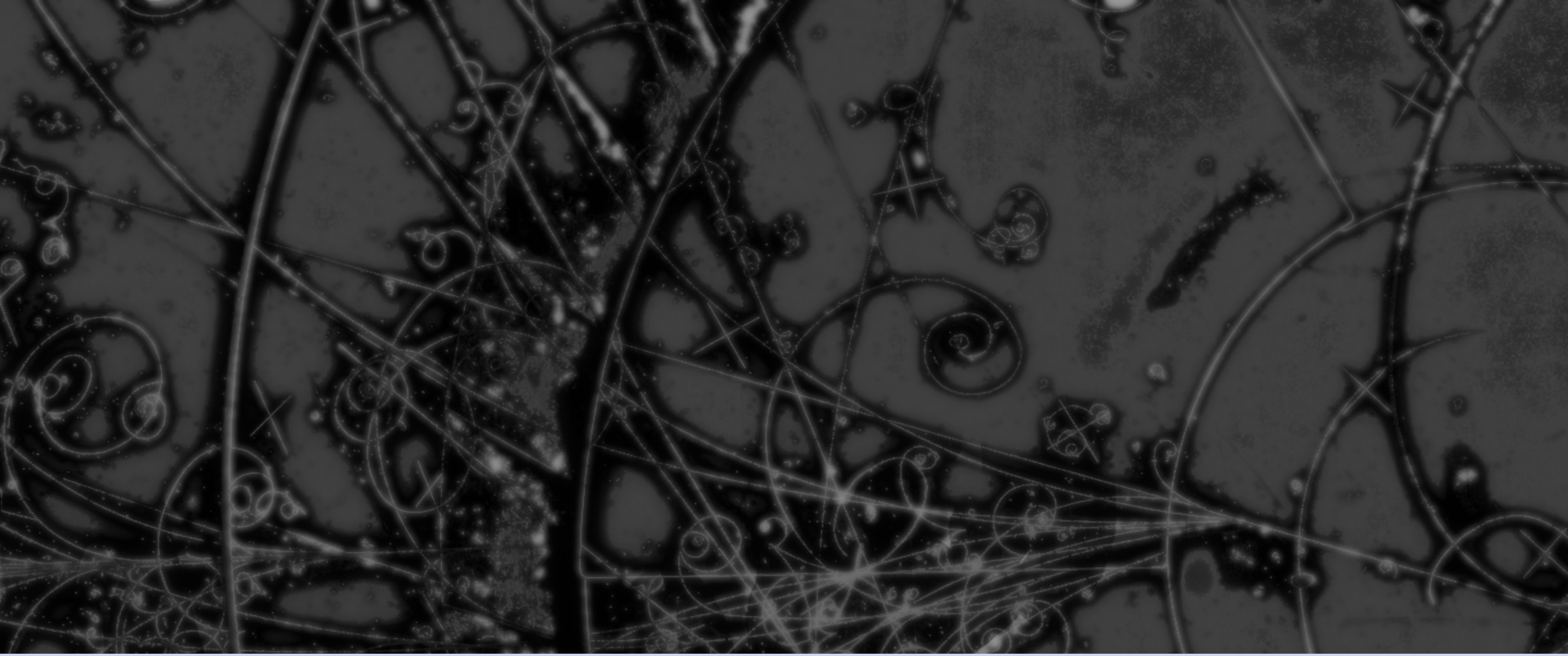
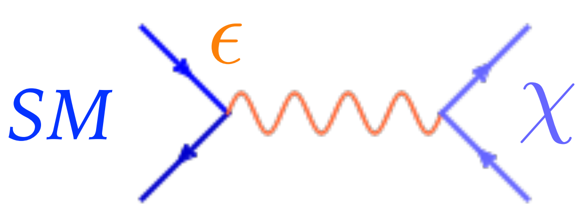


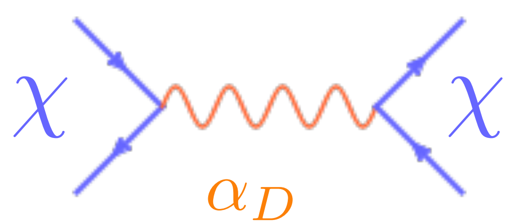
MORE FUN WITH LIGHT DARK MEDIATORS

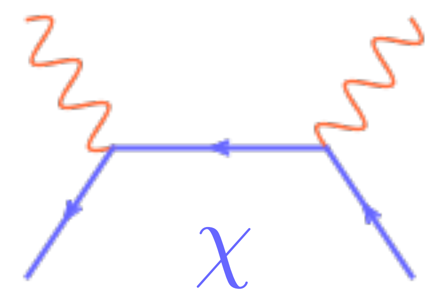
Jessie Shelton
Illinois Center for the Advanced Center of the Universe, UIUC
Brookhaven National Laboratory, May 26, 2022

TWO EXERCISES WITH LIGHT MEDIATORS

- Dark matter that interacts via a long-range dark force does interesting things! This talk:
  - gravitational capture
  - freeze-in
- Reference model:
  - Dirac fermion DM, interacting with light dark photon





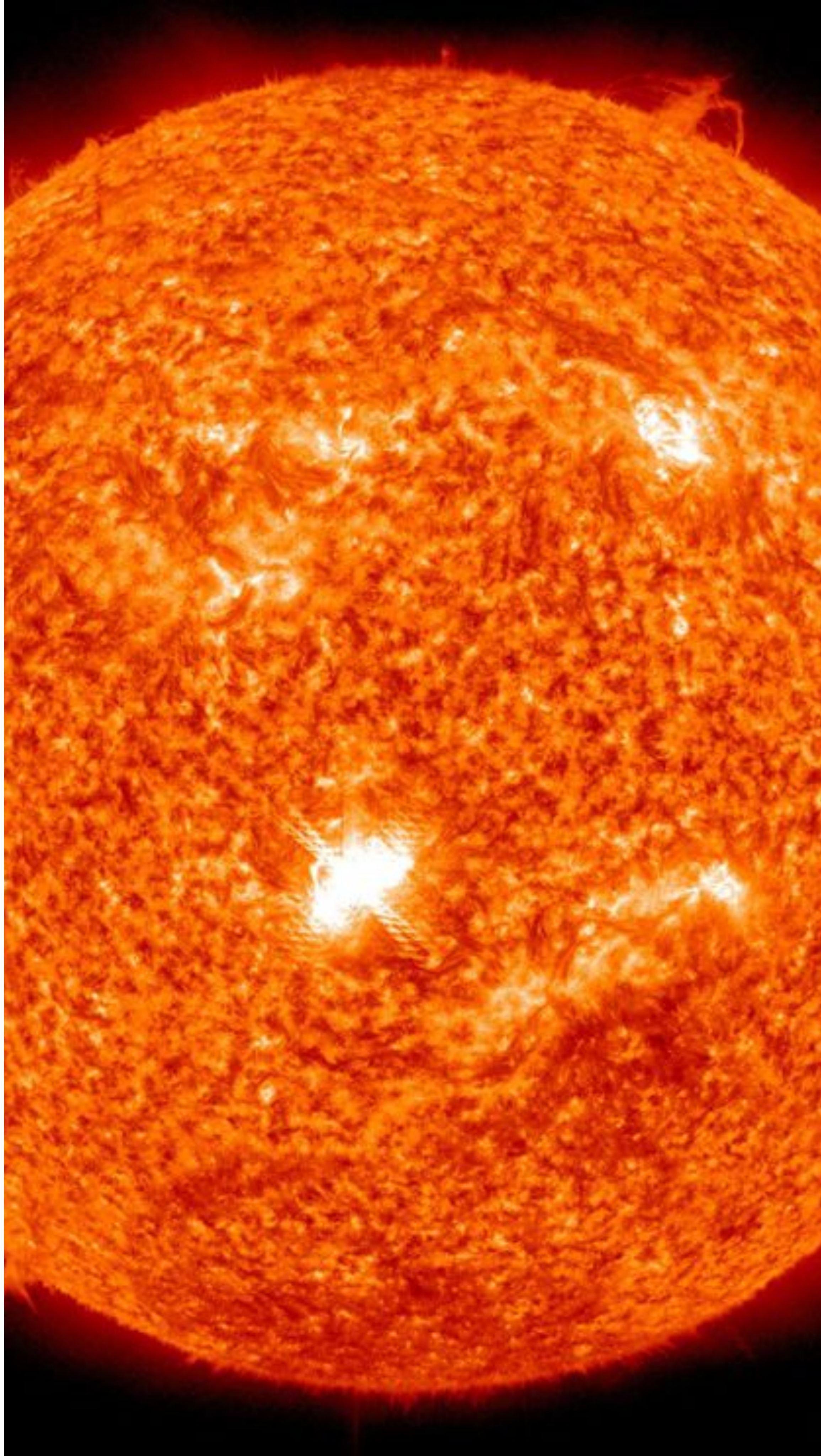


  - mass basis: SM photon does not couple to DM (but couplings, effective mass modified in medium)

PART I

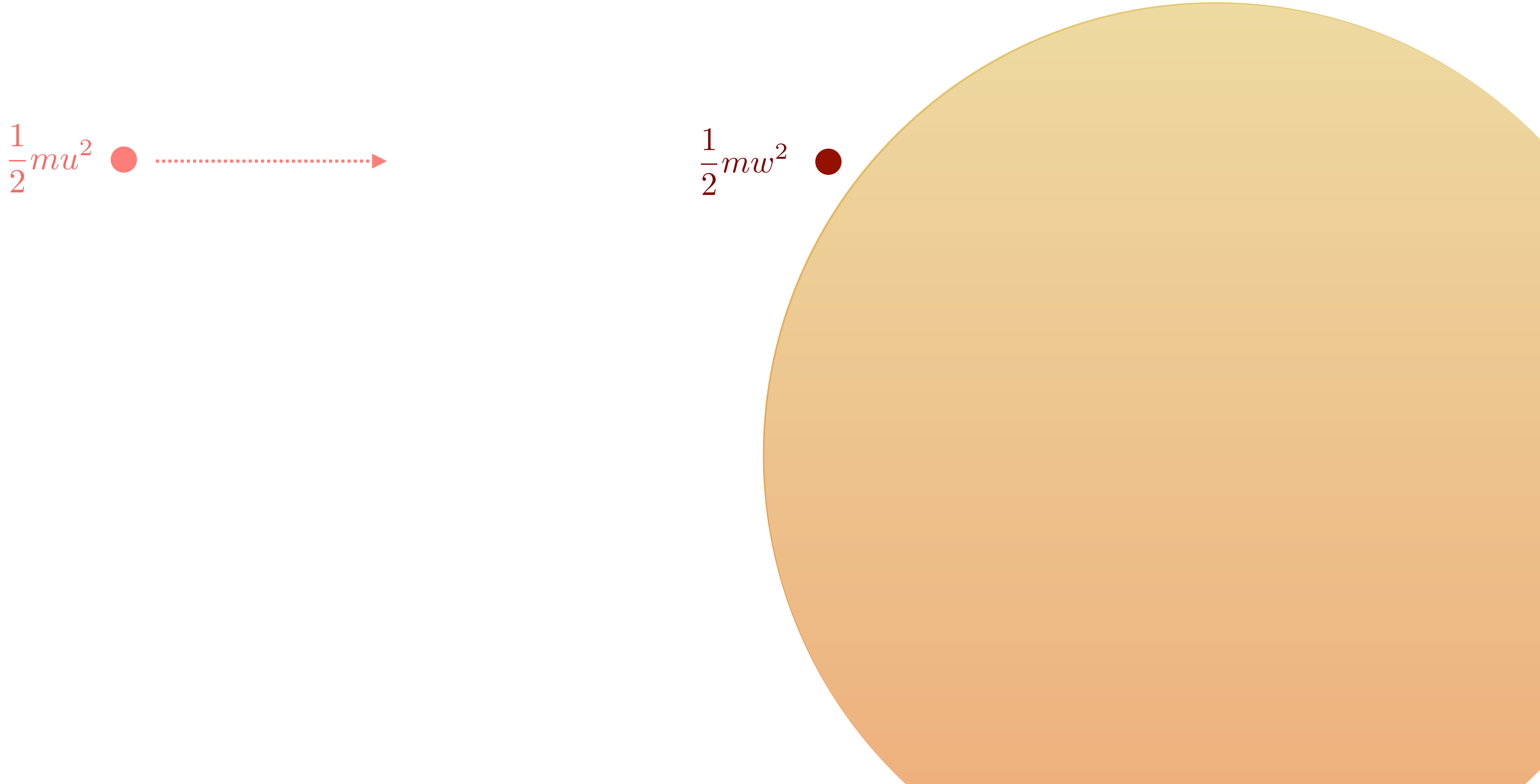
long-range capture

arXiv:2110.02234 with Cristian Gaidau



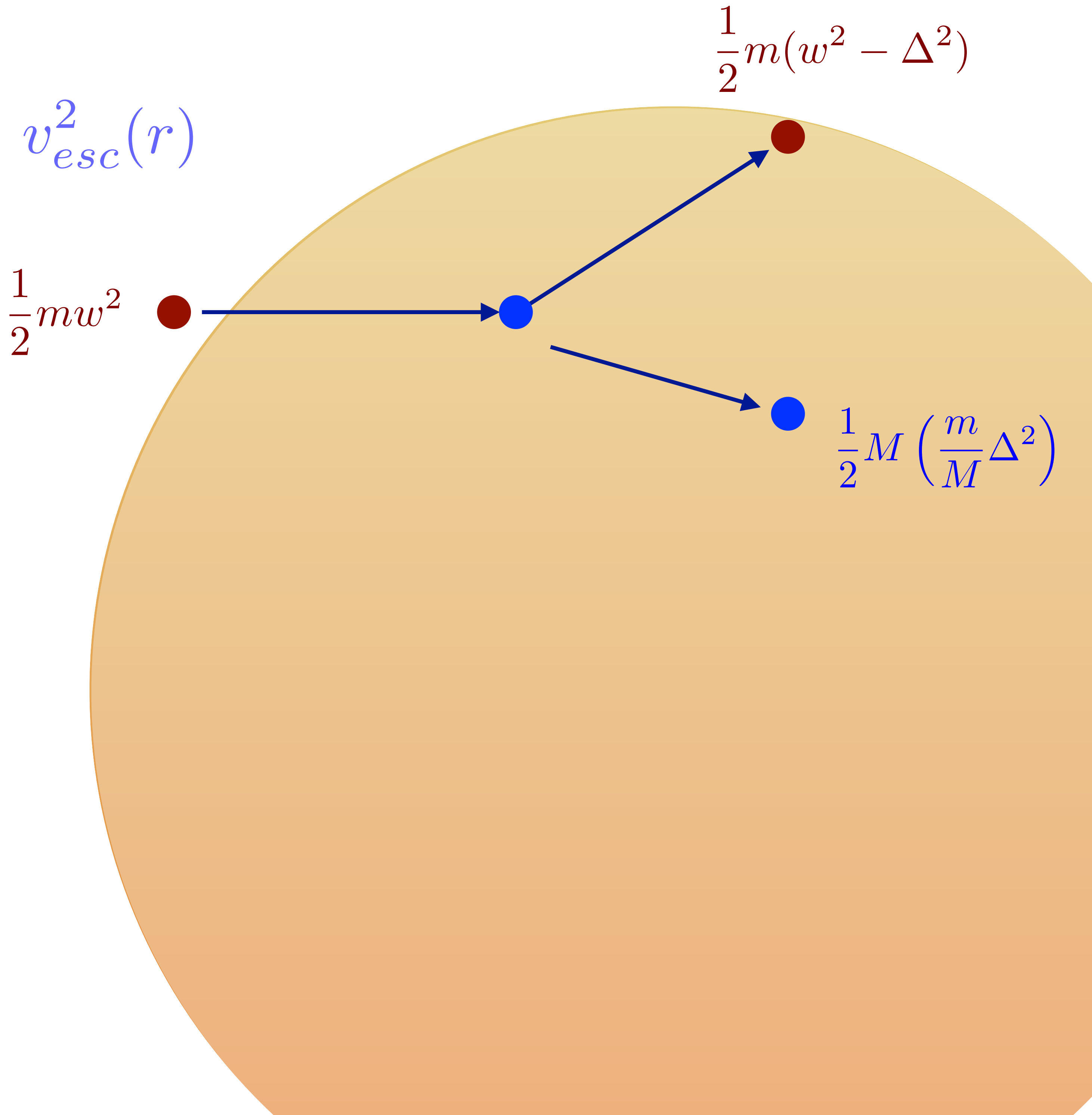
GRAVITATIONAL CAPTURE IN THE SUN

Infall: $w^2 = u^2 + v_{esc}^2(r)$



GRAVITATIONAL CAPTURE IN THE SUN

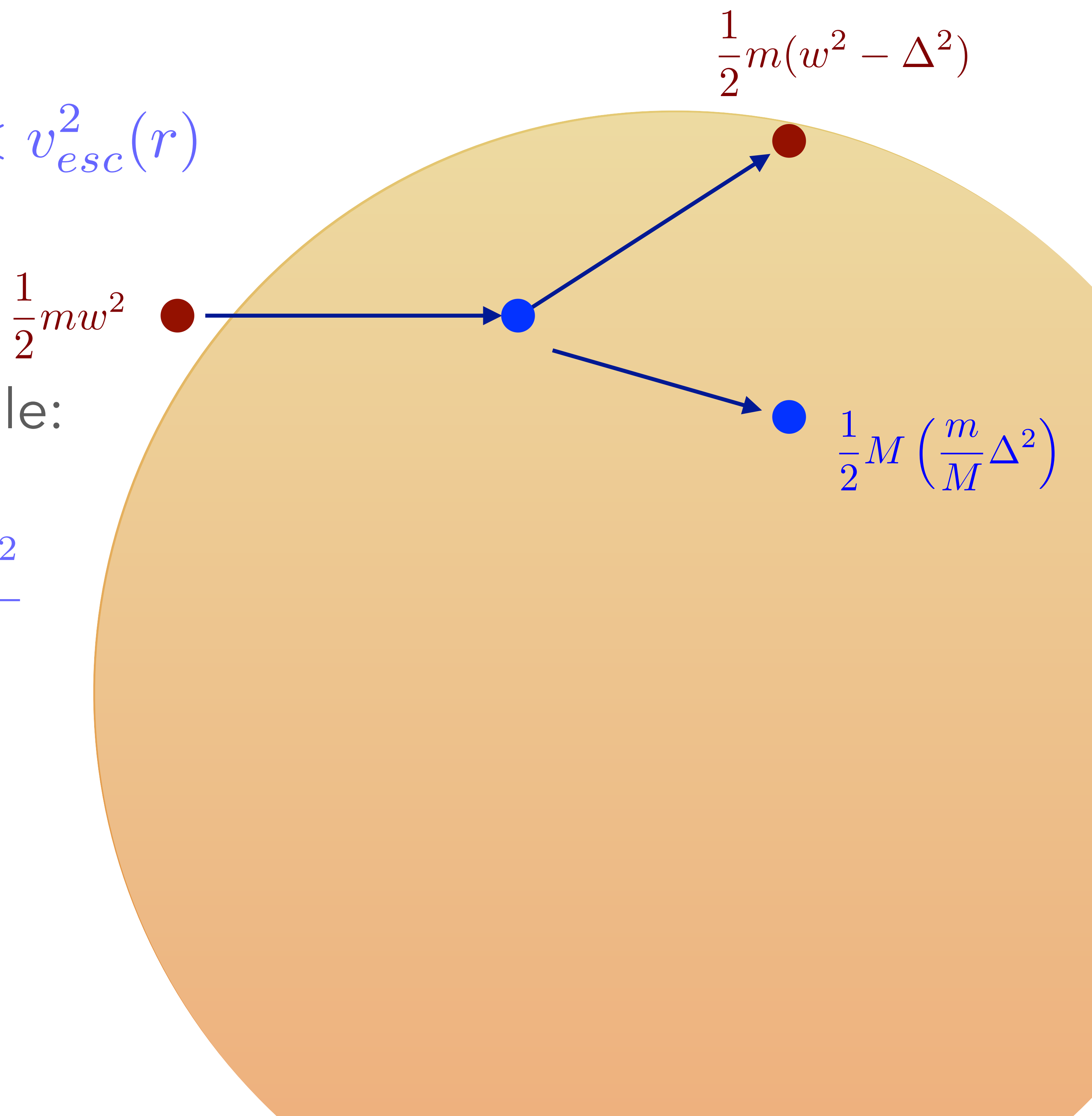
- Infall: $w^2 = u^2 + v_{esc}^2(r)$
- Capture: $w^2 - \Delta^2(\cos\theta) < v_{esc}^2(r)$



GRAVITATIONAL CAPTURE IN THE SUN

- Infall: $w^2 = u^2 + v_{esc}^2(r)$
- Capture: $w^2 - \Delta^2(\cos\theta) < v_{esc}^2(r)$
- Minimum CM scattering angle:

$$1 - \cos\theta \geq \frac{u^2}{u^2 + v_{esc}(r)^2}\frac{(M+m)^2}{2mM}$$



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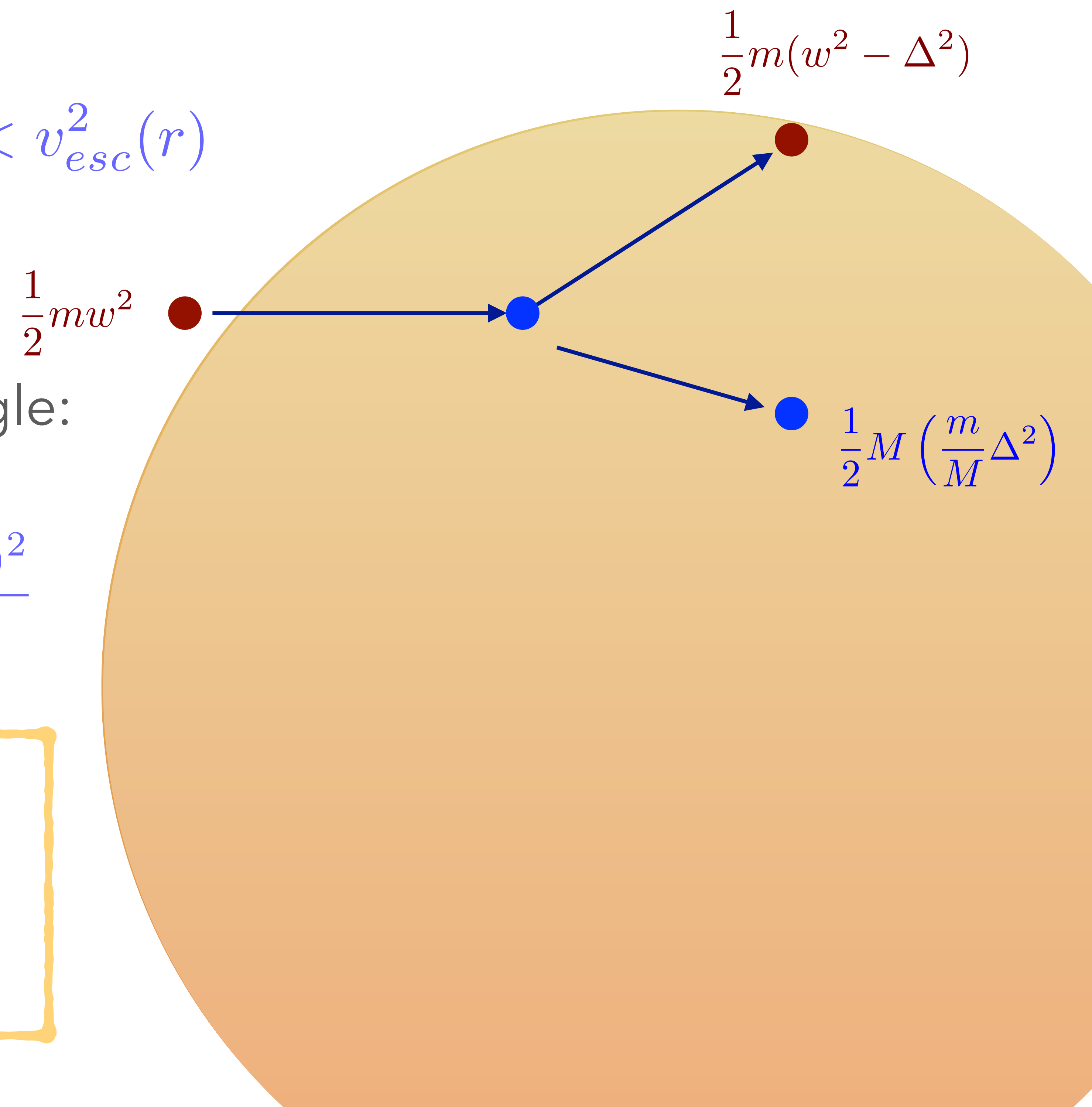


- Minimum CM scattering angle:

$$1 - \cos\theta \geq \frac{u^2}{u^2 + v_{esc}(r)^2}\frac{(M+m)^2}{2mM}$$

Per-particle capture rate at *r*:

$$\Omega(w) = n_N(r)w\int^{\cos\theta_{max}} d\cos\theta\frac{d\sigma}{d\cos\theta}$$

GRAVITATIONAL CAPTURE IN THE SUN

- Total capture rate depends on depth of potential well: $w^2 = u^2 + v_{esc}(r)^2$

velocity distribution outside potential well

gravitational focusing

$$\frac{dC_c}{dV} = n_\chi \int_0^\infty du\, f(u) \frac{w}{u} \Omega(w)$$

capture rate at r

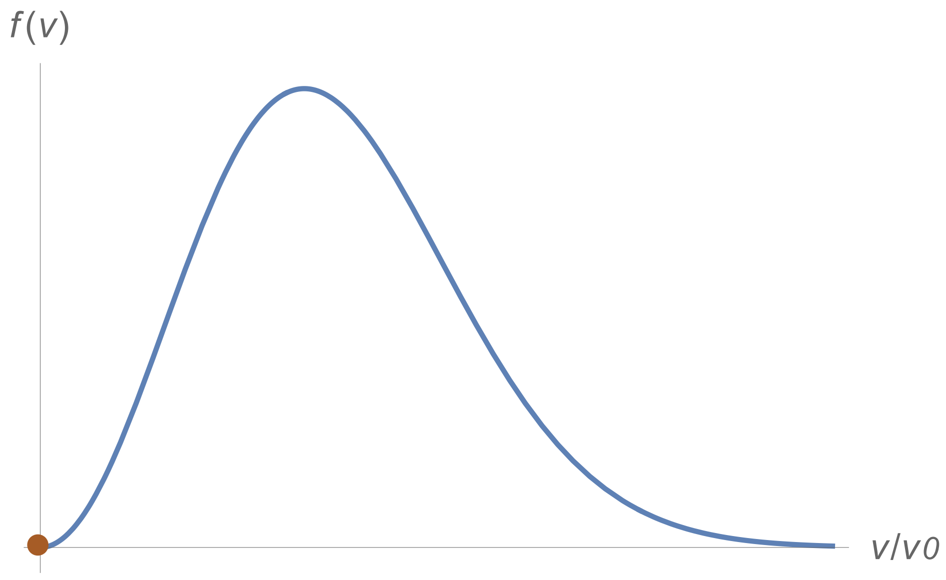
local number density of dark matter

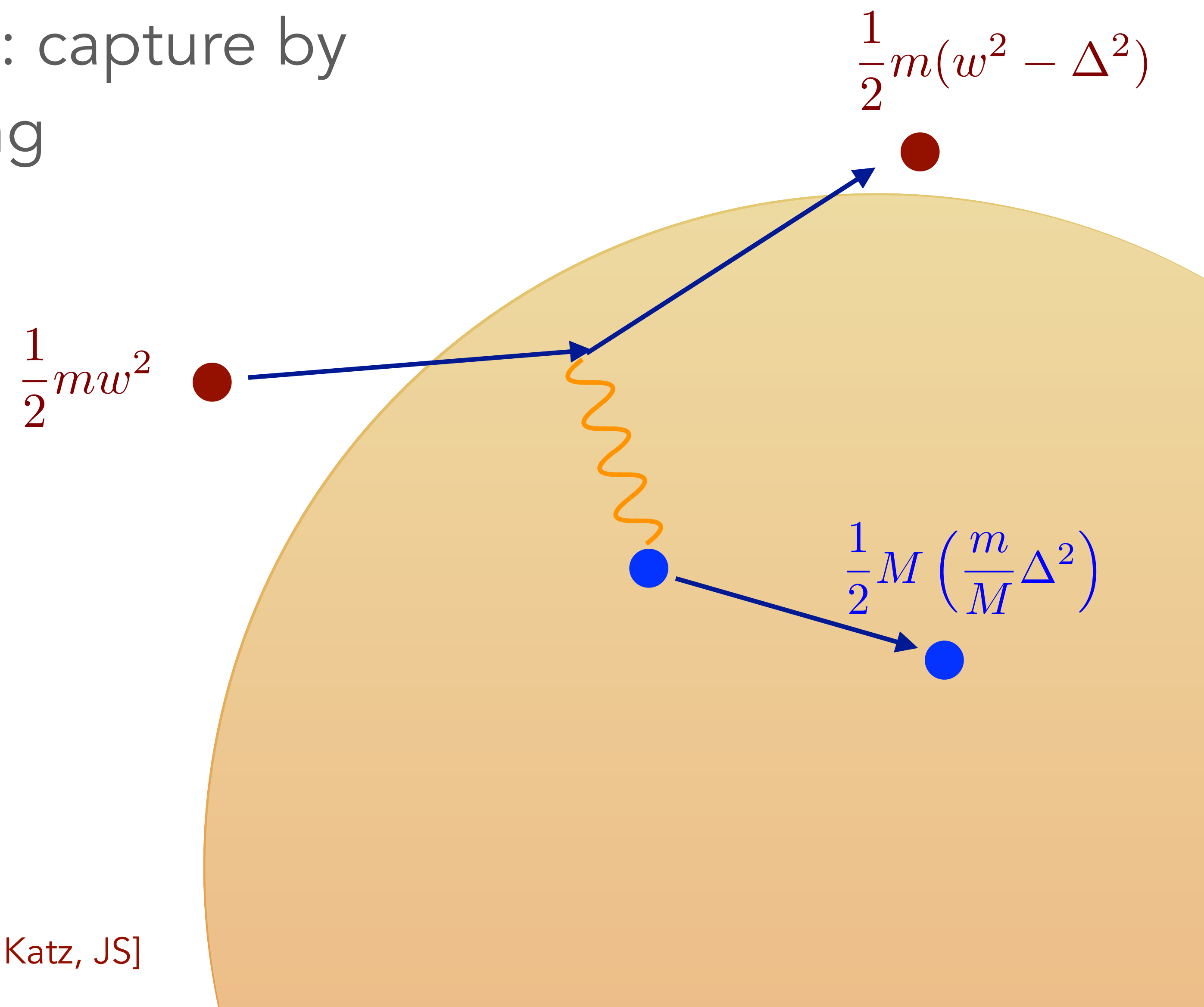
- $v_{esc}(r)$ at center of Sun: ~1300 km/s
- rms halo speed: ~290 km/s

[Gould]

CAPTURE THROUGH LONG-RANGE INTERACTIONS

- Long-range scattering: forward singularity
  - regulated collision-by-collision by minimum scattering angle for capture
  - log divergent as u to 0: capture by arbitrarily soft scattering

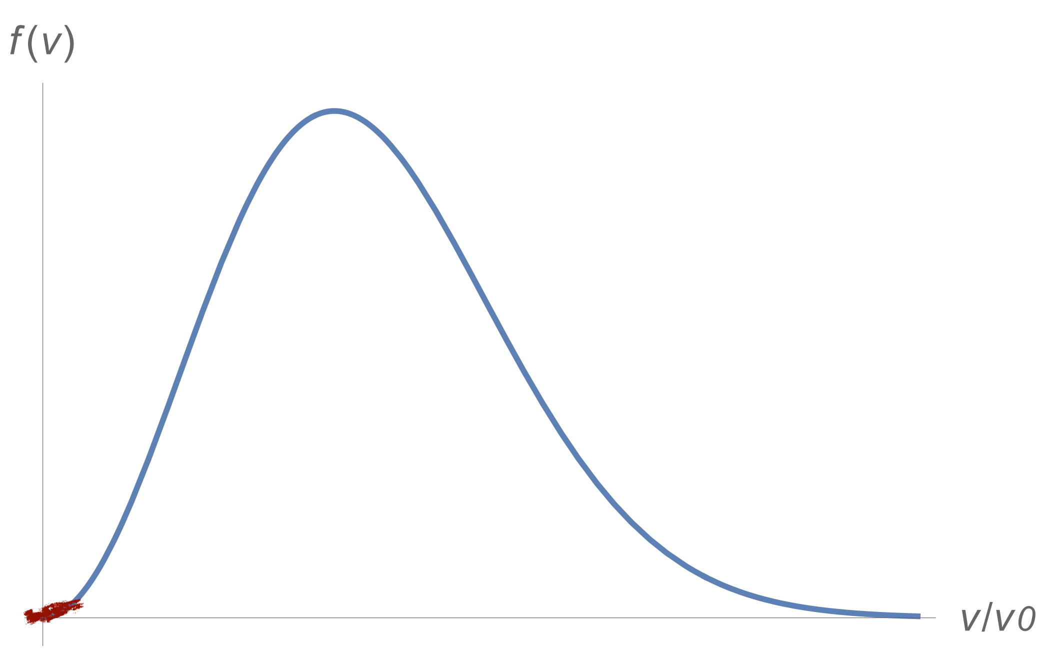


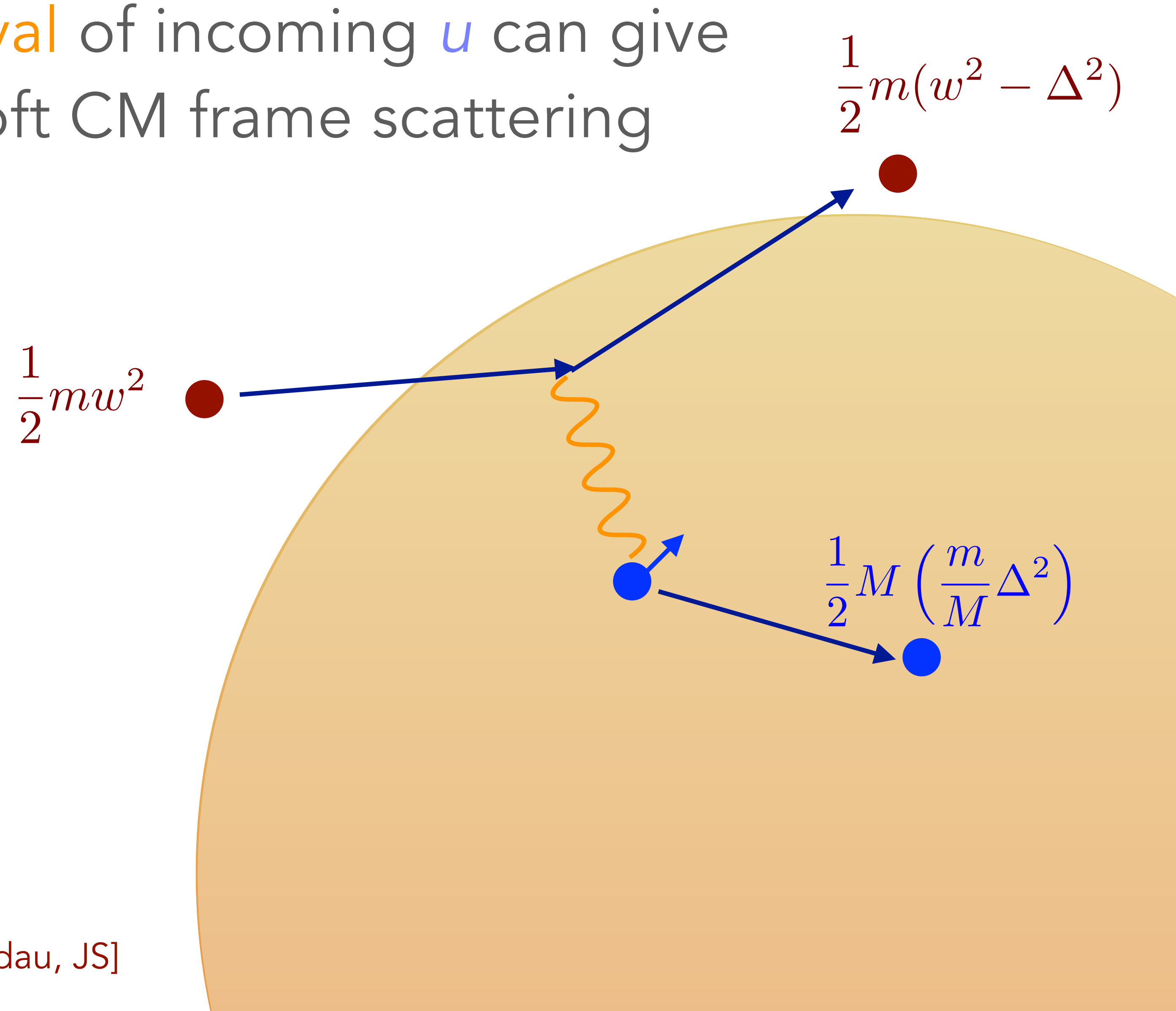


[Fan, Katz, JS]

CAPTURE AT FINITE TEMPERATURE

- Nuclei have finite thermal velocity:
  - short-range: small increase in average CM frame energy, reduces phase space for capture
  - long-range: small interval of incoming u can give capture by arbitrarily soft CM frame scattering

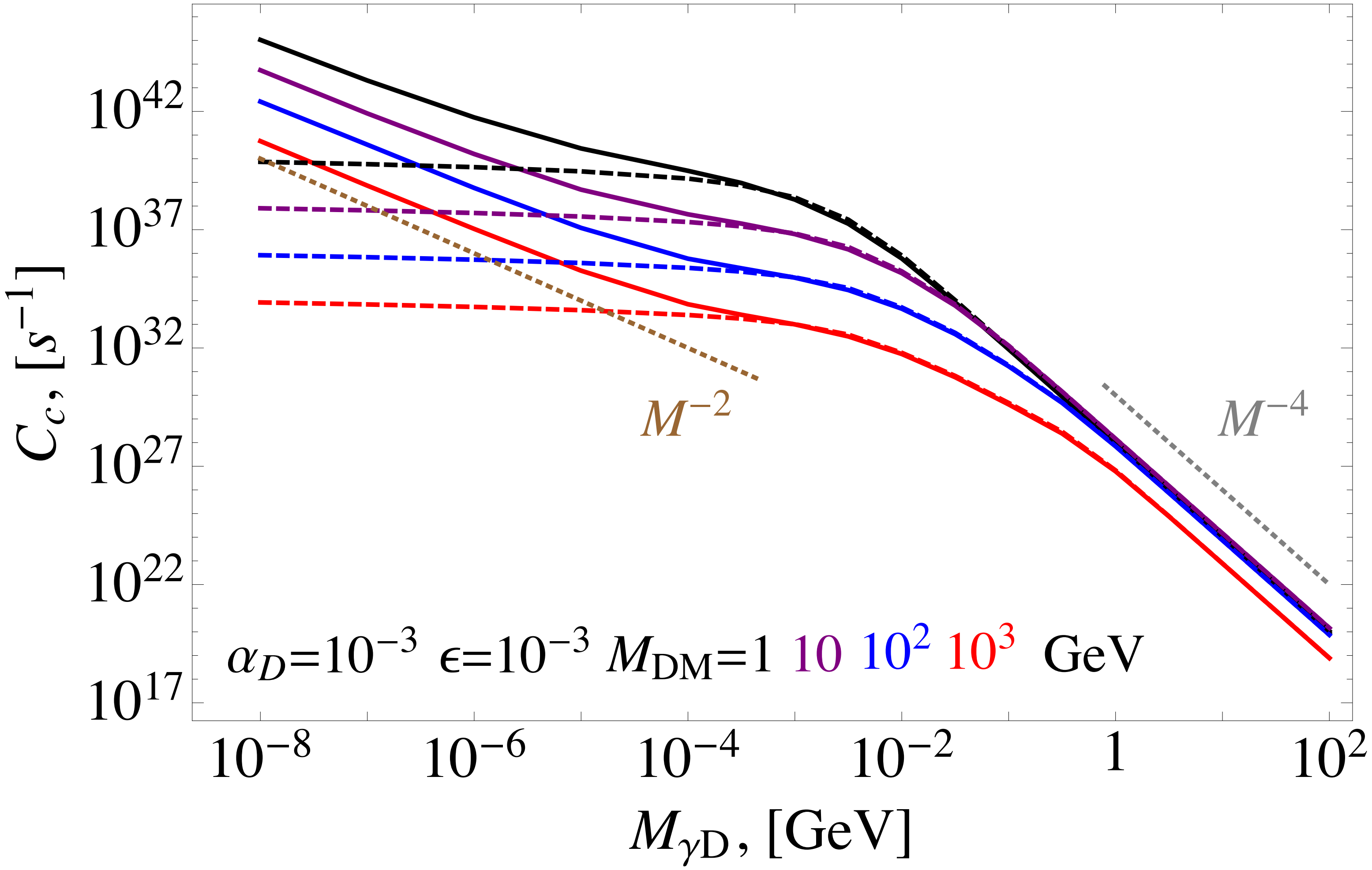




[Gaidau, JS]

NUCLEAR CAPTURE AT FINITE TEMPERATURE

- At finite temperature, $C_c \propto \frac{1}{M^2}$: quadratic sensitivity to IR regulator

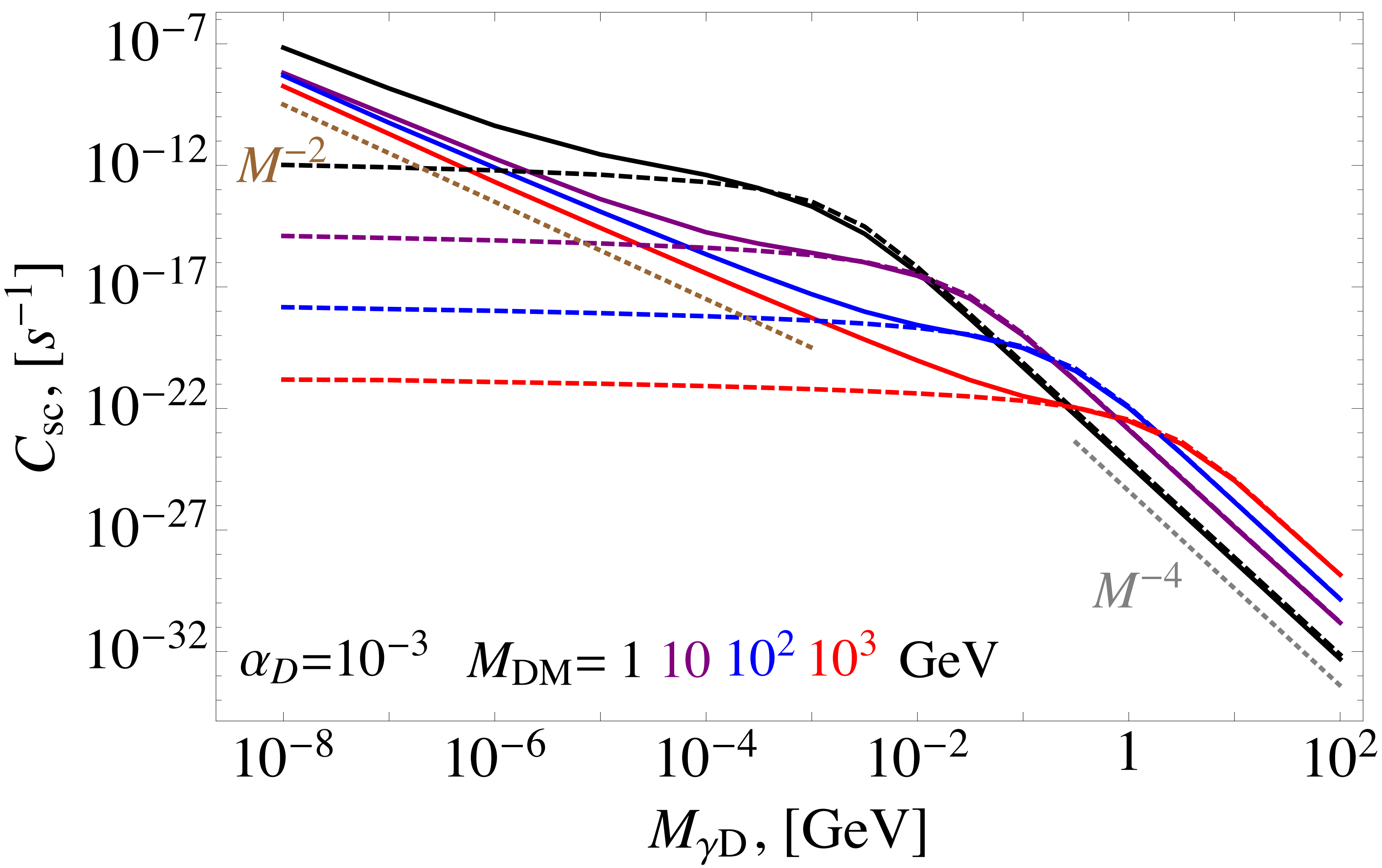


- fine print: dark photon, so spin-independent, isospin-violating scatterings with nucleons

[Gaidau, JS]

SELF-CAPTURE AT FINITE TEMPERATURE

- DM also has long-range self-interactions: self-capture



[Gaidau, JS]

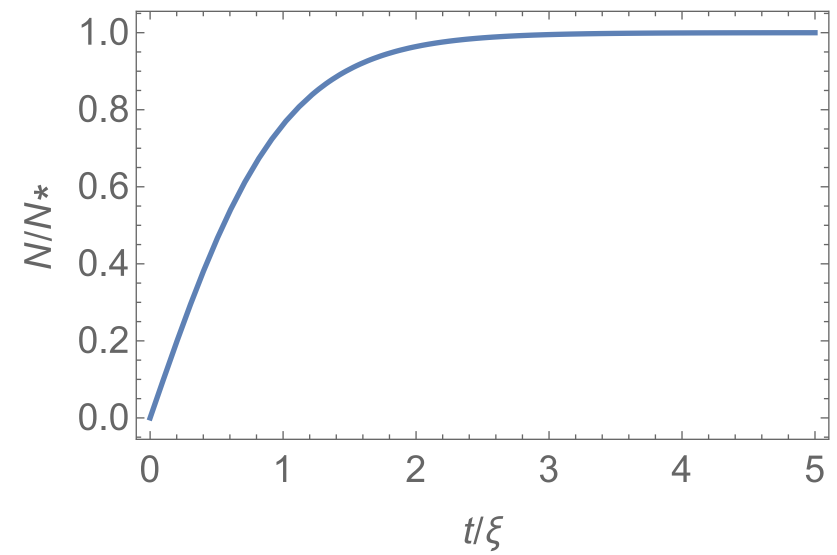
DARK MATTER POPULATION IN THE SUN

- Number of bound DM particles:

$$\frac{dN}{dt} = C_c + NC_{sc} - N^2 C_A$$

$$N(t) = \frac{C_c \tanh\left(\frac{t}{\xi}\right)}{\frac{1}{\xi} - \frac{C_{sc}}{2}\tanh\left(\frac{t}{\xi}\right)}$$

$$\xi^{-1} = \sqrt{C_c C_A + C_{sc}^2/4}$$

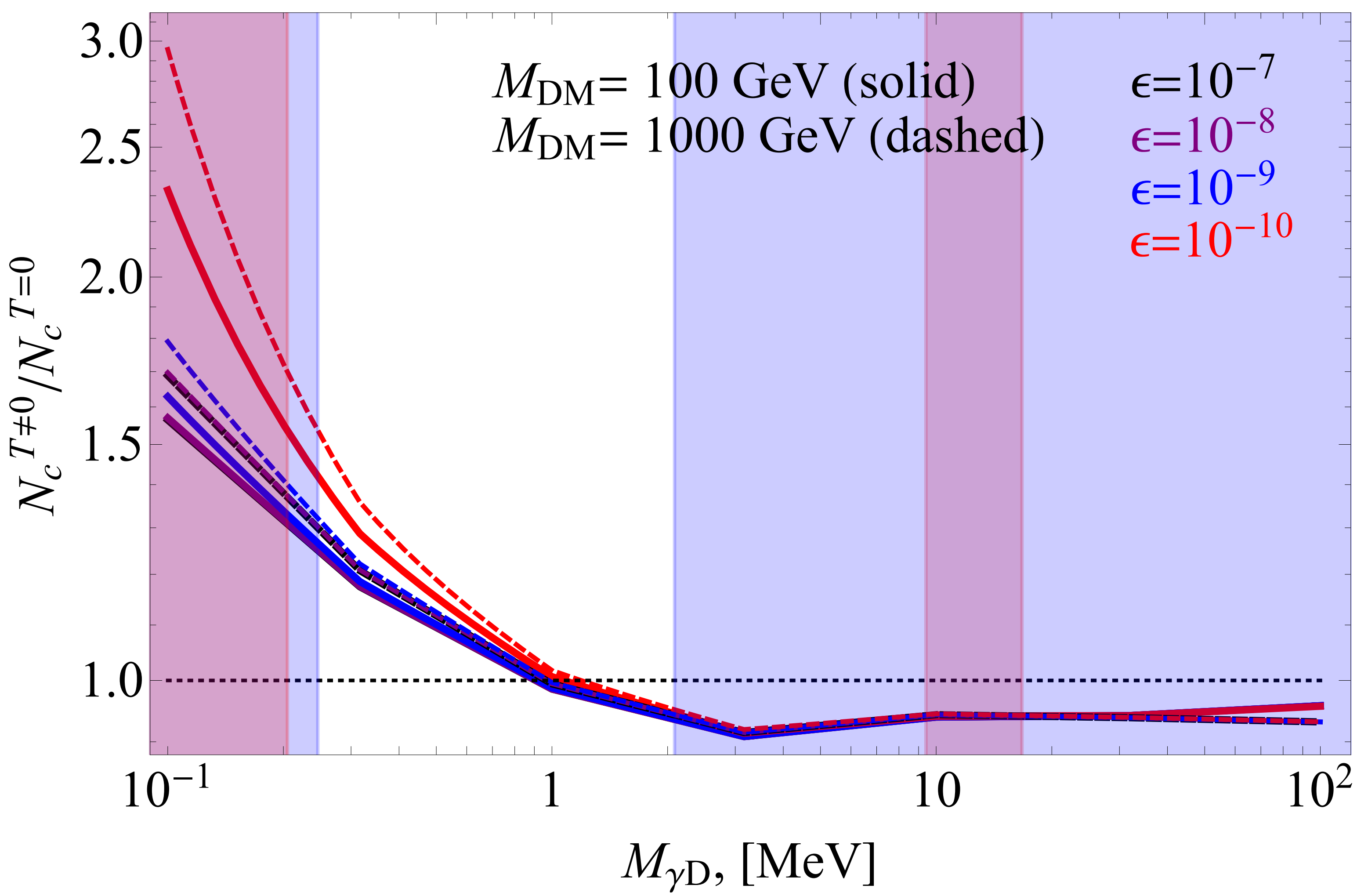


- For the sun, typical halo-bound momentum transfer ~ 16 MeV (oxygen), ~m x 10^{-3} (self-capture)

[Zentner]

DARK MATTER POPULATION IN THE SUN

- Thermal corrections limited for visibly-decaying mediators

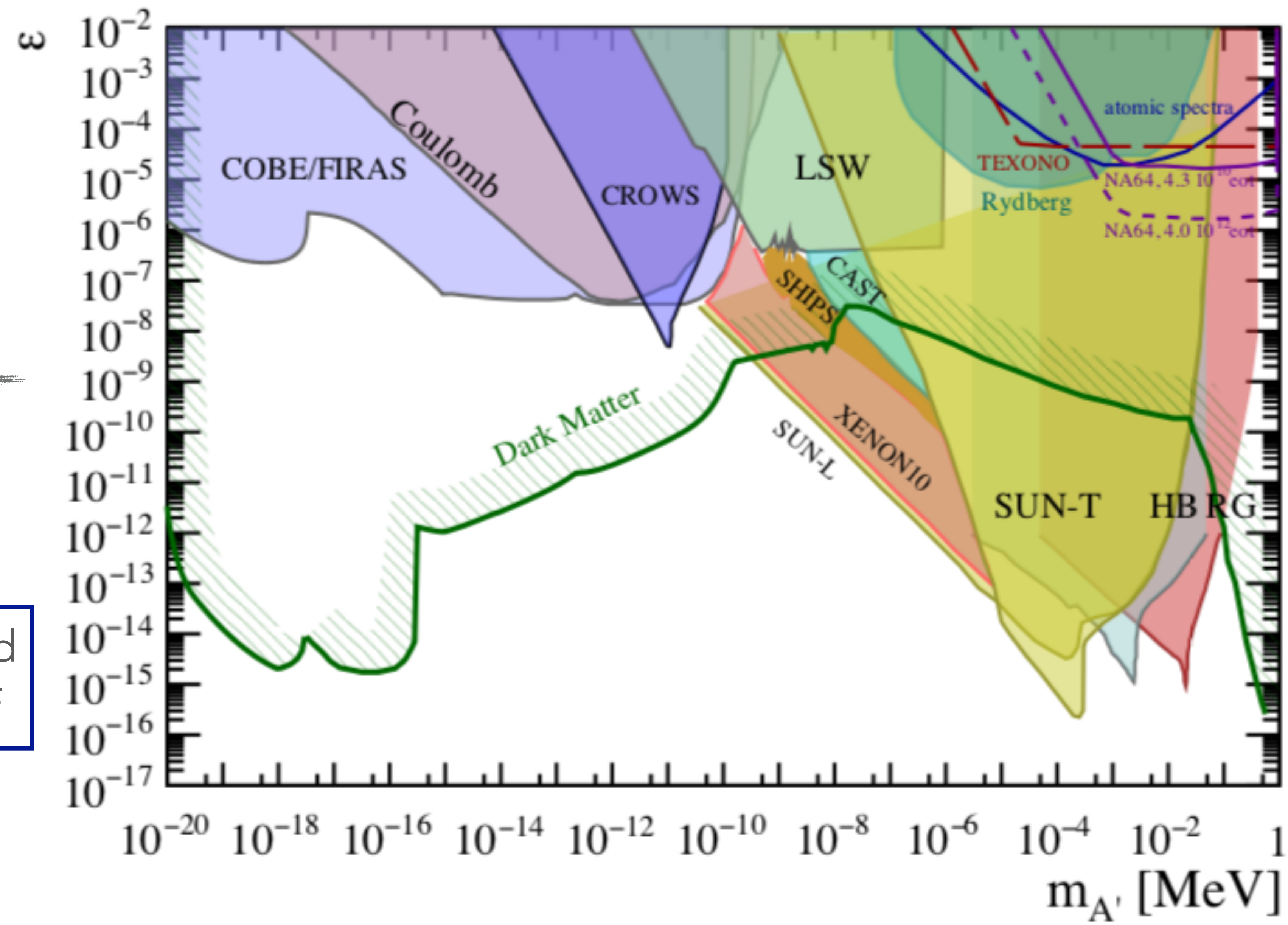


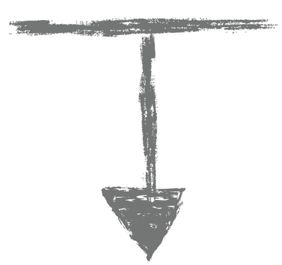
- broadly applicable for other mediators: stellar cooling bounds
- thermal enhancement more important for more massive objects

[Gaidau, JS]

DARK MATTER POPULATION IN THE SUN

➤ Ultra-light dark photons?



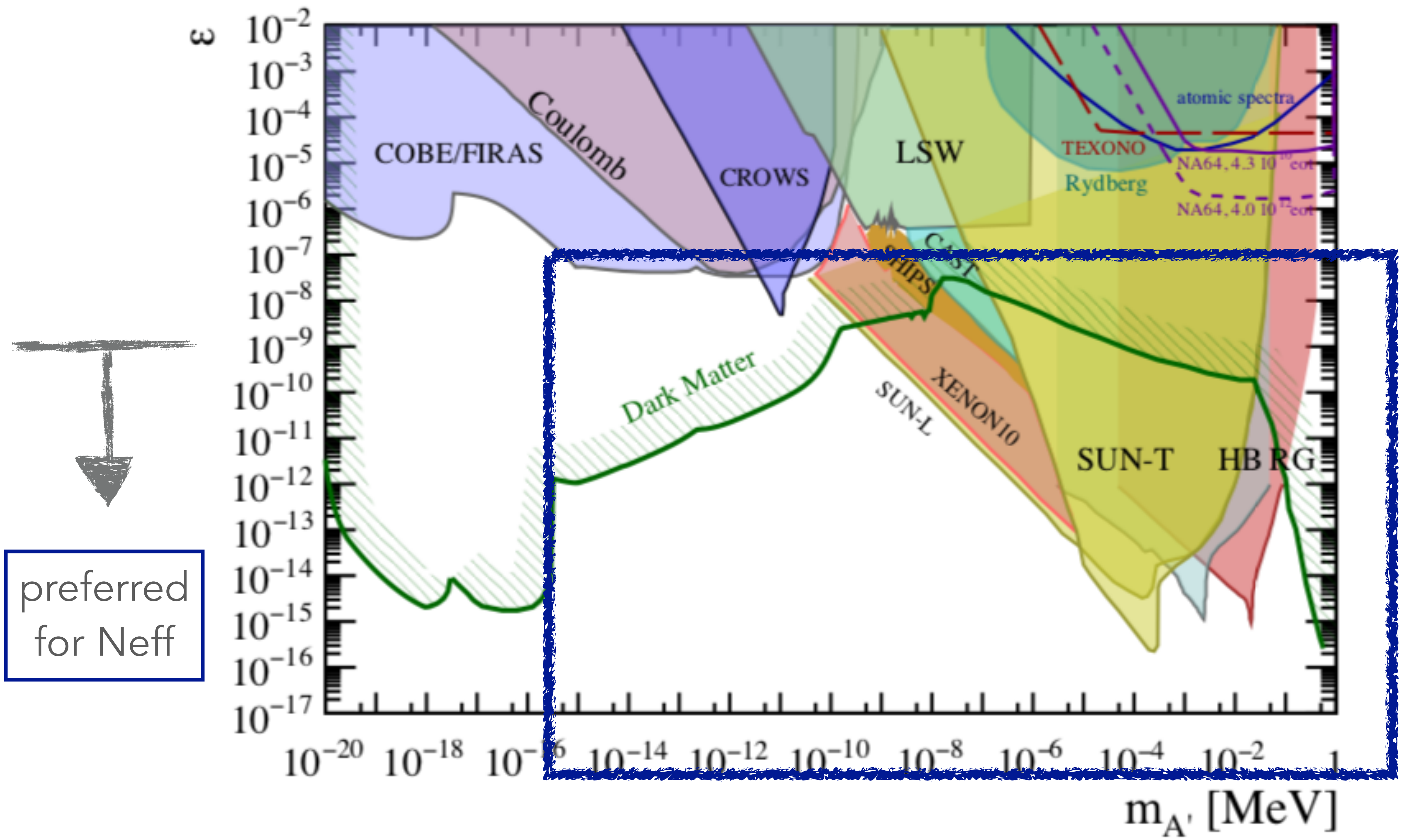


preferred for Neff

[Fabbrichesi, Gabrielli, Lanfranchi]

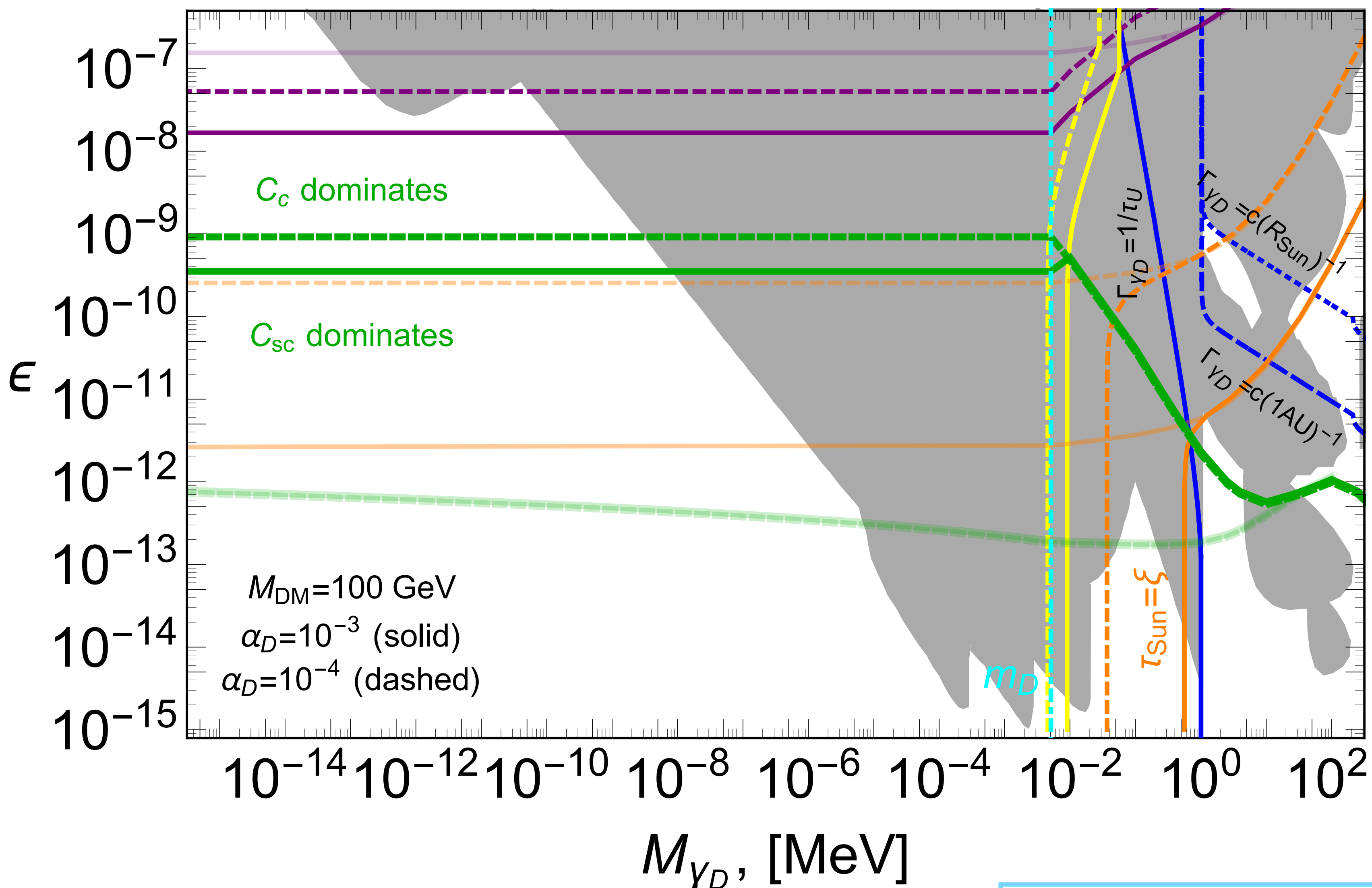
DARK MATTER POPULATION IN THE SUN

- Ultra-light dark photons?



[Fabbrichesi, Gabrielli, Lanfranchi]

DARK MATTER POPULATION IN THE SUN

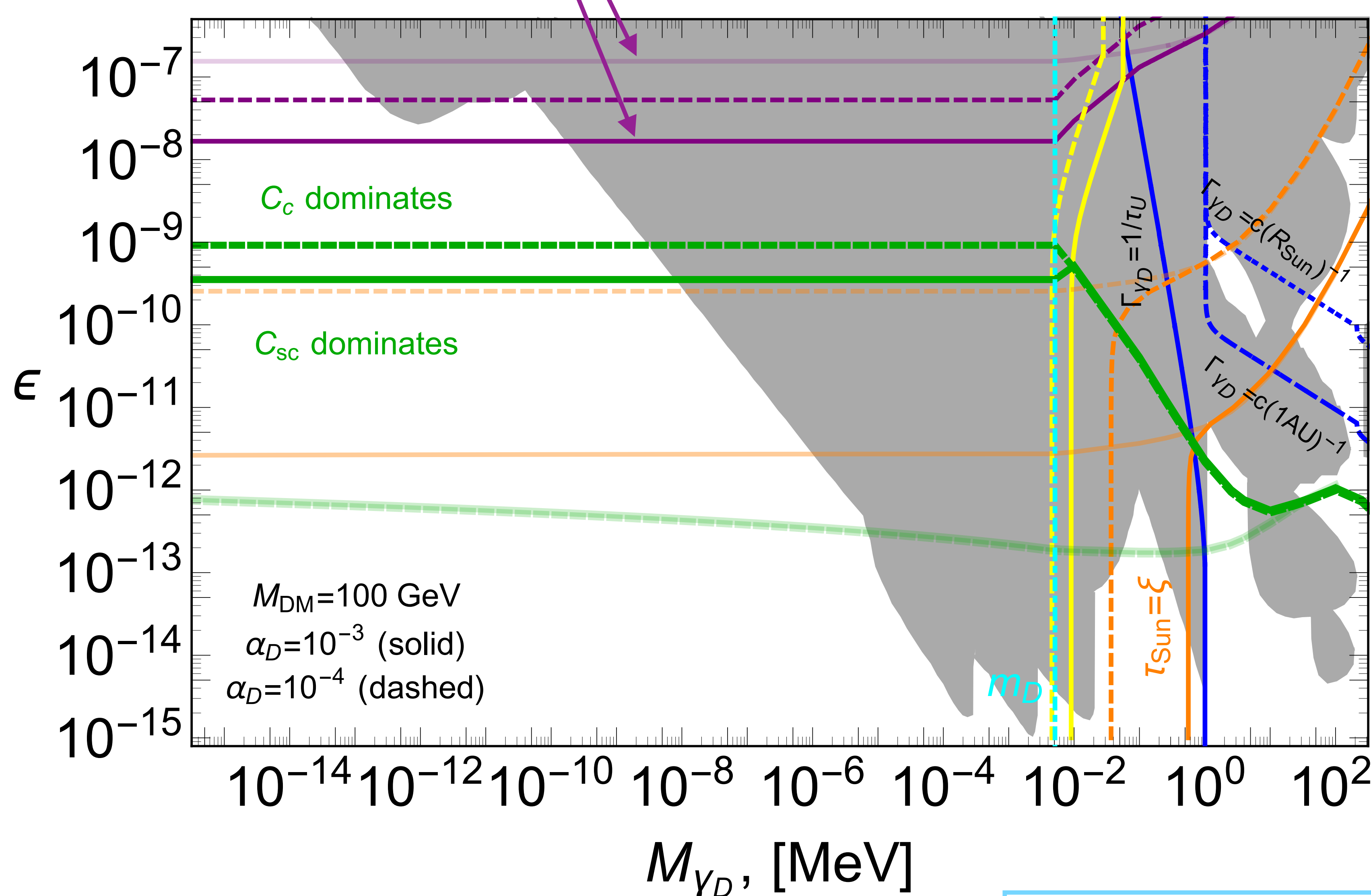


solar Debye mass

[Gaidau, JS]

DARK MATTER POPULATION IN THE SUN

geometric limit for nuclear capture



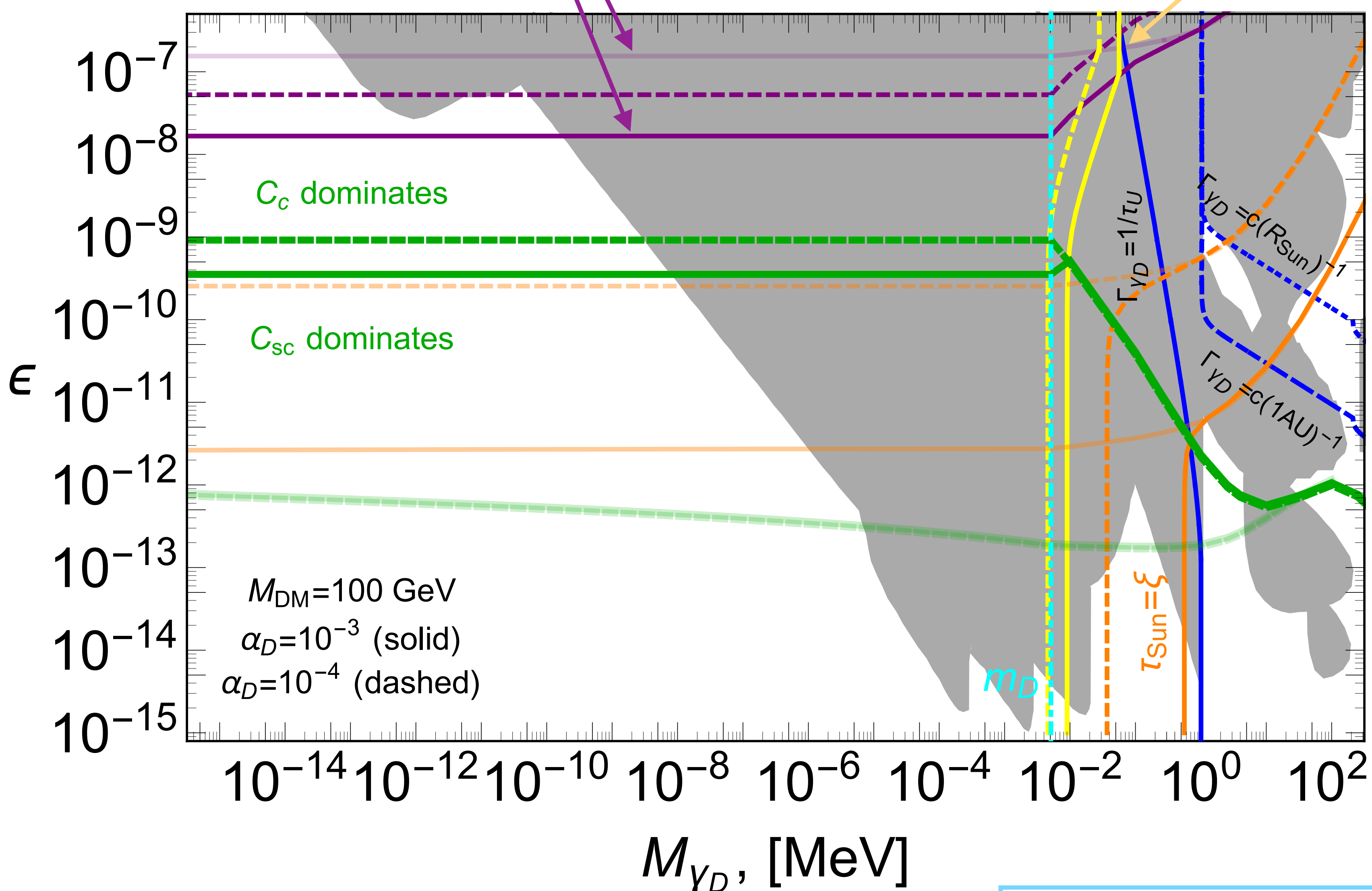
solar Debye mass

[Gaidau, JS]

DARK MATTER POPULATION IN THE SUN

geometric limit for nuclear capture

geometric limit for self capture



solar Debye mass

[Gaidau, JS]

CAVEAT

- Subsequent related work by DeRocco, Galanis, and Lasenby also finds a parametric enhancement of capture rate for light mediators, but 1/m
  - status unclear: calculational approaches very different
  - resolution in progress

PART II

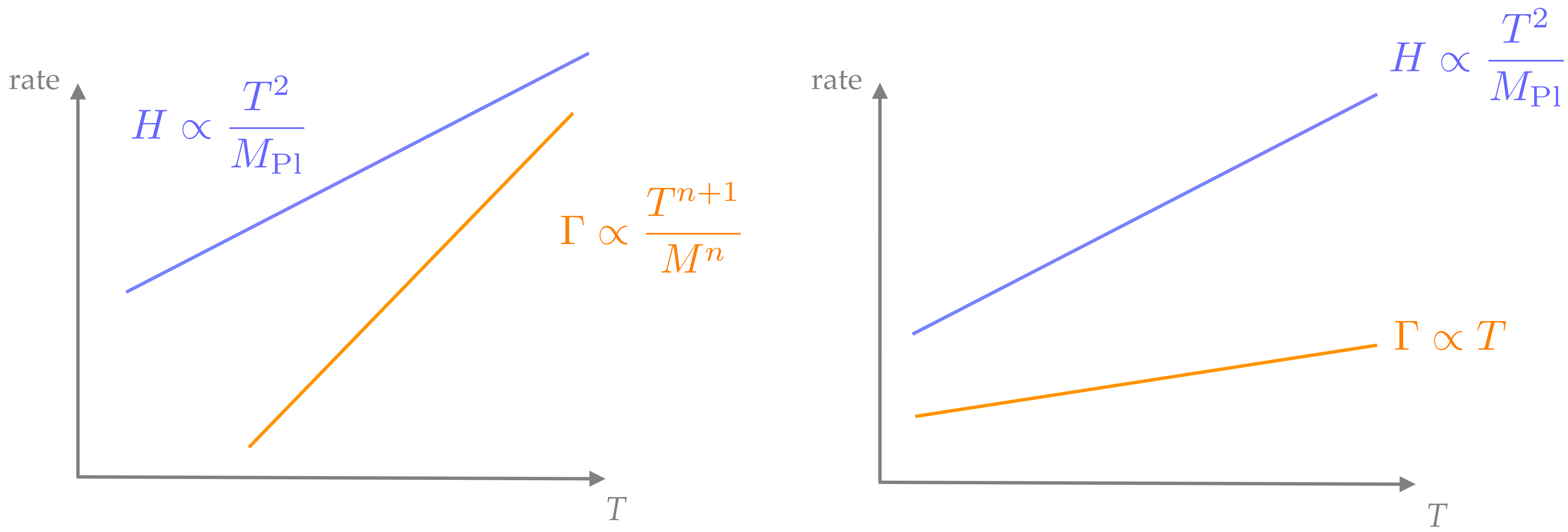
freeze-in vs glaciation

arXiv: 2111.13709 with Nico Fernandez and Yoni Kahn

FREEZE-IN DARK MATTER

- freeze-in dark matter: DM produced via out-of-equilibrium interactions with SM thermal bath

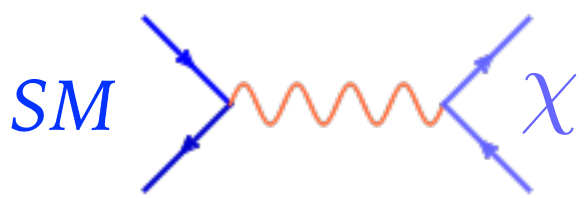
- cosmological history strongly depends on scale of production rate: non-renormalizeable vs renormalizeable



FREEZE-IN DARK MATTER

- Freeze-in through renormalizeable interactions is IR-dominated and therefore UV-insensitive:

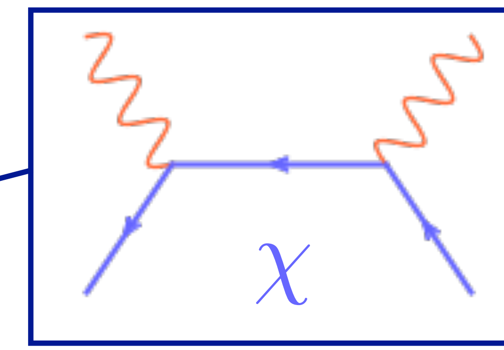
$$\dot{n}_\chi + 3Hn_\chi = 2\langle\sigma v\rangle n_f^2$$



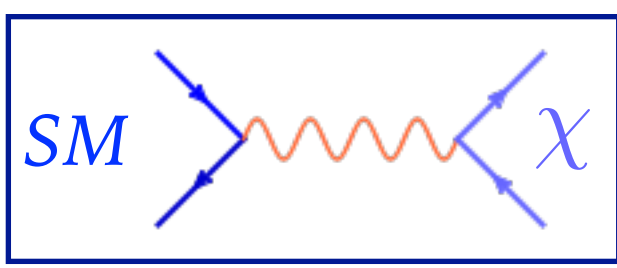
- SM source term shuts off at $T \sim m_\chi$
- Residual UV sensitivity: initial condition on n_χ
  - (small) constant offset in final abundance
- Dark photon-mediated freeze-in: important benchmark for low-mass direct detection
- Have implicitly assumed DM does not interact after it is produced

FREEZE-IN, FREEZE-OUT

- However in models with a light mediator, subsequent interactions among the dark particles can be very important
- Assuming dark sector is in kinetic equilibrium:



$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\frac{1}{2}\langle\sigma v\rangle_{\rm fo}(n_{\rm DM}^2 - n_{\rm eq}^2(\tilde{T}))$$



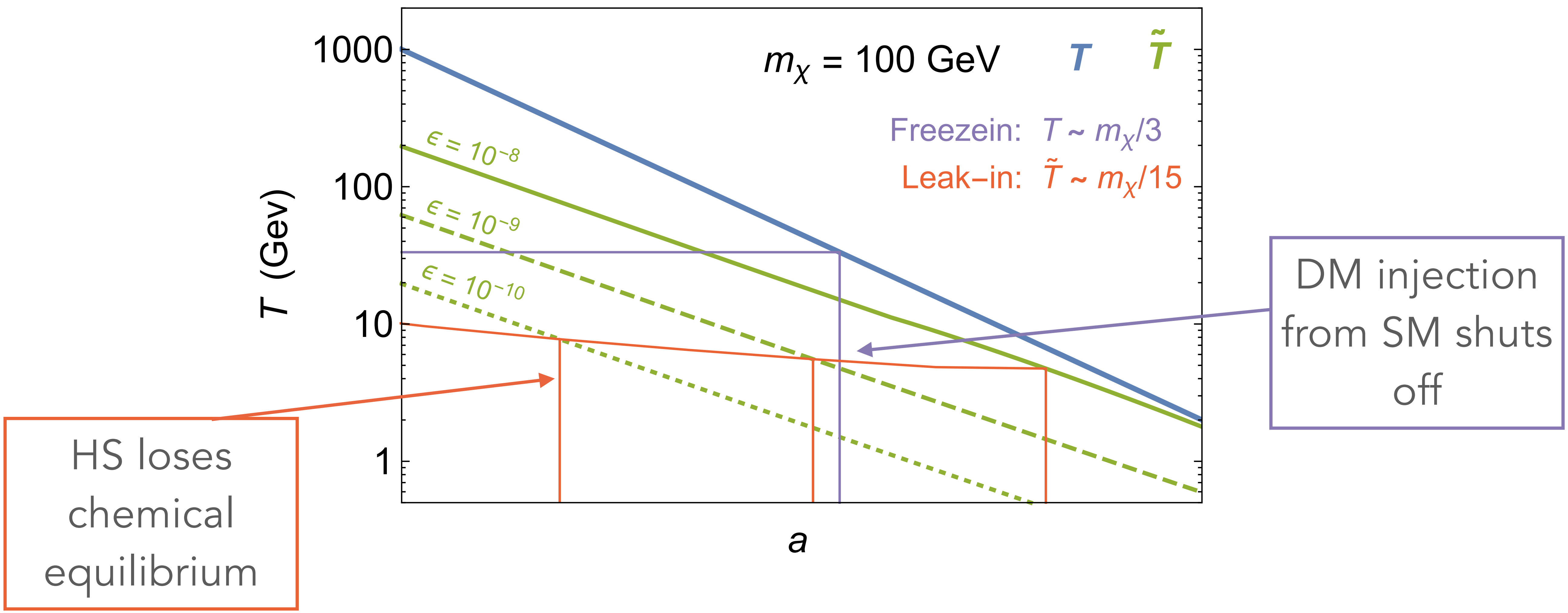
$$+2\sum_f \langle\sigma v\rangle_{\rm fi} n_f^2(T) + 2\langle\Gamma\rangle_Z n_Z(T)$$

$$\dot{\rho}_{\rm HS} + 3H\left(\rho_{\rm HS} + P_{\rm HS}\right) = \sum_f \langle\sigma v E\rangle_{\rm fi}\, n_f^2(T) + \langle\Gamma E\rangle_Z n_Z(T)$$

[Chu, Hambye, Tytgat; Krnjaic; Berger et al; Evans, Gaidau, JS; Hambye et al; …]

FREEZE-IN, FREEZE-OUT

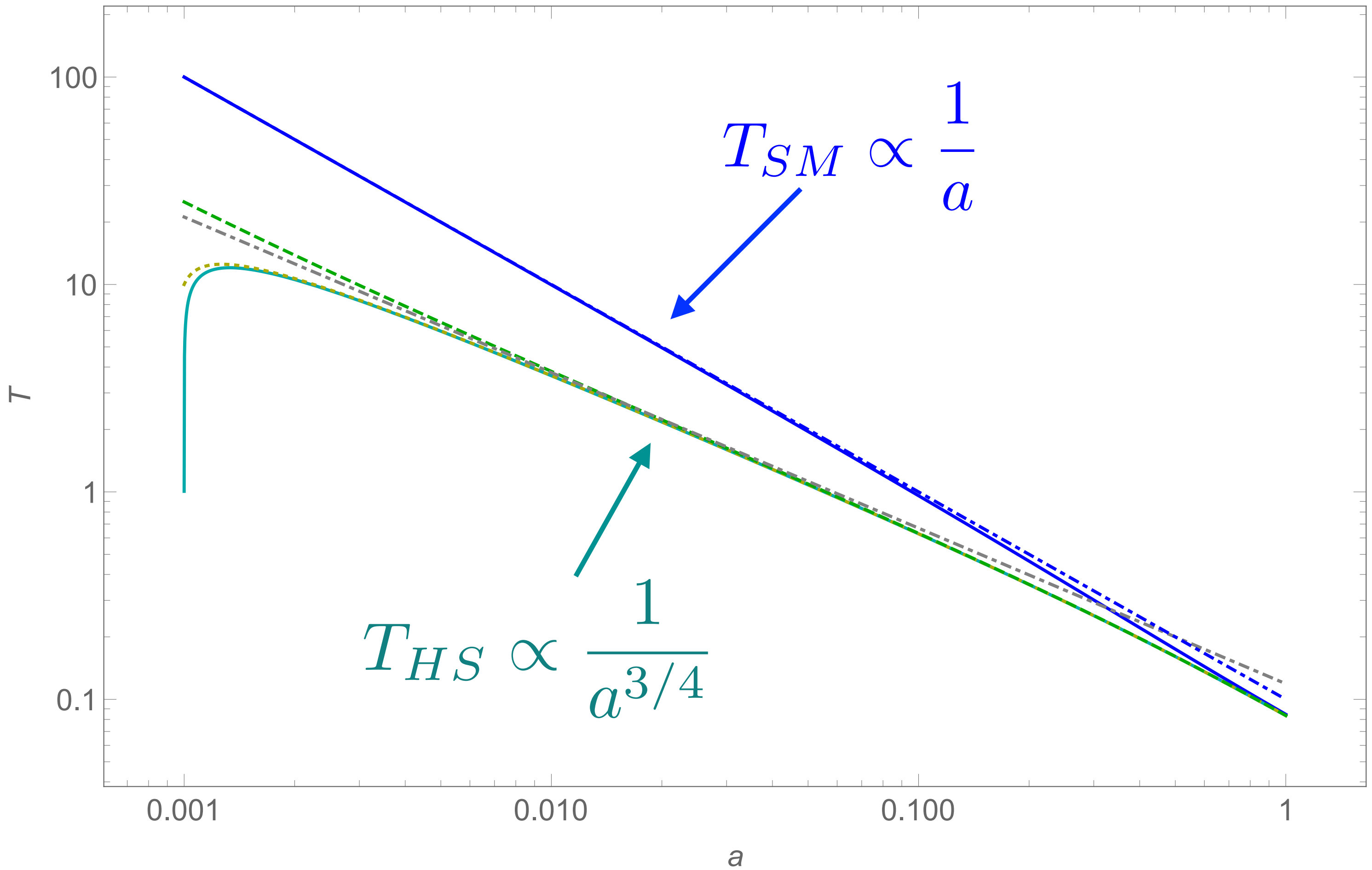
- interplay of out-of-equilibrium injections from SM with the freezeout of interactions within the dark sector sensitive to ordering of events:



[Evans, Gaidau, JS]

TEMPERATURE EVOLUTION: LEAK-IN

- Energy injection into hidden radiation bath makes it evolve non-adiabatically:

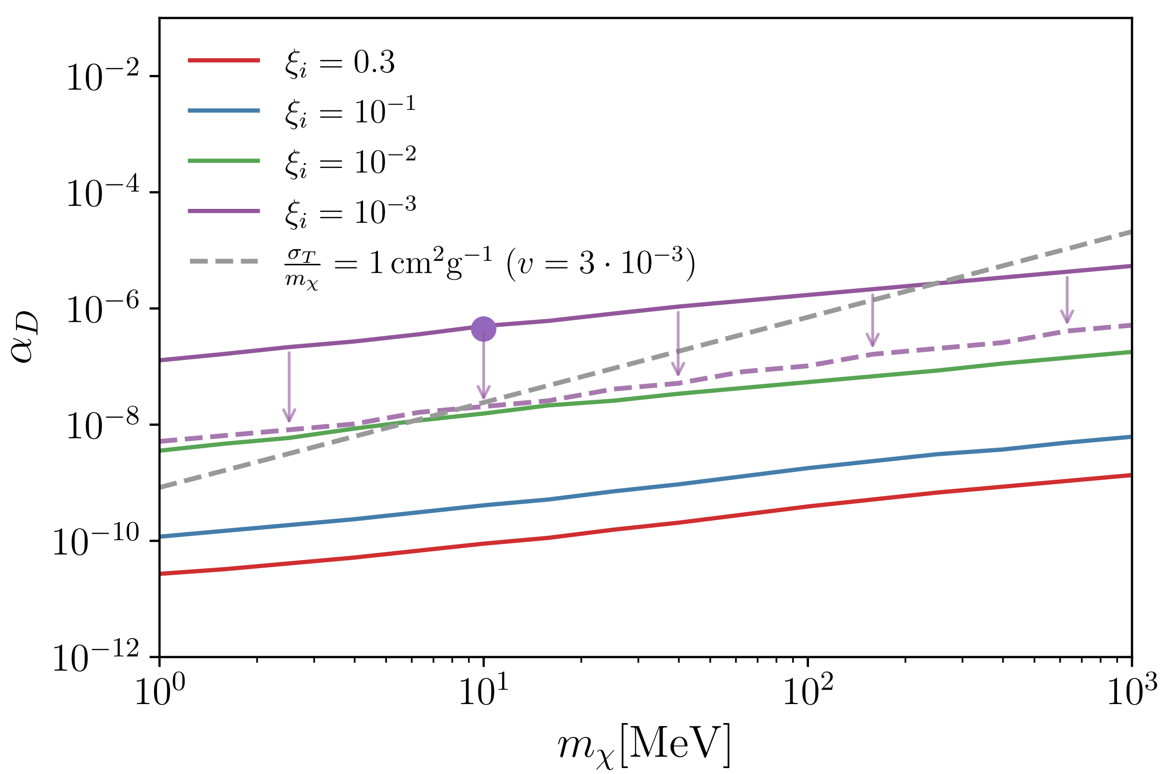


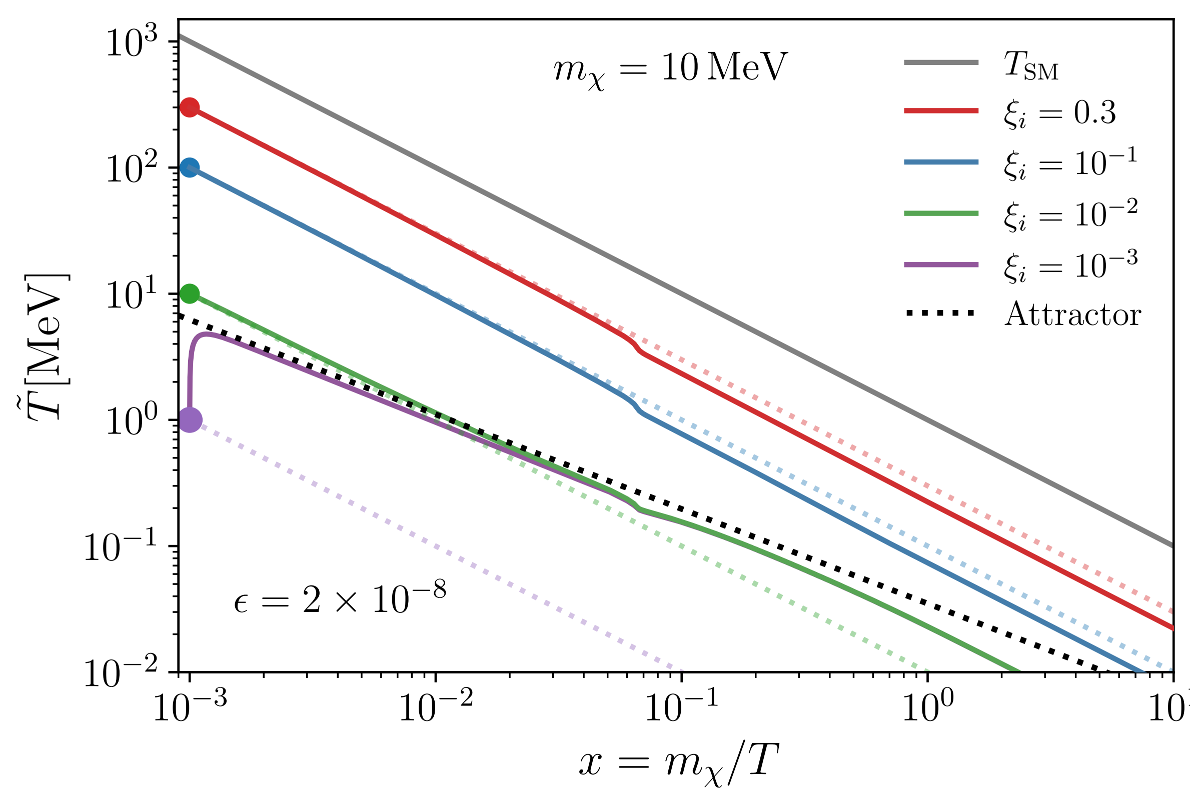
- UV-insensitive quasi-static equilibrium phase: leak-in
  - attractor solution: $\propto \epsilon^2 \alpha_D$

[Chu, Hambye, Tytgat; Evans, Gaidau, JS]

CONDITIONS FOR INSTANTANEOUS KINETIC EQUILIBRATION

➤ this attractor solution helps extend region where instantaneous kinetic equilibration is a good approximation:





[Fernandez, Kahn, JS]

INITIAL CONDITION DEPENDENCE?

- For freeze-in with light mediators we expect DM abundance to depend on the initial light mediator abundance as well
- initial temperature ratio $\xi_i = \tilde{T}(a_i)/T(a_i)$
- intuition: attractor solution for HS temperature will erase much initial condition dependence

[Fernandez, Kahn, JS]

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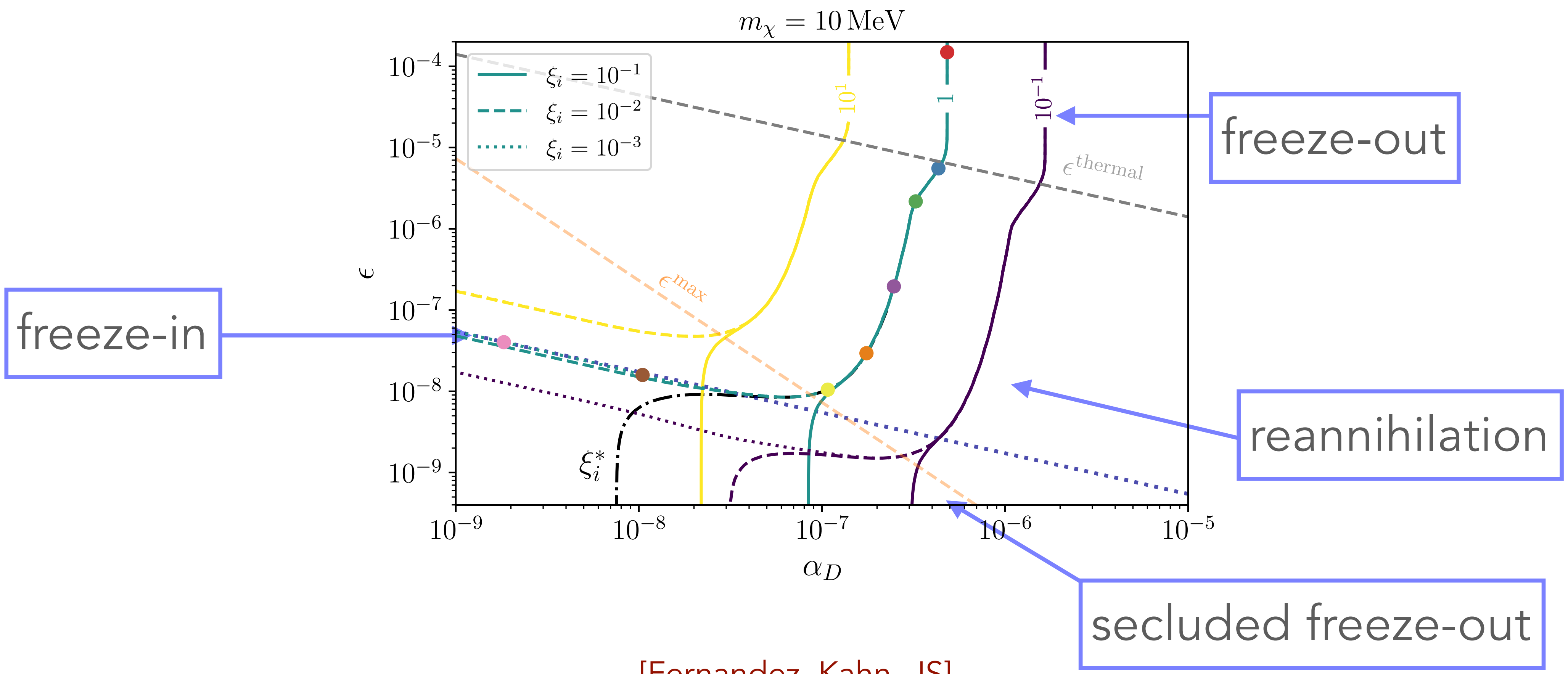
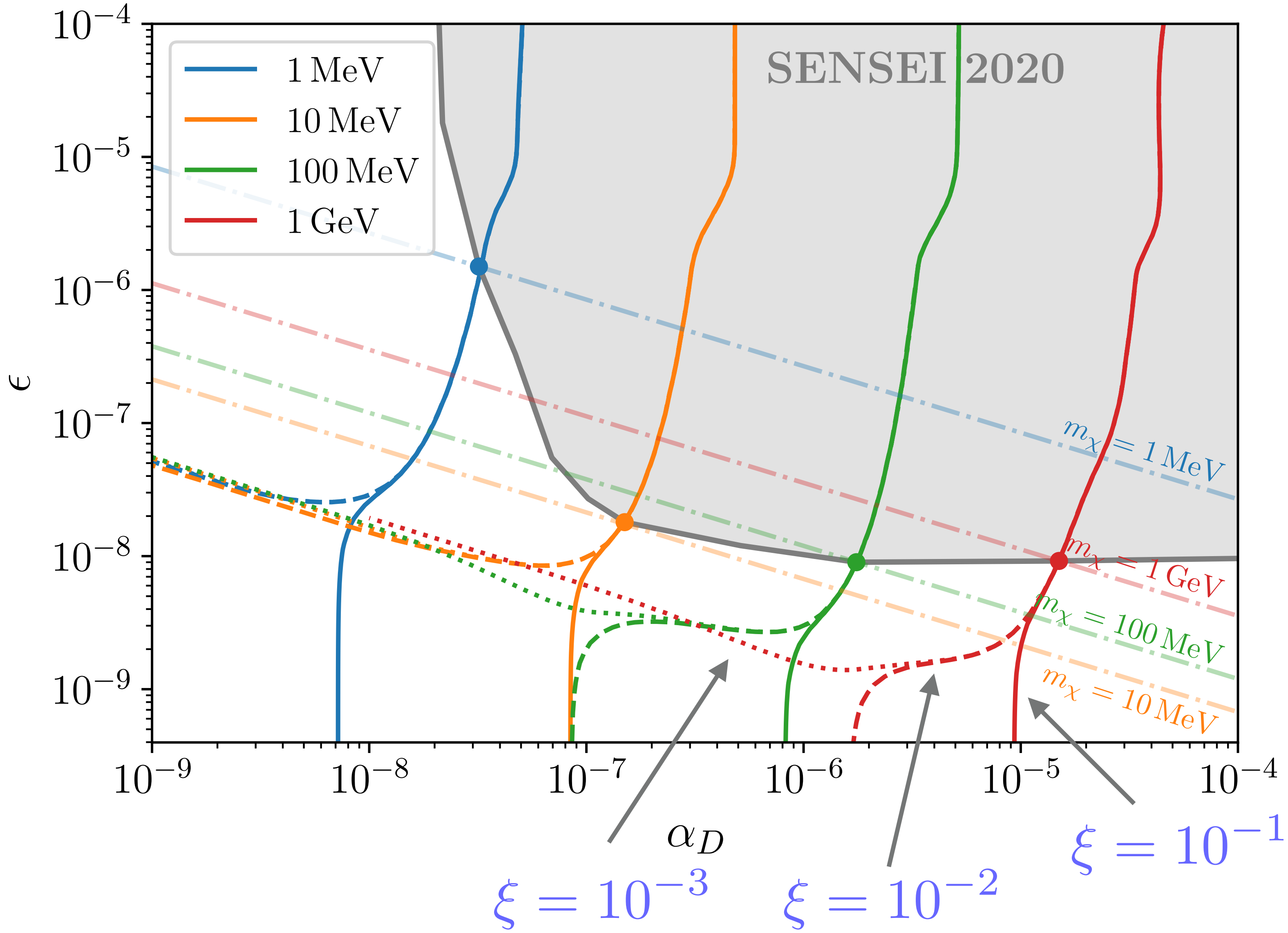


[Fernandez, Kahn, JS]

INITIAL CONDITION DEPENDENCE

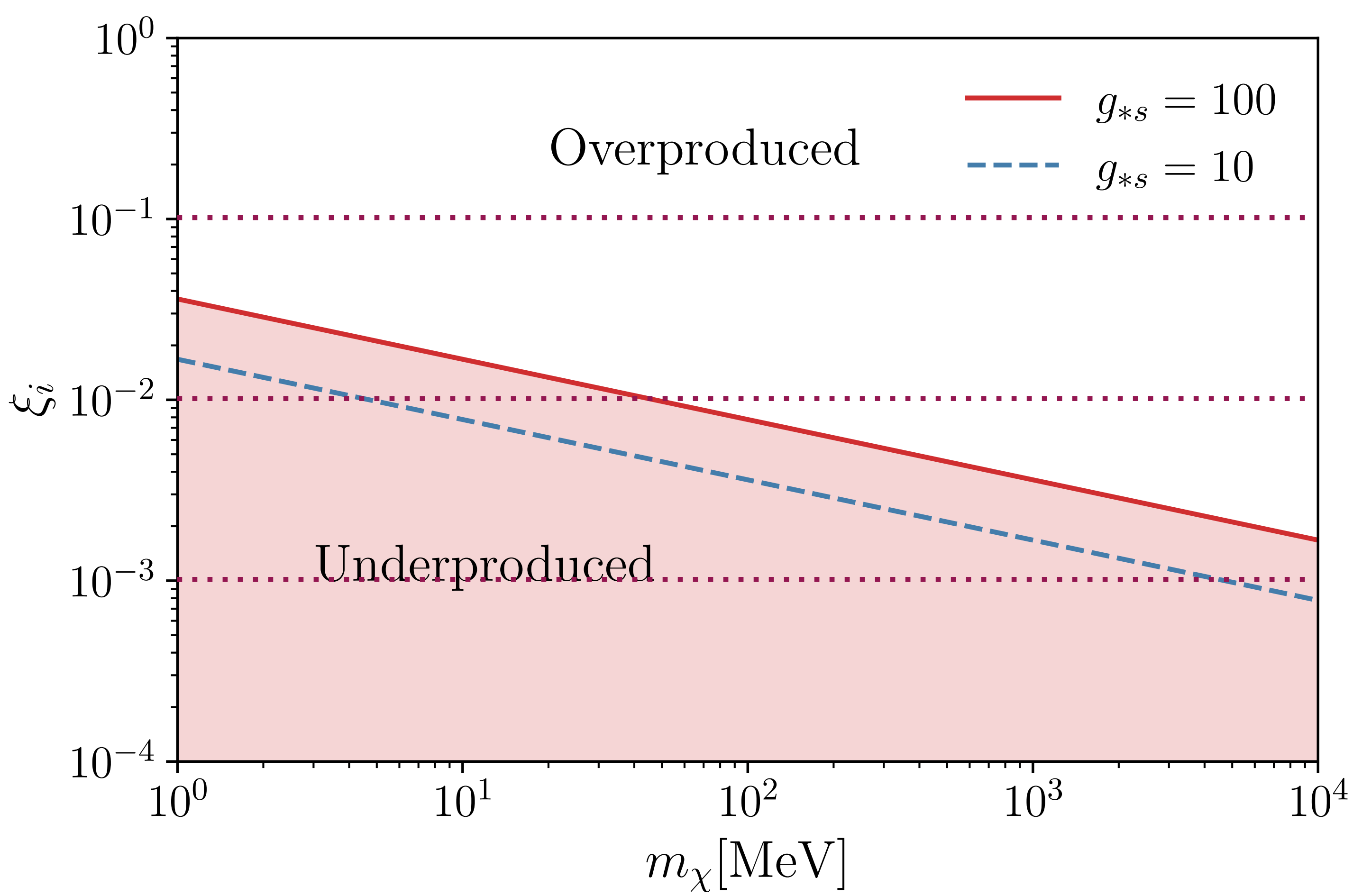
- values of parameters needed for relic abundance can depend on initial temperature ratio



[Fernandez, Kahn, JS]

INITIAL CONDITION DEPENDENCE

- postdictions: boundary between initially over/under abundant DM is robust against attractor solution for (α_D, ϵ) near end of FI line



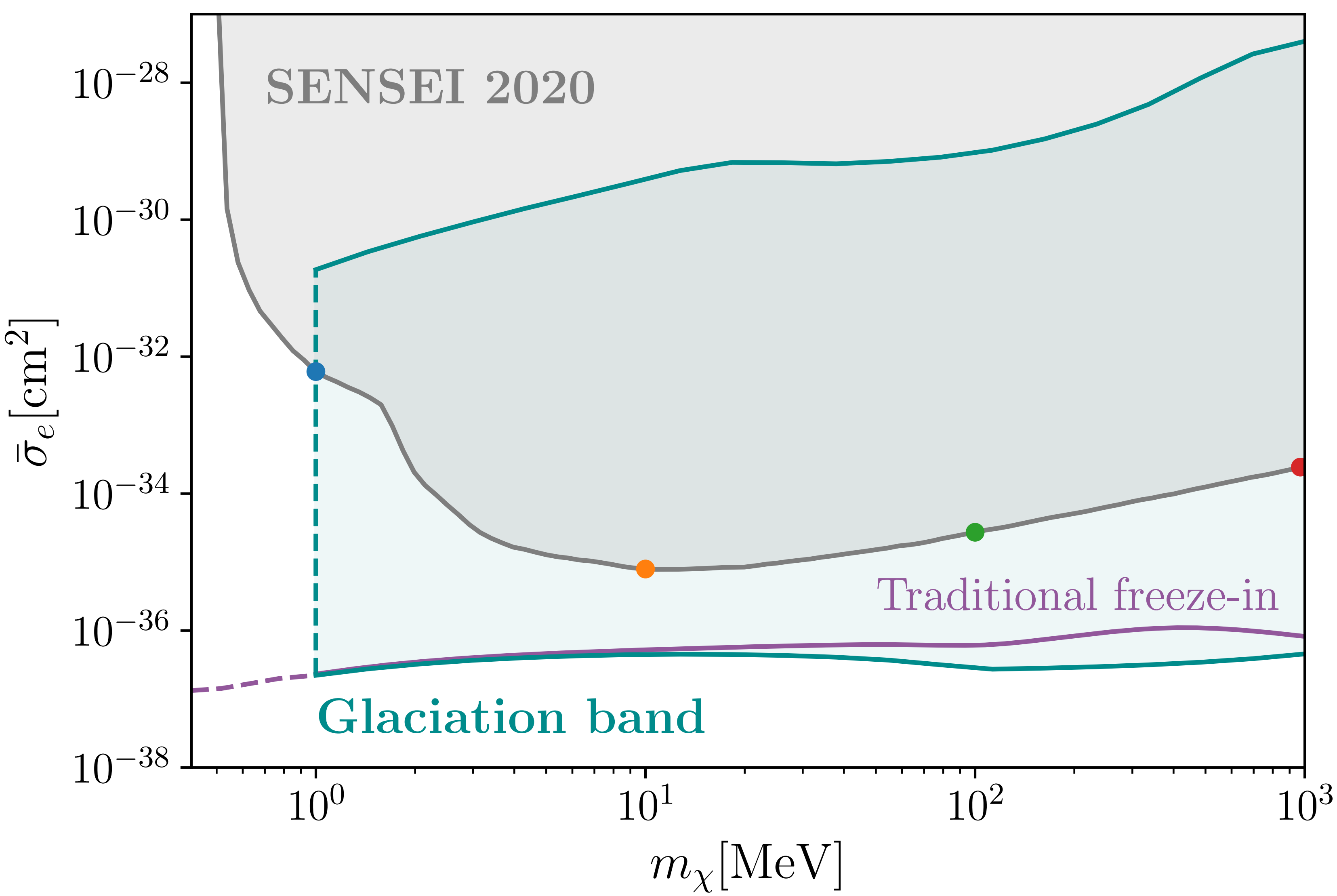
$n_\chi(\tilde{T}_i) > n_{obs}$

$n_\chi(\tilde{T}_i) < n_{obs}$

[Fernandez, Kahn, JS]

DIRECT DETECTION LANDSCAPE

- what this region looks like in direct detection:



[Fernandez, Kahn, JS]

SUMMARY AND CONCLUSIONS

- Dark matter that interacts with a long-range dark force can behave dramatically unlike WIMPs
- Gravitational capture via long-range interactions
  - finite-temperature capture rate in non-degenerate bodies is quadratically*, not logarithmically, sensitive to IR regulator
  - visibly-decaying mediators: small corrections in Sun, perhaps bigger corrections in more massive objects
- Initial condition dependence in freeze-in models
  - final relic abundance depends on initial conditions on temperature ratio, much more involved than constant offset
  - implications for next generation of low-threshold direct detection experiments
  - Phase space distribution as well as relic density UV-sensitive