University of Cagliari, June 20, 2016

Compact Objects as Dark-Matter Probes

Phys.Rev. D92 (2015) 12, 123530, Lect.Notes Phys. 906 (2015), Phys.Rev. D88 (2013) 2, 023514,

Astrophys.J. 774 (2013) 48, Phys.Rev. D88 (2013) 041301, Phys.Rev.Lett. 109 (2012) 131102, … + work in progress

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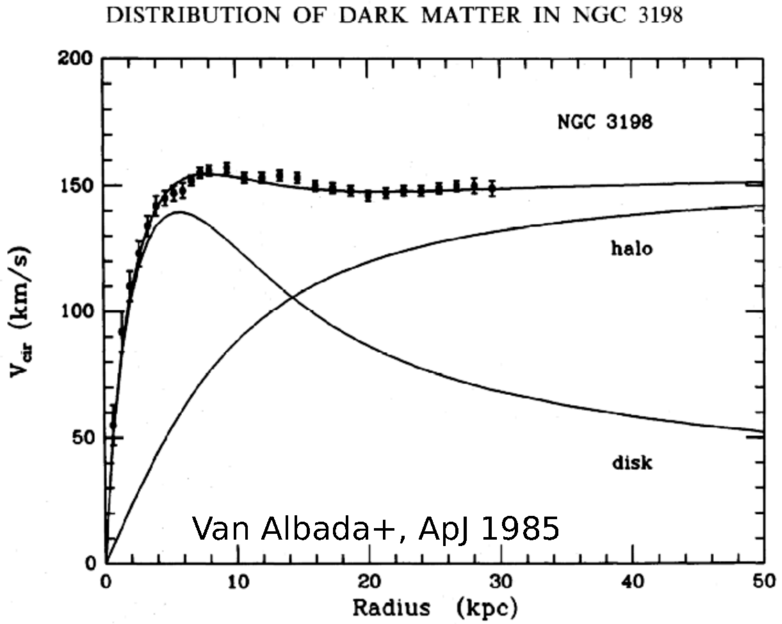
The Dark-Matter (DM) Problem



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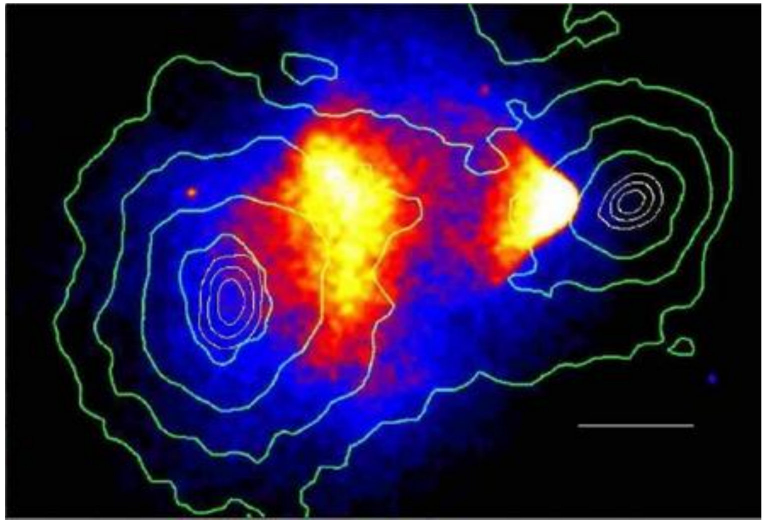
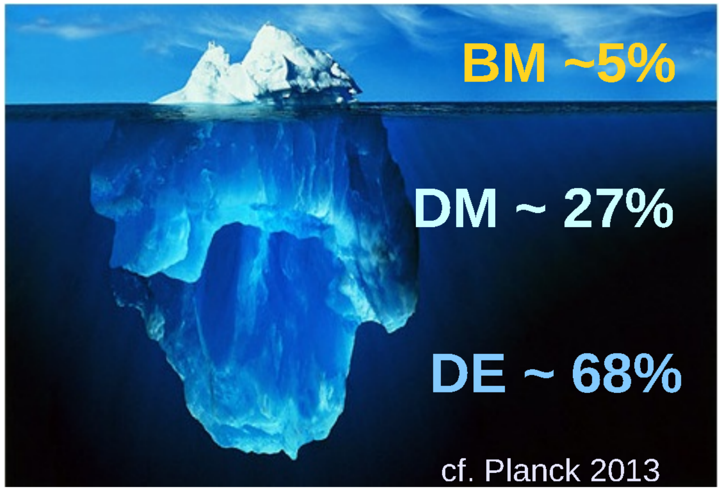
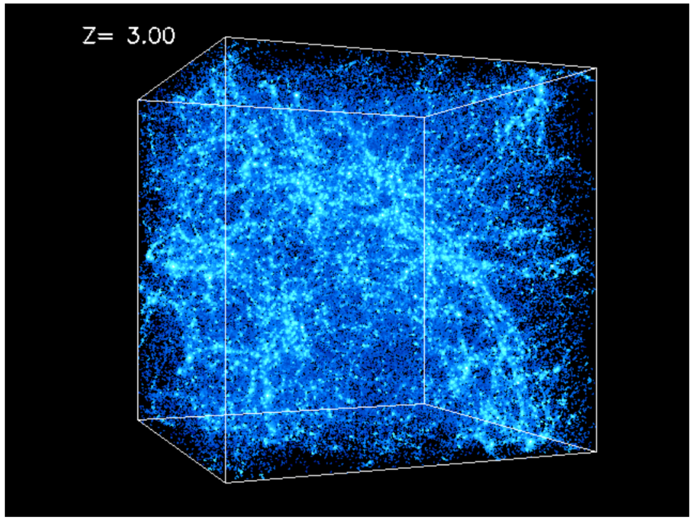


- **Weak leansing**



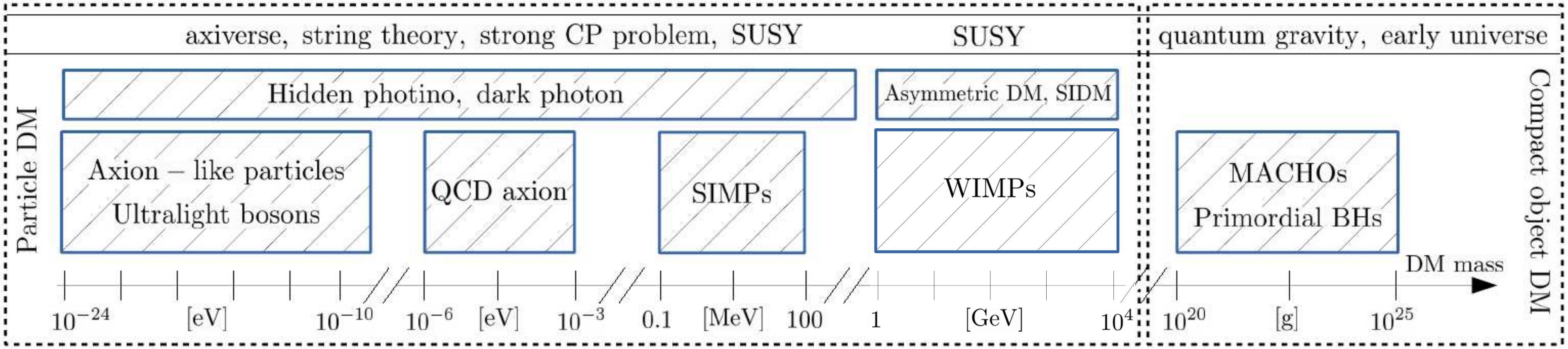
- **Cosmology**



- **Structure formation**

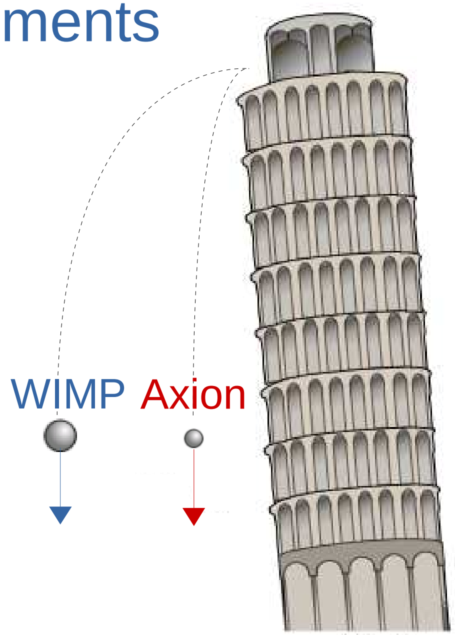
The DM candidate problem

- What's the nature of DM? Each experiment focuses on a specific candidate



- Problems: constraint DM spectrum, interface with experiments

  - Stronghold: DM (only?) gravitates
  - Equivalence principle → gravity is universal
  - Model-independent tests of DM?
  - Complementary to direct searches



Outline

- What I will discuss
  - Binary pulsars as dark-matter (DM) probes
  - Constraints on ultralight bosons from black-hole (BH) superradiance
  - Constraints on primordial black holes (PBHs)

- What I will NOT discuss
  - DM accretion in neutron stars (NSs) and white dwarfs
  - DM-triggered gravitational collapse inside NSs

[Bertone & Fairbairn, Phys. Rev. D77 (2008) 043515, Kouvaris & Tinyakov, Phys. Rev. D82 (2010) 063531, …]

Part I
Binary pulsars as DM probes

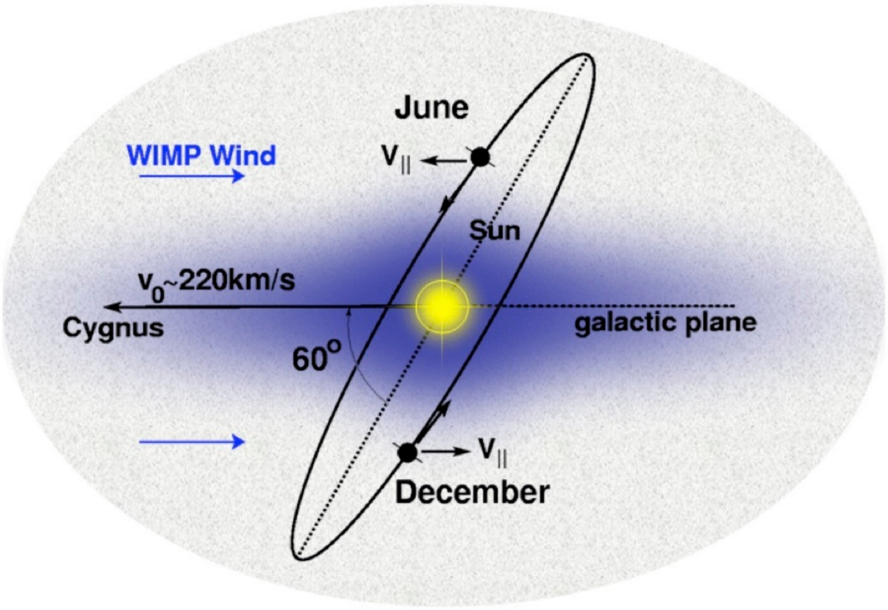
based on

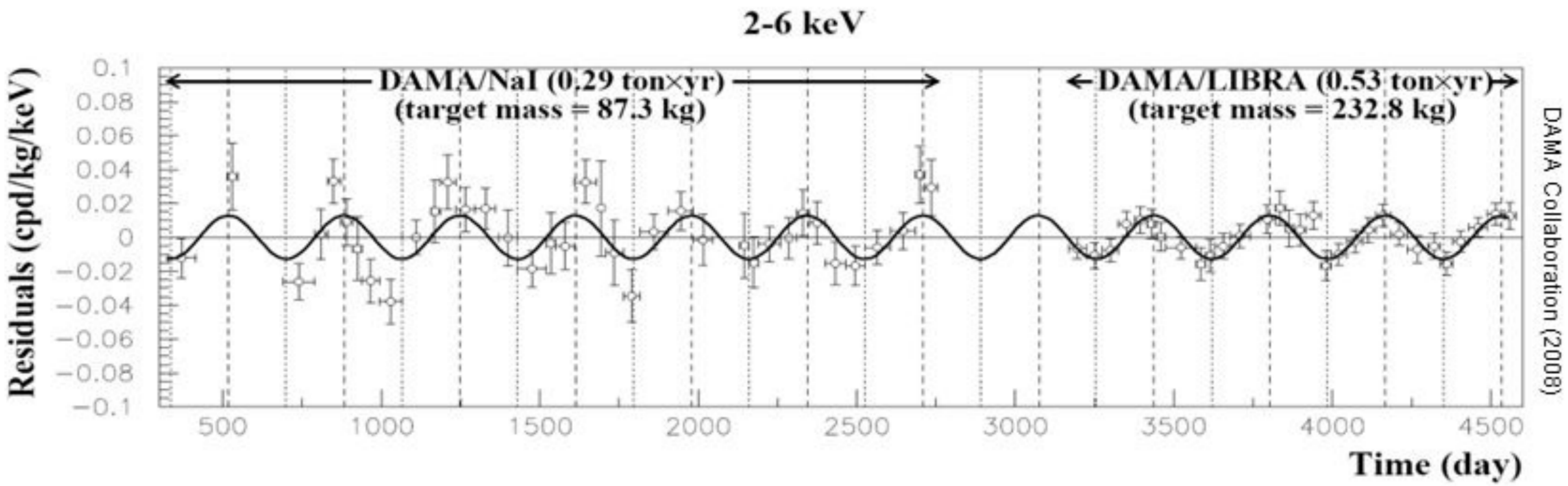
PP, *Phys.Rev. D92 (2015) 12, 123530*

DM "monsoons" on Earth

[Drukier, Freese, Spergel, Phys.Rev. D33 (1986) 3495-3508, Freese Rev. Mod. Phys. 85, 1561 2013]

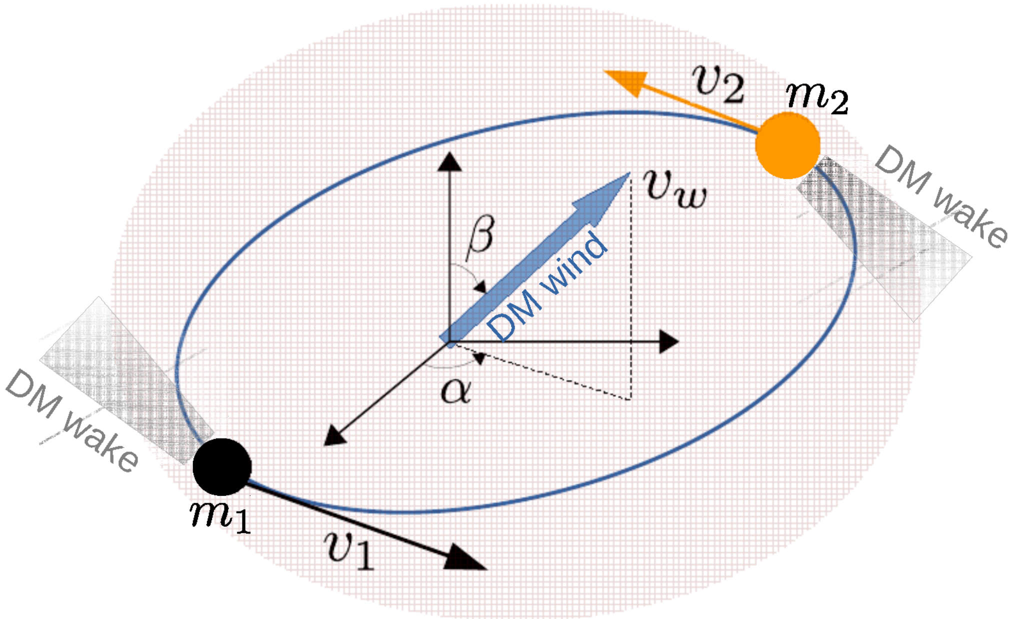
- Seasonal modulation
- Depends on DM distribution
- Velocity dependence

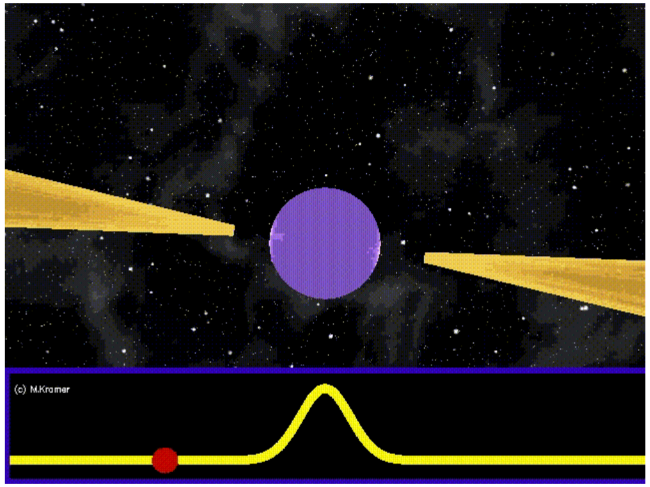




DM monsoons in pulsar binaries

$$m_i \ddot{\mathbf{r}}_i = \pm \frac{G m_1 m_2}{r^3} \mathbf{r} + \mathbf{F}_i^{\rm ext}$$





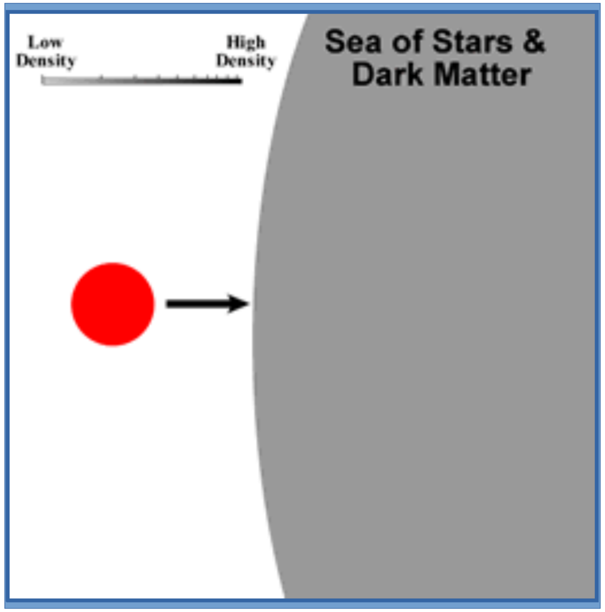
$$\mathbf{F}_i^{\rm DF} = -A b_i \frac{m_i^2}{M} \tilde{\mathbf{v}}_i \qquad \tilde{\mathbf{v}}_i = \dot{\mathbf{r}}_i + \mathbf{v}_w$$

$$\dot{\mathbf{v}} = -\frac{GM}{r^3}\mathbf{r} + a_1 \eta \mathbf{v} + a_2 \left(\mathbf{v}_w + \mathbf{V}\right) \qquad \dot{\mathbf{V}} = a_2 \eta \mathbf{v} + a_3 \left(\mathbf{v}_w + \mathbf{V}\right)$$

Dynamical friction

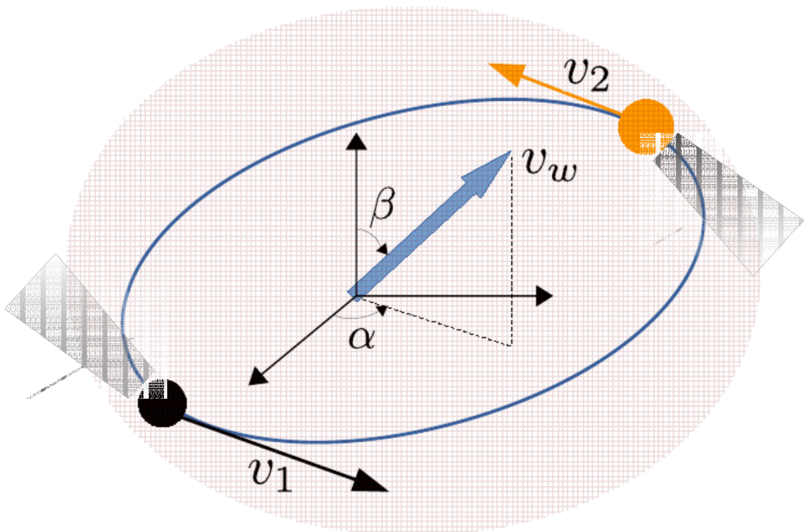
Chandrasekhar, 1940s, Binney & Tremain, “Galactic Dynamics”, 1987

$$\mathbf{F}_i^{\rm DF} = -4\pi\rho_{\rm DM}\lambda\frac{G^2 m_i^2}{\tilde{v}_i^3}\left(\mathrm{erf}\,(x_i) - \frac{2x_i}{\sqrt{\pi}}e^{-x_i^2}\right)\tilde{\mathbf{v}}_i,$$



- Linear motion, collisionless medium
- Approximate for binary systems:

Bekenstein & Zamir, ApJ 1990



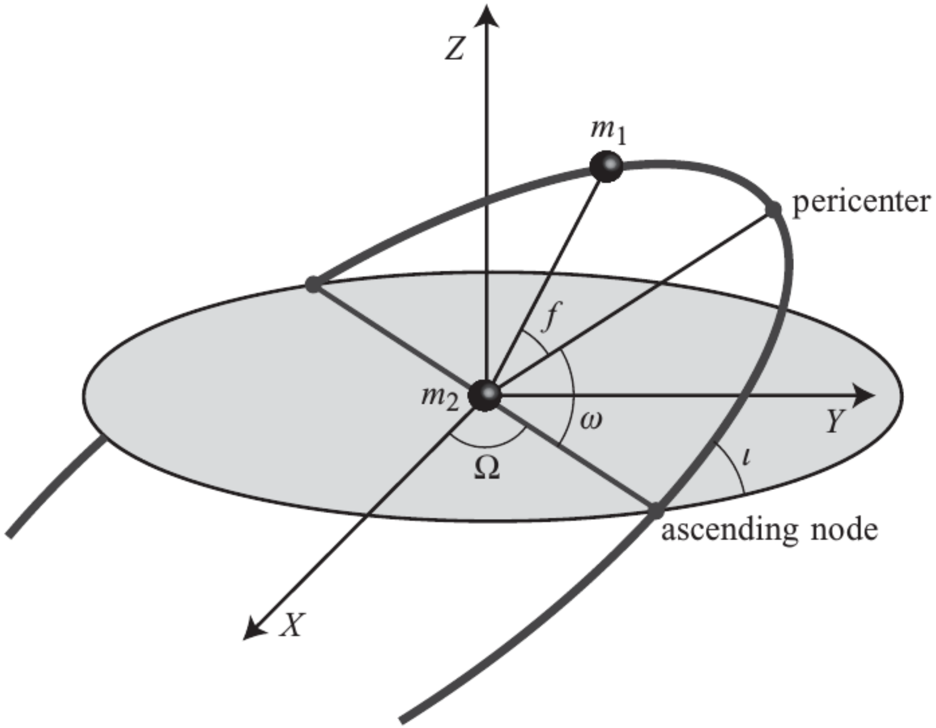
$$\frac{d\mathbf{v}}{dt} \sim -4\pi\frac{G^2(m_1+m_{\rm DM})m_{\rm DM}}{v^3}\mathbf{v} \times \left[\log(qv^2)\underbrace{\int_0^v d^3u f(u)}_{\text{Slow perturbers}} + \frac{2}{3}v^3\underbrace{\int_v^\infty d^3u\frac{f(u)}{u^3}}_{\text{Fast perturbers}}\right]$$

$$P_b \gg \frac{Gm_i}{\sigma^3} \sim 0.6\left(\frac{m_i}{1.3\,M_\odot}\right)\left(\frac{150\,\mathrm{km/s}}{\sigma}\right)^3\,\mathrm{day}$$

Perturbed Newtonian dynamics

e.g. Poisson & Will "Gravity", 2014

$$\dot{\mathbf{v}} = -\frac{GM}{r^3}\mathbf{r} + a_1\eta\mathbf{v} + a_2\left(\mathbf{v}_w + \mathbf{V}\right) \qquad \dot{\mathbf{V}} = a_2\eta\mathbf{v} + a_3\left(\mathbf{v}_w + \mathbf{V}\right)$$



- Osculating orbits:

$$\dot{a} = 2\sqrt{\frac{r_0^3}{GM}}\mathcal{S}(t)\,,$$

$$\dot{e} = \sqrt{\frac{r_0}{GM}}\left[\mathcal{R}(t)\sin\Omega_0 t + 2\mathcal{S}(t)\cos\Omega_0 t\right]\,,$$

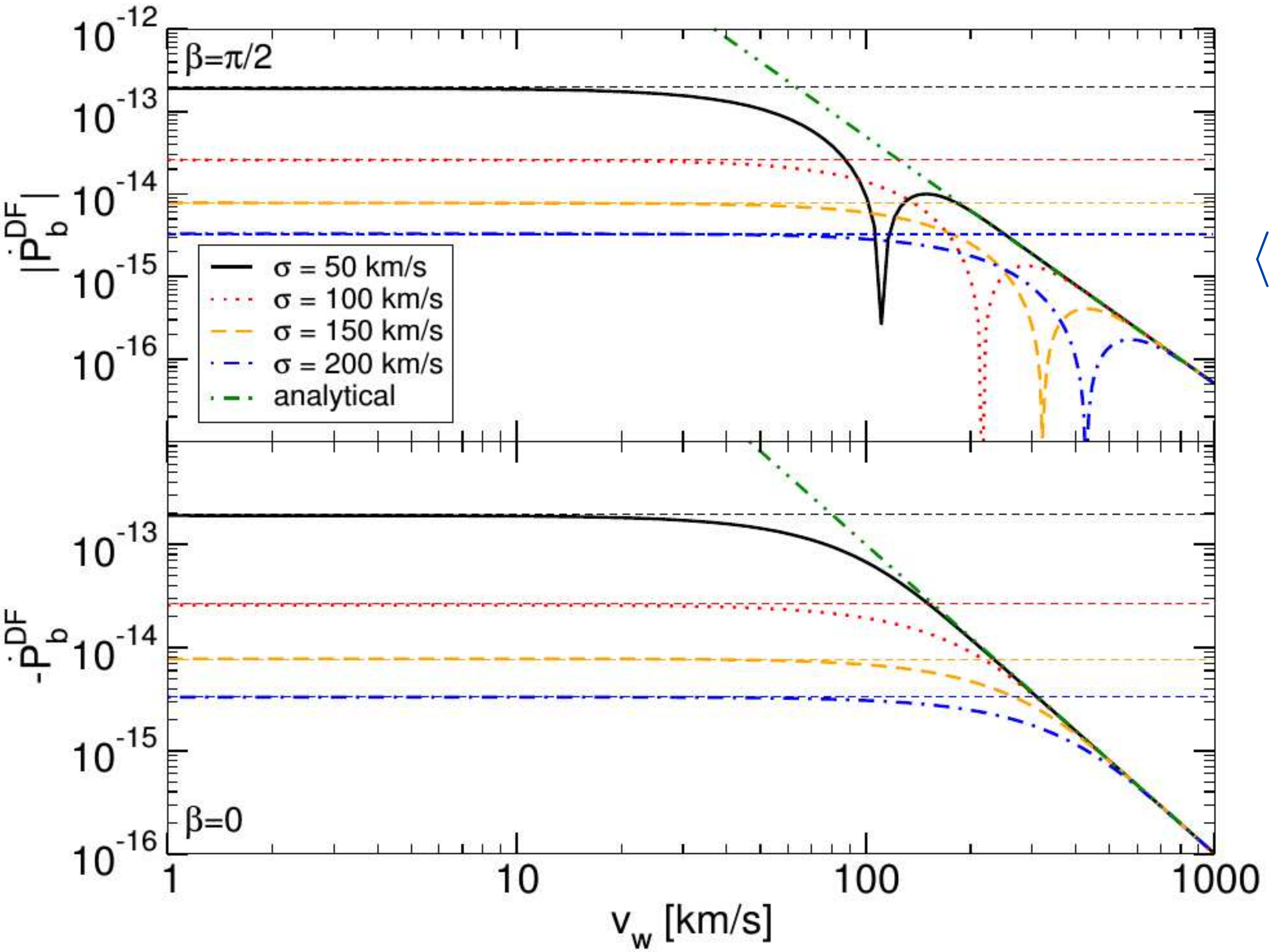
$$\dot{\iota} = \sqrt{\frac{r_0}{GM}}\mathcal{W}(t)\cos(\Omega_0 t + \omega)\,,$$

$$\dot{\Omega} = \frac{1}{\sin\iota}\sqrt{\frac{r_0}{GM}}\mathcal{W}(t)\sin(\Omega_0 t + \omega)\,,$$

$$\mathcal{R} := \mathbf{f}\cdot\mathbf{n} \quad \mathcal{S} := \mathbf{f}\cdot\lambda \quad \mathcal{W} := \mathbf{f}\cdot\mathbf{e}_z$$

- Secular changes: $\langle X\rangle := P_b^{-1}\int_0^{P_b} dt X(t)$

Secular changes of the orbital period



$$\langle \dot{P}_b^{\rm DM} \rangle = f(m_i, P_b, v_w, \alpha, \beta, \sigma)$$

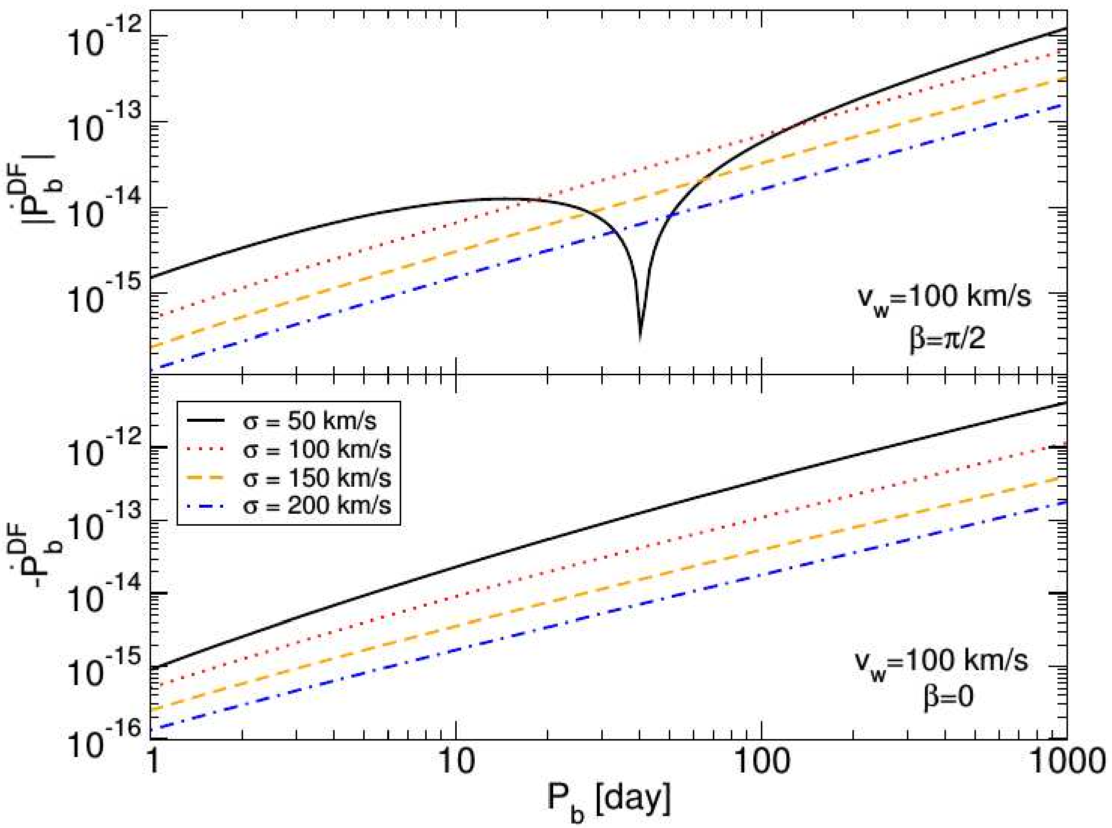
$$\langle \dot{P}_b^{\rm DF} \rangle \sim -8\sqrt{2\pi} G^2 \frac{\mu \lambda \rho_{\rm DM} P_b}{\sigma^3}$$

in the large-sigma limit

[Gould 1991]

$$\langle \dot{P}_b^{\rm DF} \rangle \approx -3\times 10^{-14} \left(\frac{\lambda}{20}\right)\left(\frac{\mu}{M_\odot}\right)\left(\frac{\rho_{\rm DM}}{2\times 10^3\,{\rm GeV/cm}^3}\right)\left(\frac{P_b}{100\,{\rm day}}\right)\left(\frac{150\,{\rm km/s}}{\sigma}\right)^3$$

Secular changes of the orbital period



Other contributions:

$$\dot{P}_b^{\rm cm} = P_b \dot{\mathbf{V}} \cdot \mathbf{e}_Z$$

Center-of-mass acceleration

$$\dot{P}_b^{\iota} = \frac{3}{2} \tan \iota P_b \dot{i}$$

Apparent change due to inclination

$$55^\circ \lesssim \beta \lesssim 125^\circ \Rightarrow \langle \dot{P}_b^{\rm DF} \rangle > 0$$

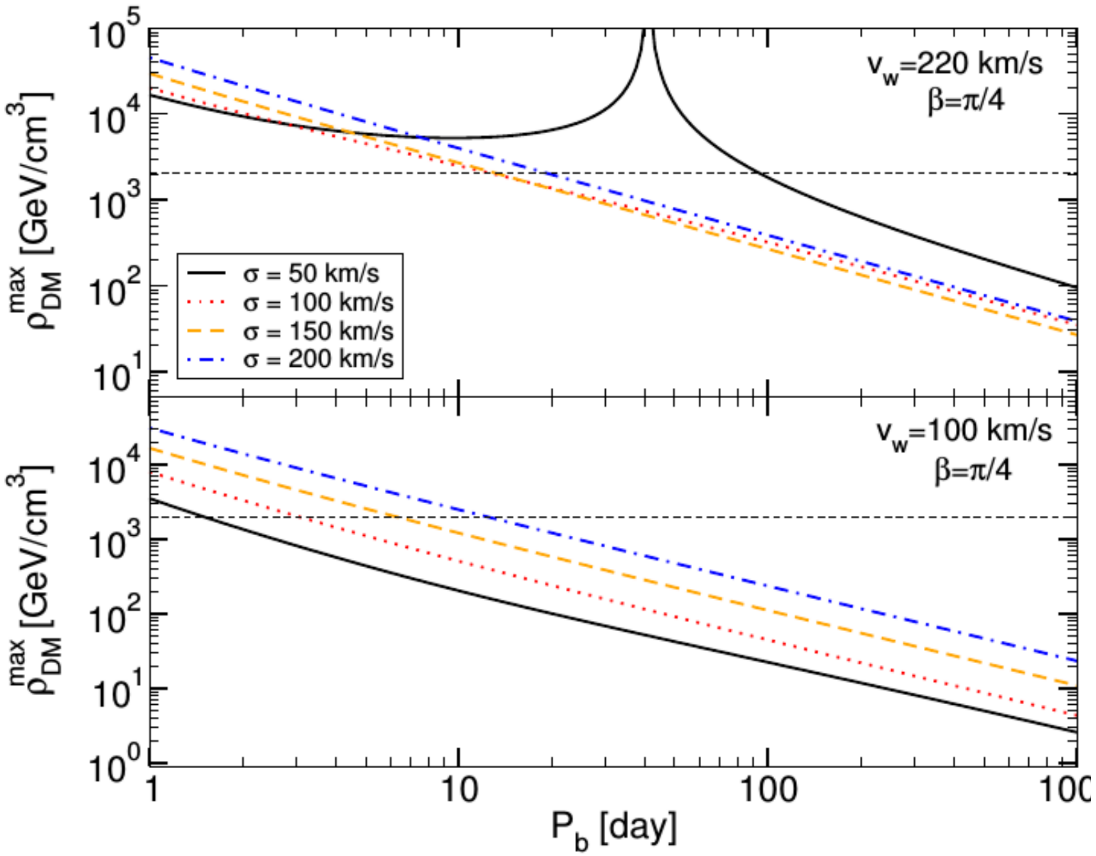
Violation of Heggie's law

"Hard binaries ($E_b \gg m_{\rm DM}\sigma^2$) get harder, soft binaries get softer"

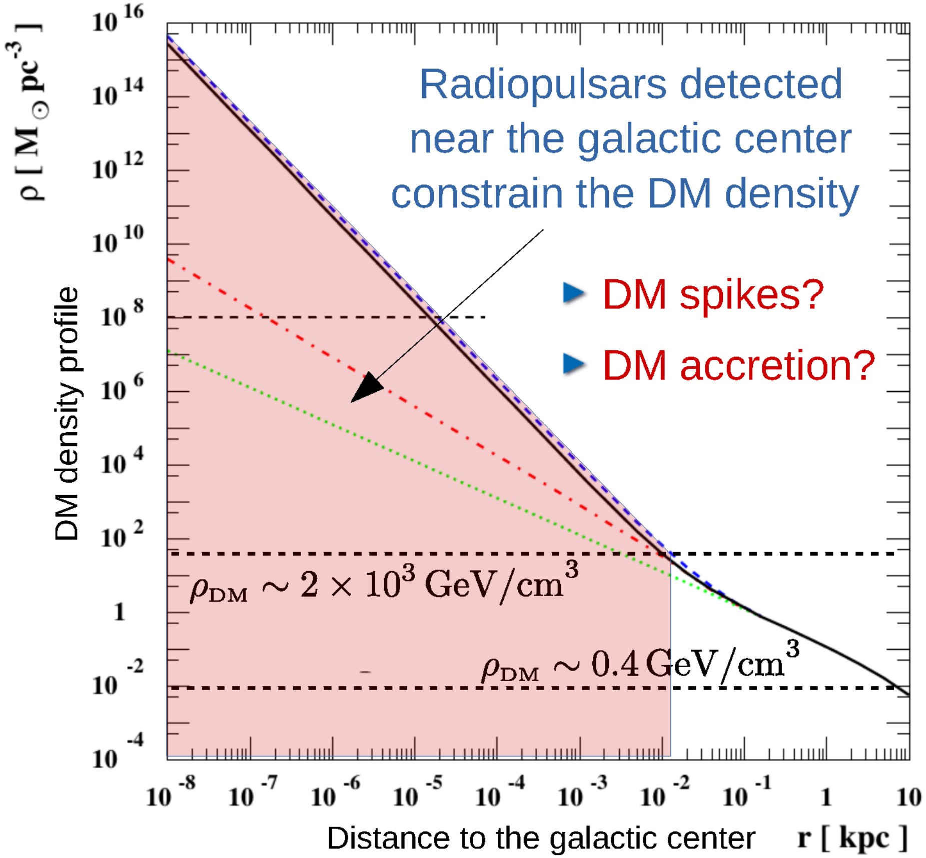
[Heggie 1975]

Probing DM with pulsar timing

$$|\langle \dot{P}_b^{\rm DF} + \dot{P}_b^{\rm cm} + \dot{P}_b^{\iota}\rangle| \lesssim \dot{P}_b^{\rm xs} \Rightarrow \rho_{\rm DM} < \rho_{\rm DM}^{\rm max}$$



Navarro-Frenk-White profile



SKA will improve current sensitivity by 2 orders of magnitude!

Bounds on local DM density

$$\langle \dot{P}_b^{\rm DF} \rangle \approx -3 \times 10^{-14} \left(\frac{\rho_{\rm DM}}{2\times 10^3\,{\rm GeV/cm^3}} \right) \left(\frac{P_b}{100\,{\rm day}} \right) \left(\frac{150\,{\rm km/s}}{\sigma} \right)^3$$

J1738+0333

$$\langle \dot{P}_b^{\rm xs} \rangle \lesssim 2 \times 10^{-15}$$ [Freire+, 2012]

$$P_b \sim 0.3547907398724(13)\,{\rm day}$$

J1713+0747

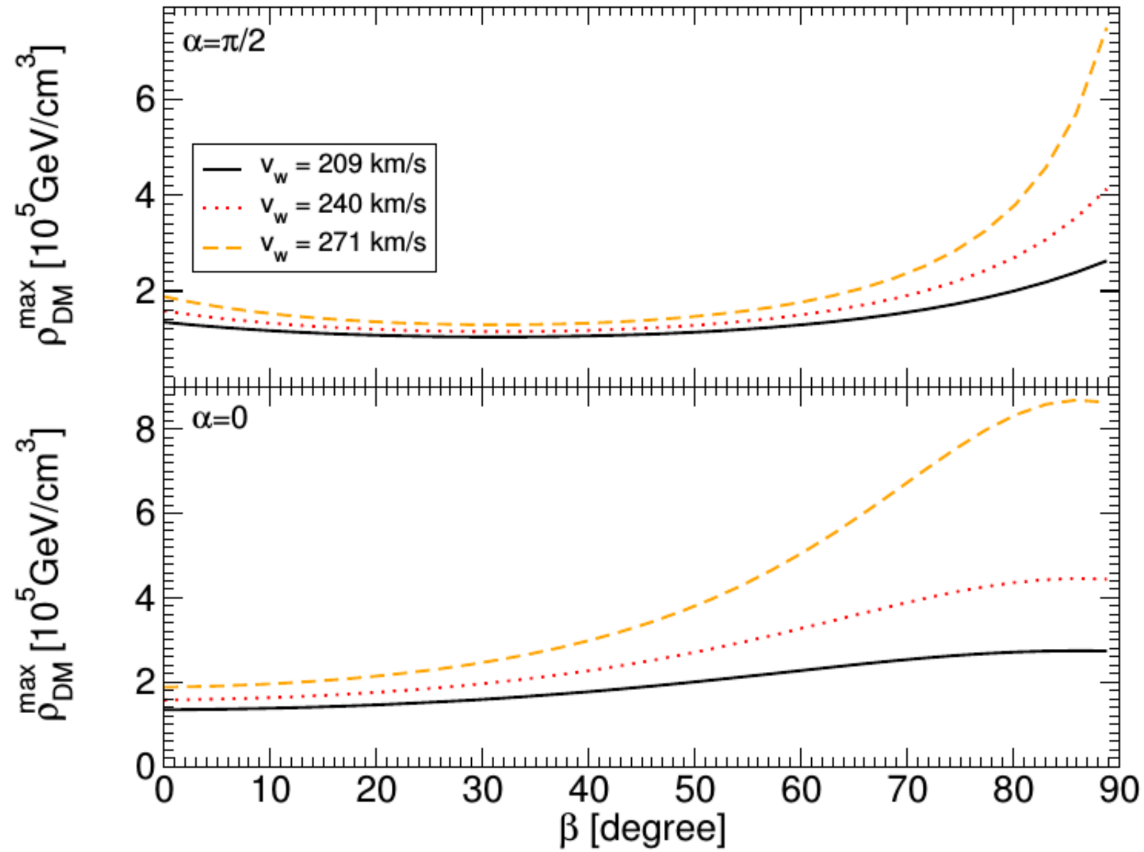
$$\langle \dot{P}_b^{\rm xs} \rangle \lesssim 2 \times 10^{-13}$$ [Zhu+, 2015]

$$P_b \sim 67.82513682426(16)\,{\rm day}$$

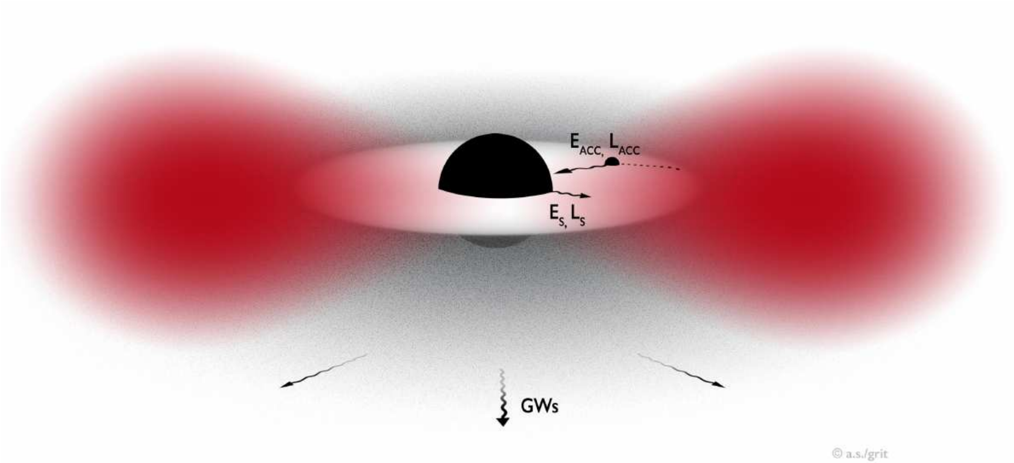
$$\dot{P}_b^{\rm GW} \approx -6 \times 10^{-18}$$

J1024−0719 → $P_b > 200\,{\rm yr}$

[Bassa+, 2016]



Part II
BHs as detectors of ultralight particles



R. Brito, V. Cardoso, PP, *"Superradiance"*

Springer's Lect.Notes Phys. 906 (2015)

arXiv:1501.06570

Superradiant instability

Press & Teukolsky, 1972; Deruelle, Damour & Ruffini, Detweiler, Zouros & Eardley 1980s;...

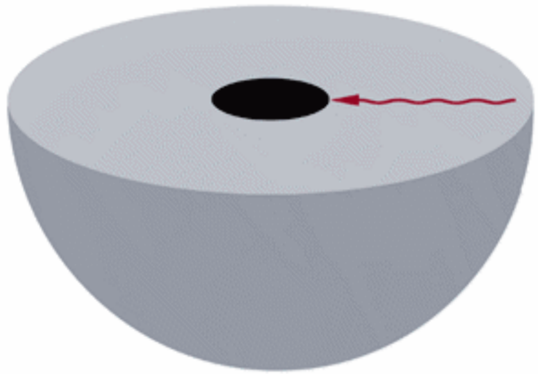
- Massive fields around spinning BHs are **unstable**
- $$\Box\phi - \frac{\mu^2 c^2}{\hbar^2}\phi = 0 \quad \Rightarrow \quad \phi \sim e^{t/\tau}$$

Formal proof:
[Shlapentokh-Rothman (2015)]

- Superradiant scattering off a Kerr BH when $\omega/m < \Omega_H$

Zeldovich, 1972

- Yukawa-type effective potential



Superradiance requires **dissipation,** depends on the **nature of the bosonic field**

$$\frac{G}{\hbar c}M\mu \sim \left(\frac{M}{M_\odot}\right)\left(\frac{\mu c^2}{10^{-8}\,\mathrm{eV}}\right)$$

Coupling parameter

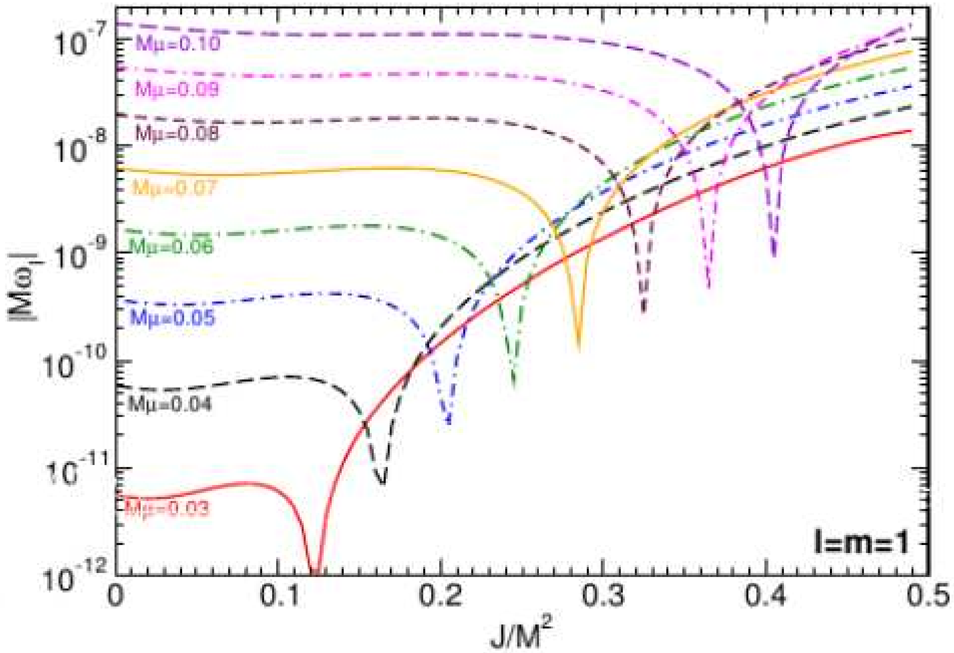
$$\frac{G}{\hbar c}\mu M \sim 1 \to \tau \sim 10^6 M \sim 0.1\left(\frac{M}{10^6 M_\odot}\right)\mathrm{yr}$$

for scalar fields

Instability of bosonic fields

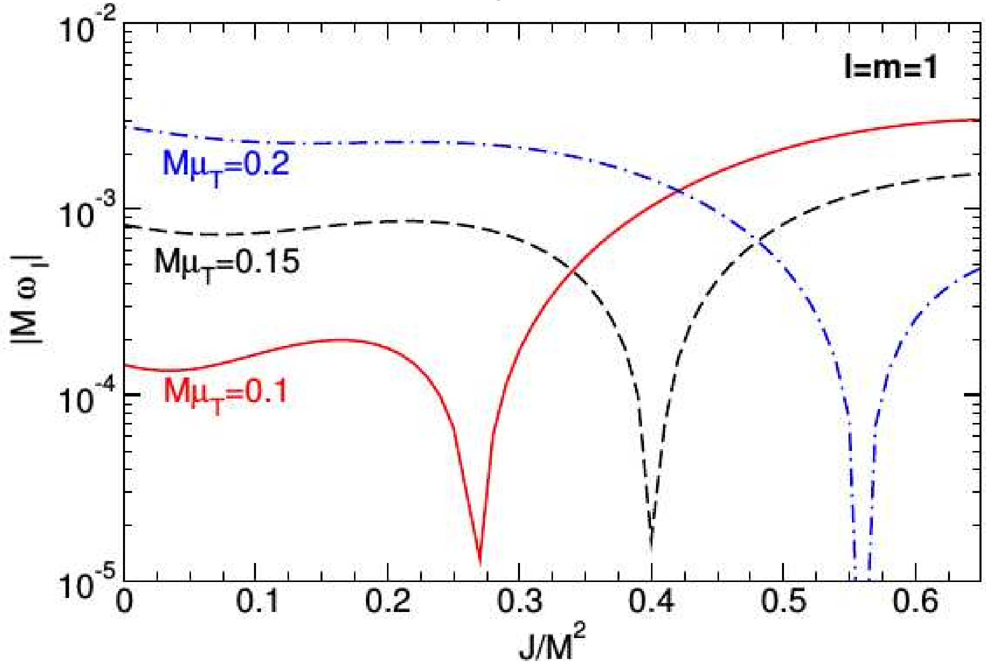
Proca field (massive spin-1)

Pani+, Phys.Rev.Lett. 109 (2012)



Massive spin-2

Brito, Cardoso, PP, Phys.Rev. D88 (2013) 2, 023514

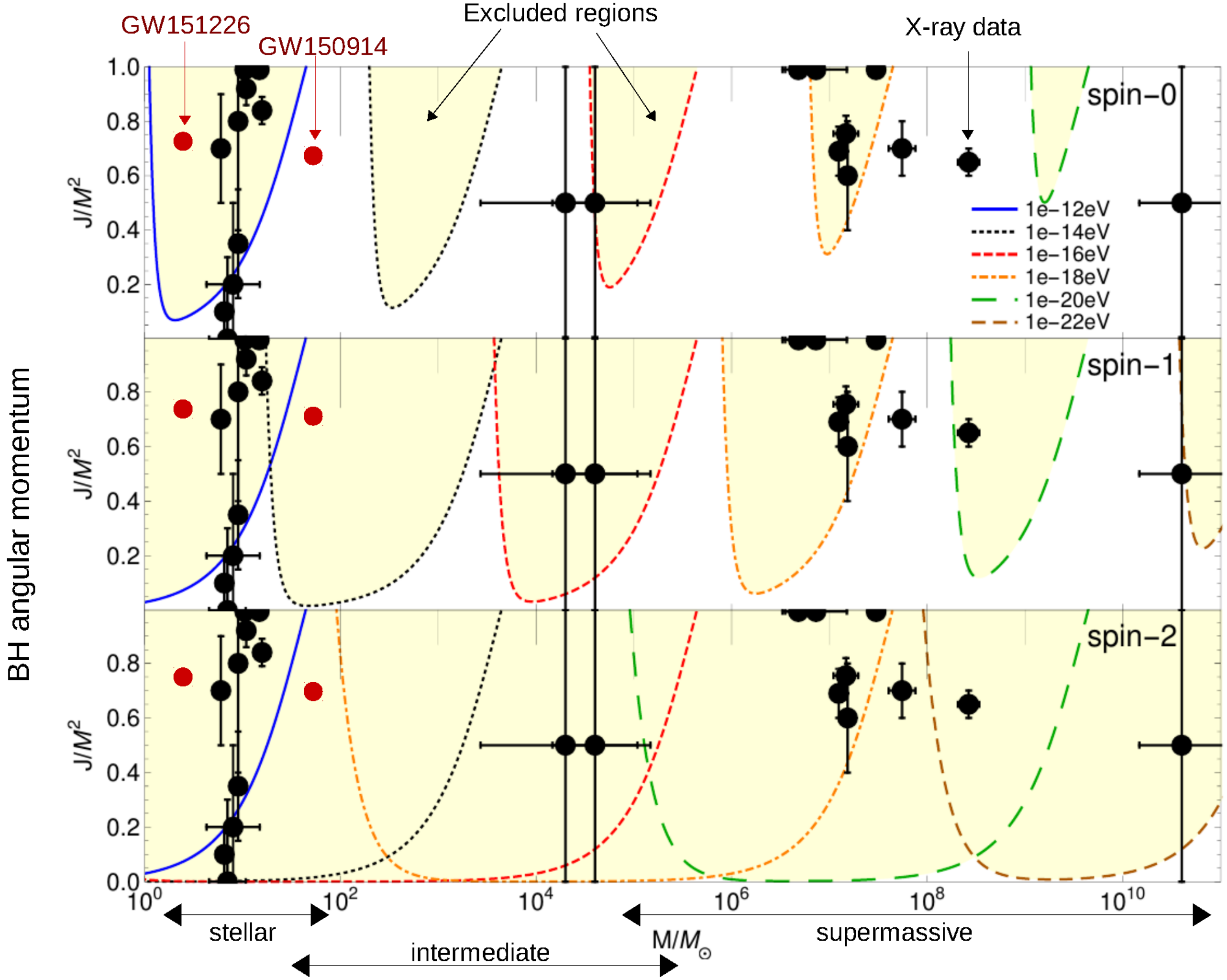


Strongest instability of a Kerr BH to date

$$\omega_R \sim \mu - \frac{\mu(M\mu)^2}{2(\ell+n+S+1)^2} \qquad \omega_I \sim -\left(\omega_R - m\Omega_H\right)(M\mu)^{4\ell+5+2S}$$

SlowRot approximation agrees well with exact numerical results   Witek+, Phys.Rev. D87 (2013) 043513

Bounds on light bosons



String axiverse
Arvanitaki+, '11-'14
QCD axion

Axion-like particles

Dark photons

Hidden U(1) sector

Massive photon

Massive spin-2

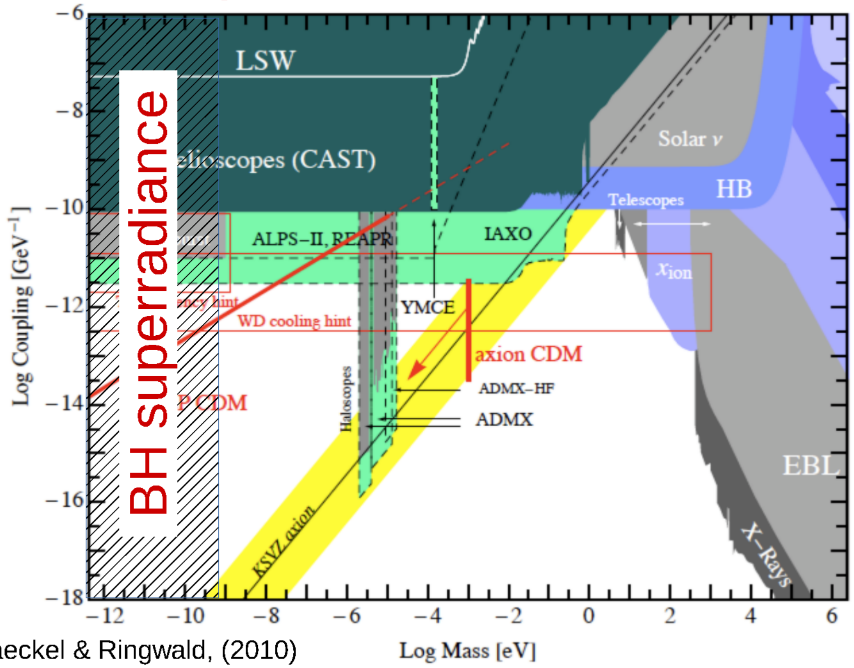
Massive graviton

If ultralight particles exist in nature → no highly-spinning BHs!

Bounds on ALPs and dark photons

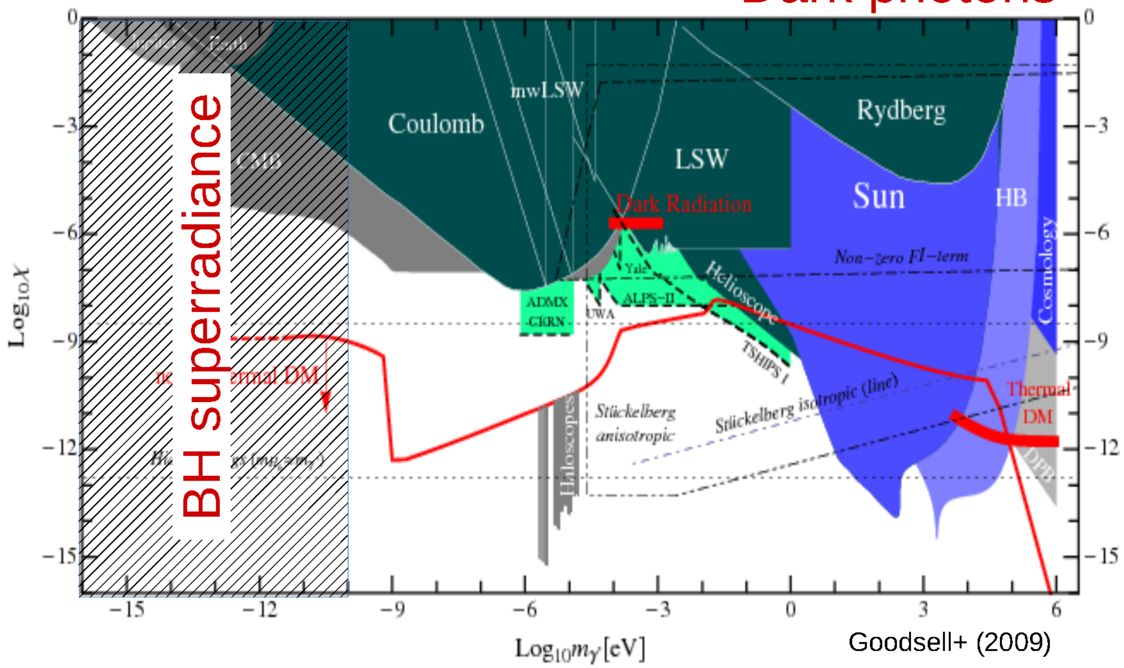
$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi G} - \frac{1}{4g_a}F^{(a)}_{\mu\nu}F^{\mu\nu}_{(a)} + \frac{1}{2}(\partial_\mu a\partial^\mu a - m_a^2 a^2) + \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}{}^*F^{\mu\nu} - \frac{1}{4g_b^2}F^{(b)}_{\mu\nu}F^{\mu\nu}_{(b)} + \frac{\chi_{ab}}{2g_a g_b}F^{(a)}_{\mu\nu}F^{(b)\mu\nu} + \frac{m_{ab}^2}{g_a g_b}A^{(a)}_\mu A^{(b)\mu}\right)$$

ALPs



Jaeckel & Ringwald, (2010)

Dark photons



Goodsell+ (2009)

- Preliminary bounds on dark photons [Pani+, Phys.Rev.Lett. 109 (2012) 131102]
- Constraints on graviton mass better than GW150914 [Brito+, Phys. Rev. D88 (2013) 023514]

Evolution of the instability

Brito, Cardoso, PP, 2015 Class. Quantum Grav. 32 134001

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi} - \frac{1}{2} g^{\mu\nu} \Psi^*_{,\mu} \Psi_{,\nu} - \frac{\mu^2}{2} \Psi^* \Psi \right)$$

- Separation of scales → adiabatic approximation
- Superradiance extraction → linearized analysis
- GW emission → quadrupole fails, relativistic computation
- Accretion of gas → Eddington accretion + geodesics

$$\dot{M} + \dot{M}_S = -\dot{E}_{\rm GW} + \dot{M}_{\rm accr}$$

$$\dot{J} + \dot{J}_S = -\dot{J}_{\rm GW} = -\frac{1}{\mu}\dot{E}_{\rm GW} + \dot{J}_{\rm accr}$$

$$\dot{M} = -\dot{E}_S + \dot{M}_{\rm accr} \qquad \dot{J} = -\frac{1}{\mu}\dot{E}_S + \dot{J}_{\rm accr}$$

$$\dot{E}_{\rm GW} \sim (M\mu)^{14} \left[M_{\rm S}/M\right]^2$$

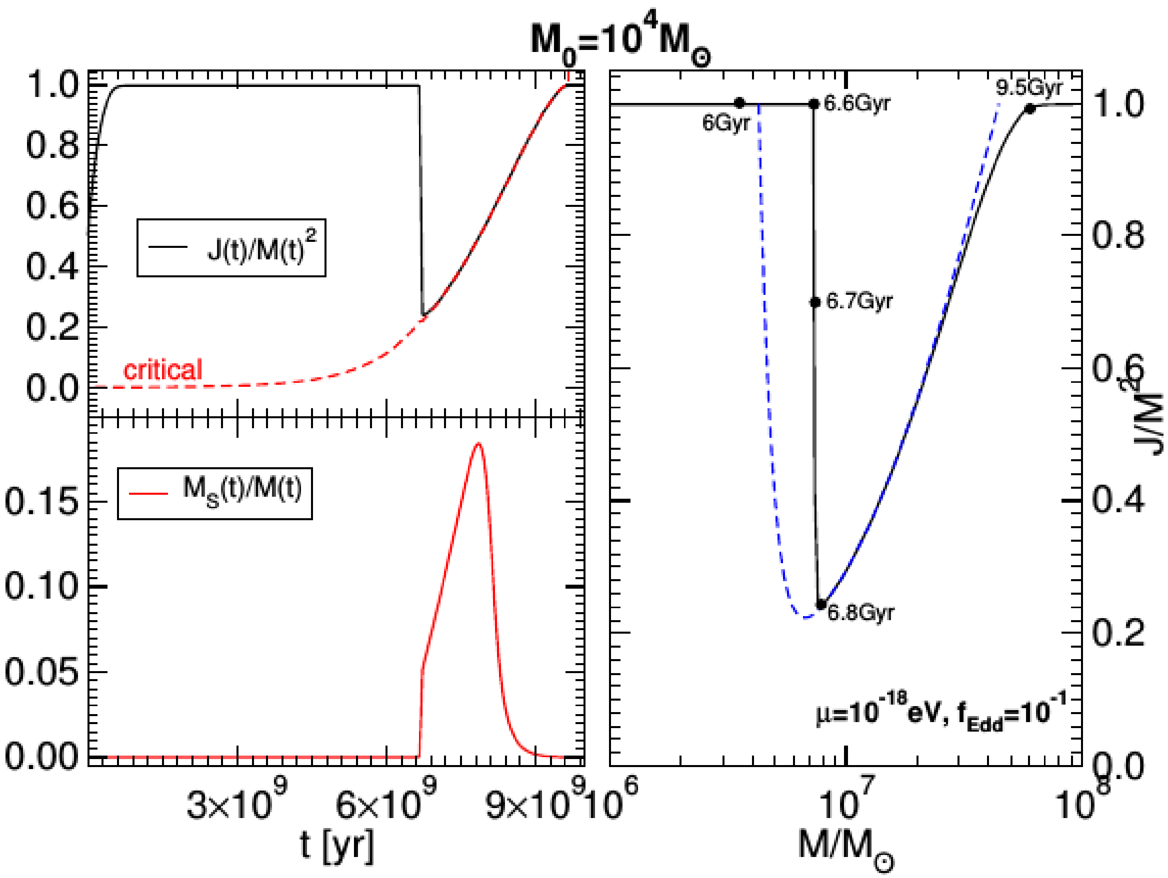
Yoshino & Kodama, PTEP 2014 (2014) 043E02

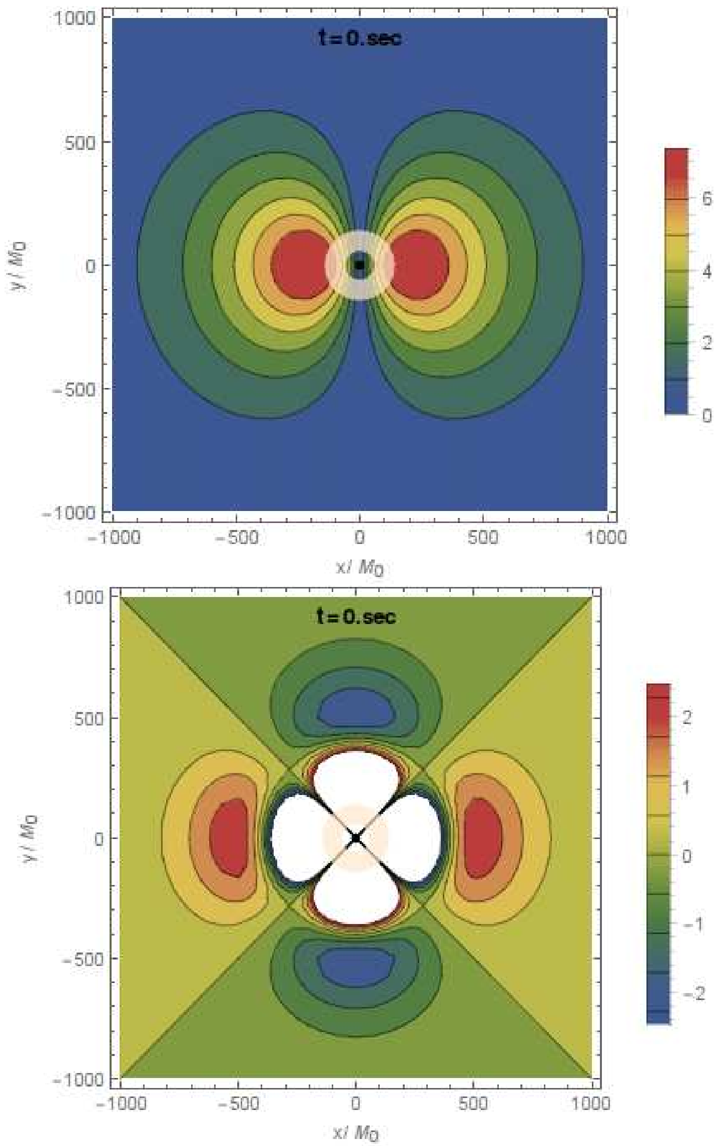
$$\dot{M}_{\rm accr} \sim 0.02 f_{\rm Edd} \frac{M}{10^6 M_\odot} M_\odot {\rm yr}^{-1}$$

Barausse, Cardoso, PP, Phys.Rev. D89 (2014) 104059

Evolution of the instability

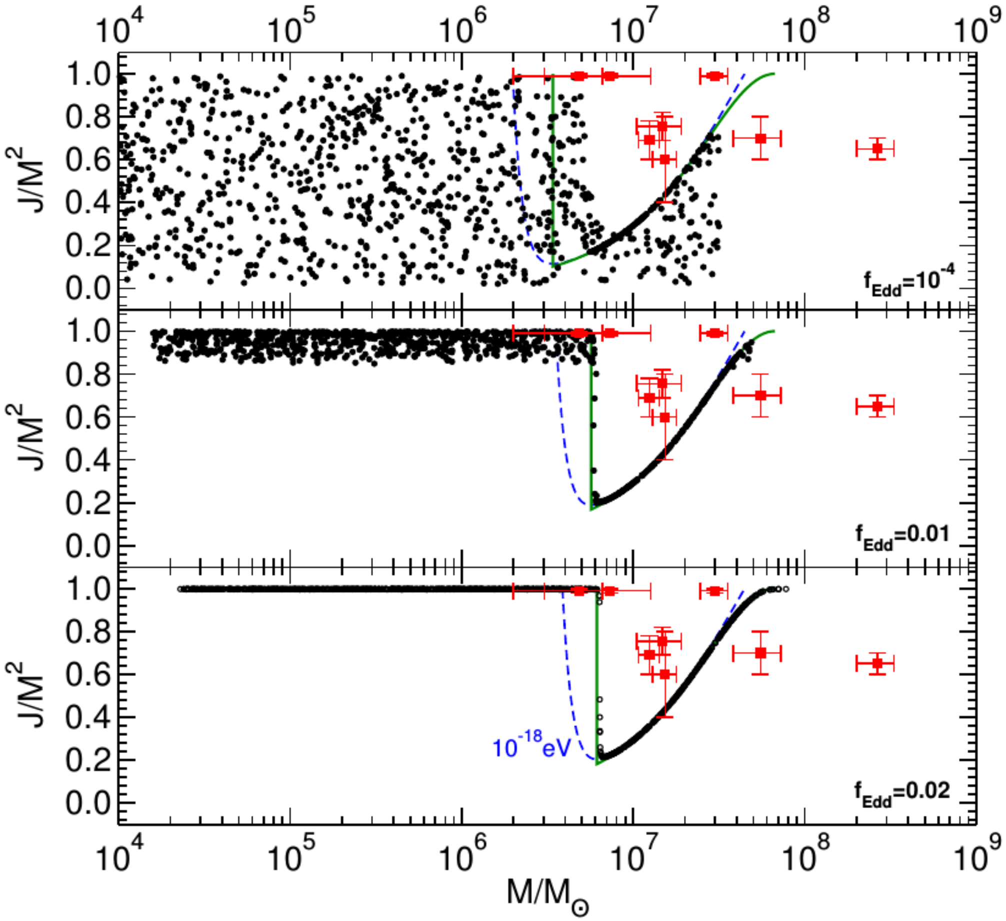
Brito, Cardoso, PP, 2015 Class. Quantum Grav. 32 134001



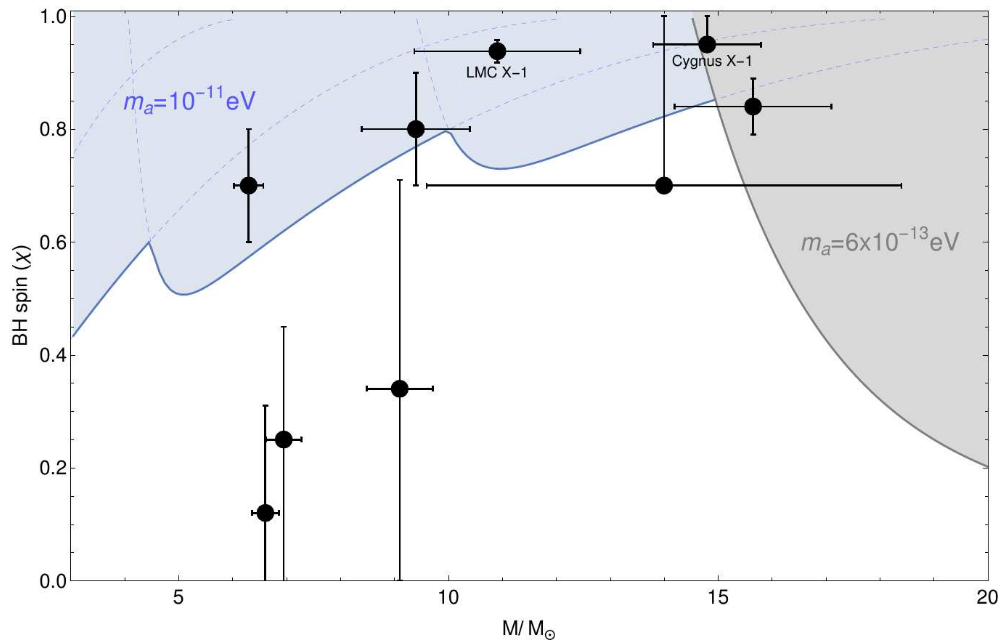


Evolution of the instability

supermassive BHs



solar-mass BHs

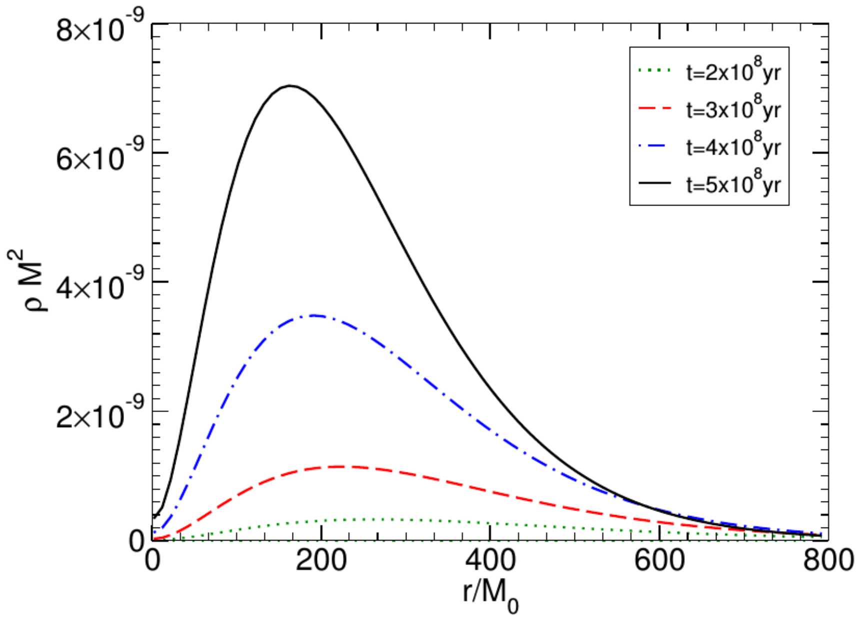


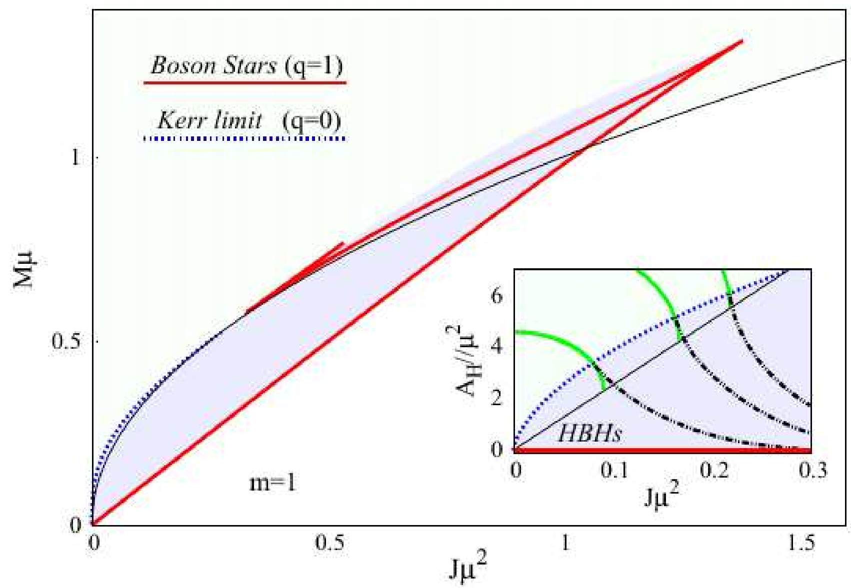
Work in progress with Matt Middleton, 2016

Generic prediction: “holes” in the Regge plane

Arvanitaki+, Phys.Rev. D83 (2011) 044026

BHs and bosonic clouds





Herdeiro & Radu, PRL 112 (2014) 221101

- Complex fields → stationary hairy BHs, formation mechanism?
- Real fields → spontaneously formed ultralong-lived states
- Backreaction is negligible → Kerr metric
  - No EM signature, but various GW signals

    Arvanitaki, Baryakhtar, Huang, PRD 91, 084011 (2015)

    Yoshino & Kodama CQG 32 (2015) 21, 214001

Part III
Primordial BH bombs

based on

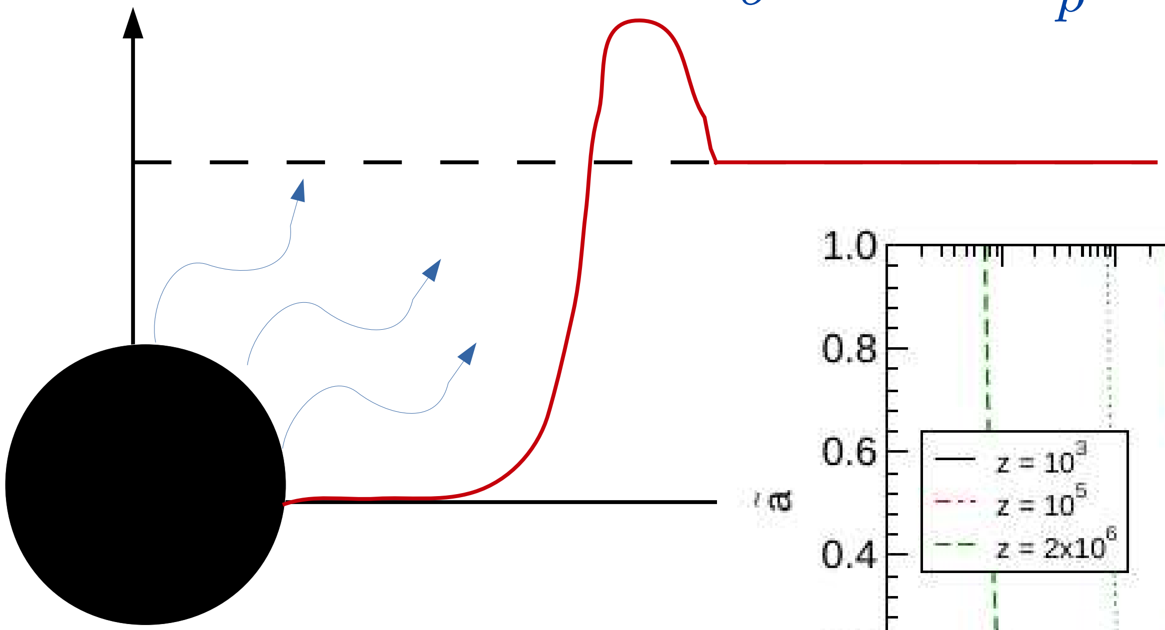
PP & Loeb, Phys.Rev. D88 (2013) 041301

Primordial BH bombs

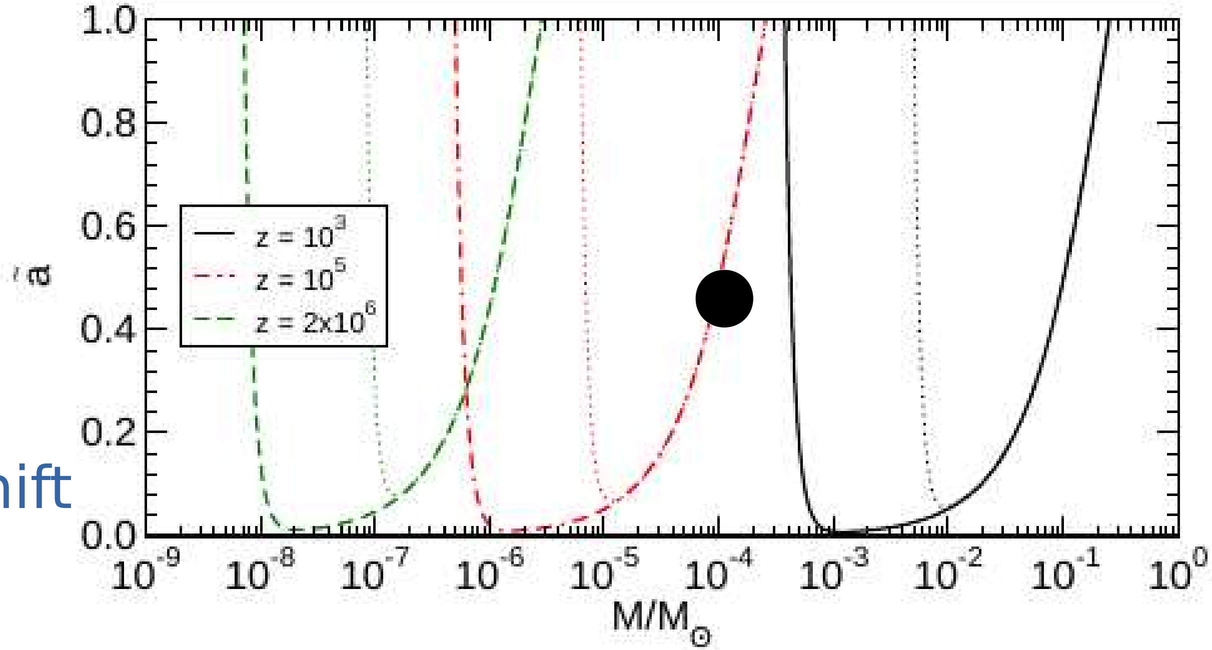
$$\nabla_\sigma F^{\sigma\nu} = \omega_p^2 A^\nu$$

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

Plasma frequency



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

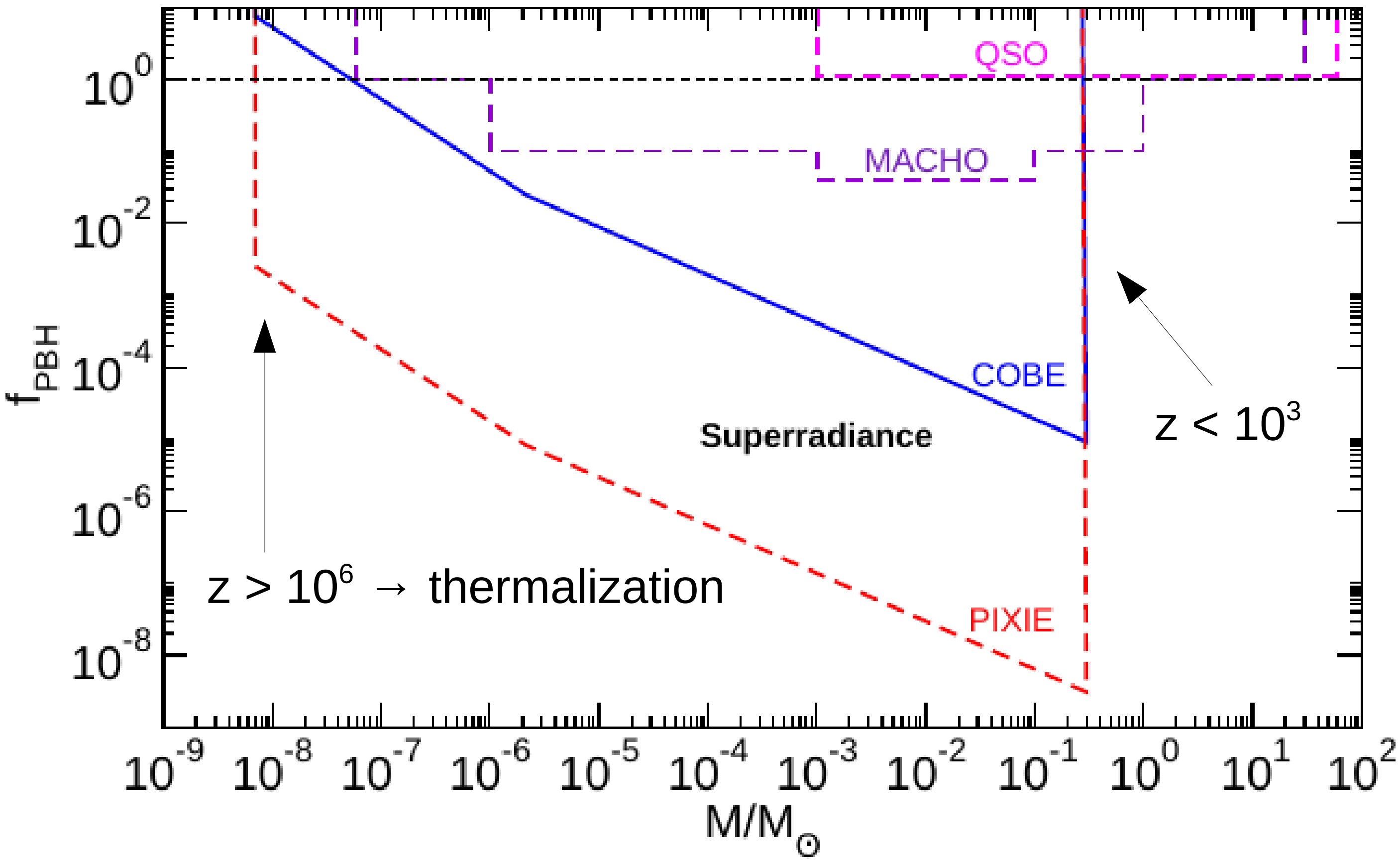


- Instability at different redshift

$$\frac{\Delta M}{M} \approx \frac{\tilde{a} M \omega_R}{1-2\tilde{a}M\omega_R} \approx 10^{-3}\left(\frac{1+z}{10^3}\right)^{3/2}\left(\frac{\tilde{a}M}{10^{-3}M_\odot}\right)$$

Primordial BH bombs

$$\frac{\Delta U}{U} = \langle \tilde{a} \rangle f_{\rm PBH} M \frac{\rho^0_{\rm crit}\Omega_{\rm DM}}{\sigma T_0^4}\sqrt{\frac{4\pi e^2 n_0}{m_e}}\,(1+z)^{1/2}$$



- 95% confidence-level bounds due to μ and y CMB distortions

Conclusions & Outlook

- Compact objects are unique labs for beyond-SM physics and extensions of GR
- Probing DM with binary pulsars *is* possible
  - SKA will improve current bounds by 2 orders of magnitude
  - Model-independent constraints on DM profiles, DM spikes, clumps
- Probing ultralight bosons with BHs
  - Lack of highly spinning BHs → stringent constraints
  - monochromatic GW signal in the aLIGO/aVIRGO band
- Bounds on primordial BHs from plasma-triggered superradiant instabilities

- **Work in progress**
  - Pulsars: generic orbital period, accretion, DM interactions, timing model
  - BHs: GW signal, nonlinear interactions, other massive fields, time evolution