a brief history of

bla k
holes

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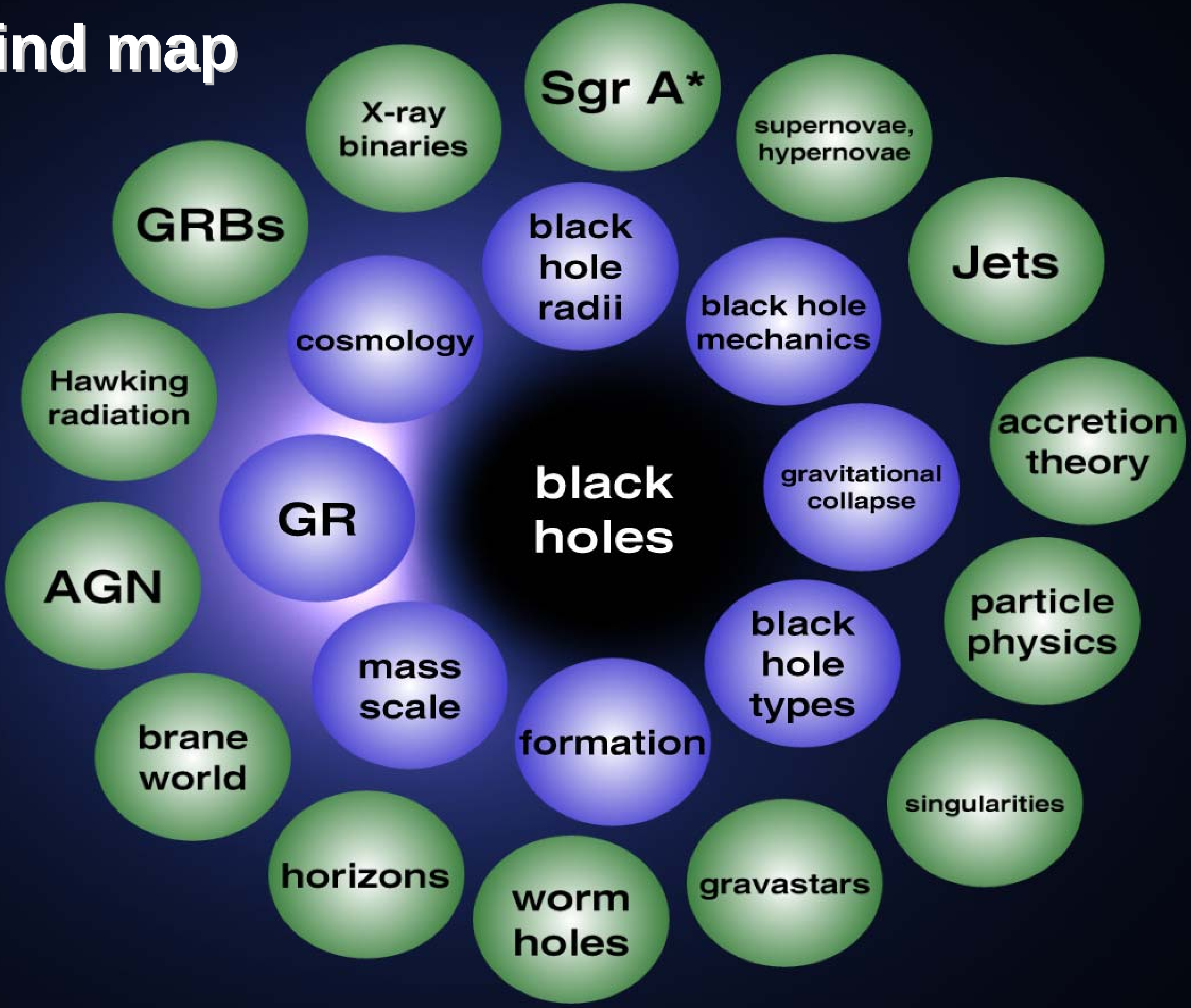
student seminar
mpia & lsw
january 2004

talk organisation

- basics ☺
- standard knowledge
- advanced knowledge
- edge of knowledge and verifiability ☠

mind map



black holes

black hole radii

black hole mechanics

gravitational collapse

black hole types

formation

mass scale

GR

cosmology

Sgr A*

supernovae, hypernovae

Jets

accretion theory

particle physics

singularities

gravastars

worm holes

horizons

brane world

AGN

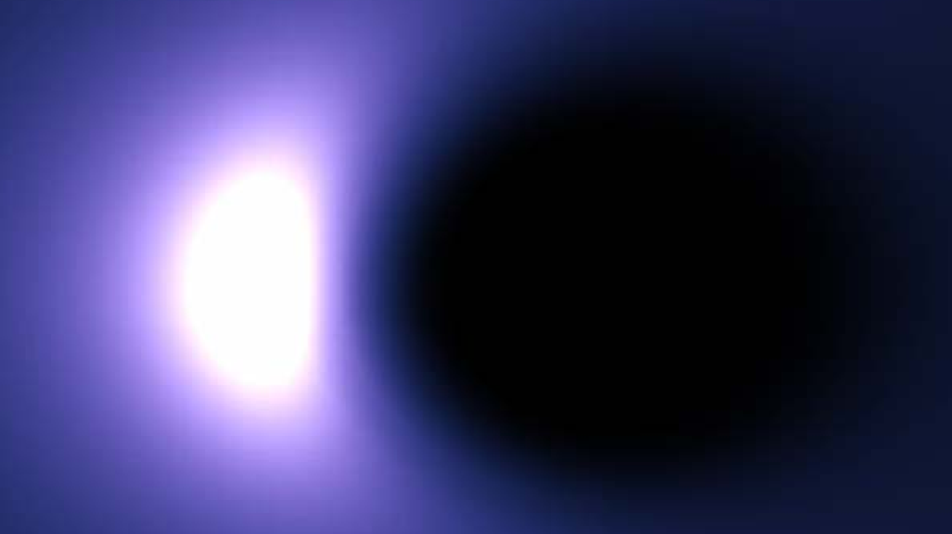
Hawking radiation

GRBs

X-ray binaries

what is a black hole?

black → escape velocity c

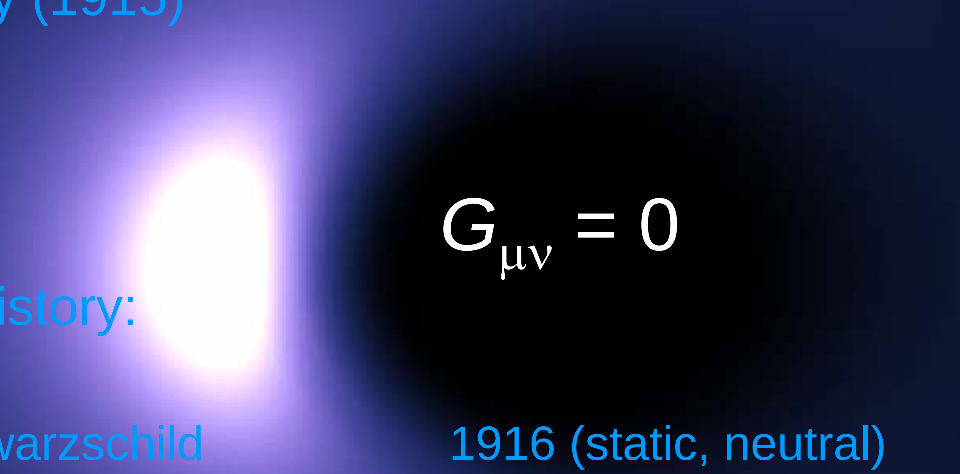


hole → singularity in space-time

notion „*black hole*“ from relativist *john archibald wheeler* (1968),
but first speculation from geologist and astronomer *john michell* (1783)

black holes in relativity

- solutions of the vacuum field equations of einsteins general relativity (1915)



$$G_{\mu\nu} = 0$$

- some history:

schwarzschild	1916 (static, neutral)
reissner-nordstrøm	1918 (static, electrically charged)
kerr	1963 (rotating, neutral)
kerr-newman	1965 (rotating, charged)

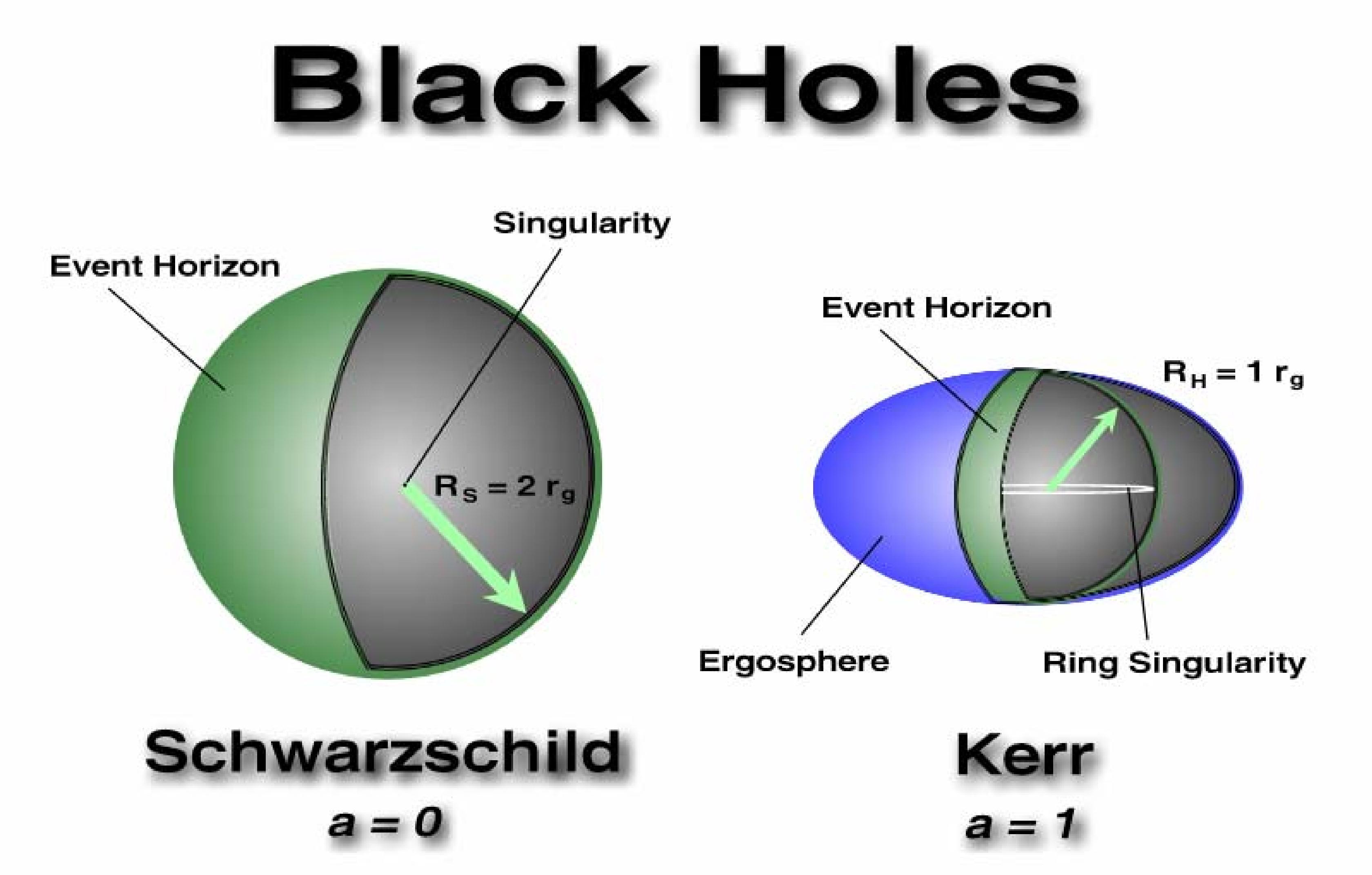
- all are petrov type-d space-times
- plug-in metric $g_{\mu\nu}$ to verify solution ;-)
- black hole mass hidden in (point or ring) singularity

black holes have no hair!

- schwarzschild
  $\{M\}$
- reissner-nordstrom
  $\{M,Q\}$
- kerr
  $\{M,a\}$
- kerr-newman
  $\{M,a,Q\}$

wheeler: no-hair theorem

black holes – schwarzschild vs. kerr



black holes – kerr in boyer-lindquist

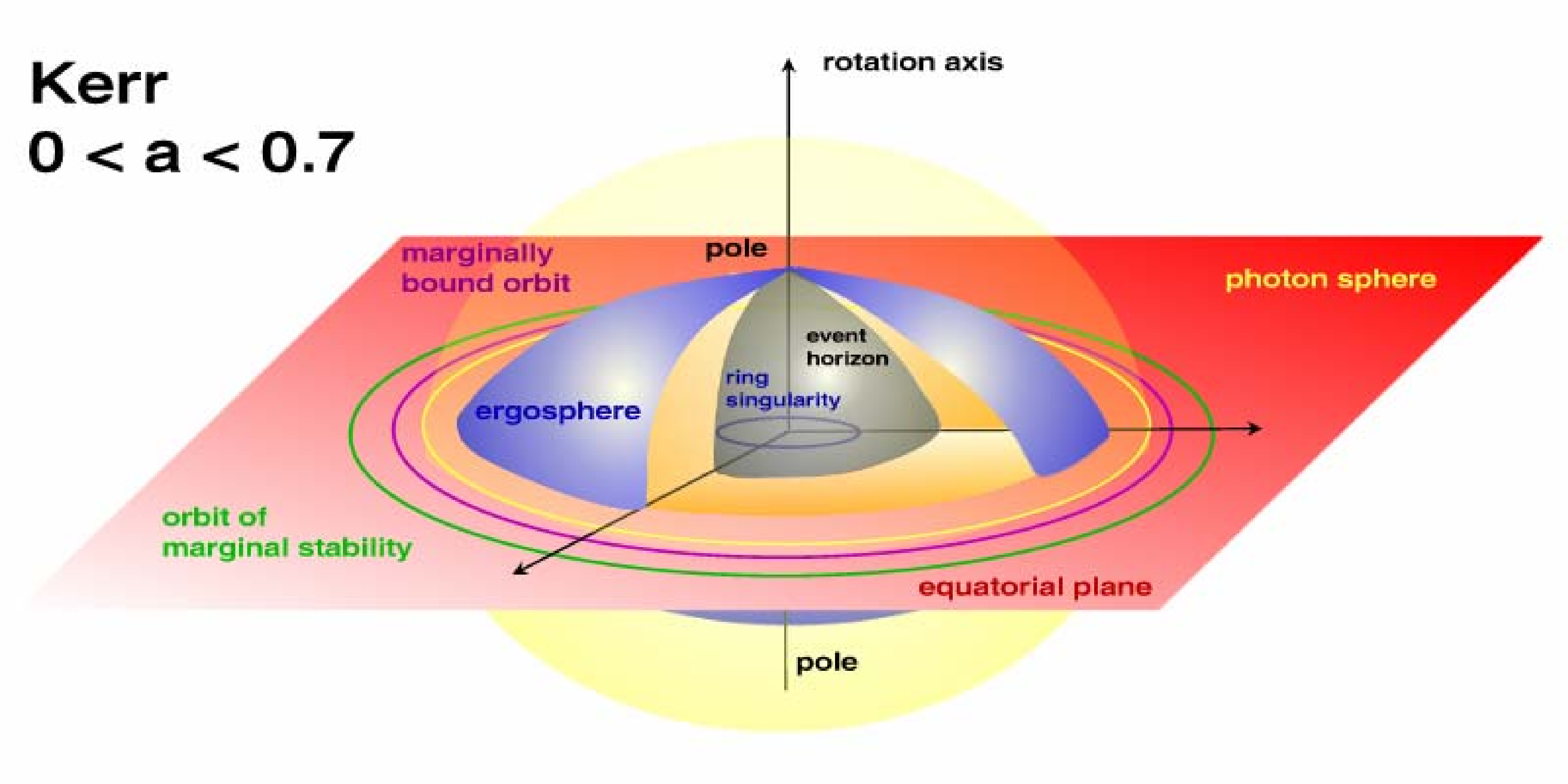
$$ds^2 = -\alpha^2 dt^2 + \tilde{\omega}^2 (d\Phi - \omega dt)^2 + \left(\rho^2/\Delta\right) dr^2 + \rho^2 d\Theta^2$$

black hole mass *M*

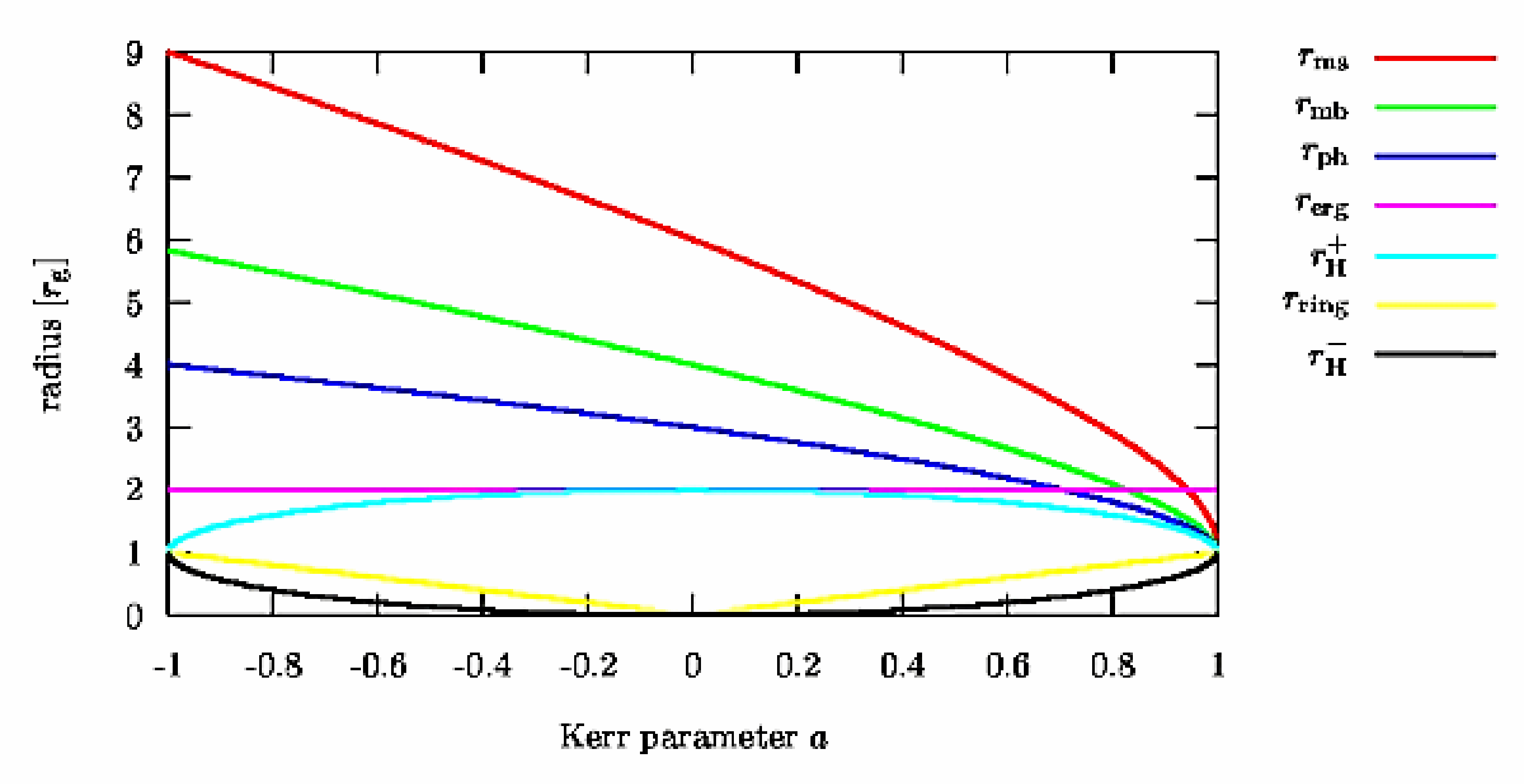
spin parameter *a*

$\alpha = \frac{\rho\sqrt{\Delta}}{\Sigma}$	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
$\omega = \frac{2aMr}{\Sigma^2}$	frame-dragging frequency
$\tilde{\omega} = \frac{\Sigma}{\rho} \sin\theta$	cylindrical radius

black hole topology

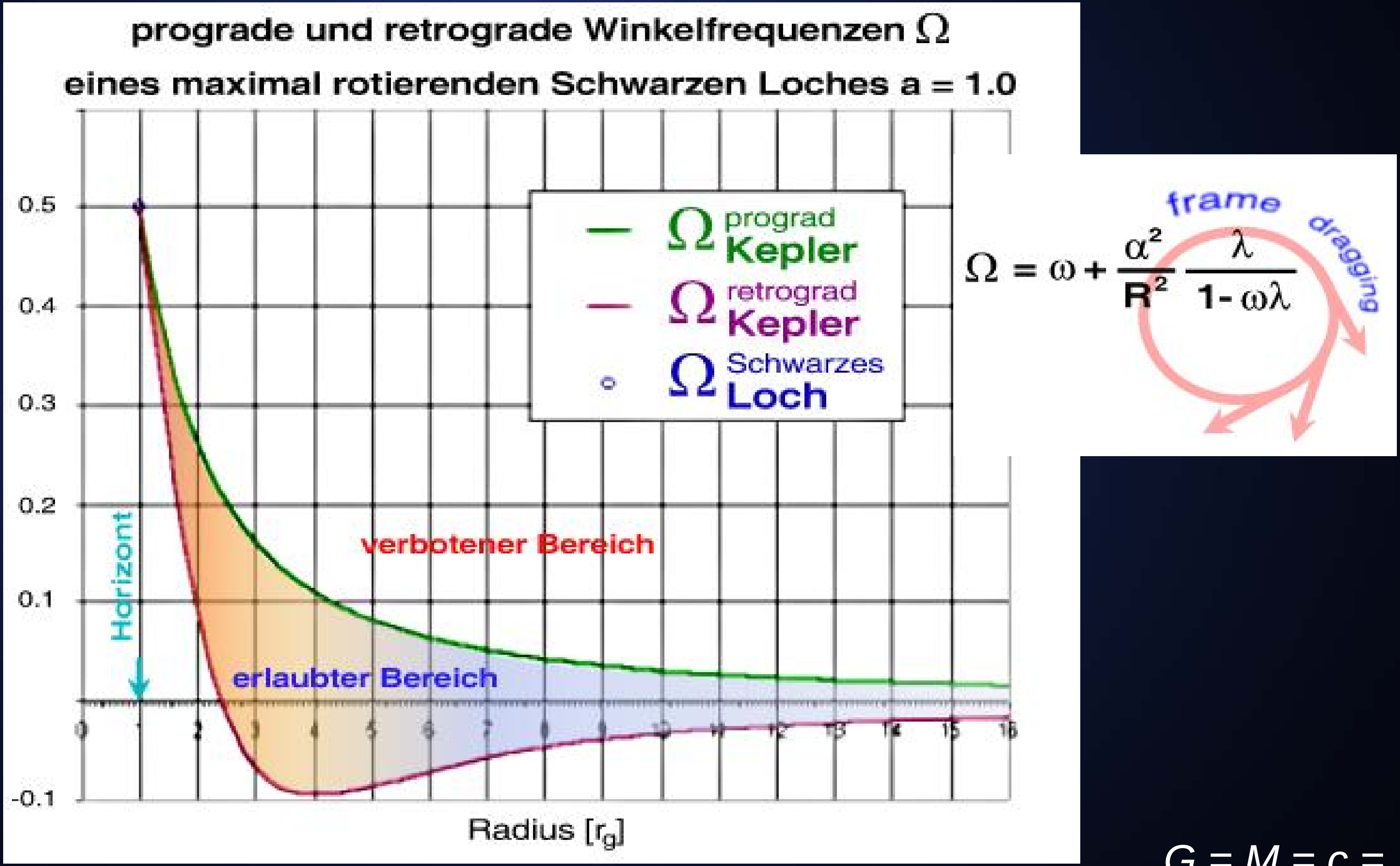


black hole – characteristic radii



G = M = c = 1

black hole - frame drag



$$\Omega = \omega + \frac{\alpha^2}{R^2}\,\frac{\lambda}{1-\omega\lambda}$$

$G = M = c = 1$

black holes – mass scale

TeV	$M_{BH} \sim 1$ TeV
primordial	$M_{BH} \sim 10^{18}$ g
stellar	$1\ M_\odot < M_{BH} < 100\ M_\odot$
massive	$100\ M_\odot < M_{BH} < 10^5\ M_\odot$
supermassive	$10^5\ M_\odot < M_{BH} < 10^{10}\ M_\odot$

TeV	mini holes in particle accelerators (?)
primordial	early universe, galactic seeds (?)
stellar	fate of massive stars, microquasars
massive	globular clusters (?)
supermassive	galactic centers and agn

stellar bh indicators: hypernovae, grbs, supernovae

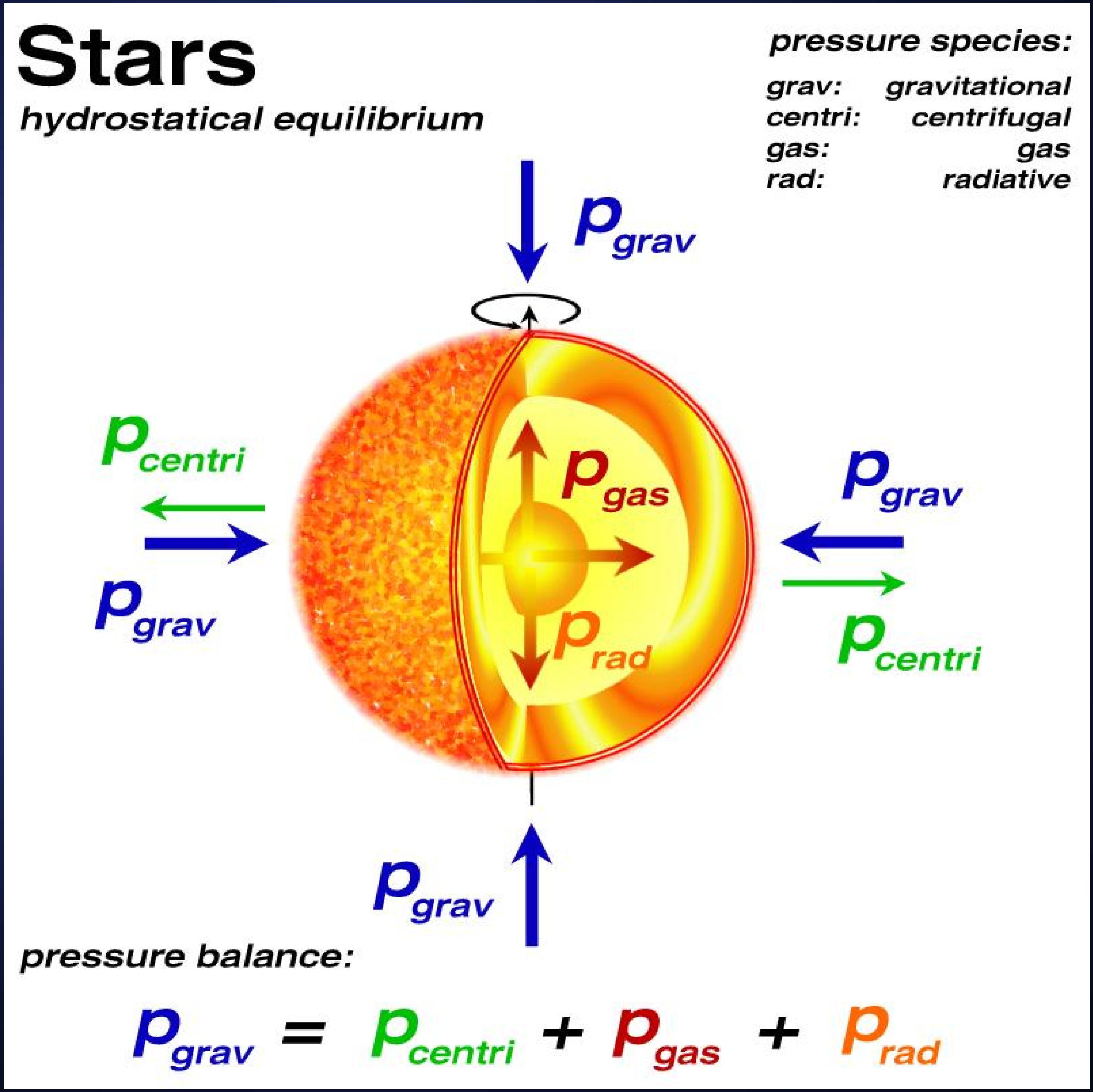
supermassive bh indicators: M-σ relation

black hole formation

▪ TeV	relativistic heavy ion collisions?
▪ primordial	hen-egg problem...
	brill waves
	topological defects after ssb?
▪ stellar	gravitational collapse
	supernova type Ia: exploding wd
	ns-ns merging
	ns-bh merging
▪ massive	accreting black holes
	cluster merging?
	popIII vms relics?
	podourets-zel‘dovich instabilities
▪ supermassive	accreting black holes
	podourets-zel‘dovich instabilities
	galaxy merging

in principle all types (?): super-critical brill waves

black hole from stellar collapse

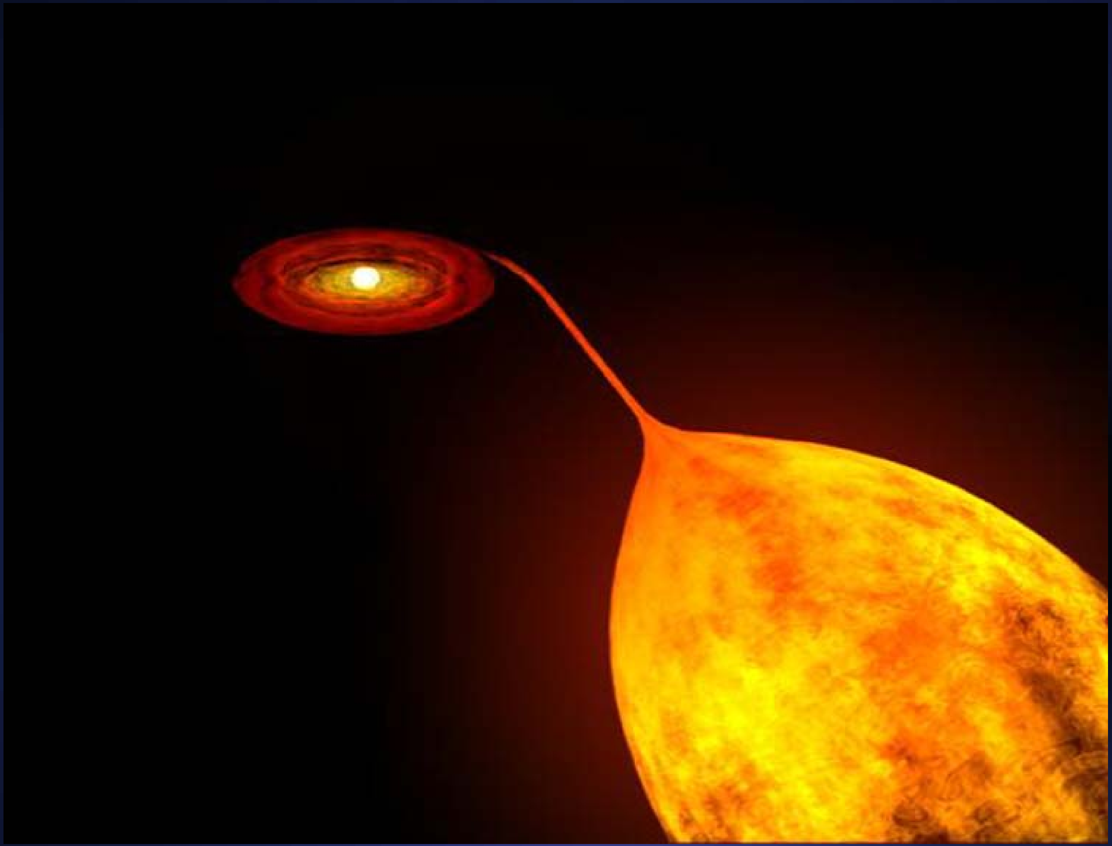


$$p_{grav} = p_{centri} + p_{gas} + p_{rad}$$

black hole from stellar collapse

- canonical scenario:
  gravitational collapse of massive stars
- $M_{progenitor} > 1.65\ M_{\odot}$ (*burgio et al. 2001*)
- hydrostatic equilibrium: $p_{grav} = p_{centri} + p_{gas} + p_{rad}$
- after silicon burning:
  thermonuclear burning chain breaks
- p_{rad} and p_{gas} decrease rapidly
  ⇨ $p_{grav} > p_{centri} + p_{gas} + p_{rad}$ **dominant gravitation!**
- star implosion and explosion from back-bounce:
  ⇨ supernovae, hypernovae (grbs)
  ⇨ stellar black hole
  ⇨ possibly detectable in a binary system

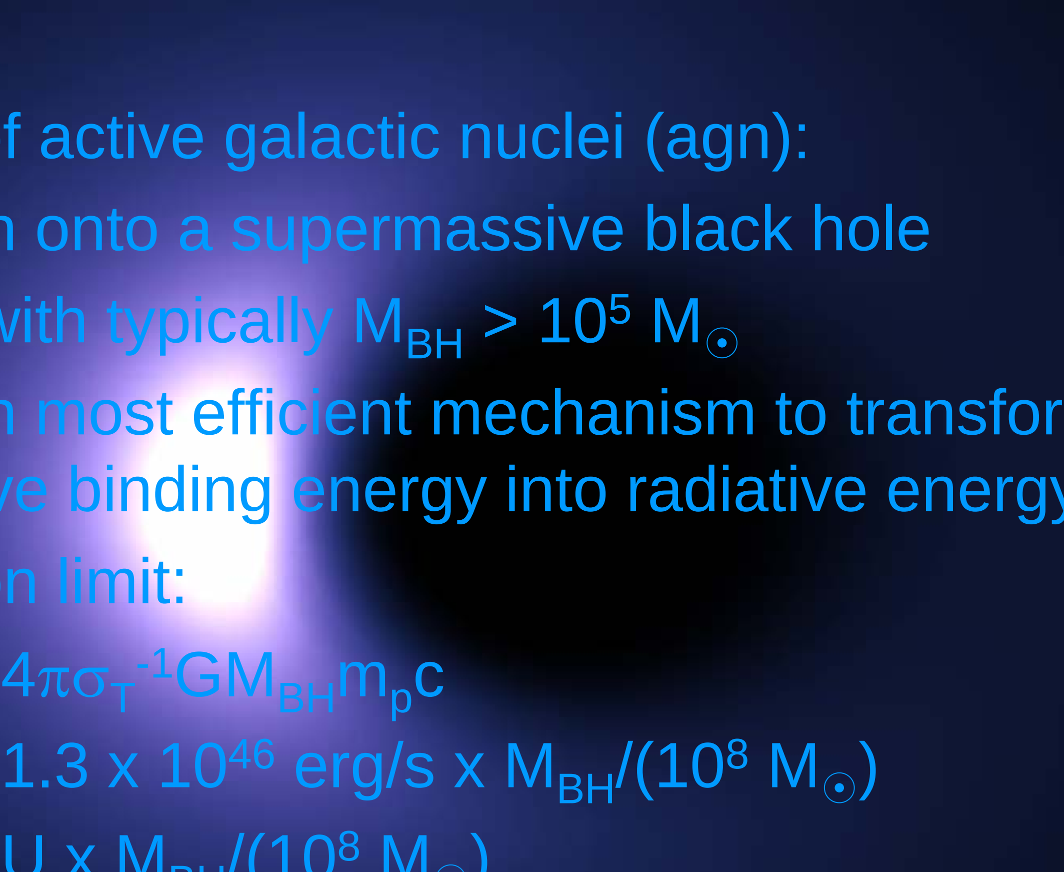
black holes in x-ray binaries



sketch,
chandra homepage

- stellar black holes: $1\ M_\odot < M_{BH} < 100\ M_\odot$
- roche lobe overflow through inner lagrange point
- hot accretion flow radiates x-rays
- spin-up to nearly extreme kerr, $a \sim 1$, by accretion of angular momentum

black holes in agn



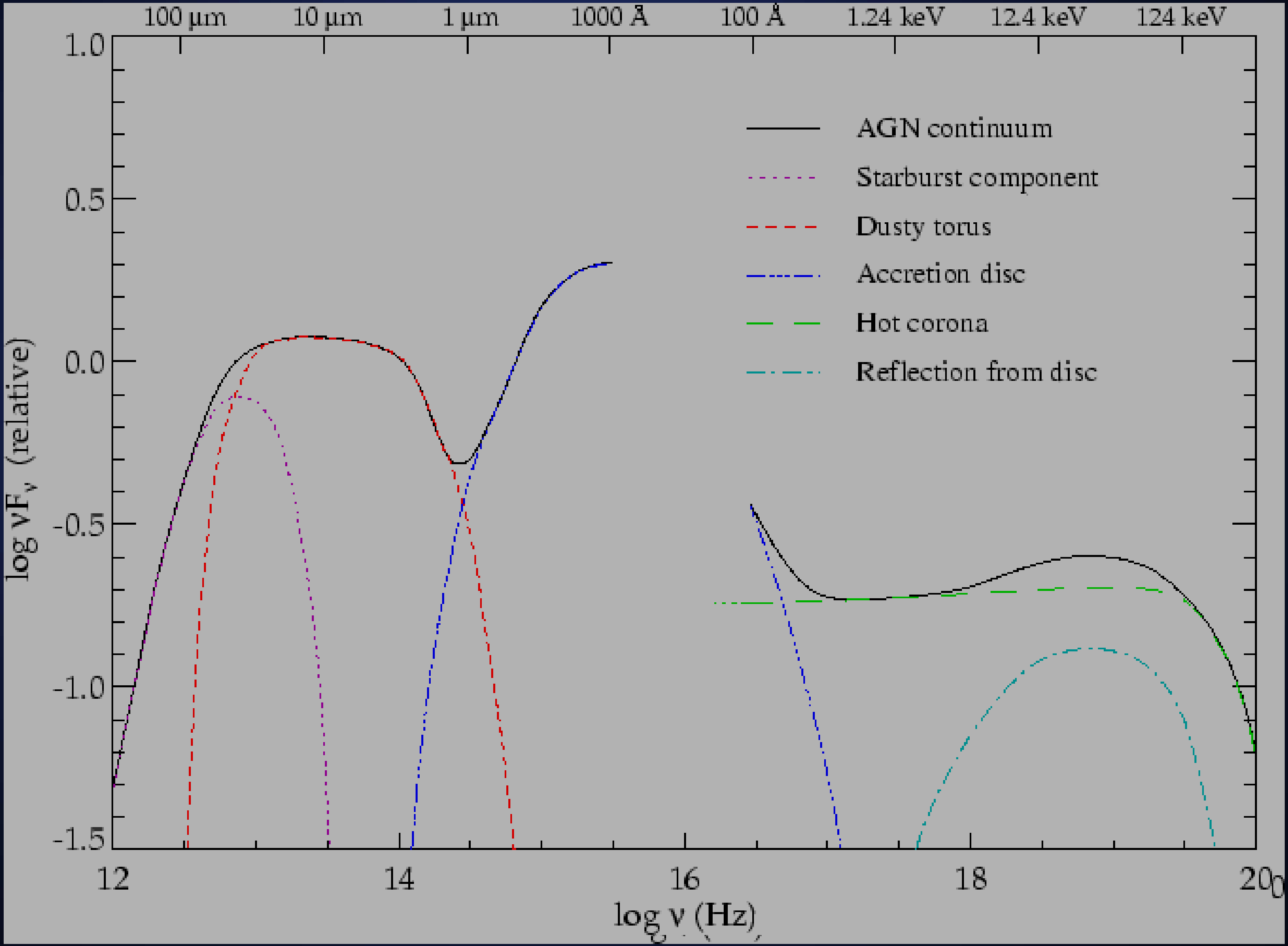
- engine of active galactic nuclei (agn): accretion onto a supermassive black hole (smbh) with typically $M_{BH} > 10^5\ M_\odot$
- accretion most efficient mechanism to transform gravitative binding energy into radiative energy
- eddington limit:

  $L_{edd} = 4\pi\sigma_T^{-1} G M_{BH} m_p c$

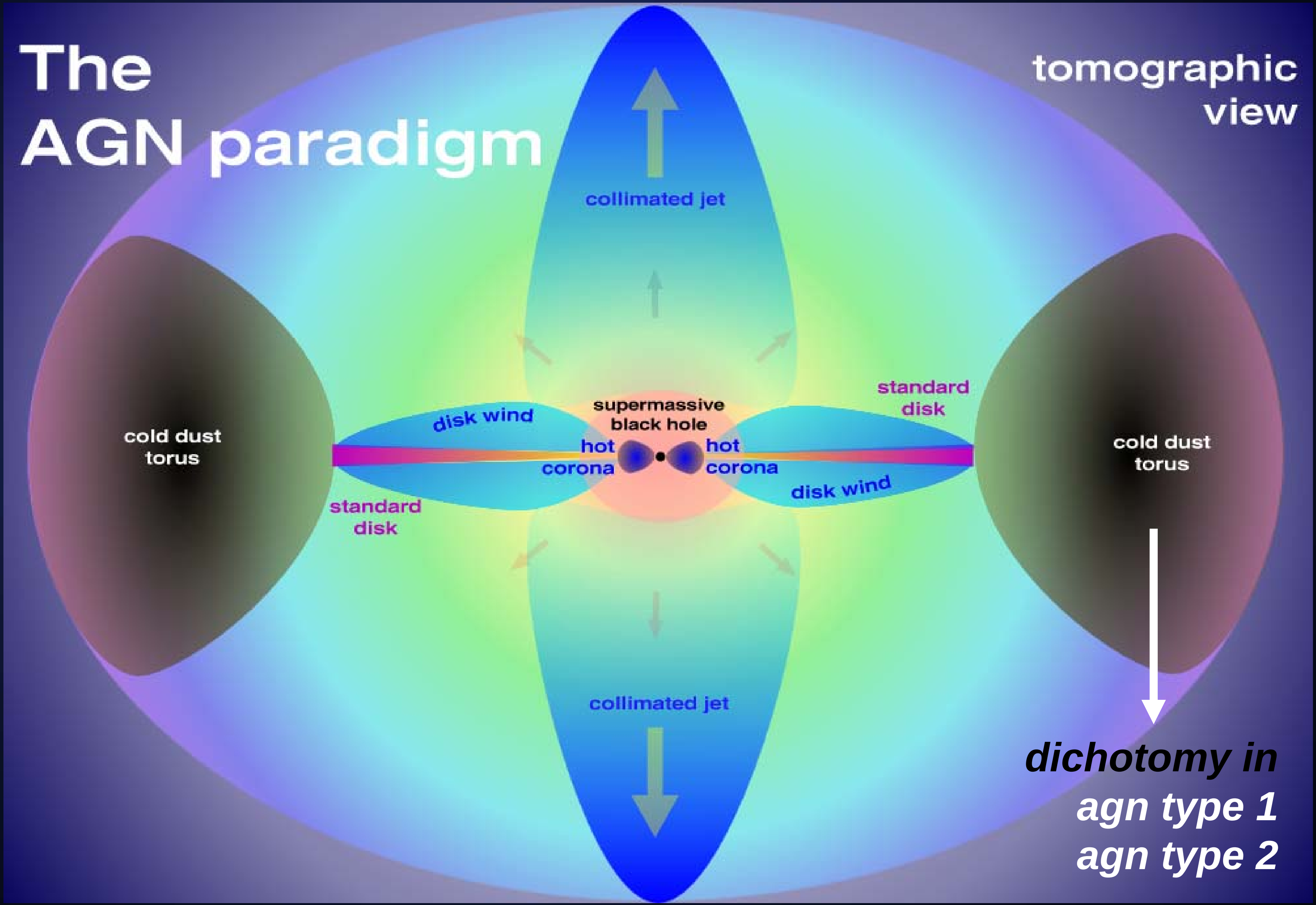
  $\sim 1.3 \times 10^{46}$ erg/s x $M_{BH}/(10^8\ M_\odot)$
- $R_S = 2$ AU x $M_{BH}/(10^8\ M_\odot)$
- typical agn luminosities:
  - $L_{qso} \sim 10^{47}$ erg/s
  - $L_{seyf} \sim 10^{43}$ erg/s

camenzind, quasar script, 2002

agn triple bump spectra

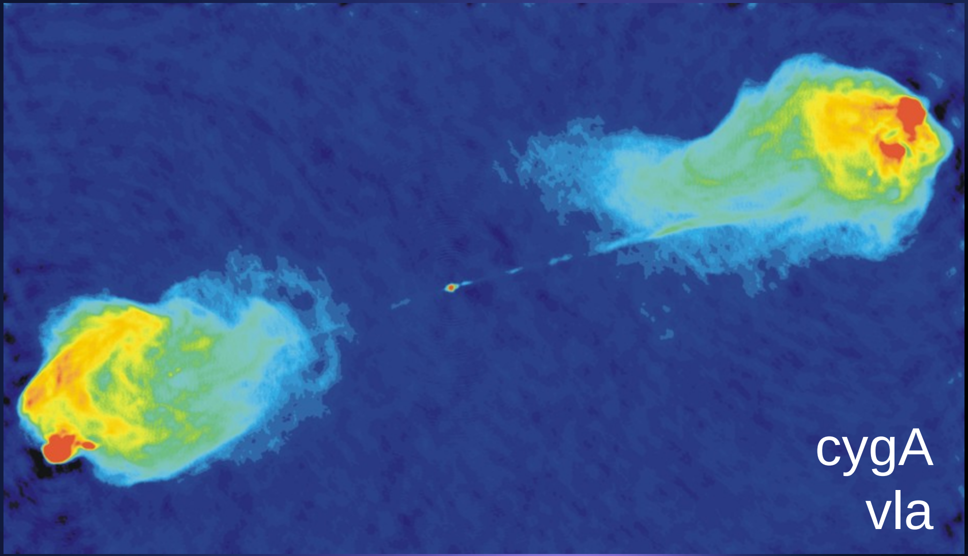


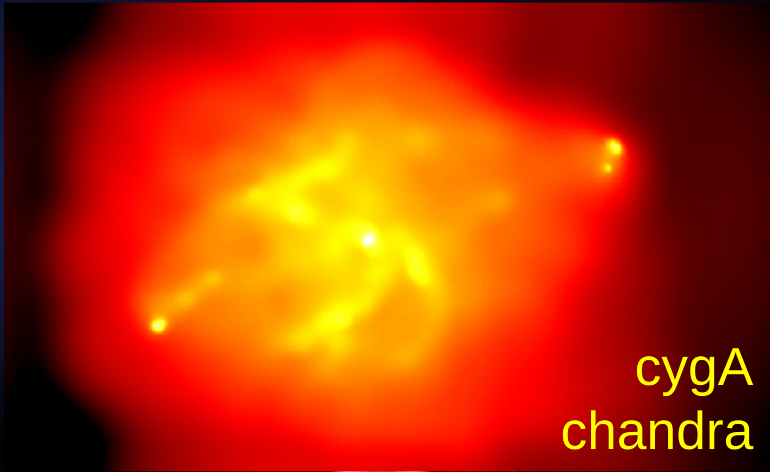
black holes and agn paradigm

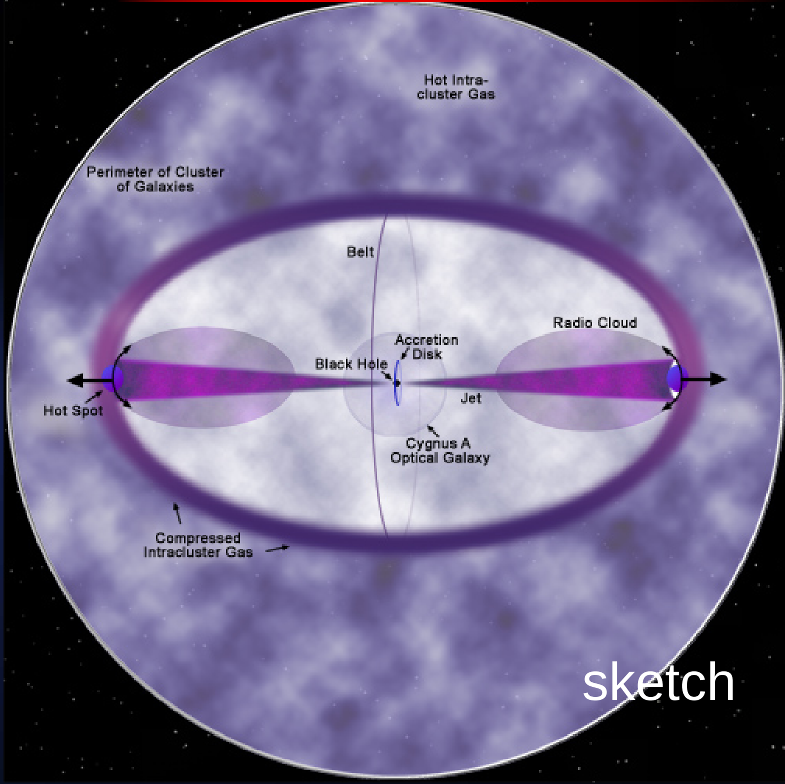


dichotomy in
agn type 1
agn type 2

black holes in centers of galaxies and agn


cygA
vla


cygA
chandra



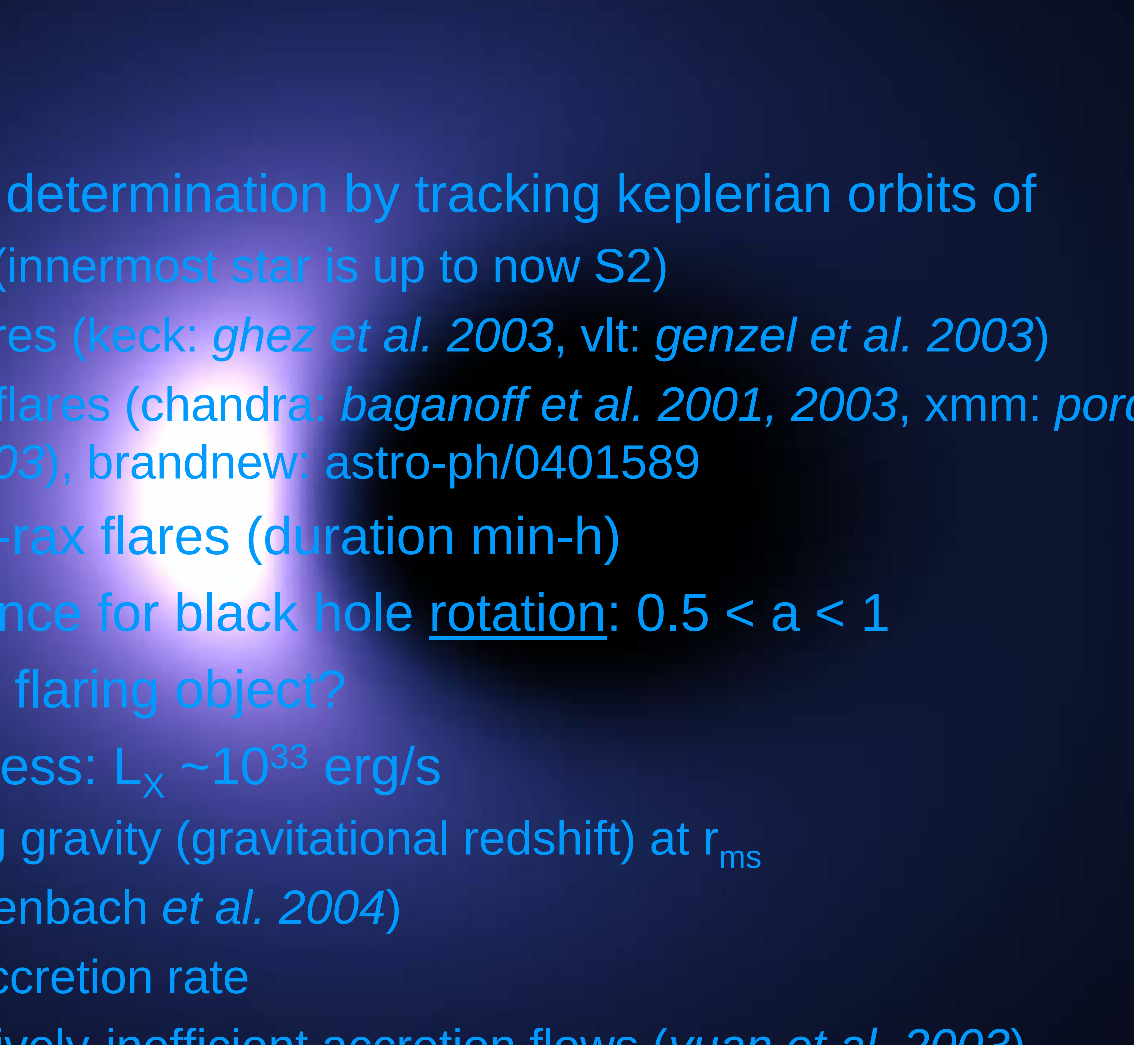
sketch

- supermassive black holes: $M_{BH} > 10^5 M_{\odot}$
- growth on accretion time scale
- spin-up to nearly extreme kerr, a ~ 1, by accretion of angular momentum

black holes in centers of galaxies: sgr a*

- compact radio source sgr a*
- radio synchrotron emission from thermal and non-thermal e^- distributions in compact region
- gravitomagnetic dynamo effects in black hole magnetosphere: dominantly toroidal B-field at r_{ms}
- sub-mm bump
- nuclear star cluster of massive stars and x-ray binaries (lmxbs, magnetic cvs) on 1“ scale
- sgr a* associated with supermassive black hole $2.6 \times 10^6\ M_\odot < M_{BH} < 4.8 \times 10^6\ M_\odot$

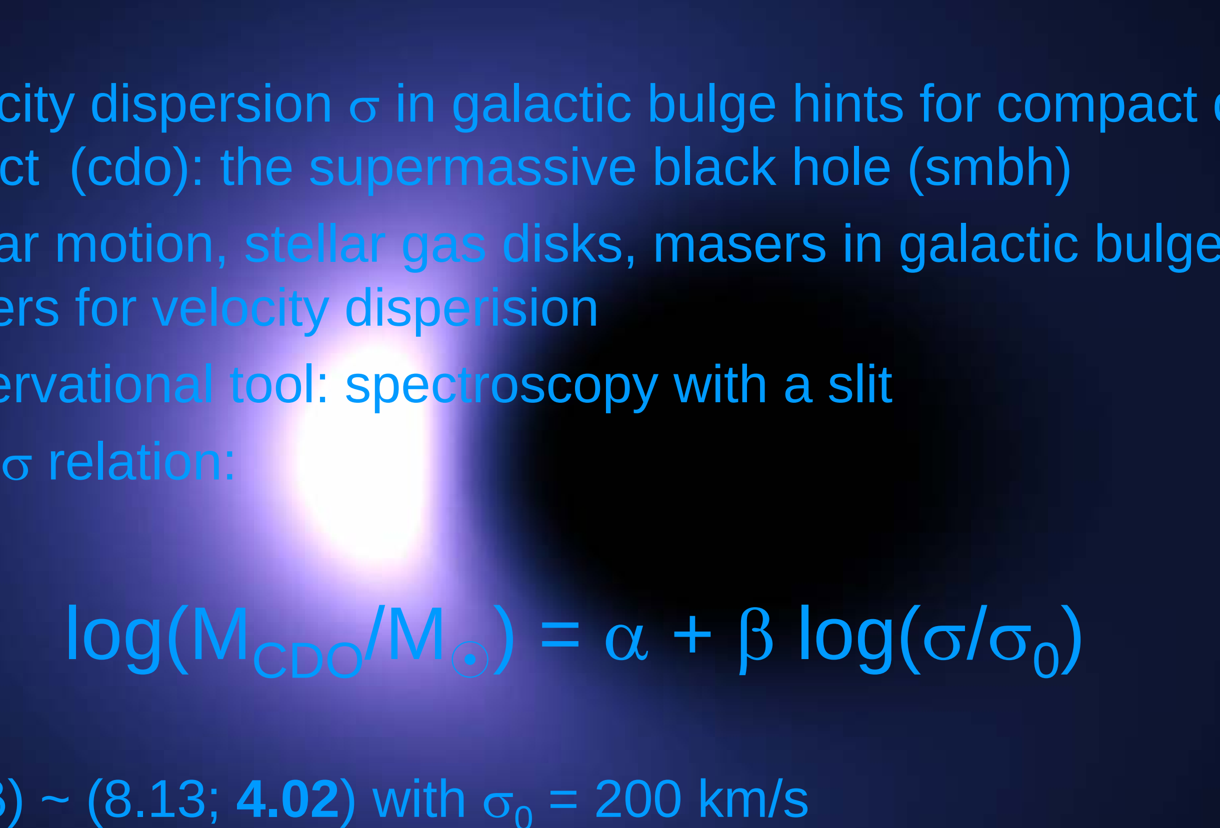
black holes in centers of galaxies: sgr a*



- bh mass determination by tracking keplerian orbits of
  - ➢ stars (innermost star is up to now S2)
  - ➢ nir flares (keck: *ghez et al. 2003*, vlt: *genzel et al. 2003*)
  - ➢ x-ray flares (chandra: *baganoff et al. 2001, 2003*, xmm: *porquet et al. 2003*), brandnew: astro-ph/0401589
- nir and x-rax flares (duration min-h)

  ⇨ evidence for black hole rotation: $0.5 < a < 1$
- nature of flaring object?
- GC dimness: $L_X \sim 10^{33}$ erg/s
  - ➢ strong gravity (gravitational redshift) at r_{ms} (aschenbach *et al. 2004*)
  - ➢ low accretion rate
  - ➢ radiatively-inefficient accretion flows (*yuan et al. 2003*),
  - ➢ cold inactive disks (*sunyaev et al. 2003*)

black holes in centers of galaxies: M - σ relation



- velocity dispersion σ in galactic bulge hints for compact dark object (cdo): the supermassive black hole (smbh)
- stellar motion, stellar gas disks, masers in galactic bulge are tracers for velocity disperision
- observational tool: spectroscopy with a slit
- M – σ relation:

$$\log(M_{CDO}/M_{\odot}) = \alpha + \beta \log(\sigma/\sigma_0)$$

- (α; β) ~ (8.13; **4.02**) with σ_0 = 200 km/s
- M – σ relation is an estimator for smbh determinations in galaxies and agn

tremaine et al., astro-ph/0203468

black holes in centers of galaxies: M - σ relation

- ✌ stellar kinetics
- △ gas kinematics
- * maser kinematics
- 👎 nuker measurements

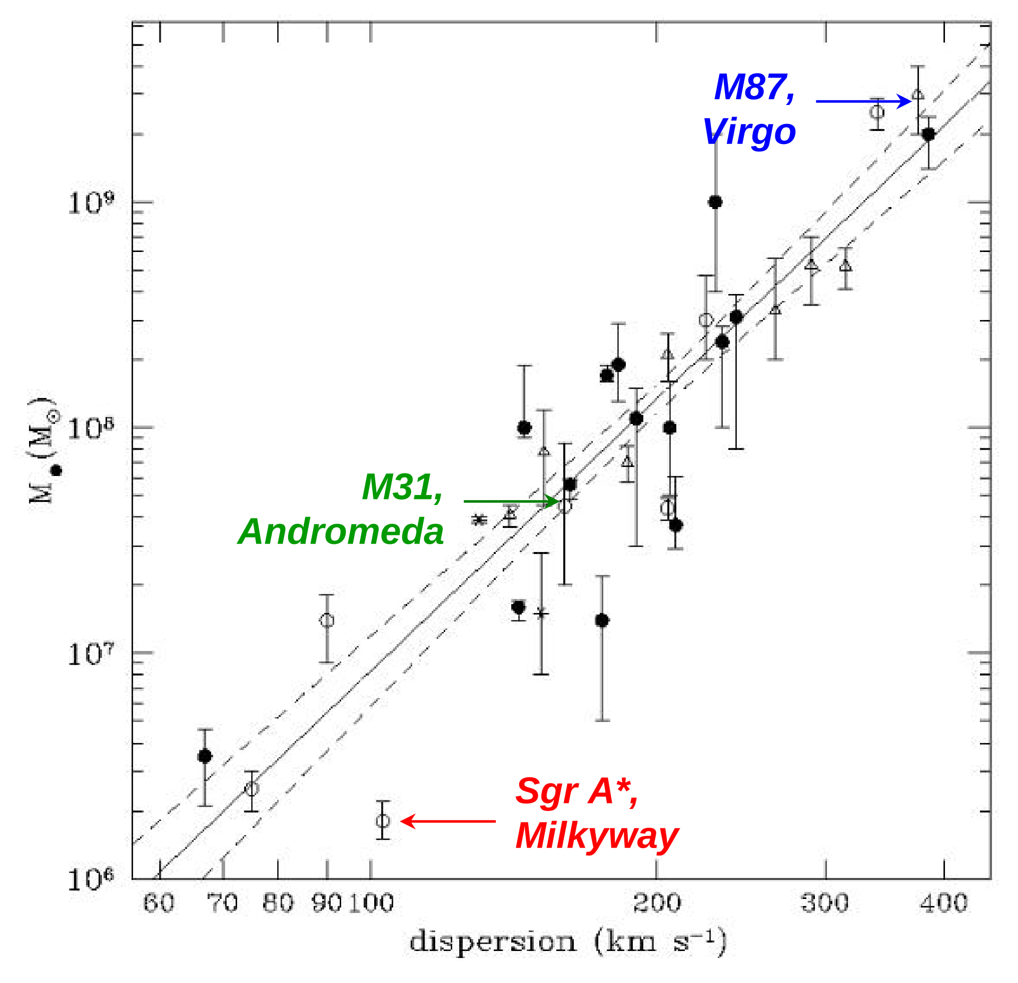
solid:

best fit $\alpha = 8.13$, $\beta = 4.02$

dashed:

1σ

$$\boxed{M \sim \sigma^4}$$



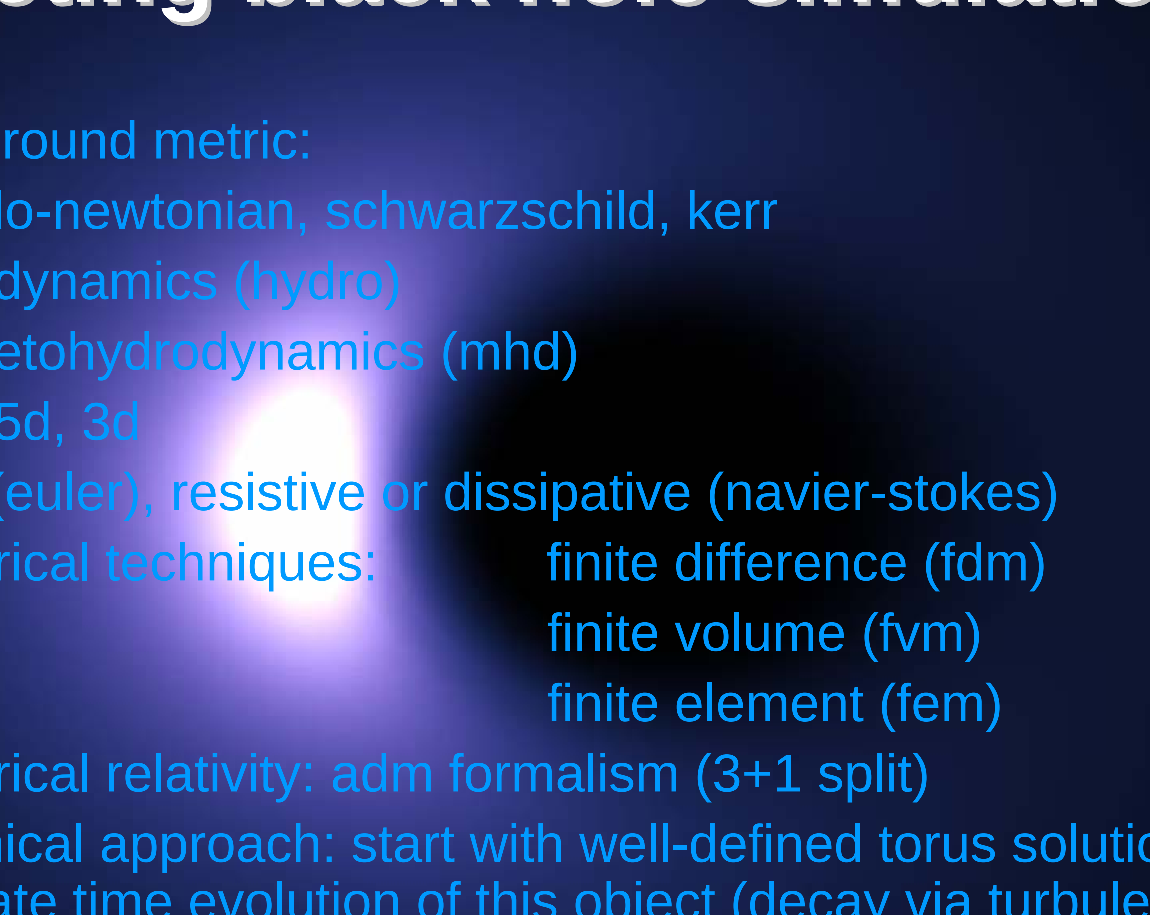
M87, Virgo

M31, Andromeda

Sgr A*, Milkyway

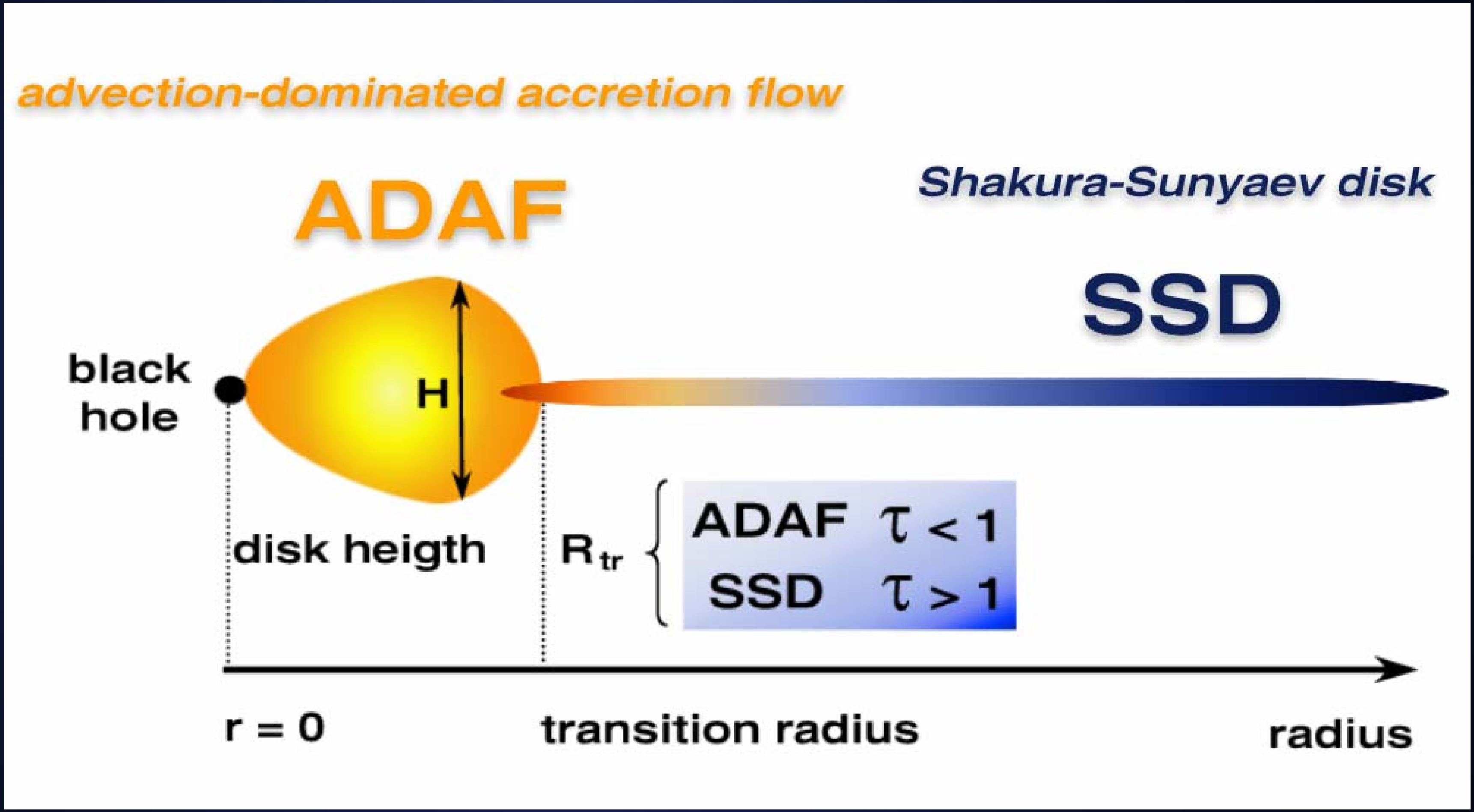
tremaine et al., astro-ph/0203468

accreting black hole simulation



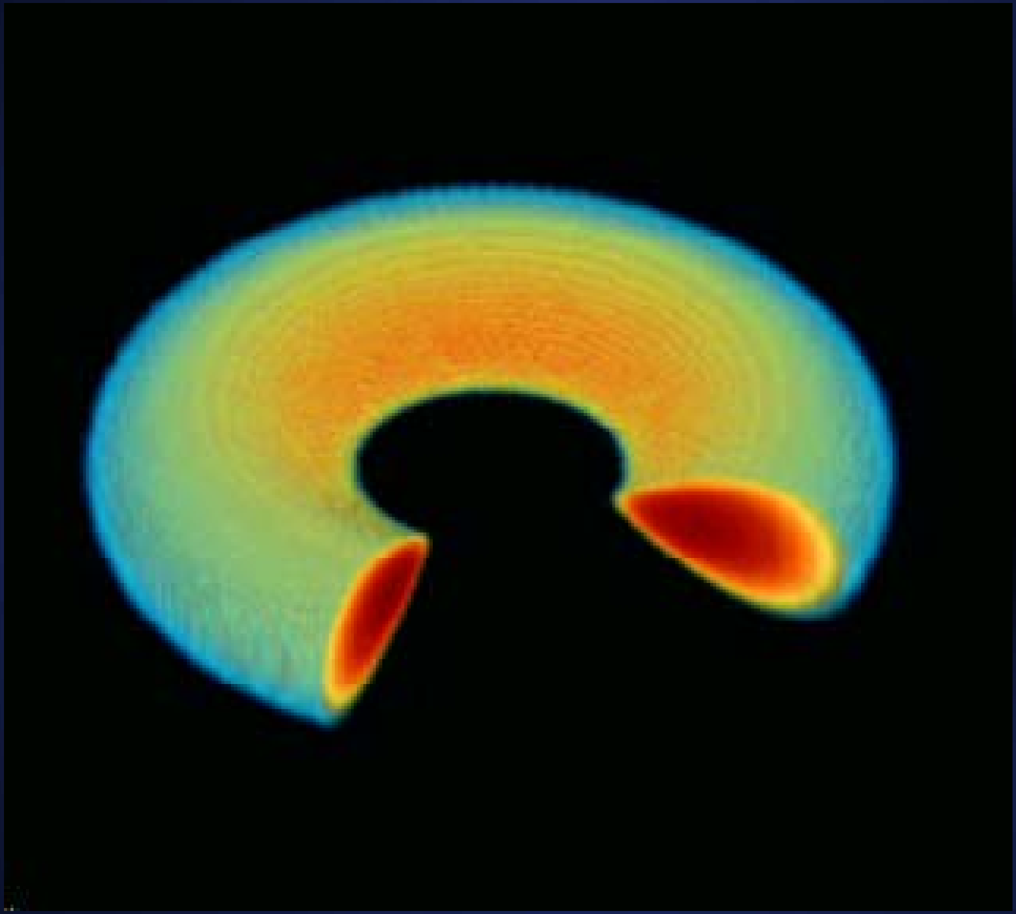
- background metric:
  pseudo-newtonian, schwarzschild, kerr
- hydrodynamics (hydro)
- magnetohydrodynamics (mhd)
- 2d, 2.5d, 3d
- ideal (euler), resistive or dissipative (navier-stokes)
- numerical techniques:
  - finite difference (fdm)
  - finite volume (fvm)
  - finite element (fem)
- numerical relativity: adm formalism (3+1 split)
- canonical approach: start with well-defined torus solution and simulate time evolution of this object (decay via turbulence, mri)
- co-ordinate systems: boyer-lindquist, kerr-schild
- challenge: boundary at the horizon

accreting black holes - ssd



gracia et al., mnras 344, 468, 2003

accreting pseudo black holes



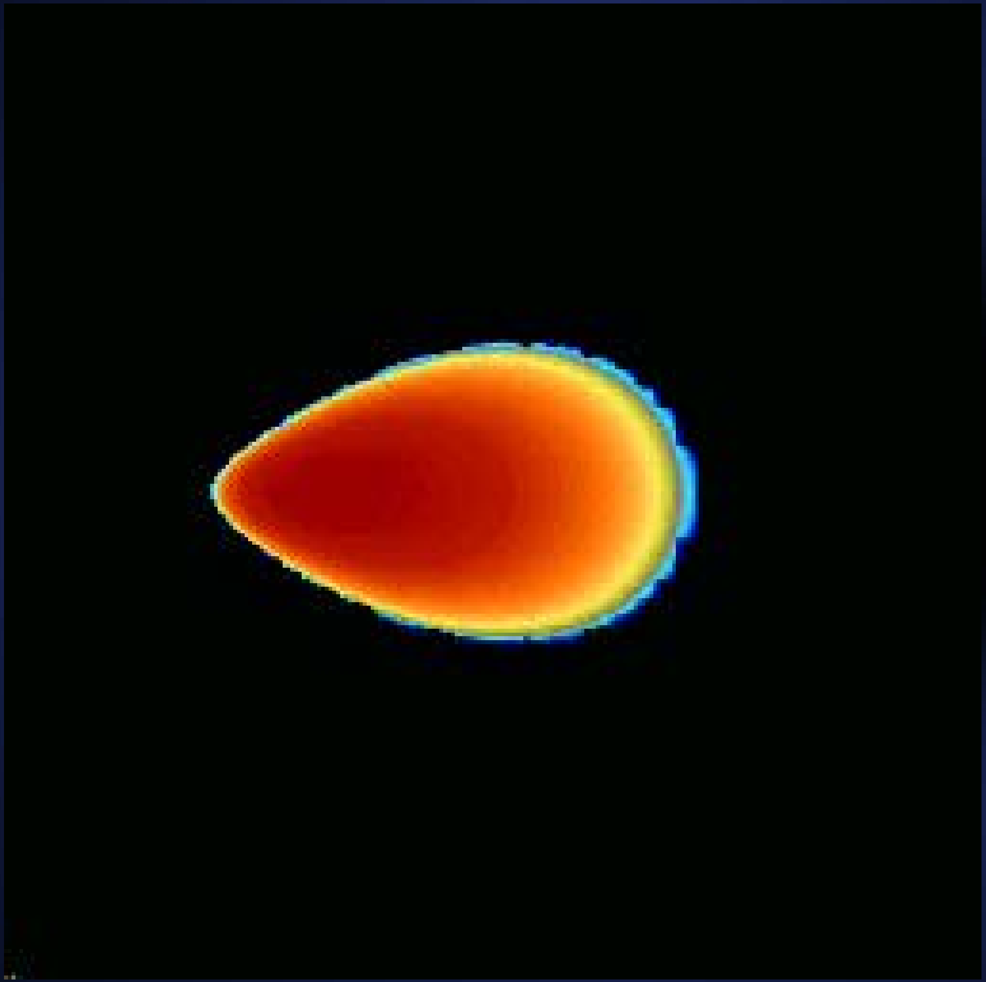
- pseudo-newtonian
  (paczýnski-wiita potential)

$$\Phi = -\frac{GM}{r - r_g}$$

- 3D ideal mhd
- mhd turbulence
- magneto-rotational instability (mri)
- large-amplitude waves at r_{ms}

hawley & krolik 2001,
http://www.astro.virginia.edu/VITA/papers/pndisk/pndisk.html

accreting black holes - grmhd



- 3D grmhd on kerr
- initial torus configuration
- mhd turbulence
- magneto-rotational instability (mri)
- initial magnetic field in poloidal loops, $\beta = 100$
- movie: 10 orbits at p_{max}
- gas density shown

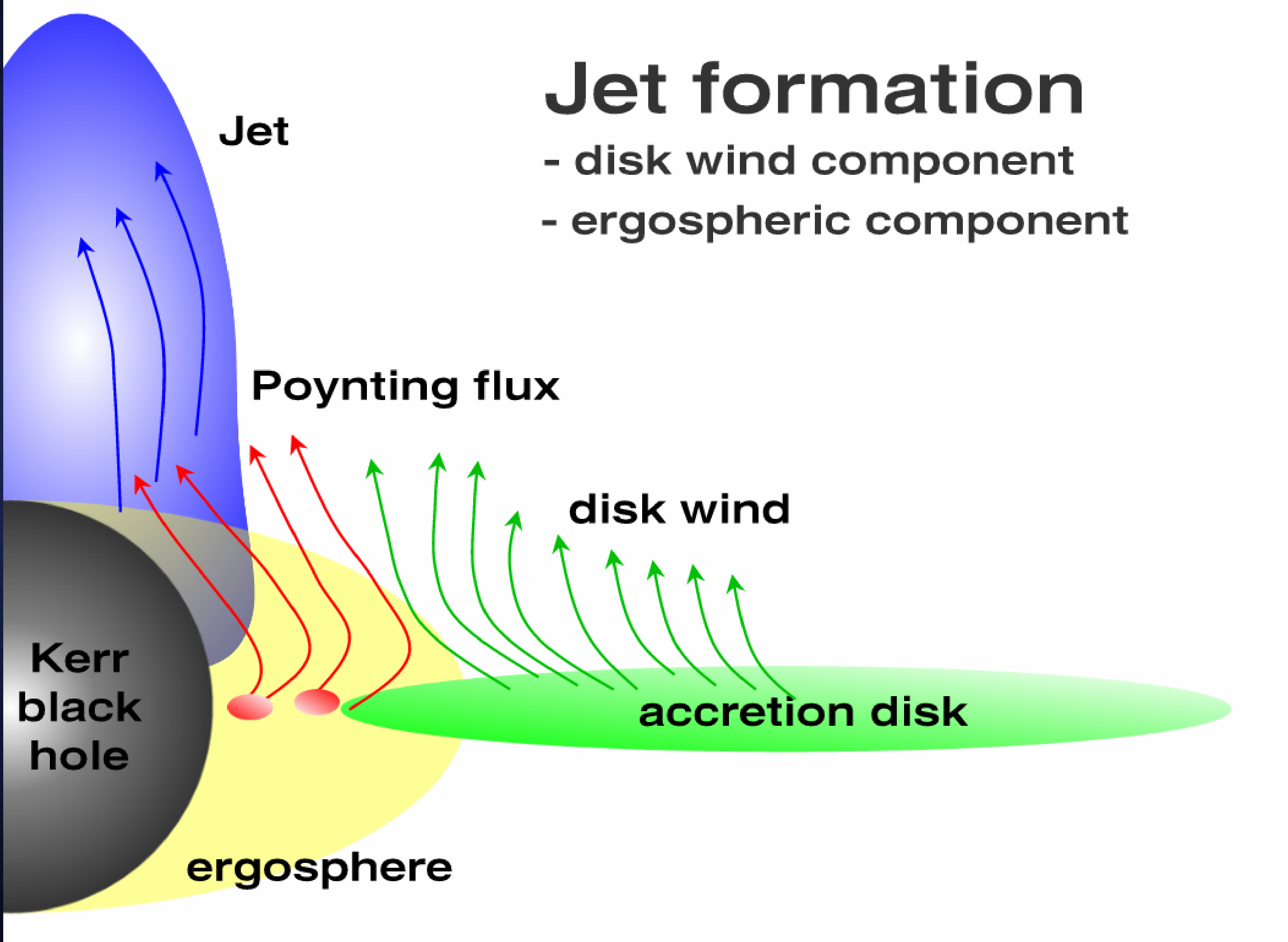
de villiers & hawley 2003,
http://www.astro.virginia.edu/~jd5v/KD_movies.htm

accreting black holes - challenges

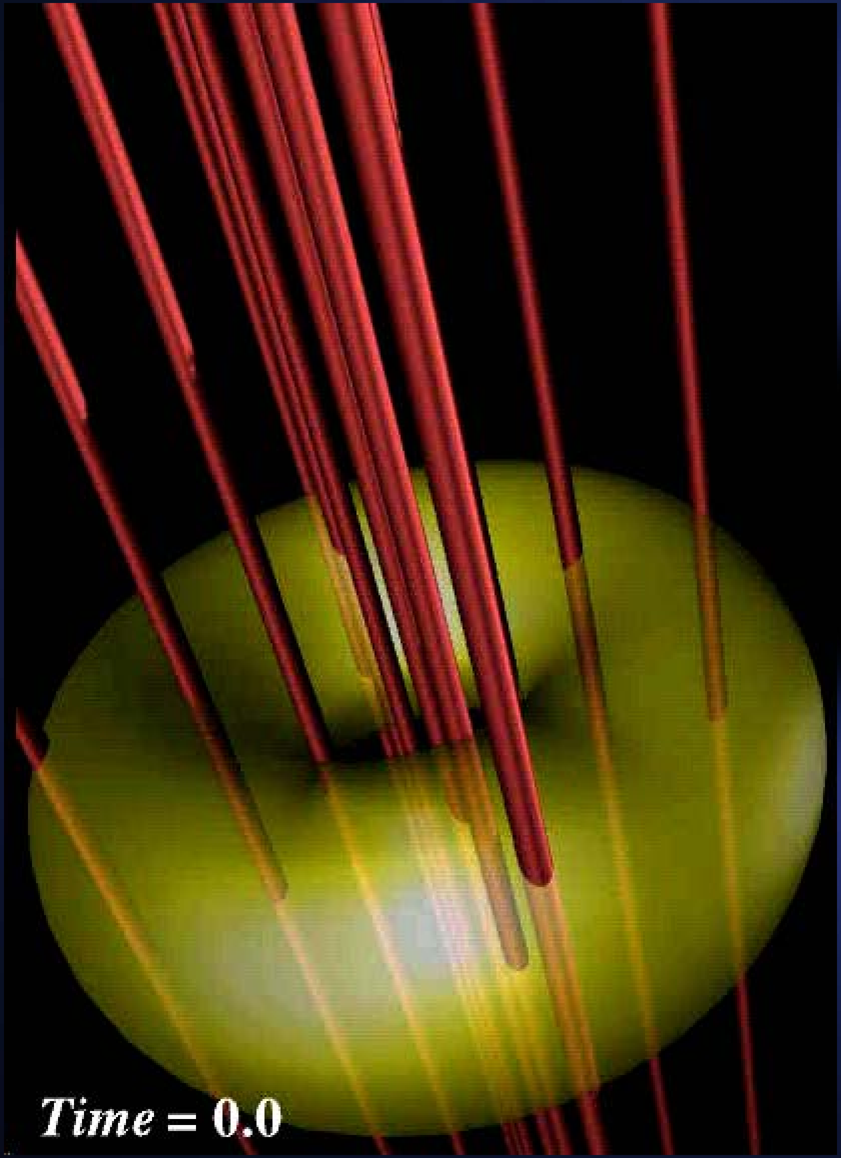
- accretion theory gives solution
  - shakura-sunyaev disk (ssd)
  - advection-dominated accretion flow (adaf)
  - non-radiative accretion flow (nraf)
- nraf on kerr investigated

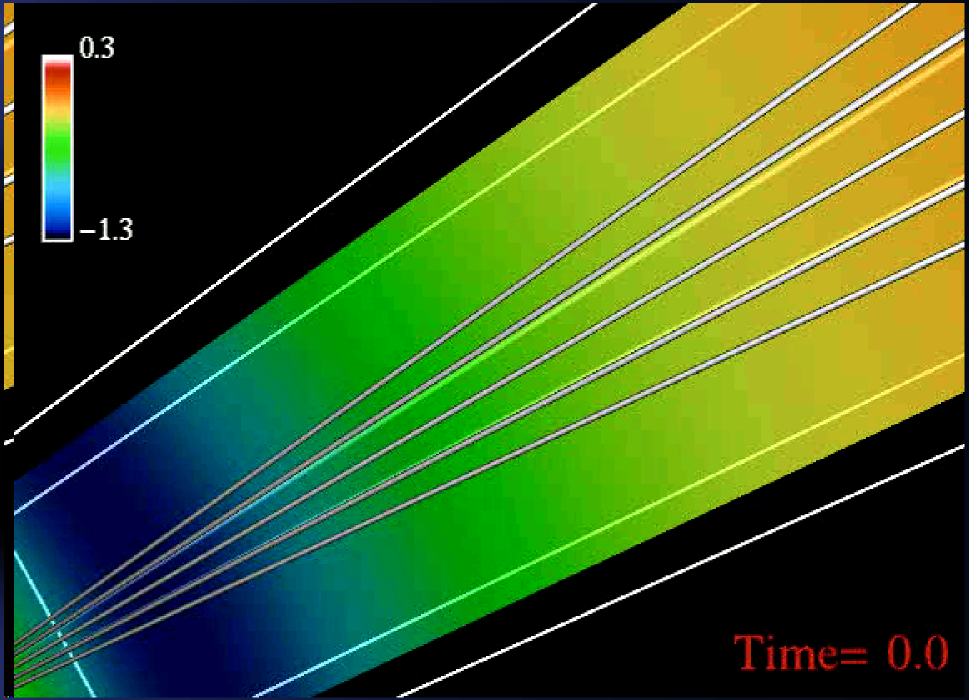
  (*koide, shibata et al. 2001*, *de villiers & hawley 2003*)
- trouble-shooting
  - radiatively cooled solutions
  - radiation transfer in curved space-time
  - neutrino cooling

black holes – jet-disk symbiosis



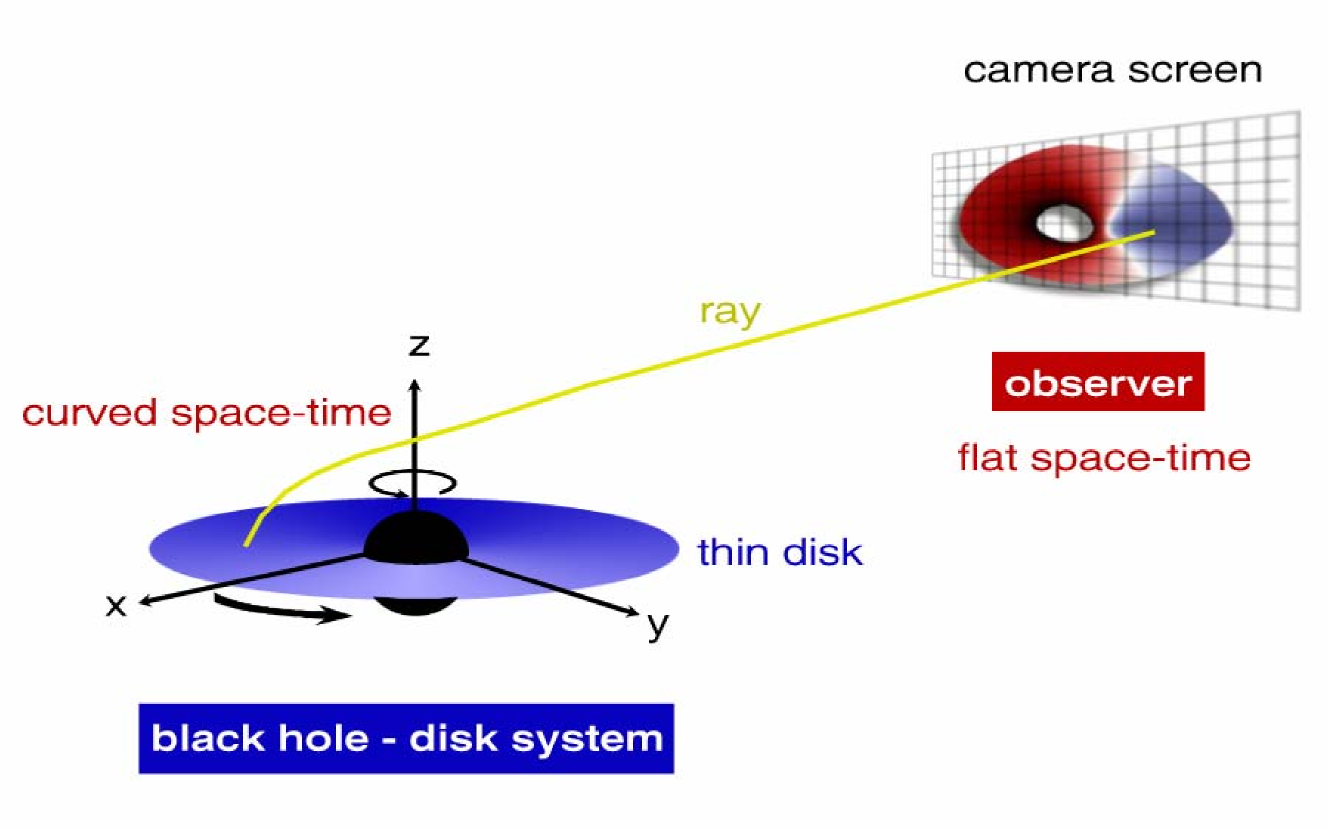
black holes – mhd jet launching





japanese group

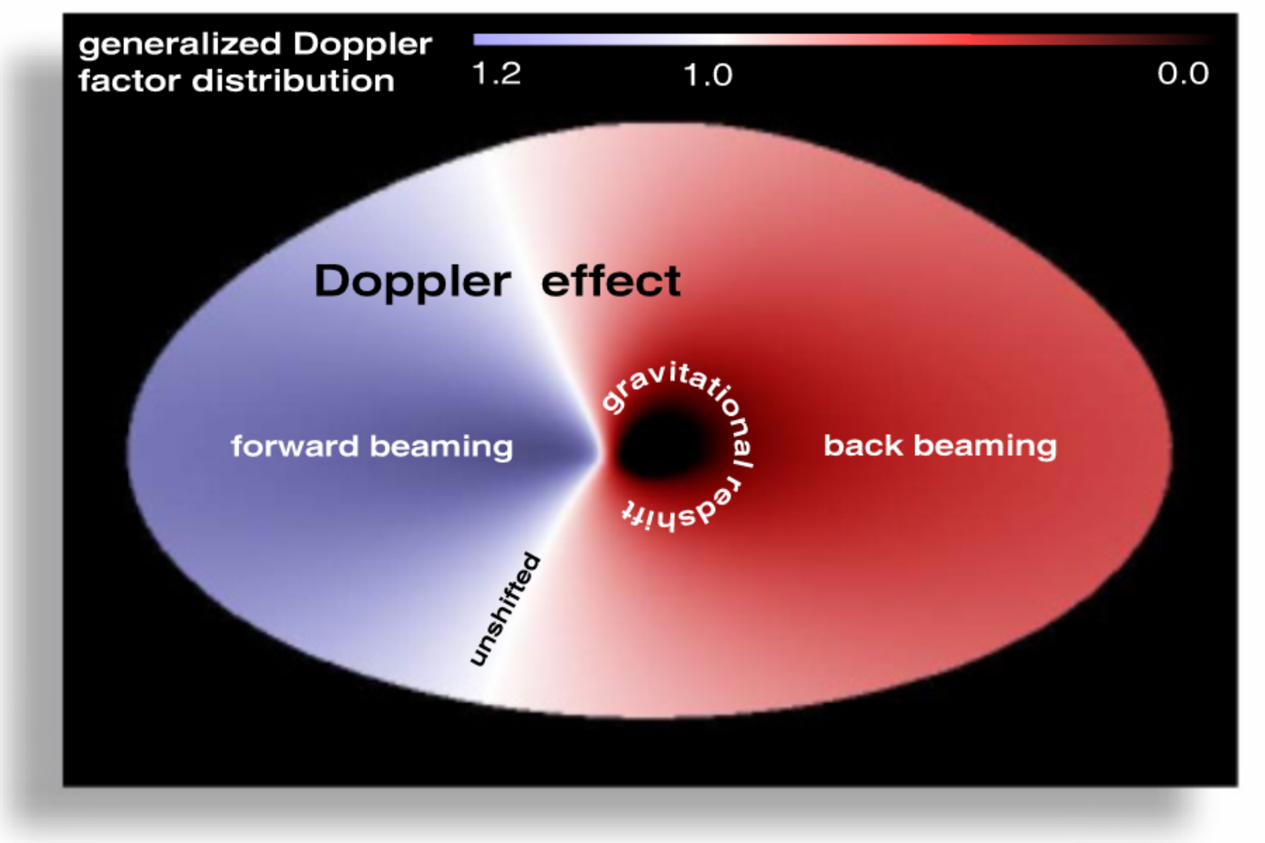
black hole - ray tracing



- solving geodesics equation on kerr geometry (carter photon momenta, 1968)
- direct integration (3D) or fast mapping via ellipt. integrals (2D)
- photons follow null geodesics of space-time

müller, diploma thesis 2000

black hole - render disk images



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

keplerian kinematics

- classical: doppler effect
- relativistic: beaming (sr) and gravitational redshift (gr)
- fully relativistic generalized doppler factor
- effects influence *any emission* in black hole systems!

müller, diploma thesis 2000

black hole – emission distribution

$a = 0.1$

$i = 40°$

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

$r_{out} = 30.0\ r_g$

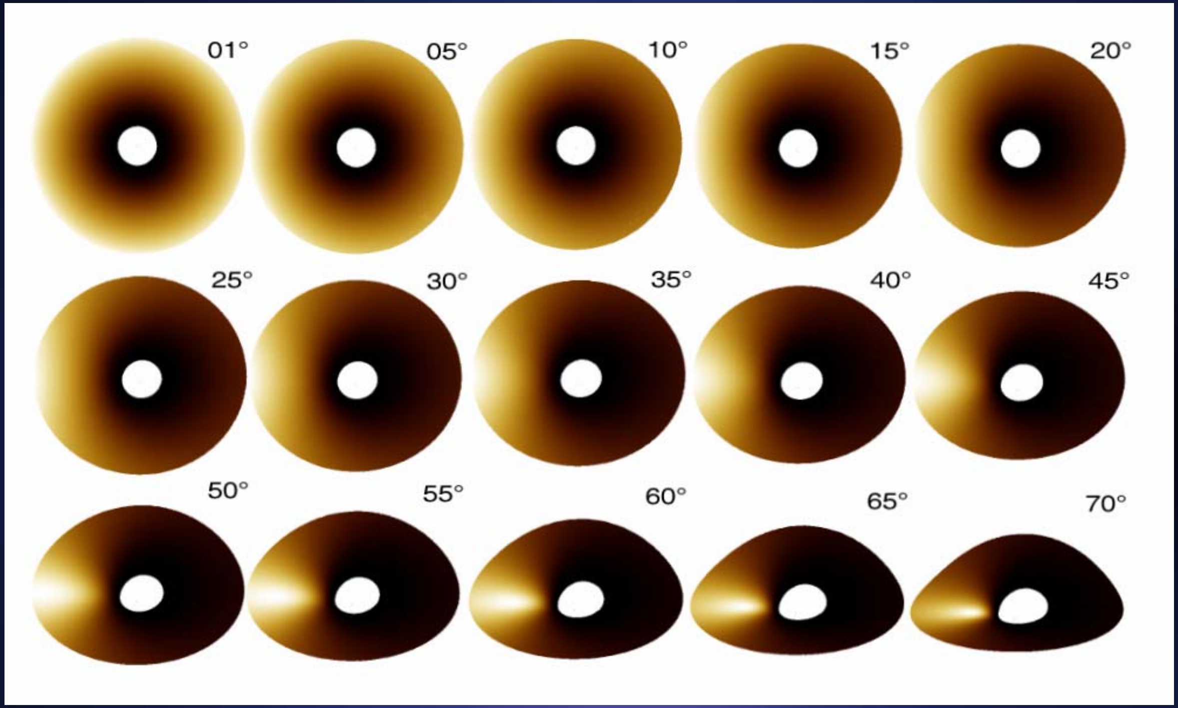
$R_t = 6.0\ r_g$

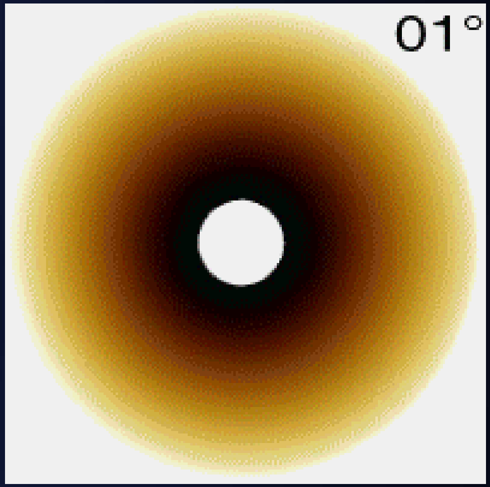
keplerian + drift

cut power law

müller, diploma thesis 2000

black hole shadow

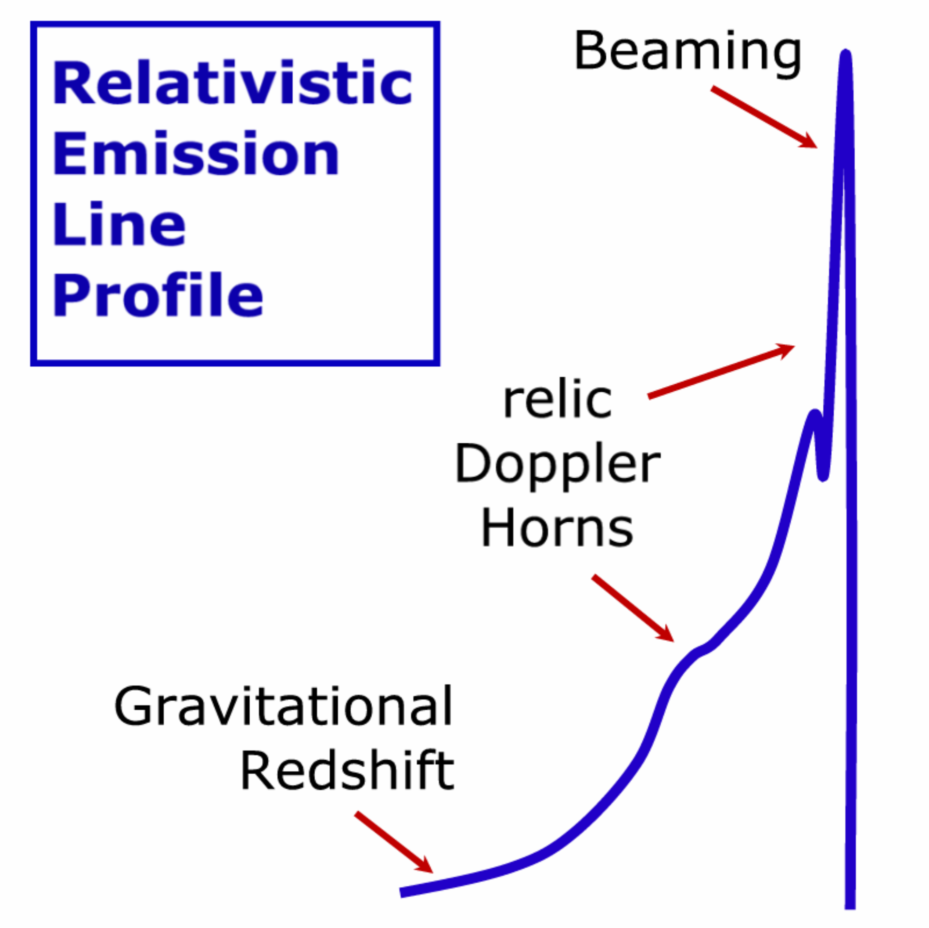




- „shadow“ (falcke et al., mpifr) due to gravitational redshift
- grasping with vla scans in near future

müller 2002,
http://www.lsw.uni-heidelberg.de/users/amueller/astro_sl.html#kbhrt

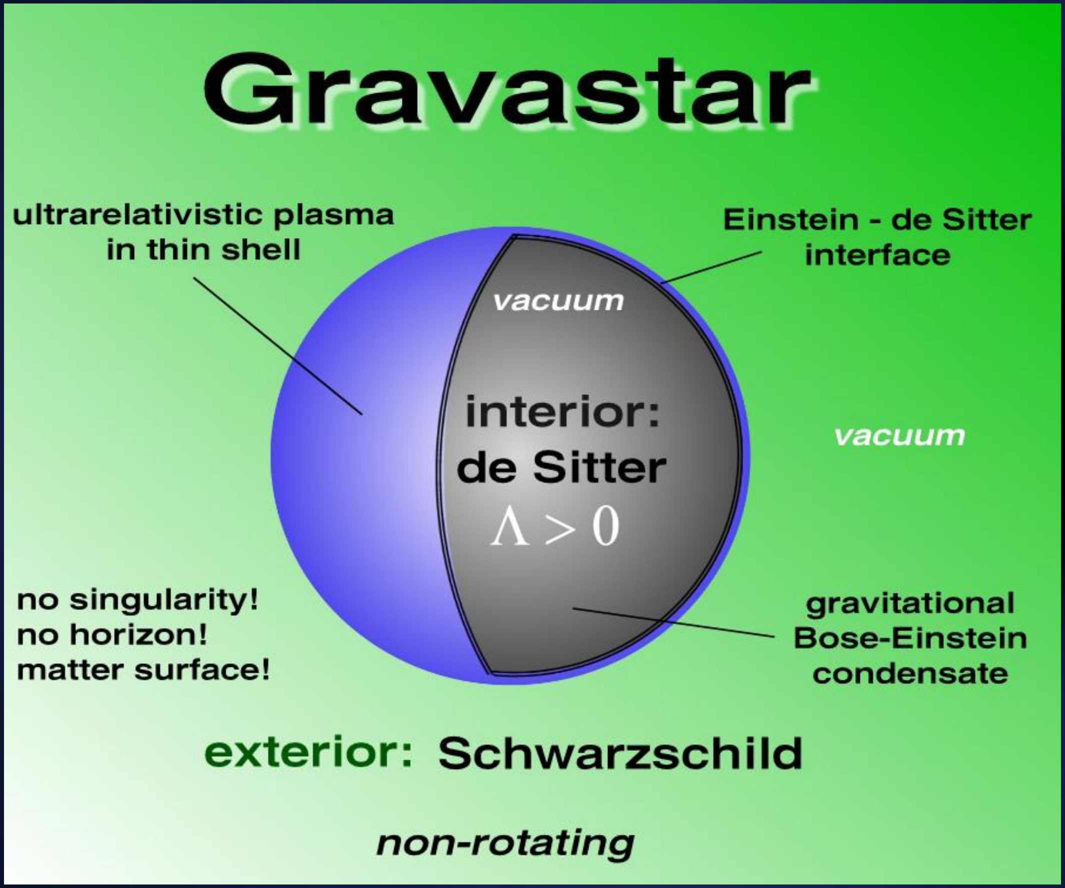
black hole – emission line diagnostics



- hot ions undergo Kα, Kβ transitions
- x-ray emission
- Fe Kα at ~ 6.4 keV dominant
- x-ray data from asca, chandra, xmm
- large parameter space!
  - $\{a, i, r_{in}, r_{out}\}$
  - emissivity law
  - plasma kinematics
- emissivity: power laws (single, double, cut) or gaussian profiles
- line zoo
- sources: seyfert 1s, quasars type 1, microquasars

müller & camenzind, a&a, 413, 861 (2004) (= astro-ph/0309832)

black hole crisis – gravastars

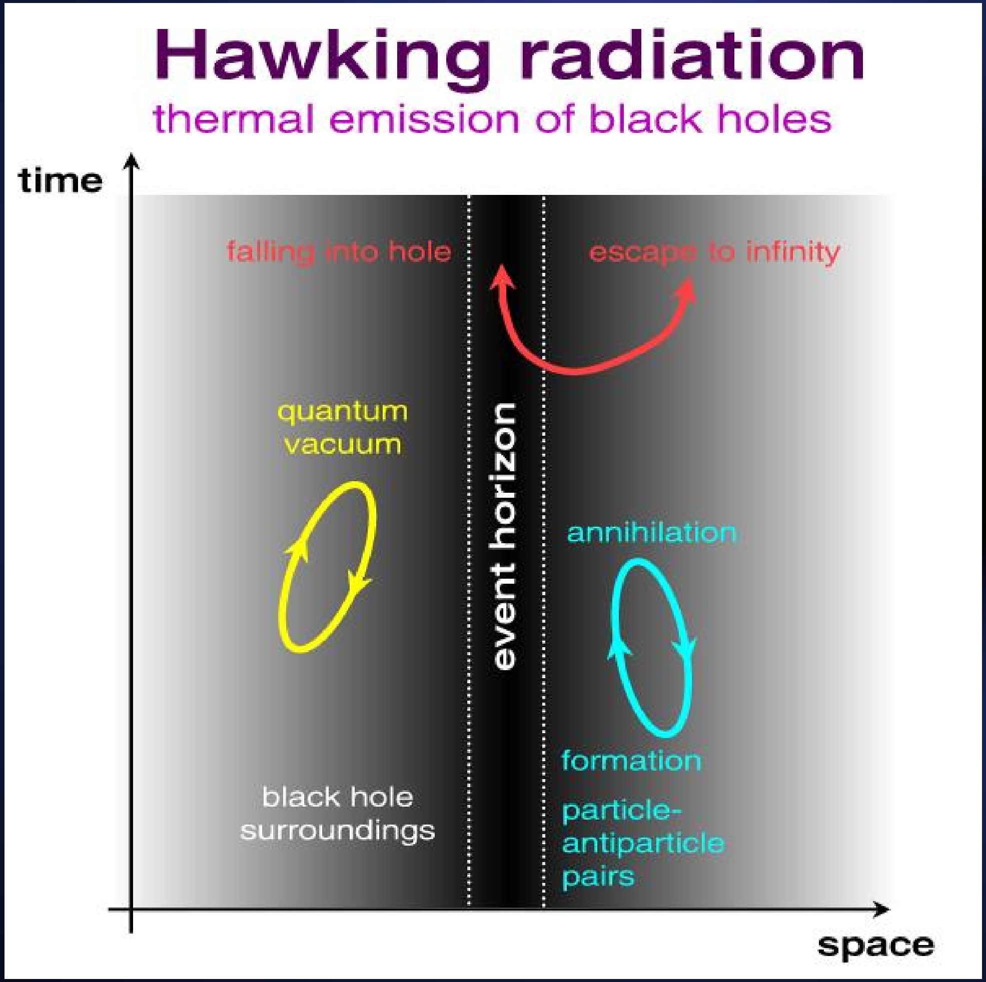


- alternative metric
  to black hole
- stabilized by antigravitative Λ fluid (dark energy)
- regular!
- no horizon:
  escape velocity < c
  finite redshift z_{grav}
  redshift factor $g \sim \varepsilon > 0$

but: **non-rotating**

mazur & mottola, 2001, gr-qc/0109035
visser & wiltshire, 2003, gr-qc/0310107

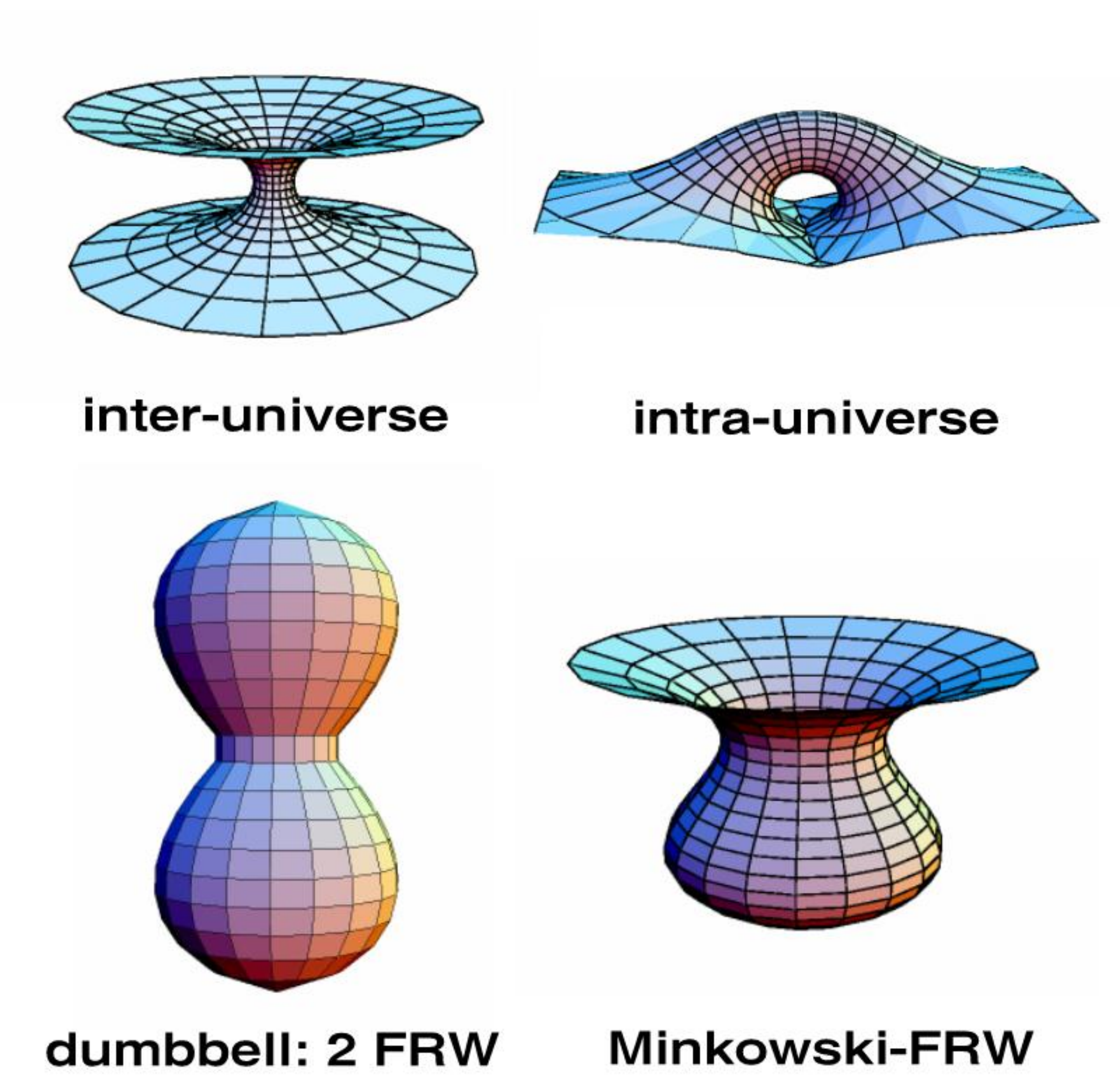
black hole evaporation



- pair production at horizon (heisenberg uncertainty)
- energy transfer from curved space-time to virtual particle so that it becomes real
- planck emitter with bekenstein-hawking temperature
- **hawking radiation**
- only relevant for very light, non-stellar black holes
- typical decay time scale for stellar bh 10^{60} a
- hawking radiation is analogue to acceleration radiation, the **unruh effect** (equivalence principle)

hawking, commun. math. phys. 43, 199, 1975

worm hole - topologies



visser & hochberg 1997, gr-qc/9710001; gr-qc/9704082

worm hole

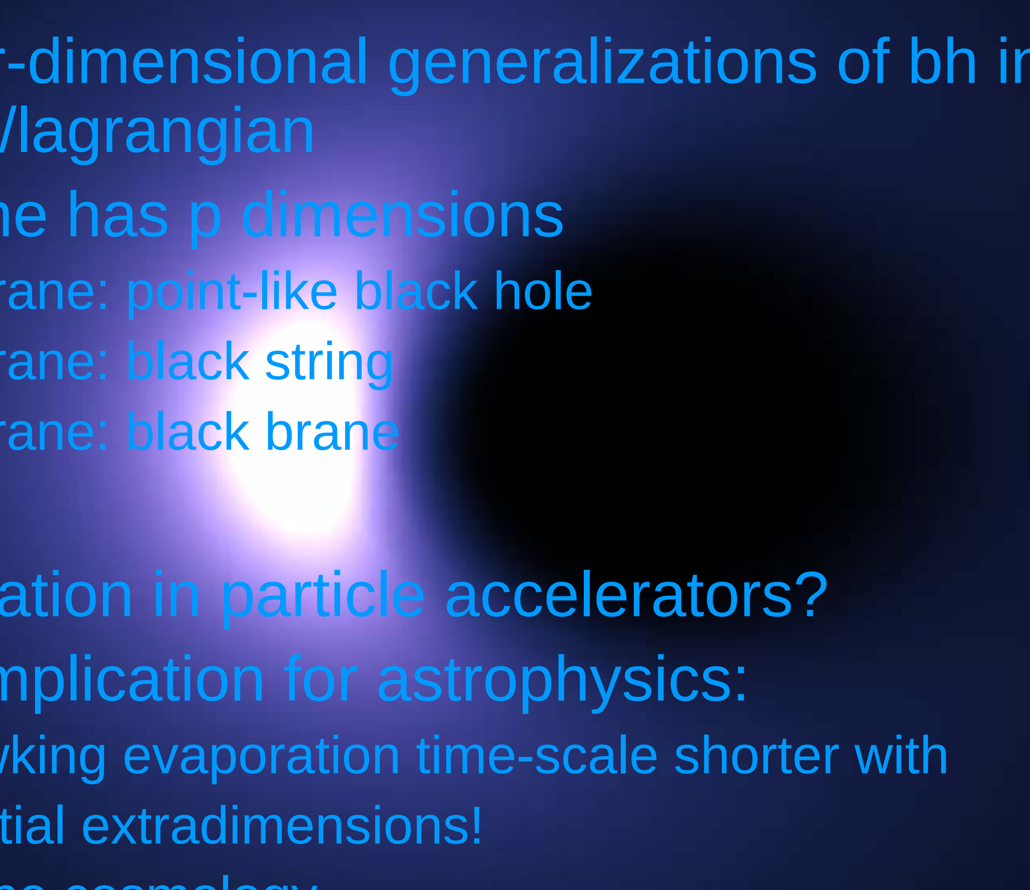
- consists of black hole and white hole
- white hole: inverse time-translated black hole
- naked singularity injures cosmic censorship (*penrose*)
- kruskal solution: maximal, analytic extension of schwarzschild solution (kruskal-szekeres coordinates)
- einstein-rosen bridge: channel to other universe?
- stabilization via matter with negative energy density: „exotic matter“ (*morris & thorne 1988*)
- exotic matter generated locally by quantum fields (*hochberg et al. 1997*)
- wormhole may be traversable by humanoid (*kuhfittig 2004*)
- time conjecture hypothesis (*hawking 1992*)
- **never ever observed** in our universe!

black holes – dynamical horizon

- event horizon: teleological character
- isolated black holes vs. accreting black holes
- new notion: ‚*dynamical horizon*‘
- growth by infalling matter, radiation, gravitational waves
- use of full non-linear general relativiy
- flux equation!
- generalization of black hole mechanics (hawking, 1971)
- application in numerical relativity: simulation of bh-bh merging and gravitational wave output (aei potsdam, germany)

ashtekar & krishnan, 1999 - 2003

black holes in string theories

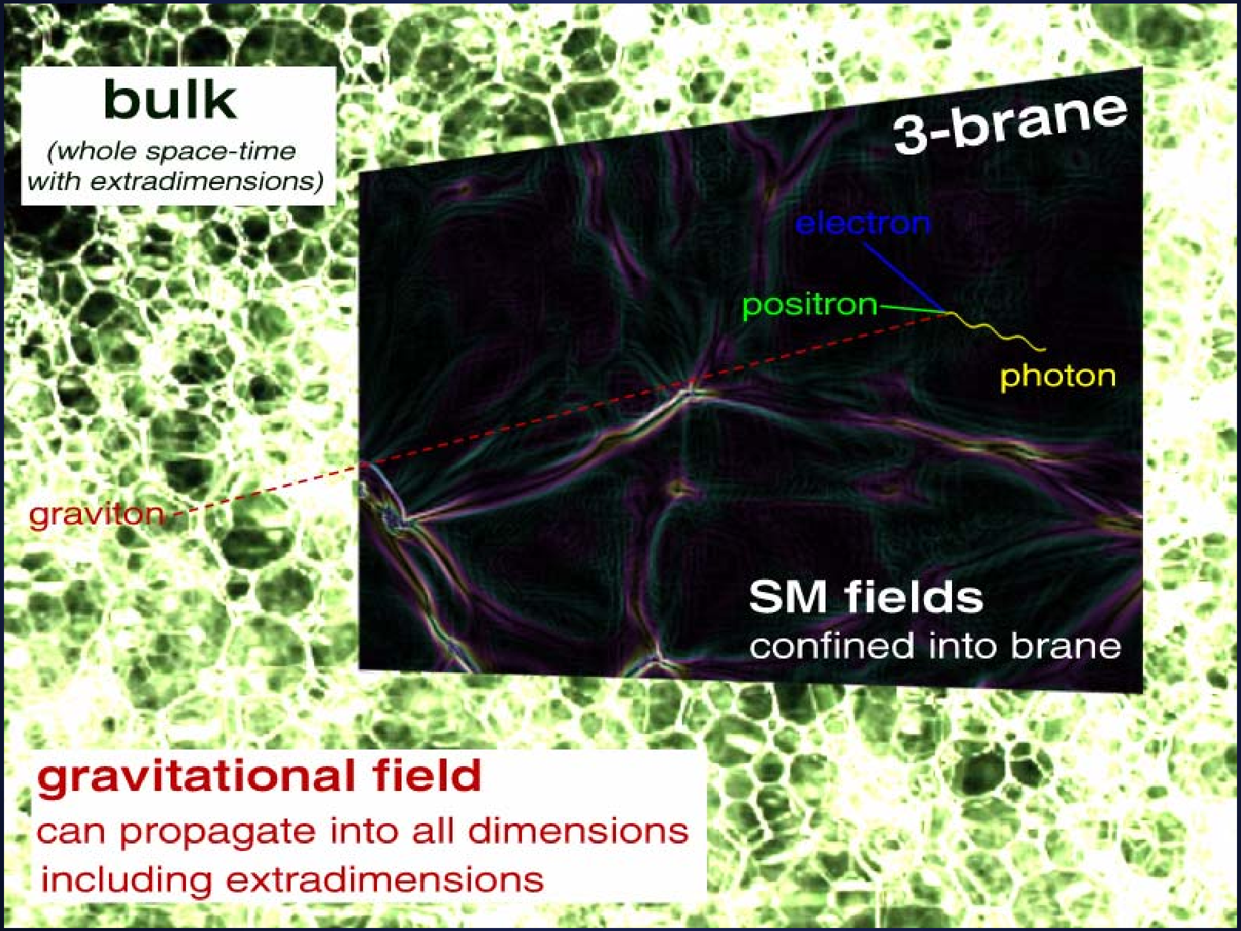


- higher-dimensional generalizations of bh in gr, depending on action/lagrangian
- p-brane has p dimensions
  - 0-brane: point-like black hole
  - 1-brane: black string
  - 2-brane: black brane

- application in particle accelerators?
- new implication for astrophysics:
  - hawking evaporation time-scale shorter with spatial extradimensions!
  - brane cosmology

cavaglia 2002, hep-ph/0210296 (nice review)

black holes in brane worlds



- extradimensions assumed!
- black hole as 3-brane
- TeV quantum gravity: reduced planck scale
- formation of mini black holes
- decay via hawking radiation on short time scale, 10^{-24} s
- **not yet observed!**

cavaglia 2002
brax & bruck, hep-th/0303095

black holes on the web

http://www.lsw.uni-heidelberg.de/users/amueller/astro_sl.html

more details, more formulae, more images...

have fun!

this talk is available as powerpoint and postscript

http://www.lsw.uni-heidelberg.de/users/amueller/astro_ppt.html

have a look into my german web dictionary for astrophysics

http://www.lsw.uni-heidelberg.de/users/amueller/astro_ppt.html