Models of Inefficient Accretion onto a Black Hole and Pair Production in Jets

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Radiatively Inefficient Accretion Flows (RIAFs)

- RIAF in theory
  - $\dot{m} < \dot{m}_{crit}$ = few x 10^{-7} ($\dot{m} = \dot{M}_{acc}/\dot{M}_{Edd}$, $\dot{M}_{Edd}$=10% L_{Edd} c^2 $L_{Edd} = 4\pi G M_{bh} c m_p/\sigma_T$)
  - $t_{rad} \gg t_{dyn}$, weak radiative cooling, energy advection (ADAF, Narayan & Yi 1994)
  - Accretion flow → geometrically thick and optically thin + accretion flow dynamics decoupled from radiation
  - collisionless plasma→ T_p/T_e != 1
- RIAF in practice, BH systems with $L \ll L_{Edd}$
  - quiescent GN: Sgr A* ($L/L_{Edd}=10^{-9}$)
  - BLLac/FRI: M87 ($L/L_{Edd}=10^{-5.5}$)
  - many nearby galactic nuclei, BHB in quiescent state

Outline

- Numerical realization of RIAF models (GRMHD simulations)

- Radiative properties of RIAFs from Monte Carlo simulations
  - application to *Sgr A**

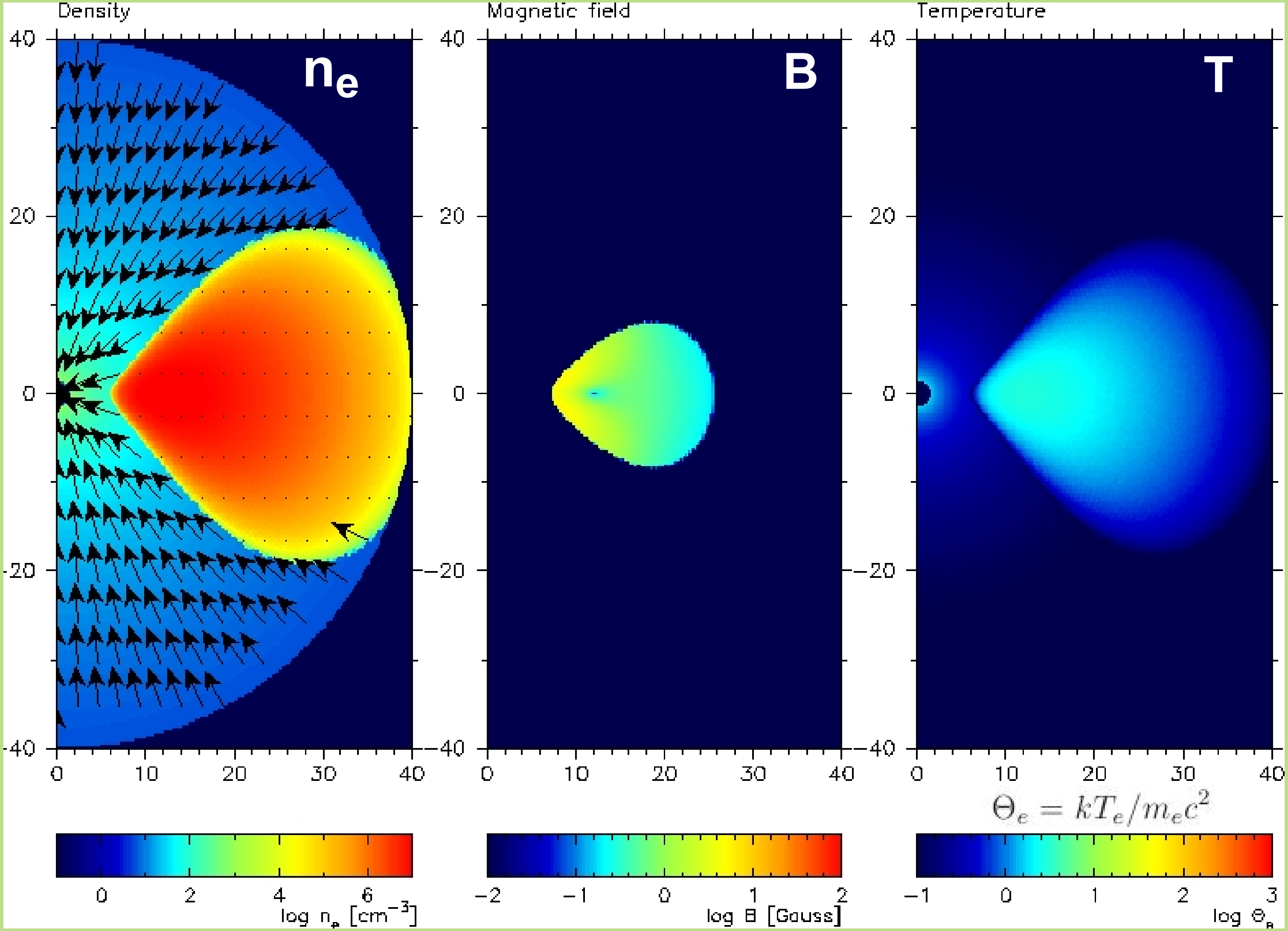
- Non-equilibrium electron-positron pair production in the jet (magnetized funnel)
  - $\gamma + \gamma \rightarrow e^+ + e^-$
  - pair production is balanced by pair escape rather than pair annihilation

Goals

- Understand physics of accretion in underluminous X-ray sources such as *Sgr A**

- Understand composition of jets and conditions to produce jets
  - during RIAF phase
  - during transition from RIAF to efficient accretion mode
  - Selfconsistent model of accretion disk and jet

Accretion disk model – initial setup

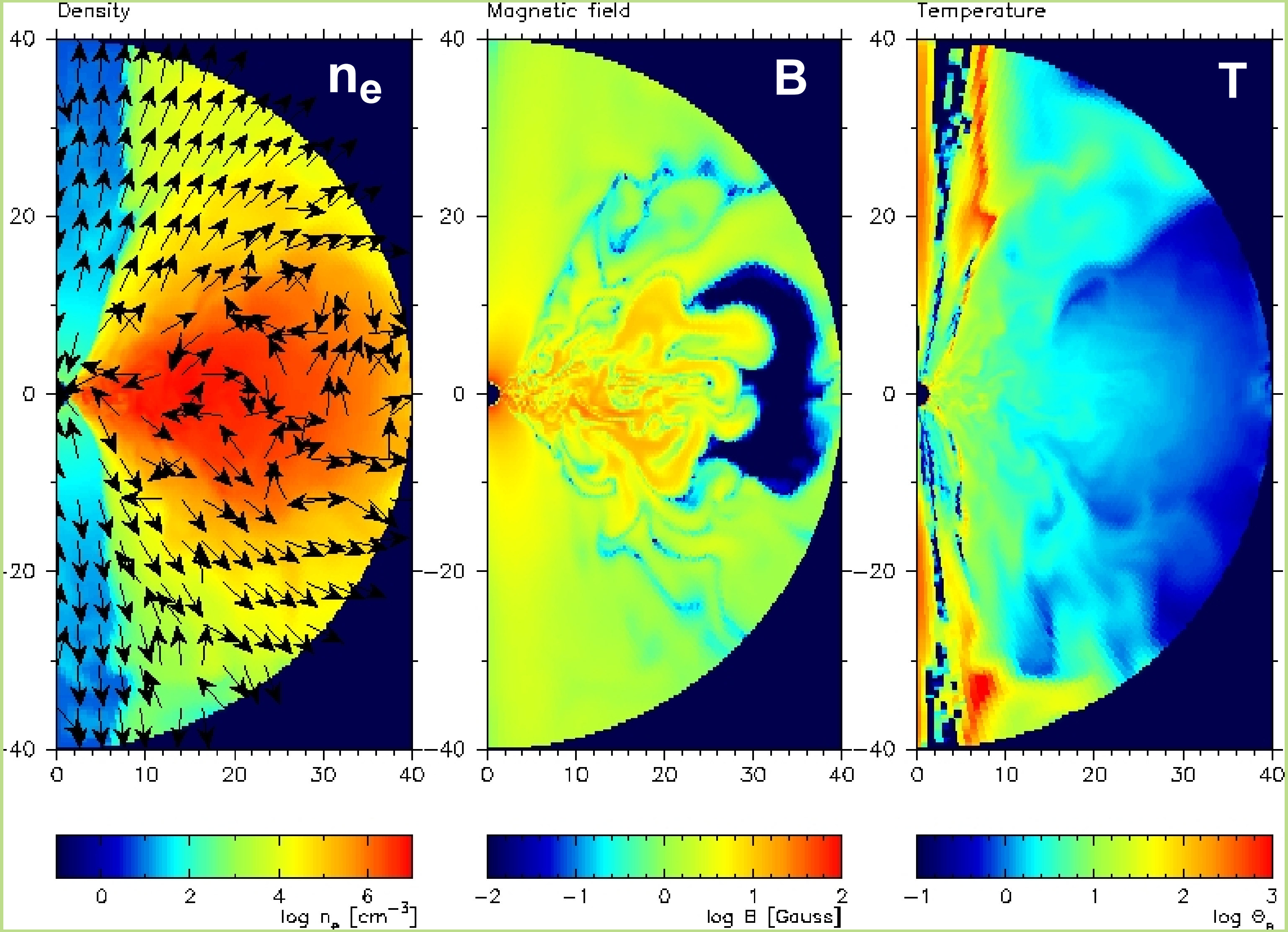


• Equilibrium torus (Fishbone & Moncrief 1976, Abramowicz et al. 1978) + weak magnetic field

• MHD equations solved with HARM (2D Gammie et al. 2003, 3D Noble et al. 2006, 2009), conservative, shock capturing scheme to solve GRMHD eq,

• radial range = r_h - 40 R_g (Kerr -Schild coordinates-no singularity at r_h)

Accretion disk model – later times



- All simulations show a similar, statistically steady final state
- We assume that the inner parts of this torus are the inner parts of large RIAF
- Scaling depends on M_{bh} and $\dot{M}_{acc}$

Model comparison to observation - radiative transfer

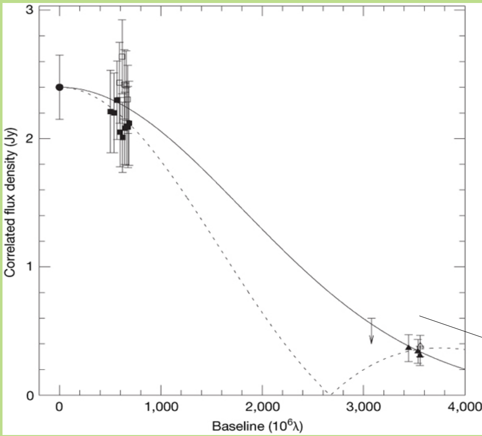
- Monte Carlo technique for radiative transfer:
  - Generate photon $E=h\nu$ and $\vec{p}$ based on the emissivity of the physical radiative process
  - trace individual photons to the observer

- Important emission processes in RIAF:
  - synchrotron radiation (relativistic thermal distribution of electrons)
  - Compton scattering
  - Absorption

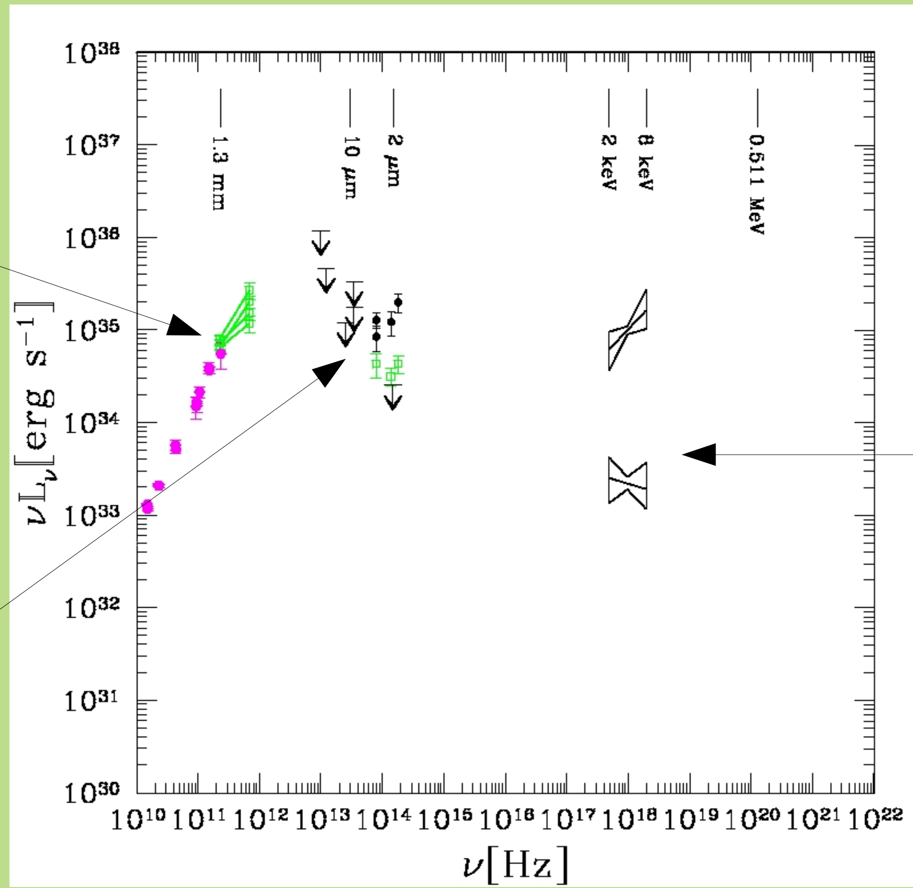
- All relativistic effects are included: photons move on geodesics, Doppler boosting, gravitational redshift etc. (Dolence et al. 2010)

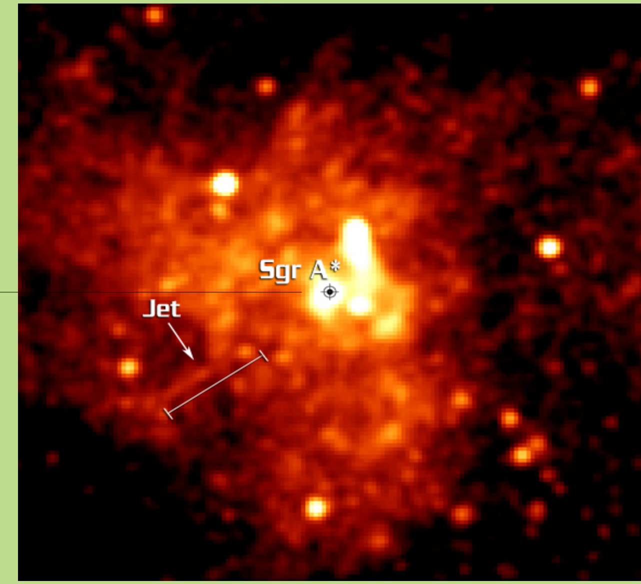
Observations of Sgr A* ($M_{bh}=4\ 10^6\ M_\odot$)

- Quiescent emission (radio, sub-mm,NIR,X-rays) + flares (NIR and X-rays)
- VLBI size of emission at 1.3 mm FWHM=37 μas , apparent size of horizon 55μas

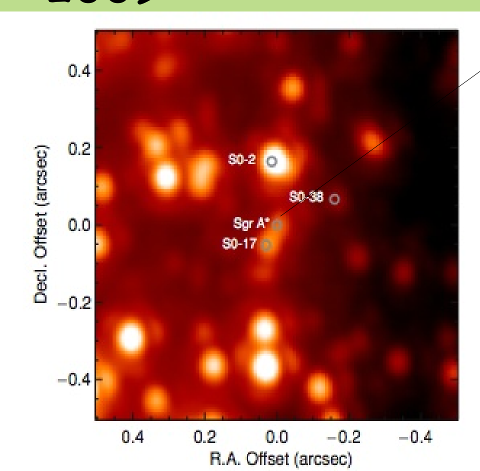


VLBI, 230 Ghz
Doeleman et al.
2009





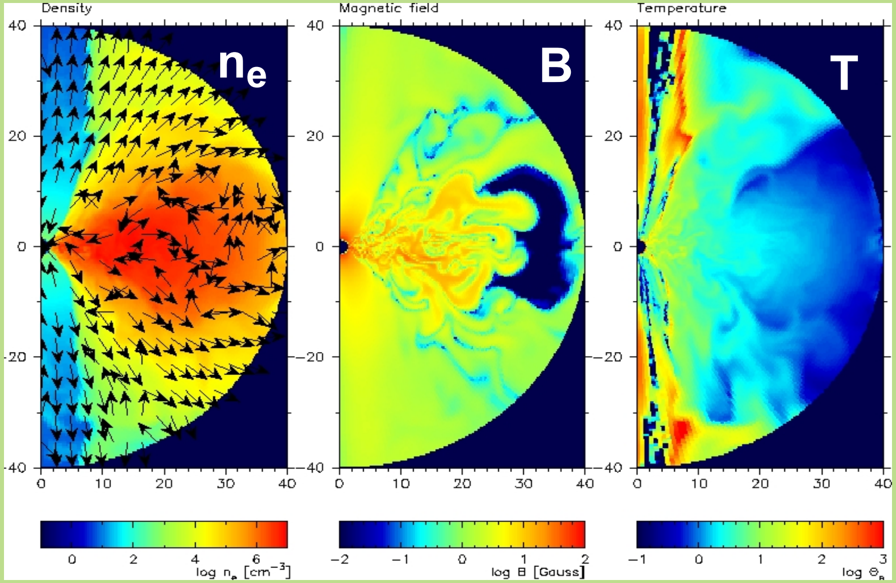
Chandra,2-8 keV
1.25 arcmin

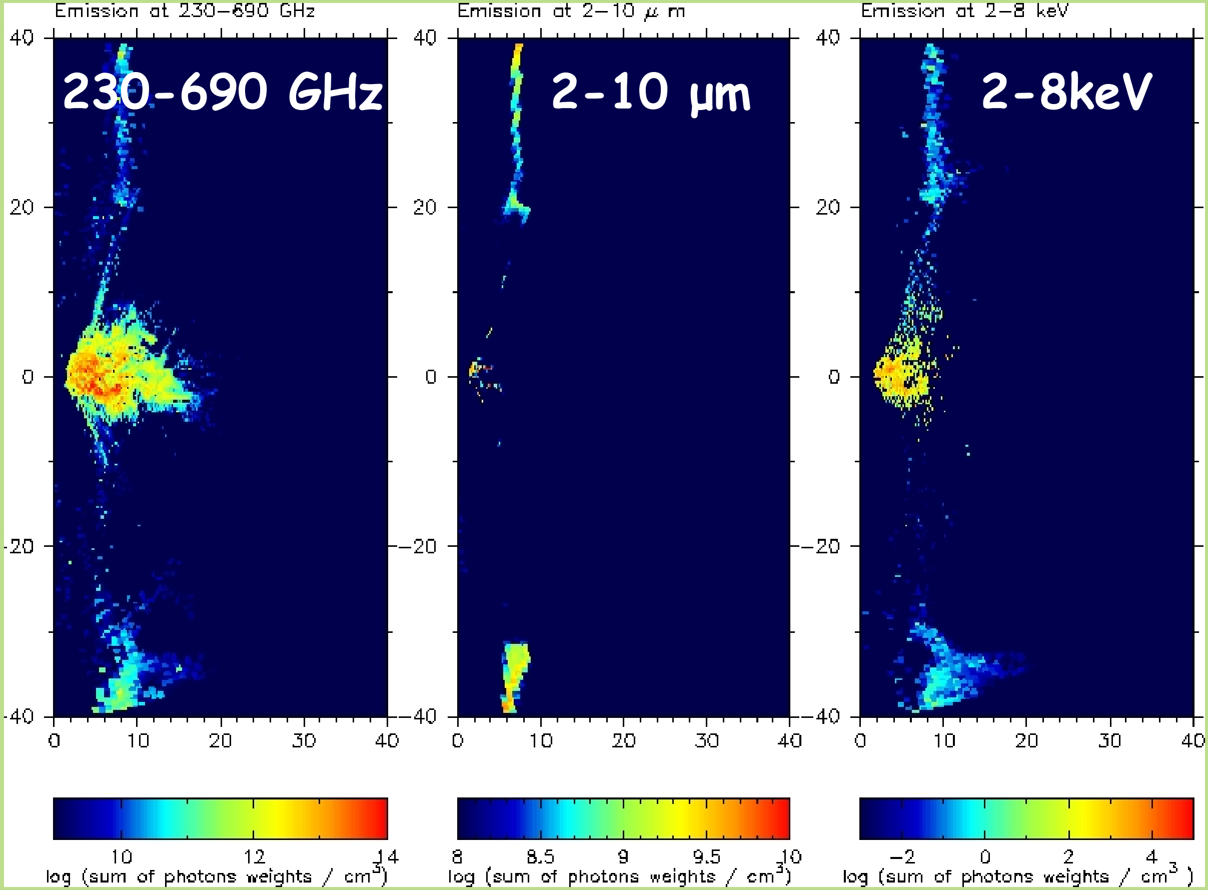


Keck, NIR,
UCLA group

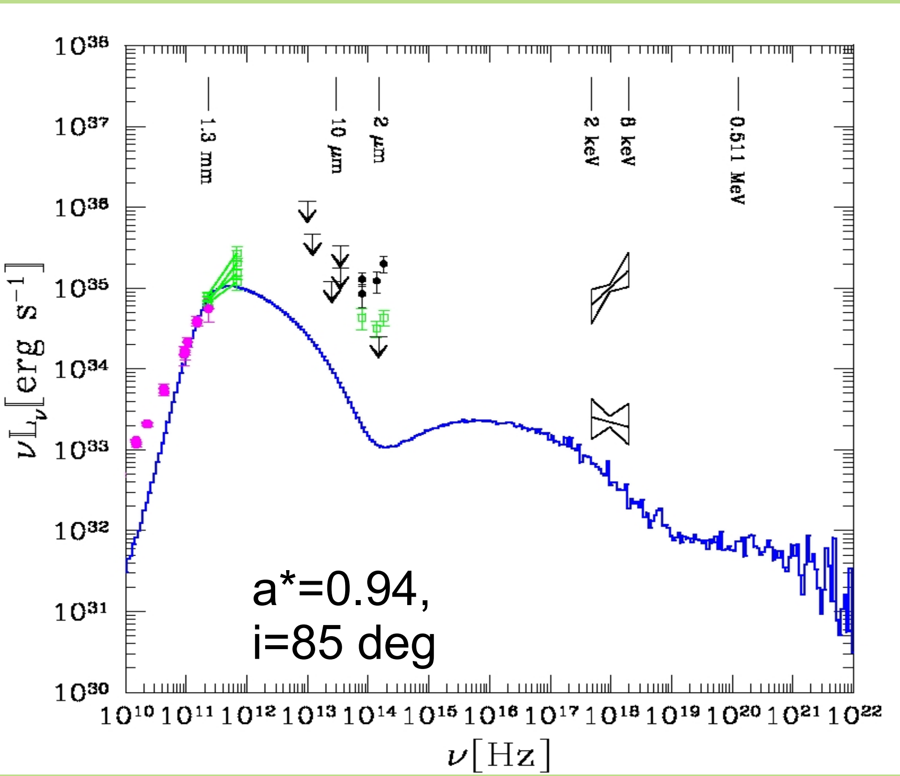
- model free parameters: $\dot{m}$, a*, T_p/T_e, i
- fit model SED to sub-mm obs., do not overproduce limits at high energies + fit the size from VLBI

Emission from turbulent disk from Monte Carlo radiative transfer



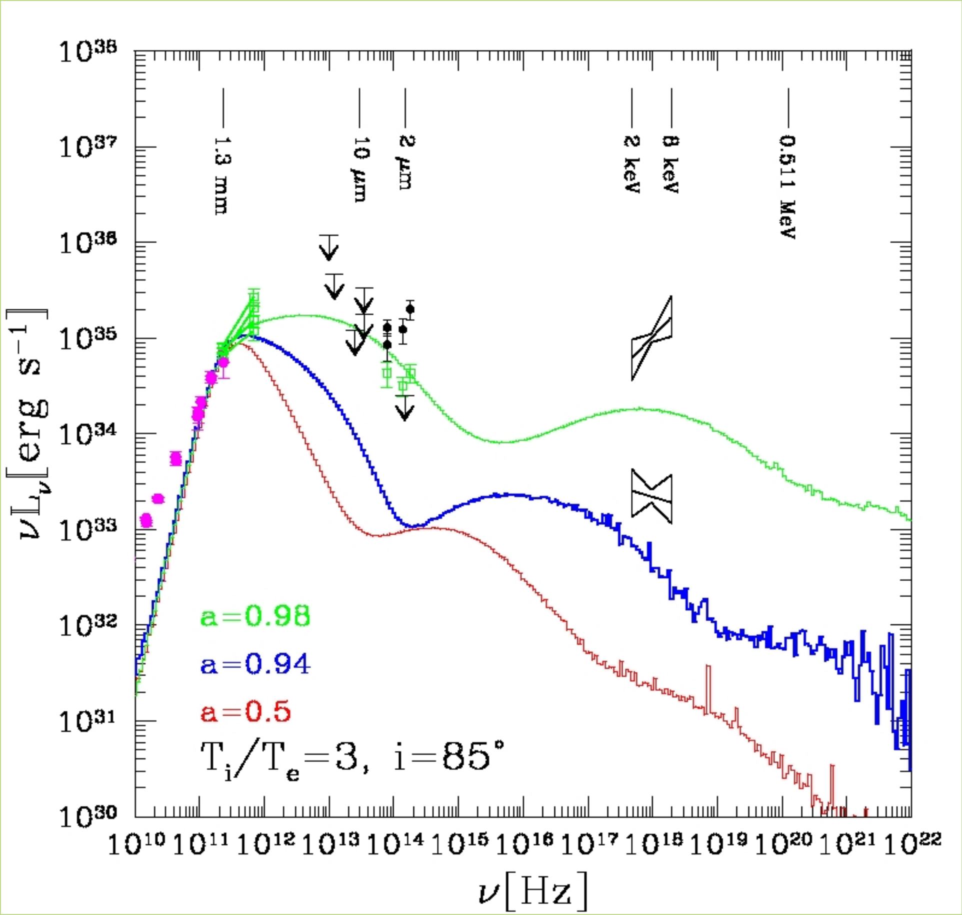


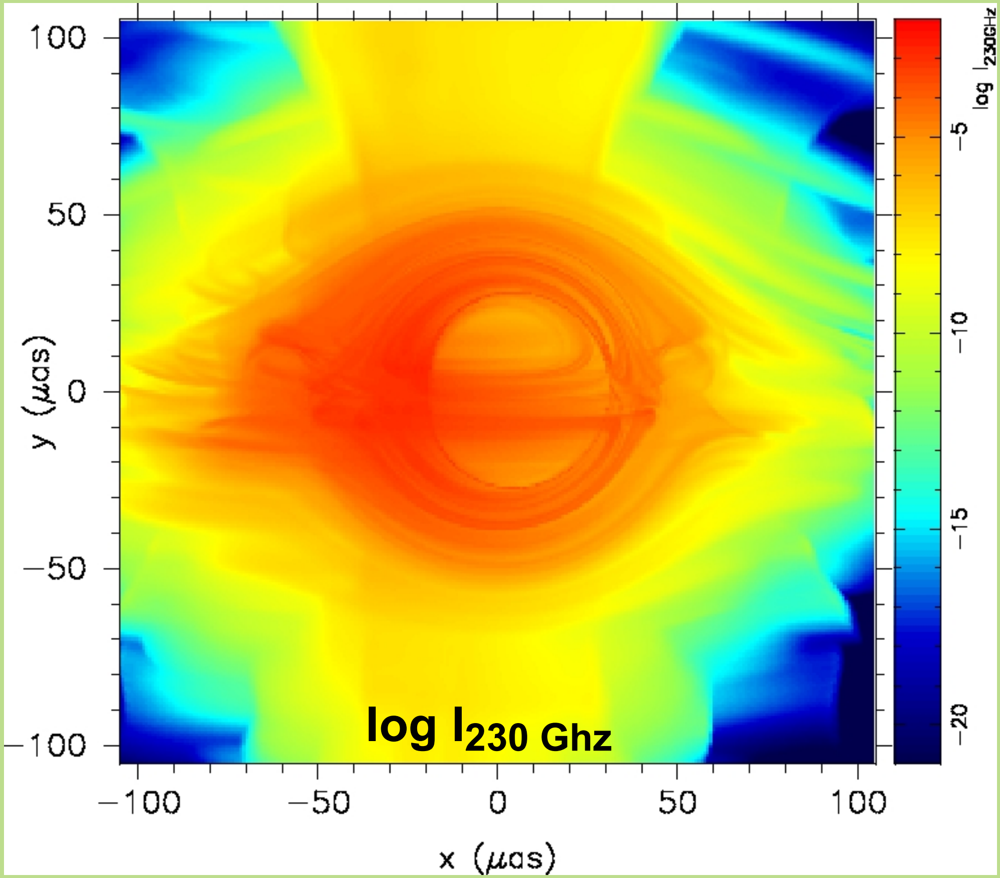
Origin of photons at different frequencies, Moscibrodzka et al. 2009



← Spectral energy distribution (SED)

SEDs (vs. radio, NIR and X-ray) Images (vs.VLBI observations)



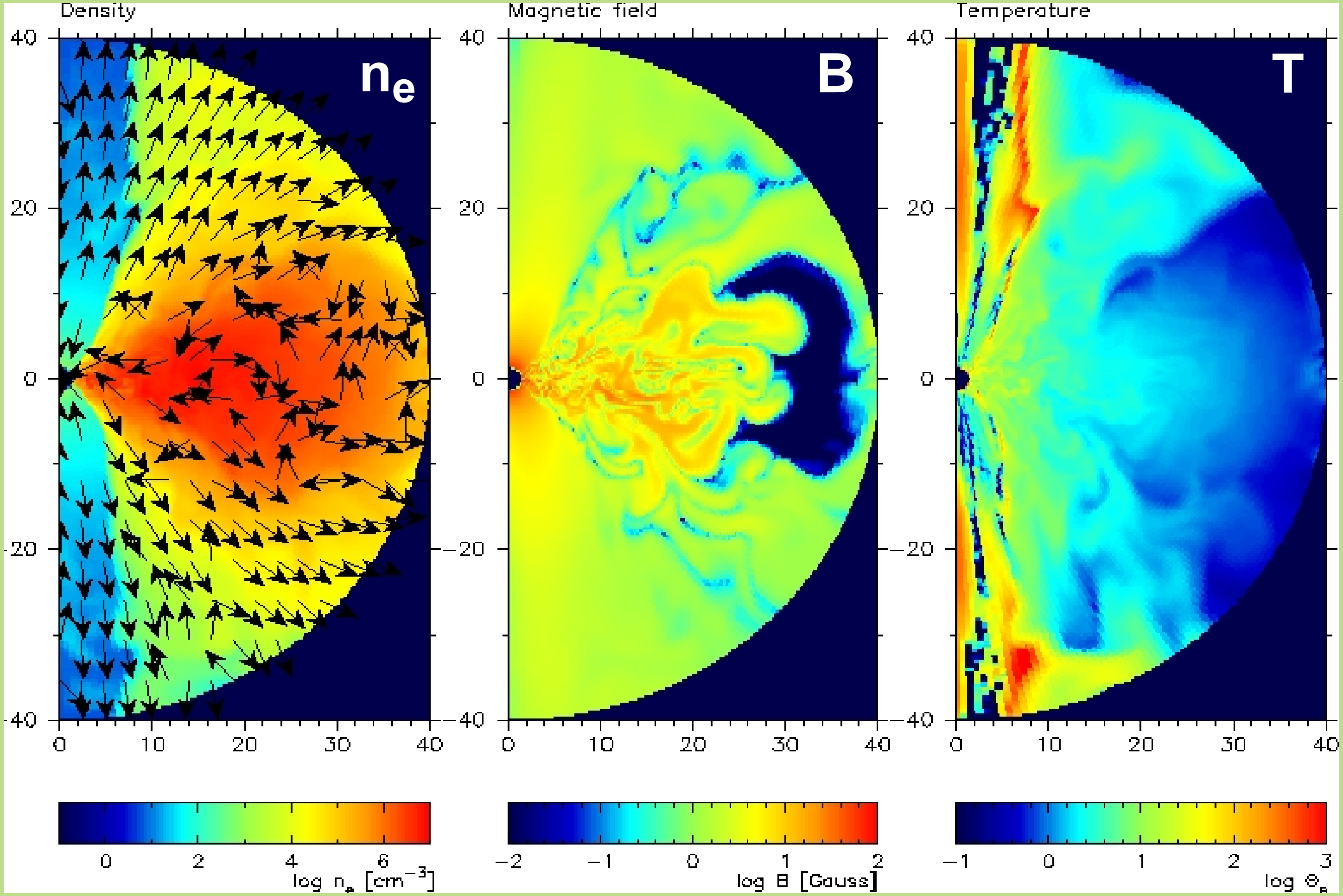


SED calculated with Monte Carlo code, Moscibrodzka et al. 2009

230 GHz image of the model (Moscibrodzka et al. 2009) calculated with ray-tracing code (Noble et al. 2007)

- 'Best-bet' model for Sgr A* gives a=0.94, Tp/Te=3, i≈90 deg, $\dot{m}=10^{-7}$
- a* <0.94 and Tp/Te=1 give poor fit to sub-mm observations
- a*> 0.94 overestimate X-rays observations
- T_p/T_e > 3 wrong sub-mm slope, overestimate NIR and X-rays + produce too large images

What are the physical conditions in the funnel ?



- In the funnel matter free to fall out
  - numerically → floor density
- What is real density in the funnel?
- In nature funnel density in LLGN determined by γγ pair production (Phinney 1983)
- What is the actual pair production ?

Electron-positron jets – how many pairs do we expect?

- We do not expect much of pairs to be created at all (compactness parameter, or optical depth to pair production, is small $l = L\sigma_{th}/Rm_ec^3 \approx 10^{-5} \ll 1$)

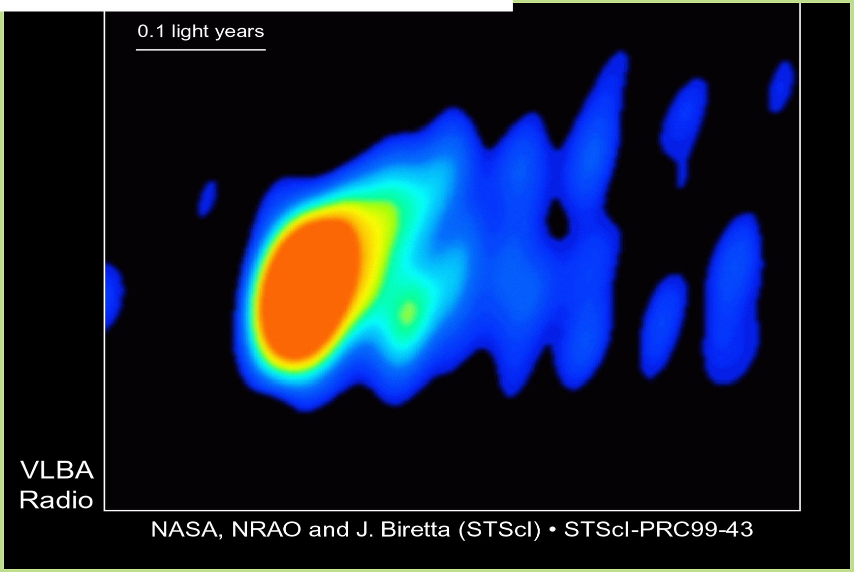
- $\dot{n}_{+/-} = n_\gamma^2 \sigma_{\gamma\gamma} c$, crosssection for $\gamma+\gamma=e^+ + e^-$ (Breit-Wheeler)

$$\frac{\sigma_{\gamma\gamma}}{\sigma_T} = \frac{3}{8\,\epsilon_{[CM]}^6}\left[(2\,\epsilon_{[CM]}^4 + 2\,\epsilon_{[CM]}^2 - 1)\cosh^{-1}\epsilon_{[CM]} - \epsilon_{[CM]}(\epsilon_{[CM]}^2 + 1)\sqrt{\epsilon_{[CM]}^2 - 1}\right]$$

- Estimate of pair plasma density
- $n_\gamma = L_\gamma / m_ec^3R^2$, $t_{esc} = R/c$, $R \sim GM_{bh}/c^2$

  (pair production balanced by escape)

  - Sgr A*: $n_{+/-} = 10^{-4}\ \mathrm{cm}^{-3}$
  - M87: $n_{+/-} = 10^{4}\ \mathrm{cm}^{-3}$



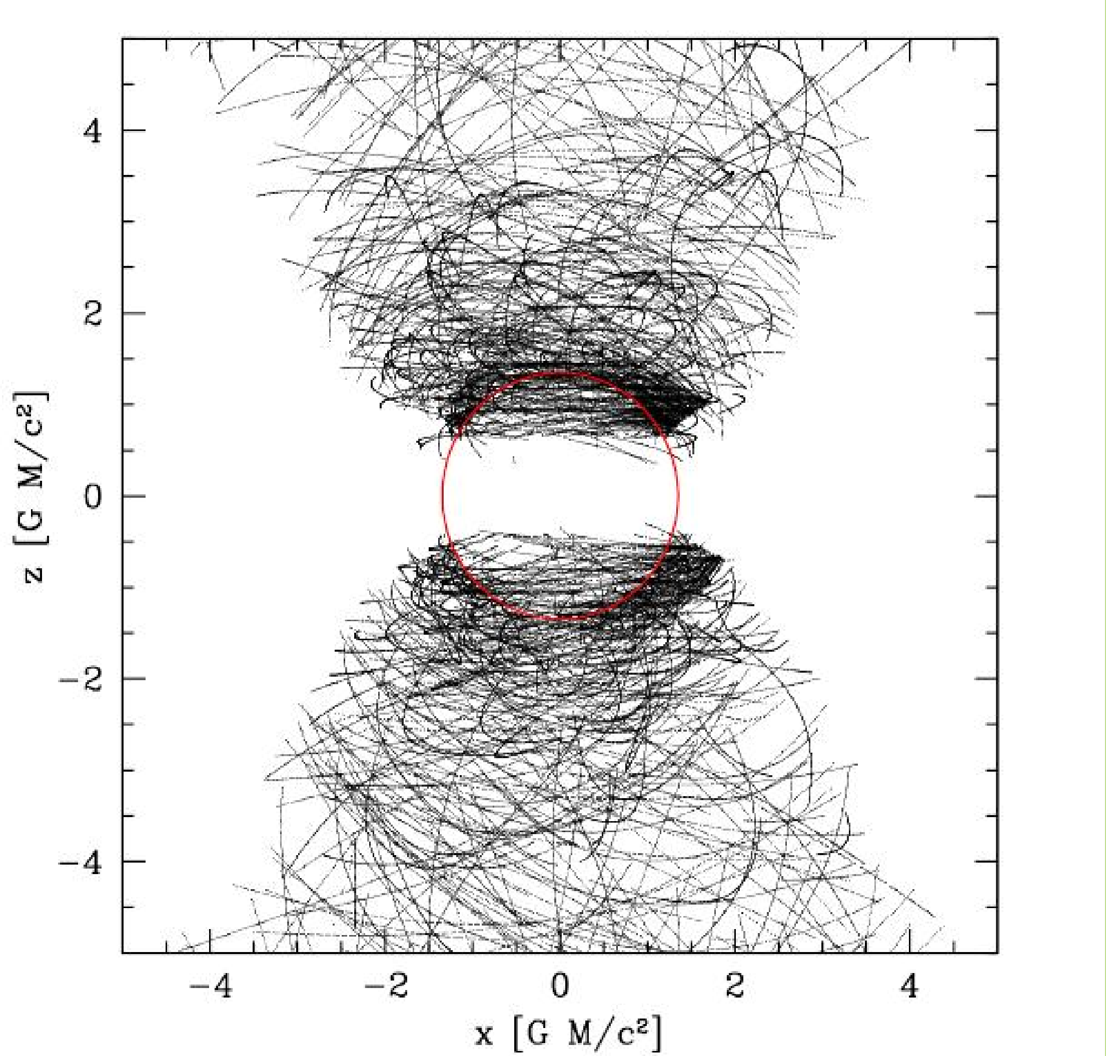
0.1 lyr $= 1000\ R_g$ $M_{bh} = 3\ 10^9\ M_\odot$, $n_{+/-} = 1\ \mathrm{cm}^{-3}$

- Problem is particularly interesting in case of M87

With Monte Carlo radiative transfer we can do better job !

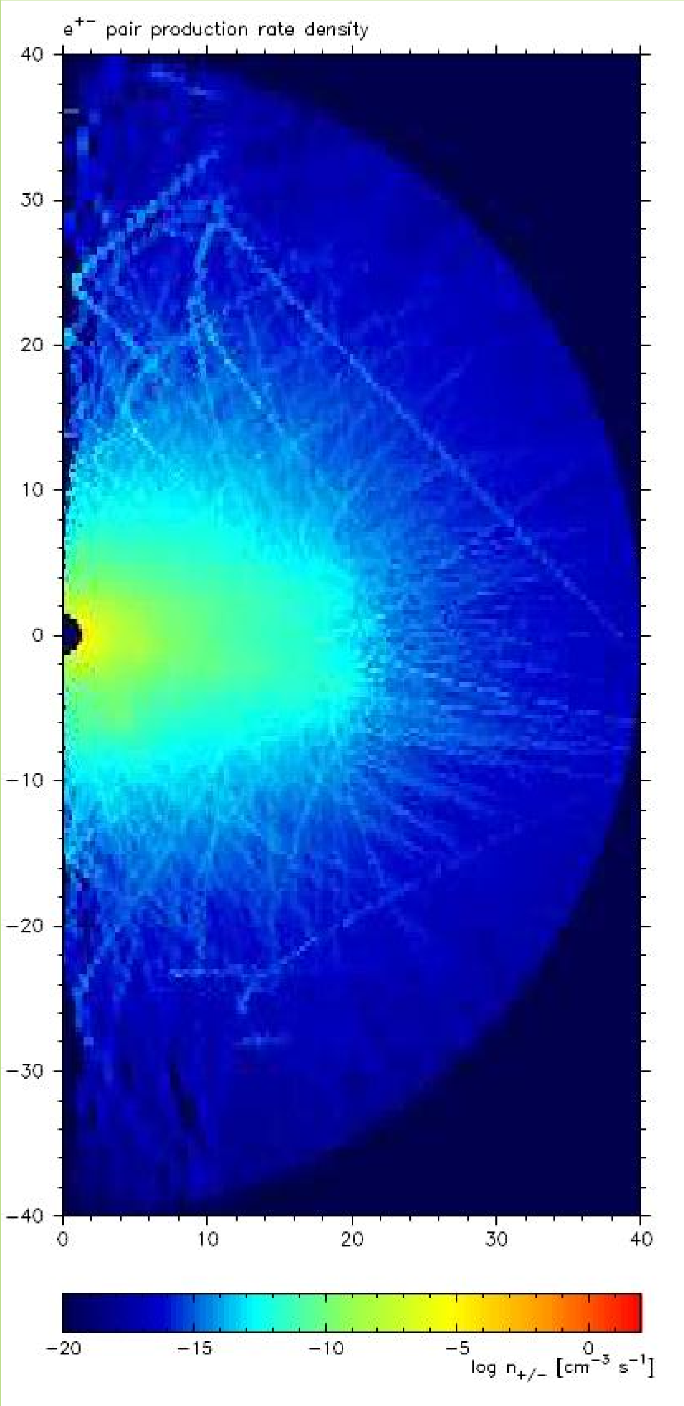
$e^{+/-}$ pair production-Monte Carlo method

- Monte Carlo techniques allow to follow collisions between individual photons (photon packets) everywhere
- Pair production opacity assumed small
- We need to store information about the radiation field above 1 MeV (in the center-of-momentum frame)



hν > 1 MeV photon trajectories in the jet, Gammie 2009, private com.

$e^{+/-}$ pair production rates in RIAF



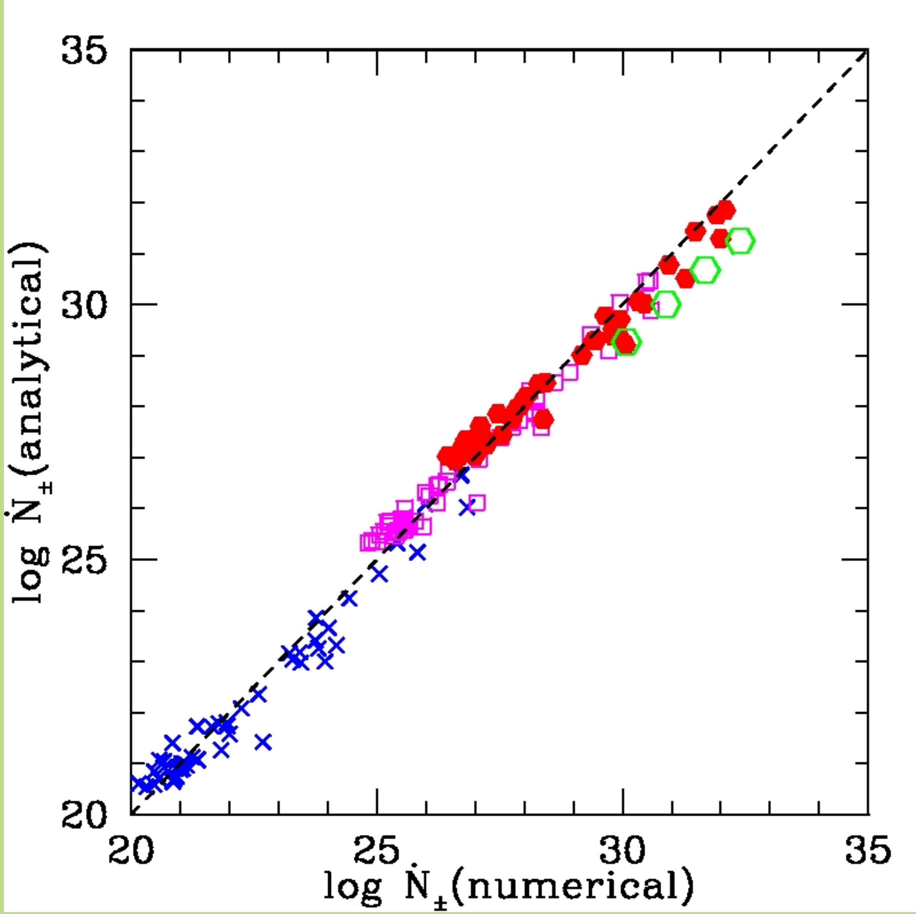
e^{+-} pair production rate !

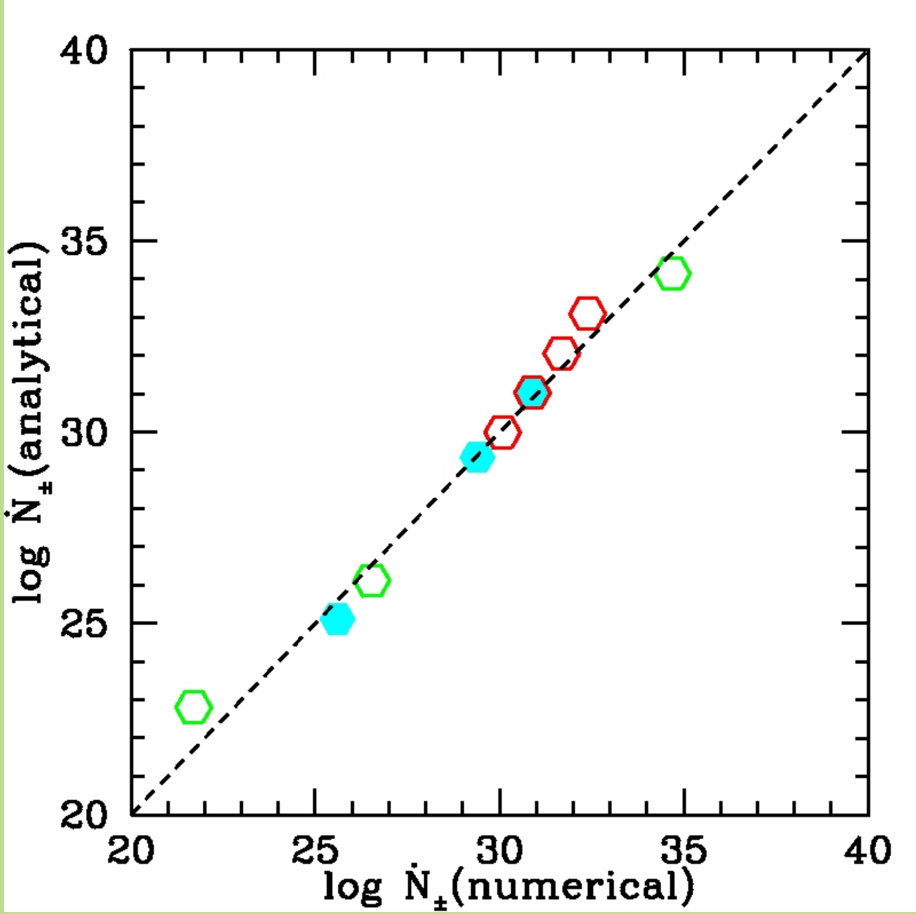
- Disk turbulent but at a given time radiation field is smooth, pair prod. distribution is smooth
- Individual rays is Monte Carlo noise
- Beaming effects → most of pairs created in the disk plane, μ = cos(θ)

$$\dot{n}_{\pm}(r,\mu) \sim r^{-6} e^{-\mu^2/0.4}$$

10-20% created in the magnetically dominated funnel

$e^{+/-}$ pair production - dependence on observables and model parameter





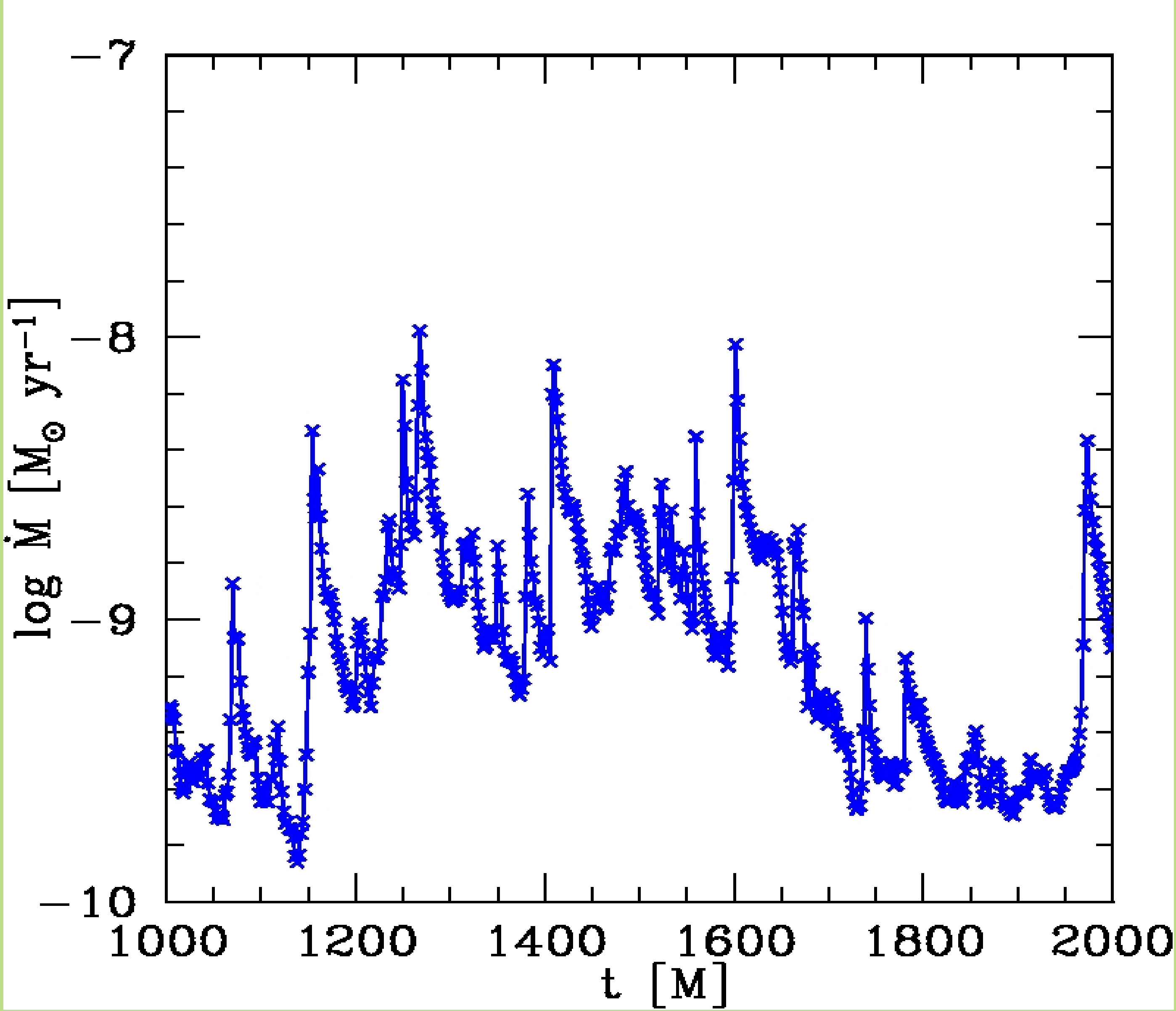
Observable parameters: L_X, α_X, M_{bh}

$$\dot{N}_{\pm} \sim L_X^2 e^{9.26\alpha_X} M_{BH}^{-1}$$

Model parameters: $\dot{m}$, M_{bh}, r_{ISCO}

$$\dot{N}_{\pm} \sim \left(\frac{2.044}{r_{isco}}\right)^{26} \dot{m}^7 M_{BH}^2$$

$e^{+/-}$ pair production - dependence on model parameters



Mass accretion rate vs. time at later times of simulation

$e^{+/-}$ pair production - observational consequences

- **Can we see emission from pairs? To calculate SED :**
  - need pair density and distribution of pair kinetic energy
  - so need to solve dynamical equations of the pair plasma (in preparation)

Sgr A*

- During quiescence – small number of pairs
- During strong X-ray flare ($L_X = 10^{35}$ ergs/s) → arising compact pair jet?
- activity in the past $L_X = 10^{39}$ ergs/s – might have produced stronger pair jet in the past

M87

- number of pairs slightly larger than observed one: $n_{+/-} = 100\ cm^{-3}$
- need to couple dynamics with radiative transfer (in preparation)
- pair production suppressed by cooling

Summary

- We model inefficient accretion onto spinning black holes using GRMHD simulations, we model multiwavelength (radio-gamma rays) radiative properties of GRMHD simulations using GR Monte Carlo techniques
- We have models of Sgr A* quiescent emission (Moscibrodzka et al. 2009) and variability (Dolence et al. 2010, in press), a*=0.94, Tp/Te~1, i=90 ^{deg}
- For first time we compute non-equilibrium electron-positron pair production rates by γγ from turbulent accretion disk around spinning black hole
- Production of pairs sensitive to X-ray luminosity, very sensitive to mass accretion rate and spin of the BH
- More to be done in near future !

END

Test of pair production code

- 3D Cartesian space, 2 point sources of high energy radiation