Constraints on Asymmetric Dark Matter from Neutron Stars

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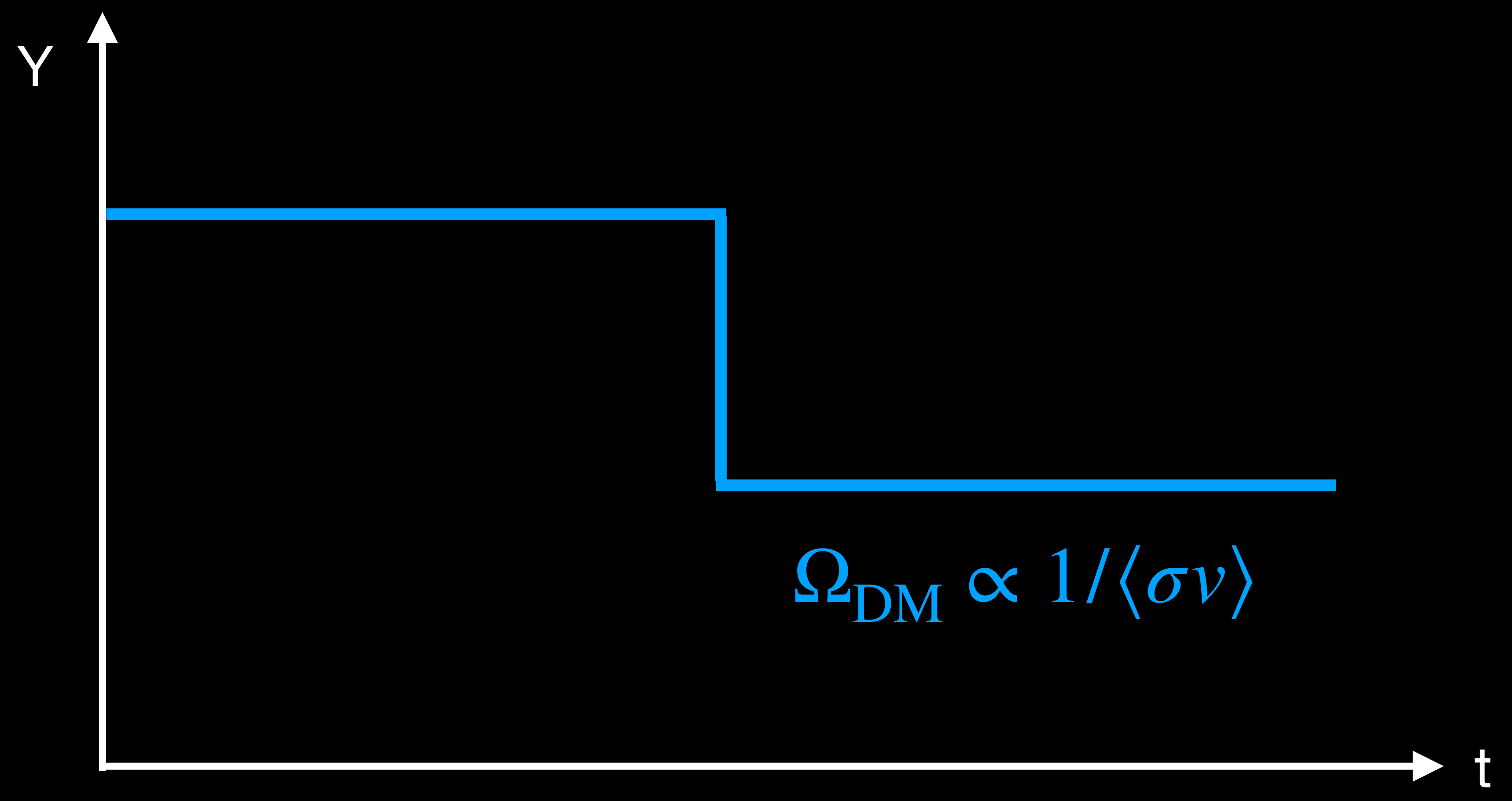
arXiv: 2507.xxxx

CSIC · Universitat de València · IFIC Institut de Física Corpuscular · Generalitat Valenciana · AsYmmetry Essential Asymmetries of Nature

Dark Matter

WIMPS as thermal relics

Thermal freeze-out of Weakly Interacting Massive Particles

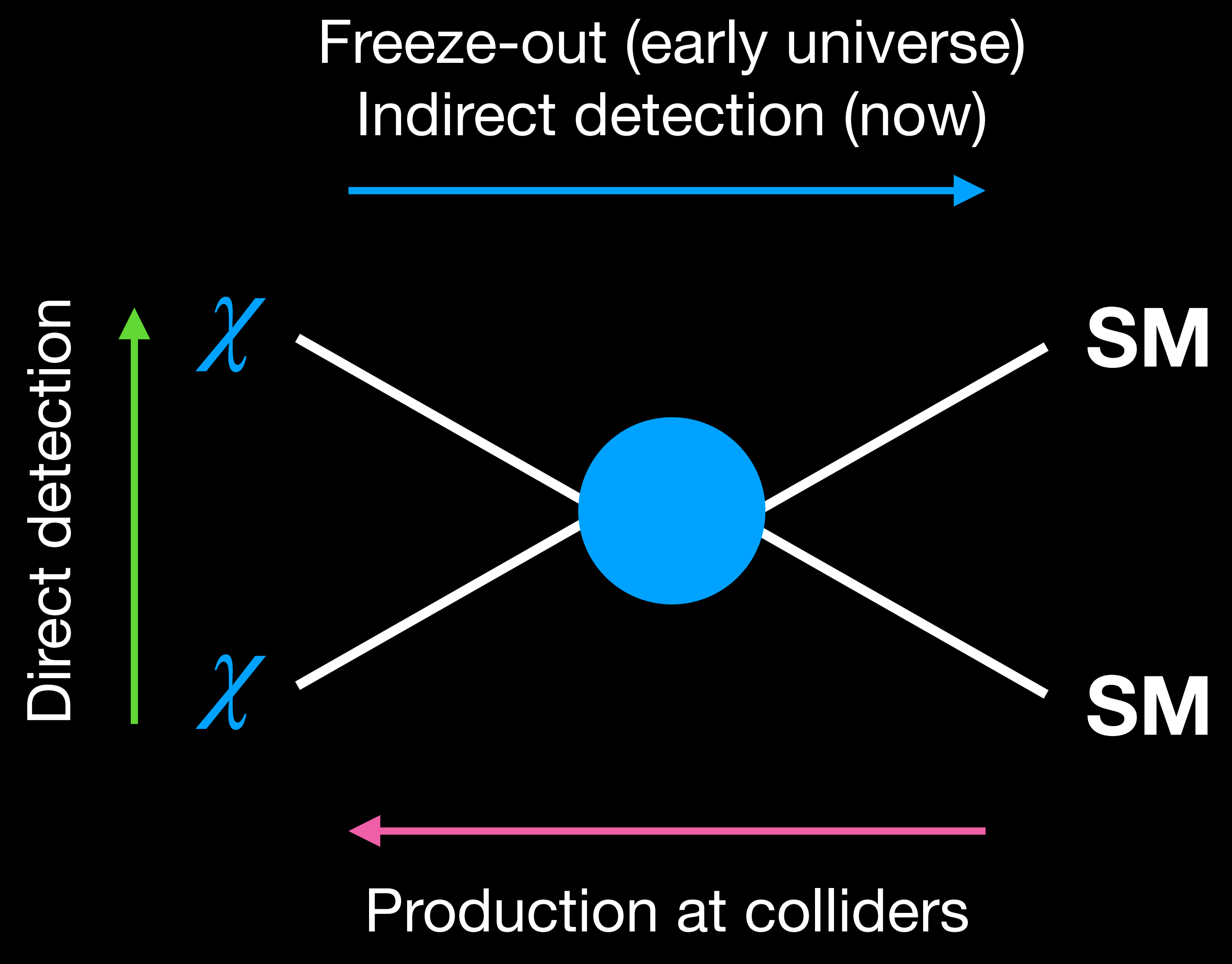


$\langle \sigma v \rangle \sim 2.2 \cdot 10^{-26}\,{\rm cm}^3/{\rm s}$

Produces the correct relic abundance

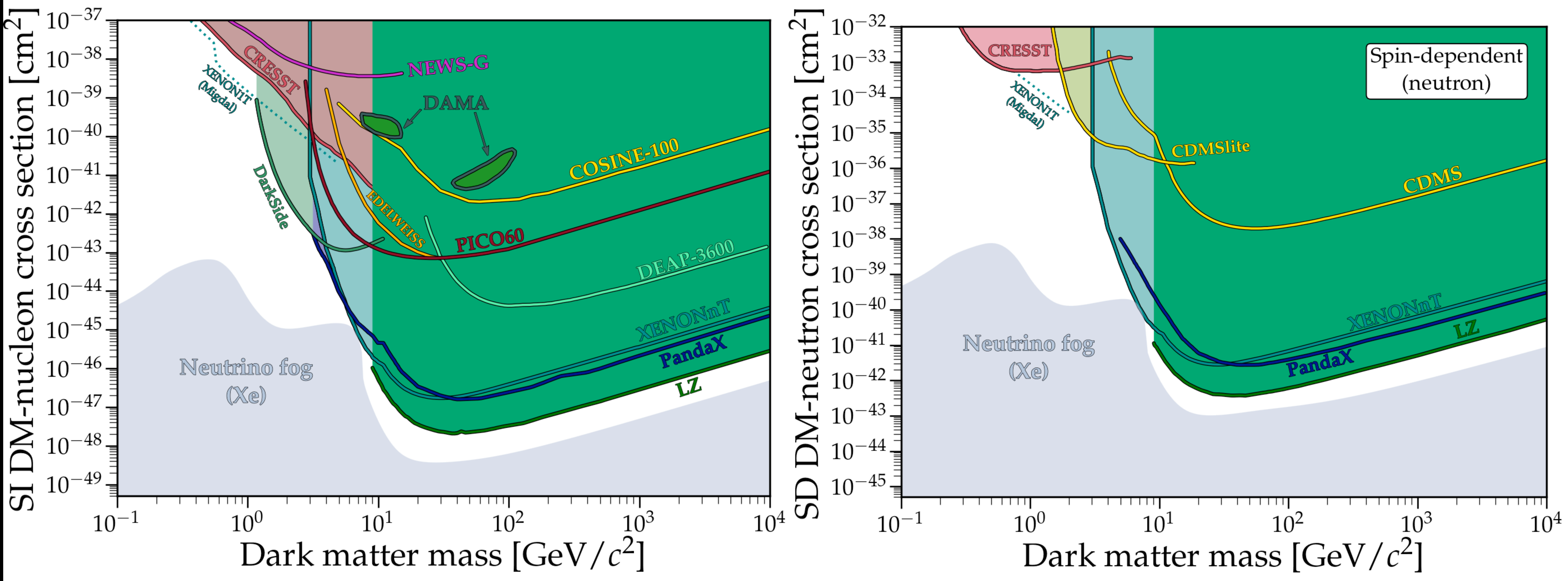
Symmetric DM

WIMPS



Dark Matter

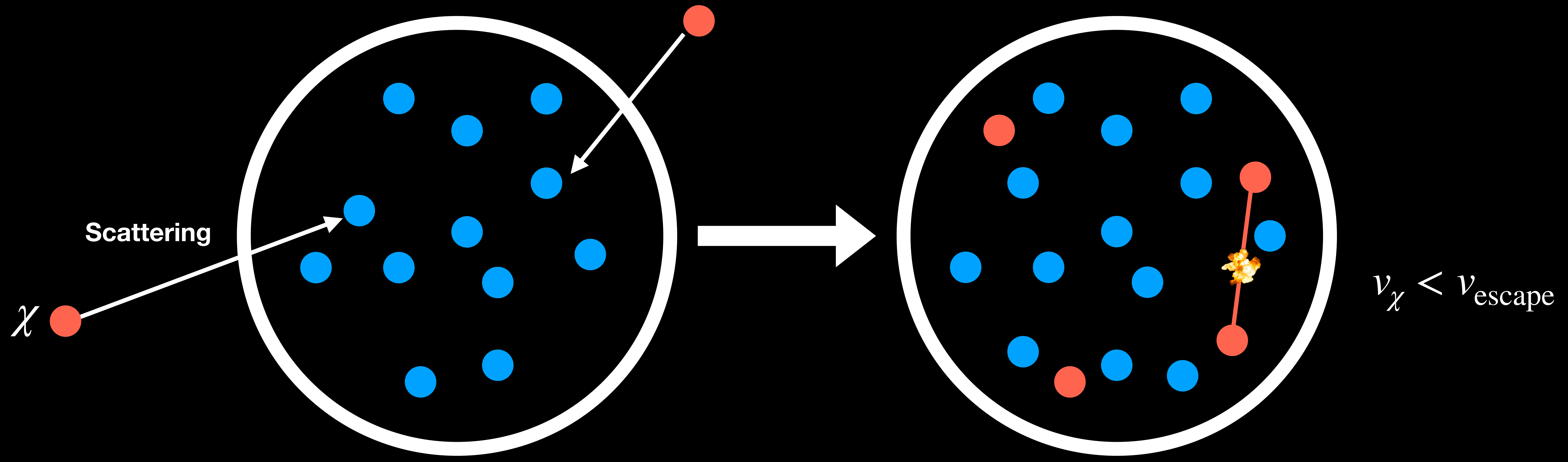
Direct Detection



Credits: Ciaran O'Hare

Dark Matter

Capture in Astrophysical Bodies

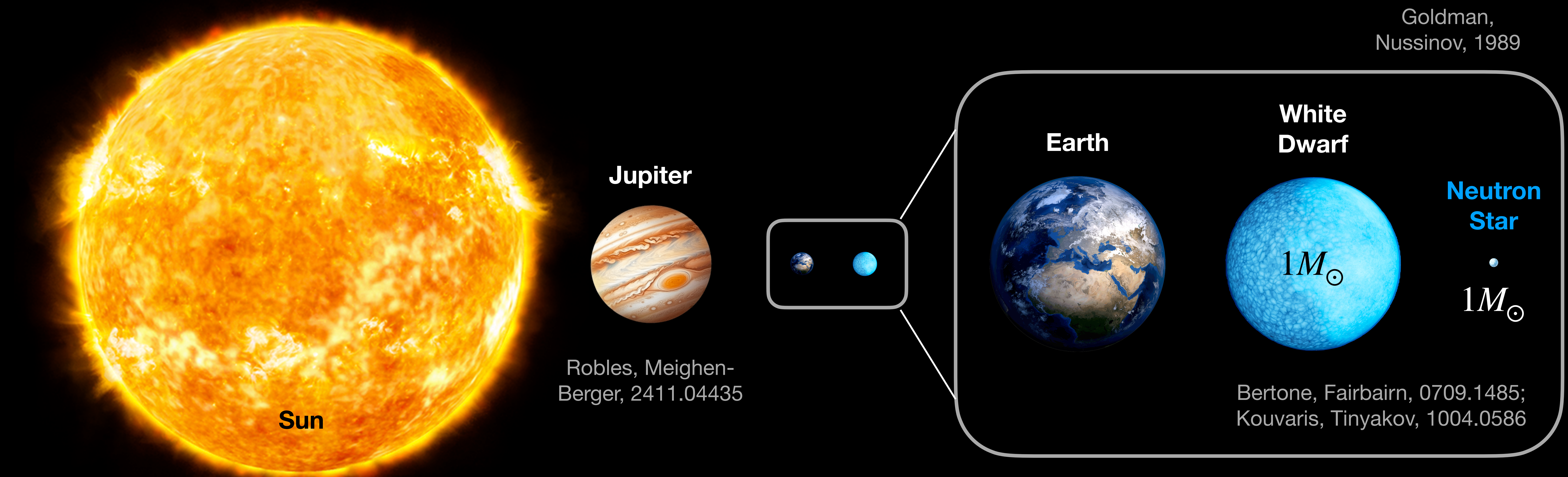


DM scatters off constituents → Loses energy → Becomes gravitationally bound:
Capture rate $\propto \sigma_{i\chi}$ (Complementary to DD)

Annihilation of captured DM → Indirect Detection

Dark Matter

Capture in Astrophysical Bodies



Gould, 1987
Spergel, Press, 1985

Larger gravitational potential → More efficient capture → Densest stars are extremely efficient

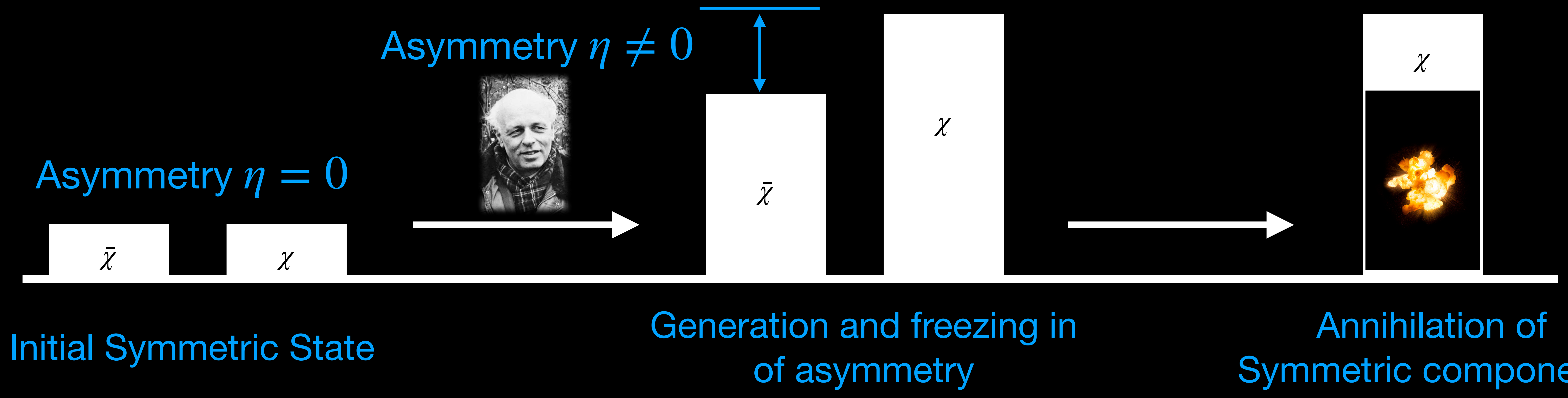
ID signals: Annihilation products, eq. νs in the sun; heating up of NS

Asymmetric Dark Matter

Overview

Visible matter density determined by Baryon Asymmetry η_B

DM abundance may be set by an initial asymmetry in the dark sector $\eta_D \equiv n_\chi - n_{\bar{\chi}}$



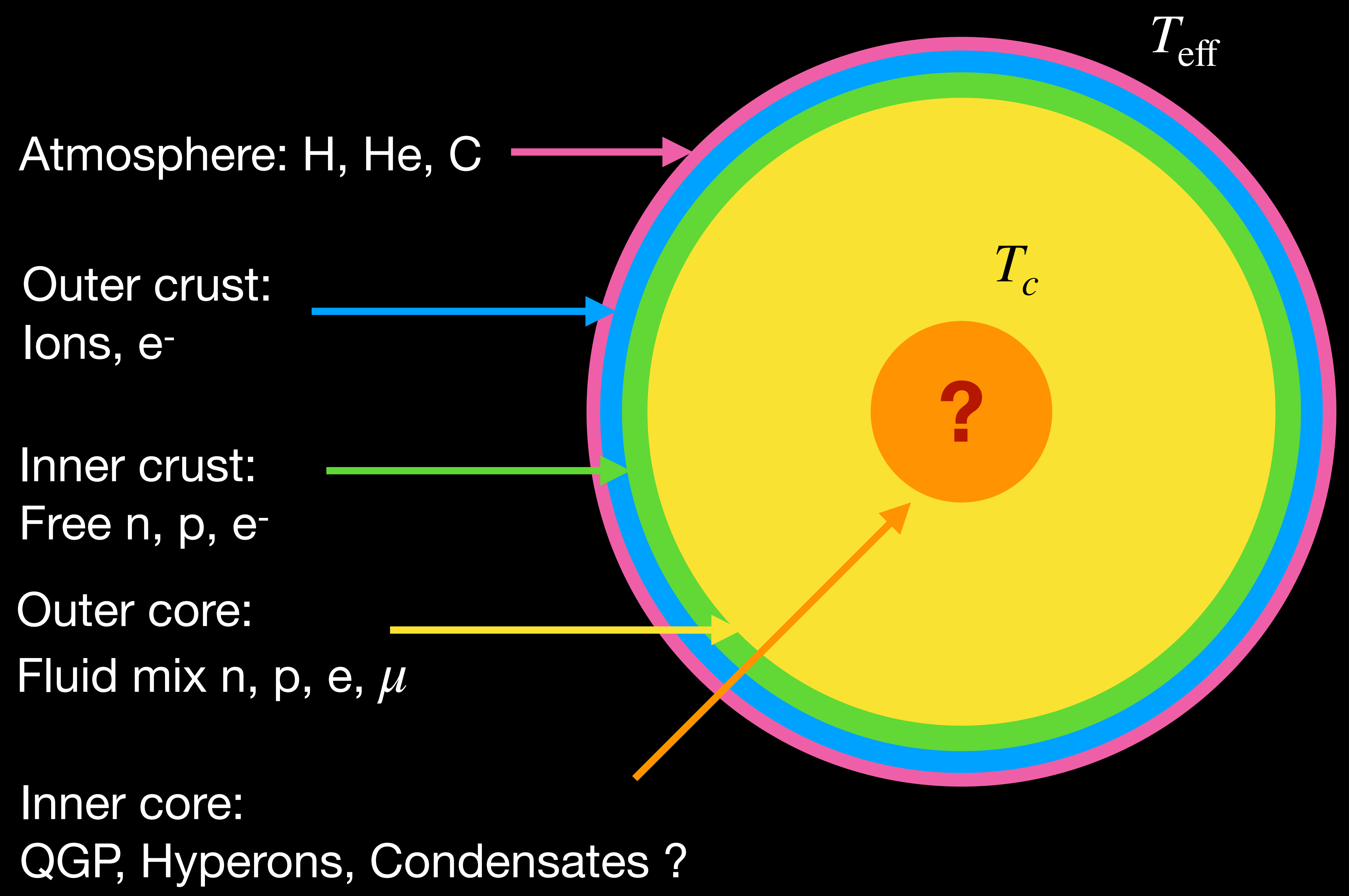
$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \sim 5 \simeq \frac{\eta_D\, m_\chi}{\eta_B\, m_p}$$

Zurek,1308.0338

Remnant asymmetric population → Annihilations negligible → Accumulation in compact objects

Neutron Stars

Overview



Core: 99%, Crust: 1% of NS Mass

Composed of highly degenerate matter → Outward degeneracy pressure balances inward gravitational pressure

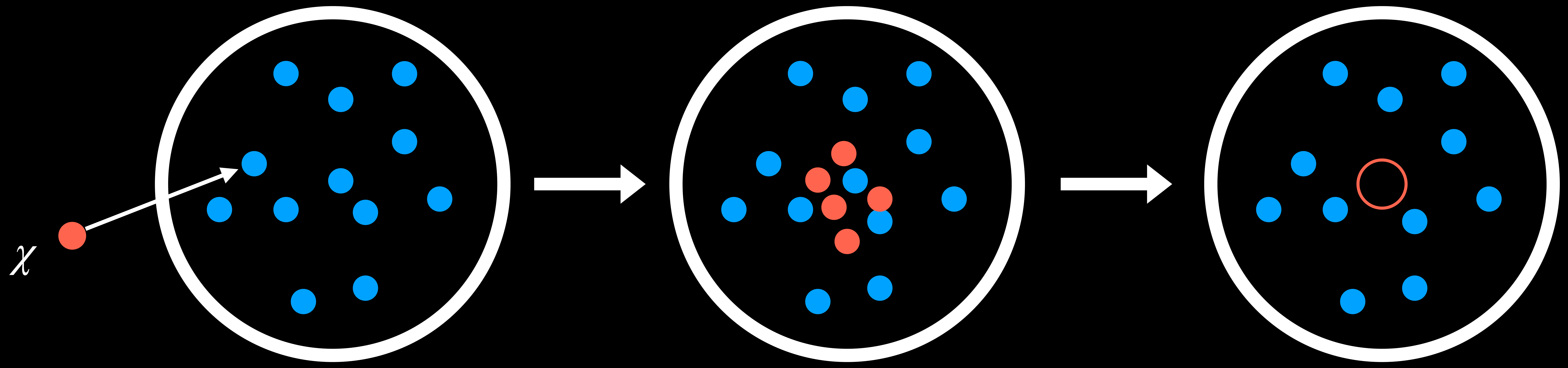
Exact composition still not known → Theoretical models used for description

NS Structure calculations → Equation of state (EoS): $P = P(\rho)$ coupled to Tolman-Oppenheimer-Volkoff (TOV) equations

Relativistic EoS: Quark Meson Coupling (QMC) model → Allows modelling NS up to 2 $M_{\odot}$

Asymmetric Dark Matter

Constraints from NS



Capture

DM is captured in the NS after initial and further scatterings

Thermalisation

Captured DM loses energy via scatterings and thermalises in the NS core

BH Formation

Thermalised DM reaches the self-gravitation condition to form a Black Hole in the NS core

BH can consume the entire NS → Observations of Old NS → Constraints on ADM

Capture
Rates

Total DM captured after time t: $N_\chi(t) = C \times t$

$$C = \frac{4\pi\rho_\chi}{m_\chi}\int_0^\infty du_\chi \frac{f_{MB}(u_\chi)}{u_\chi} \times \int_0^{R_*} dr r^2 \frac{\sqrt{1-B(r)}}{B(r)} \eta^{\text{multi}}(r)\, \Omega^-(r)$$

GR effects

Multiple Scatterings

Relativistic kinematics

$$\Omega^-(r) = \frac{1}{32\pi^3}\int dt\, dE_i\, ds \frac{s\,|\bar{M}(s,t,m_i^{\text{eff}})|^2}{s^2 - [(m_i^{\text{eff}})^2 - m_\chi^2]^2}\frac{E_i}{m_\chi} \times \sqrt{\frac{B(r)}{1-B(r)}}$$

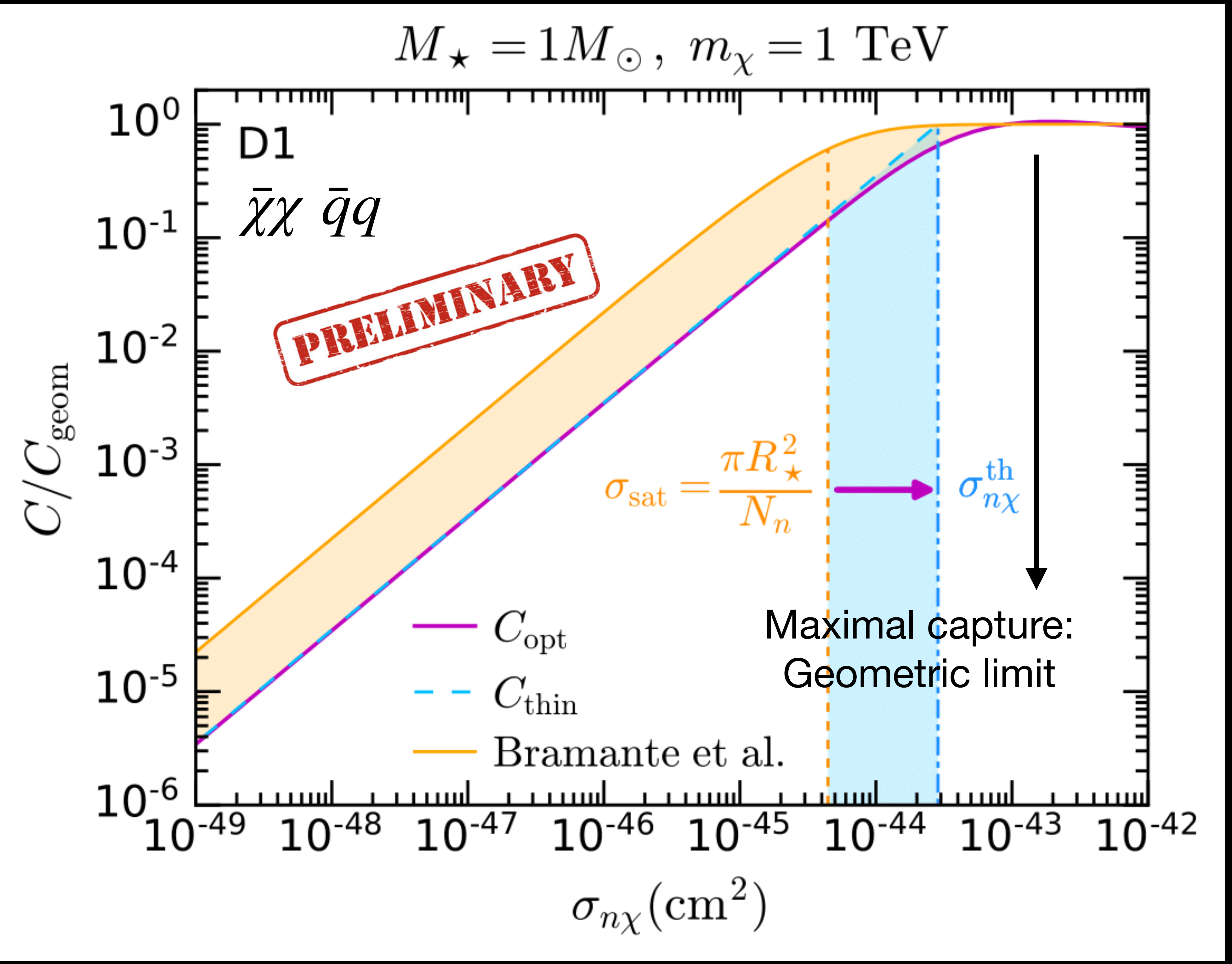
$$\times \frac{f_{\text{FD}}(E_i, r)(1 - f_{\text{FD}}(E_i', r))}{\sqrt{[s - (m_i^{\text{eff}})^2]^2 - 4(m_i^{\text{eff}})^2 m_\chi^2}}$$

Pauli blocking

Nucleon structure & interactions

Bell, Busoni, Robles, Virgato, 2004.14888, 2312.11892

Bramante, Delgado, Martin, 1703.04043

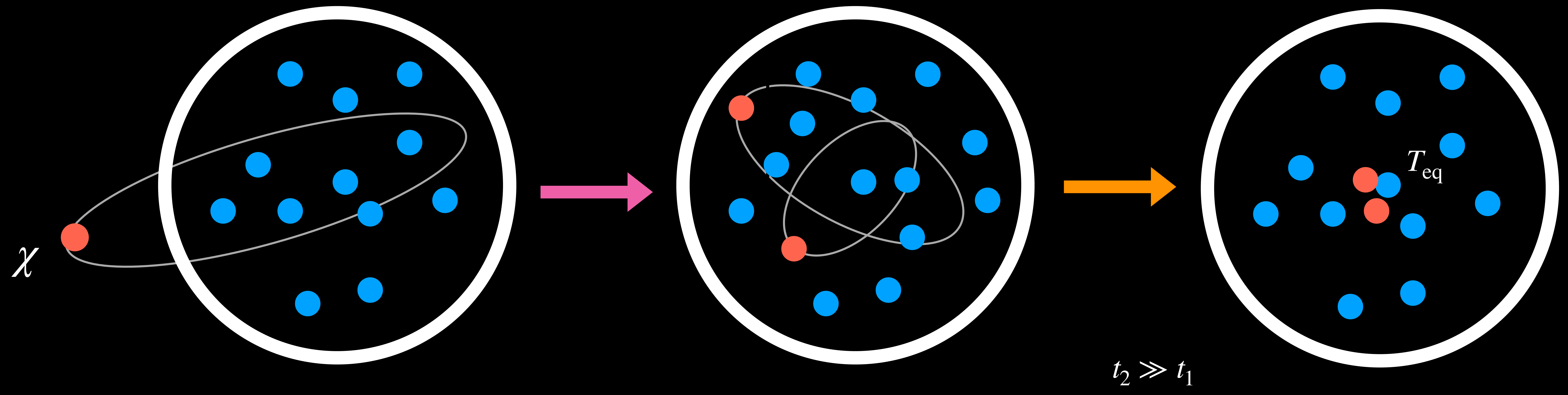


Improved treatment → Suppression of rates

Thermalisation

Energy loss & timescale

Captured DM orbits the NS → Continues to scatter off NS material → Loses energy → Settles in the NS centre



Time taken for an orbiting DM in and out of NS to be contained in NS: t_1

Time taken for DM orbiting within NS to reach thermal equilibrium with NS matter at $T_{\rm eq}$: t_2

Total thermalisation time: $t_1 + t_2 \approx t_2$

Garani, Genolini, Hambye, 1812.08773

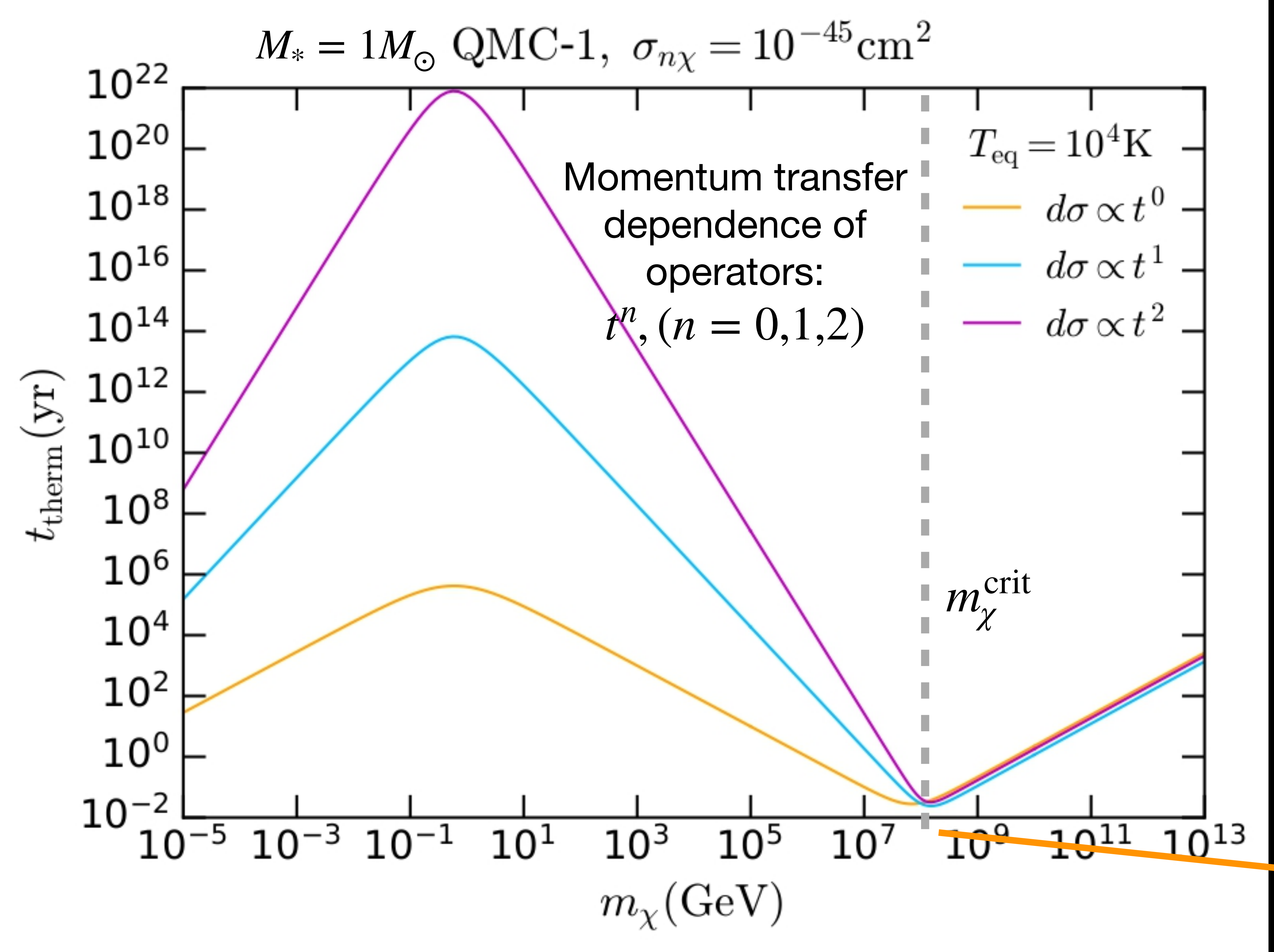
Thermalisation
Timescale

$m_\chi \lesssim m_\chi^{\rm crit}$

$$t_{\rm therm}^{(n=0)} \sim \frac{147\pi^2 m_\chi}{16(m_i^{\rm eff}(0)+m_\chi)^2 \sigma_{i\chi}^{n=0} T_{\rm eq}^2}$$

Pauli blocking delays thermalisation process (discrete)

Determined by the last few scatterings in the centre that take the longest to occur



$m_\chi > m_\chi^{\rm crit}$

$$t_{\rm therm}^{(n=0)} \sim \frac{3\pi^2 m_\chi}{8(m_i^{\rm eff}(0))^2 \varepsilon_{F,i}^2 \sigma_{i\chi}^{n=0}} \log\left[\frac{m_\chi}{T_{\rm eq}}\left(\frac{1}{\sqrt{B(R_*)}} - 1\right)\right]$$

Non Pauli blocked (continuous)

Transition regime: Sum of both contributions (PB & no PB)

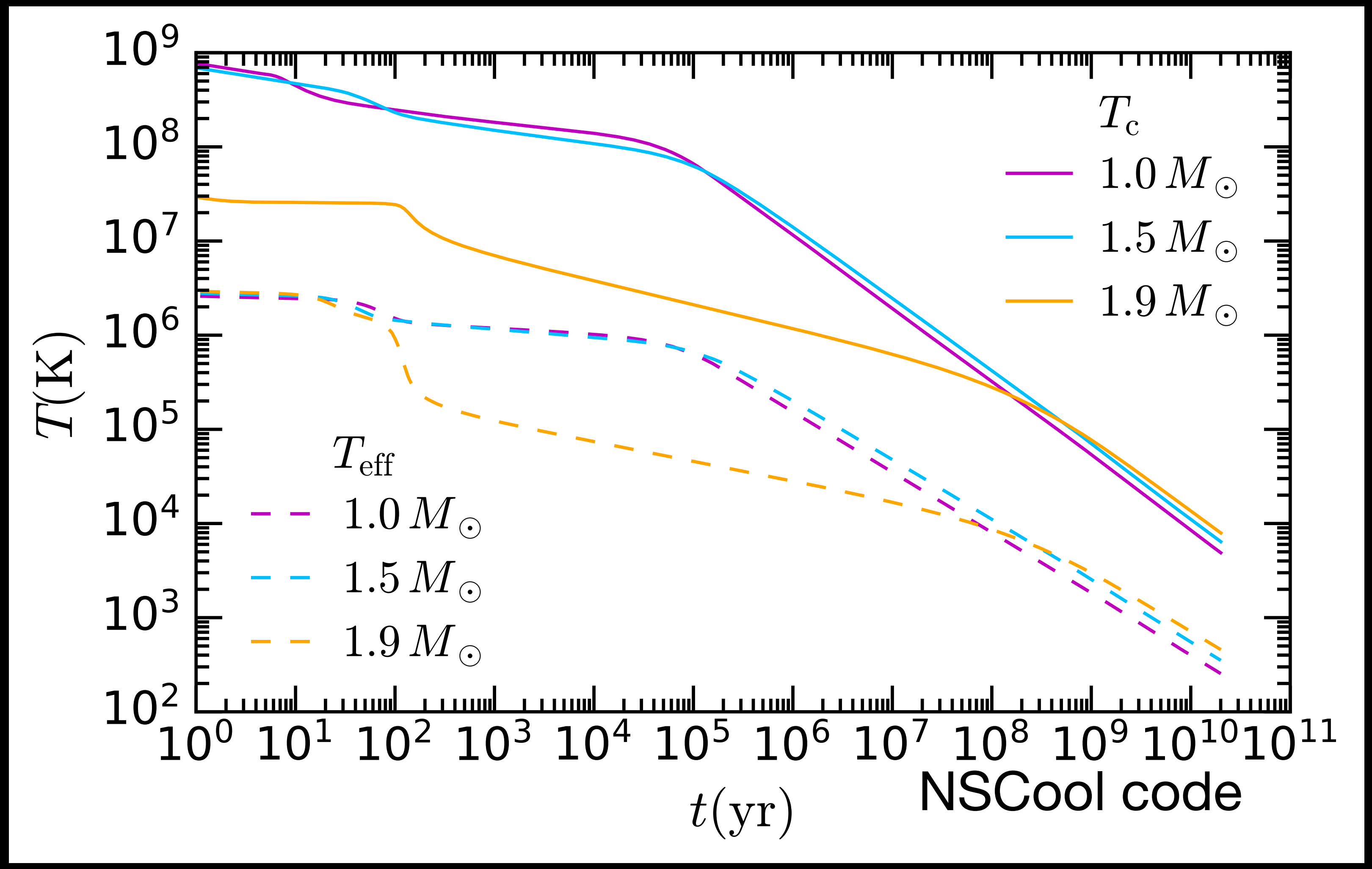
$$m_\chi^{\rm crit} = \frac{2\varepsilon_{F,i}(2m_i^{\rm eff}i + \varepsilon_{F,i})}{T_{\rm eq}}$$

Bell, Busoni, Robles, Virgato, 2312.11892

Thermalisation

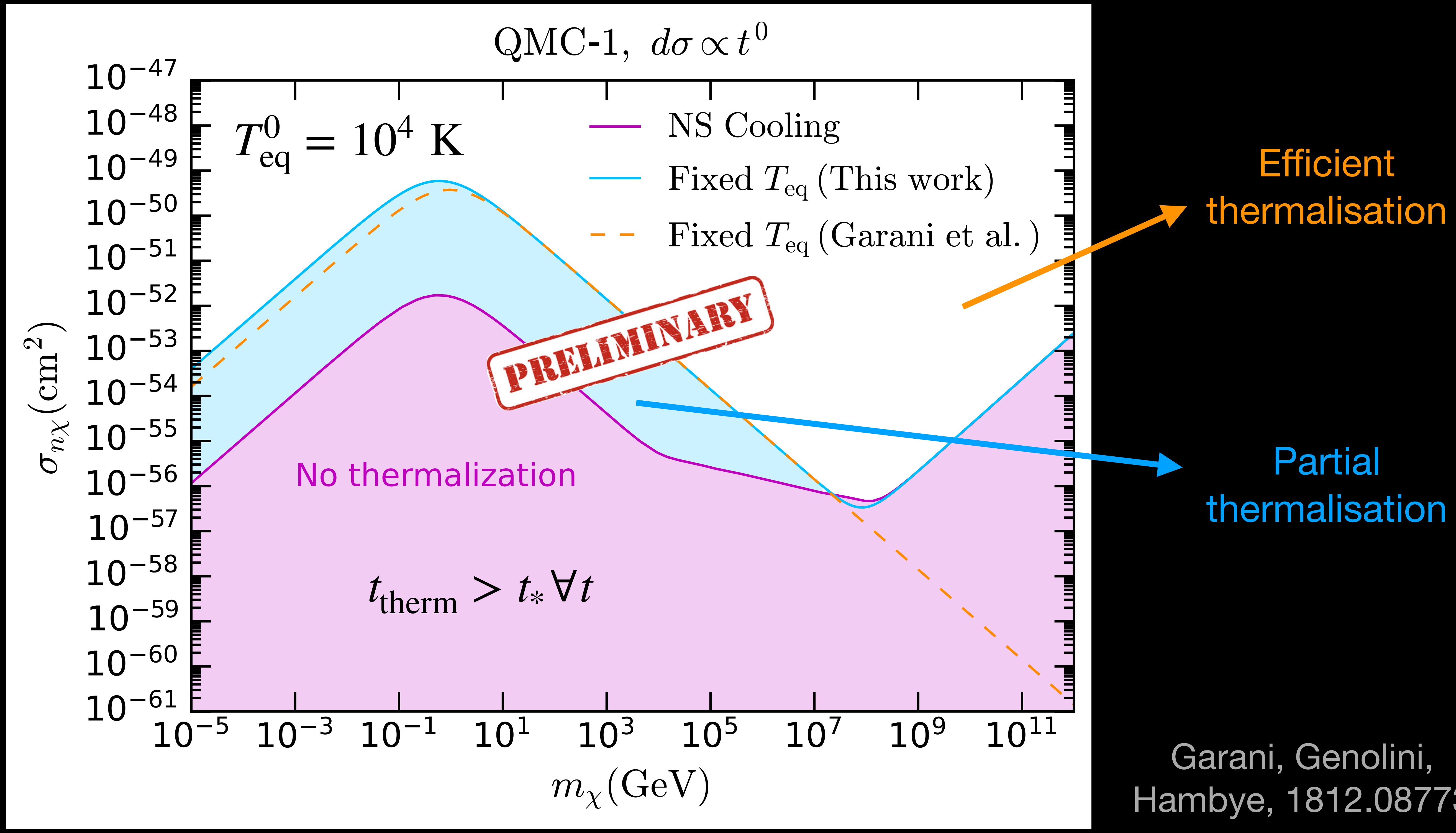
ADM in NS

$t_{\text{therm}} < t_*$ → Captured DM cannot thermalise efficiently in NS core → No constraints can be placed



NS cooling: $T_{\text{eq}} \sim T_c$ changes with time

At earlier times T_{eq} is higher, thermalisation is faster

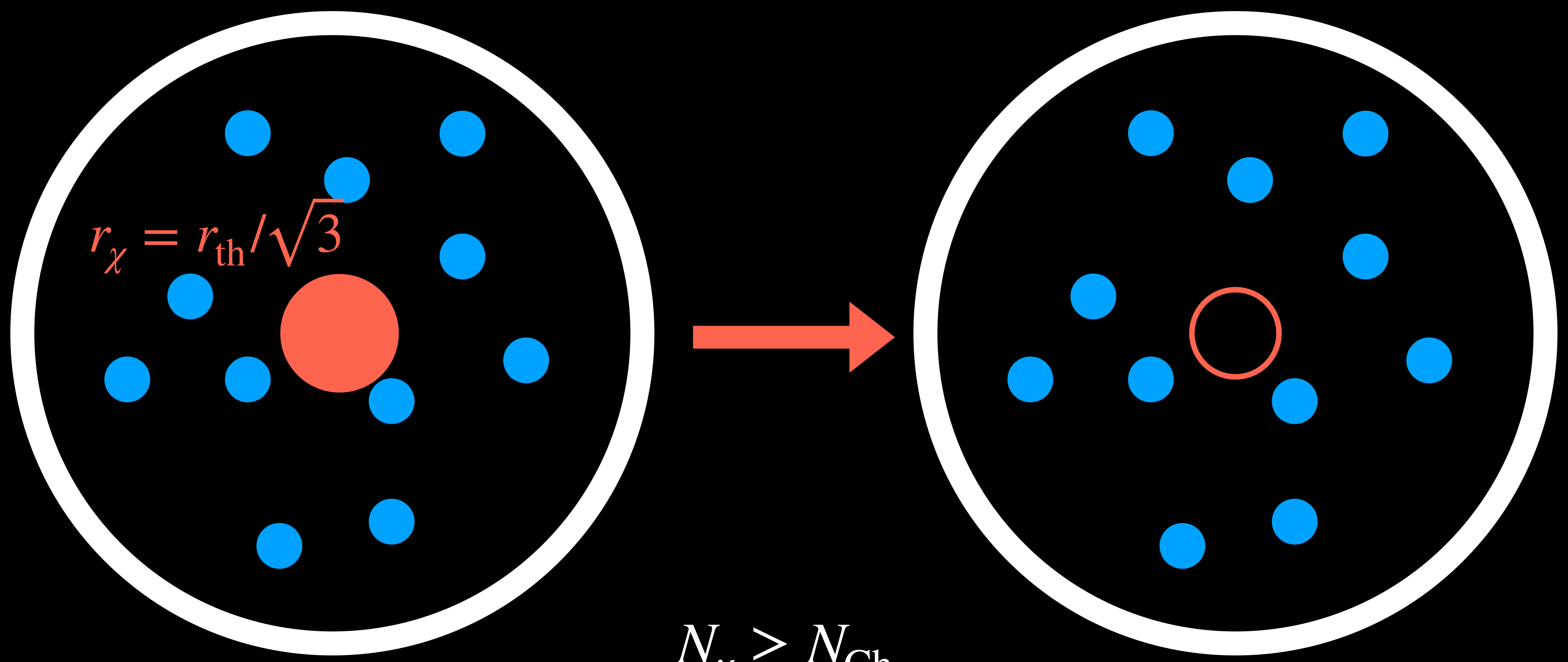


Garani, Genolini, Hambye, 1812.08773

Destruction of NS

BH formation

Population of thermalised ADM in the NS core grows over time → DM can achieve self-gravitation



$$N_\chi \geq N_{\rm Ch}$$

$$M_\chi^{\rm Ch} = m_\chi N_{\rm Ch}$$

$$N_\chi(t) \geq \frac{2\sqrt{2}\pi^{3/2} r_{\rm th}^3 (\rho_c + 3P_c)}{3\sqrt{3} m_\chi} = N_{\rm self}$$

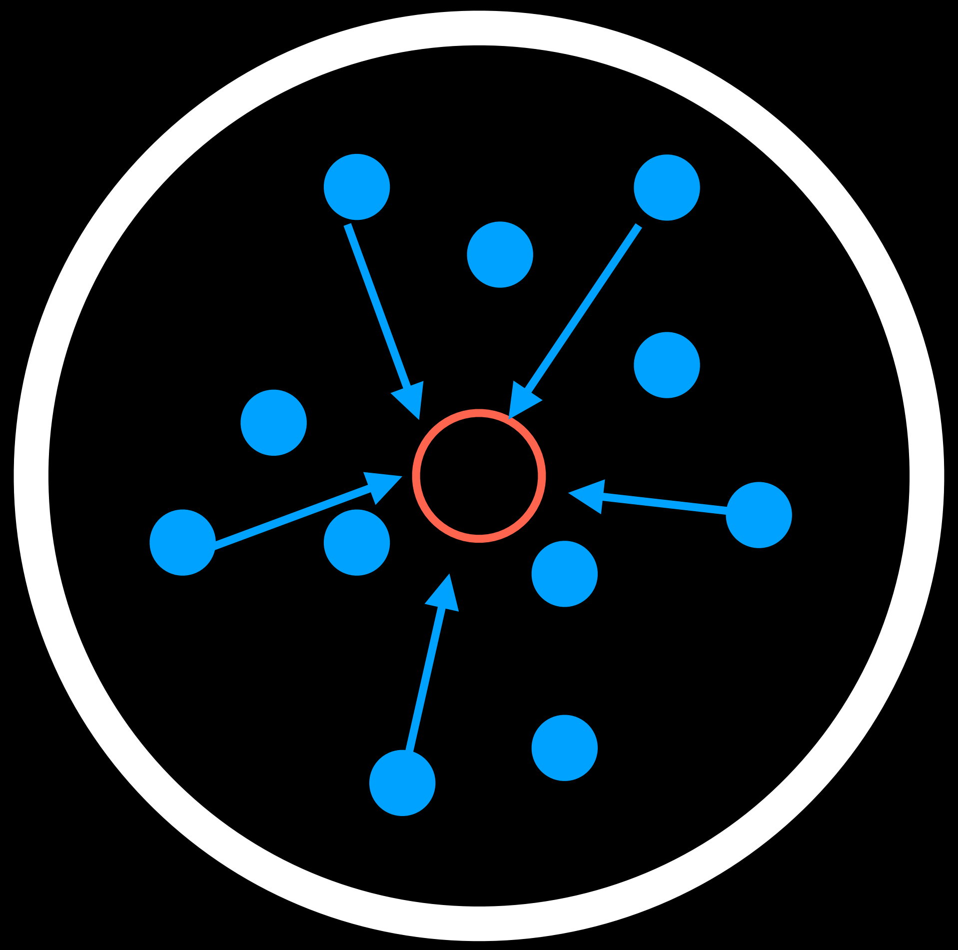
Fermionic DM → Chandrasekhar limit

$$\frac{G m_\chi^2 N_\chi(t)}{\sqrt{2\pi} r_\chi} > E_{F,\chi} \implies N_{\rm Ch} = (2)^{3/4}\pi\sqrt{3}\left(\frac{M_{\rm Pl}}{m_\chi}\right)^3$$

~10 times higher than previous results

Destruction of NS

BH Accretion



BH feeds on NS matter

Bondi, 1952; Bondi, Hoyle, 1944

Standard treatment:

$$\frac{dM}{dt} = \frac{4\pi\lambda_s\rho_\infty G^2M^2}{c^3_{s,\infty}}$$

Bondi accretion

$$\frac{dM}{dt} = \frac{4\pi\bar{\lambda}\rho_\infty G^2M^2}{(c^2_{s,\infty}+v^2_\infty)^{3/2}}$$

Bondi-Hoyle accretion

✗

Relativistic effects:

Fermi velocity of neutrons > c_s + Degeneracy of NS matter

$$\left.\frac{dM_{\rm BH}}{dt}\right|_A = \frac{4}{\pi}\sqrt{B(r)}m_i^{\rm eff}(r)r^2 \times \int_0^{p_{F,i}} \frac{p^3}{\sqrt{p^2+(m_i^{\rm eff})^2}}dp$$

Accretion rate at $R_{\rm Sch}$

Quantum effects:

$$R_{\rm Sch} < \lambda_{\rm dB} = 2\pi/p_{F,i}$$

$$\left.\frac{dM_{\rm BH}}{dt}\right|_U = \frac{\sqrt{B}m_i^{\rm eff}}{\pi^2}\int_0^{p_F} dp\,\frac{p^3}{E_i}\sigma_U(M_{\rm BH}, m_i^{\rm eff}, p)$$

Unruh Absorption cross section

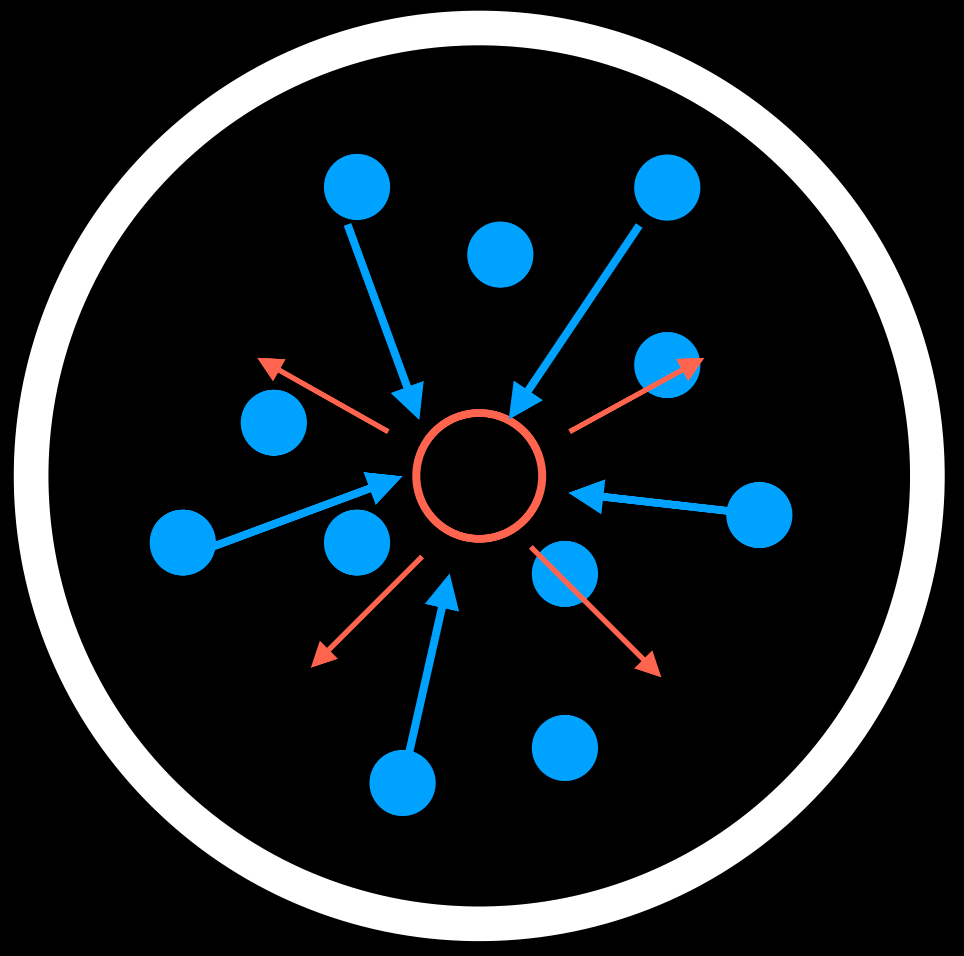
Giffin, Lloyd, McDermott, Profumo, 2105.06504

✓

Destruction of NS

BH Evaporation & Evolution

BH feeds on NS matter
+ Hawking radiation



$$\frac{dM_{BH}}{dt} = \left.\frac{dM_{BH}}{dt}\right|_{Acc} - \left.\frac{dM_{BH}}{dt}\right|_{H}$$

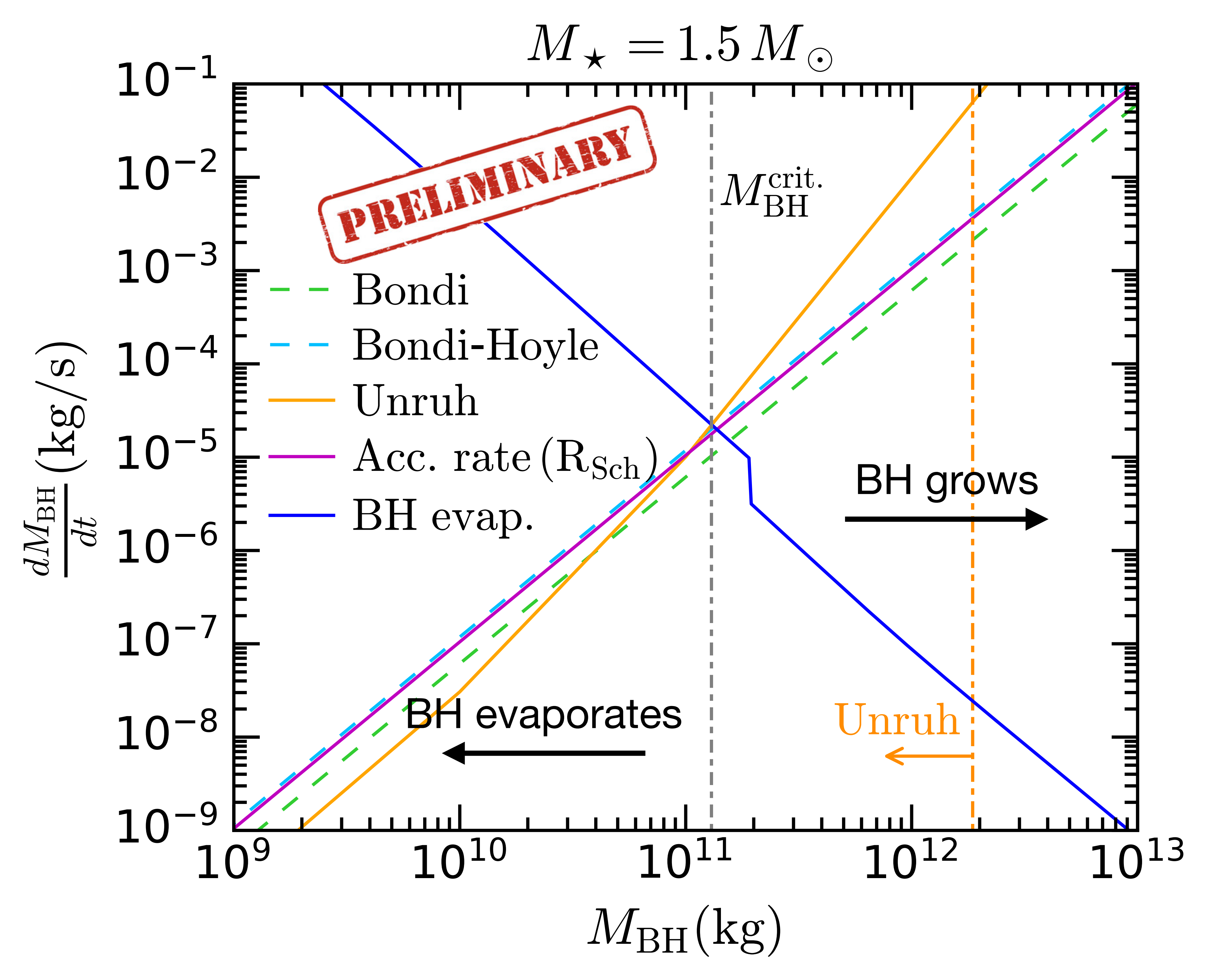
$$\left.\frac{dM_{BH}}{dt}\right|_{H} = 5.34 \times 10^{16} f(M_{BH}) \left(\frac{kg}{M_{BH}}\right)^2 \ kg/s$$

Takes into account the number of d.o.f emitted

$$\tau(M_{BH}^0) = \int_{M_{BH}^0}^{M_\star} dM_{BH} \left(\left.\frac{dM_{BH}}{dt}\right|_{Acc} - \left.\frac{dM_{BH}}{dt}\right|_{H} \right)^{-1}$$

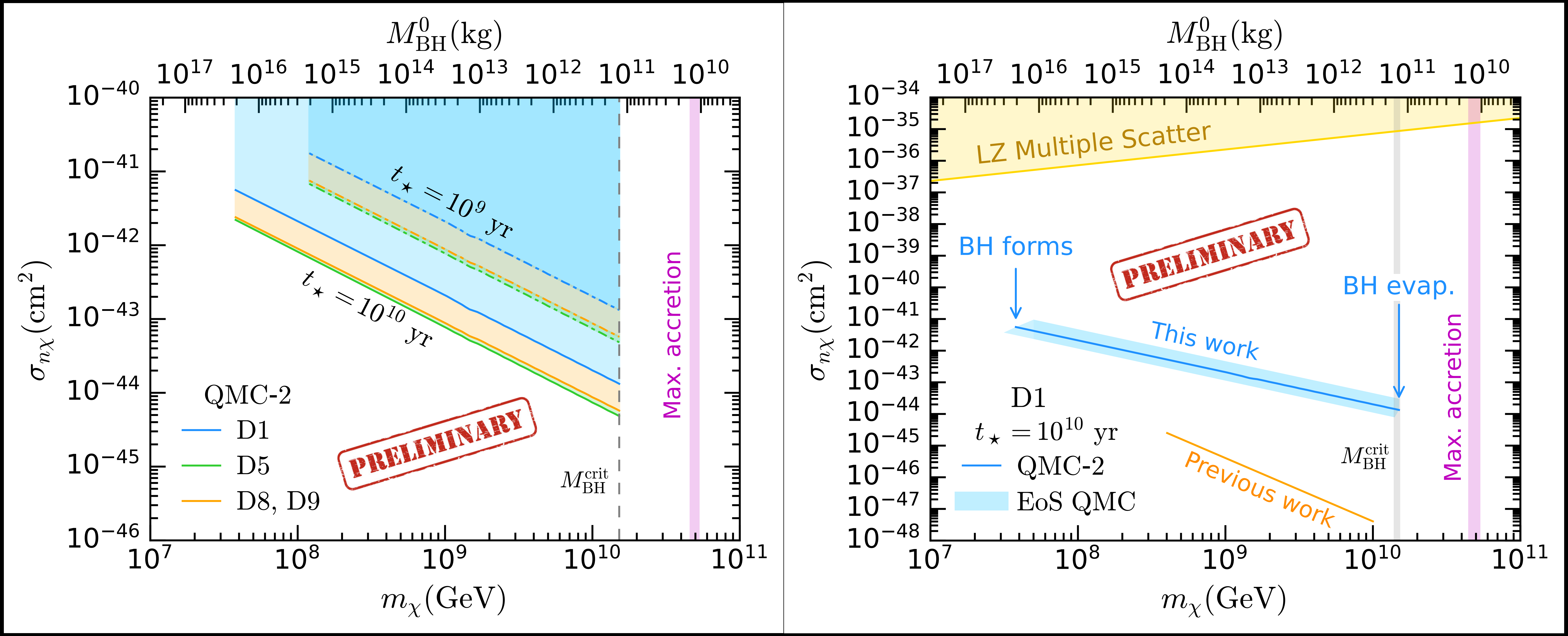
NS Liftetime

Hawking, 1975; Page 1976; MacGibbon, 1991



Putting it all together

Constraints on Fermionic ADM



D1: $\bar{\chi}\chi\ \bar{q}q$ D5: $\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$ D8: $\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$ D9: $\bar{\chi}\sigma_{\mu\nu}\chi\ \bar{q}\sigma^{\mu\nu}\gamma^5 q$

Summary

Neutron star probes → Complementary to DD experiments, better sensitivity

Improved capture rates → Capture rate is suppressed by 2-3 orders of magnitude

(Non) Pauli blocking effects for DM themalisation → Increase in thermalisation time for super heavy DM

NS temperature evolution → Efficient thermalisation at early times

BH accretion → Relativistic and quantum effects are important

Including all effects → Improved (relaxed) bounds on fermionic ADM models

Backup

Dim-6 Operators

Name	Operator	g_q	$g_i^2(t)$	$\lvert M(s,t,m_i)\rvert^2$	Dominant term $t_{\rm term}$
D1	$\overline{\chi}\chi\ \overline{q}q$	$\frac{y_q}{\Lambda_q^2}$	$\frac{c_i^S(t)}{\Lambda_q^4}$	$g_i^2(t)\frac{(4m_\chi^2-t)(4m_\chi^2-\mu^2 t)}{\mu^2}$	t^0
D2	$\overline{\chi}\gamma^5\chi\ qq$	$i\frac{y_q}{\Lambda_q^2}$	$\frac{c_i^S(t)}{\Lambda_q^4}$	$g_\chi^2(t)\frac{t(\mu^2 t-4m_\chi^2)}{\mu^2}$	t^1
D3	$\overline{\chi}\chi\ \overline{q}\gamma^5 q$	$i\frac{y_q}{\Lambda_q^2}$	$\frac{c_i^P(t)}{\Lambda_q^4}$	$g_\chi^2(t)t(t-4m_\chi^2)$	t^1
D4	$\overline{\chi}\gamma^5\chi\ \overline{q}\gamma^5 q$	$\frac{y_q}{\Lambda_q^2}$	$\frac{c_i^P(t)}{\Lambda_q^4}$	$g_\chi^2(t)t^2$	t^2
D5	$\overline{\chi}\gamma_\mu\chi\ \overline{q}\gamma^\mu q$	$\frac{1}{\Lambda_q^2}$	$\frac{c_i^V(t)}{\Lambda_q^4}$	$2g_i^2(t)\frac{2(\mu^2+1)^2 m_\chi^4-4(\mu^2+1)\mu^2 s m_\chi^2+\mu^4(2s^2+2st+t^2)}{\mu^4}$	t^0
D6	$\overline{\chi}\gamma_\mu\gamma^5\chi\ \overline{q}\gamma^\mu q$	$\frac{1}{\Lambda_q^2}$	$\frac{c_i^V(t)}{\Lambda_q^4}$	$2g_i^2(t)\frac{2(\mu^2-1)^2 m_\chi^4-4\mu^2 m_\chi^2(\mu^2 s+s+t)+\mu^4(2s^2+2st+t^2)}{\mu^4}$	t^0
D7	$\overline{\chi}\gamma_\mu\chi\ \overline{q}\gamma^\mu\gamma^5 q$	$\frac{1}{\Lambda_q^2}$	$\frac{c_i^A(t)}{\Lambda_q^4}$	$2g_i^2(t)\frac{2(\mu^2-1)^2 m_\chi^4-4\mu^2 m_\chi^2(\mu^2 s+s+t)+\mu^4(2s^2+2st+t^2)}{\mu^4}$	t^0
D8	$\overline{\chi}\gamma_\mu\gamma^5\chi\ \overline{q}\gamma^\mu\gamma^5 q$	$\frac{1}{\Lambda_q^2}$	$\frac{c_i^A(t)}{\Lambda_q^4}$	$2g_i^2(t)\frac{2(\mu^4+10\mu^2+1)m_\chi^4-4(\mu^2+1)\mu^2 m_\chi^2(s+t)+\mu^4(2s^2+st+t^2)}{\mu^4}$	t^0
D9	$\overline{\chi}\sigma_{\mu\nu}\chi\ \overline{q}\sigma^{\mu\nu}\gamma^5 q$	$\frac{1}{\Lambda_q^2}$	$\frac{c_i^T(t)}{\Lambda_q^4}$	$8g_i^2(t)\frac{4(\mu^4+4\mu^2+1)m_\chi^4-2(\mu^2+1)\mu^2 m_\chi^2(4s+t)+\mu^4(2s+t)^2}{\mu^4}$	t^0
D10	$\overline{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \overline{q}\sigma^{\mu\nu} q$	$\frac{1}{\Lambda_q^2}$	$\frac{c_i^T(t)}{\Lambda_q^4}$	$8g_i^2(t)\frac{4(\mu^2-1)^2 m_\chi^4-2(\mu^2+1)\mu^2 m_\chi^2(4s+t)+\mu^4(2s+t)^2}{\mu^4}$	t^0

Thermalisation