



THE UNIVERSITY
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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

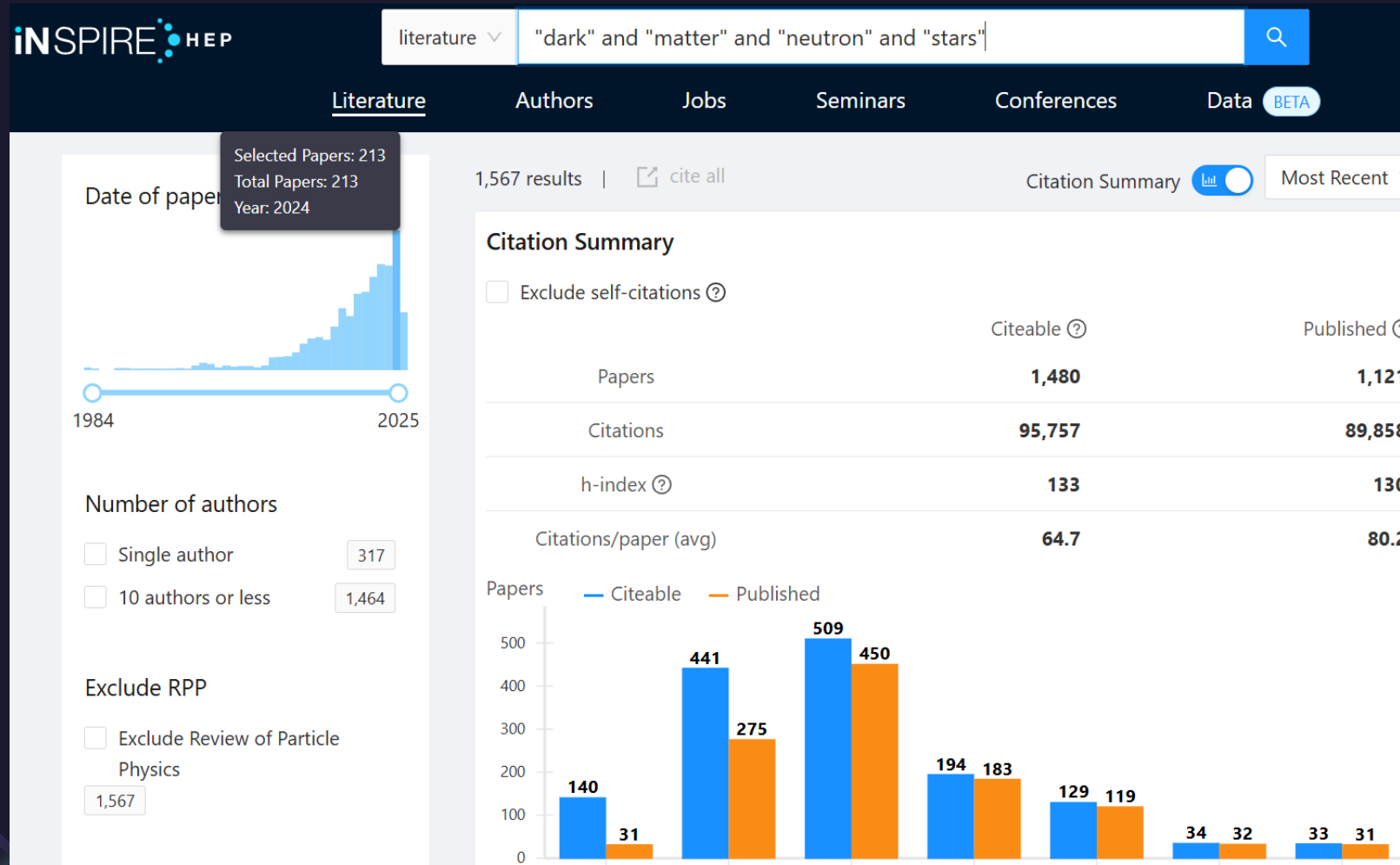
Outline

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)

N.Bell



M.Virgato



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

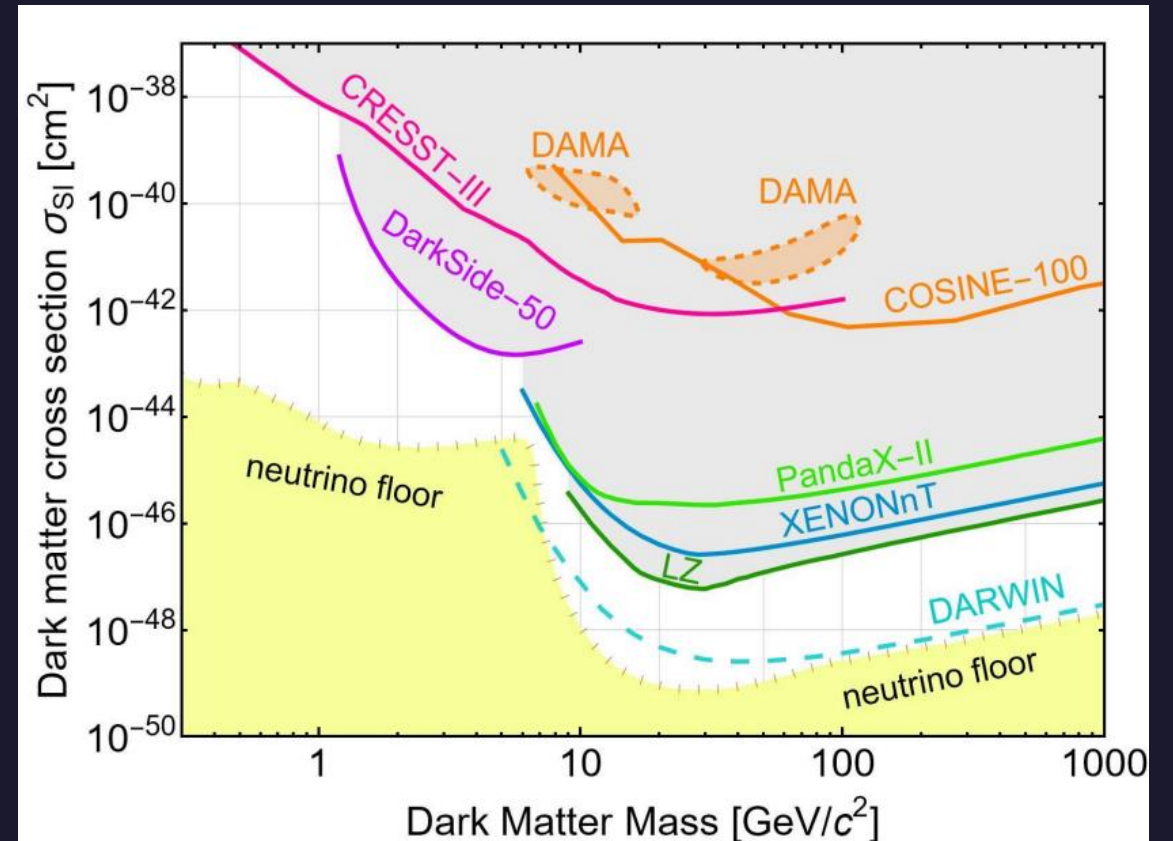
S. Robles



See Sandra's Talk

Why (stars)?

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



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

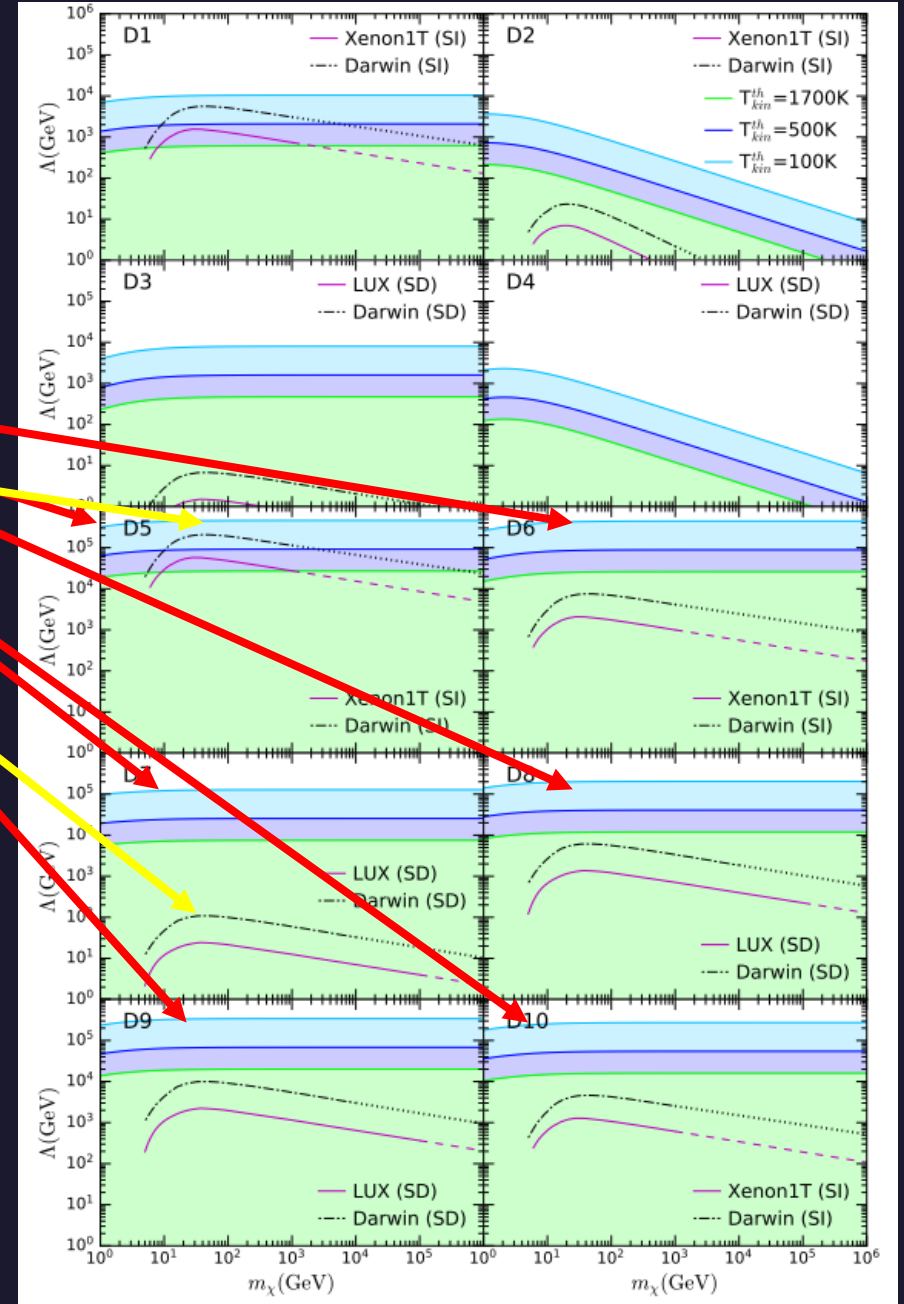
$$\sigma \sim \frac{1}{nR} \sim 10^{-45} \text{ cm}^2$$

Why (compact stars)?

1807.02840

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

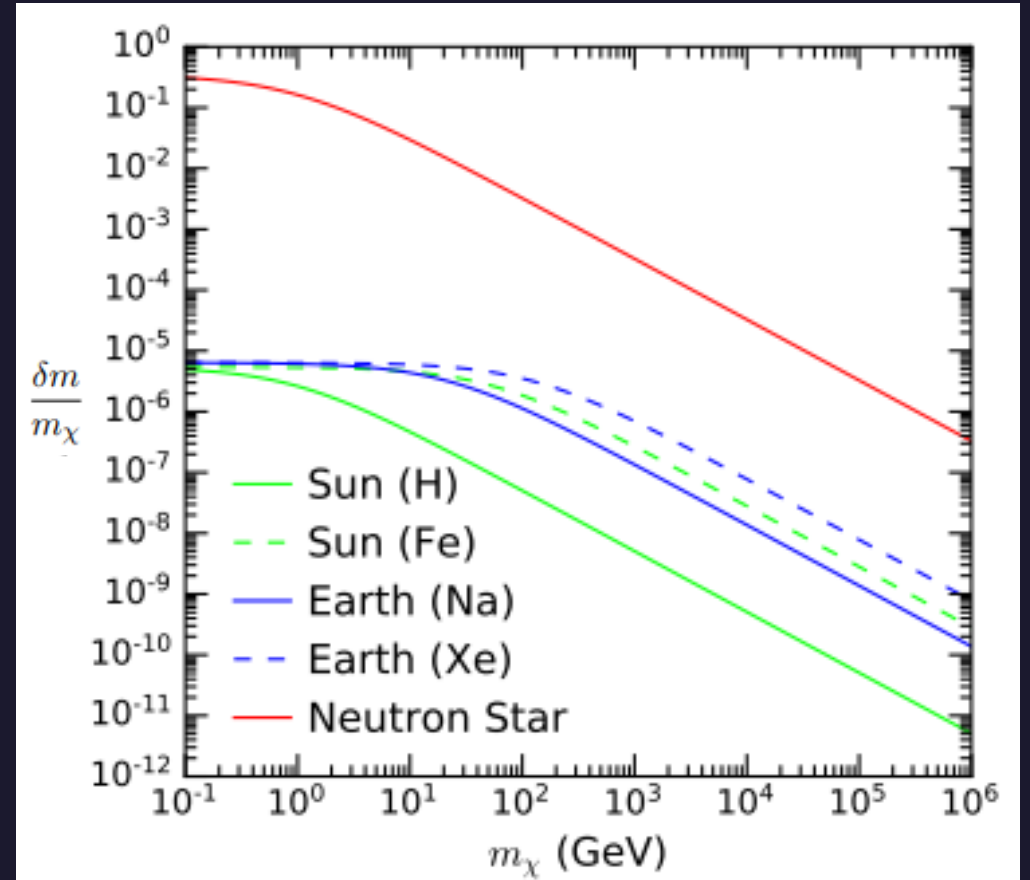
- Wash away non-relativistic suppressions of some DD operators
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Why (compact stars)?

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
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Why (compact stars)?

Neutron Stars

- Very large density
- Competing sensitivities with DD
- Relativistic kinematics
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- Ideal to probe models with DM-muon interactions, like $U(1)_{\mu-\tau}$

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\mu-\tau} + \mathcal{L}_{\chi} \\ \mathcal{L}_{\mu-\tau} &= -\frac{1}{4}F_{\mu\tau}^{\alpha\beta}F_{\mu\tau\alpha\beta} + \frac{\varepsilon_0}{2}F_{\mu\tau}^{\alpha\beta}B_{Y\alpha\beta} + \frac{1}{2}m_{Z'}^2Z'^{\alpha}Z'_{\beta} + J_{Z'}^{\alpha}Z'_{\alpha} \\ J_{Z'}^{\alpha} &= g_{\mu\tau}(\bar{\mu}\gamma^{\alpha}\mu - \bar{\tau}\gamma^{\alpha}\tau + \bar{\nu}_{\mu}\gamma^{\alpha}\nu_{\mu} - \bar{\nu}_{\tau}\gamma^{\alpha}\nu_{\tau}), \\ \mathcal{L}_{\chi} &= \bar{\chi}(i\not{\partial} - m_{\chi})\chi + Q_{\chi}g_{\mu\tau}\bar{\chi}\gamma^{\alpha}\chi Z'_{\alpha},\end{aligned}$$



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

$$N = Ct_*$$

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

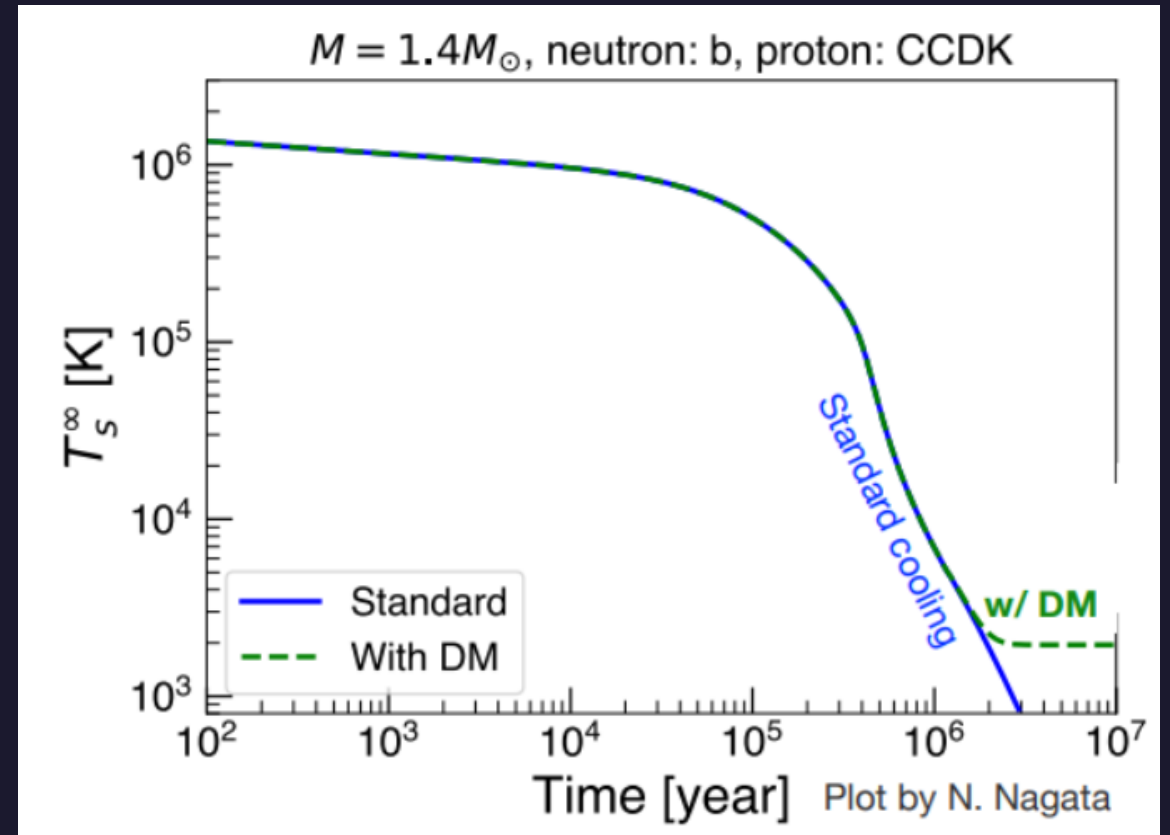
- Collapse to BH/instability
 - **Altering the internal structure/EOS**
 - Heating
- Usually requires a considerable fraction of the star mass to be DM
 - Requires a mechanism different from capture

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:

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

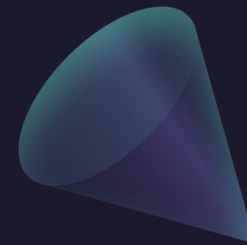
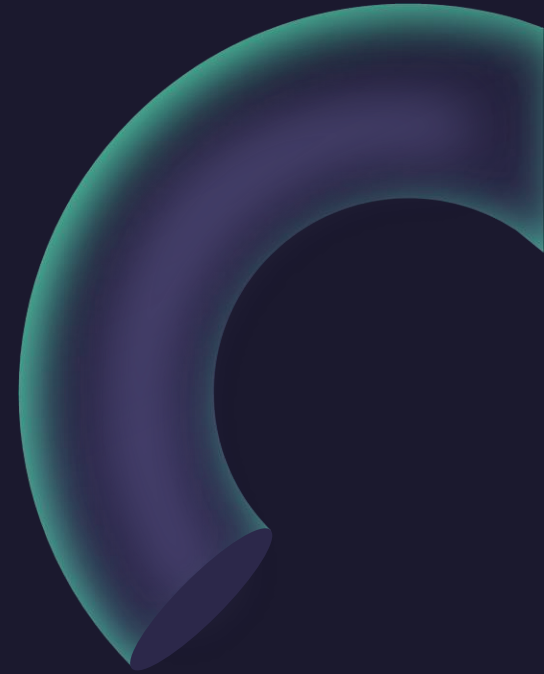
- Average energy transfer

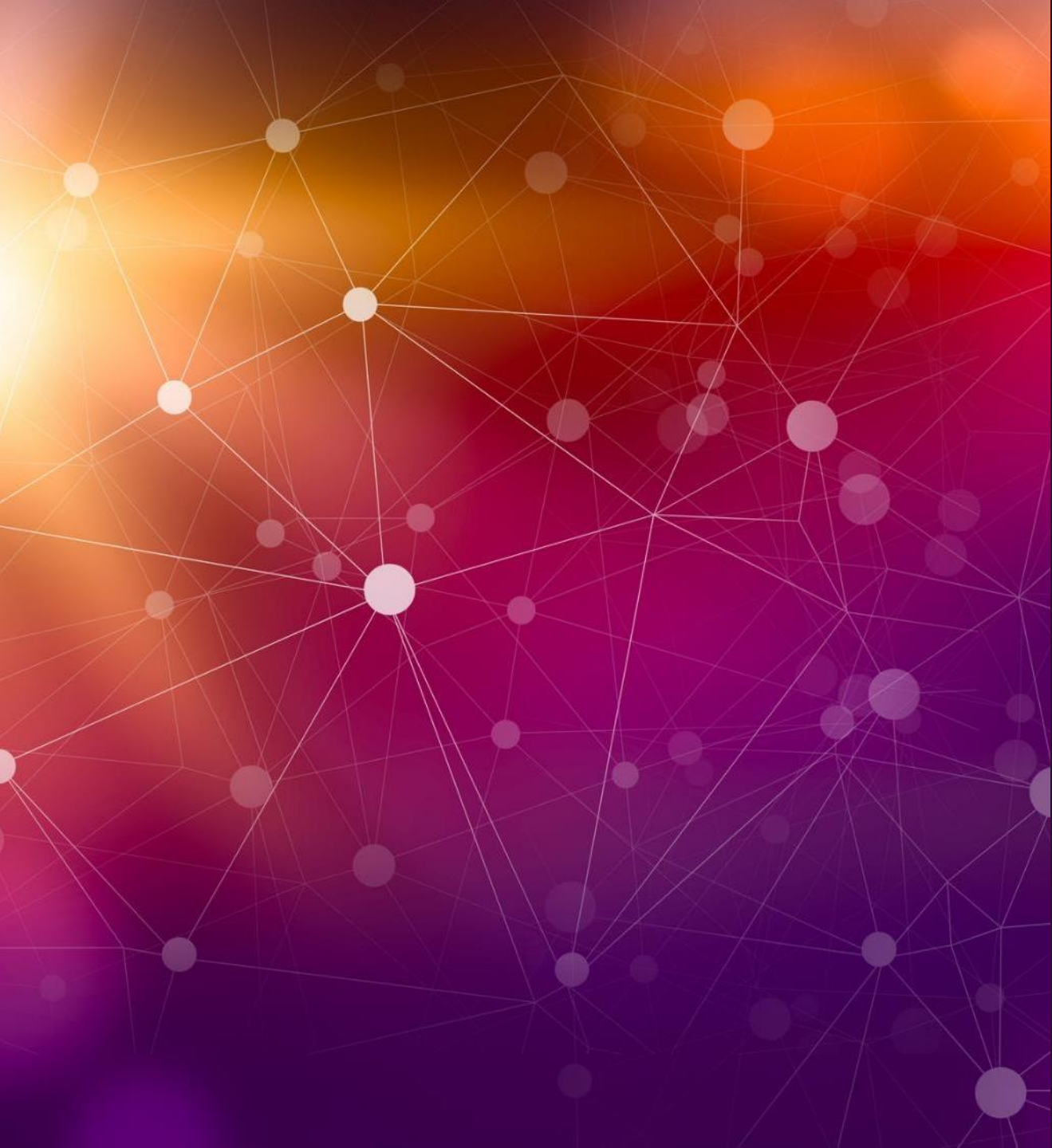
$$\langle \delta K \rangle \sim m_\chi$$

- Energy balance

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

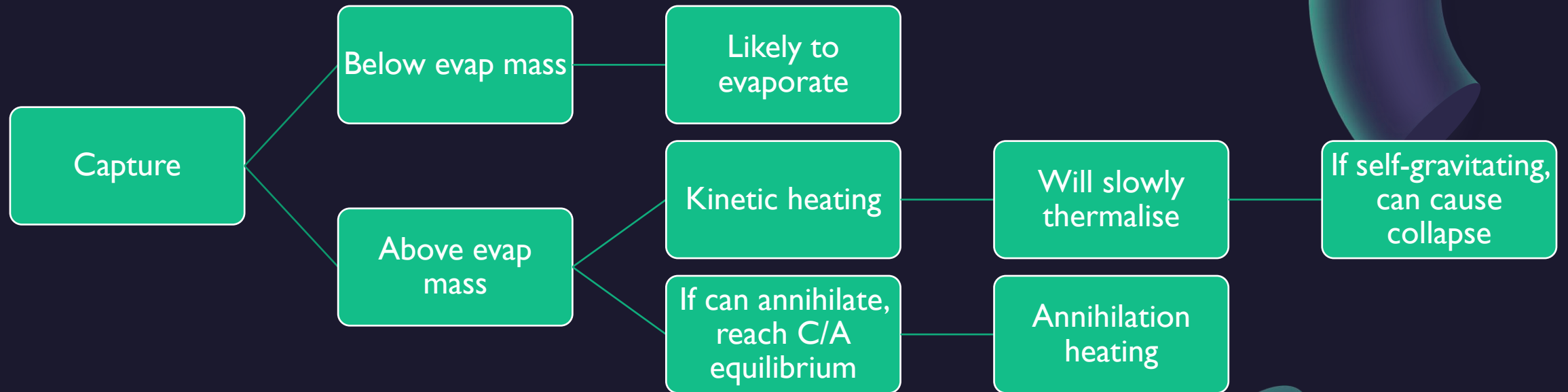
- Kinetic heating: $\langle \delta K \rangle \sim m_\chi, T_{eq}^{MAX} \sim 1800K$
- Annihilation heating: an additional $\langle \delta K \rangle \sim m_\chi, T_{eq}^{MAX} \sim 2300K$



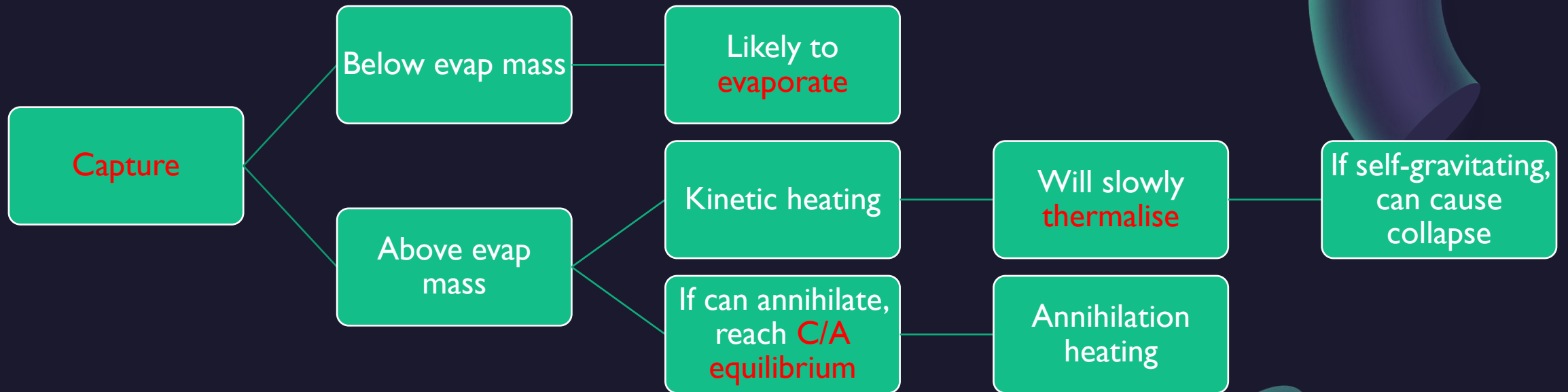


How?

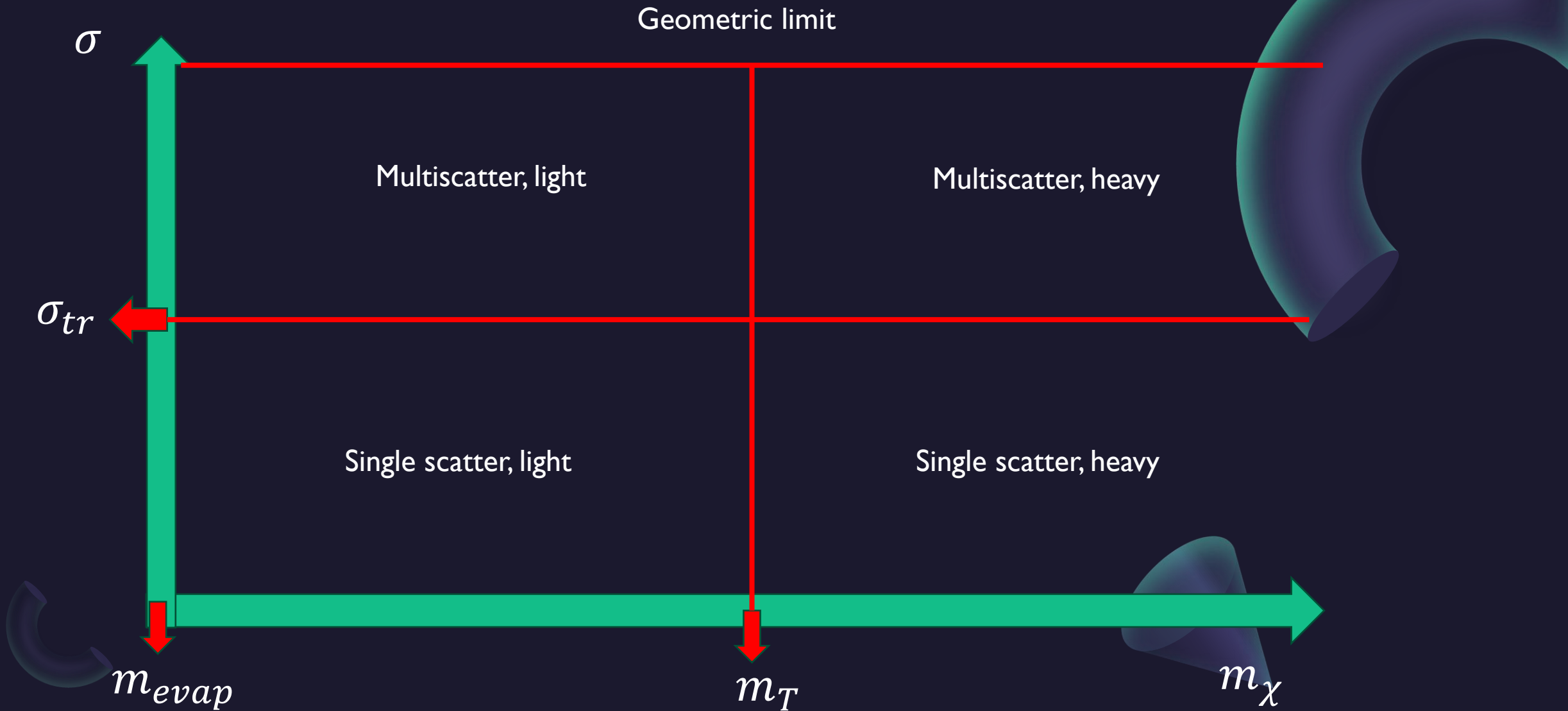
Dark Matter path in a Neutron Star



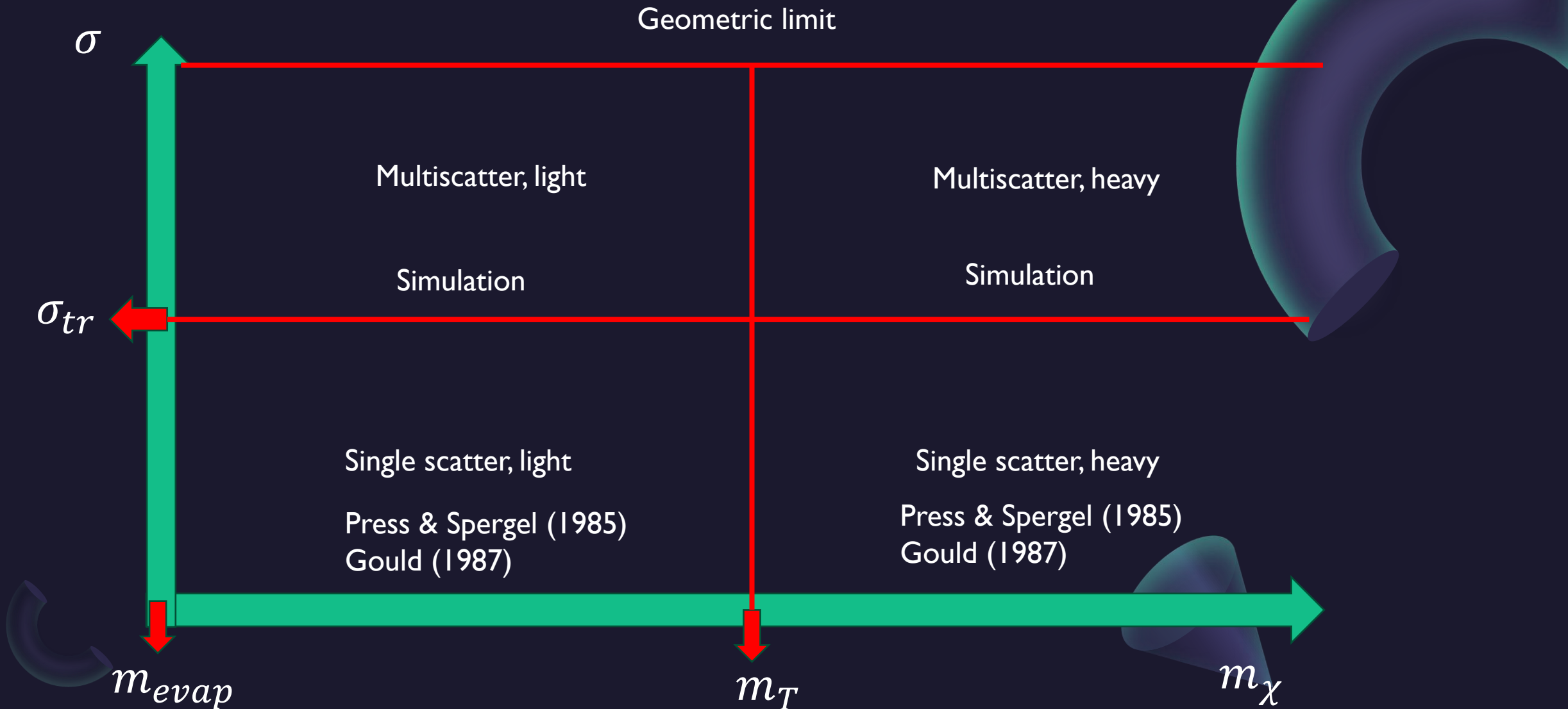
Dark Matter path in a Neutron Star



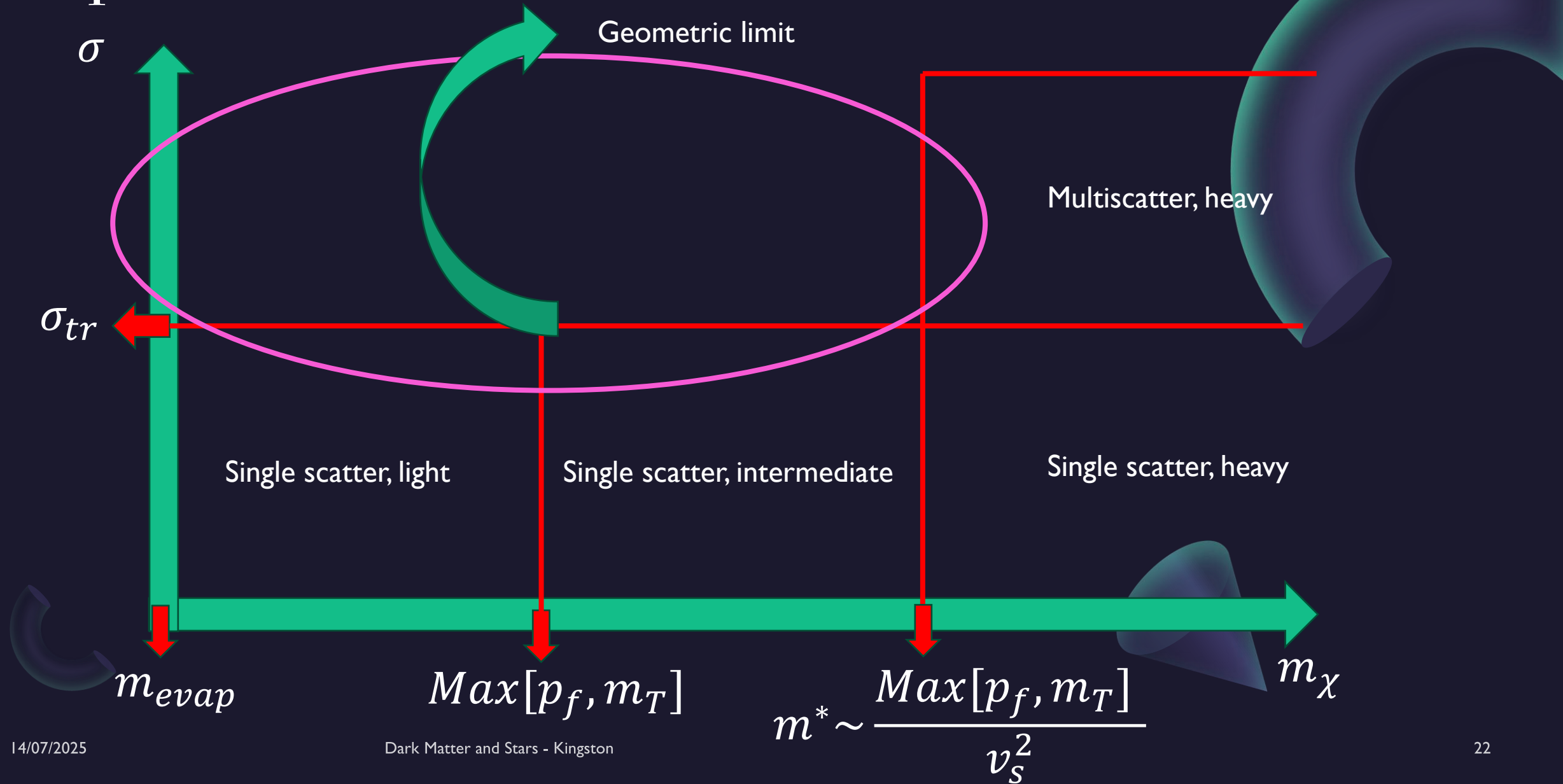
Capture in the Sun



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)

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

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

$$m \lesssim 10^6 \text{ GeV}$$

Capture in NS ~2015

Geometric limit

σ

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

Single scatter, light

Single scatter, intermediate

Single scatter, heavy

???

???

???

m_{evap}

$Max[p_f, m_T]$

$m^* \sim \frac{Max[p_f, m_T]}{v_s^2}$

m_χ

Capture in NS

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- [87] R. Garani, A. Gupta, and N. Raj, “Observing the thermalization of dark matter in neutron stars,” *Phys. Rev. D* **103** no. 4, (2021) 043019, [arXiv:2009.10728 \[hep-ph\]](#).
- [88] N. F. Bell, G. Busoni, M. E. Ramirez-Quezada, S. Robles, and M. Virgato, “Improved Treatment of Dark Matter Capture in White Dwarfs,” *JCAP* **10** (4, 2021) 083, [arXiv:2104.14367 \[hep-ph\]](#).
- [89] A. Strumia, “Dark Matter interpretation of the neutron decay anomaly,” *JHEP* **02** (2022) 067, [arXiv:2112.09111 \[hep-ph\]](#).
- [90] W. Husain, T. F. Motta, and A. W. Thomas, “Consequences of neutron decay inside neutron stars,” *JCAP* **10** (2022) 028, [arXiv:2203.02758 \[hep-ph\]](#).
- [91] N. F. Bell, G. Busoni, S. Robles, and M. Virgato, “Improved Treatment of Dark Matter Capture in Neutron Stars,” *JCAP* **09** (2020) 028, [arXiv:2004.14888 \[hep-ph\]](#).
- [92] N. F. Bell, G. Busoni, S. Robles, and M. Virgato, “Improved Treatment of Dark Matter Capture in Neutron Stars II: Leptonic Targets,” *JCAP* **03** (2021) 086, [arXiv:2010.13257 \[hep-ph\]](#).
- [93] J. Bramante and N. Raj, “Dark matter in compact stars,” *Phys. Rept.* **1052** (2024) 1–48, [arXiv:2307.14435 \[hep-ph\]](#).
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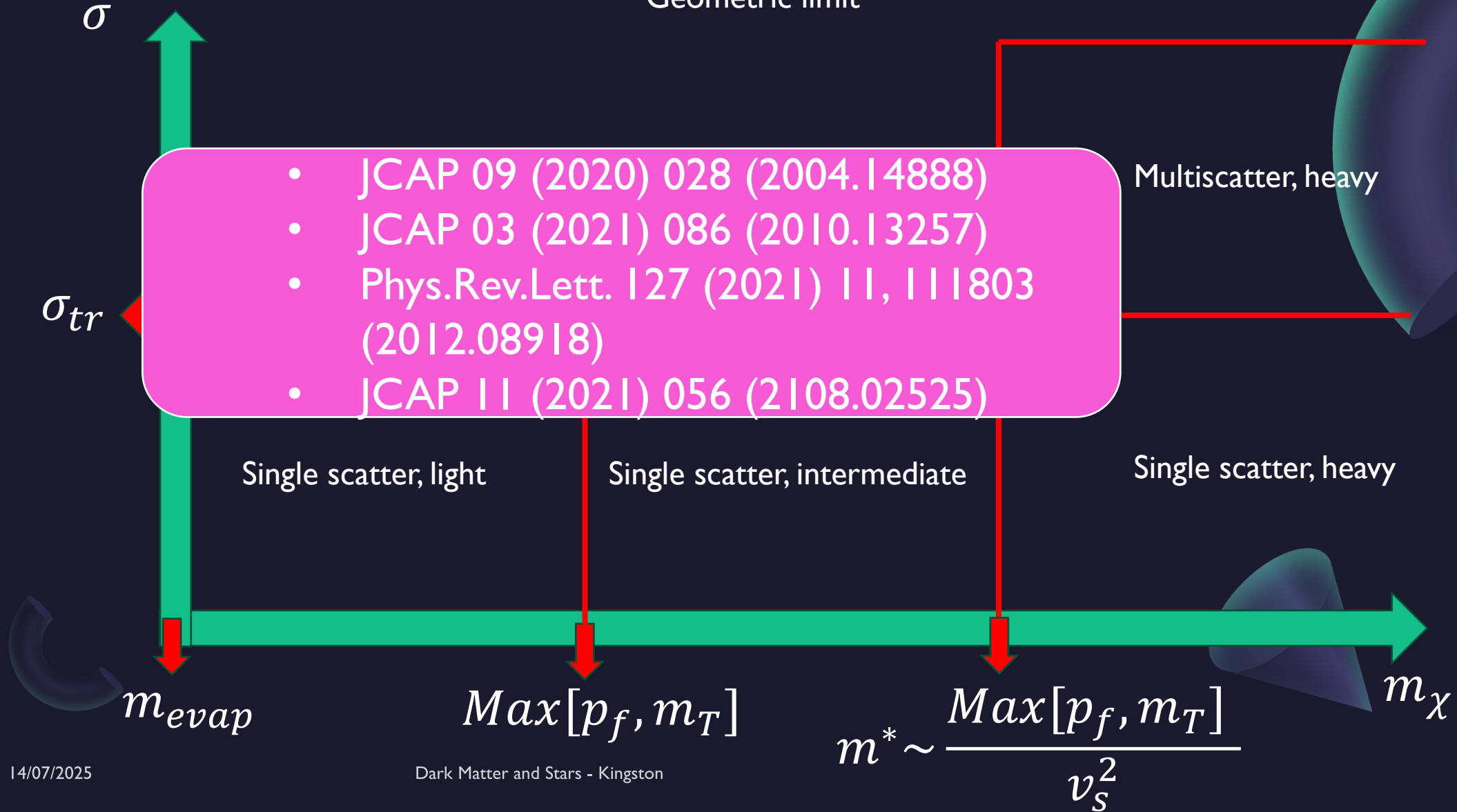


Non-comprehensive list

Capture in NS

~2025

Geometric limit



Interaction rates in degenerate matter

- Derived in full generality in the relativistic regime

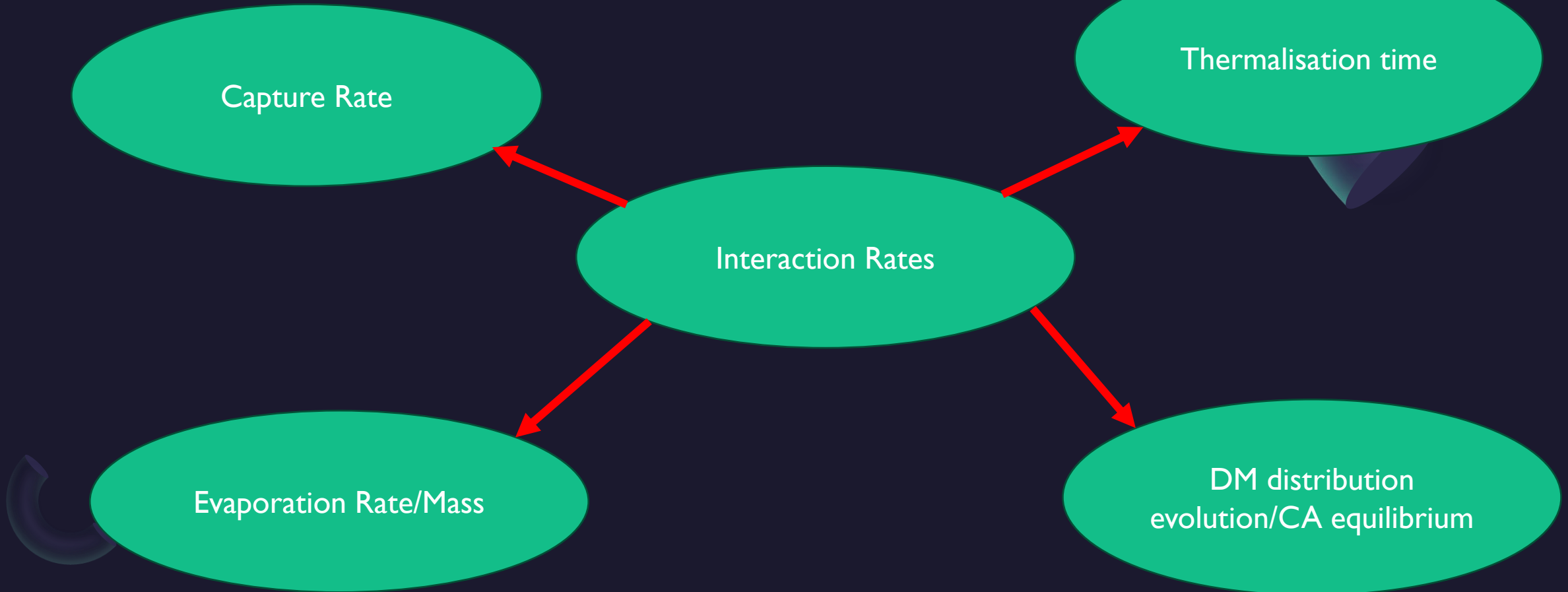
$$\Gamma = \int \frac{d^3 k'}{(2\pi)^3} \frac{1}{(2E_\chi)(2E'_\chi)(2m_\ell)(2m_\ell)} \Theta(E'_\chi - m_\chi) \Theta(q_0) S(q_0, q),$$
$$S(q_0, q) = 2 \int \frac{d^3 p}{(2\pi)^3} \int \frac{d^3 p'}{(2\pi)^3} \frac{m_i^2}{E_\ell E'_\ell} |\overline{M}|^2 (2\pi)^4 \delta^4(k_\mu + p_\mu - k'_\mu - p'_\mu)$$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

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

JCAP 03 (2021) 086 (2010.13257)

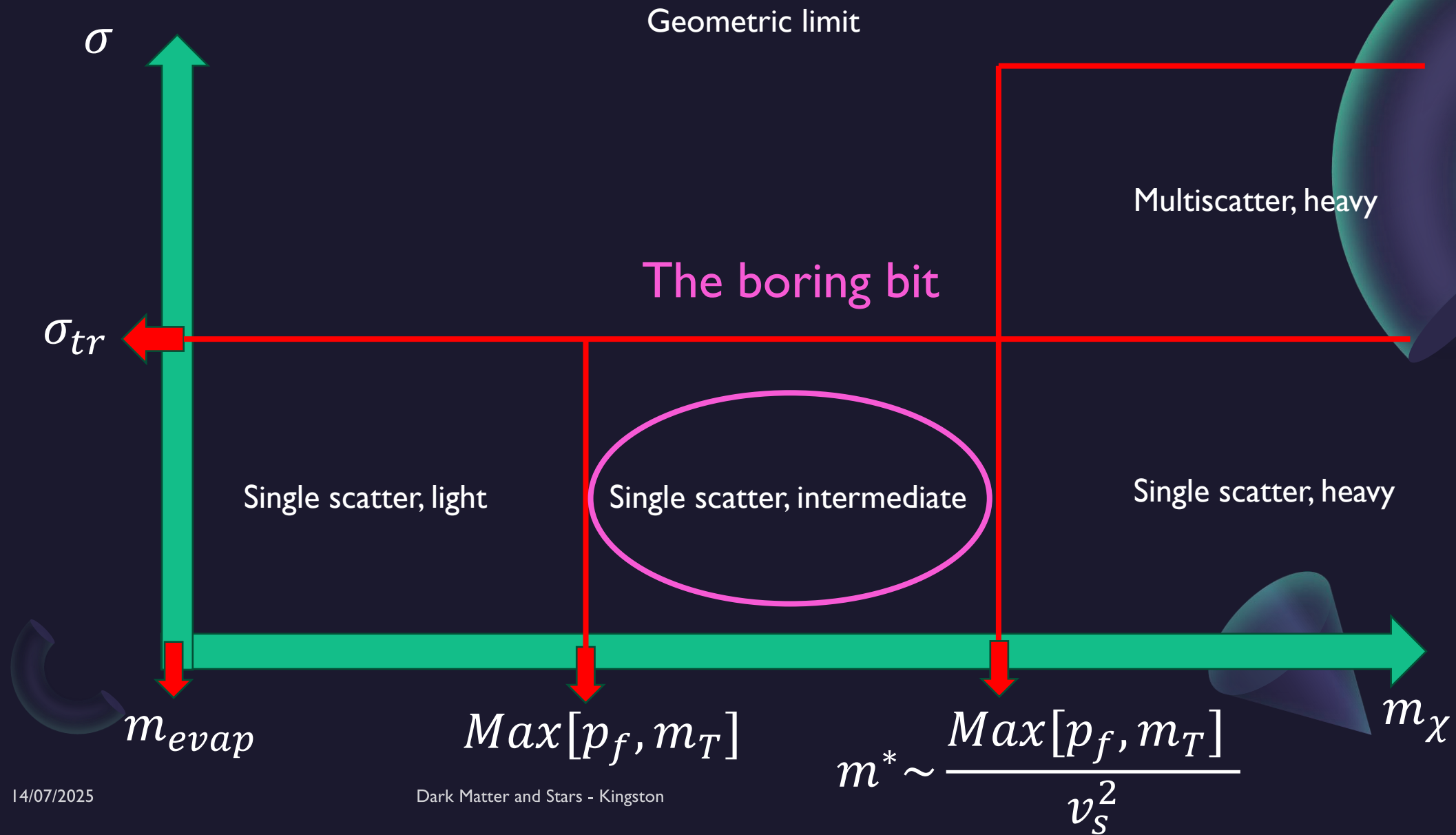
Interaction rates in degenerate matter

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Capture in NS

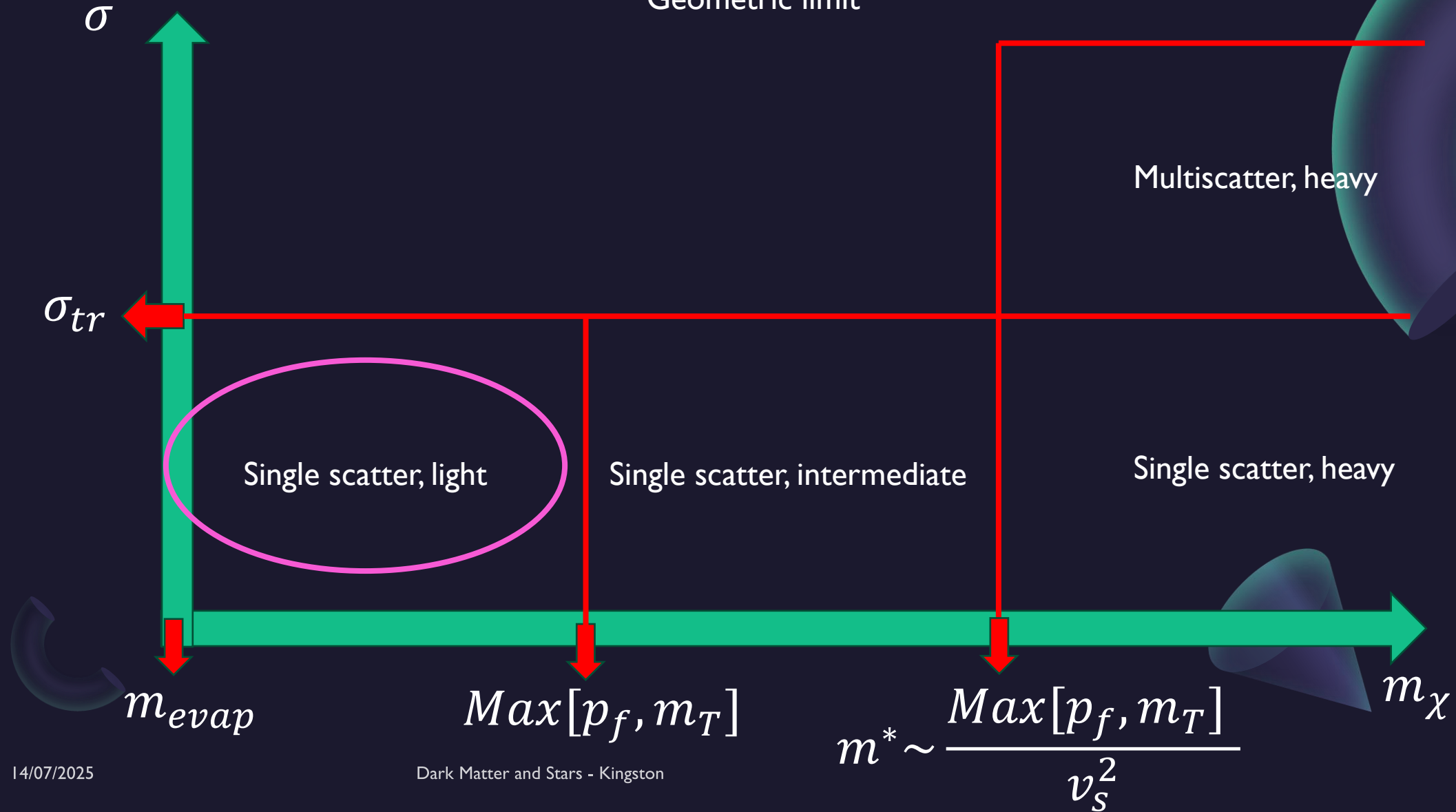
~2025



Capture in NS

~2025

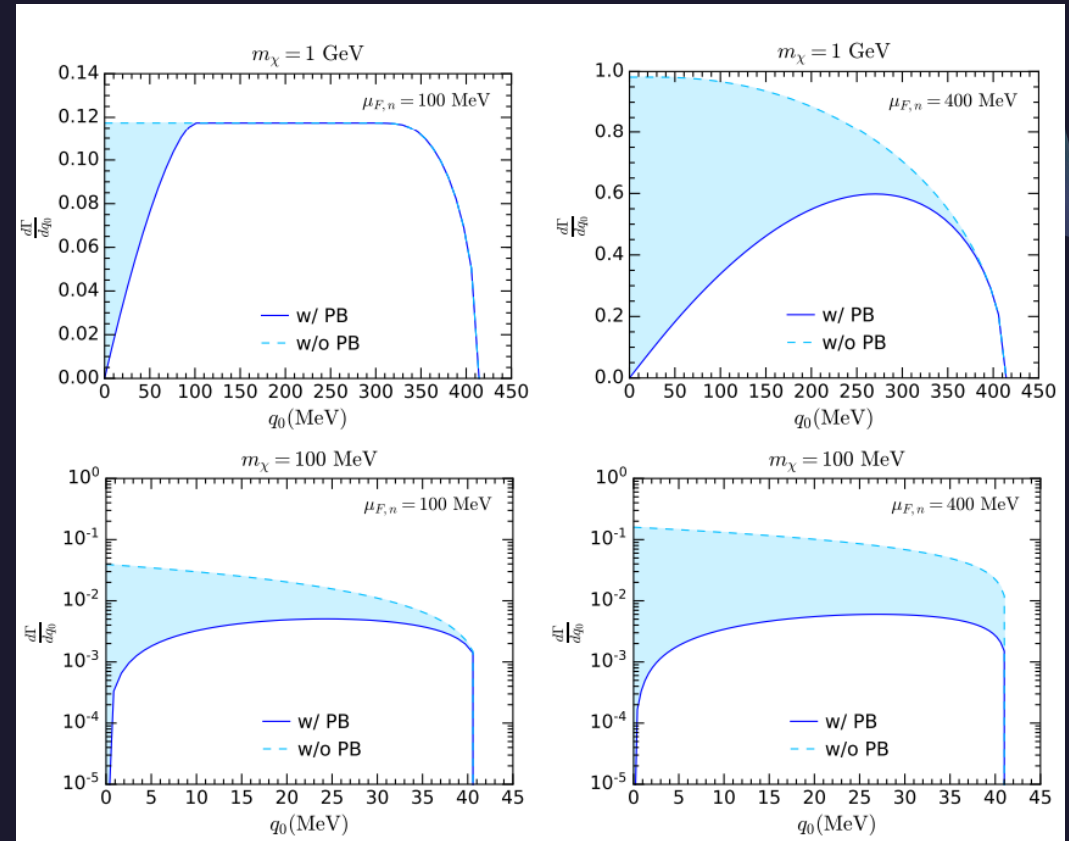
Geometric limit



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

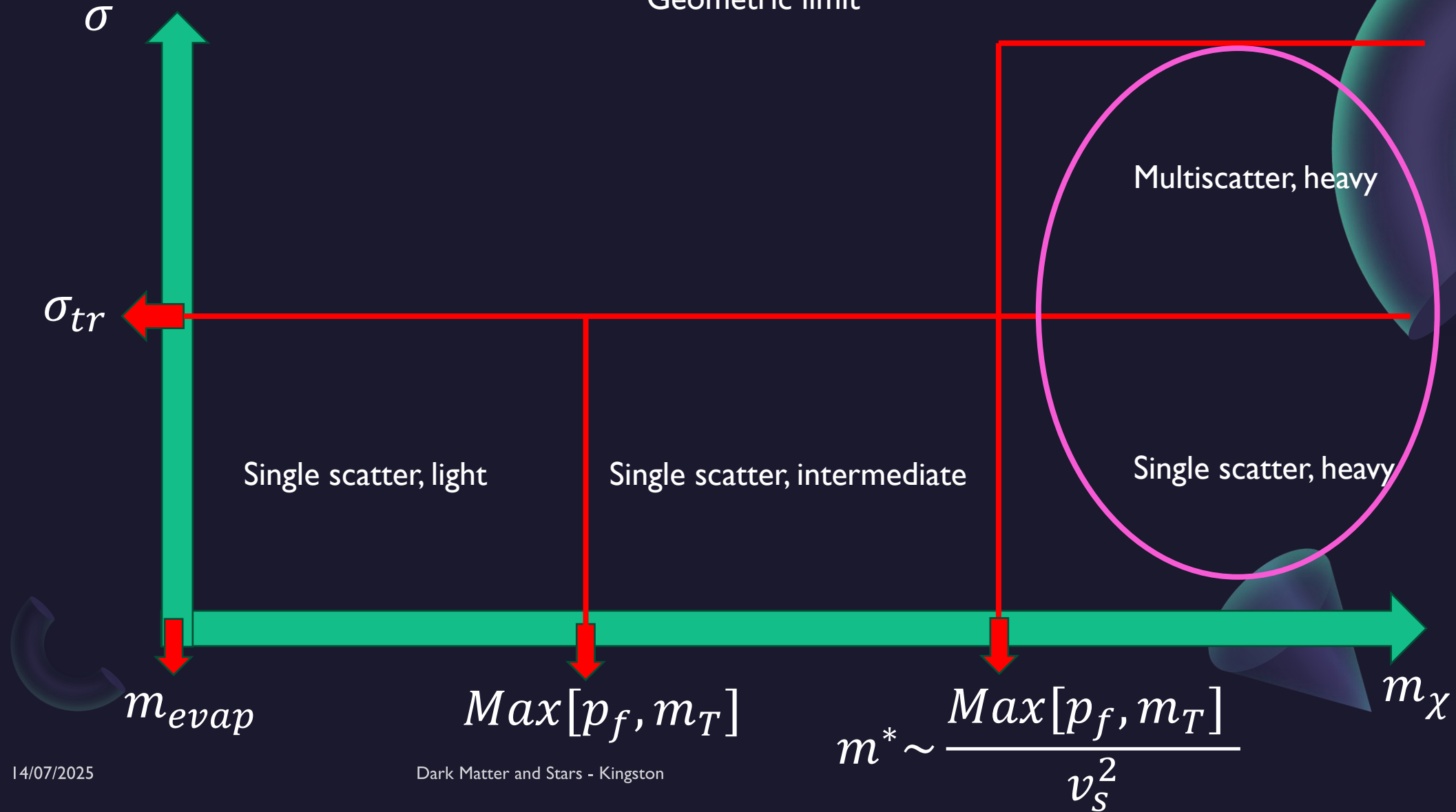
$$\frac{m_\chi}{\text{Max}[p_f, m_T]}$$



Capture in NS

~2025

Geometric limit



Single Scatter, heavy: energy loss

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

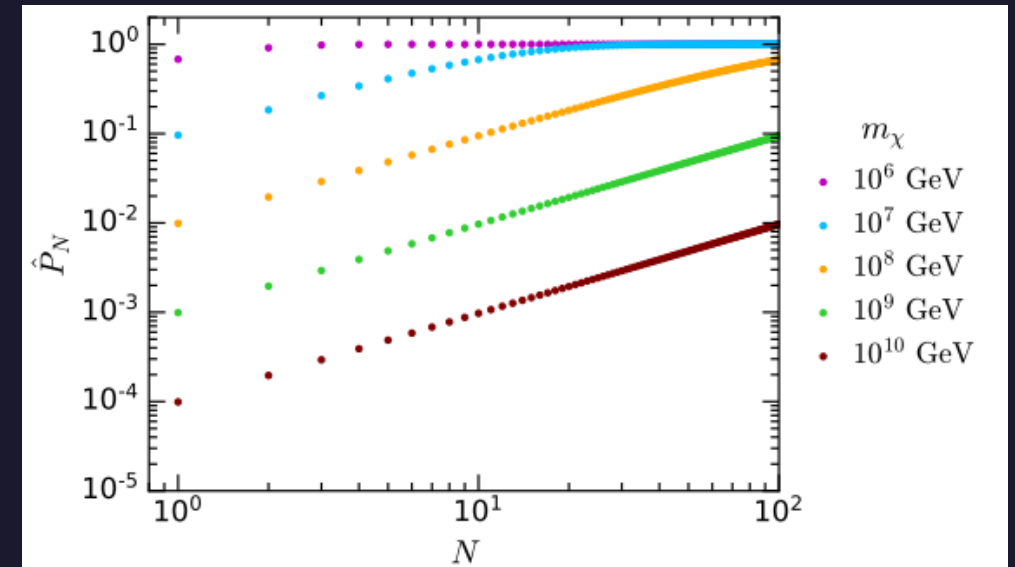
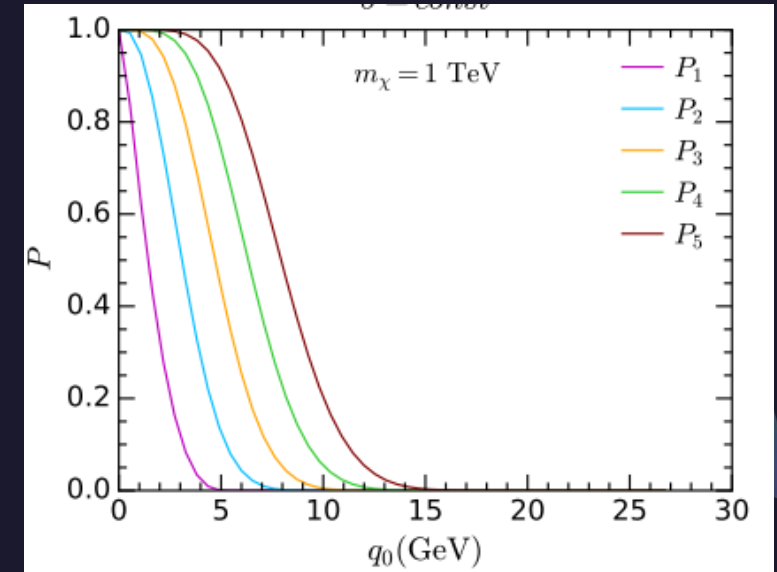
$$\hat{P}_N \sim 1 - e^{-\frac{Nm^*}{m_\chi}}$$

With

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

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

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



Capture in NS

- Intermediate mass region

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

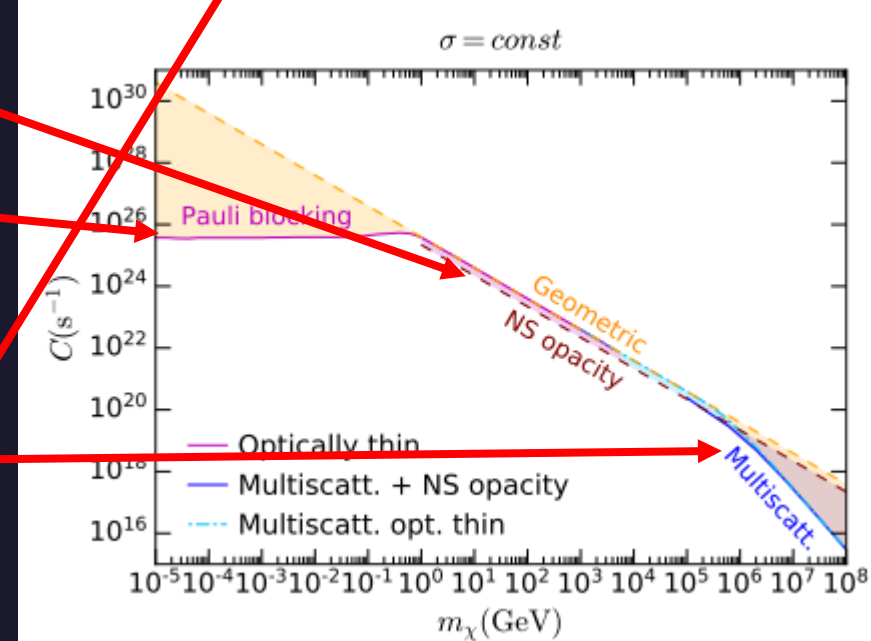
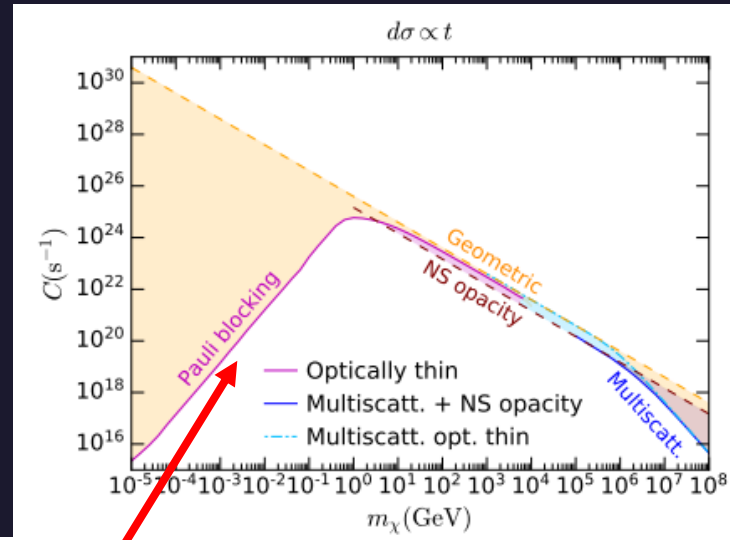
- Low mass region, additional m_χ factor:

$$C \propto \text{const}$$

- 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

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

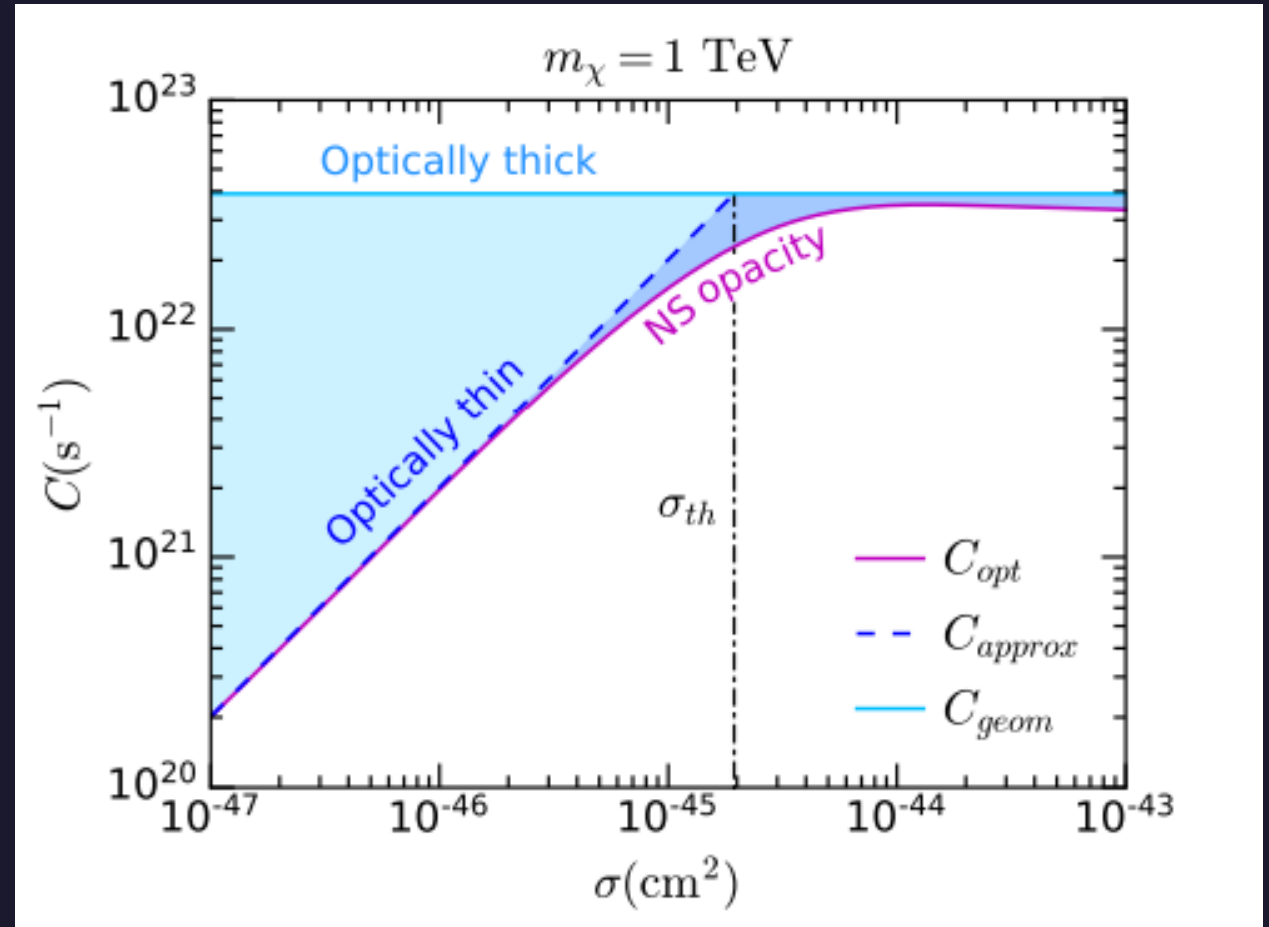
- For Dark Kinetic Heating, Equilibrium Temperature scales as

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

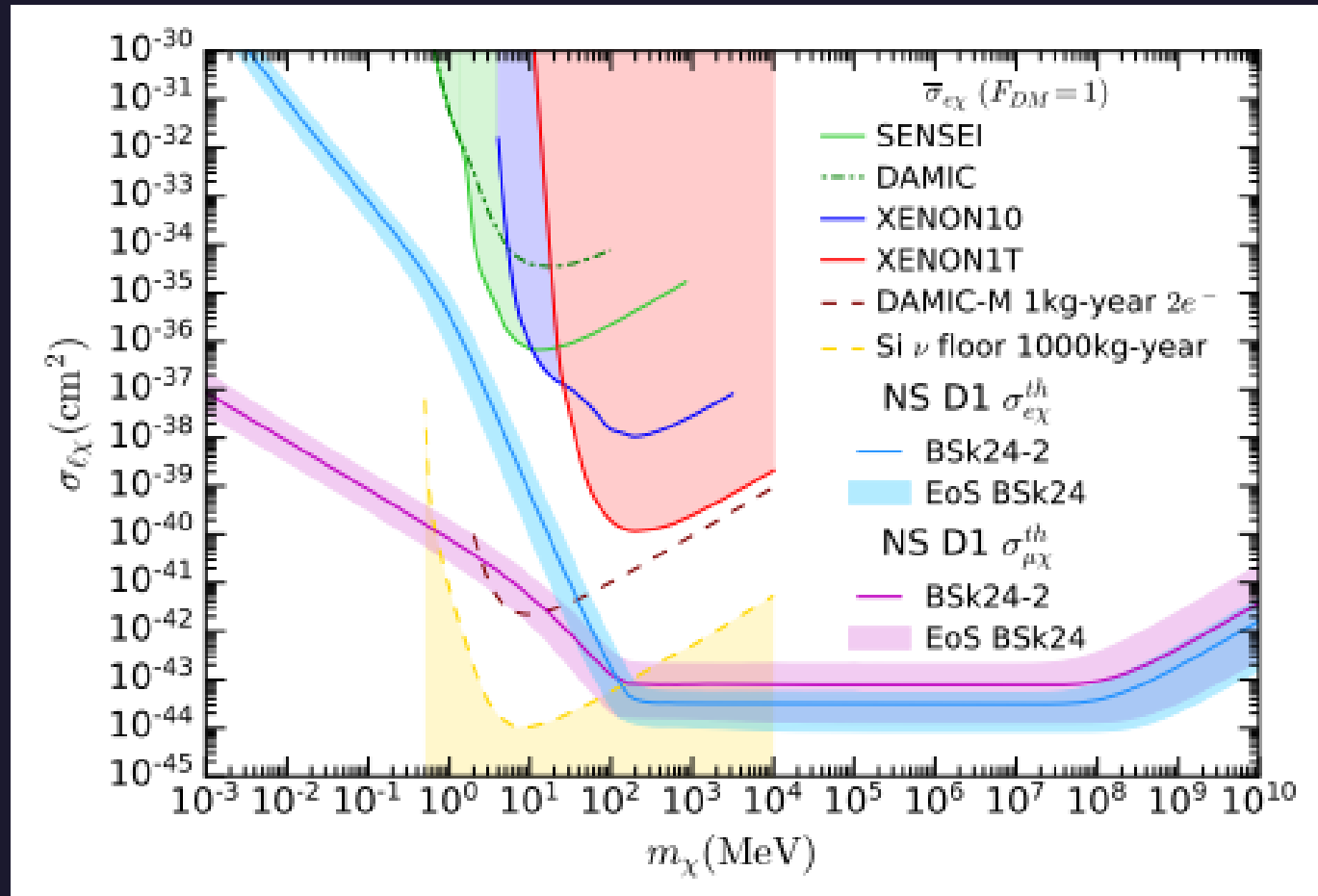
- Detect NS with $T < T_{eq}^{MAX}$



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

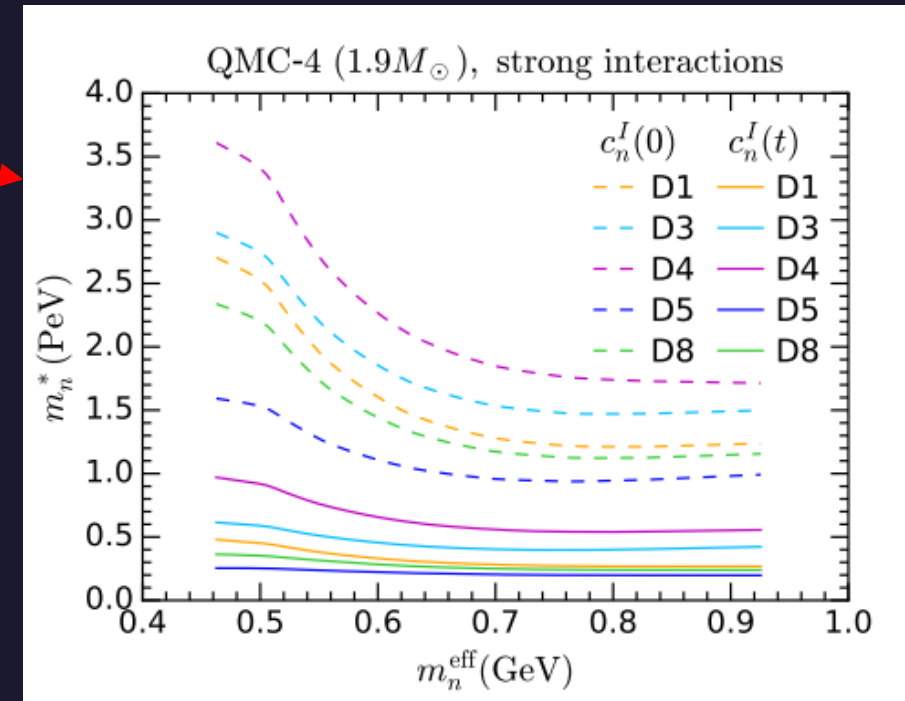
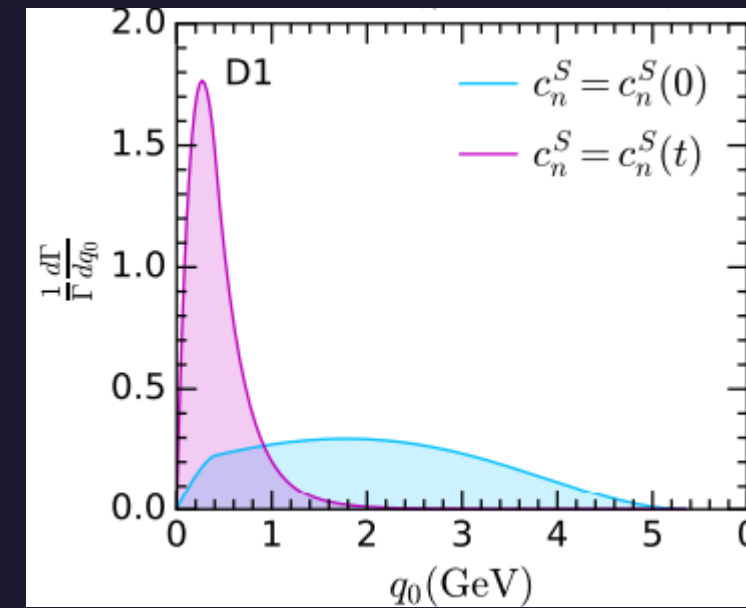


Capture in NS: leptons



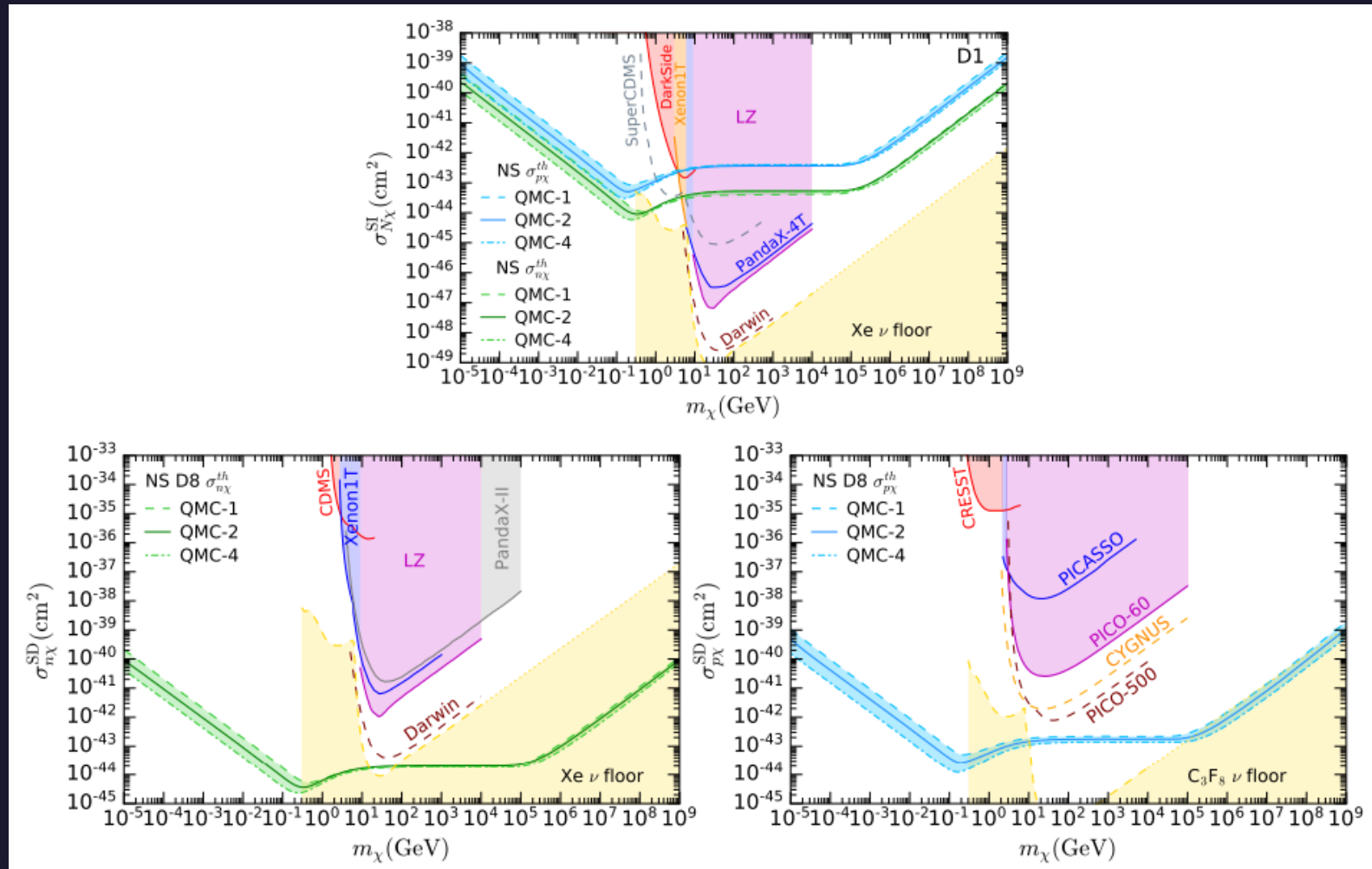
Capture in NS: hadrons

- 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



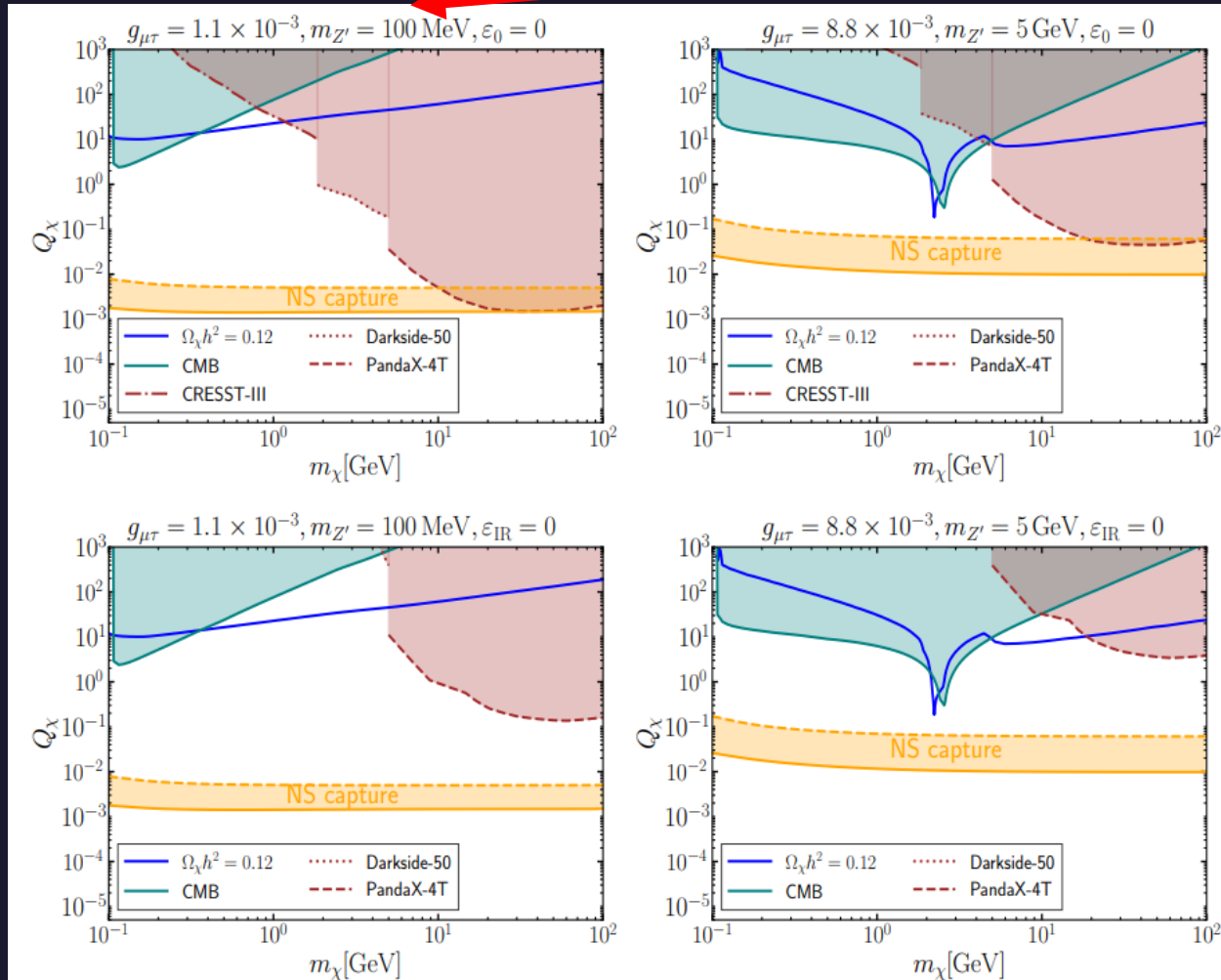
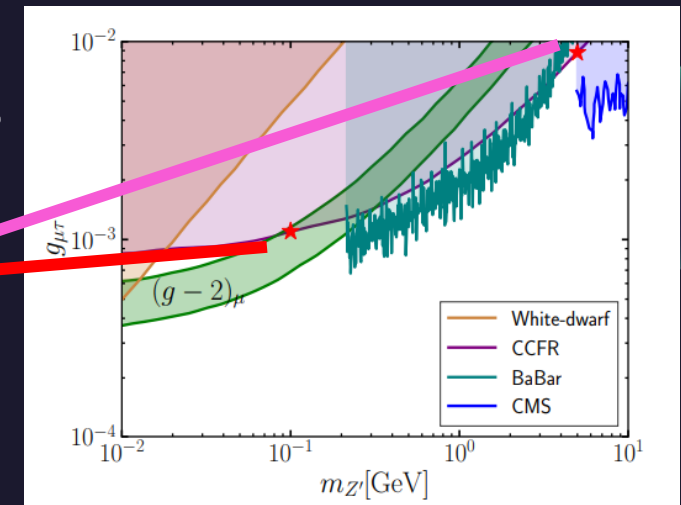
- Phys.Rev.Lett. 127 (2021) 11, 111803 (2012.08918)
- JCAP 11 (2021) 056 (2108.02525)

Capture in NS: hadrons



Capture in NS: muons/light mediator

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



2505.06506

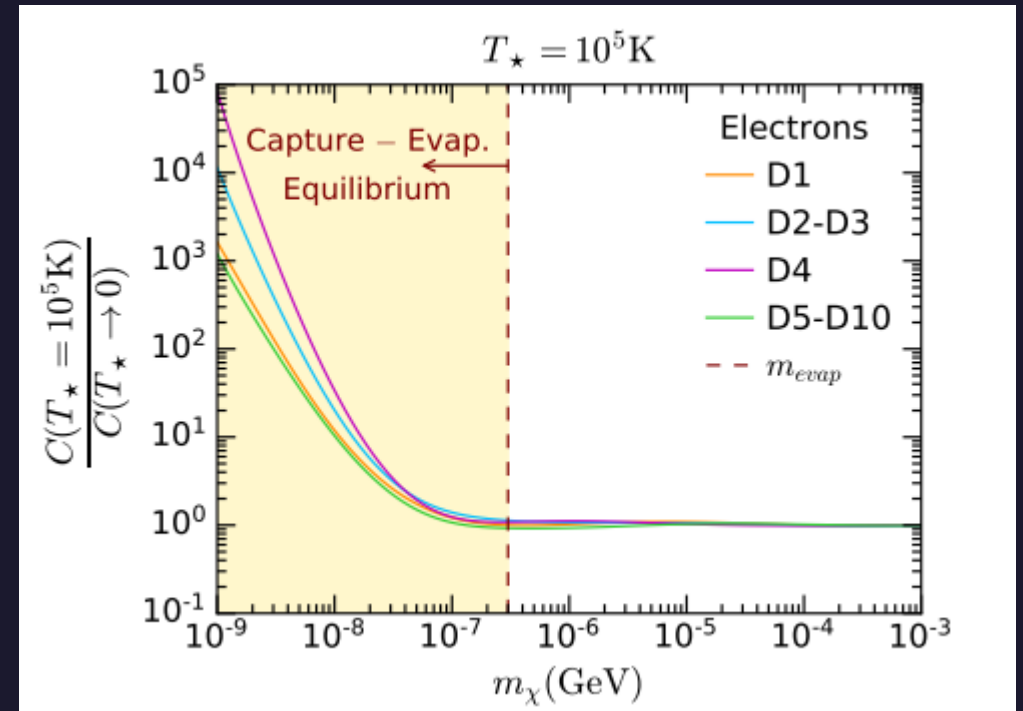
Evaporation mass is NS

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

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

- Previous estimates (non-relativistic)

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

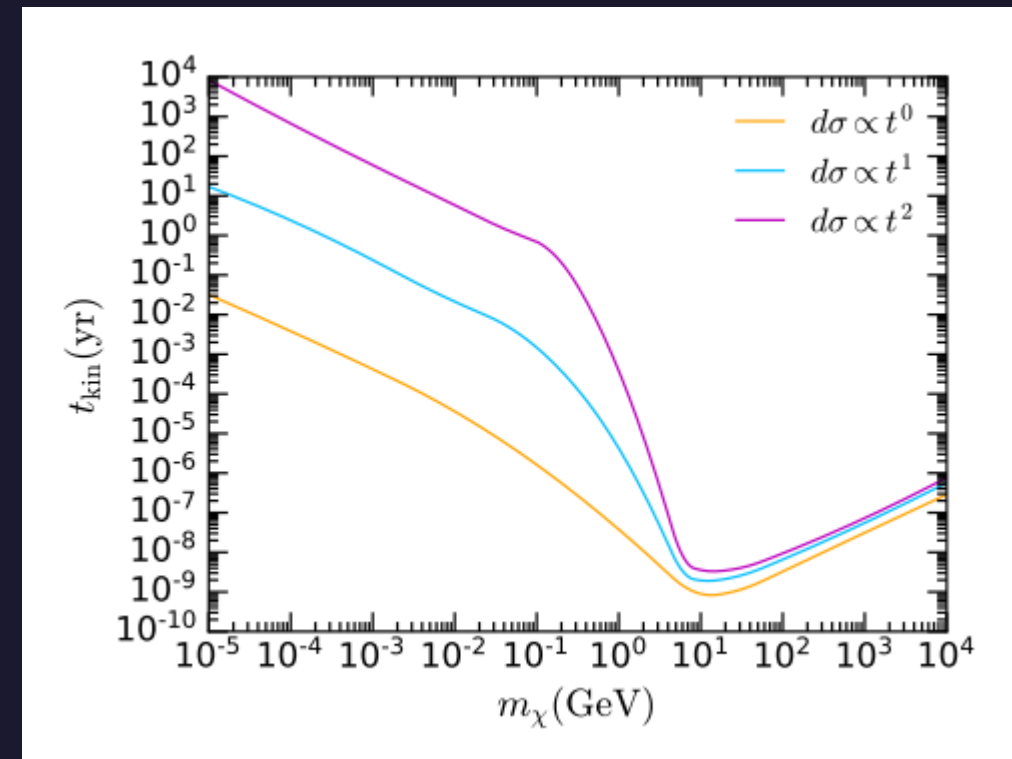


Thermalisation and C/A equilibrium

JCAP 04 (2024) 006

DM energy distribution time evolution:

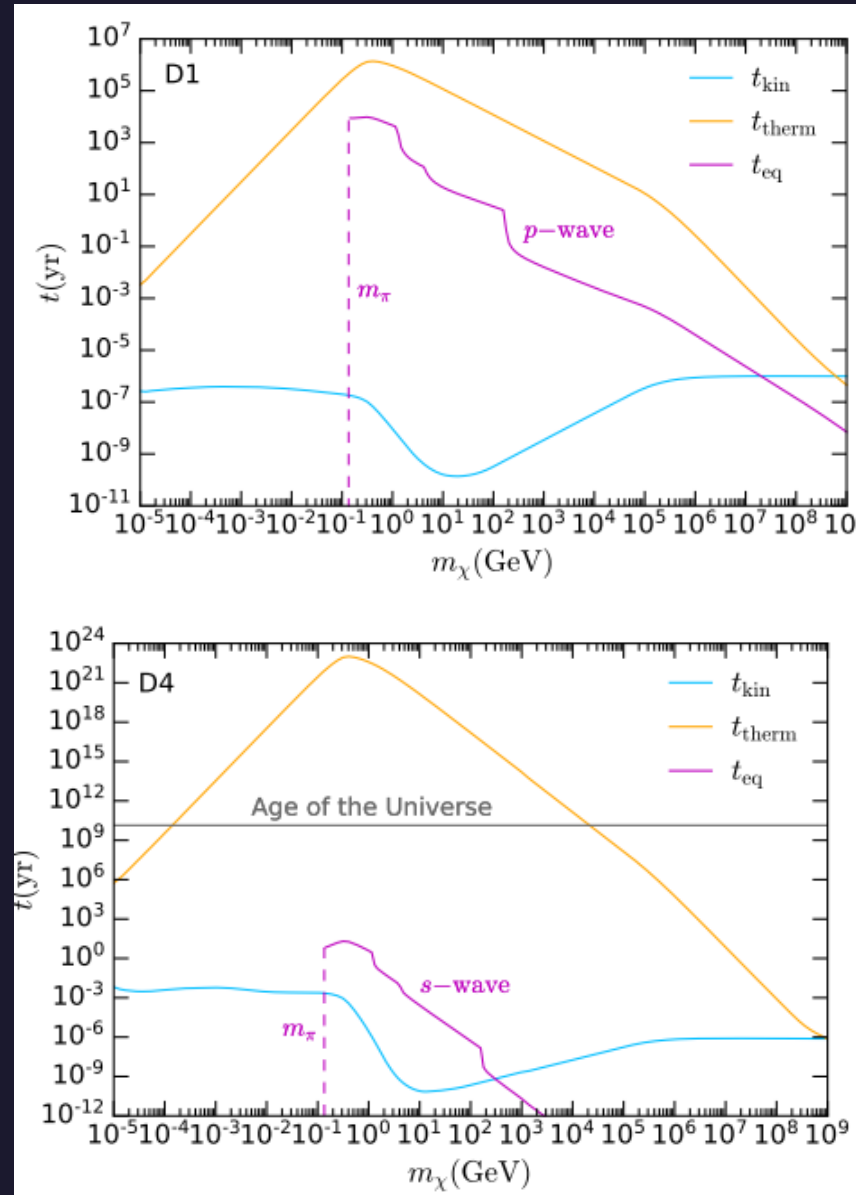
- Kinetic heating always happens
($t_{kin} \ll t_{star}$)
- Annihilation heating always happens
($t_{CA} \ll t_{star}$)
- Thermalisation depends on the cross section scaling with q_{tr}^2



Thermalisation and C/A equilibrium

DM energy distribution evolution:

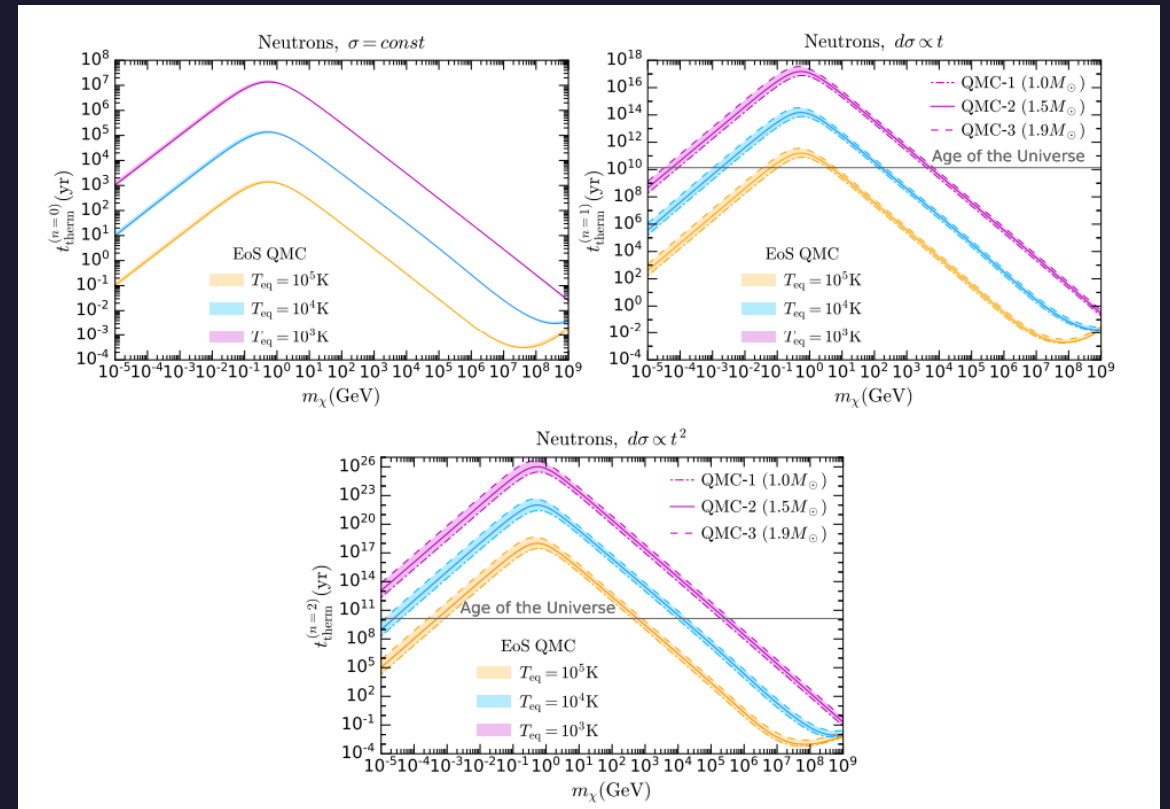
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($t_{kin} \ll t_{star}$)
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($t_{CA} \ll t_{star}$)
- Thermalisation depends on the cross section scaling with q_{tr}^2



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



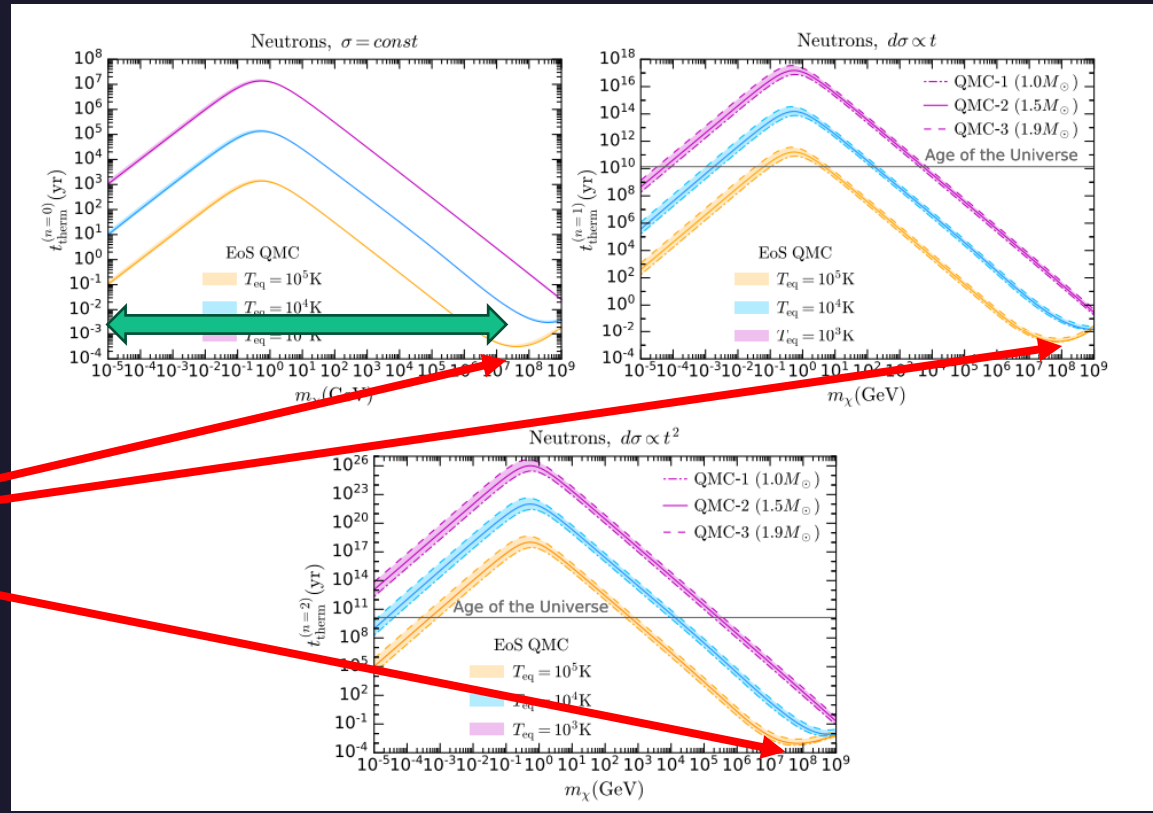
Thermalisation

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

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

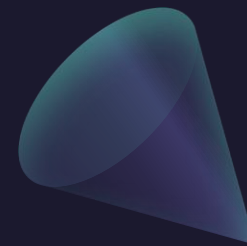
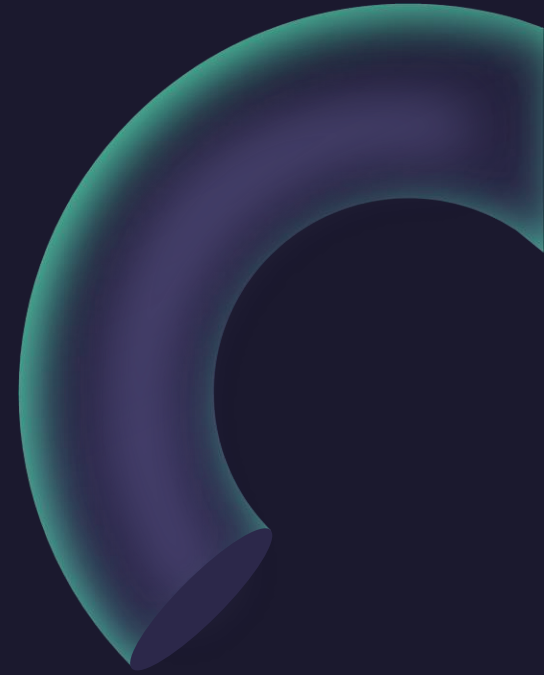
Not affected by PB

Pauli-blocked



Conclusions

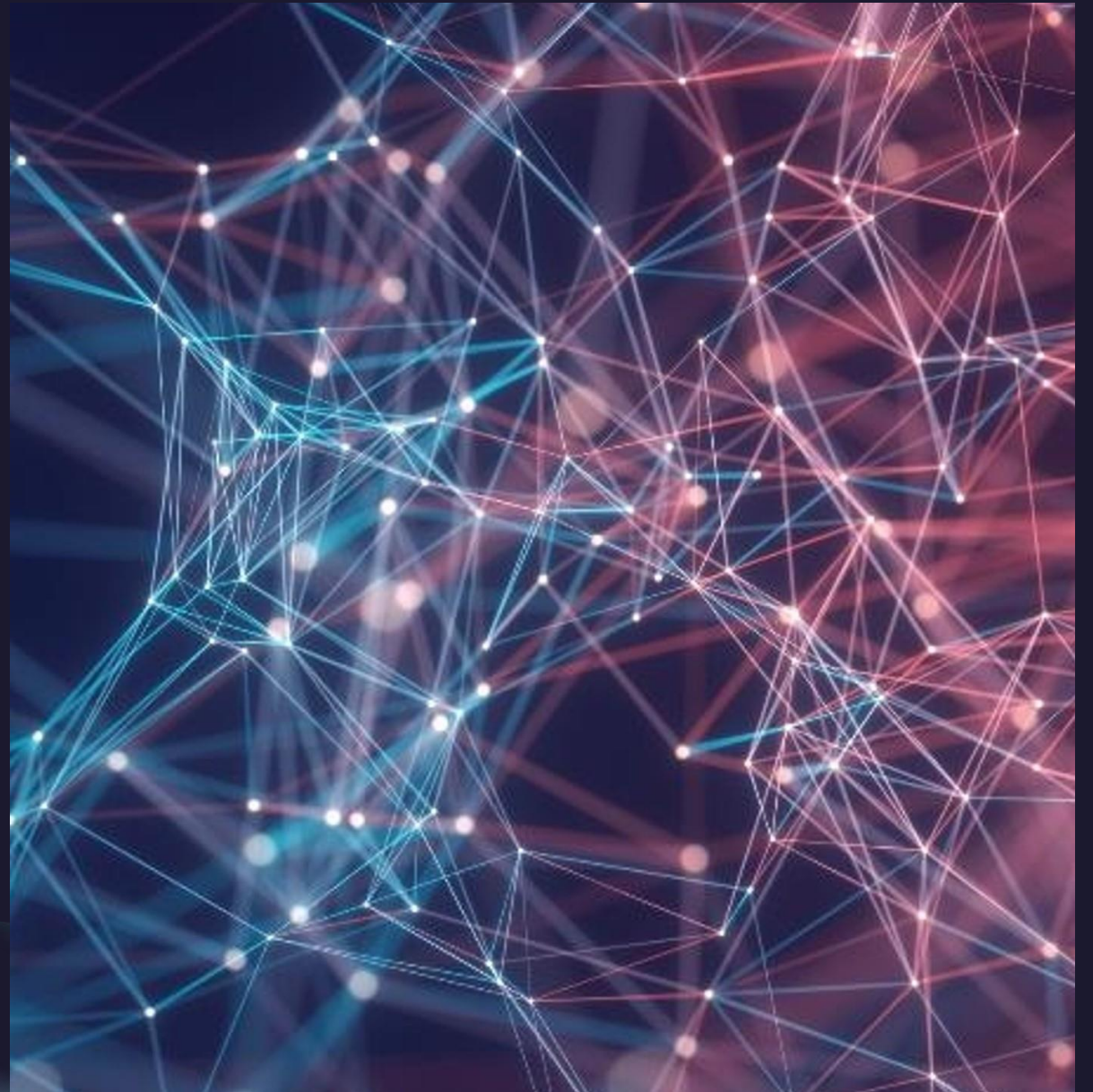
- NS interesting astrophysical laboratory to probe and constraint DM physics
 - Wash away non-relativistic suppressions in DD
 - No SD suppression
 - Sensitivities below neutrino floor for SD
- Large interest in the field and huge theoretical progress in the last decade
 - Rates for most common scenarios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



Thanks

Giorgio Busoni

Adelaide University



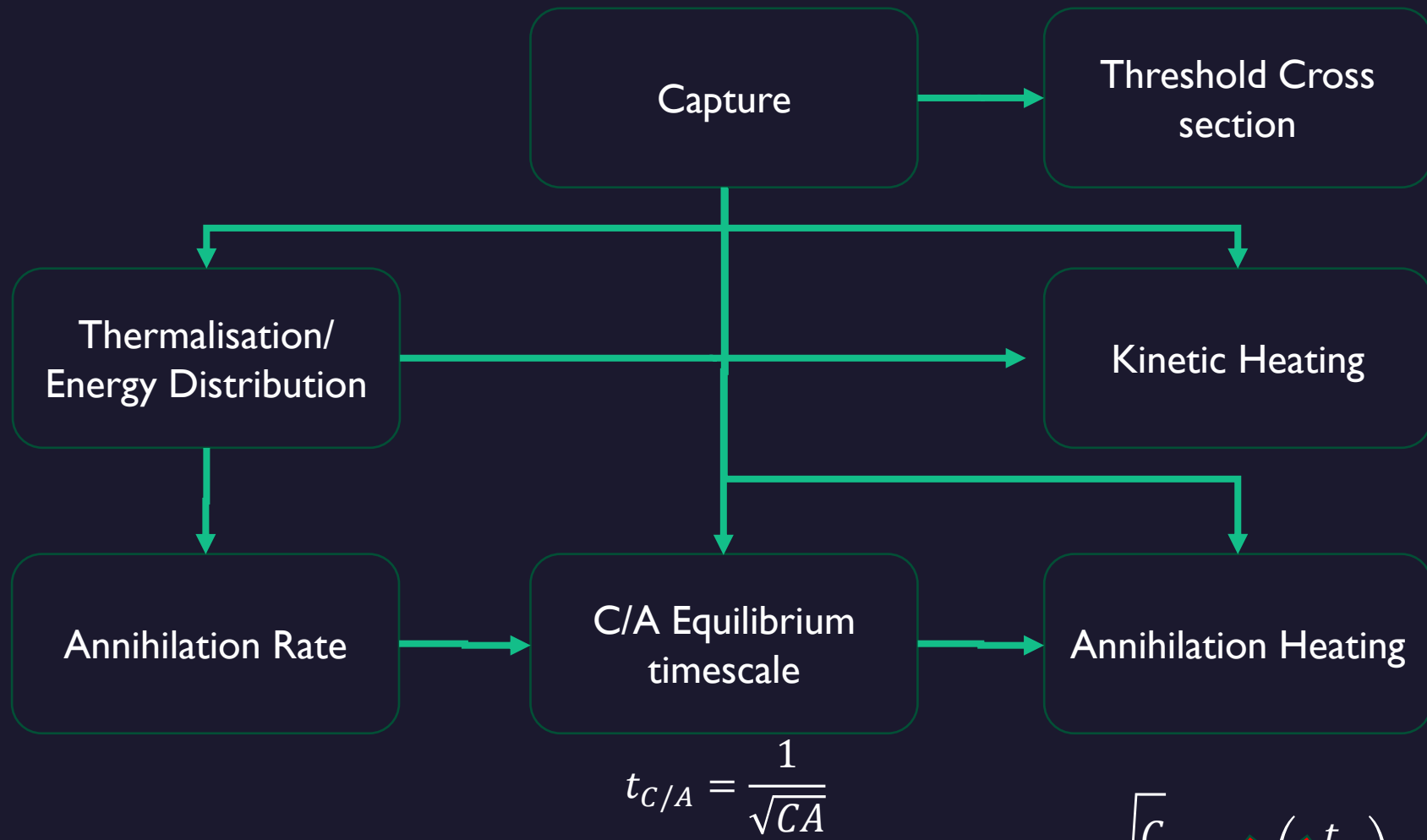


Backup

• 0 |

MOTIVATIONS (NS)

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



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

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

$$\dot{E} = AN^2 \times K^A$$

$$= Cm_\chi T \tanh\left(\frac{t}{t_{C/A}}\right)$$

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

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

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

• 0 | MOTIVATIONS (NS)

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

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



- Requires $m_\chi \lesssim 10^6 \text{ GeV}$
- Energy transferred to the star by Capture $K^G \sim m_\chi \left(\frac{1}{\sqrt{B}} - 1 \right)$
- Energy transferred to the star by subsequent annihilation $K^A \sim m_\chi$

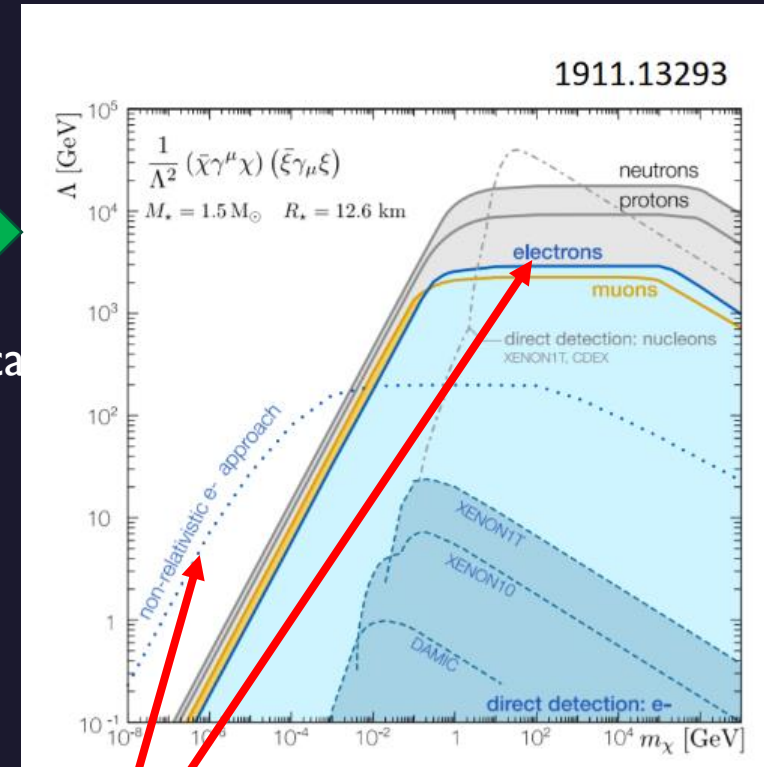
$$T_{eq}^{MAX} \sim 1800 \text{ K} \quad (\text{Kinetic Heating})$$

$$T_{eq}^{MAX} \sim 2300 \text{ K} \\ (\text{Kinetic + Annihilation Heating})$$

•02 CAPTURE (NS)

Need to use/include:

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



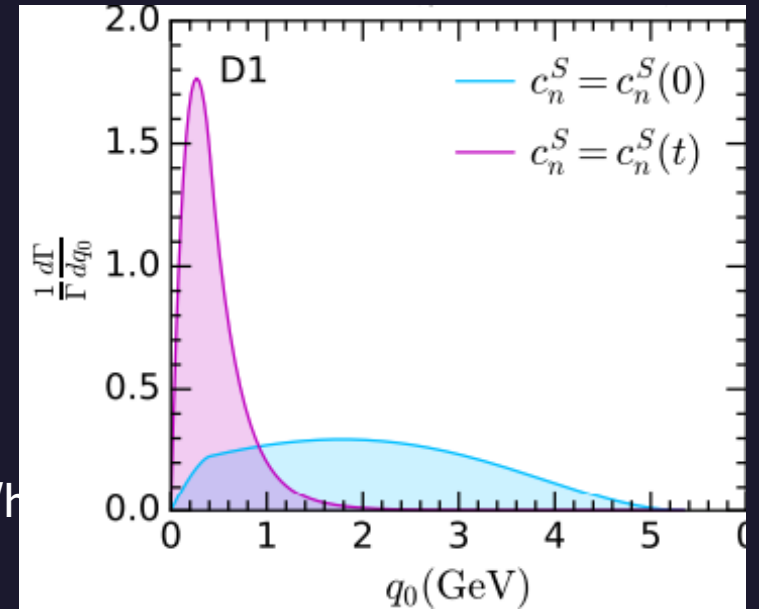
Non-relativistic kinematics vs relativistic kinematics

•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**

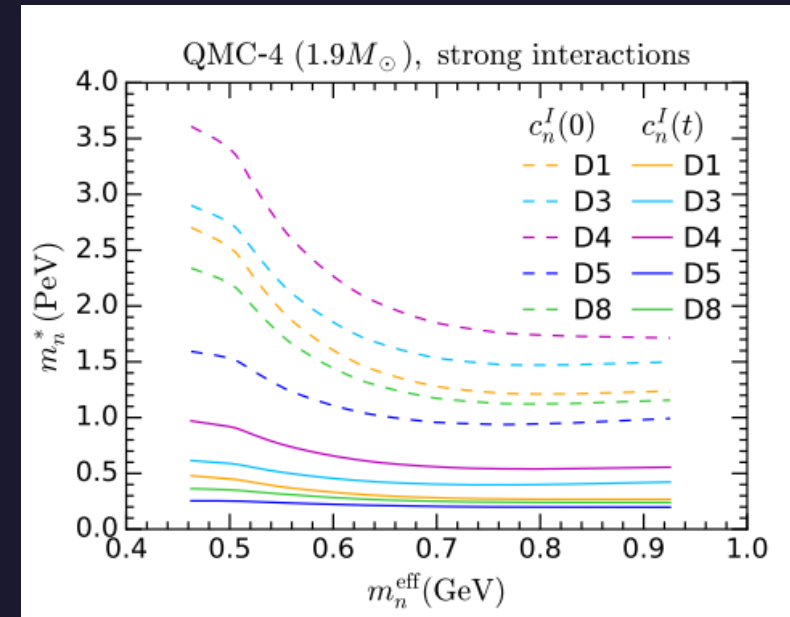
$$F(t) = \frac{1}{(1 - t/Q_0^2)^4}$$



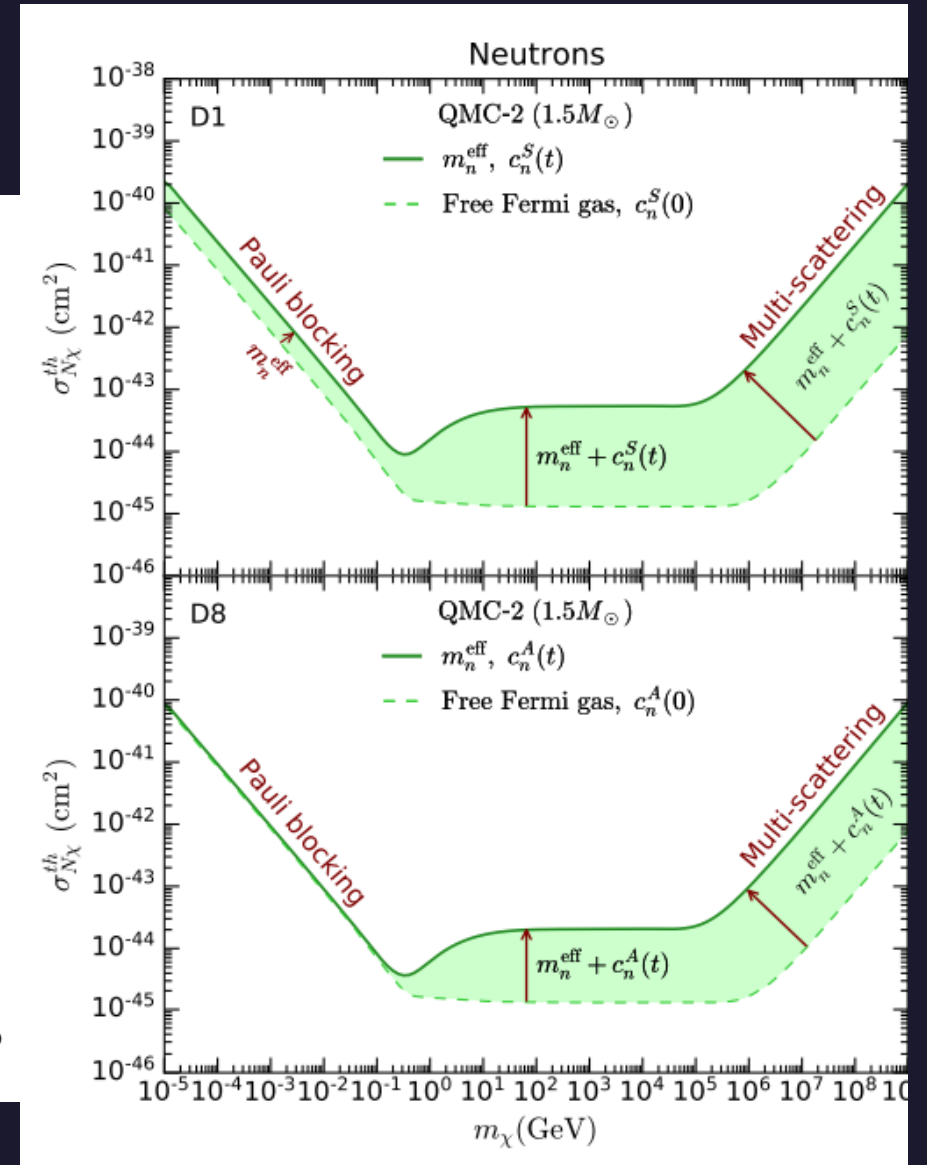
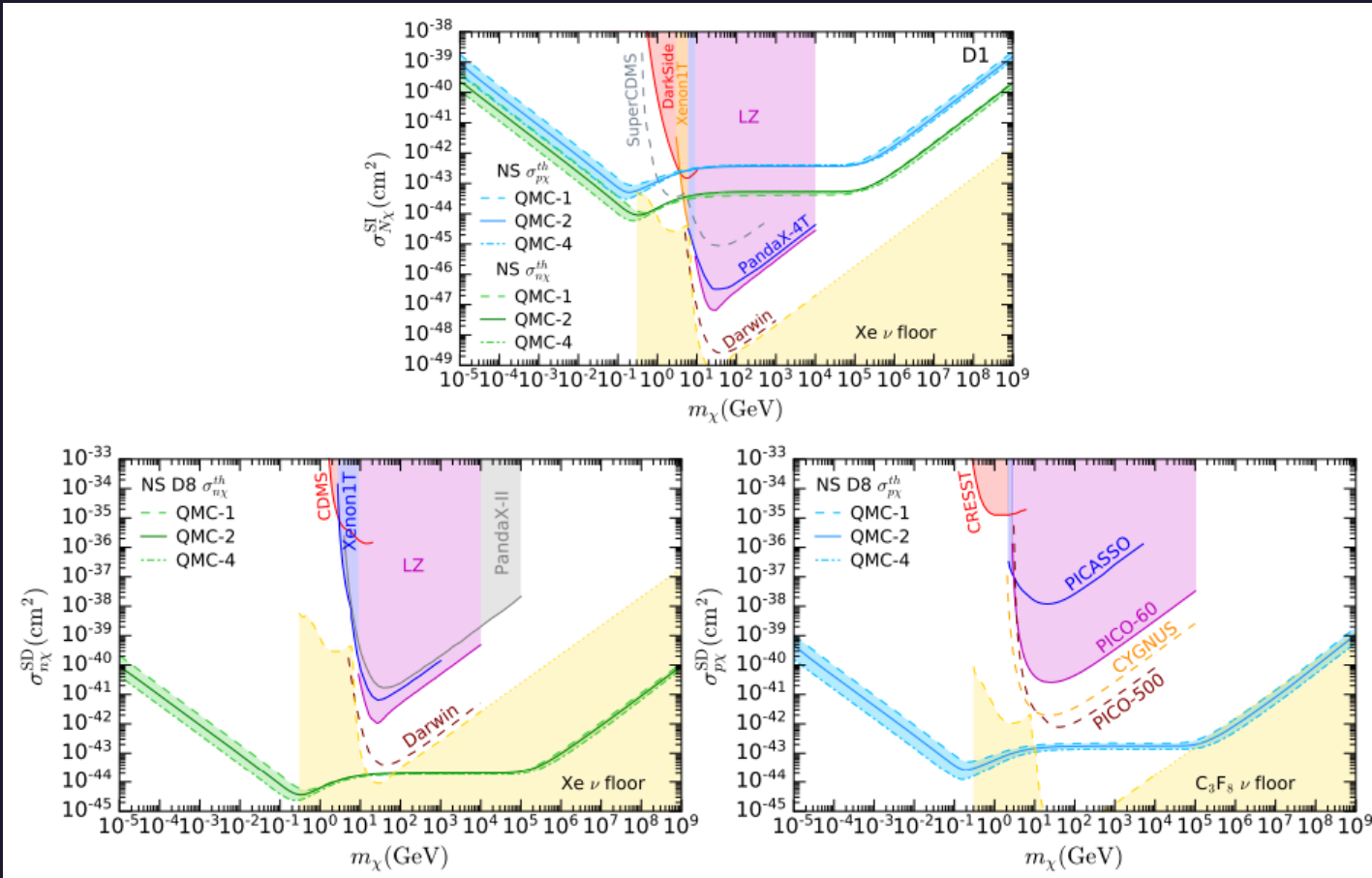
Lower average energy transfer



Large suppression at large mass

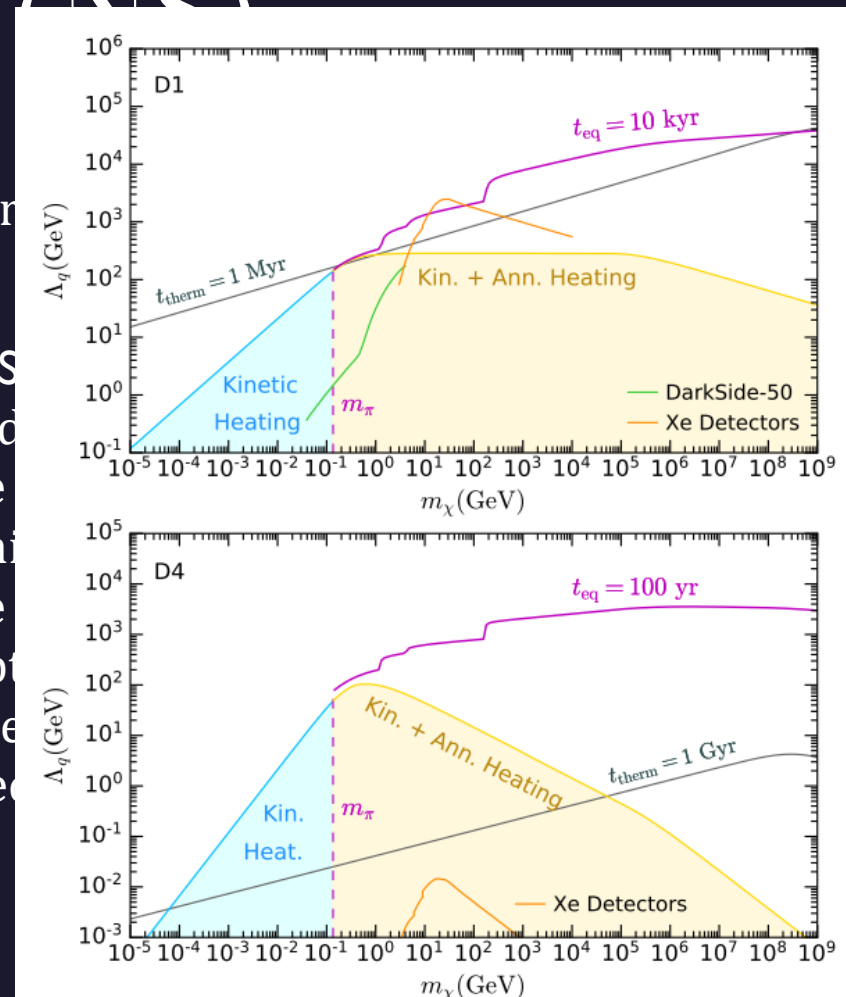


•02 CAPTURE (NS)



•03 THERMALISATION (MS)

- Ultimate goal: is DM energy released in the star on a timescale smaller than
 - 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 NOT thermalize:
 - Find DM temperature
 - 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



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