Capture of primordial black holes by neutron stars

Yoann Genolini

A work in collaboration with :
Pasquale Serpico & Peter Tinyakov

Based on : Phys. Rev. D 102, 083004 (2020)

Credit: ESO/L.Calçada

TUG, December 2021

LAPTh/USMB

Outline

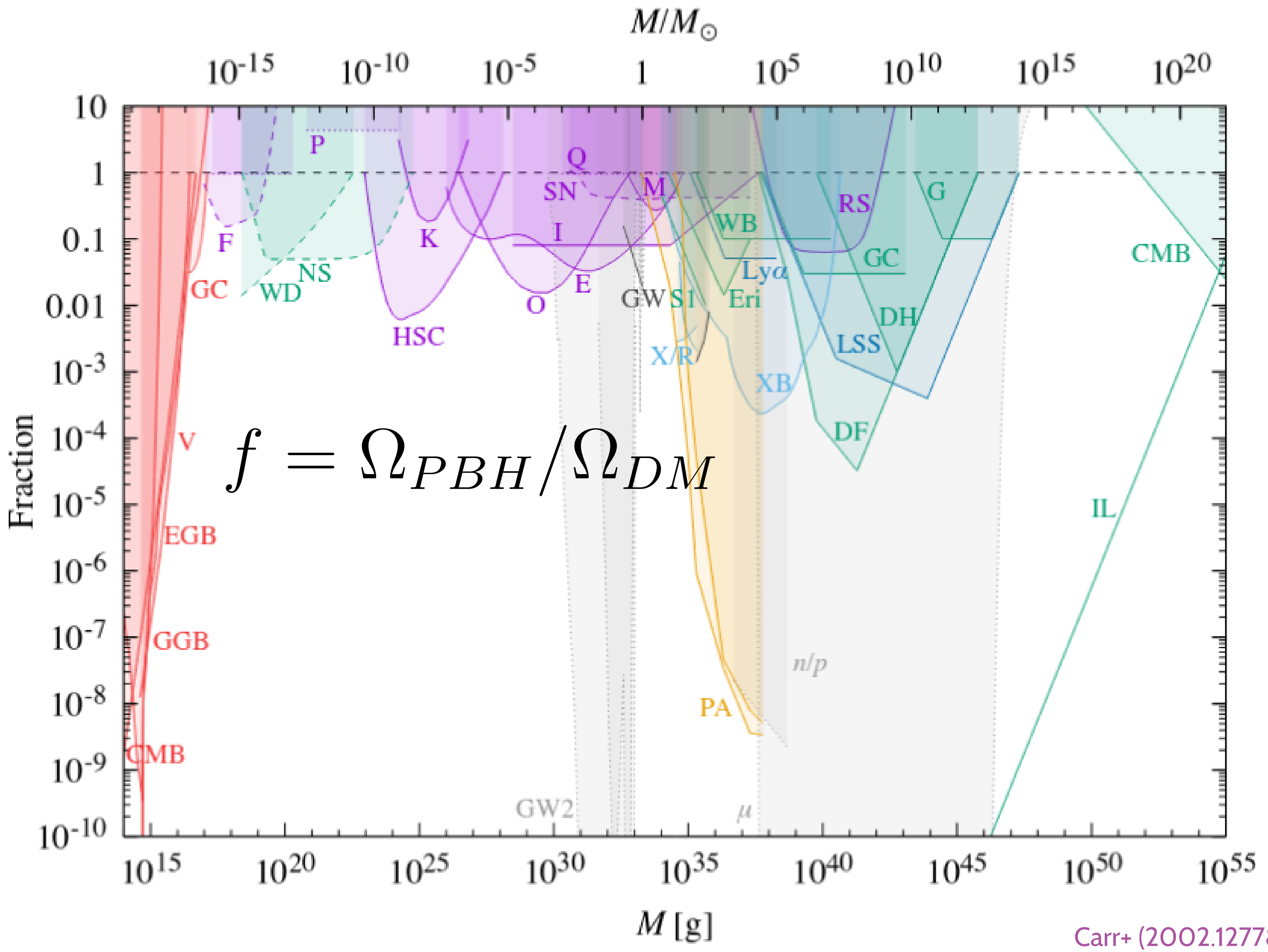
Overview and motivations

PBH interactions with a NS

Capture of a PBH

Post capture dynamic

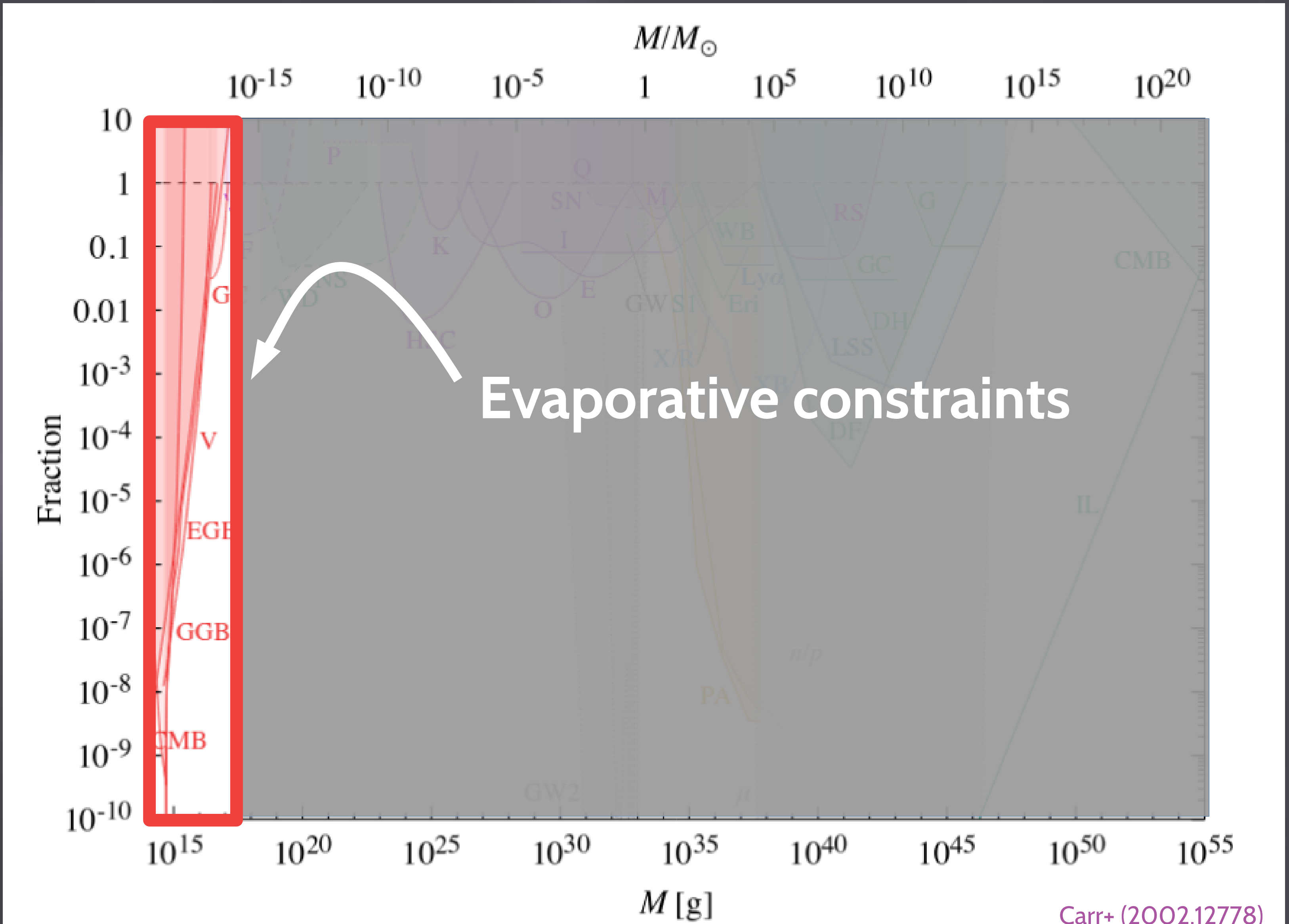
Signatures



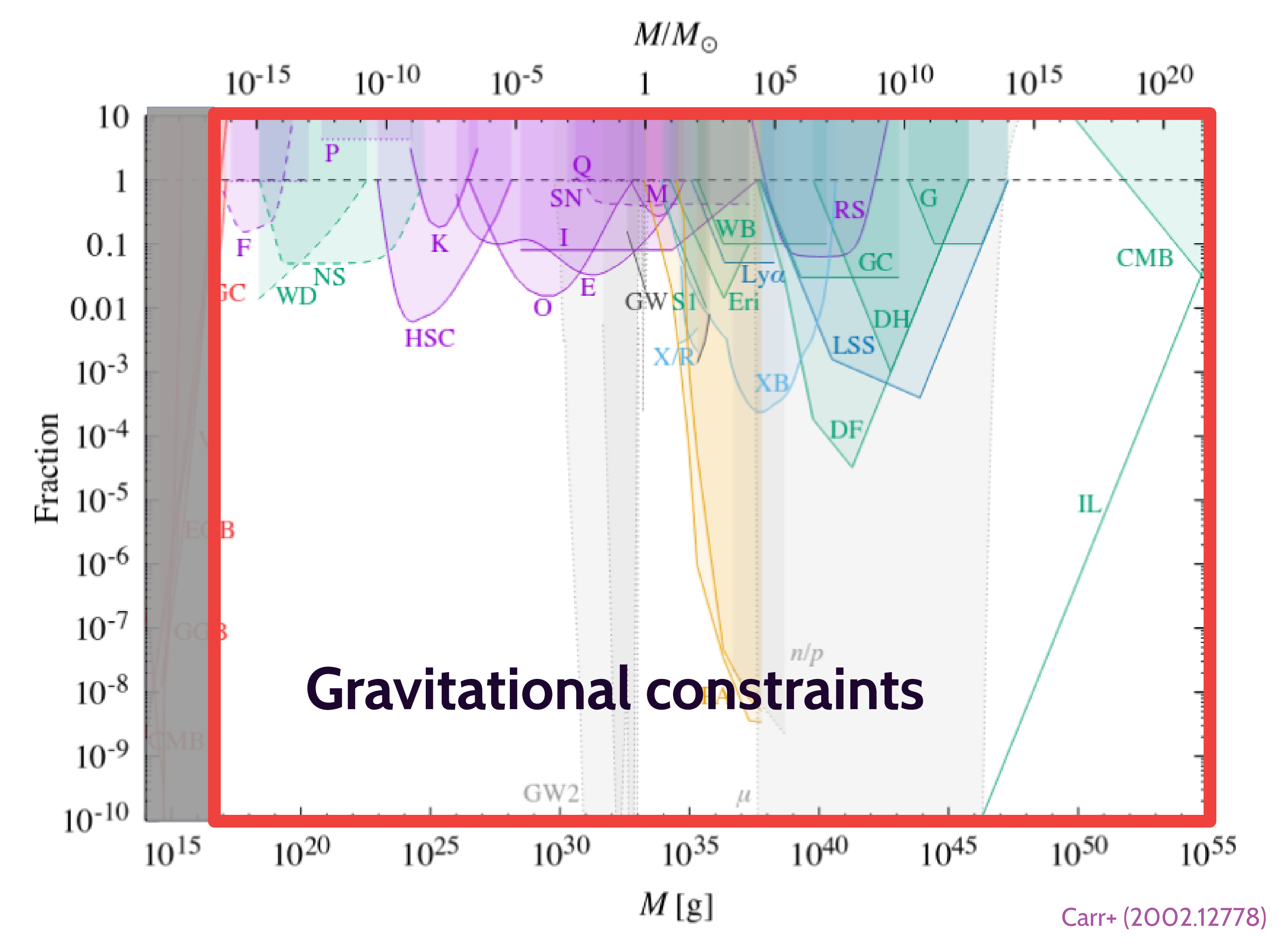
$$f = \Omega_{PBH}/\Omega_{DM}$$

Carr+ (2002.12778)

Credit: ESO/L.Calçada



Carr+ (2002.12778)



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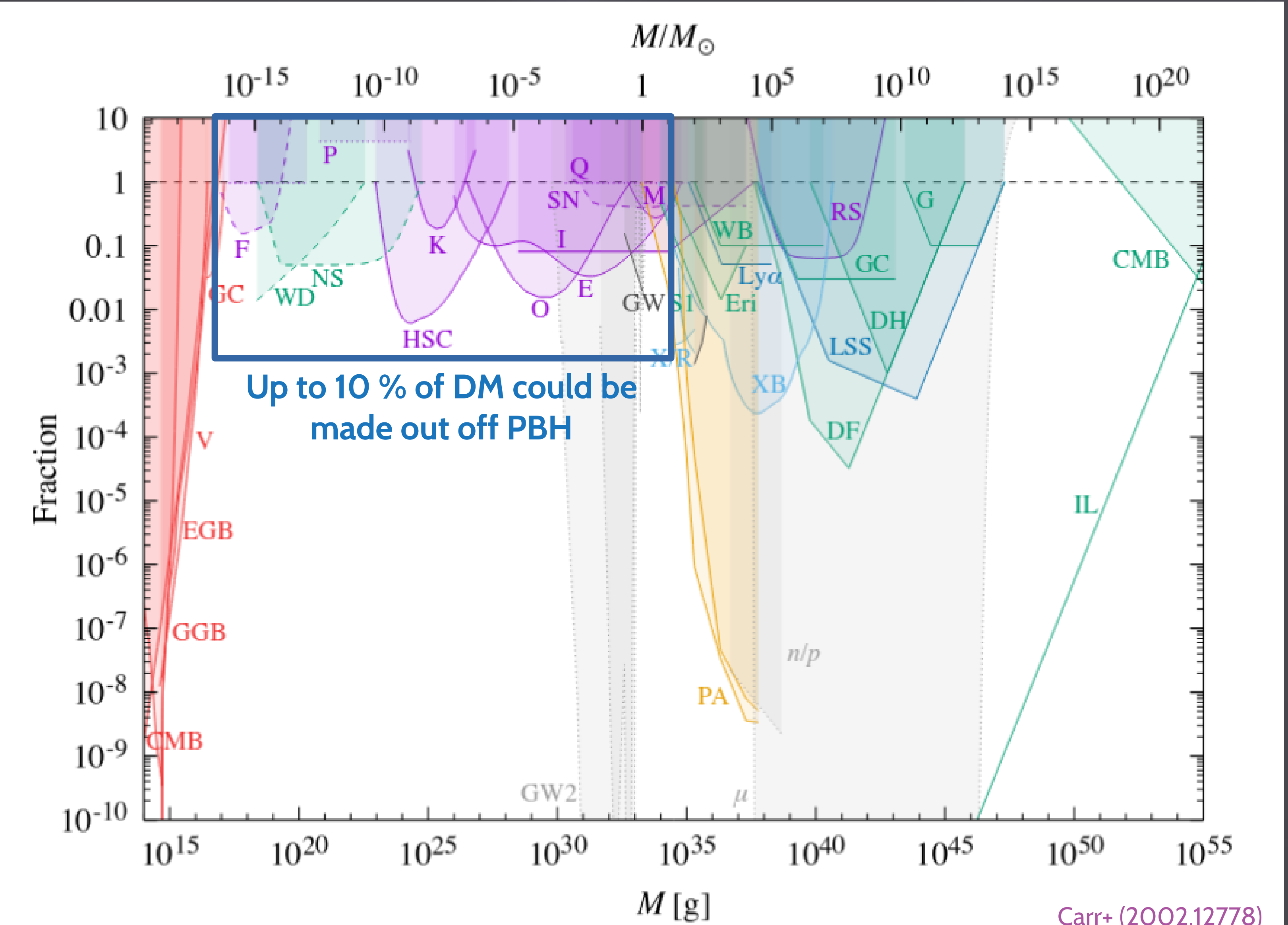

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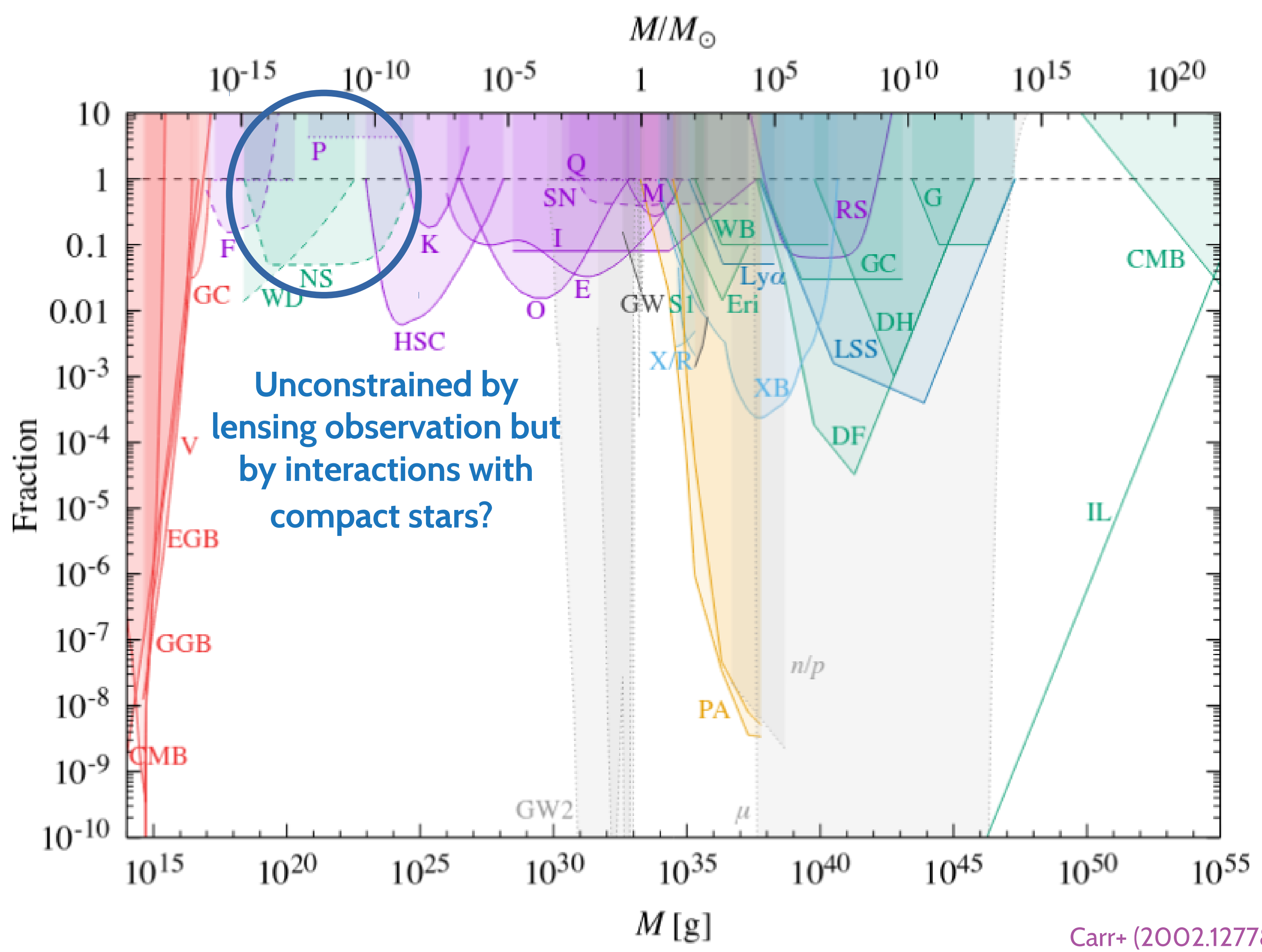
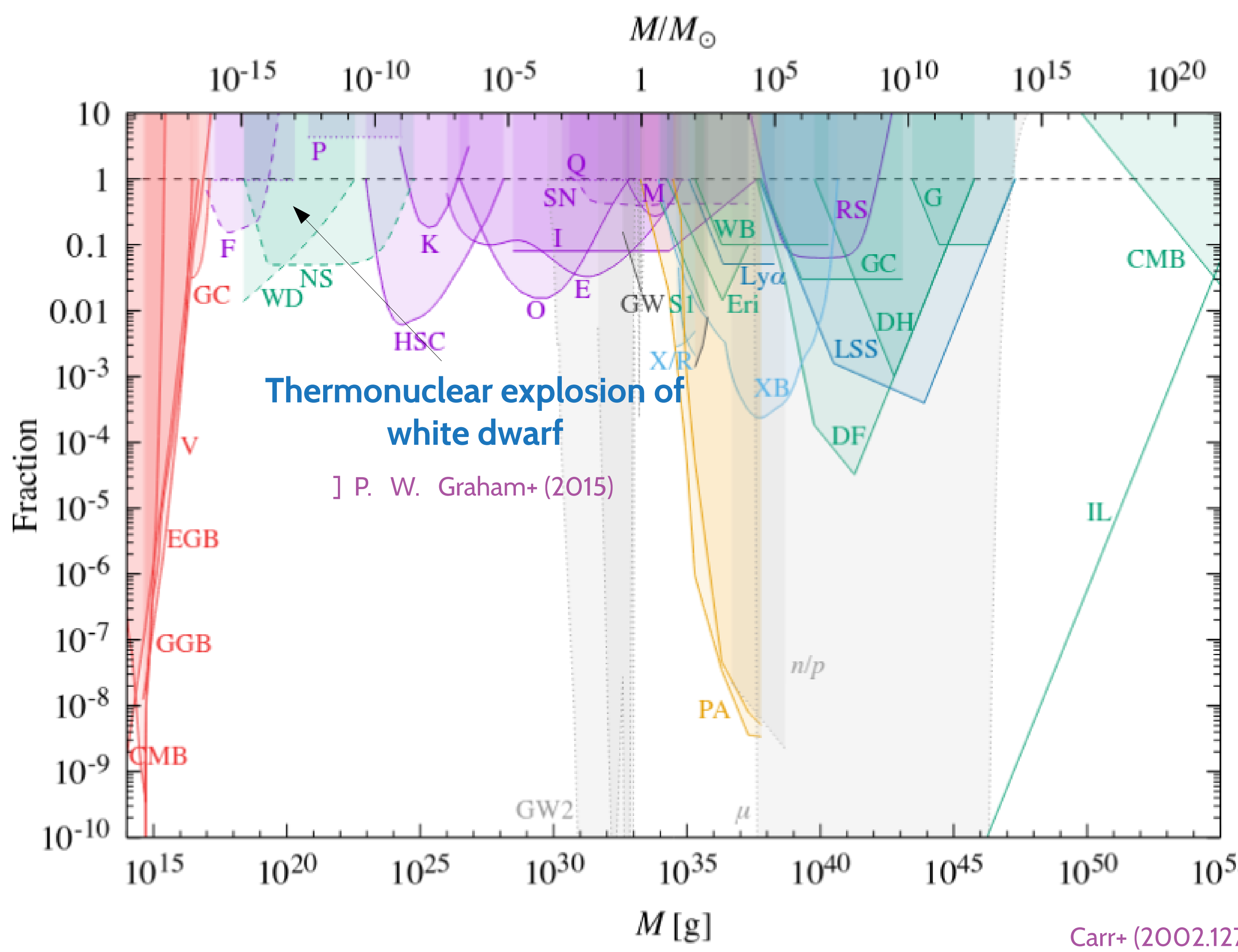
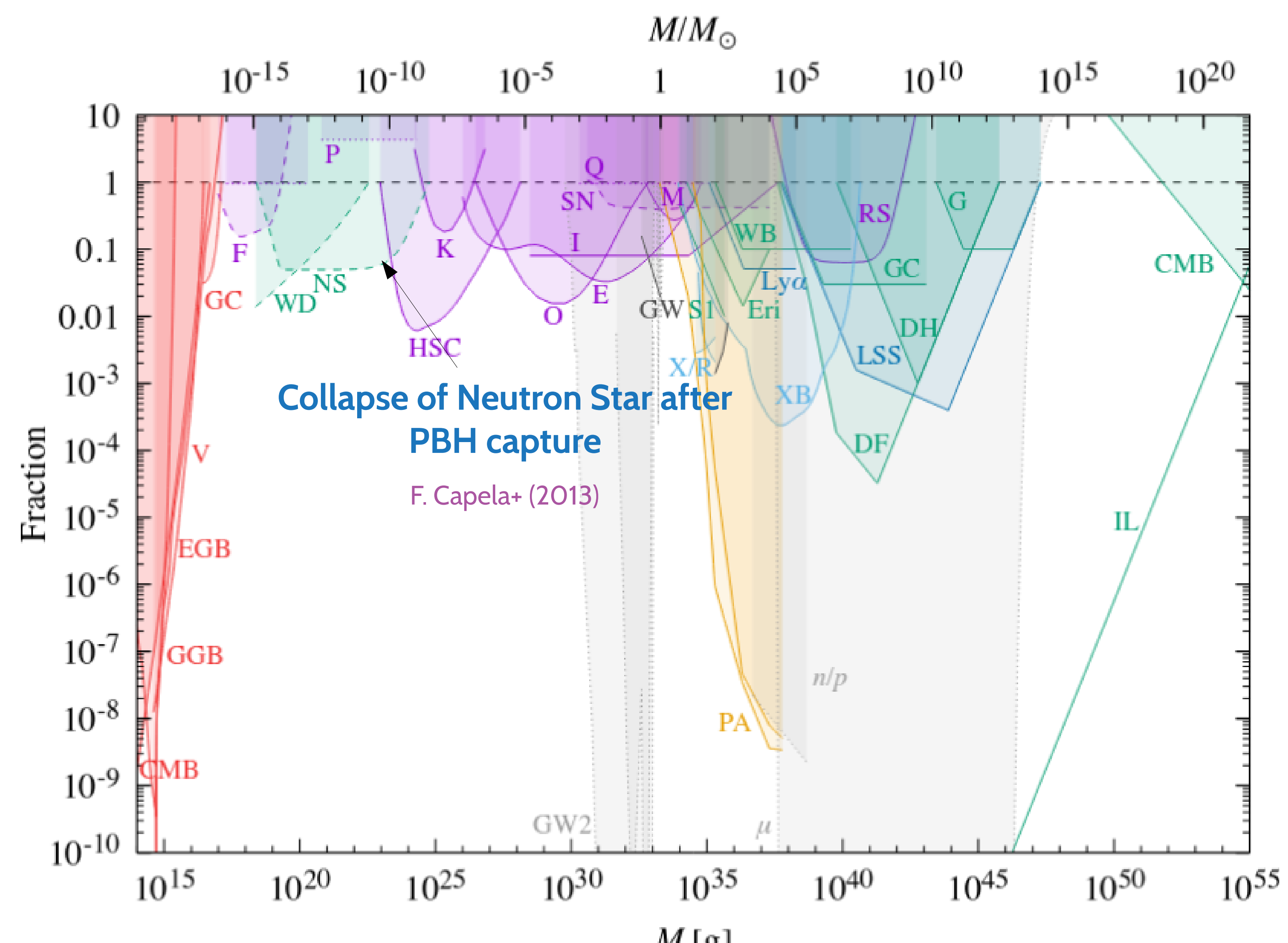


Unconstrained by lensing observation but by interactions with compact stars?

Carr+ (2002.12778)

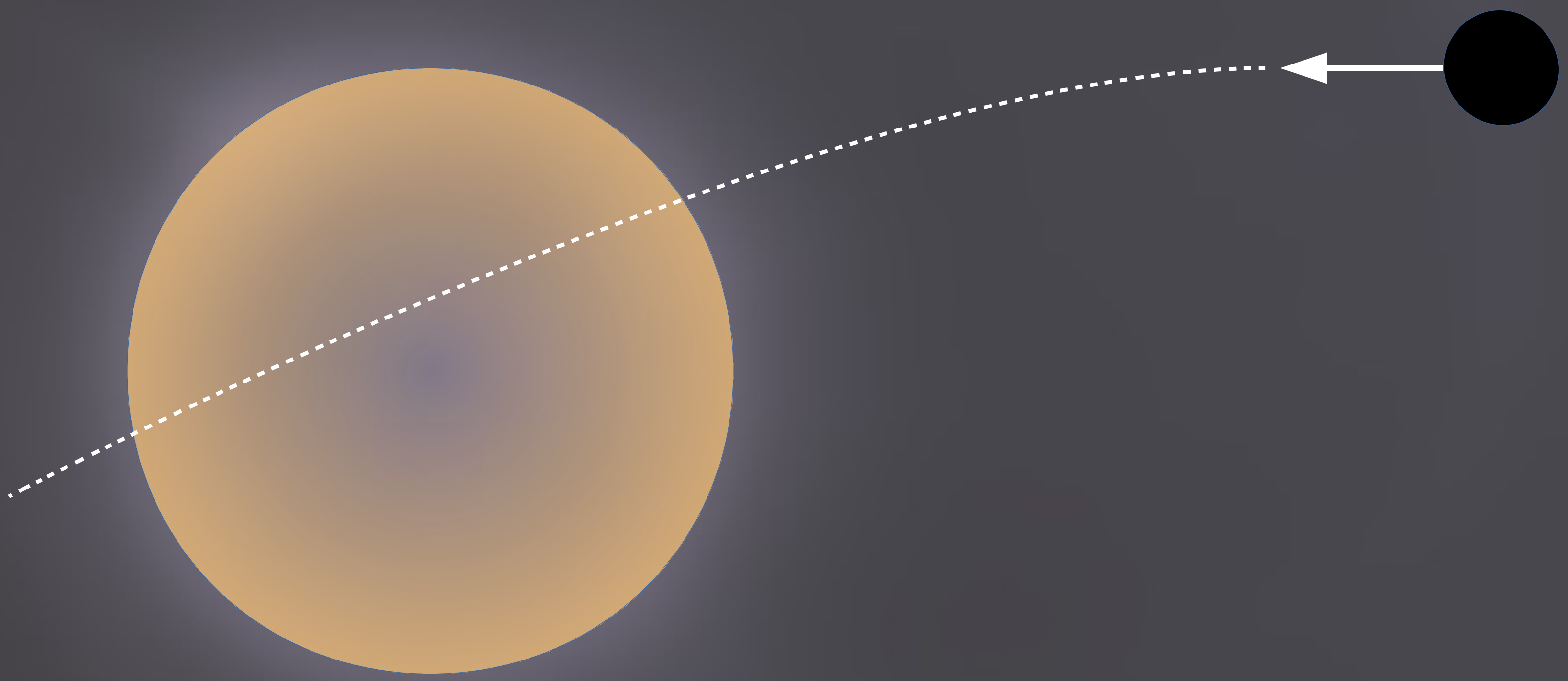


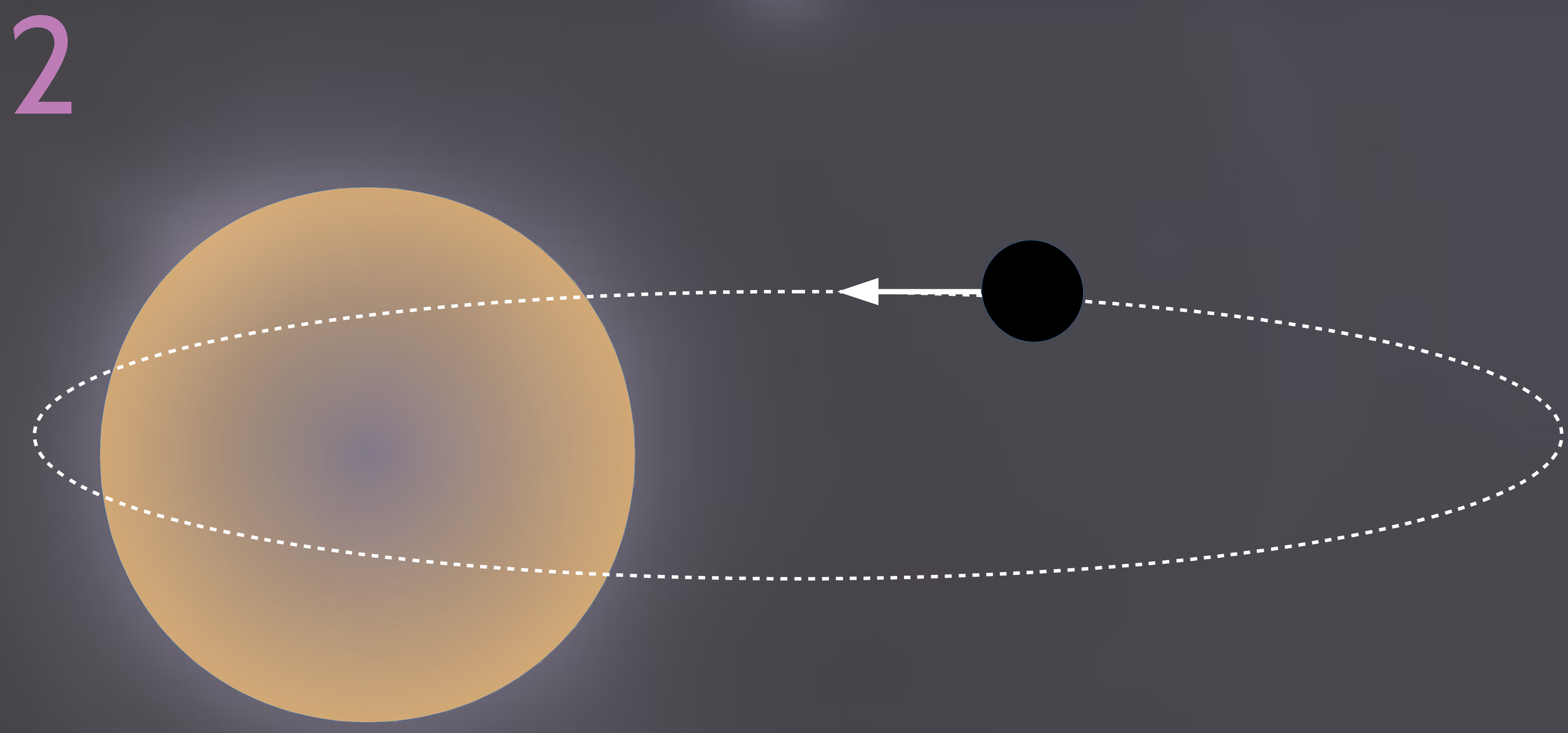
Carr+ (2002.12778)



Carr+ (2002.12778)

1



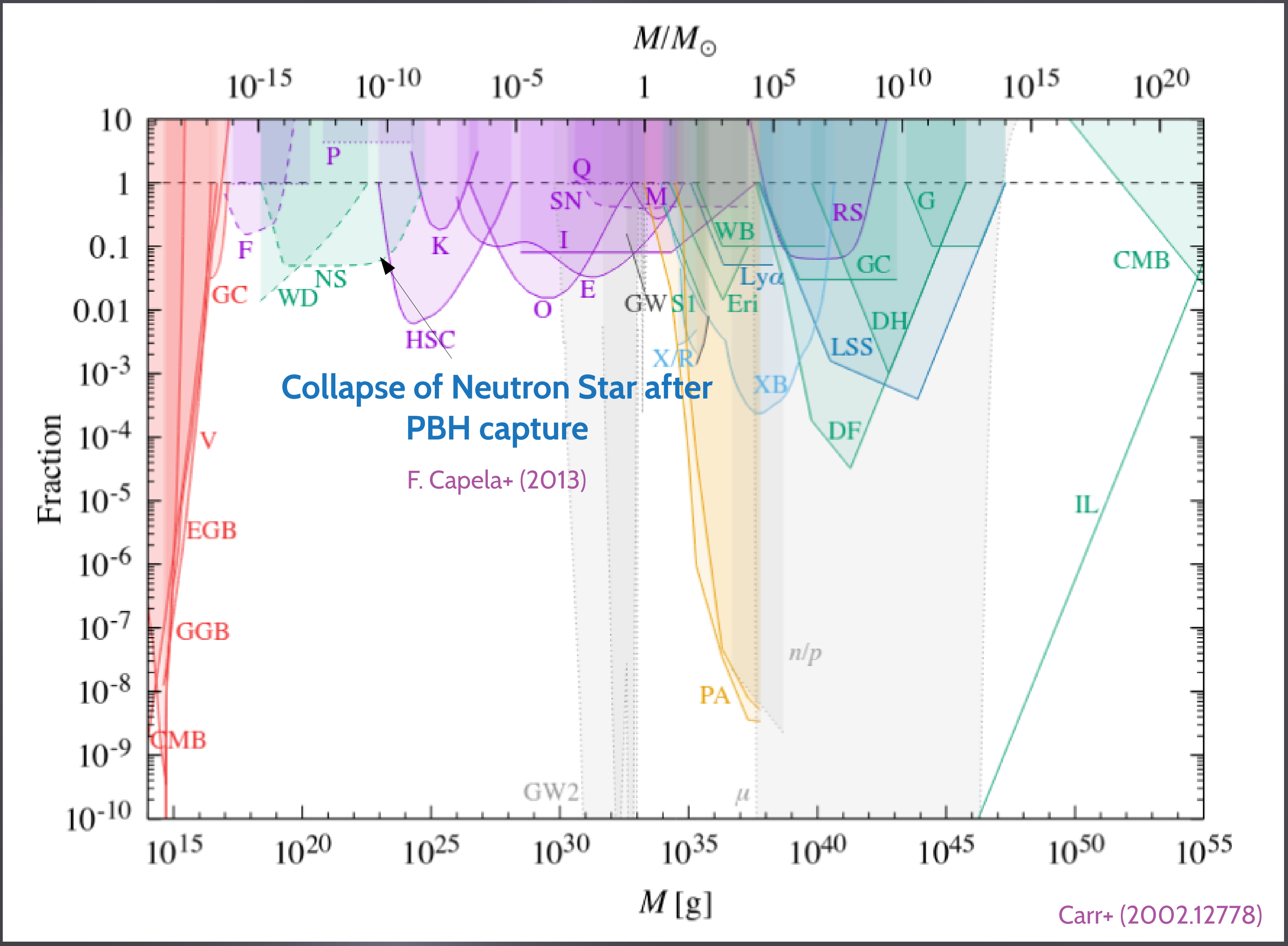

2

3

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

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

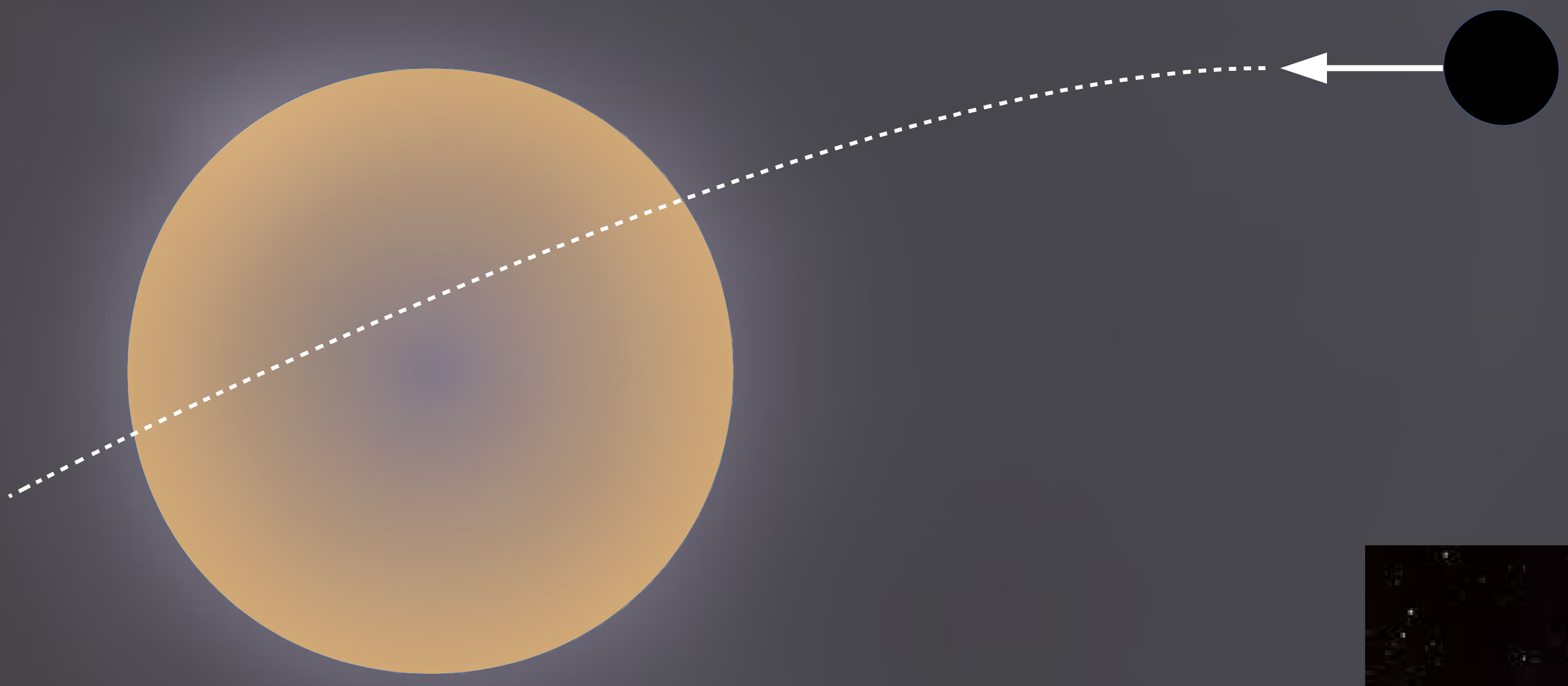
⟹ Constraints on f_{PBH}



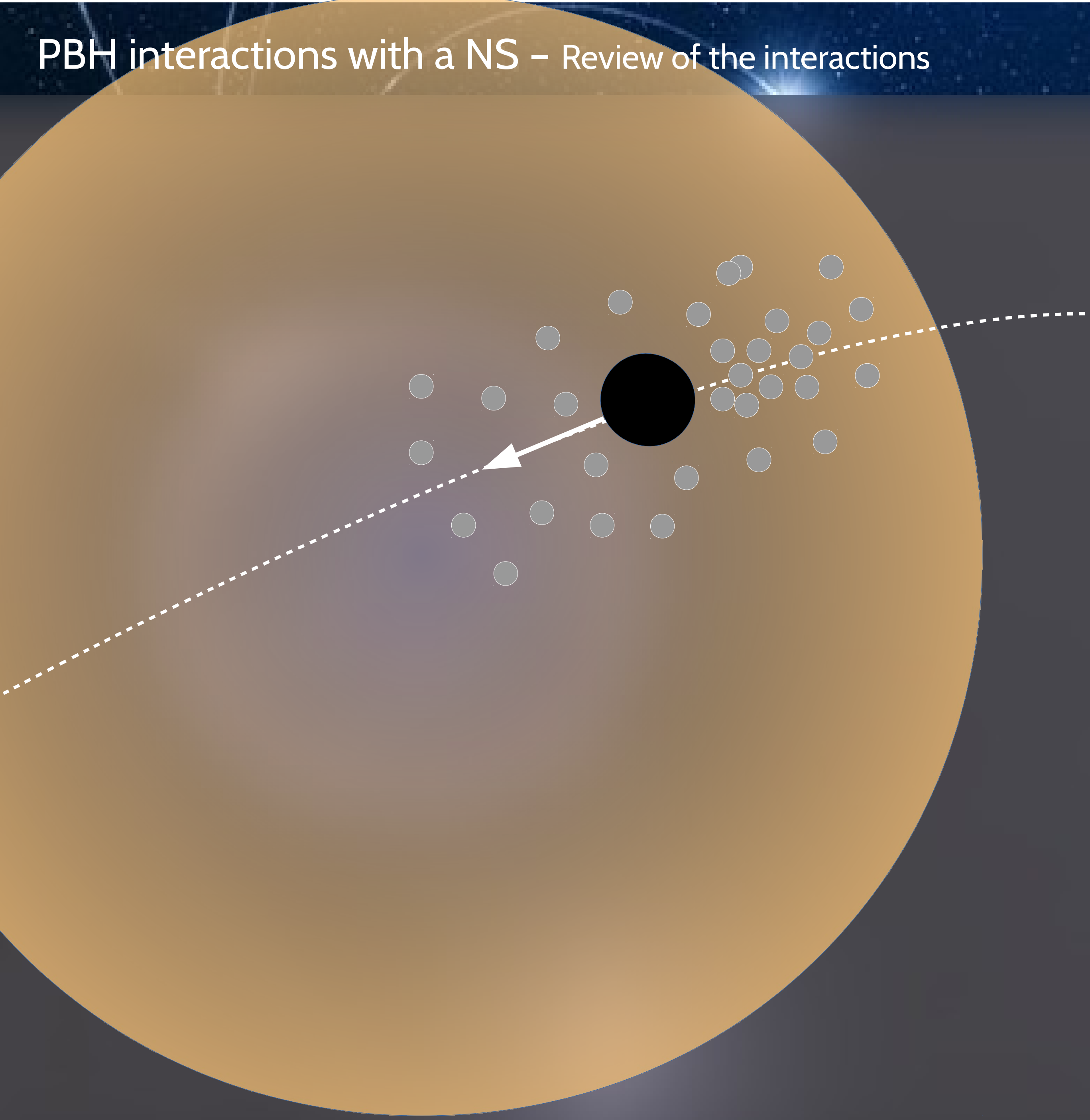
M/M⊙
10-15
10-10
10-5
1
10^5
10^10
10^15
10^20
10
1
0.1
0.01
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
Fraction
P
Q
SN
M
RS
G
WB
F
K
I
GC
Lyα
CMB
NS
GC
WD
E
GW
S1
Eri
O
DH
HSC
LSS
X/R
XB
DF
V
IL
EGB
GGB
n/p
PA
CMB
GW2
μ
10^15
10^20
10^25
10^30
10^35
10^40
10^45
10^50
10^55
M [g]
Collapse of Neutron Star after PBH capture
F. Capela+ (2013)
Carr+ (2002.12778)

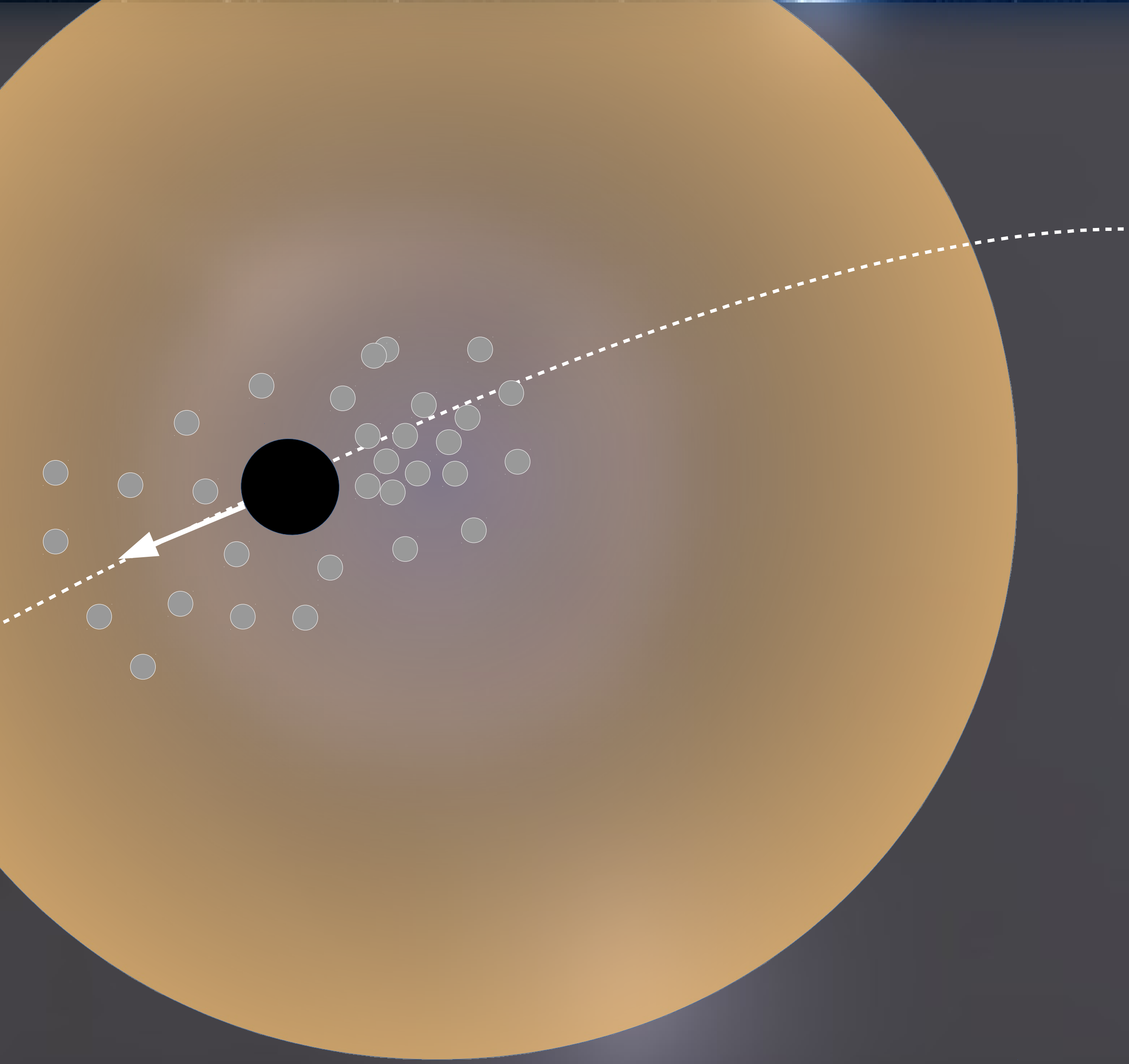
Yet, such a catastrophic event should be observable!

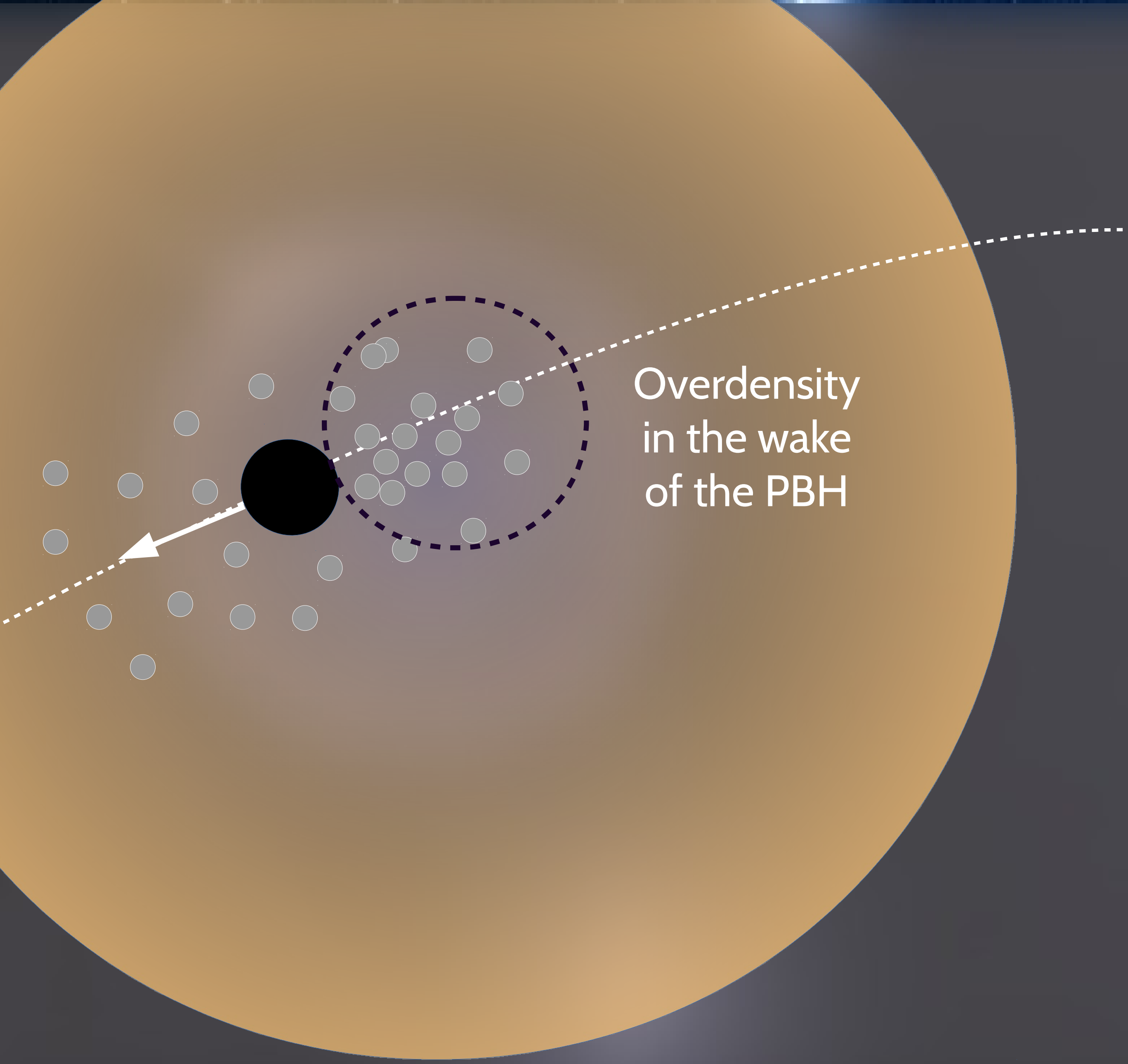
1 - Dynamical Friction

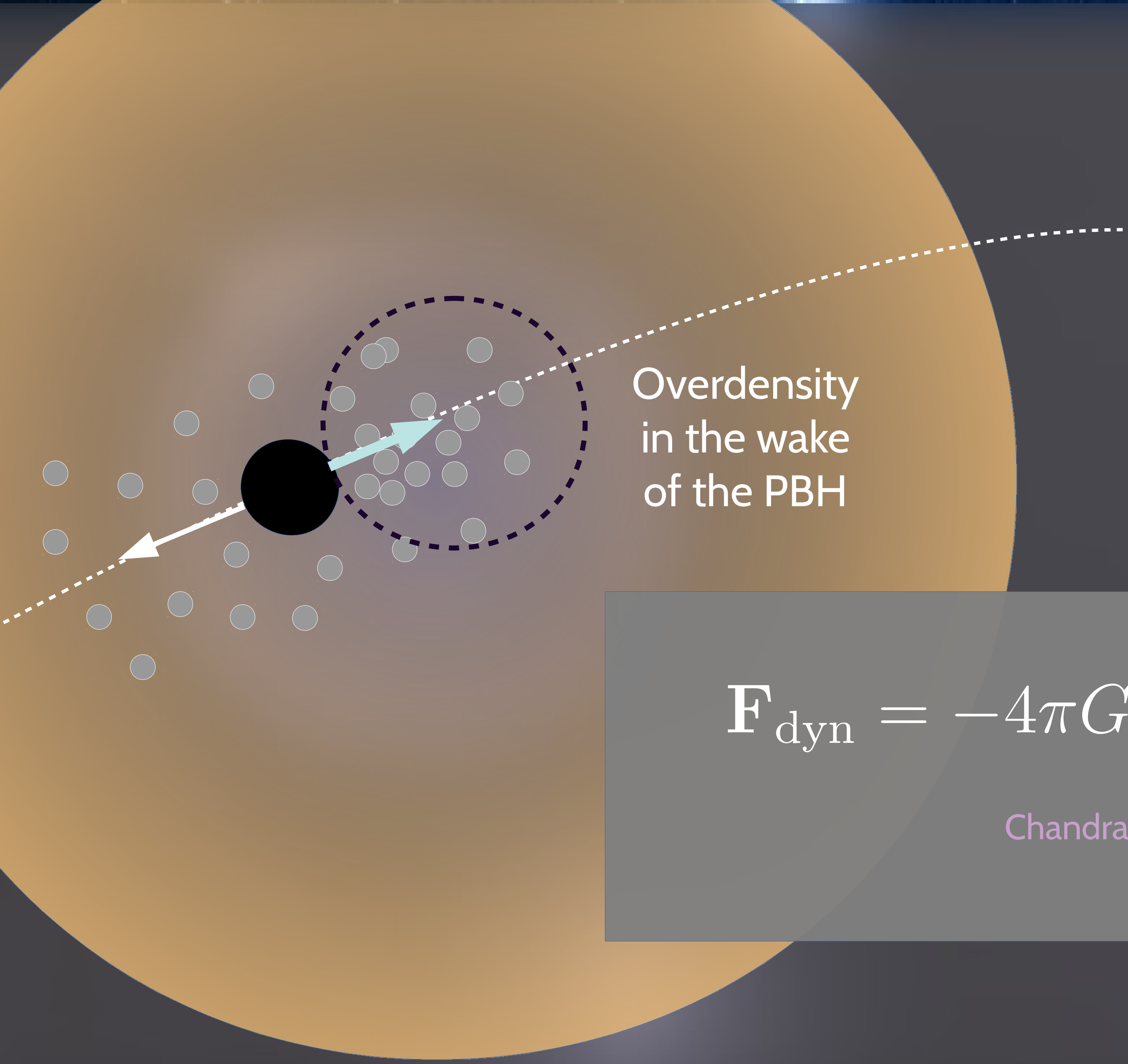


Credit: ESO/L.Calçada



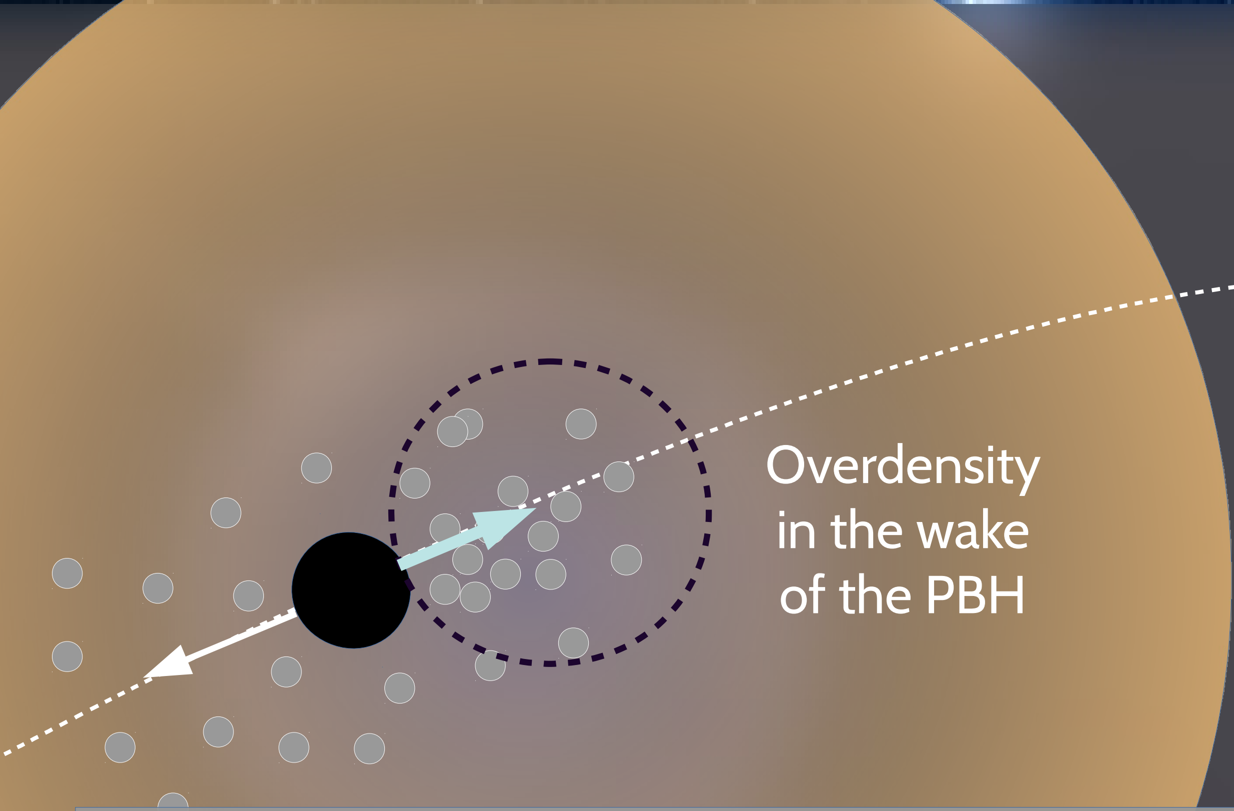


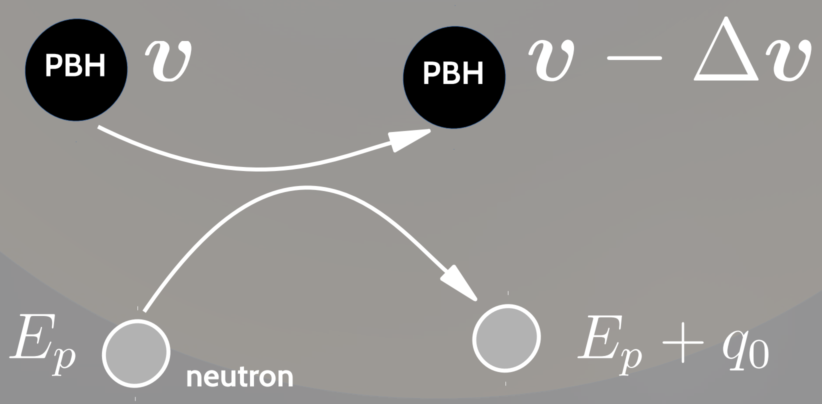

Overdensity
in the wake
of the PBH



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

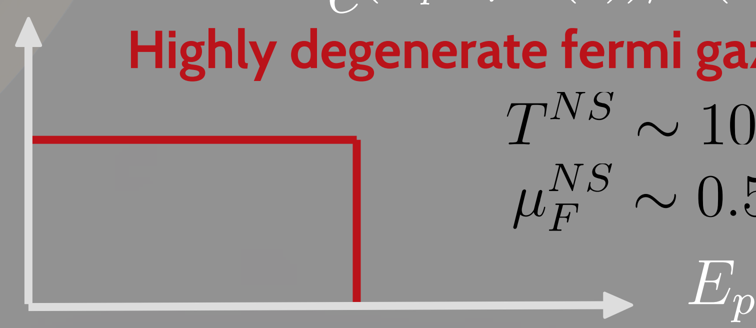
Chandrasekhar (1949)



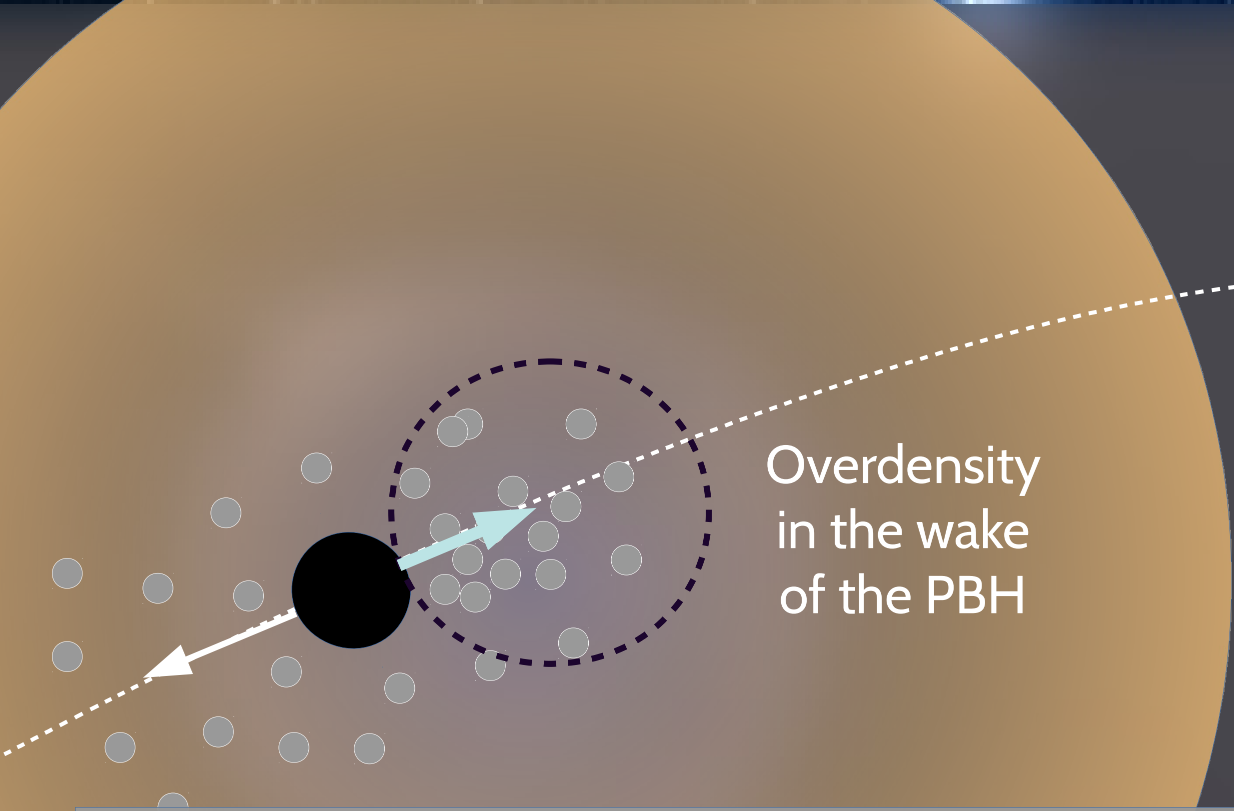


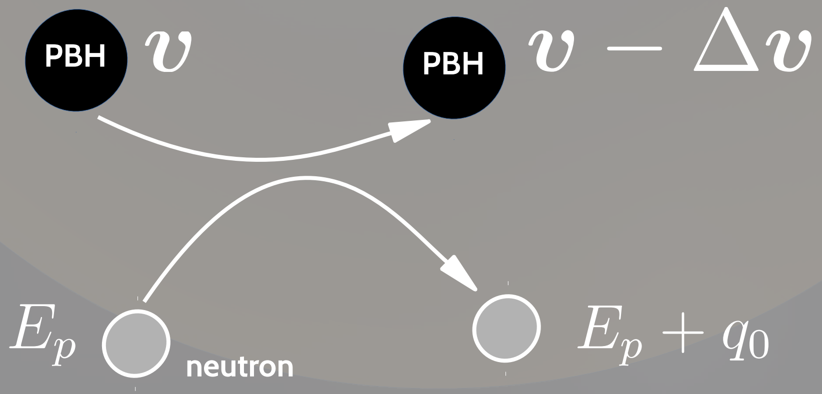
$$f_p(E_p, r) = \frac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$$

Highly degenerate fermi gaz !



$$T^{NS} \sim 10^{-8}\,\mathrm{GeV}$$
$$\mu_F^{NS} \sim 0.5\,\mathrm{GeV}$$





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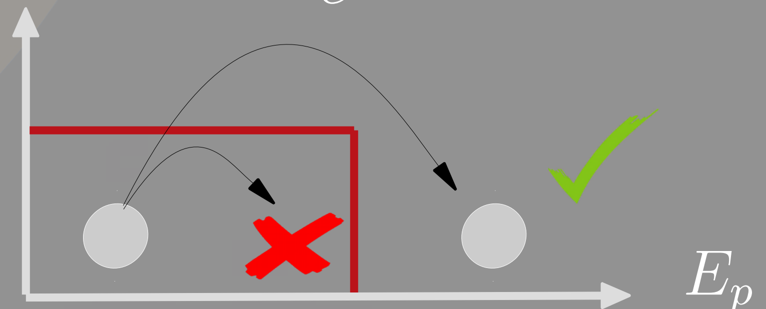

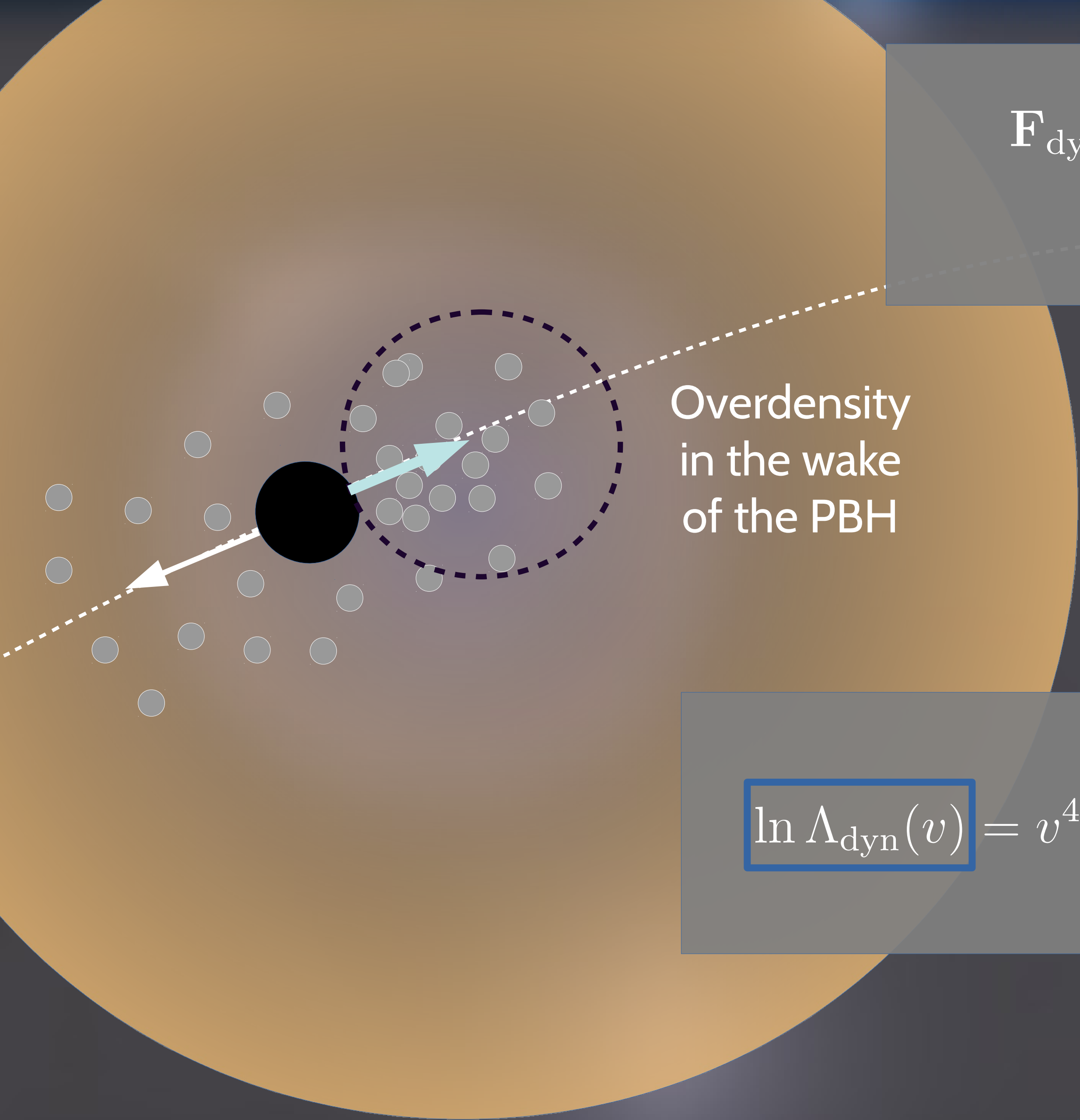

$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

Chandrasekhar (1949)

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

Capela+ (2013)

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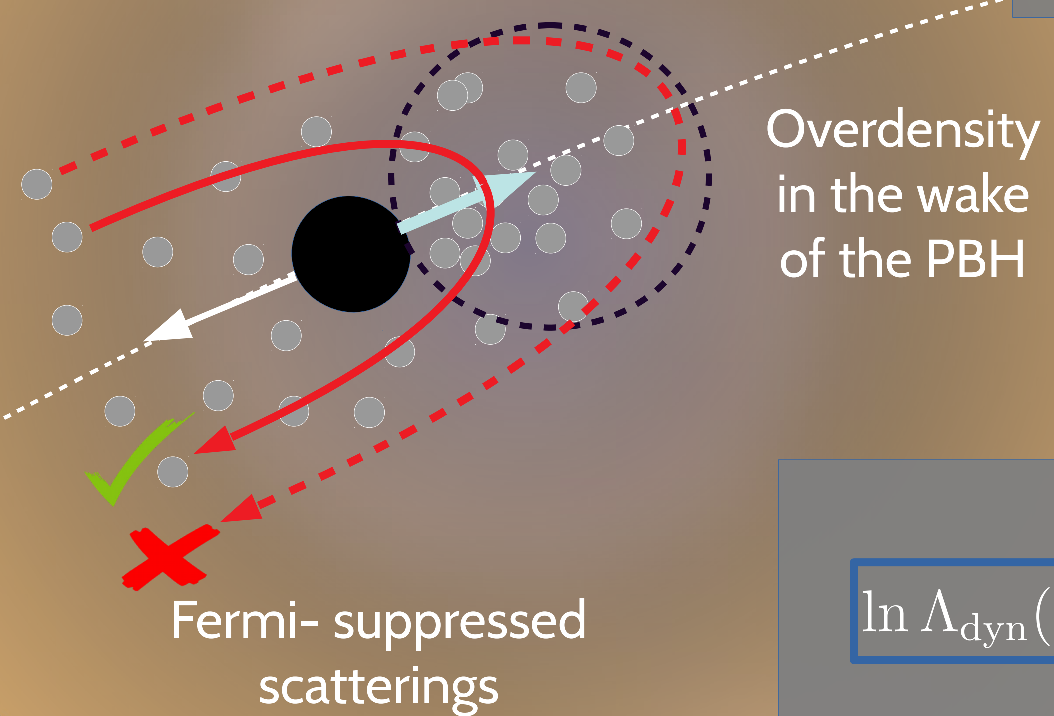

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Capela+ (2013)

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

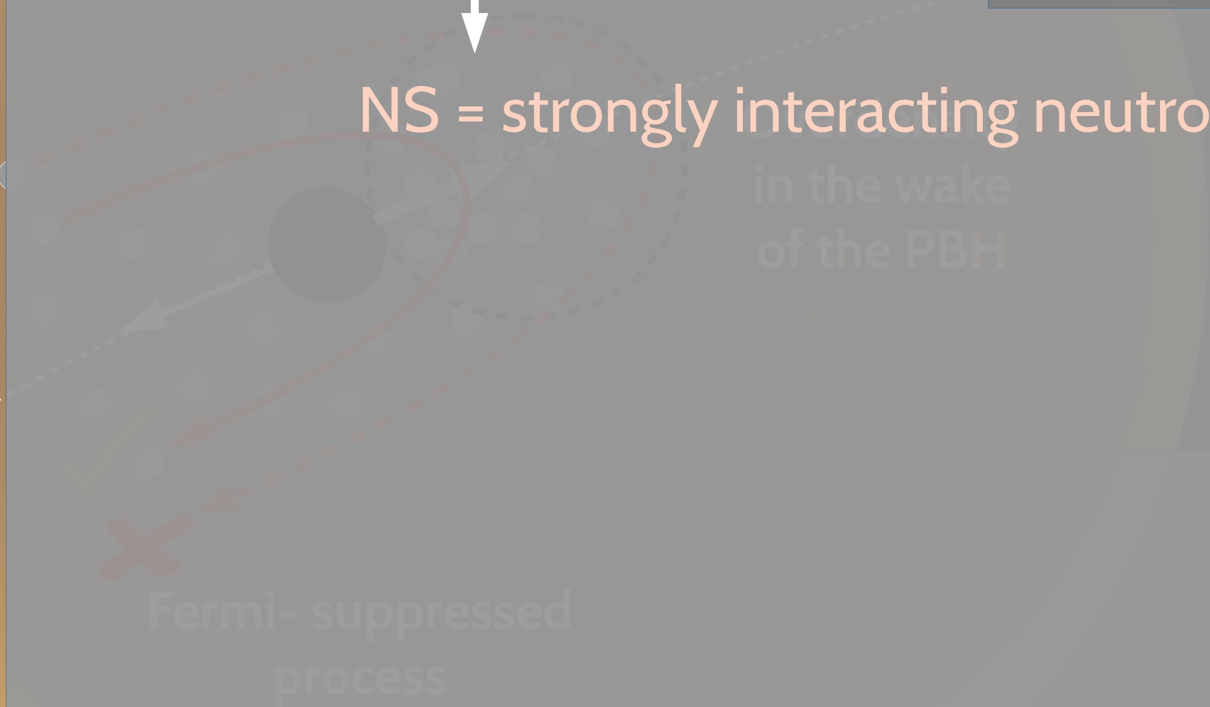
$$\mathbf{F}_{\mathrm{dyn}} = -4\pi G^2 m^2 \rho \ln \Lambda_{\mathrm{dyn}}(v) \frac{\boldsymbol{v}}{v^3}$$

Chandrasekhar (1949)

Derived for a collisionless medium

↓

NS = strongly interacting neutron fluid



Dynamical friction is suppressed by a factor of a few, up to 10.

Credit: ESO/L.Calçada

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

Chandrasekhar (1949)

Derived for a collisionless medium

↓

NS = strongly interacting neutron fluid

↓

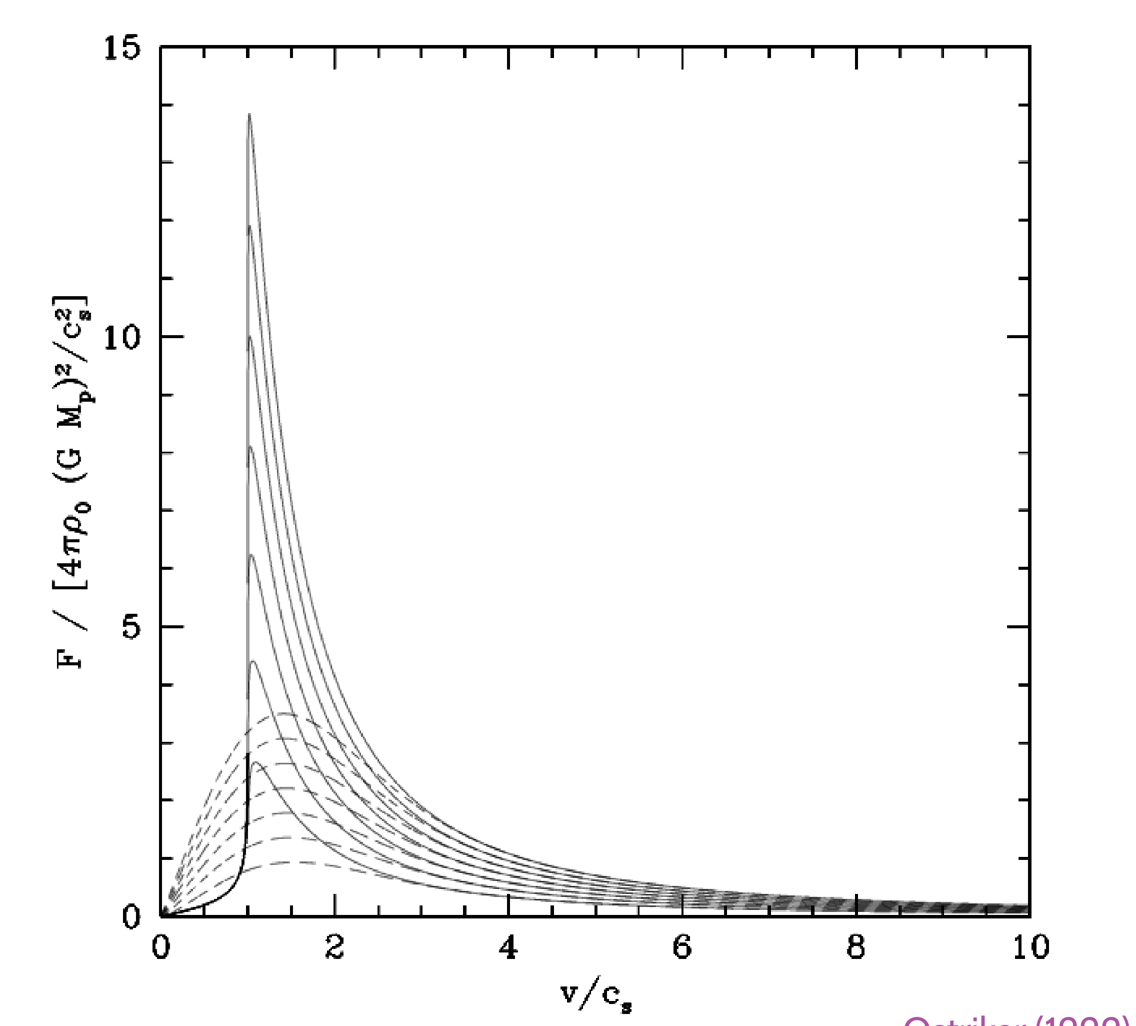
Collisionless if $\tau_{gravitation} \ll \tau_{causal}$

$$v \gg c_s$$

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

1 - Dynamical Friction:

In a collisionless or a collisional medium?



Ostriker (1999)

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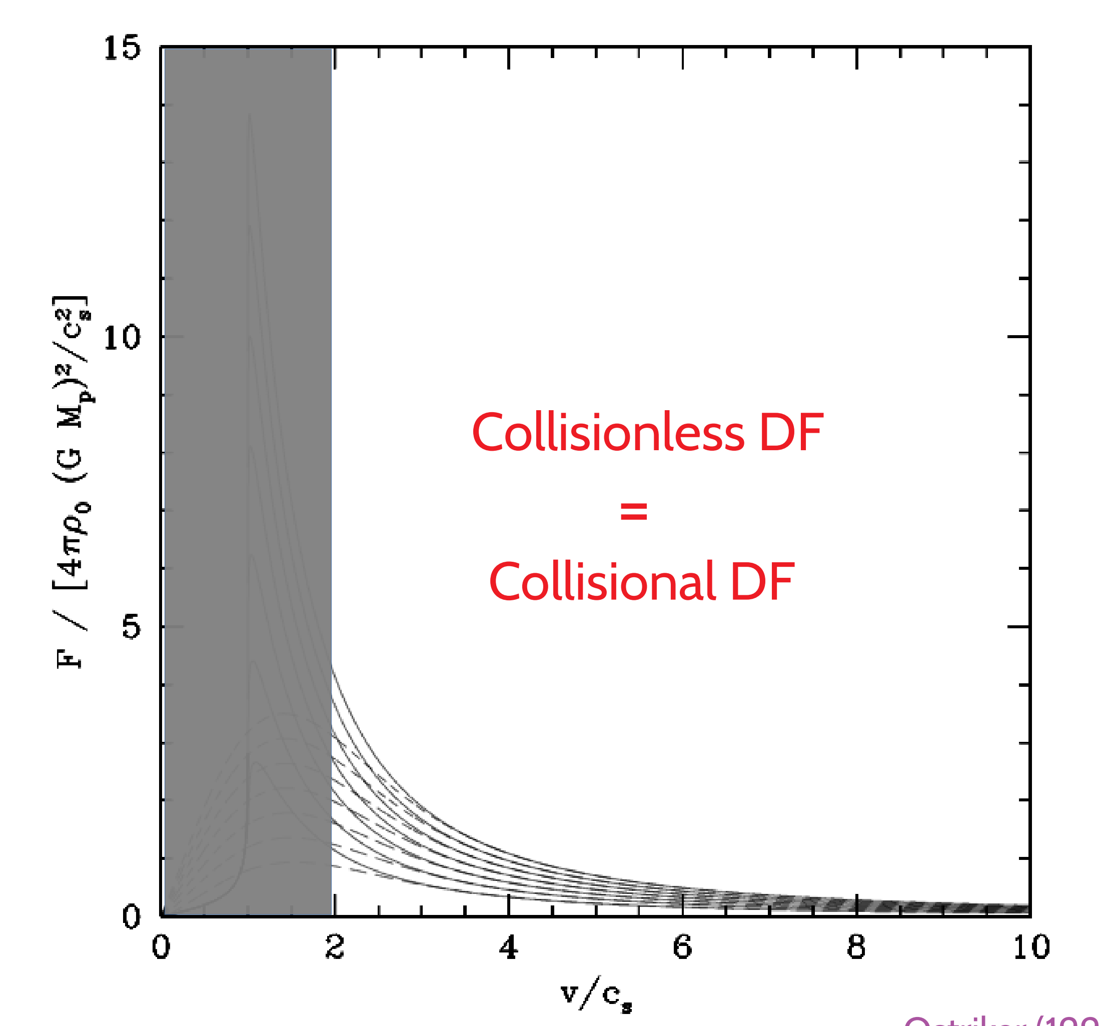

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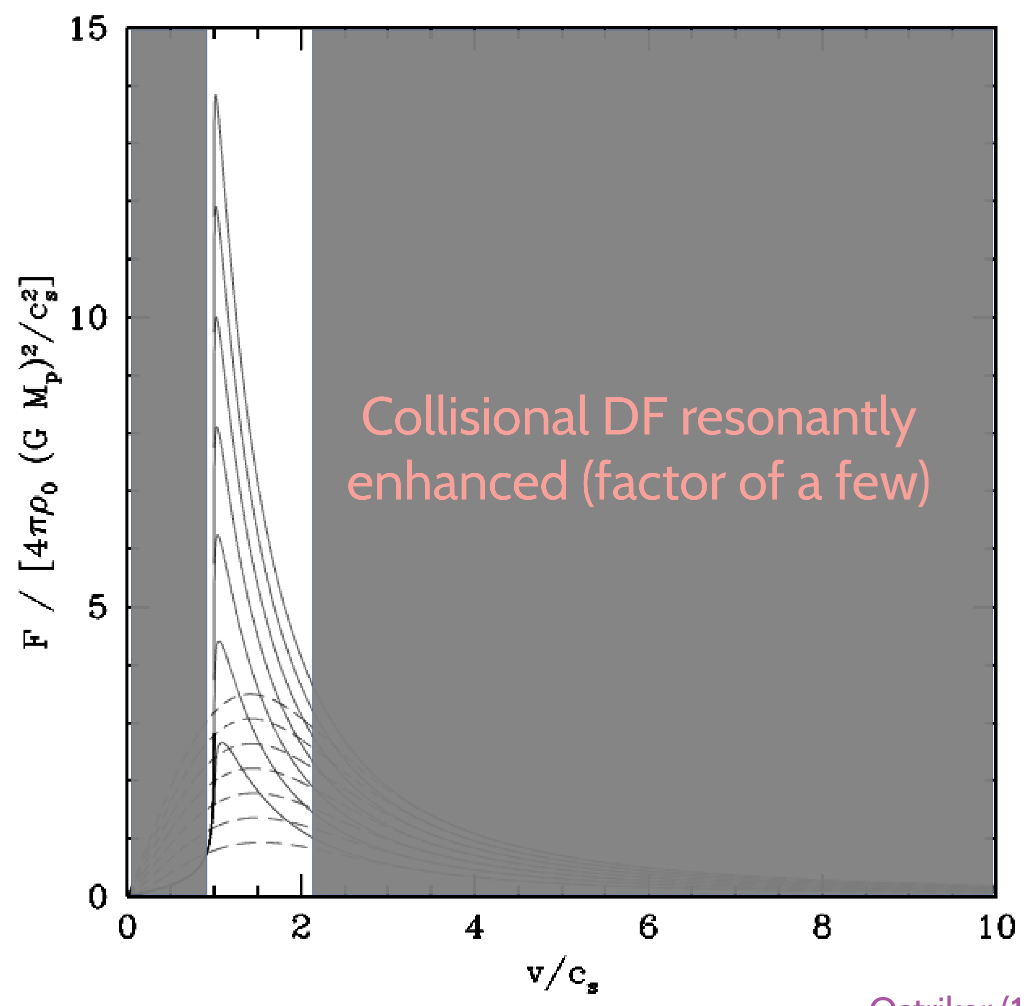

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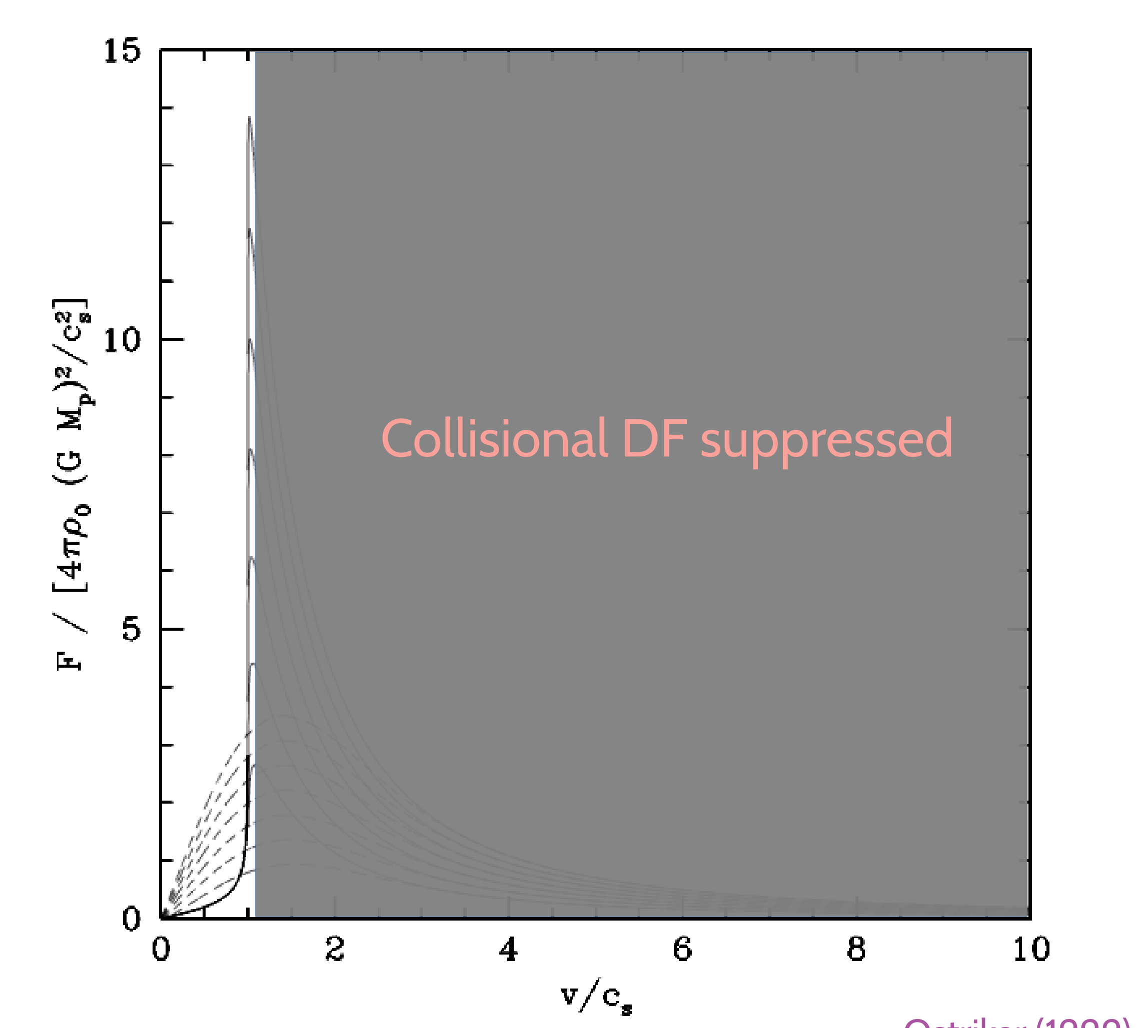

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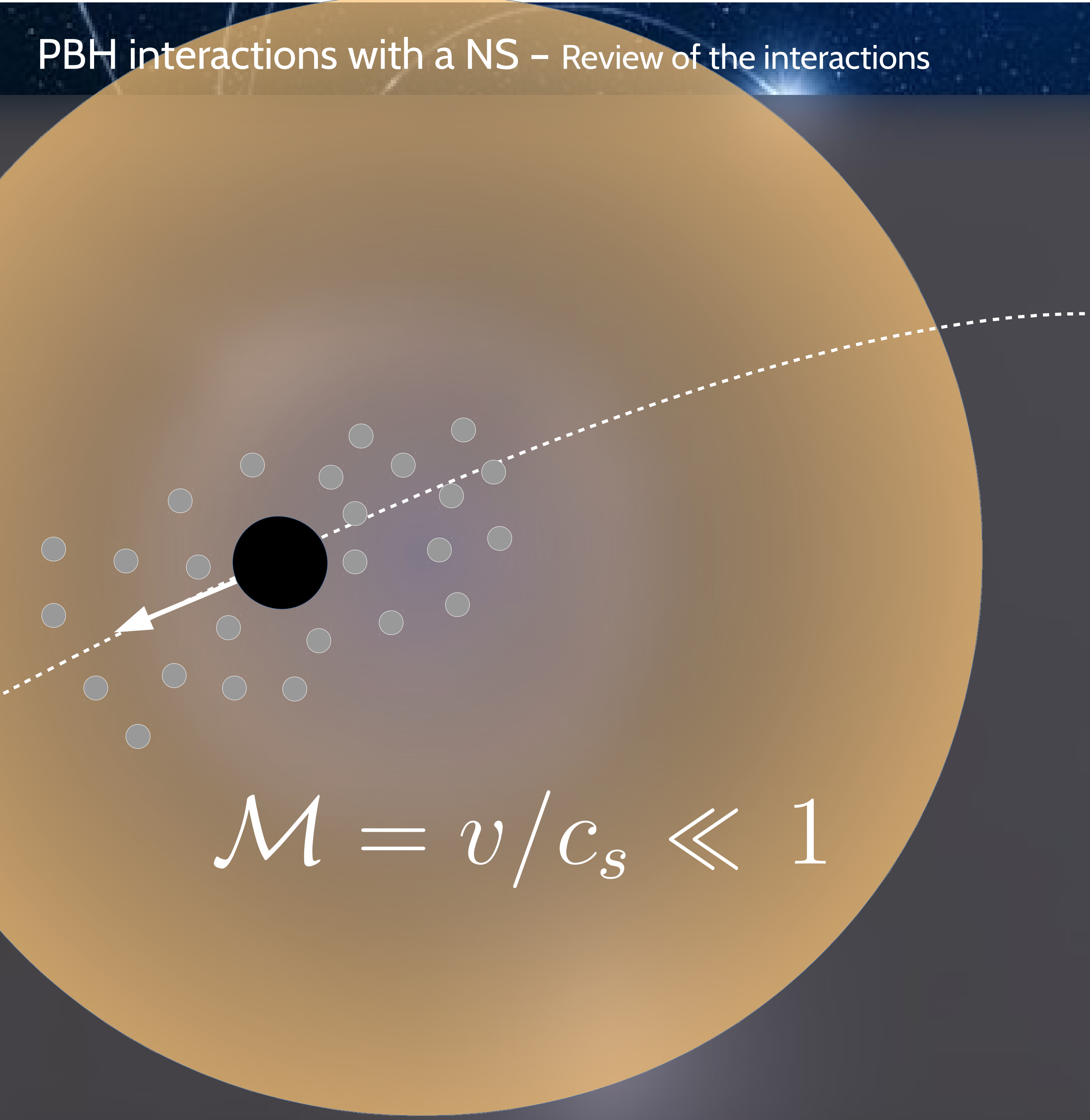
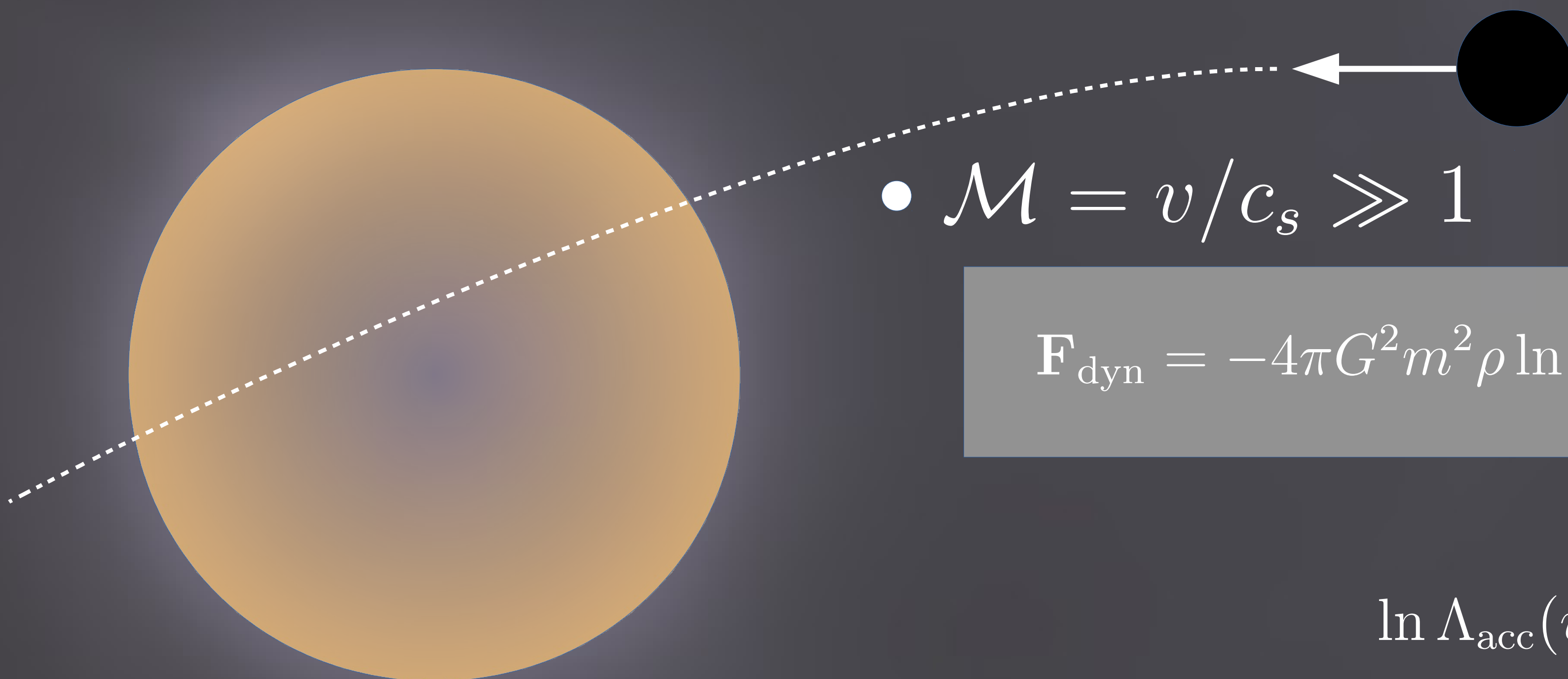


$$\mathcal{M} = v/c_s \ll 1$$

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)

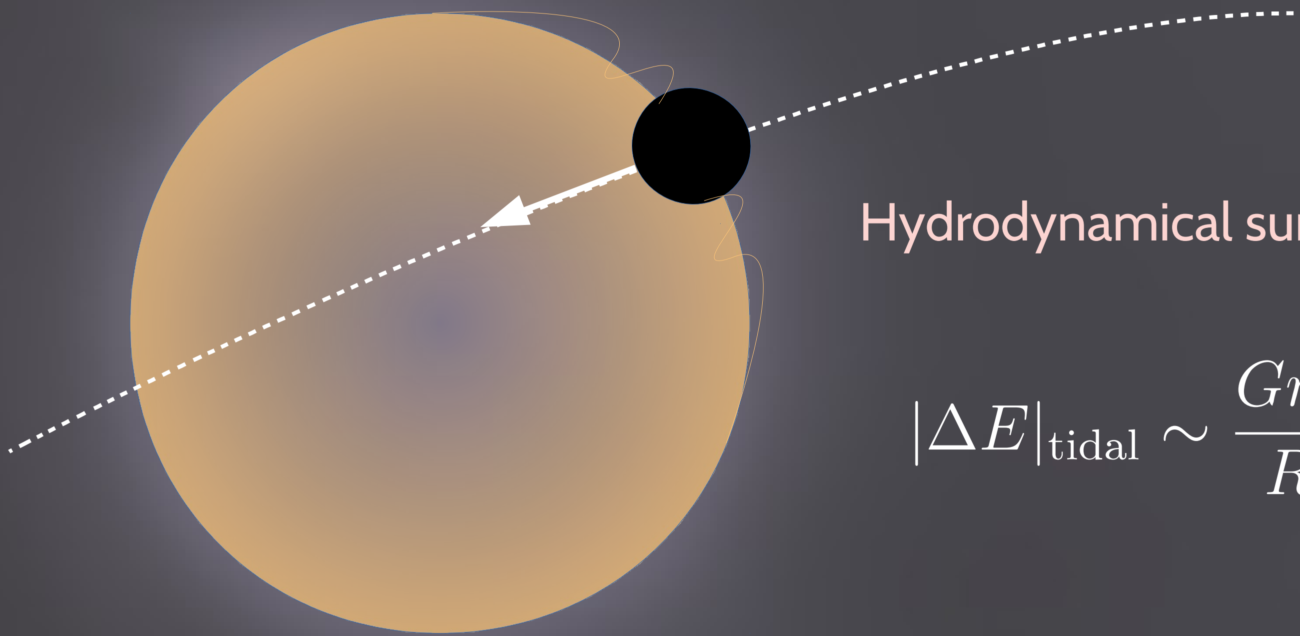
$$\ln \Lambda_{\rm acc}(v) = v^4 \gamma^2 \frac{d_{\rm crit}^2}{R_g^2}$$

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

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

Y.G. et al. PRD (2020)

3 - Surface waves

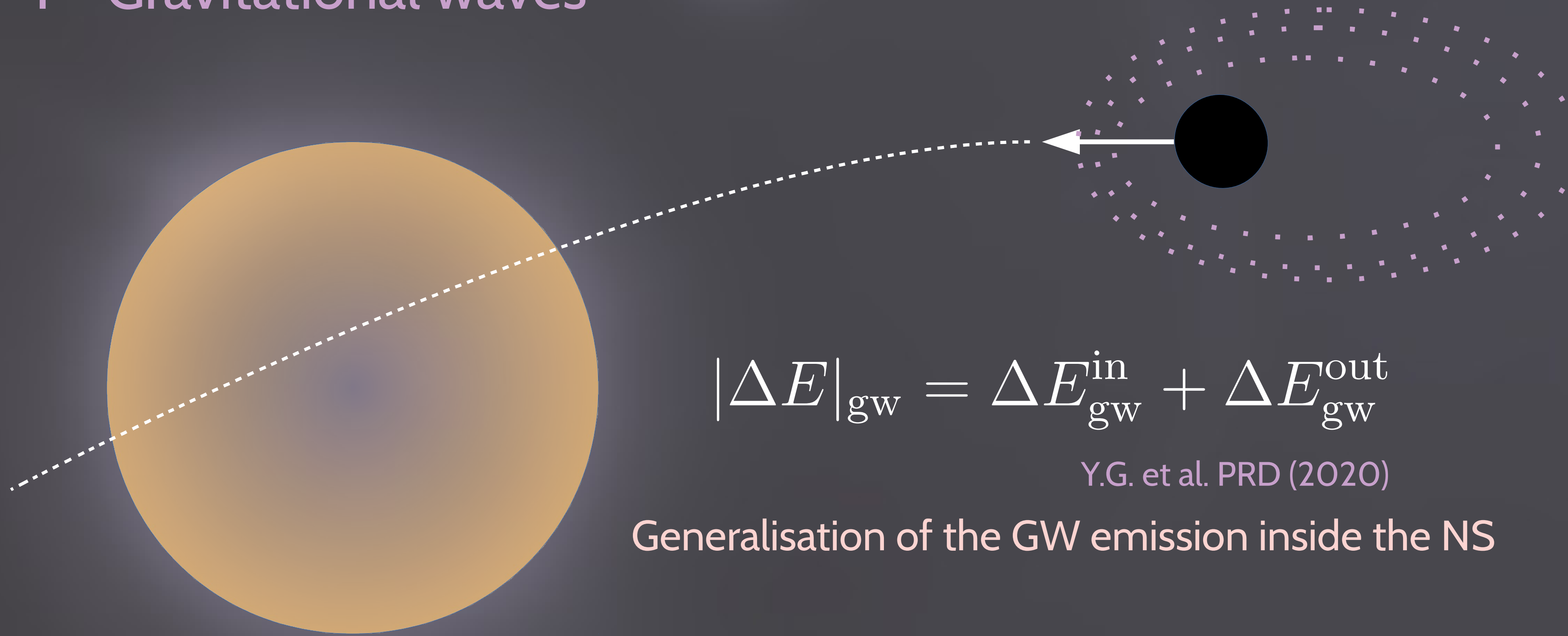


Hydrodynamical surface waves:

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

Defillon+ (2014)
Press&Teukolsky (1977)

4 - Gravitational waves

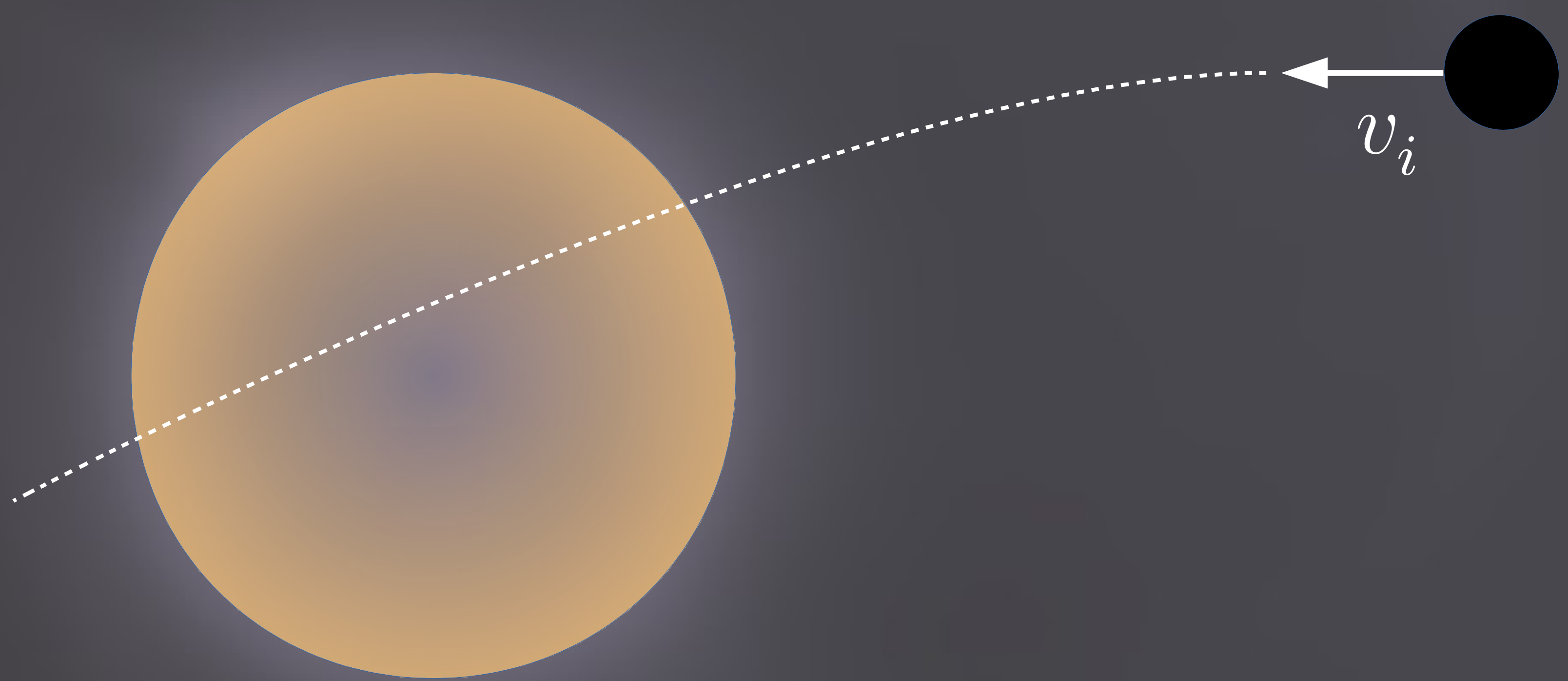


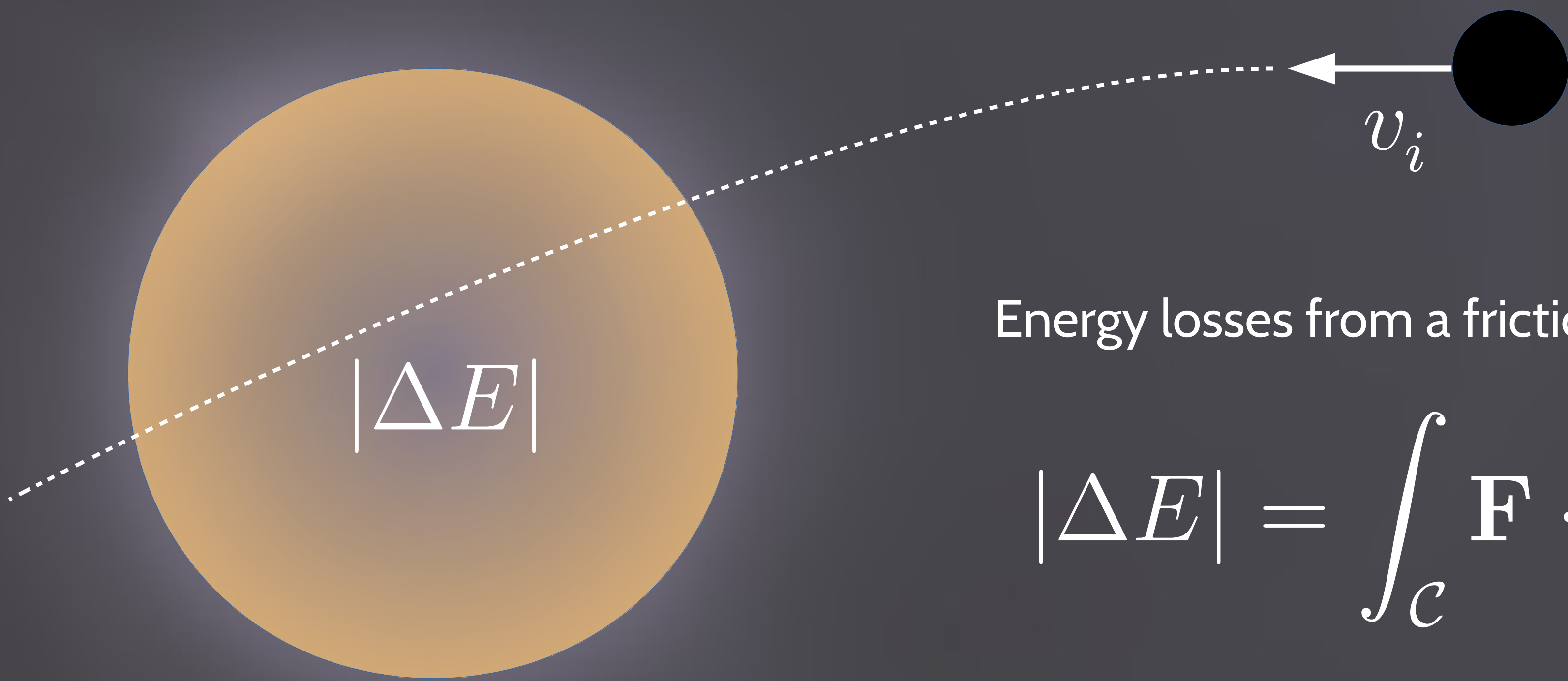
$$|\Delta E|_{\rm gw} = \Delta E_{\rm gw}^{\rm in} + \Delta E_{\rm gw}^{\rm out}$$

Y.G. et al. PRD (2020)

Generalisation of the GW emission inside the NS

Credit: ESO/L.Calçada


v_i

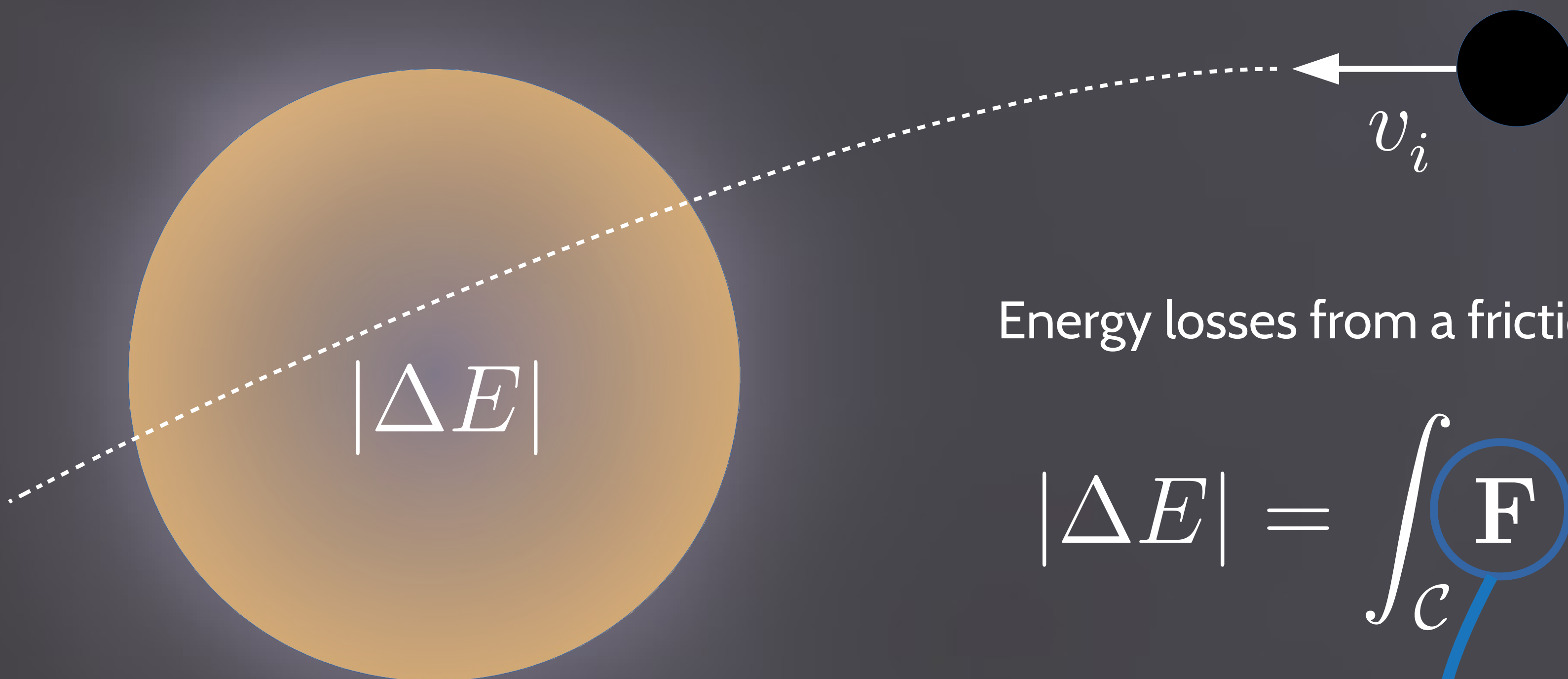


Energy losses from a friction force

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

Capture condition

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



Energy losses from a friction force

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Forces we saw

Capture condition

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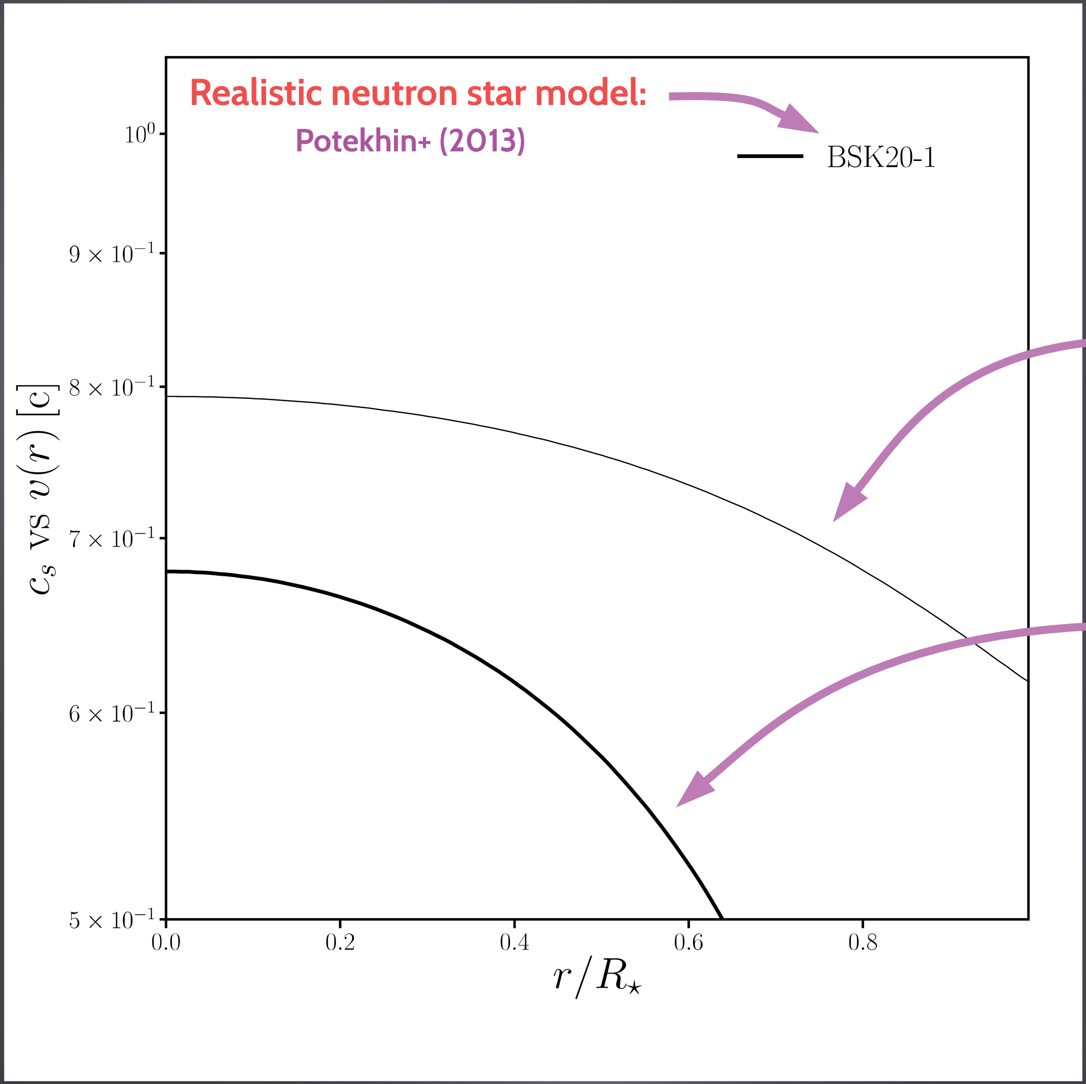
What is the speed regime for capture ?

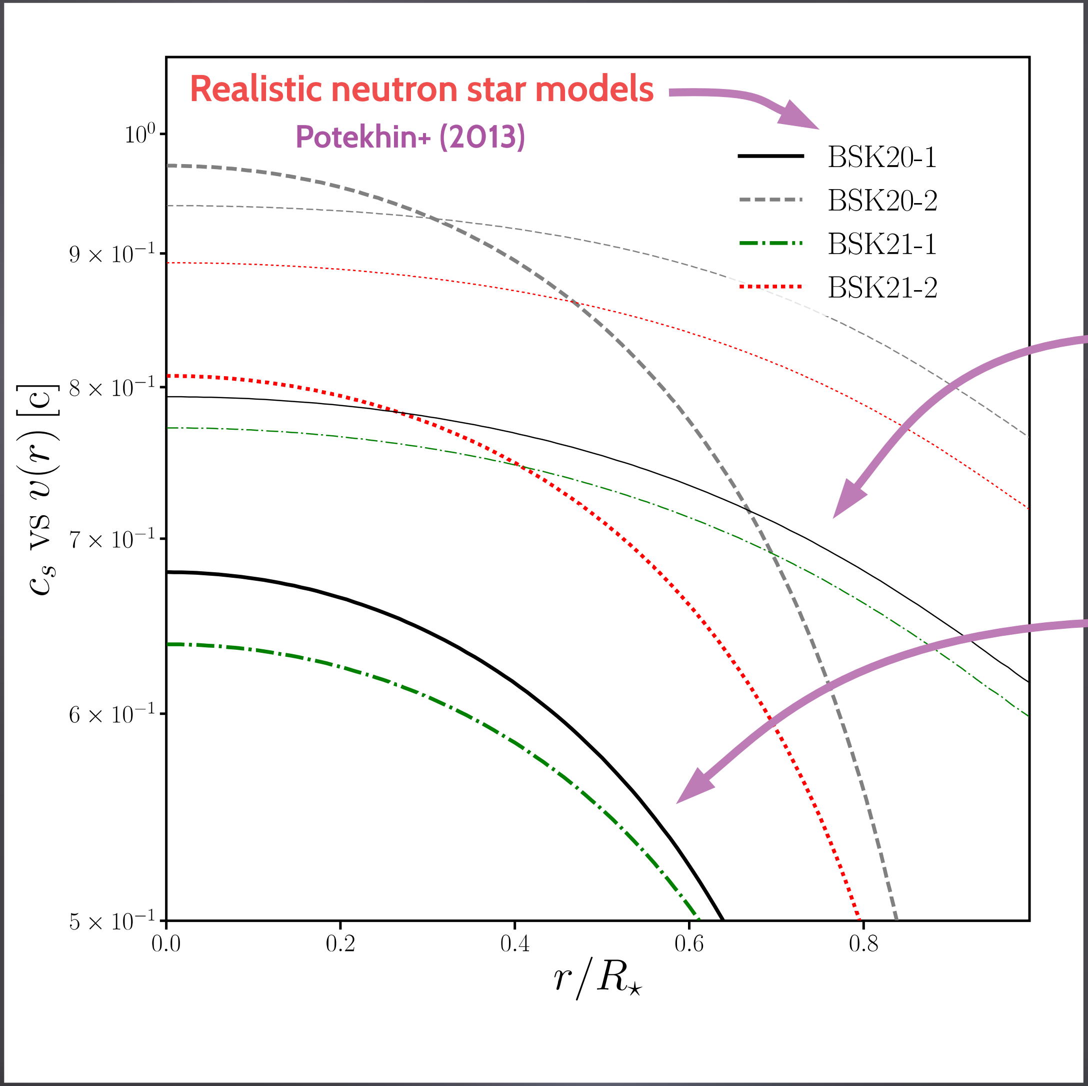


$$v(r) = \sqrt{1 - e^{2(\Phi(\infty)-\Phi(r))}}$$

$$c_s(r)$$

Capture happens in the supersonic regime!

What is the speed regime for capture ?



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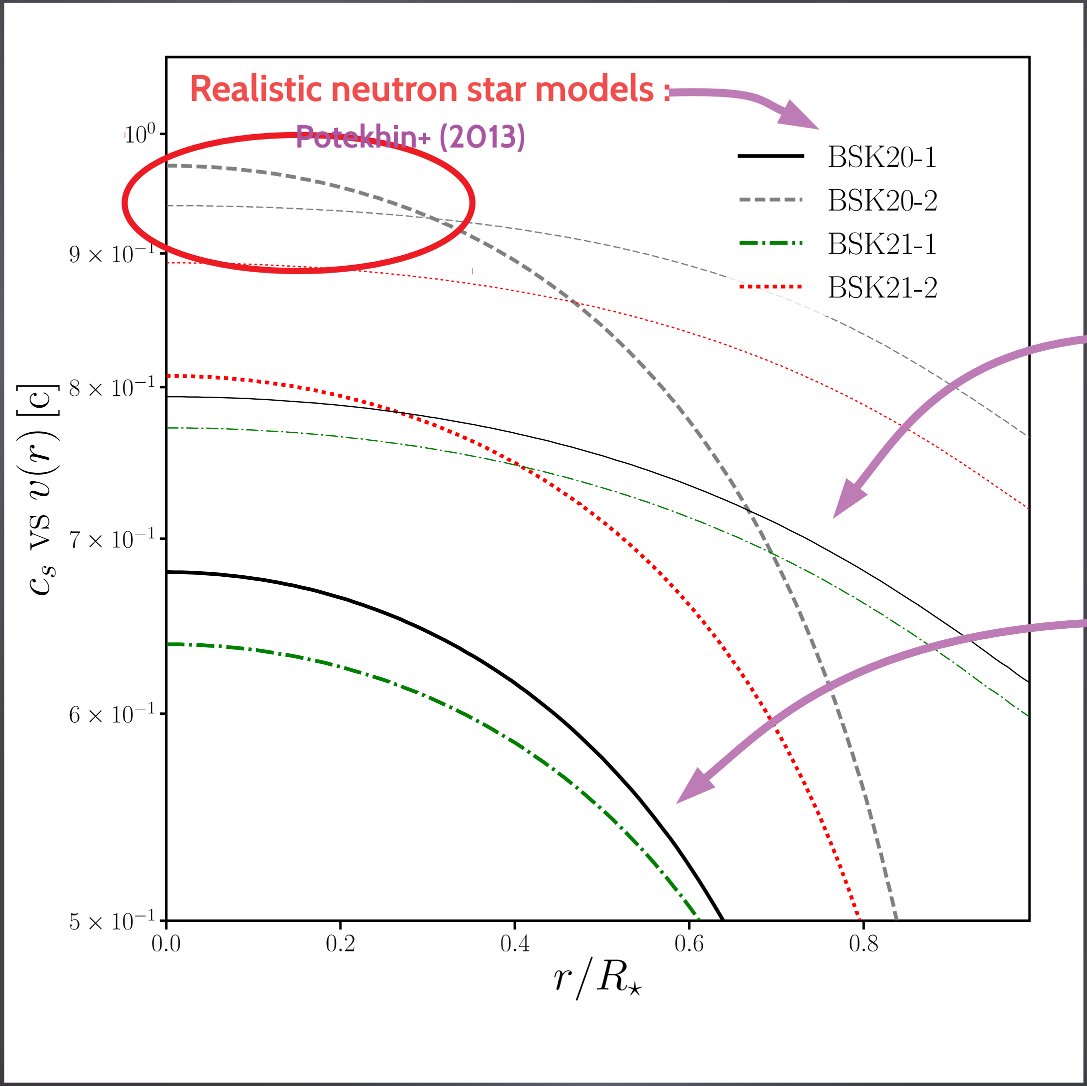


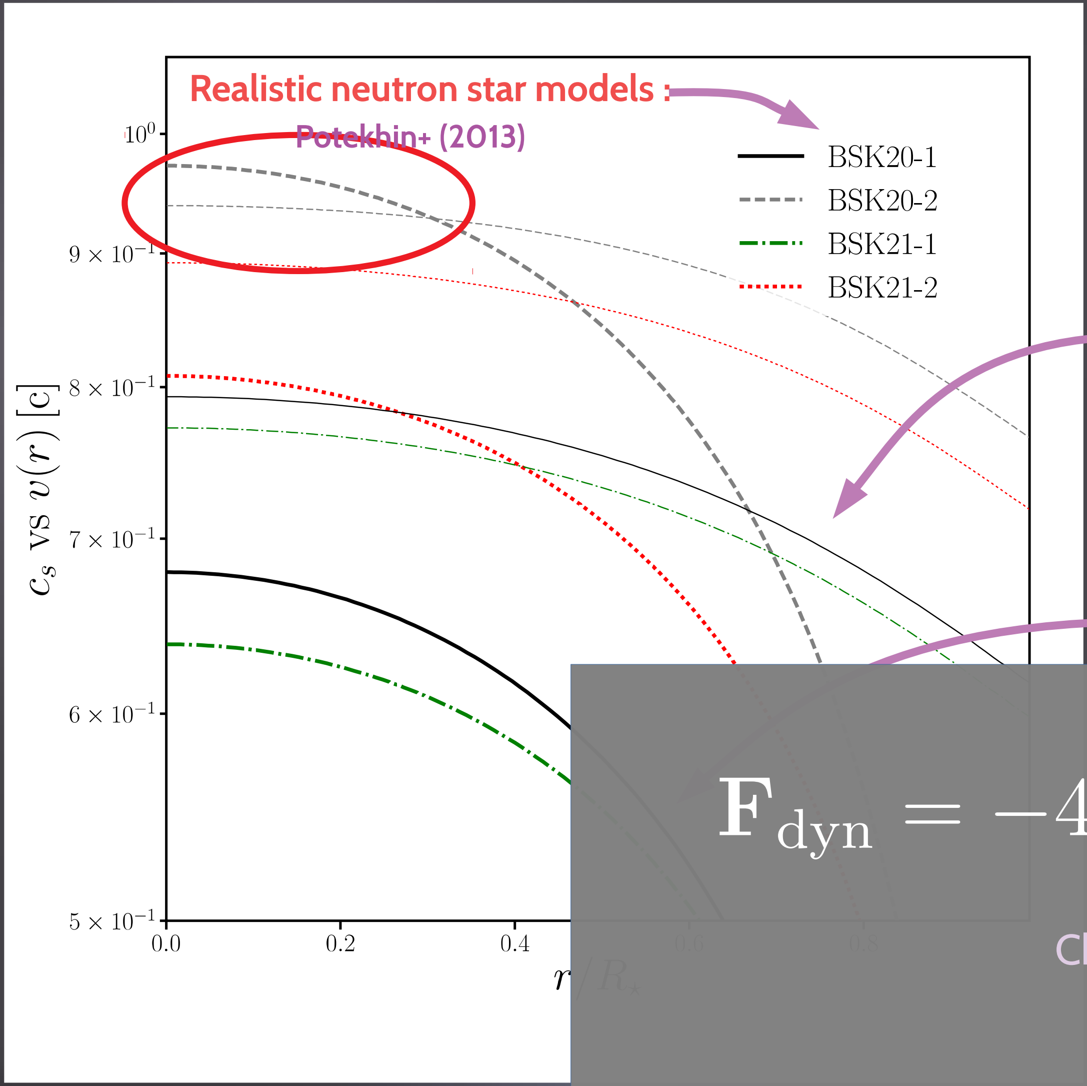
$$v(r) = \sqrt{1 - e^{2(\Phi(\infty) - \Phi(r))}}$$

$$c_s(r)$$

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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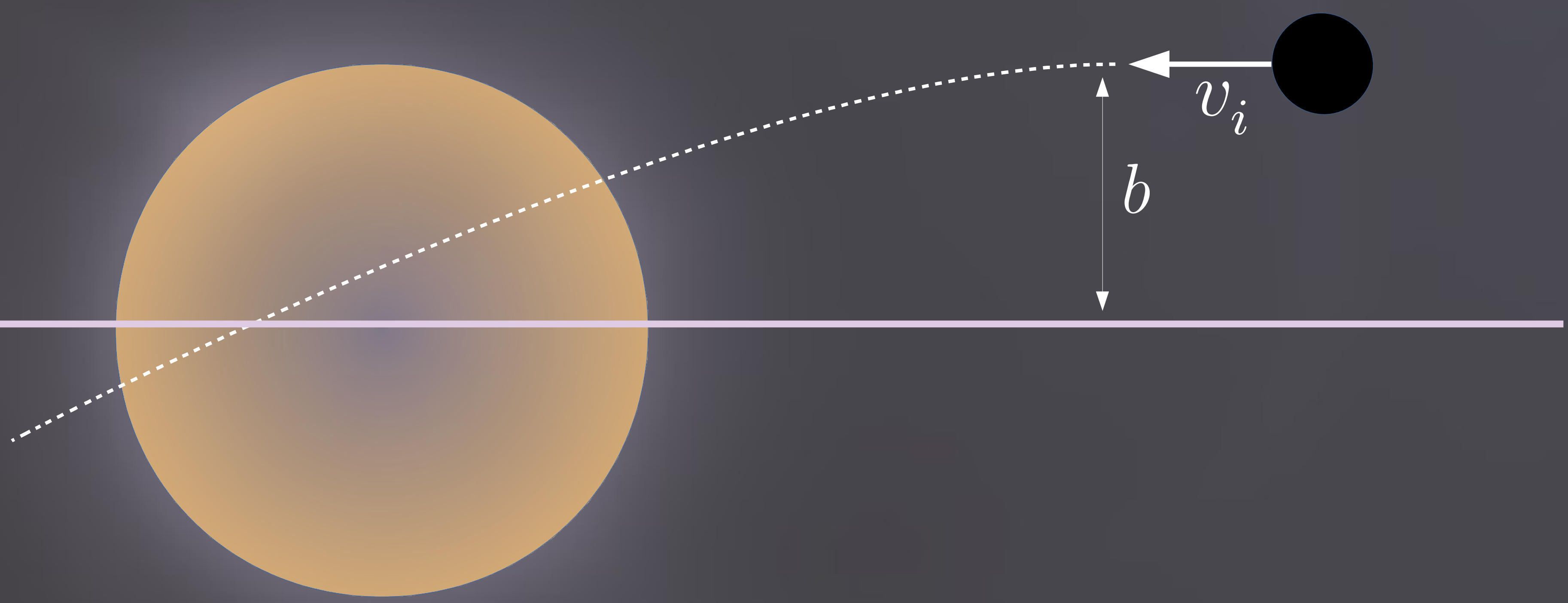
Chandrasekhar (1949)

What is the dominant process for capture?



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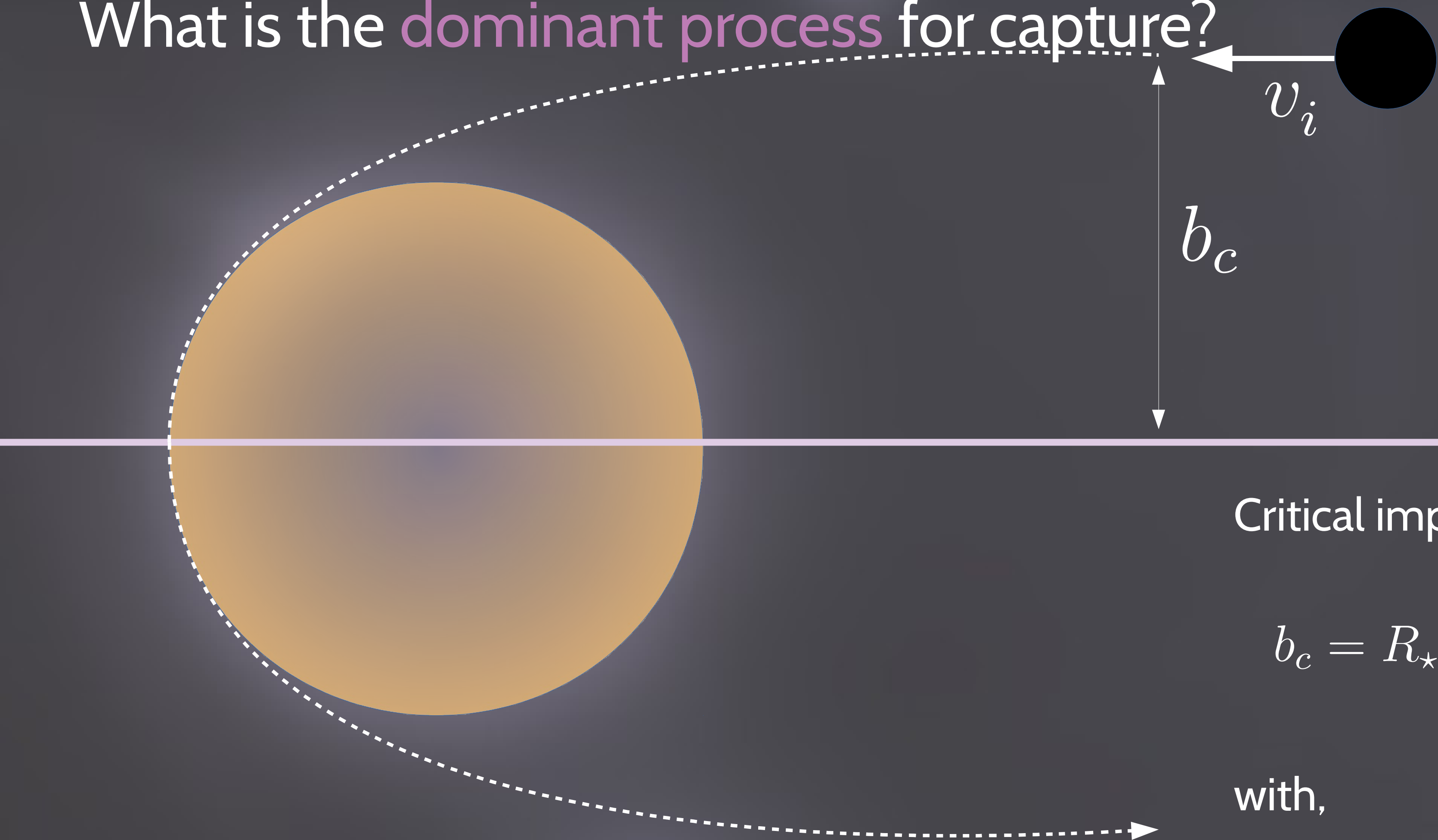


Critical impact parameter

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

with,

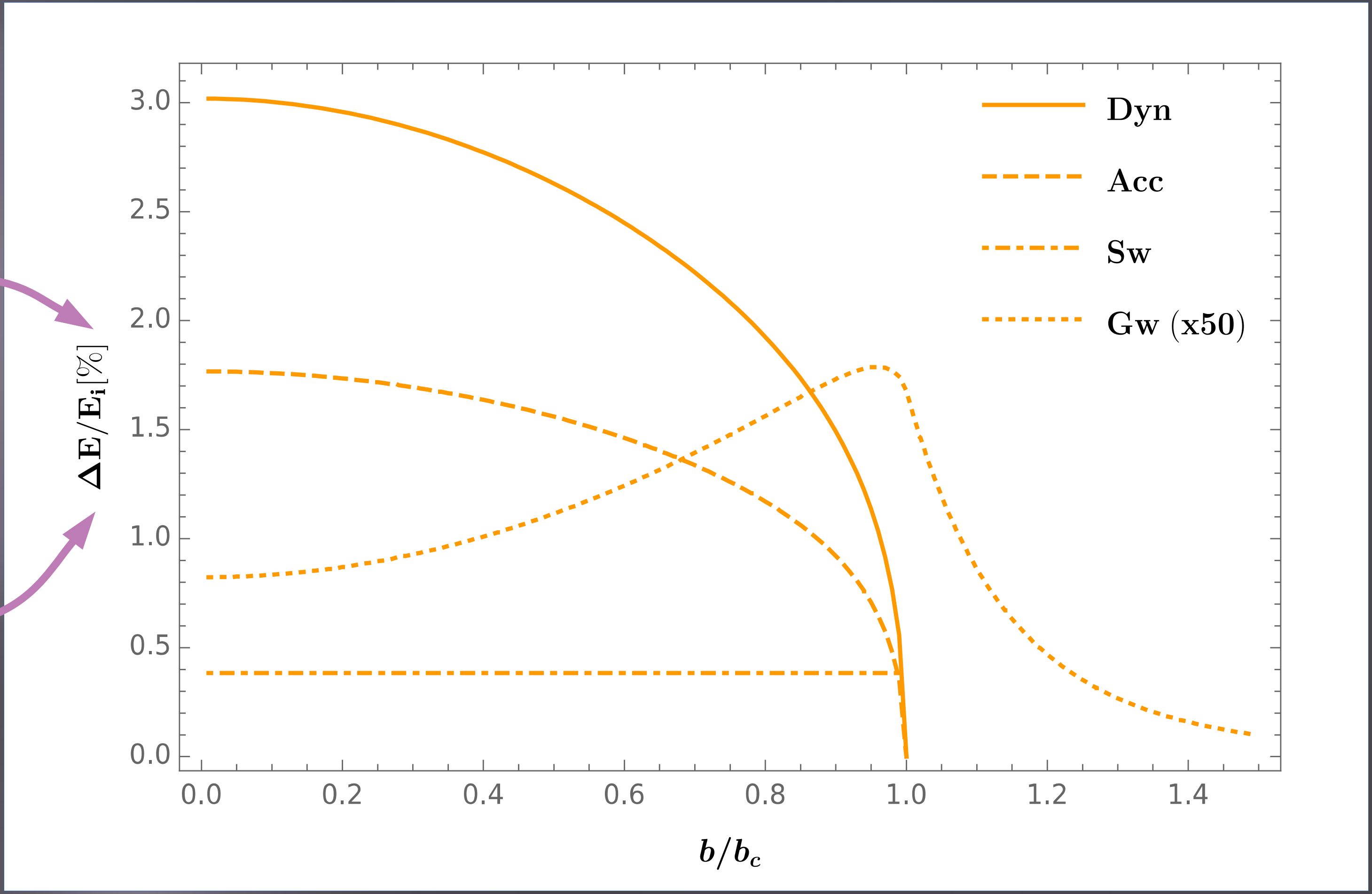
$$v_\star = \sqrt{\frac{GM_\star}{R_\star}}$$

What is the dominant process for capture?

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

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

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



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

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

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

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

Compare with the rate of NS-PBH encounter

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

Similar to the GRB rate in the Galaxy

Estimate of the number of event in the Galaxy

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Rate of NS-PBH encounter leading to capture

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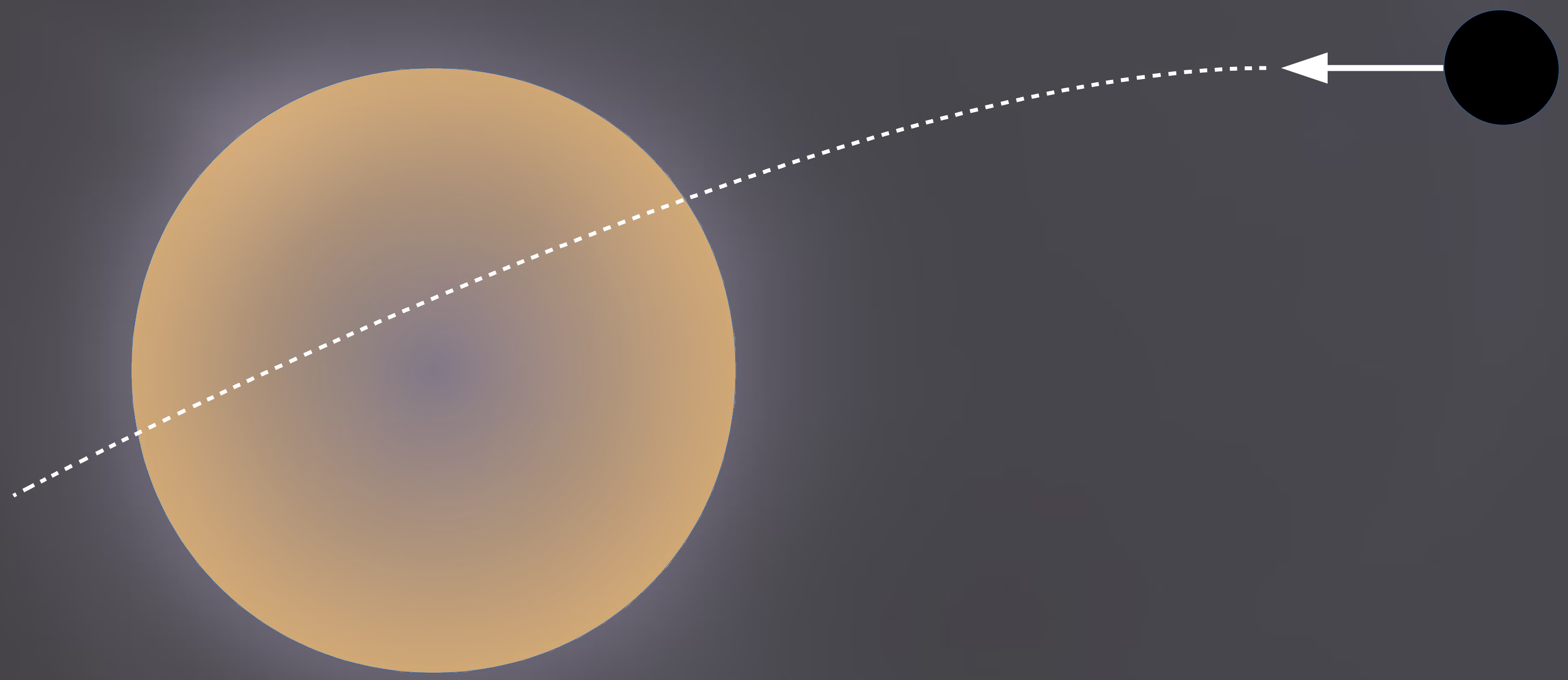
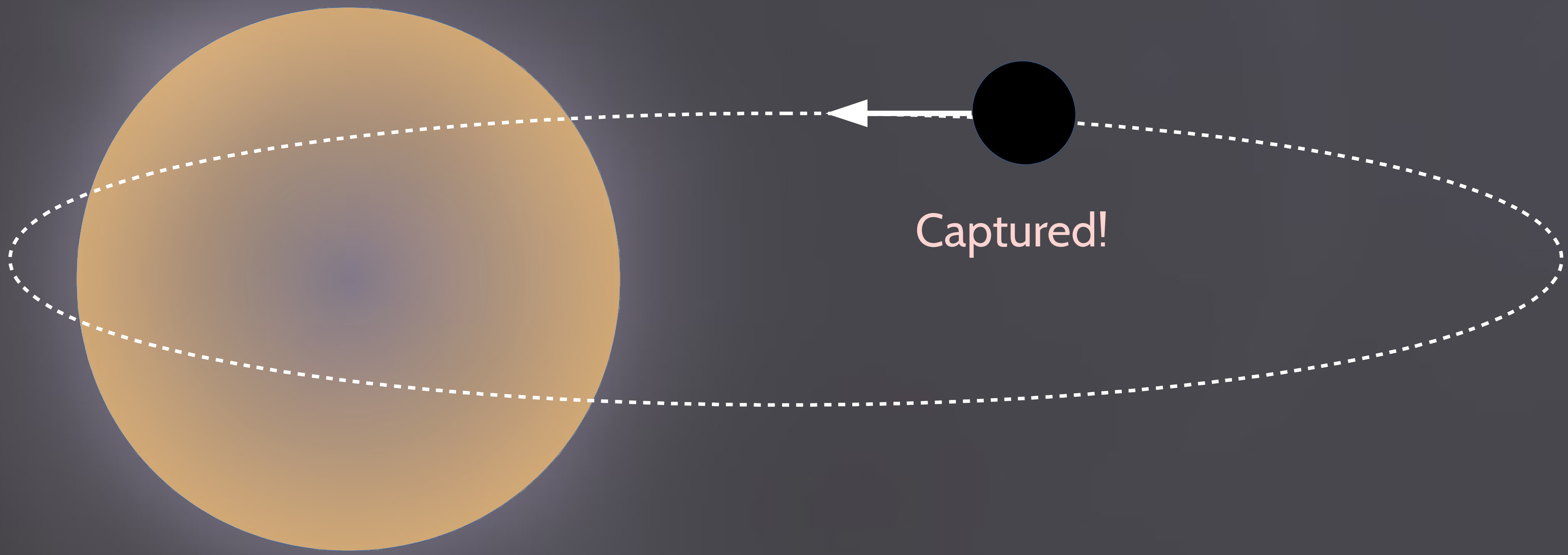
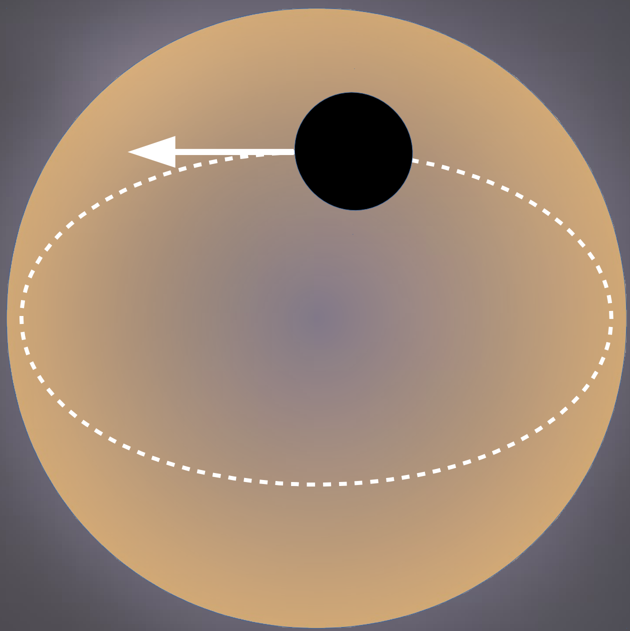
→ Rare events !



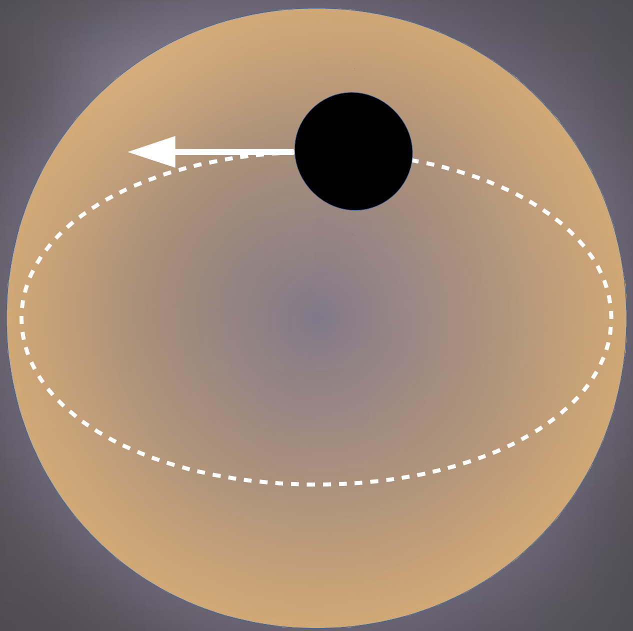

Captured!



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)



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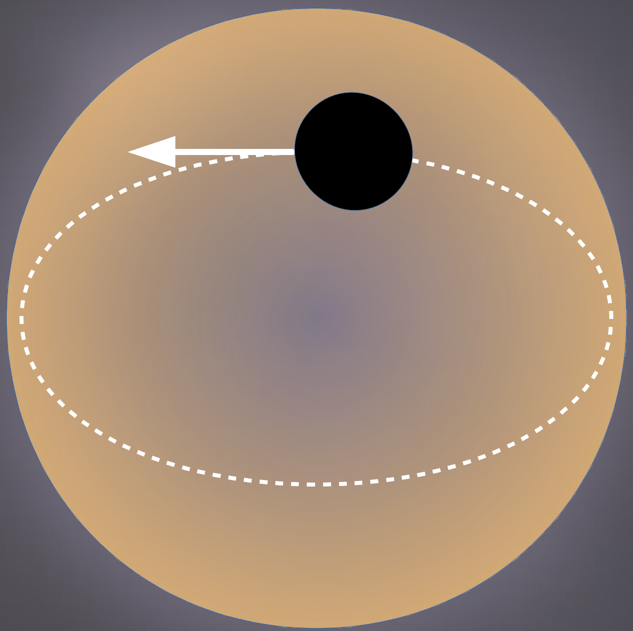
The motion becomes subsonic for

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



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

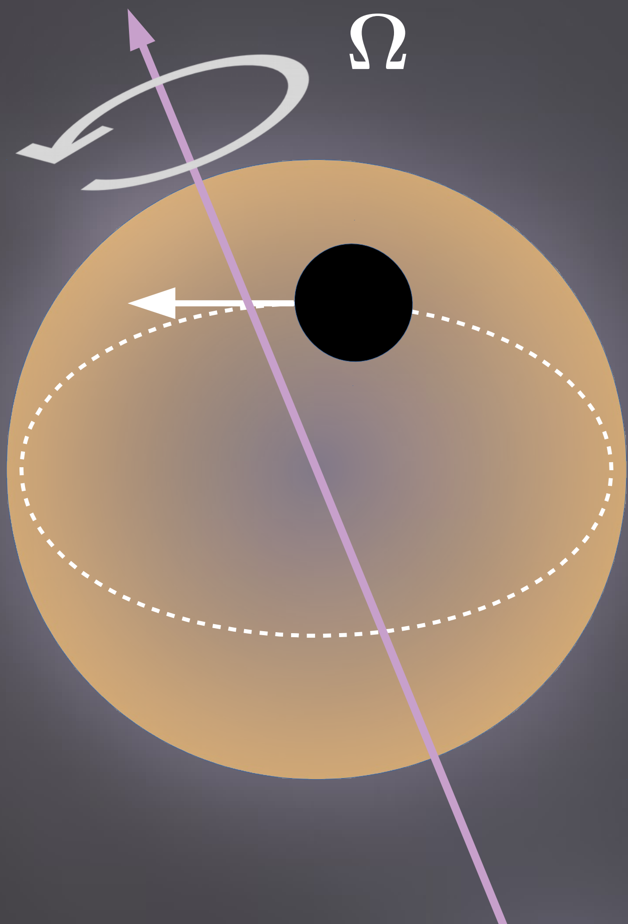
Capela+ (2013)

The motion becomes subsonic for

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

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

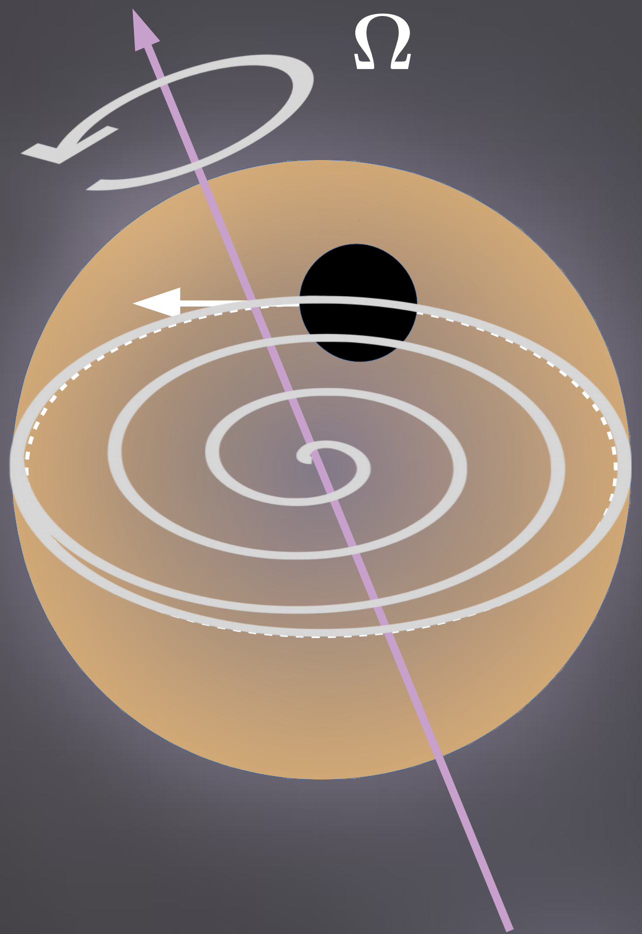
Realistic neutron star models Potekhin+ (2013)



Subsonic regime

↓

DF negligible & accretion dominates



Subsonic regime

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DF negligible & accretion dominates

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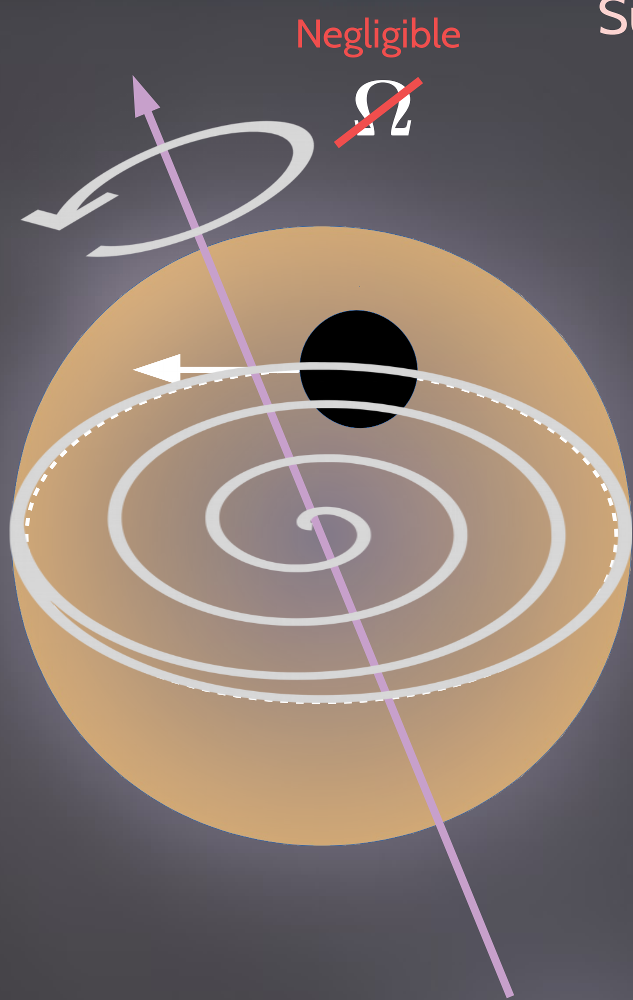
Equation of motion

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

Y.G. et al. PRD (2020)



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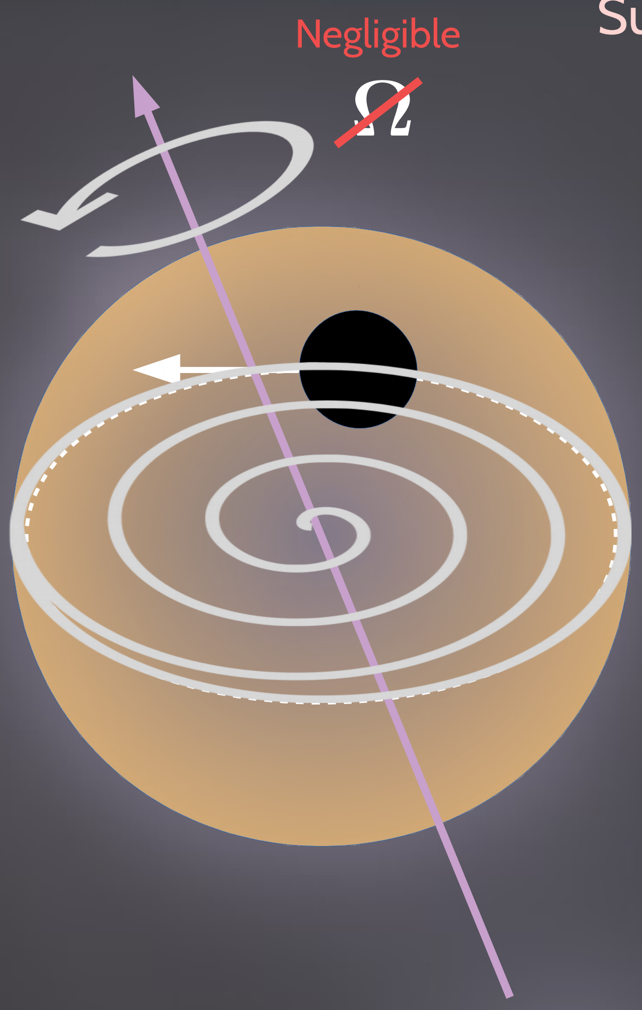

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Y.G. et al. PRD (2020)

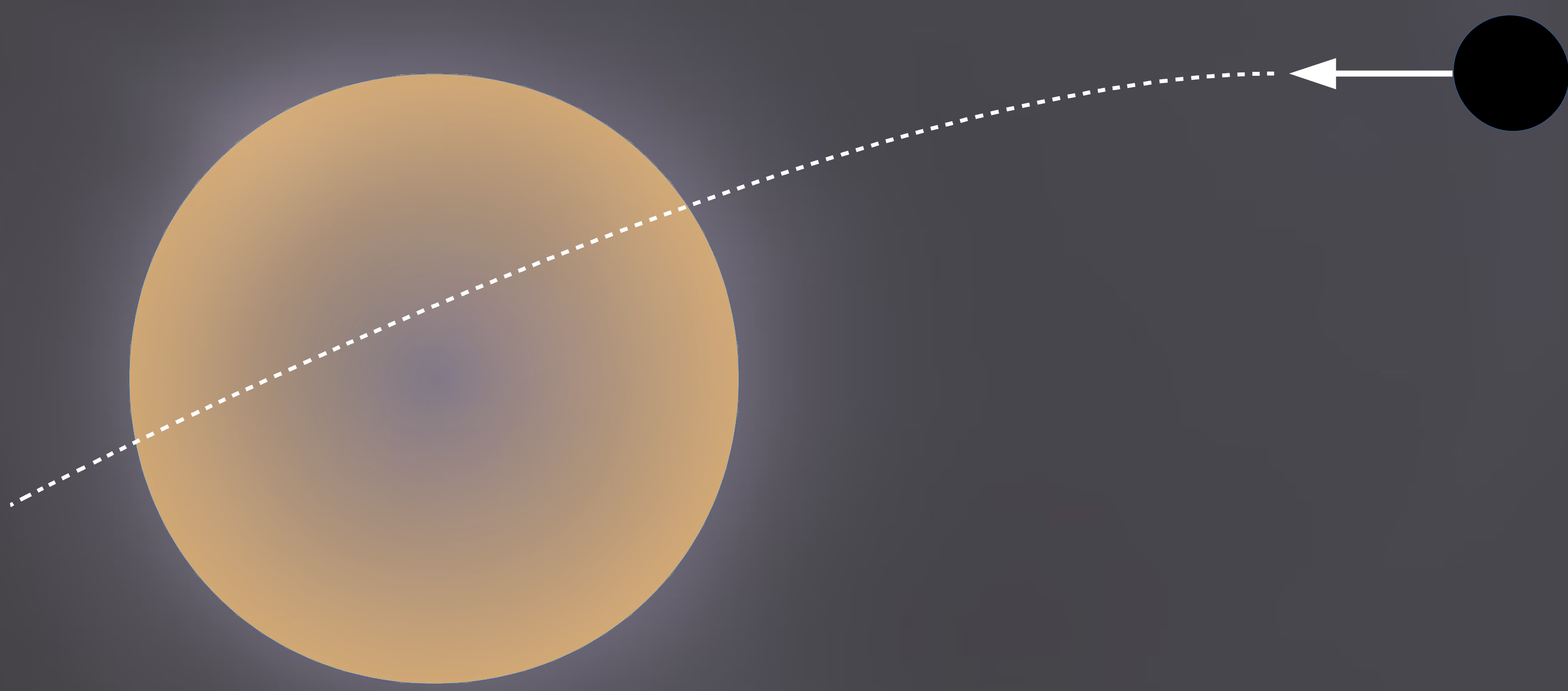
↓

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

Signatures PBH – NS encounter



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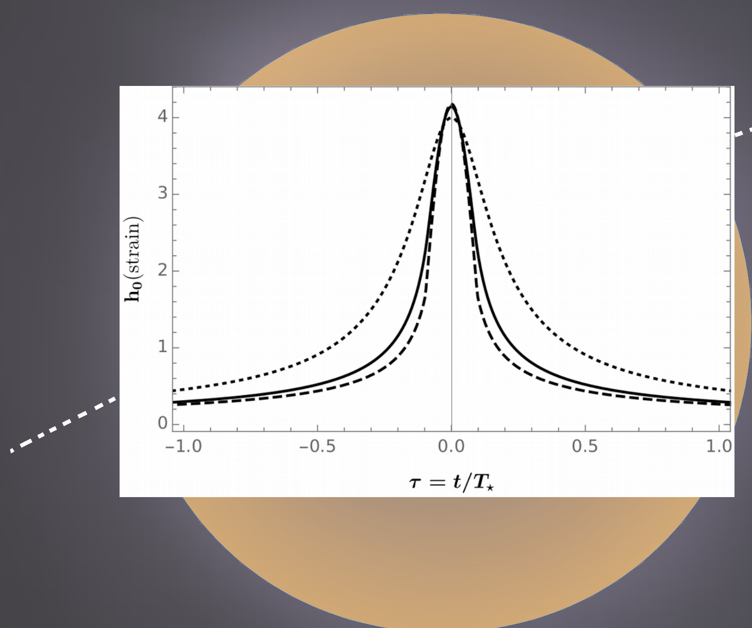
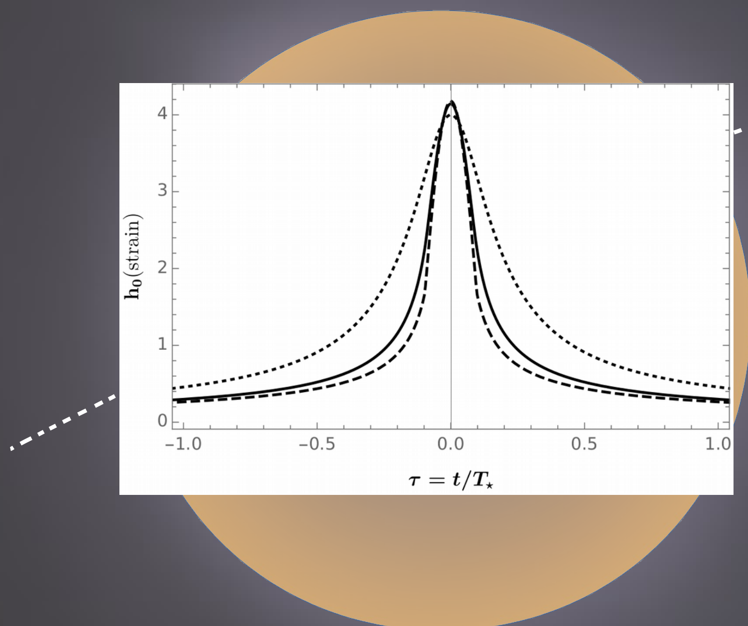
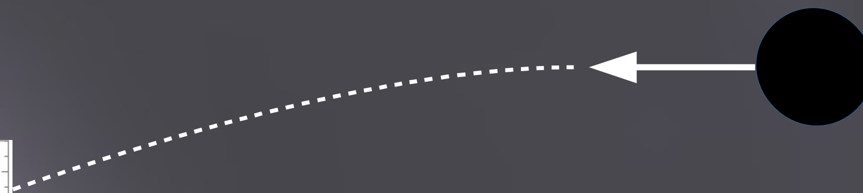


→ Gravitational wave burst

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

Signatures PBH – NS encounter





→ Gravitational wave burst

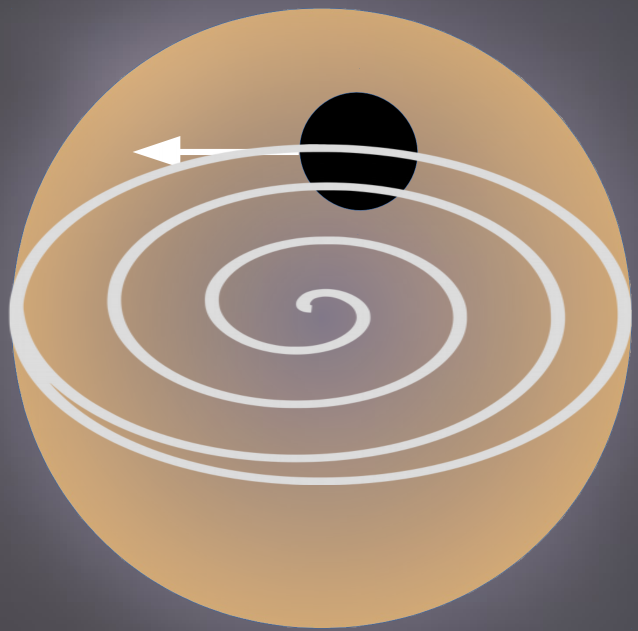
$$h_0 \sim 10^{-25} \left(\frac{m}{10^{25}\,\mathrm{g}}\right) \left(\frac{1\,\mathrm{kpc}}{d}\right)$$

→ 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

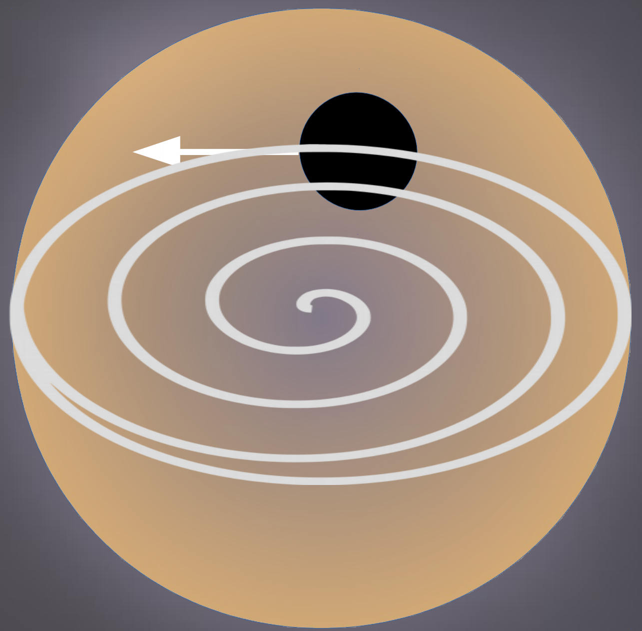


Signatures captured PBH

→ GW emission from the inspiral motion

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

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



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

Signatures captured PBH

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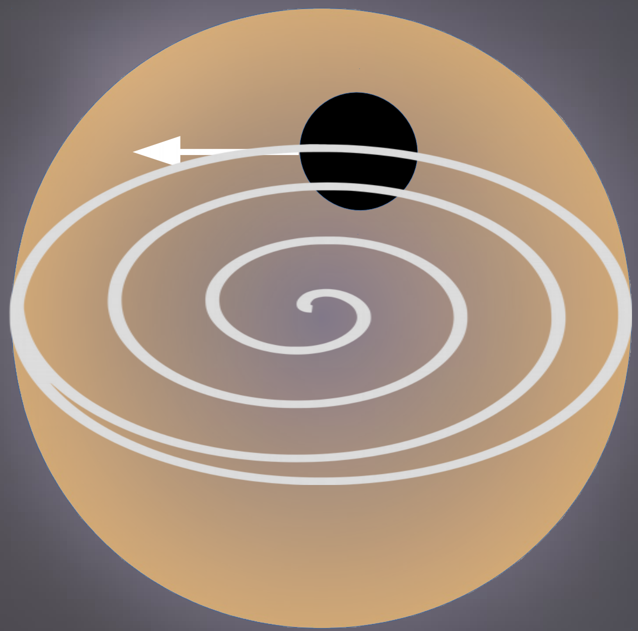

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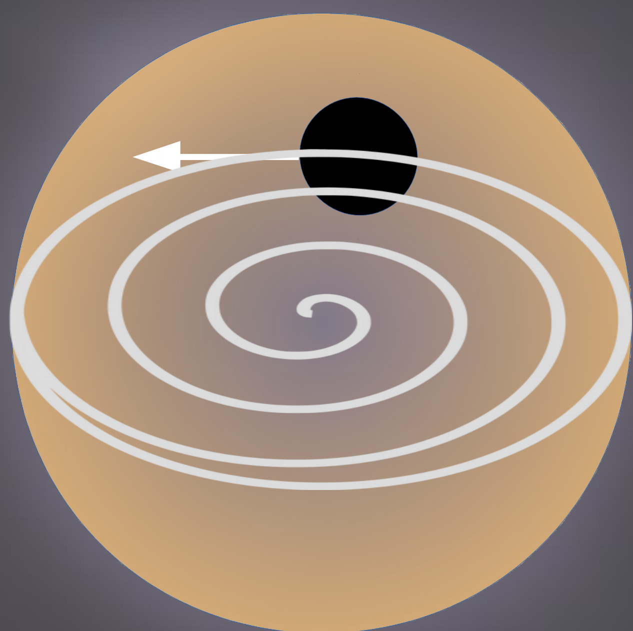
Emission sustained during the all accretion phase

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



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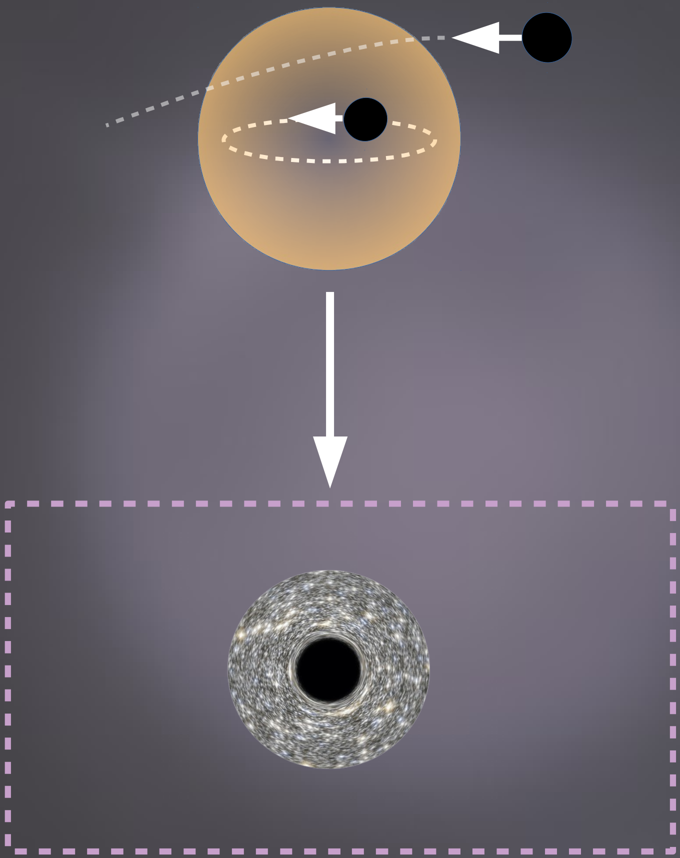
→ Multiwavelength signature from the final collapse
Might depend on the final asymmetry

Final radius

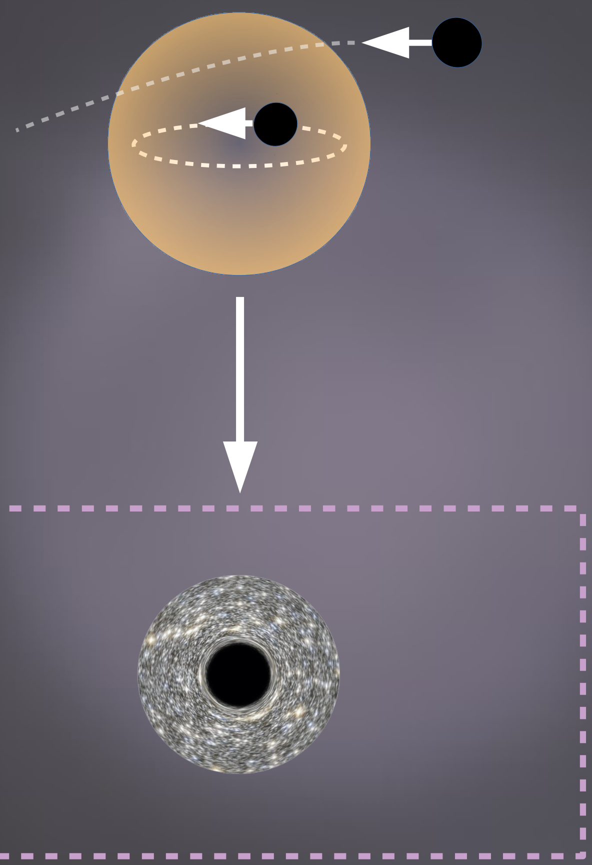
$$R_f = R_\star \sqrt{\frac{m_i}{f\, M_\star}}$$

Initial PBH mass

Fraction of the star mass accreted



The collapse



The collapse

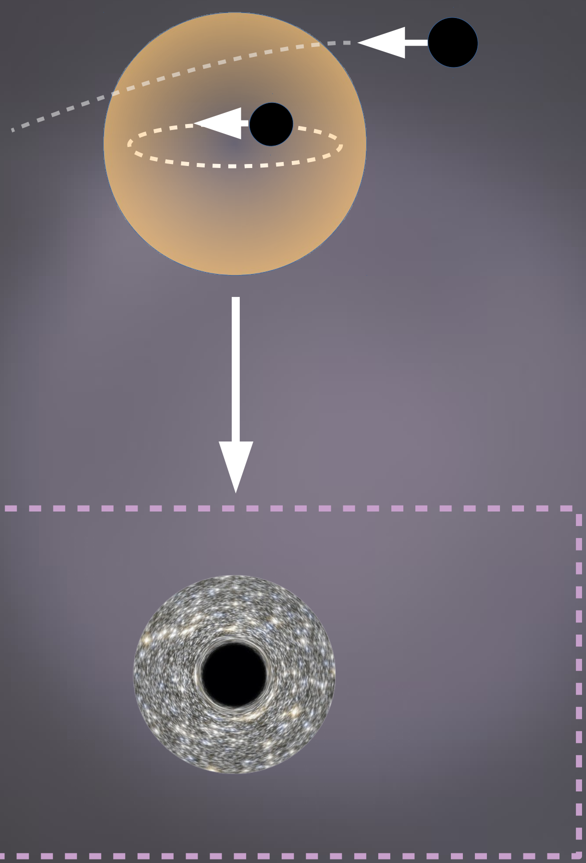
Direct emissions

→ 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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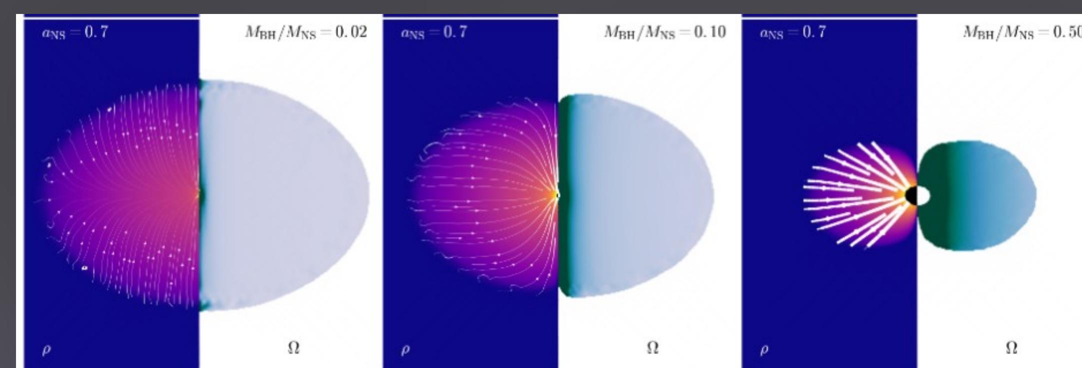
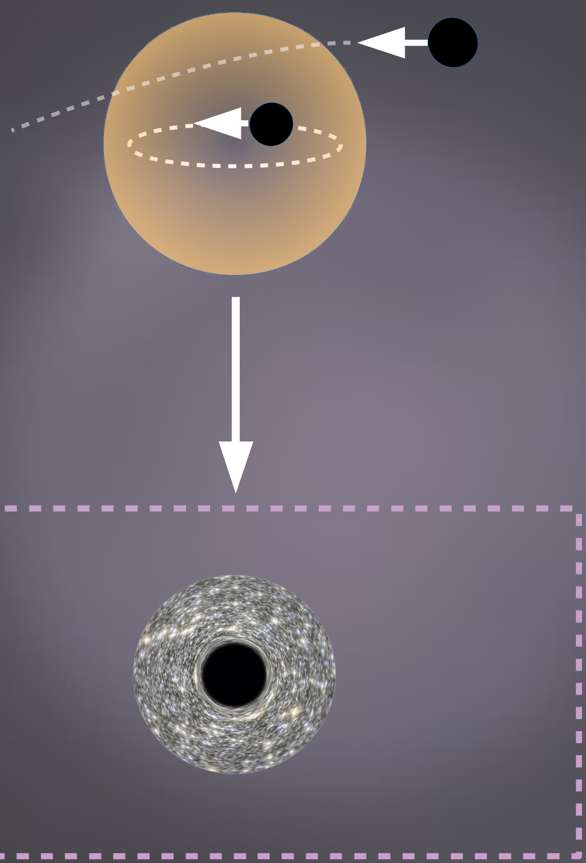


East+ (2019)

But PBH at the center and no magnetic field



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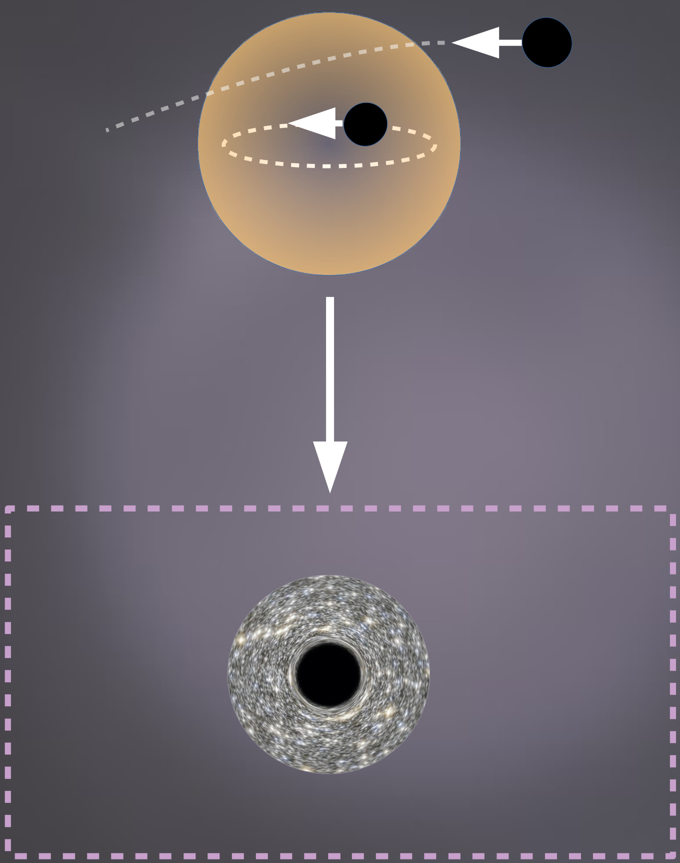
→ Observing quiet kilonovae?

e.g. Bramante+ (2016,2017)



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Later detection

→ Leading mecanism for « light » BH formation?

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

→ Solving the missing pulsar problem?

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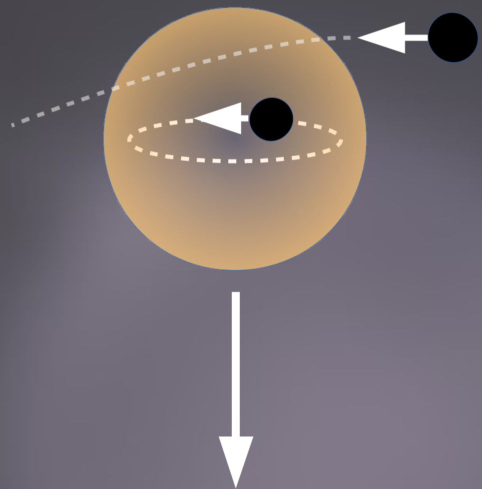
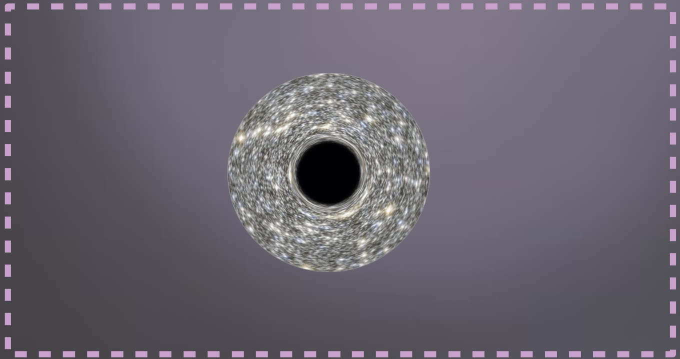
The collapse





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Thank you for listening!

Backups!

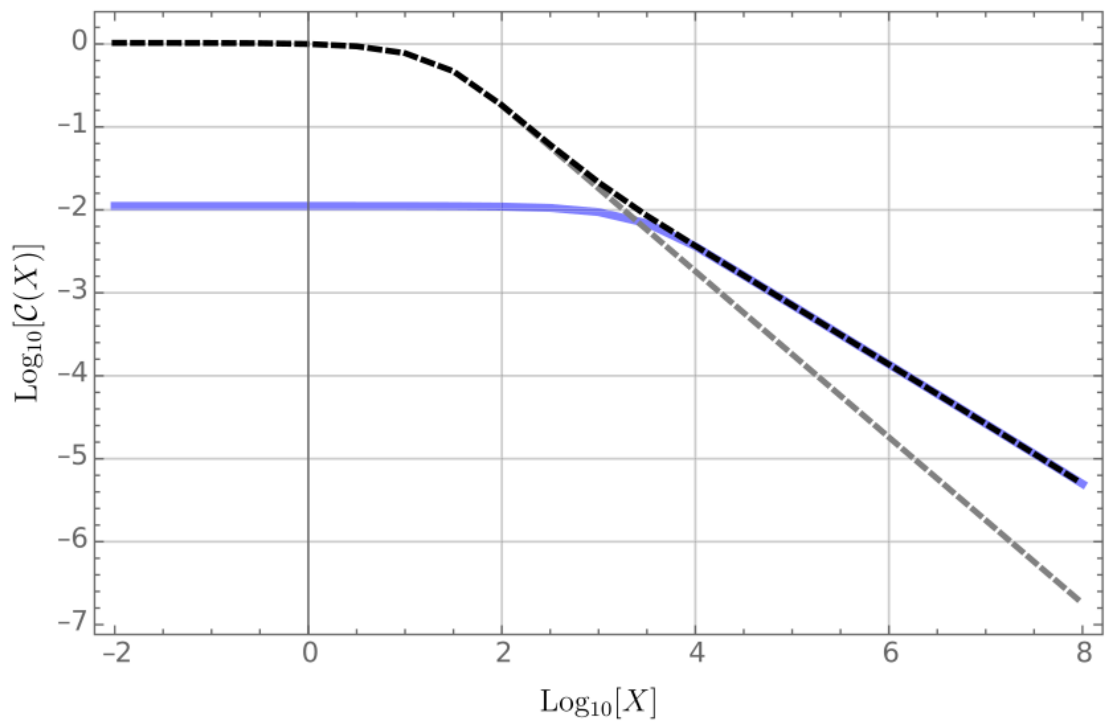
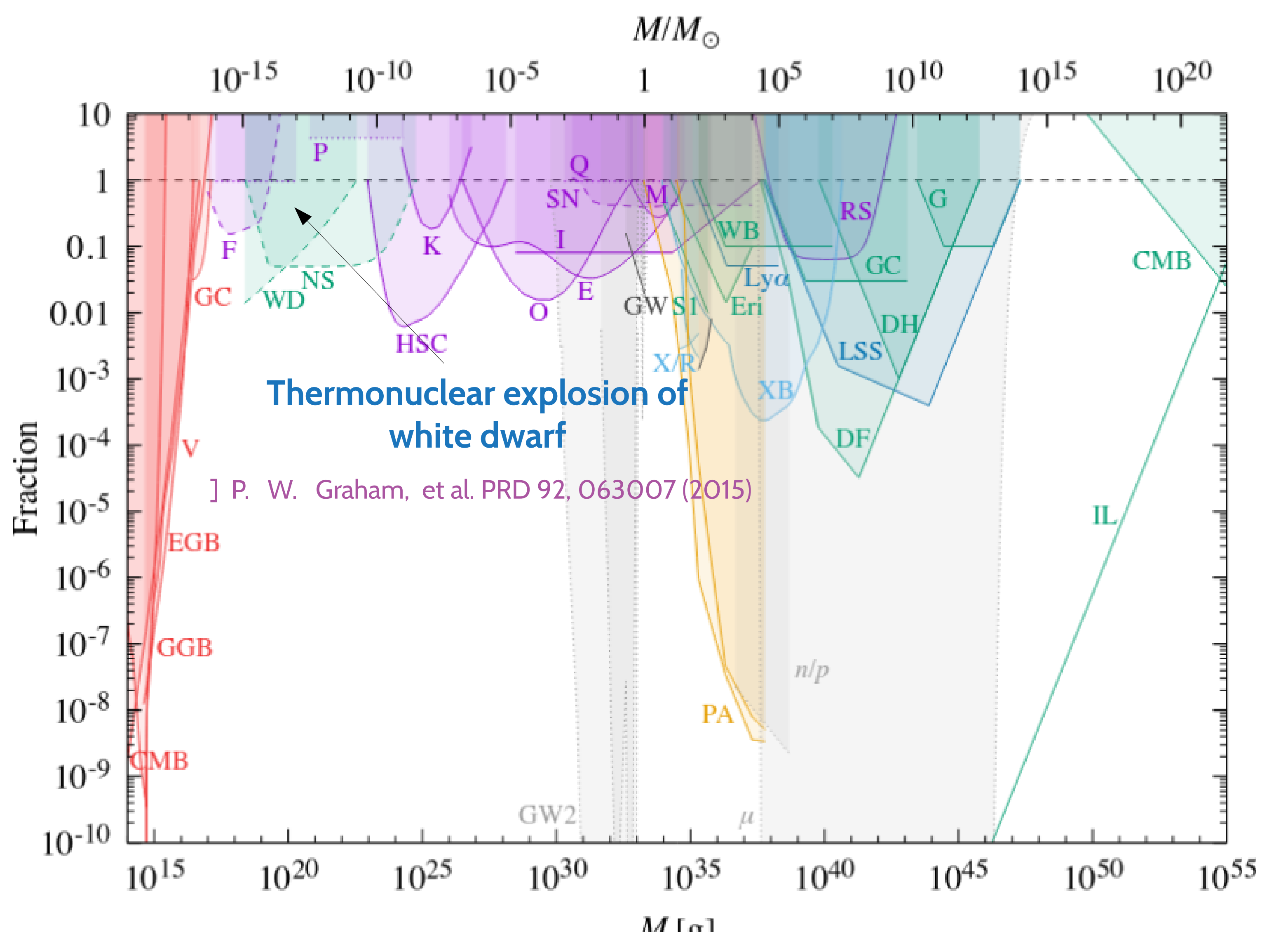


FIG. 3. Evolution of the function $\mathcal{C}$ (black-dashed line) of Eq. (27) as a function of X defined in Eq. (28). The sole contribution of GW capture is displayed in blue and the difference with the total is shown with a dashed gray line.



Carr et al. : arXiv:2002.12778