Title: Compact objects as dark-matter probes

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Abstract: In the last few years the possibility of constraining dark matter with astrophysical observations of compact objects, such as white dwarfs, neutron stars and black holes, has been explored. The ultra-high density interior of neutron stars and the strong-curvature regions near massive black holes make these objects unique laboratories to test weakly-interacting particles. In the first part of this talk I will review some recent work on the potential of compact objects as dark-matter detectors, including the consequences of dark-matter accretion on compact stars and superradiant black-hole instabilities triggered by ultralight bosons. In the second part I will discus how observations of neutron stars can be used to constrain the dark-matter fraction in primordial black holes. In a close encounter with a neutron star, a primordial black hole can get gravitationally captured due to accretion, dynamical friction and tidal heating. Within a short time, the black hole is trapped inside the star and disrupts it by rapid accretion. The mere existence of old neutron stars limits the abundance of primordial black holes in the only mass range that was still unconstrained, thus suggesting that these objects cannot be the dominant dark matter constituent.

Compact objects as dark matter probes

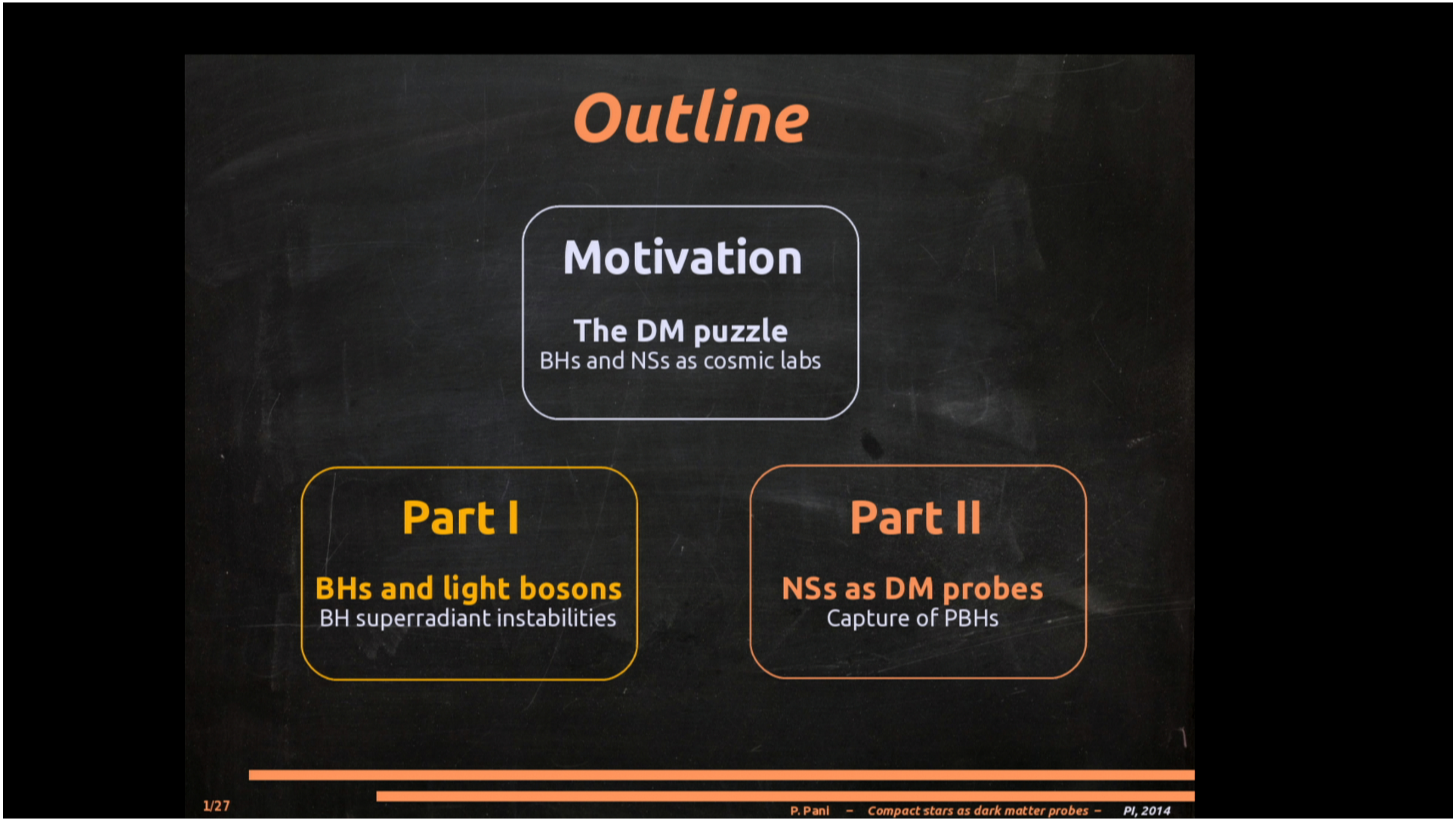
blackholes.ist.utl.pt

Paolo Pani

IST - Lisbon (PT)

Harvard-Smithsonian CfA

In collaboration with: Berti, Brito, Cardoso, Gualtieri, Ishibashi, Loeb, Yunes



Outline

Motivation

The DM puzzle
BHs and NSs as cosmic labs

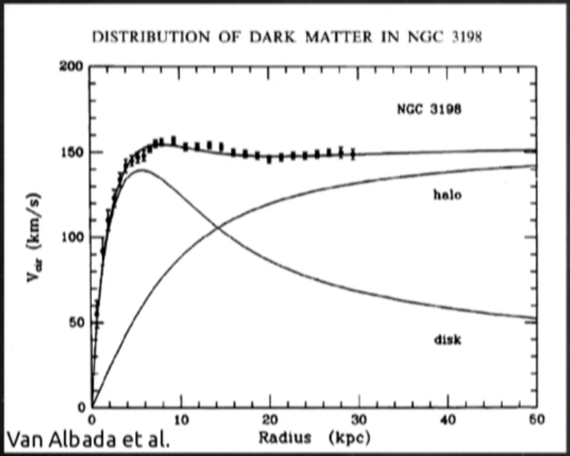
Part I

BHs and light bosons
BH superradiant instabilities

Part II

NSs as DM probes
Capture of PBHs

The DM puzzle

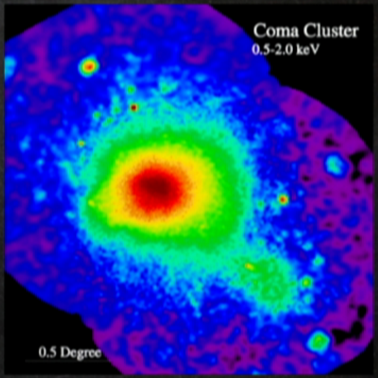


Van Albada et al.

Galaxy rotation curves

cf. latest Planck 2013 results

?



Confined hot gas in clusters

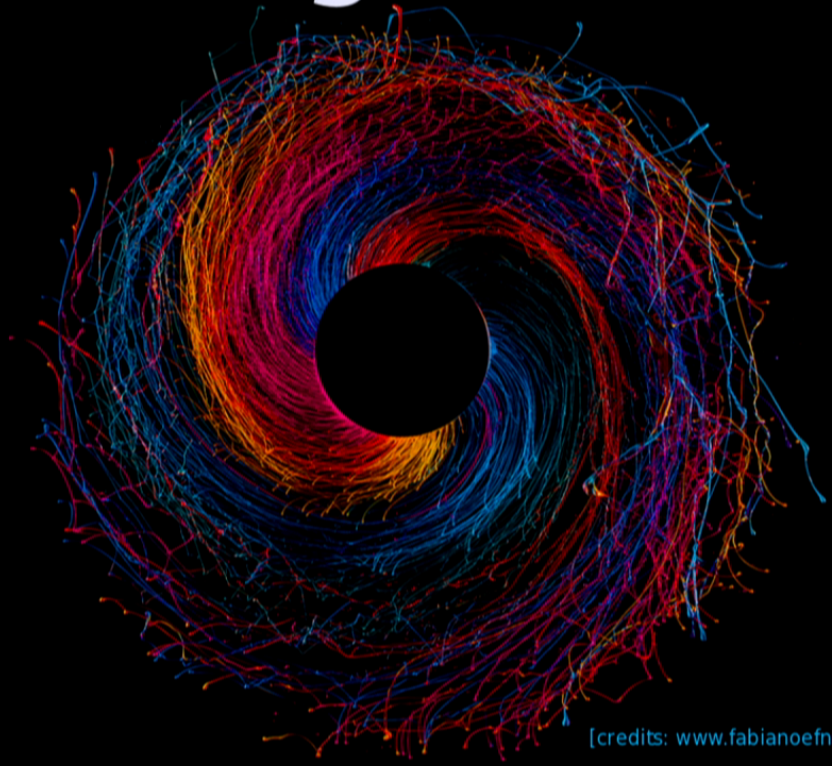
Gravitational lensing

The DM Zoo & compact objects

- **DM candidates**
  - WIMPs
  - Axions
  - Light bosons
  - MACHOs
  - Primordial BHs (PBHs)
  - exotica...
- **BHs**
  - no hair
  - equivalence principle
- **NSs**
  - ultradense
  - abundant in the Universe

Part I

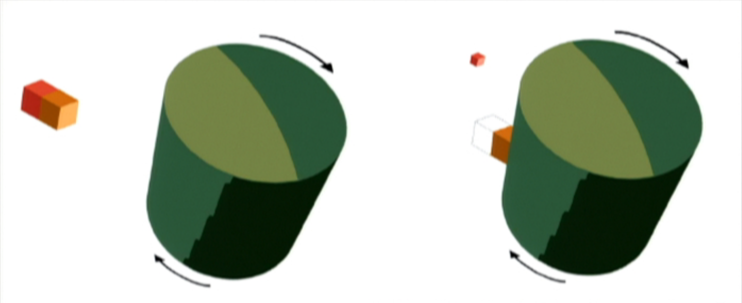
BHs & light bosons



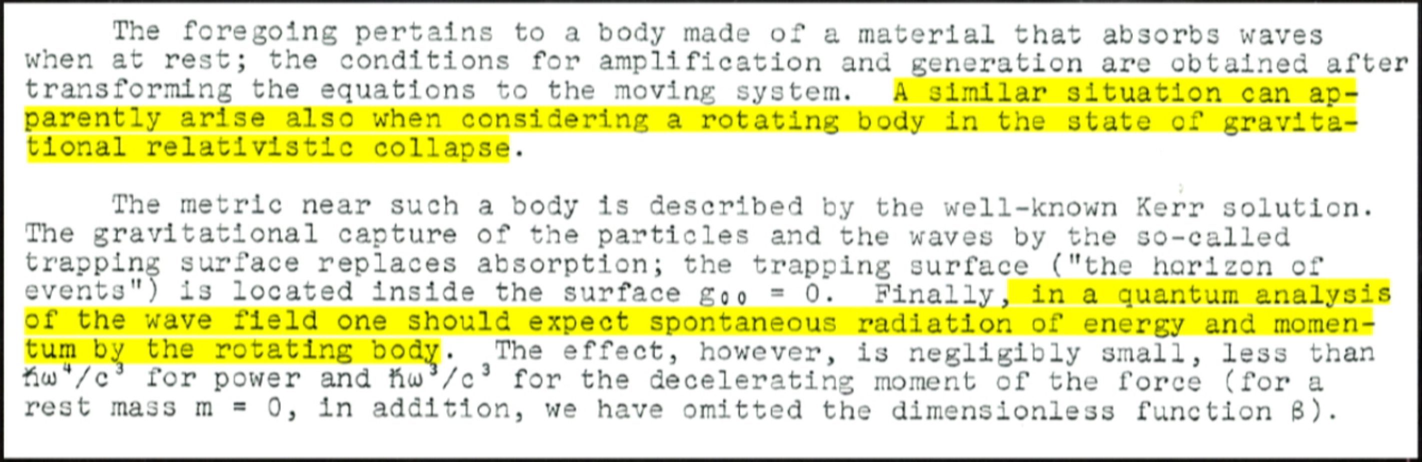
[credits: www.fabianoefner.com]

Superradiance

Klein, Ginzburg, Dicke...



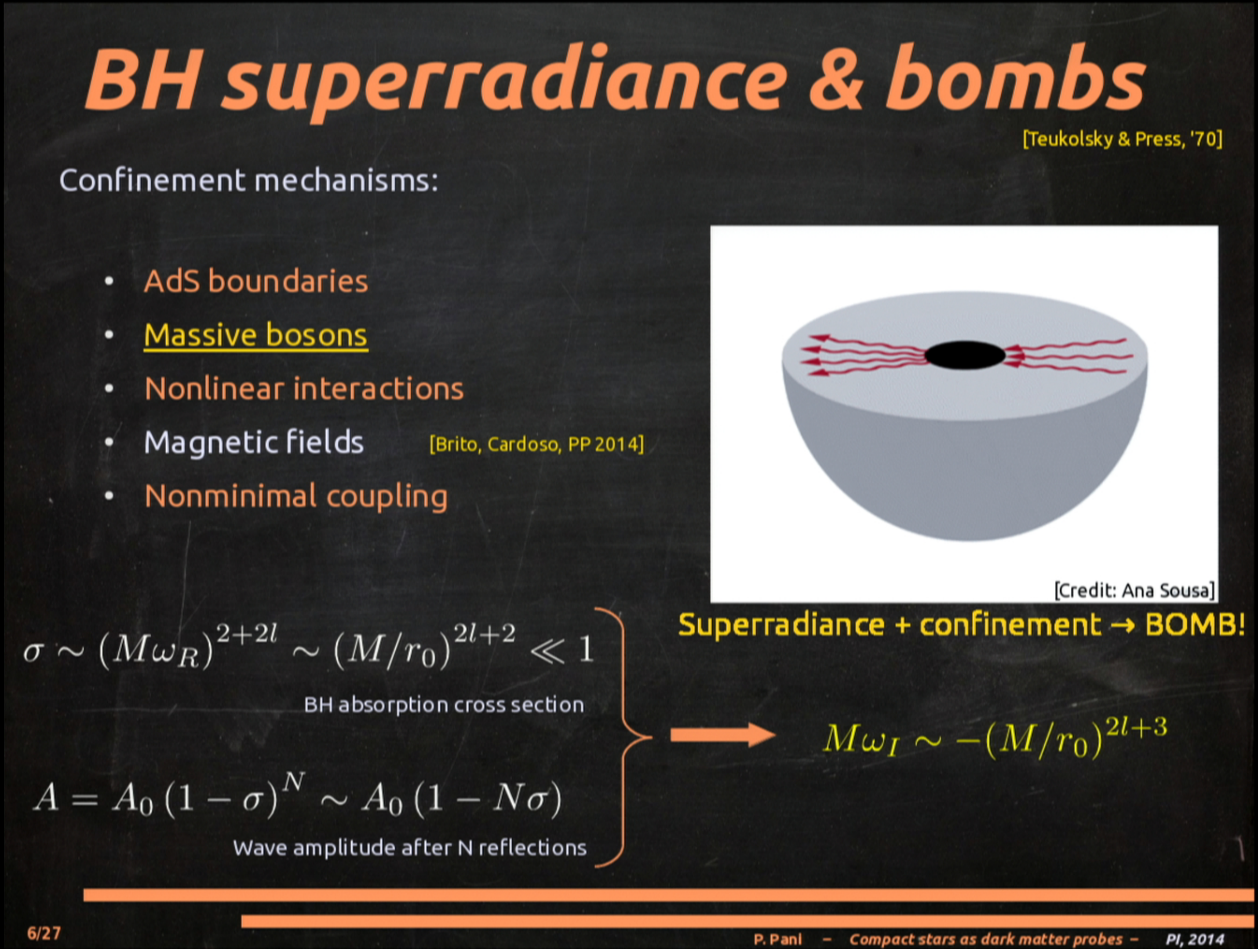
Zel'dovich effect. [Credit: Ana Sousa]



The foregoing pertains to a body made of a material that absorbs waves when at rest; the conditions for amplification and generation are obtained after transforming the equations to the moving system. A similar situation can apparently arise also when considering a rotating body in the state of gravitational relativistic collapse.

The metric near such a body is described by the well-known Kerr solution. The gravitational capture of the particles and the waves by the so-called trapping surface replaces absorption; the trapping surface ("the horizon of events") is located inside the surface $g_{00} = 0$. Finally, in a quantum analysis of the wave field one should expect spontaneous radiation of energy and momentum by the rotating body. The effect, however, is negligibly small, less than $\hbar\omega^4/c^3$ for power and $\hbar\omega^3/c^3$ for the decelerating moment of the force (for a rest mass m = 0, in addition, we have omitted the dimensionless function β).

ZhETF Pis. Red. 14, No. 4, 270 - 272 (20 August 1971)



BH superradiance & bombs

[Teukolsky & Press, '70]

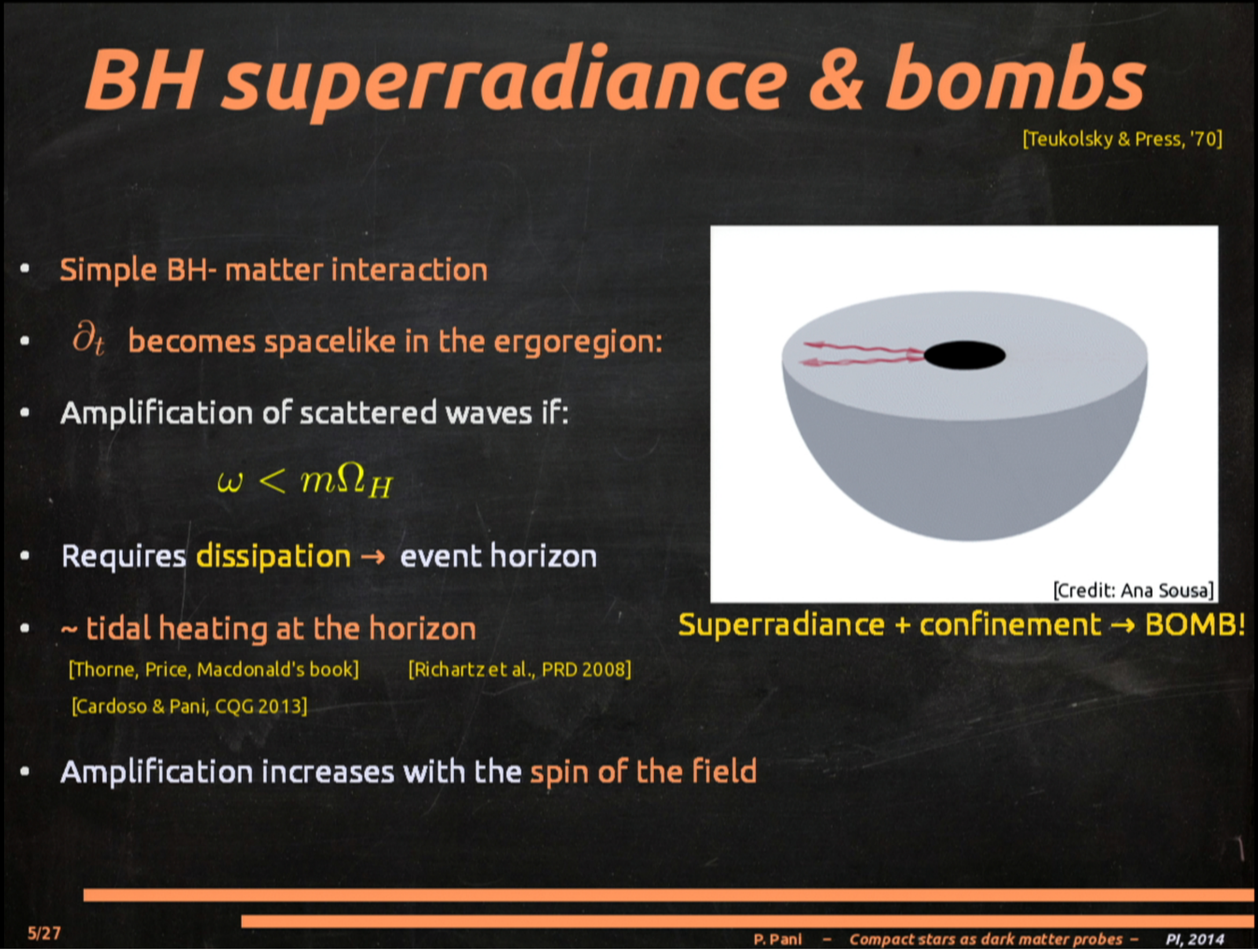
Confinement mechanisms:

- AdS boundaries
- Massive bosons
- Nonlinear interactions
- Magnetic fields [Brito, Cardoso, PP 2014]
- Nonminimal coupling

[Credit: Ana Sousa]

Superradiance + confinement → BOMB!

$$\left.\begin{array}{l} \sigma \sim (M\omega_R)^{2+2l} \sim (M/r_0)^{2l+2} \ll 1 \\ \qquad\qquad \text{BH absorption cross section} \\[1em] A = A_0\,(1-\sigma)^N \sim A_0\,(1-N\sigma) \\ \qquad\qquad \text{Wave amplitude after N reflections} \end{array}\right\} \Longrightarrow \quad M\omega_I \sim -(M/r_0)^{2l+3}$$



BH superradiance & bombs

[Teukolsky & Press, '70]

- Simple BH- matter interaction
- ∂_t becomes spacelike in the ergoregion:
- Amplification of scattered waves if:

$$\omega < m\Omega_H$$

- Requires dissipation → event horizon
- ~ tidal heating at the horizon

  [Thorne, Price, Macdonald's book] [Richartz et al., PRD 2008]

  [Cardoso & Pani, CQG 2013]
- Amplification increases with the spin of the field

[Credit: Ana Sousa]

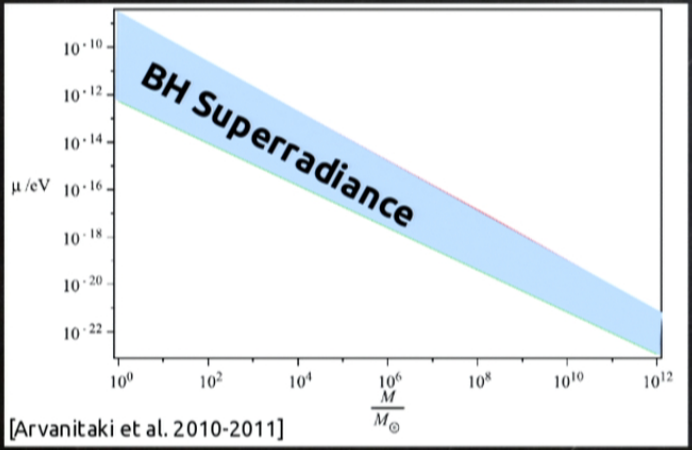
Superradiance + confinement → BOMB!

Scalar fields & BH bombs

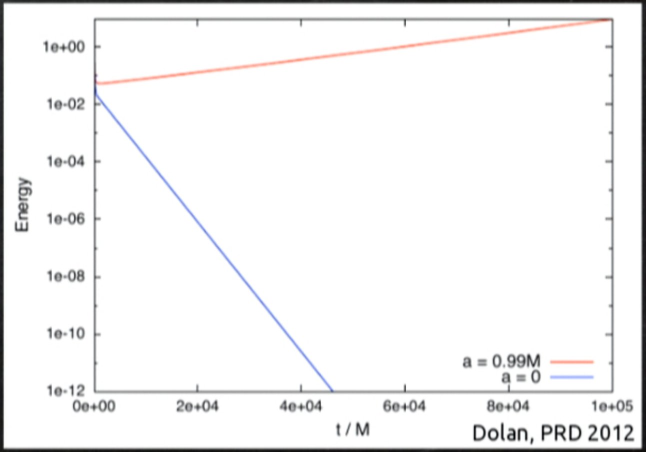
$$\Box\phi - \mu^2\phi = 0$$

[Damour et al. 1976]
[Detweiler, 1980]
[Earley & Zouros 1979]
[Cardoso & Yoshida 2005]
[Dolan 2007]
[Rosa 2010, 2012]

- Massive fields around spinning BHs are unstable
- Strongest instability when $\mu M \sim 1 \rightarrow \tau \sim 10^6 M$



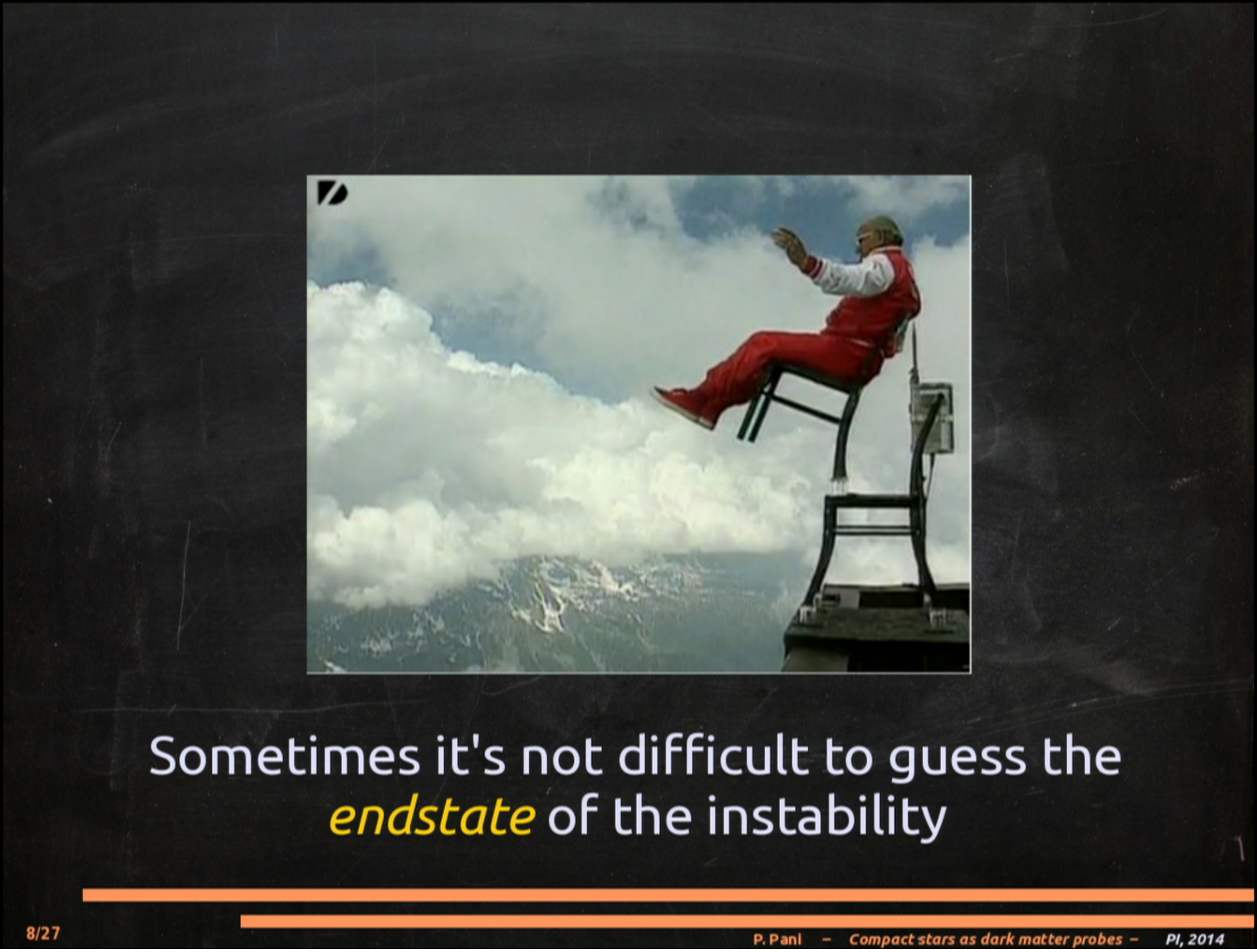
[Arvanitaki et al. 2010-2011]



Dolan, PRD 2012

- Numerical simulation are challenging!

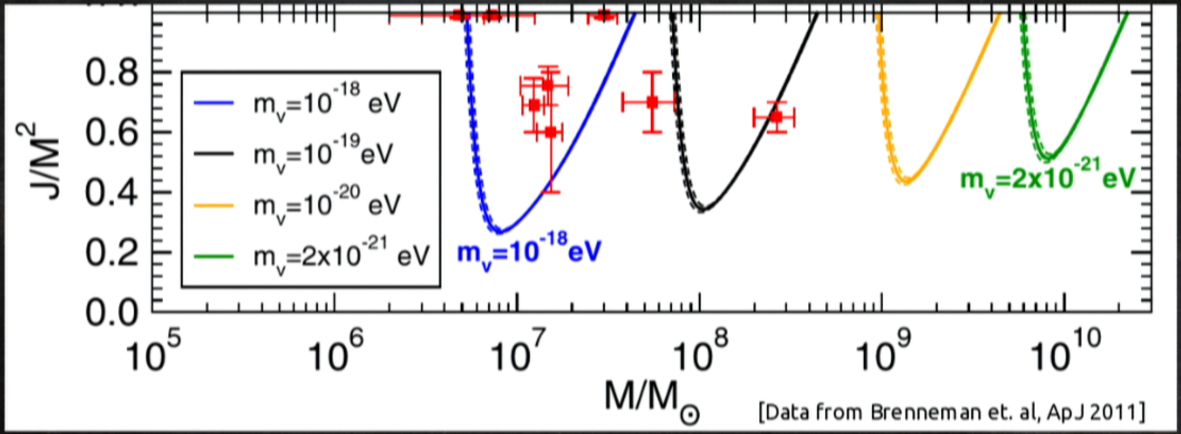
[Kodama & Yoshino 2011-2012]
[Witek et al, PRD 2012, Okawa et al. 2013-2014]



Sometimes it's not difficult to guess the *endstate* of the instability

If ultralight axions exist,
we shouldn't observe highly-spinning BHs

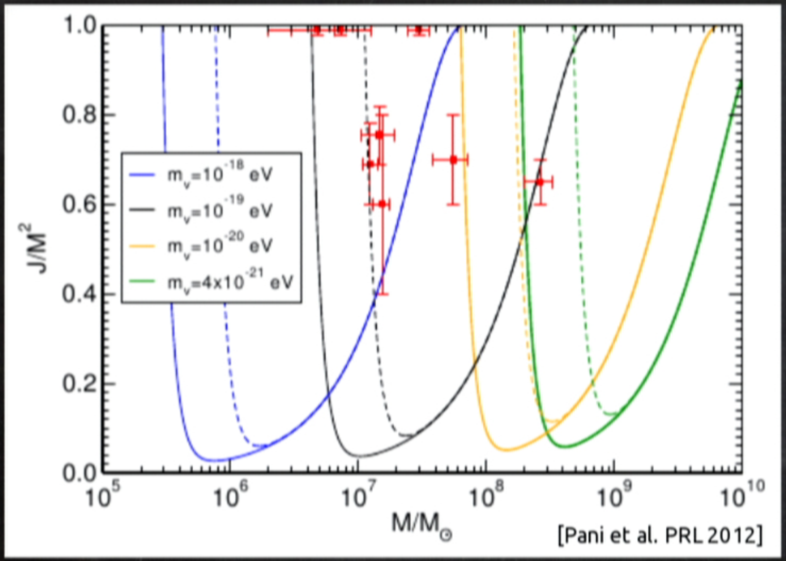
[Arvanitaki et al. 2010-2011]



[Data from Brenneman et. al, ApJ 2011]

Constraints on axion parameters from BH observations and future GW detection

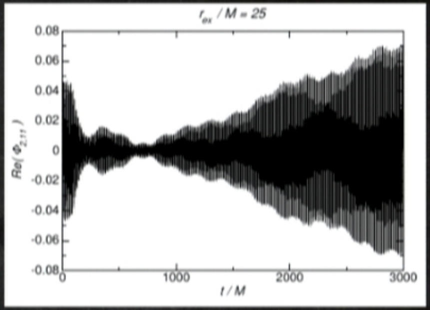
Proca instability. Regge plane



[Pani et al. PRL 2012]

$$\nabla_\sigma F^{\sigma\nu} - \mu^2 A^\nu = 0$$

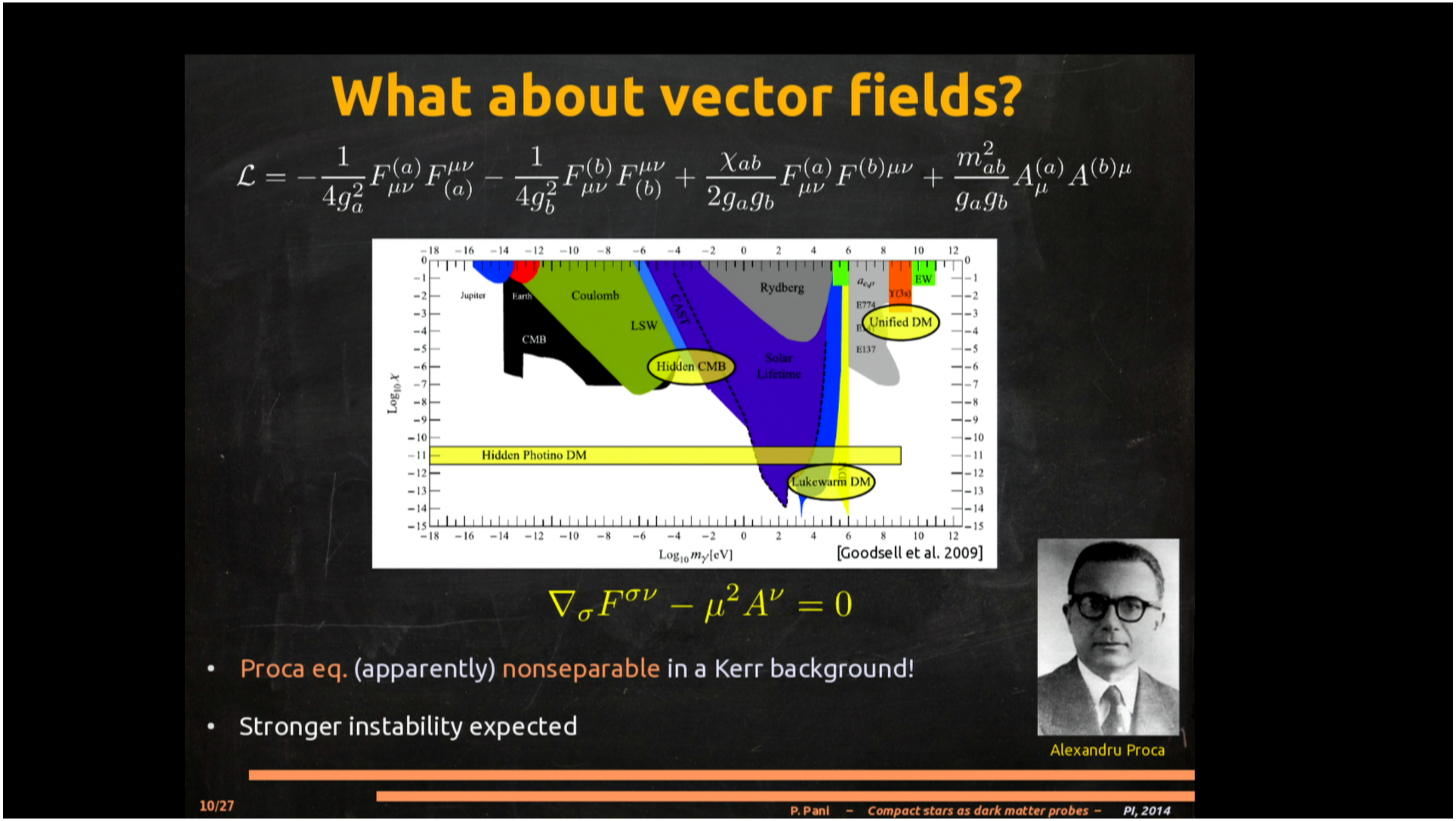
[Witek et al. PRD 2012]



- Highly-spinning BHs?
- Backreaction?

- Instability is effective roughly for any non-vanishing spin
- Constraints on massive vector DM from BH observations
- Massive spin-2 fields are also unstable [Brito, Cardoso, PP PRD 2013]

$$\omega_R \sim \mu \qquad \omega_I \sim (\tilde{a}m - 2r_+\mu)\,(M\mu)^\alpha$$



What about vector fields?

$$\mathcal{L} = -\frac{1}{4g_a^2}F^{(a)}_{\mu\nu}F^{\mu\nu}_{(a)} - \frac{1}{4g_b^2}F^{(b)}_{\mu\nu}F^{\mu\nu}_{(b)} + \frac{\chi_{ab}}{2g_ag_b}F^{(a)}_{\mu\nu}F^{(b)\mu\nu} + \frac{m^2_{ab}}{g_ag_b}A^{(a)}_{\mu}A^{(b)\mu}$$

[Goodsell et al. 2009]

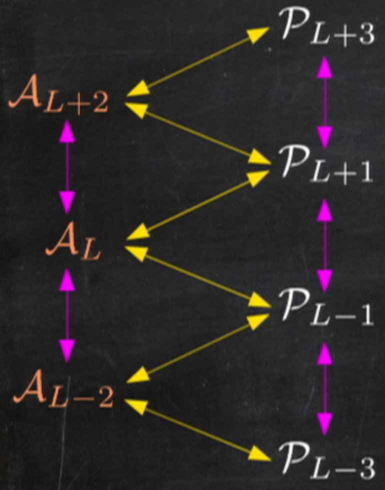
$$\nabla_\sigma F^{\sigma\nu} - \mu^2 A^\nu = 0$$

- Proca eq. (apparently) nonseparable in a Kerr background!
- Stronger instability expected

Alexandru Proca

Proca instability of Kerr BHs

Slow-rotation approximation



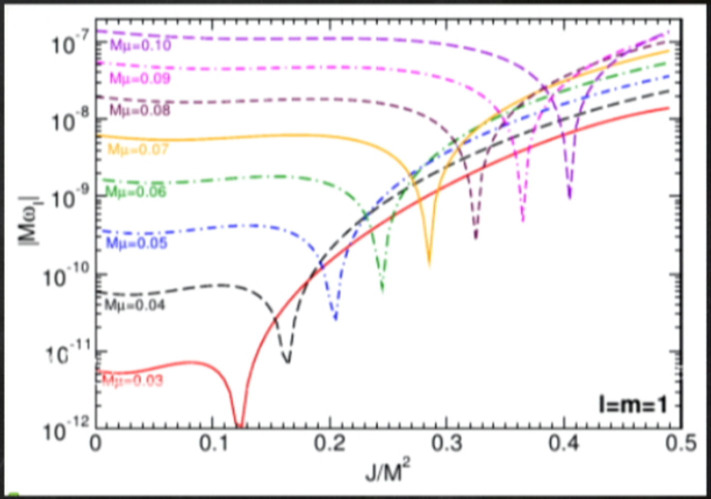
Zeroth order: decoupled

First order: polar-axial l±1

Second order: l±2

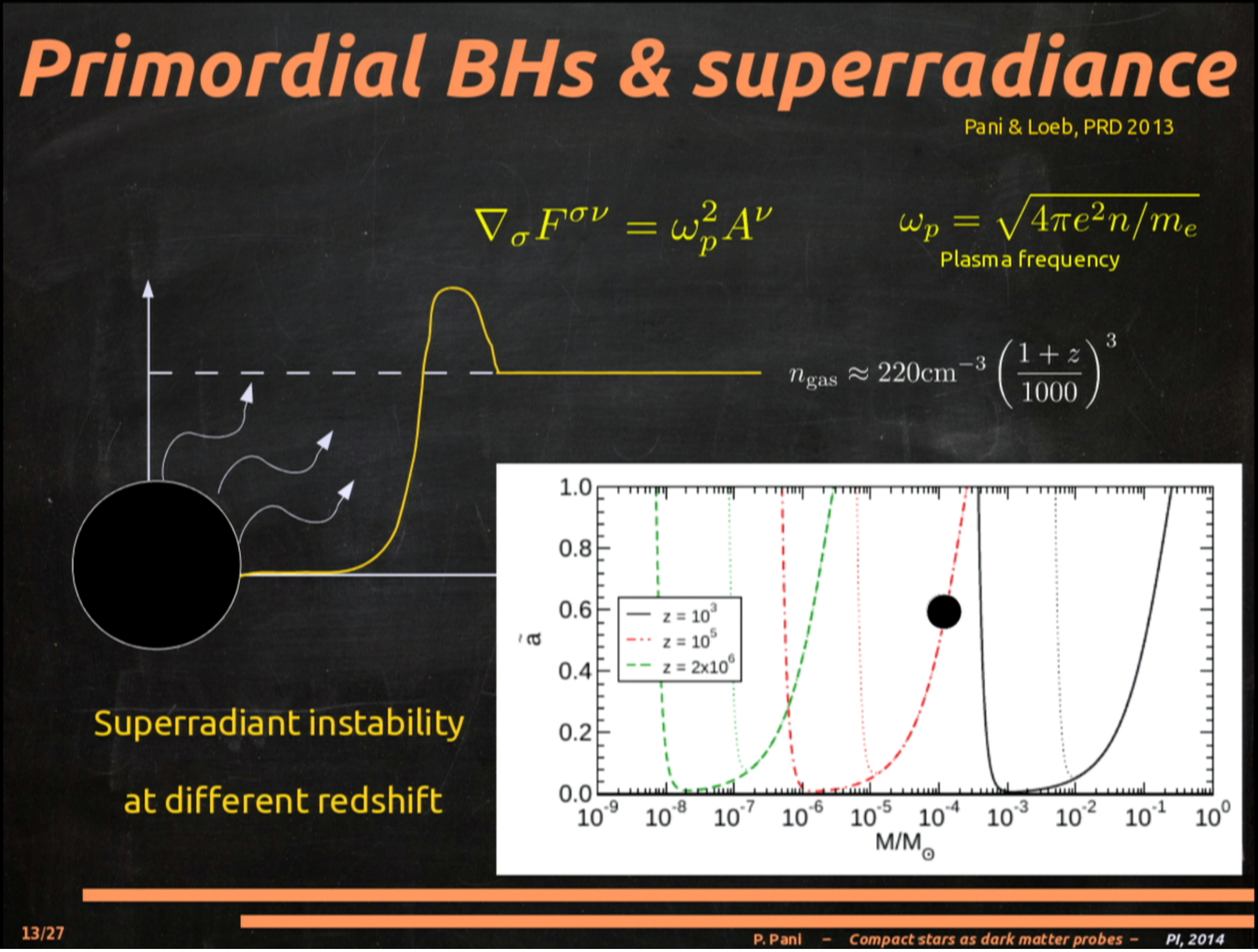
[PP, review IJMPA 2013]

Polar modes (S=+1,-1)



$$\omega_R \sim \mu - \frac{\mu(M\mu)^2}{2(\ell+n+S+1)}$$

$$M\omega_I \sim \gamma_{S\ell}\,(\tilde{a}m - 2r_+\mu)\,(M\mu)^{4\ell+5+2S}$$



Primordial BHs & superradiance

Pani & Loeb, PRD 2013

$$\nabla_\sigma F^{\sigma\nu} = \omega_p^2 A^\nu$$

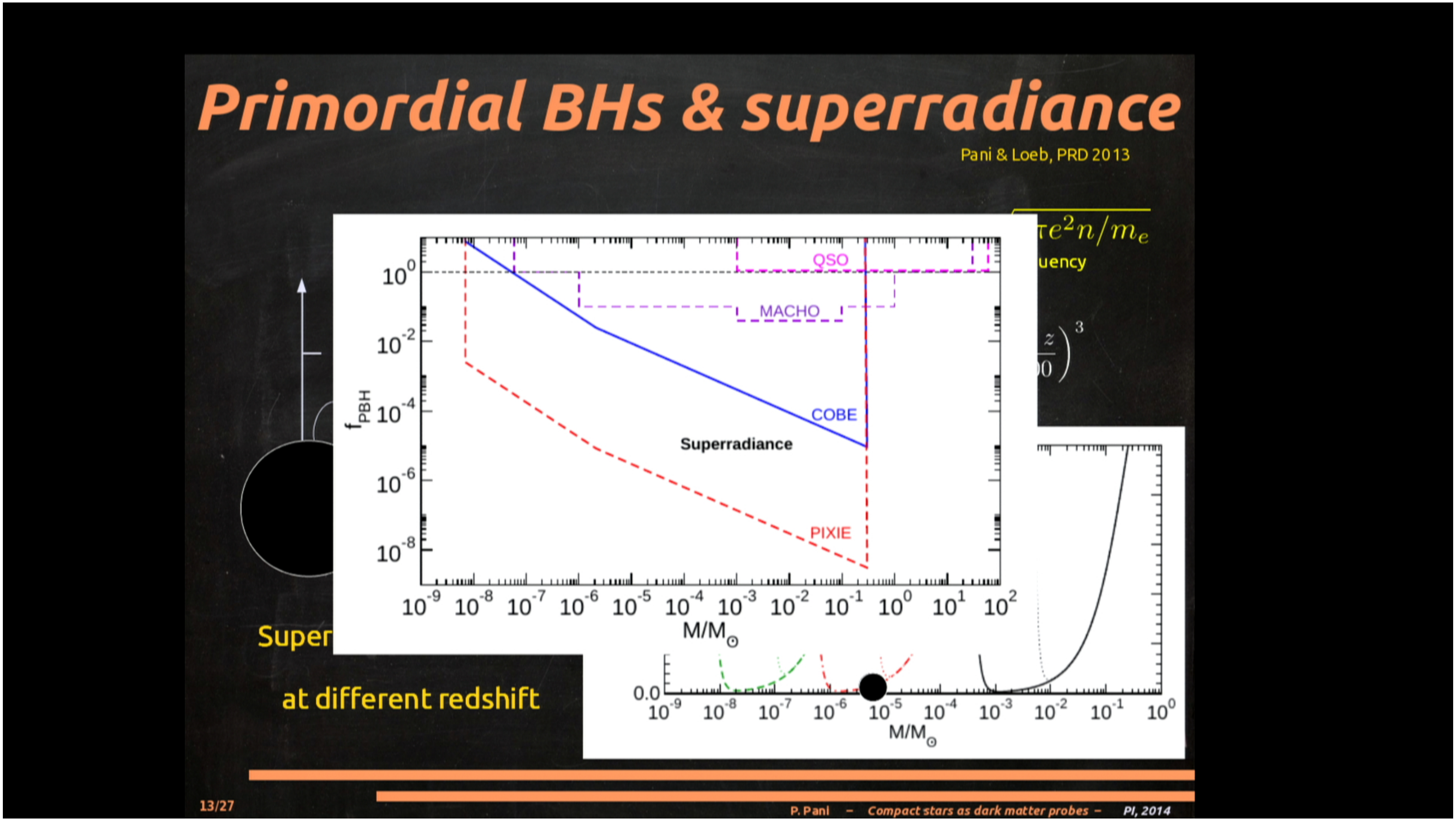
$$\omega_p = \sqrt{4\pi e^2 n/m_e}$$

Plasma frequency

$$n_{\rm gas} \approx 220\text{cm}^{-3}\left(\frac{1+z}{1000}\right)^3$$

Superradiant instability

at different redshift



Primordial BHs & superradiance

Pani & Loeb, PRD 2013

$\overline{\tau e^2 n/m_e}$

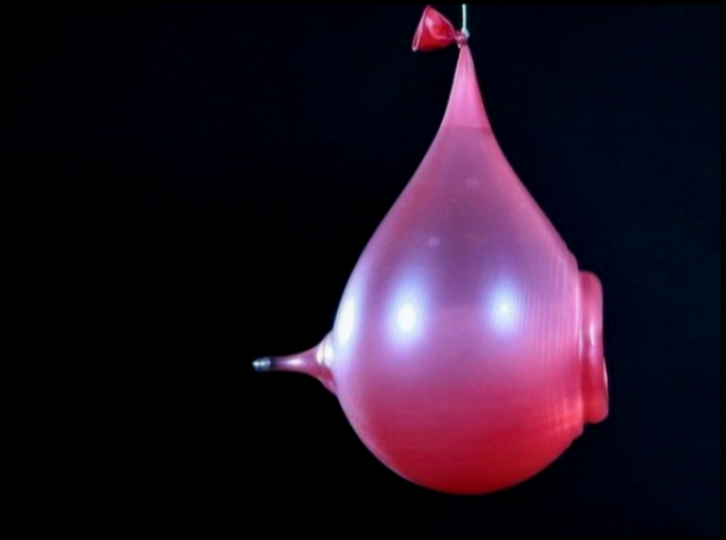
uency

Super

at different redshift

Part II

NSs as DM probes



Mostly based on Pani & Loeb, arXiv:1401.3025

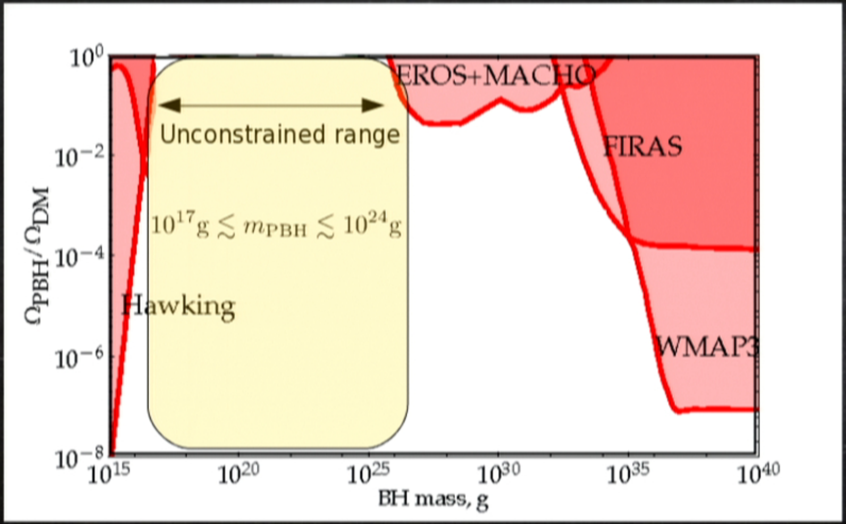
PBHs as DM candidates

Review: Carr 2004

- Most natural DM candidates?

$$M \sim \frac{c^3 t}{G} \sim 10^{15}\left(\frac{t}{10^{-23} s}\right) \mathrm{g}$$

- *"A gravitational solution to a gravitational problem"*
- Cold, weakly interacting, do not require extensions of the SM

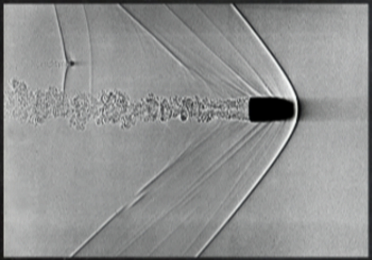


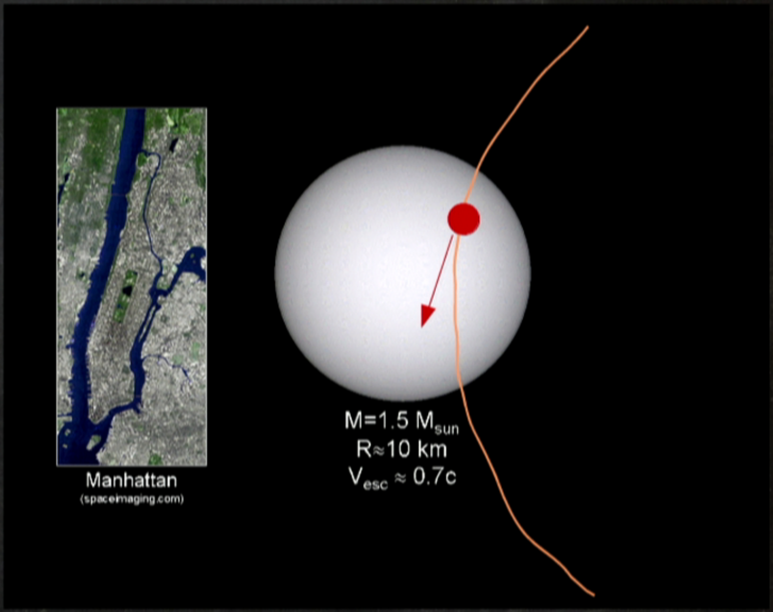
Adapted from Capela et al., PRD 2013

NS-PBH encounter

Accretion and dynamical friction

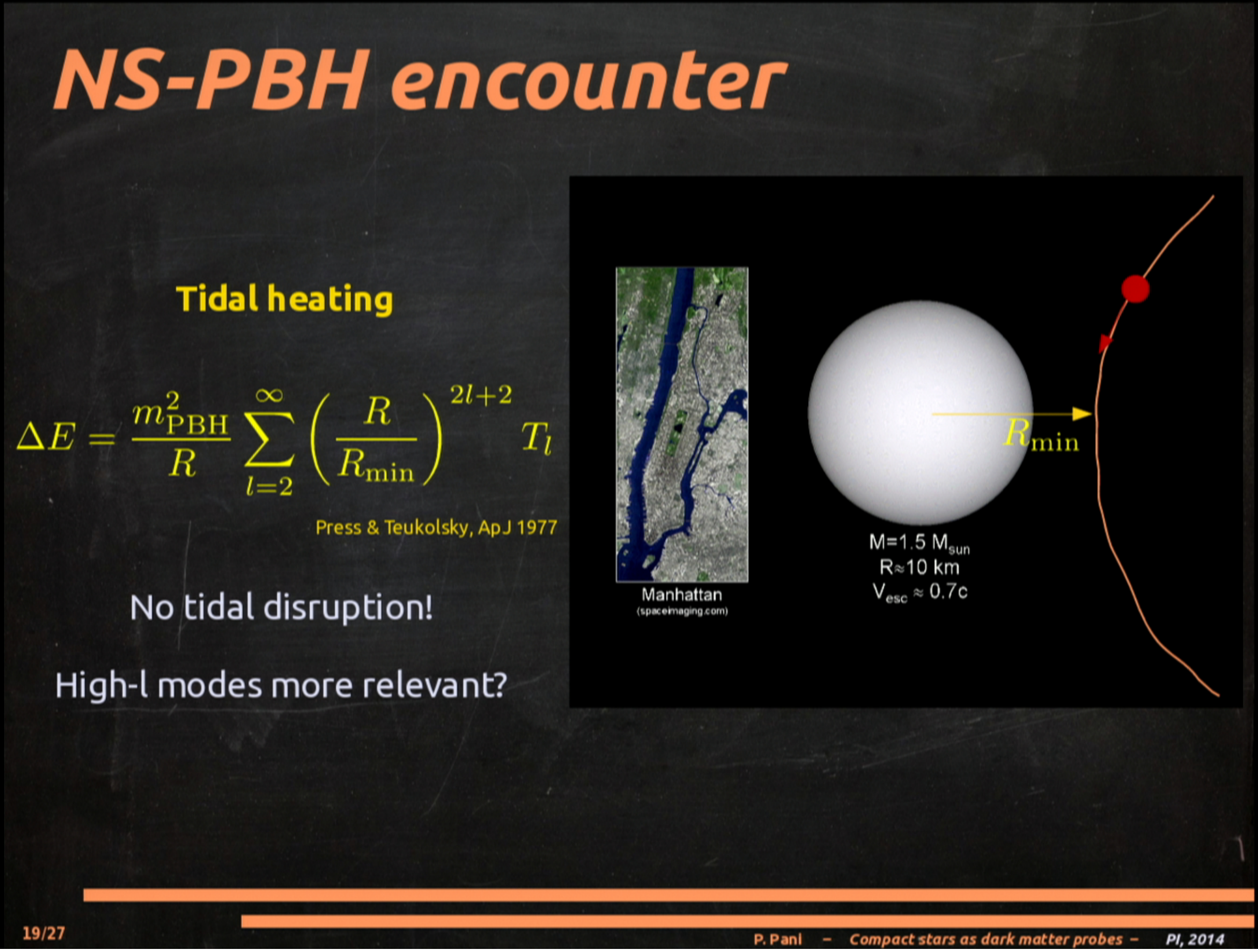
Chandrasekhar, Ostriker





$$\Delta E \sim \frac{m_{\rm PBH}^2}{M}$$

Capela et al., PRD 2013



NS-PBH encounter

Tidal heating

$$\Delta E = \frac{m_{\rm PBH}^2}{R}\sum_{l=2}^{\infty}\left(\frac{R}{R_{\rm min}}\right)^{2l+2} T_l$$

Press & Teukolsky, ApJ 1977

No tidal disruption!

High-l modes more relevant?

Enhanced tidal heating

Seismic energy:

Luo et al. ApJ 2012
Kesden & Hanasoge, PRL 2011

$$s(\boldsymbol{x},t) = -\mathrm{Re}\sum_{\mathrm{n}l} \frac{c_{\mathrm{n}l}}{\omega_{\mathrm{n}l}^2} e^{i\omega_{\mathrm{n}l}t} \boldsymbol{s}_{\mathrm{n}l}$$

Fluid displacement

$$\Delta E \equiv \sum_l E_l = \frac{1}{2}\sum_l \frac{|c_l|^2}{\omega_l^2}$$

$$c_{\mathrm{n}l} = \int dt\, e^{-i\omega_{\mathrm{n}l}t} \int_{\mathrm{star}} d\boldsymbol{x}^3 \partial_t \boldsymbol{f}(\boldsymbol{x},t)\cdot \boldsymbol{s}_{\mathrm{n}l}^*(\boldsymbol{x})$$

Excitation coefficients

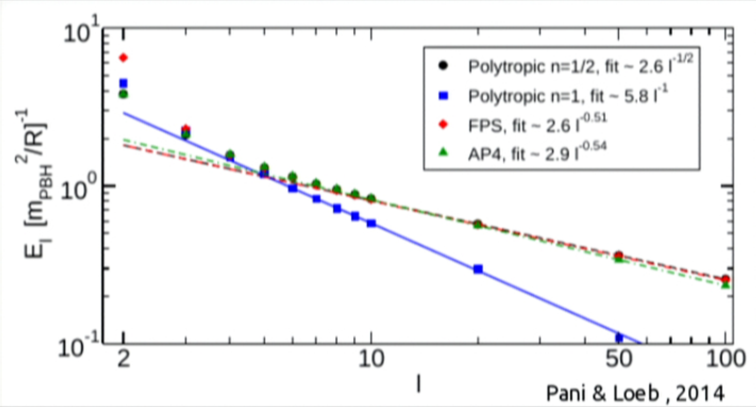
Mass ratio < 10^{-8} → point particle source

$$\boldsymbol{f}(\boldsymbol{x},t) = m_{\mathrm{PBH}}\rho(\boldsymbol{x})\boldsymbol{\nabla}\frac{1}{|\boldsymbol{x}-\boldsymbol{x}_p(t)|}$$

$$E_l \sim \frac{m_{\mathrm{PBH}}^2}{R}\frac{\gamma}{l^n}$$

"divergence" for stiff EOS

$$P(\rho) = k\rho^{1+1/n}$$



Pani & Loeb , 2014

Enhanced tidal heating

Seismic ene

$$\Delta E \equiv \sum_l$$

$$\frac{c_{nl}}{\omega_{nl}^2} e^{i\omega_{nl}t} s_{nl}$$

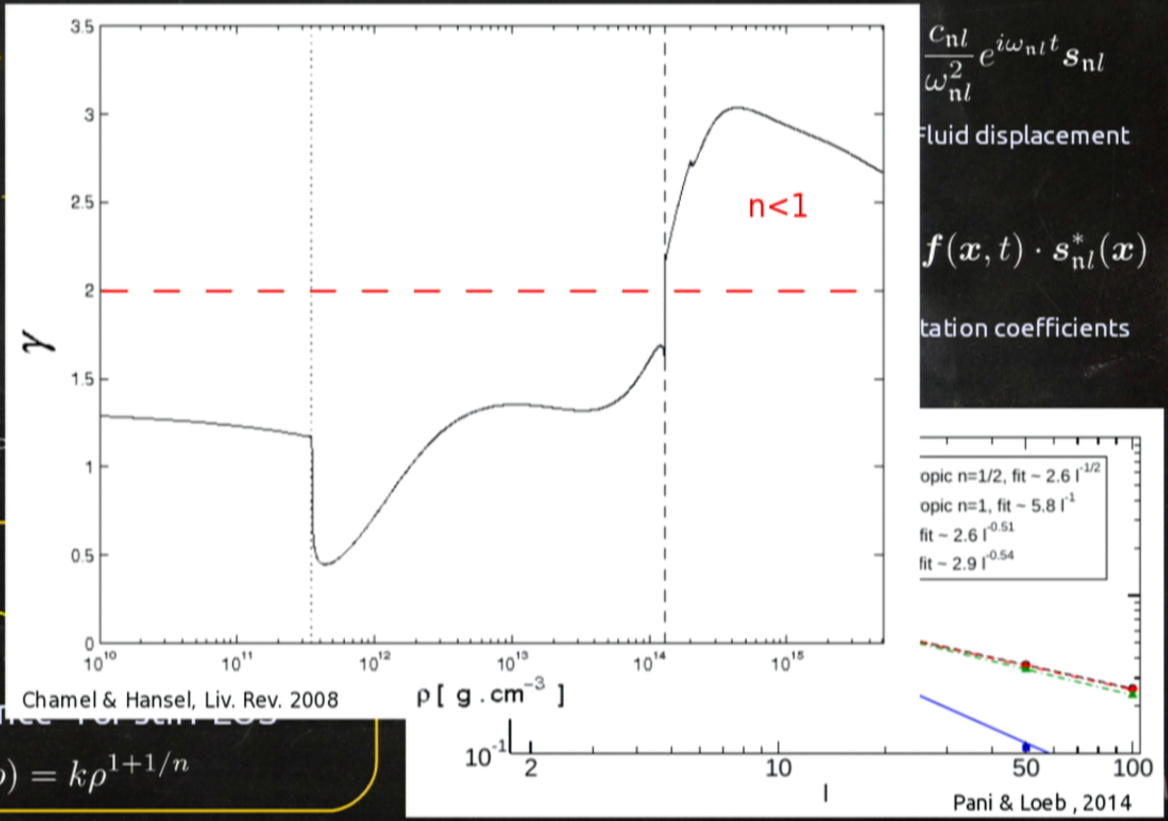
Fluid displacement

$$f(x,t) \cdot s^*_{nl}(x)$$

tation coefficients

Mass ratio <

$$f(x,t) = m_P$$



Chamel & Hansel, Liv. Rev. 2008

Pani & Loeb , 2014

$$E_l \sim$$

“divergen

$$P(\rho) = k\rho^{1+1/n}$$

Enhanced tidal heating

$$E_l \sim \frac{m_{\rm PBH}^2}{R}\frac{\gamma}{l^n}$$

Incompressible fluid toy model

$$c_l^{\rm ext} = \frac{m_{\rm PBH}(l+1)\sqrt{Ml}}{\sqrt{3\pi}R^2}E_N(z)$$

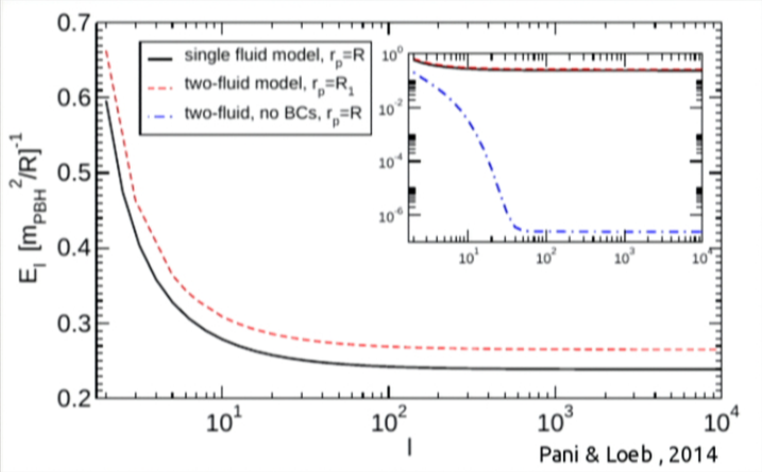
$$\downarrow$$

$$E_l \to \frac{3}{4\pi}\frac{m_{\rm PBH}^2}{R}$$

Constant energy at large l

Same results for the BH case

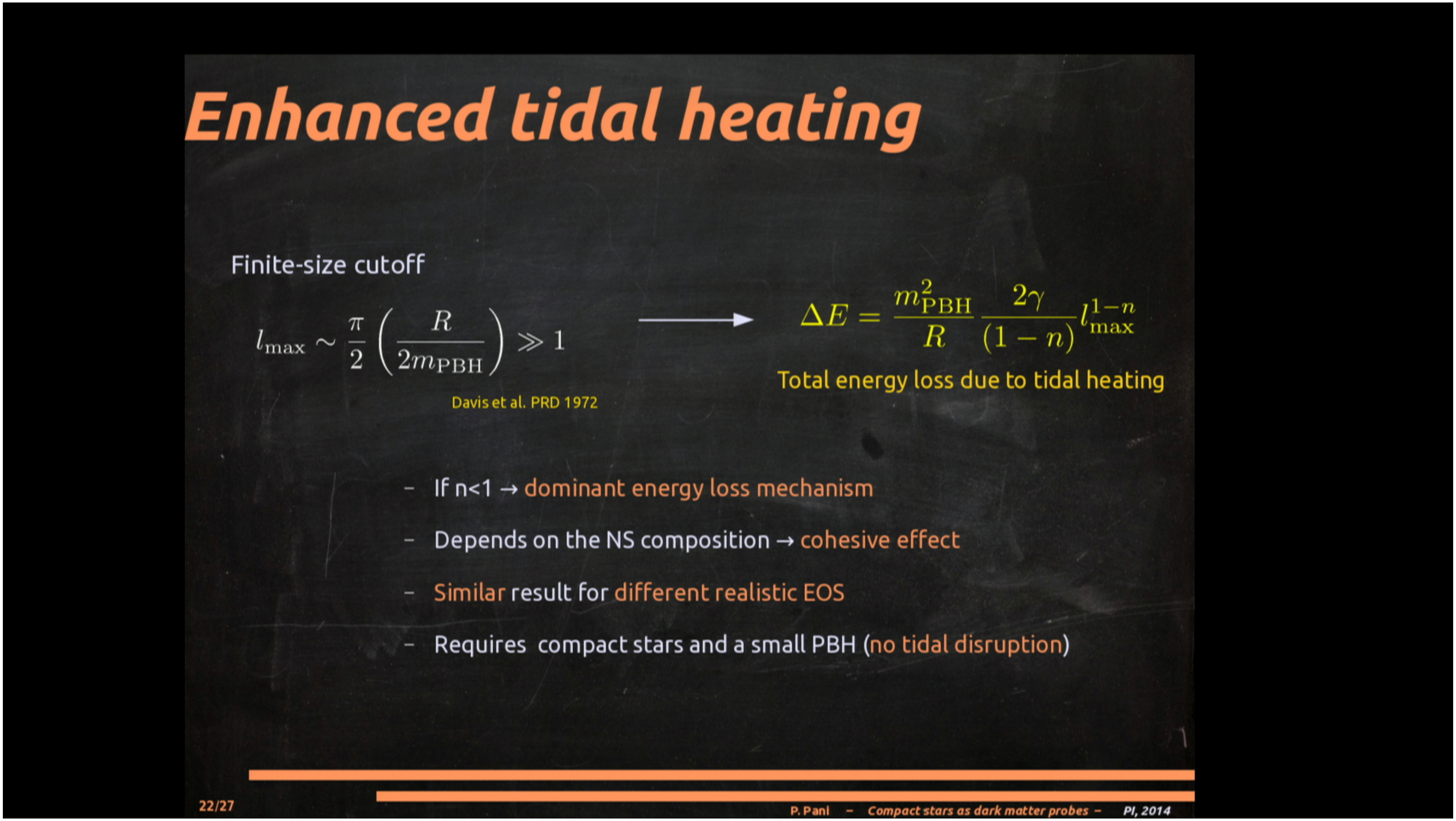
Davis et al. PRD 1972



Pani & Loeb , 2014

- Different from dynamical friction
- Unrelated to the PBH motion
- Insensitive to core-crust transition

see comment by Capela et al, 2014



Enhanced tidal heating

Finite-size cutoff

$$l_{\max} \sim \frac{\pi}{2}\left(\frac{R}{2m_{\rm PBH}}\right) \gg 1 \longrightarrow \Delta E = \frac{m_{\rm PBH}^2}{R}\frac{2\gamma}{(1-n)}\, l_{\max}^{1-n}$$

Davis et al. PRD 1972

Total energy loss due to tidal heating

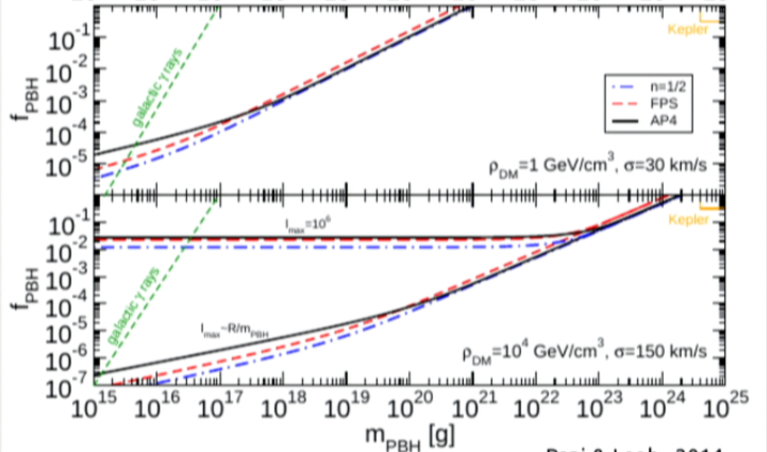
- If n<1 → dominant energy loss mechanism
- Depends on the NS composition → cohesive effect
- Similar result for different realistic EOS
- Requires compact stars and a small PBH (no tidal disruption)

Tidal capture of PBHs by a NS

$$t_{\rm loss} \sim 2\pi \frac{m_{\rm PBH}}{\Delta E}\sqrt{M r^0_{\rm max}} \longrightarrow m_{\rm PBH} \gtrsim 10^{16}\left(\frac{10^6}{l_{\rm max}}\right)^{1/2}\left(\frac{M}{1.4M_\odot}\right)^{2/3}\left(\frac{R}{12{\rm km}}\right)\,{\rm g}$$

capture time scale

Capture rate: $$F = \sqrt{6\pi}\frac{\rho_{\rm PBH}}{m_{\rm PBH}}\frac{2MR}{\sigma(1-2M/R)}\left[1-e^{-\frac{3\Delta E}{m_{\rm PBH}\sigma^2}}\right]$$ [Kouvaris 2007]



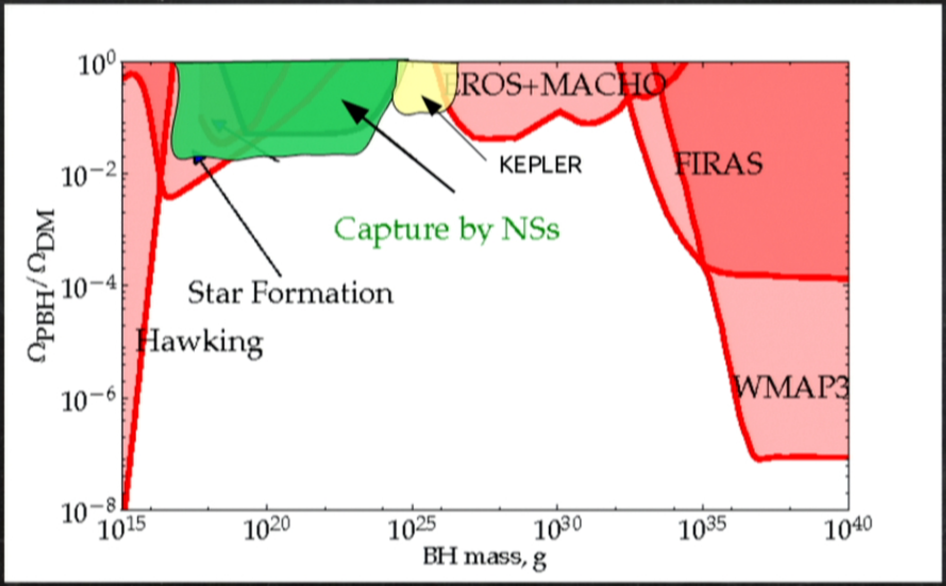
Pani & Loeb, 2014

$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}$$

DM fraction in PBHs

New constraints on DM PBHs

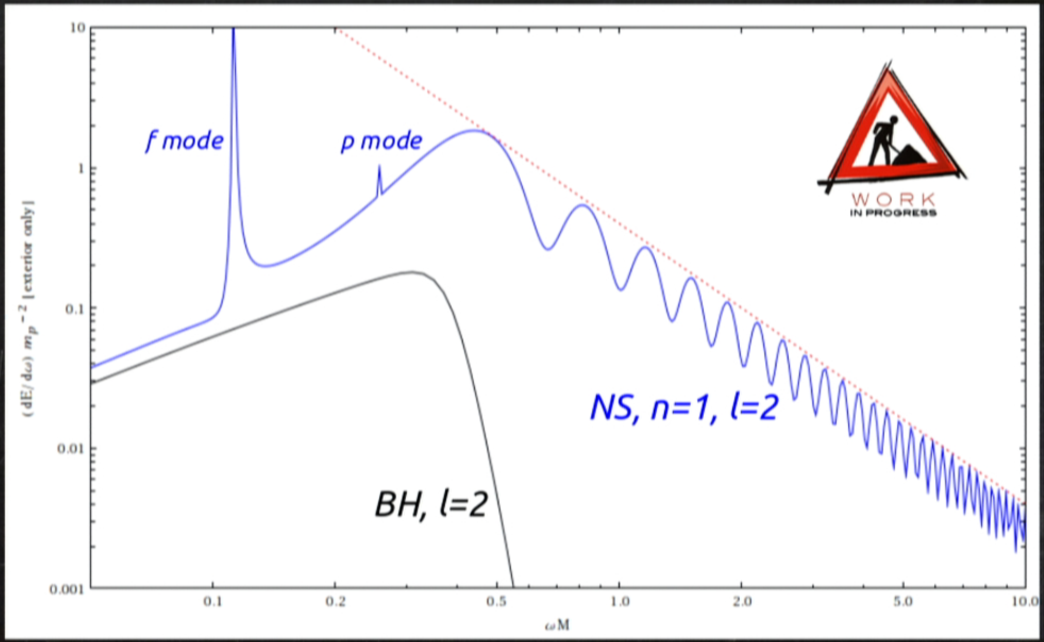
Pani & Loeb , 2014

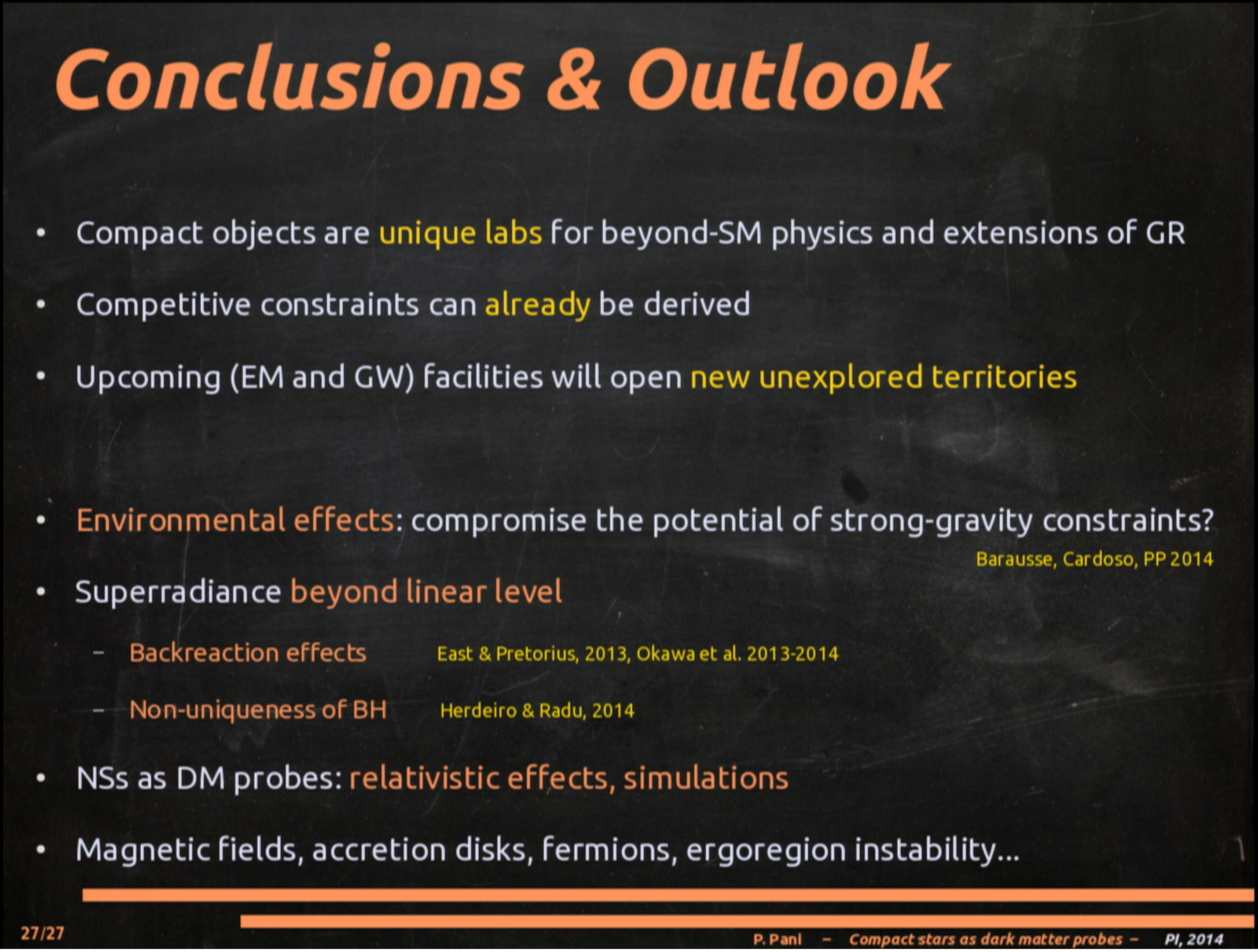


Adapted from Capela et al., PRD 2013

A very unlikely gravitational solution to a gravitational problem

Relativistic analysis

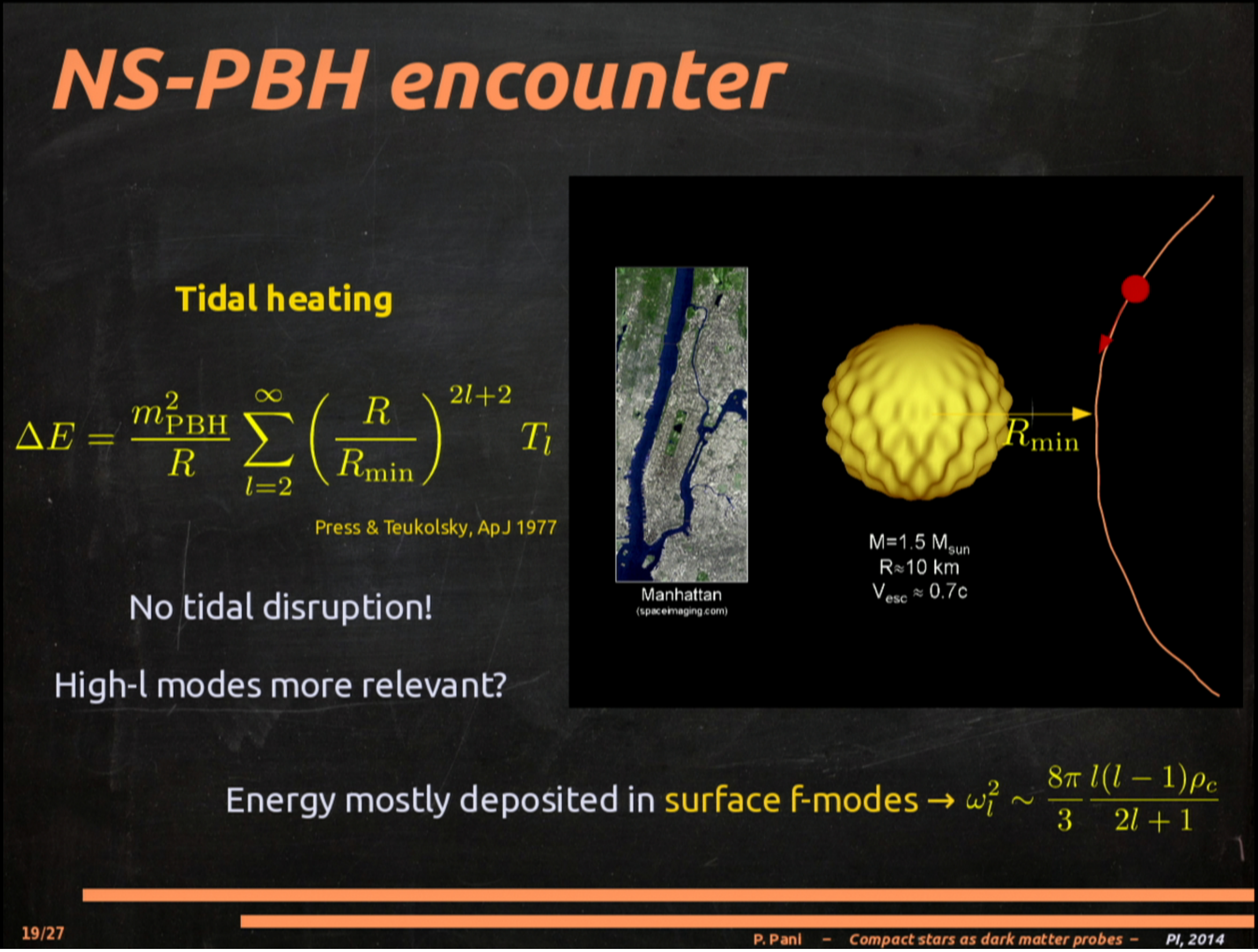




Conclusions & Outlook

- Compact objects are unique labs for beyond-SM physics and extensions of GR
- Competitive constraints can already be derived
- Upcoming (EM and GW) facilities will open new unexplored territories

- Environmental effects: compromise the potential of strong-gravity constraints? Barausse, Cardoso, PP 2014
- Superradiance beyond linear level
  - Backreaction effects East & Pretorius, 2013, Okawa et al. 2013-2014
  - Non-uniqueness of BH Herdeiro & Radu, 2014
- NSs as DM probes: relativistic effects, simulations
- Magnetic fields, accretion disks, fermions, ergoregion instability...



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Press & Teukolsky, ApJ 1977

No tidal disruption!

High-l modes more relevant?

Manhattan
(spaceimaging.com)

M=1.5 $M_{\rm sun}$
$R \approx 10$ km
$V_{\rm esc} \approx 0.7c$

$R_{\rm min}$

Energy mostly deposited in surface f-modes → $\omega_l^2 \sim \frac{8\pi}{3}\frac{l(l-1)\rho_c}{2l+1}$