Fellini
Fellowship for Innovation at INFN
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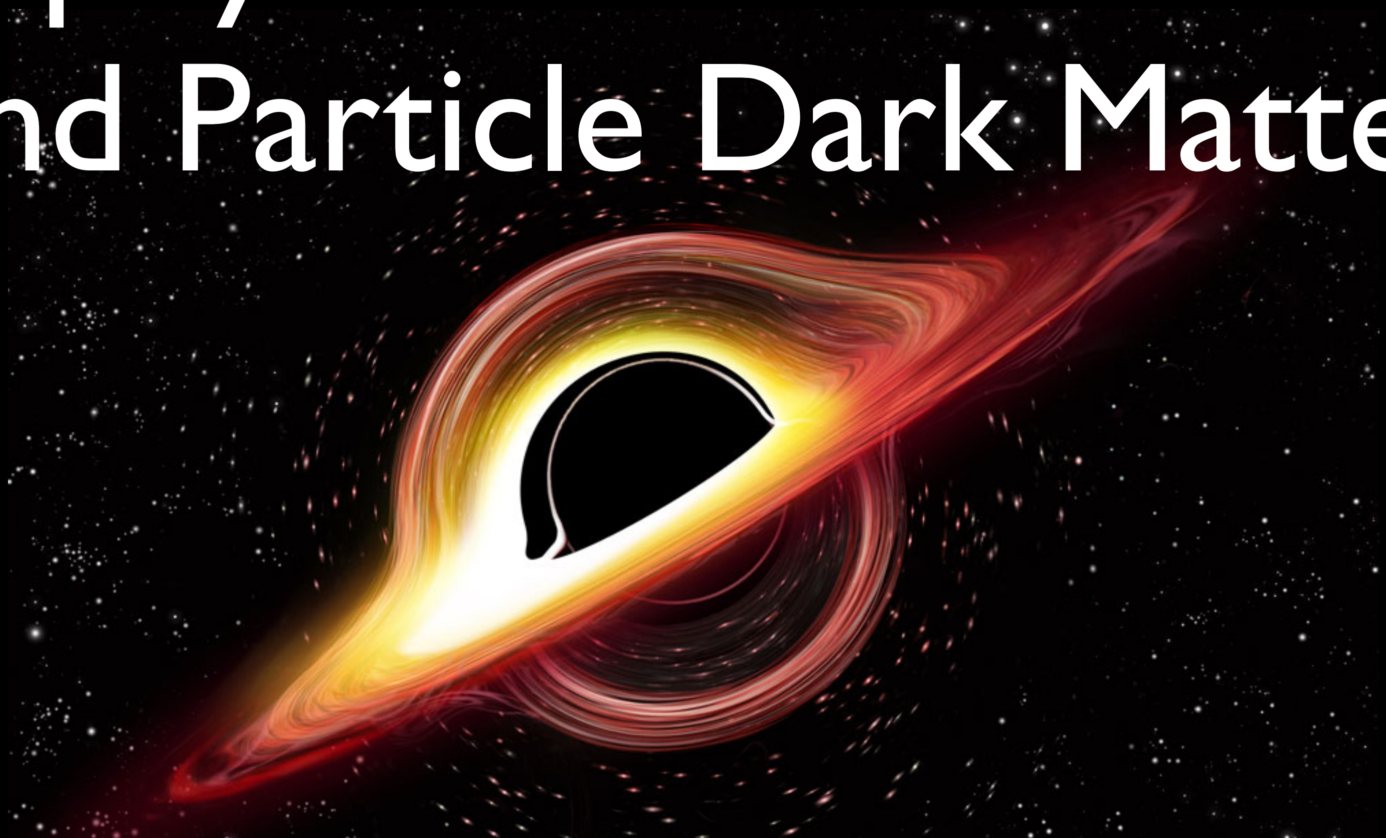
The interplay of Primordial Black Holes and Particle Dark Matter



Luca Visinelli (INFN Laboratori Nazionali di Frascati)

Based on: Carr, Kühnel, **LV**, 2008.08077, 2011.0193
Vagnozzi, Bambi, **LV**, 2001.02986
Vagnozzi, **LV**, 1905.12421
Bambi, Freese, **LV**, Vagnozzi, 1904.12983

Three memories that relate me to Tokyo:

1) I visited IMPU at its dawn in 2009! (Indirect DM detection)

2) The talk today is on work done with Bernard Carr

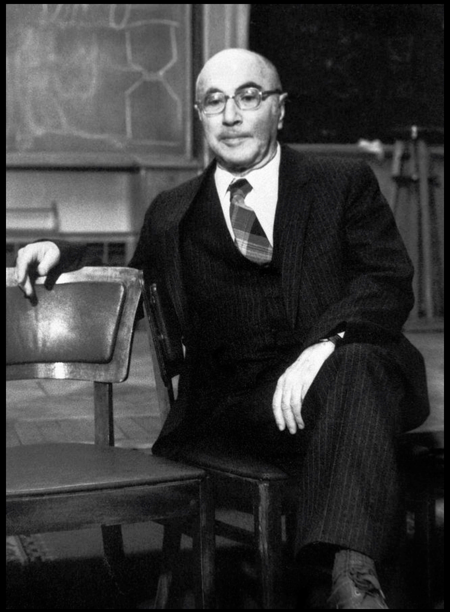
3) I plan to collaborate with prof. Yanagida

OUTLINE

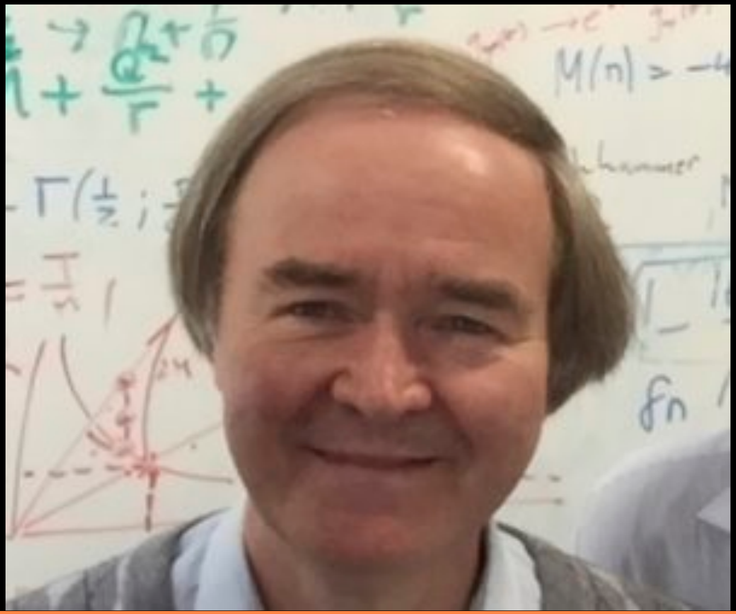
1. Prelude on PBH formation
2. BHs and WIMPs
3. BHs and light bosons
4. New physics and BH shadow

Primordial black holes

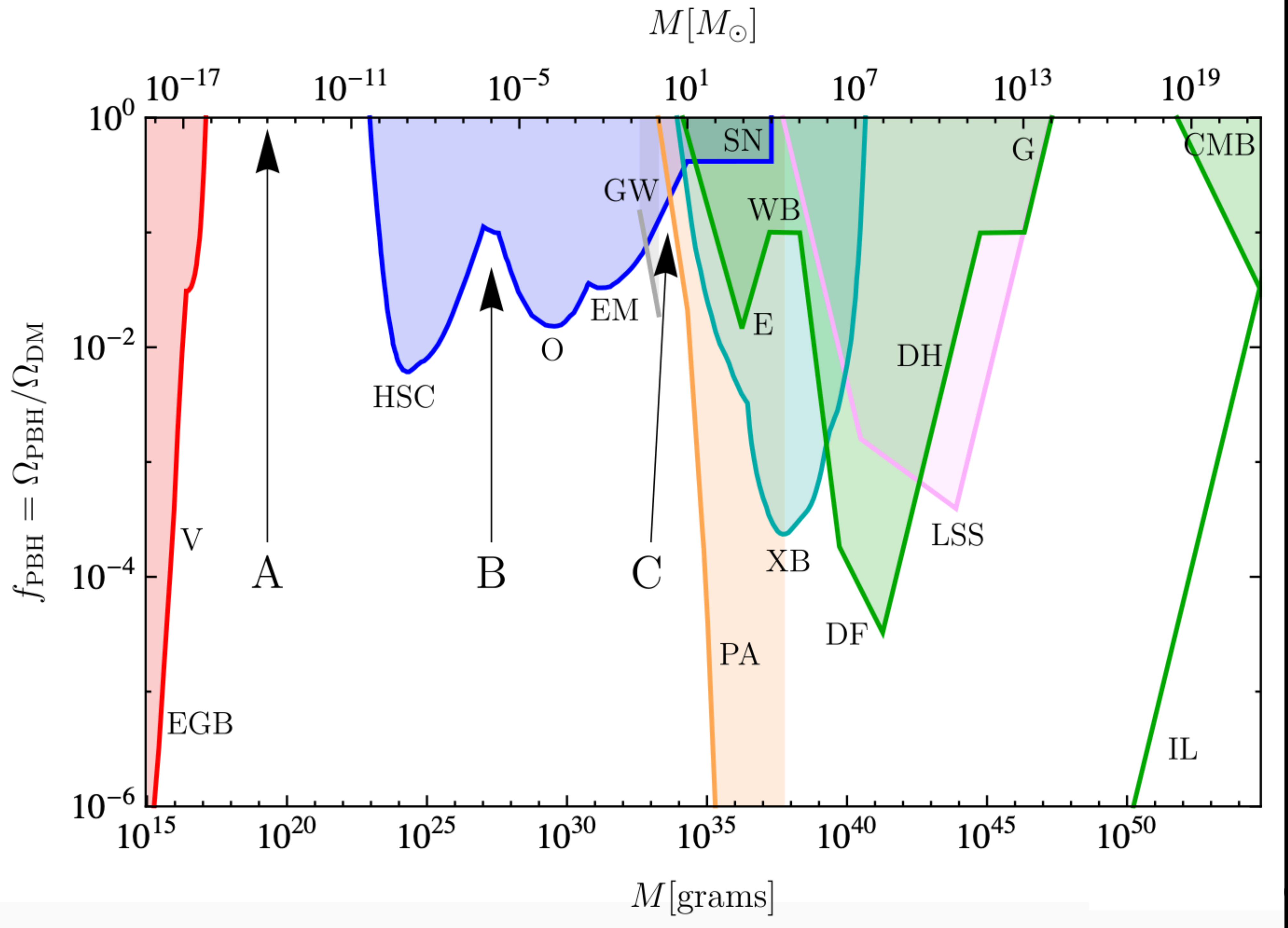
First proposed in the late 60s by Novikov & Zel'dovic



Explored by Hawking & Carr in the 70s



Primordial black holes



Carr&Kühnel 20

BH formation and evaporation

$$R_S = \frac{2GM}{c^2} \approx 3\,\mathrm{km}\left(\frac{M}{M_\odot}\right) \qquad \rho_S \approx 10^{18}\,\mathrm{g\,cm^{-3}}\left(\frac{M}{M_\odot}\right)^{-2}$$

In the early Universe BHs can form at all masses

The cosmological density is $\rho \sim \frac{1}{Gt^2} \sim 10^6\,\mathrm{g\,cm^{-3}}\,(t/\mathrm{s})^{-2}$

$$M_{\rm PBH} \sim \frac{c^3\,t}{G} =$$

$10^{-5}\,\mathrm{g}$ at $10^{-43}\,\mathrm{s}$ **(Planck)**

$1\,M_\odot$ at $10^{-5}\,\mathrm{s}$ **(QCD phase)**

$10^5\,M_\odot$ at $1\,\mathrm{s}$ **($e^+ - e^-$ annihilation)**

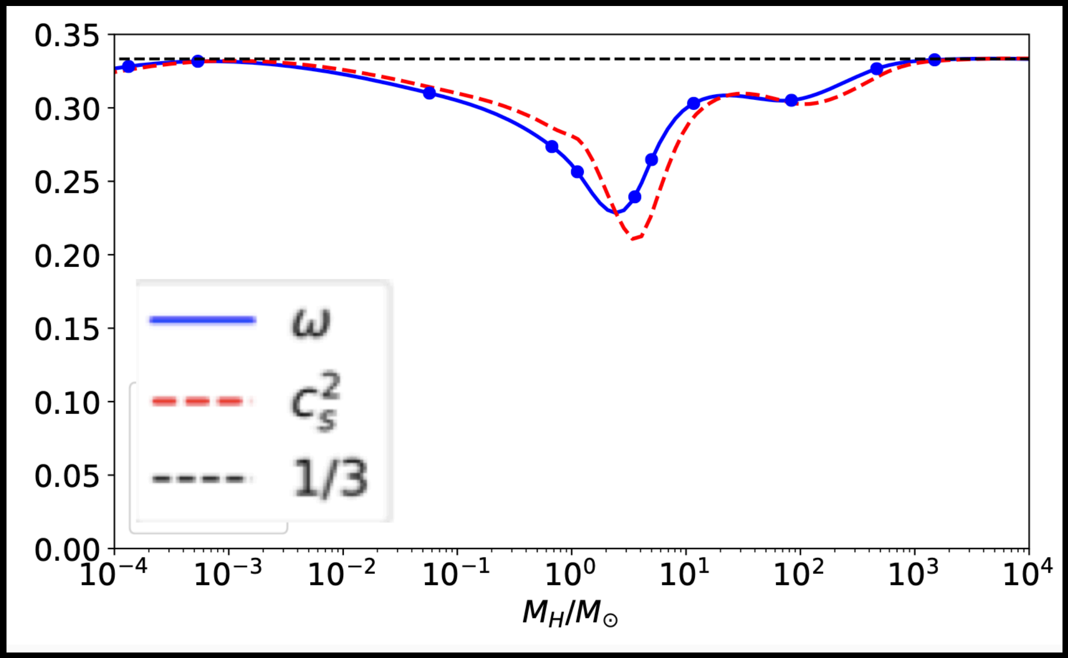
BH formation and evaporation

Density contrast $\delta\rho/\rho \gtrsim 0.1$ (Harada+13 1309.4201)

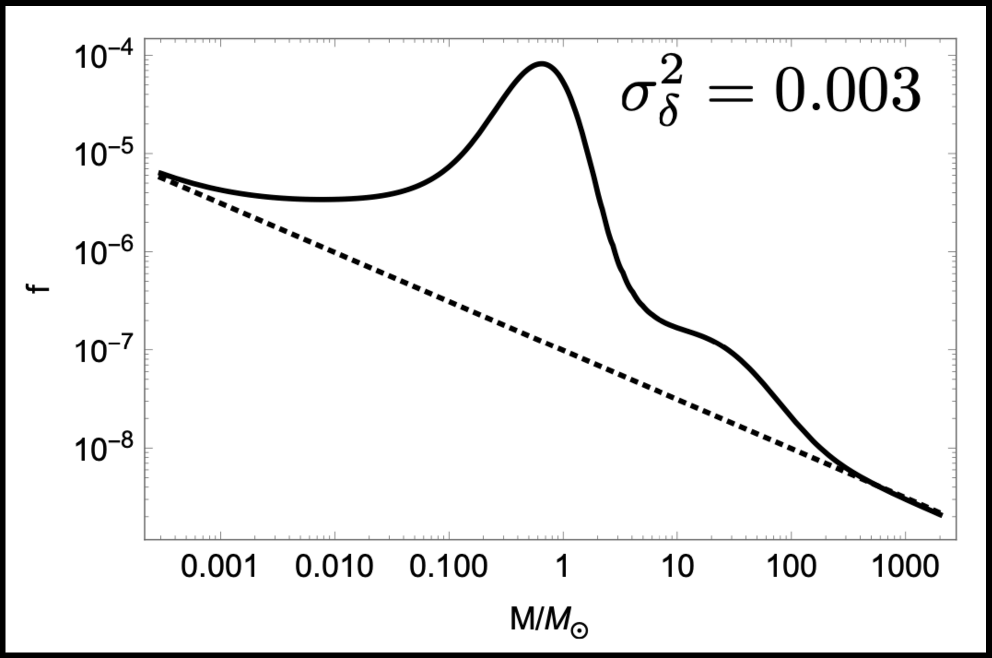
Various mechanisms to produce such a contrast:

1) Cosmology phase transitions e.g. Jedamzik&Niemeyer 99

$$f \equiv \frac{1}{\Omega_{\rm CDM}}\frac{{\rm d}\Omega_{\rm PBH}}{{\rm d}\ln M} \propto M^{-1/2} e^{-\frac{\delta_c^2}{2\sigma_\delta^2}}$$



Borsanyi+16



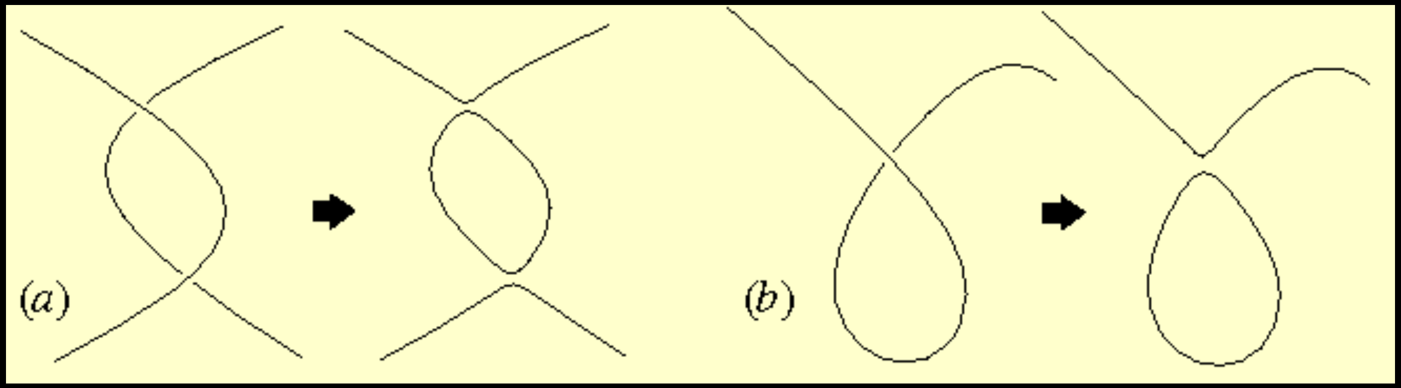
Byrnes+19

BH formation and evaporation

Density contrast $\delta\rho/\rho \gtrsim 0.1$ (Harada+13 1309.4201)

Various mechanisms to produce such a contrast:

1) Cosmology phase transitions
2) Topological defects Hawking 88; Polnarev&Zembowicz 91
   (collapse of loops, collision of strings)



$G\mu \lesssim 2 \times 10^{-6}$

Caldwell&Casper 96

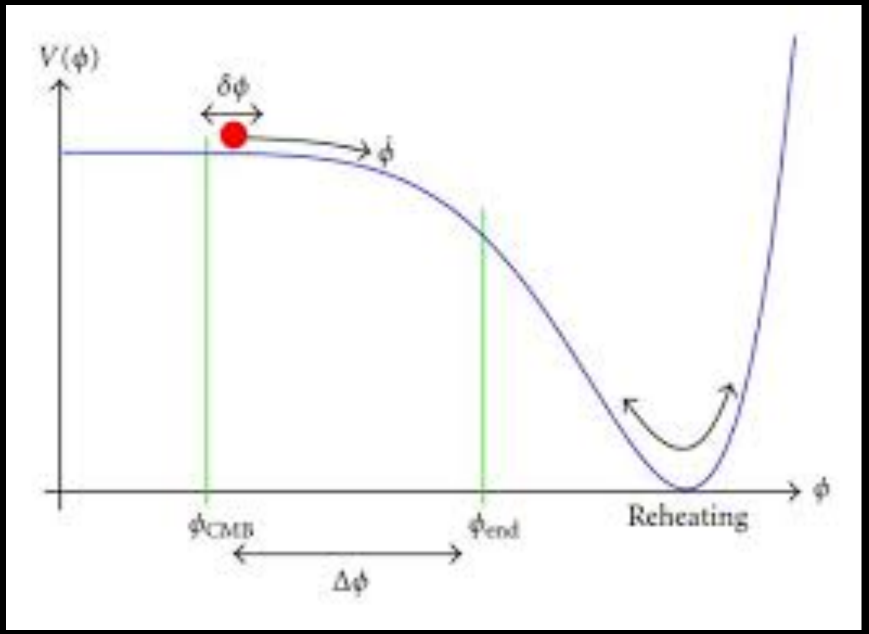
BH formation and evaporation

Density contrast $\delta\rho/\rho \gtrsim 0.1$ (Harada+13 1309.4201)

Various mechanisms to produce such a contrast:

1) Cosmology phase transitions
2) Topological defects
3) (P)reheating e.g. Suyama+04

$$V(\phi,\chi) = \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\chi^2.$$



Back-reaction prevents PBH overproduction

BH formation and evaporation

Density contrast $\delta\rho/\rho \gtrsim 0.1$ (Harada+13 1309.4201)

Various mechanisms to produce such a contrast:

1) Cosmology phase transitions
2) Topological defects
3) (P)reheating
4) Nucleation of false vacuum bubbles Kusenko+20

Fundamental questions

Is the DM a new particle, or could (part of) it be PBHs?

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Can you see coalescent PBH binaries in GWs?

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How can you find signatures of PBHs?

Can you see coalescent PBH binaries in GWs?

If PBHs are only a fraction of the DM ($f \ll 1$), how do they affect the main DM component?

Excellent recent reviews:

Green&Kavanagh 2007.10722; Carr&Kühnel 2006.02838

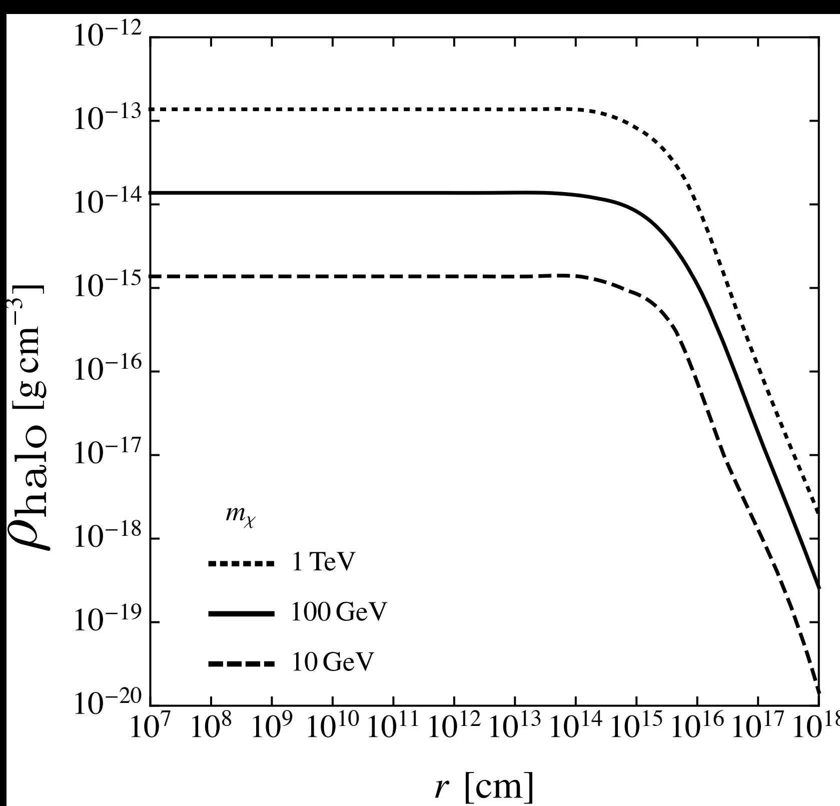
Black holes and WIMPs interplay

BHs accrete a WIMP halo through secondary infall

$$M_{\rm halo} \sim 100 \left(\frac{31}{1+z}\right) M_{\rm BH}$$

$$\rho_{\rm halo} \propto r^{-9/4}$$

Bertschinger 85; Mack+ 07



The inner cusp part is consumed by WIMP annihilation

$$\rho_{\rm max} \sim \frac{m_{\rm DM}}{\langle\sigma v\rangle_{\rm ann}\, t_0}$$

Decay rate of WIMPs in a PBH halo

$$\Gamma = \frac{4\pi\langle\sigma v\rangle_{\rm ann}\rho_{\rm max}^2 r_{\rm cut}^3}{2m_{\rm DM}^2}$$

We treat each BH as a decaying DM particle of mass $M_{\rm BH}$, decay rate Γ, abundance f

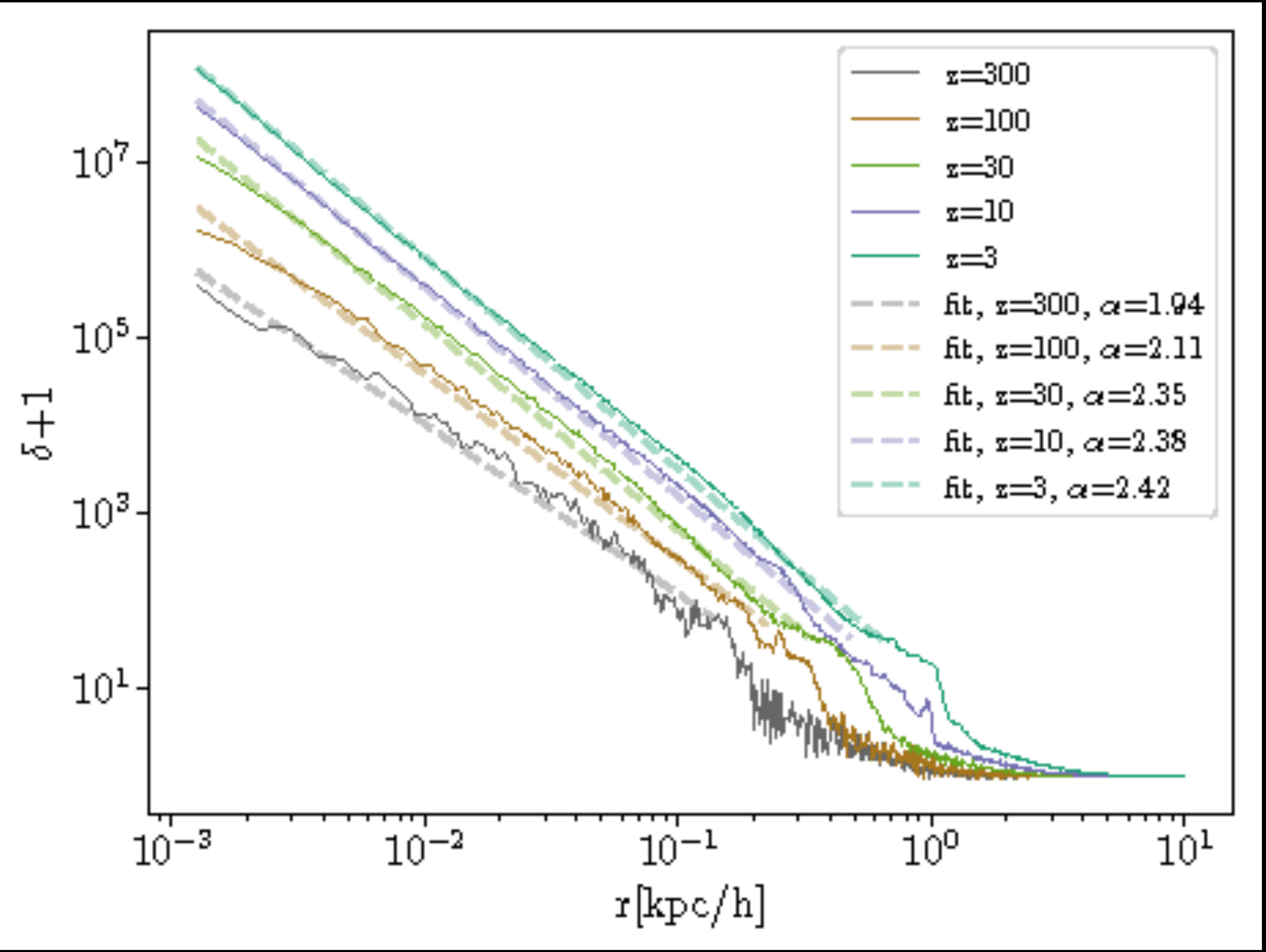
Galactic source at distance d

$$\Phi_{\rm BH}^{\rm point}(E) = \frac{\Gamma}{4\pi d^2}\frac{{\rm d}N_\gamma}{{\rm d}E}(E)$$

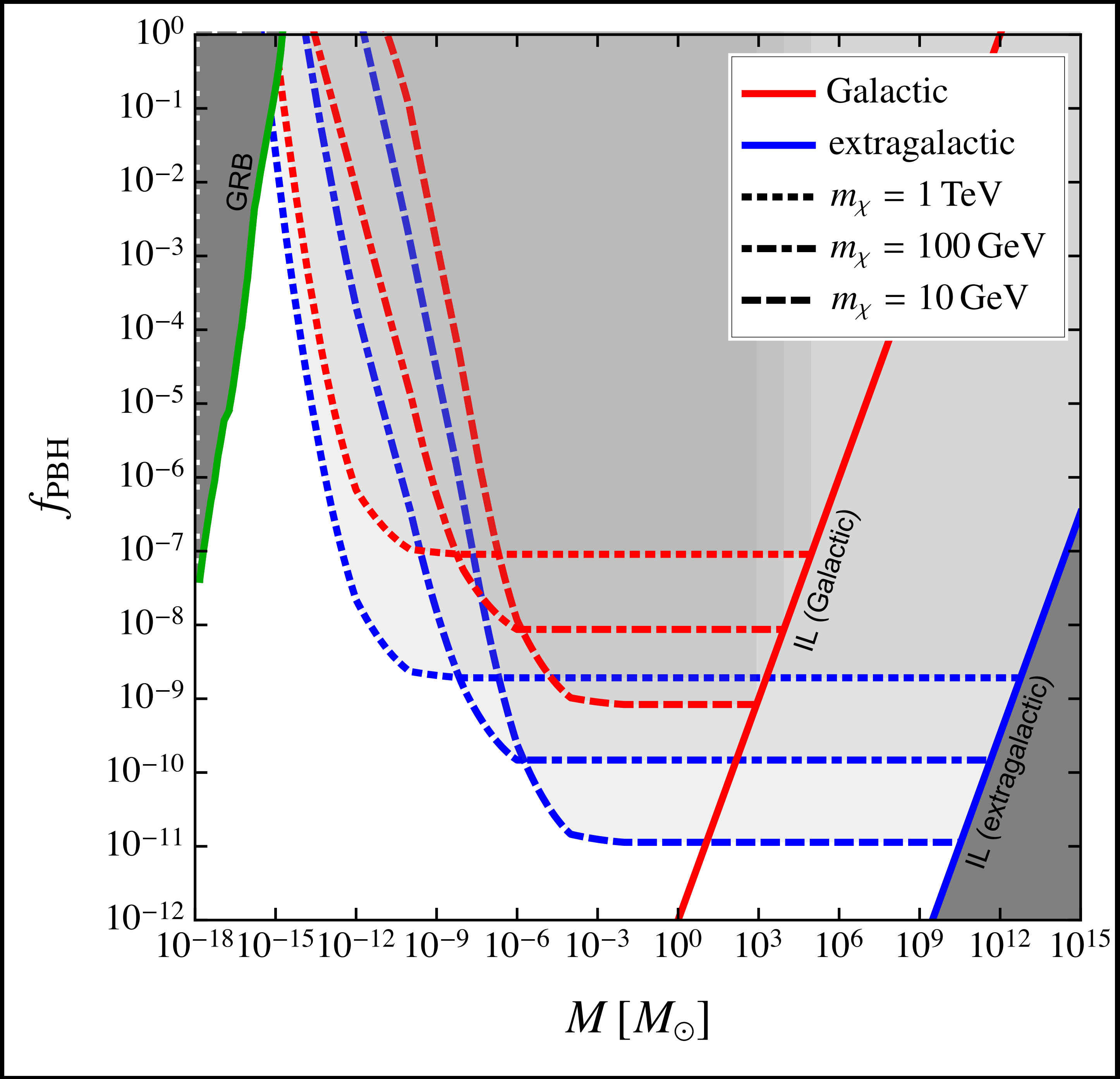
Extragalactic diffuse background to redshift z

$$\Phi_{\rm BH}^{\rm e.g.}(E) = \frac{\Gamma}{4\pi}\frac{f\rho_{\rm DM}}{M_{\rm BH}}\int_0^z {\rm d}z'\,\frac{e^{-\tau(E,z')}}{H(z')}\frac{{\rm d}N_\gamma}{{\rm d}E}((1+z')E)$$

see e.g. Bertone+19



3D N-body simulation, Gosenca+17

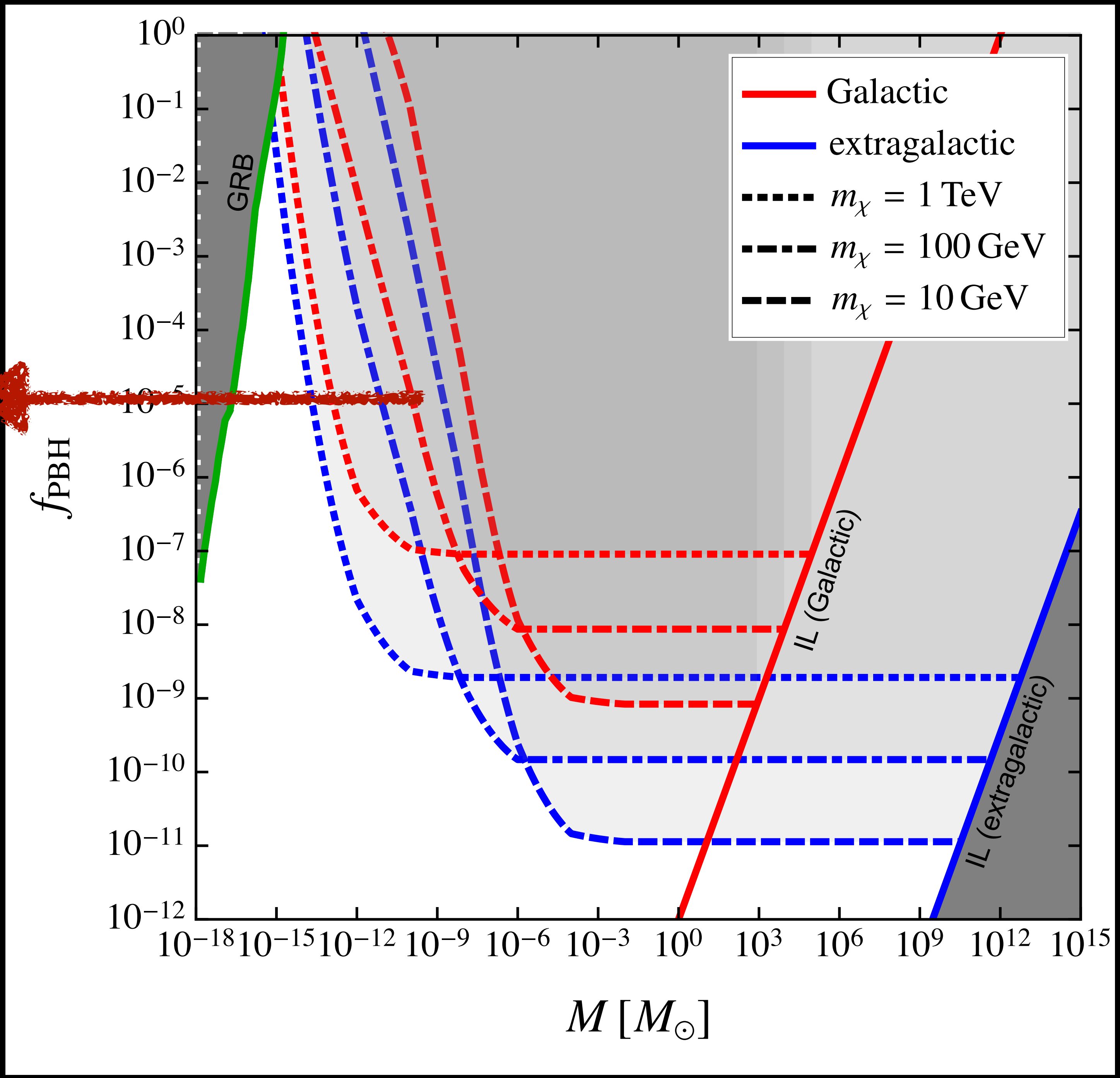


Carr, Kühnel, **LV** 20 a,b; see also Boucenna,**LV**+18; Adamek+19

Taking Fermi analysis on decaying DM from Ando&Ishiwata 15

WIMP kinetic energy

(Eroshenko 16)



Carr, Kühnel, **LV** 20 a,b; see also Boucenna,**LV**+18; Adamek+19

Taking Fermi analysis on decaying DM from Ando&Ishiwata 15

Black holes and bosons interplay

Spinning BHs can host a boson condensate “cloud”

Arvanitaki+11a,b

This cloud can extract energy and $\vec{J}$ from the BH if:

$$\omega < \frac{\mu}{R_S} \frac{a_*}{1+\sqrt{1-a_*^2}}$$

ω Frequency of the boson

μ Azymuthal number

$a_* \equiv |\vec{J}|/M^2$

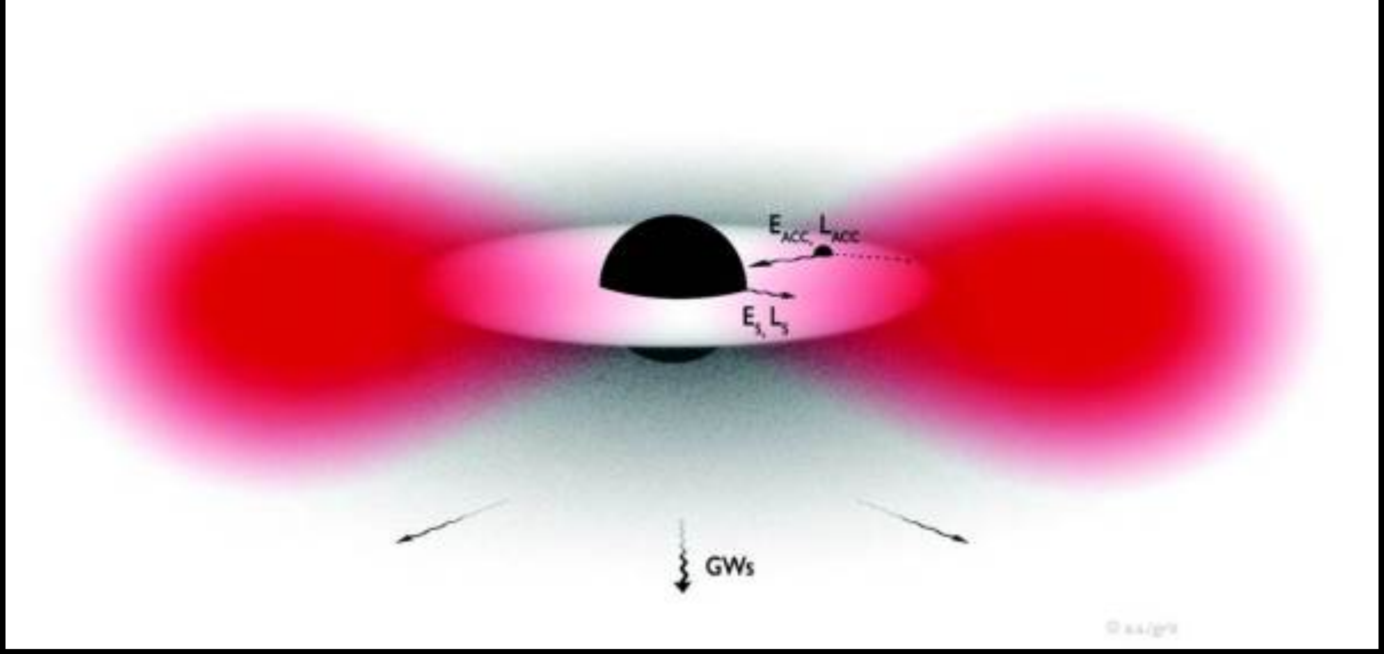


Figure from Pani+15

PBHs are born with $\vec{J} = 0$
and acquire spin through accretion (keeping $a_* < 1$)

If a light boson of the right mass m_ϕ exists,
superradiance slows down maximally-spinning BHs

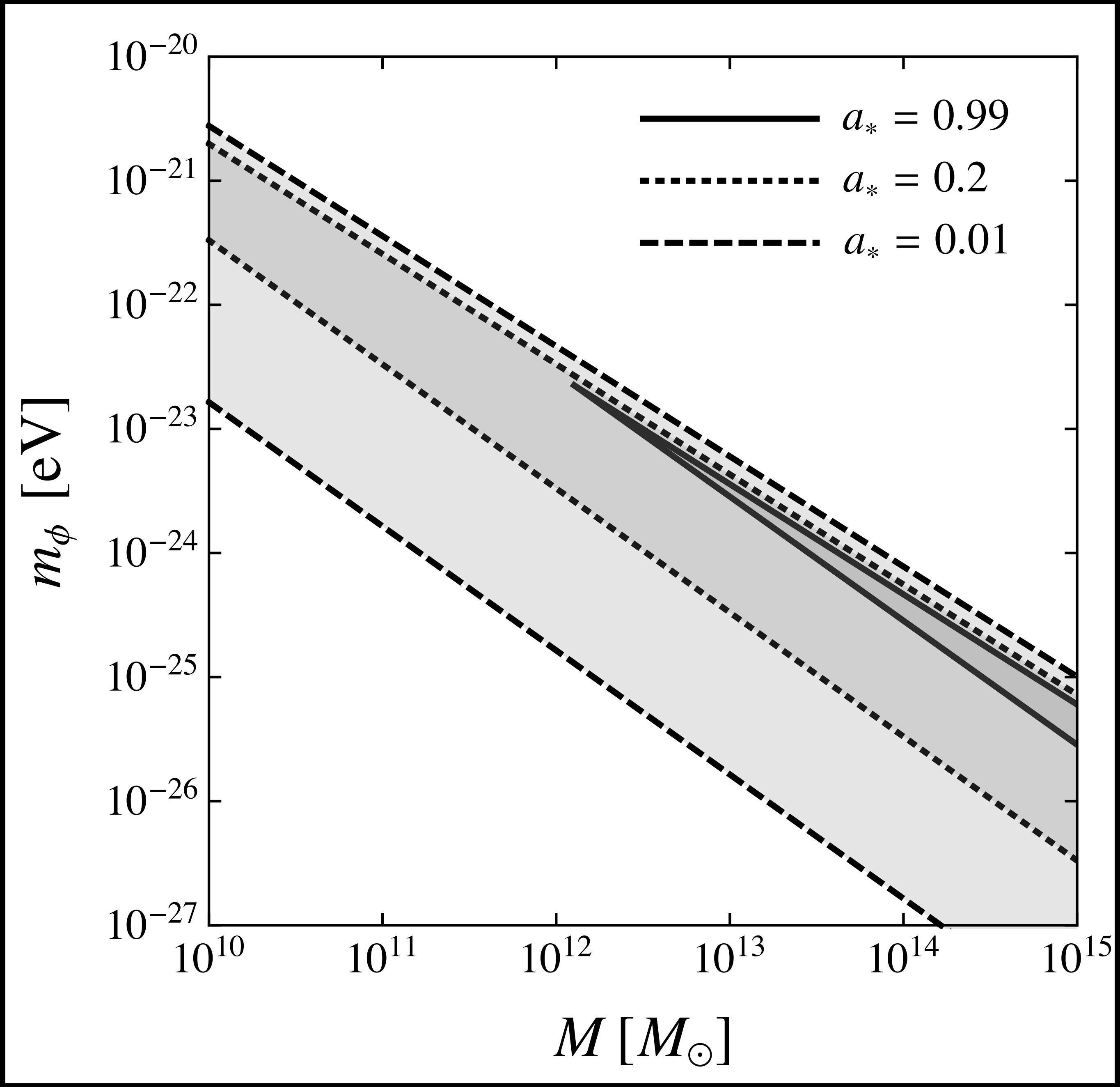
$$\frac{\mathrm{d}M}{\mathrm{d}t} = f_{\mathrm{Edd}} \frac{\mathrm{d}M_{\mathrm{Edd}}}{\mathrm{d}t} - m_\phi \frac{\mathrm{d}N_\phi}{\mathrm{d}t}$$

$$\frac{\mathrm{d}N_\phi}{dt} = \Gamma\, N_\phi$$ superradiance growth

+ equation for the evolution of $\vec{J}$

This picture holds for adiabatic approximation $GMm_\phi \lesssim 1$

Supermassive black holes and boson clouds



Carr, Kühnel, **LV** 20a

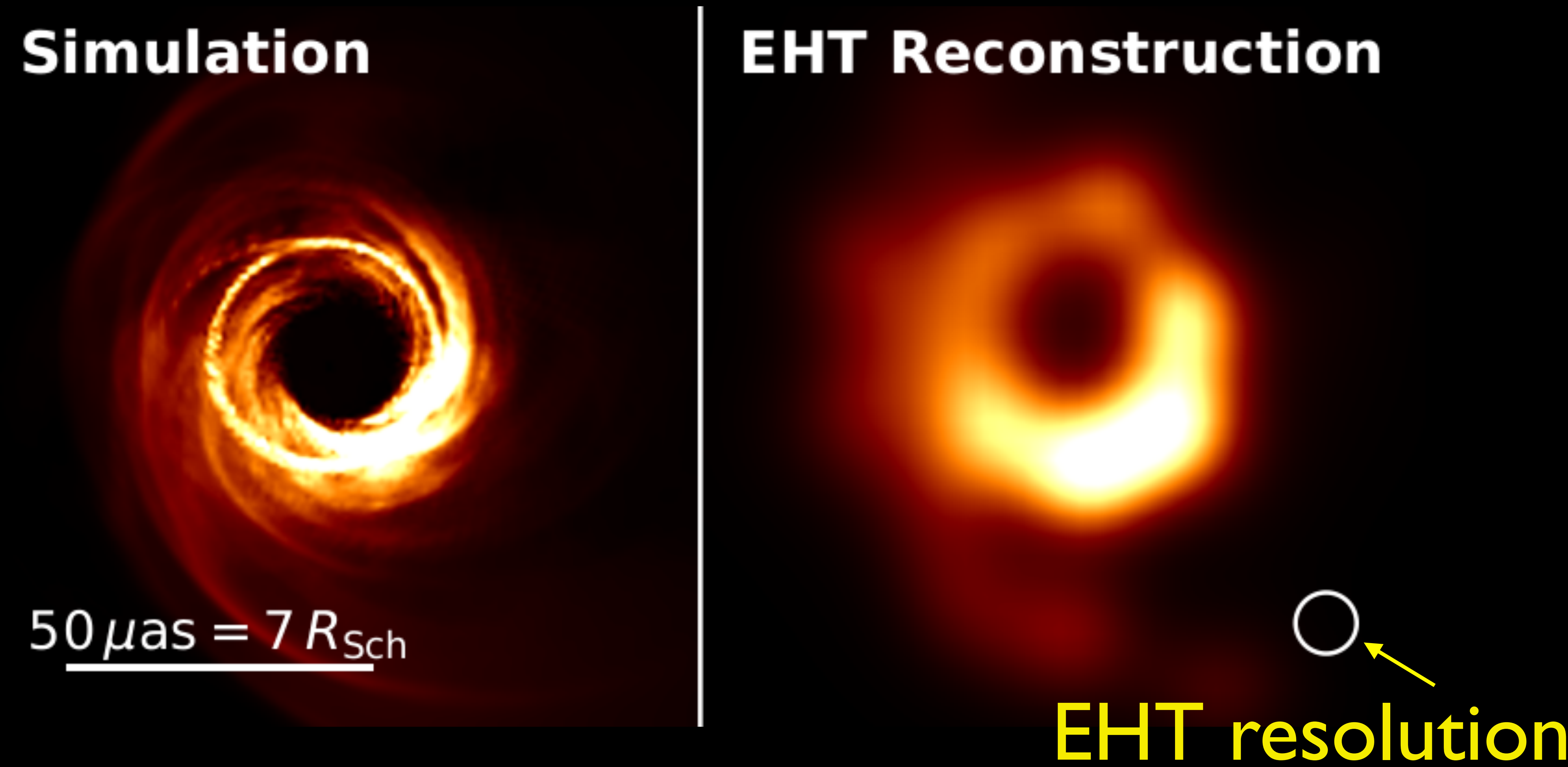
Black hole shadows

Event Horizon Telescope

VLBI observing M87* and Sagittarius A* at $\lambda = 1.3\,\mathrm{mm}$

Resolution at $10\,\mu\mathrm{arcsec}$

Event Horizon Telescope



Left: simulation of M87* at 230GHz (or $\lambda = 1.3\,\mathrm{mm}$)

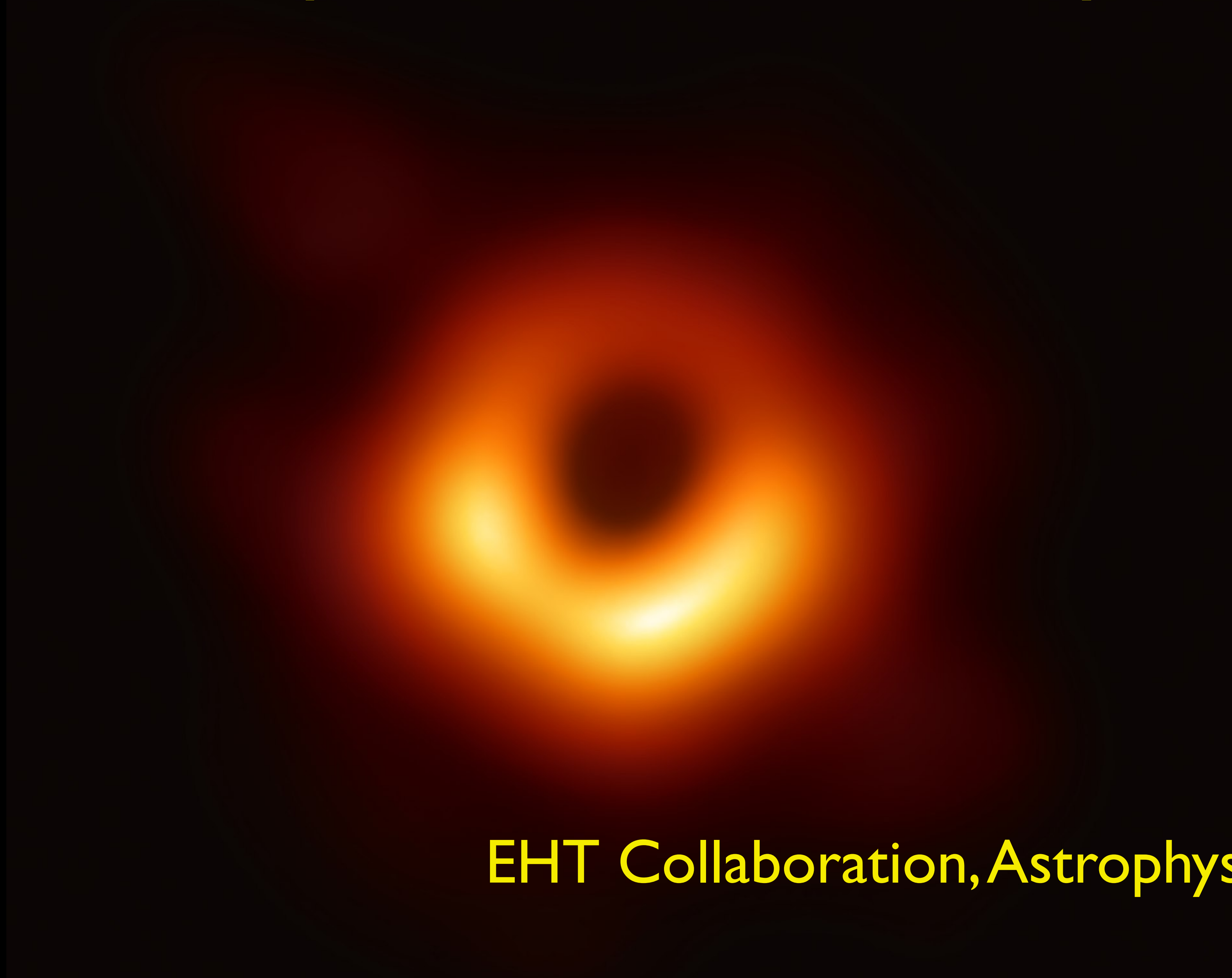
Right: Image reconstructed from simulated data using https://github.com/achael/eht-imaging

The picture of the century

EHT Collaboration, Astrophys. J. **875** (2019)

- Event Horizon Telescope (April 2019)
- 10 days acquisition + 2 years analysis

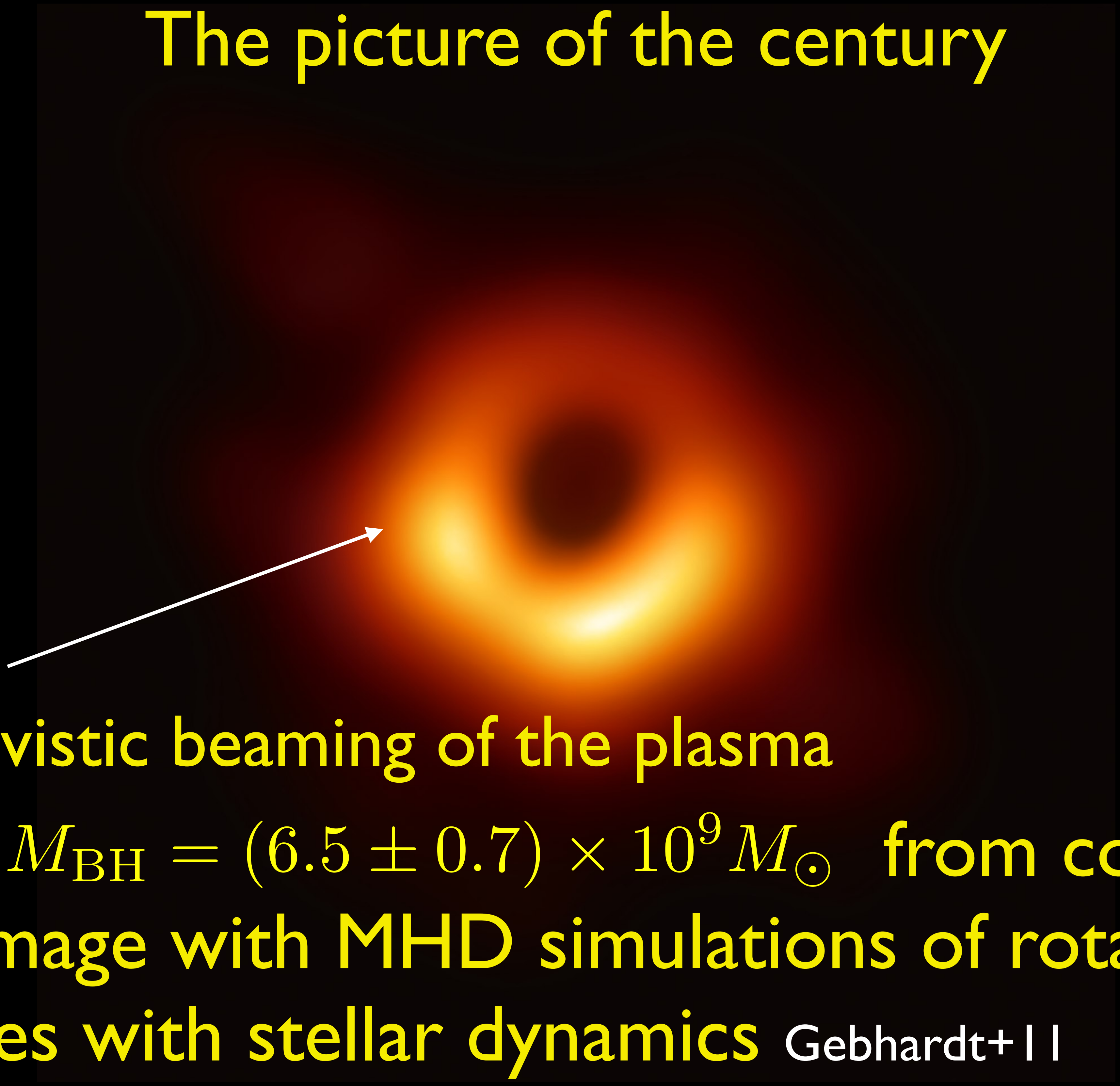
The picture of the century



EHT Collaboration, Astrophys. J. **875** (2019)

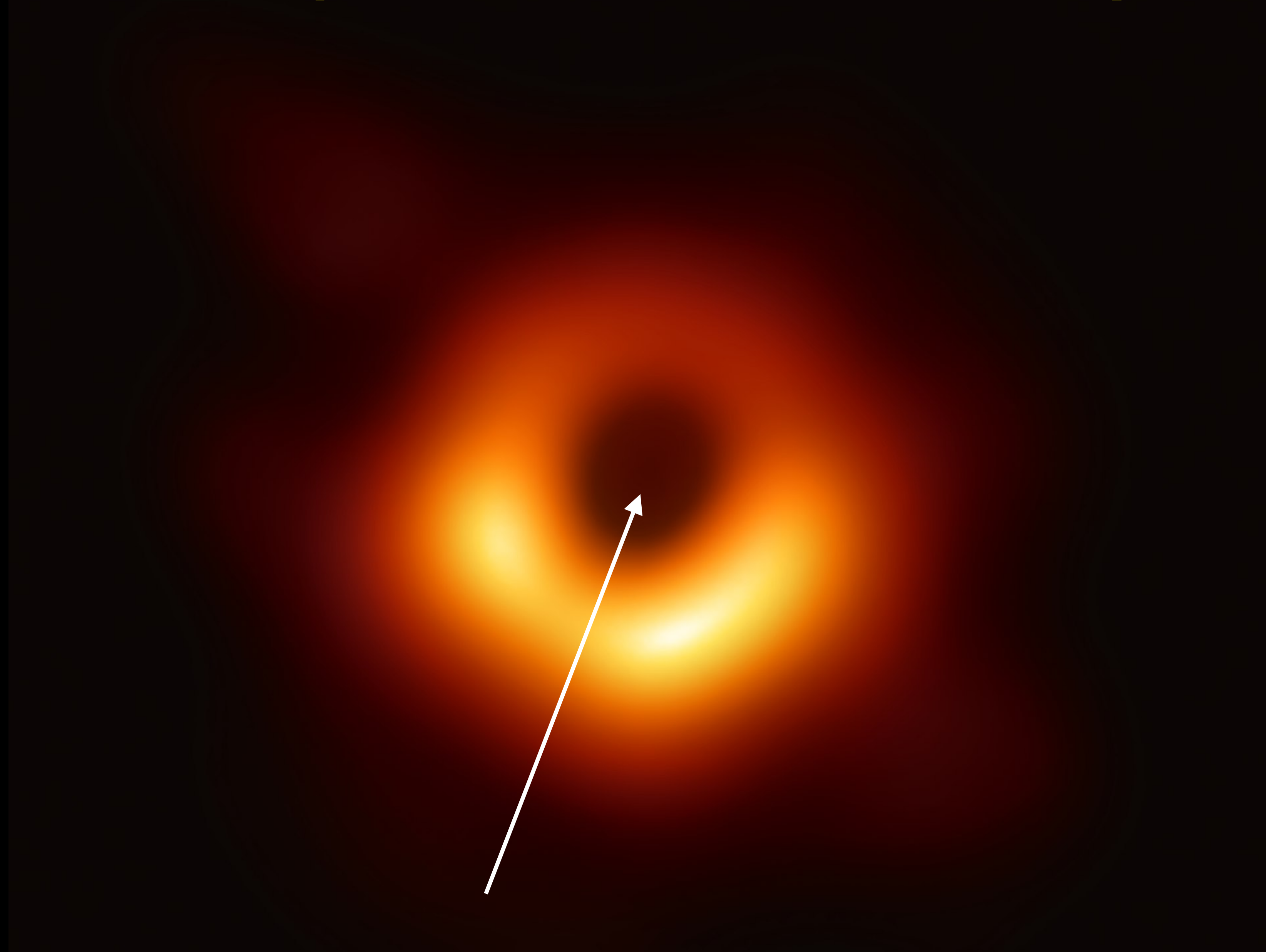
- EHT has sufficient resolution
- The SMBH is a strong emitter of radio waves
- Little foreground radio pollution

The picture of the century



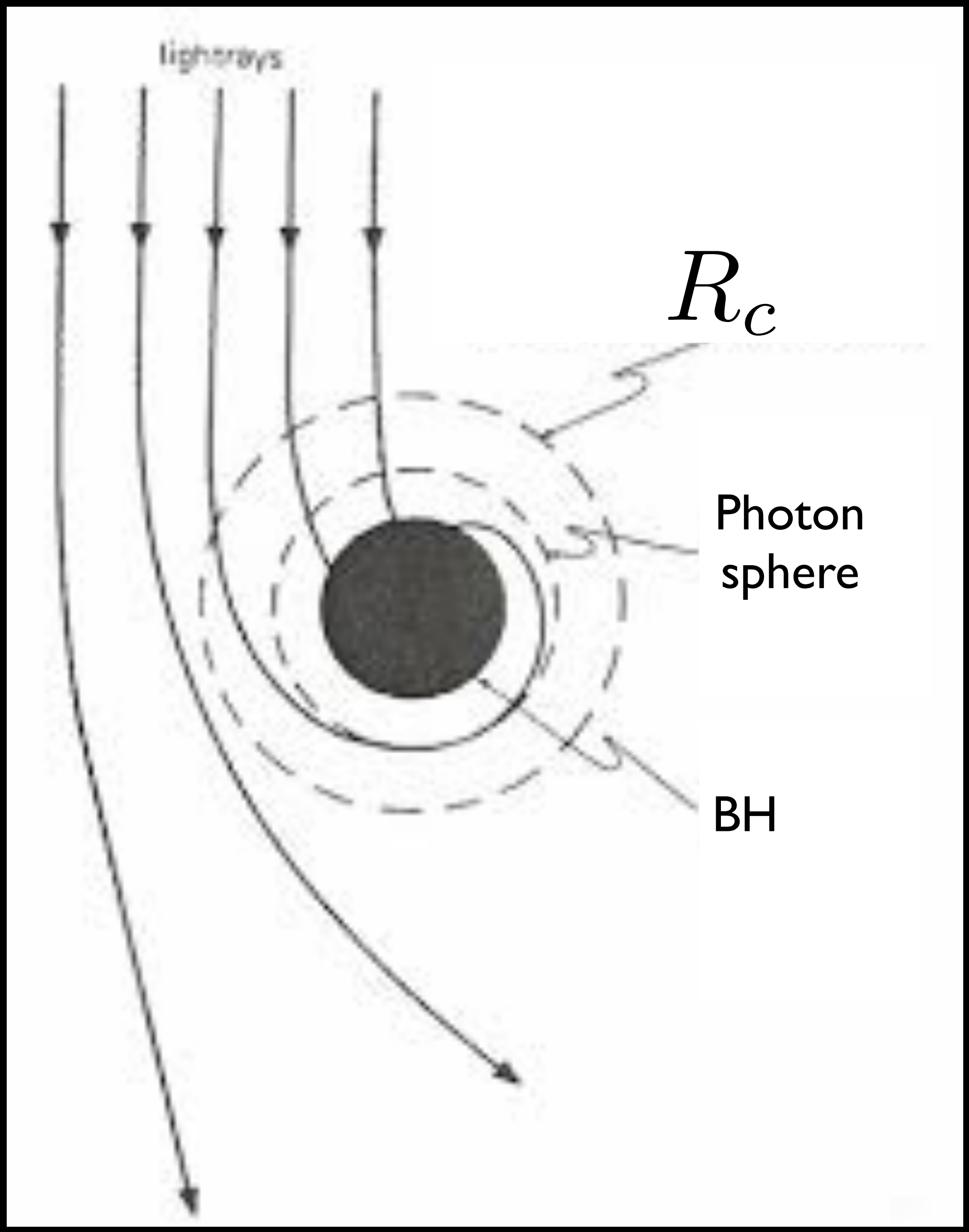
- Relativistic beaming of the plasma
- Mass $M_{\rm BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$ from comparing the image with MHD simulations of rotating BH
- Agrees with stellar dynamics Gebhardt+11
- Angular diameter $(42 \pm 3)\,\mu$as

The picture of the century



Shadow of a BH: dark area in the image of an optically thin region around the compact object.

Shadow ⟷ photon capture radius



Non-rotating BH:

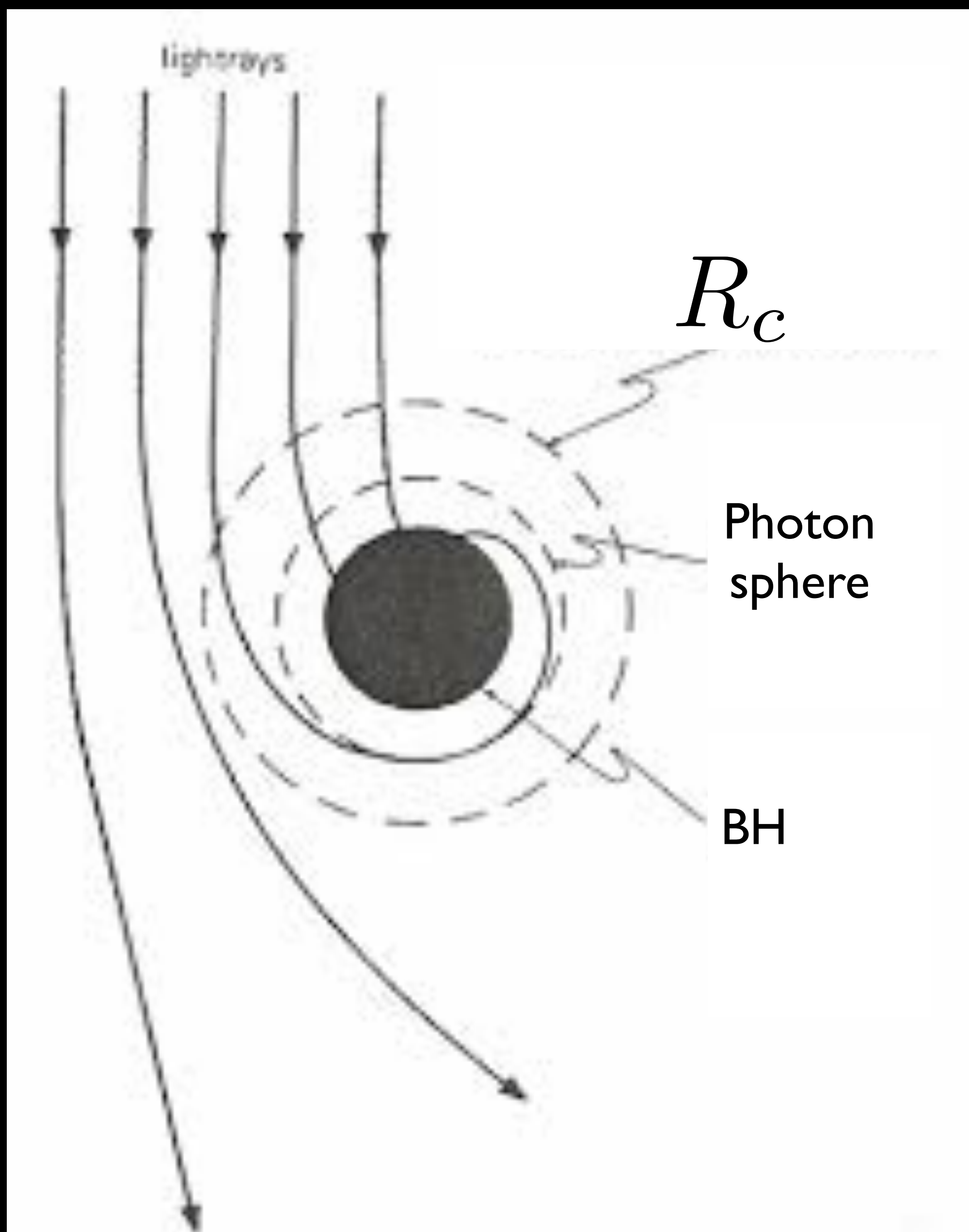
$$r_g = GM_{\rm BH}/c^2$$
$$R_s = 2r_g$$
$$R_c = \sqrt{27}r_g$$

Image angular diameter:

$$\theta = \frac{2R_c}{D} \approx 42\,\mu\text{arcsec}$$

(Measured $(42 \pm 3)\,\mu\text{as}$)

Shadow ⟷ photon capture radius



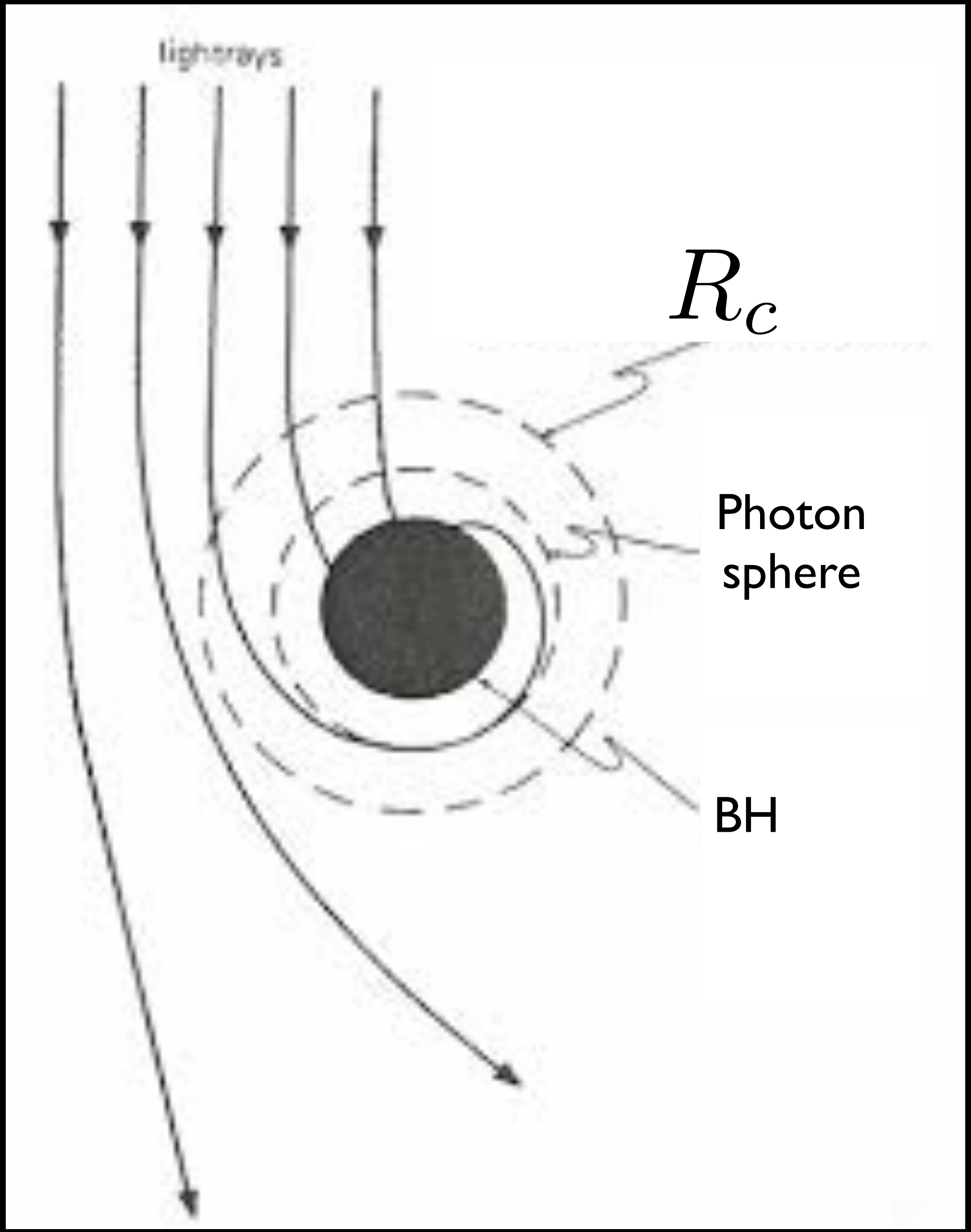
Rotating BH:

$$r_h = M + \sqrt{M^2 - a^2}$$

Kerr bound: $|a| \leq M$

(or $a_* \leq 1$ **)**

Shadow ⟷ photon capture radius



Rotating BH:

Photon geodesic

$$(r^2 + a^2 \cos^2 \theta_{\rm obs}) \left(\frac{dr}{d\lambda}\right) = \sqrt{\mathcal{R}}$$

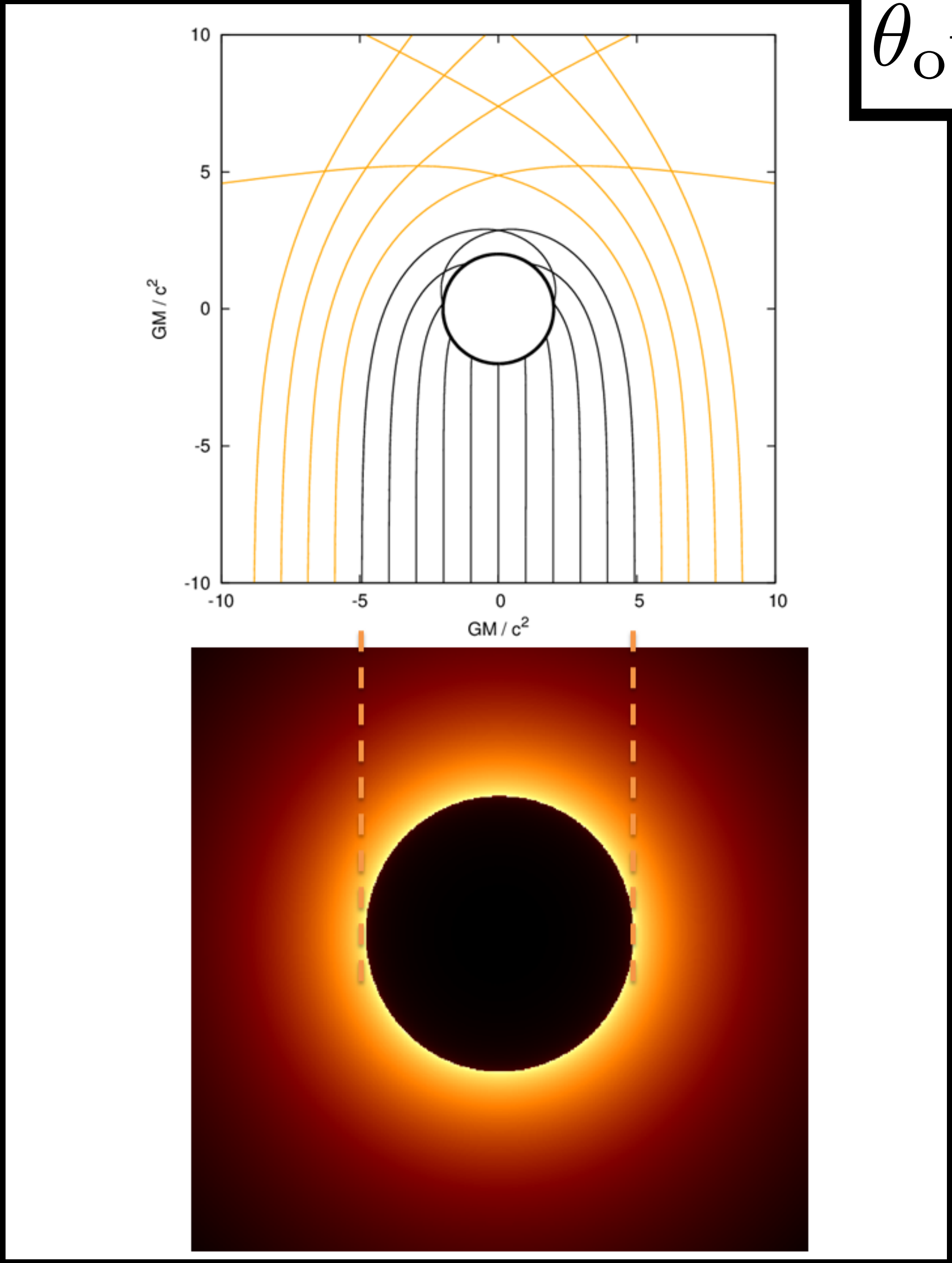
Depends only on:

- BH spin a
- Obs angle $\theta_{\rm obs}$

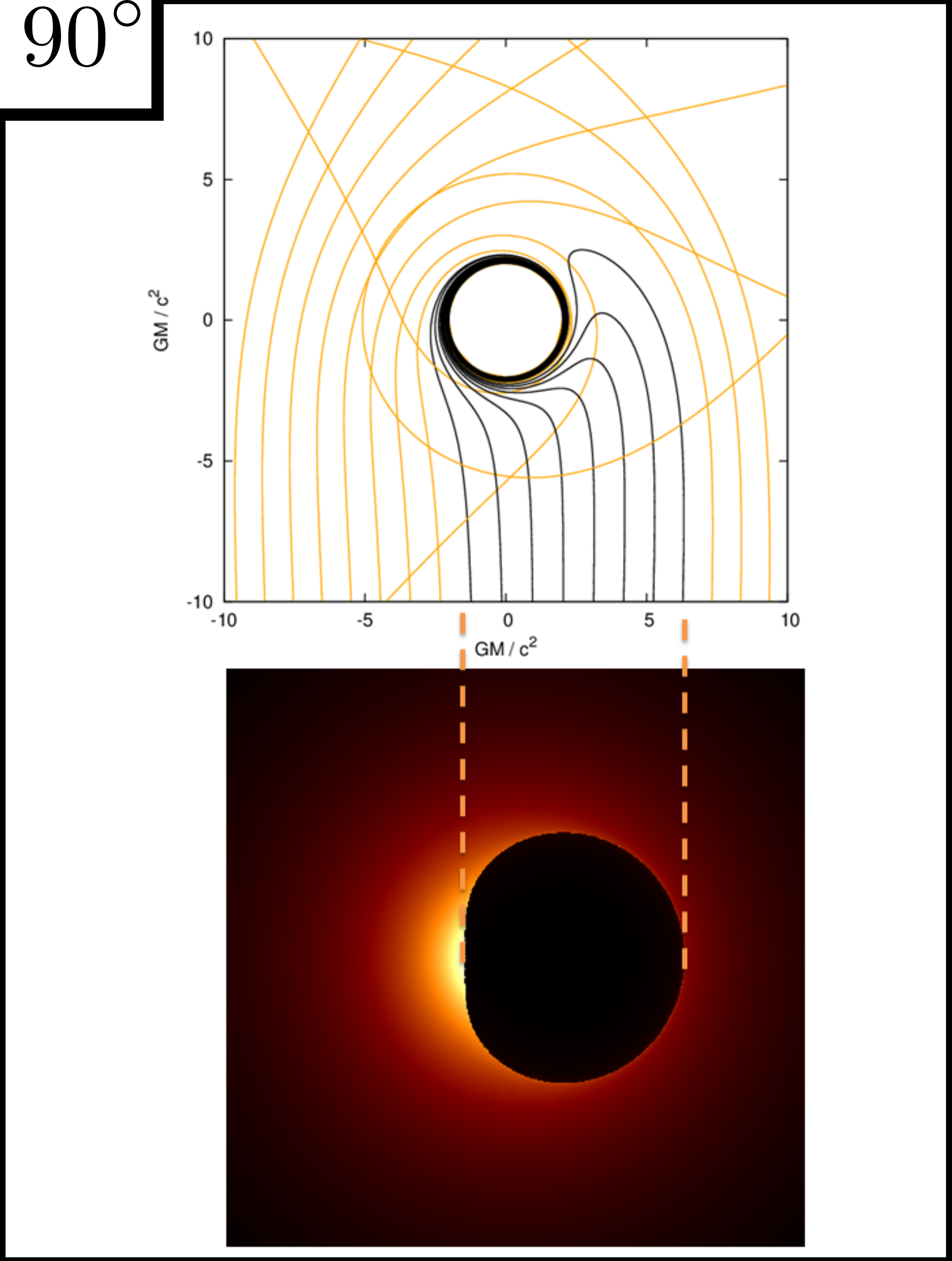
The roots of $\mathcal{R}(r) \geq 0$ define bound orbits (if exist)

Photon trajectories around a BH + shadow image

$\theta_{\rm obs} = 90°$

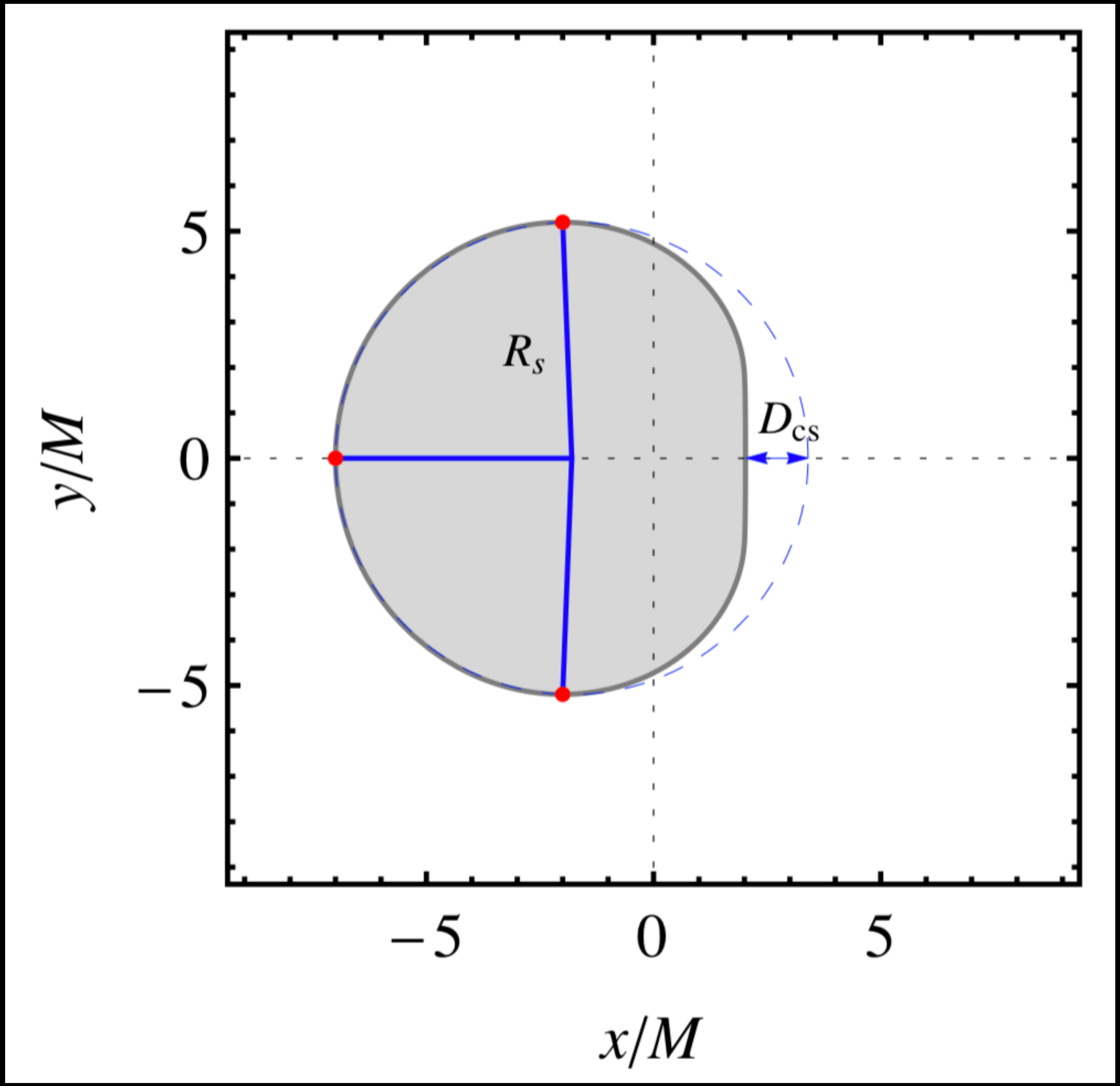


Non-rotating



Rotating

BH Shadow for rotating BH

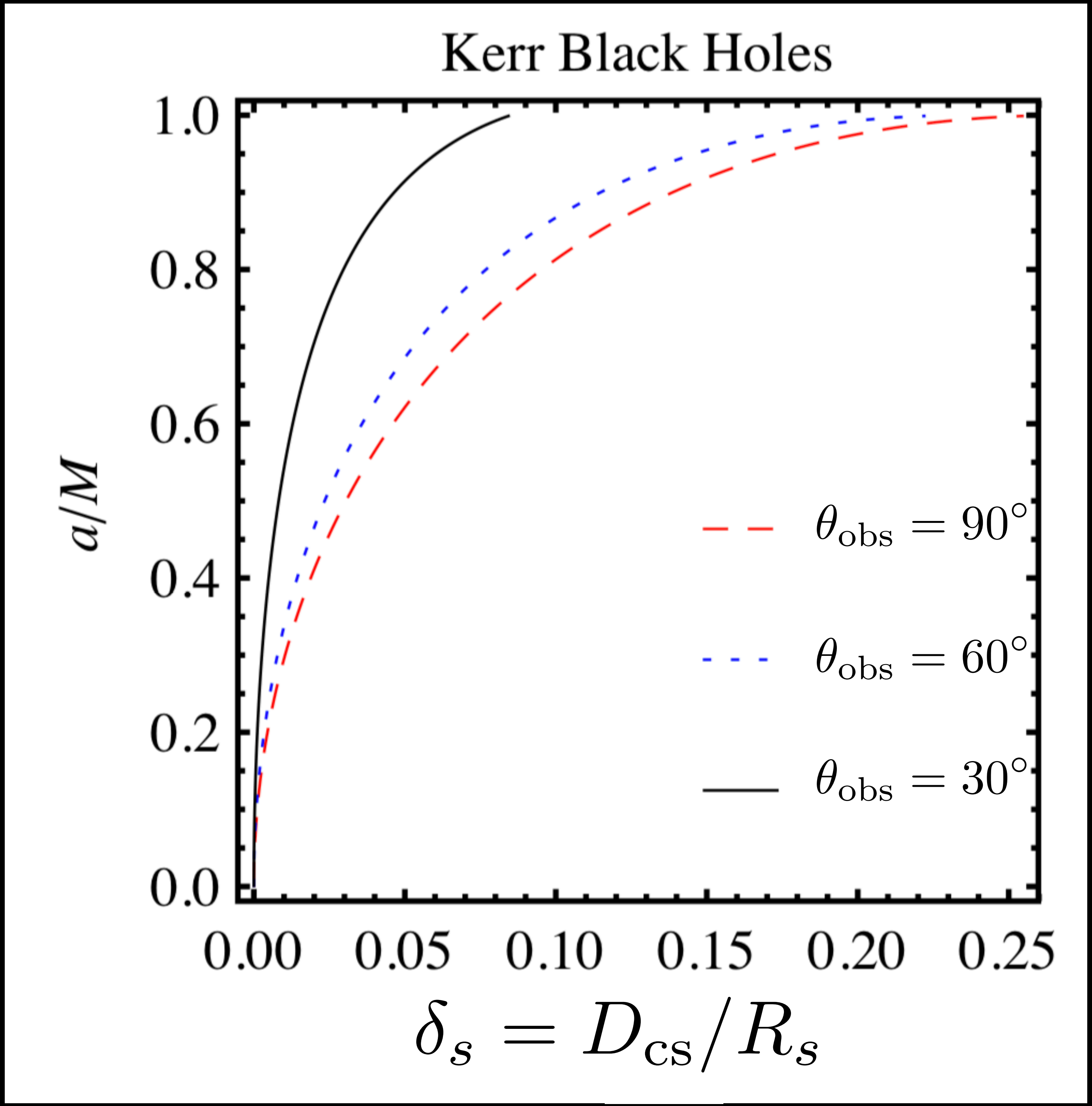


Define the distortion:

$$\delta_s = D_{\rm cs}/R_s$$

Spin-orbit is repulsive for photons with orbital angular momentum aligned to the BH spin

Inclination matters

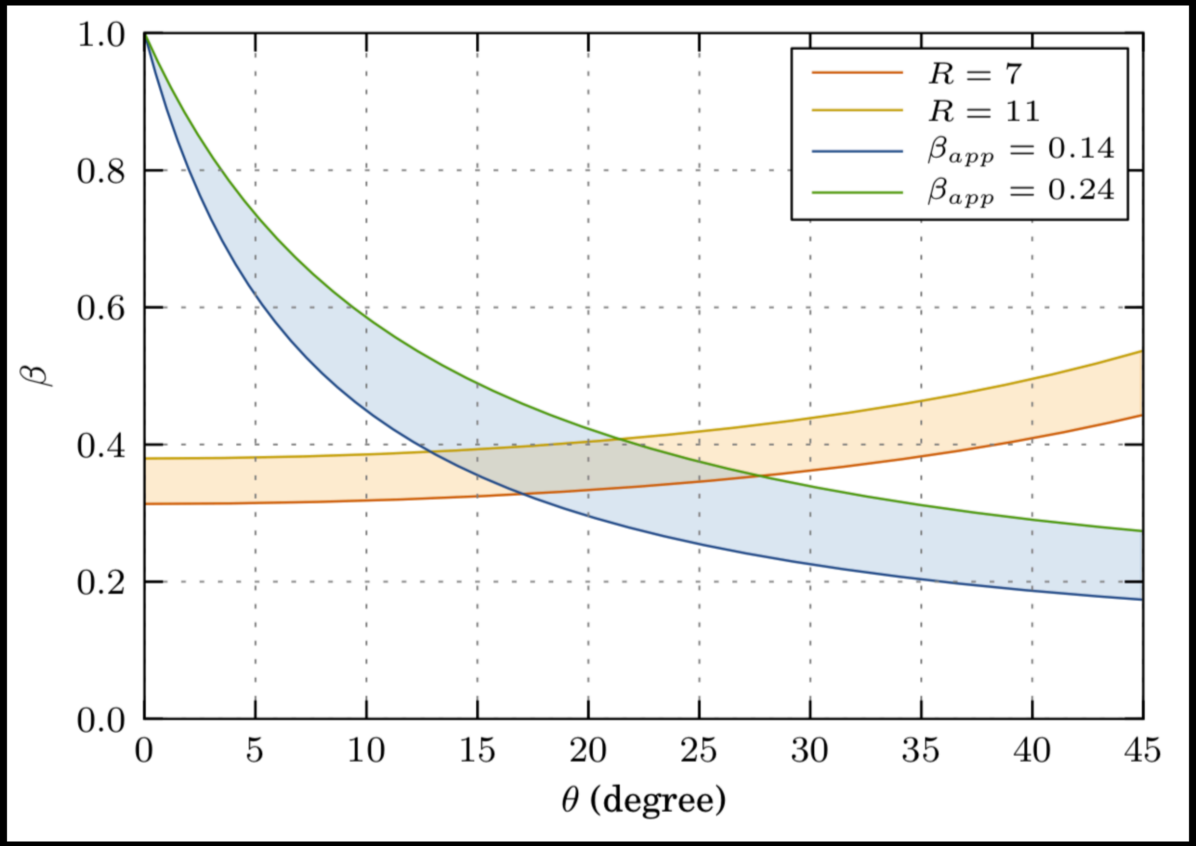


For given inclination, distortion is related to the BH spin

M87* inclination and spin

: Jet to counter-jet intensity

: Apparent speed

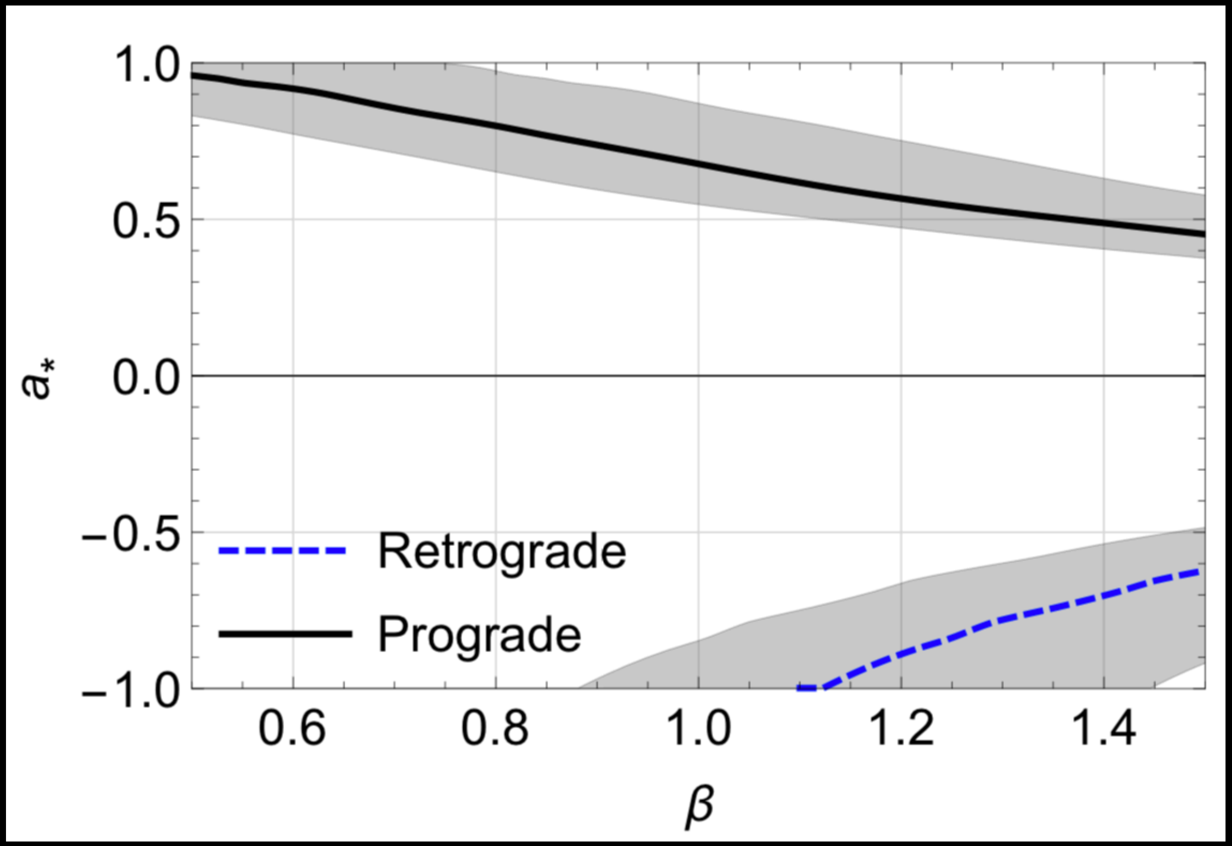


Mertens+16

$$\theta_{\rm obs} = (17.2 \pm 3.3)^\circ$$

Accretion density radial profile

$$\rho(r) \propto r^{-\beta}$$



Nemmen 19

$|a^*| \gtrsim 0.4$ (Prograde)

$|a^*| \gtrsim 0.5$ (Retrograde)

Excerpt from EHT paper

associating to the shape of the shadow a deviation from the circularity—measured in terms of root-mean-square distance from an average radius in the image—that is $\lesssim 10\%$, we can set an initial limit of order four on relative deviations of the quadrupole moment from the Kerr value (Johannsen & Psaltis 2010). Stated differently, if Q is the quadrupole moment of a Kerr black hole and ΔQ the deviation as deduced from circularity, our measurement—and the fact that the inclination angle is assumed to be small—implies that $\Delta Q/Q \lesssim 4$ ($\Delta Q/Q = \varepsilon$ in Johannsen & Psaltis 2010).

EHT Collaboration, Astrophys. J. **875** 1 (2019)

Using the circularity to constrain the parameter space

Cosimo Bambi (Fudan U.)

Katherine Freese

(UT Austin&Stockholm U.)

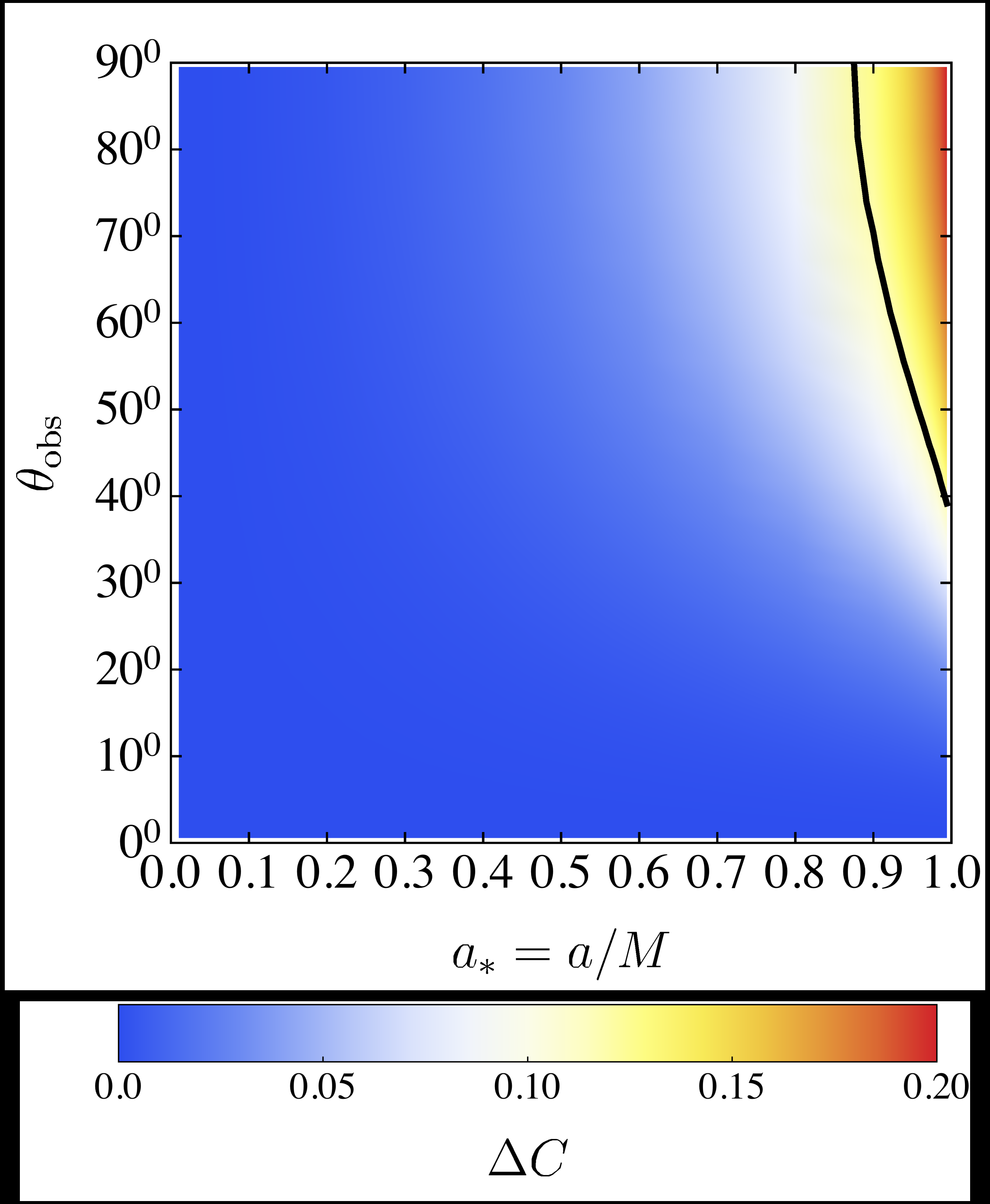
Sunny Vagnozzi

(KICC Cambridge)

$$\Delta C \equiv \frac{1}{\bar{R}} \sqrt{\frac{1}{2\pi} \int_0^{2\pi} d\phi \left(\ell(\phi) - \bar{R}\right)^2}$$

Bambi, Freese, Vagnozzi, **LV** Phys.Rev. D**100** 044057 (2019) 1904.12983

Using the circularity to constrain the parameter space



Can we test physics beyond GR?

Some of such exotic compact objects can already be shown to be incompatible with our observations given our maximum mass prior. For example, the shadows of naked singularities associated with Kerr spacetimes with $|a_*| > 1$ are substantially smaller and very asymmetric compared to those of Kerr black holes (Bambi & Freese 2009). Also, some commonly used types of wormholes (Bambi 2013) predict much smaller shadows than we have measured.

Superspinars

- The Kerr BH requires $a < M$
- Solutions with $a \geq M$ show a naked singularity!
- No-hair theorem: BH solutions of GR are characterized only by $M,\ a,\ Q$

Idea: maybe quantum gravity cures the GR effects and hides the singularity even for $a \geq M$

Gimon&Horava 09

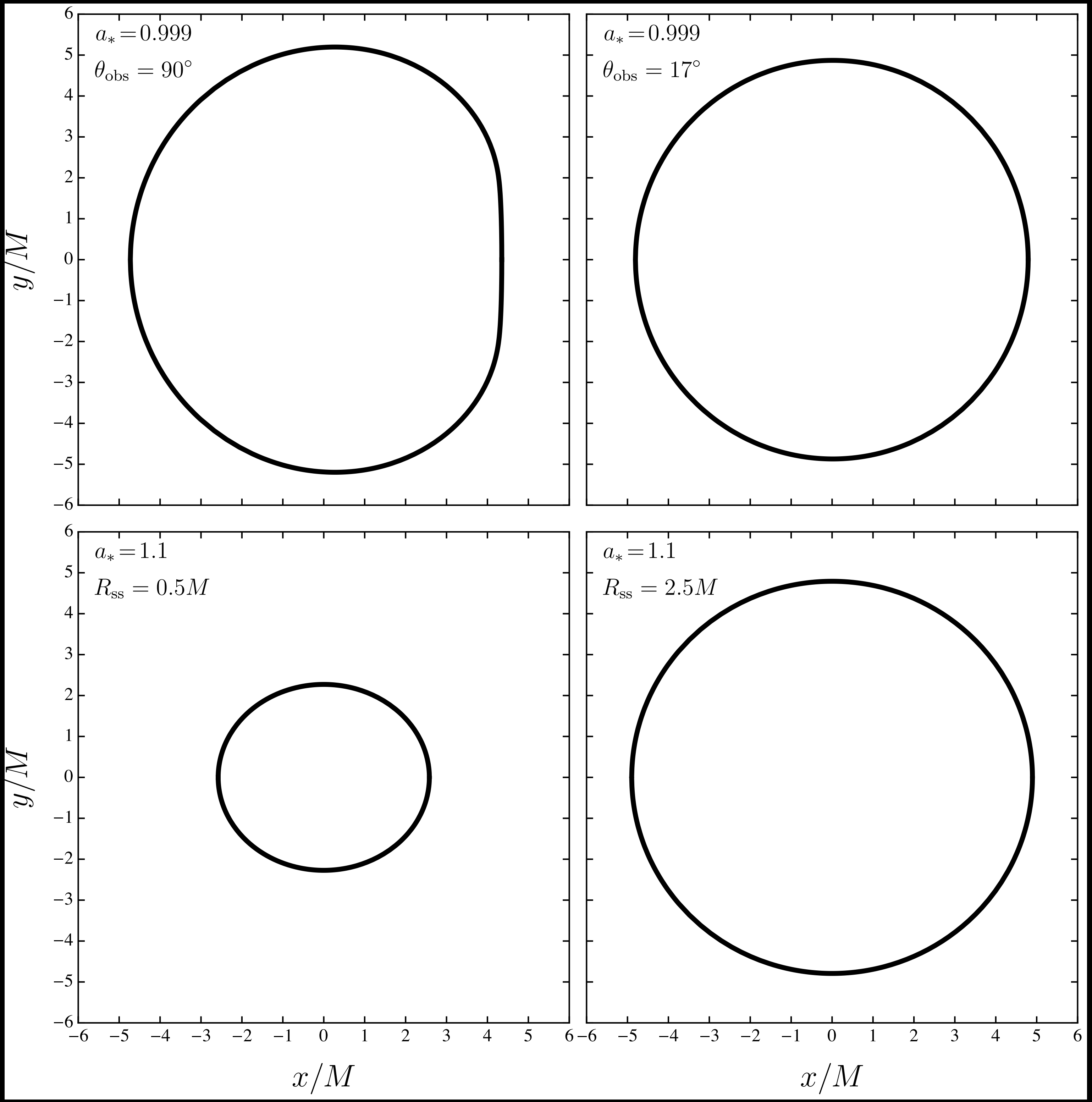
Superspinars

We introduce a new parameter $R_{\rm ss}$

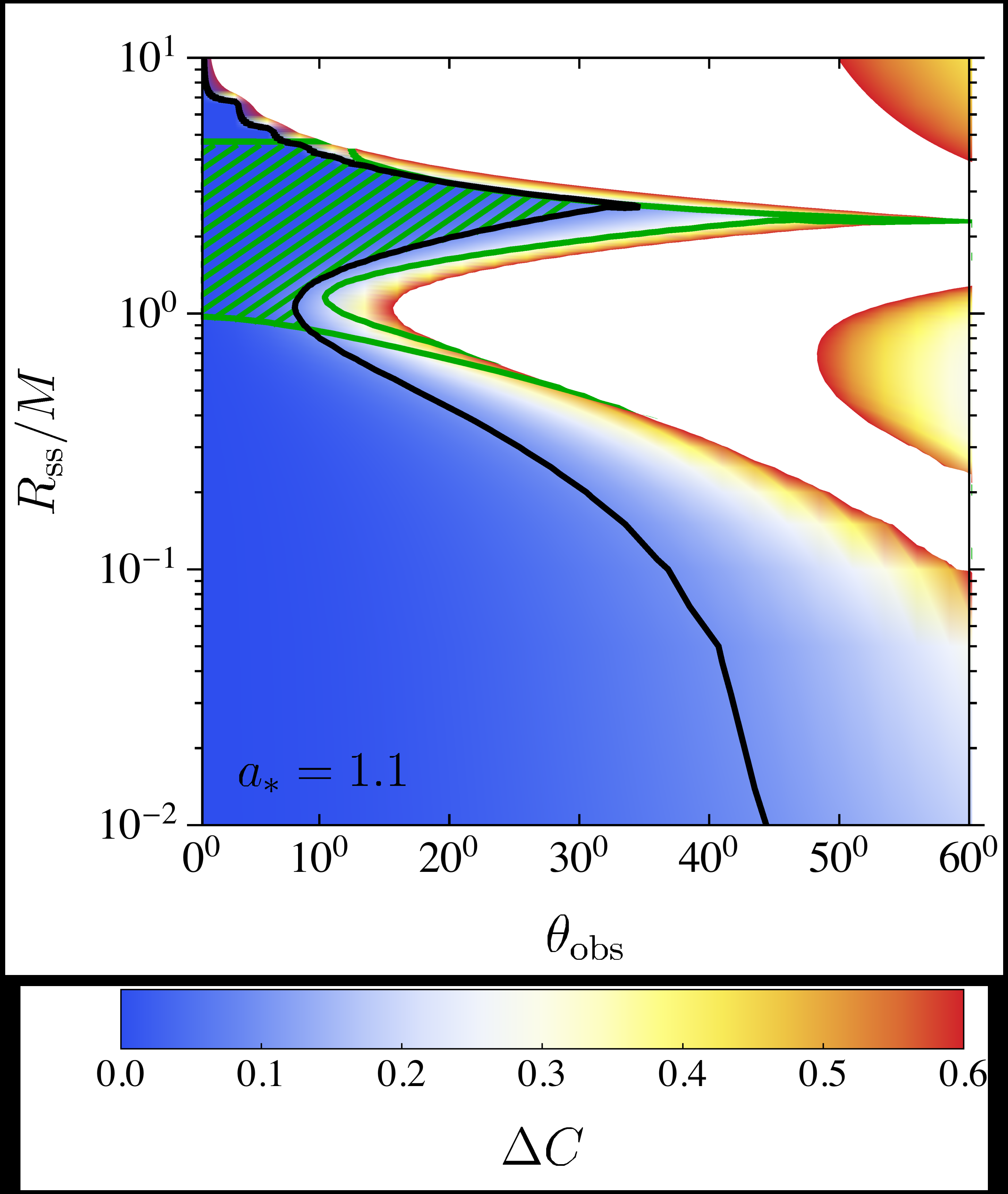
The singularity at $r = 0$ is replaced by an object of finite size $R_{\rm ss}$ that covers the singularity

GR works for $r > R_{\rm ss}$

Superspinars might be remnants from a phase of the Universe when string theory was relevant



Bambi, Freese, Vagnozzi, **LV** Phys.Rev. D**100** 044057 (2019) 1904.12983



Bambi, Freese, Vagnozzi, **LV** Phys.Rev. D**100** 044057 (2019) 1904.12983

Conclusions

Black holes are a gateway to new physics:

- Probe new particles and sectors
- Probe the very early Universe
- Testing physics beyond GR
- New physics (superspinars, extra dimensions…)

hiding in the shadow??