Probing the nature of Dark Matter..

..with compact objects

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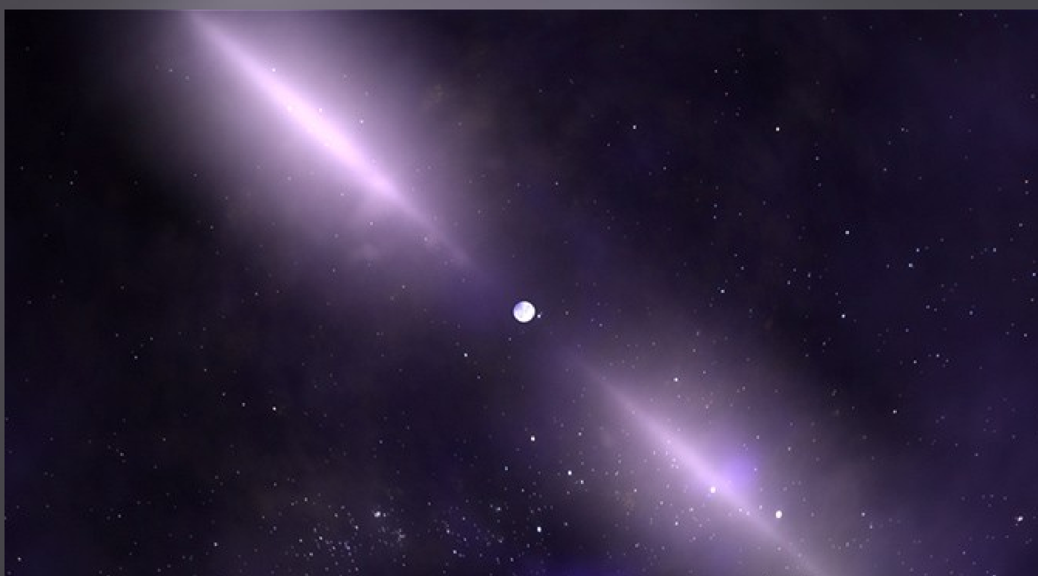
Outline

- Context and motivations
- DM accretion in a NS
- Dynamic of PBH captured by NS
- Common signatures and prospects of detection

New strategies to probe other candidates

Use extreme properties of compact stars and look for new interactions!



Example of neutron star

-> Density

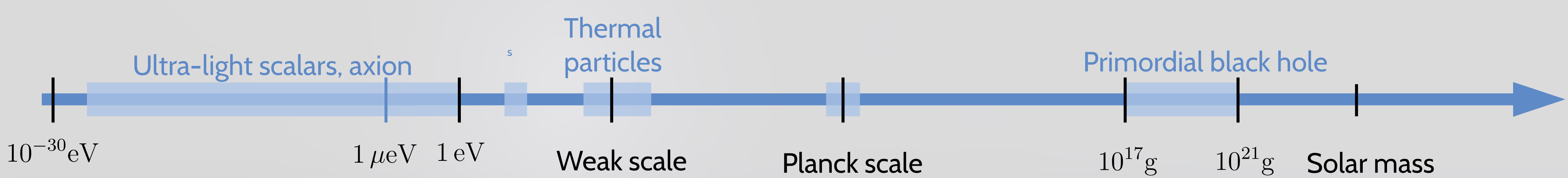
$$\rho_{\rm NS} \sim 1\,{\rm GeV/fm^3}$$

-> Magnetic field

$$B_{\rm NS} \in [10^4 - 10^{11}]\ {\rm T}$$

-> Gravitational field

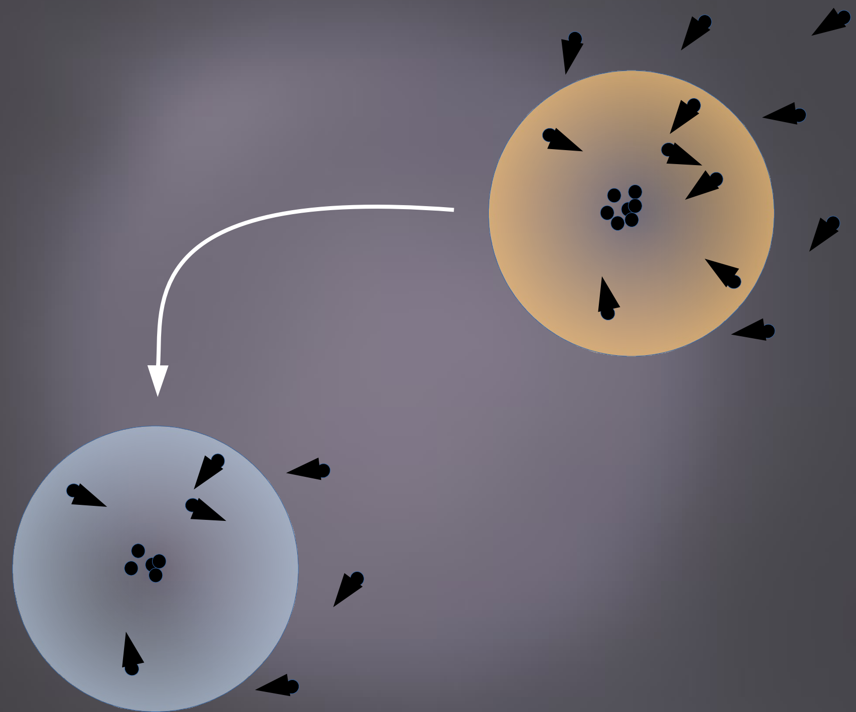
$$g_{\rm NS} \sim 10^{10}\, g_{\rm sun} \sim 10^{11}\, g_{\rm earth}$$



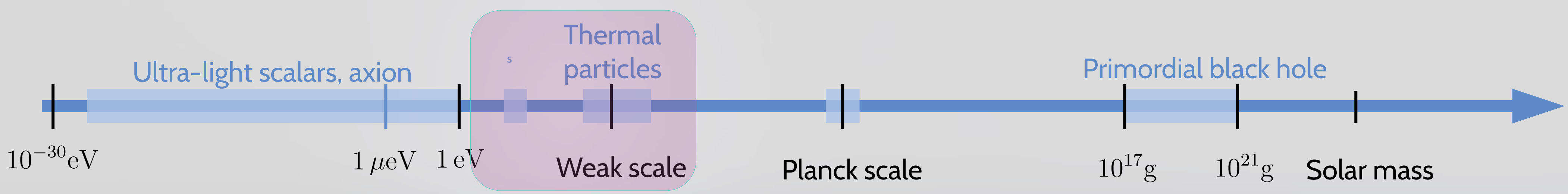
Credit: ESO/L.Calçada

New strategies to probe new candidates

Particles **Black holes**



→ **Impact NS cooling/temperature**



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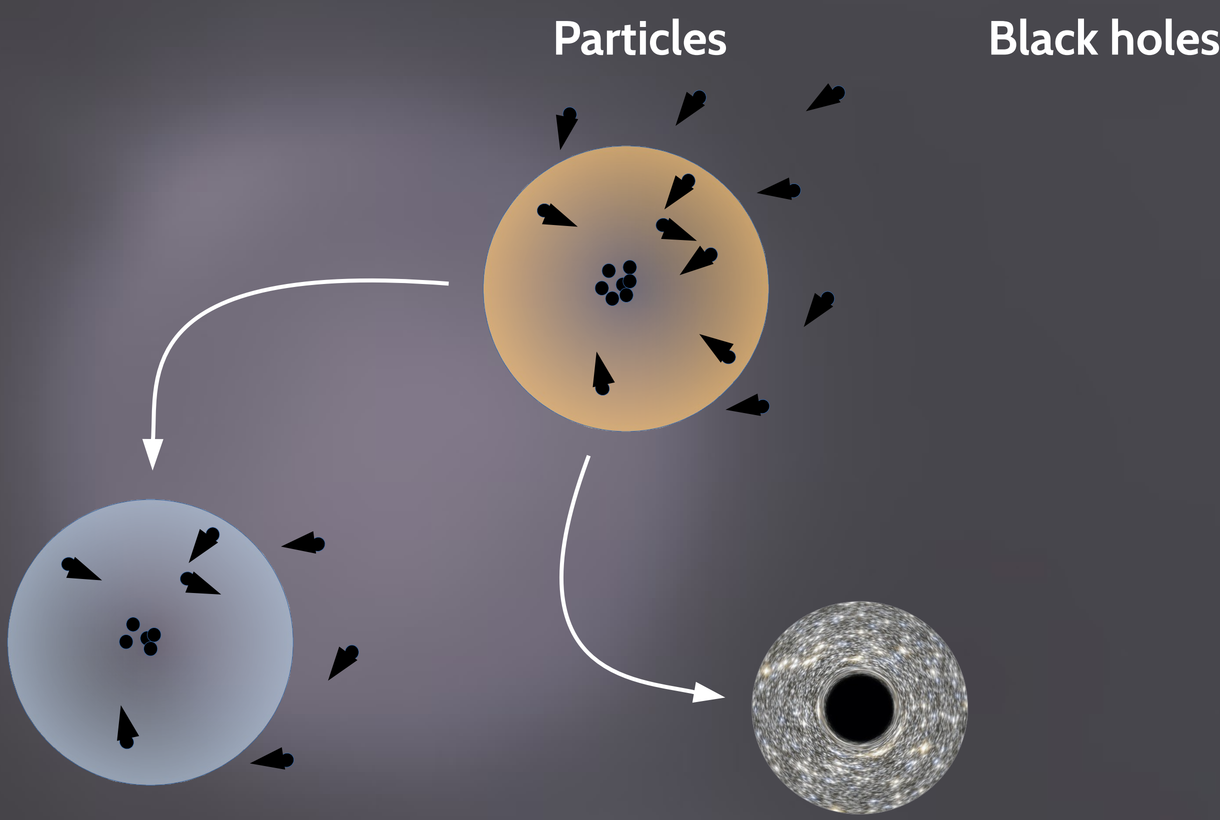

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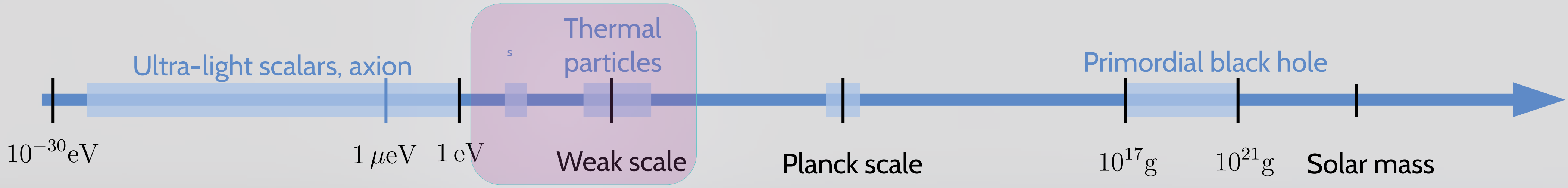

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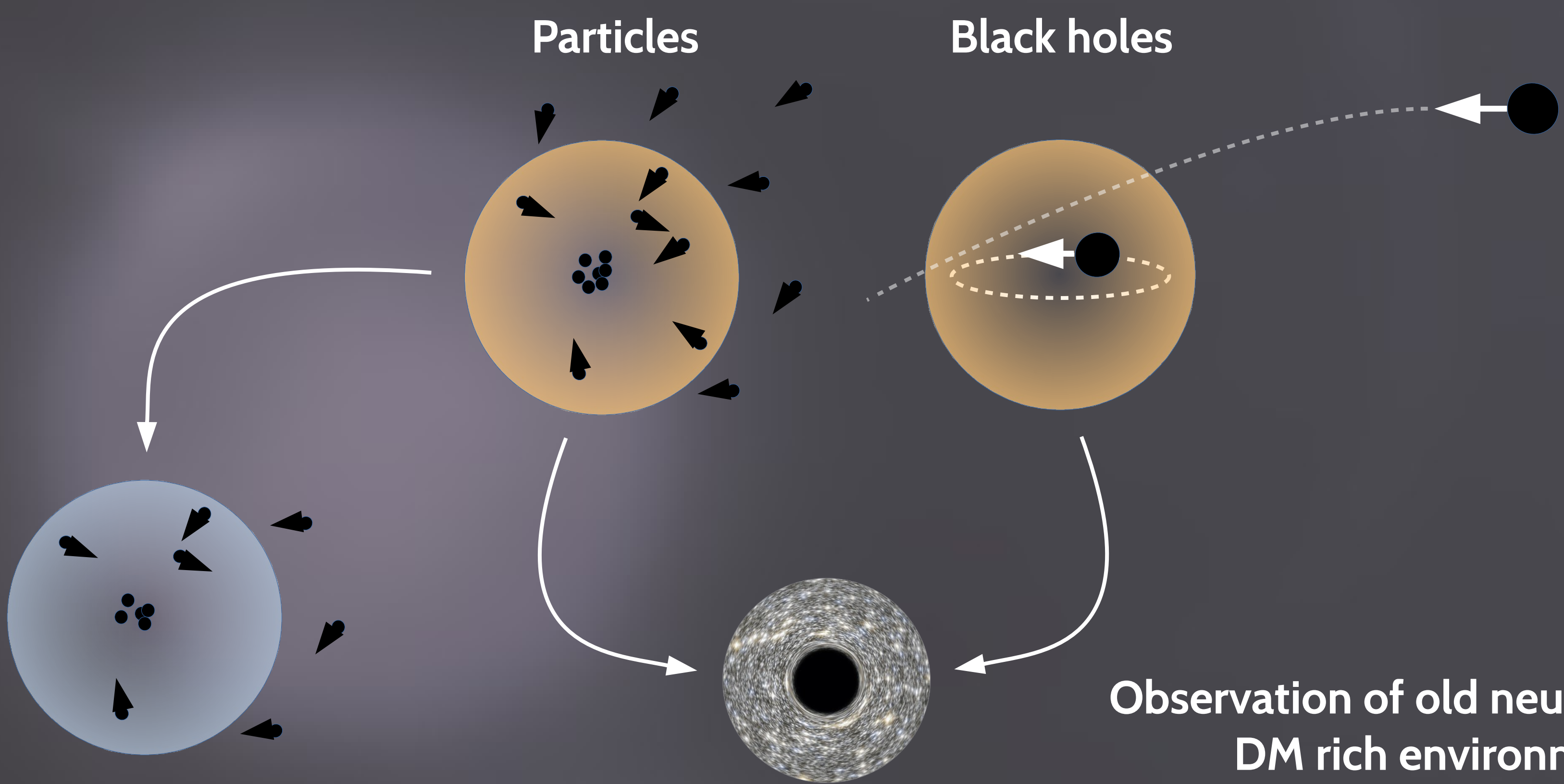
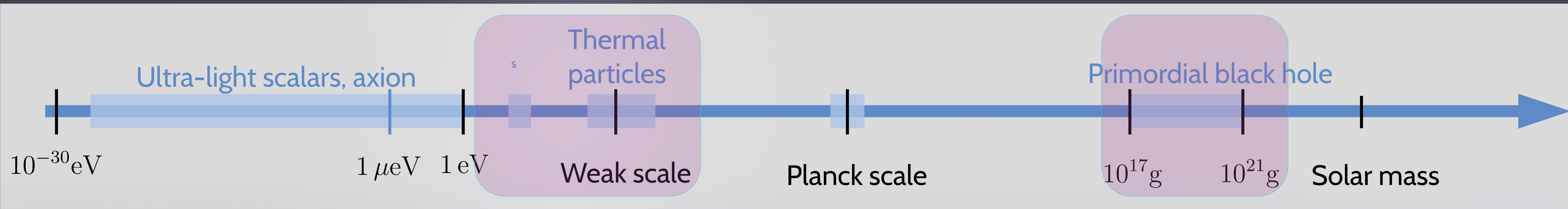
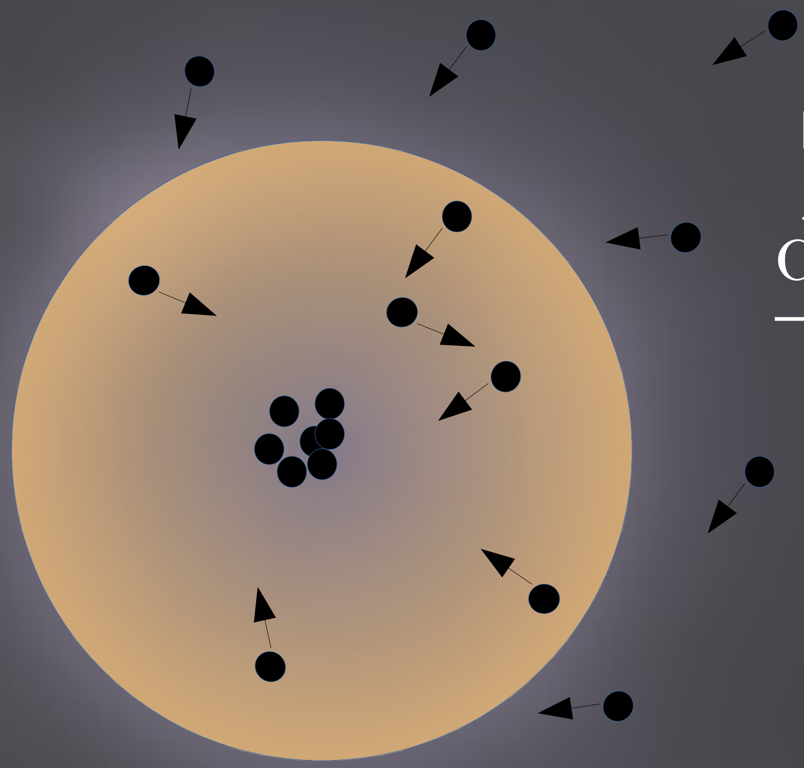


→ Impact NS cooling/temperature

Observation of old neutron stars in DM rich environment
→ constraint on DM density



DM accretion in NS



Symmetric Dark Matter

Boltzmann equation

$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C_\odot - A_\odot \mathrm{N}_\chi^2 - E_\odot \mathrm{N}_\chi$$

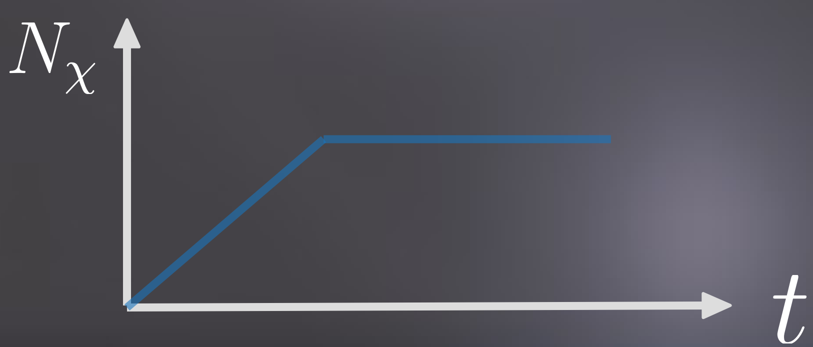
Indirect DM signature!

Solar neutrino flux $$\frac{d\Phi}{dE_\nu} = \frac{\Gamma_A}{4\pi d_\odot^2} \frac{dN_\nu}{dE_\nu}$$

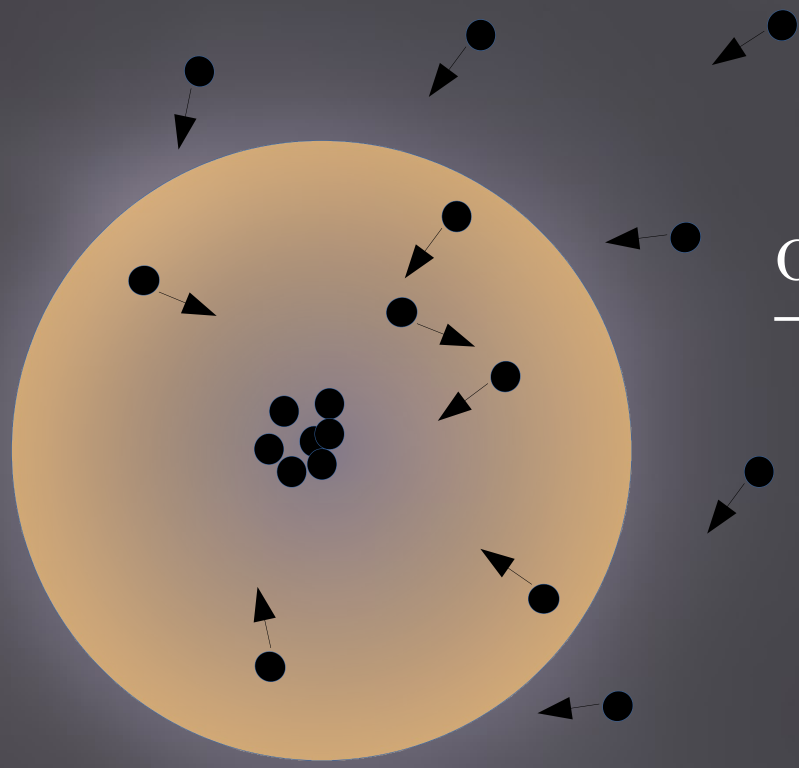
Press&Spergel (1985), Gould (1987), Silk+ (1985) ...

Reheating NS surface $$\frac{dT}{dt} = \frac{-\epsilon_\gamma - \epsilon_\nu + \epsilon_{DM}}{C_V}$$

Lavallaz&Fairbairn (2010), Kouvaris&Tinyakov (2010) ...



Extensively studied!



Asymmetric Dark Matter

Boltzmann equation

$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C_\odot - A_\odot \mathrm{N}_\chi^2 - E_\odot \mathrm{N}_\chi$$

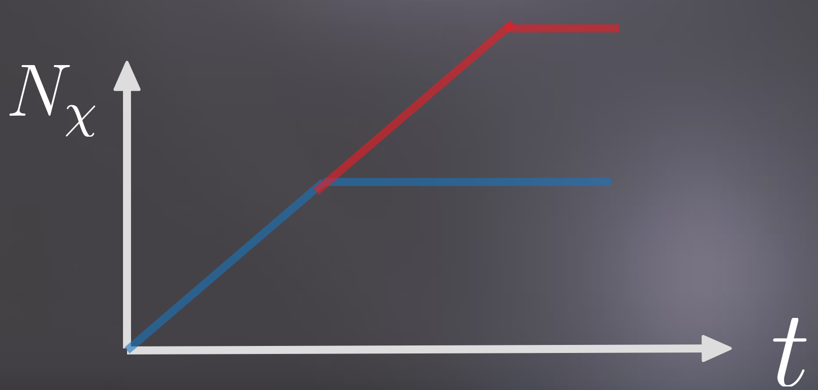
Accumulate more DM particles!

Modify temperature gradient -> seismology

Ilopes+ (2014), Vincent&Scott (2014), Geytenbeek+ (2018)

Black hole formation and collaspe of the star:

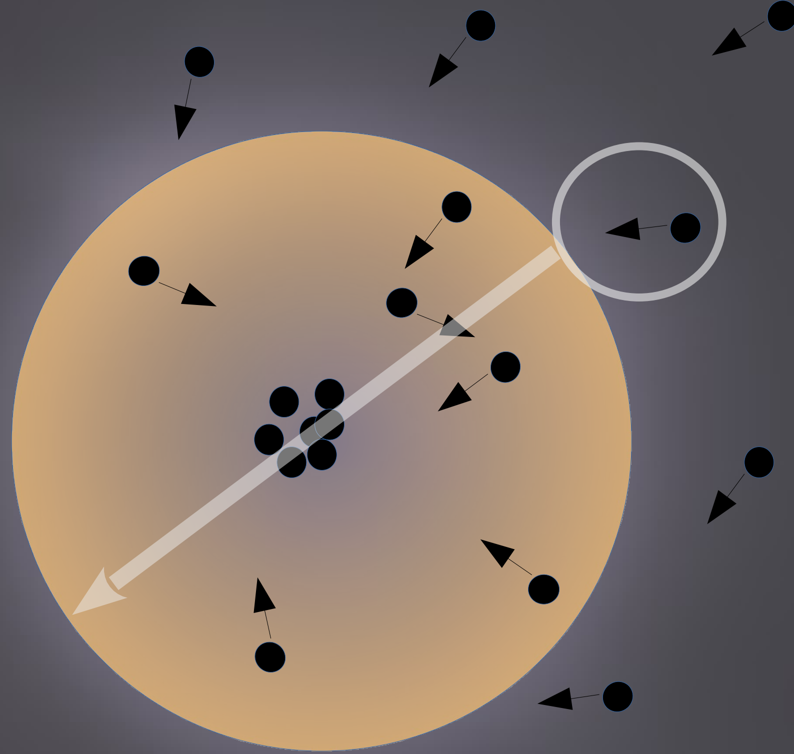
Goldman+ (1989), Kouvaris (2008), Bertone+ (2008), McCullough+ (2010), Kouvaris&Tinyakov (2011), McDermott+ (2012) ...



Extensively studied too! ...

But accretion rate never properly computed

1



DM capture by NS

Best case scenario for capture $\sigma_\chi \geqslant \sigma_{\text{geom}}$

$$\sigma^{sun}_{\text{geom}} \approx 1.3 \times 10^{-35}\ \text{cm}^2 \left(\frac{R_\star}{R_\odot}\right)^2 \left(\frac{M_\odot}{M_\star}\right).$$

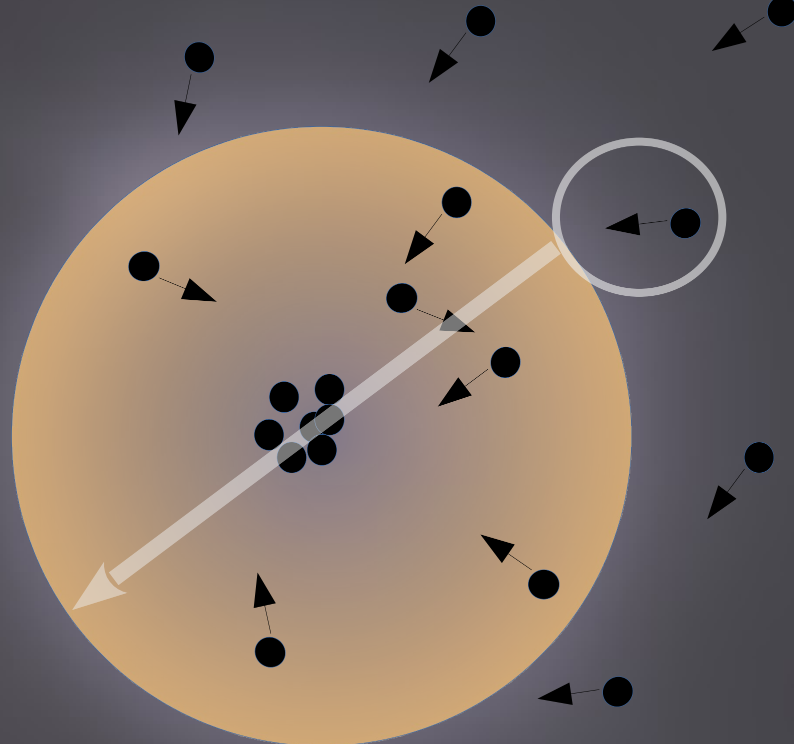
$$\sigma^{wd}_{\text{geom}} \approx 1.3 \times 10^{-39}\ \text{cm}^2.$$

$$\sigma^{NS}_{\text{geom}} \approx 2 \times 10^{-45}\ \text{cm}^2.$$

Geometrical cross-section

$$\sigma_{\text{geom}}\ n_b R_\star \approx 1$$

1



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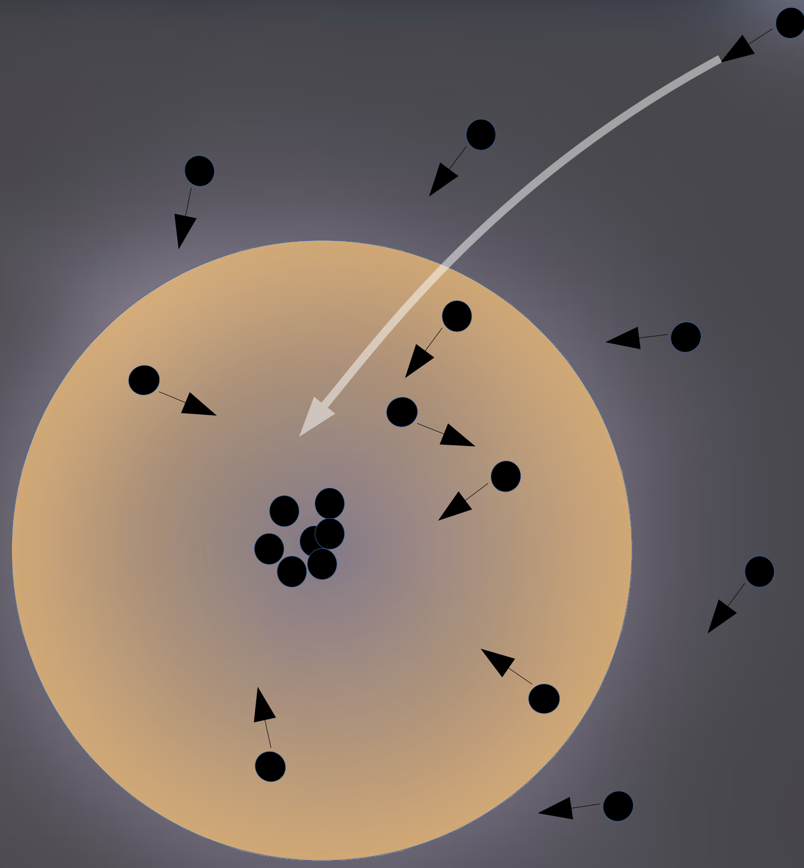
Capture rate $\propto$ interaction probability

$$C_\odot \propto \frac{\sigma_\chi}{\sigma_{\rm geom}}.$$

1



DM capture by NS

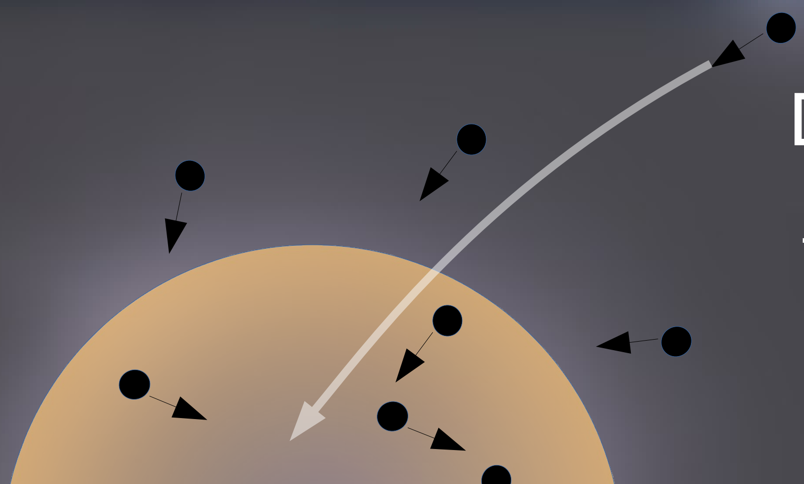
The capture rate is proportional to

$$C_\star \sim \pi b^2 \times v_\infty \, \rho_{DM} \times \frac{\sigma_\chi}{\sigma_{\rm geom}}.$$

Gravitational cross-section

$$\pi b^2 = \pi \left(1 + \frac{2GM}{R_\star v_\infty^2}\right) R_\star^2$$

1



DM capture by NS

The capture rate is proportional to:

$$C_\star \sim \pi b^2 \times v_\infty \, \rho_{DM} \times \frac{\sigma_\chi}{\sigma_{\rm geom}}.$$

For $\sigma_\chi \leq \sigma_{\rm geom}$:

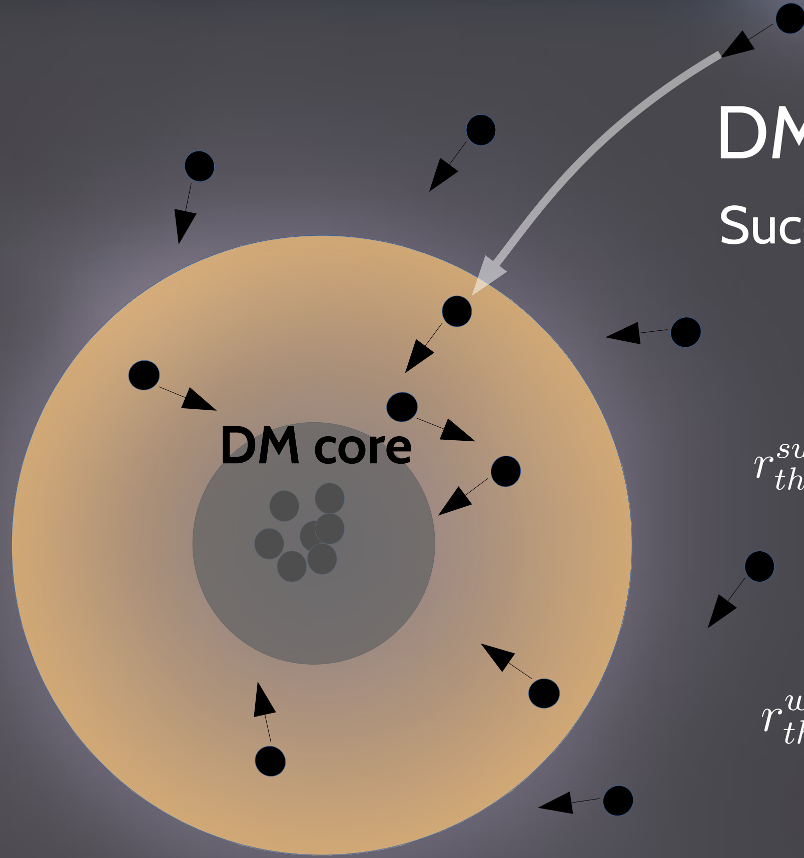
$$C_{sun} \approx 3.6 \times 10^{-21}\ \mathrm{M}_\odot.\mathrm{Gyr}^{-1} \left(\frac{M_\star}{\mathrm{M}_\odot}\right)^2 \left(\frac{\sigma_\chi}{\sigma_{\rm geom}^{NS}} \cdot \frac{\rho_{DM}}{0.3\ \mathrm{GeV.cm}^{-3}} \cdot \frac{R_\odot}{R_\star}\right)$$

$$C_{wd} \approx 3.6 \times 10^{-19}\ \mathrm{M}_\odot.\mathrm{Gyr}^{-1}$$

$$C_{NS} \approx 5.7 \times 10^{-16}\ \mathrm{M}_\odot.\mathrm{Gyr}^{-1}$$

Compact objects accrete DM more efficiently!

2



DM **thermalization** in the NS

Succesive collisions → DM looses energy
→ DM accumulates at the center

$$r_{th}^{sun} = 0.15\ \mathrm{R}_\odot \left(\frac{T_{core}}{10^7\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2} \left(\frac{10^2\,\mathrm{g.cm}^{-3}}{\rho_{core}}\right)^{1/2}$$

$$r_{th}^{wd} = 80\ \mathrm{km} \left(\frac{T_{core}}{10^5\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2} .$$

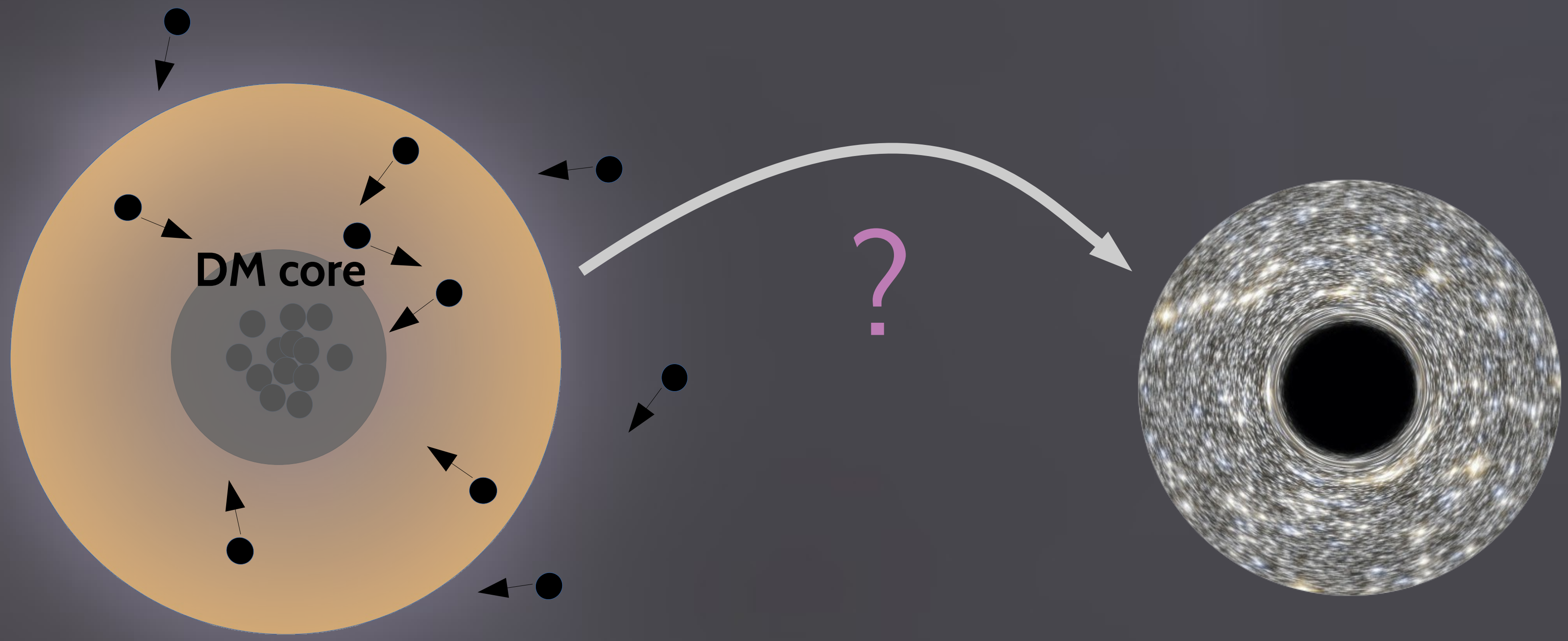
Thermal radius r_{th} of the core

$$\frac{3}{2}\,k_b\,T_{core} = \frac{GM_\star(r_{th})\,m_\chi}{r_{th}}$$

$$r_{th}^{NS} = 4.3\ \mathrm{m} \left(\frac{T_{core}}{10^5\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2}$$

Small DM core!

3 Two conditions to collapse into a Black Hole



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3 Two conditions to collapse into a Black Hole

Self gravitation

$$\rho_{DM} \gtrsim \rho_{core}$$

→ Assuming DM particles thermalize

$$\frac{M_\chi}{\frac{4}{3}\pi r_{th}^3} \gtrsim \rho_{core}$$

→ Critical number for DM to self gravitate

$$N_{self} \simeq 4.8 \times 10^{41} \left(\frac{100\mathrm{GeV}}{m_\chi}\right)^{5/2} \left(\frac{T_{core}}{10^5\,\mathrm{K}}\right)^{3/2} .$$

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Chandrasekhar limit

$$E_{tot} = -\frac{G N_\chi m_\chi^2}{R} + E_k \ .$$

→ When bosons become relativistic

$$E_k = \frac{3}{2} k_b T_{core} \to \frac{1}{R} \ .$$

→ Critical number gravity > kinetic energy

$$N_{Cha}^{boson} \simeq 1.5 \times 10^{34} \left(\frac{100\mathrm{GeV}}{m_\chi}\right)^2 .$$

Credit: ESO/L.Calçada

DM constraints from black hole formation

For a given σ_χ and m_χ

1– Compute the total number of DM particles accreted

2– Assume DM particles have thermalized

3– Compare with black hole formation conditions

Accretion time τ_{acc} to  ?

DM constraints from black hole formation

Constraints on σ_χ and m_χ

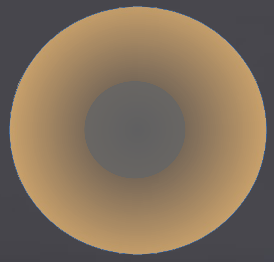
1– Compute the total number of DM particles accreted

2– Assume DM particles have thermalized

3– Compare with black hole formation conditions

Observation of old NS in DM-rich environment

PSR J2124-3358
PSR J2124-3358 → $\tau_{old}^{NS} = 10\,\mathrm{Gyr}$



DM constraints from black hole formation

Constraints on σ_χ and m_χ

New formalism for the capture rate

1– Compute the total number of DM particles accreted

New treatment for thermalization

2– Assume DM particles have thermalized

3– Compare with black hole formation conditions

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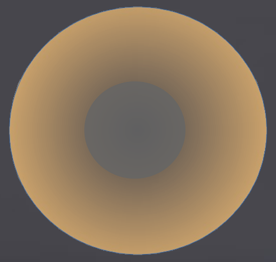


Capture rate formalism

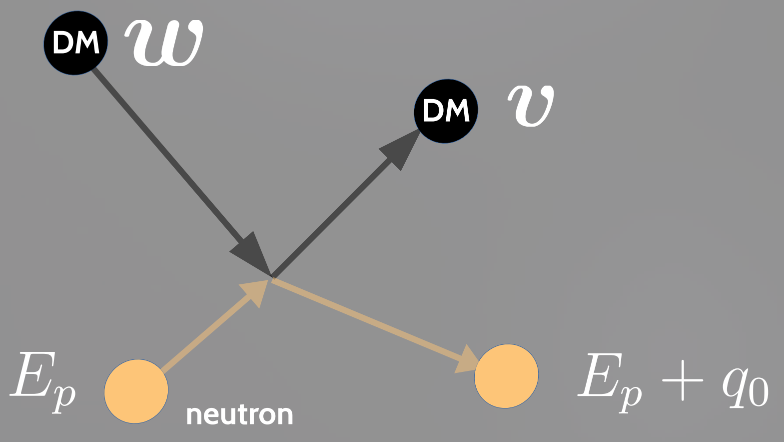
$$C_\star^{\rm w} = \int_0^{R_\star} 4\pi r^2 \mathrm{d}r \int_0^\infty \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_{v_\star}(u_\chi)}{u_\chi} w(r) \int_0^{v_e(r)} R_i^-(w\to v)\,\mathrm{d}v$$

Gould (1987)

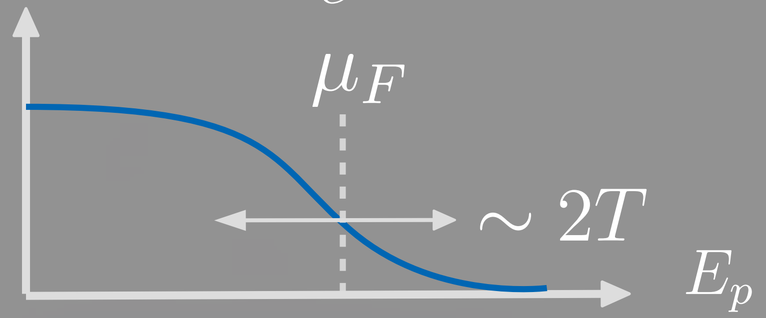
$$R(w\to v) = \int n(r)\frac{\mathrm{d}\sigma}{\mathrm{d}v}|\boldsymbol{w}-\boldsymbol{u}| f_p(E_p,r)(1-f_{p'}(E_p+q_0,r))\mathrm{d}^3\boldsymbol{u}$$

Garami, YG, and Hambye, JCAP (2018)

Scattering on a degenerate Fermi gaz



$$f_p(E_p,r) = \frac{1}{e^{(E_p-\mu_F(r))/T(r)}+1}$$



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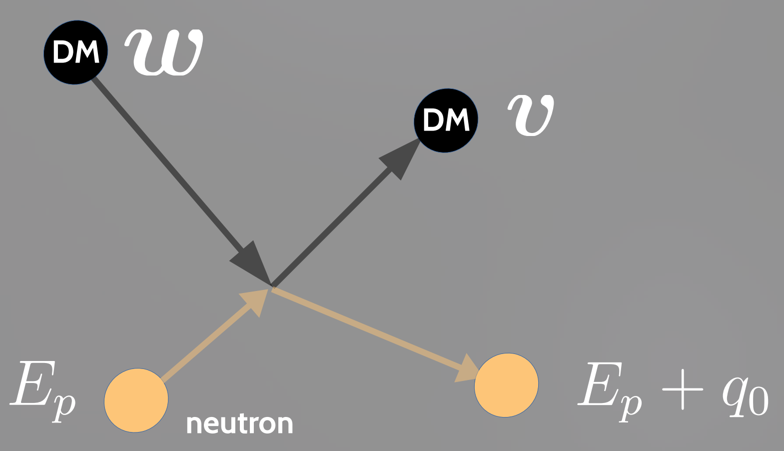

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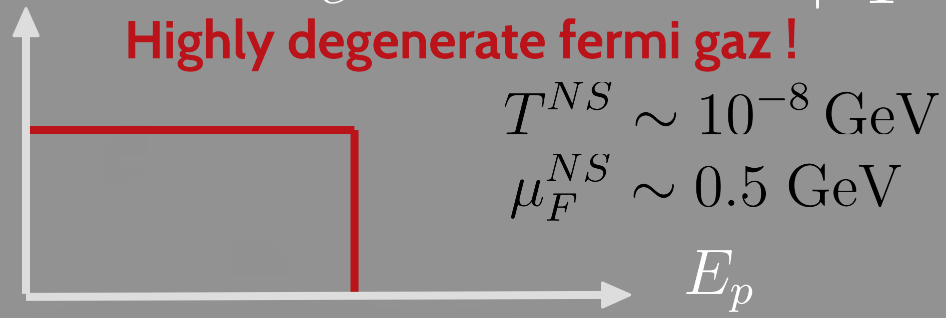

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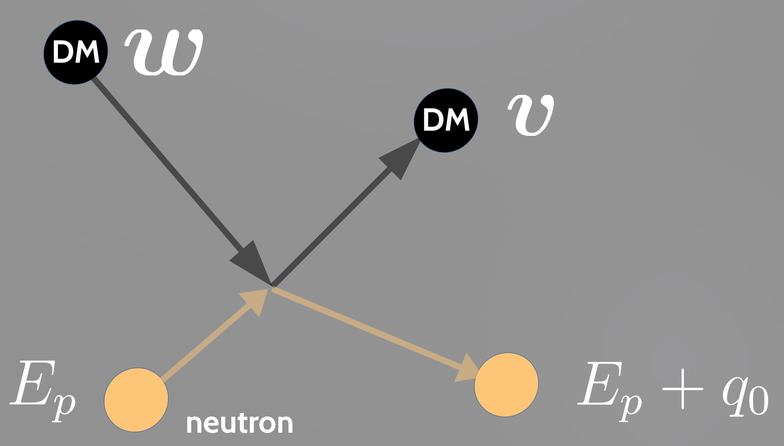

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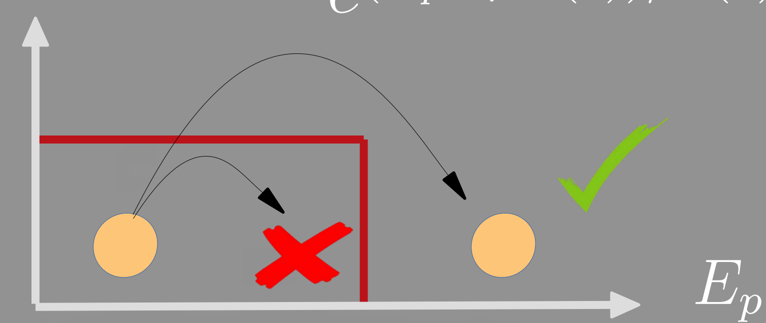
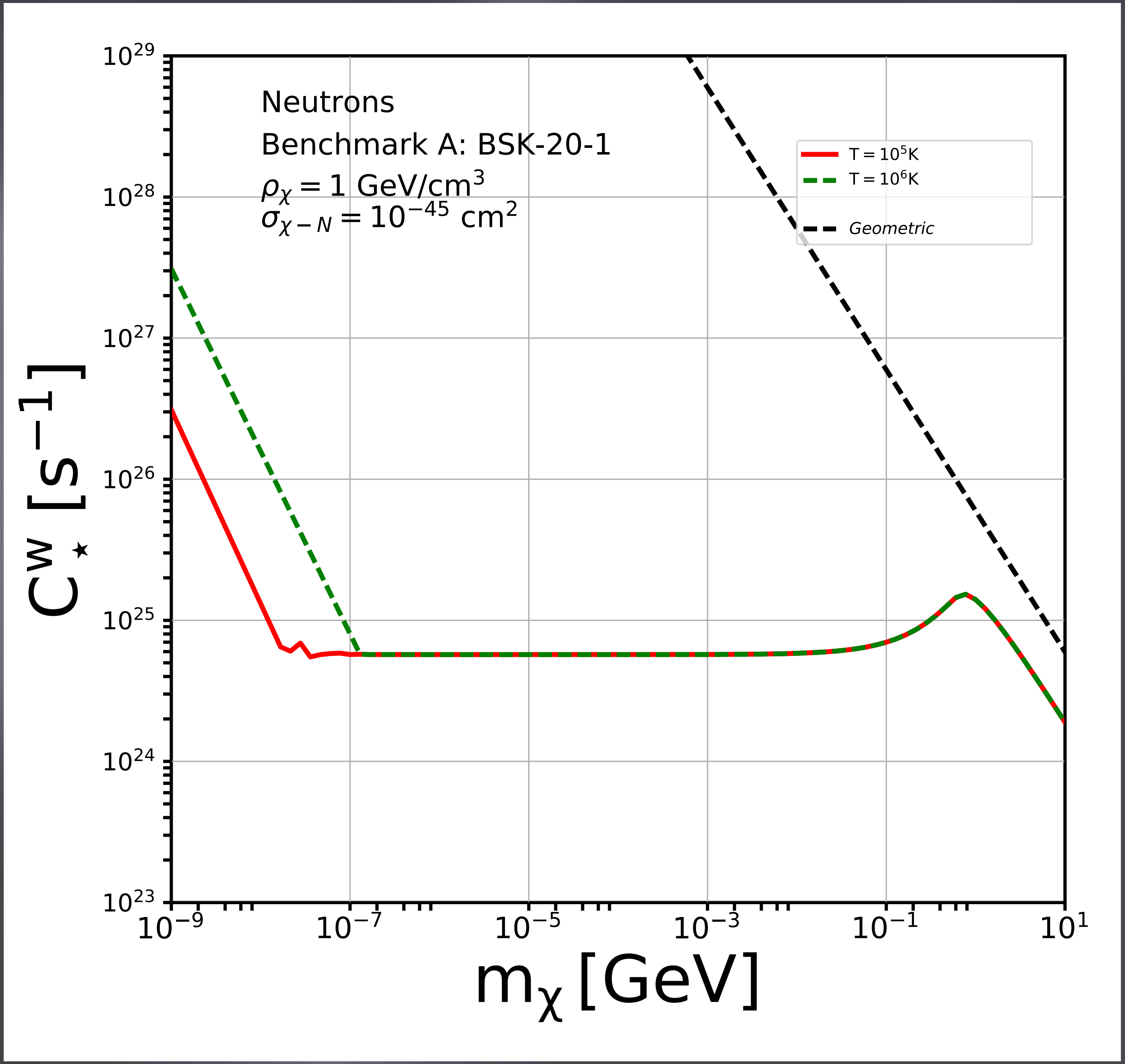
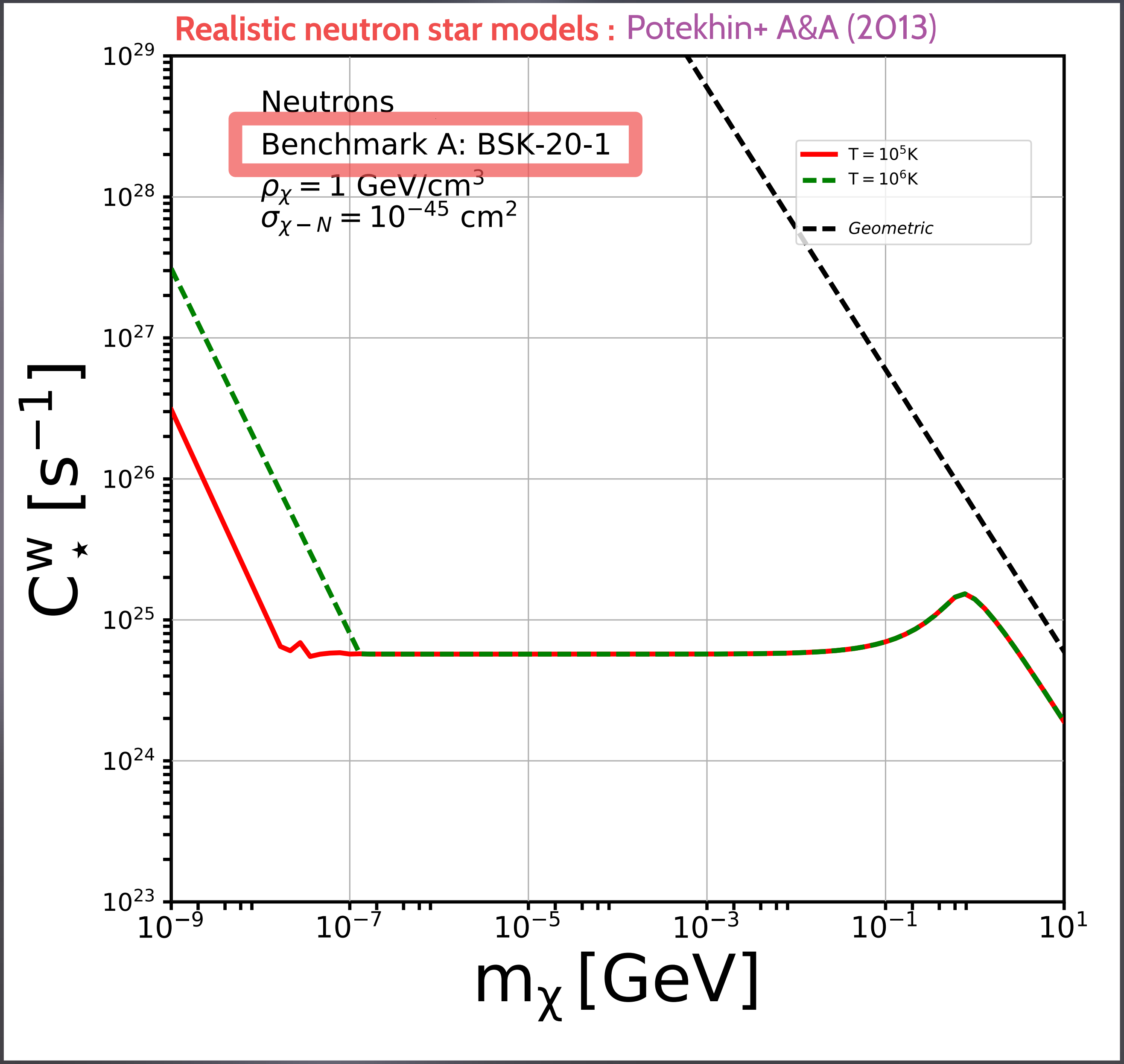
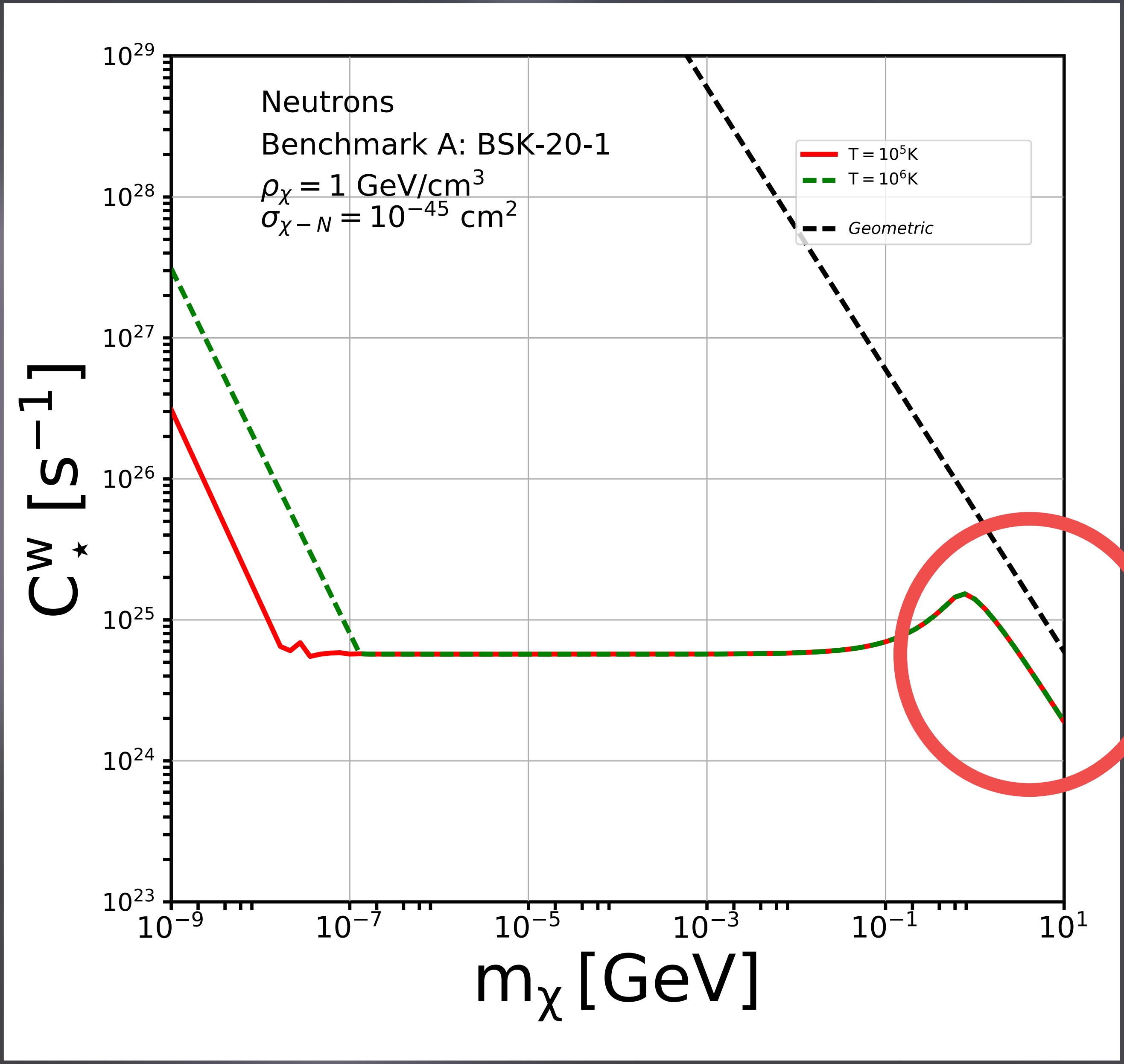



Neutrons
Benchmark A: BSK-20-1
$\rho_\chi = 1$ GeV/cm^3
$\sigma_{\chi-N} = 10^{-45}$ cm^2
T = 10^5K
T = 10^6K
Geometric
$C^{w}_{\star}$ [s^{-1}]
m_χ [GeV]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}

DM accretion in NS - New formalism for capture

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Regime I

Capture rate formalism

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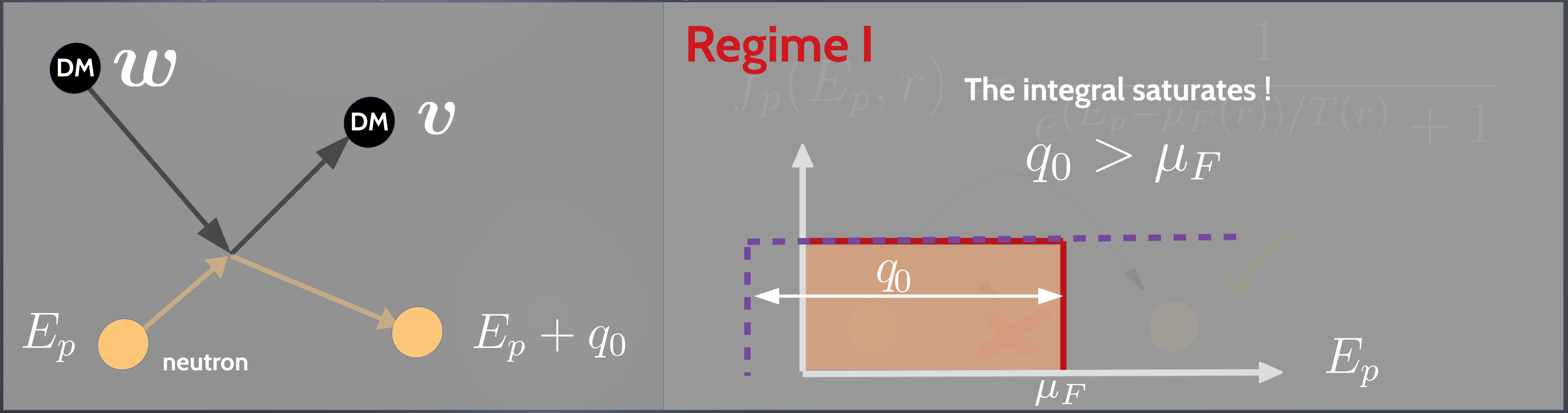

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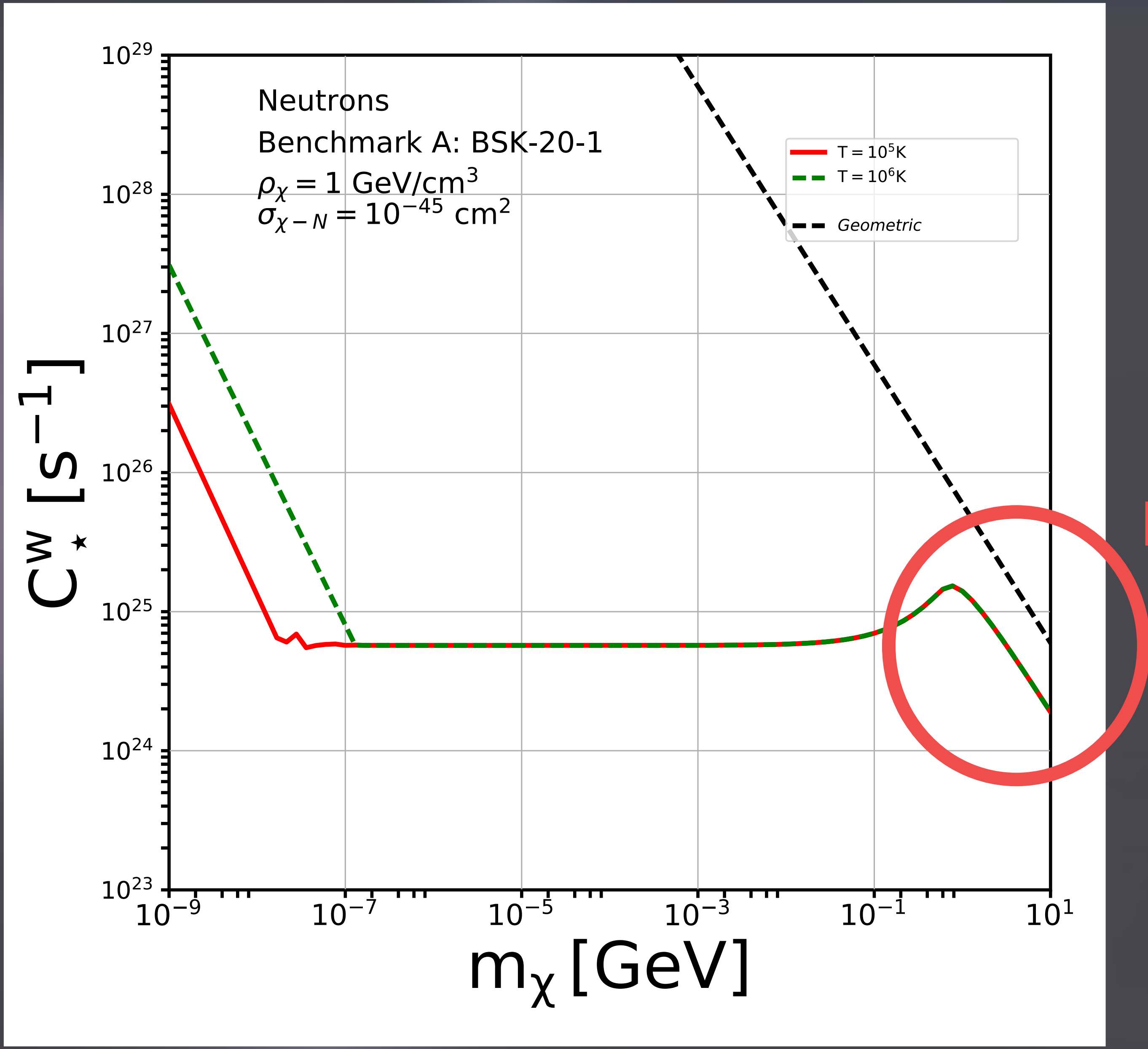

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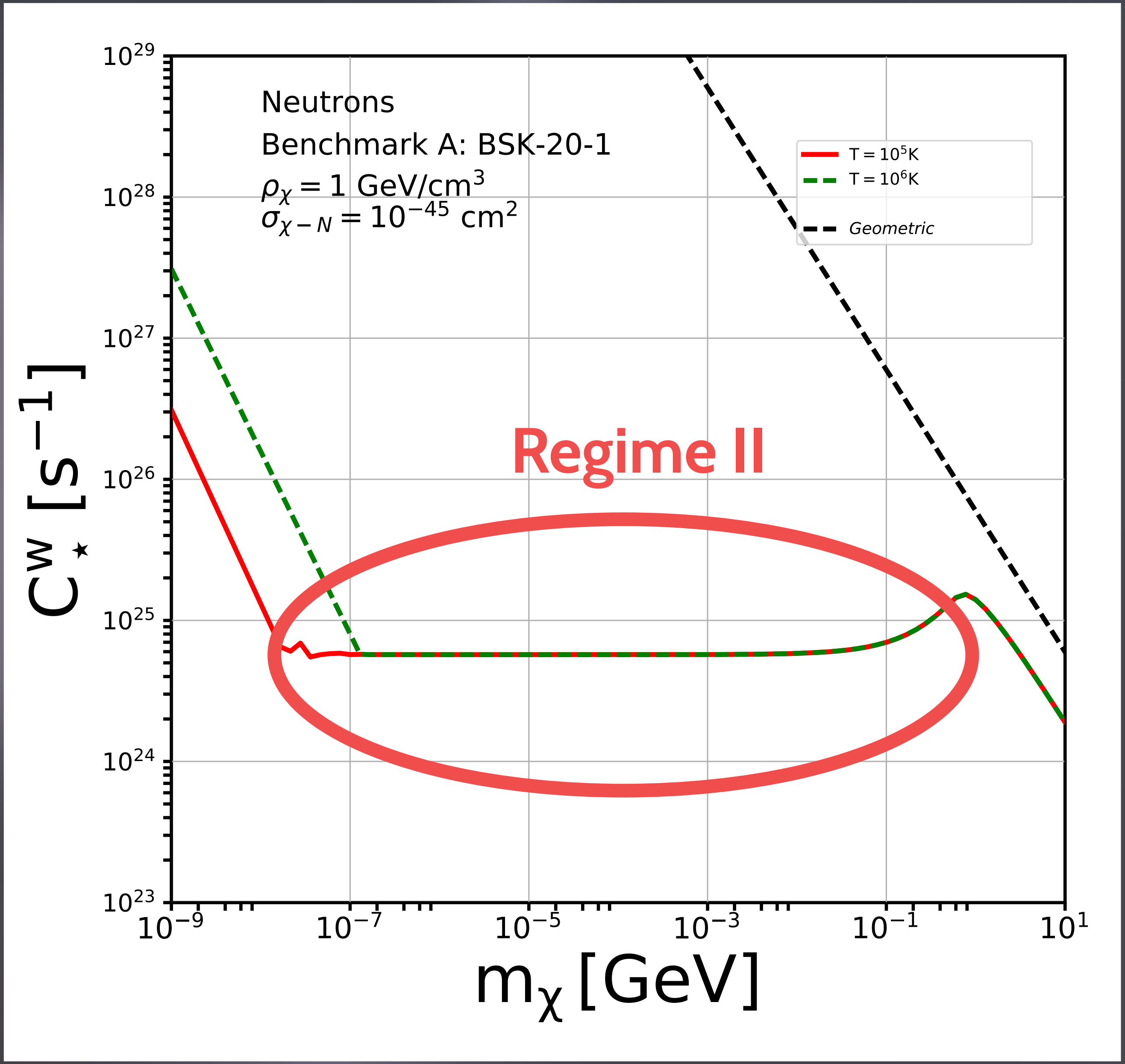
Regime I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Geometric
Regime II
$C_\star^w$ [s^{-1}]
m_χ [GeV]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{-9}
10^{-7}
10^{-5}
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10^{1}

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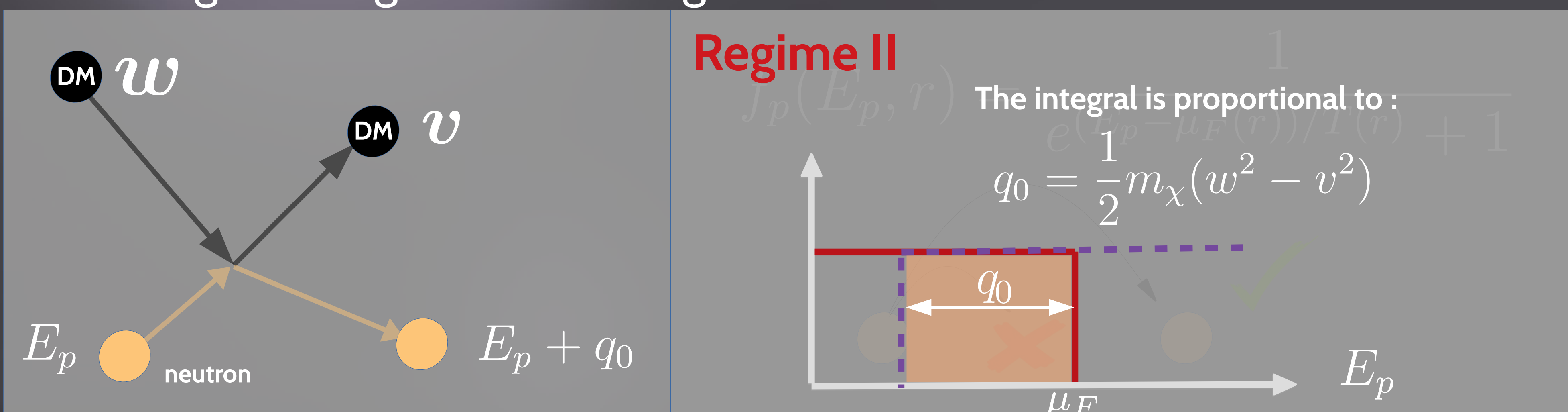

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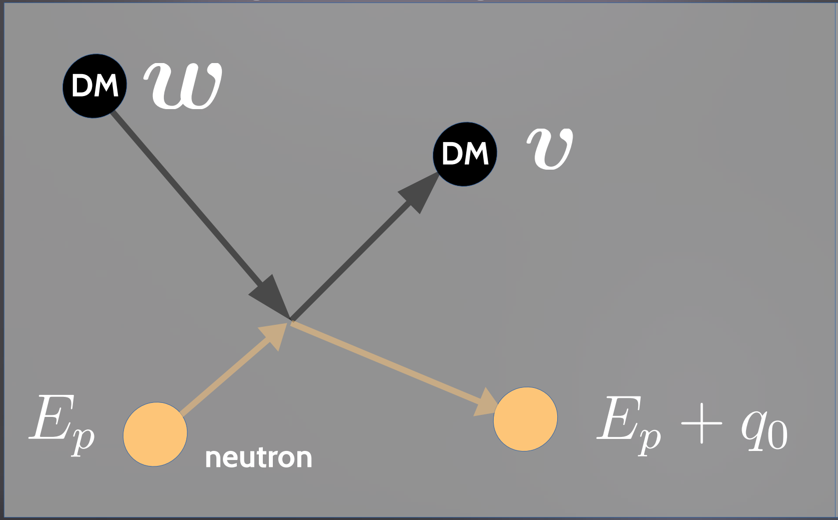
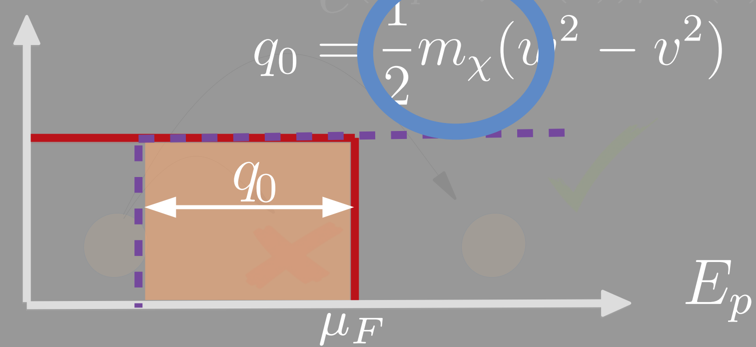


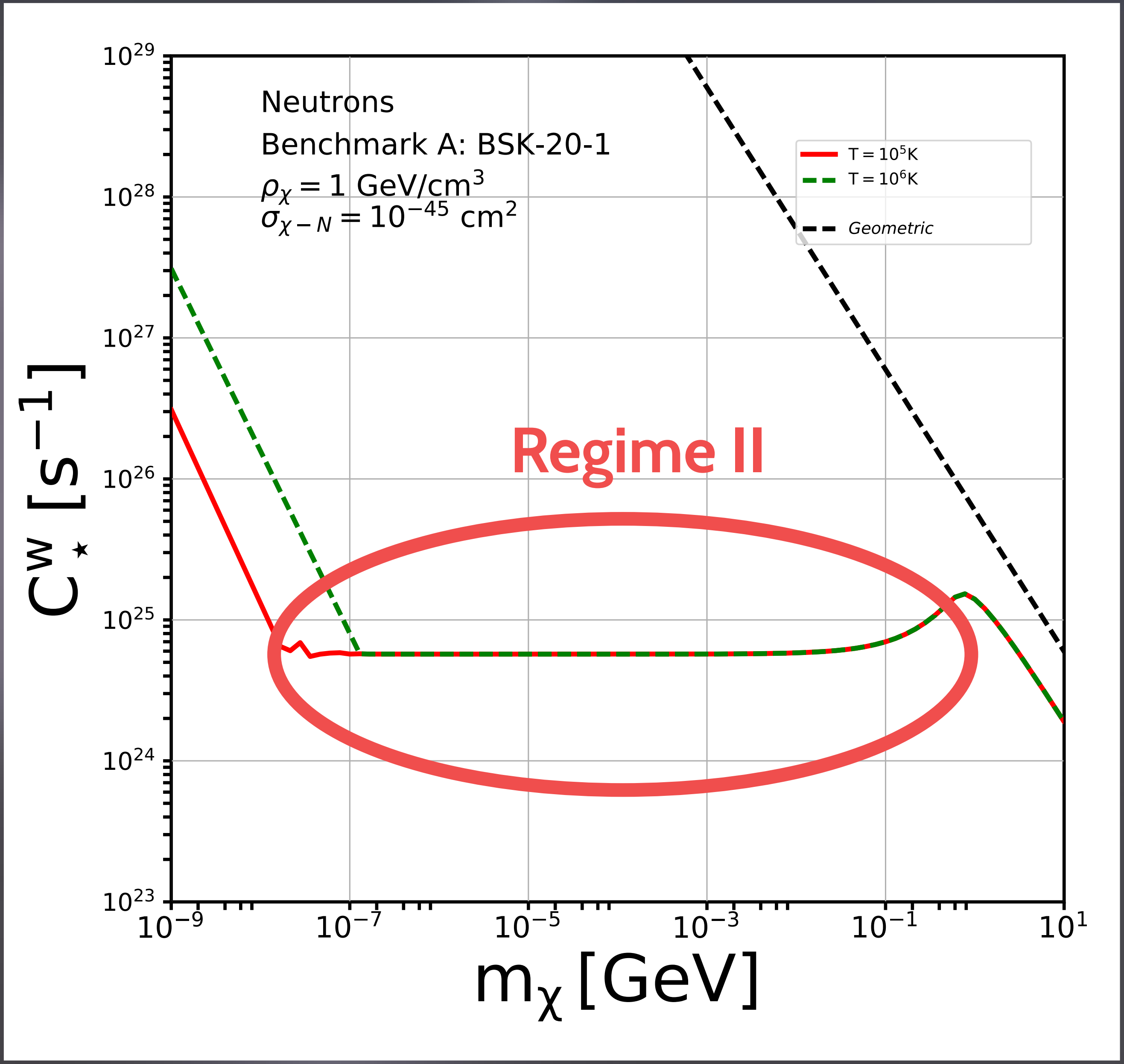
Regime II

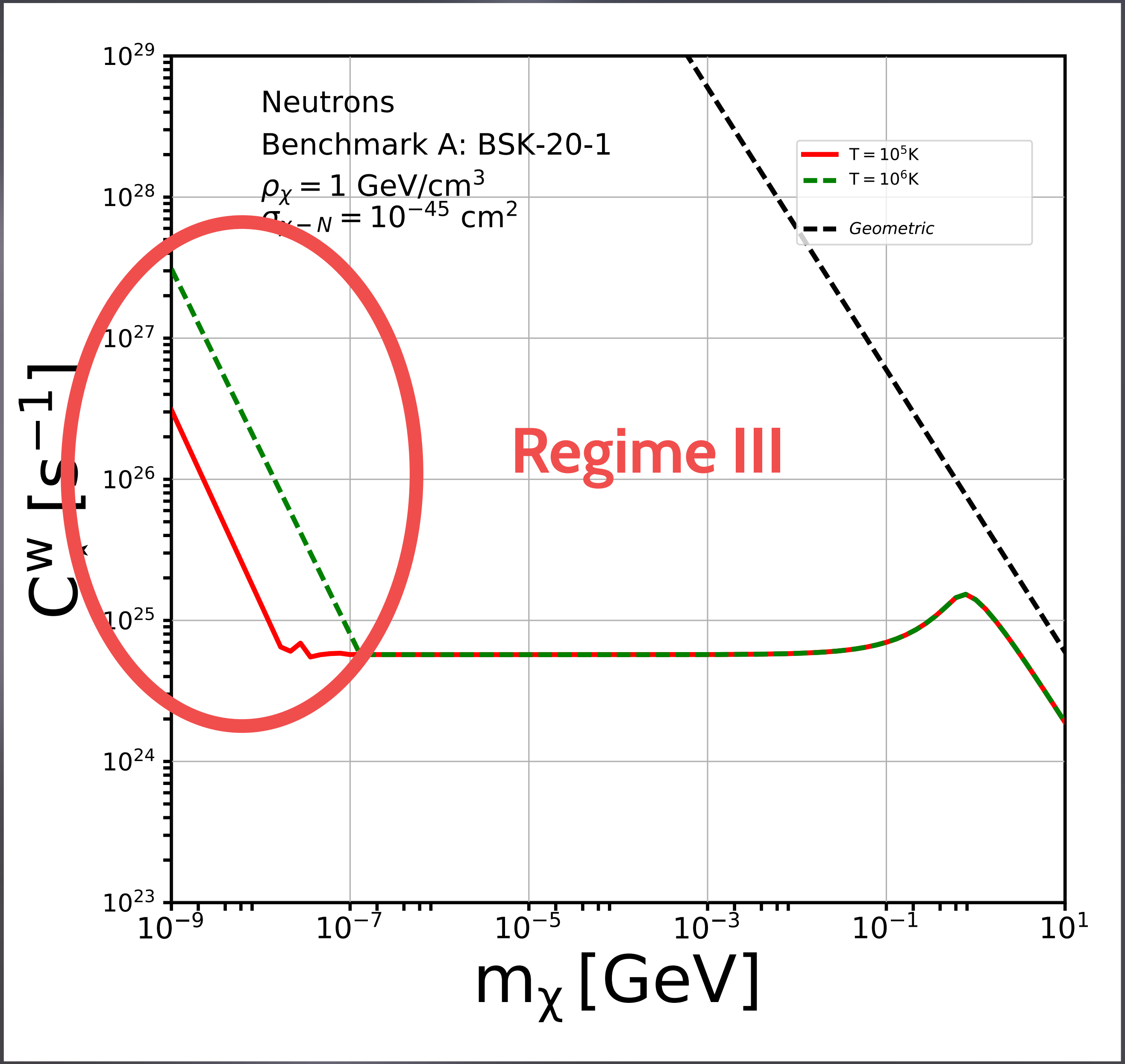
The integral is proportional to :

$$q_0 = \frac{1}{2} m_\chi (w^2 - v^2)$$



Credit: ESO/L.Calçada
Yoann Genolini


Neutrons
Benchmark A: BSK-20-1
$\rho_\chi = 1$ GeV/cm^3
$\sigma_{\chi-N} = 10^{-45}$ cm^2
T = 10^5K
T = 10^6K
Geometric
Regime II
$C_\star^w\ [s^{-1}]$
m_χ [GeV]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}


Neutrons
Benchmark A: BSK-20-1
$\rho_\chi = 1$ GeV/cm^3
$\sigma_{\chi-N} = 10^{-45}$ cm^2
$T = 10^5$K
$T = 10^6$K
Geometric
Regime III
C^w_χ [s^{-1}]
m_χ [GeV]
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
10^{23}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}

Capture rate formalism

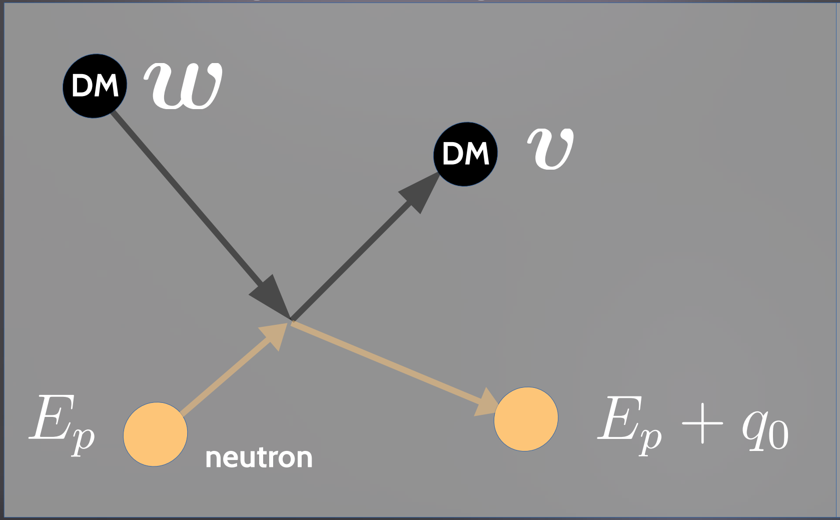
$$C_\star^{\rm w} = \int_0^{R_\star} 4\pi r^2 \mathrm{d}r \int_0^\infty \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_{v_\star}(u_\chi)}{u_\chi} w(r) \int_0^{v_e(r)} R_i^-(w \to v)\, \mathrm{d}v$$

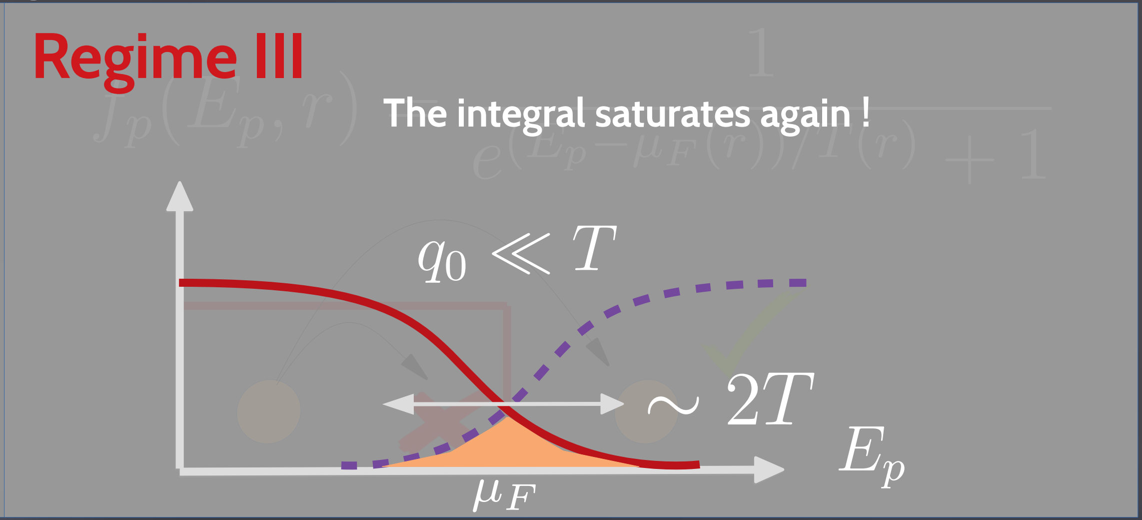
Gould (1987)

$$R(w \to v) = \int n(r) \frac{\mathrm{d}\sigma}{\mathrm{d}v} |\boldsymbol{w} - \boldsymbol{u}| f_p(E_p, r)(1 - f_{p'}(E_p + q_0, r))\mathrm{d}^3\boldsymbol{u}$$

Garami, YG, and Hambye, JCAP (2018)

Scattering on a degenerate Fermi gaz



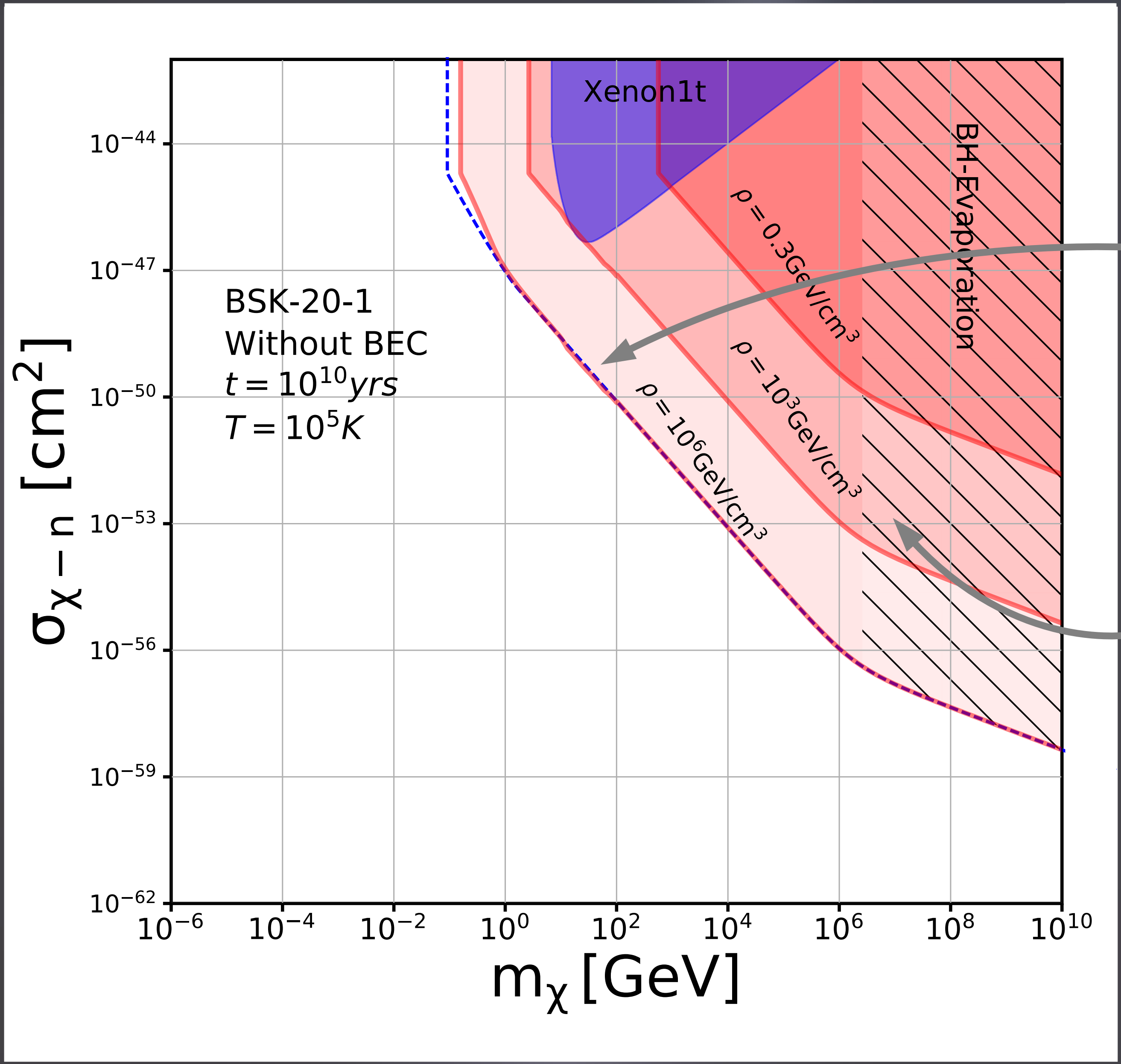


Credit: ESO/L.Calçada

Novel DM constraints

Self-gravitation condition

$$C_\star^W \times \tau_{old}^{NS} = N_{self}$$



Novel DM constraints

Self-gravitation condition

$$C_\star^W \times \tau_{old}^{NS} = N_{self}$$

BH evaporates too fast

Confirmation of previous results using heuristic arguments

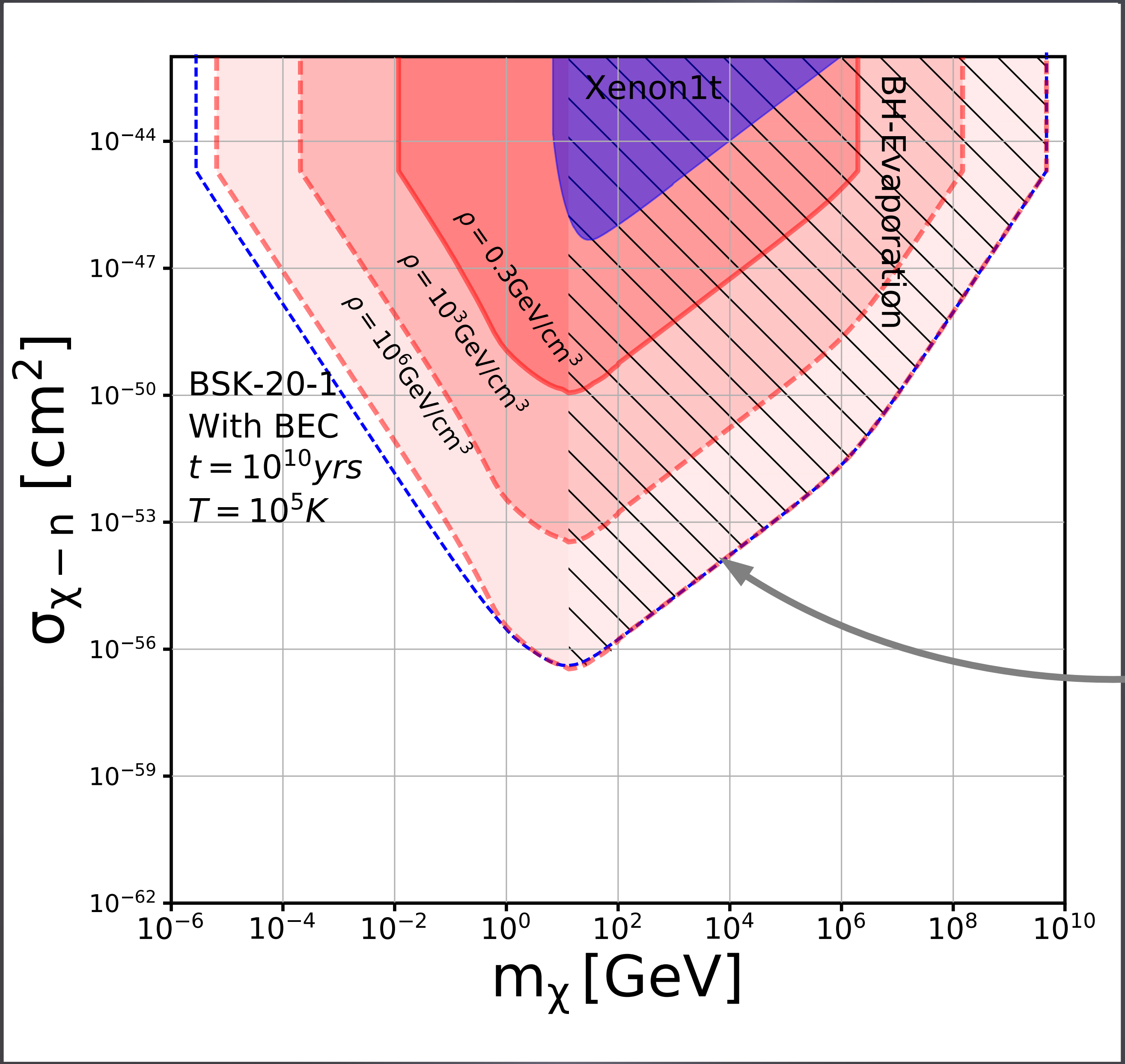
Novel DM constraints

Bose Einstein Condensate

↓

$$N_{self}^{BEC} \ll N_{Chan}^{boson}$$

NEW limiting condition



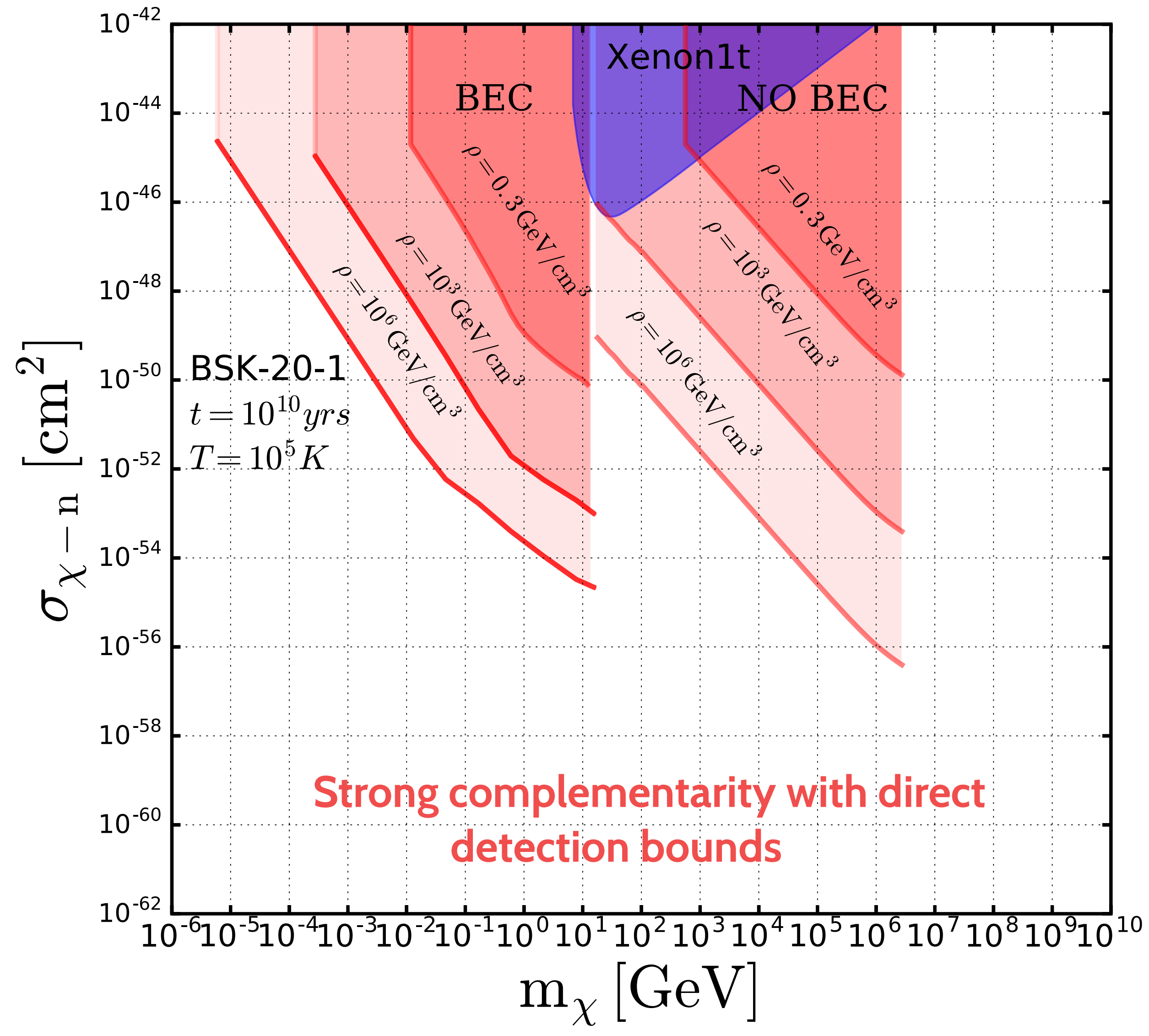
Novel DM constraints

Bose Einstein Condensate

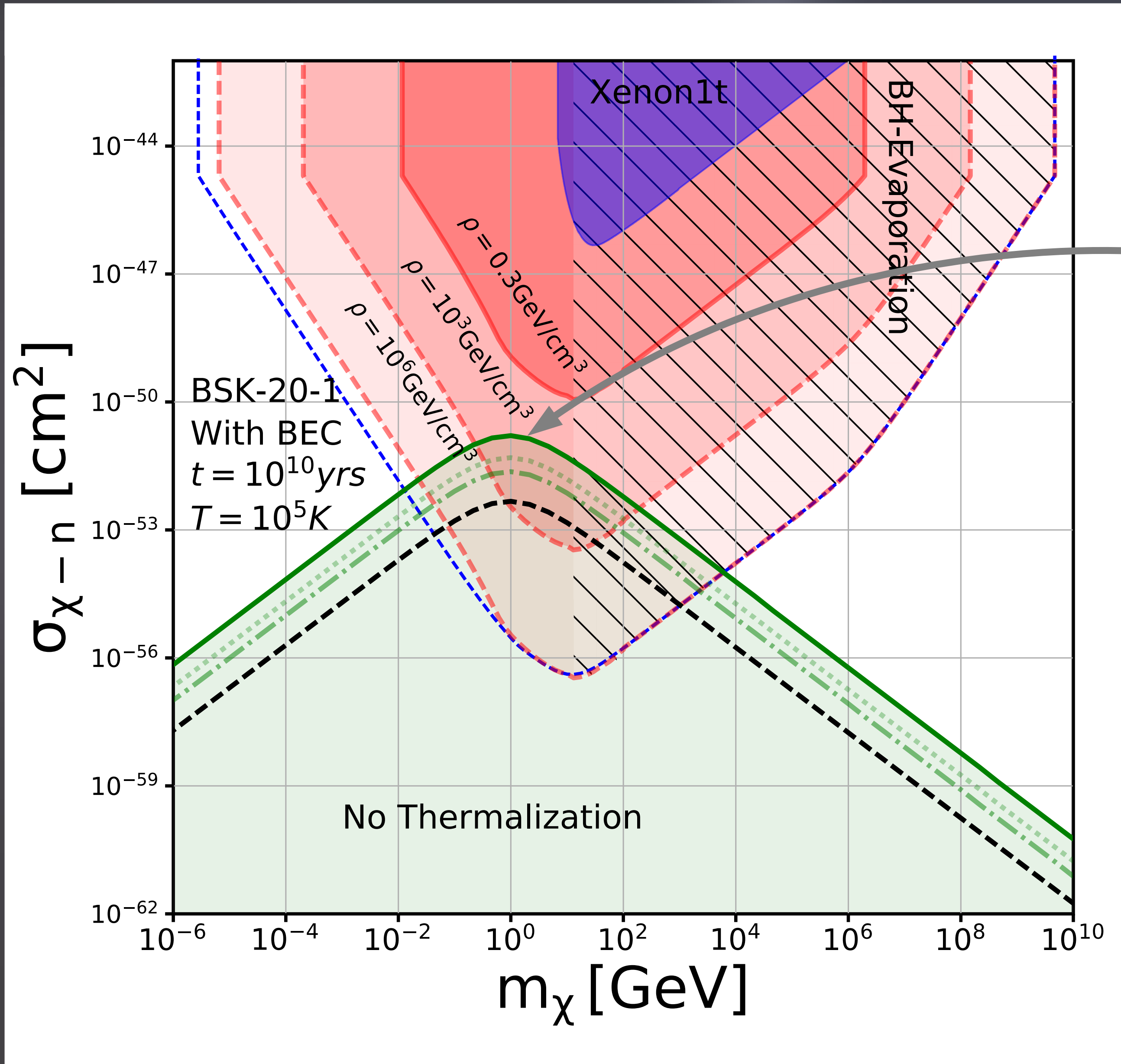
$$N^{BEC}_{self} \ll N^{boson}_{Chan}$$

NEW limiting condition

$$C^W_\star \times \tau^{NS}_{old} = N^{boson}_{Chan}$$

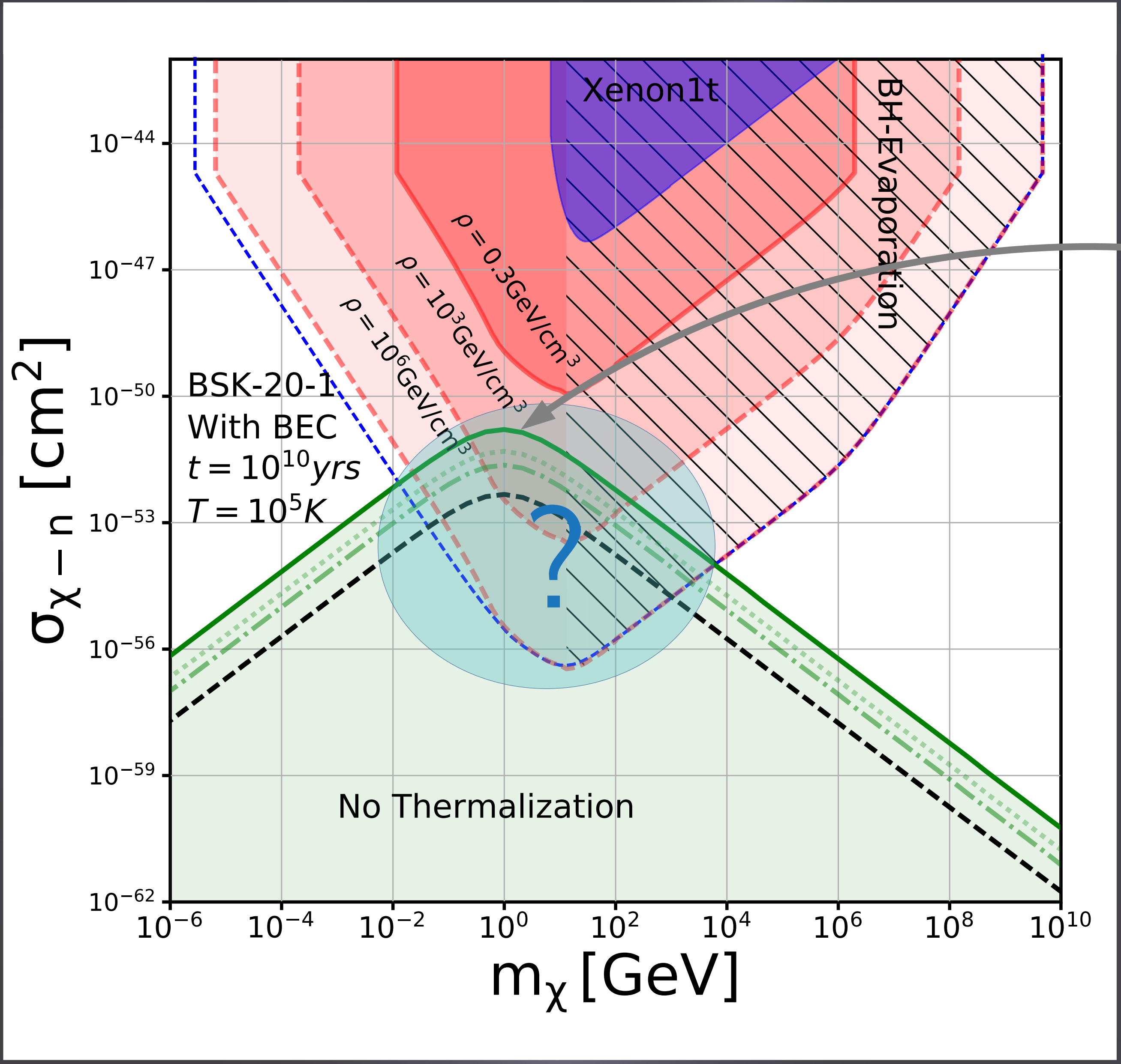


Strong complementarity with direct detection bounds



Novel Thermalisation bound

90 % of the particles
In thermal equilibrium



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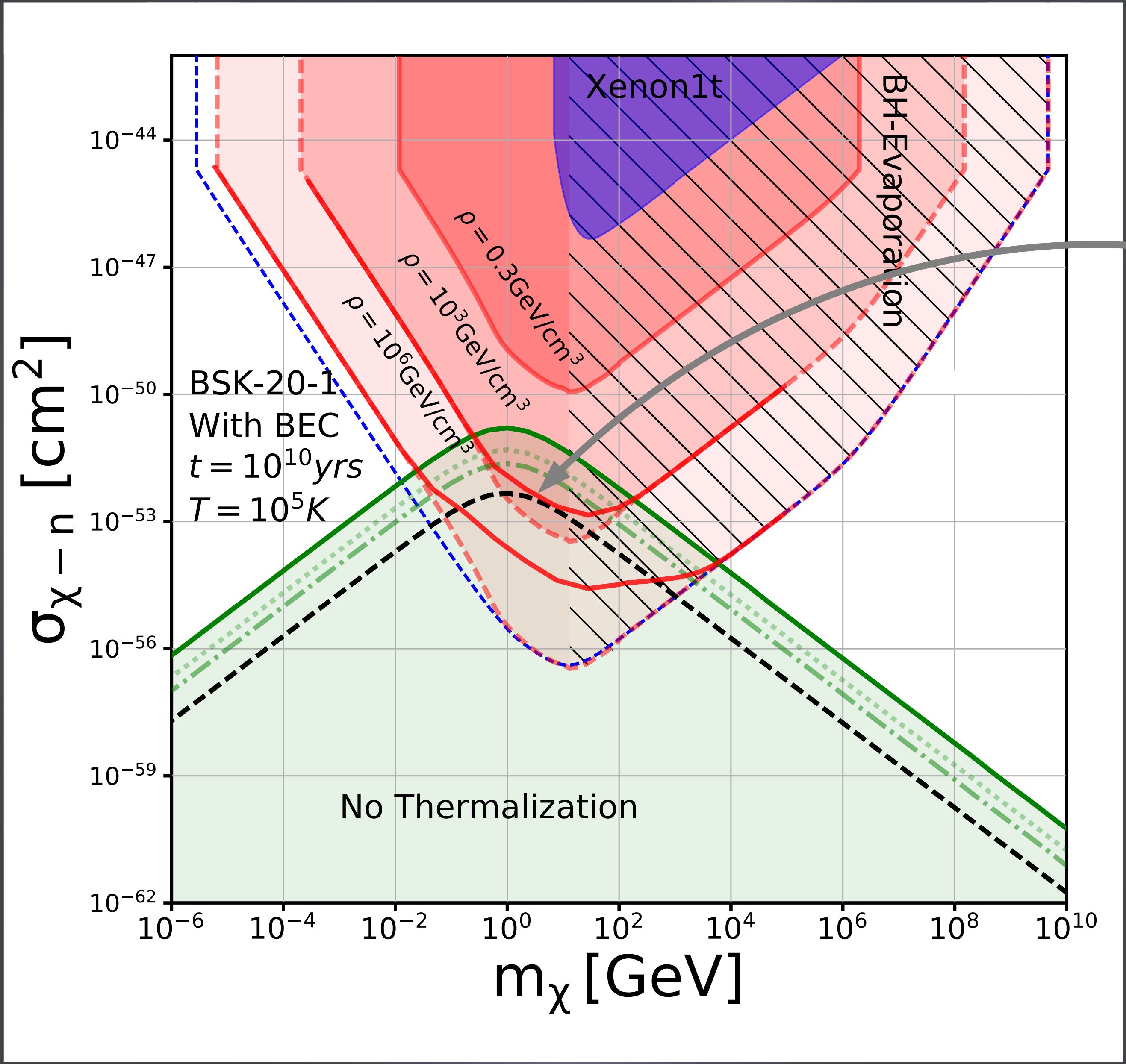
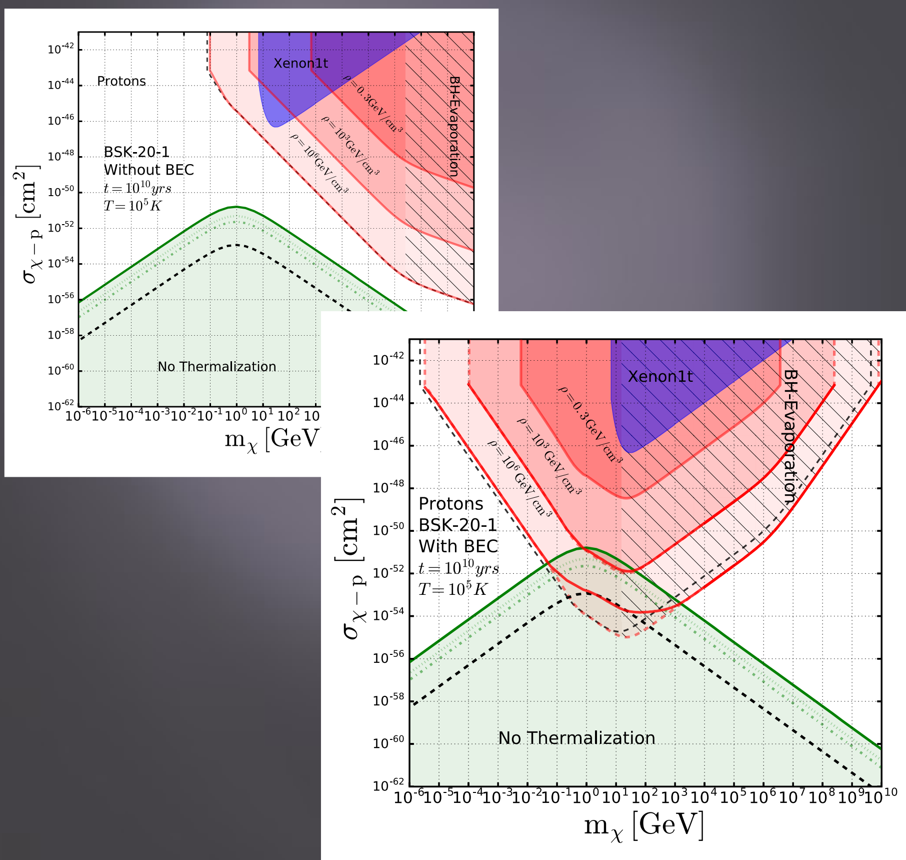


Novel Thermalisation bound

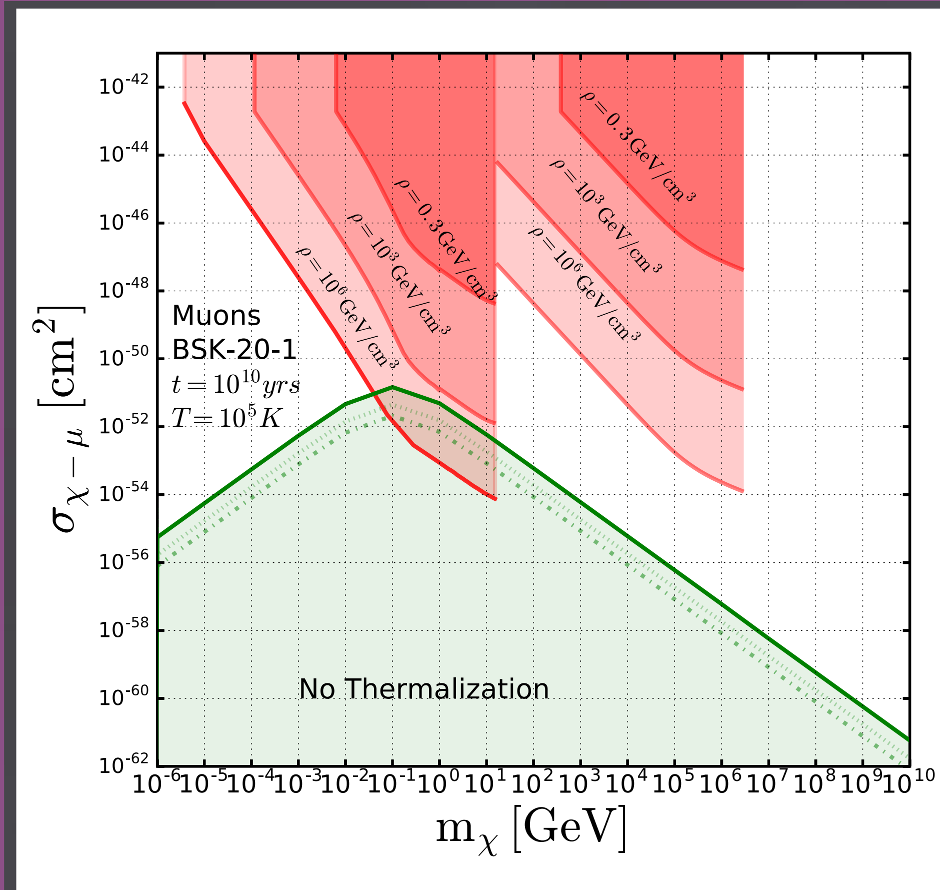
NEW bounds!

Gain of orders of magnitudes from observations of old NS in dense environement!

Other components of NS!



Protons



Muons !

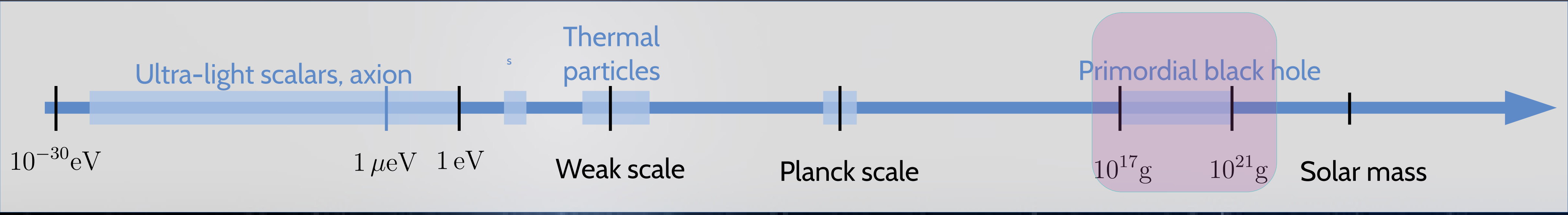
Summary

Extension of DM constraints → Including Fermi Dirac kinematic
→ Realistic NS EOS
→ Other components of NS
→ Proper treatment of thermalization

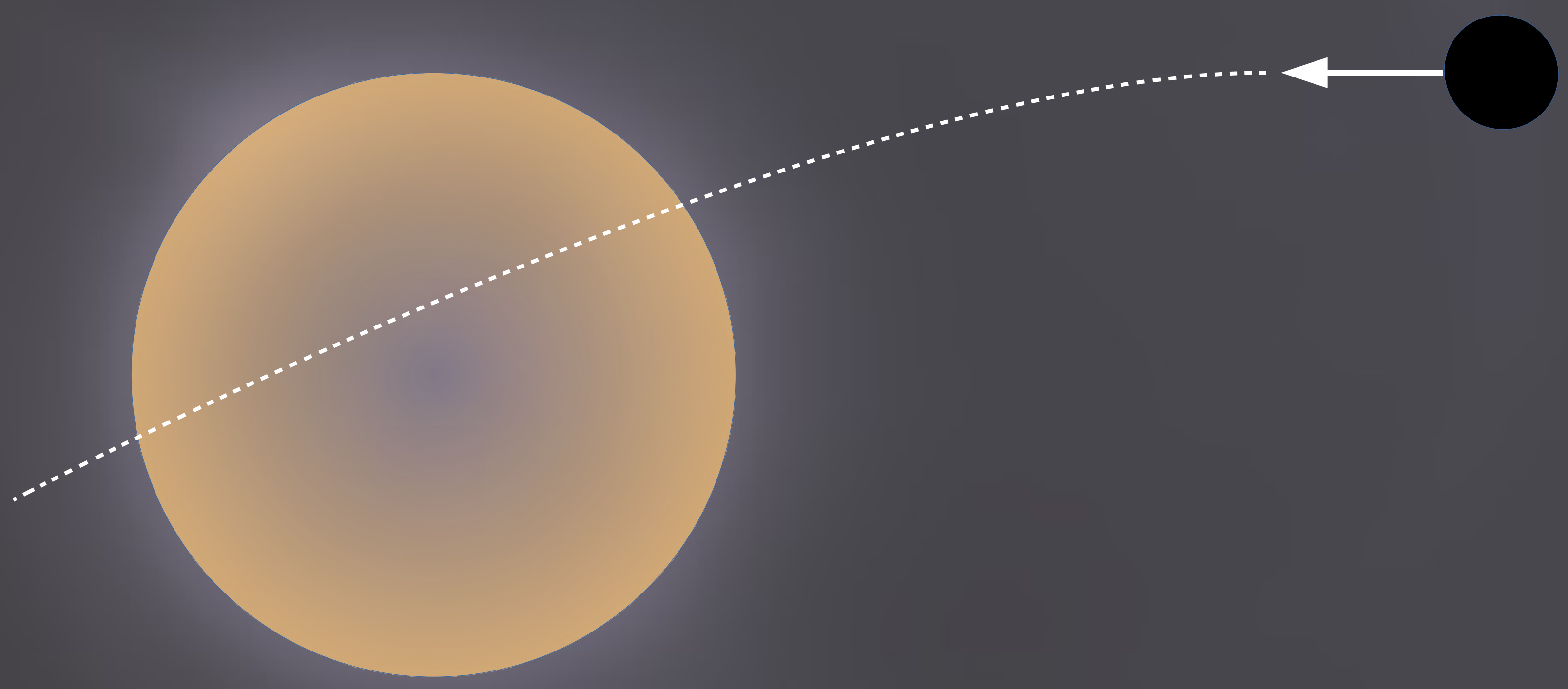
Other developments

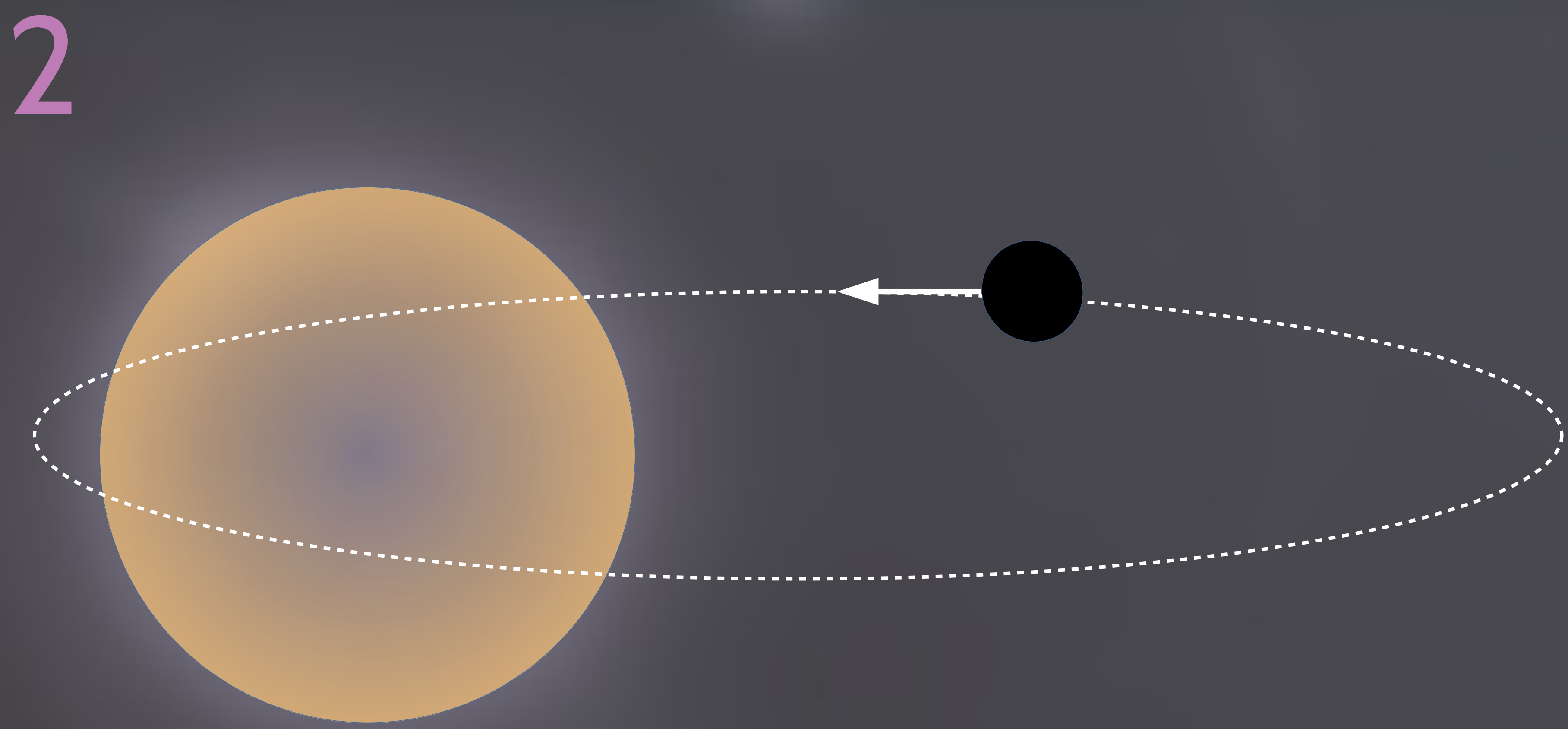
→ Different EFT operators / multiscatering e.g. Joglekar+ (2020), Bell+ (2020),
→ Dark matter self interactions e.g. Bell+ (2013), Güver+ (2014), Garani+ (2021)
→ Relativistic formalism e.g. Joglekar+ (2020), Bell+ (2021)
→ Strong interaction effects / hadronic form factors e.g. Bell+ (2021)
→ Thermalization e.g. Garani+ (2020),

PBH interactions with a NS



1





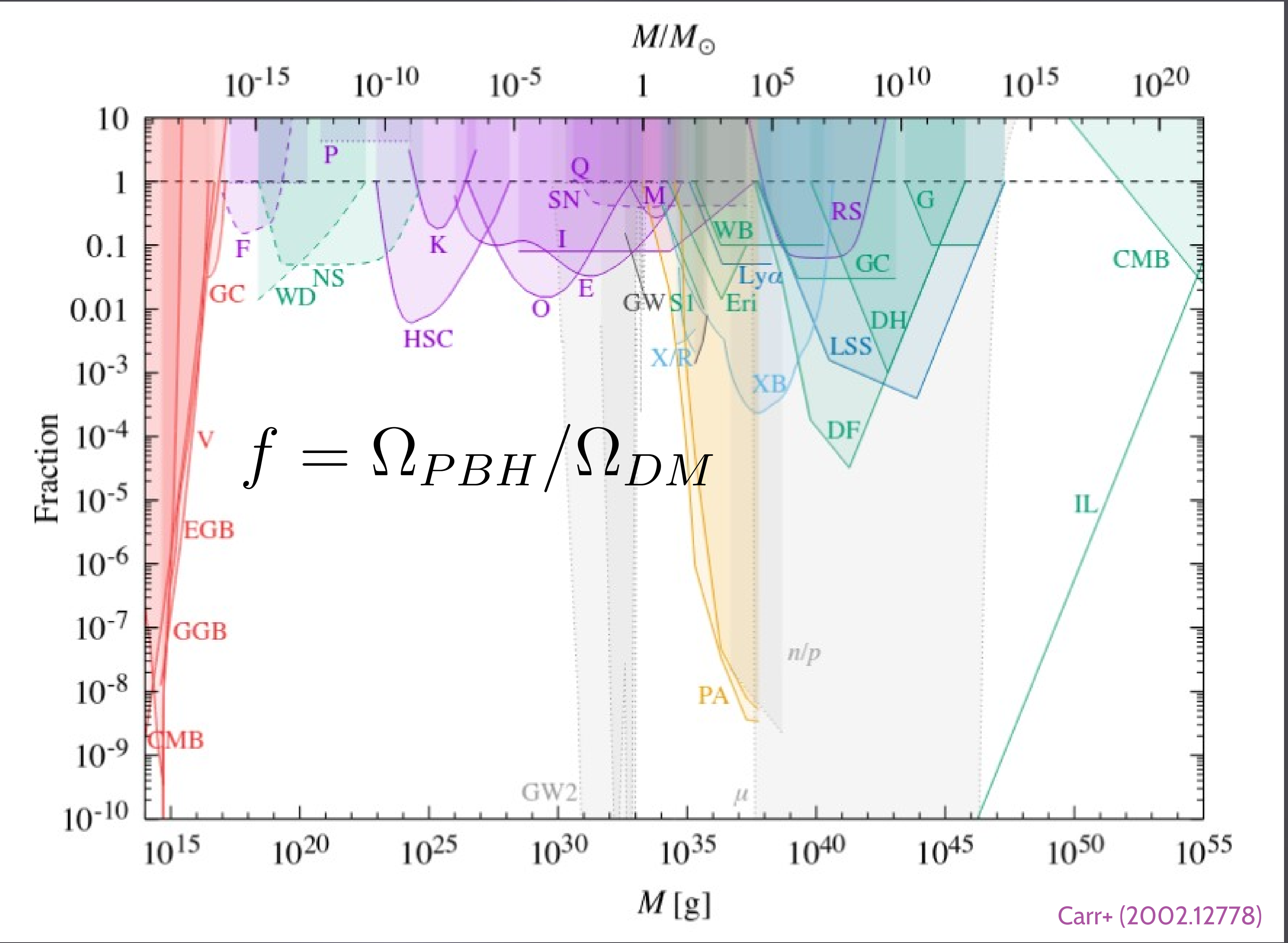
Credit: ESO/L.Calçada

3

Observation of old NS in PBH-**rich environment**.

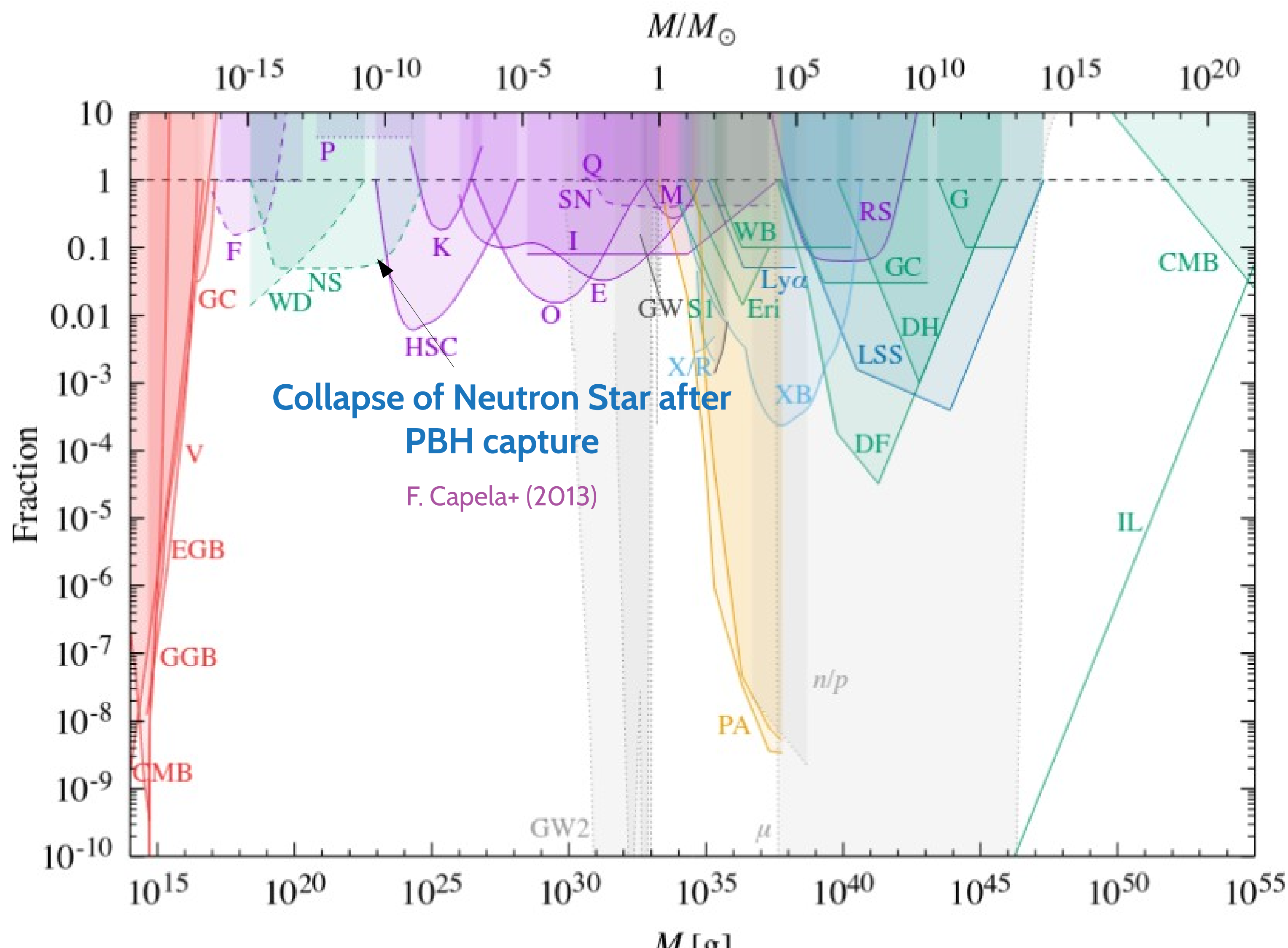
$$\tau_{old}^{NS} = 10\,\mathrm{Gyr}$$

→ Constraints on f_{PBH}



$$f = \Omega_{PBH}/\Omega_{DM}$$

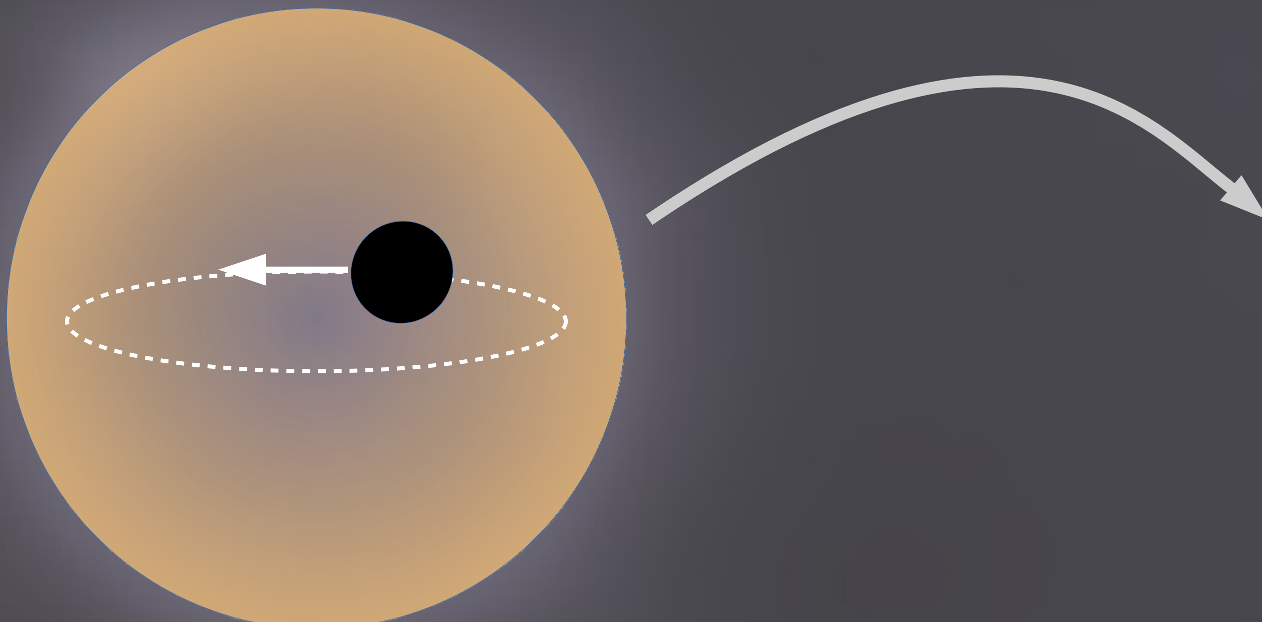
Carr+ (2002.12778)

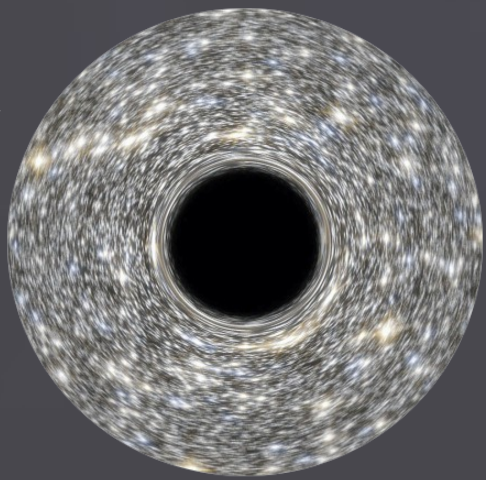


Collapse of Neutron Star after PBH capture

F. Capela+ (2013)

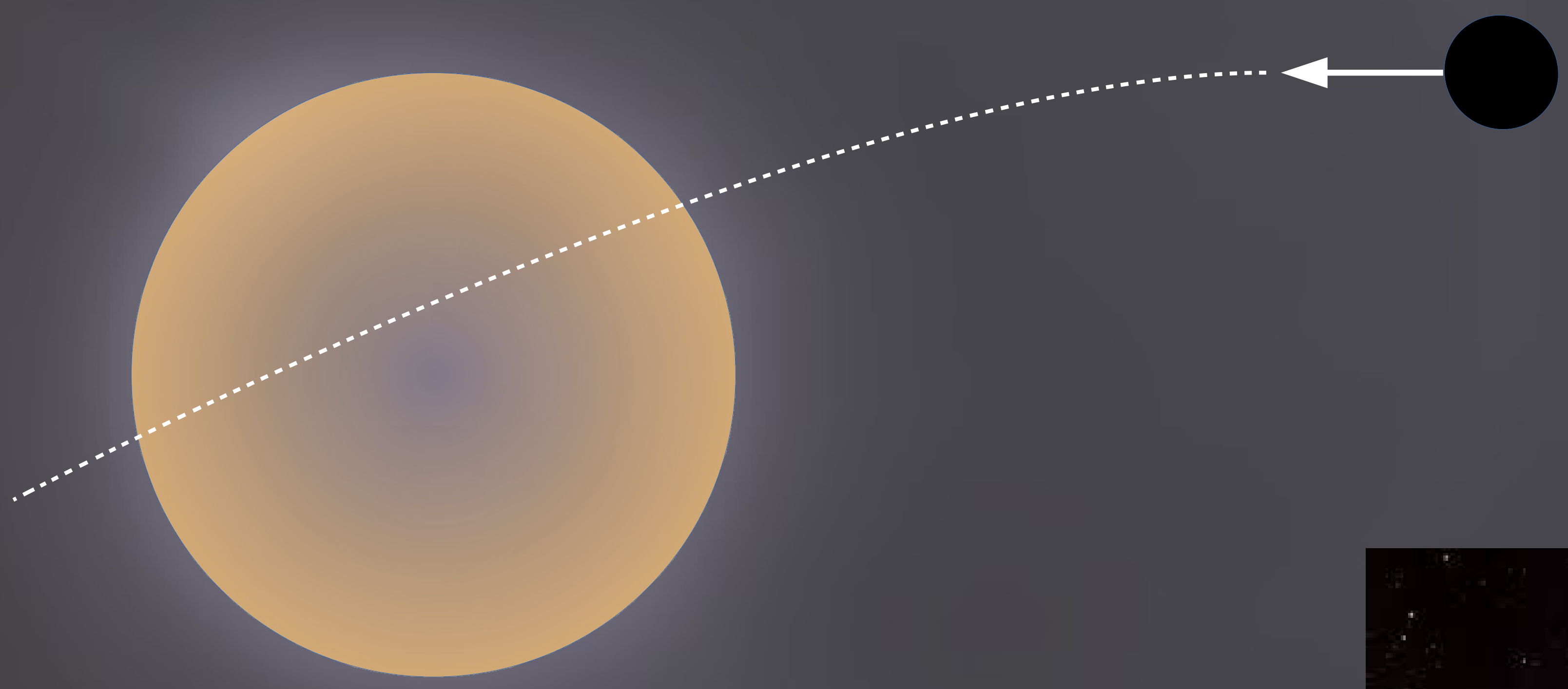
Carr+ (2002.12778)

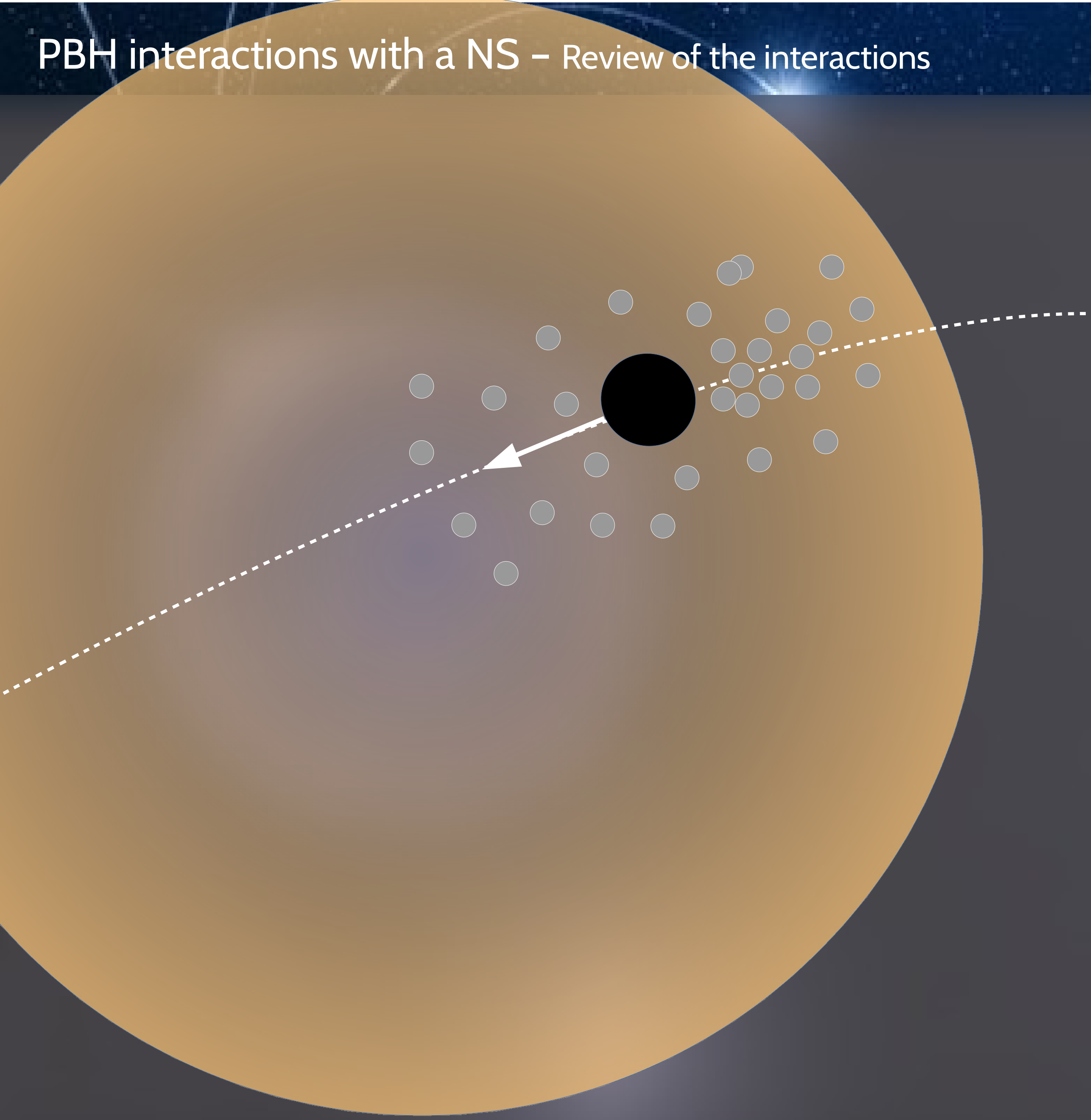


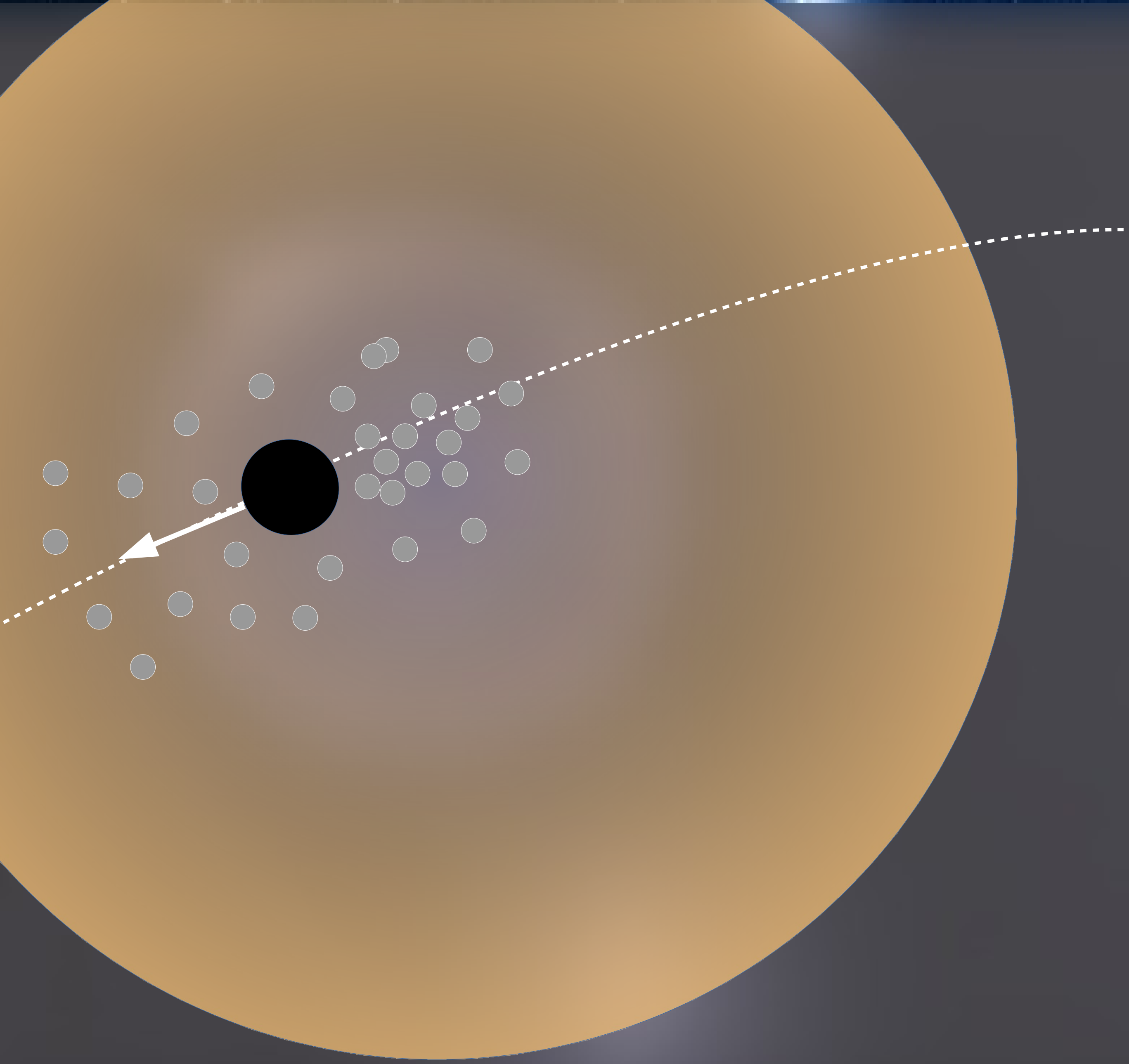


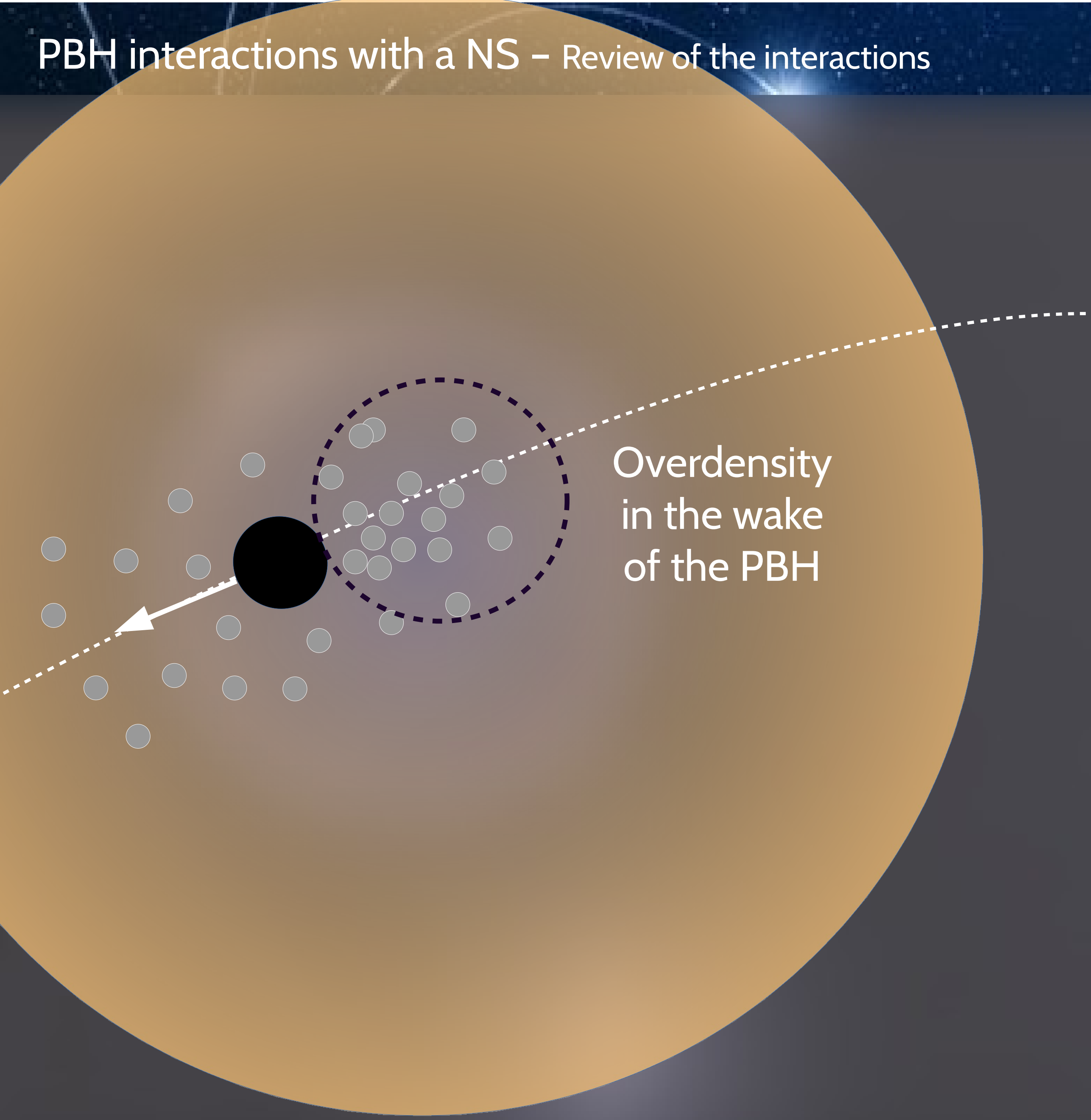
Yet, such a catastrophic event should be observable!

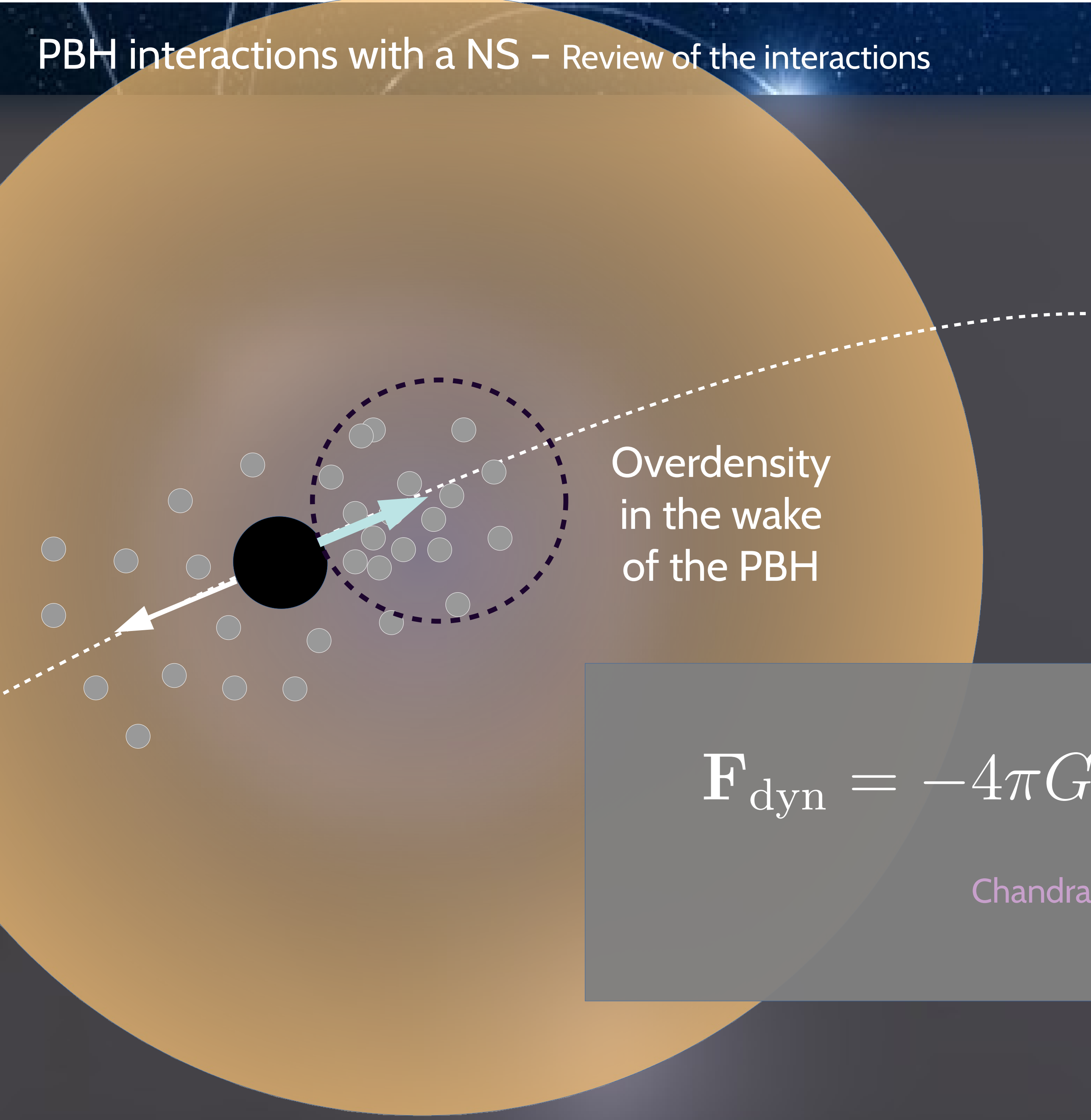
1 - Dynamical Friction





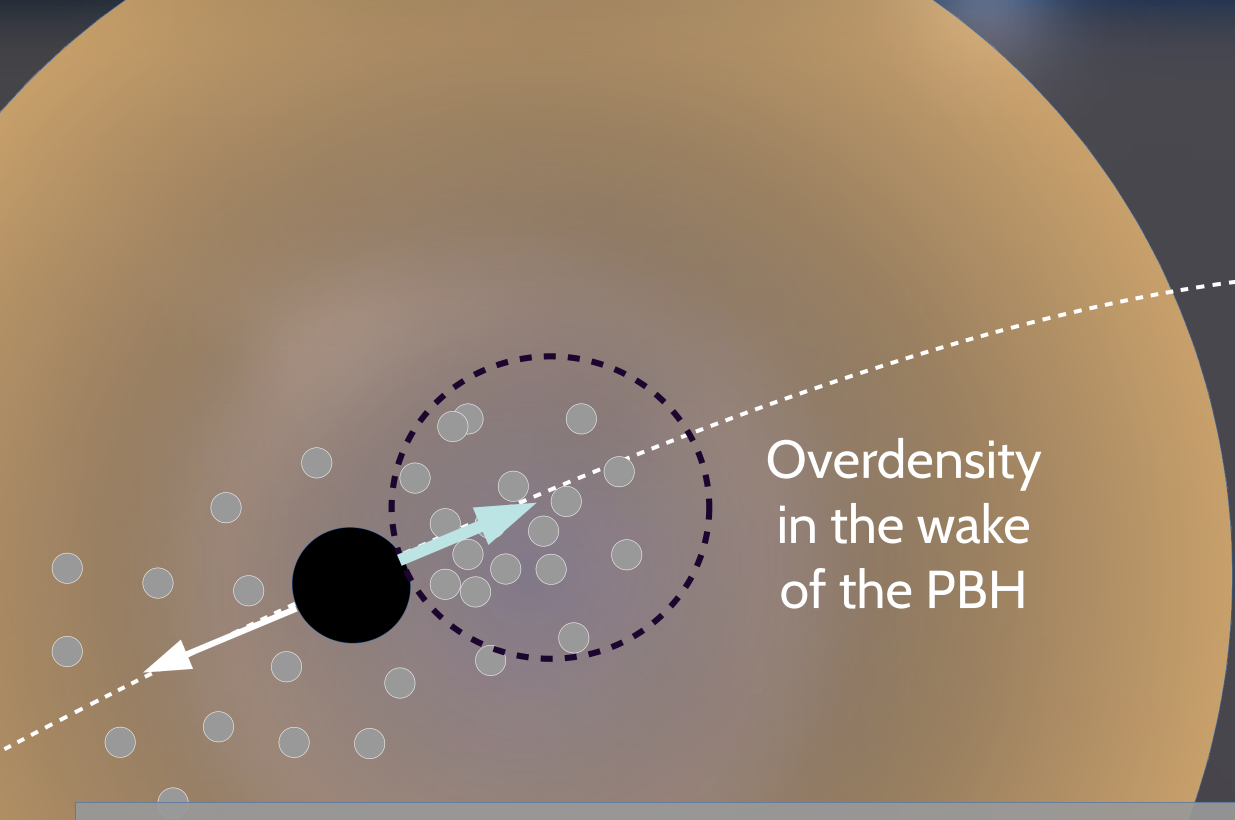


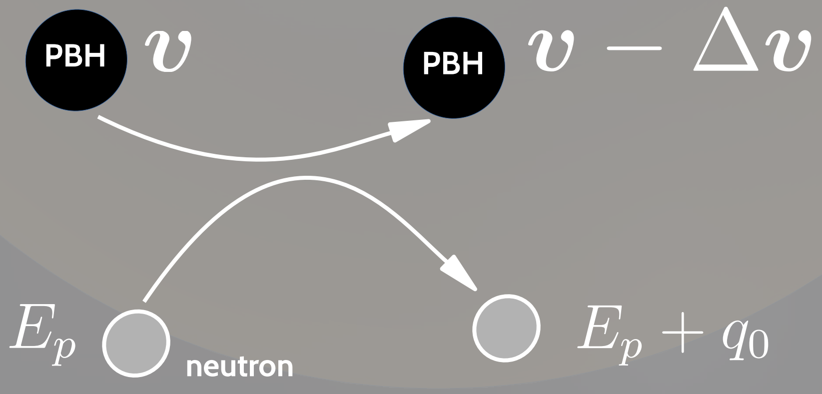

Overdensity
in the wake
of the PBH



$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

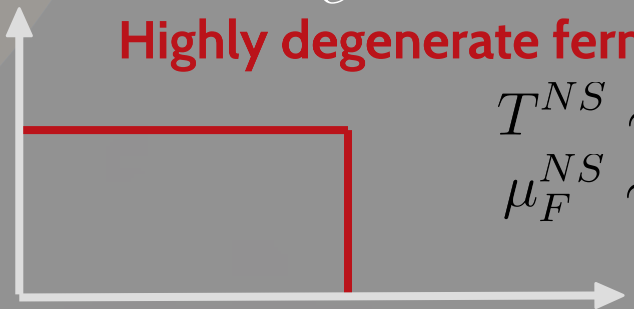
Chandrasekhar (1949)





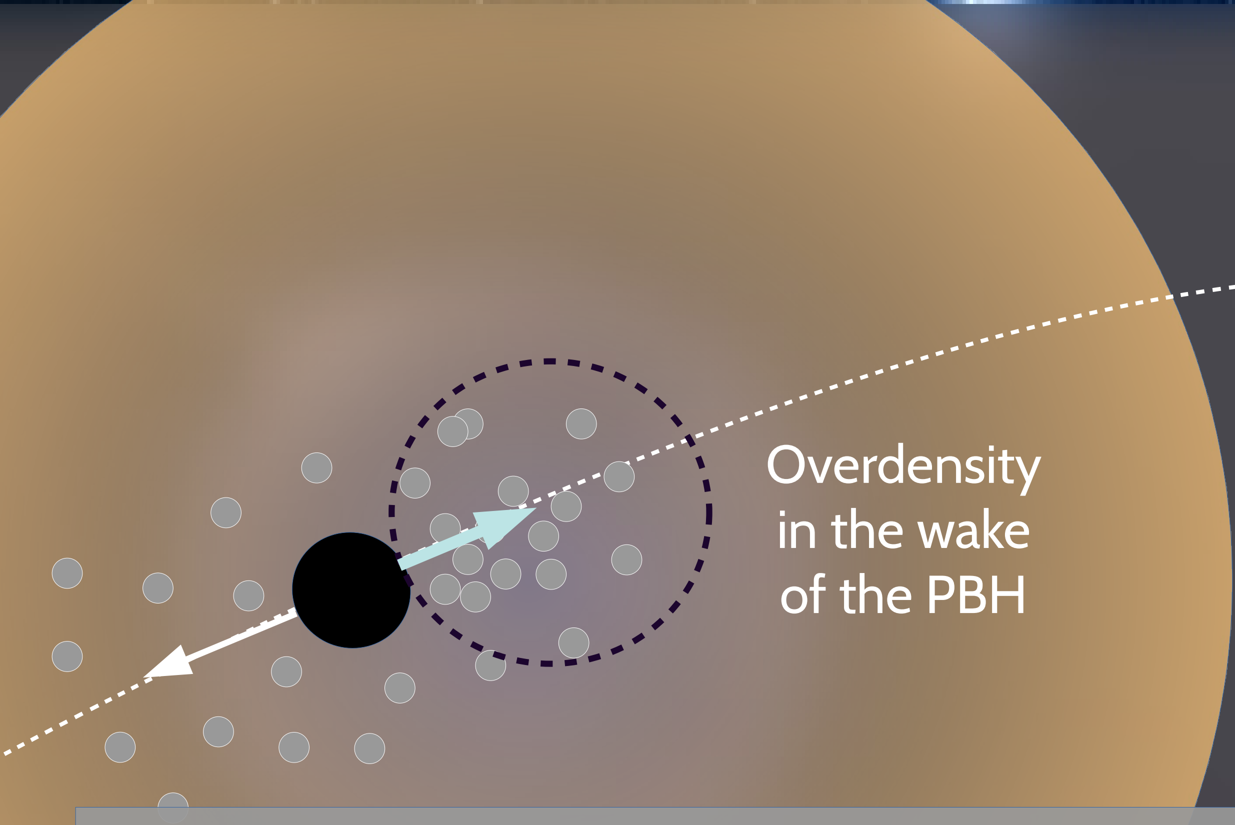
$$f_p(E_p, r) = \frac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$$

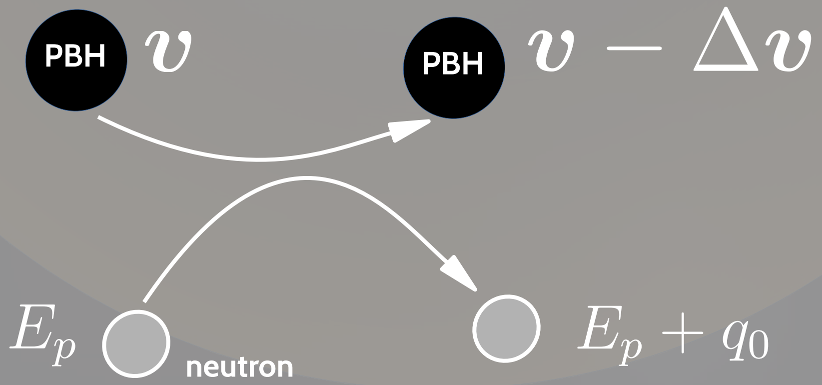
Highly degenerate fermi gaz !



$T^{NS} \sim 10^{-8}$ GeV

$\mu_F^{NS} \sim 0.5$ GeV





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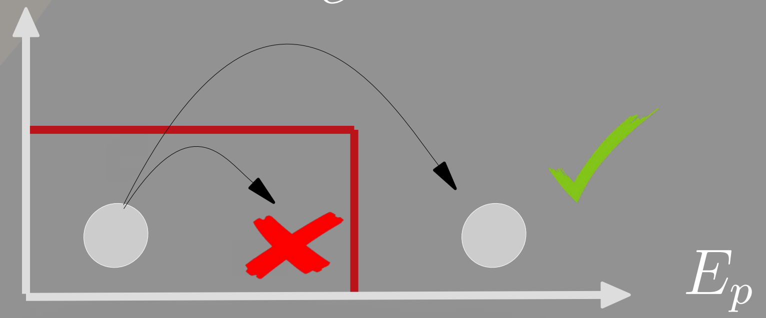
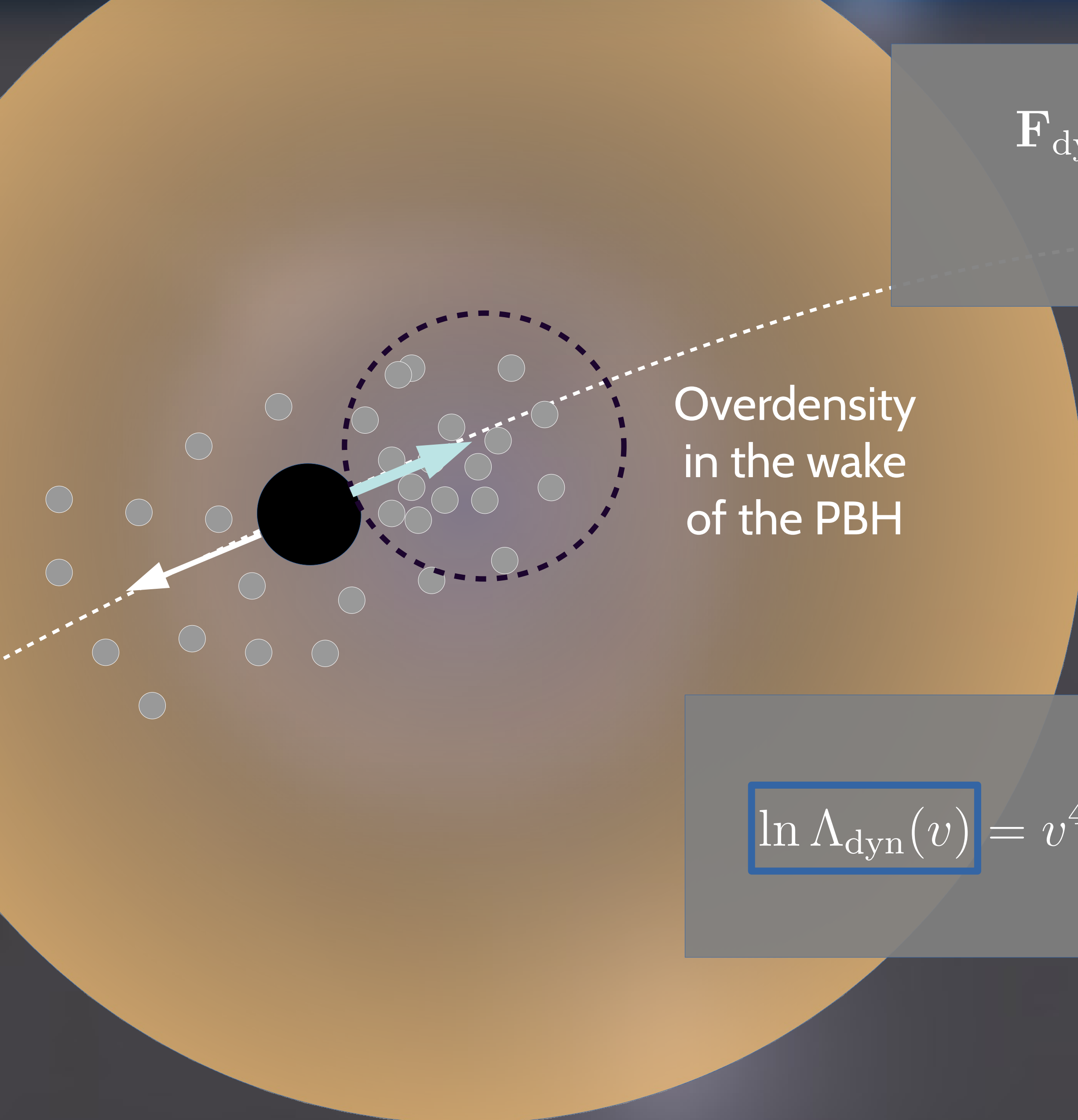


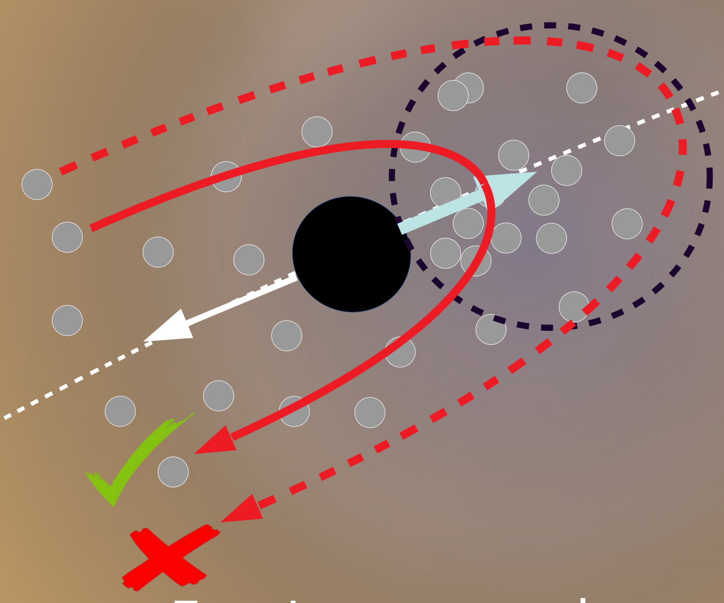


$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

Chandrasekhar (1949)

$$\ln \Lambda_{\rm dyn}(v) = v^4 \gamma^2 \frac{2}{R_g^2} \int_{d_{\rm crit}}^{d_{\rm max}} \mathrm{d}x \, x(1 - \cos \varphi(x))$$

Capela+ (2013)



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Capela+ (2013)

-> DF is suppressed by a factor of a few, up to 10

Derived for a collisionless medium

↓

NS = strongly interacting neutron fluid

$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

Chandrasekhar (1949)

$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

Chandrasekhar (1949)

Derived for a collisionless medium

↓

NS = strongly interacting neutron fluid

↓

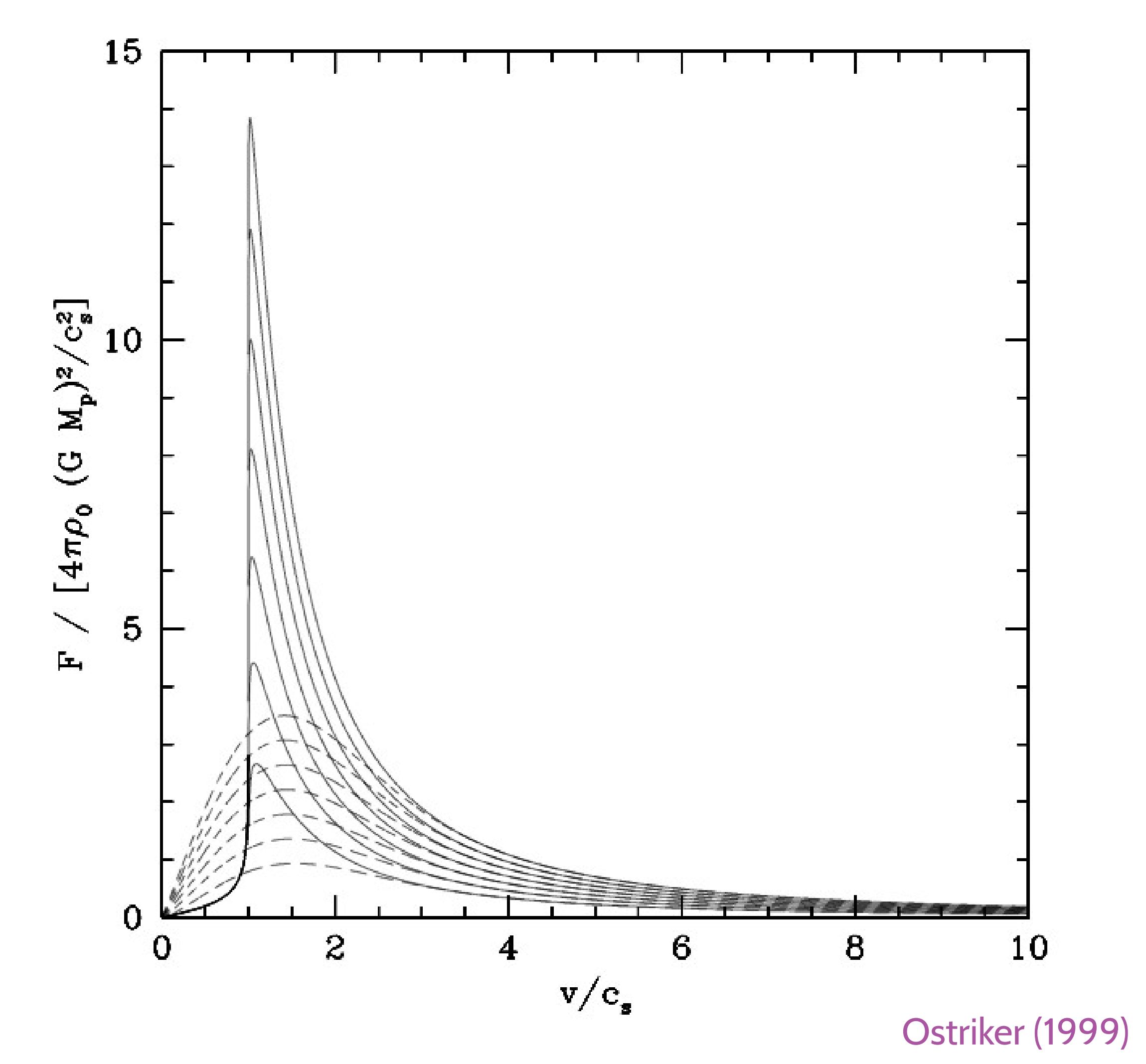
Collisionless if $\tau_{gravitation} \ll \tau_{causal}$

$$v \gg c_s$$

$$\mathcal{M} = v/c_s \gg 1$$

1 - Dynamical Friction:

In a collisionless or a collisional medium?



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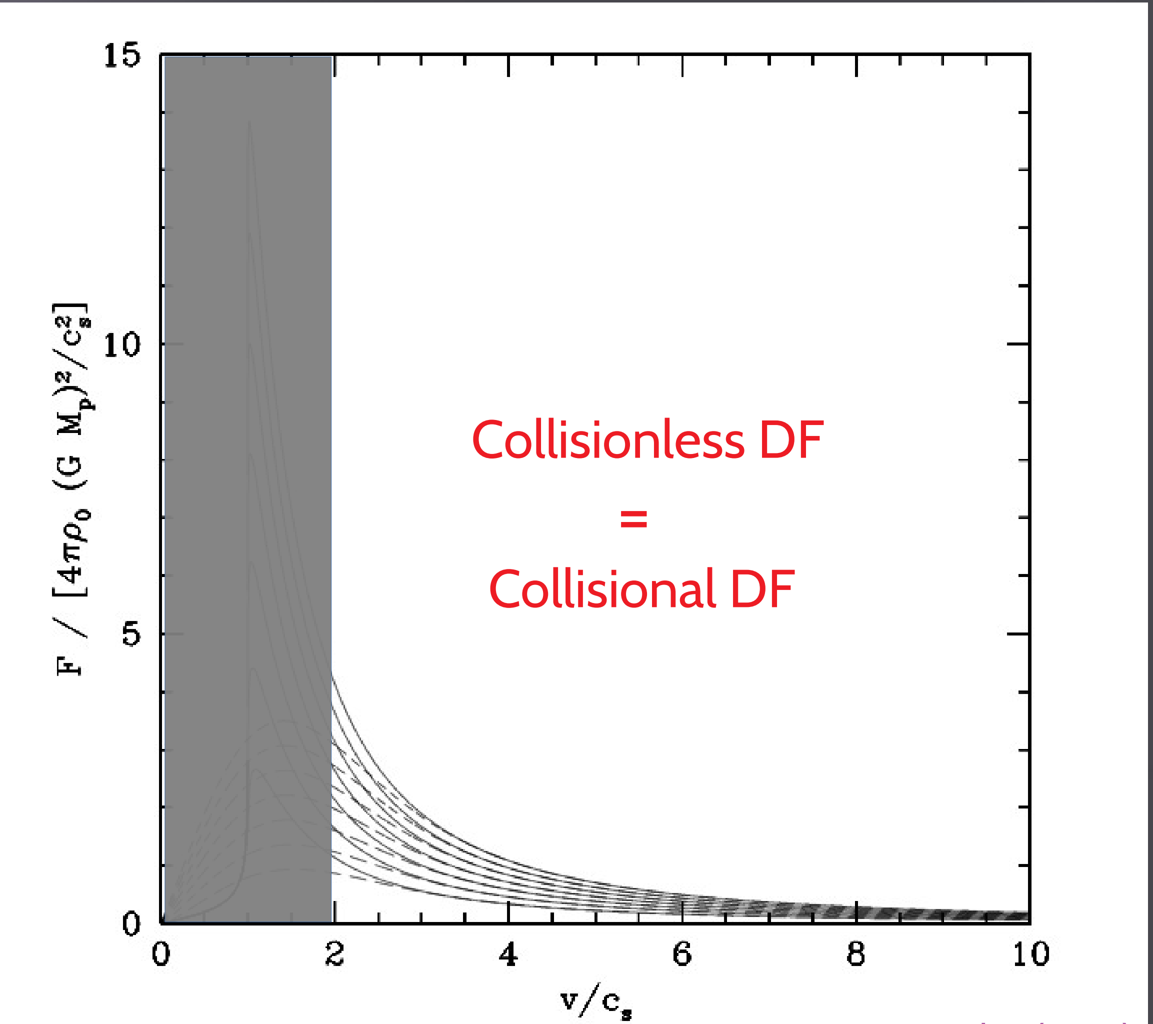

Ostriker (1999)

Credit: ESO/L.Calçada

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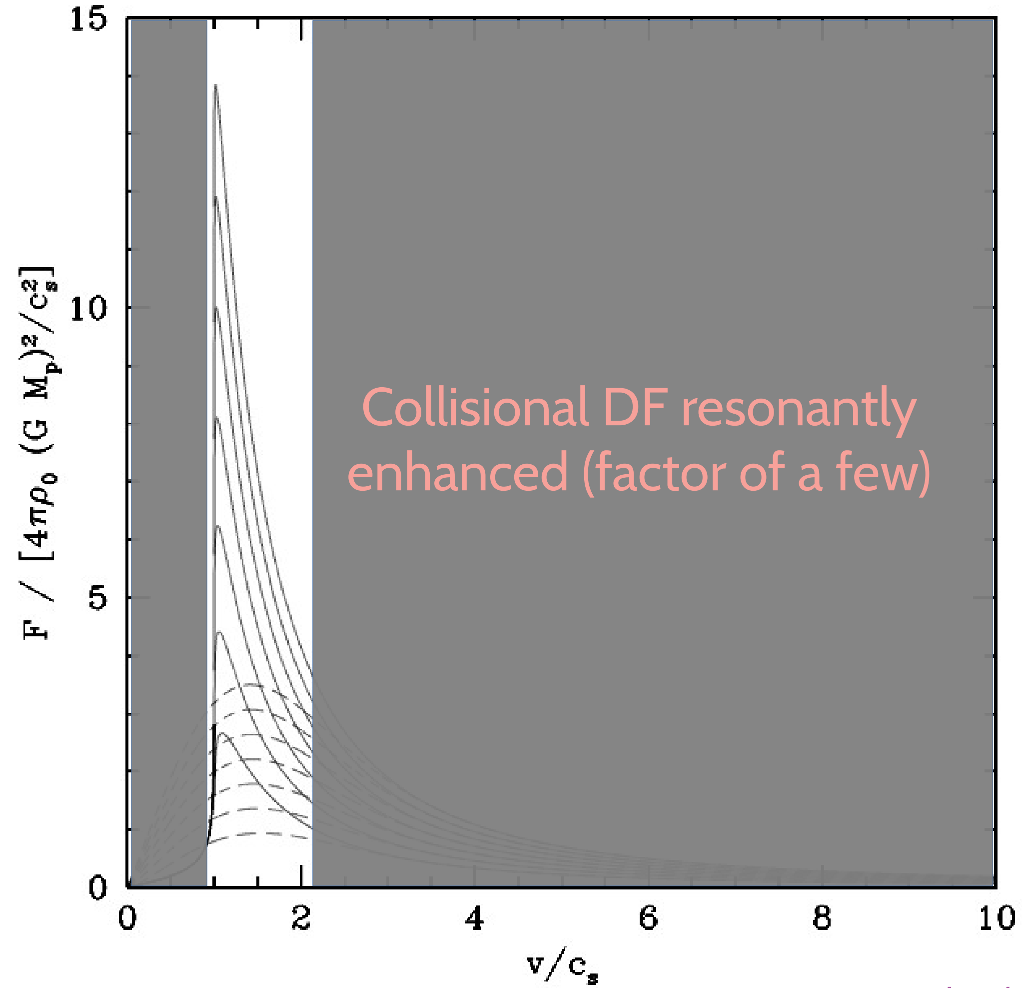

Ostriker (1999)

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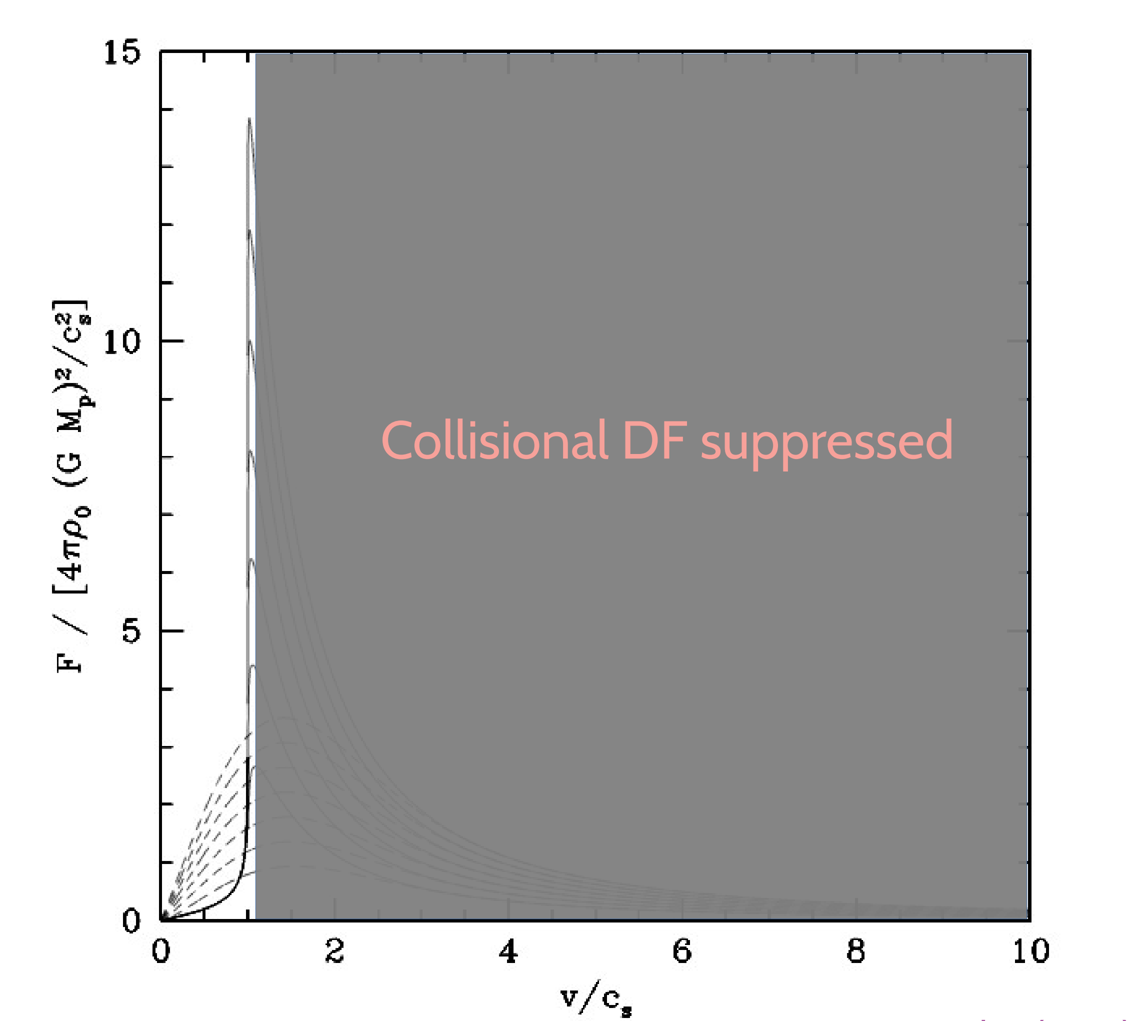
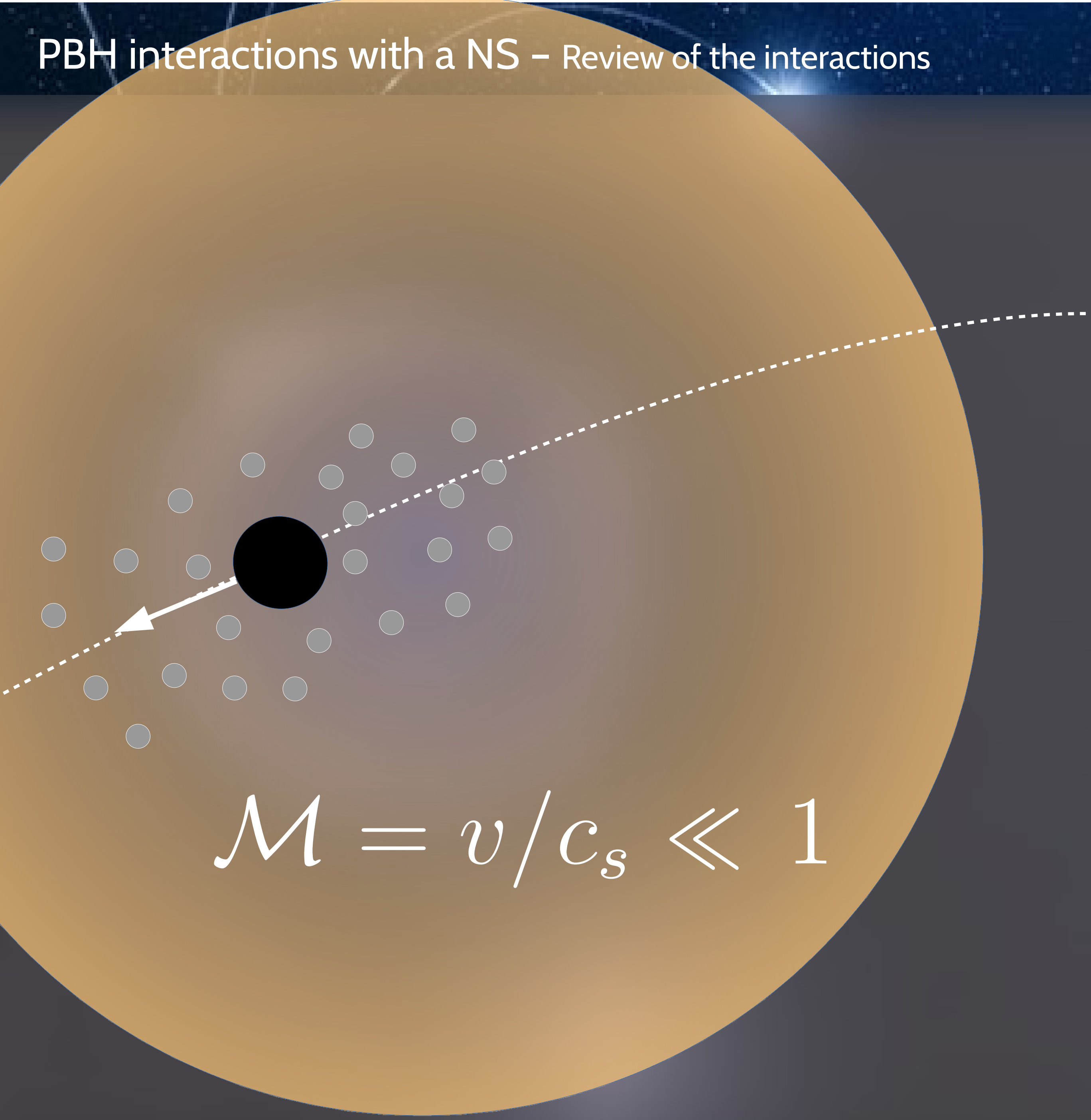


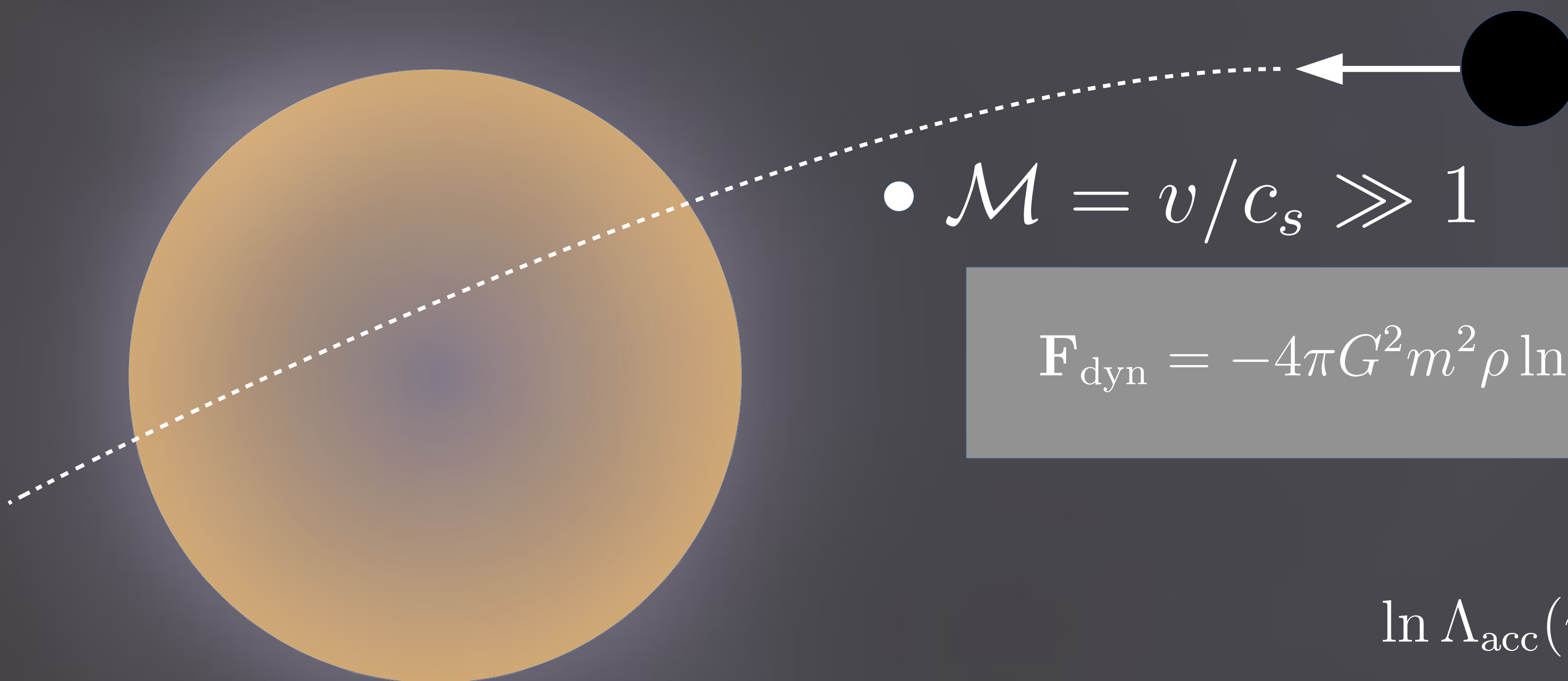
Ostriker (1999)



$$\mathcal{M} = v/c_s \ll 1$$

Credit: ESO/L.Calçada

2 - Accretion



- $\mathcal{M} = v/c_s \gg 1$

$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

Capela+ (2013)

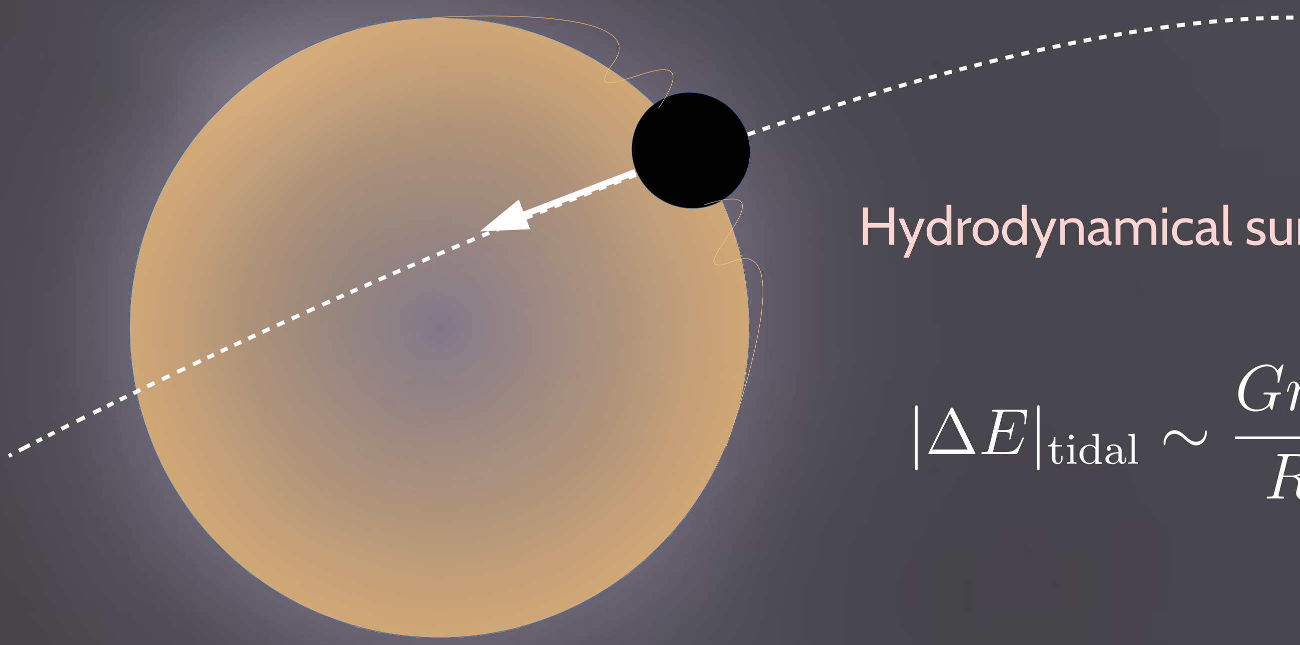
$$\ln \Lambda_{\rm acc}(v) = v^4 \gamma^2 \frac{d_{\rm crit}^2}{R_g^2}$$

- $\mathcal{M} = v/c_s \ll 1$

$$\mathbf{F}_{\rm drag} = -\dot{m}\boldsymbol{v} = -4\pi G^2 m^2 \rho \frac{\boldsymbol{v}}{c_s^3}$$

Y.G. et al. PRD (2020)

3 - Surface waves

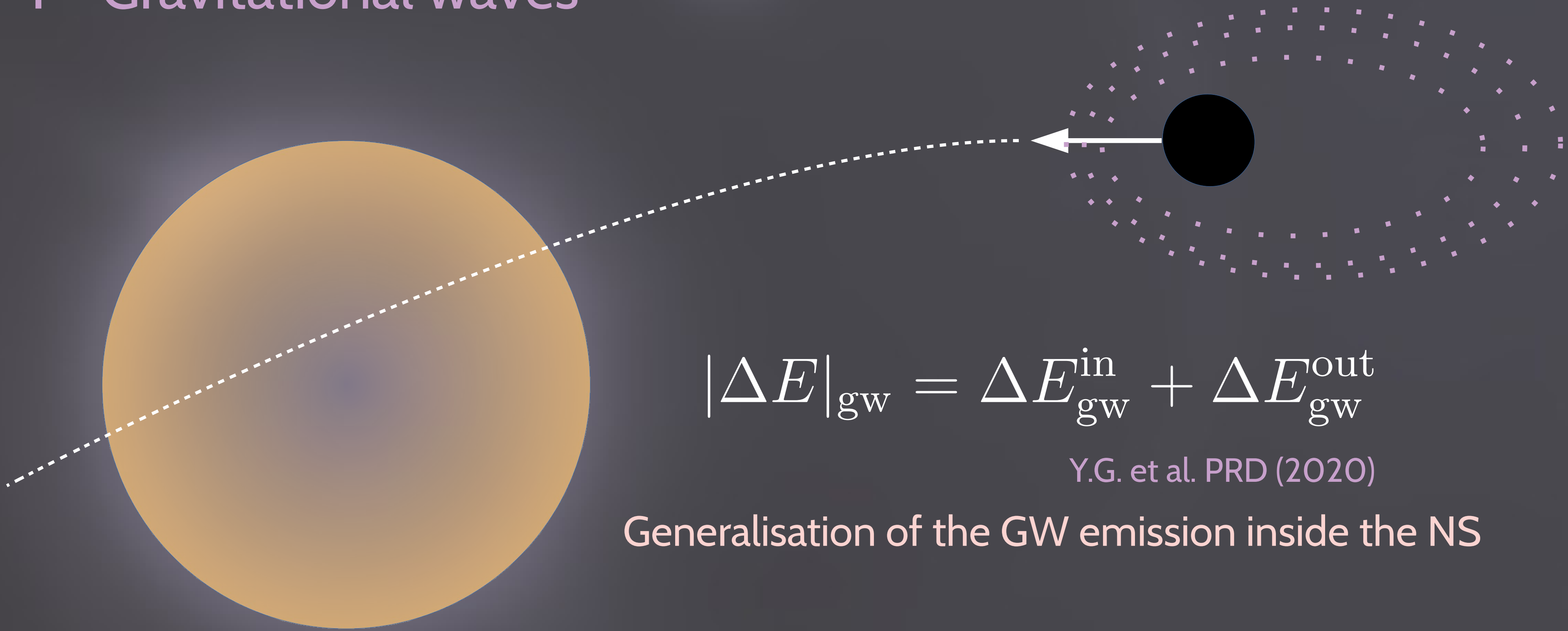


Hydrodynamical surface waves:

$$|\Delta E|_{\text{tidal}} \sim \frac{Gm^2}{R_\star} \sum_{l=2}^{\infty} \left(\frac{R_\star}{r_{\text{min}}} \right)^{2\ell+2} T_\ell,$$

Defillon+ (2014)
Press&Teukolsky (1977)

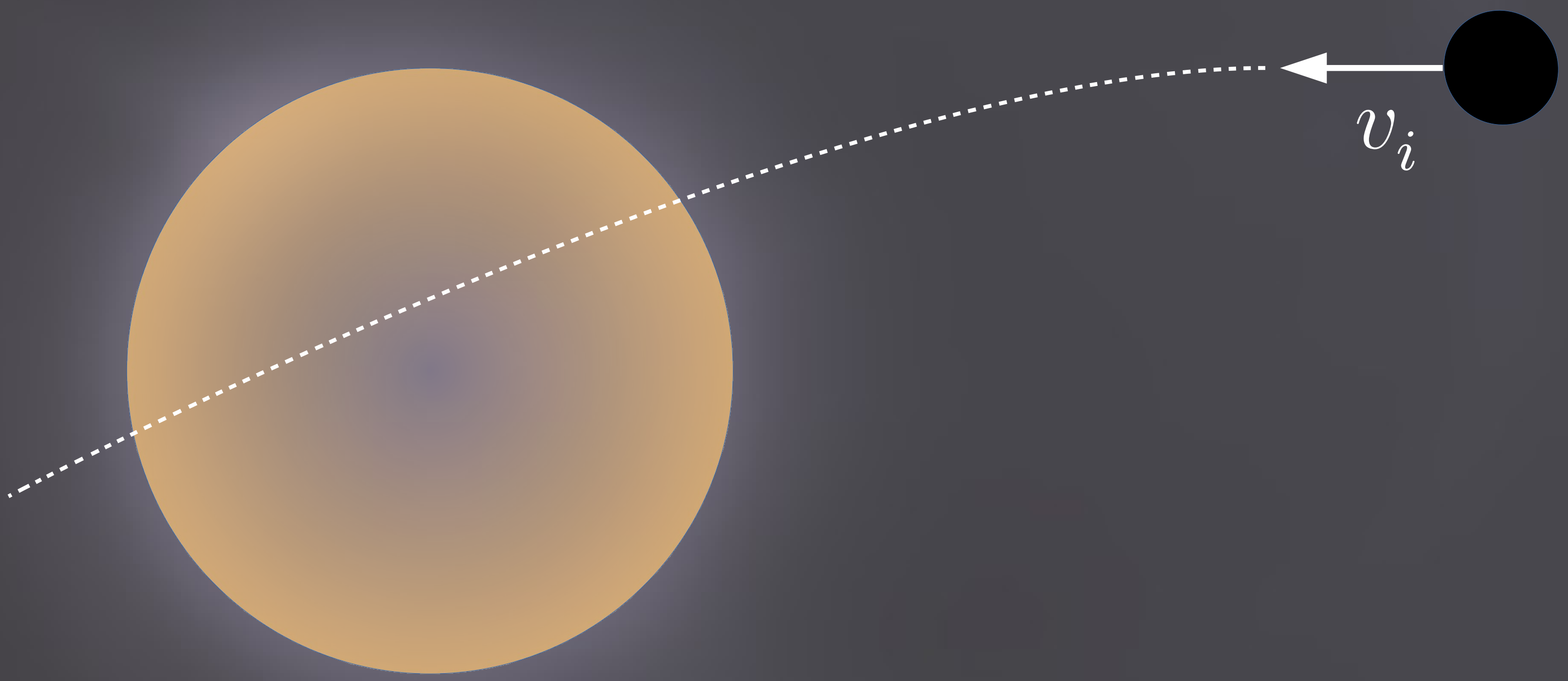
4 - Gravitational waves

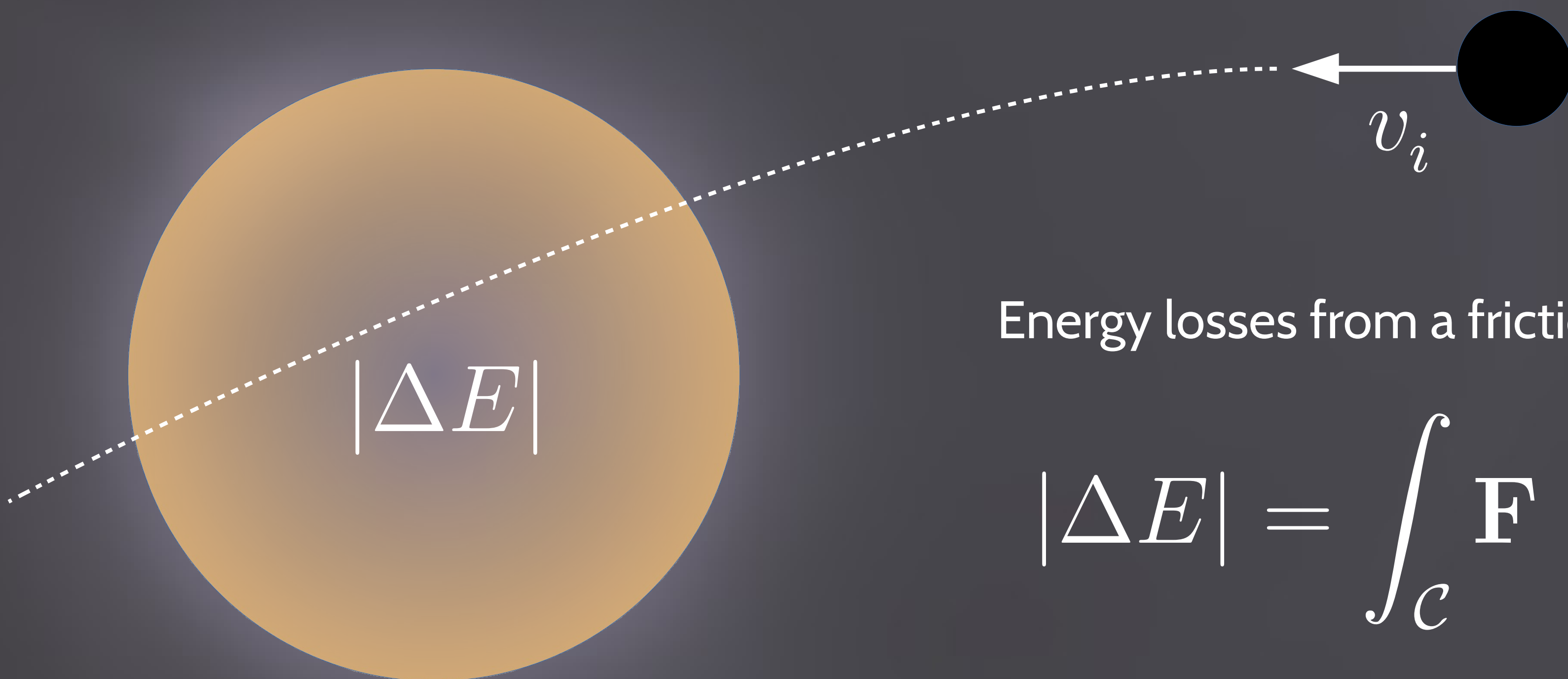


$$|\Delta E|_{\rm gw} = \Delta E_{\rm gw}^{\rm in} + \Delta E_{\rm gw}^{\rm out}$$

Y.G. et al. PRD (2020)

Generalisation of the GW emission inside the NS


v_i

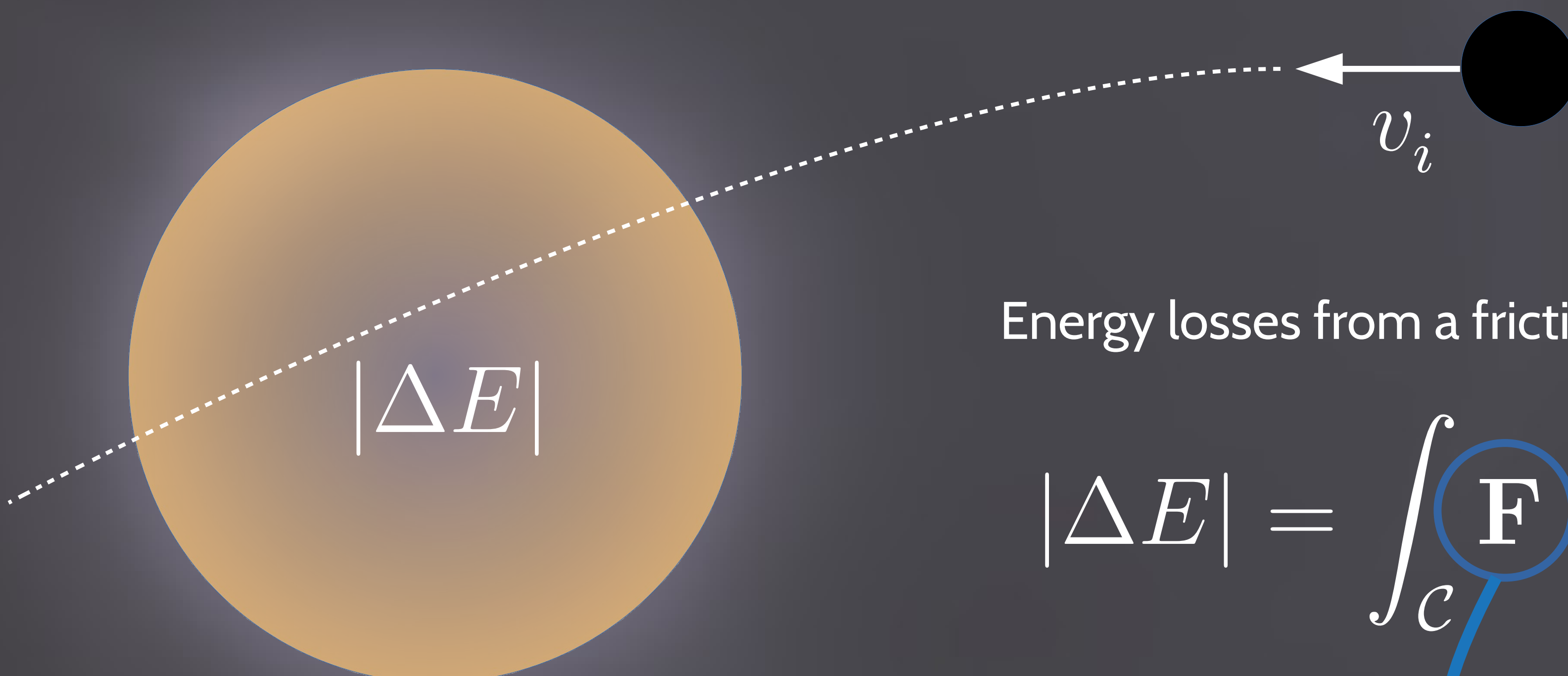


Energy losses from a friction force

$$|\Delta E| = \int_{\mathcal{C}} \mathbf{F} \cdot \mathrm{d}\mathbf{l}$$

Capture condition

$$|\Delta E| > E_i = \frac{1}{2} m v_i^2$$



Energy losses from a friction force

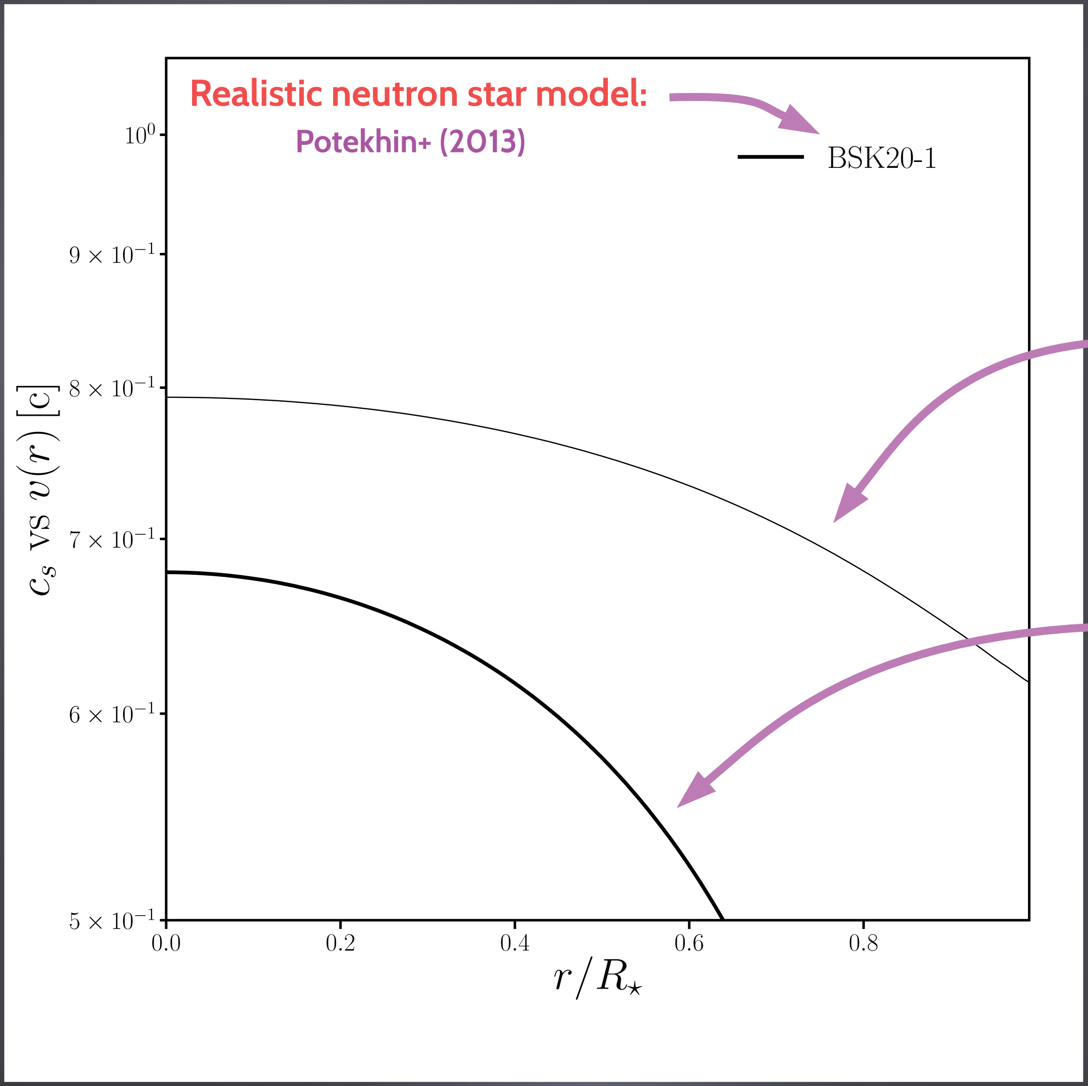
$$|\Delta E| = \int_{\mathcal{C}} \mathbf{F} \cdot \mathrm{d}\mathbf{l}$$

Forces we saw

Capture condition

$$|\Delta E| > E_i = \frac{1}{2} m v_i^2$$

What is the speed regime for capture ?

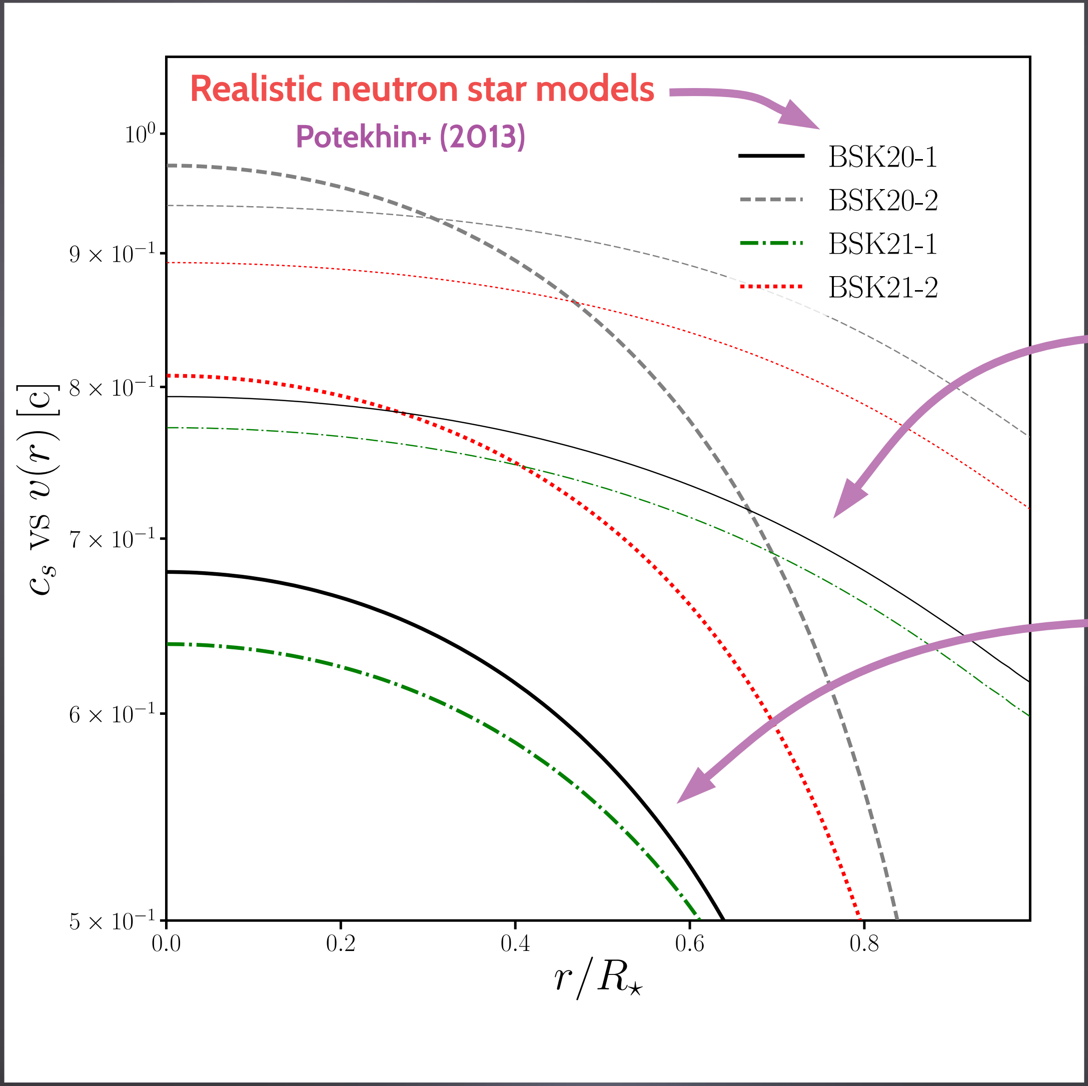


$$v(r) = \sqrt{1 - e^{2(\Phi(\infty)-\Phi(r))}}$$

$$c_s(r)$$

Capture happens in the supersonic regime!

What is the speed regime for capture ?



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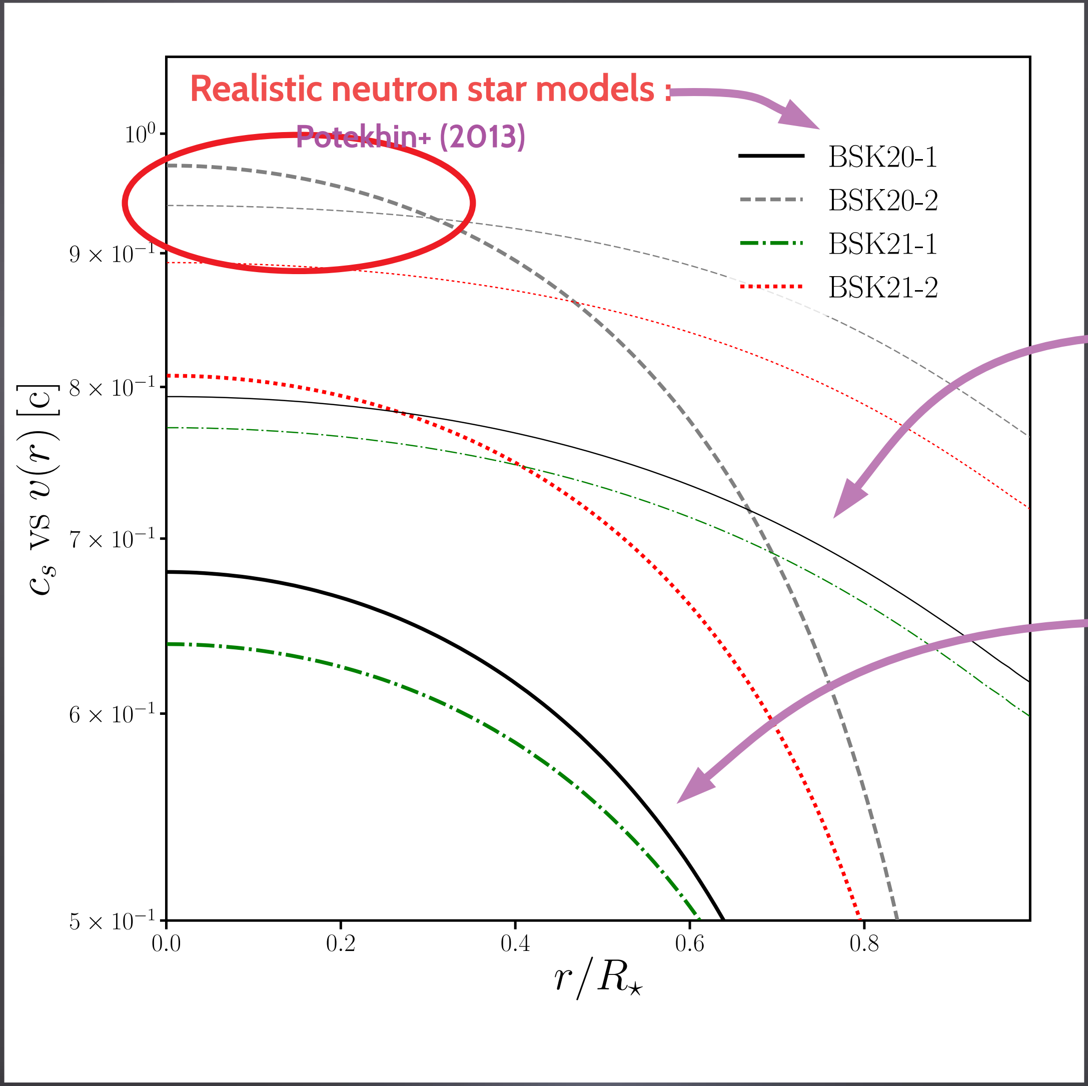


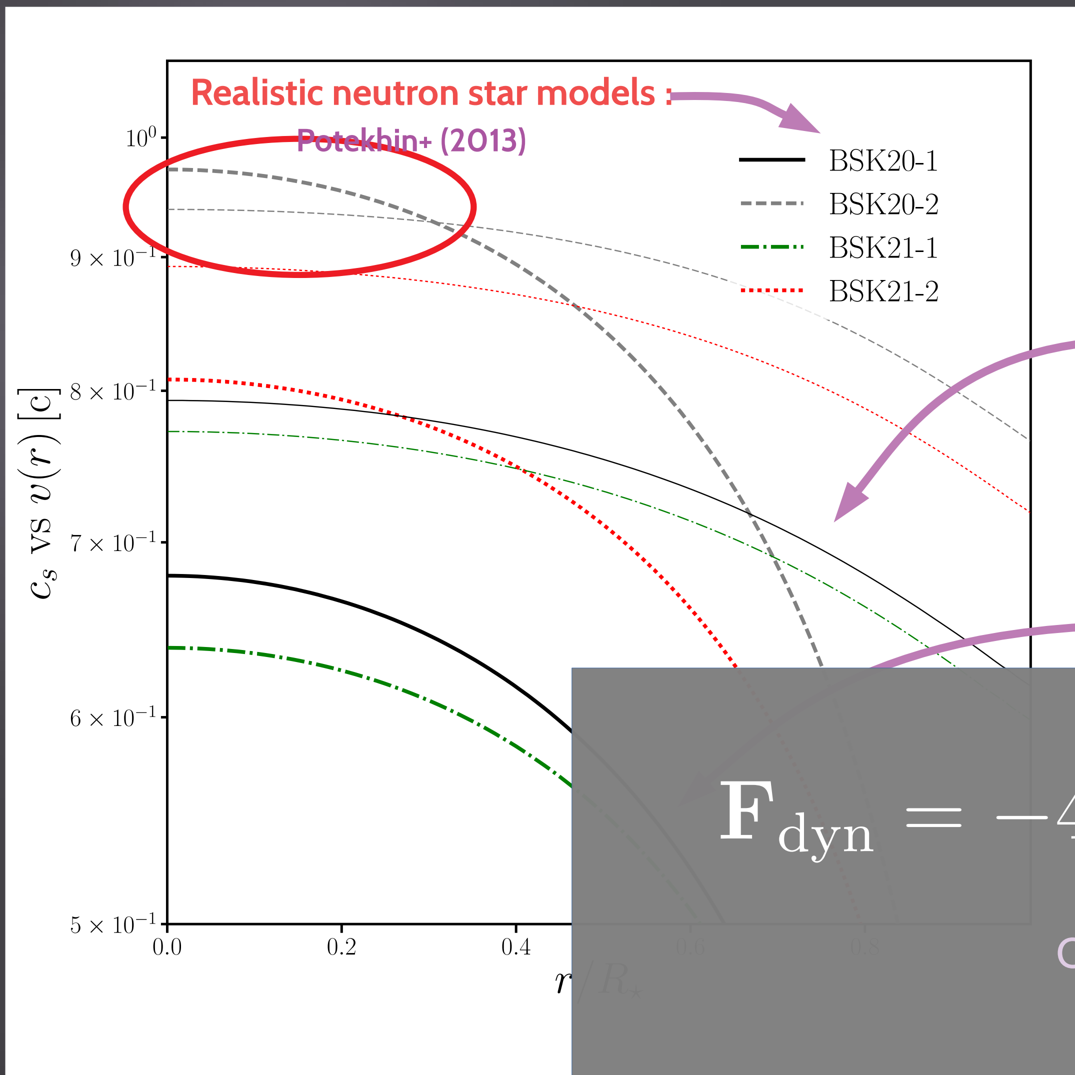
$$v(r) = \sqrt{1 - e^{2(\Phi(\infty) - \Phi(r))}}$$

$$c_s(r)$$

Capture can also happens in the subsonic regime!

But most of the time in the supersonic regime.

What is the speed regime for capture ?



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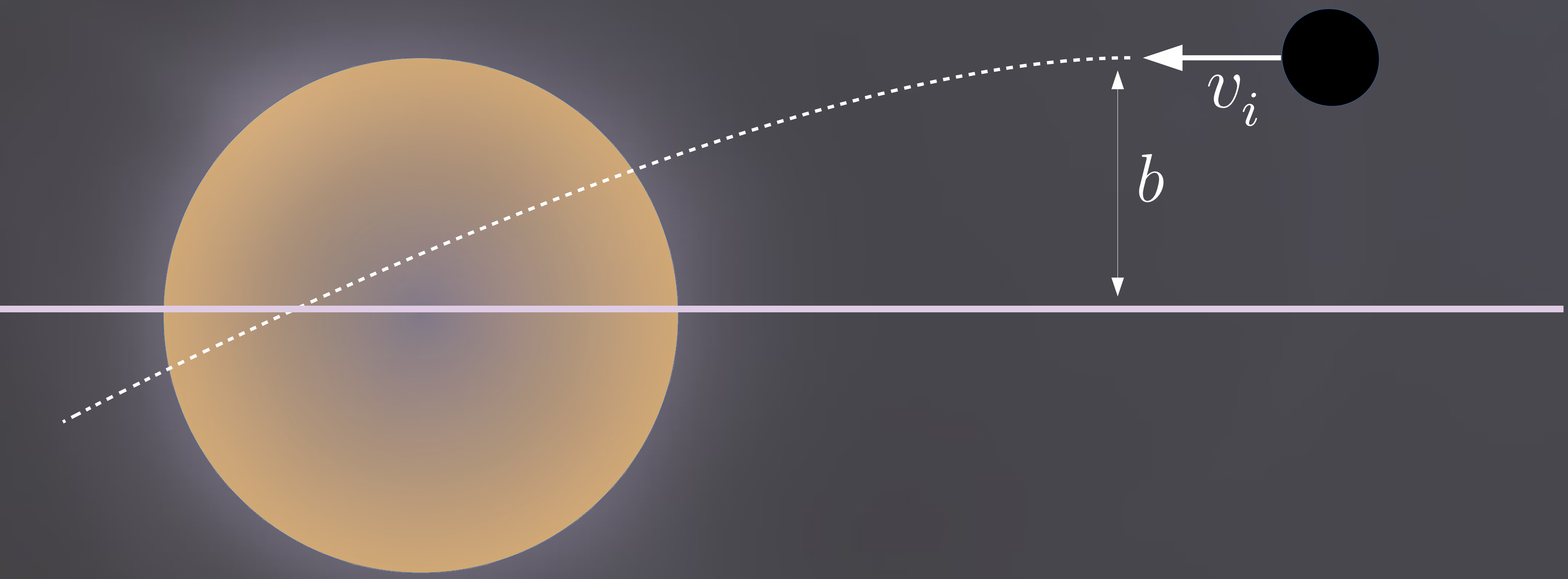
$$c_s(r)$$

$$\mathbf{F}_{\mathrm{dyn}} = -4\pi G^2 m^2 \rho \ln \Lambda_{\mathrm{dyn}}(v) \frac{\boldsymbol{v}}{v^3}$$

Chandrasekhar (1949)

What is the dominant process for capture?



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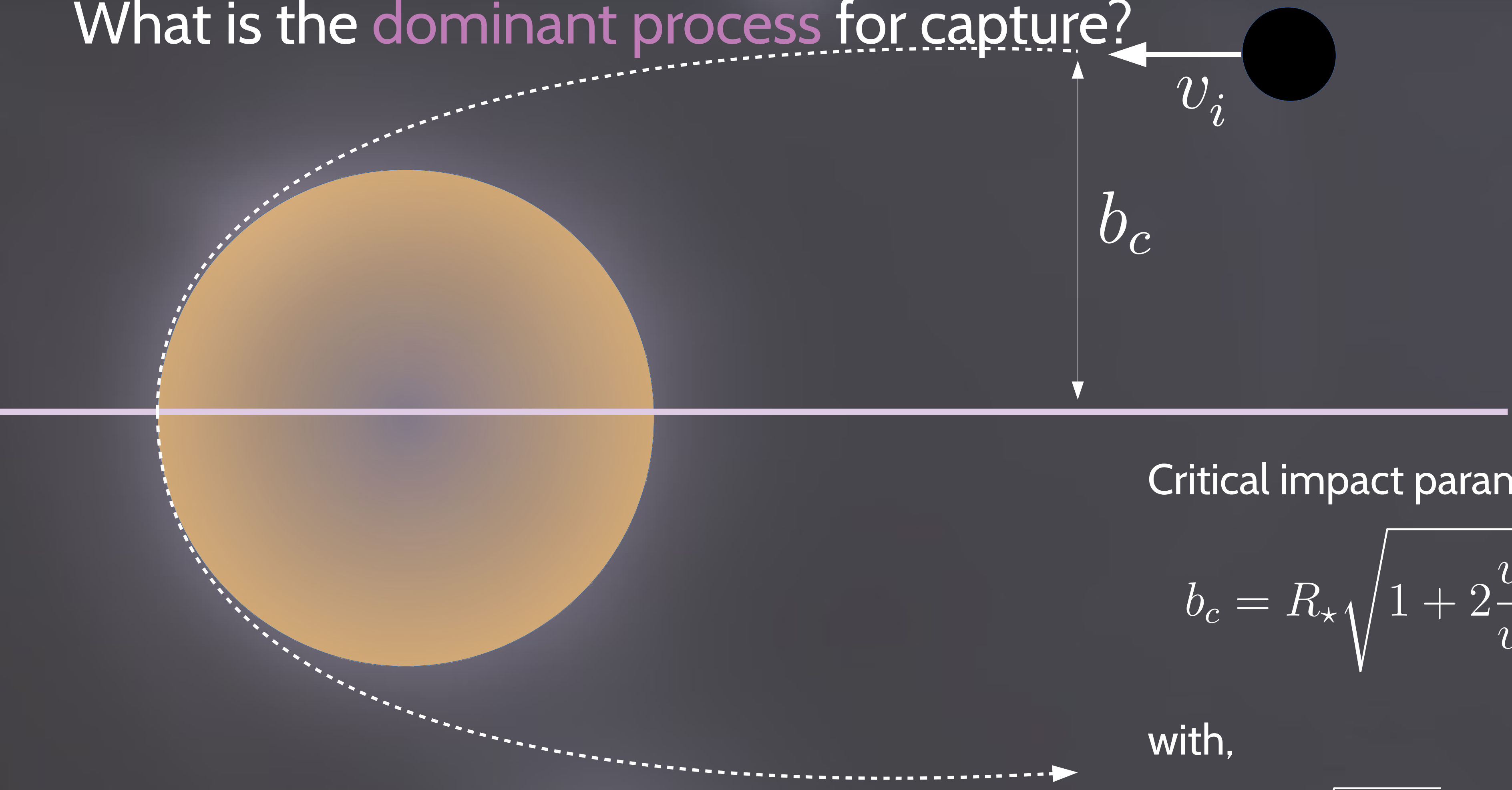


Critical impact parameter

$$b_c = R_\star \sqrt{1 + 2\frac{v_\star^2}{v_i^2}}$$

with,

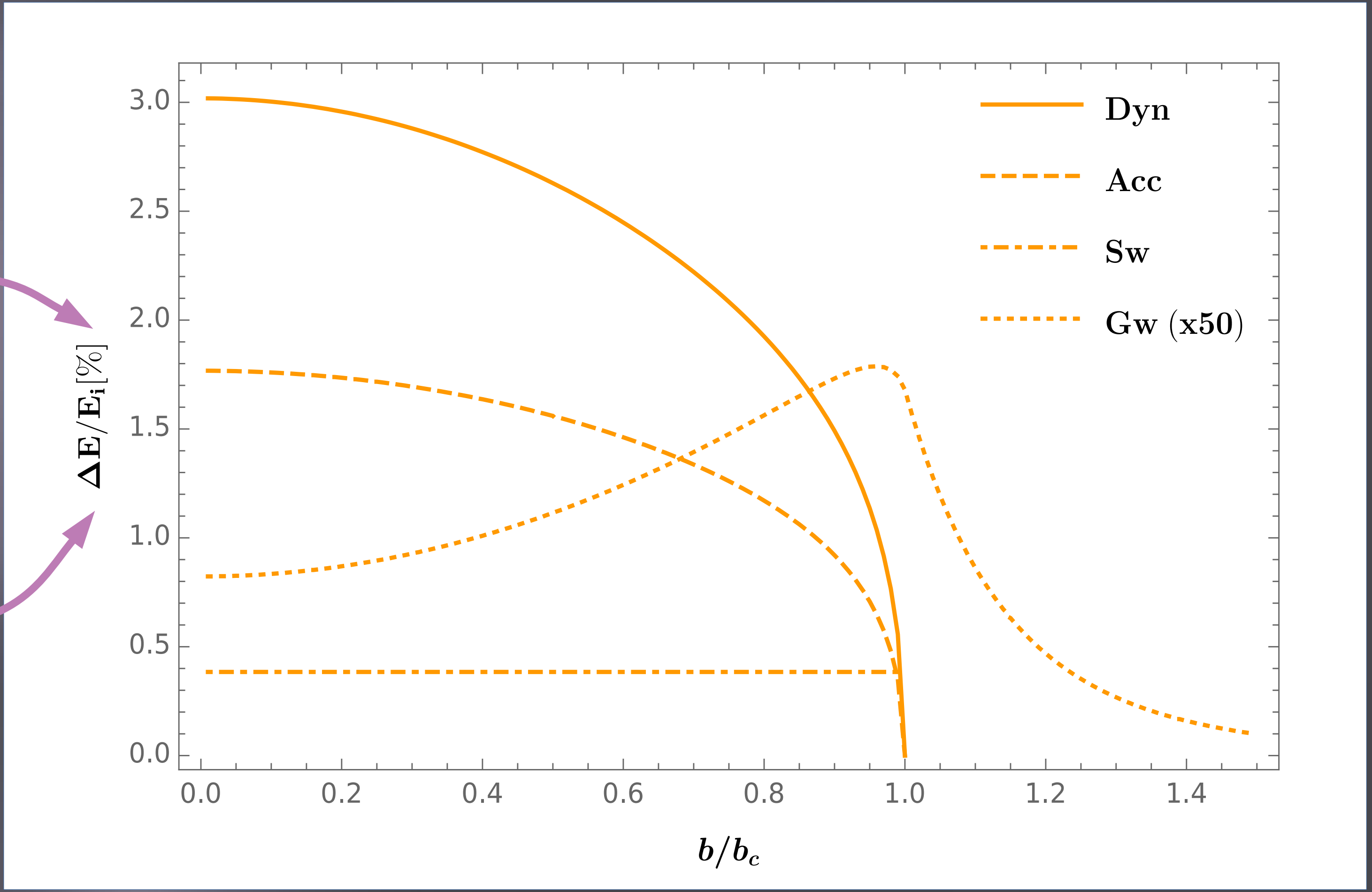
$$v_\star = \sqrt{\frac{GM_\star}{R_\star}}$$

What is the dominant process for capture?

$$E_i = \frac{1}{2} m v_i^2$$

(Here for $v_i = 10^{-3}$)

$$|\Delta E| = \int_c \mathbf{F} \cdot \mathrm{d}\mathbf{l}$$



Yoann Genolini

Estimate of the number of event

The PBH distribution follows a Maxwellian in velocities

$$\mathrm{d}^3 n = n_{\mathrm{PBH}} \left(\frac{3}{2\pi \bar{v}^2} \right)^{3/2} \exp\left\{ \frac{-3v^2}{2\bar{v}^2} \right\} \mathrm{d}^3 v,$$

Rate of NS-PBH encounter leading to capture

$$\mathcal{G}_\star = \int \frac{\mathrm{d}^3 n}{\mathrm{d}v^3} \, \mathcal{S}(v) \; v \; \mathrm{d}^3 v \qquad \text{with:} \qquad \mathcal{S}(v) = \pi \; b_{\mathcal{G}}^2$$

Estimate of the number of event in the Galaxy

$$N_\star \simeq 10^9$$

Rate of NS-PBH encounter leading to capture

$$\mathcal{G}_\star N_\star \simeq 0.021 \left(\frac{\rho_{\mathrm{PBH}}}{\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{10^{-3}}{\bar{v}}\right)^3 \mathcal{C}\,[X]\,\mathrm{Myr}^{-1}$$

with $X = X(m,\bar{v}) \equiv \left(\frac{m}{10^{25}\mathrm{g}}\right)\left(\frac{10^{-3}}{\bar{v}}\right)^2$

Within $\tau_U = 10^{10} yr$, few ~ 100 of NS transmutted into BH.

Compare with the rate of NS-PBH encounter

$$\Gamma_\star \mathcal{N}_\star \simeq 0.38 \left(\frac{\rho_{\mathrm{BH}}}{\mathrm{GeV\,cm}^{-3}}\right)\left(\frac{10^{25}\mathrm{g}}{m}\right)\left(\frac{10^{-3}}{\bar{v}}\right)\mathrm{Myr}^{-1}$$

Similar to the GRB rate in the Galaxy

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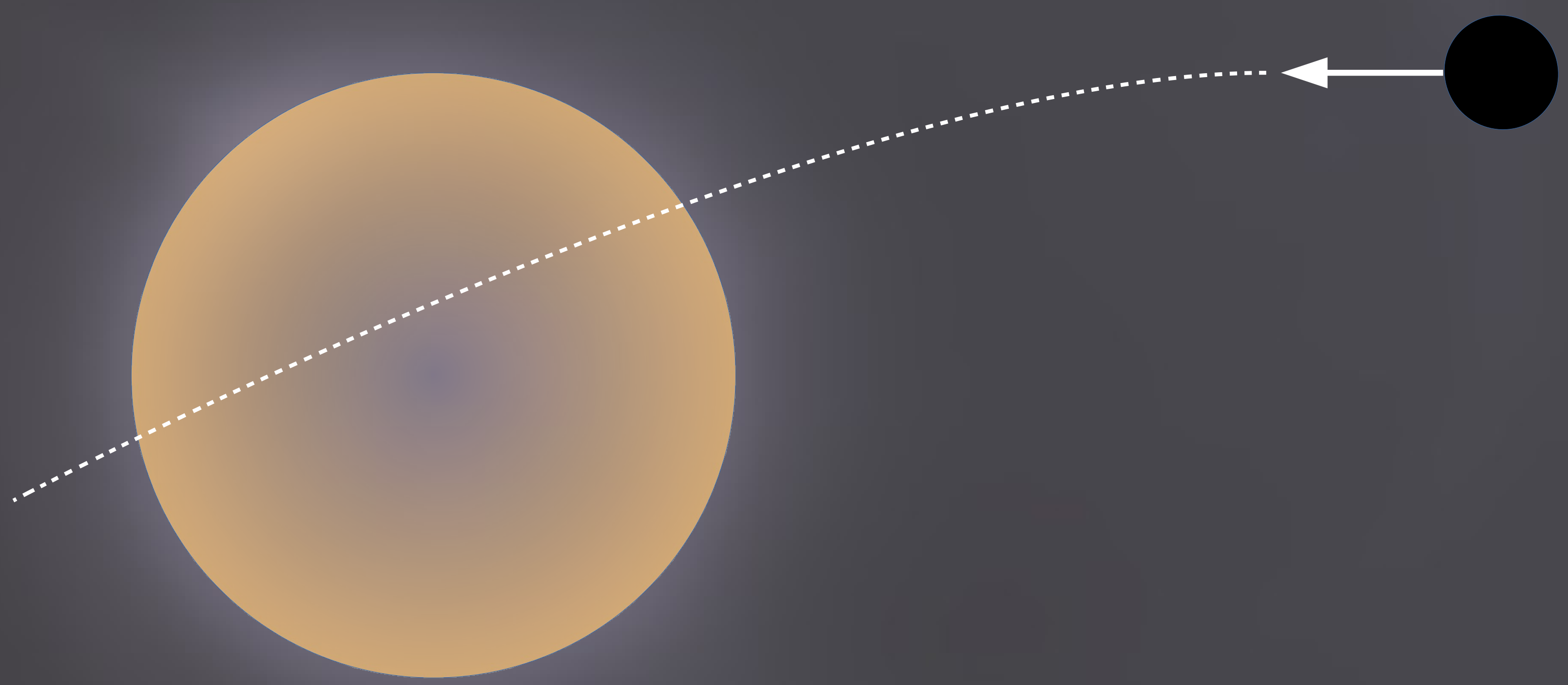
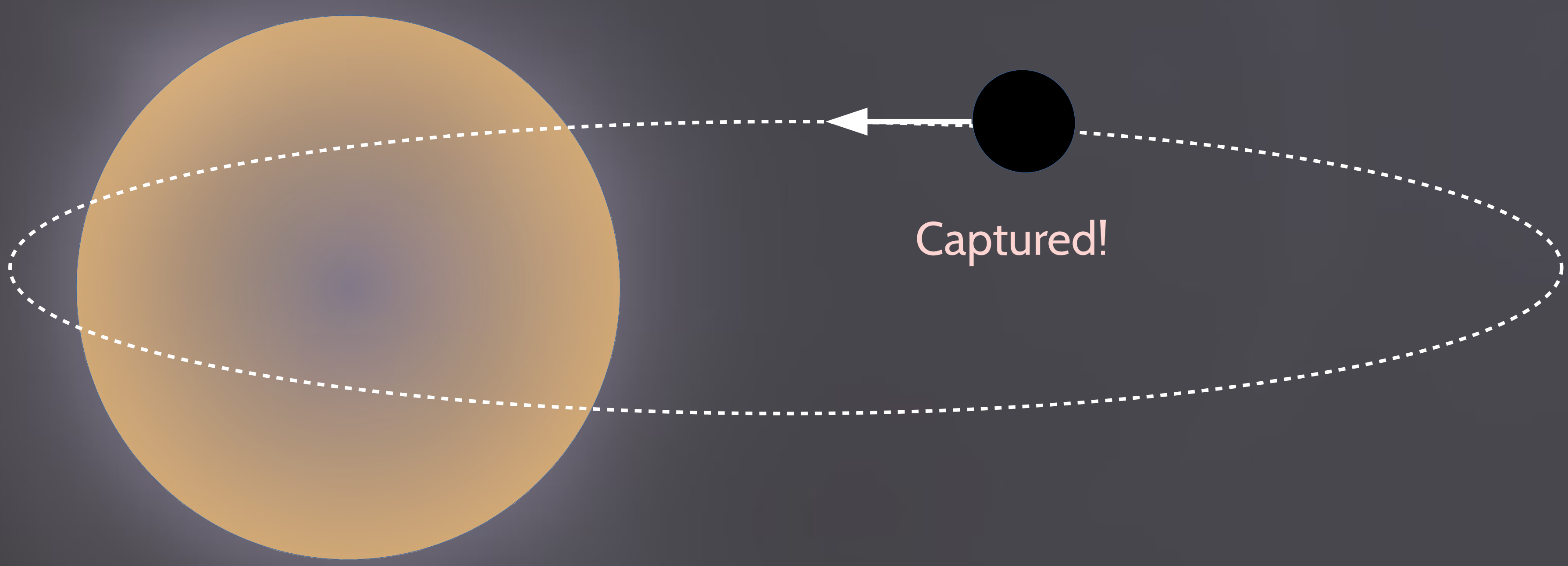
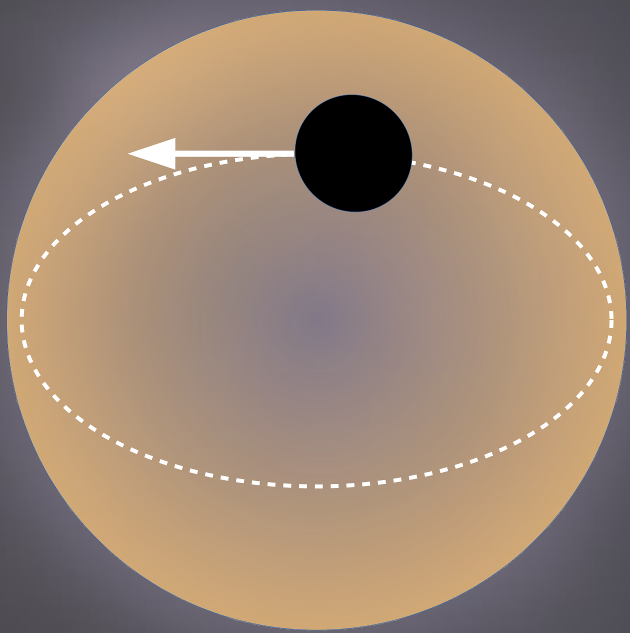
→ Rare events !

PBH interactions with a NS – Post capture dynamic




Captured!

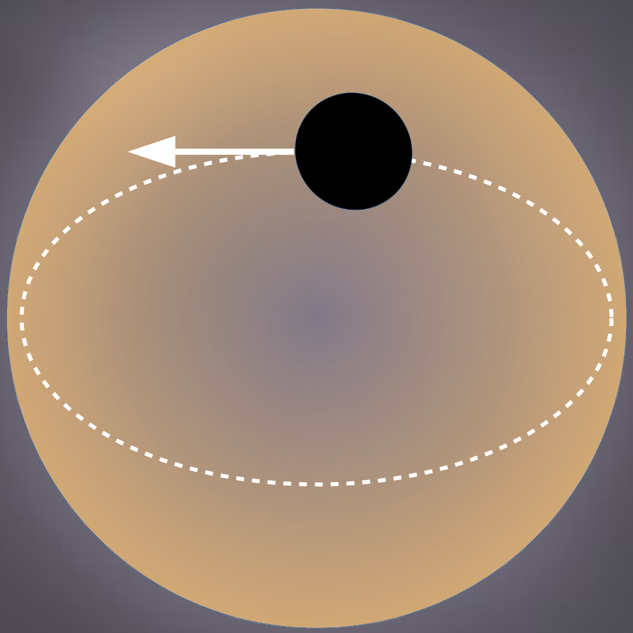


Settling time within the NS

$$t_{\rm settle} \lesssim 4 \times 10^4 \left(\frac{m}{10^{22}\,{\rm g}} \right)^{-3/2} {\rm yr}$$

Capela+ (2013)

Credit: ESO/L.Calçada



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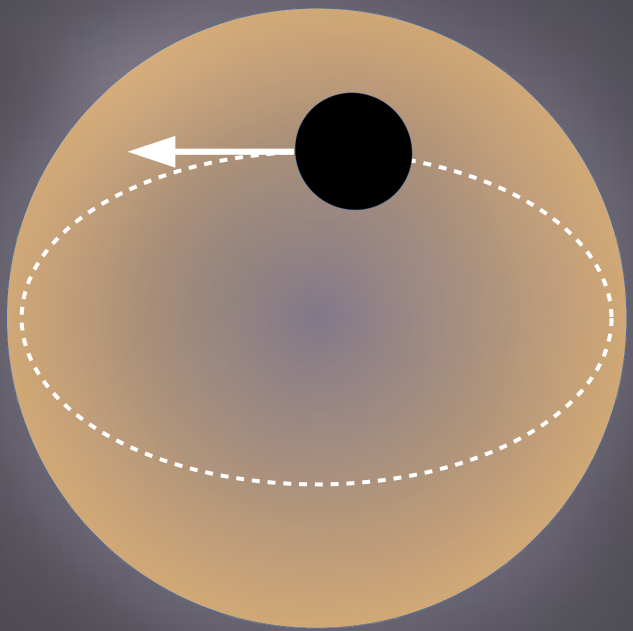
The motion becomes subsonic for

$$r \lesssim R_\star \frac{c_s}{v_\star}$$



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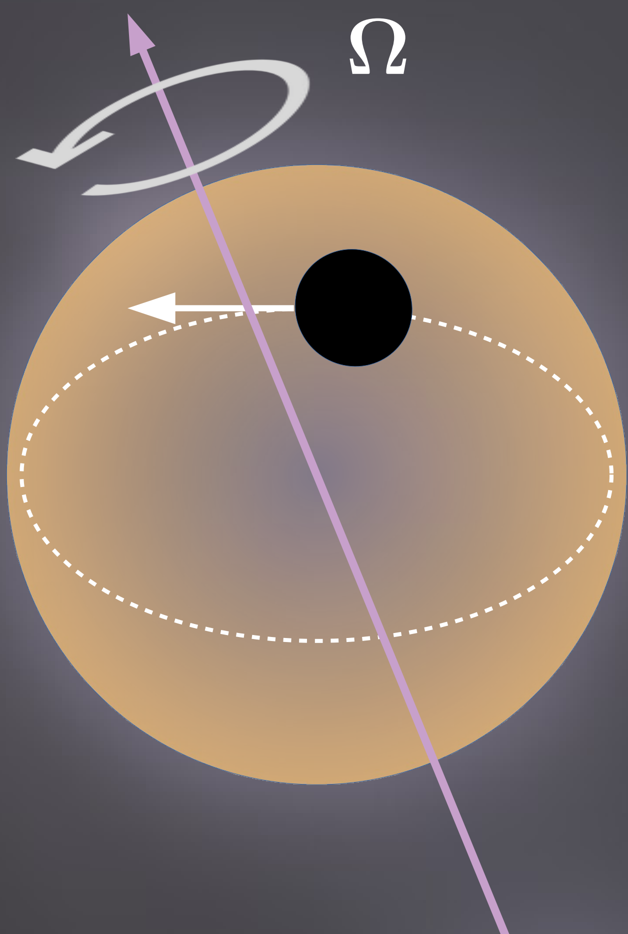
Model	BSK-20-1	BSK-20-2	BSK 21-1	BSK 21-2
Radius $R_\star$ [km]	11.6	10.7	12.5	12.0
Mass $M_\star$ [$M_\odot$]	1.52	2.12	1.54	2.11
$v_\star$ [c]	0.44	0.54	0.43	0.50
$f_\star = 1/T_\star$ [kHz]	1.8	2.4	1.6	2.0
c_s (core) [c]	0.68	0.97	0.64	0.81
μ_n (core) [GeV]	0.27	0.81	0.24	0.51

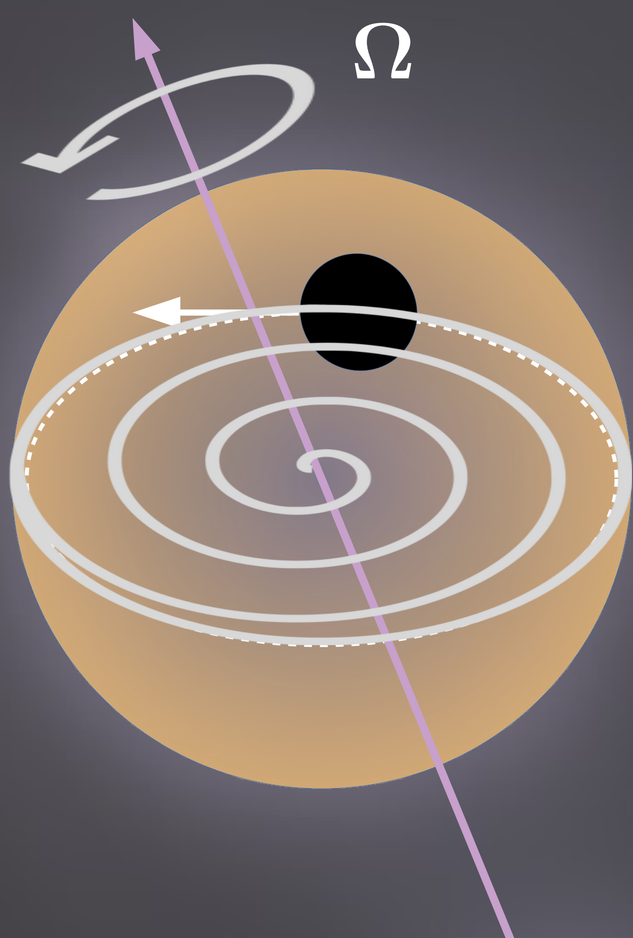
Realistic neutron star models Potekhin+ (2013)



Subsonic regime

↓

DF negligible & accretion dominates



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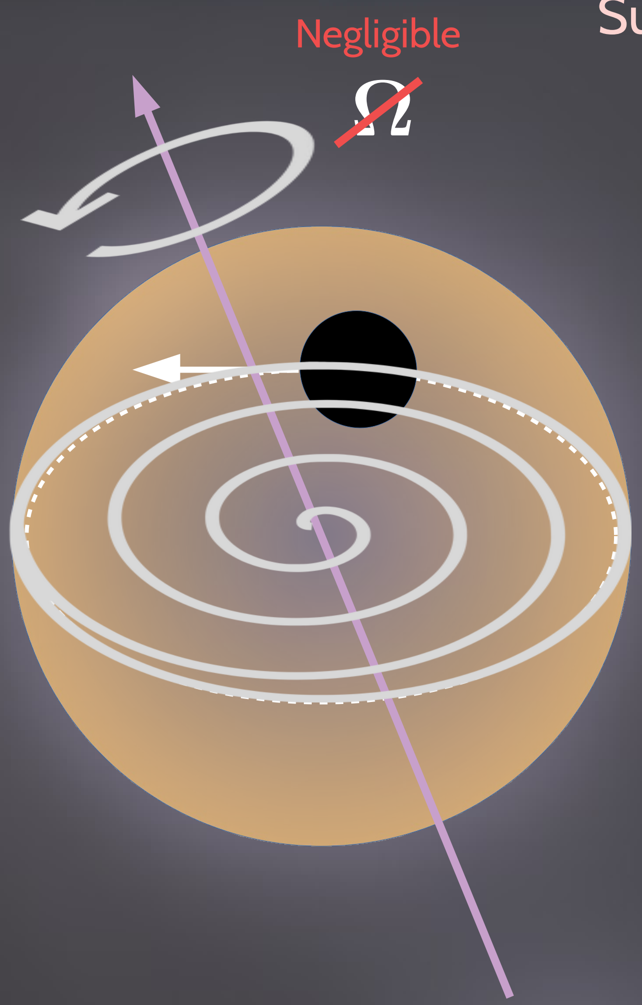
Equation of motion

$$\ddot{\boldsymbol{r}} + \mathcal{D}(t)\left[\dot{\boldsymbol{r}} - \boldsymbol{\Omega} \times \boldsymbol{r}\right] + \omega_\star^2 \boldsymbol{r} = 0$$

Y.G. et al. PRD (2020)



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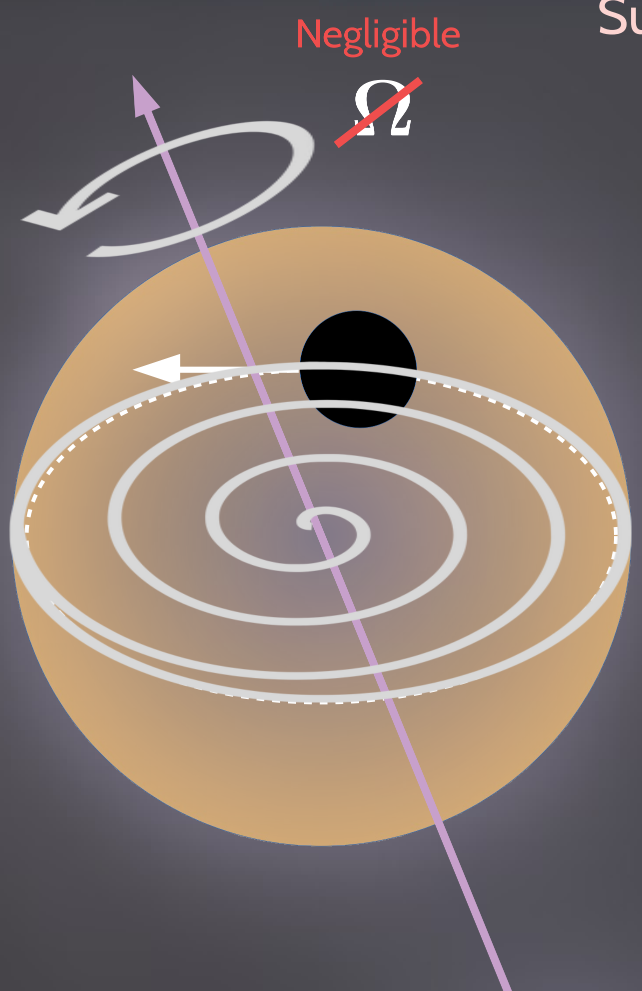

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Y.G. et al. PRD (2020)

↓

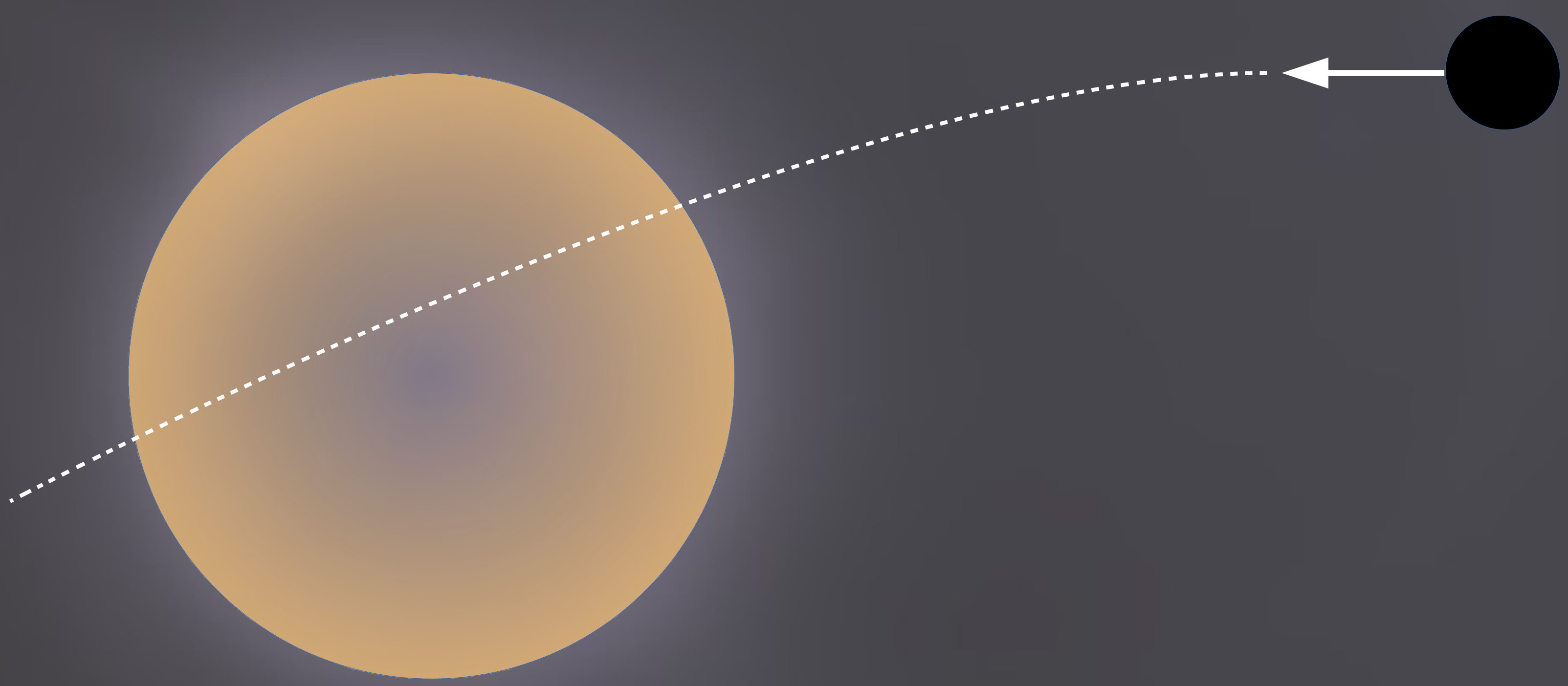
For $\dfrac{\mathcal{D}}{\omega_\star} \sim 2.8 \times 10^{-12} \left(\dfrac{m}{10^{22}\mathrm{g}}\right) \ll 1$

conserved quantity $m\, r^2 = \mathrm{const}$

whatever accretion regime

Yoann Genolini

Signatures PBH – NS encounter



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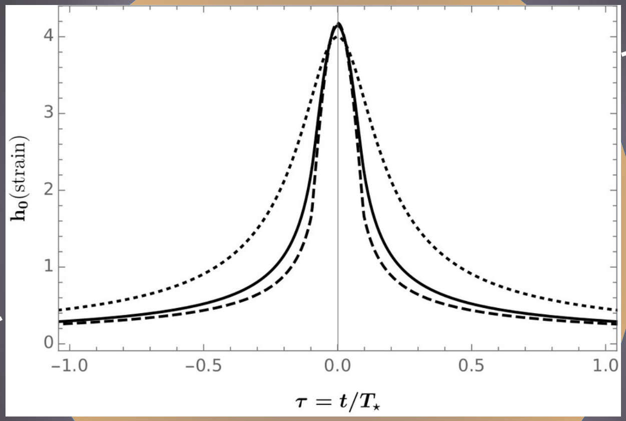

→ Gravitational wave burst

$$h_0 \sim 10^{-25} \left(\frac{m}{10^{25}\mathrm{g}}\right) \left(\frac{1\,\mathrm{kpc}}{d}\right)$$

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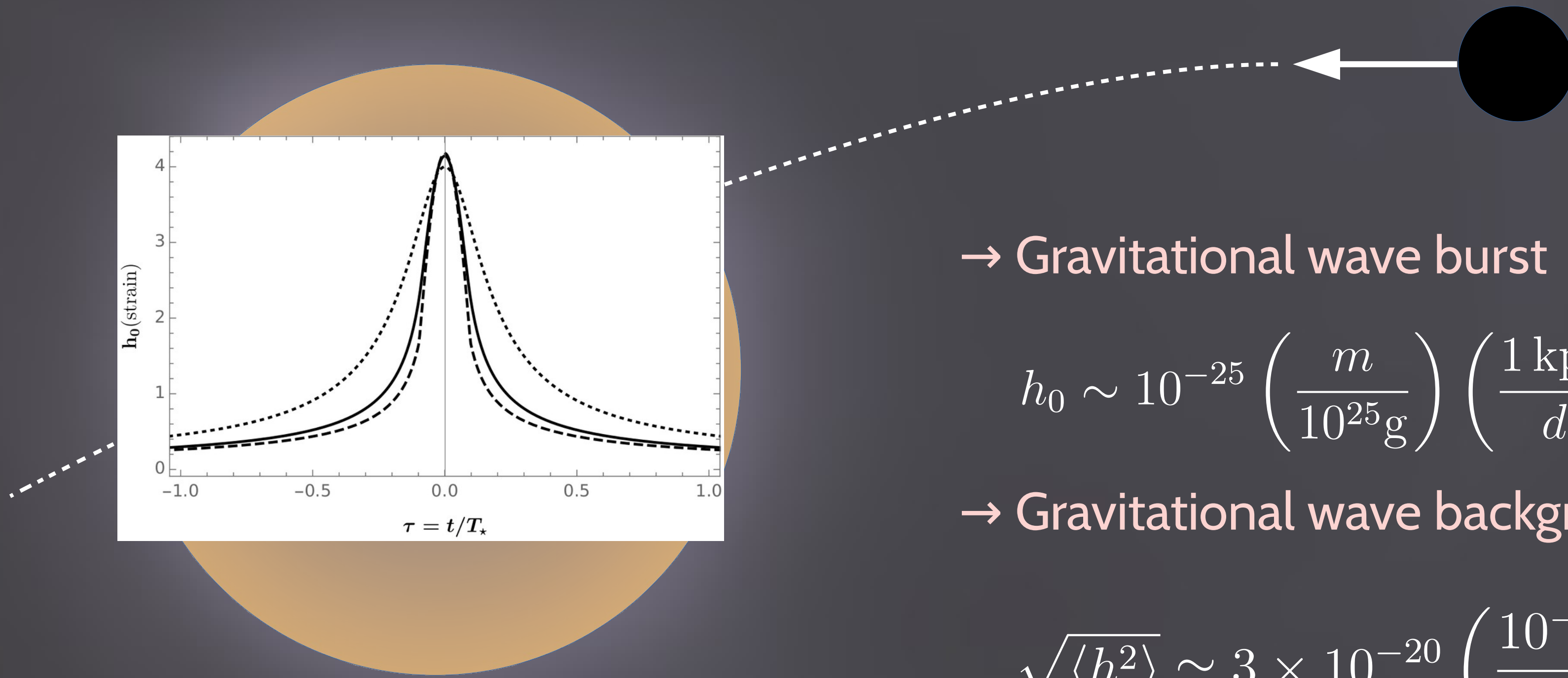


→ Gravitational wave burst

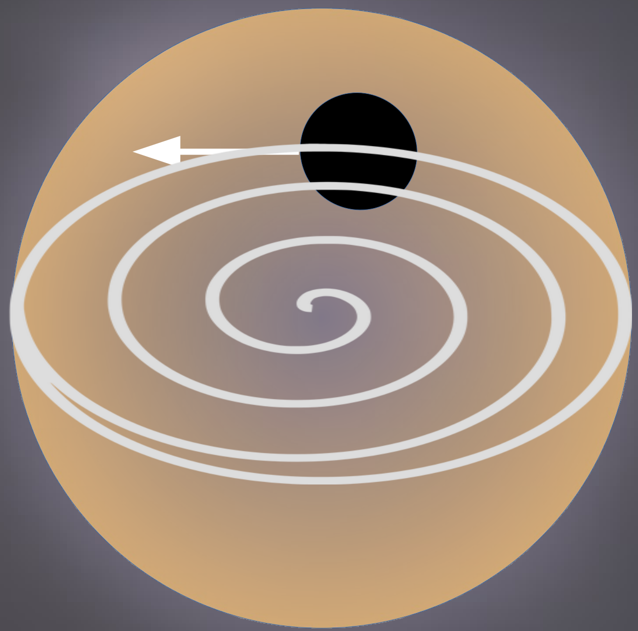
$$h_0 \sim 10^{-25} \left(\frac{m}{10^{25}\,\mathrm{g}}\right) \left(\frac{1\,\mathrm{kpc}}{d}\right)$$

→ Gravitational wave background

$$\sqrt{\langle h_c^2 \rangle} \simeq 3 \times 10^{-20} \left(\frac{10^{-10}\,\mathrm{Hz}}{f}\right)^2$$

far below SKA sensitivity

Signatures captured PBH

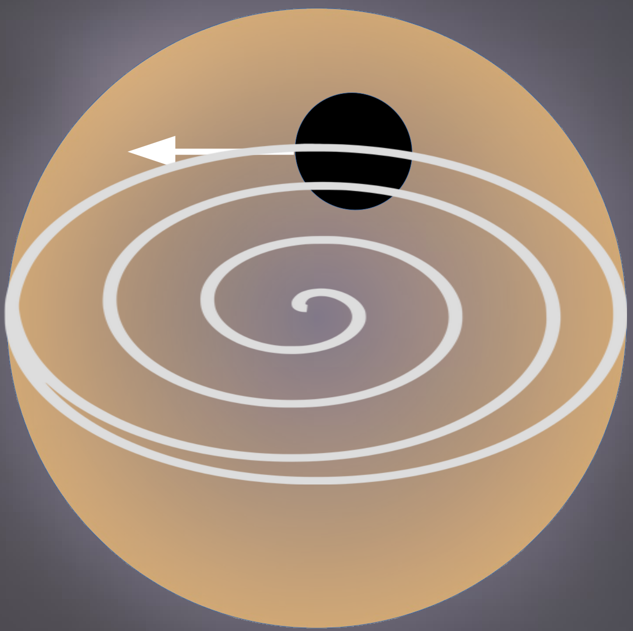


Signatures captured PBH

→ GW emission from the inspiral motion

$$h_0 = \frac{4\sqrt{2}G}{dc^4} m r^2 \omega_\star^2 \approx 2.5 \times 10^{-25} \left(\frac{m}{10^{25}\mathrm{g}}\right) \left(\frac{1\ \mathrm{kpc}}{d}\right)$$

$$f_\star \sim \mathrm{kHz}$$



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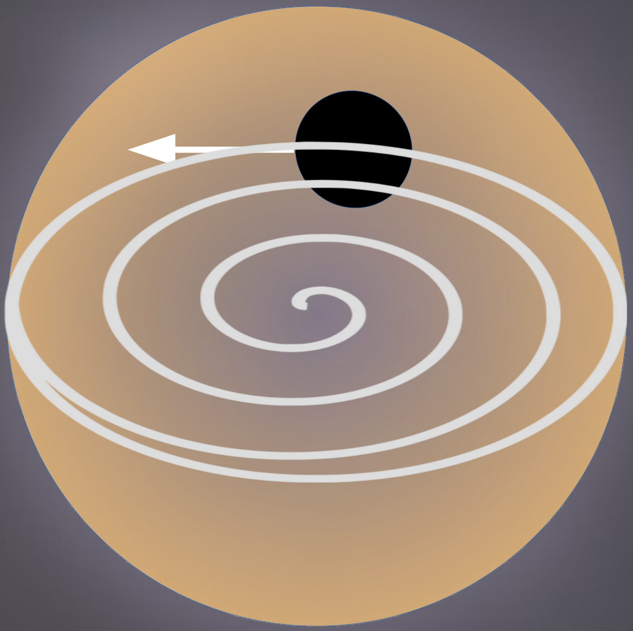

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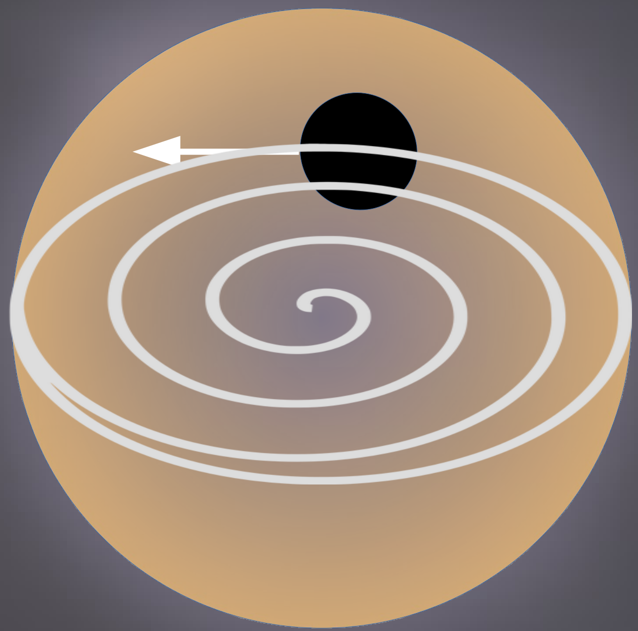
Emission sustained during the all accretion phase

$$t_B = \frac{c_s^3\, R_\star^3}{3\, G^2\, M_\star\, m} \approx 9 \left(\frac{10^{25}\mathrm{g}}{m}\right) \mathrm{hours}$$



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→ Multiwavelength signature from the final collapse
Might depend on the final asymmetry

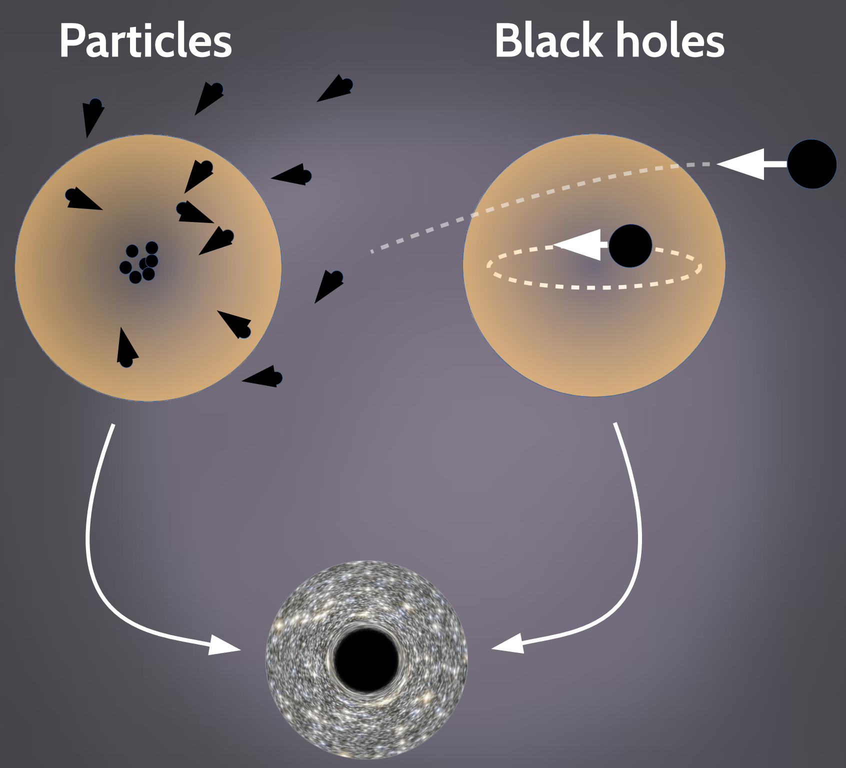
Final radius

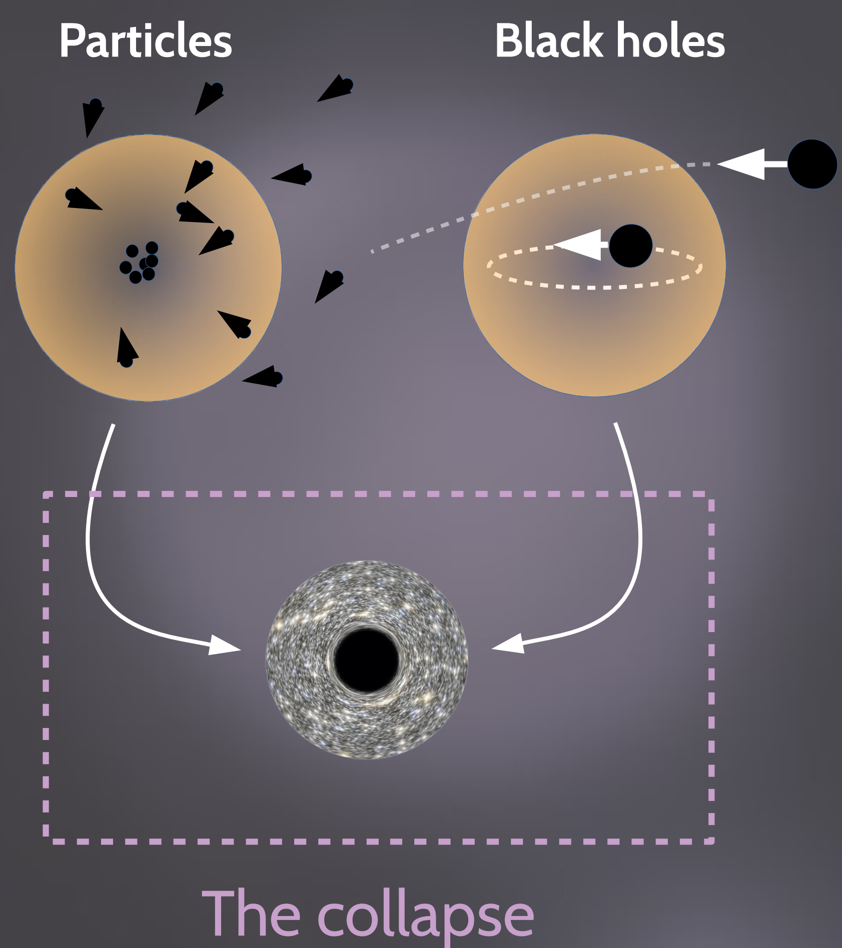
$$R_f = R_\star \sqrt{\frac{m_i}{f\, M_\star}}$$

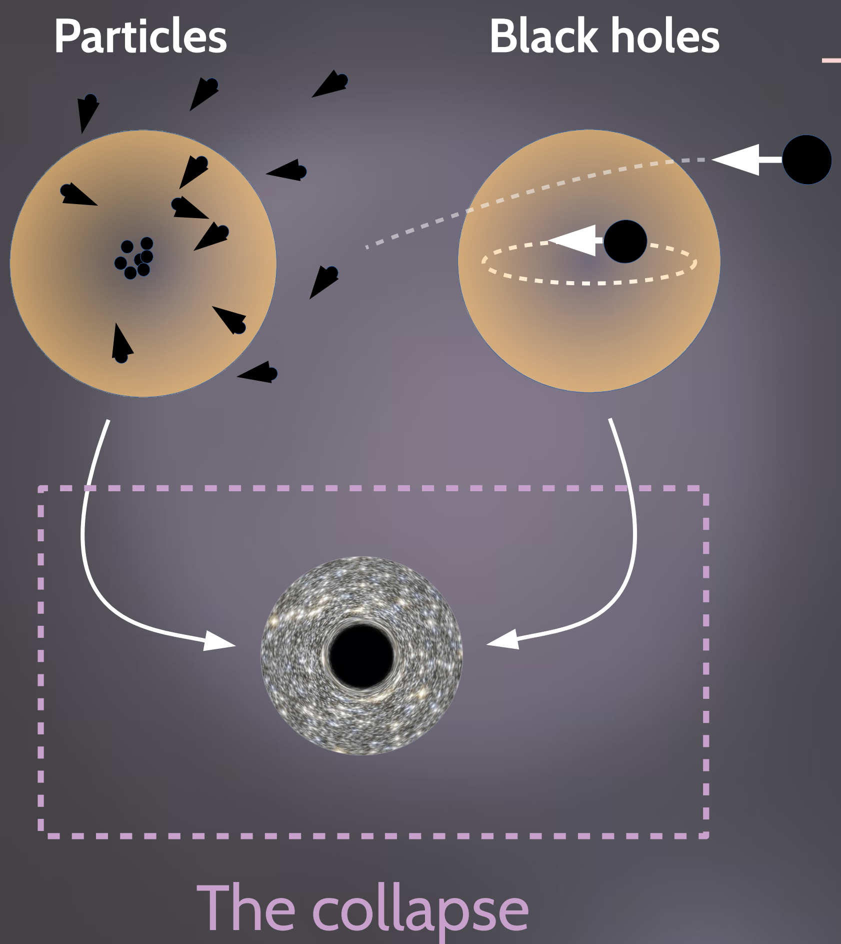
Initial PBH mass

Fraction of the star mass accreted

Common signatures and prospects


Particles
Black holes


Particles
Black holes
The collapse



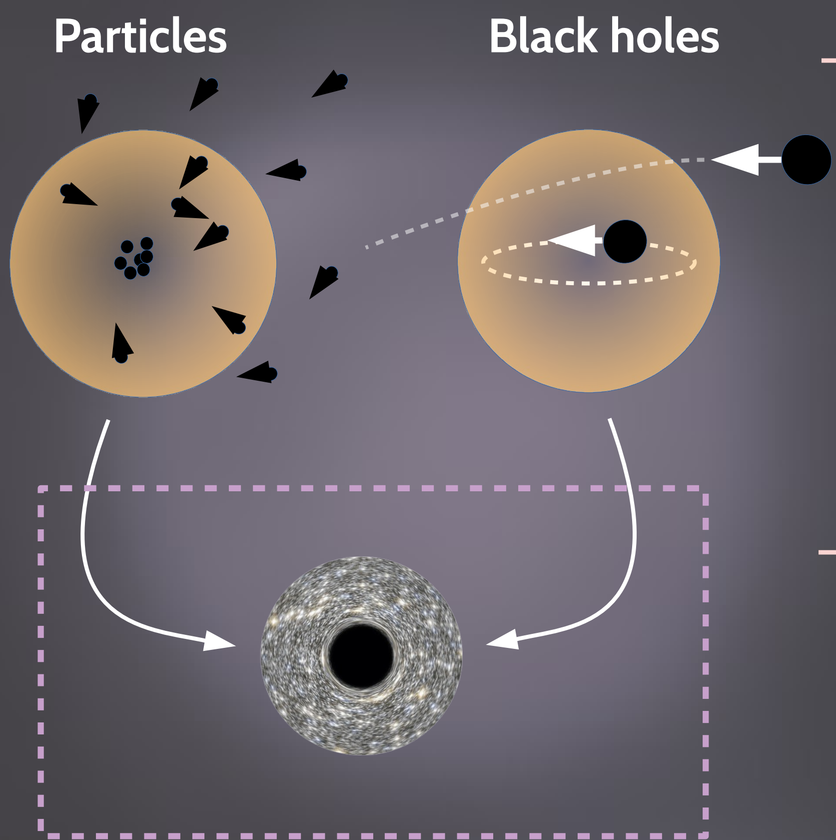
Direct emissions

→ Electromagnetic waves: promising ! GRB? FRB?

No-hair theorem

$$E_B = \frac{B^2}{8\pi}\frac{4\pi}{3}R_\star^3 \simeq 2\times 10^{41}\left(\frac{B}{10^{12}\mathrm{G}}\right)^2\left(\frac{R_\star}{10\,\mathrm{km}}\right)^3 \mathrm{erg}$$

Fuller&Ott (2015), Abramowicz+ (2018), Chirenti+ (2019),…



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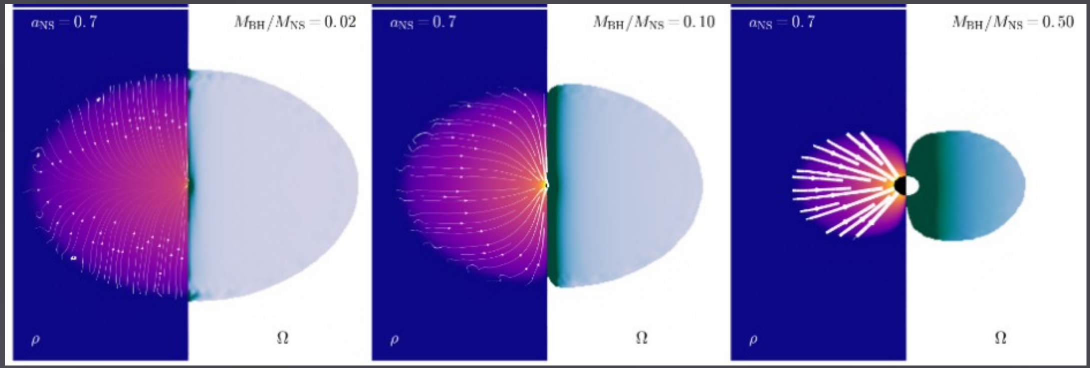
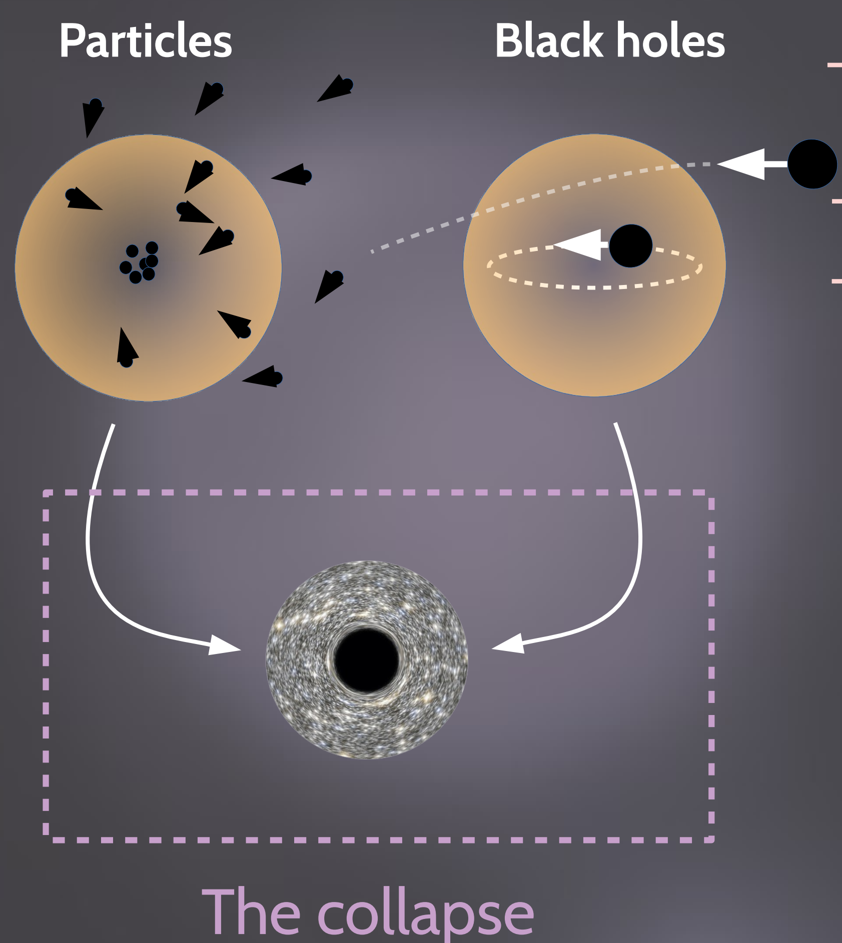


East+ (2019)

But PBH at the center and no magnetic field



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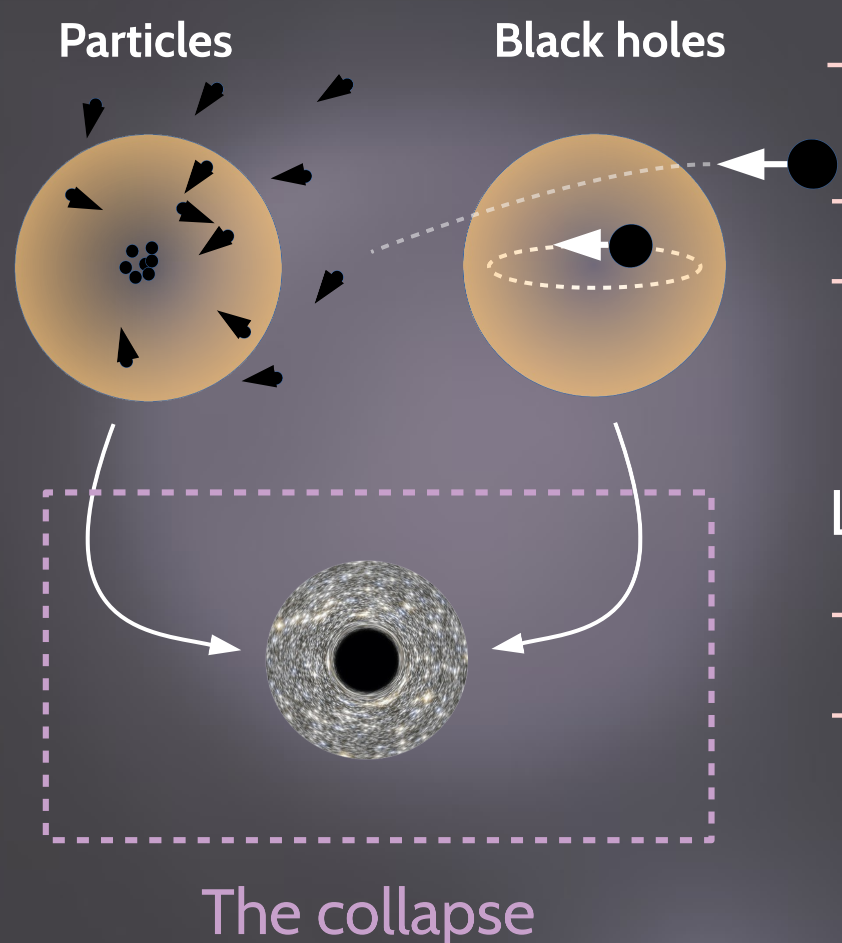
→ Observing quiet kilonovae?

e.g. Bramante+ (2016,2017)



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e.g. Bramante+ (2016,2017)

Later detection

→ Leading mecanism for « light » BH formation?

e.g. Takhistov+ (2021), Dexter+(2014)

→ Solving the missing pulsar problem?

e.g. Bramante+ (2016,2017)