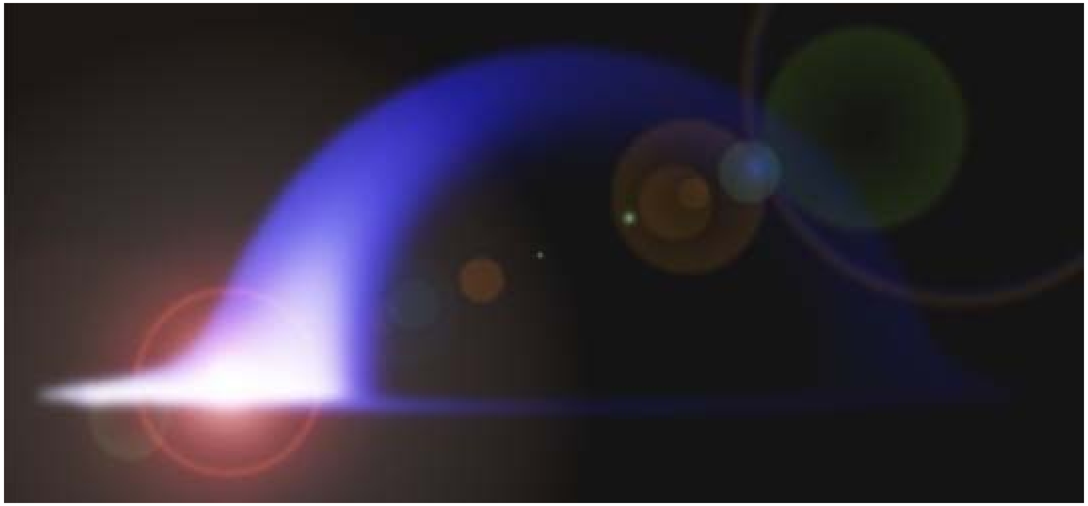
Experimental Evidence of Black Holes



School on Particle Physics,
Gravity and Cosmology

Dubrovnik 2006 September 1st

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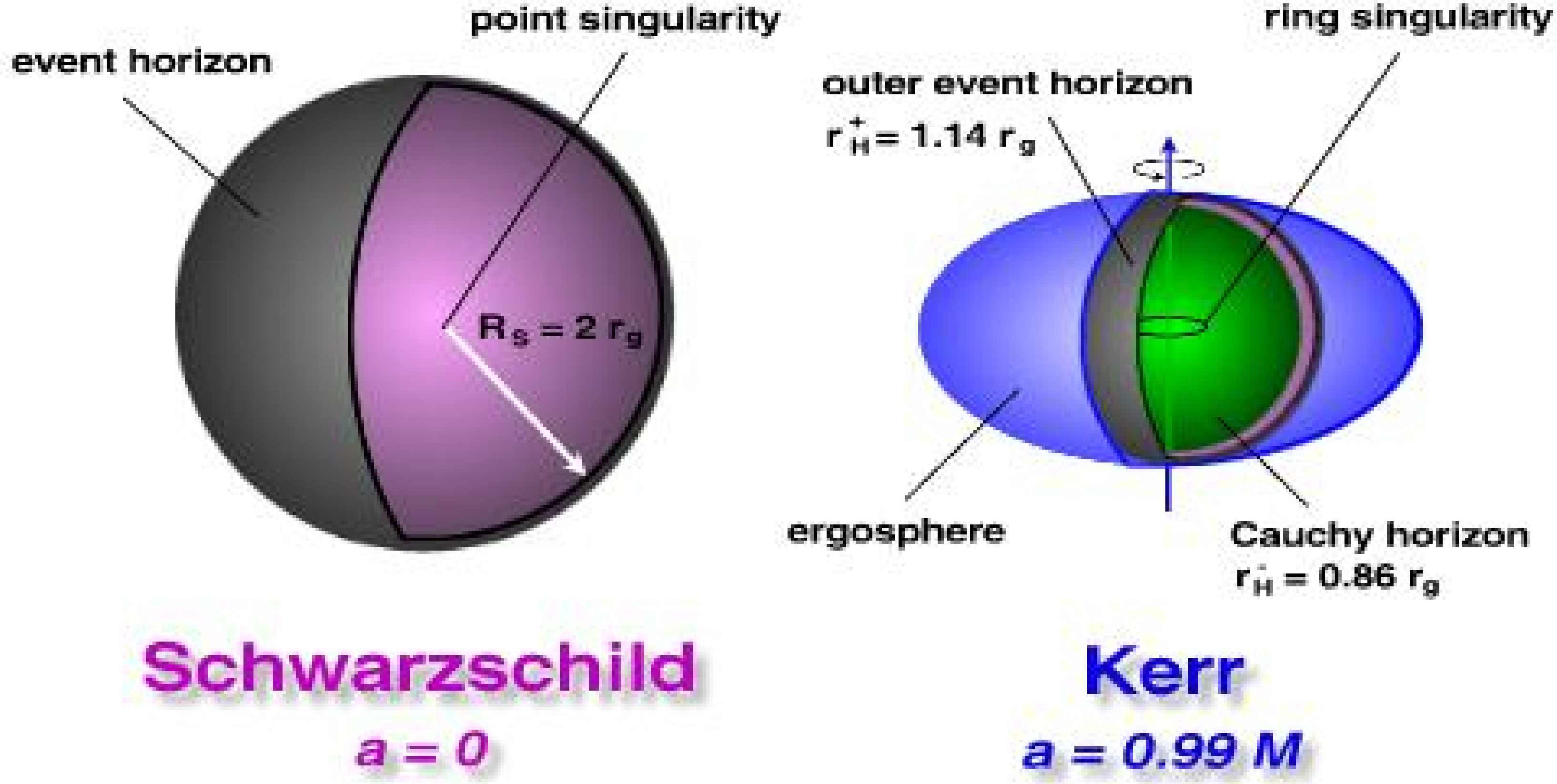
Plan of the talk

- Black hole basics
- Stellar-mass BHs
- Active galactic nuclei (AGN)
- Accretion onto BHs
- Ray tracing techniques
- Detection methods
- Probing BH spin
- What do we observe?

Black hole basics

Schwarzschild vs. Kerr



Kerr solution

- Roy P. Kerr (1963)
- in Boyer-Lindquist-Form (1967)

$$ds^2 = -\alpha^2 dt^2 + \tilde{\omega}^2 (d\phi - \omega dt)^2 + \rho^2/\Delta \; dr^2 + \rho^2 d\theta^2$$

(G = c = 1)

$\alpha = \dfrac{\rho\sqrt{\Delta}}{\Sigma}$	lapse function
$\Delta = r^2 - 2Mr + a^2$	delta potential
$\rho^2 = r^2 + a^2 \cos^2\theta$	generalized radius
$\Sigma^2 = (r^2 + a^2)^2 - a^2 \Delta \sin^2\theta$	sigma potential
$\omega = \dfrac{2aMr}{\Sigma^2}$	frame-dragging frequency
$\tilde{\omega} = \dfrac{\Sigma}{\rho} \sin\theta$	cylindrical radius

black hole mass *M*
spin parameter *a*

Black Hole mass scale

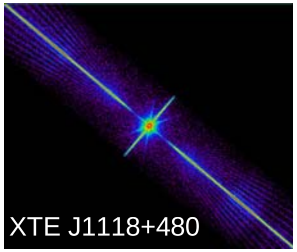
TeV (particle-like):
1000 protons ~ 10^{-21} g

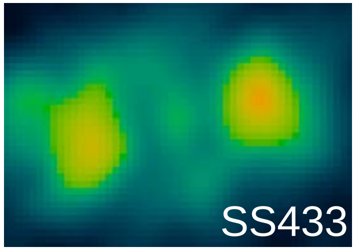
?

primordial:
10^{18} g ~ mountain mass

?

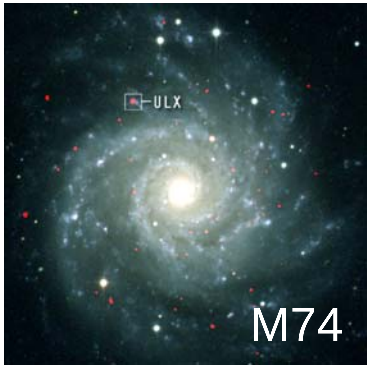
stellar:
3…100 $M_\odot$



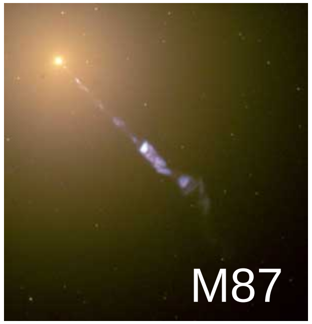


intermediate-mass:
100…1000 000 $M_\odot$

?



supermassive:
1000 000…10 000 000 000 $M_\odot$



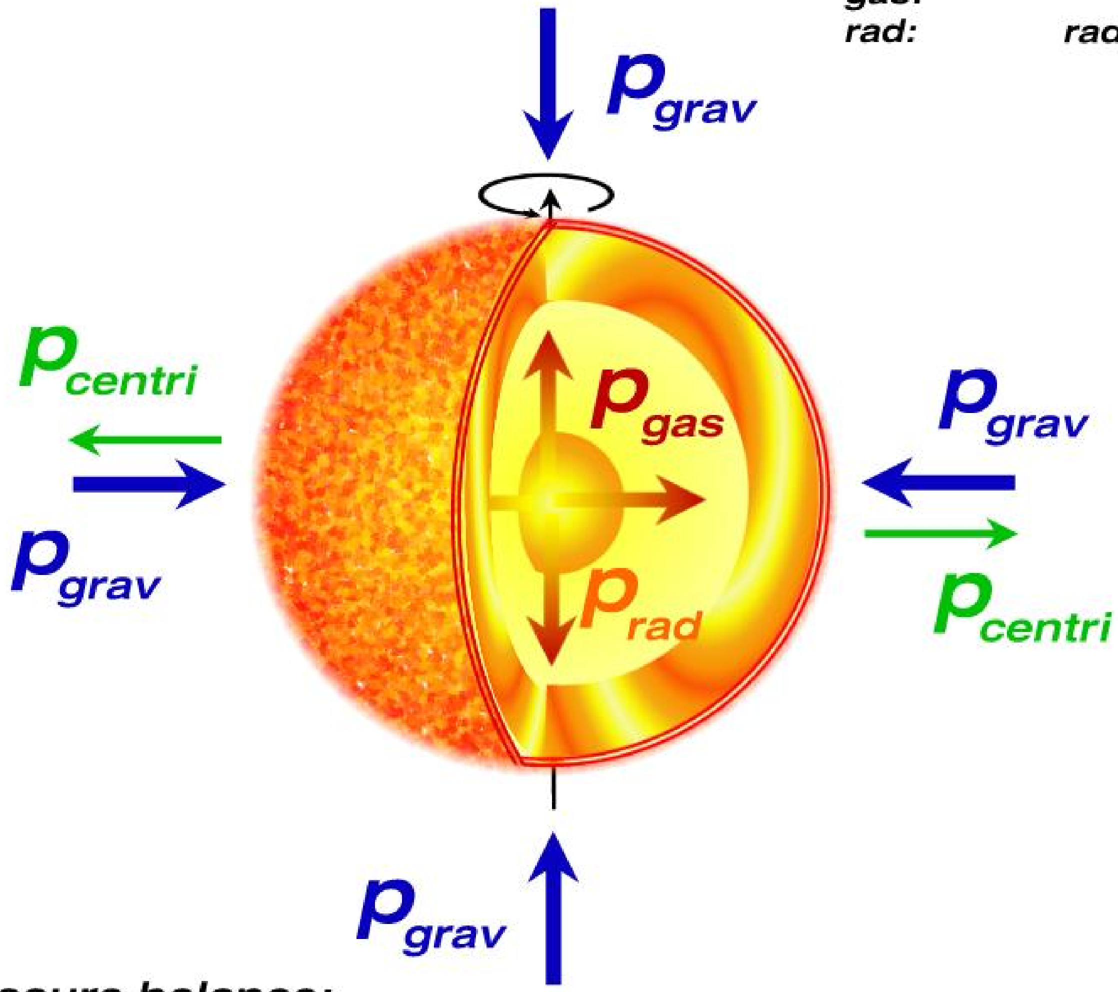
images: Chandra, HST, NASA

Stars

hydrostatical equilibrium

pressure species:

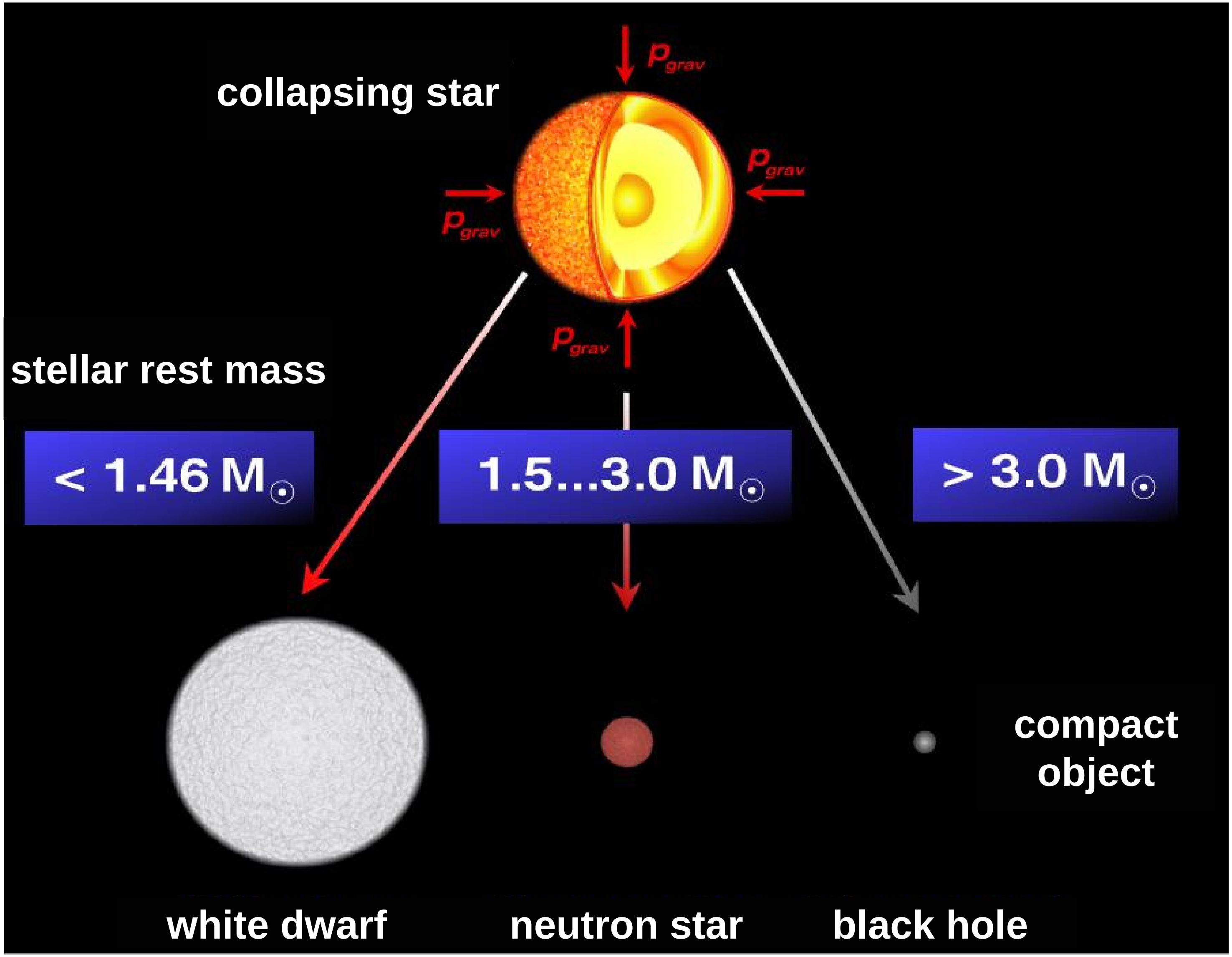
grav:	*gravitational*
centri:	*centrifugal*
gas:	*gas*
rad:	*radiative*



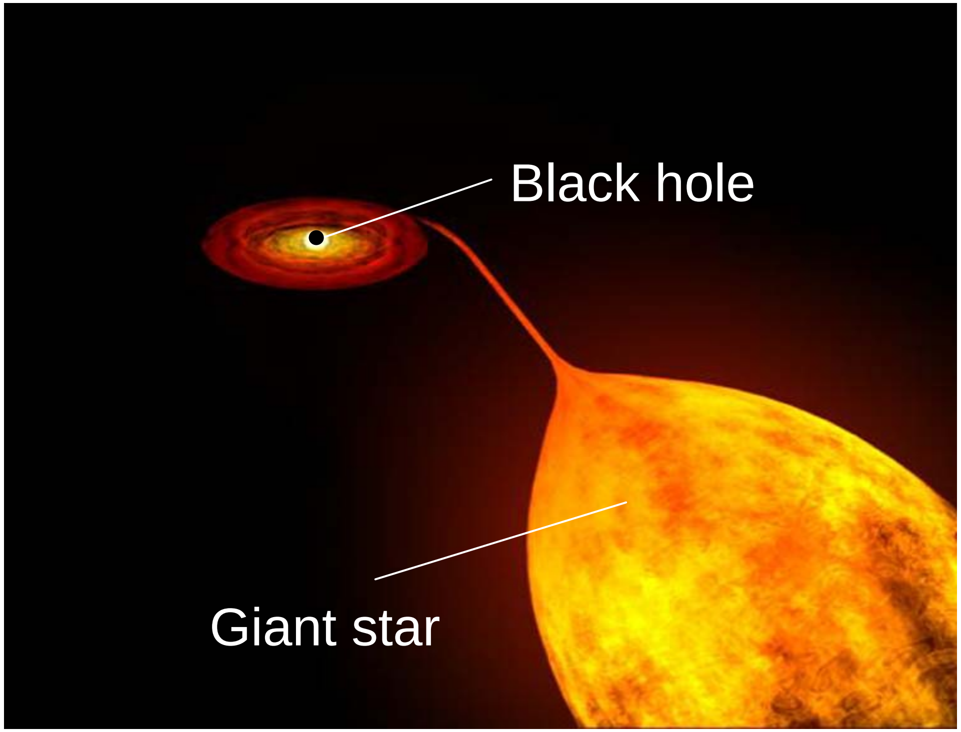
pressure balance:

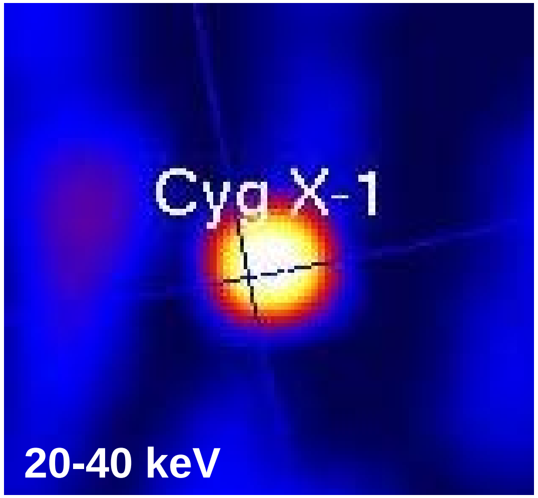
$$p_{grav} = p_{centri} + p_{gas} + p_{rad}$$

Gravitational collapse of stars



X-ray binary Cyg X-1





Sketch from Chandra Website

$M_{BH} \sim 10\ M_{\odot}$

D ~ 2 kpc

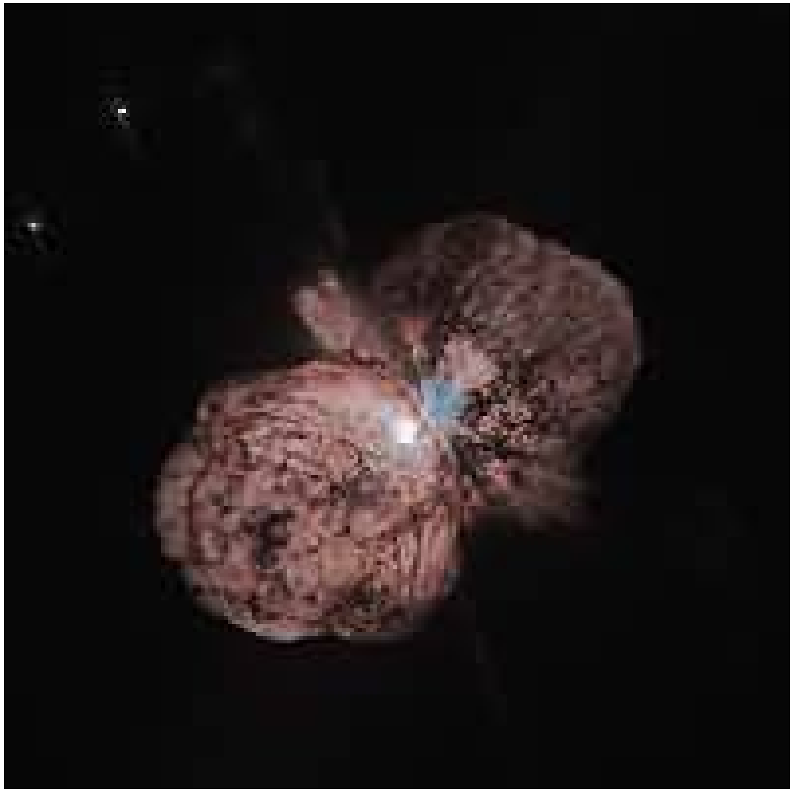
Observation: Integral, ESA, Beckmann et al. 2003

Candidate η Carinae

- Southern sky: Carina
- Super star M >100 $M_\odot$
- distance: 7500 Lj
- Luminous Blue Variable (LBV)

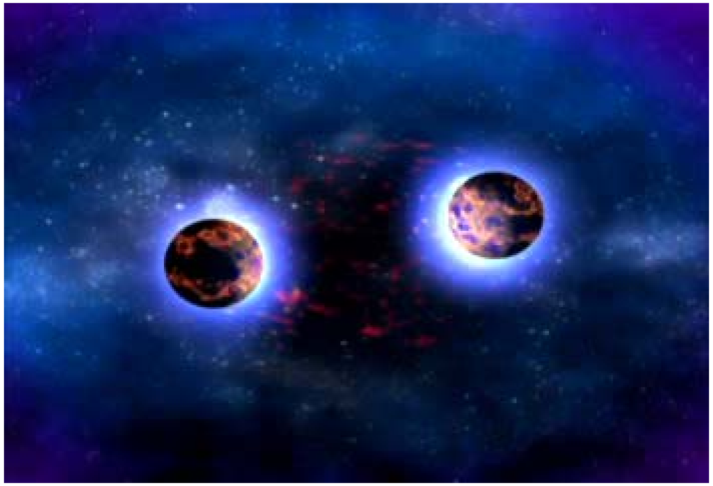
- Gigantic stellar explosion: **hypernova**
- E ~ 10^{53} erg = 10…100 x E_{SN}

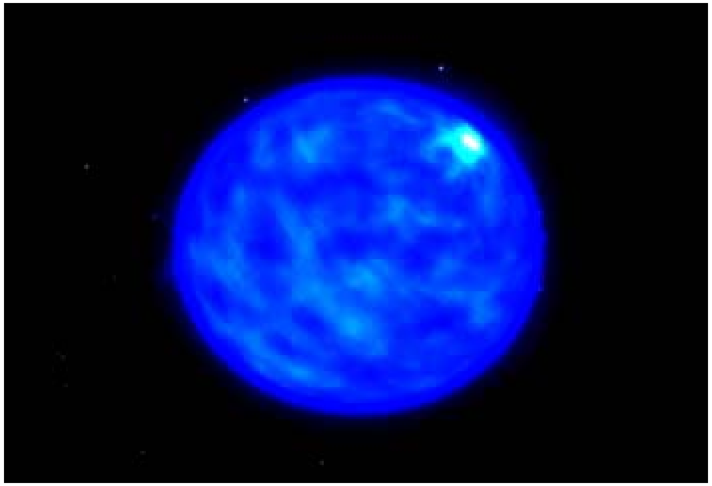
- expected relic object: **stellar black hole**



Hubble space telescope 1996

Gamma ray bursts (GRBs)





Animations from Swift website

I) short duration

(0.01s < t < 2s)

merging compact objects

e.g. NS-NS

II) long duration

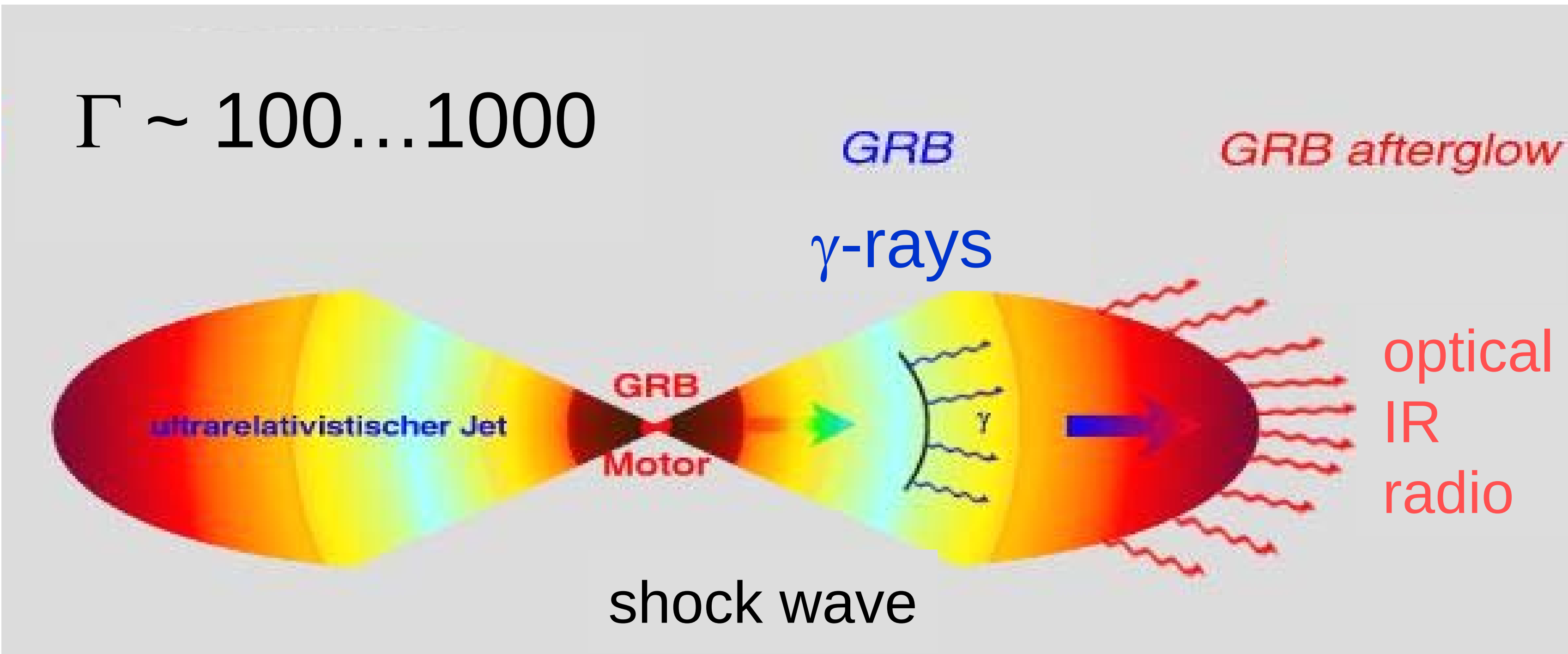
(2s < t < 1000s)

collapse of a massive star

GRBs: **forming black holes caught in the act!**

isotropic distribution over sky – cosmological origin

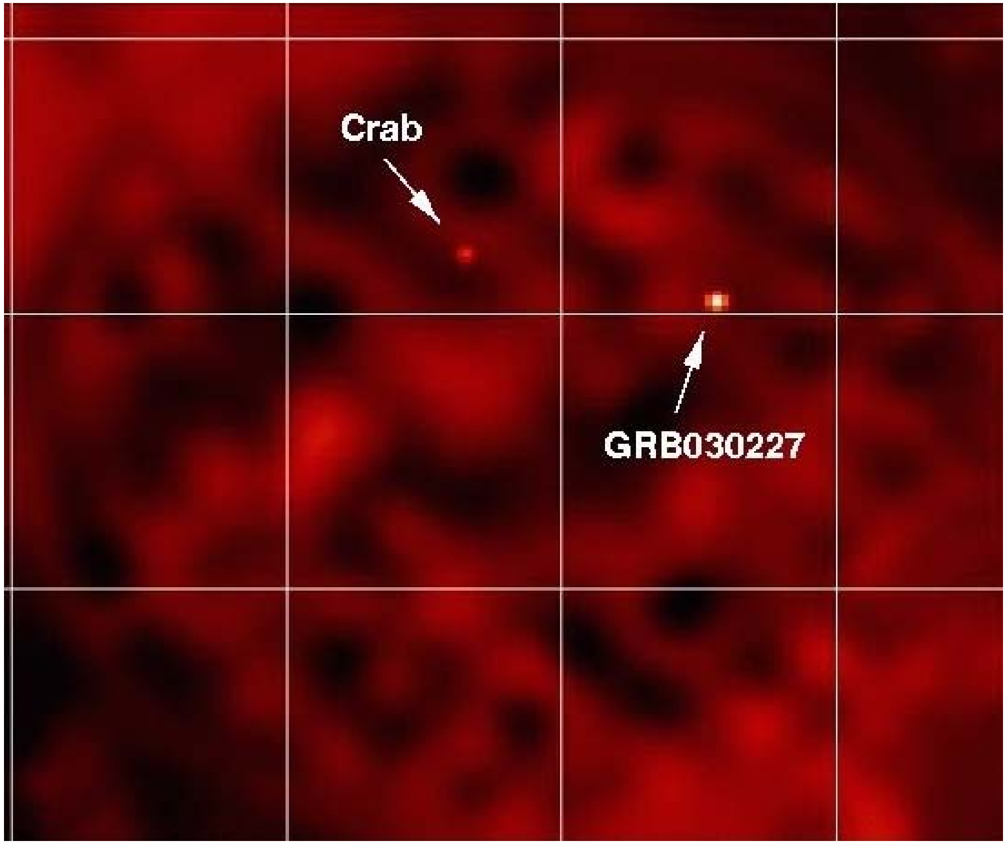
Anisotropic fireball model for GRBs



Model established by Meszaros & Rees 1993, 1997;
Paczynski & Rhoads 1993

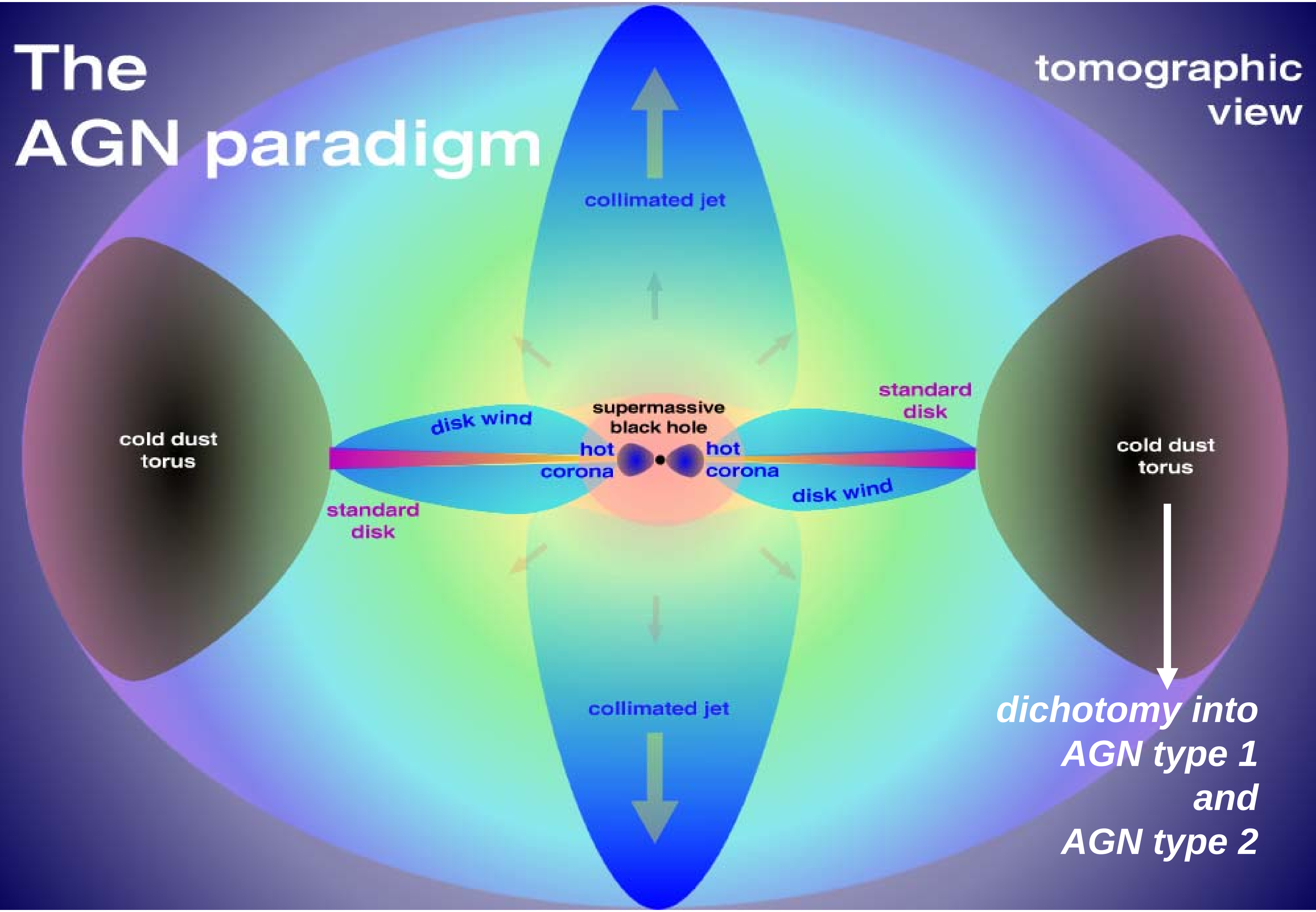
GRB observation – Example

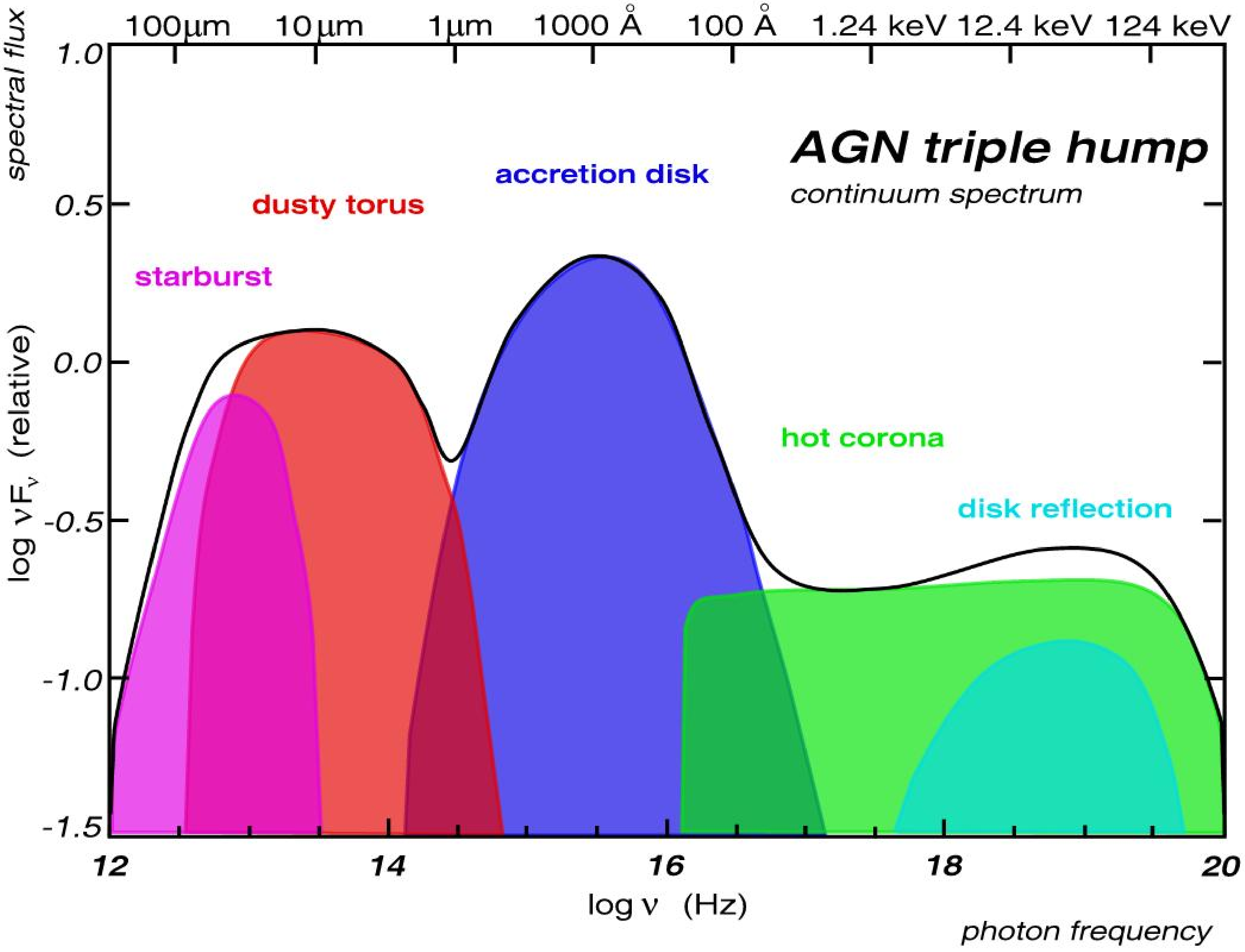
- GRB030227
- t ~ 20 s
- E_γ ~ 20 – 200 keV
- X-ray afterglow 8 hr after prompt emission
- Optical afterglow 12 hr after prompt emission



observation: Integral, ESA, Beckmann et al. 2003

Active galactic nuclei (AGN)


The
AGN paradigm
tomographic
view
collimated jet
standard
disk
supermassive
black hole
disk wind
cold dust
torus
hot
corona
hot
corona
cold dust
torus
disk wind
standard
disk
collimated jet
dichotomy into
AGN type 1
and
AGN type 2



spectral flux
100µm 10µm 1µm 1000 Å 100 Å 1.24 keV 12.4 keV 124 keV
1.0
0.5
0.0
-0.5
-1.0
-1.5
AGN triple hump
continuum spectrum
accretion disk
dusty torus
starburst
hot corona
disk reflection
log νF$_ν$ (relative)
12
14
16
18
20
log ν (Hz)
photon frequency

Accretion onto black holes

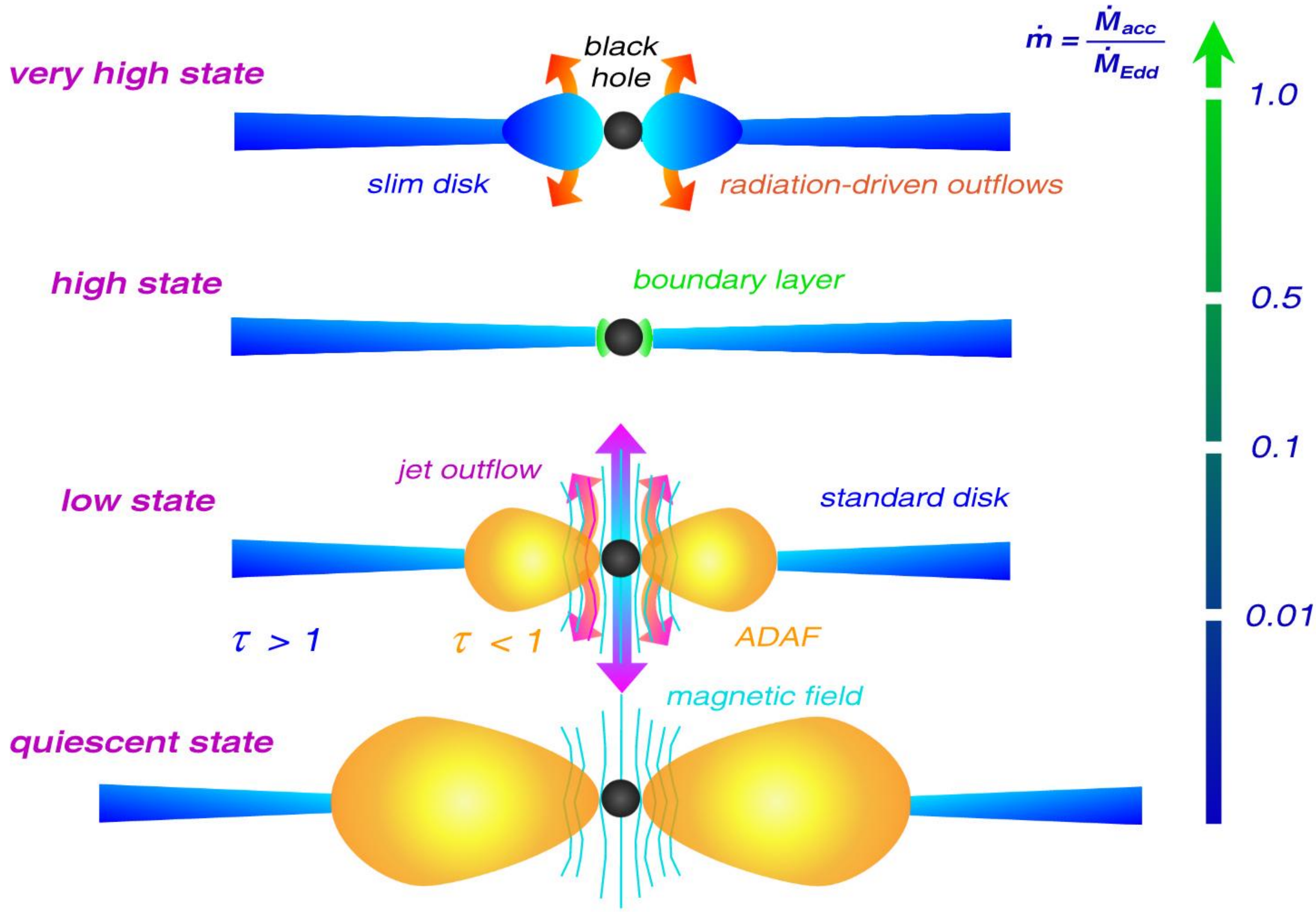
Eddington's argument

$$L_{\rm Edd} = \frac{4\pi G M\,{\rm m_p} c}{\sigma_{\rm T}} \approx 1.3 \times 10^{46}\,{\rm erg\,s^{-1}}\,\left(\frac{M}{10^8\,{\rm M_\odot}}\right)$$

$$\dot{M}_{\rm Edd} \simeq 20\,{\rm M_\odot\,yr^{-1}}\,\left(\frac{0.1}{\epsilon}\frac{L}{10^{47}\,{\rm erg\,s^{-1}}}\right)$$

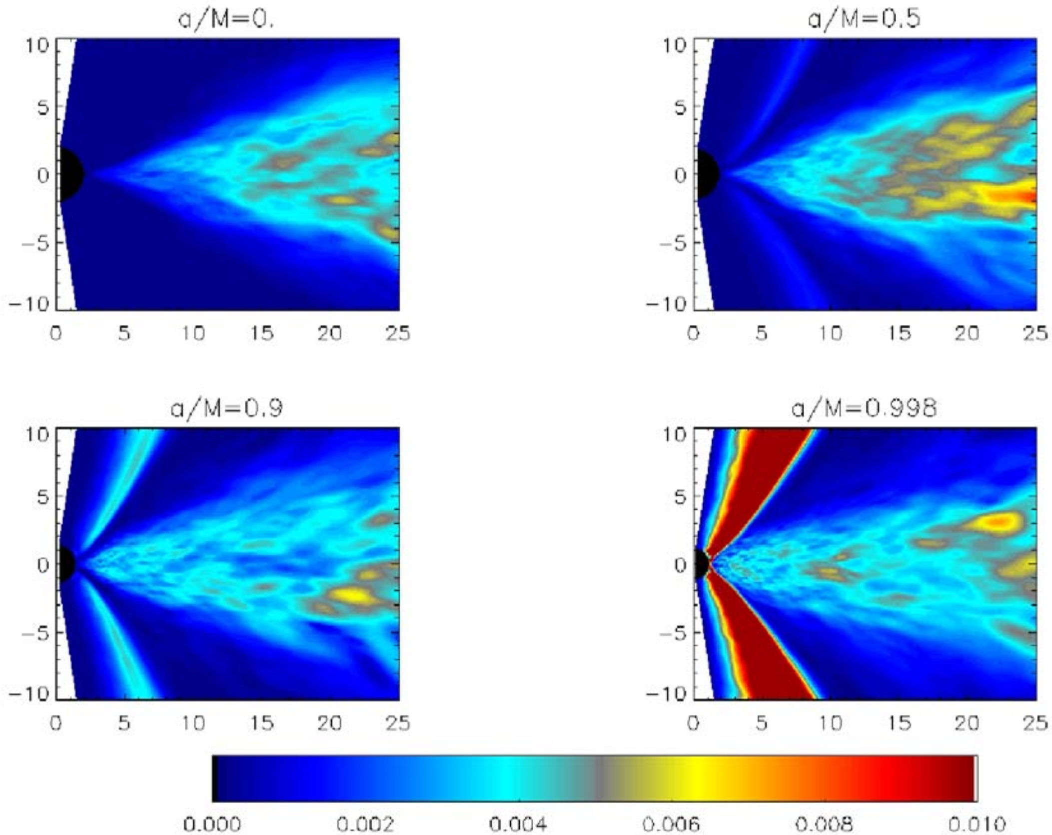
- observed luminosity hints for BH mass
- accretion rate related to luminosity

- Super-Eddington accretion possible e.g. in disk accretion


very high state
black hole
slim disk
radiation-driven outflows
high state
boundary layer
low state
jet outflow
standard disk
$\tau > 1$
$\tau < 1$
ADAF
magnetic field
quiescent state
$\dot{m} = \frac{\dot{M}_{acc}}{\dot{M}_{Edd}}$
1.0
0.5
0.1
0.01

Jet launching: Need for Kerr

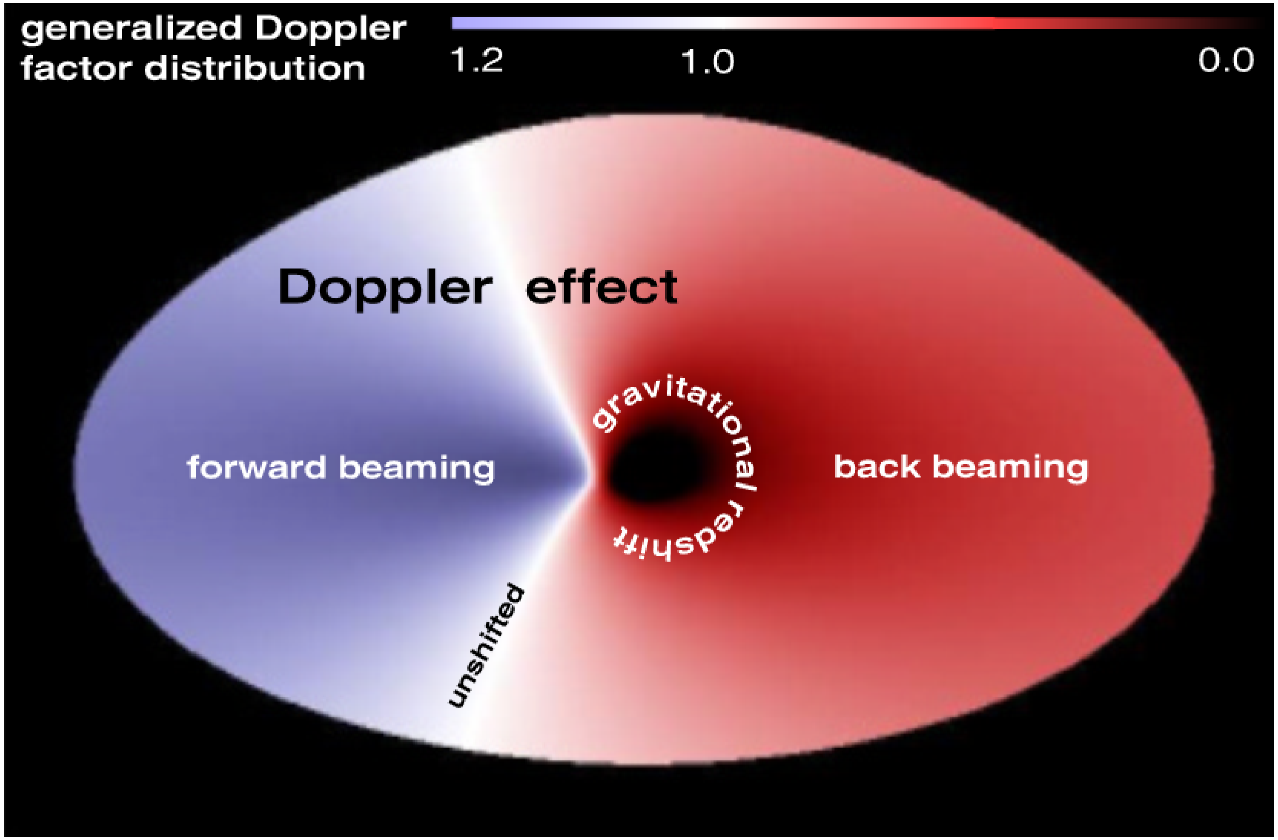
- Supercomputer simulations: non-radiative, ideal general relativistic magneto--hydrodynamics
- Poynting flux from rapidly <u>spinning</u> BH drives ‚funnel-wall' outflow!
- becomes > 10% rest-mass accretion rate at high spins
- however outflow has Γ_{sim} ~ 2 only whereas Γ_{obs} ~ 10



Krolik et al. 2004

Ray tracing techniques

Kerr ray tracing - render disk images



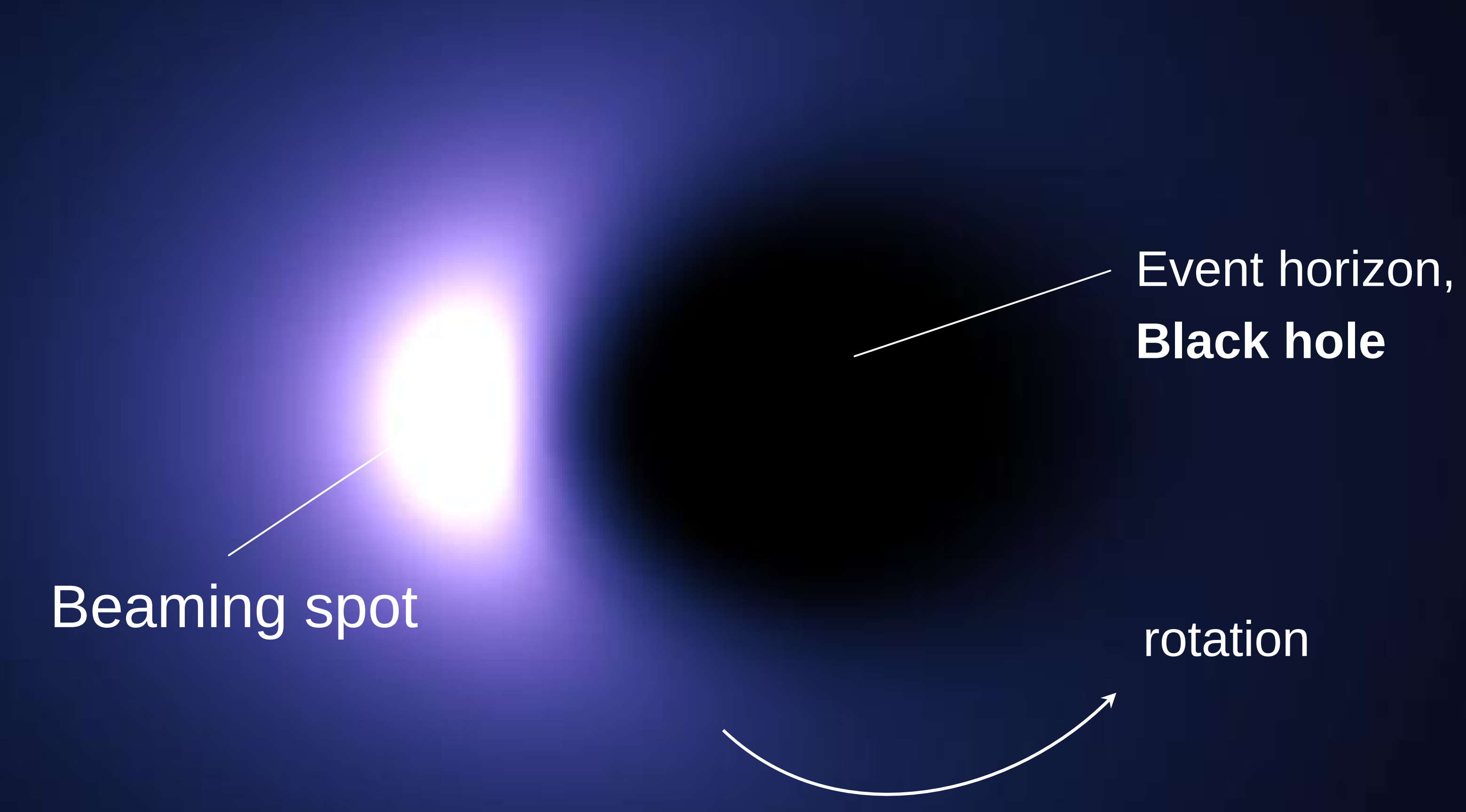
i = 60°
a = 0.99 M
$r_{in} = r_H$
$r_{out} = 30.0\ r_g$

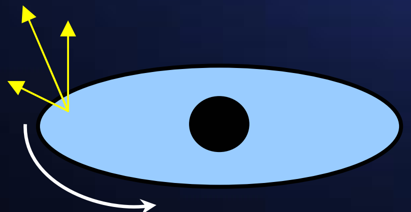
Keplerian kinematics

Müller, diploma thesis 2000

- Doppler effect distorted by beaming (SR) and gravitational redshift (GR)
- fully relativistic generalized Doppler factor
- effects influence *__any emission__* in black hole systems!

Kerr ray tracing





Computer simulation of rotating thin gas disk Müller PhD 2004

Kinematical methods

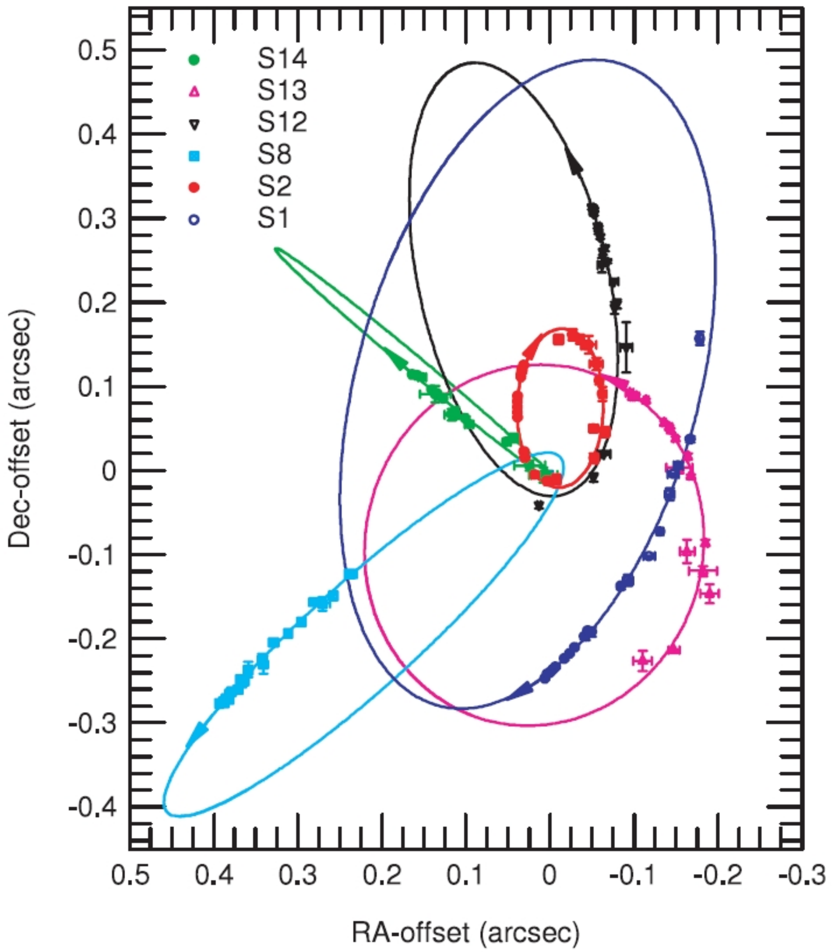
Hightech in Atacama desert

- four 8m-telescopes on 2635m mountain, optical and near-infrared
- interferometry ⇨ resolving power comparable to space telescope (0.05“ to mas! Full moon / 40000)

*Stellar Orbits at Sgr A**

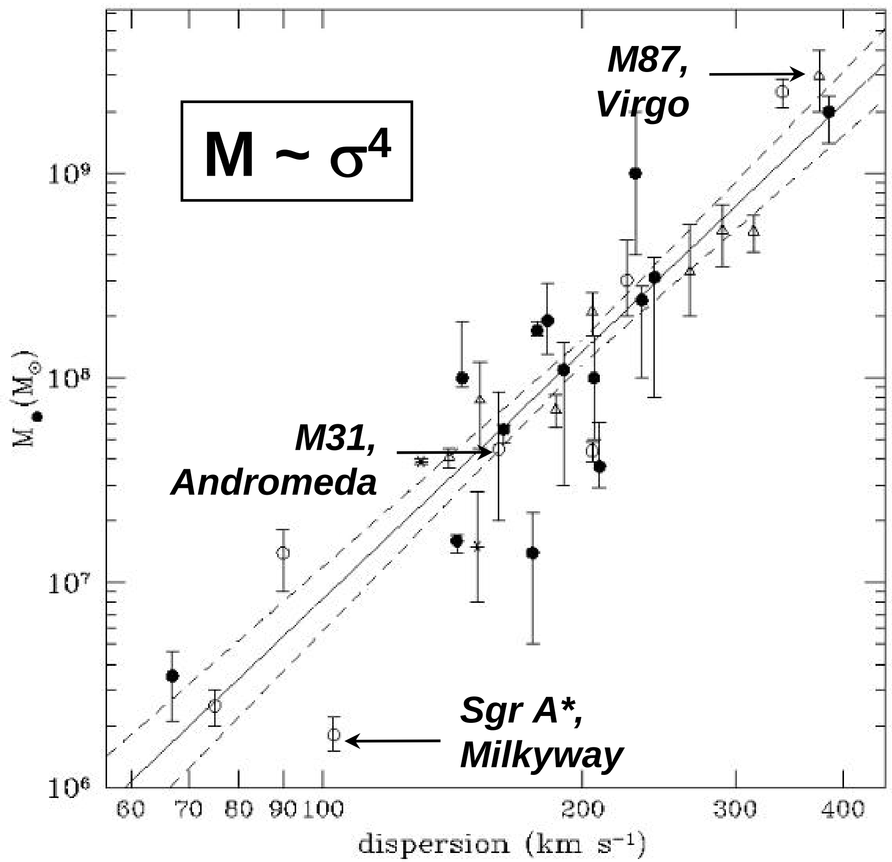
- probe stellar motion of stars in NIR
- S stars
- Keplerian laws:
  $M = 3.6 \times 10^6\ M_\odot$

- *Genzel group MPE:*
  Eckart et al. 1992
  Schödel et al. 2002
  Eisenhauer et al. 2005
- *Ghez et al. 1998, 2000, 2003*



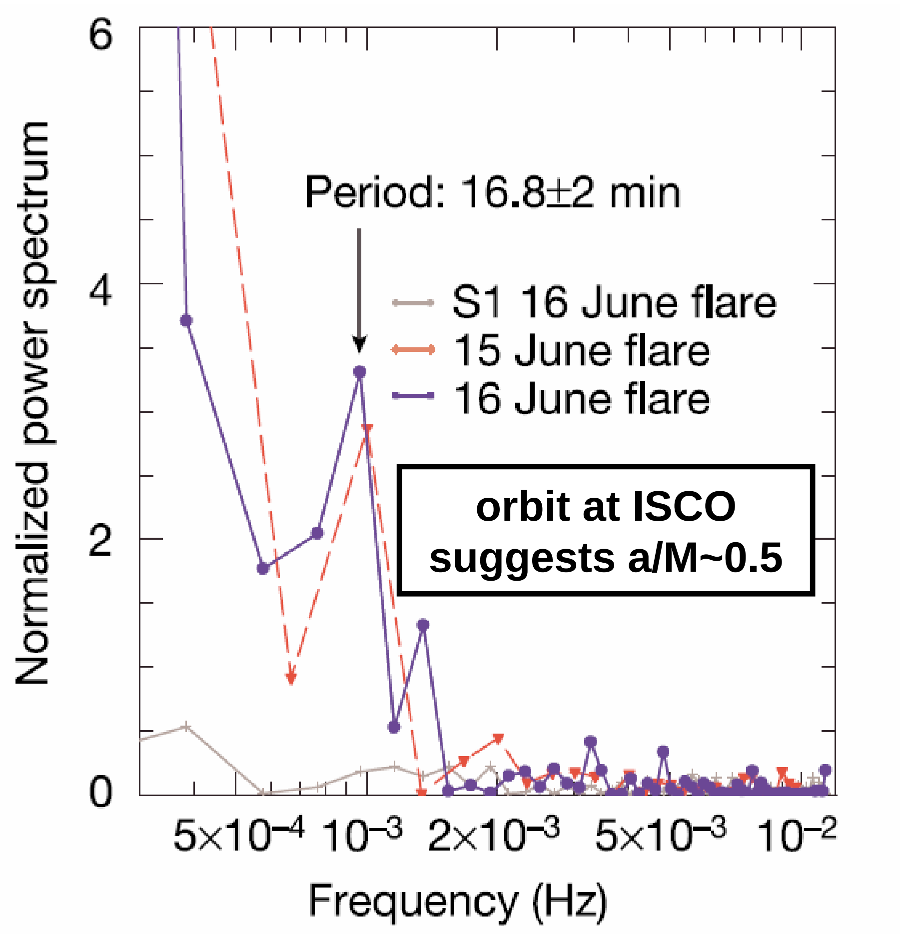
M-σ relation

- tight correlations between black hole and surrounding spheroid
- *Magorrian et al. 1998*
- *Hähnelt & Kauffmann 2000*
- *Tremaine et al. 2002* ⟶
- *Ferrarese & Merritt 2002*
- conflicts with $M\text{-}L_V$
- *Lauer et al. astro-ph/0606739*
- curved M-σ, brightest cluster galaxies: low σ for their high L
- *Wyithe 2006*



Other kinematical methods

- QPOs at microquasars
  - *Abramowicz et al. 2001*
  - *Aschenbach et al. 2004*
- Flares (NIR + X at Sgr A*)
  - *Genzel et al. 2003*
  - *Aschenbach et al. 2004*
- reverberation mapping
  - ➢ optical
    - *Peterson et al.*
  - ➢ X-rays
    - *Reynolds et al.*



Obscurative methods

obscura, Latin: darkness

Measurements of Black spot

Kerr ray tracing:

$a/M = 0.1$

$i = 40°$

$r_{in} = r_H^+ = 1.995\ r_g$

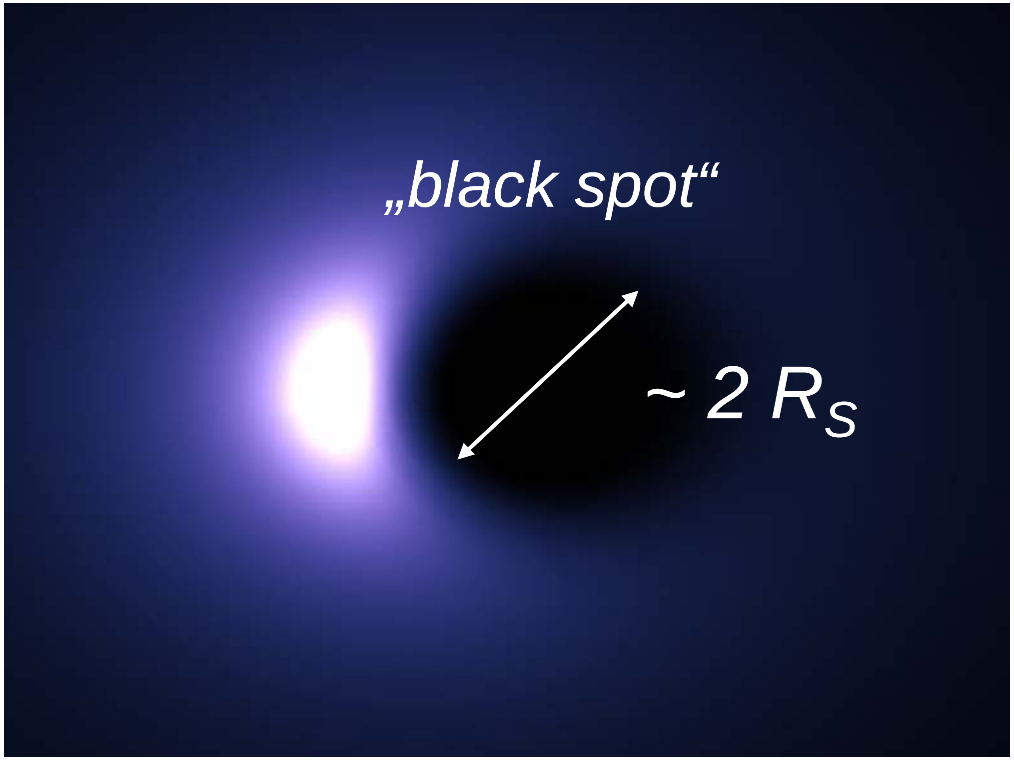
$r_{out} = 30.0\ r_g$

$R_{trunc} = 6.0\ r_g$

Kepler rotation

+ radial drift

truncated emissivity



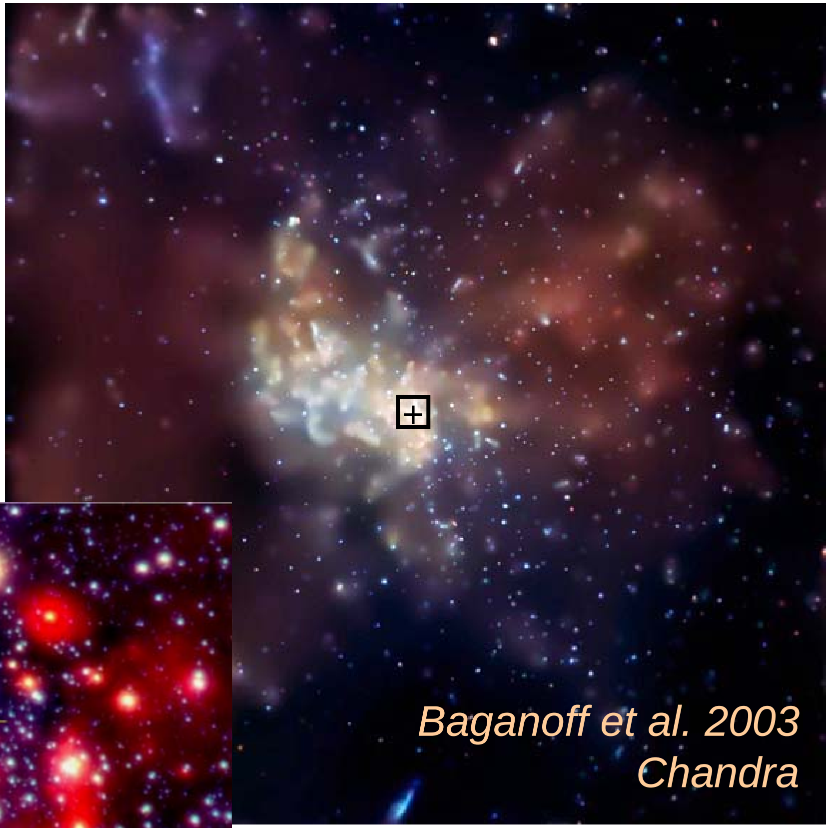
Müller & Camenzind, A&A 2004

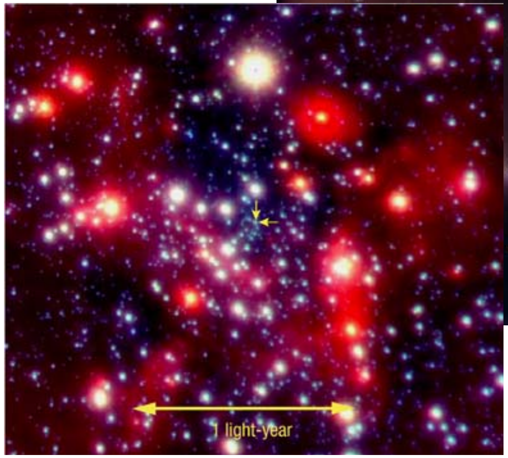
*Candidate: Sgr A**

$$\begin{aligned}\theta_{\rm BH} &= 2\,\arctan\left(R_{\rm S}/d\right)\\ &\simeq 2\,R_{\rm S}/d\\ &\simeq 39.4\times\left(\frac{M}{10^6\ {\rm M}_\odot}\right)\times\left(\frac{1\,{\rm kpc}}{d}\right)\,\mu{\rm as}\end{aligned}$$

- best BH candidates for obscurative: Sgr A*, M87*

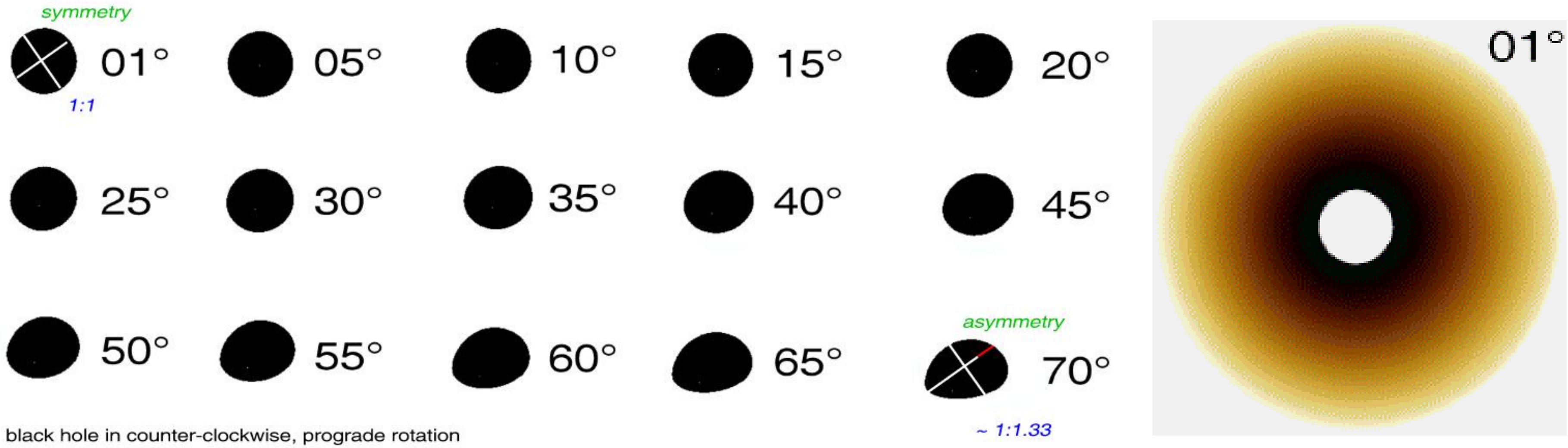
- *Krichbaum et al. 2006*
- *Takahashi 2004*
- *Falcke et al. 2000*
- *Bardeen 1970ies*





VLT, NACO 2002

Spot depends on orientation & spin

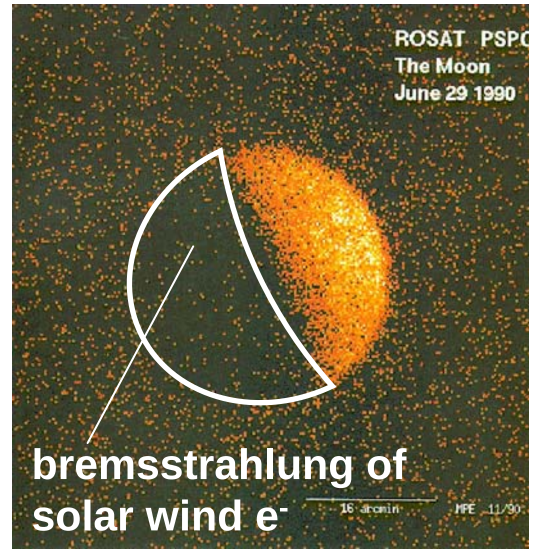


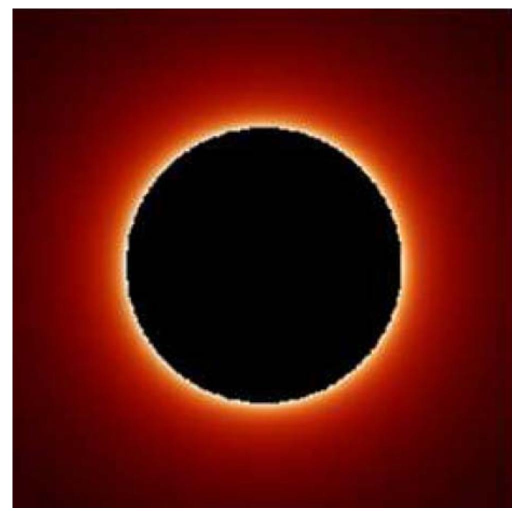
Müller PhD 2004

- gravitational redshift causes BH main characteristic
- black spot is smaller if disk is present (here) as cp. to non-disk case
- inclination and spin deform shape of the event horizont (spherical vs. ellipsoidal)

An analogue

- solar X-rays are scattered of the Moon
- high S/N: shadow of the moon in X-rays detected as immersed in bright XRB
- this is *really* a shadow
- *Schmitt et al. 1991*
- similar: isolated BHs immersed into CMB
- *Carter 2006*

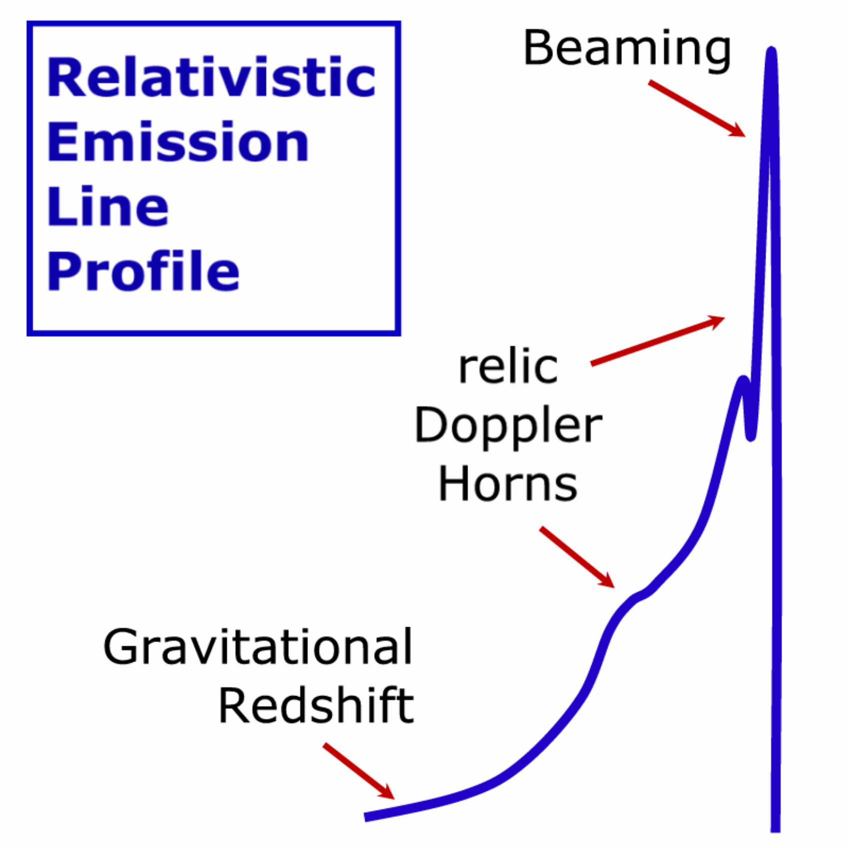




Spectro-relativistic methods

Broad Iron K lines

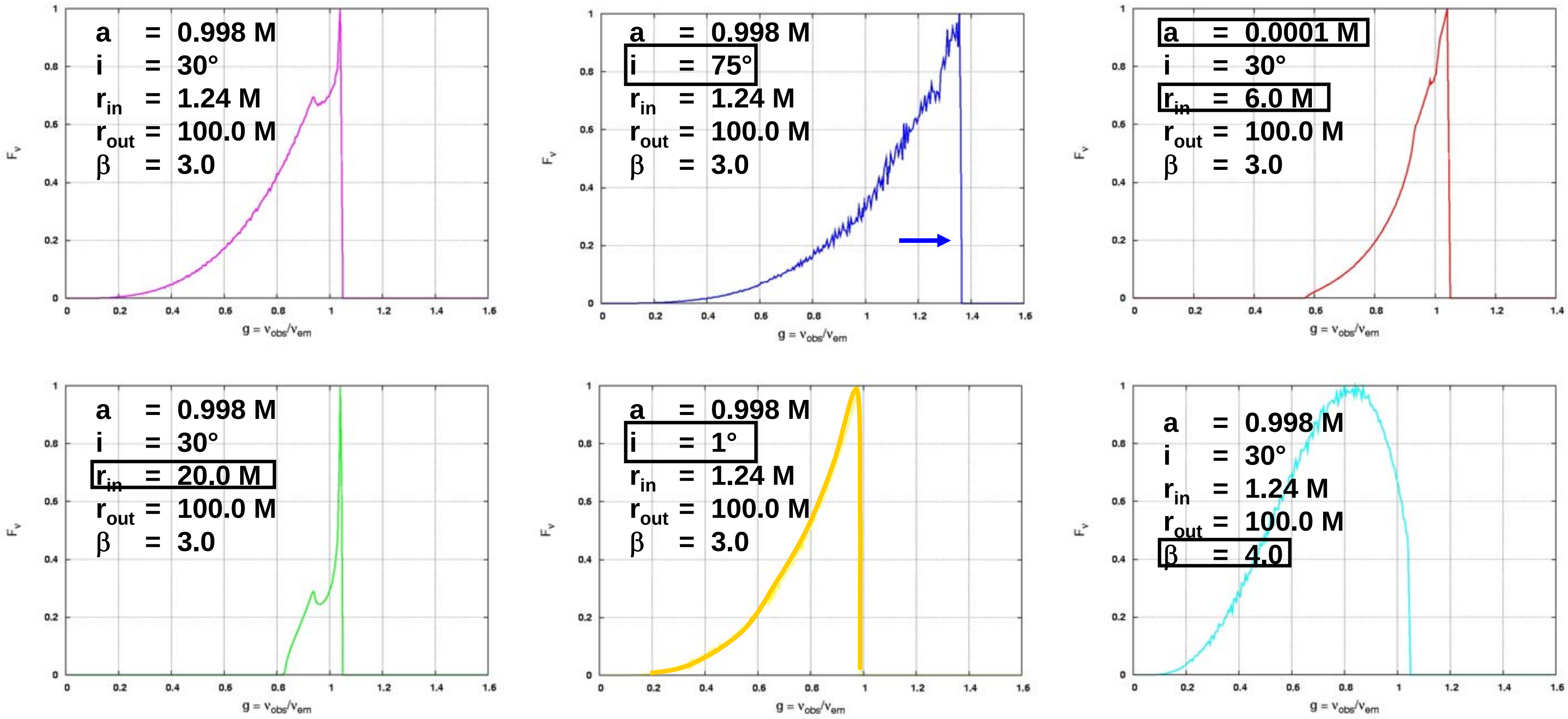
- relativistically broadened emission lines near BHs
- dominant: Fe Kα at 6.4 keV rest frame energy
- observed in AGN, and GBH with ASCA, RXTE, XMM, Chandra, Suzaku
- precondition: primary HX source illuminates cold accretion disk
- probe {*M, a*}



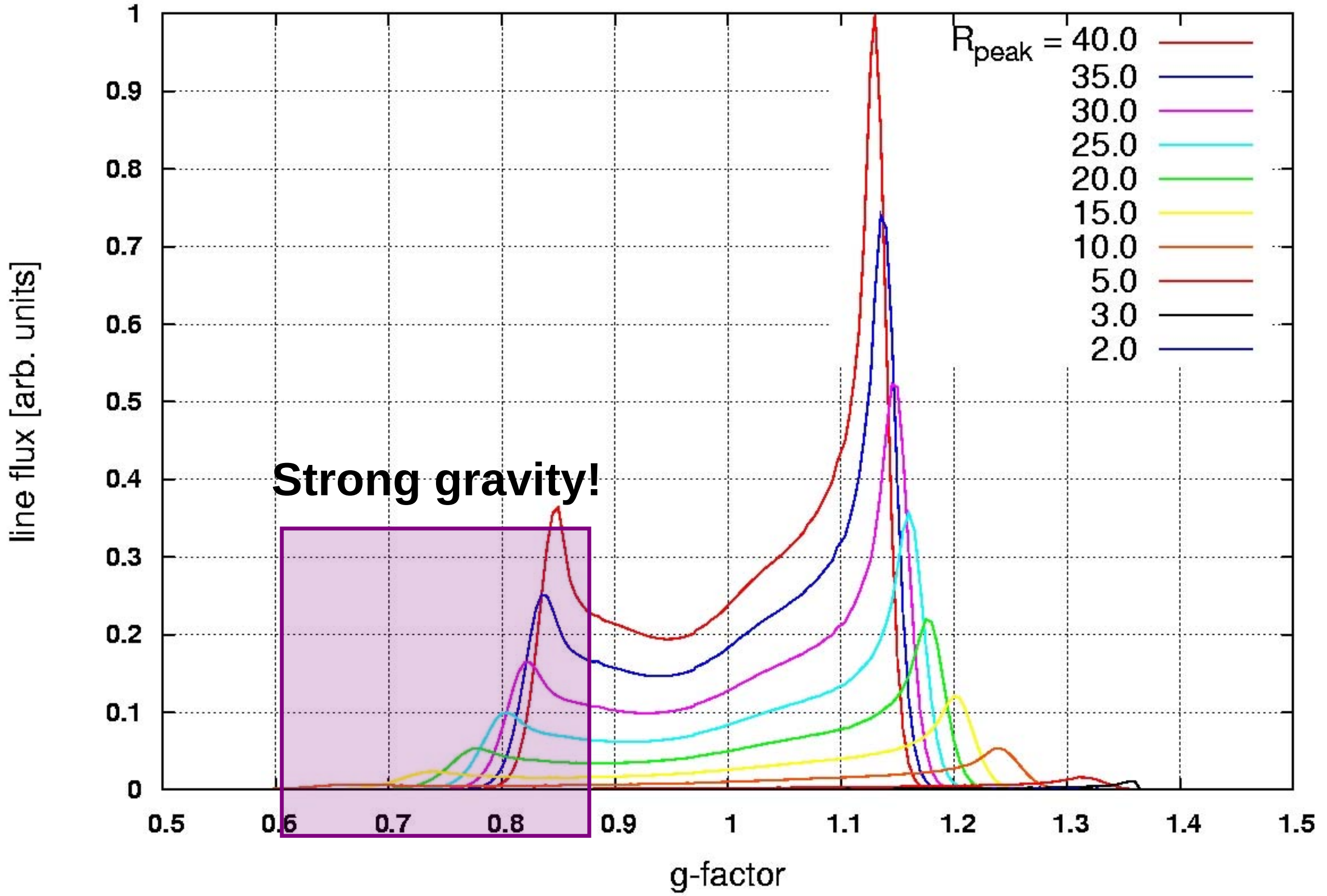
A Fe Line Gallery

observations: subtract power law and fit relativistic broad disk line

here: ray tracing simulations



Gravitational redshift



i = 75°

a/M = 0.998

Keplerian rotating rings,

Gaussian emissivity:

~ 1 r_g narrow

$g = \nu_{obs} / \nu_{em}$

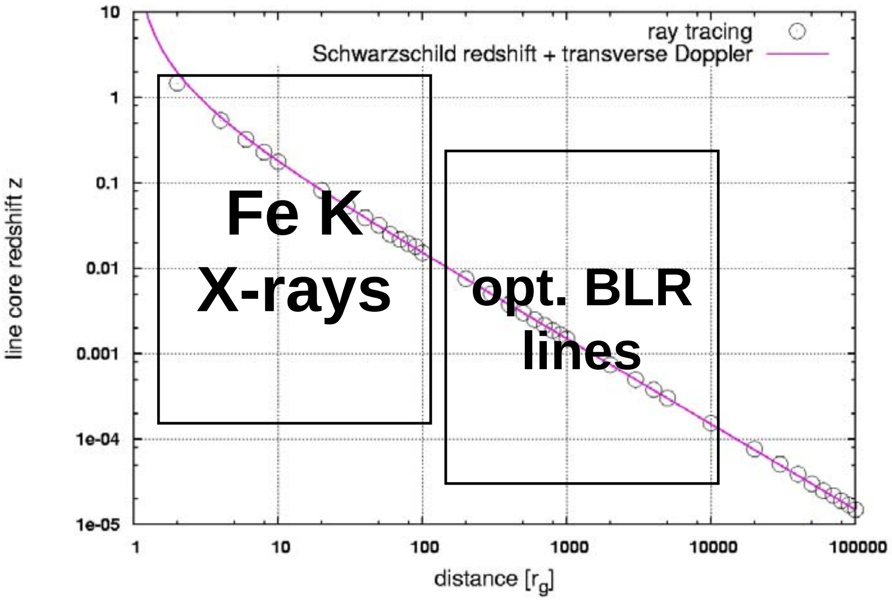
Müller & Wold 2006, A&A in press, astro-ph/0607050

Redshift gradient

- relativistic emission lines from Keplerian rotating rings are characterised by line core redshift z_{core}

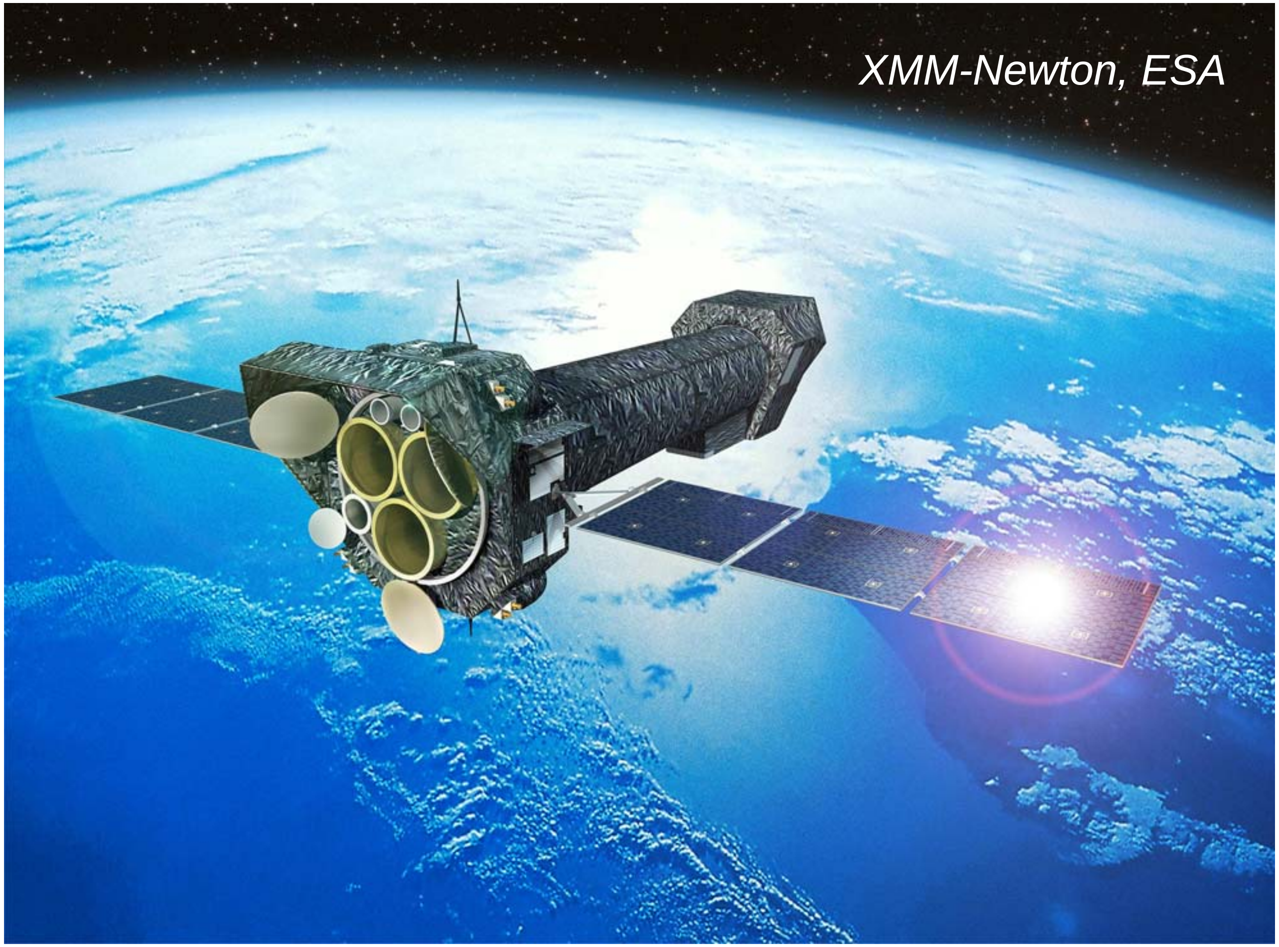
$$g_{\mathrm{core}} = \frac{\sum_i \ g_{\mathrm{i}} \ F_{\mathrm{i}}}{\sum_i \ F_{\mathrm{i}}}$$

- gravitational redshift decays linearly in far-field
- probe {M, a, i}
- Mrk 110: opt. BLR lines
- suggests **multi-wavelength search** for gravitationally redshifted features



Müller & Wold 2006
A&A in press
astro-ph/0607050

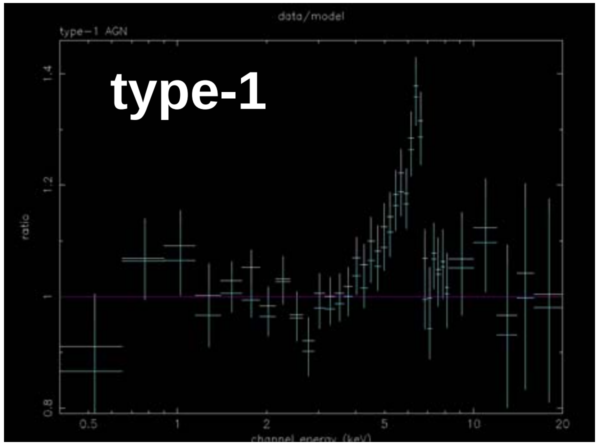
Hightech in Earth orbit

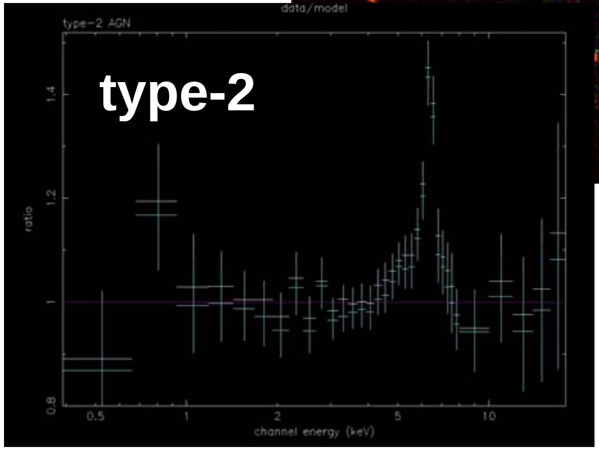


X-ray range 0.5 – 10 keV

Cosmic X-ray Background

- stacked relativistic broad emission lines from ~100 active SMBHs in X-ray background
- Fe Kα feature at 6-7 keV for AGN type-1 and 2





Streblyanska et al. 2005

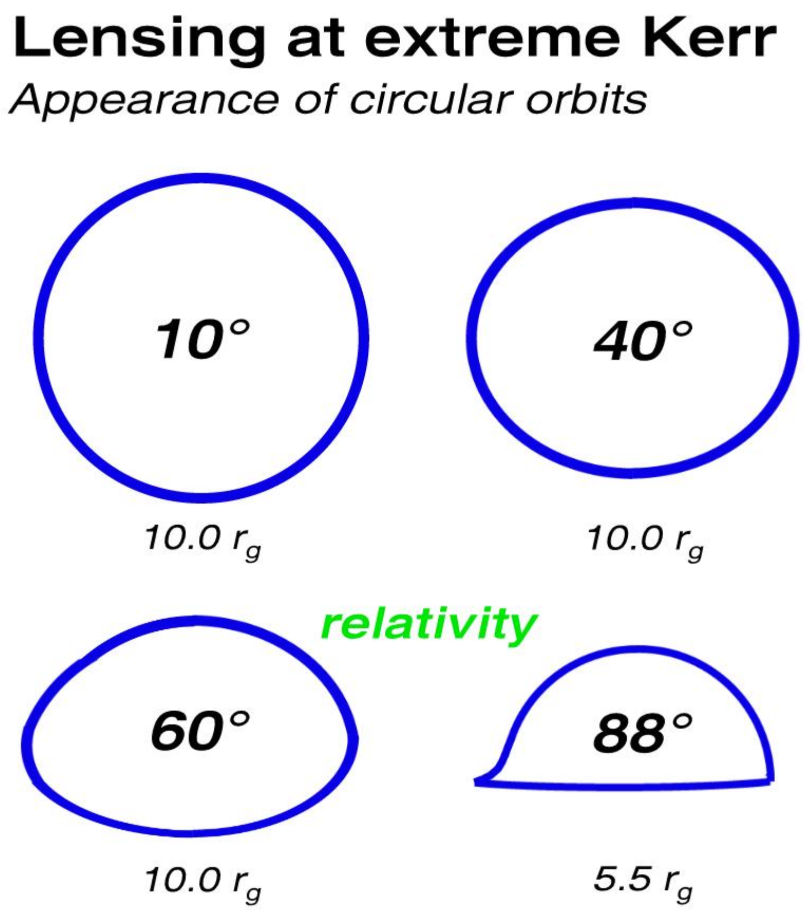
Brusa et al. 2005

Müller & Hasinger 2005

Aberrative methods

Lensing of orbital shapes

- use relativistic light bending effects (lensing)
- right: tight intrinsically circular orbits around a Kerr BH
- deformation of classical Kepler ellipses to skewed shapes
- dependence on inclination of orbital plane
- *pioneering papers:*
- *Luminet 1972*
- *Cunningham & Bardeen 1973*
- also microlensing (indirect method using light curve)



higher order images neglected

Schwarzschild vs. Kerr

- $r_{orb} = 6\ r_g$
- lensed orbits:

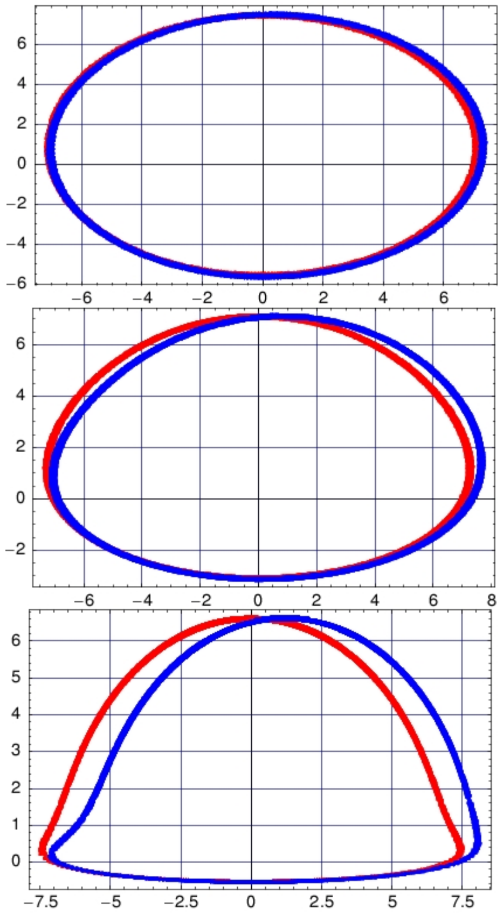
  discriminate Schwarzschild (symmetric) from Kerr (asymmetric)

- spin breaks mirror symmetry

i = 30°

i = 60°

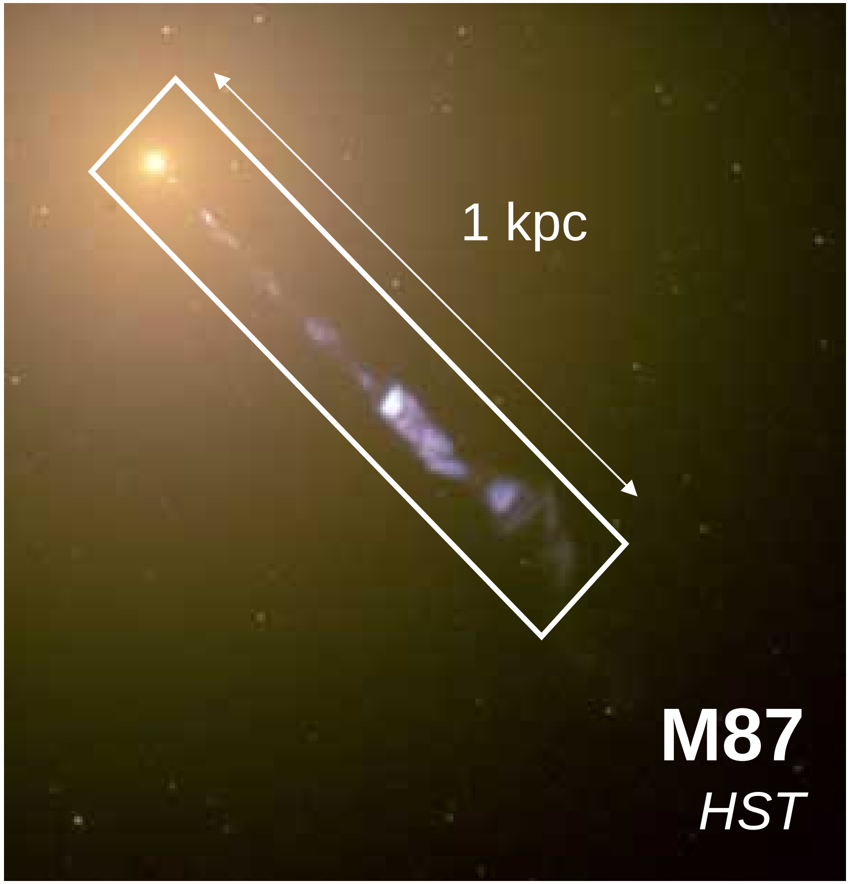
i = 85°



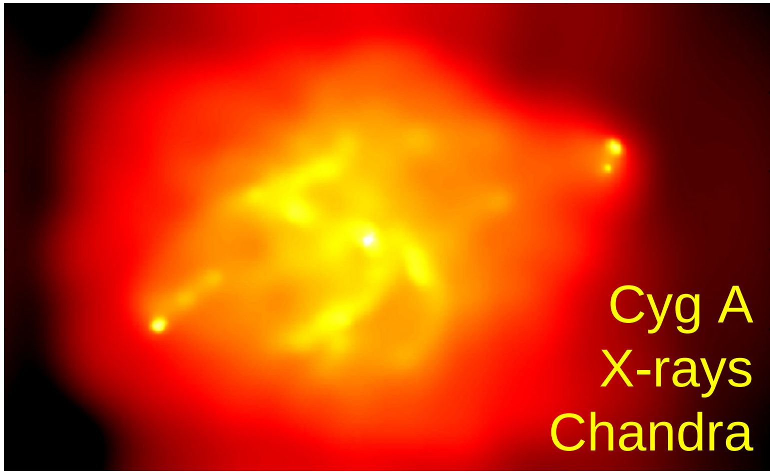
Accretive methods

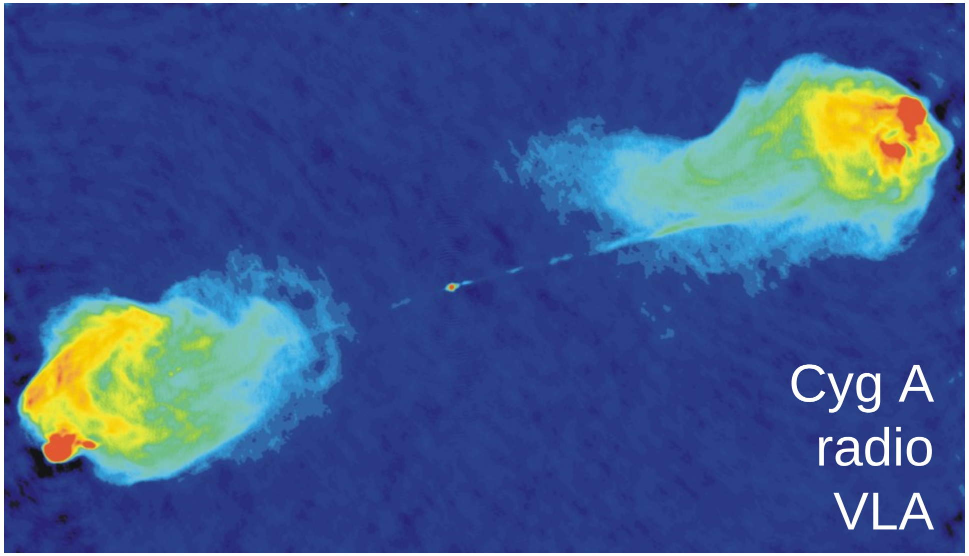
AGN activity – M87

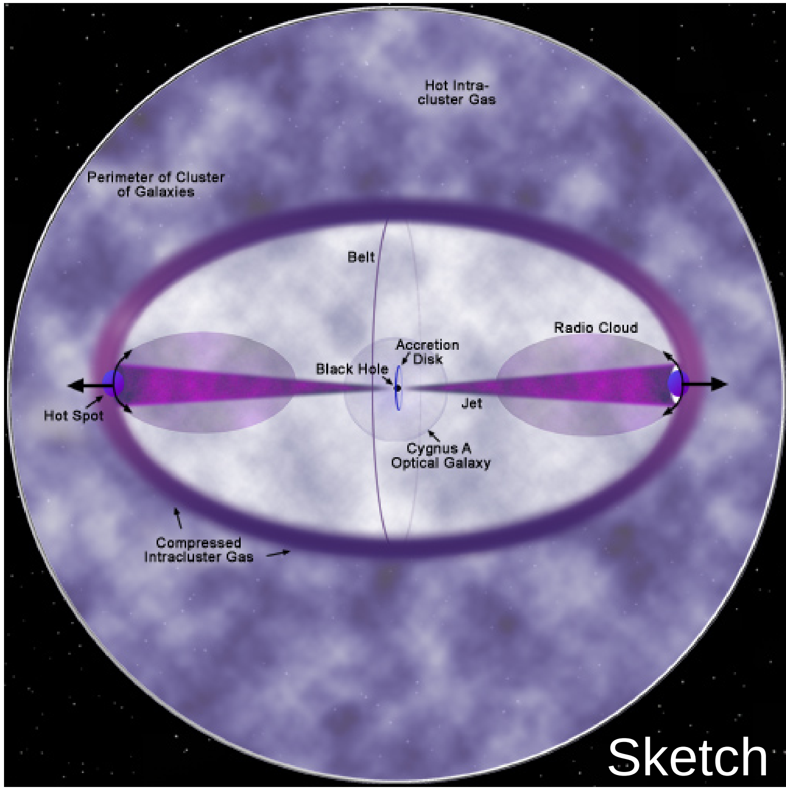
- Eddington's argument: use luminosity to estimate BH mass
- $M_{BH} \sim 3 \times 10^9 M_\odot$
- D ~ 16 Mpc
- **Outflow drivers:**
- relativistic AGN-Jets hint for active rotating SMBH
- *Blandford & Znajek 1977*
- alternative: rotating MHD disk
- *Blandford & Payne 1982*



AGN activity – Cyg A







- $M_{BH} \sim 2.5 \times 10^9\ M_\odot$
- $D \sim 230$ Mpc

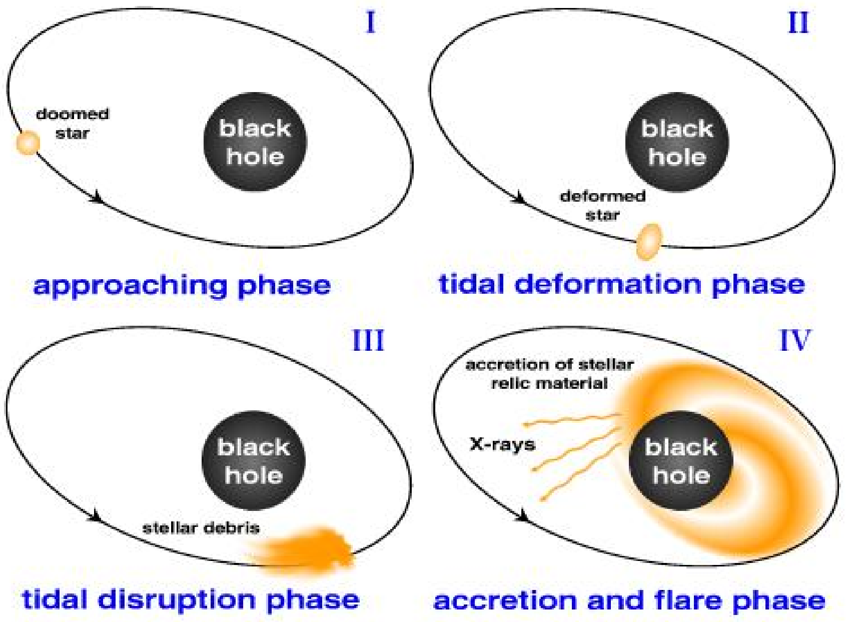
Eruptive methods

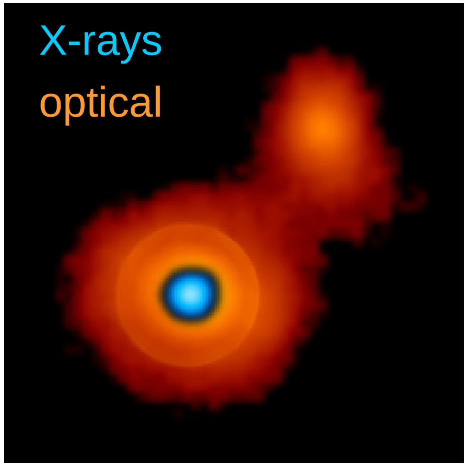
Stellar tidal disruption

- accretion burst event: X-ray flare
- L_X decay with $t^{-5/3}$
- ROSAT, Chandra
- detected in 2004 at RX J1242-1119, z = 0.05
- happens every 10^4 yrs
- tidal radius:

$$R_\mathrm{T} = 1.1\,\mathrm{R_S} \times \left(\frac{M}{10^8\,\mathrm{M_\odot}}\right)^{-2/3}$$

- *Komossa et al. 2004*
- *Halpern et al. 2004*





Other eruptive methods

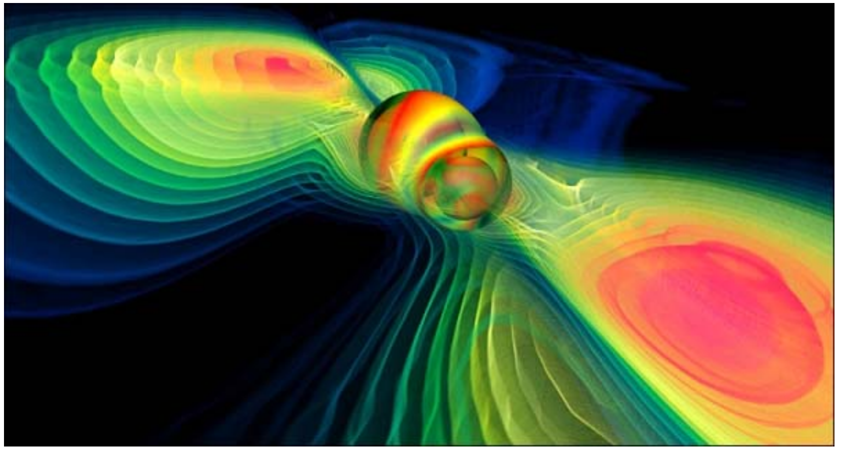
- GRBs

- flares
  - see kinematical methods

- Hawking radiation
  - tough job for cosmic BHs
  - 2008 in reach with particle accelerators (LHC)?

Gravitational-wave induced method

- characteristic GW spectrum and GW frequencies e.g. BH-BH merger in 10 to 500 Hz range
- chirp, inspiral, ringdown



Courtesy: W. Benger, MPI for Gravitational Physics

- Is there a chance to prove *event horizons* with GW signals?
- Is there a chance to probe BH *spin* with GW spectra?

- Yes, indeed! (Berti & Cardoso 2006, gr-qc/0605101)

Most confidental methods

- need to come close to BH to probe ergosphere and event horizon, $r < R_S$
- strongest clues for BH existence from:
  - GRBs (no alternative according to current knowledge)
  - stellar orbits (i.e. Galactic Centre)
  - Quasi-periodic Oscillations (QPOs)
  - broad iron K lines

Black hole spin

Probing BH spin

- Study orbital and other characteristic frequencies
  - QPOs
- Coupling of r_{ms} and a
  - widely used in broad line business
  - flare orbiting at r_{ms}
- BH growth argument (e.g. Shapiro 2005)
  - spin-up by accretion and merging, a ~ 0.9….0.99
- Jet launching argument
  - GRMHD in the Kerr geometry
- Proximity required: steep gradient of frame-dragging frequency: $\omega \sim r^{-3}$

What do we observe?

What do we observe?

- it is **massive**
- it is **compact**
- it is **dark**

- neither event horizon,
- nor curvature singularity observed

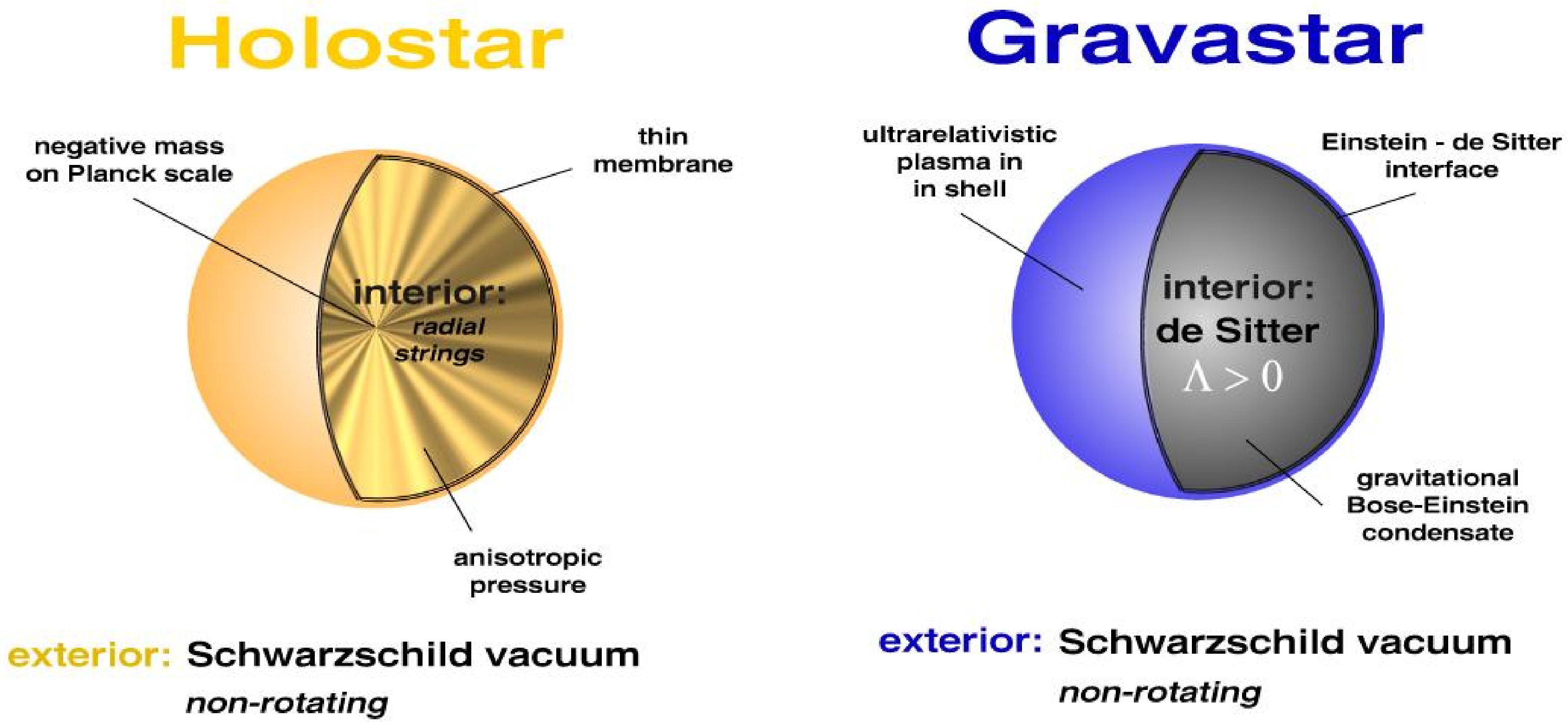
- can we do?

Black Hole Observability

- dissipation argument to distinguish NS from BH
- ADAF argument:
  BHs are dimmer
- g ~ 0 suppresses any electromagnetic signal
- testing BHs vs. BH alternatives by em impossible

- claim for *evidence*
  - *Narayan et al. 1997*
  - *Remillard et al. 2005*
  - *Broderick & Narayan 2006*
- claim for *non-observability*
  - *Abramowicz et al. 2002*

Static black hole alternatives



Petri 2003 *Mazur & Mottola 2001*

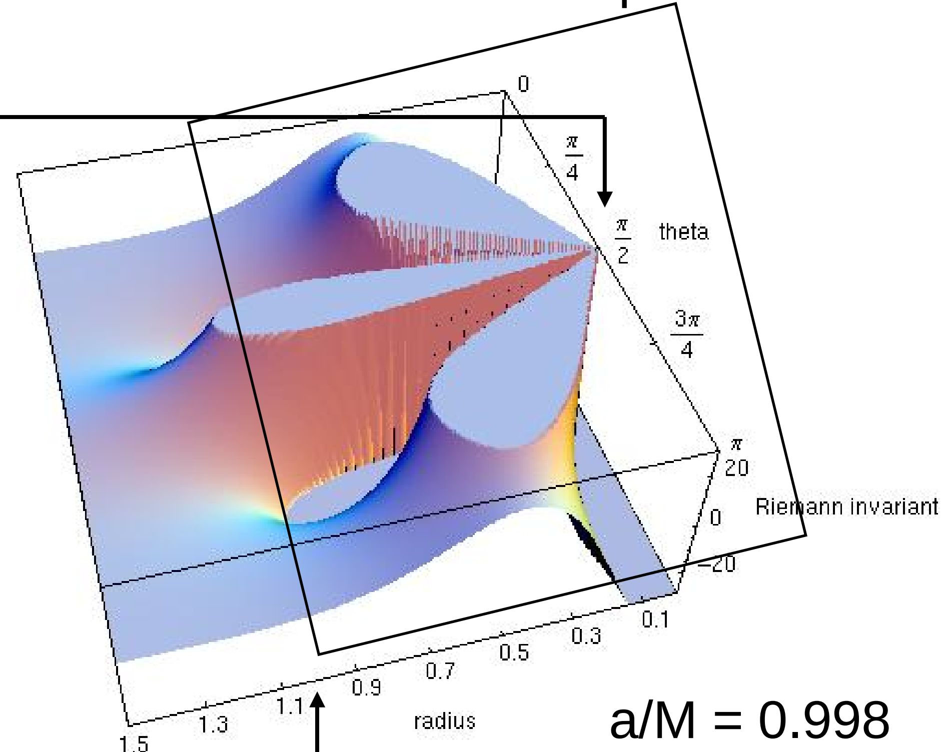
only <u>an</u>isotropic version is stable (*Cattoen et al. 2005*)

Curvature invariants

$$R_{\kappa\lambda\mu\nu}\,R^{\kappa\lambda\mu\nu} = 48\frac{M^2}{r^6}\,\frac{1-(a/r)^2\cos^2\theta}{\left(1+(a/r)^2\cos^2\theta\right)^6}\,\left(1-14\,(a/r)^2\cos^2\theta+(a/r)^4\cos^4\theta\right)$$

- Kretschmann scalar
- ring singularity

cosmic censorship?



- current observations (fits with iron K lines) reach r_{min} ~ few r_g

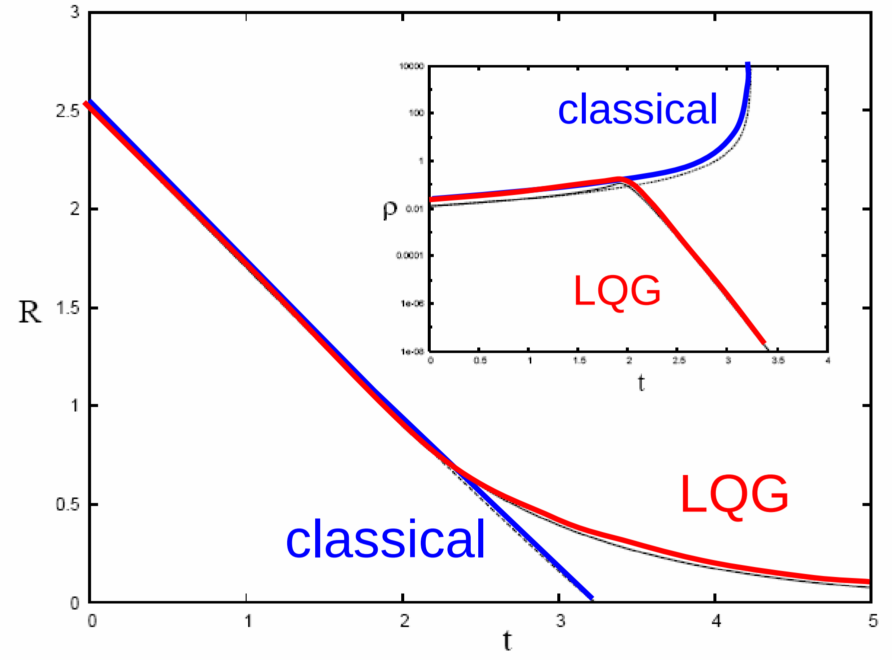
a/M = 0.998

$r_H^+ = 1.063\ r_g$

The LQG back bounce

- Wheeler: emergence of true singularities signals breakdown of classical GR
- Loop effects: negative pressure develops in gravitational collapse to avoid singularity

- *Goswami et al. 2006*
- *Bojowald et al. 2005*



evolution of area radius
and energy density (inset)

Conclusions

Observations hint for *massive dark objects* (MDOs)

Event horizons and singularities are **NOT** yet proven

Kerr black hole currently best choice

Be open-minded for **new** Gravity issues!

2008: **mini BHs** at LHC?

Einstein & Holes

„Why socks?
They only get holes!“

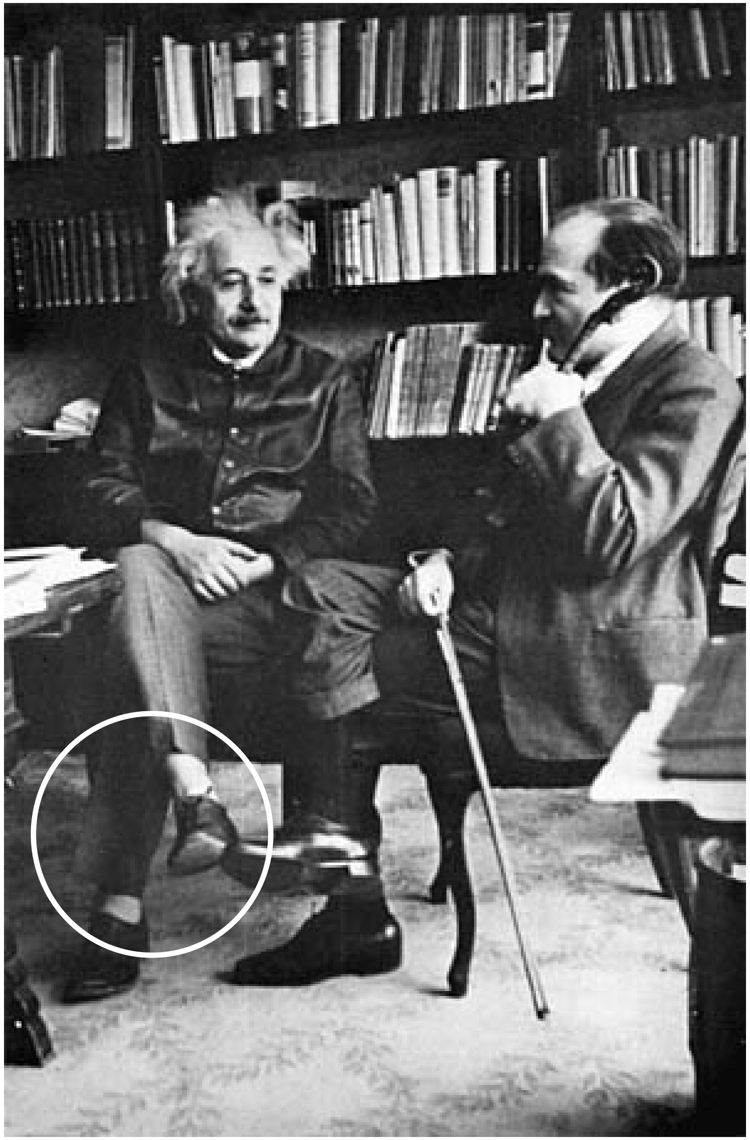


photo: http://www.physics.ox.ac.uk/users/foster/Public/