Revisiting PBH capture into NEUTRON STARS

Yoann Genolini

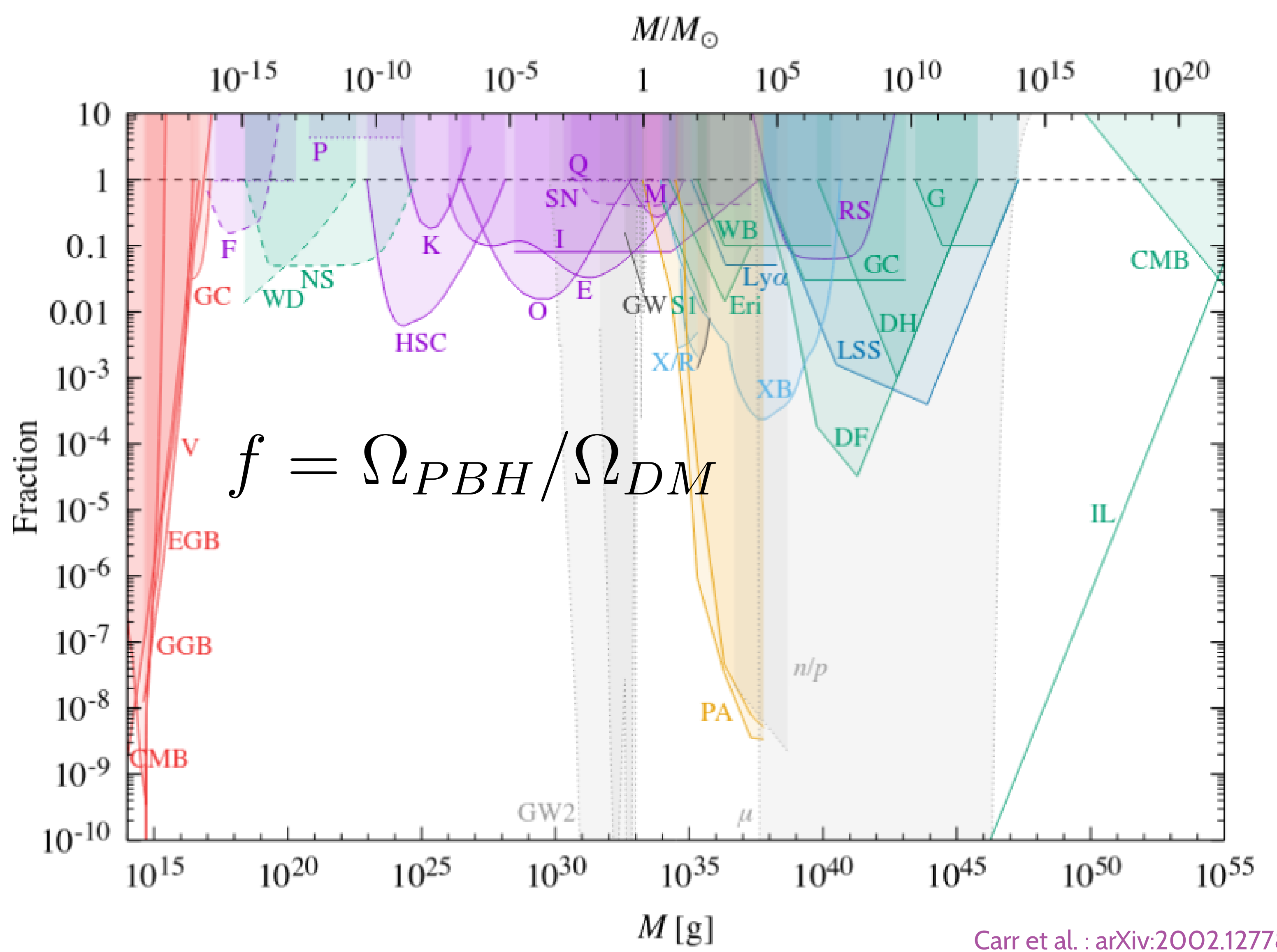
A work in collaboration with :
Pasquale Serpico & Peter Tinyakov

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

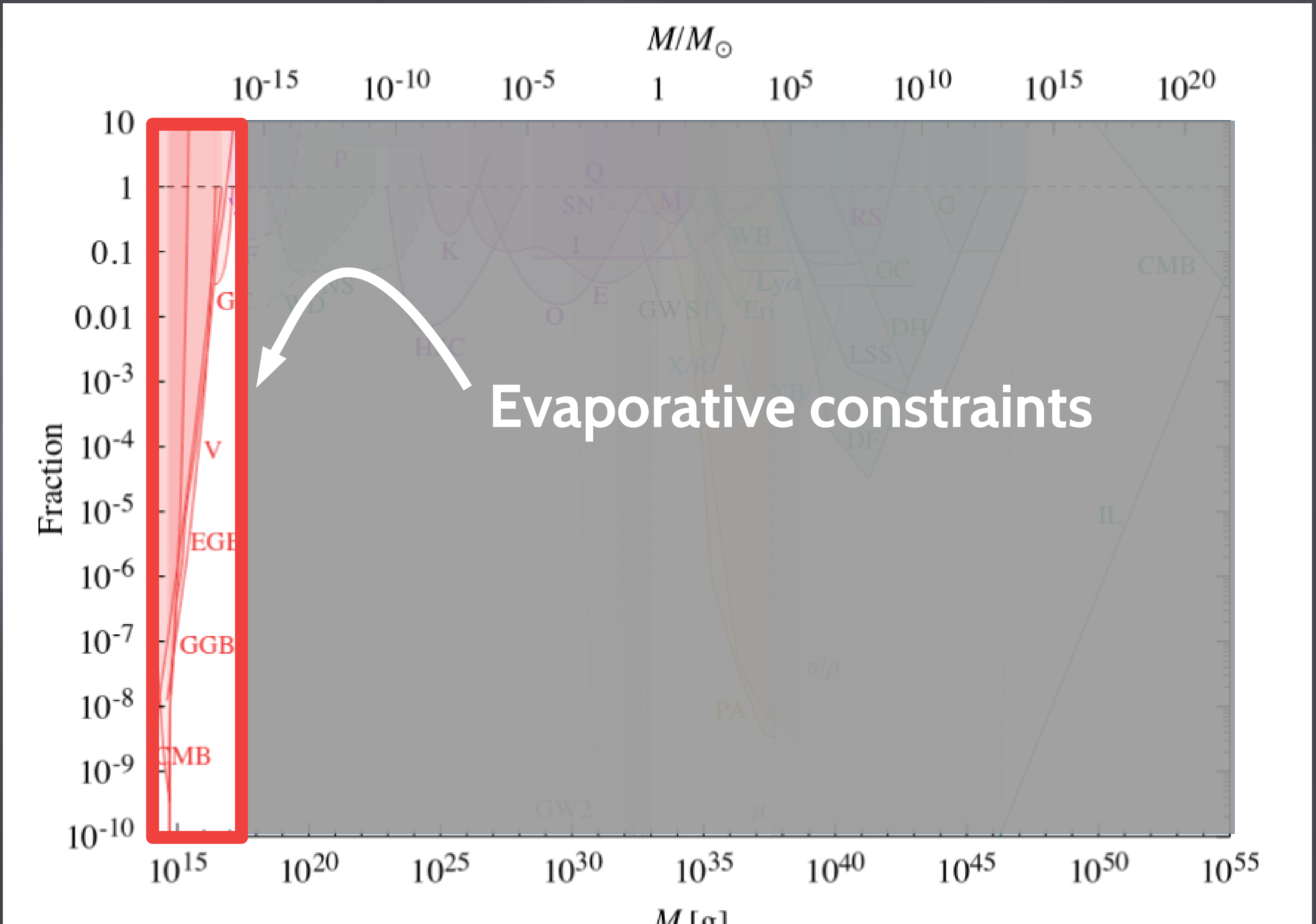
INR Terascale, November 2020

Niels Bohr Institute

Outline



Carr et al. : arXiv:2002.12778



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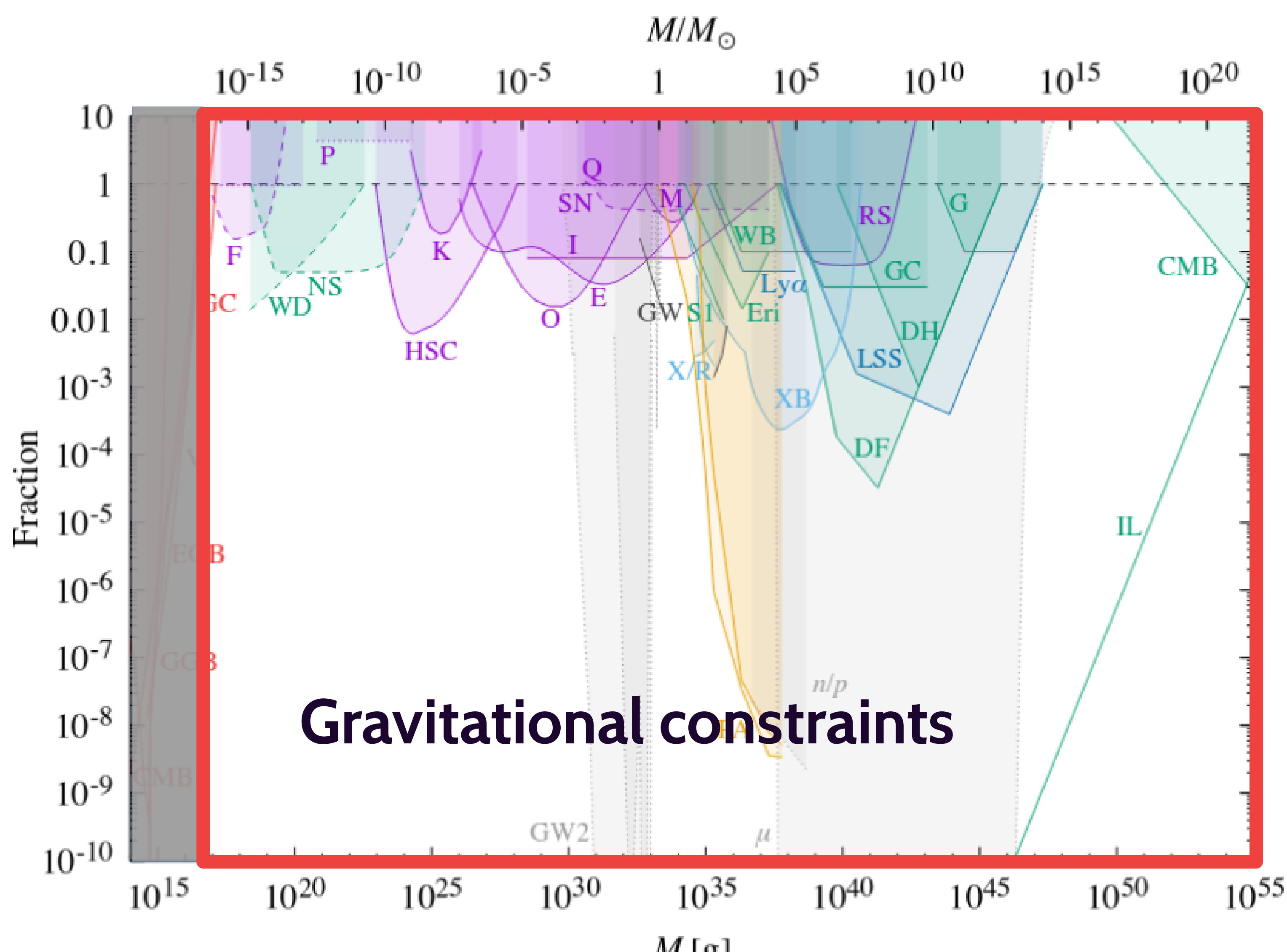

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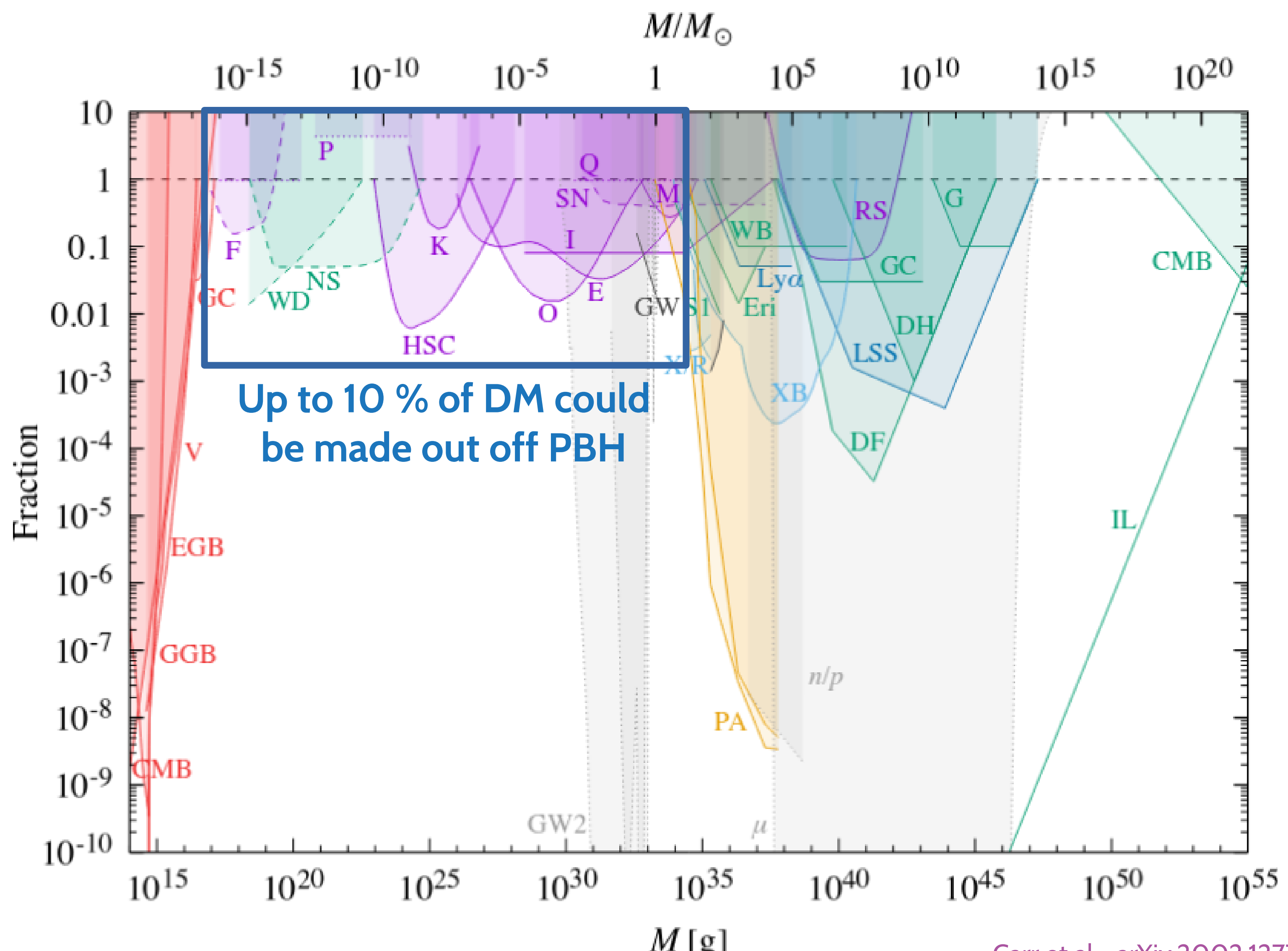
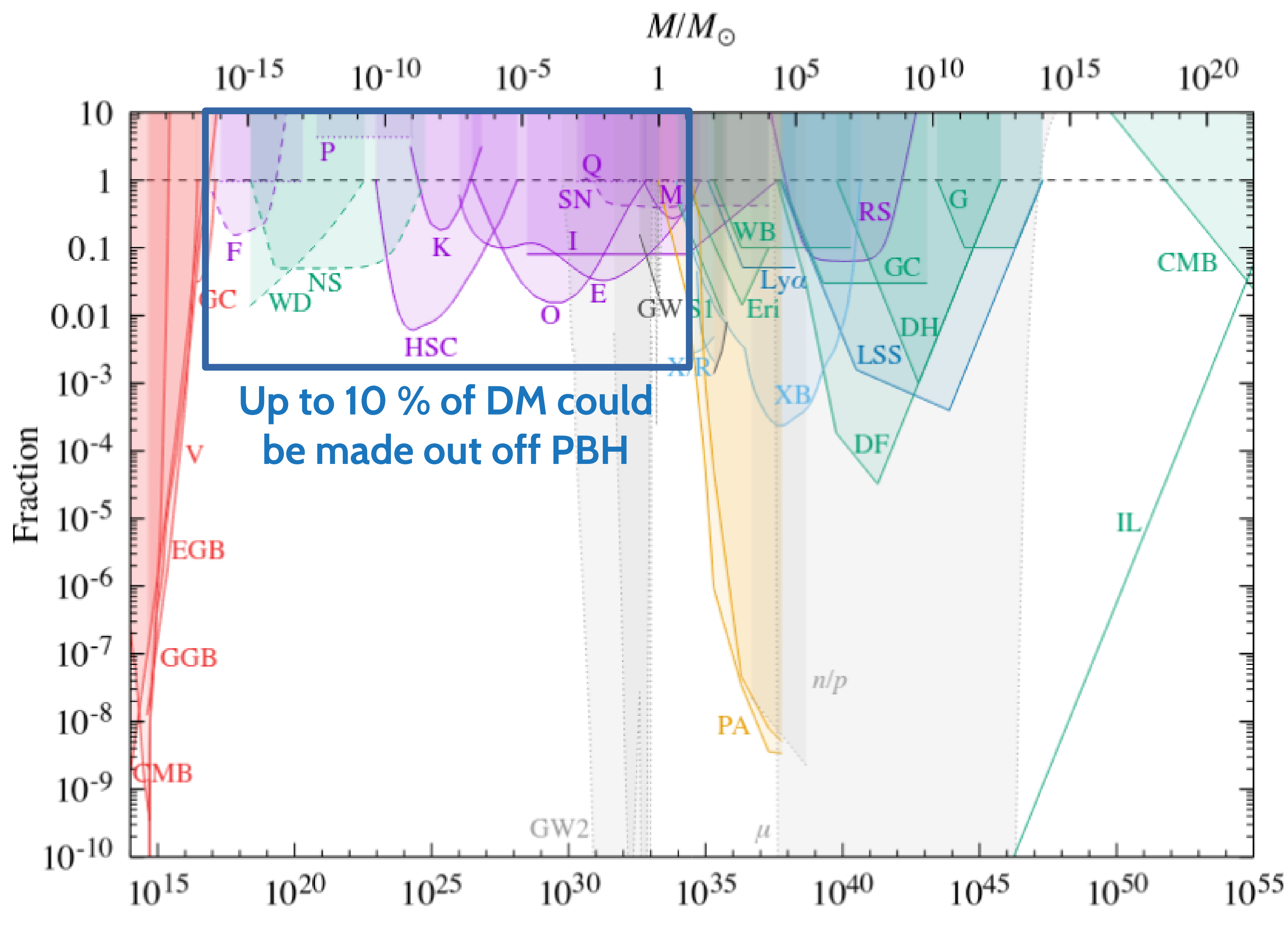


Up to 10 % of DM could be made out off PBH

Carr et al. : arXiv:2002.12778



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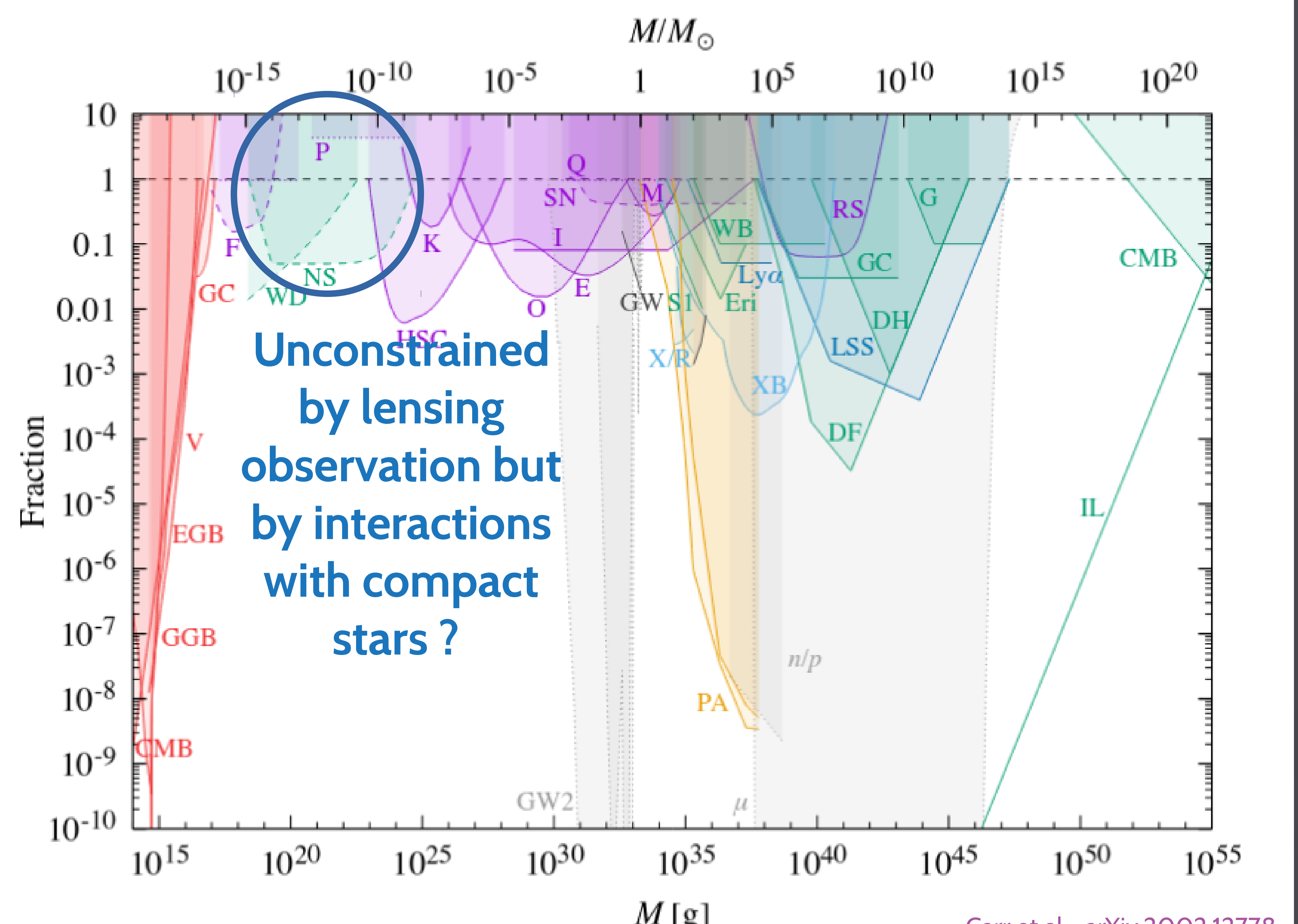

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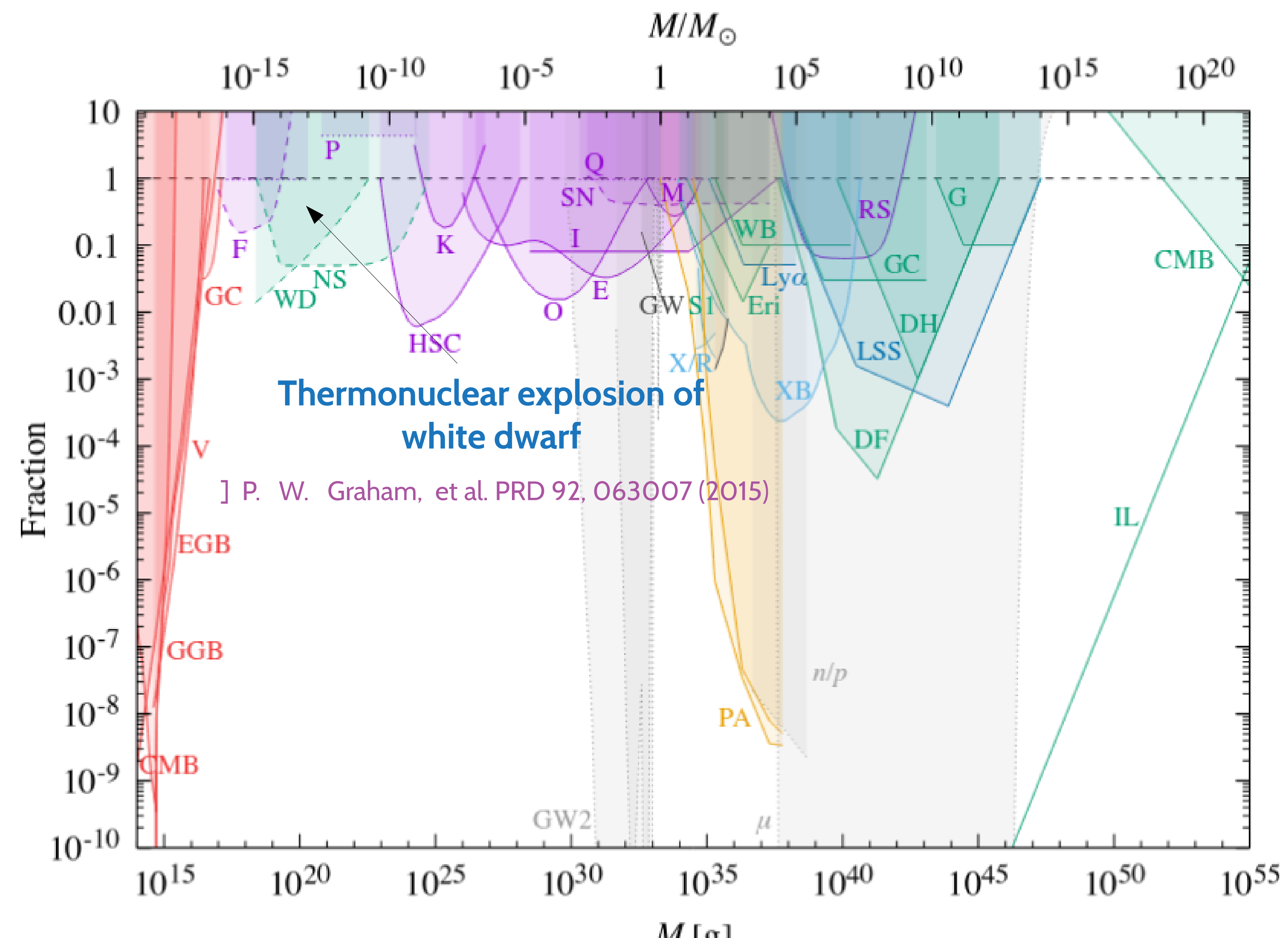
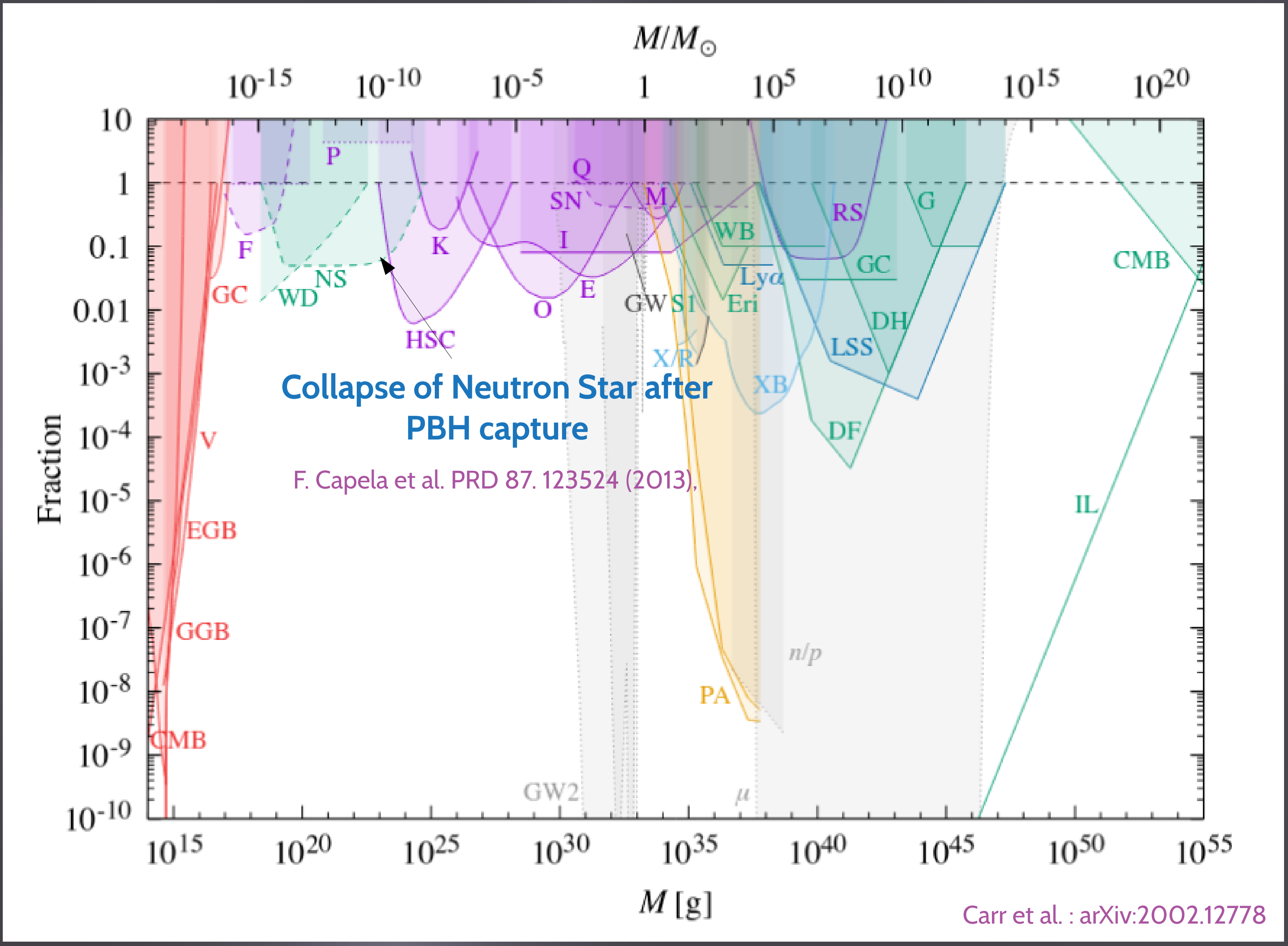
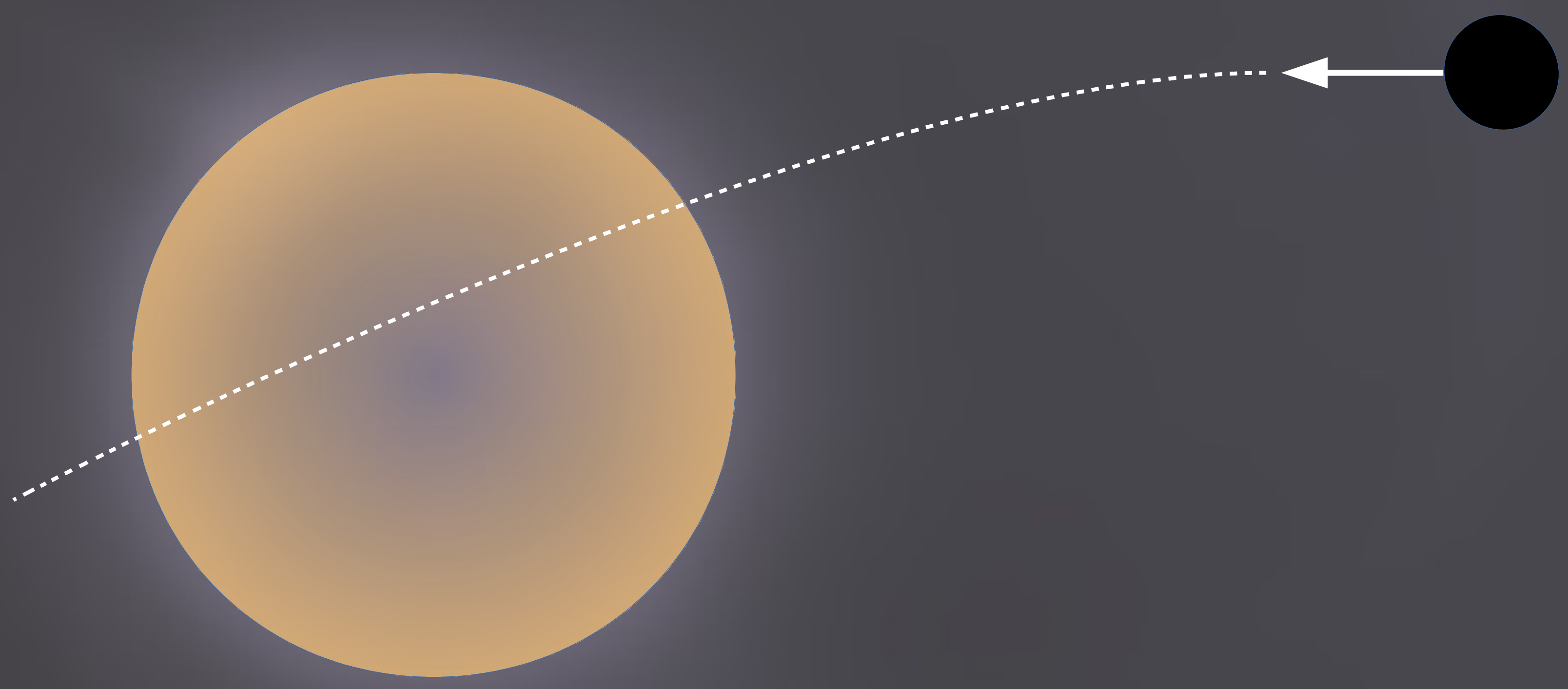


Carr et al. : arXiv:2002.12778

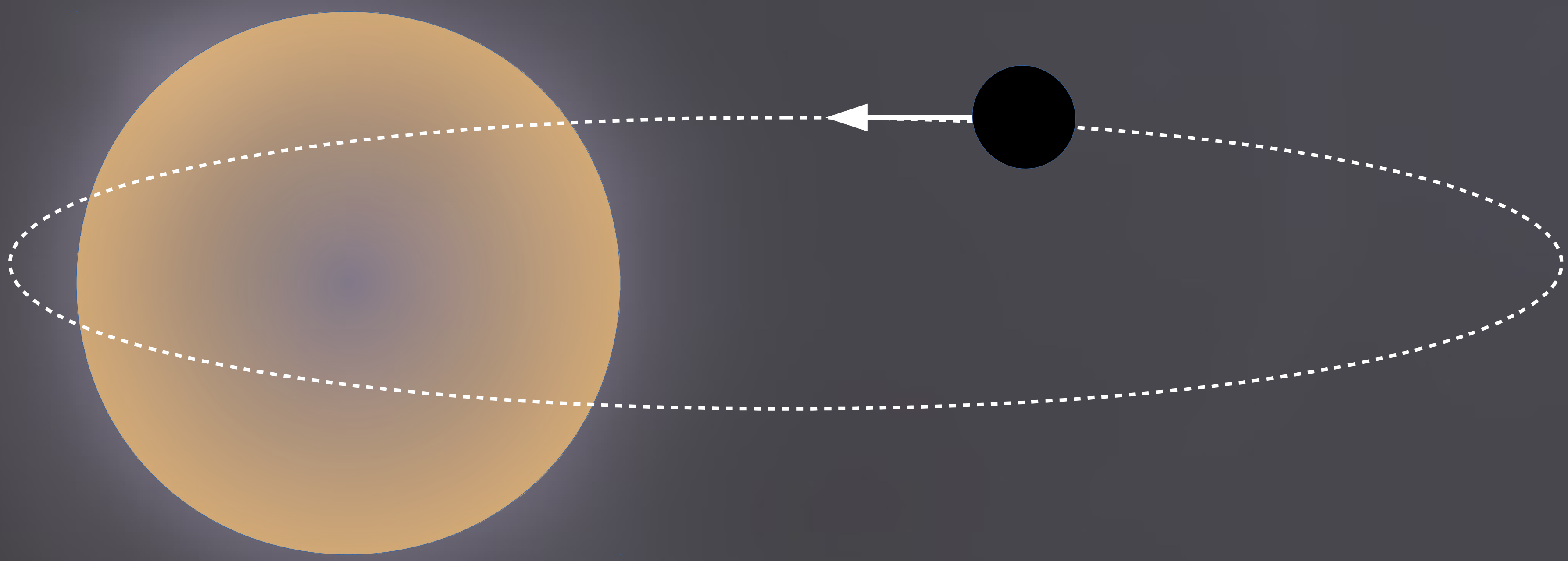

M/M⊙
10-15
10-10
10-5
1
10^5
10^10
10^15
10^20
Fraction
M [g]
P
Q
SN
M
I
K
F
GC
WD
NS
HSC
O
E
GW
S1
WB
RS
G
GC
Lyα
Eri
DH
LSS
X/R
XB
DF
CMB
IL
V
EGB
GGB
CMB
PA
n/p
GW2
μ
Collapse of Neutron Star after PBH capture
F. Capela et al. PRD 87. 123524 (2013),
Carr et al. : arXiv:2002.12778

1



Credit: ESO/L.Calçada
Yoann Genolini

2



Credit: ESO/L.Calçada

3

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

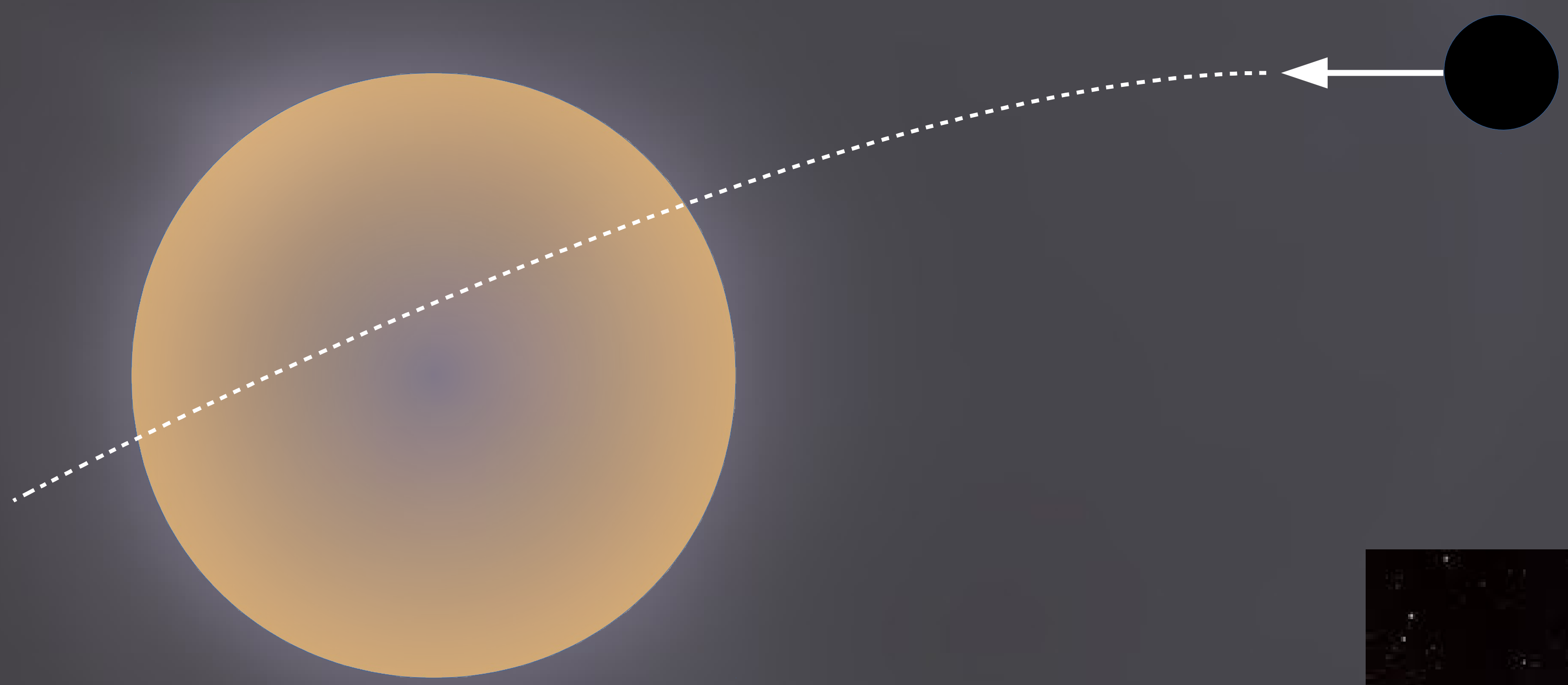
$$\tau_{old}^{NS} = 10\,\mathrm{Gyr}$$

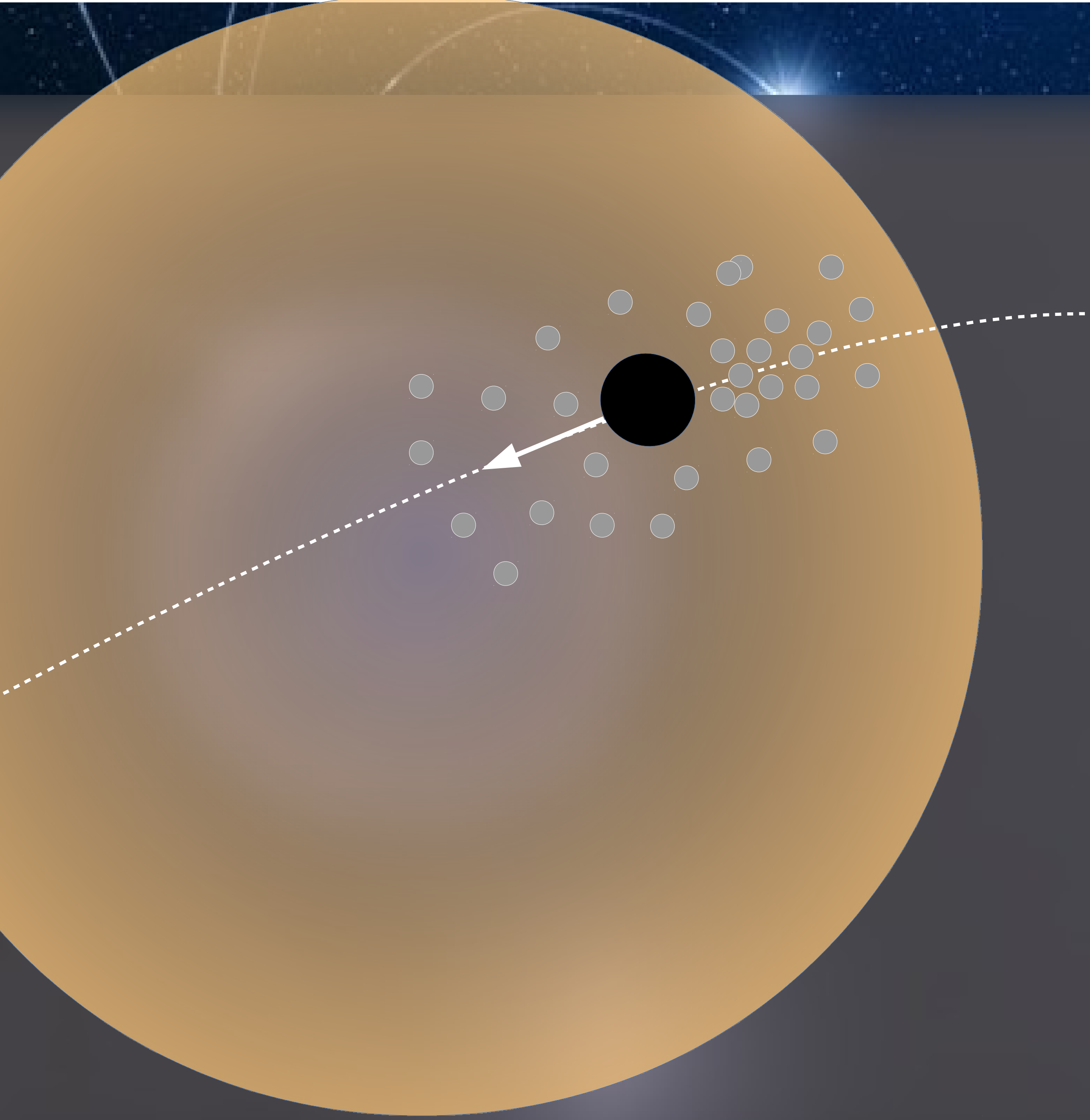
Constraints on f_{PBH}

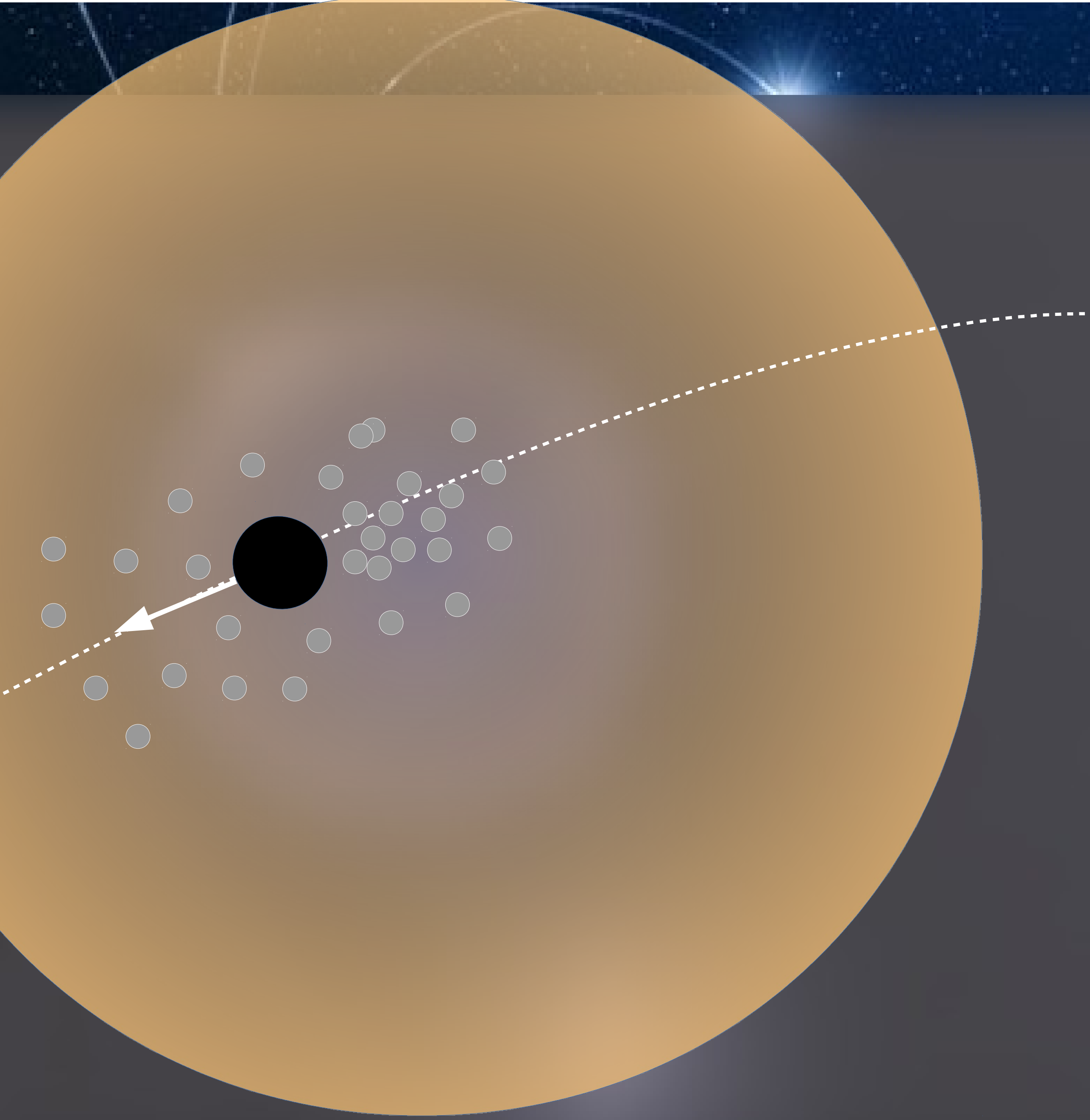
Yet, such a catastrophic event should be observable!

II- PBH interactions with a NS

1 - Dynamical Friction



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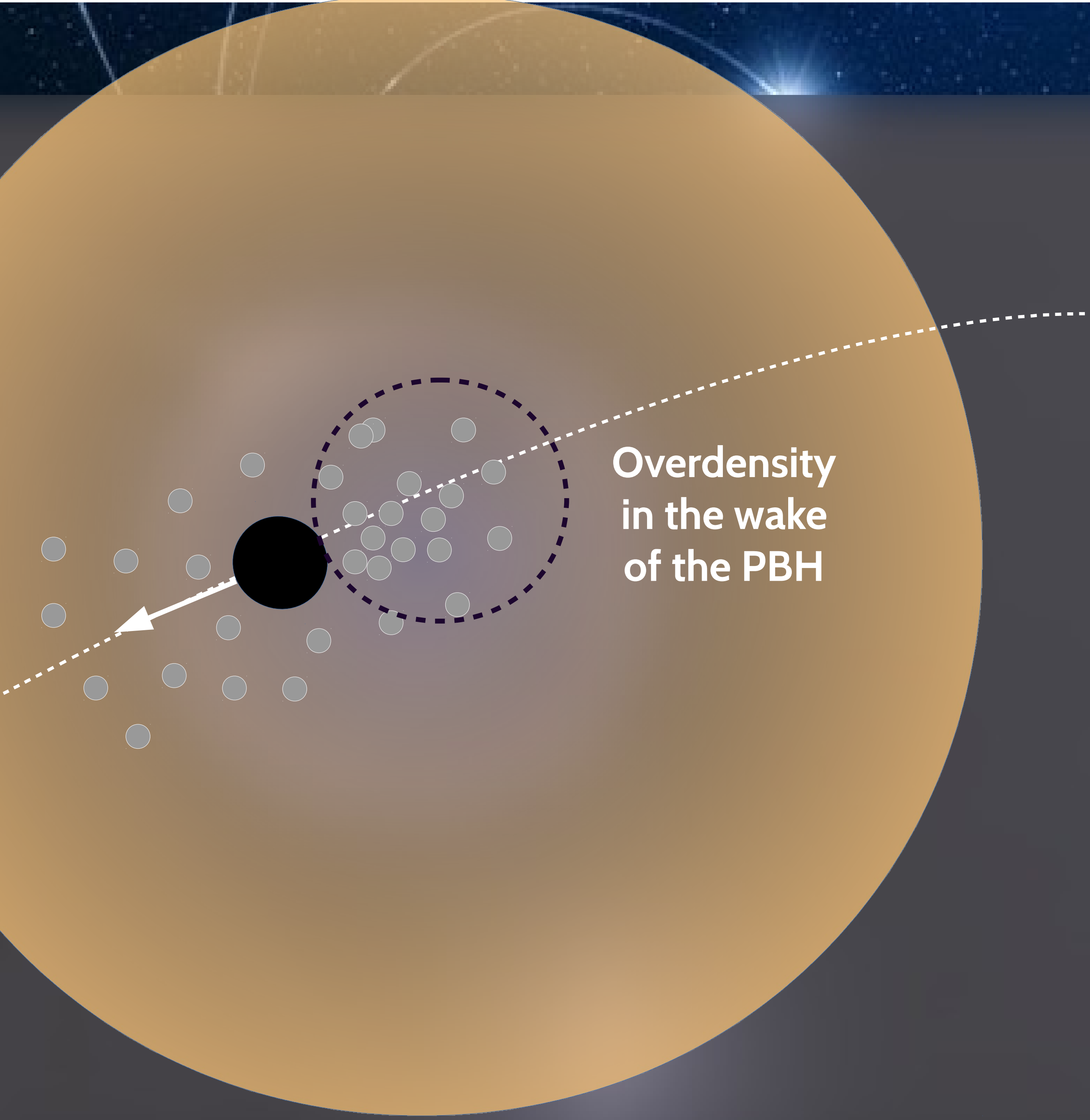
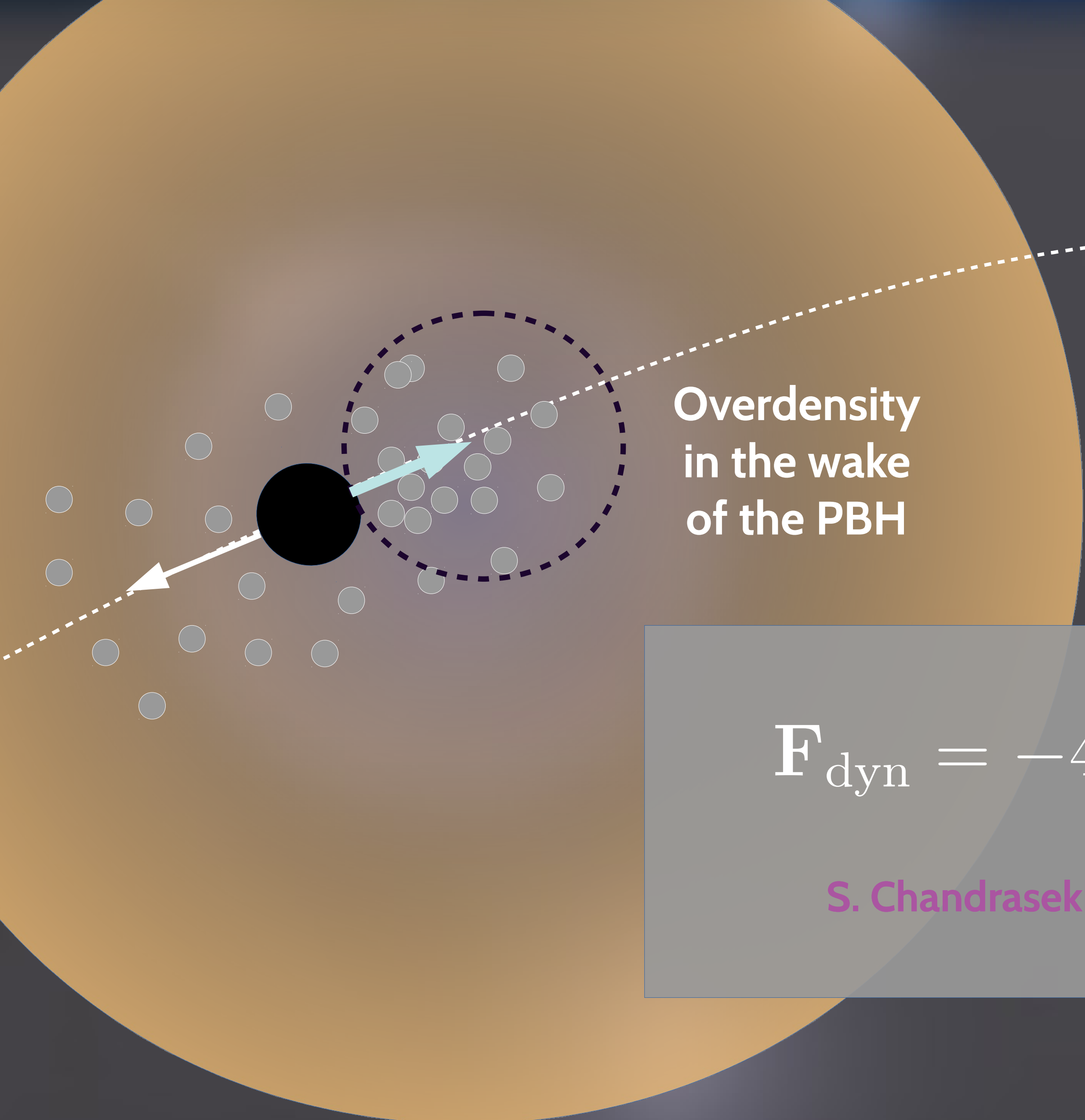


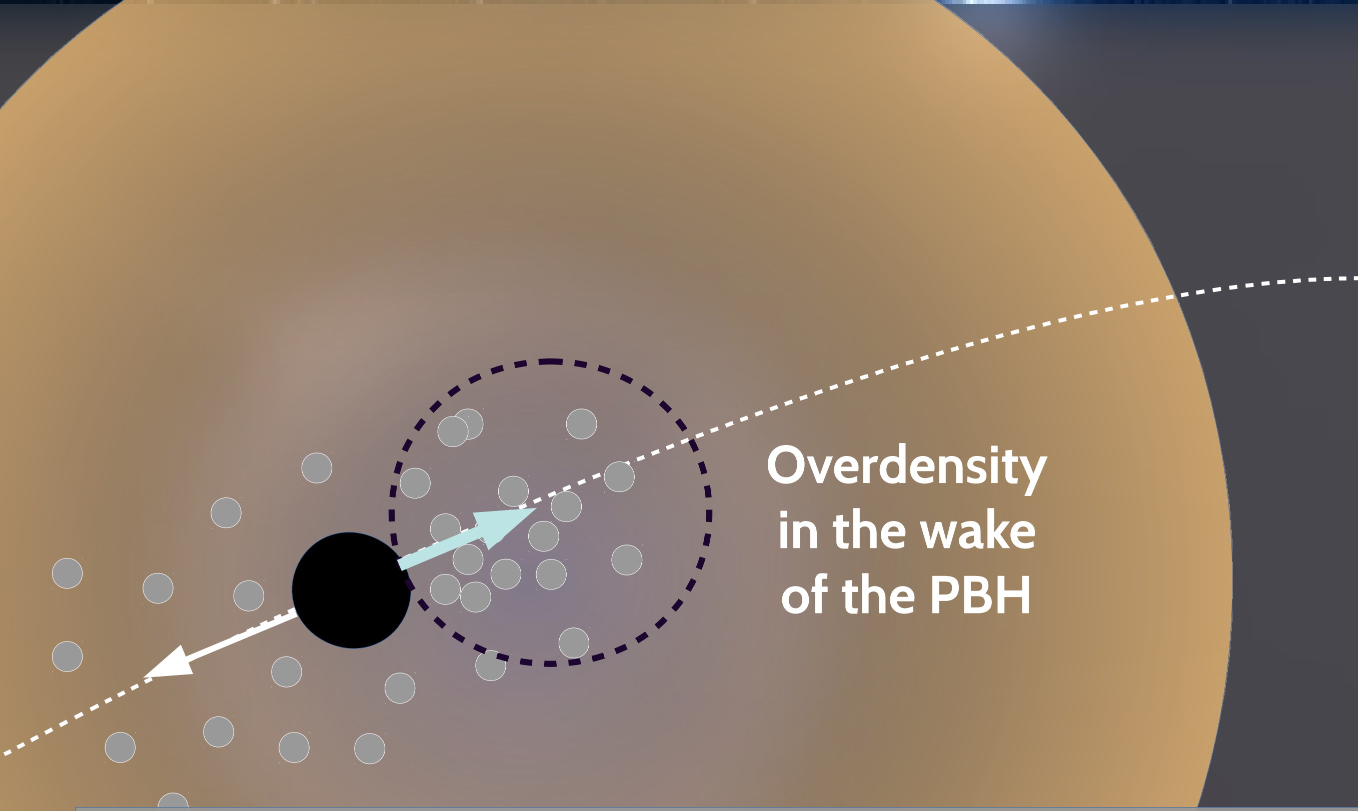
Credit: ESO/L.Calçada

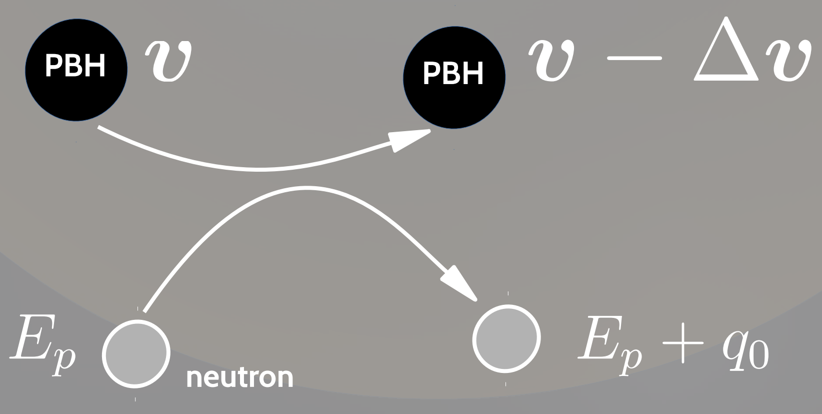


$$\mathbf{F}_{\rm dyn} = -4\pi G^2 m^2 \rho \ln \Lambda_{\rm dyn}(v) \frac{\boldsymbol{v}}{v^3}$$

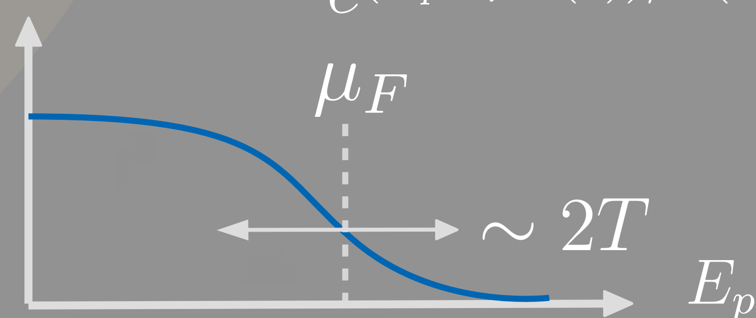
S. Chandrasekhar, Rev. Mod. Phys.21, 383 (1949).

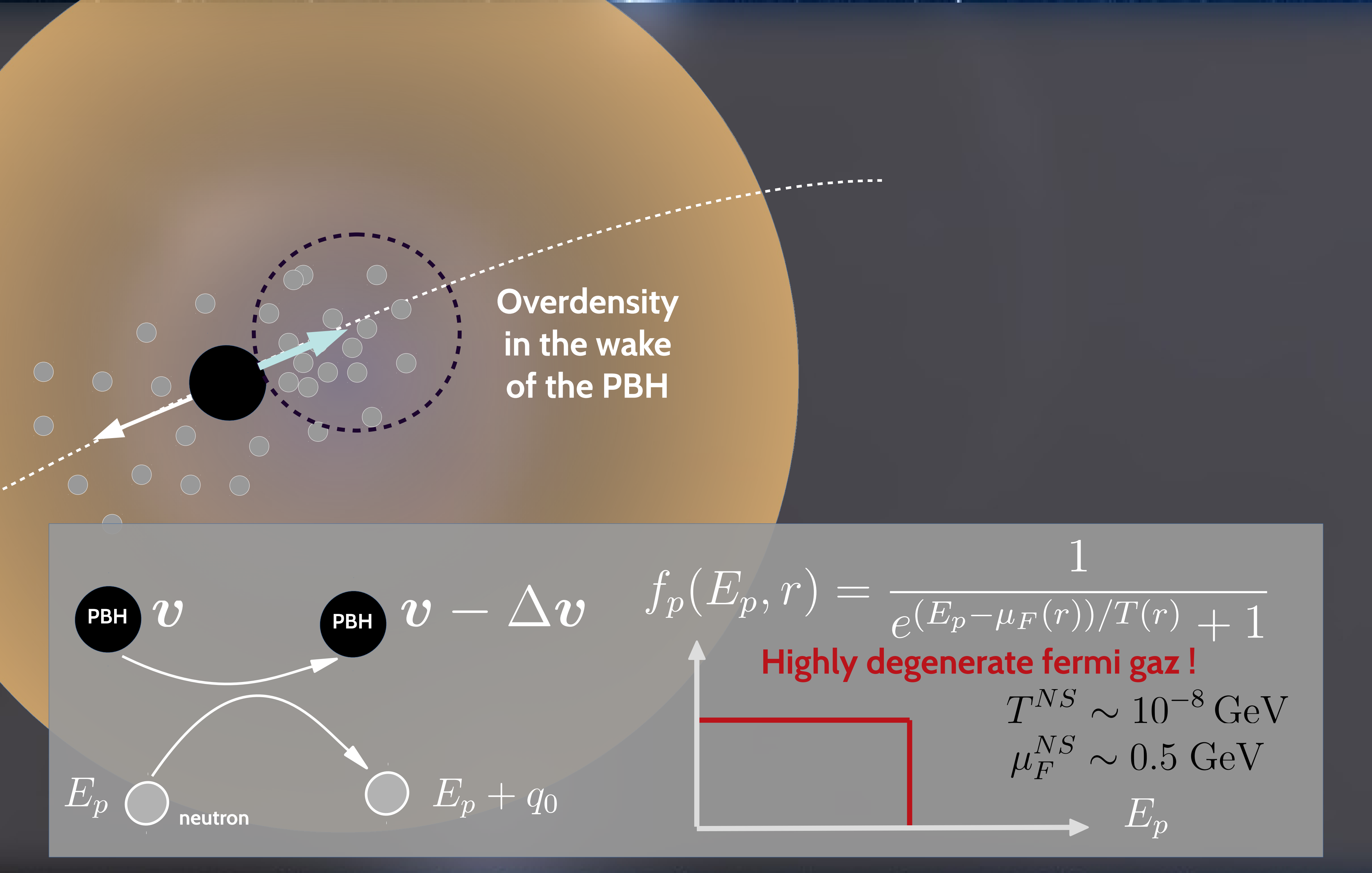
Credit: ESO/L.Calçada

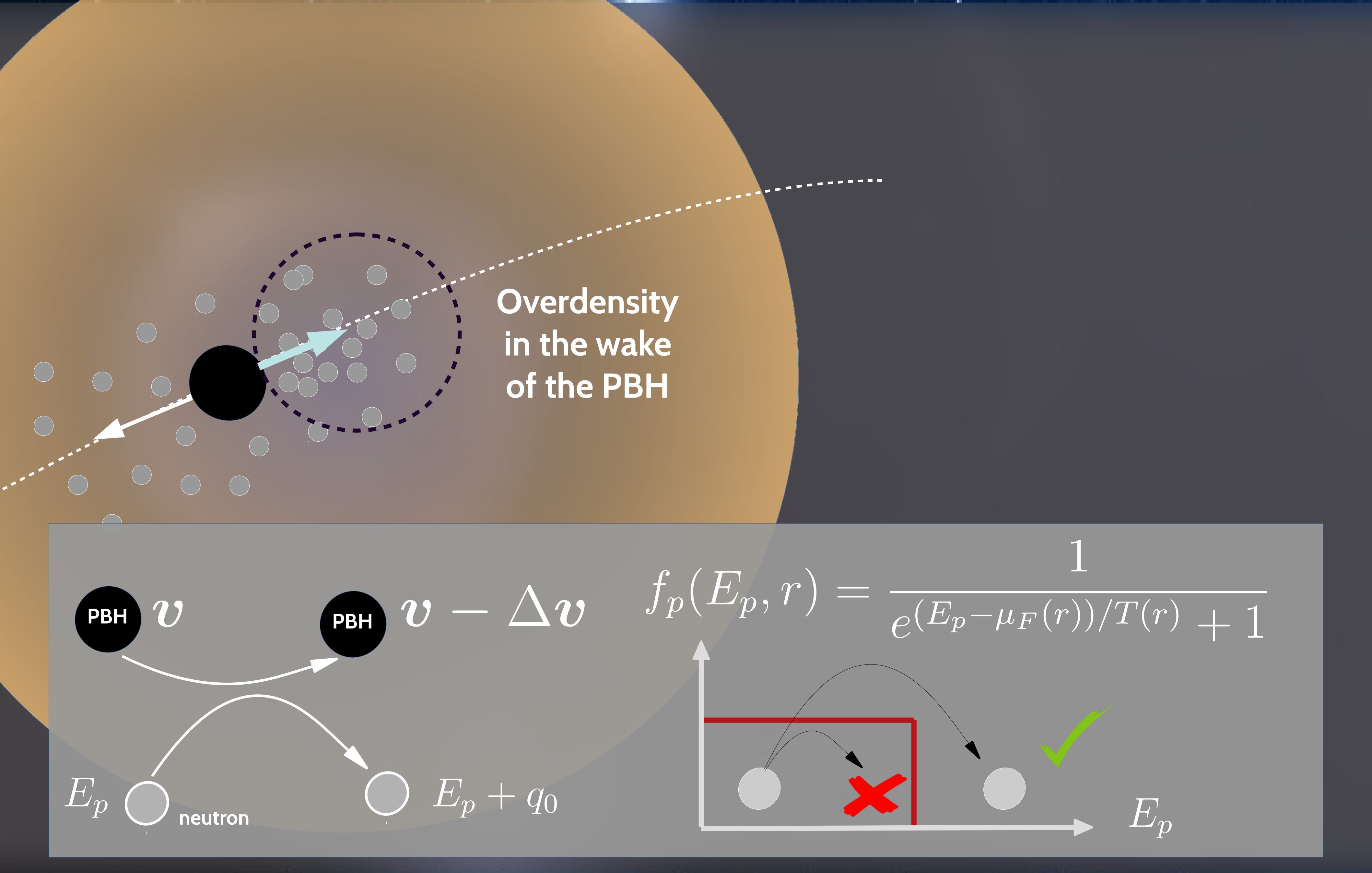




$$f_p(E_p, r) = \frac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$$




Overdensity
in the wake
of the PBH
PBH $\boldsymbol{v}$
PBH $\boldsymbol{v} - \Delta\boldsymbol{v}$
E_p
neutron
$E_p + q_0$
$f_p(E_p, r) = \dfrac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$
Highly degenerate fermi gaz !
$T^{NS} \sim 10^{-8}\,\mathrm{GeV}$
$\mu_F^{NS} \sim 0.5\,\mathrm{GeV}$
E_p
Credit: ESO/L.Calçada


Overdensity
in the wake
of the PBH
PBH v
PBH $v - \Delta v$
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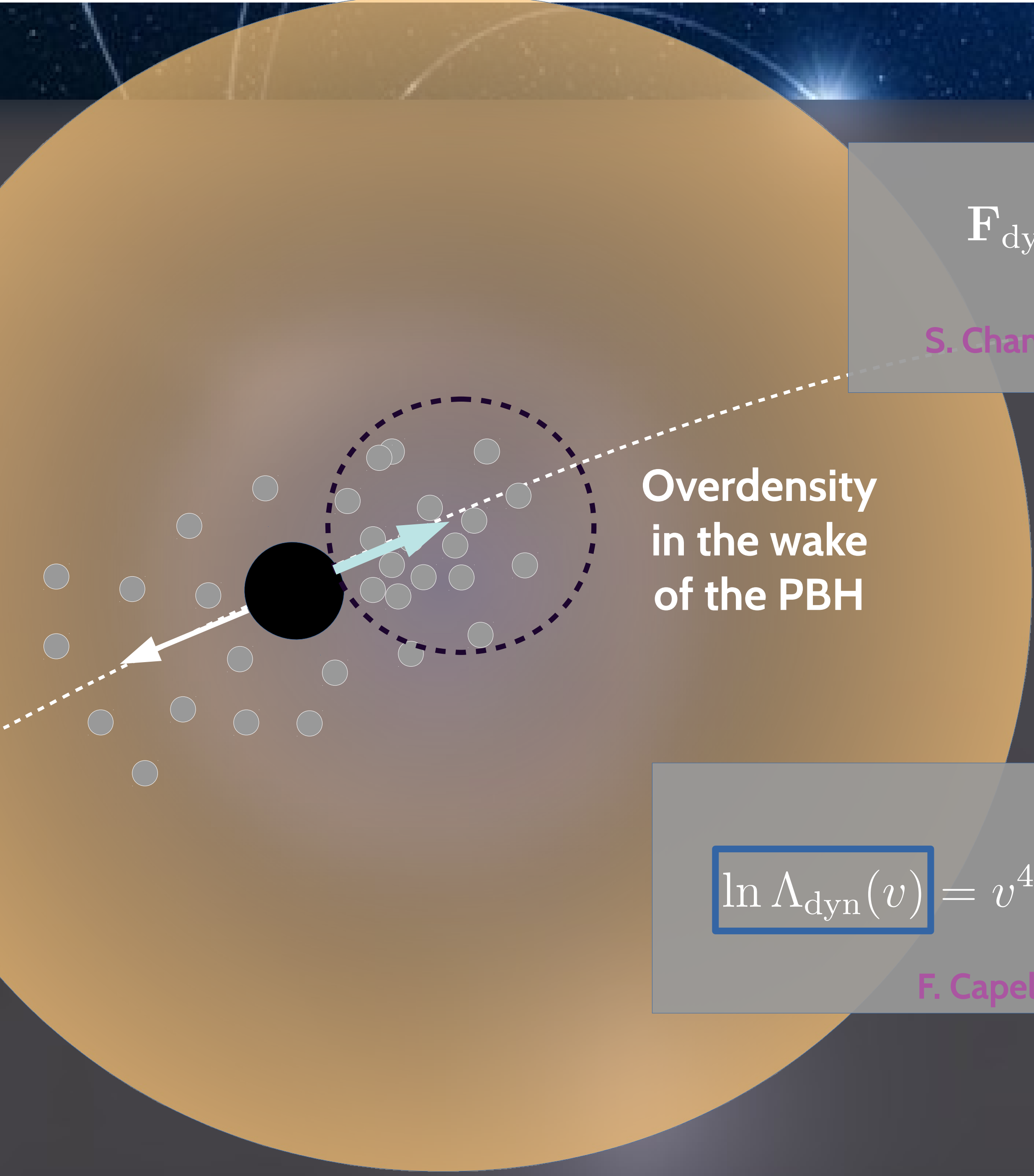

$$\ln \Lambda_{\rm dyn}(v) = v^4 \gamma^2 \frac{2}{R_g^2} \int_{d_{\rm crit}}^{d_{\rm max}} \mathrm{d}x\, x(1 - \cos\varphi(x))$$

F. Capela et al. PRD 87, 123524 (2013)

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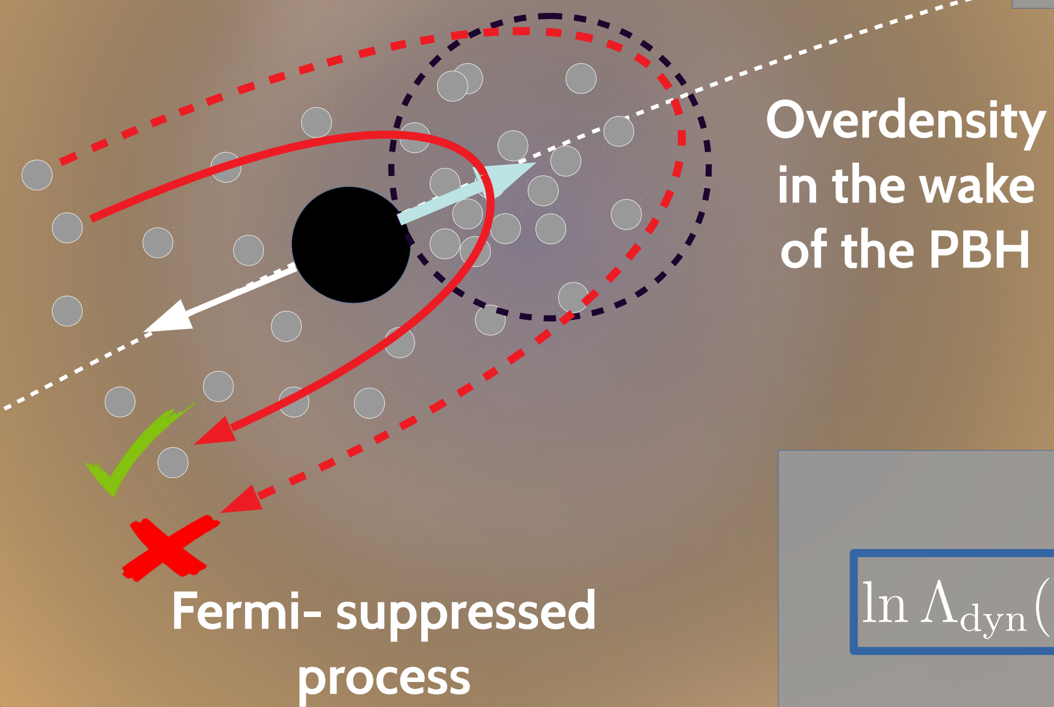

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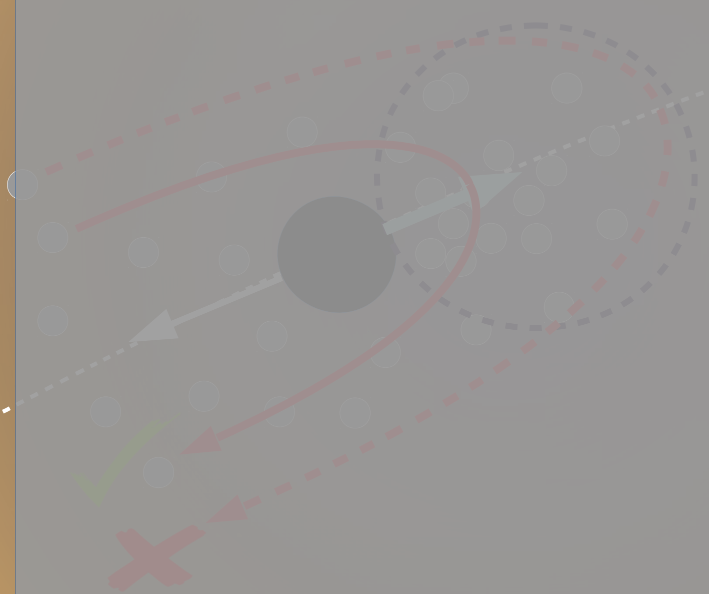
Dynamical friction is suppressed by a factor of a few, up to 10.

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

These equations strictly apply to a collisionless medium!



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Credit: ESO/L.Calçada

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Strongly interacting neutron fluid?

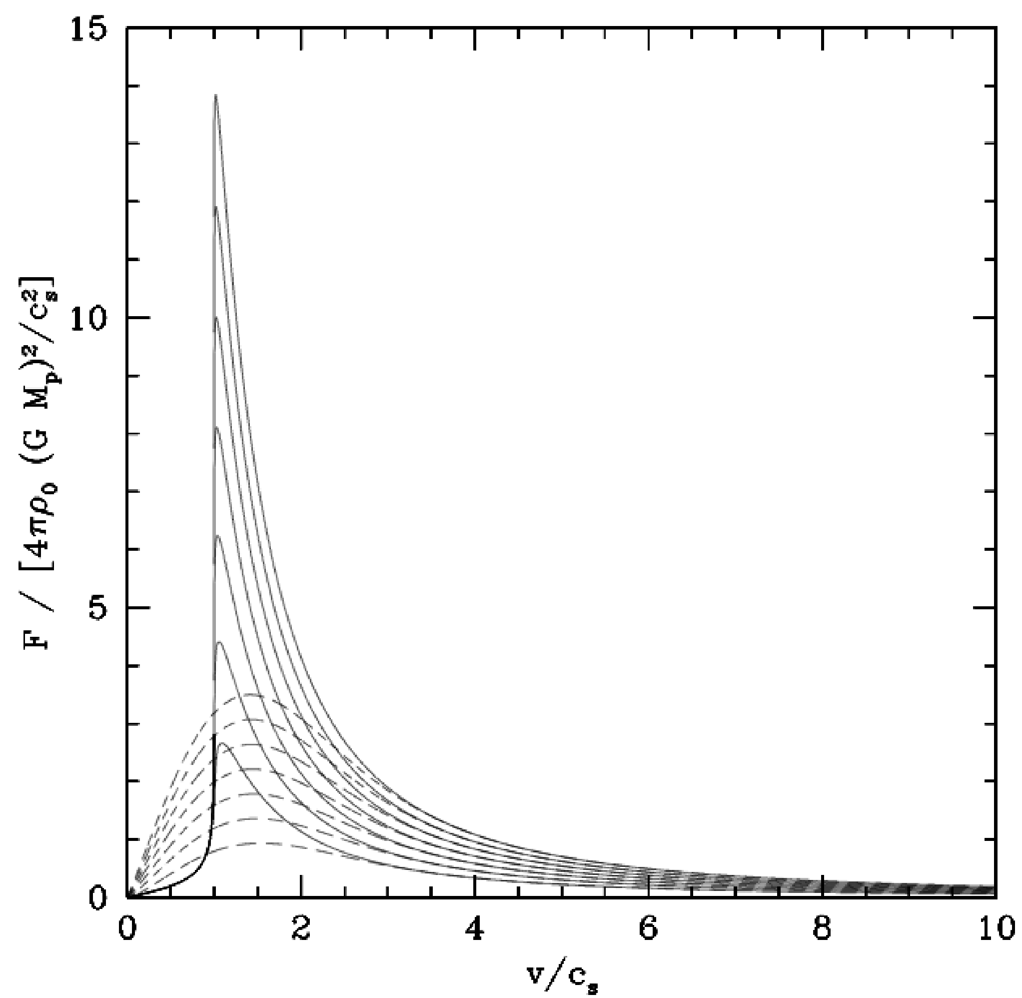
Apply if: $\tau_{gravitation} \ll \tau_{causal}$

$$v \gg c_s$$

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

1 - Dynamical Friction:

In a collisionless or a collisional medium?



E. C. Ostriker, ApJ 513, 252 (1999)

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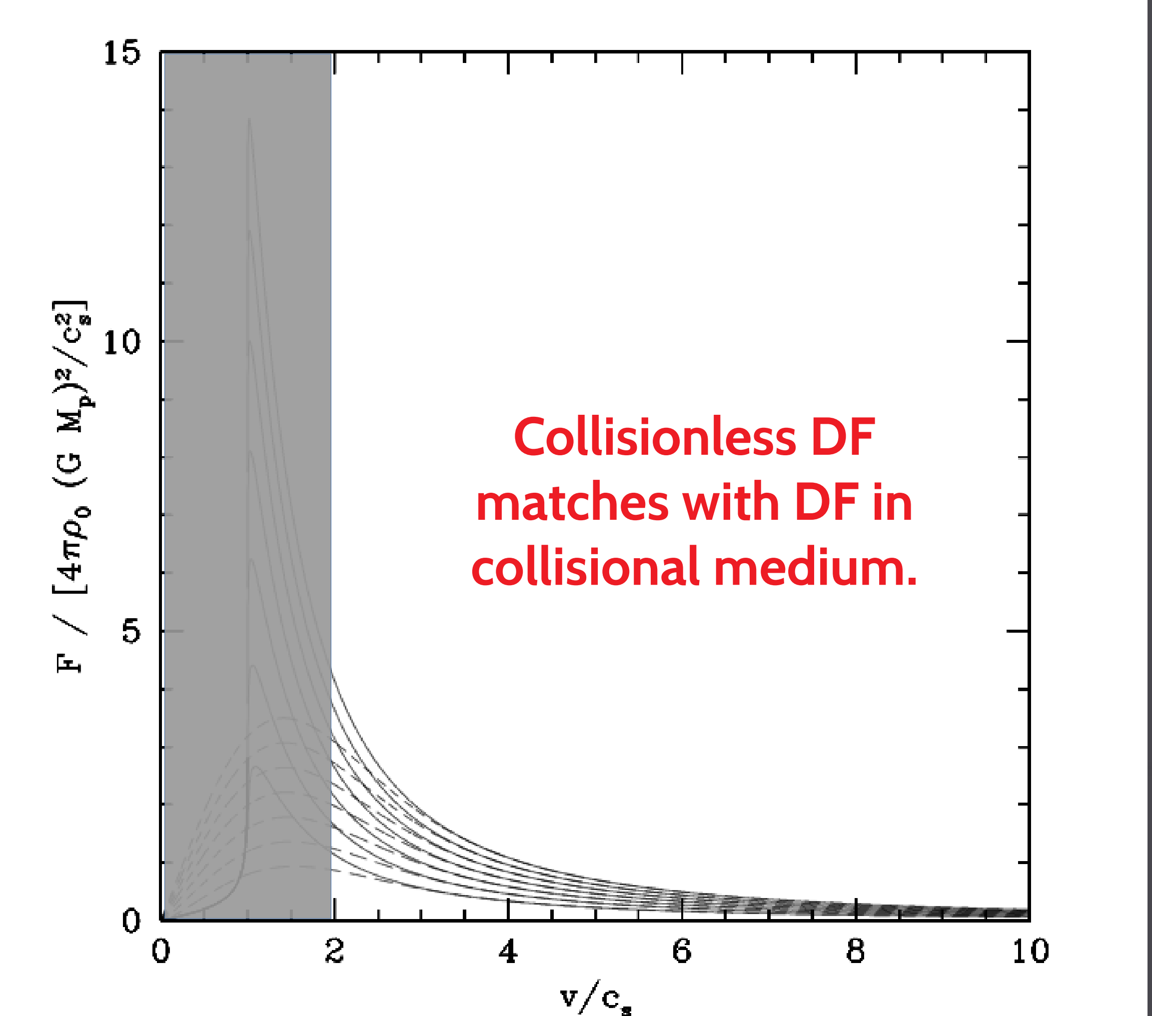

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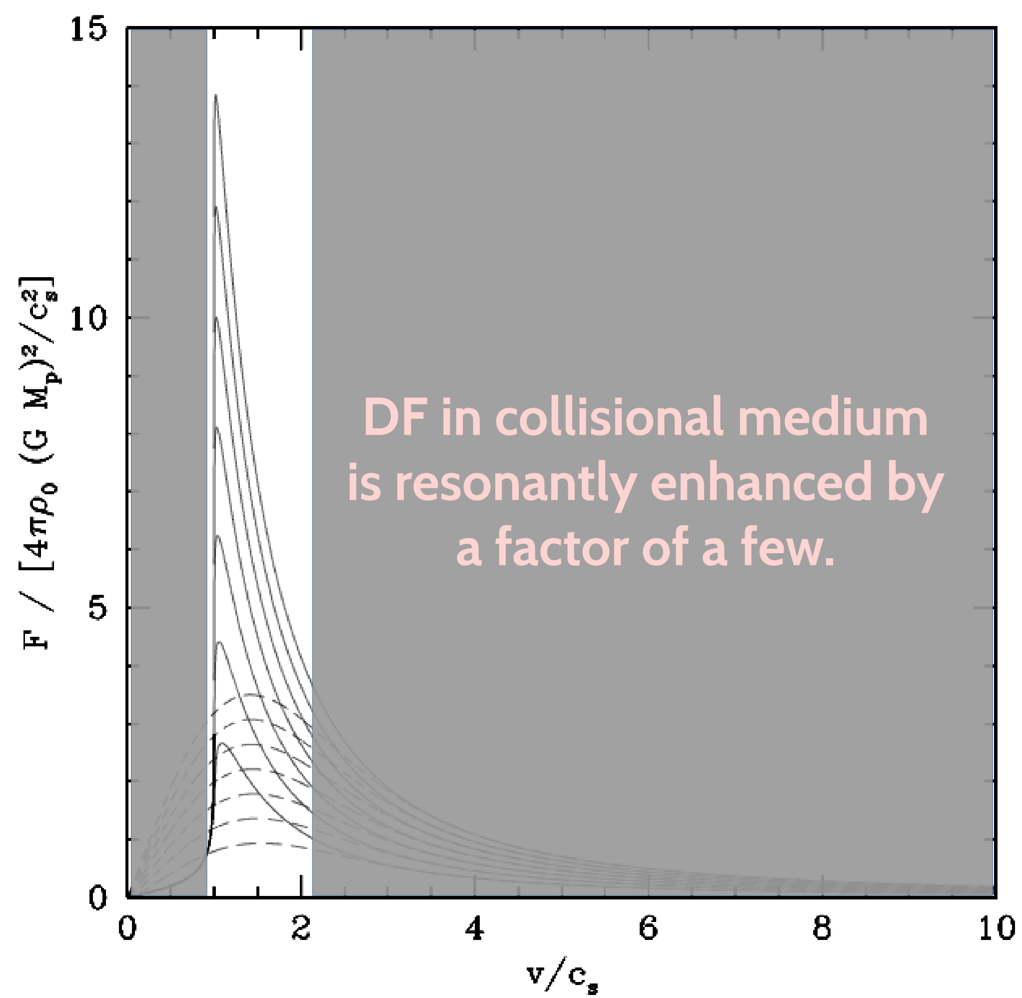

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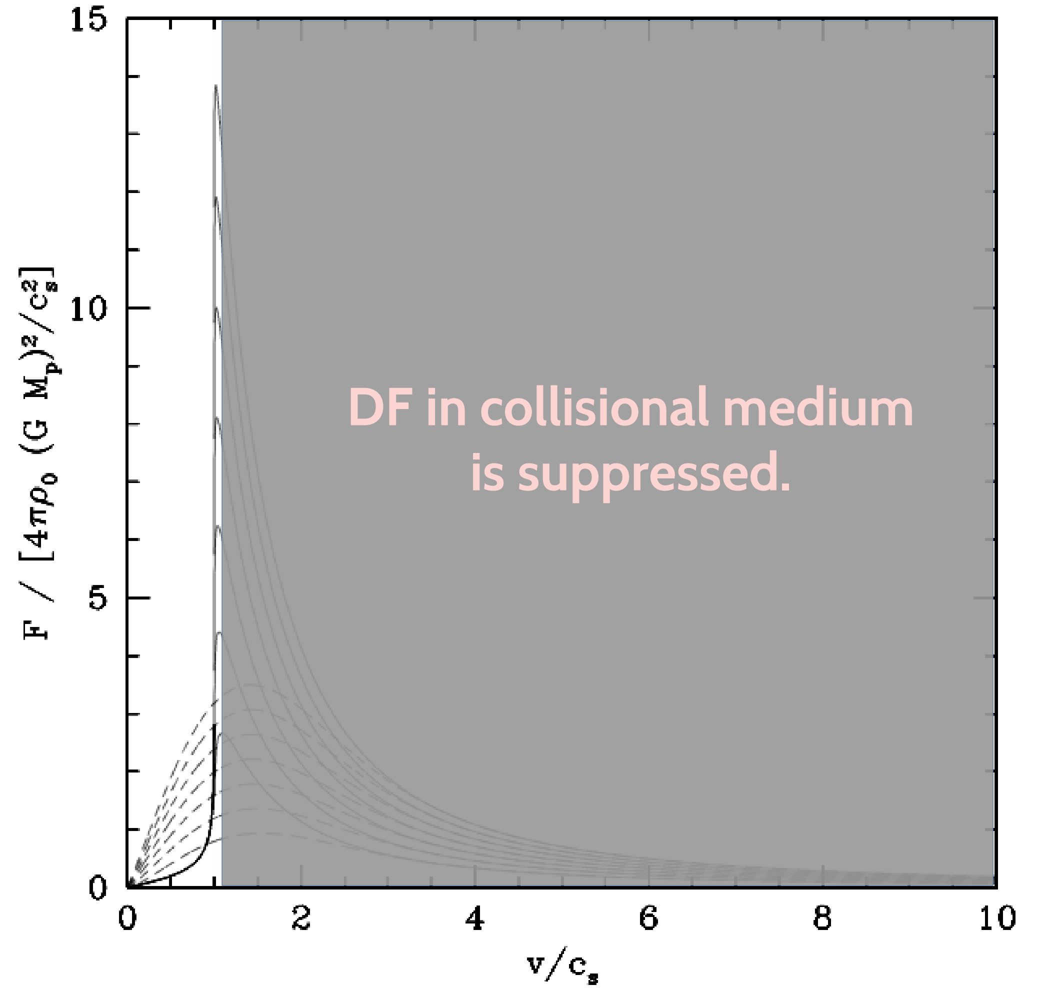

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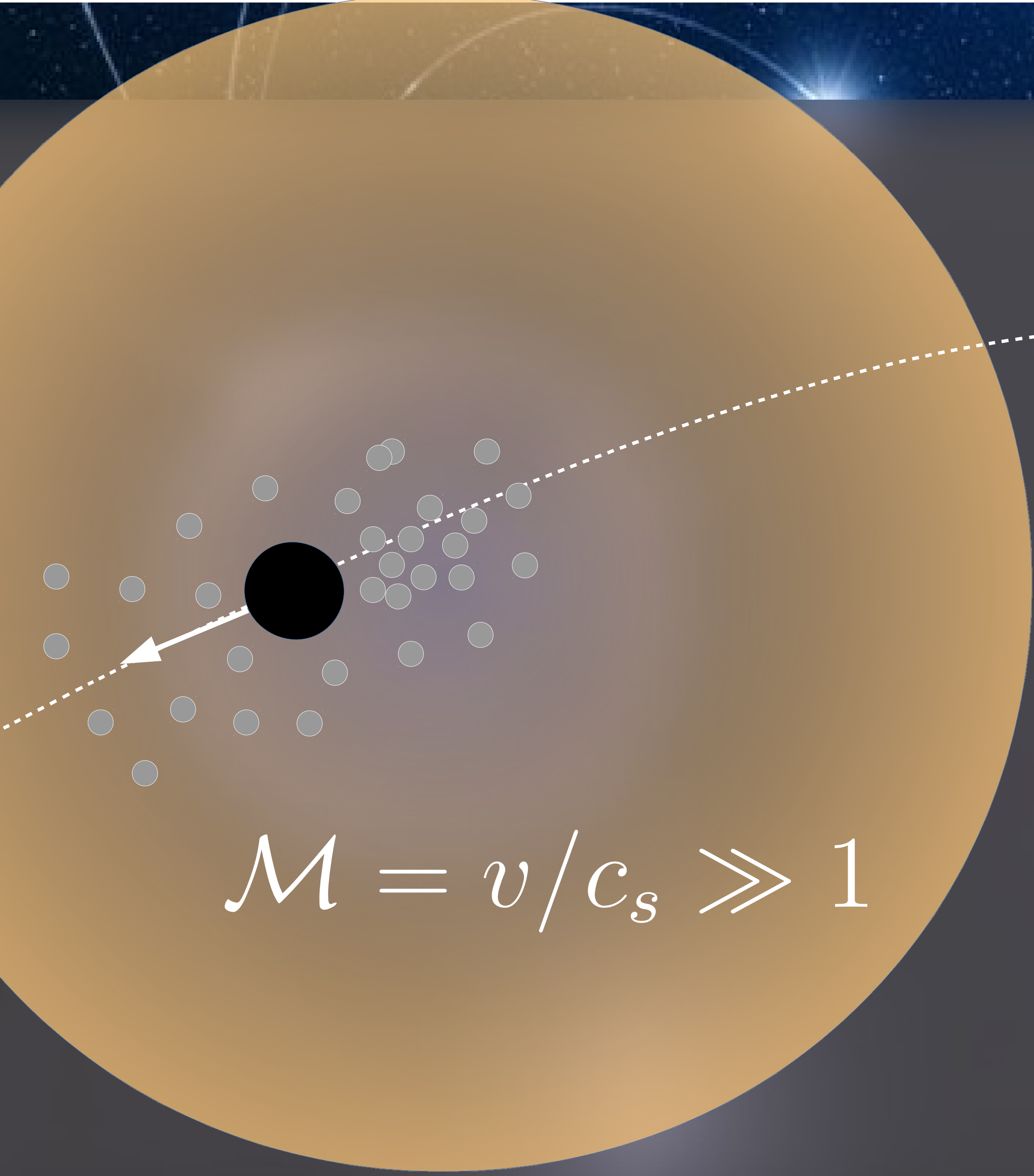
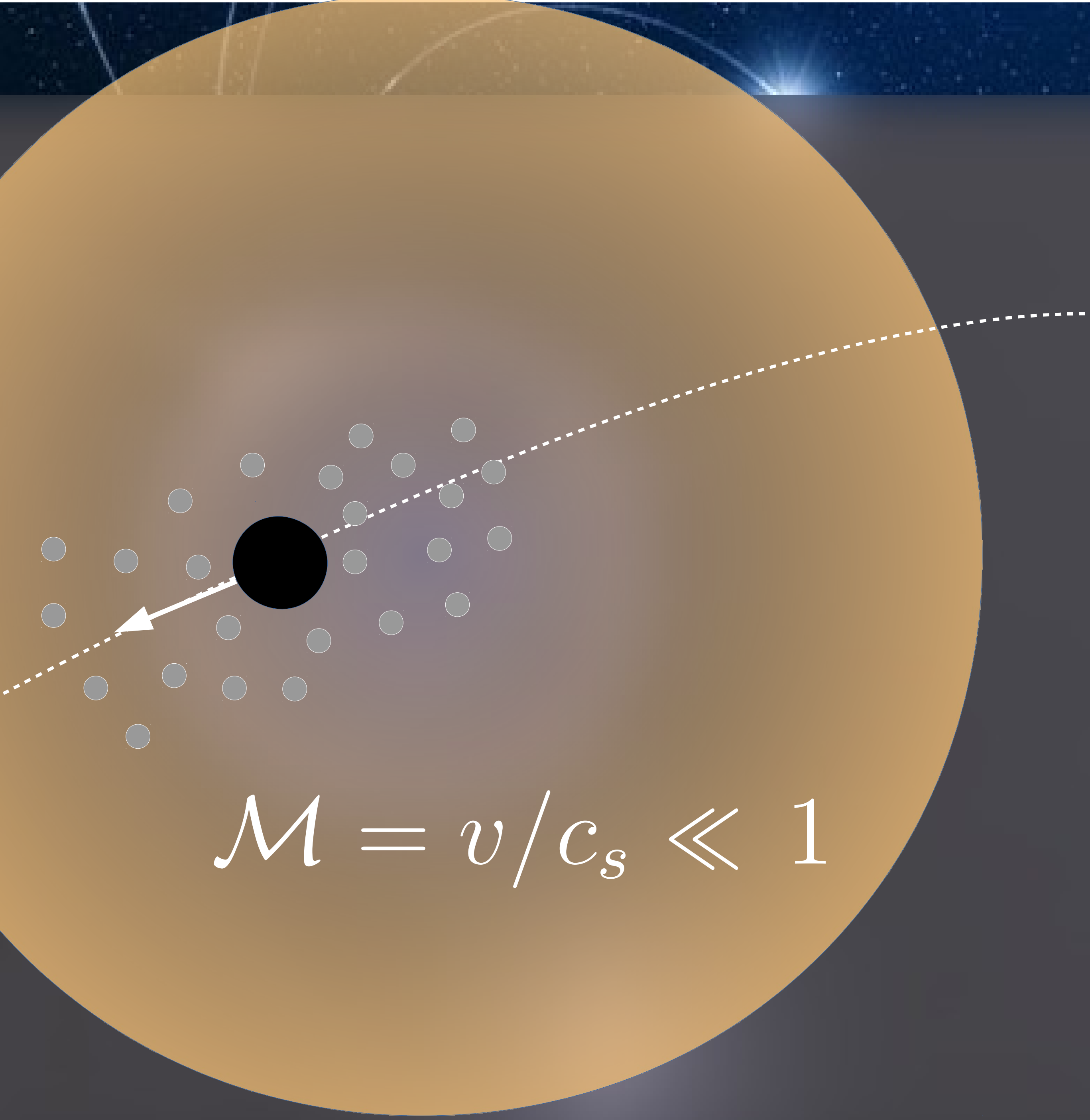
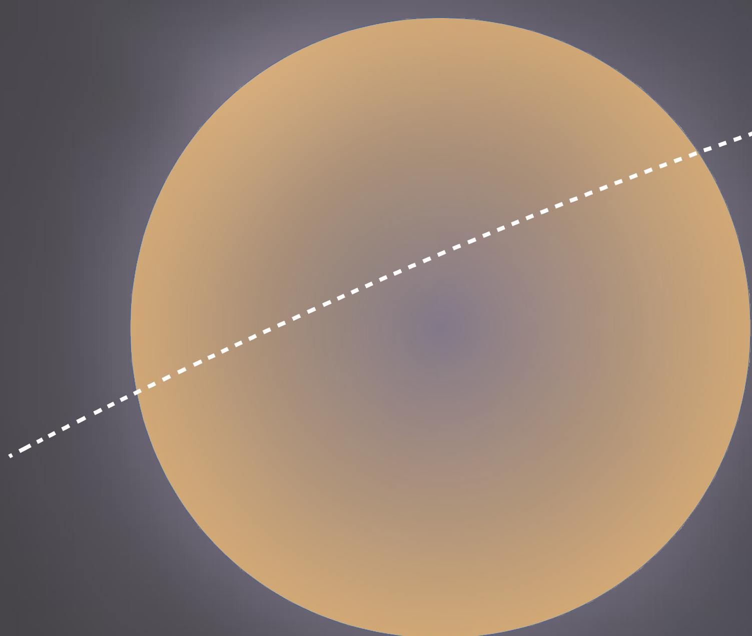


$$\mathcal{M} = v/c_s \gg 1$$


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

2 - Accretion



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

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

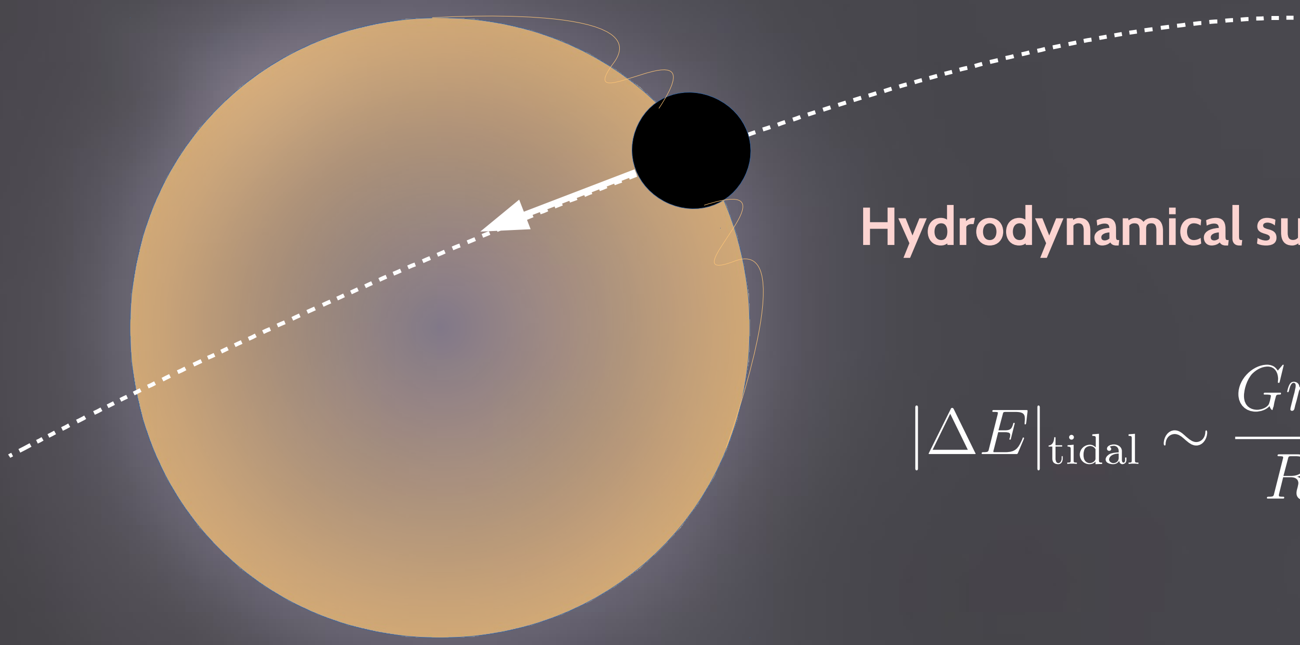
F. Capela et al. PRD 87, 123524 (2013)

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

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

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

3 - Surface waves

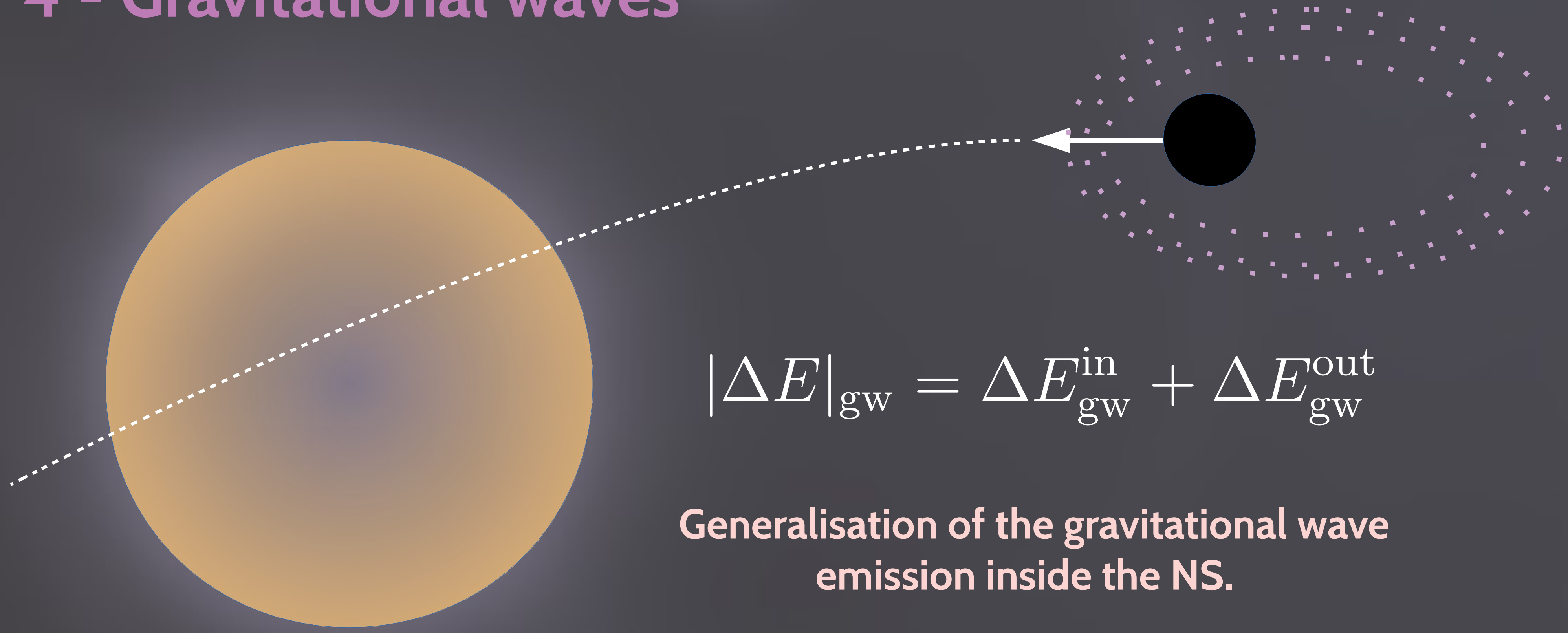


Hydrodynamical surface waves:

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

G. Defillon, et al. PRD 90, 103522 (2014)
W. H. Press and S. A. Teukolsky, ApJ 213, 183 (1977).

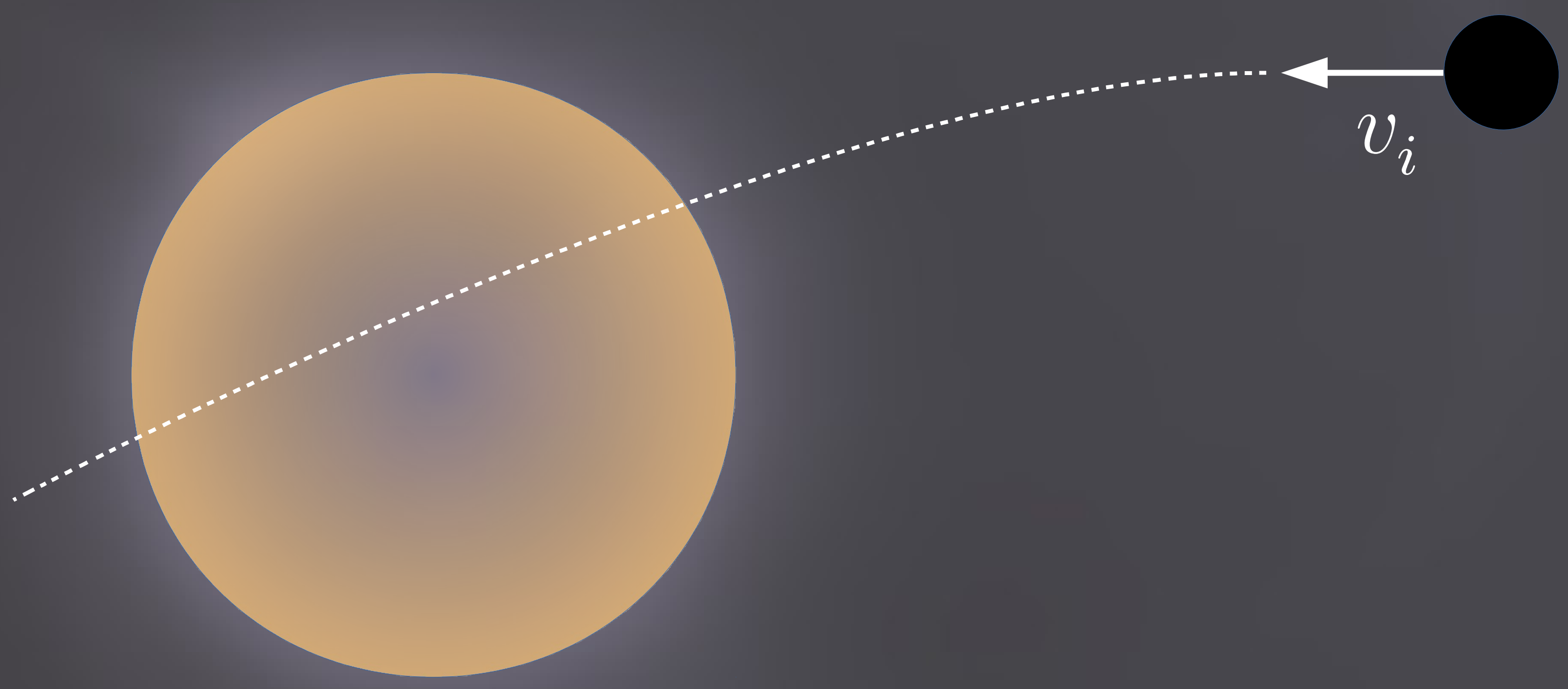
4 - Gravitational waves

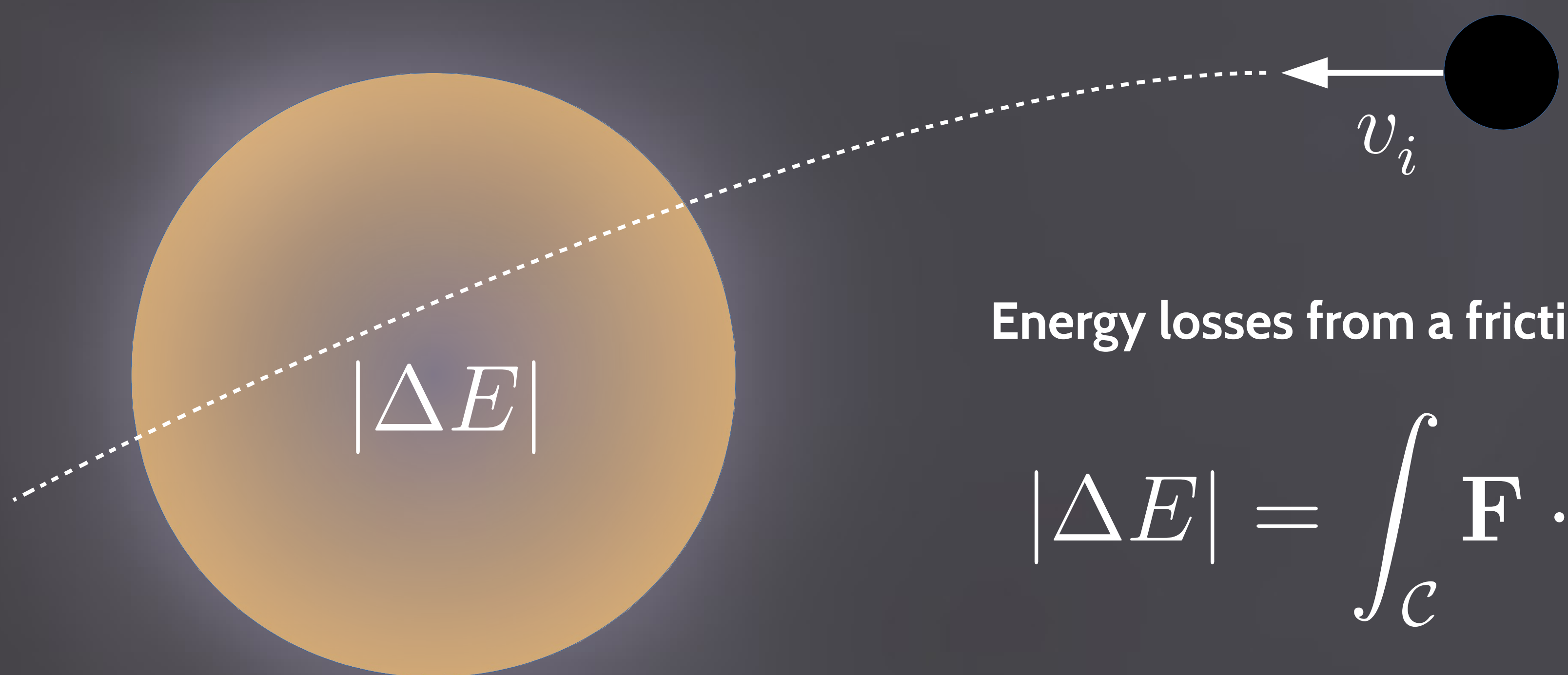


$$|\Delta E|_{\mathrm{gw}} = \Delta E_{\mathrm{gw}}^{\mathrm{in}} + \Delta E_{\mathrm{gw}}^{\mathrm{out}}$$

Generalisation of the gravitational wave emission inside the NS.

III- Capture of a PBH


v_i

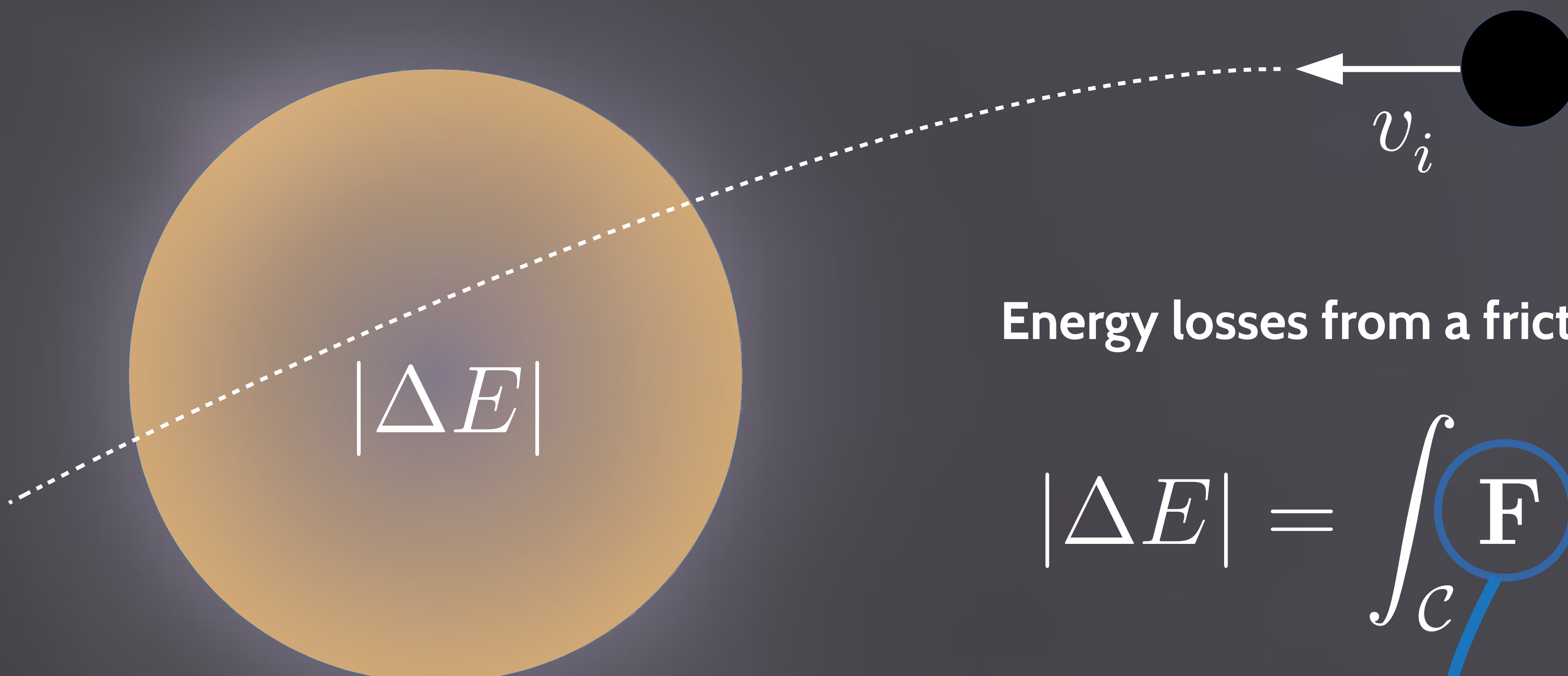


Energy losses from a friction force:

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

Capture condition:

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



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Several physical phenomena

Capture condition:

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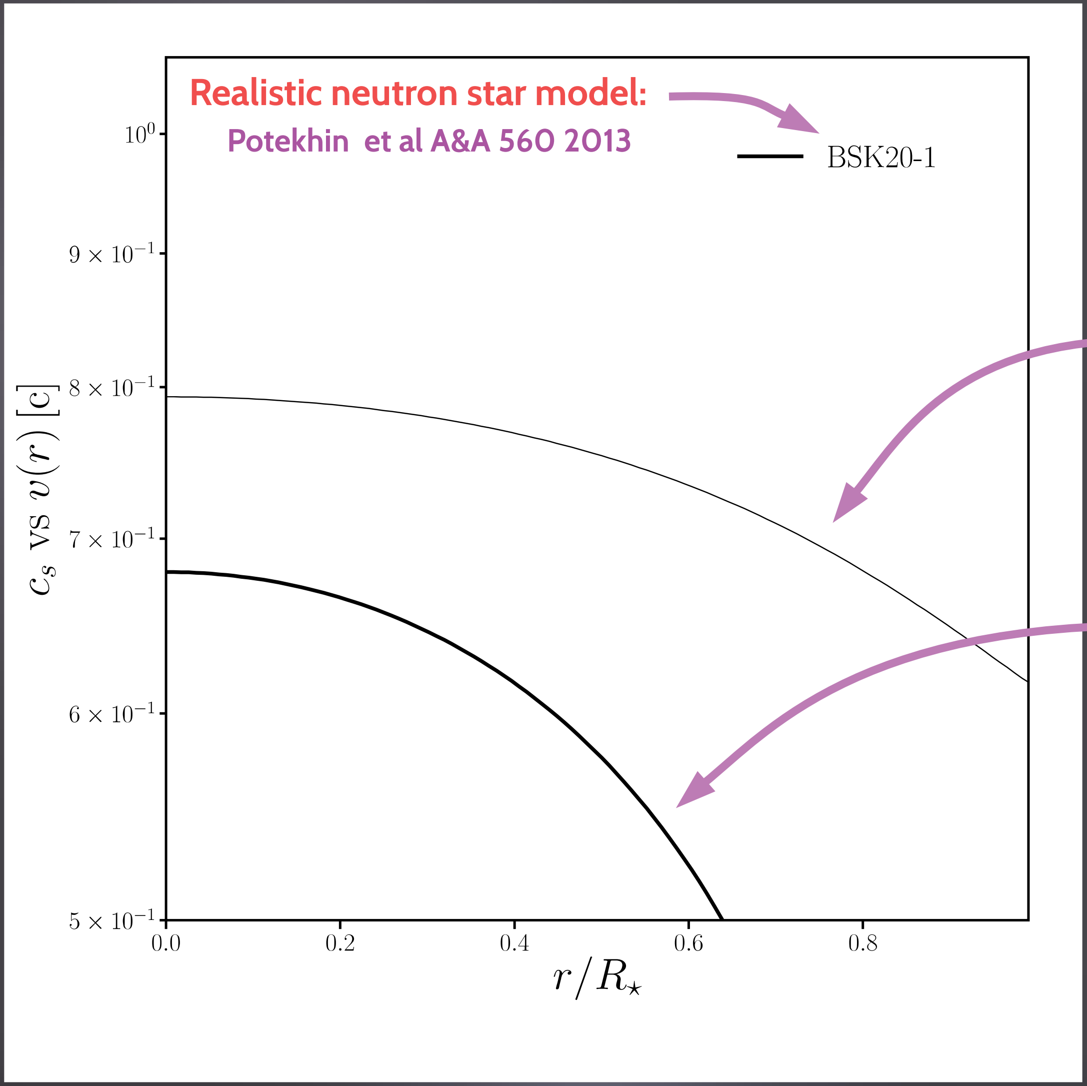
What is the speed regime for capture ?

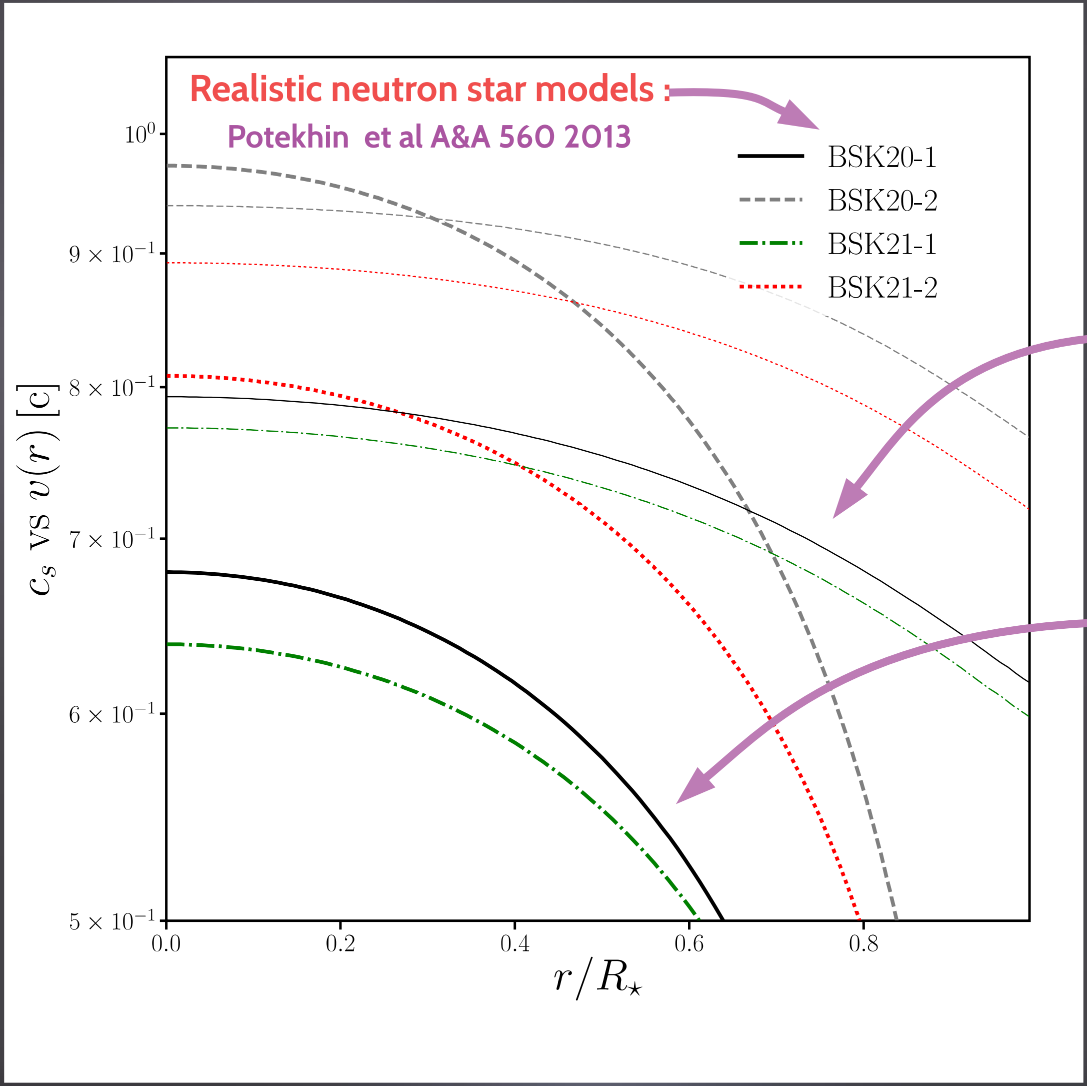


$$v(r) = \sqrt{1 - e^{2(\Phi(\infty) - \Phi(r))}}$$

$$c_s(r)$$

Capture happens in the supersonic regime!

What is the speed regime for capture ?



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Capture can also happens in the subsonic regime!

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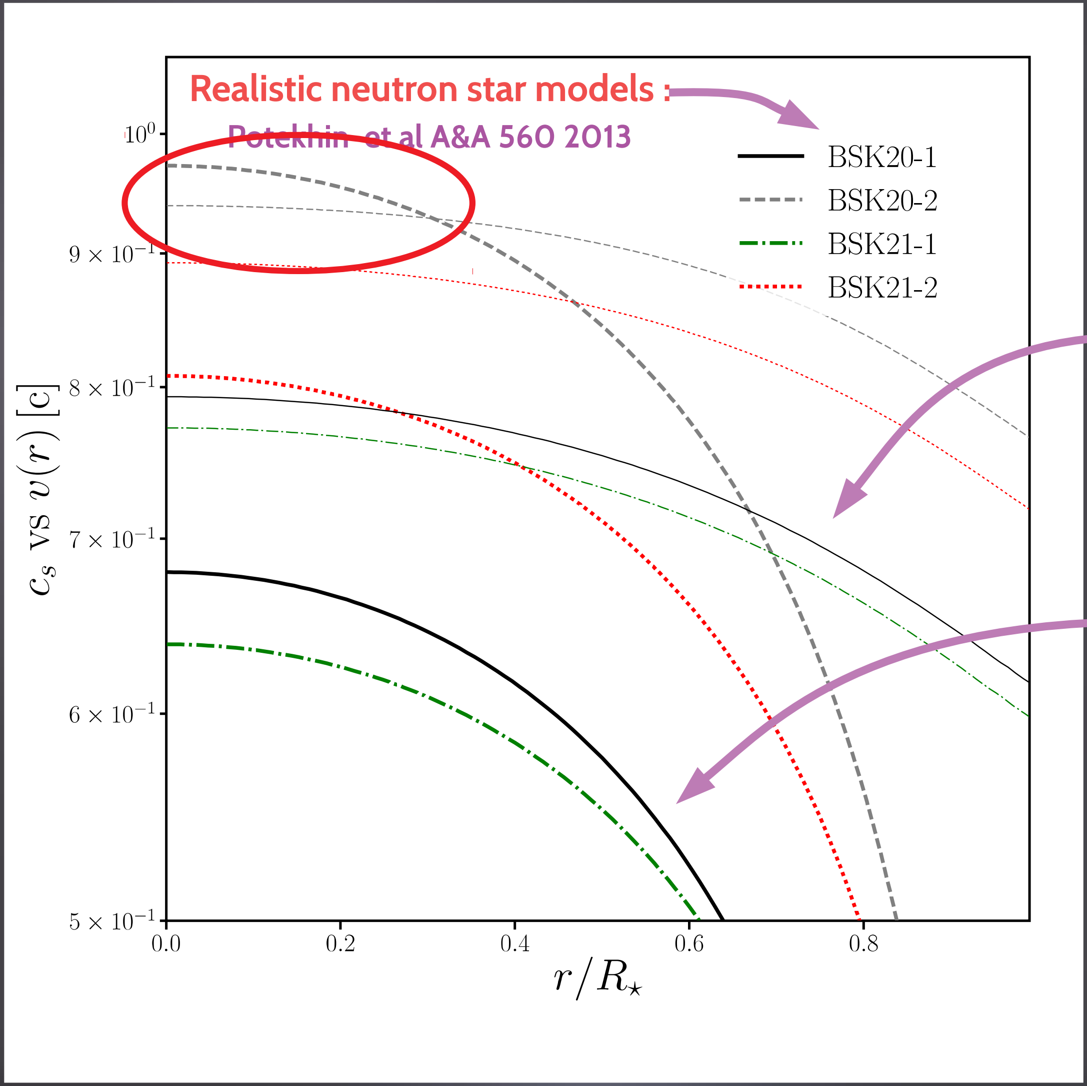

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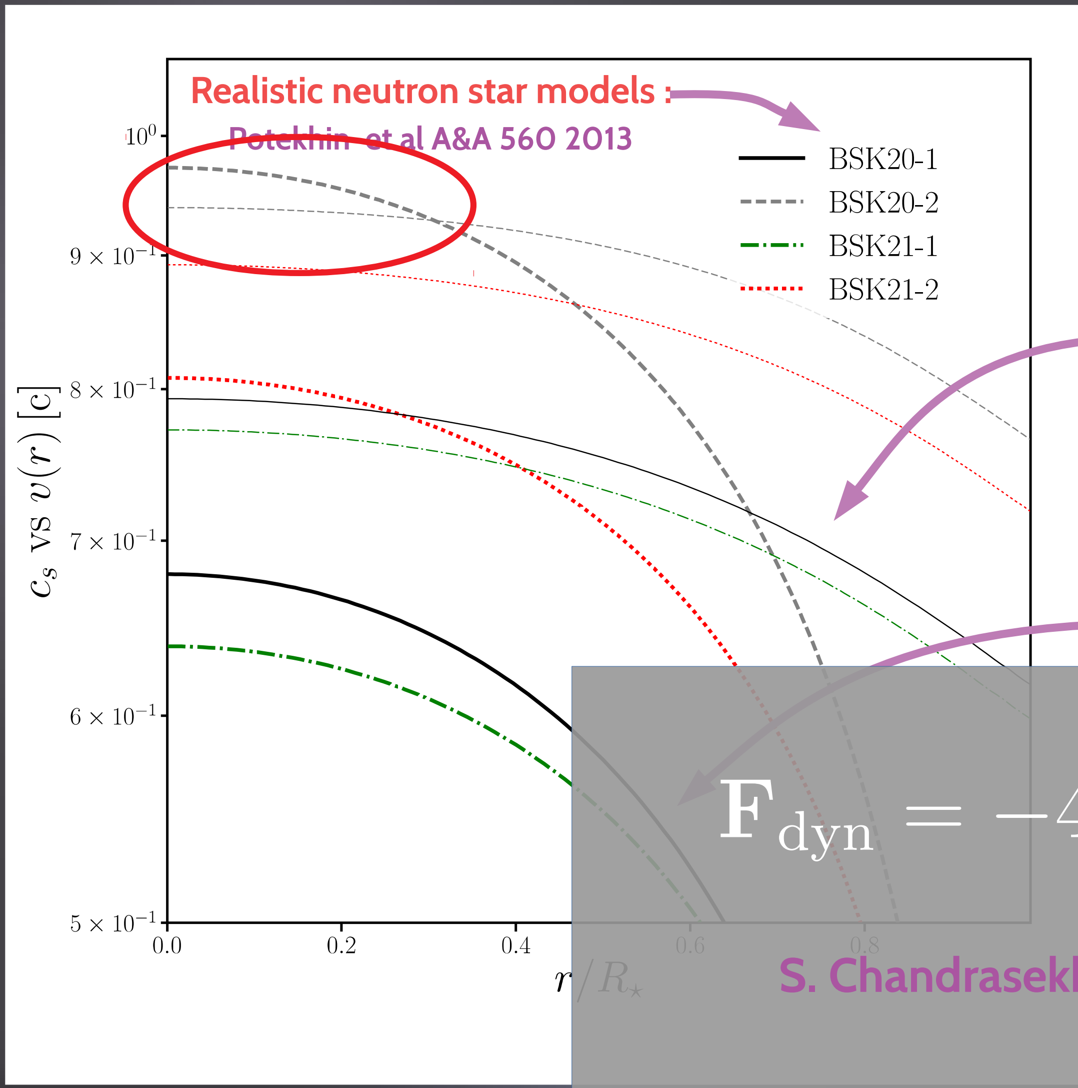

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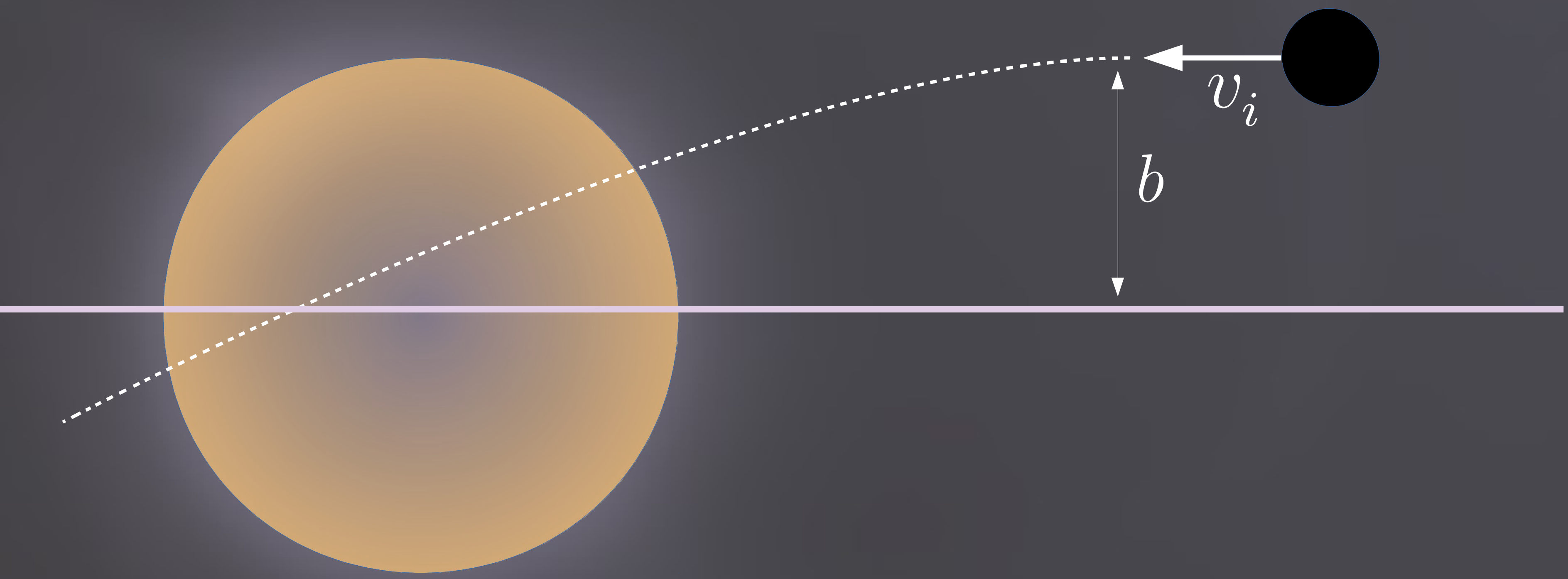
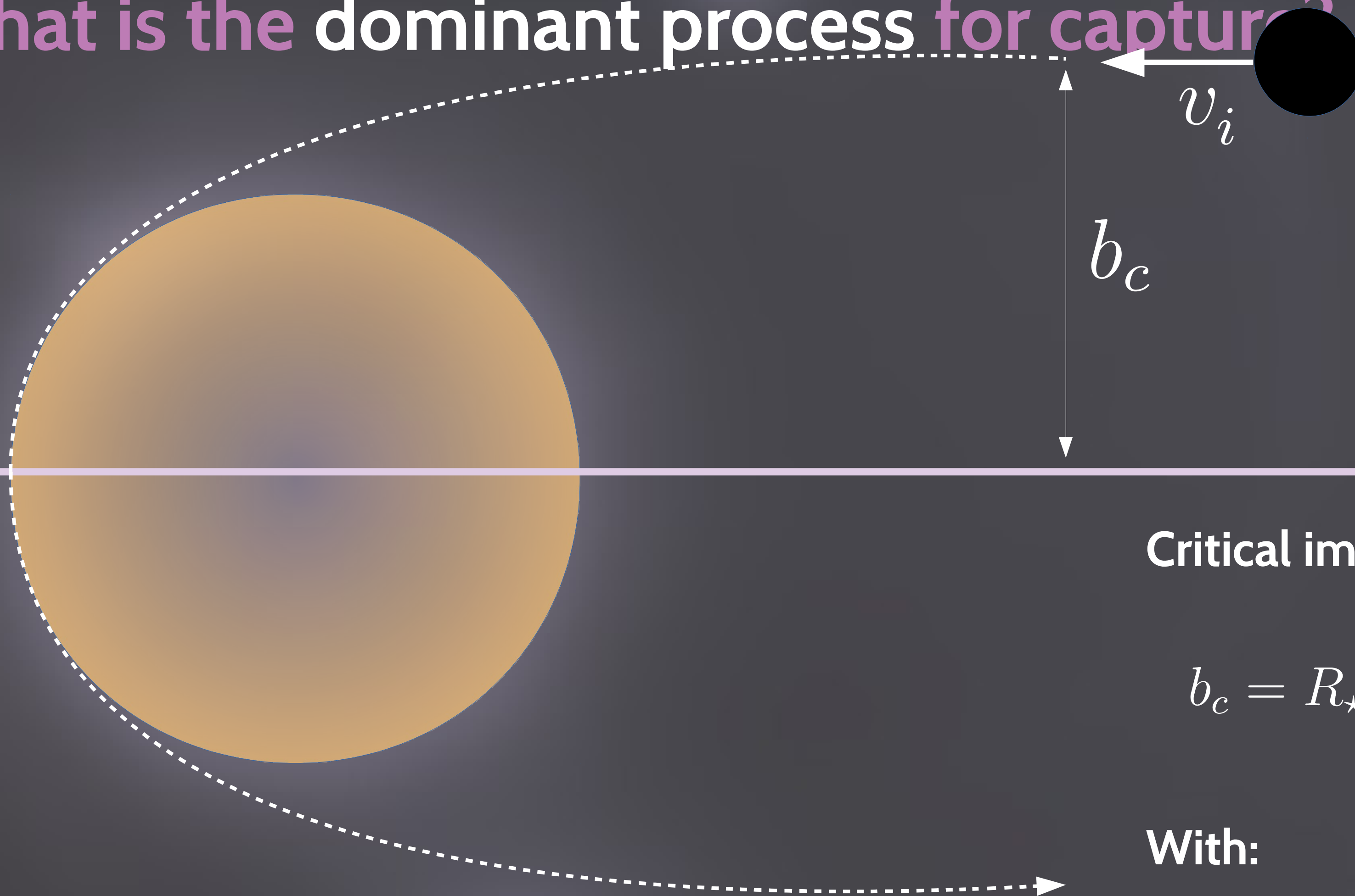
What is the dominant process for capture?



What is the **dominant process** for capture?



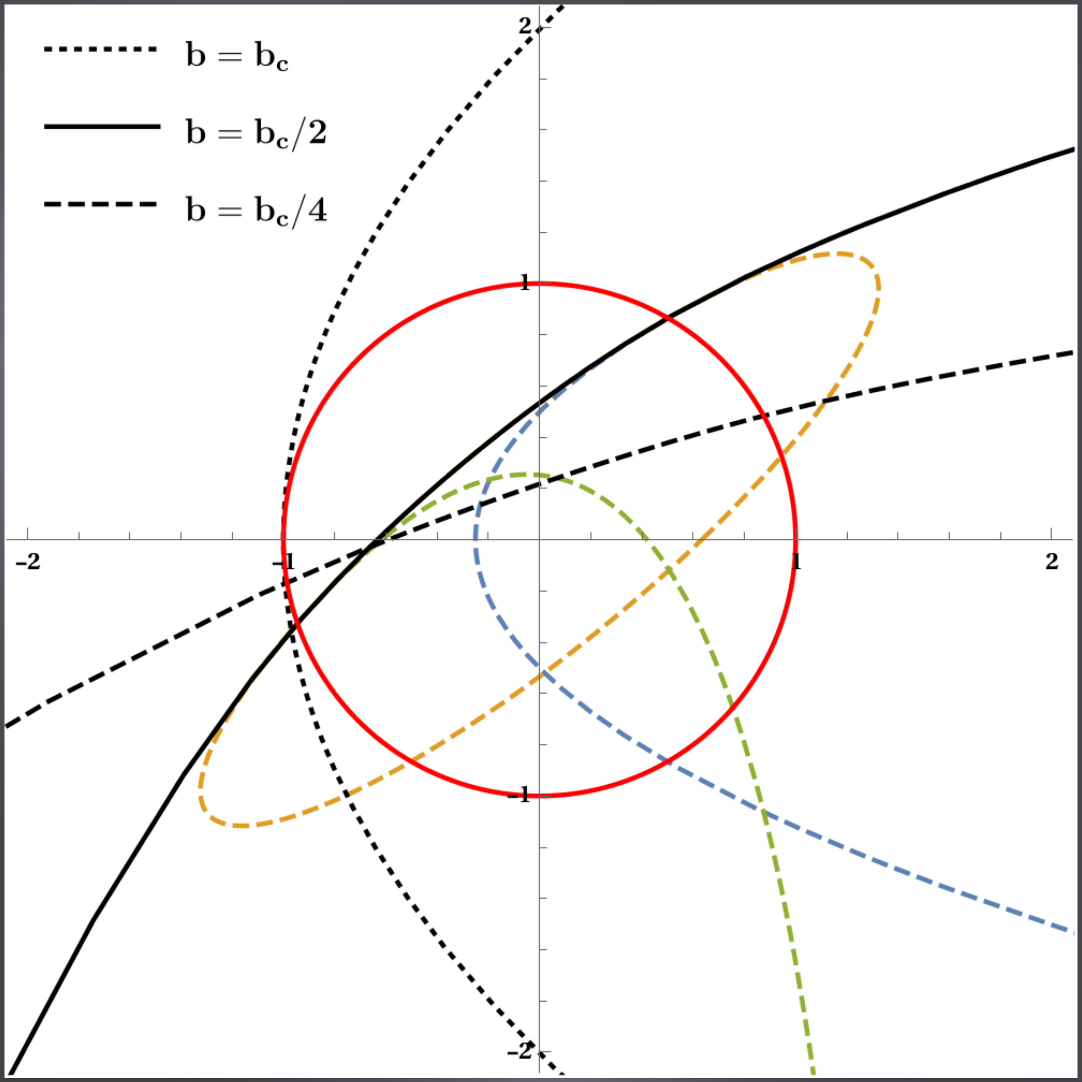
Critical impact parameter:

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

With:

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

What is the dominant process for capture?



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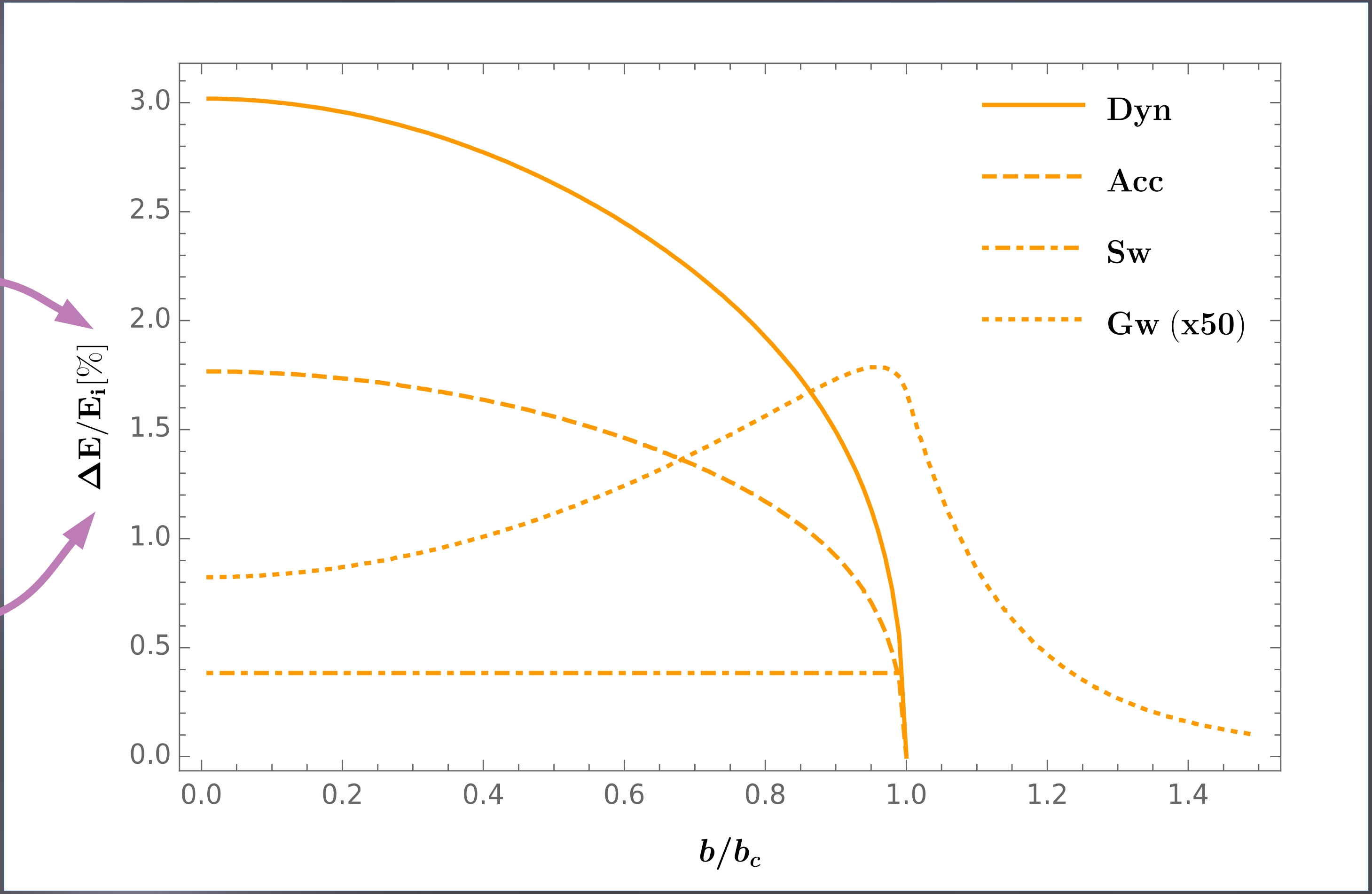
$$E_i = \frac{1}{2} m v_i^2$$

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

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



Estimate of the number of event

We assume the PBH follow a Maxwellian distribution in velocities:

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

The rate of NS-PBH encounter leading to capture is:

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

Estimate of the number of event in the Galaxy!

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

The rate of NS-PBH encounter leading to capture is:

$$\mathcal{G}_\star N_\star \simeq 2.1 \times 10^{-8} \left(\frac{\rho_{\rm PBH}}{\rm GeV\,cm^{-3}}\right)\left(\frac{10^{-3}}{\bar{v}}\right)^3 \mathcal{C}\,[X]\,{\rm yr}^{-1}$$

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.

To be compare with the rate of NS-PBH encounter:

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

-> Similar to the GRB rate in the Galaxy

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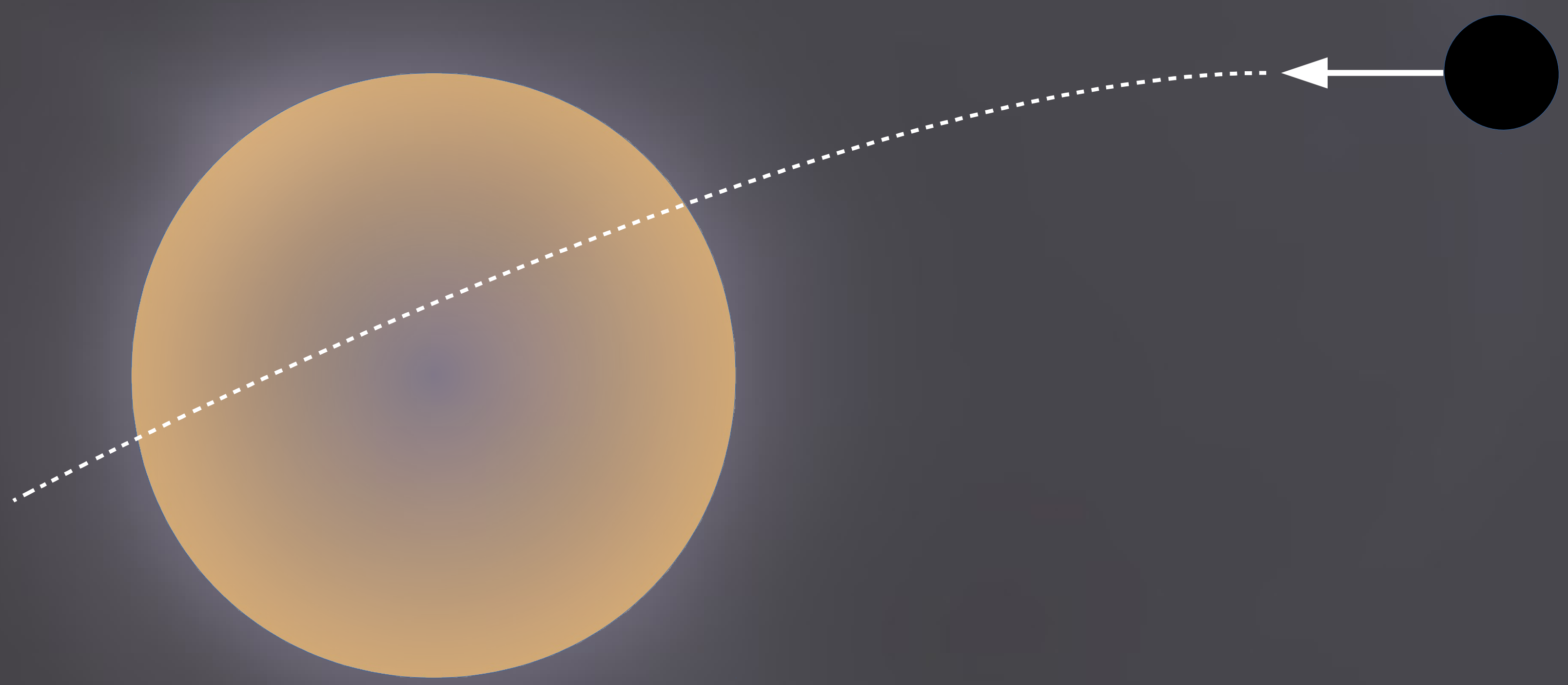
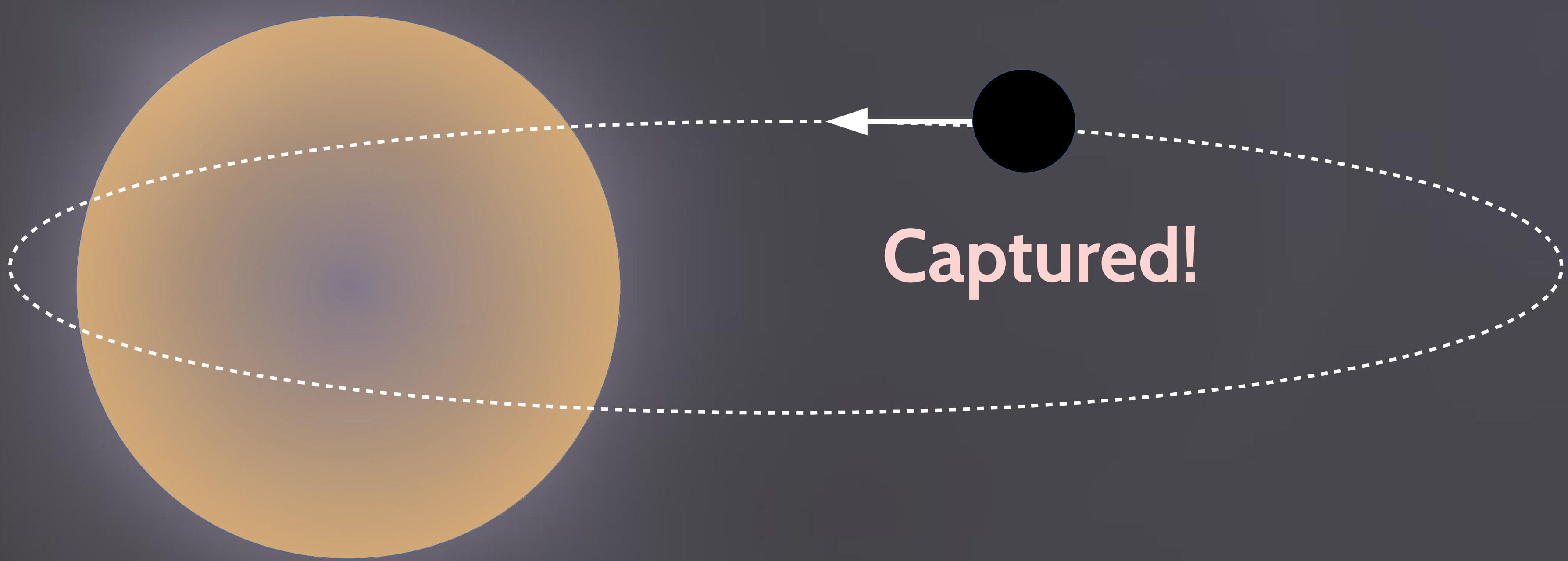
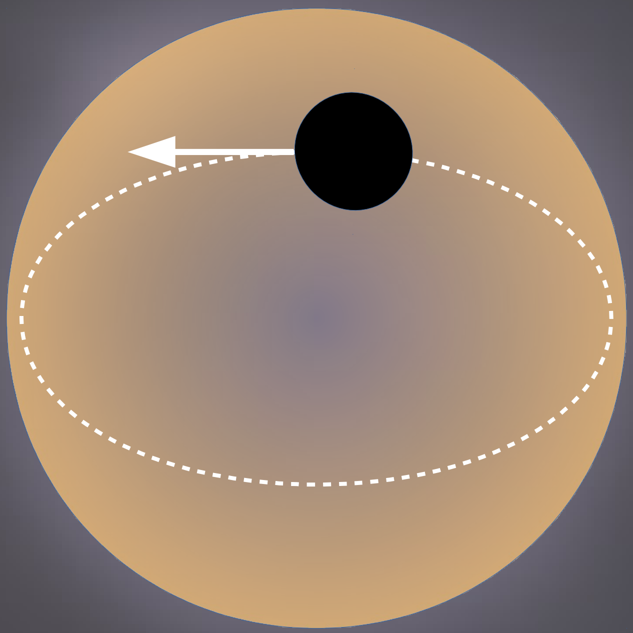
→ Rare events !

IV- Post capture dynamic





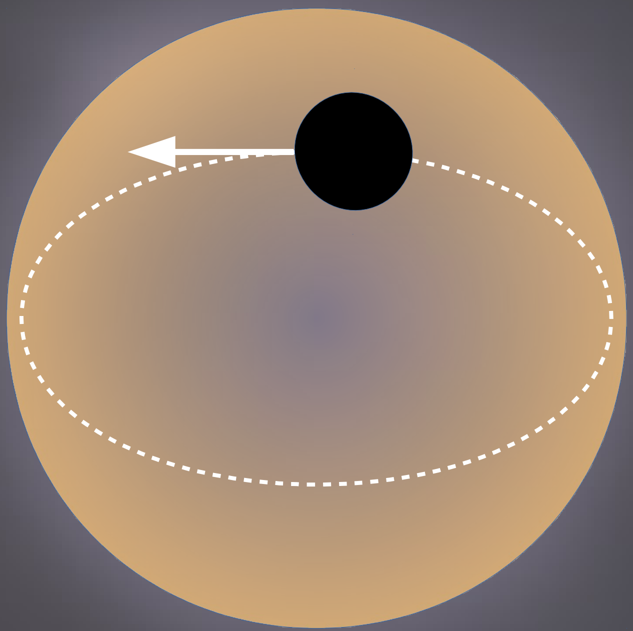
Credit: ESO/L.Calçada



Settling time within the NS:

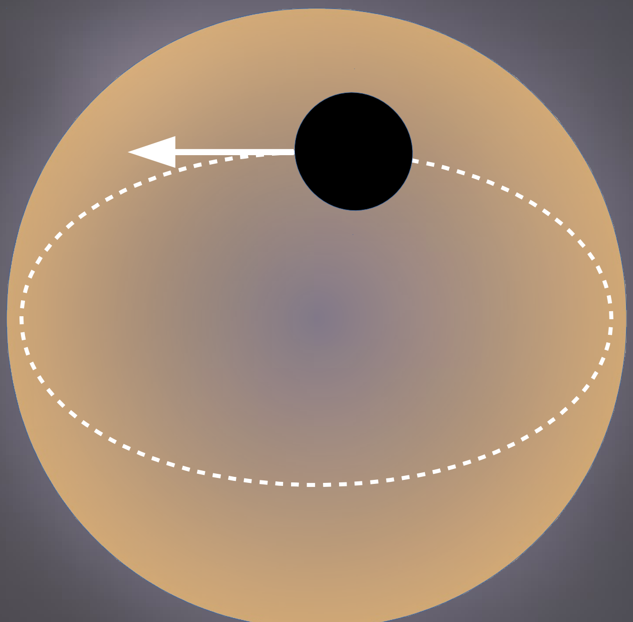
$$t_{\text{settle}} \lesssim 4 \times 10^4 \left(\frac{m}{10^{22}\ \text{g}} \right)^{-3/2} \ \text{yr}$$

F. Capela et al. PRD 87, 123524 (2013)



The motion becomes subsonic for

$$r \lesssim R_\star c_s / v_\star$$

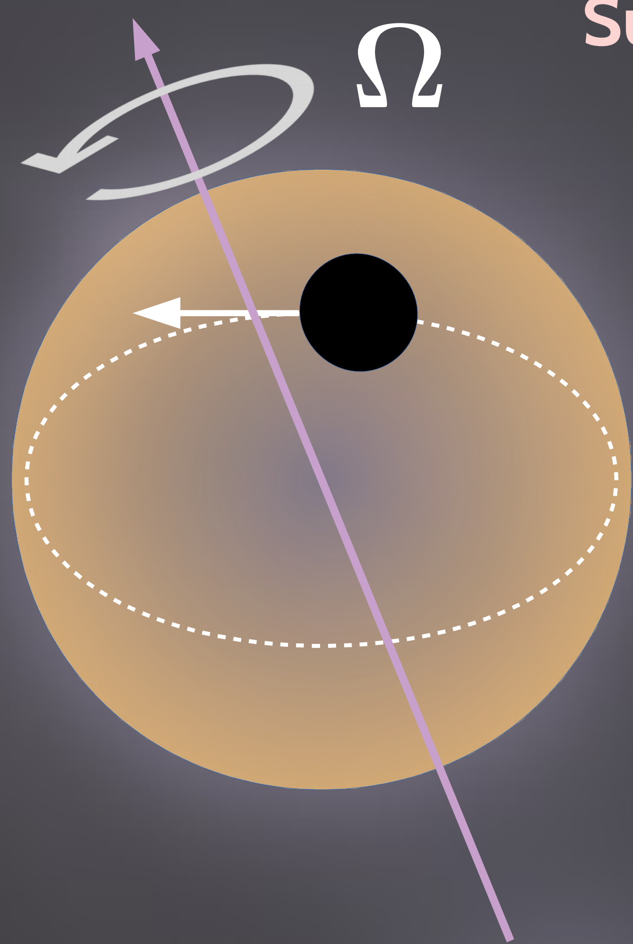


The motion becomes subsonic for

$$r \lesssim R_\star c_s / v_\star > R_\star$$

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 model:
Potekhin et al A&A 560 2013



Subsonic regime

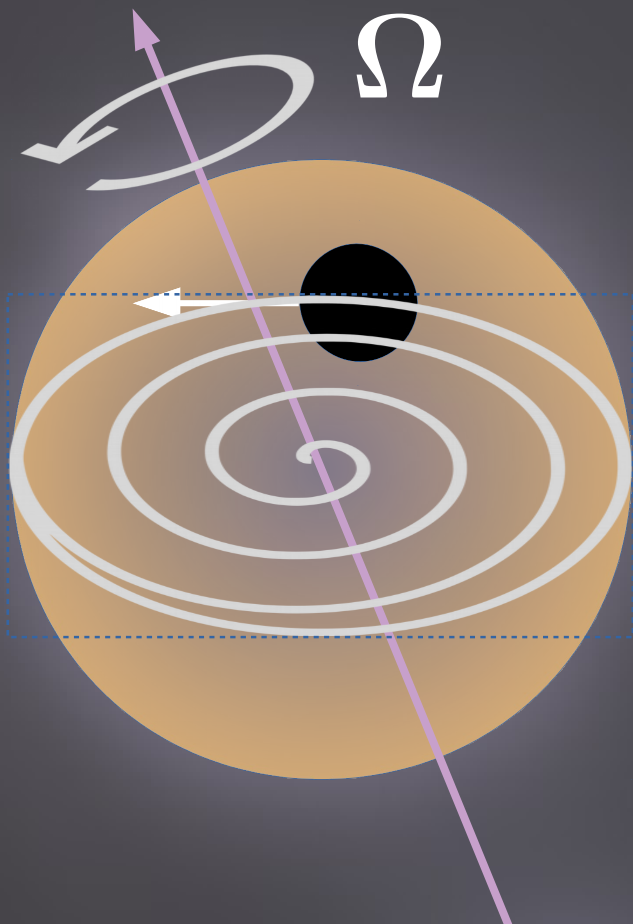
DF becomes negligible and accretion dominates:

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

(In the subsonic regime)

Equation of motion:

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



Equation of motion:

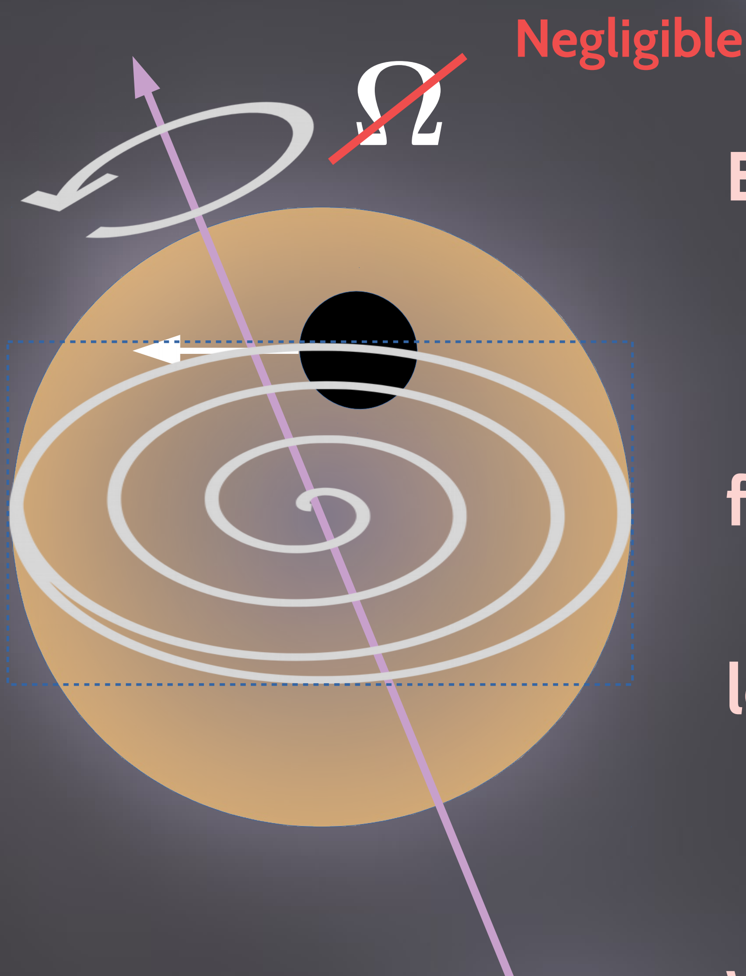
$$\ddot{\boldsymbol{r}} + \mathcal{D}(t)\left[\dot{\boldsymbol{r}} - \boldsymbol{\Omega} \times \boldsymbol{r}\right] + \omega_\star^2 \boldsymbol{r} = 0$$

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

leads to the conserved quantity:

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

whatever the accretion regime.



Equation of motion:

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

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leads to the conserved quantity:

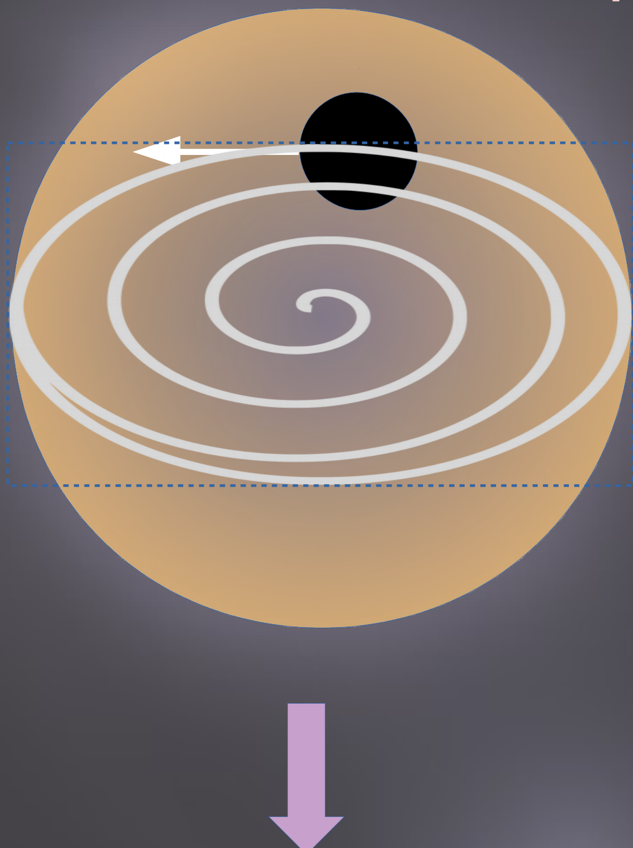
$$m\, r^2 \;=\; \mathrm{const.}$$

whatever the accretion regime.

V- Signatures

A-Signatures of a captured PBH:

1 - Gravitational wave emission from the inspiral motion:



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

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

This emission is sustained during the all accretion process

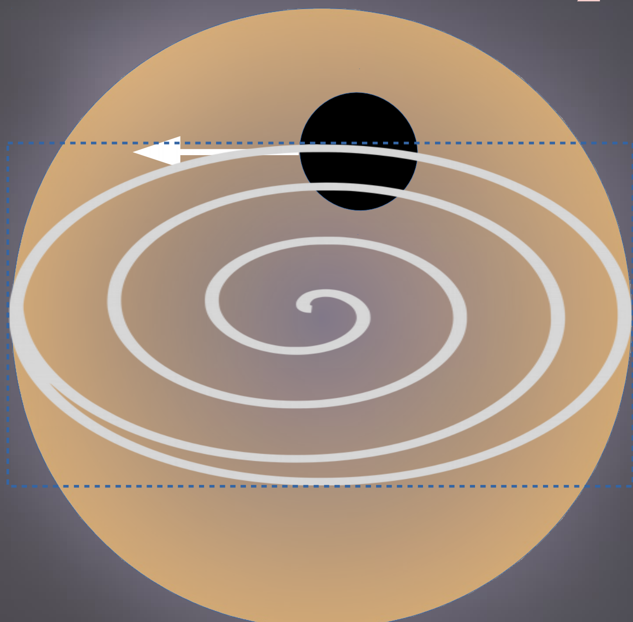
$$m(t) = \frac{m}{1 - t/t_B}$$

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

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

A-Signatures of a captured PBH:

2 – Multiwavelength signature from the final collapse:



$$m\, r^2 = \text{const.}$$

Might depend on the final asymmetry

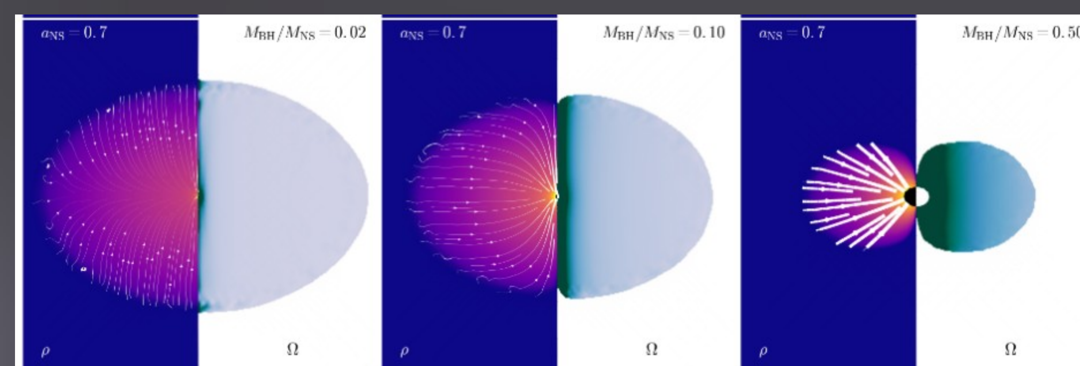
$$R_f = R_\star \sqrt{\frac{m_i}{f\, M_\star}}$$

Final radius

Initial PBH mass

Accreting PBH mass

Gravitational waves -> unpromising from simulations ?

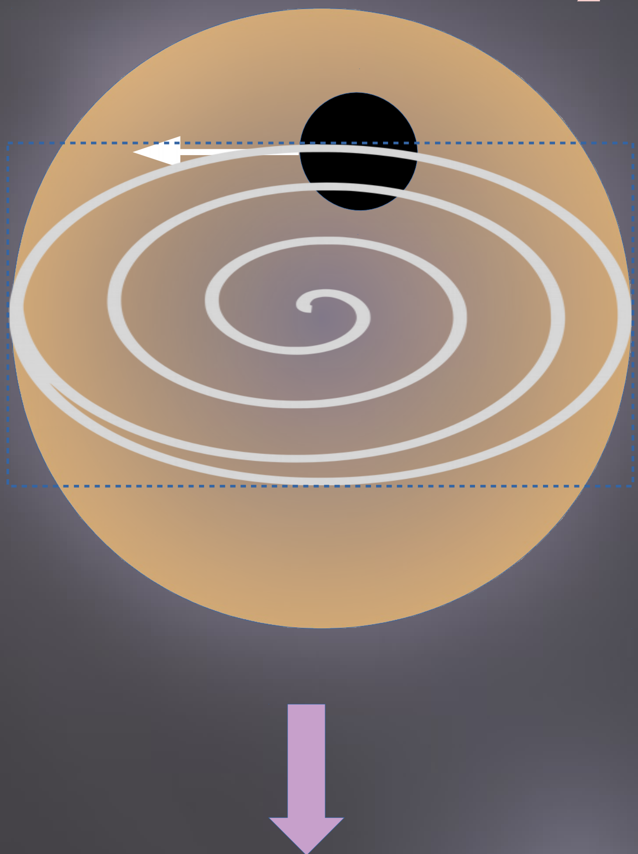


William E. East, Luis Lehner Phys. Rev. D 100, 124026 (2019)

-> But PBH at the center and no magnetic field.

A-Signatures of a captured PBH:

2 – 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

Accreting PBH mass

$$m\, r^2 = \text{const.}$$

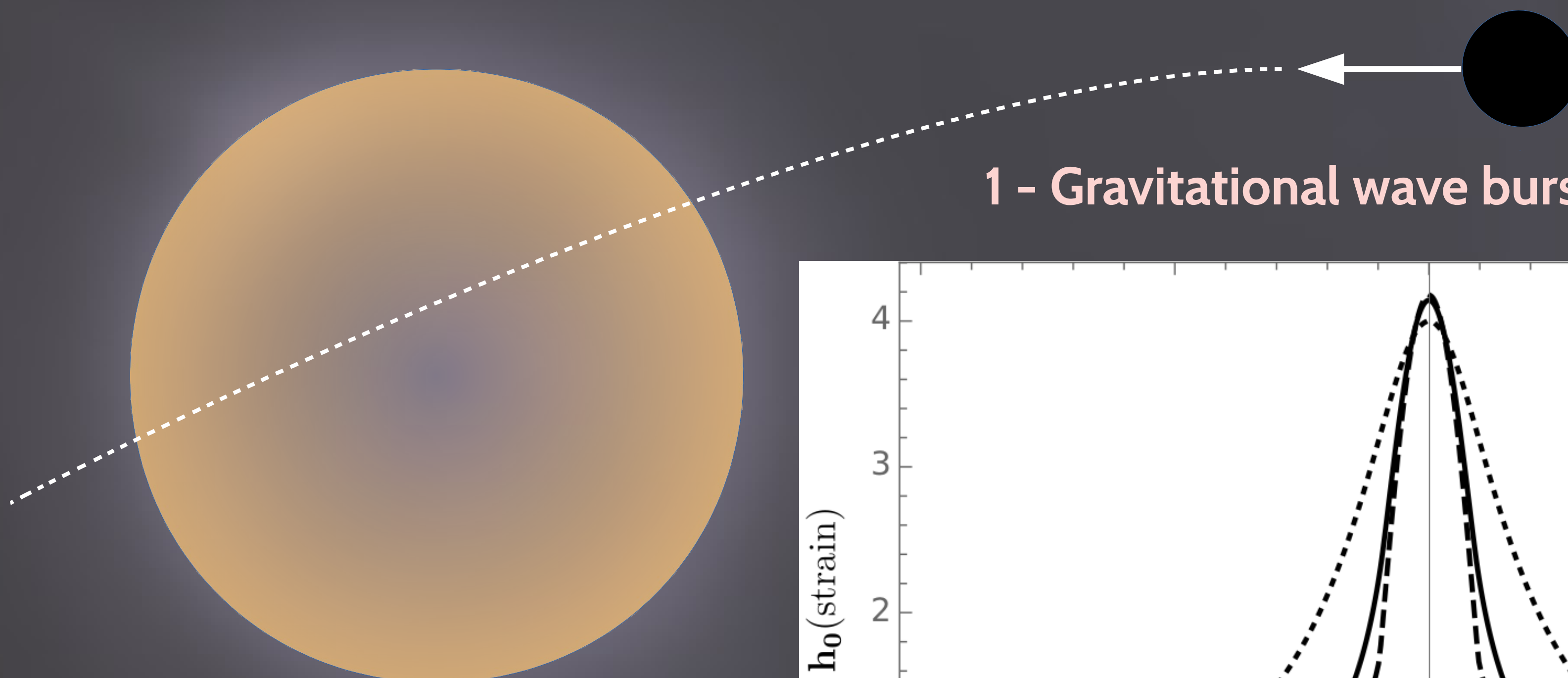
Electromagnetic waves -> promising !

No-hair theorem

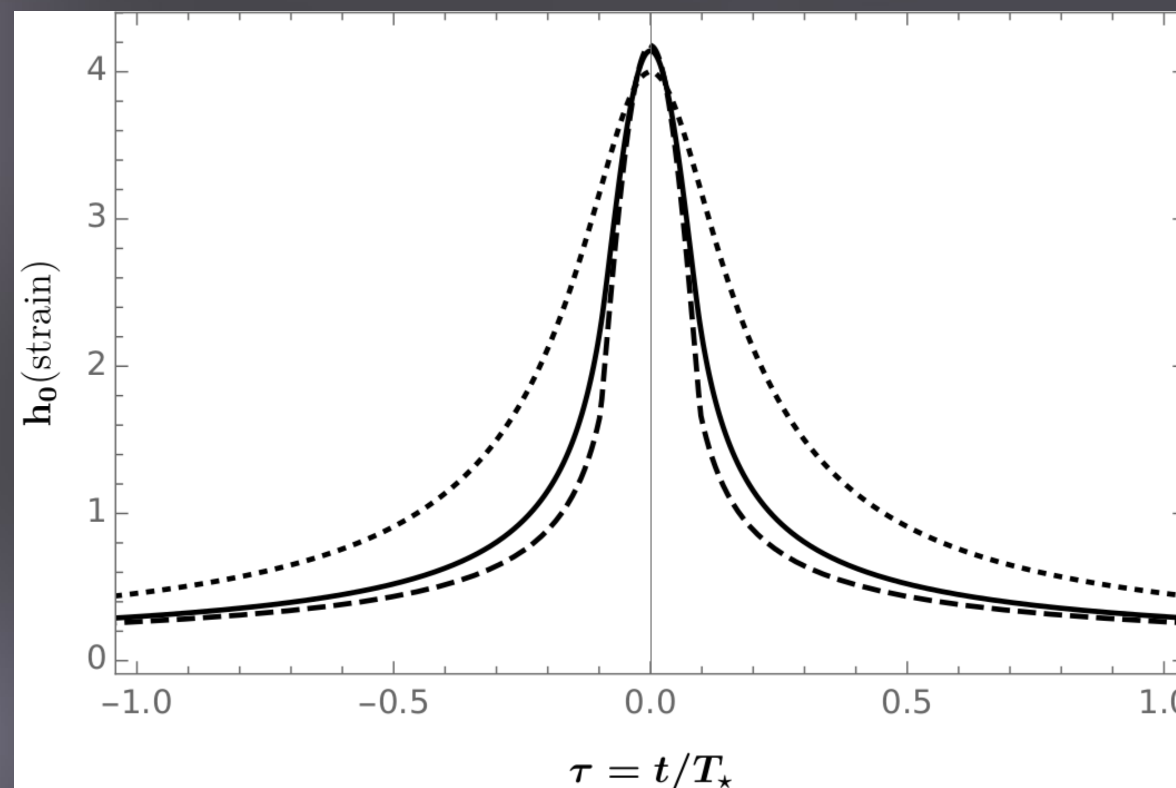
$$E_B = \frac{B^2}{8\pi}\frac{4\pi}{3}R_\star^3 \simeq 2\times 10^{41}\left(\frac{B}{10^{12}\mathrm{G}}\right)^2\left(\frac{R_\star}{10\,\mathrm{km}}\right)^3 \mathrm{erg}$$

J. Fuller and C. D. Ott, MNRAS 450, L71
M. A. Abramowicz, et al. ApJ 868, 17 (2018)
C. Chirenti, et al. Astrophys. J. Lett. 884, L16 (2019),

B-Signature of PBH encounters

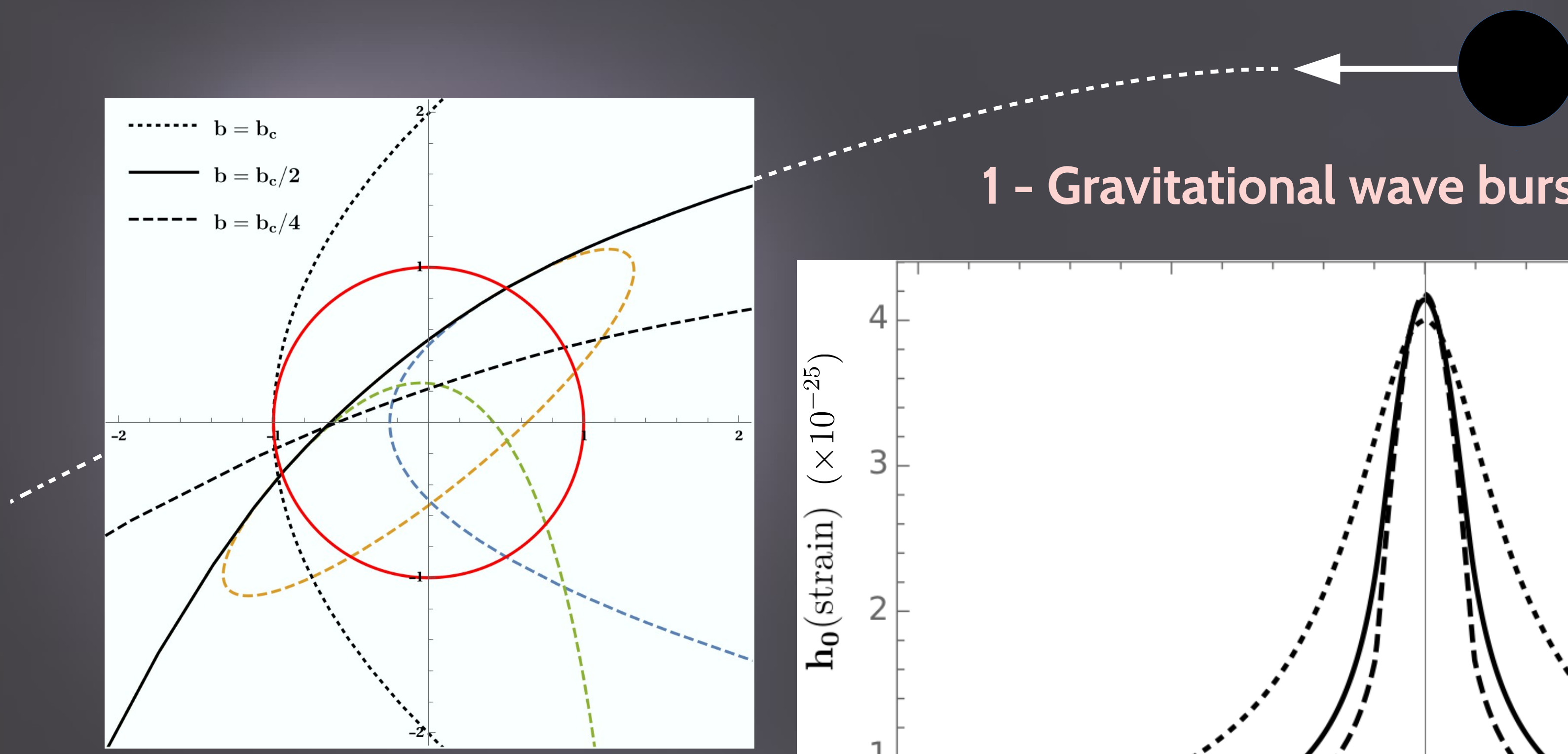


1 - Gravitational wave burst:

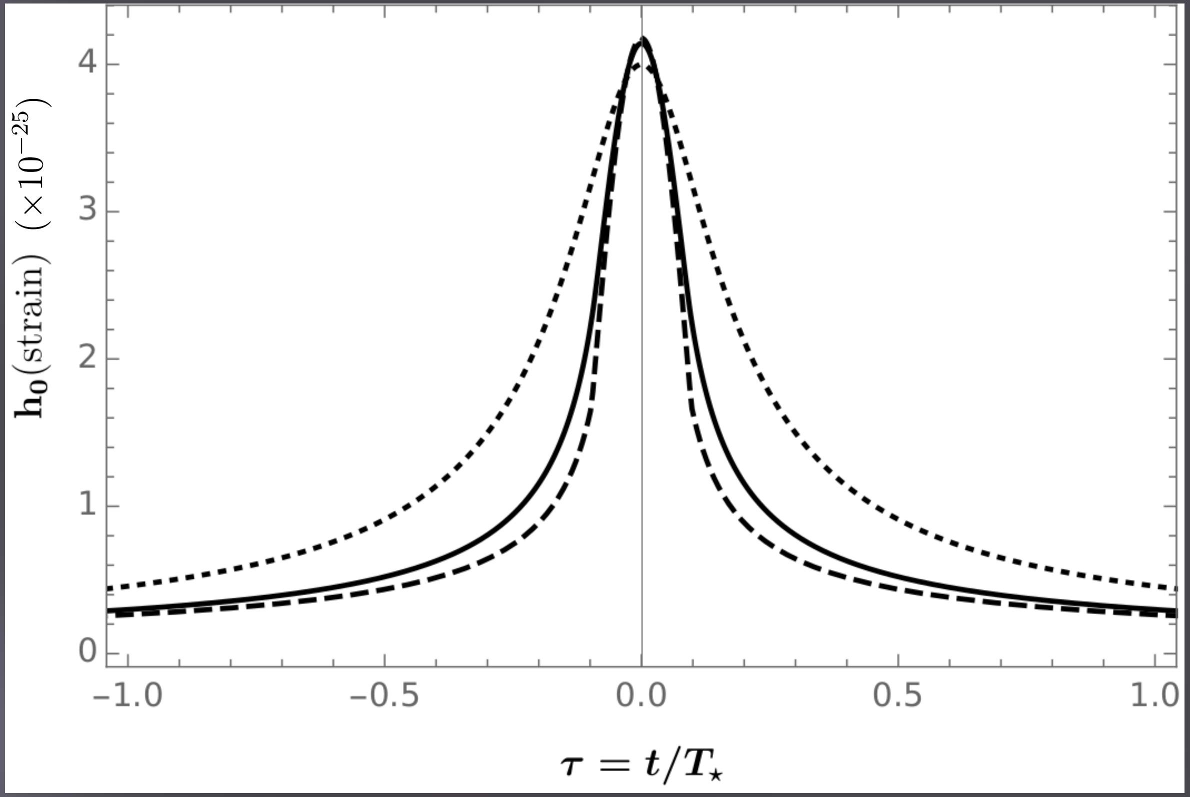


$d = 1\mathrm{kpc} \quad m = 10^{25}\mathrm{g}$

B-Signature of PBH encounters

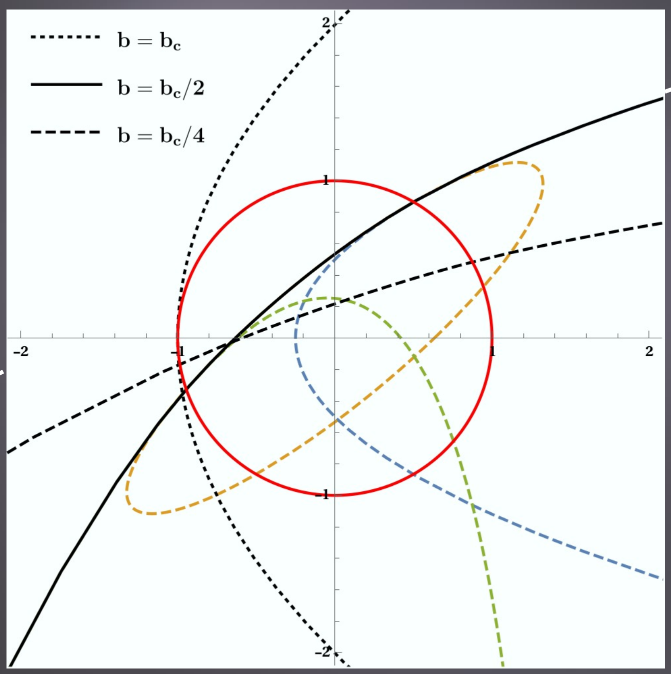


1 - Gravitational wave burst:



$d = 1\text{kpc} \quad m = 10^{25}\text{g}$

B-Signature of PBH encounters



2 - 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!

Conclusion & prospects:

- Review of the multiple interactions of PBH with a NS.

- PBH capture happens mostly in the supersonic regime : **dynamical friction** is the leading mechanism for capture. **Gravitational waves** energy losses can be the leading mechanism for capture at low dispersion speed.

- In the subsonic regime the PBH drag takes the form of a **Bondi accretion.**

Signatures:

- **PBH-NS encounter:** Gravitational wave burst.

- PBH Capture: 1- Inspiral motion: Monochromatic kHz gravitational wave lasting hours.
  2- Final Collapse: Gravitational wave and electromagnetic emissions expected, simulations required.

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

Conclusion & prospects:

Detection ?

- Rare events ! ~ 10-1000 less than supernovae rate in the Galaxy.

Transient event:

- **Gravitational waves** emission probably too small to detect.
- Electromagnetic emission detectable.

Population study:

- It could be a leading mecanism for « light » black hole formation.
- Forthcoming NS detection (Untill recently no evidence for NS outside the galaxy,)
- It could explain the « missing pulsar problem » of the Galactic center.
  (Dexter, J. and O'Leary, AJL 2014)