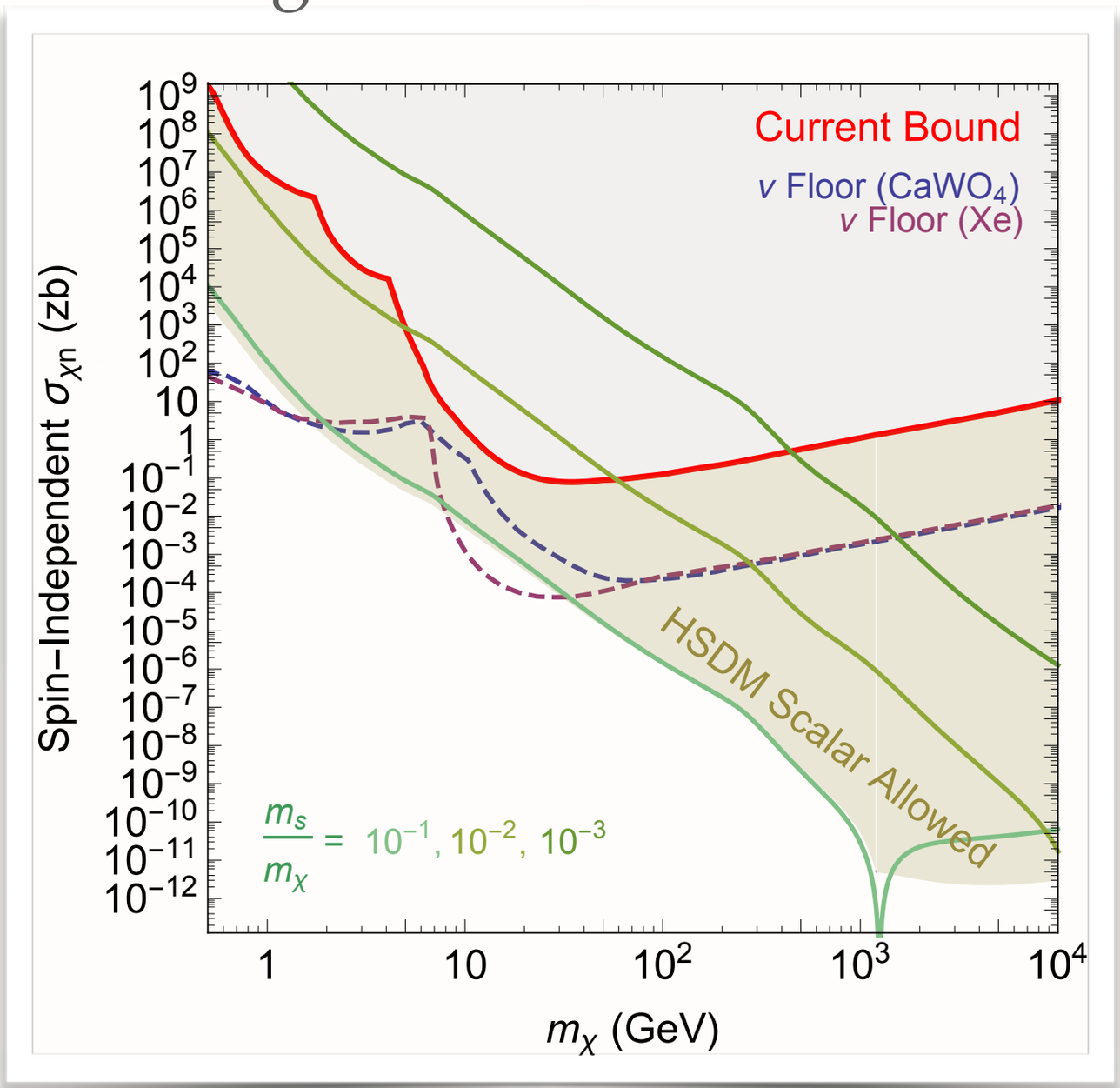
- Leading spin-independent interaction
- Yukawa-suppressed nucleon couplings lead to relatively smaller cross-sections
- Can again see down to cosmologically interesting values of portal coupling

Planck constraints from bound state formation

[Evans, Gori, JS]

Simple Higgs portal model

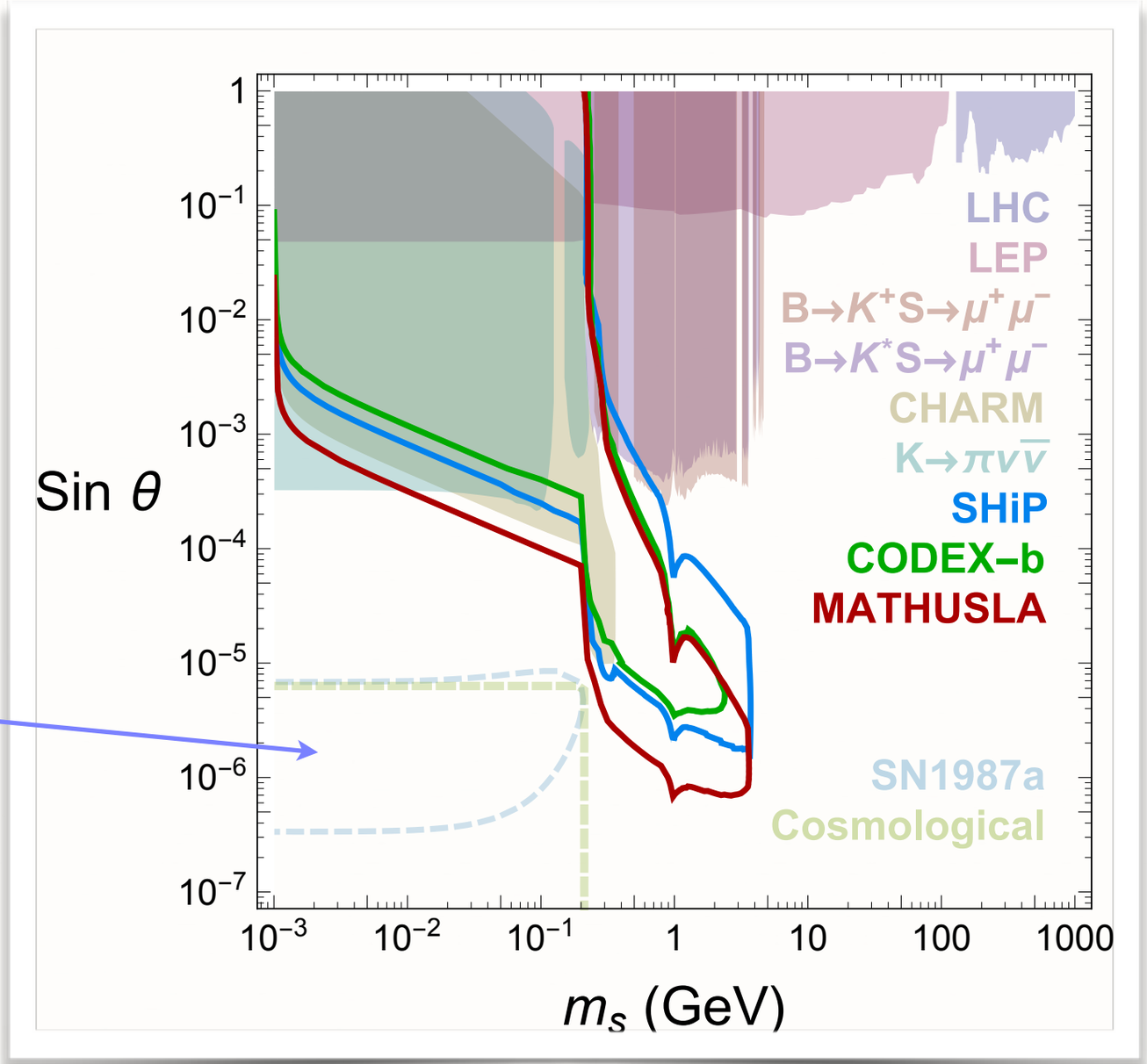
- Direct detection regions of interest below neutrino floor



[Evans, Gori, JS]

Simple Higgs portal model

- Leading accelerator searches again for mediator:

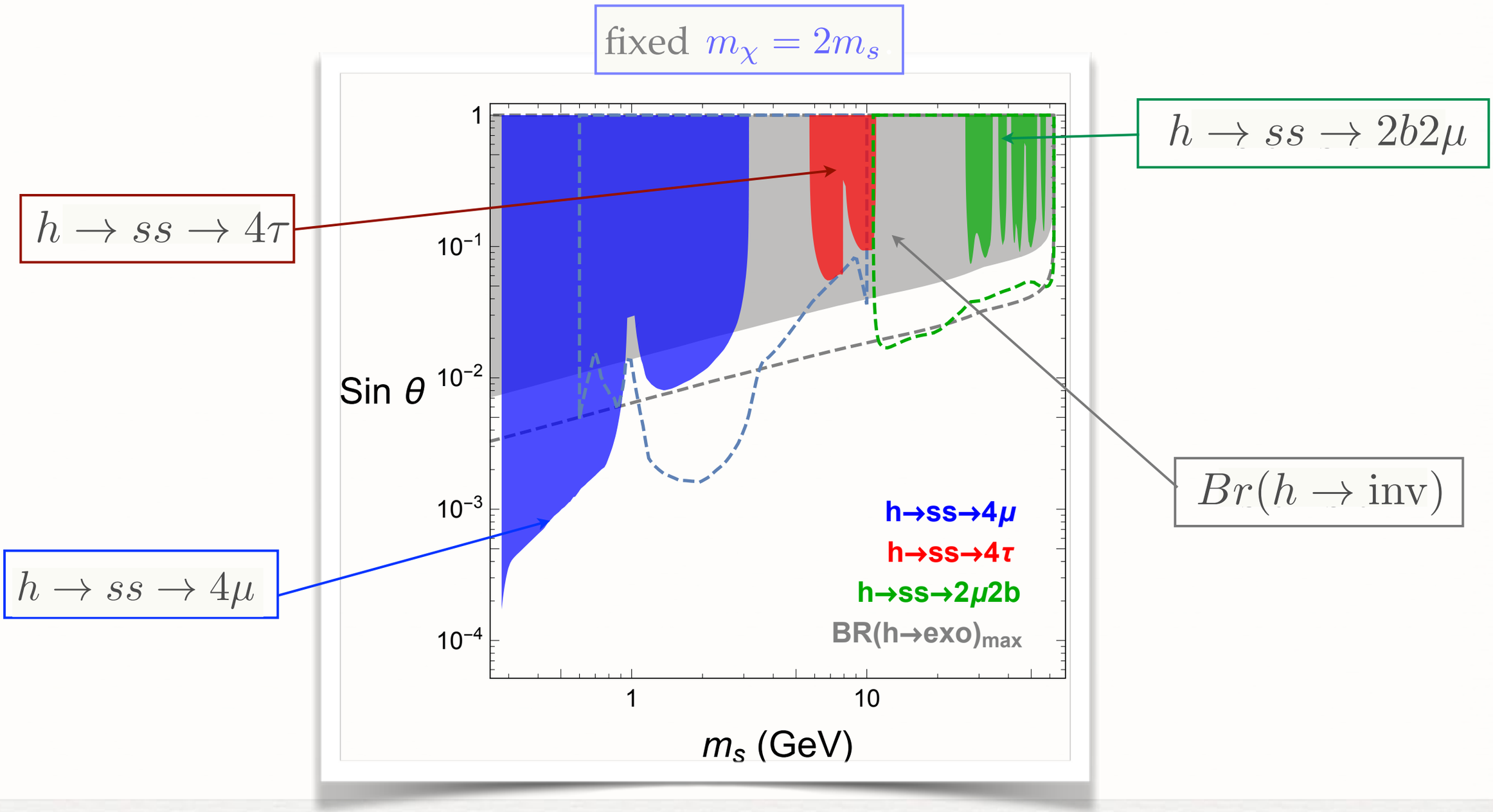


Below muon threshhold, astro / cosmo bounds

[Evans, Gori, JS]

Simple Higgs portal model

- Exotic Higgs decays additionally depend on S vev



[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