Imaging boson stars

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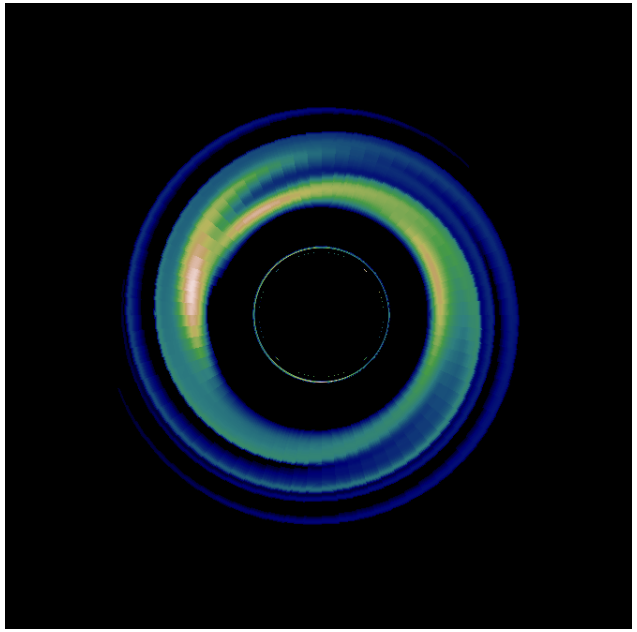
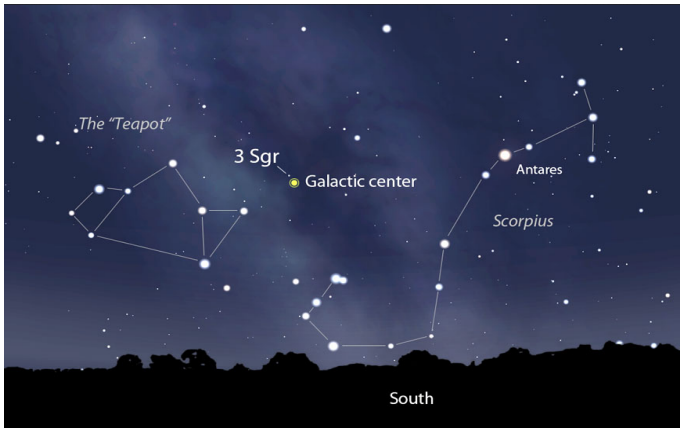
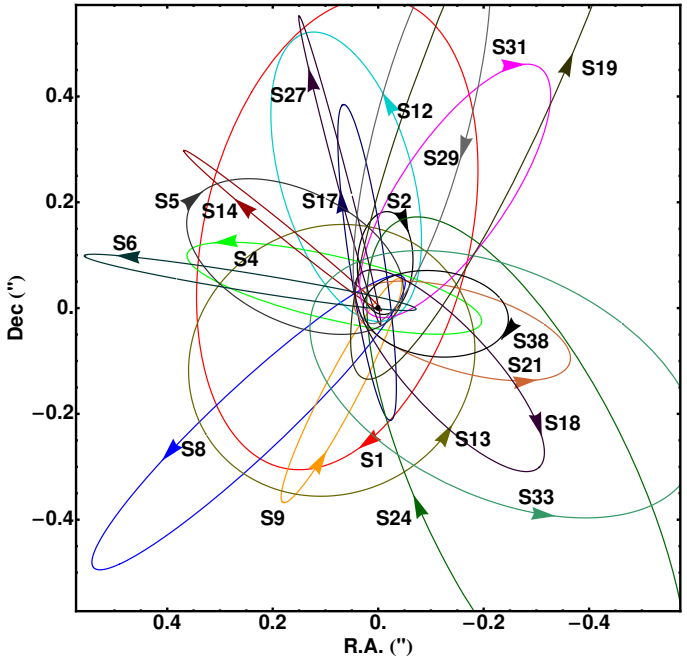




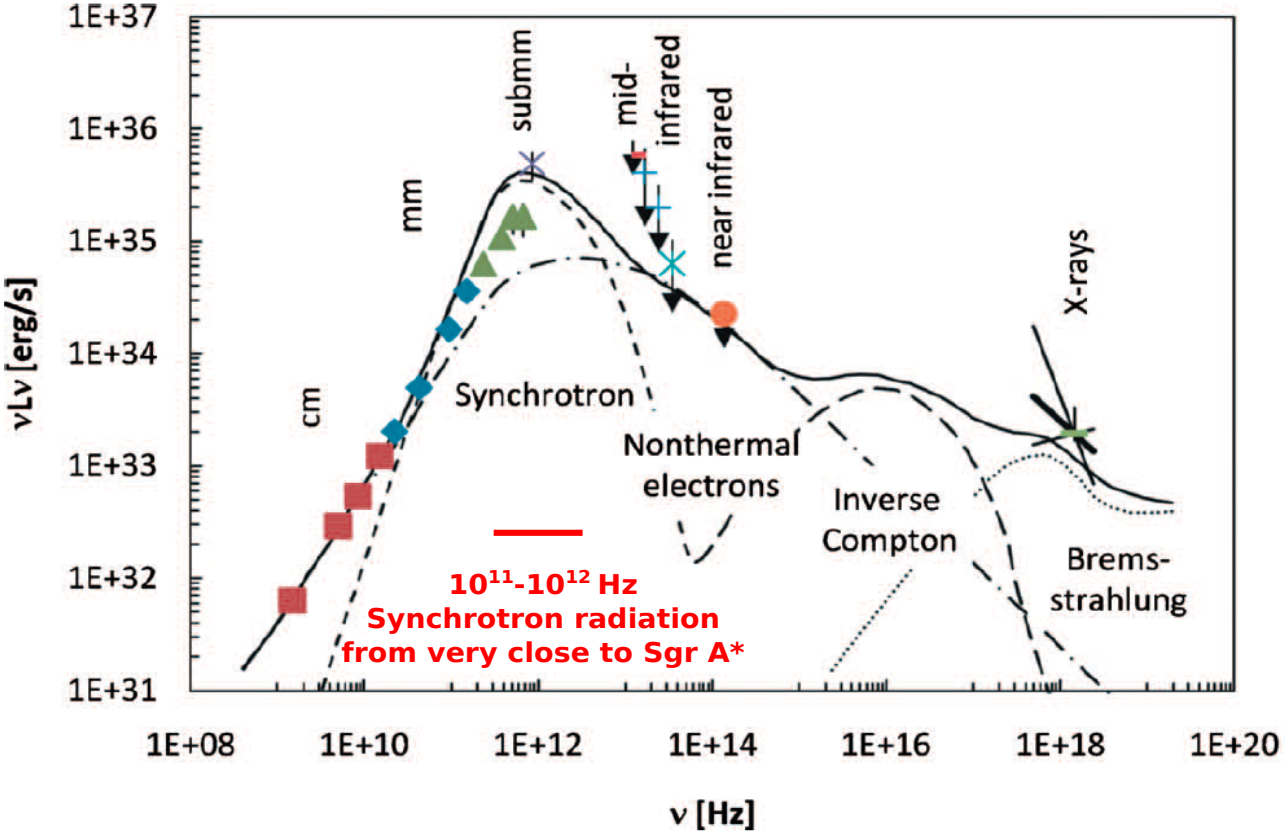
Credit : Stellarium, Bob King



S-stars cluster (Gillessen+09): size = **1" ≈ 0.05 pc**

Sgr A*: big mass in small region, SMBH

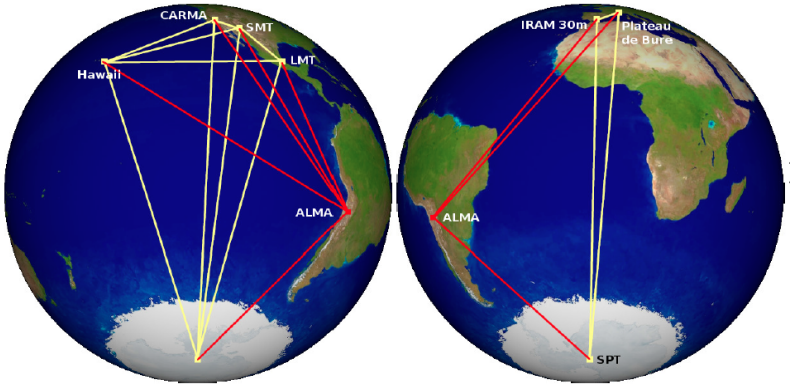
- Astrometric measurements of close stars → central mass
- Sgr A* mass is **4.3 $10^6 M_\odot$**,
  S2 at perimelanophrear at **100 AU** from Sgr A*,
  $\theta_{\mathrm{app,Sch}} \approx$ **50 μas**

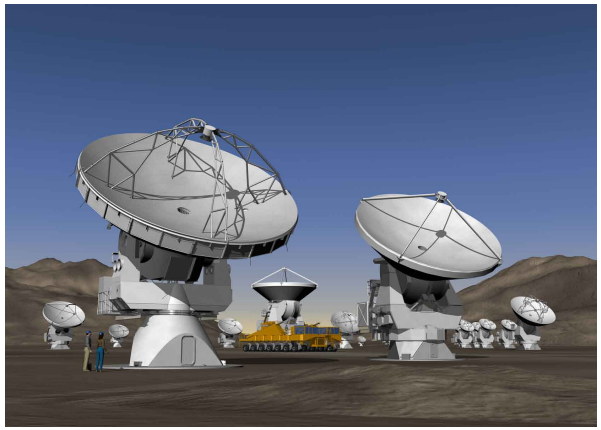


Genzel+10

Sgr A* spectrum

- Different ν $\rightarrow$ different r
- **Innermost accretion flow** at few 100 GHz
- **Thermal synchrotron** emission dominates there



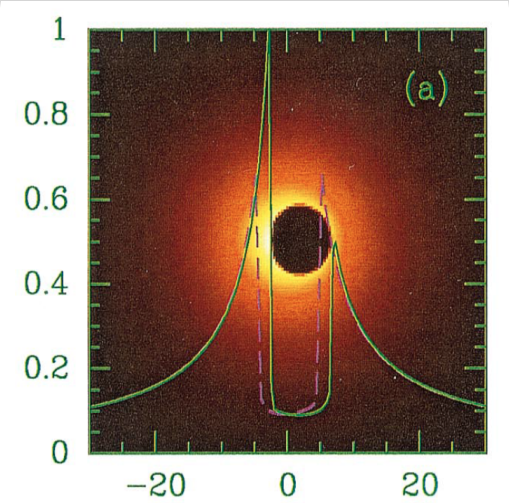


Event Horizon Telescope (2008-2020)

Quiescent state imaging

- EHT: **15** μ**as** resolution (mm; 230 and 345 GHz)

→ Doeleman+08, *Nature, 455, 78*; Doeleman+09, *Astro2010 White Paper*



Falcke+00

Strong-field observables

- **Shadow**: hallmark of an event horizon (Falcke+00)
- From it: spin? No-hair theorem?
- Constrain alternatives to GR??

Our goal

- **Compact object with no event horizon: boson star**
- How does it compare to a Kerr BH?

Cook your boson star

- Vary the action

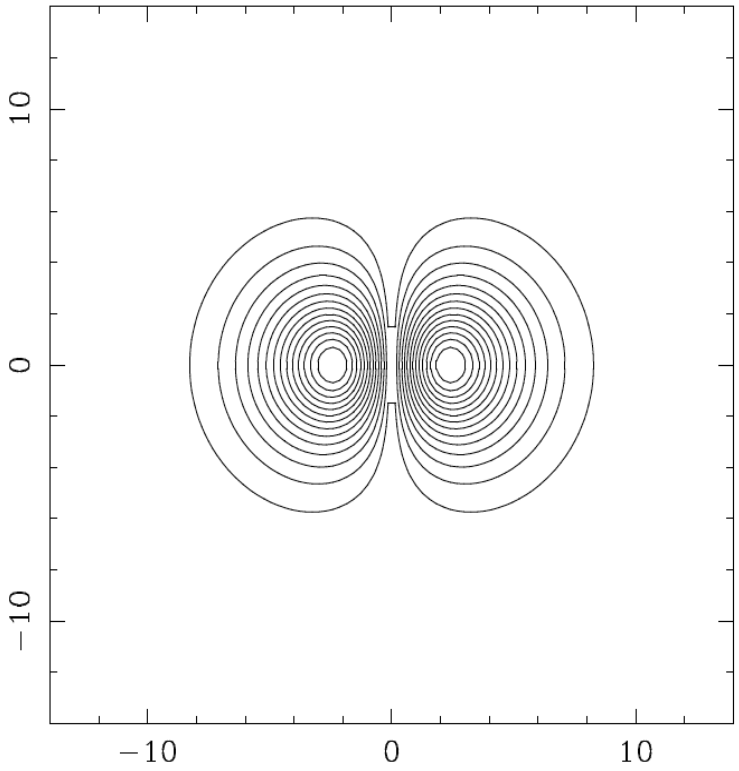
$$S = \underbrace{\int R\sqrt{-g}\,\mathrm{d}^4x}_{\text{gravitation}} - \underbrace{\frac{1}{2}\int \left(\nabla_\mu \Phi \nabla^\mu \bar{\Phi} + \frac{m^2}{\hbar^2}|\Phi|^2\right)\sqrt{-g}\,\mathrm{d}^4x}_{\text{scalar field}} \tag{1}$$

where $\Phi = \phi(r,\theta) \times \exp\left(i(\boldsymbol{\omega} t - \mathbf{k}\varphi)\right)$, $0 \leq \omega \leq m/\hbar$, k int.
describes an assembly of spin-0 bosons

m, individual boson mass, scales the problem (like in Kerr)
ω smaller, more relativistic, "stronger" scalar field ($\phi \to 0$ as $\omega \to m/\hbar$)
k bigger, higher rotation

- Find Einstein equations and Klein-Gordon equation
- Solve them! $\to$ **KADATH** code (P. Grandclément)
- One solution: $(k, \omega) \to (M_{\mathrm{ADM}}, a = J/M^2)$ [a can be > 1]

ϕ contours: a *boson torus* rather



ϕ contours, ($k = 1, \omega = 0.8m/\hbar$);
($M = 1.31 m_{\mathrm{P}}^2/m$, $a = 0.8$); Grandclément+14

Keep in mind

No horizon, no singularity; no hard surface

Polish doughnuts

- **Assumptions**: axisymmetric spacetime, perfect gas in circular orbits, $\ell = -\frac{u_\varphi}{u_t} = \text{cst}$.
  Conservation of energy-momentum:

$$\nabla_\mu T^\mu{}_\nu = 0 \tag{2}$$

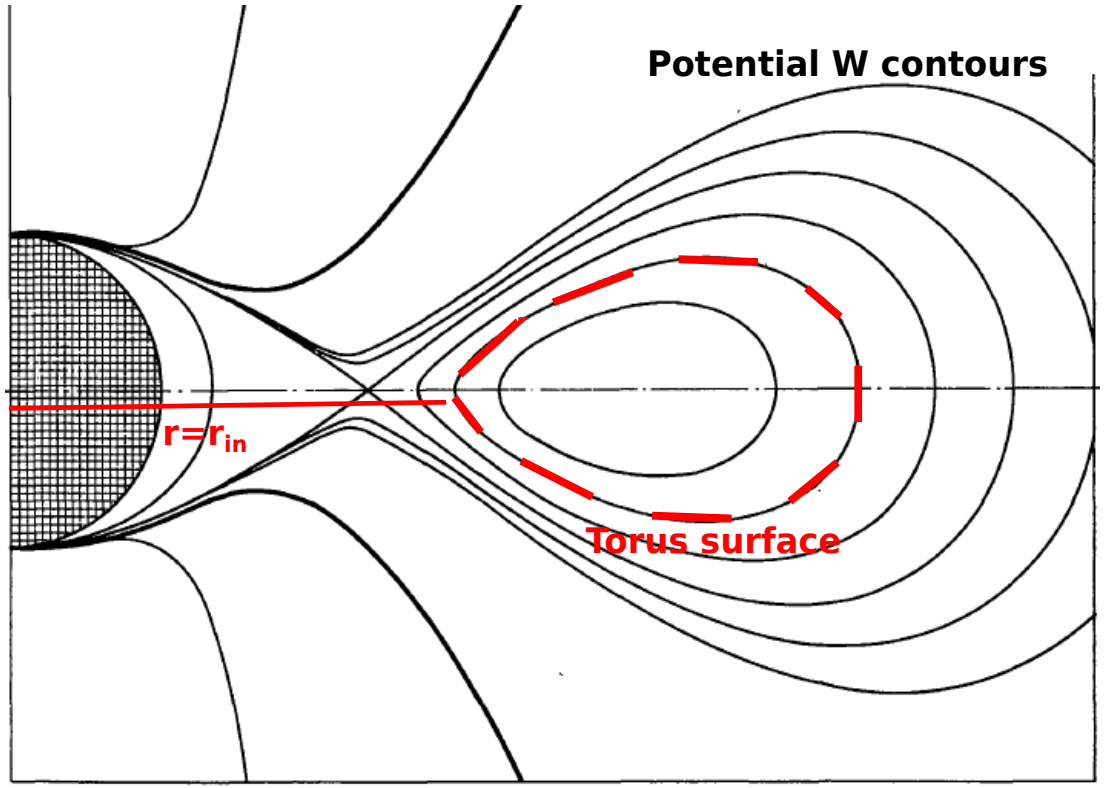
  gives

$$\frac{\nabla_\mu p}{p+\epsilon} = -\nabla_\mu \mathcal{W} \tag{3}$$

  with $\mathcal{W} = \ln(-u_t)$ the doughnut's **potential**.
- For a polytropic fluid, easy to solve for $p = p(r,\theta)$ and ρ, B
- $\rightarrow$ **Polish doughnuts**, simple accretion torus

Polish doughnuts

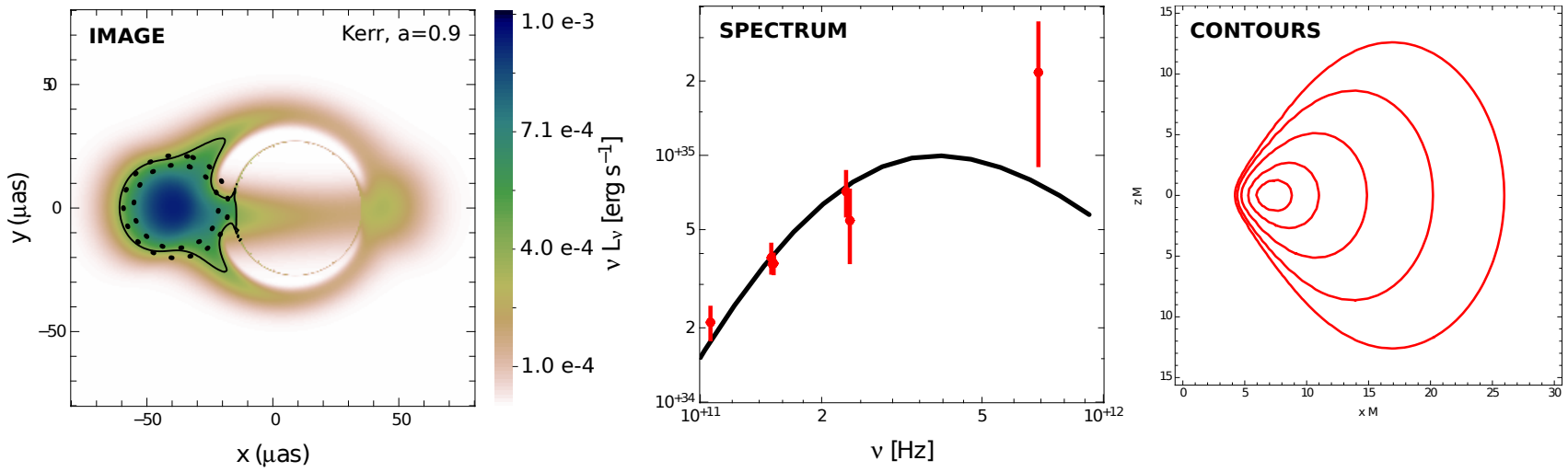
- Compute thermal synchrotron radiation in the torus
- $\rightarrow$ Images at 230 GHz and mm spectrum
- Model parameters: $(\boldsymbol{k}, \omega, \boldsymbol{i}, \ell, \boldsymbol{k}_{\mathbf{polytrope}}, \boldsymbol{r}_{\mathbf{in}}, \boldsymbol{T_c}, \rho_{\boldsymbol{c}}, \beta)$



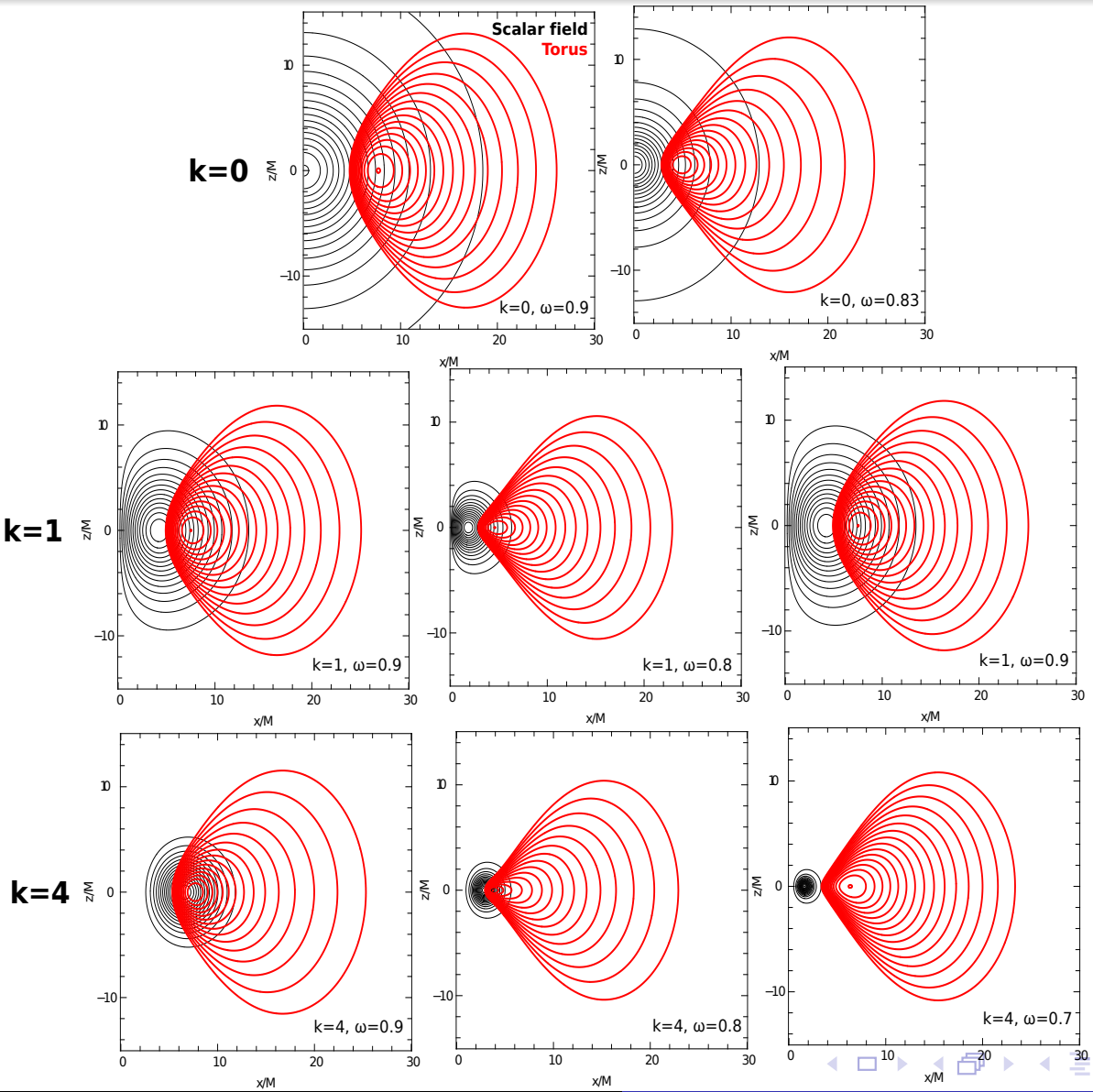
From Abramowicz+78

Setting the physics from Kerr

$(a = 0.9, i = 85^\circ, \ell = 3.2\,M, k = 5/3, r_{\rm in} = 4.2\,M,$
$T_c = 5.3\,10^{10}\ K, n_c = 6.3\,10^6\,{\rm cm}^{-3}, \beta = 0.1)$



ϕ and $\mathcal{W}$ contours



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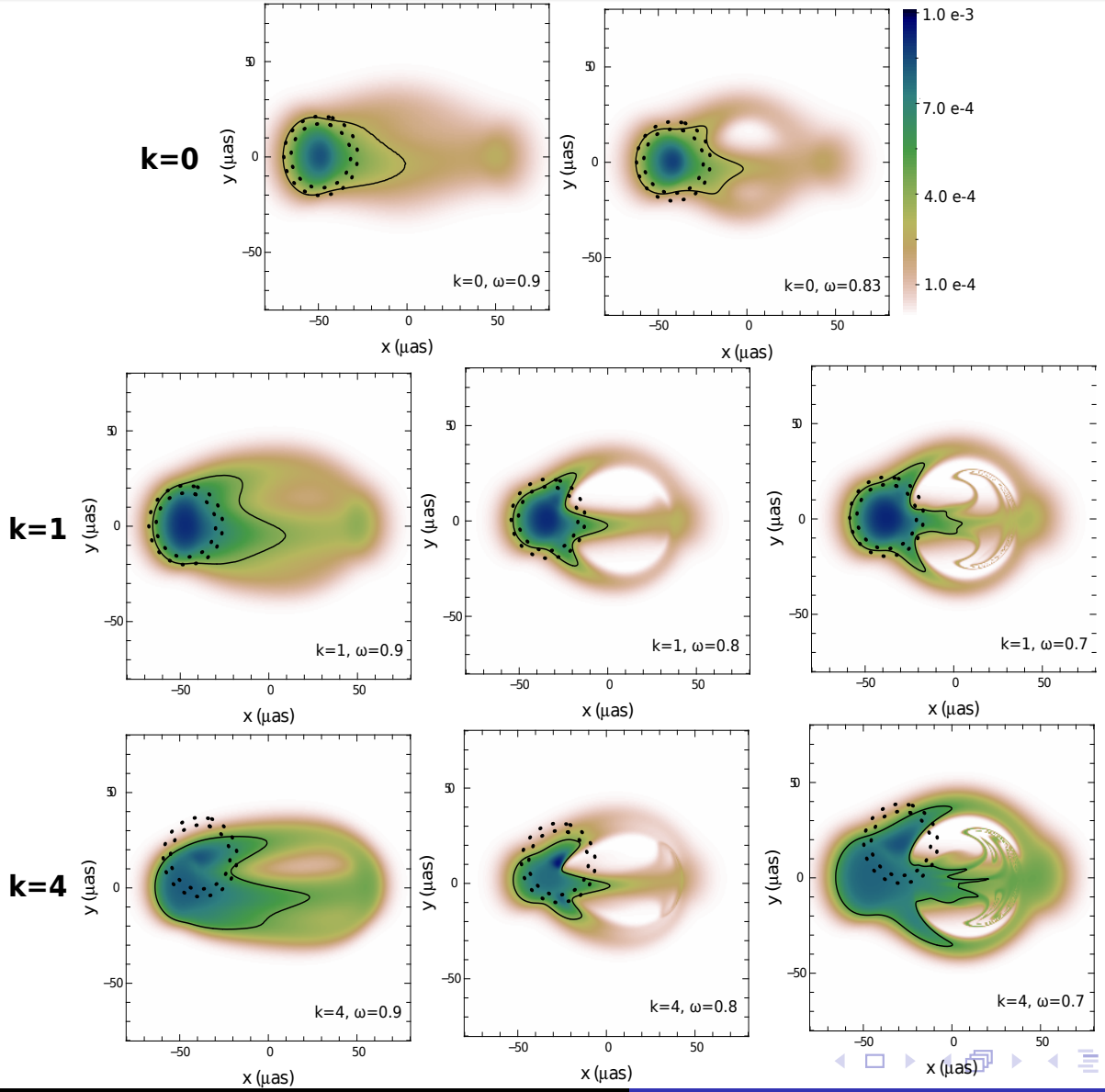
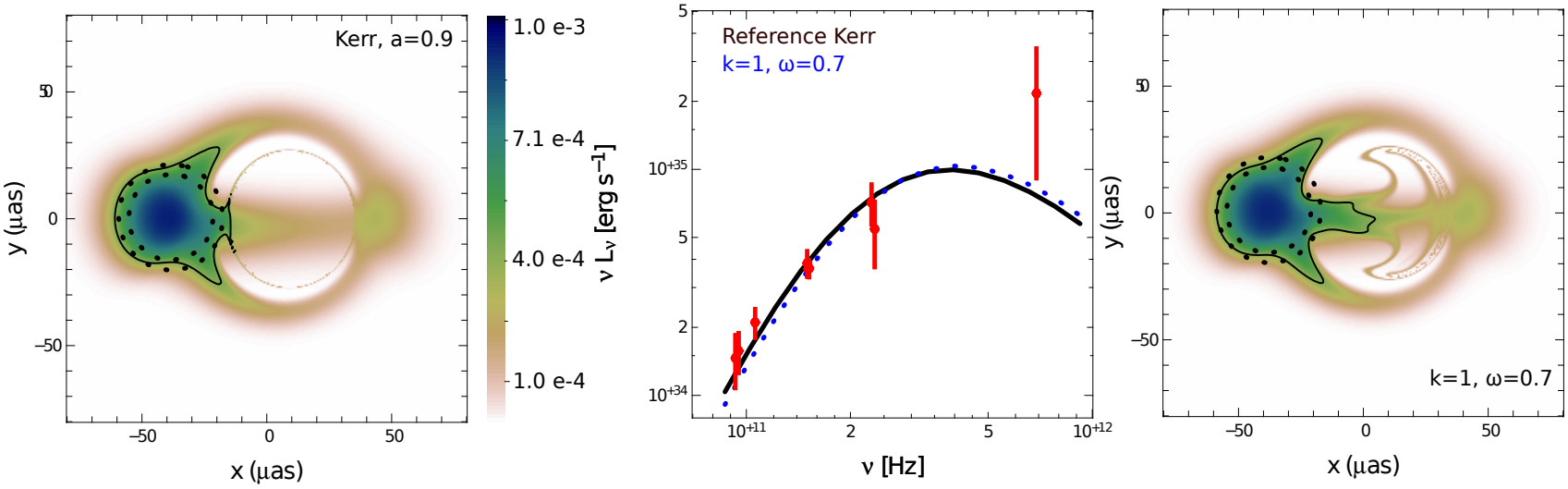
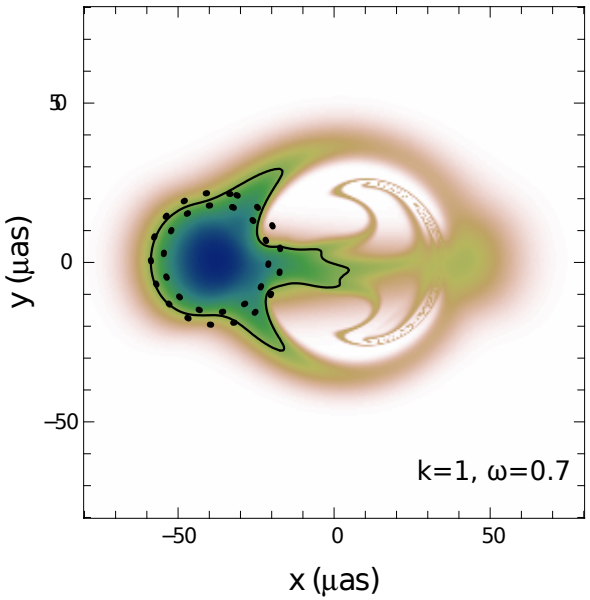
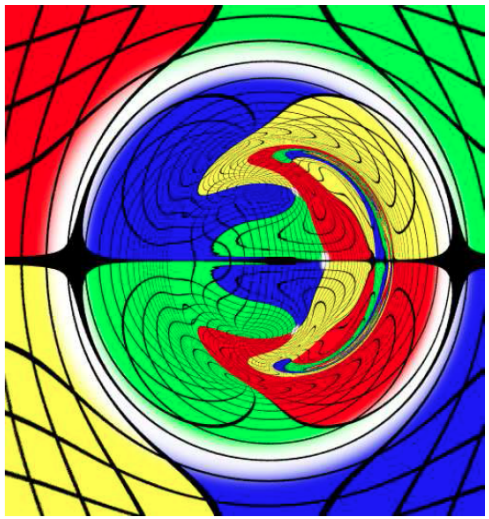


A really similar case



Comparing independent results





Cunha+15

Conclusion

- Picture of an object with no horizon/singularity/surface?
- **BS can have shadow, sharp edges, just like Kerr**
- Tell the presence of an event horizon at Sgr A*???
- Even less likely to tell a boson star from a Kerr black hole

- **Caveats**: more realistic flow / BS self-interaction / will a BH form? / no matter-boson interaction