THE UNIVERSITY of ADELAIDE

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ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

DARK MATTER AND STARS

14–16 JULY 2025

MULTI-MESSENGER PROBES OF DARK MATTER AND MODIFIED GRAVITY

Phenomenology of Dark Matter in Neutron Stars and compact objects

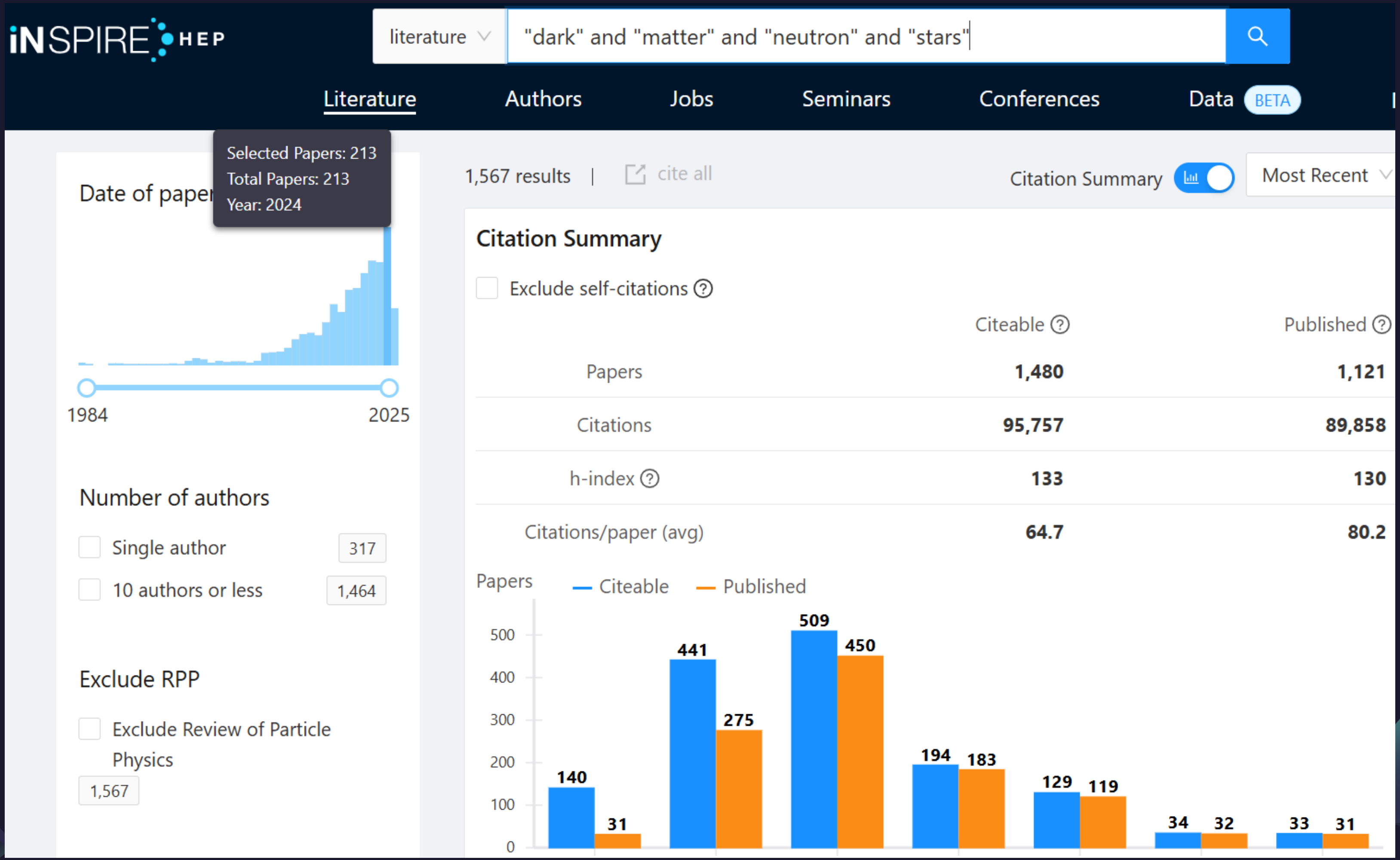
Giorgio Busoni

Dark Matter and Stars, Kingston 14/07/2025

Outline

- Why (considerer compact stars)?
- What (could we observe/constrain)?
- How (does DM interact with the stars)?

Growing interest



- Neutron Stars:
  - JCAP 09 (2018) 018 (1807.02840)
  - JCAP 06 (2019) 054 (1904.09803)
  - JCAP 09 (2020) 028 (2004.14888)
  - JCAP 03 (2021) 086 (2010.13257)
  - Phys.Rev.Lett. 127 (2021) 11, 111803 (2012.08918)
  - JCAP 11 (2021) 056 (2108.02525)
  - JCAP 04 (2024) 006 (2312.11892)
  - 2505.06506
- White Dwarfs:
  - JCAP 10 (2021) 083 (2104.14367)
  - JCAP 07 (2024) 051 (2404.16272)

See Sandra's Talk

N.Bell

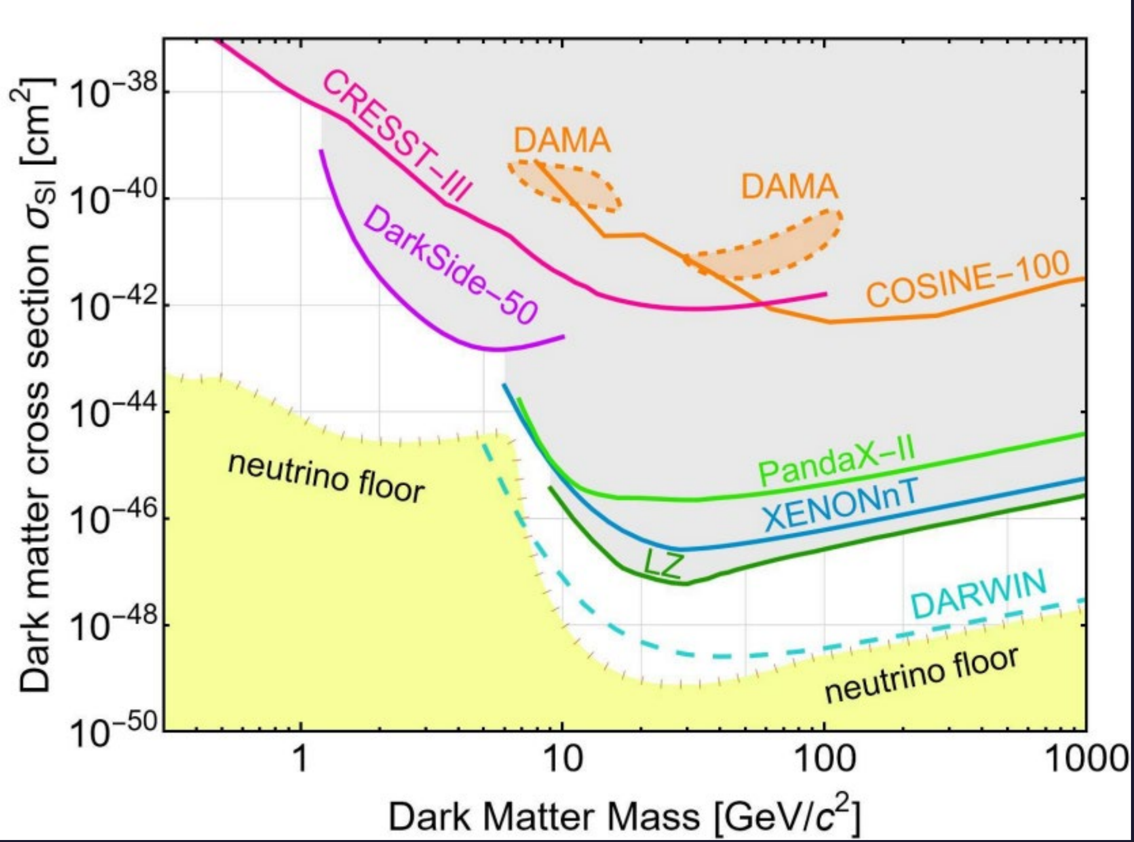
M.Virgato

Additional credits: T. Motta, A. Thomas, M. Ramirez-Quezada, F. Anzuini, A. Ghosh

S. Robles

Why (stars)?

- Direct Detection sensitivities closing up on the neutrino floor
  - Signal $\propto$ detector mass $\sim$ 1000Kg
- Direct Detection $\Longrightarrow$ elastic scattering $\Rightarrow$ Capture in Stars
  - Star mass $\sim 10^{30}$Kg



Why (compact stars)?

Neutron Stars

- Very large density
  - Competing sensitivities with DD
- Relativistic kinematics
  - Wash away non-relativistic suppressions of some DD operators
  - Larger reach for inelastic DM
- DM interactions with different kind of matter
  - No SD/SI suppression
  - Interactions with muons

White Dwarfs

- Large density
- Degenerate, relativistic electrons
- Much more common than NS!

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- Maximal capture achieved for

$$\sigma \sim \frac{1}{nR} \sim 10^{-45} cm^2$$

Why (compact stars)?

1807.02840

- Similar sensitivities for all operators for NS
  - Order of magnitude differences for DD

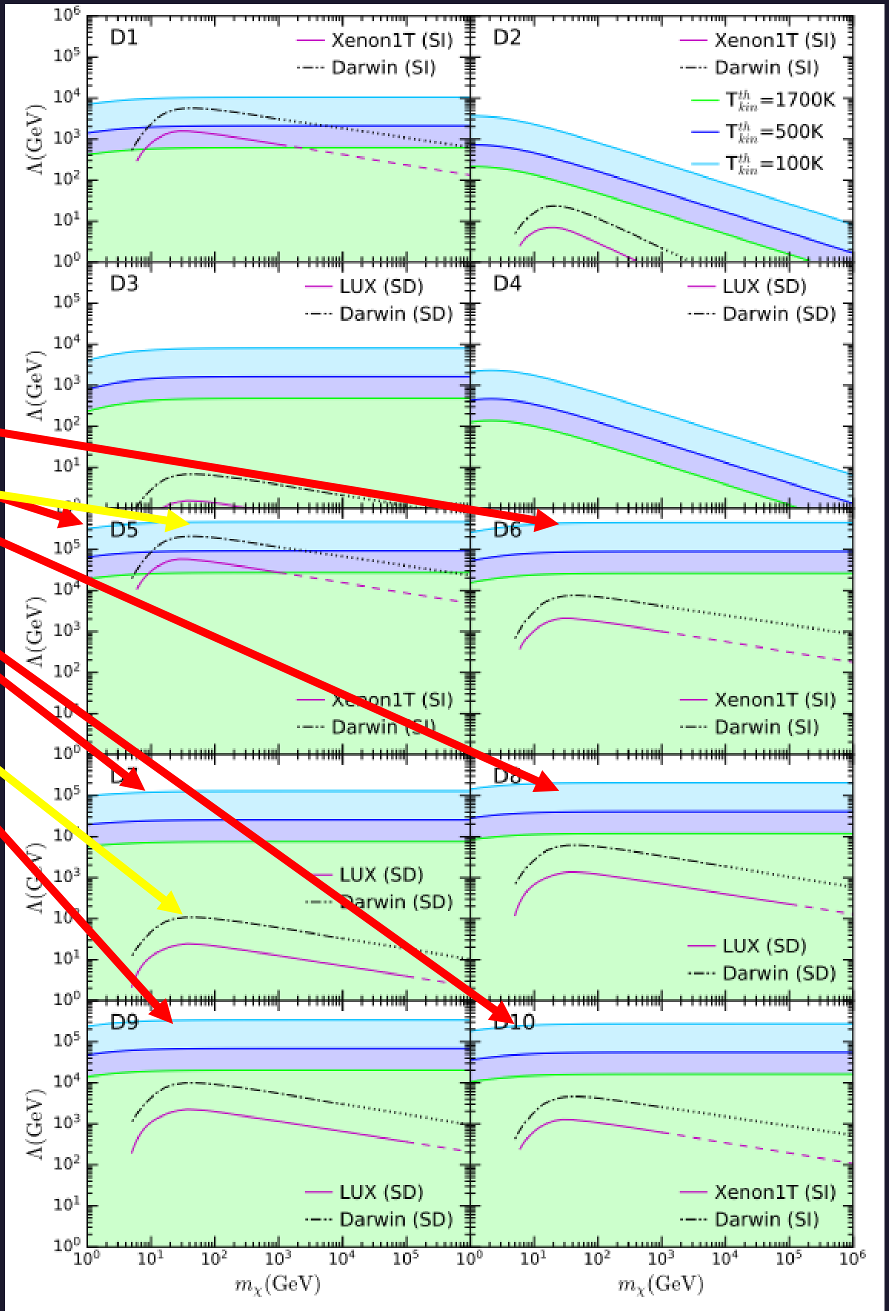
  - Wash away non-relativistic suppressions of some DD operators

  - Larger reach for inelastic DM

- DM interactions with different kind of matter

  - No SD/SI suppression

  - Interactions with muons



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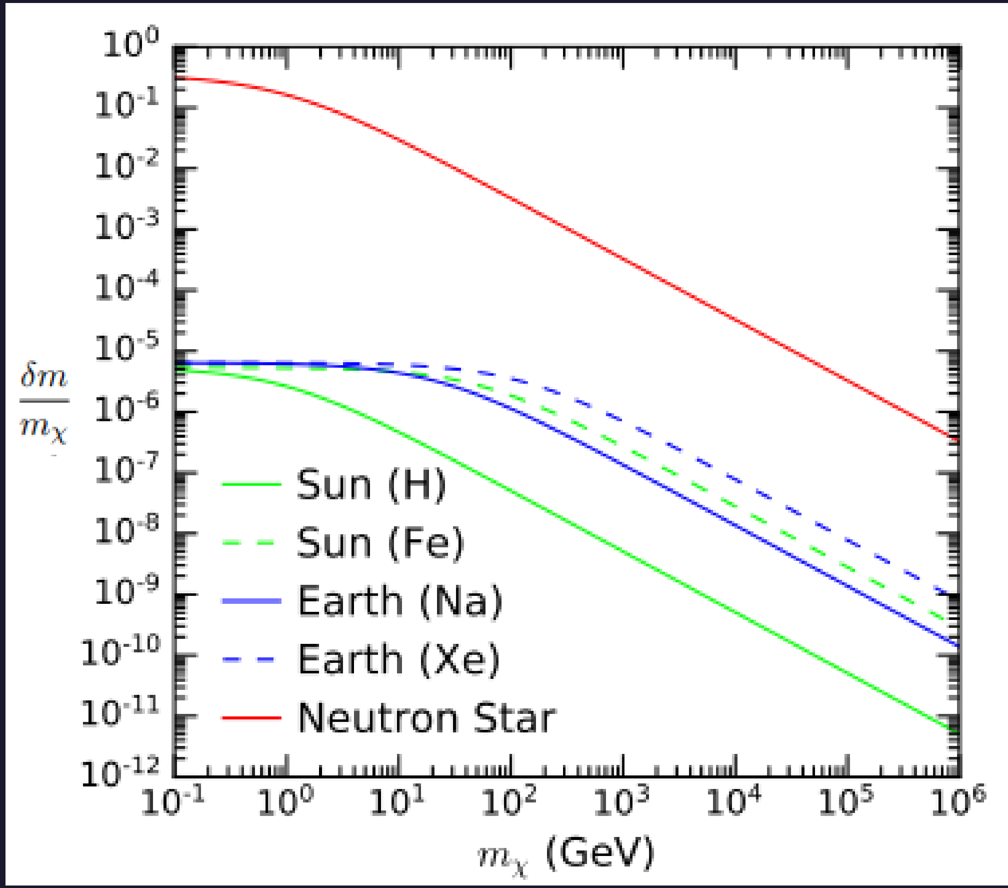

Why (compact stars)?

Neutron Stars

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- Ideal to probe models with DM-muon interactions, like $U(1)_{\mu-\tau}$

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\mu-\tau} + \mathcal{L}_\chi \\
\mathcal{L}_{\mu-\tau} &= -\frac{1}{4} F_{\mu\tau}^{\alpha\beta} F_{\mu\tau\,\alpha\beta} + \frac{\varepsilon_0}{2} F_{\mu\tau}^{\alpha\beta} B_{Y\,\alpha\beta} + \frac{1}{2} m_{Z'}^2 Z'^{\alpha} Z'^{\beta} + J_{Z'}^{\alpha} Z'_{\alpha} \\
J_{Z'}^{\alpha} &= g_{\mu\tau} \left(\bar{\mu}\gamma^\alpha \mu - \bar{\tau}\gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha \nu_\mu - \bar{\nu}_\tau \gamma^\alpha \nu_\tau \right), \\
\mathcal{L}_\chi &= \bar{\chi} \left(i\partial\!\!\!/ - m_\chi \right) \chi + Q_\chi g_{\mu\tau} \bar{\chi} \gamma^\alpha \chi Z'_\alpha,
\end{aligned}
$$

What

(could we observe/constrain)?

What?

Neutron Stars

- Collapse to BH/instability
- Altering the internal structure/EOS
- Heating

White Dwarf

- Core collapse/instability
- Altering the internal structure
- Increased luminosity

What?

Neutron Stars

- Collapse to BH/instability
  - Triggered by large DM over-density in the center
    - Heavy DM at low temperature
    - DM forms BEC
- Altering the internal structure/EOS
- Heating

- Star captures

$$N = C t_*$$

DM particles

- Particles thermalise and get confined in region of

$$r_{th} \sim \sqrt{\frac{3T}{4\pi G \rho m}}$$

- DM density

$$\rho_\chi \sim \frac{Nm}{r_{th}^3}$$

What?

Neutron Stars

- Collapse to BH/instability
- Altering the internal structure/EOS
- Heating

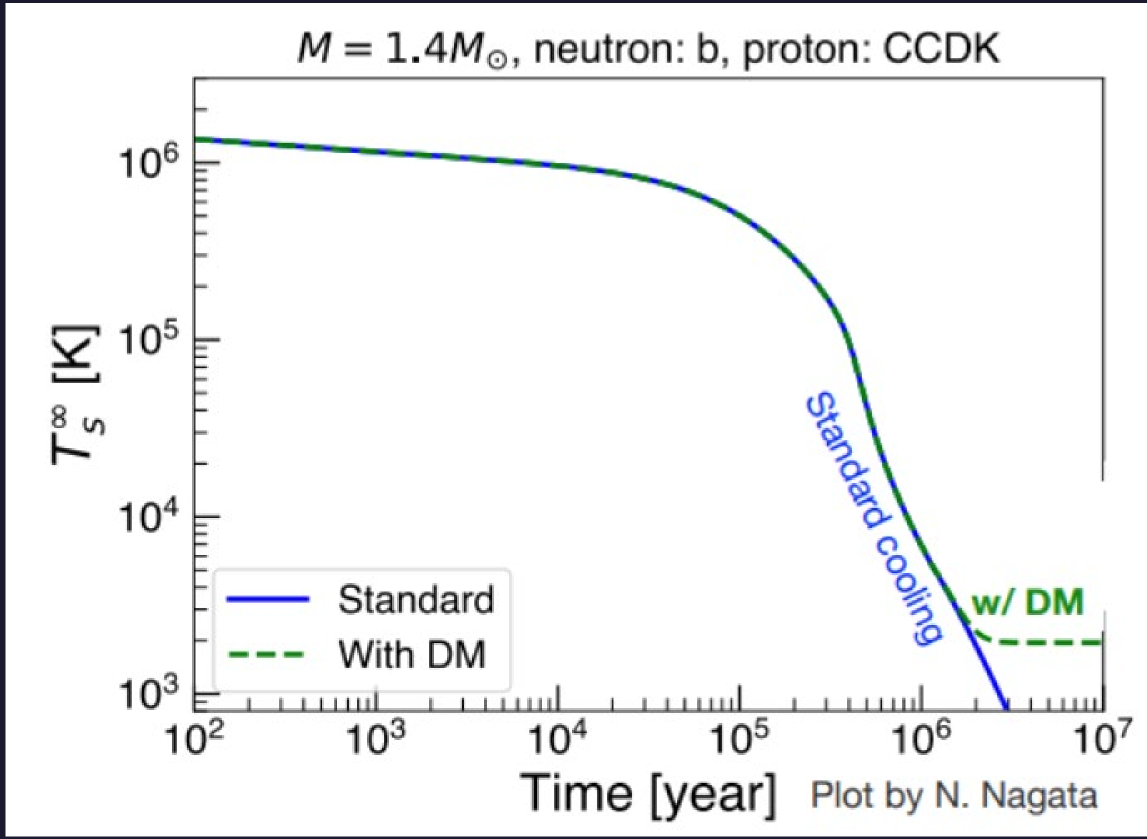
- Usually requires a considerable fraction of the star mass to be DM
  - Requires a mechanism different from capture

See Steven Harris and Violetta Sagun talks today

What?

Neutron Stars

- Collapse to BH/instability
- Altering the internal structure/EOS
- Heating
  - Energy from gravitational infall $\sim m_\chi$ (kinetic heating)
  - Energy from annihilation $\sim m_\chi$ (annihilation heating)



Kinetic and annihilation heating

- Maximum Capture rate:

$$C_{geom} = \frac{\pi R^2 (1 - B(R))}{v_s B(R)} \frac{\rho_\chi}{m_\chi} Erf\left(\sqrt{\frac{3}{2}}\frac{v_s}{v_d}\right)$$

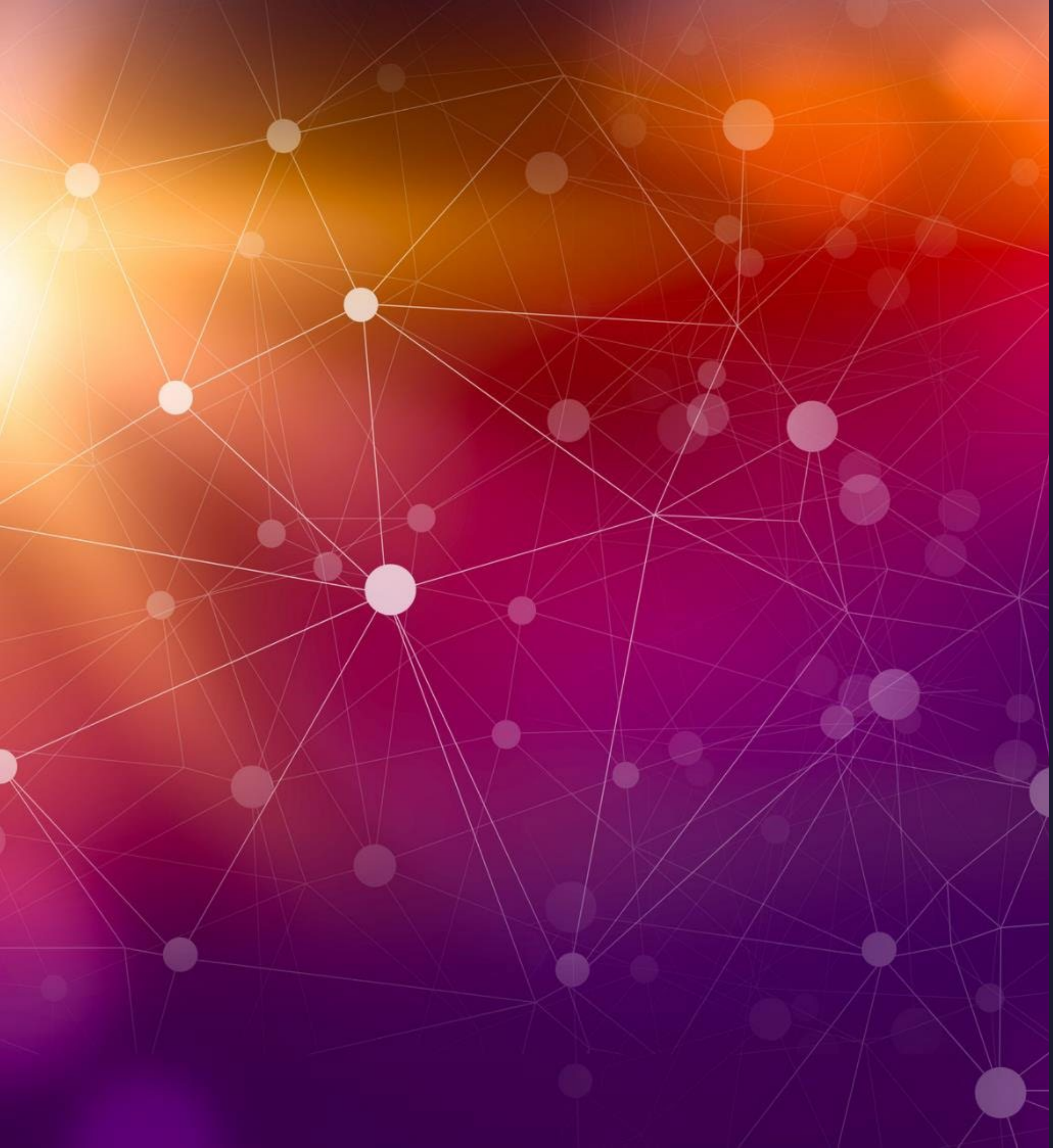
- Average energy transfer

$$\langle \delta K \rangle \sim m_\chi$$

- Energy balance

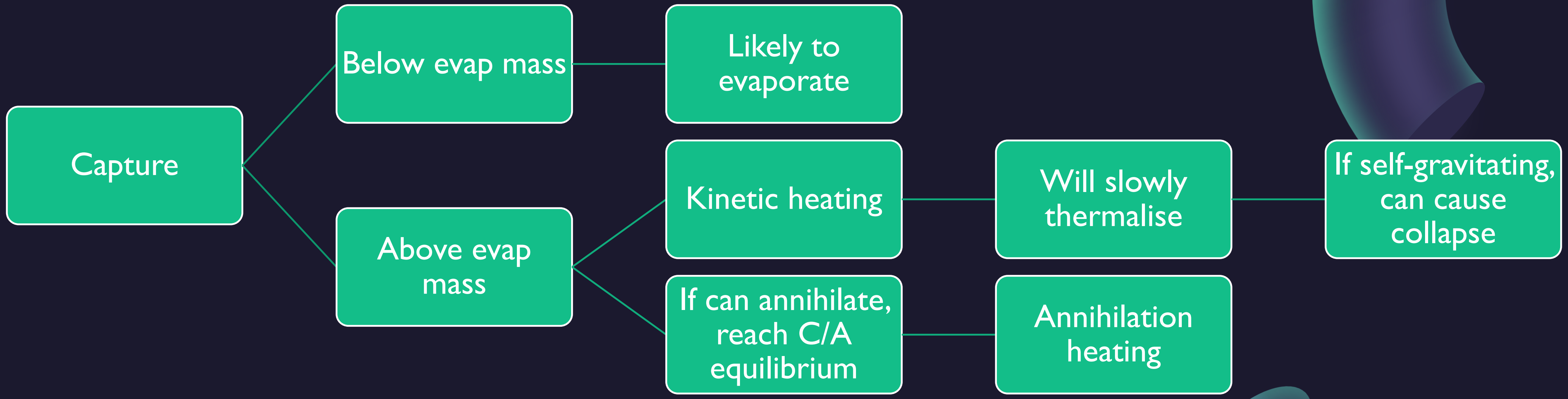
$$C_{geom} \langle \delta K \rangle = \frac{\pi R^2 (1 - B(R))}{v_s B(R)} \frac{\rho_\chi}{m_\chi} m_\chi = \sigma_{SB} \left(T_{eq}^{MAX}\right)^4 \pi R^2$$

- Kinetic heating: $\langle \delta K \rangle \sim m_\chi, T_{eq}^{MAX} \sim 1800K$
- Annihilation heating: an additional $\langle \delta K \rangle \sim m_\chi, T_{eq}^{MAX} \sim 2300K$

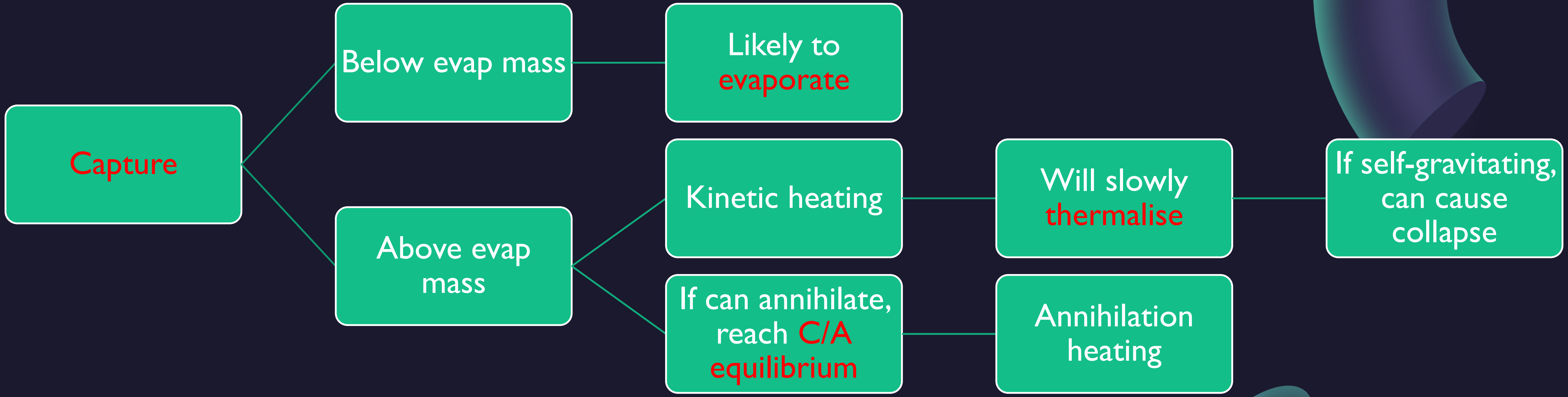


How?

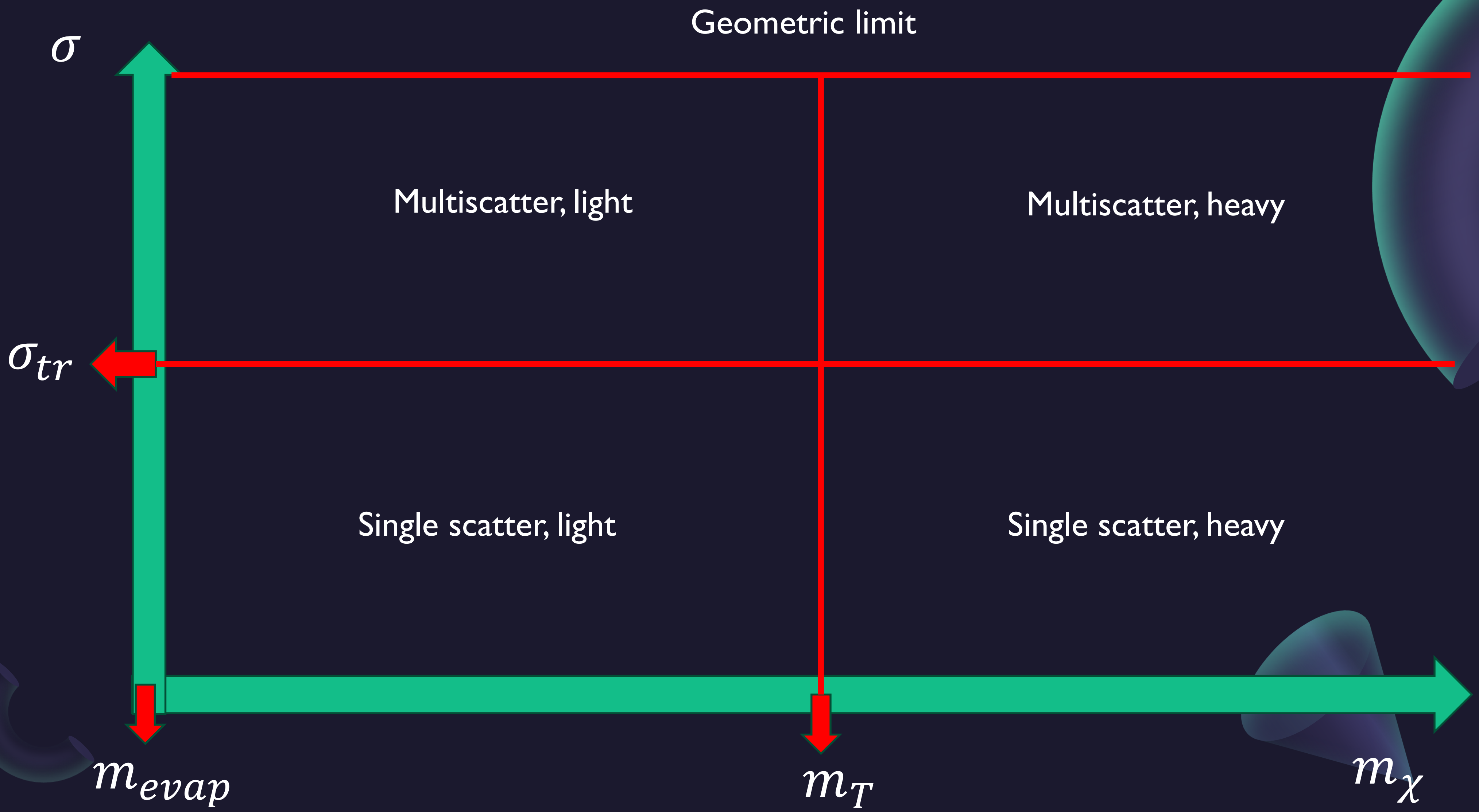
Dark Matter path in a Neutron Star



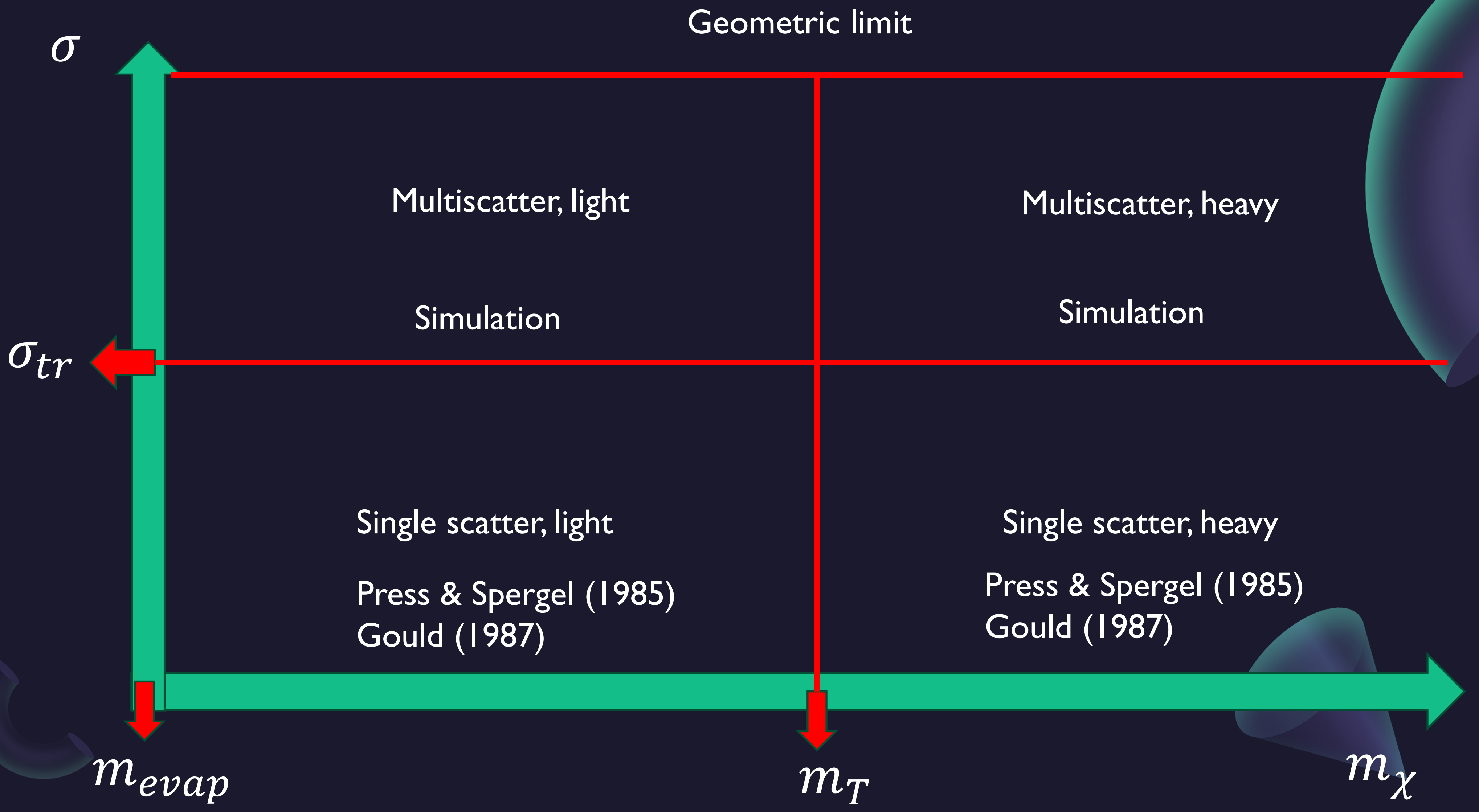
Dark Matter path in a Neutron Star



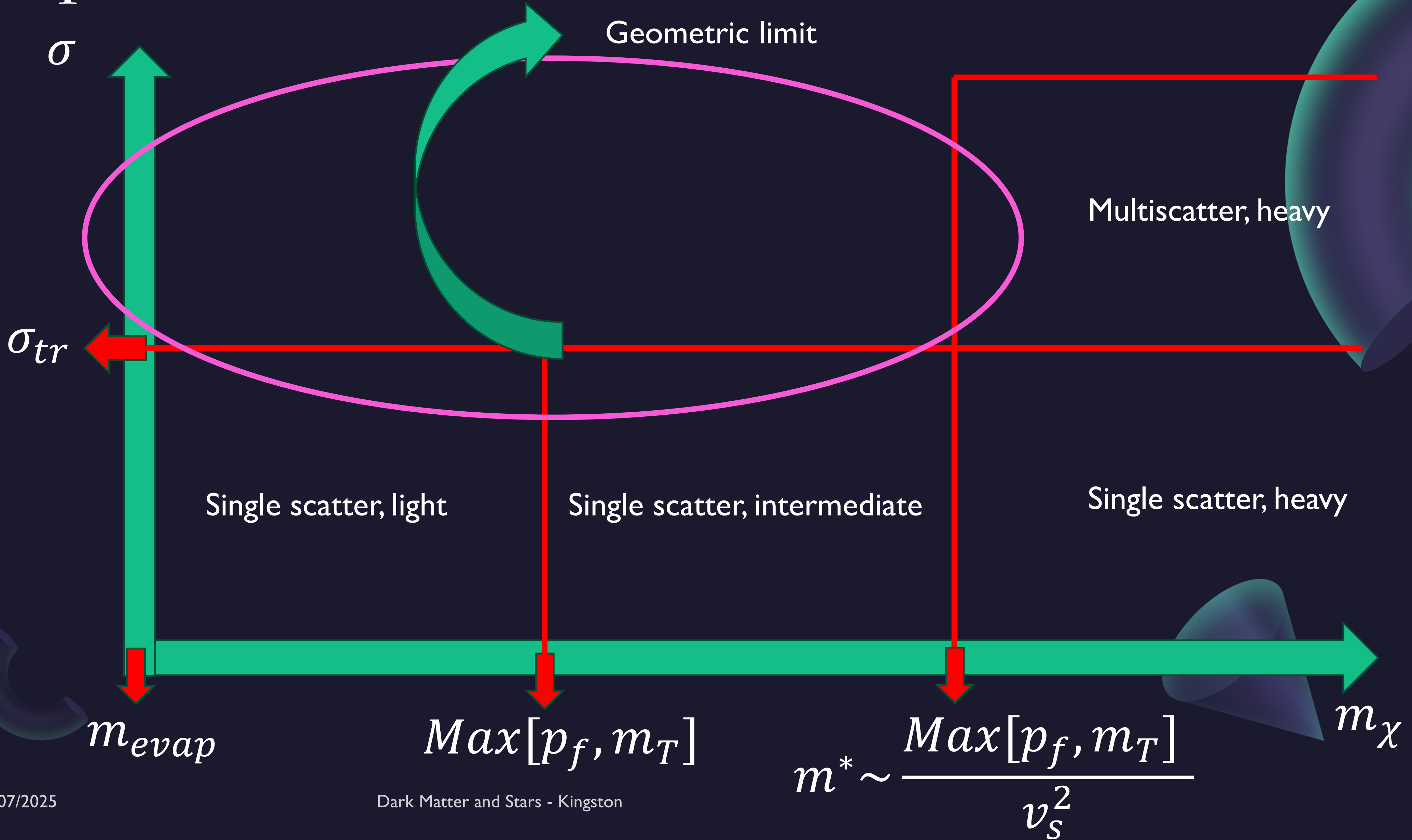
Capture in the Sun



Capture in the Sun



Capture in NS



Capture probability

- Capture probability (Sun)

$$P \leq \frac{v_e^2}{u^2 + v_e^2}$$

- In NS $v_e^2 \gg u^2$

$$P \sim 1$$

Even if not kinematically matched

- DM kinetic energy in halo

$$K^{halo} = \frac{1}{2} m u^2 \sim 10^{-6} m$$

- DM kinetic energy after infall

$$K^{infall} = m\left(\frac{1}{\sqrt{B}} - 1\right) \sim m$$

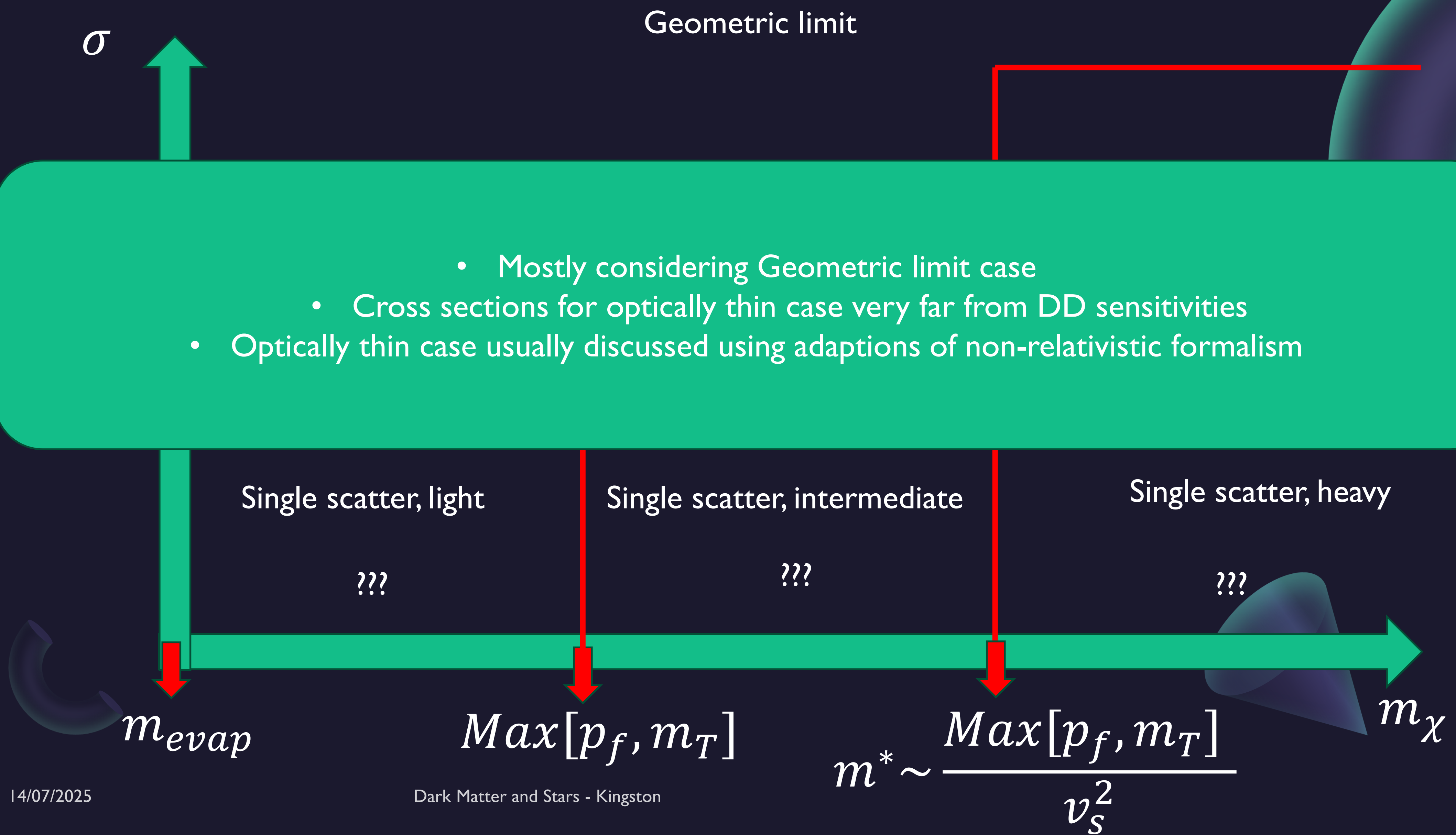
- DM energy lost in first scattering (hadron targets)

$$q_0 \sim \sigma(\mu) \sim \begin{cases} 1GeV, & m_\chi \gtrsim 10GeV \\ \sigma(m_\chi), & m_\chi \lesssim 1GeV \end{cases}$$

- Capture with single scatter for $K^{halo} < q_0$

$$m \lesssim 10^6 GeV$$

Capture in NS ~2015



- Mostly considering Geometric limit case
- Cross sections for optically thin case very far from DD sensitivities
- Optically thin case usually discussed using adaptions of non-relativistic formalism

Capture in NS

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[90] W. Husain, T. F. Motta, and A. W. Thomas, "Consequences of neutron decay inside neutron stars," *JCAP* **10** (2022) 028, arXiv:2203.02758 [hep-ph].

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⚠ Non-comprehensive list

Capture in NS ~2025

- JCAP 09 (2020) 028 (2004.14888)
- JCAP 03 (2021) 086 (2010.13257)
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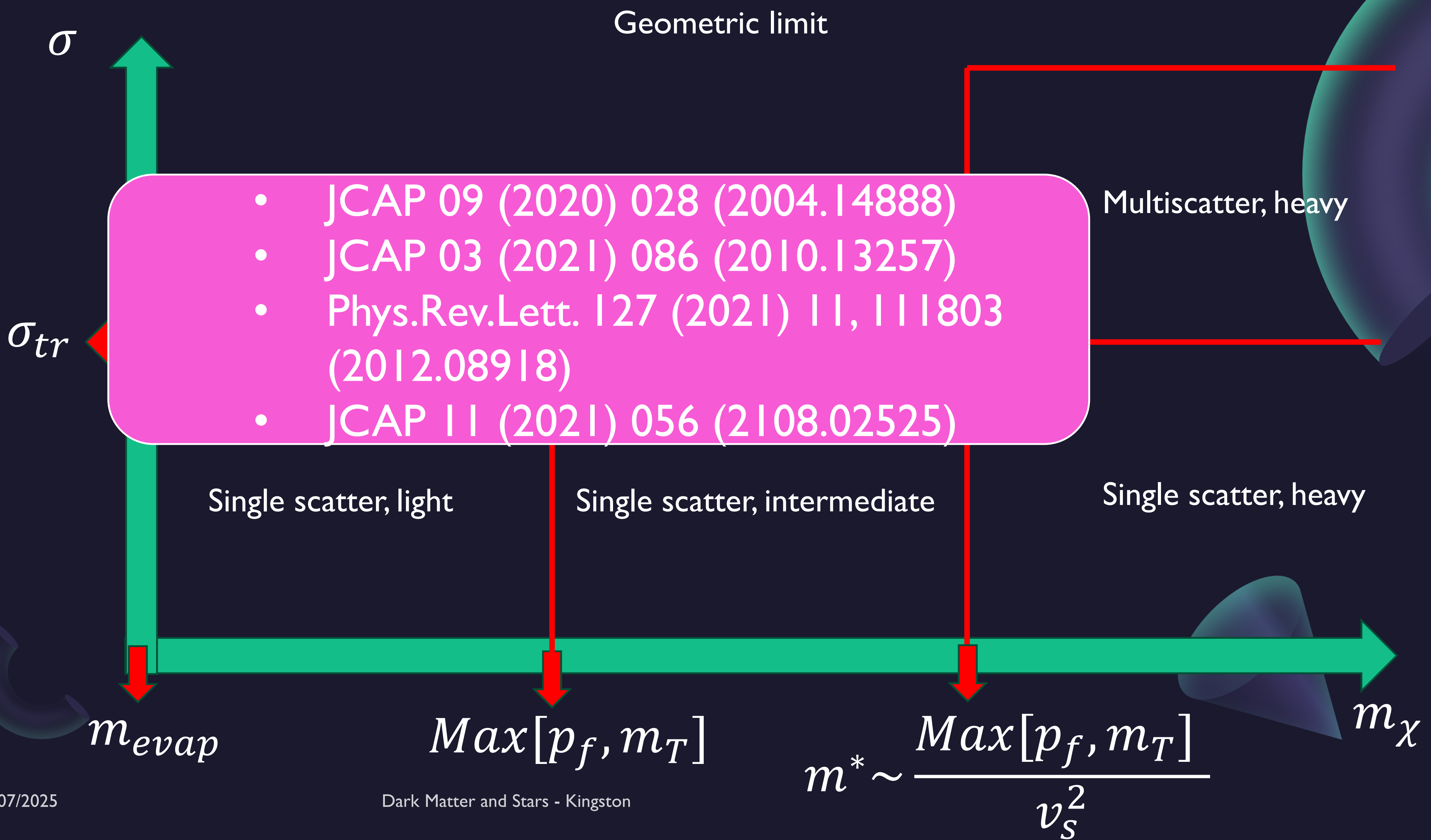


Interaction rates in degenerate matter

- Derived in full generality in the relativistic regime

$$\Gamma = \int \frac{d^3k'}{(2\pi)^3} \frac{1}{(2E_\chi)(2E'_\chi)(2m_\ell)(2m_\ell)} \Theta(E'_\chi - m_\chi)\Theta(q_0)S(q_0, q),$$

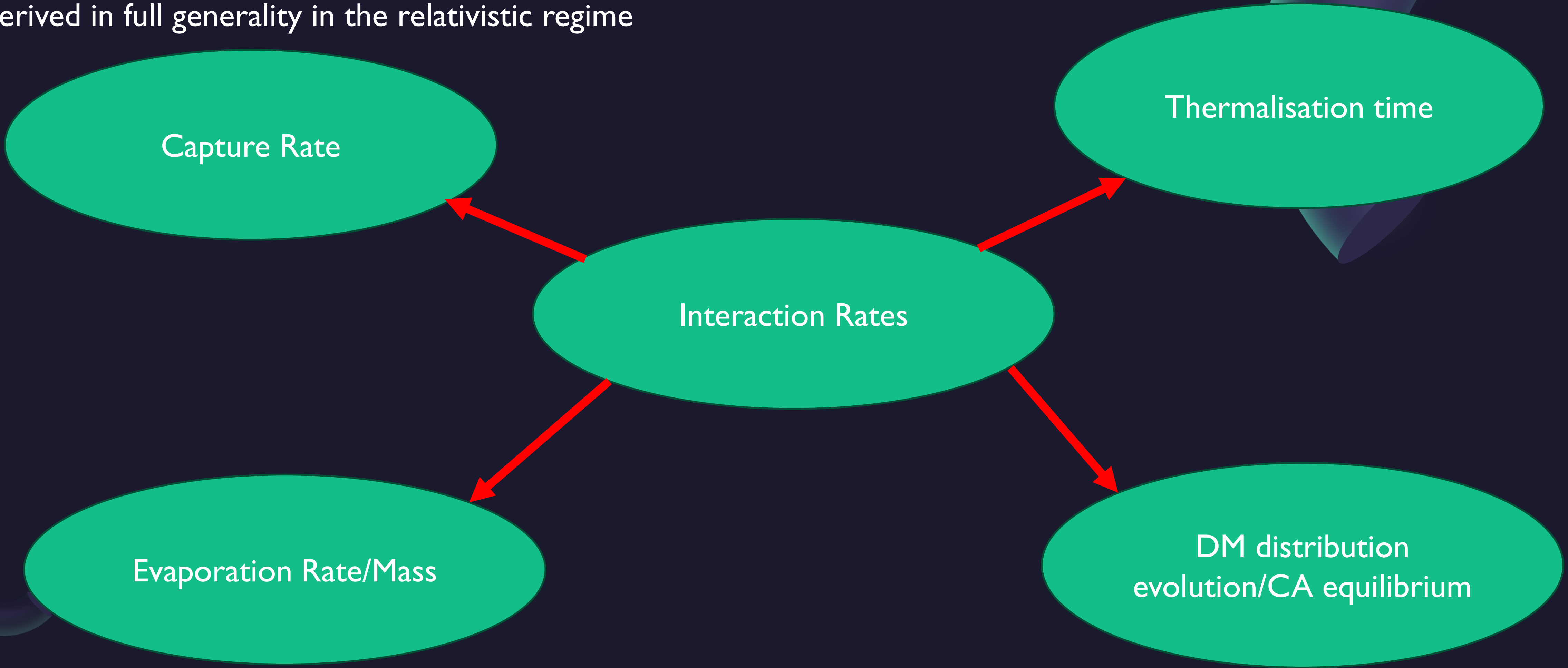
$$S(q_0, q) = 2\int \frac{d^3p}{(2\pi)^3} \int \frac{d^3p'}{(2\pi)^3} \frac{m_i^2}{E_\ell E'_\ell} |\overline{M}|^2 (2\pi)^4 \delta^4 \left(k_\mu + p_\mu - k'_\mu - p'_\mu\right)$$
$$\times f_{\rm FD}(E_\ell)(1 - f_{\rm FD}(E'_\ell))\Theta(E_\ell - m_\ell)\Theta(E'_\ell - m_\ell),$$

$$\Gamma^-(E_\chi) \propto \frac{1}{2^7\pi^3 E_\chi k} \int_0^{E_\chi - m_\chi} q_0 dq_0 \int \frac{t_E^n dt_E}{\sqrt{q_0^2 + t_E}} \left[1 - g_0\left(\frac{E_\ell^{t^-} - \mu_{F,\ell}}{q_0}\right)\right]$$

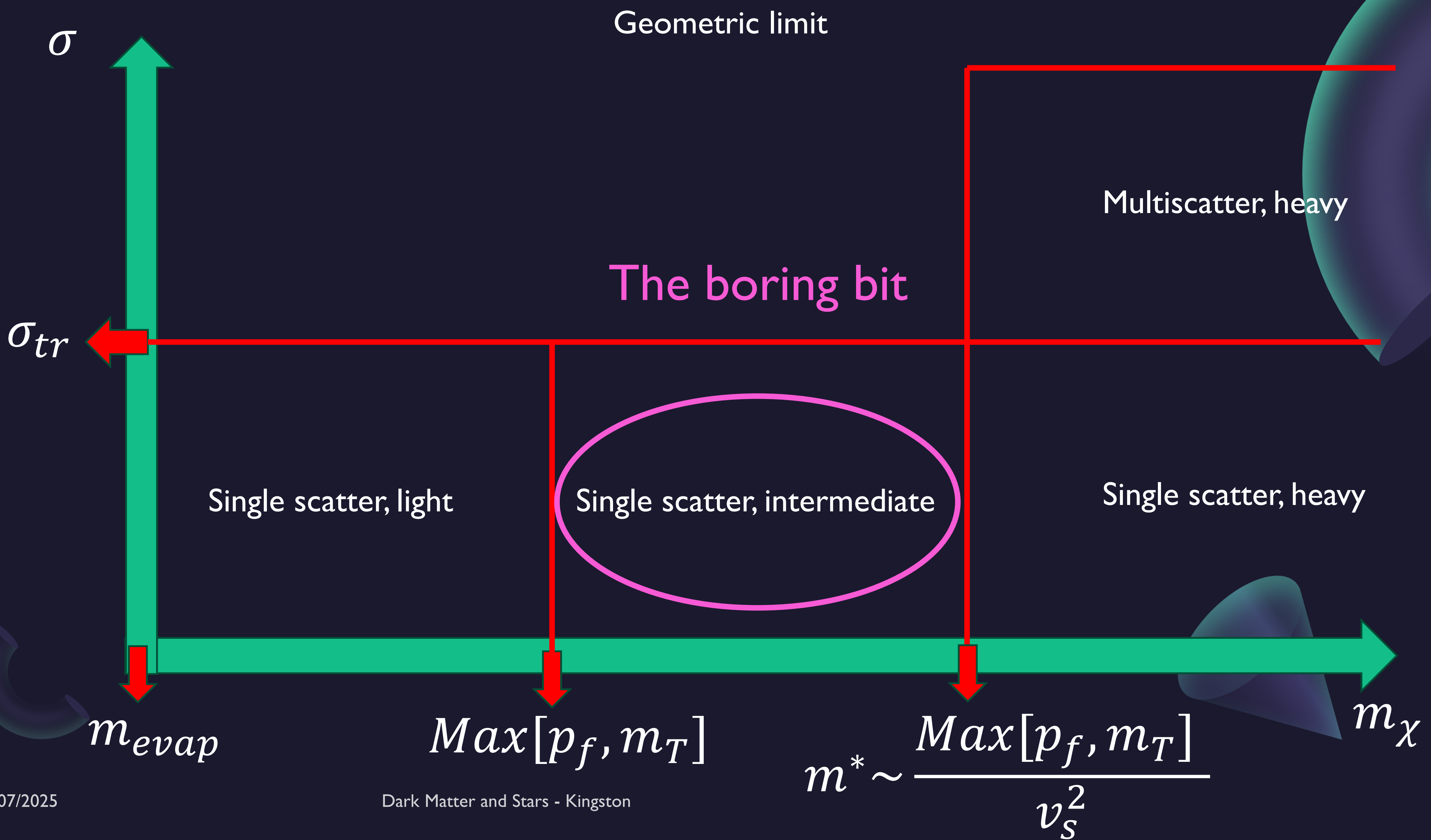
JCAP 03 (2021) 086 (2010.13257)

Interaction rates in degenerate matter

- Derived in full generality in the relativistic regime



Capture in NS ~2025



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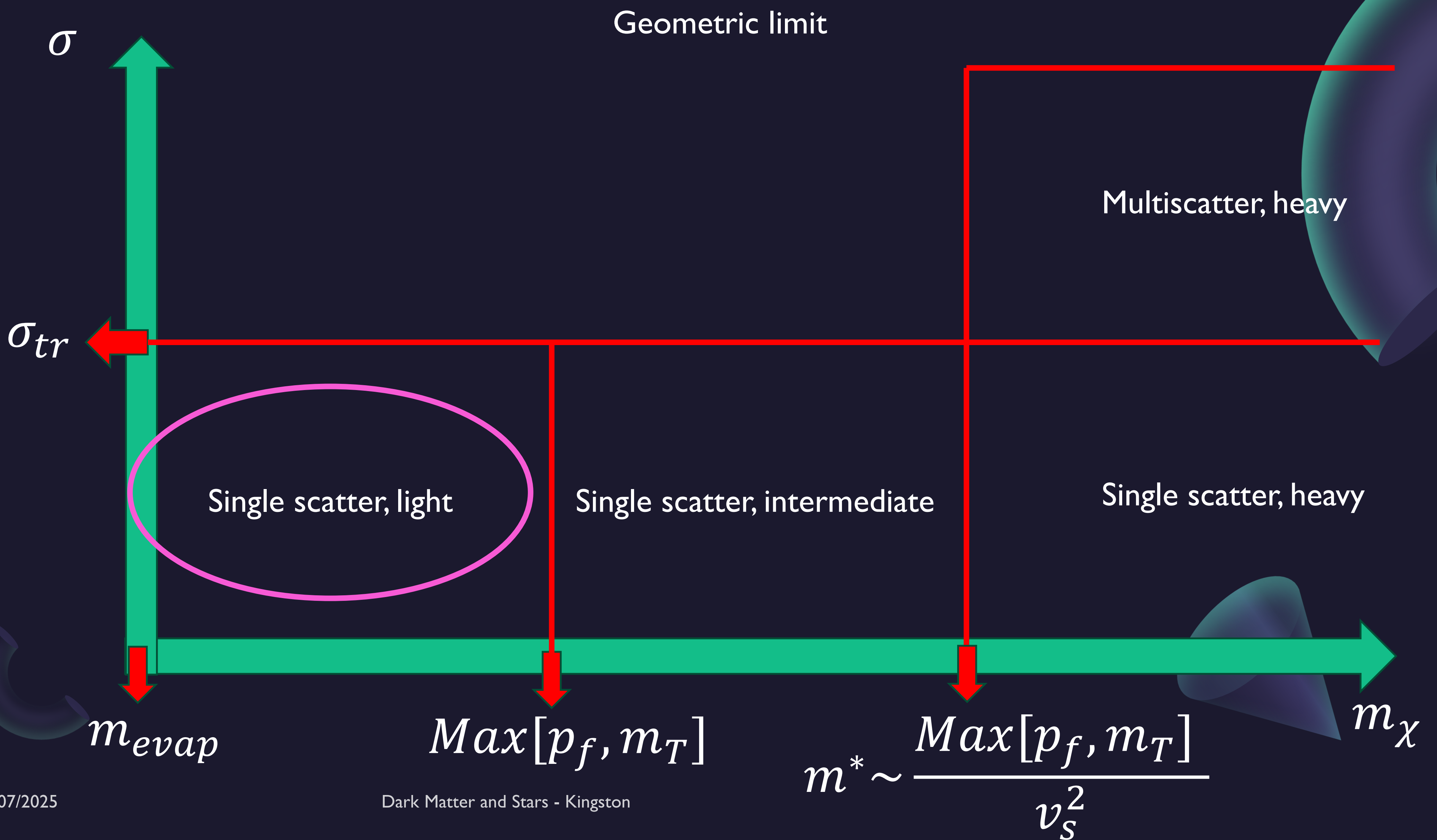
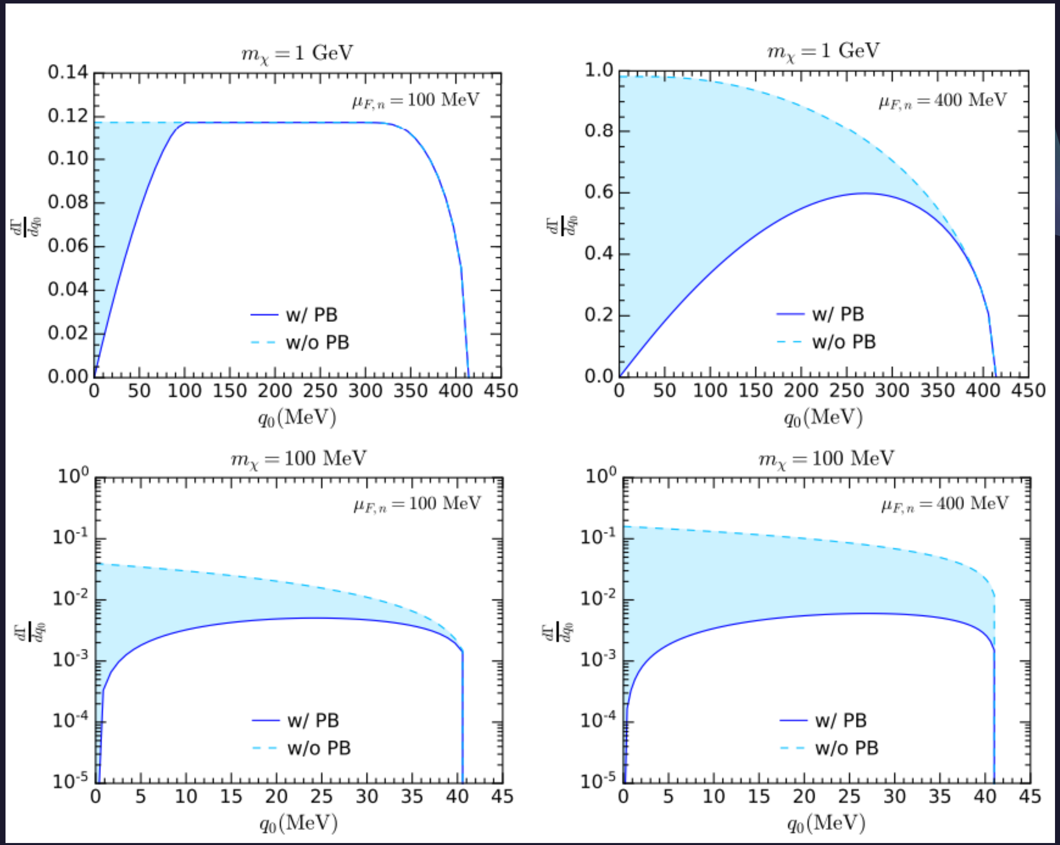


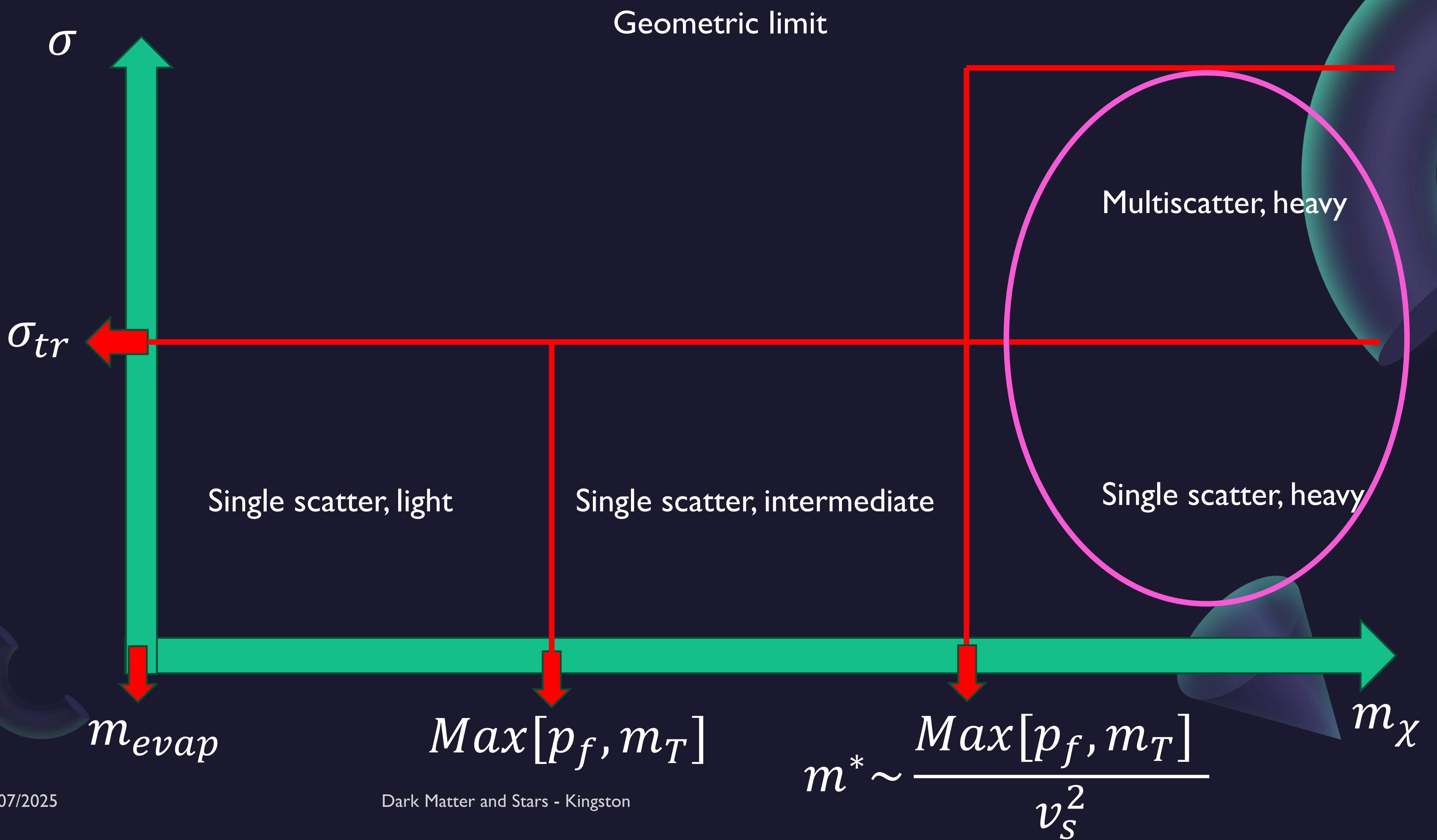
Single Scatter, light: Pauli Blocking

- DM needs to transfer enough energy/momentum to scatter degenerate fermions above the Fermi surface
- In capture, suppresses the rate by approximate scaling

$$\frac{m_\chi}{Max[p_f, m_T]}$$



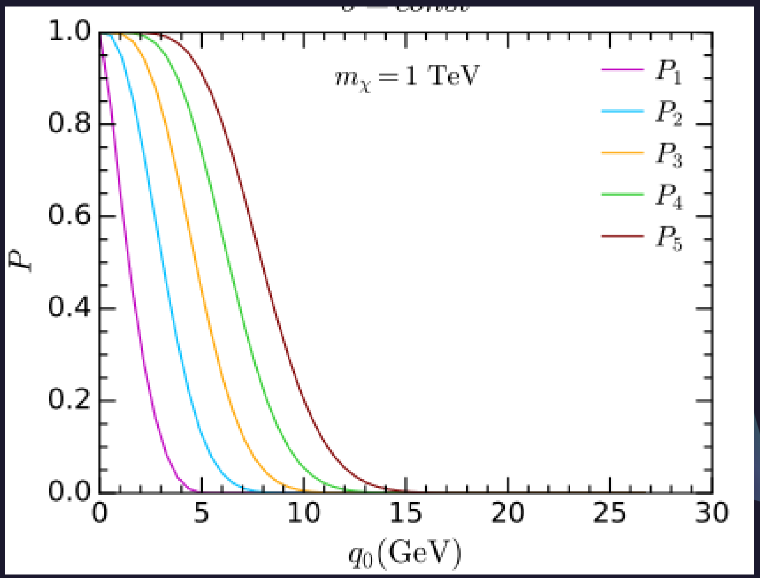
Capture in NS ~2025



Single Scatter, heavy: energy loss

- Interaction rates gives average energy loss
- Energy loss function can be used to compute capture probability P_N

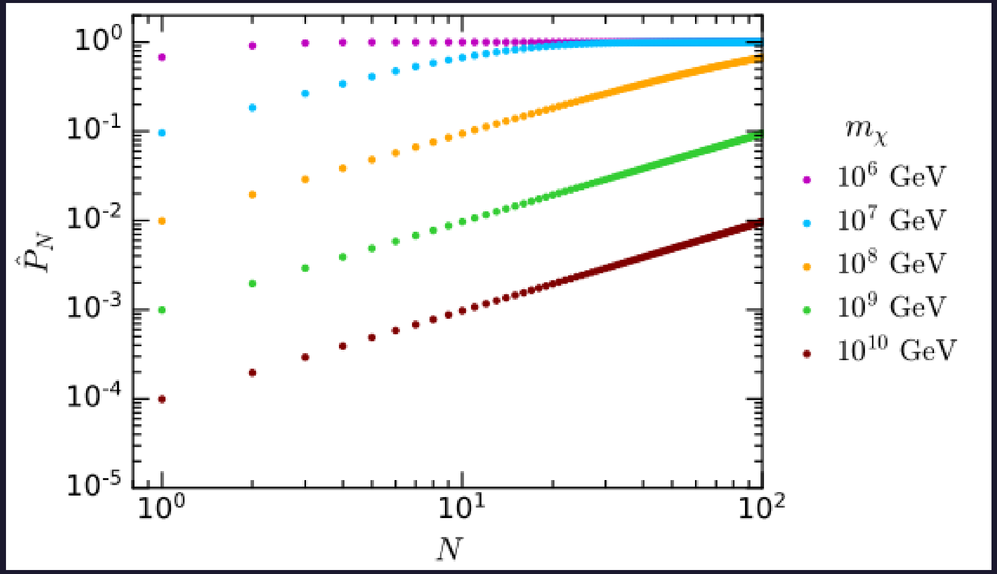
$$\hat{P}_N \sim 1 - e^{-\frac{N m^*}{m_\chi}}$$



With

$$m^* \sim \mathcal{O}(10^{5-6} GeV)(hadrons)$$

$$m^* \sim \mathcal{O}(10^{4-5} GeV)(leptons)$$



- For large mass, one has $P_1 \sim \frac{m^*}{m_\chi}$, and signle scattering the capture rate is suppressed by P_1

Capture in NS

- Intermediate mass region

$$C \propto n_\chi \propto \frac{1}{m_\chi}$$

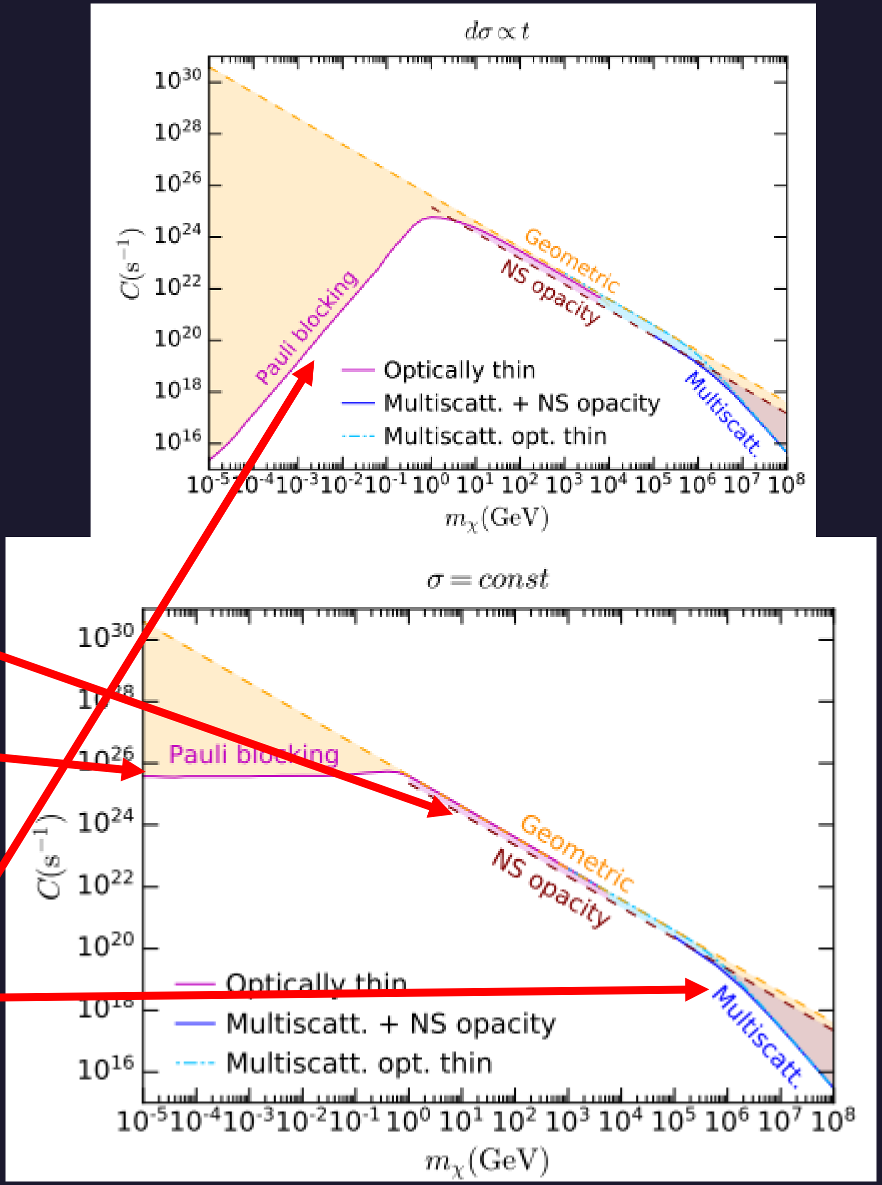
- Low mass region, additional m_χ factor:

$$C \propto const$$

- Large mass region, additional $\frac{1}{m_\chi}$ factor:

$$C \propto \frac{1}{m_\chi^2}$$

- Momentum dependent cross sections have additional m_χ factors at low mass from kinematics



Capture in NS

- Threshold cross section defined as

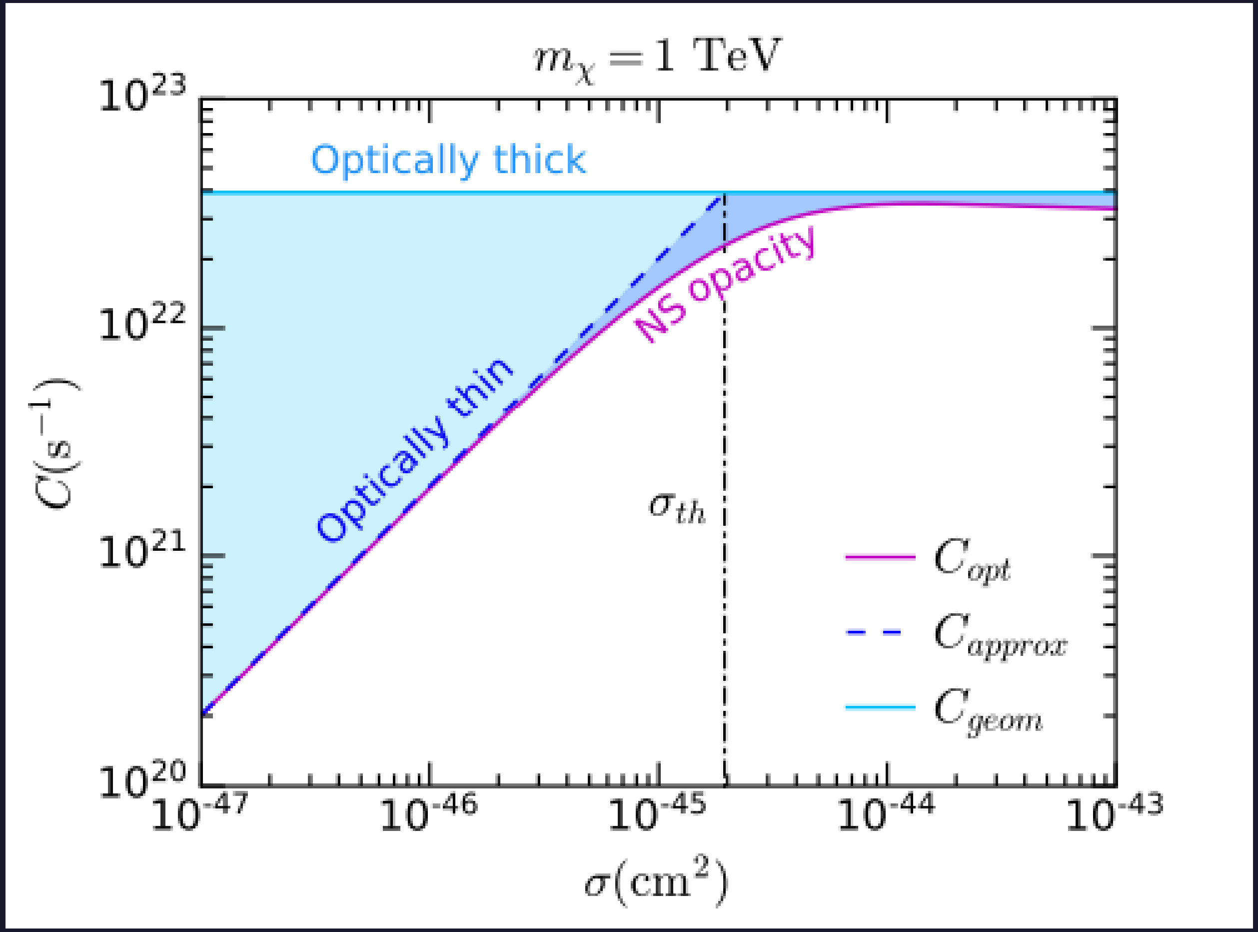
$$C = C_{geom}\frac{\sigma}{\sigma_{th}}$$

- For Dark Kinetic Heating, Equilibrium Temperature scales as

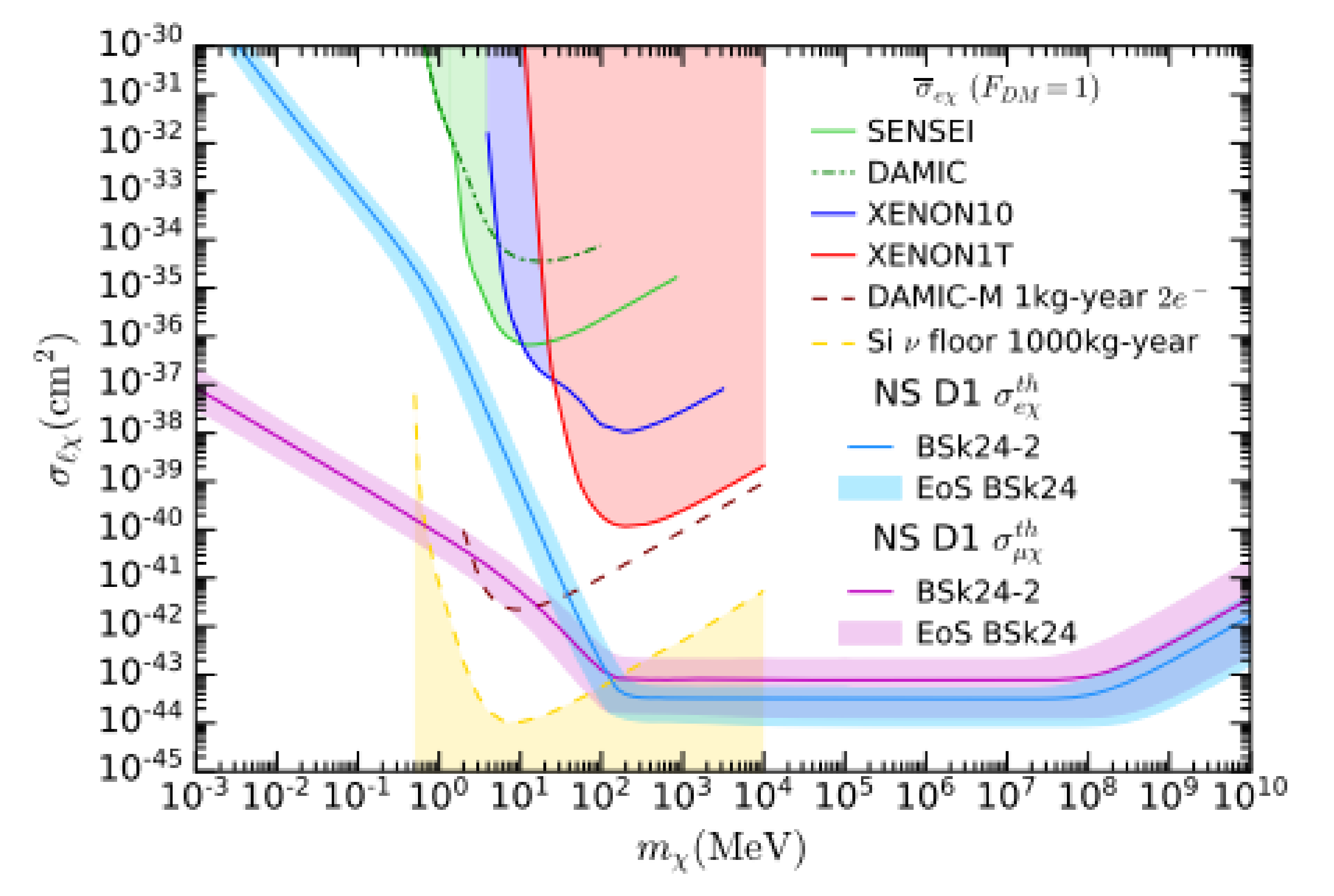
$$T_{eq} \propto \left(\frac{\sigma}{\sigma_{th}}\right)^{1/4} T_{eq}^{MAX}$$

- Detect NS with $T < T_{eq}^{MAX}$

- Exclude $\sigma > \sigma_{tr} > \left(\frac{T}{T_{eq}^{MAX}}\right)^4 \sigma_{tr}$

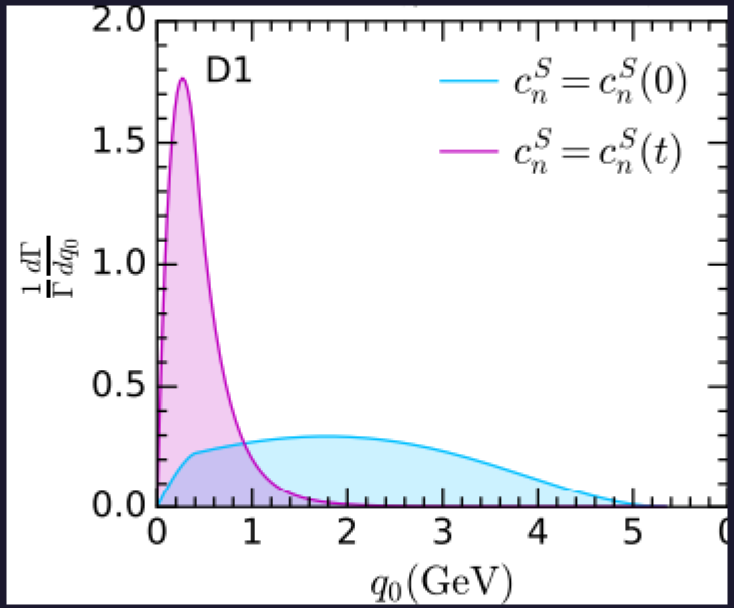


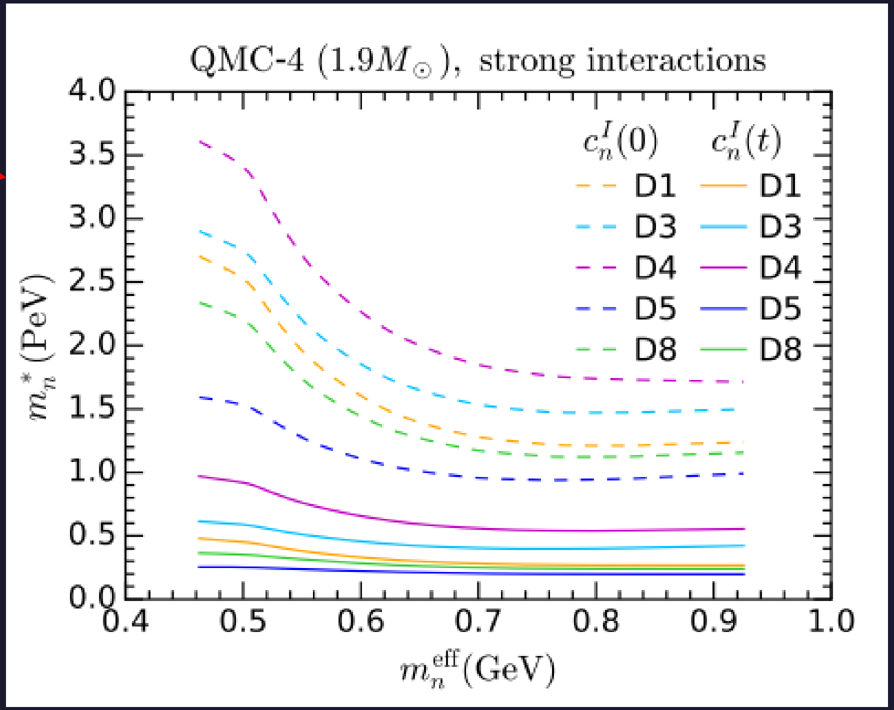
Capture in NS: leptons



Capture in NS: hadrons

- Inclusion of 2 important effects
  - Form Factors for Hadrons
  - Hadrons self interactions
- Target mass (and m^*) become position-dependent, as they depend on the target density





- Phys.Rev.Lett. 127 (2021) 11, 111803 (2012.08918)
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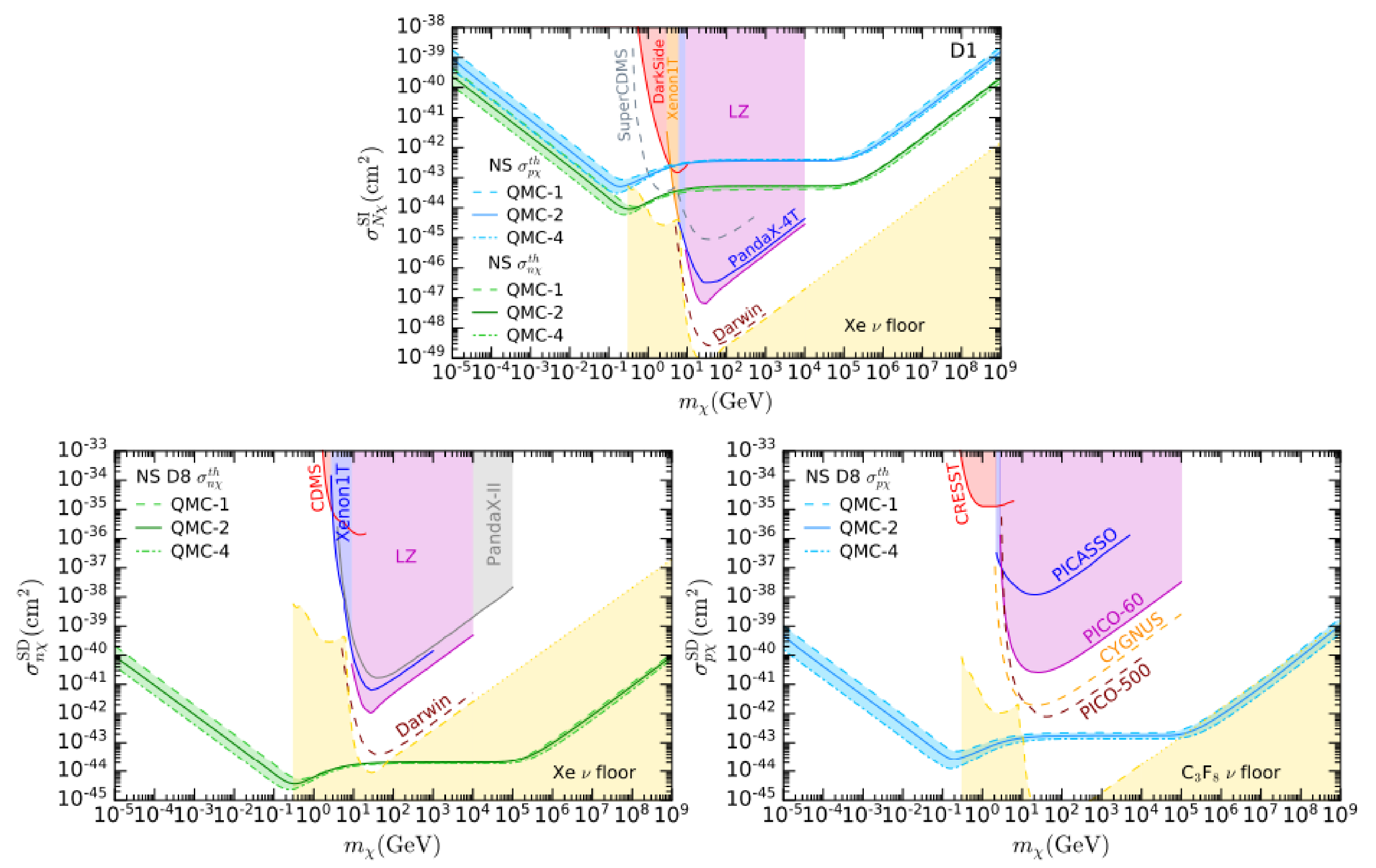
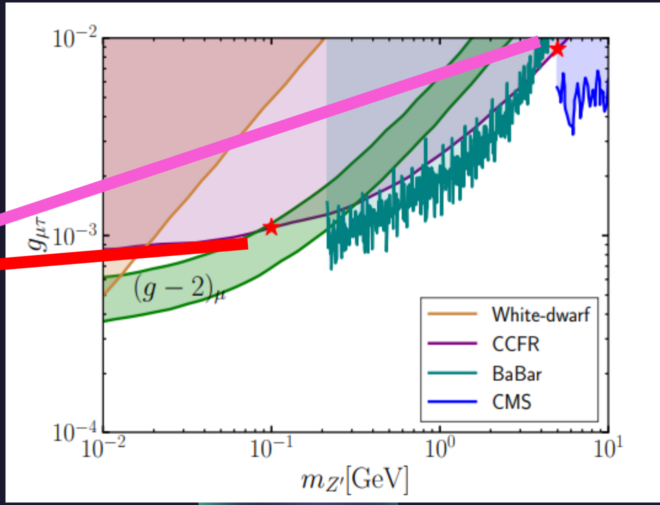
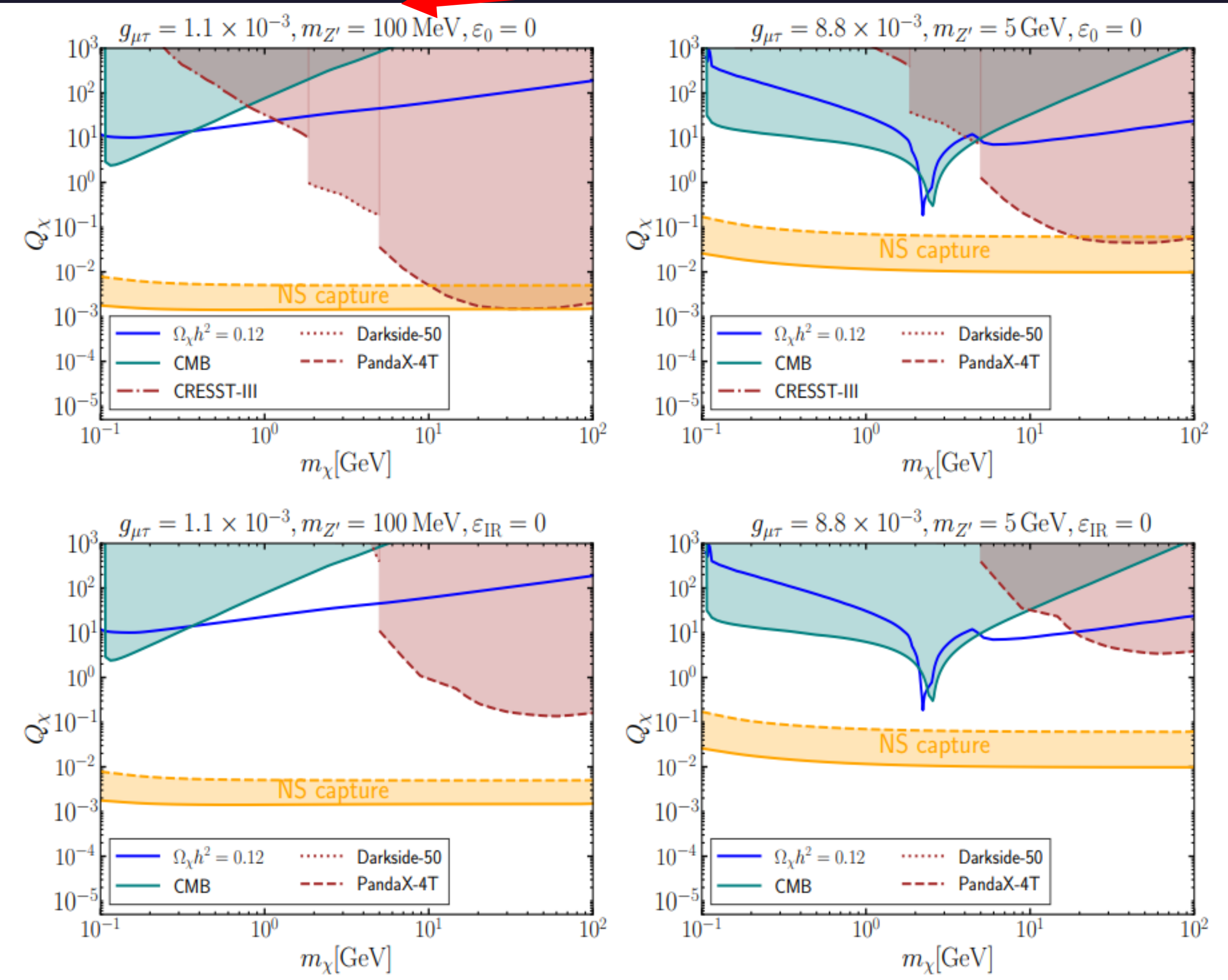
Capture in NS: hadrons



Capture in NS: muons/light mediator

$U(1)_{\mu-\tau}$ model





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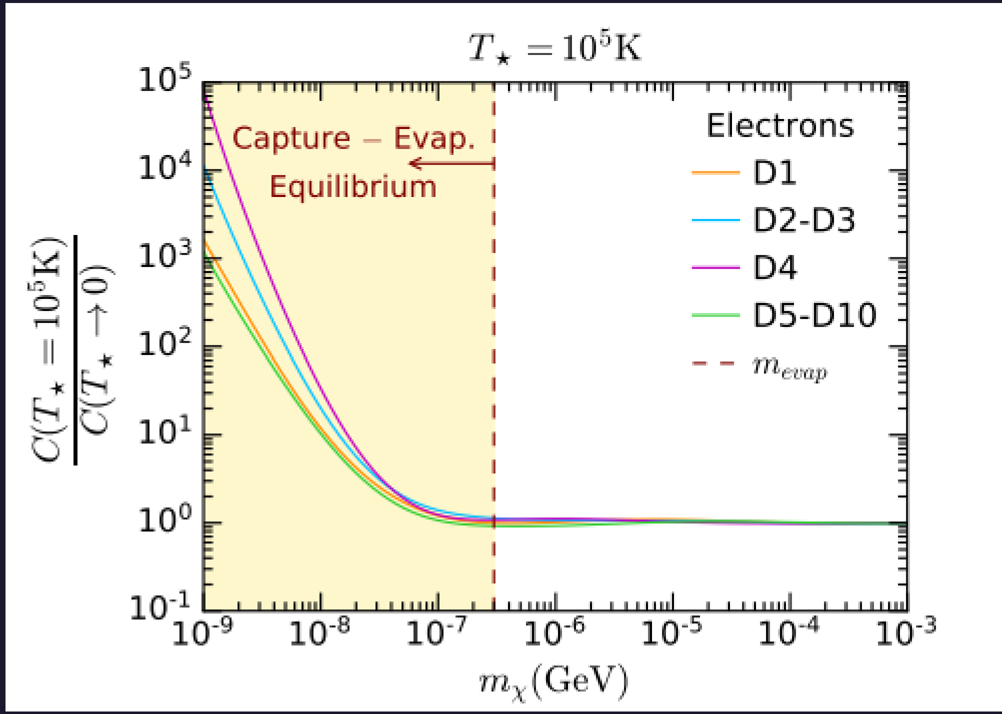
Evaporation mass is NS

- Evaporation mass ~ scale at which temperature effects and upscattering become relevant
- Estimate:

$$m_{evap} \sim 300eV \frac{T}{10^5 K}$$

- Previous estimates (non-relativistic)

$$m_{evap} \sim 20eV \frac{T}{10^5 K}$$

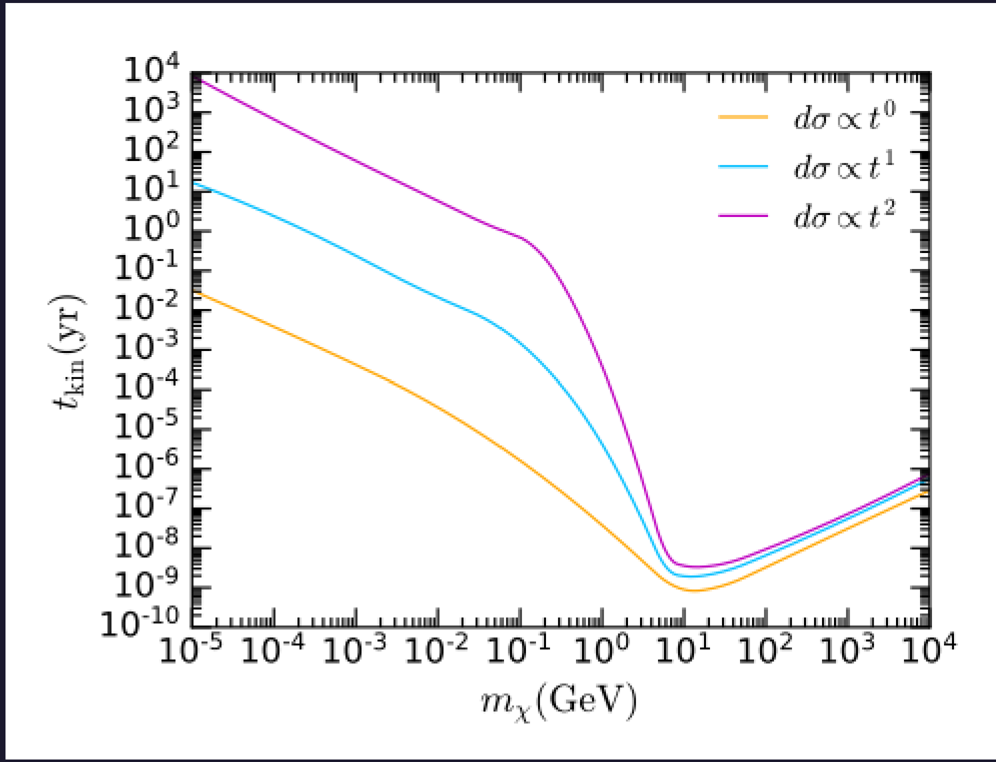


Thermalisation and C/A equilibrium

JCAP 04 (2024) 006

DM energy distribution time evolution:

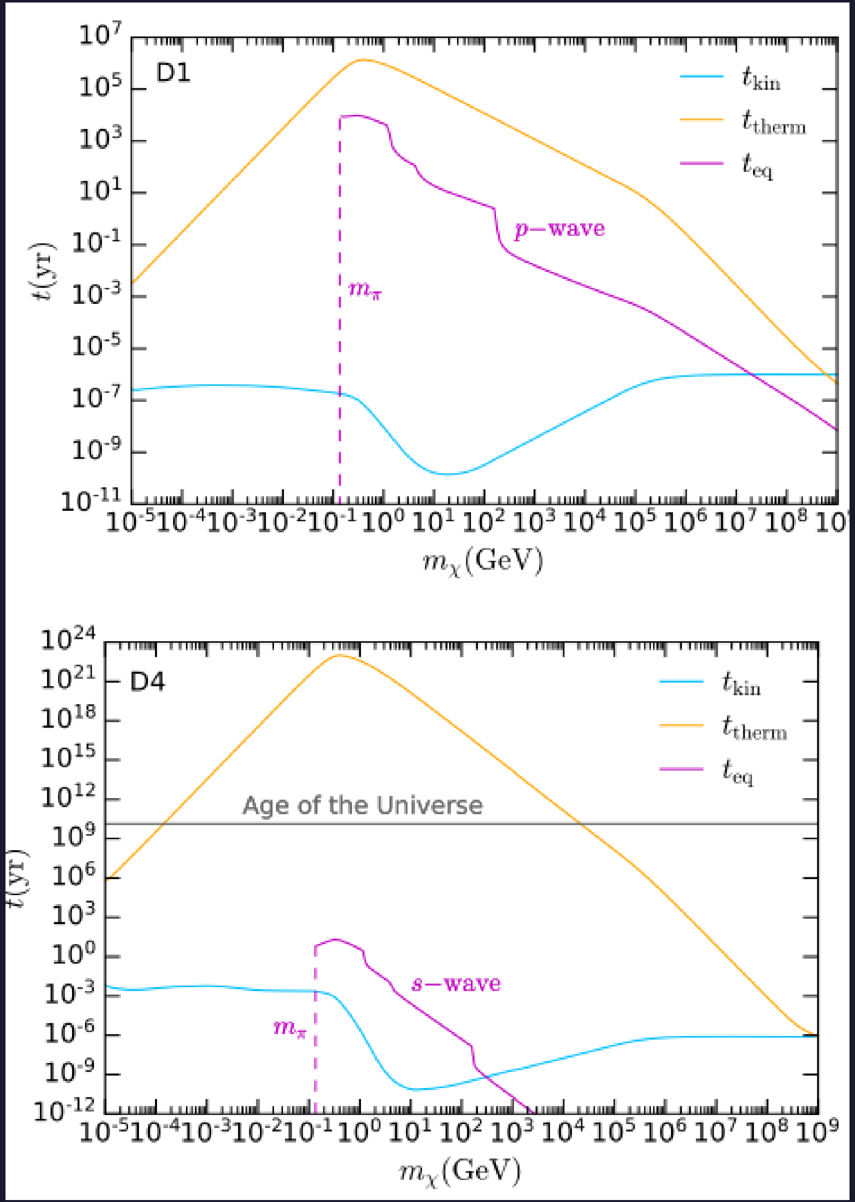
- Kinetic heating always happens ($t_{kin} \ll t_{star}$)
- Annihilation heating always happens ($t_{CA} \ll t_{star}$)
- Thermalisation depends on the cross section scaling with q_{tr}^2



Thermalisation and C/A equilibrium

DM energy distribution evolution:

- Kinetic heating always happens ($t_{kin} \ll t_{star}$)
- Annihilation heating always happens ($t_{CA} \ll t_{star}$)
- Thermalisation depends on the cross section scaling with q_{tr}^2



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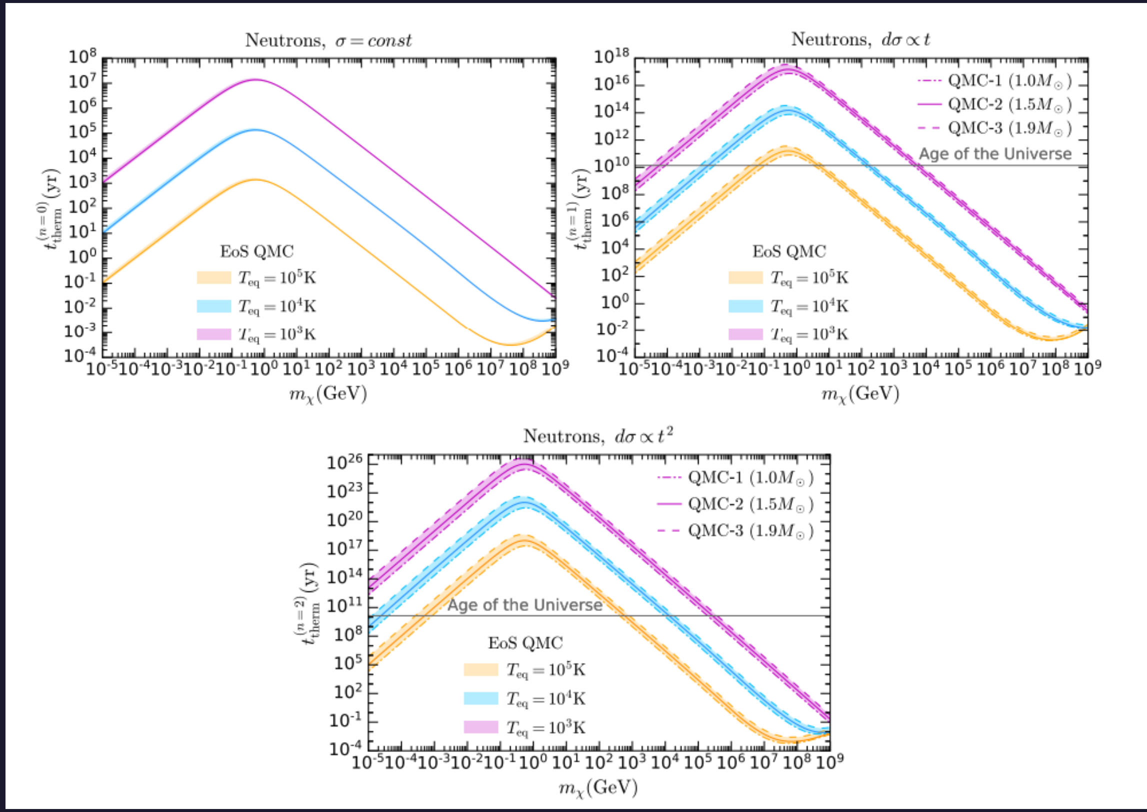


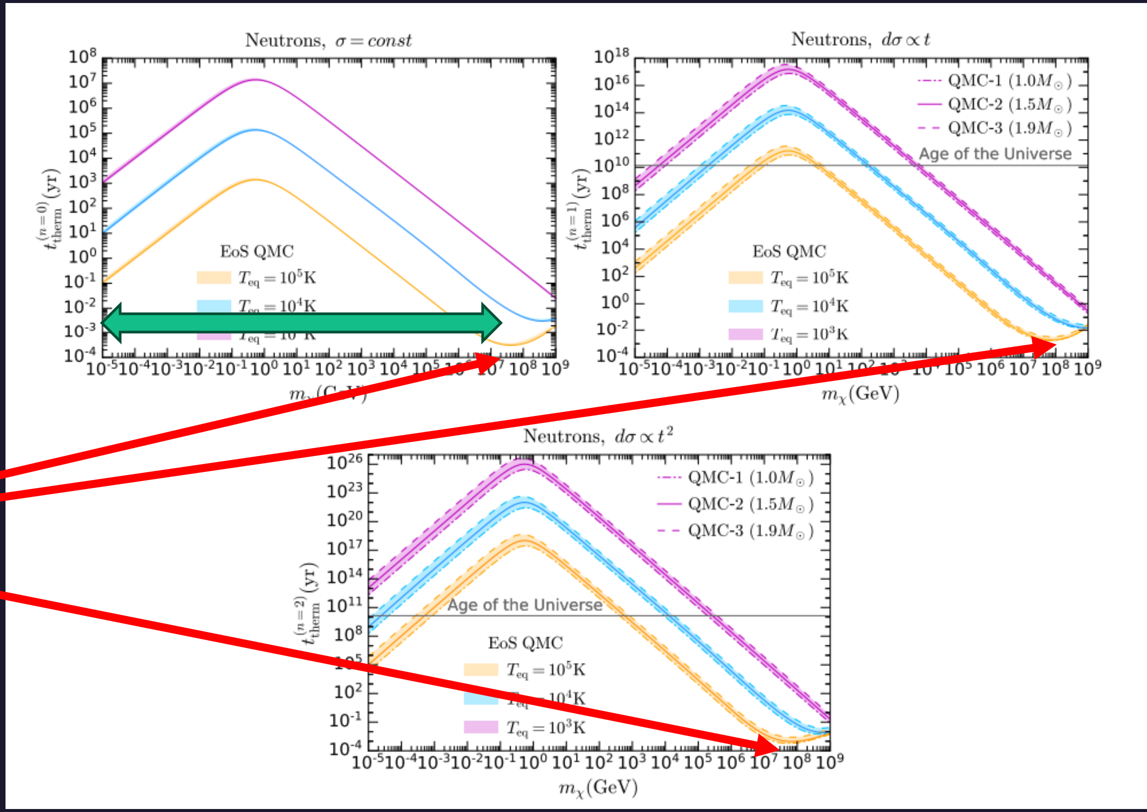
Thermalisation

Pauli-blocked

- Pauli blocking activates in the late stages of the thermalization process
- Only masses above

$$m_\chi \gtrsim 10\text{^}8 \frac{10^5 K}{T} GeV$$

Not affected by PB



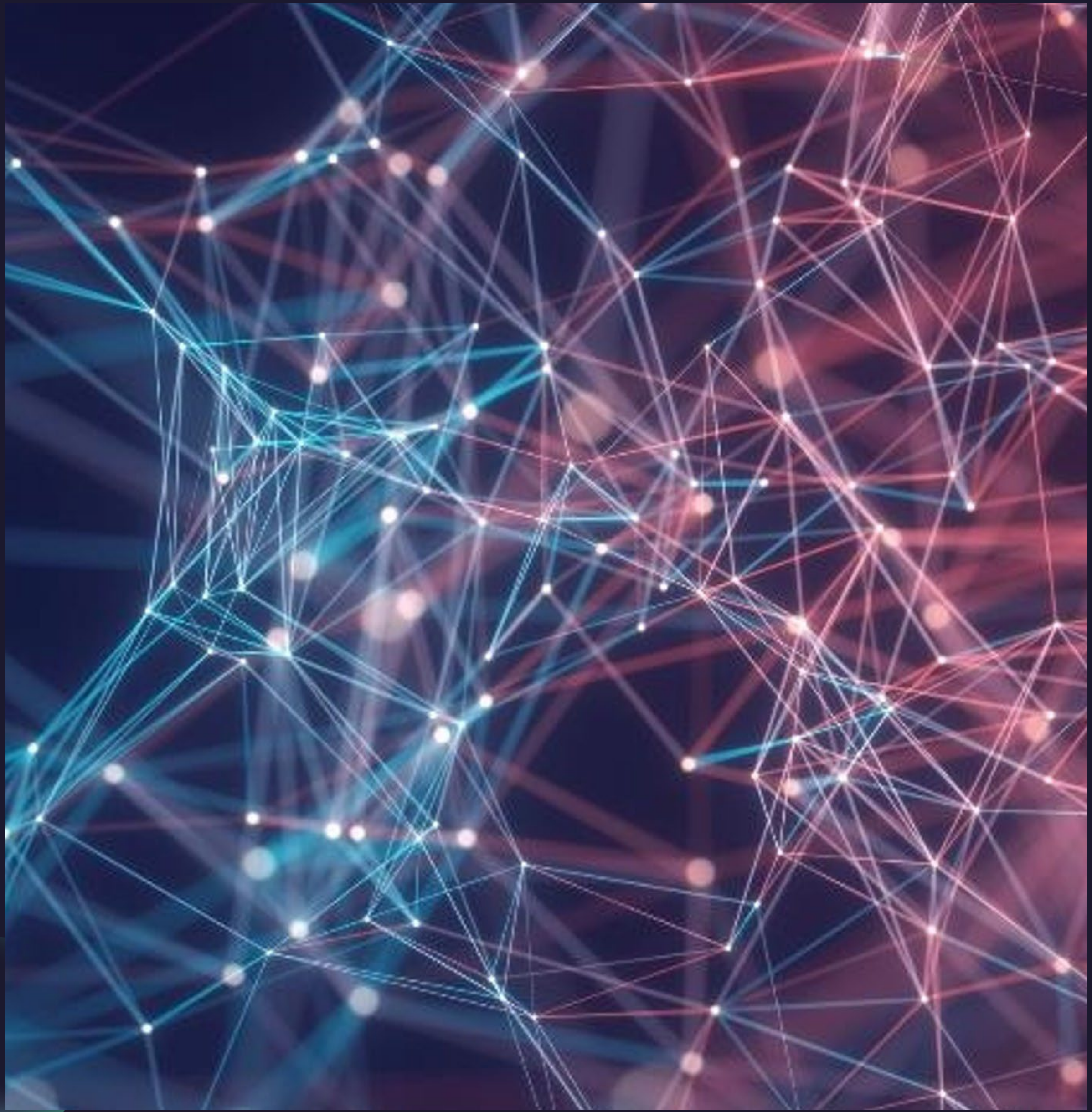
Conclusions

- NS interesting astrophysical laboratory to probe and constraint DM physics
    - Wash away non-relativistic suppressions in DD
    - No SD suppression
    - Sensitivities below neutrino floor for SD
- Large interest in the field and huge theoretical progress in the last decade
    - Rates for most common scenarios now available

Thanks

Giorgio Busoni

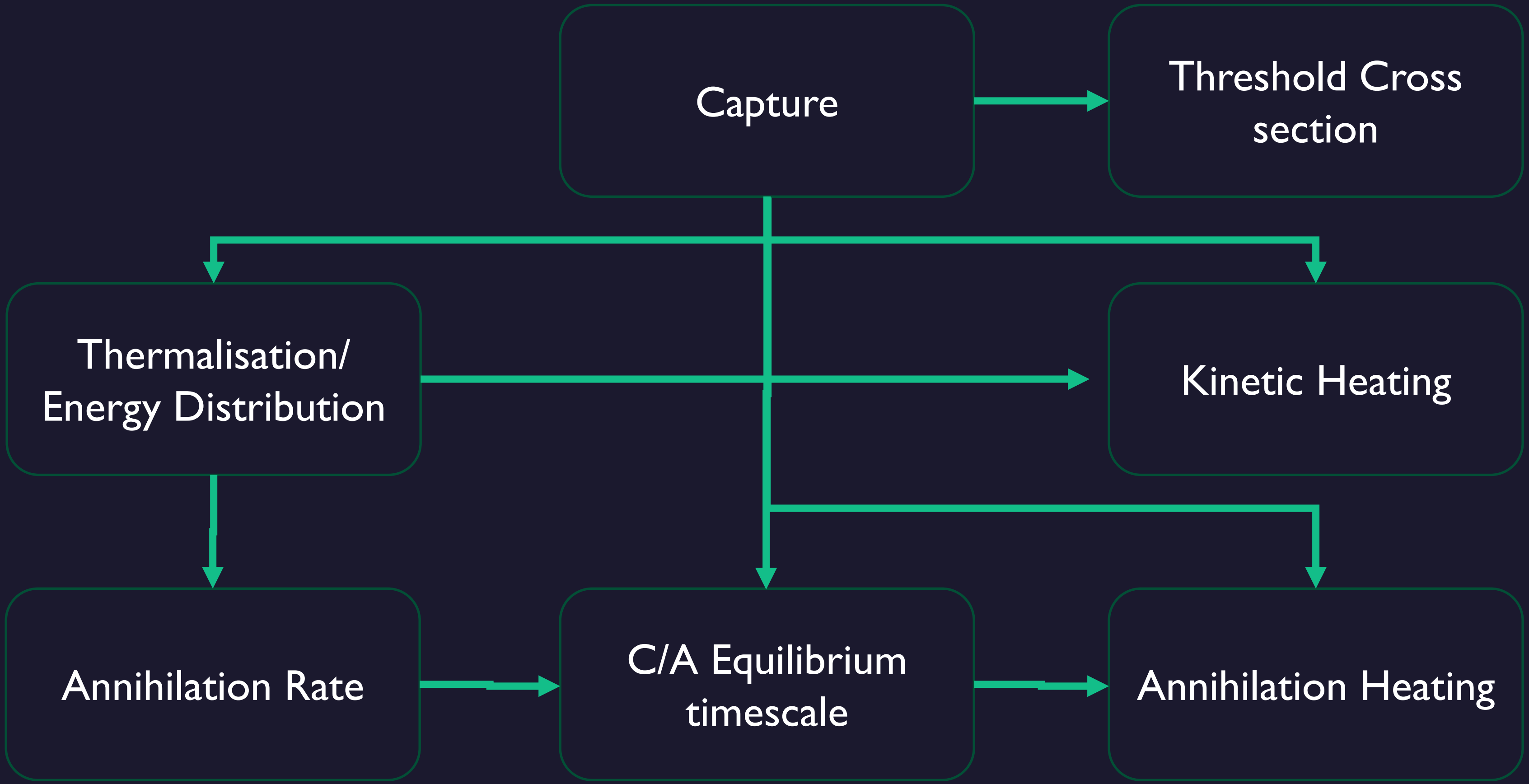
Adelaide University



Backup

•01 MOTIVATIONS (NS)

$$\frac{dN}{dt} = C - (EN) - AN^2$$



$$\dot{E} = C \times K^G$$

$$T_{eq}^{MAX} \sim 1700K$$

$$\dot{E} = AN^2 \times K^A = Cm_\chi Tanh^2\left(\frac{t}{t_{C/A}}\right)$$

$$T_{eq}^{MAX} \sim 2300K$$

$$t_{C/A} = \frac{1}{\sqrt{CA}}$$

$$N = \sqrt{\frac{C}{A}} Tanh\left(\frac{t}{t_{C/A}}\right)$$

•01 MOTIVATIONS (NS)

DM speed in halo $u \sim 300 km/s$

- DM in halo, kinetic energy $K \sim \frac{1}{2} m_\chi u^2 \sim 10^{-6} m_\chi$
- DM after gravitational infall, $K^G \sim m_\chi \left(\frac{1}{\sqrt{B}} - 1 \right) \sim \mathcal{O}(m_\chi)$
- DM energy loss in recoil $q_0 \sim \mathcal{O}(\mu) \sim \begin{cases} 1GeV, & m_\chi \gtrsim 10GeV \\ \mathcal{O}(m_\chi), & m_\chi \lesssim 1GeV \end{cases}$
- If $K < q_0$ a single scattering is enough to capture

⬇

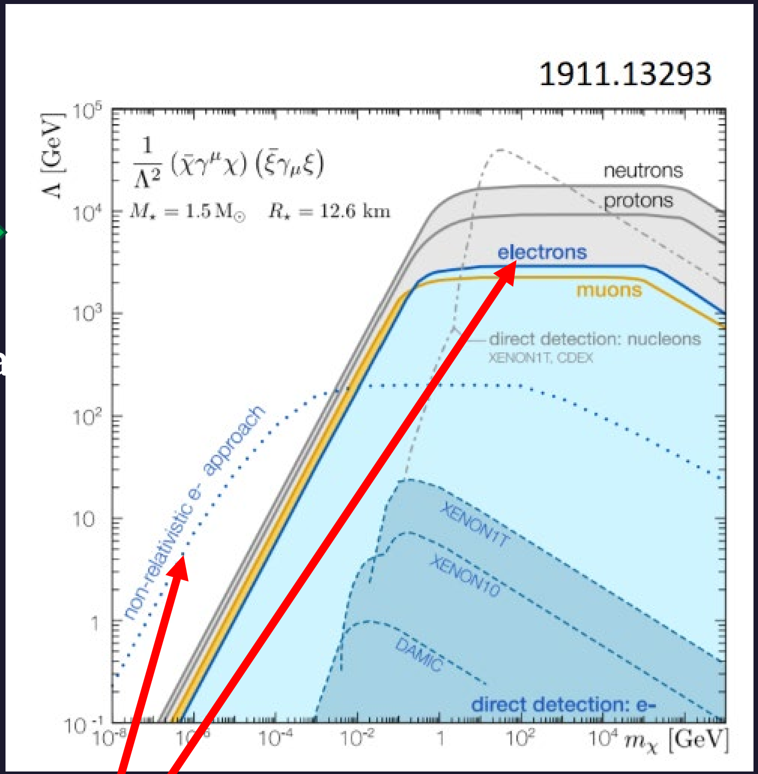
- Requires $m_\chi \lesssim 10^6 GeV$

- Energy transferred to the star by Capture $K^G \sim m_\chi \left(\frac{1}{\sqrt{B}} - 1 \right)$ — $T_{eq}^{MAX} \sim 1800K$ (Kinetic Heating)
- Energy transferred to the star by subsequent annihilation $K^A \sim m_\chi$ — $T_{eq}^{MAX} \sim 2300K$ (Kinetic + Annihilation Heating)

•02 CAPTURE (NS)

Need to use/include:

- Schwarzschild metric
- Relativistic kinematics
- Pauli blocking
- Capture probability/average energy transfer (for multiple sca
- Hadronic Form Factors
- Target effective mass due to self-interactions



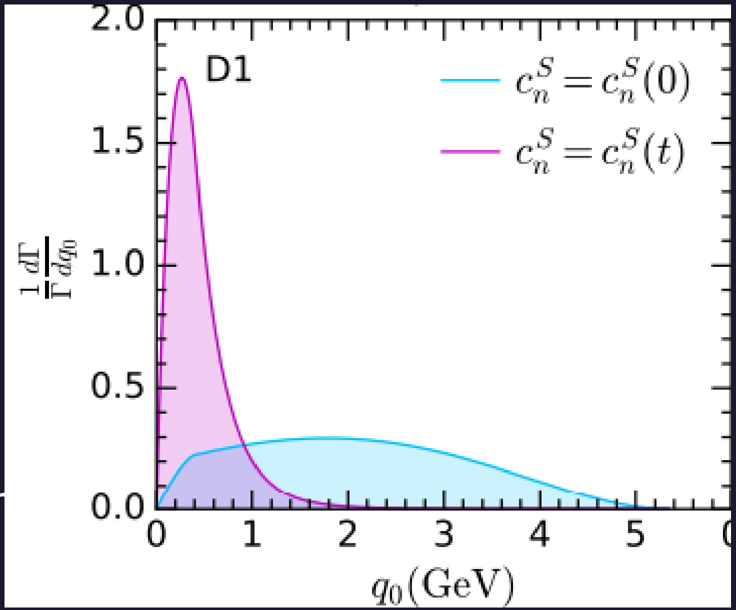
Non-relativistic kinematics vs relativistic kinematics

•02 CAPTURE (NS)

Need to use/include:

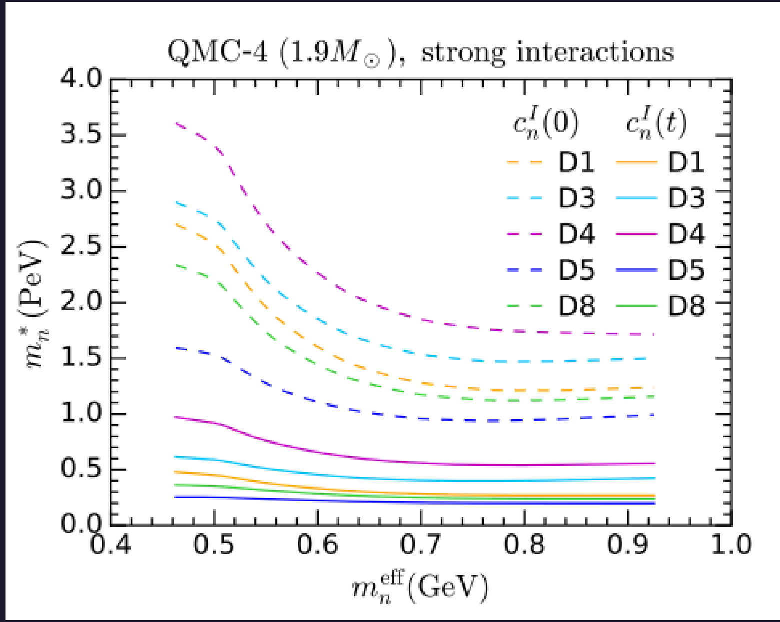
- Schwarzschild metric
- Relativistic kinematics
- Pauli blocking
- Capture probability/average energy transfer (for multiple scattering/h
- Hadronic Form Factors
- Target effective mass due to self-interactions

$$F(t) = \frac{1}{(1 - t/Q_0^2)^4}$$



Lower average energy transfer

Large suppression at large mass



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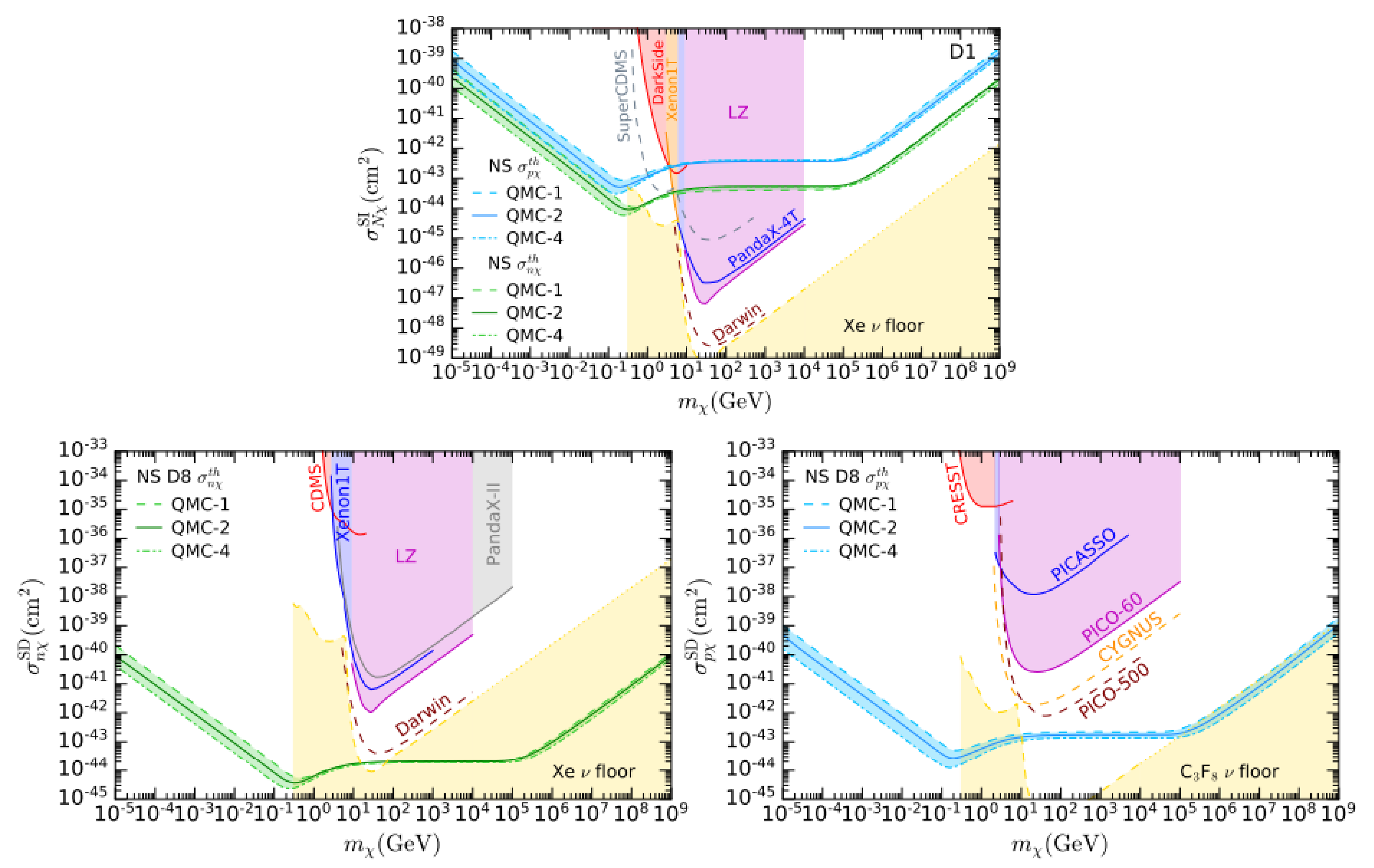
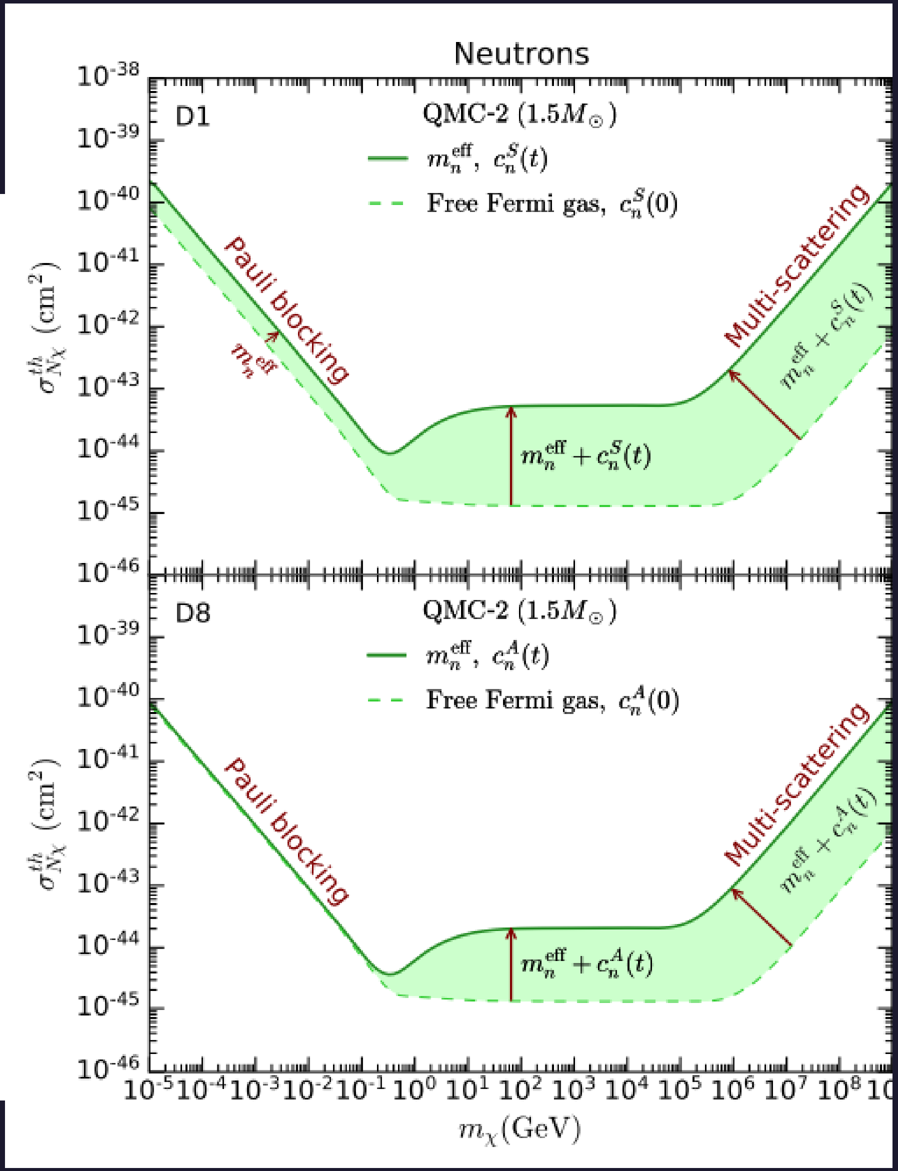
•02 CAPTURE (NS)



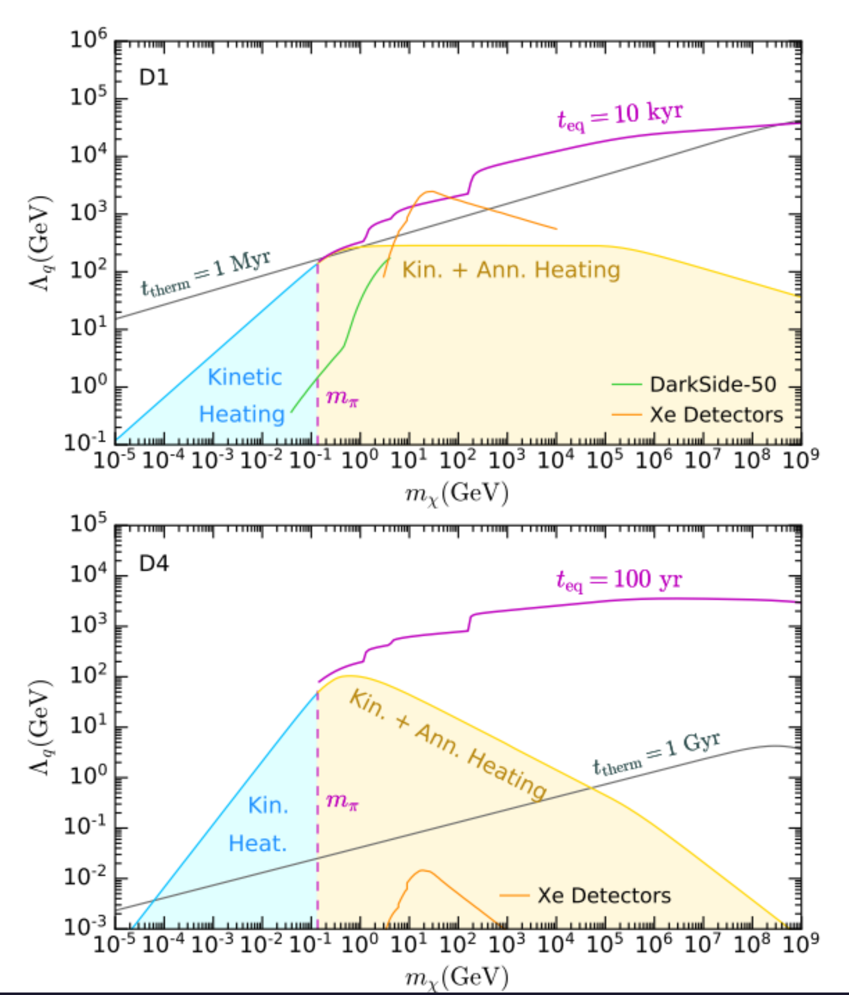


•03 THERMALISATION (NS)

- Ultimate goal: is DM energy released in the star on a timescale smaller
  - What about annihilation heating?

- If DM thermalizes within star lifetime:
  - Use DM temperature to compute annihilation rate
  - Use Annihilation rate to compute the Capture-Annihilation equilibrium timescale
  - Check that it is smaller than star age

- If DM DOES
  - Find
  - Use anni
  - Use Capt time
  - Chec



Result: Capture-Annihilation equilibrium is always reached if DM annihilation channels kinematically open