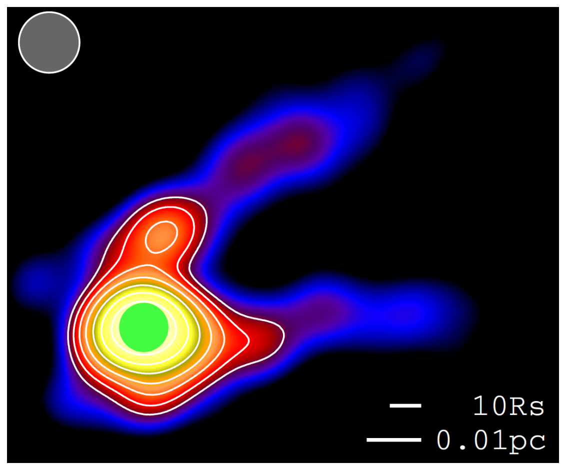
Magnetic fields at the base of AGN jets: the case of M87

AGNジェット最深部の磁場：M87の場合



紀 基樹
(Kogakuin U/NAOJ)

2017/12/21

星形成と銀河構造に置ける磁場の役割
@ Kagoshima U

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  - Black hole and jet
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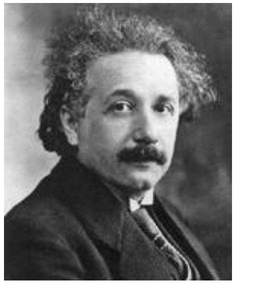
  - Energetics of "central engine" in one-zone framework
    (MK+ 15)

  - Beyond one-zone
    (Kawashima, MK *in prep*)

Introduction

Black Hole (BH)



- BH as a vacuum solution of Einstein equation is well-defined.

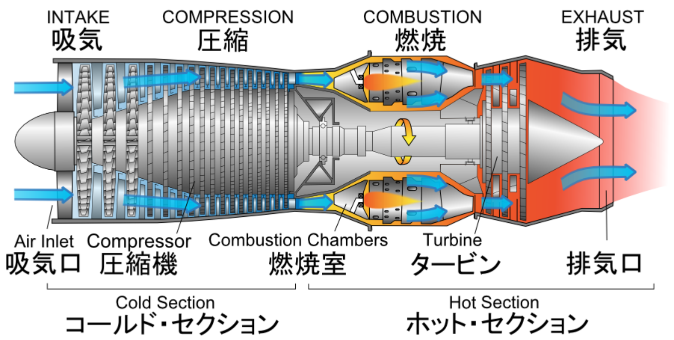
- BH as as an astronomical object is full of mystery.

BH: big issues

- Do BHs really have event horizon and spin?
  - 「事象の地平面」はまだ直接観測されていない。
  - 「スピン」についてもクリアな制限がついていない。

- How BHs produce jets/outflows?
  - central engineの仕組みはまだ理解されていない。宇宙物理学屈指の難問。
  - ブラックホール噴流が星銀河形成へ本質的影響を与えていると目される(AGN フィードバック)が、素過程は分かっていないことが多い。

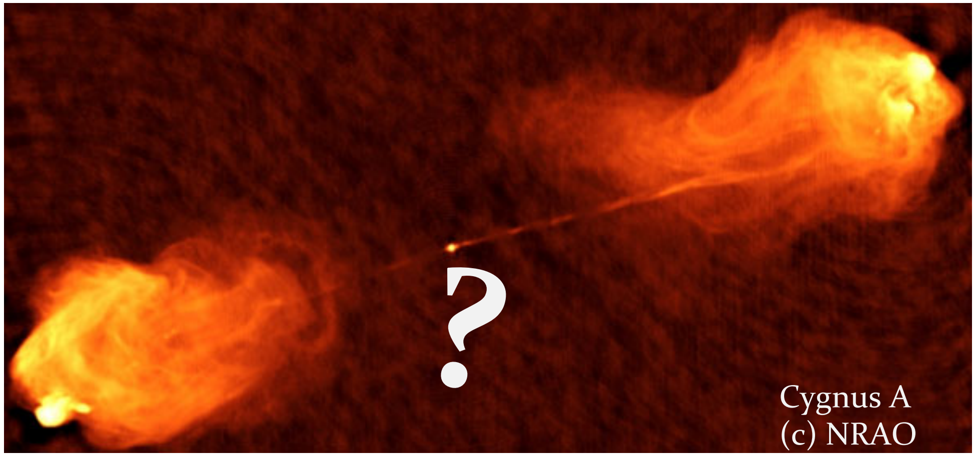
Jet engine



https://ja.wikipedia.org/wiki/ジェットエンジン

空気を吸い込み、熱を加え、動力を取り出す。
well-known heat cycle

BH jet engine?!



BHが本質的な関与していると目される。
しかし、駆動エンジンの仕組みがよく分かっていない.

Blandford & Znajek (1977) proposed the idea of spinning BH can drive a jet via magnetic-field.

Summary. When a rotating black hole is threaded by magnetic field lines supported by external currents flowing in an equatorial disc, an electric potential difference will be induced. If the field strength is large enough, the vacuum is unstable to a cascade production of electron–positron pairs and a surrounding force-free magnetosphere will be established. Under these circumstances it is demonstrated that energy and angular momentum will be extracted electromagnetically. As a further consequence it is shown that charge can never contribute significantly to the geometry of a rotating hole. The fundamental equations describing a stationary axisymmetric magnetosphere are derived and the details of the energy and angular momentum balance are discussed. A perturbation technique is developed which can be used to provide approximate solutions for slowly rotating holes. Solutions appropriate when the field lines threading the hole lie on conical and paraboloidal surfaces at large distances are described to illustrate this mechanism.

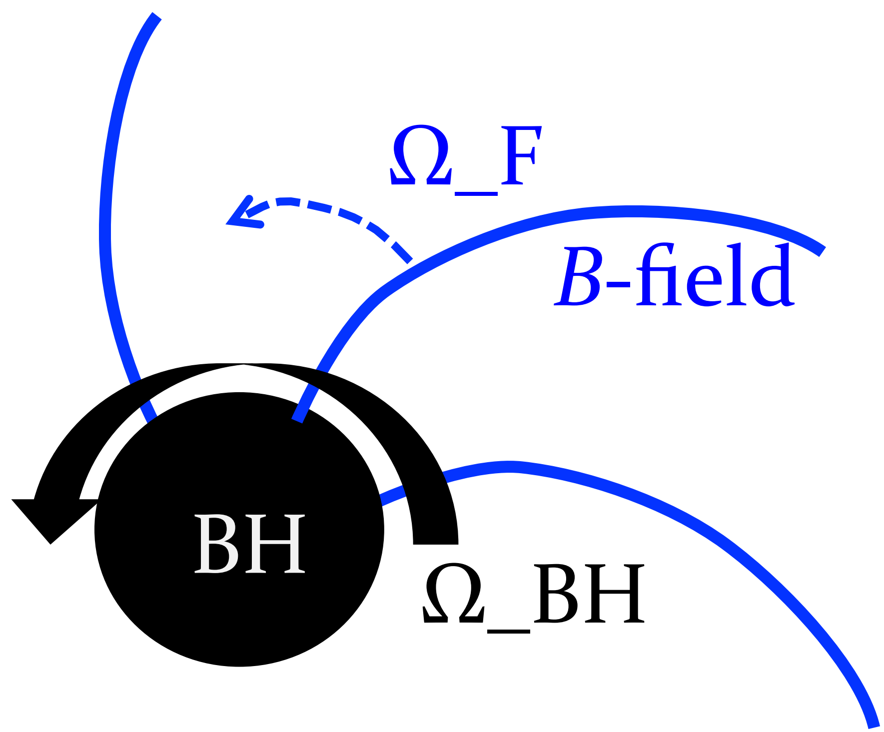
These ideas are incorporated into a discussion of a model of active galactic nuclei containing a massive black hole surrounded by a magnetized accretion disc. In this model relativistic electrons can be accelerated at large distances from the hole and therefore will not incur serious losses, which is a defect of some existing models. In addition, if the field lines have paraboloidal shape, the energy will be beamed along antiparallel directions as observations of both compact and extended radio sources seem to require.

BZ process

- EM extraction of BH-spin energy

$$W_{\rm tot} = \frac{1}{4\pi} \int \Omega_{\rm F}(\Omega_{\rm H} - \Omega_{\rm F}) \sin\theta \frac{r^2 + a^2}{r^2 + a^2 \cos^2\theta} \frac{{\rm d}\Psi}{{\rm d}\theta} {\rm d}\Psi$$

Ω_BH > Ω_F



Is the BZ77 really in action?

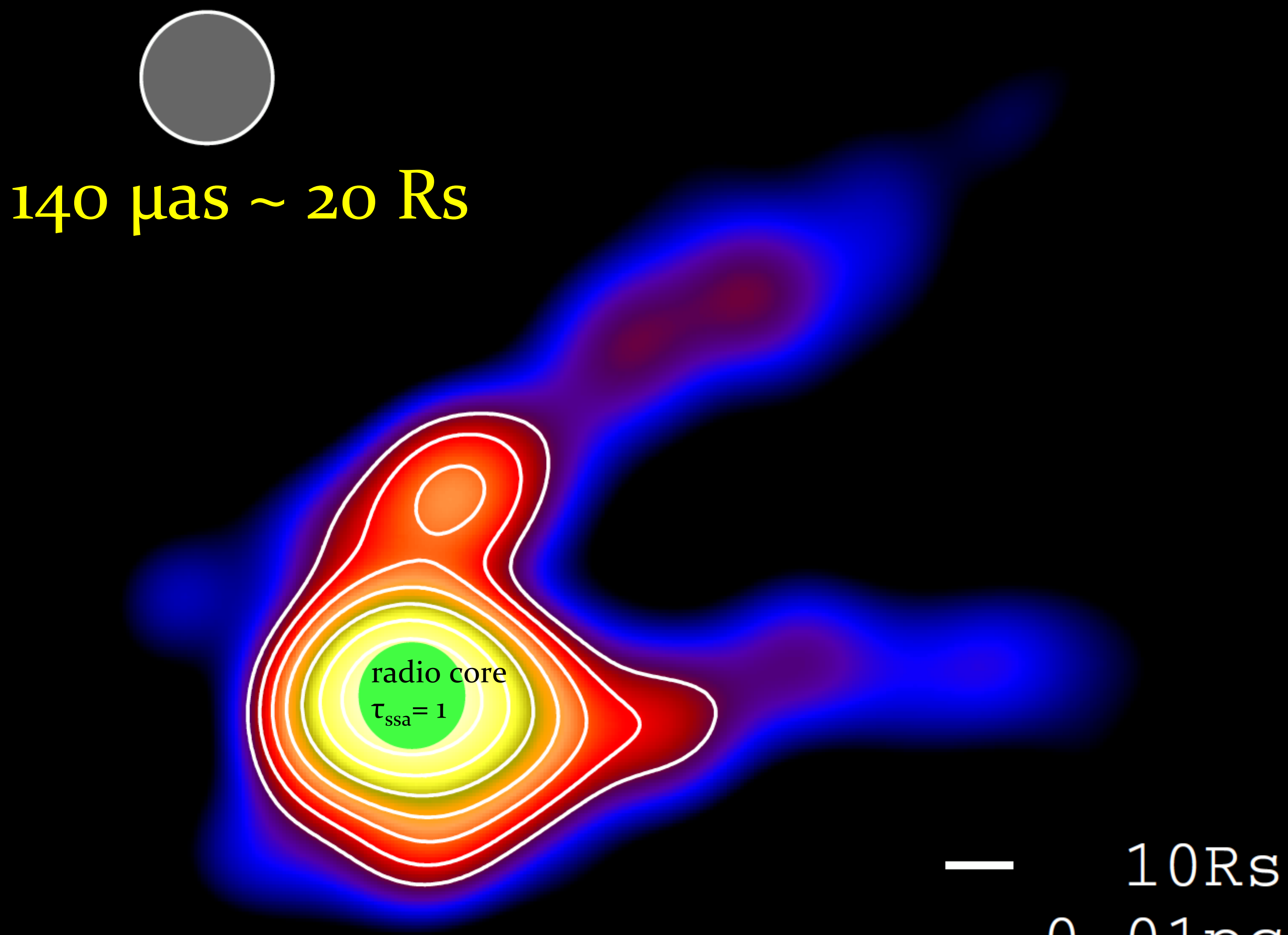
- ~2005年以降のGRMHD数値実験では、一見もっともらしいBZ駆動のジェット噴流を形成しているようにみえる。
- しかし、実際の天体の観測と比較してBZ機構をテスト(初期条件/境界条件)するという視点の研究はまだほとんど行われていない。

Best example: M87

- The angular size of BH in M87 is largest among all of AGN jets!
  - Schwarzschild radius: $R_s = 2GM/c^2 = 1.9\times10^{15}$ cm
  - Angular size of Schwarzschild radius: $\theta_s = 7$ μas

- Direct observation of "central engine" is possible w/ VLBI!

Jet base image of M87



Hada, MK, Doi et al. (2013), *ApJ*

Closest look of “central engine”

Kino et al. 2015, ApJ, 803, 30

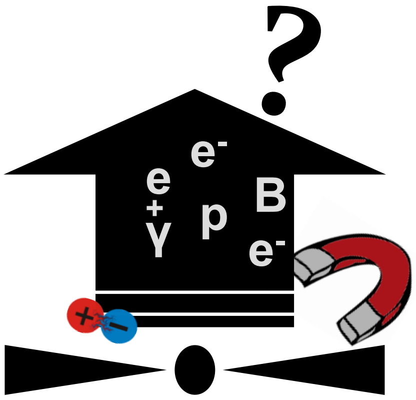
Energetics of “central engine” w/ one-zone framework

Outstanding question

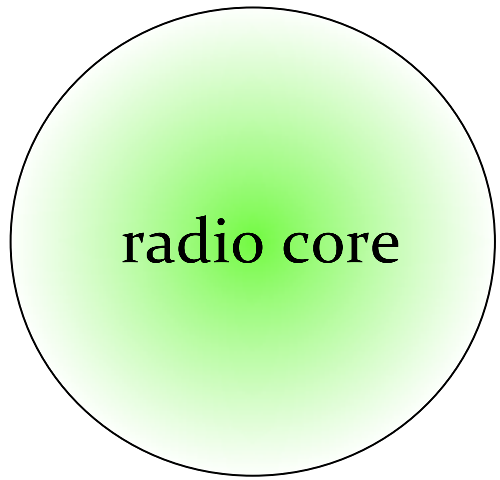
- Need to clarify energy source of "central engine"
  - B-fields?, particles?, ~~radiation?,~~ BH-spin?

- Observed synchrotron emission
  $\propto$ [B-field strength] $\times$
  [particle density].

- How to resolve the degeneracy?



Idea: usage of SSA-thick radio core!



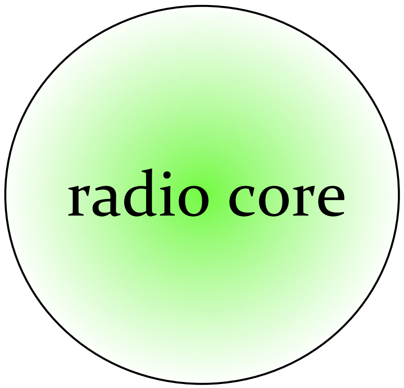
$$\tau_{ssa} = \text{size} * \alpha_{\nu\_ssa} = 1$$

Co-efficient for Synchrotron Self Absorption (SSA)

$$\alpha_\nu = \frac{\sqrt{3}e^3}{8\pi m_e}\left(\frac{3e}{2\pi m_e^3 c^5}\right)^{p/2} c_1(p) \\ \times K_e B^{(p+2)/2} \nu^{-(p+4)/2},$$

Kino+ 14, 15, ApJ

We can **uniquely** determine B and U_e/U_B



$$B = b(p)\left(\frac{\nu_{\rm ssa,obs}}{1\ {\rm GHz}}\right)^{5}\left(\frac{\theta_{\rm obs}}{1\ {\rm mas}}\right)^{4}\left(\frac{S_{\nu_{\rm ssa},\rm obs}}{1\ {\rm Jy}}\right)^{-2} \times \left(\frac{\delta}{1+z}\right)$$

$$\frac{U_e}{U_B} = \frac{8\pi}{3b^2(p)}\frac{k(p)E_{e,\rm min}^{-p+2}}{(p-2)}\left(\frac{D_{\rm A}}{1\ {\rm Gpc}}\right)^{-1}\left(\frac{\nu_{\rm ssa,obs}}{1\ {\rm GHz}}\right)^{-2p-13} \times \left(\frac{\theta_{\rm obs}}{1\ {\rm mas}}\right)^{-2p-13}\left(\frac{S_{\nu_{\rm ssa},\rm obs}}{1\ {\rm Jy}}\right)^{p+6}\left(\frac{\delta}{1+z}\right)^{-p-5} \quad ({\rm for}\ \ p>2). \tag{14}$$

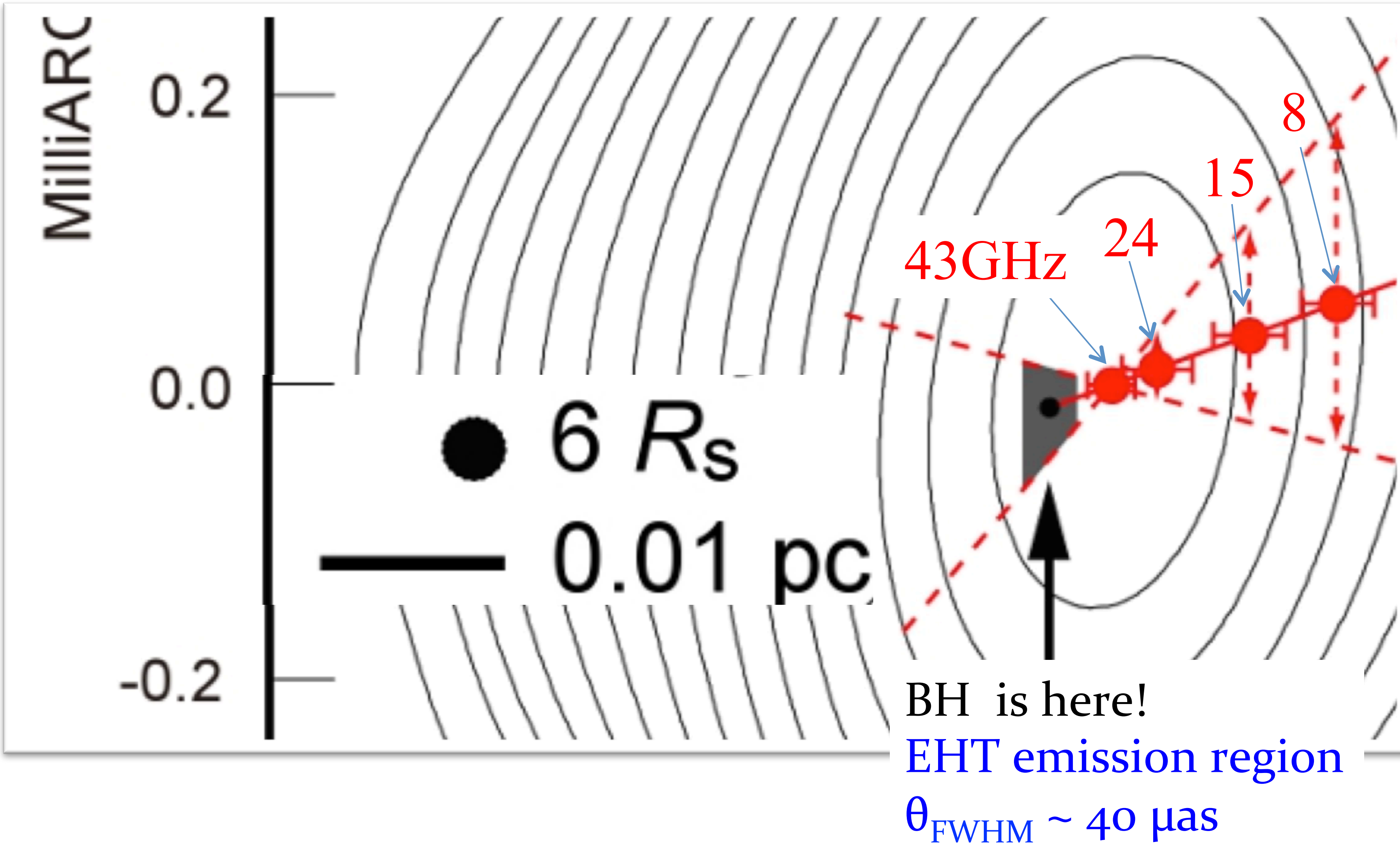
θ obs: observed angular size of the radio core <= VLBI!

S_ν_{ssa} : observed flux density of the radio core

ν_{ssa}: SSA turnover frequency (here $\nu_{ssa} = \nu_{obs}$, see next)

Hada, Doi, MK+ (2011) *Nature*

Striking evidence of SSA-thick core!
i.e., core shift



One-zone (θ_{FWHM}=40μas, 1Jy) estimate leads to B_{tot}~ 300 gauss i.e., too large L_poy…

If the field strength is,

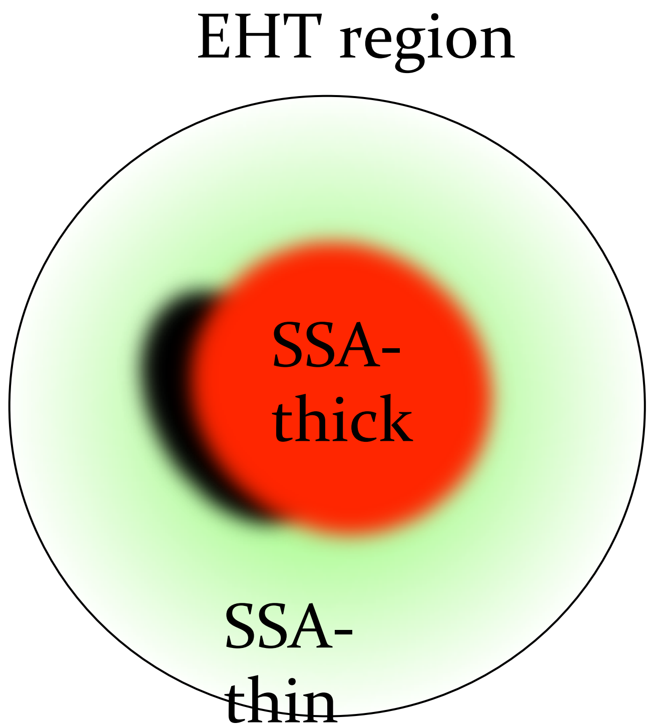
$$B_{\rm tot} \sim 3.4 \times 10^2\ {\rm G}\ \left(\frac{\nu_{\rm ssa,obs}}{230\ {\rm GHz}}\right)^5 \times \left(\frac{\theta_{\rm obs}}{72\ \mu{\rm as}}\right)^4 \left(\frac{S_{\nu_{\rm ssa},{\rm obs}}}{1.0\ {\rm Jy}}\right)^{-2} \left(\frac{\delta}{1+z}\right)$$

θ_FWHM * 1.8 =72 μas
The 1.8 factor by Marscher (1983)

then the Poynting power below exceeds L_jet, max ~ $5*10^{44}$ erg/s

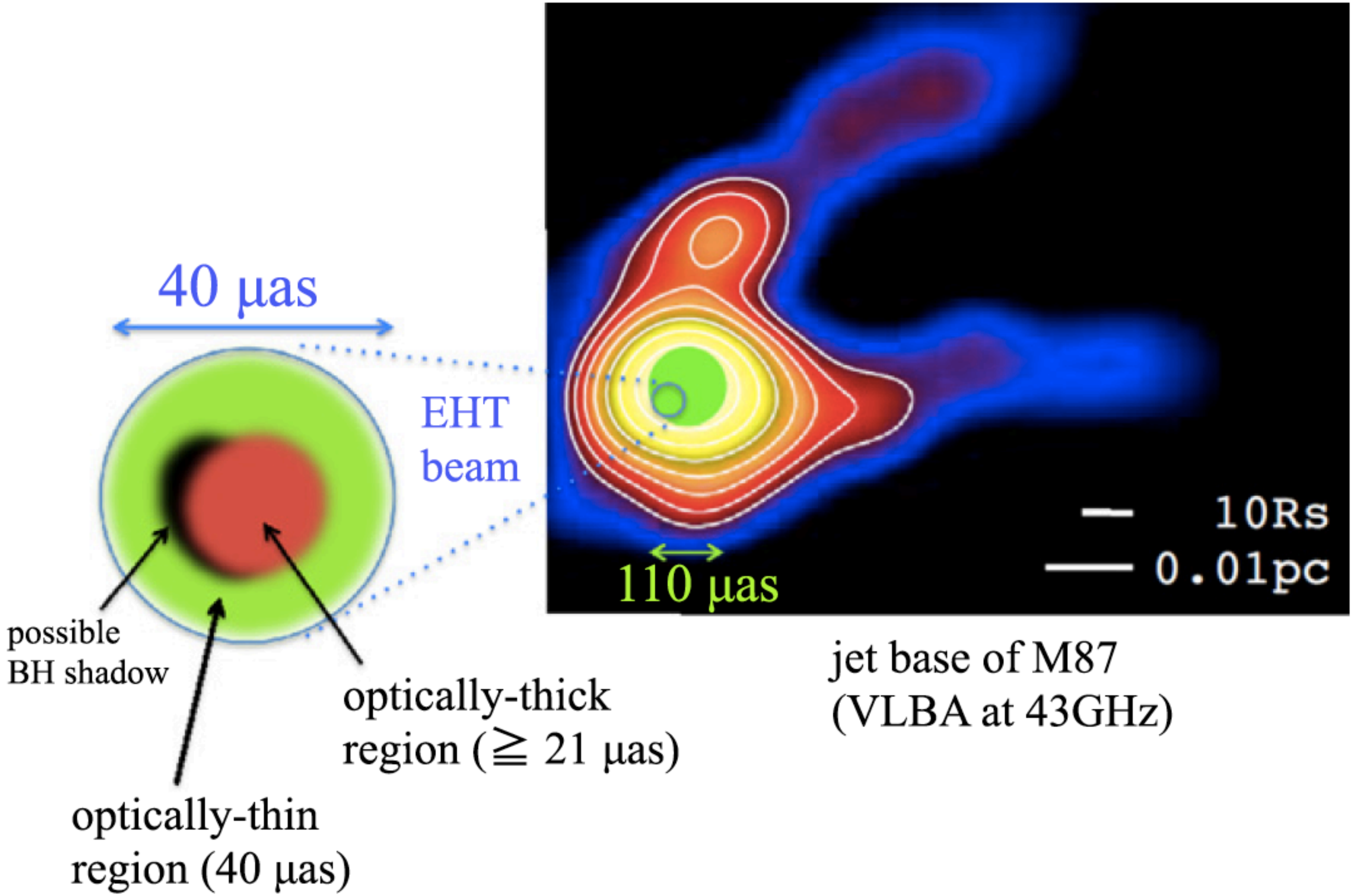
$$L_{\rm poy} = 1.5 \times 10^{47}\ {\rm erg\ s^{-1}} \times \left(\frac{B_{\rm tot}}{300\ {\rm G}}\right)^2 \left(\frac{2R}{1.8 \times 10^{16}\ {\rm cm}}\right)^2.$$

Solution: Partially SSA-thick (two-zone)



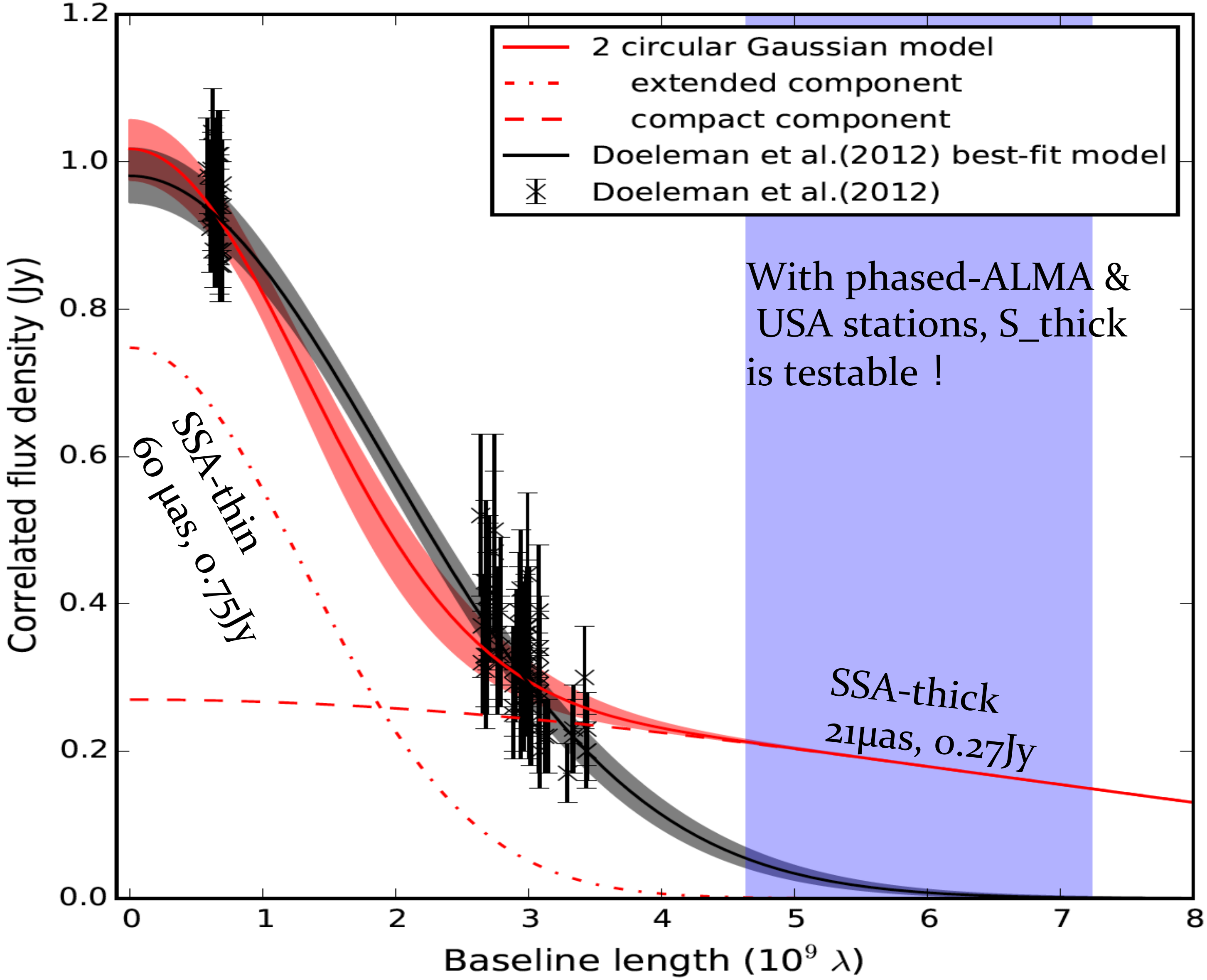
- The idea of partial-SSA-thick region can avoid too-large-L_poy problem because B ∝ ν_{ssa} ^5.
- BH-shadow may be hidden by SSA-thick region.

Kino et al. 2015, ApJ, 803, 30

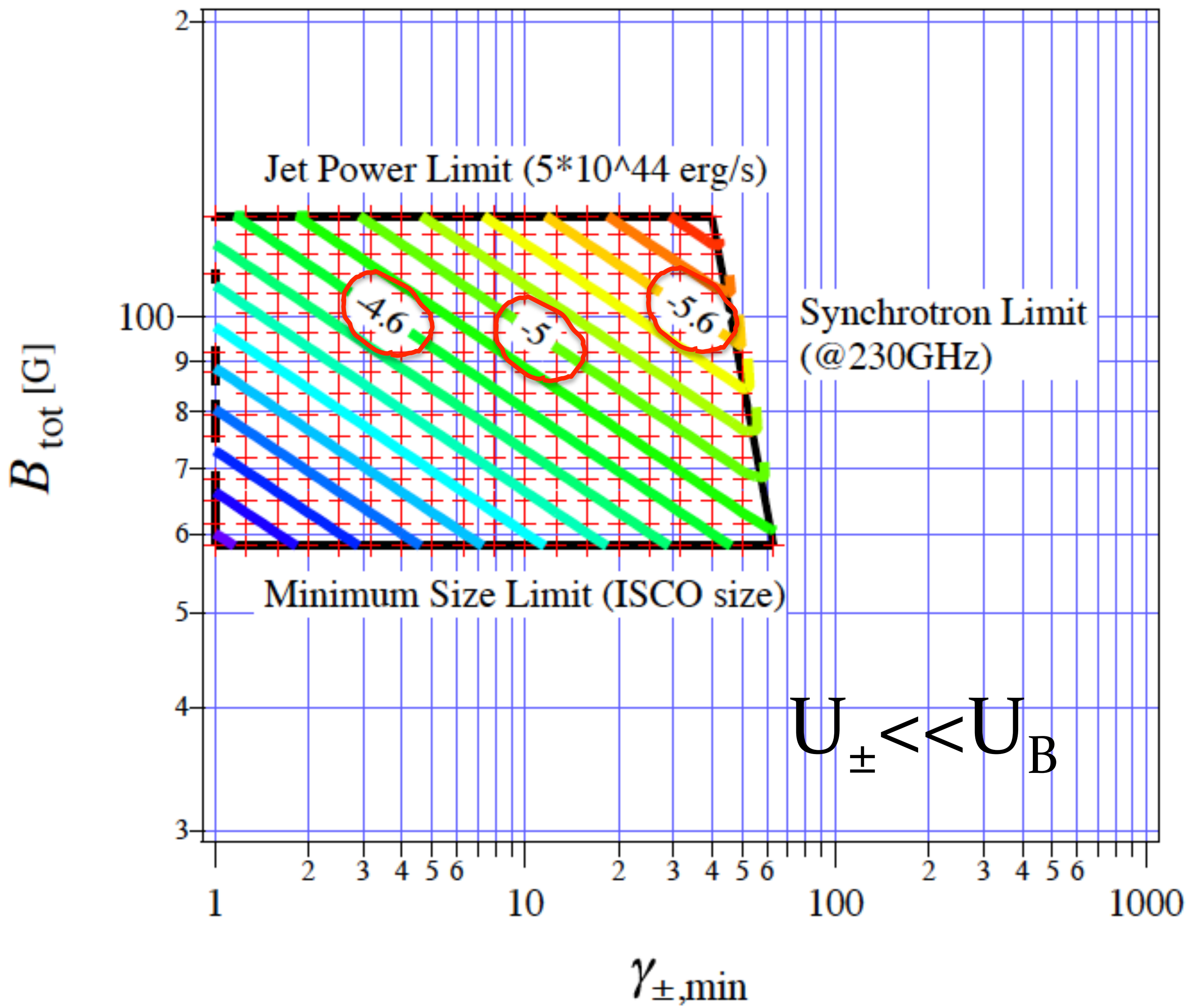


Kino+ 15

Two zone fit to the early EHT data



Allowed log $(U_{\pm}/U_B)$, B_{tot}, $\gamma_{\pm,min}$ in the SSA-thick region



A remaining issue

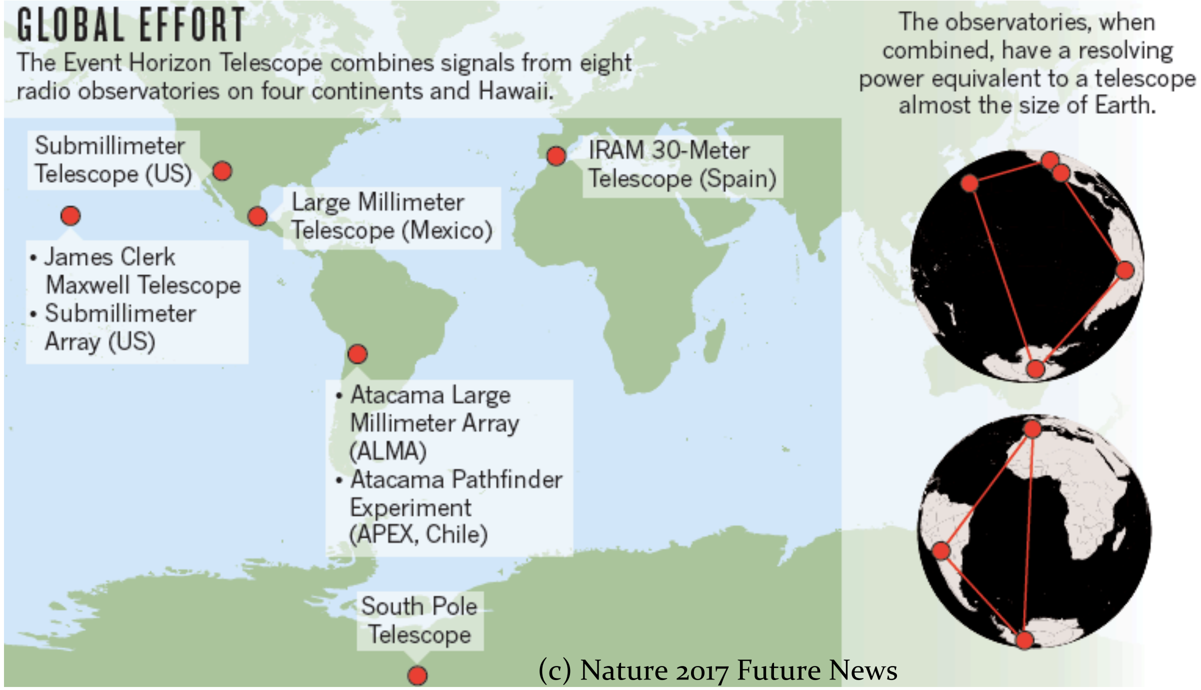
- What if General Relativistic (GR) effects significantly violate this one-zone approximation?

Kawashima, MK in prep

Beyond one-zone

Event Horizon Telescope (EHT)

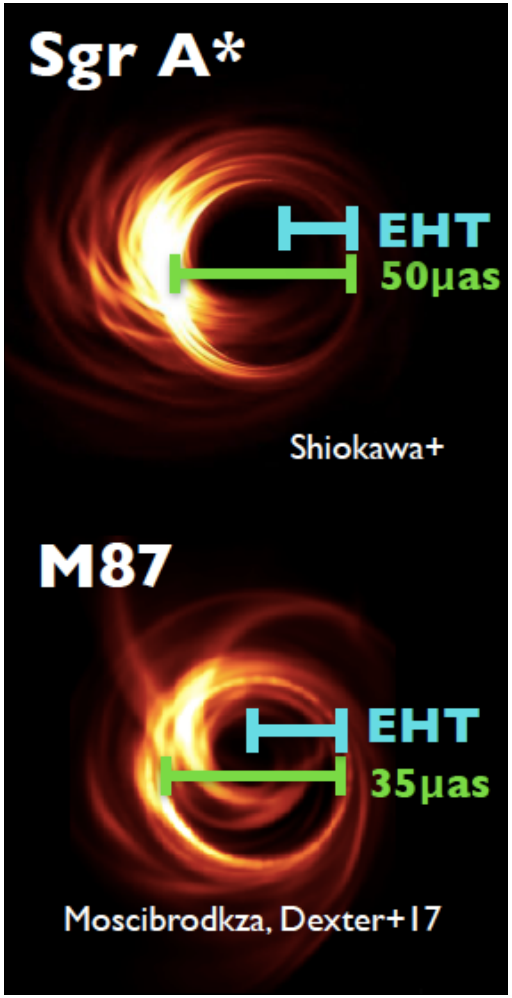
EHT is a project to assemble a VLBI network of 230 GHz wavelength dishes that can resolve GR signatures near a SMBH with spatial resolution of **~20 μas!**



(c) Nature 2017 Future News

Primal goal of EHT

The primal goal of EHT is imaging BH shadow (~photon ring w/ diameter of ~5 Rs) of Sgr A* and M87.

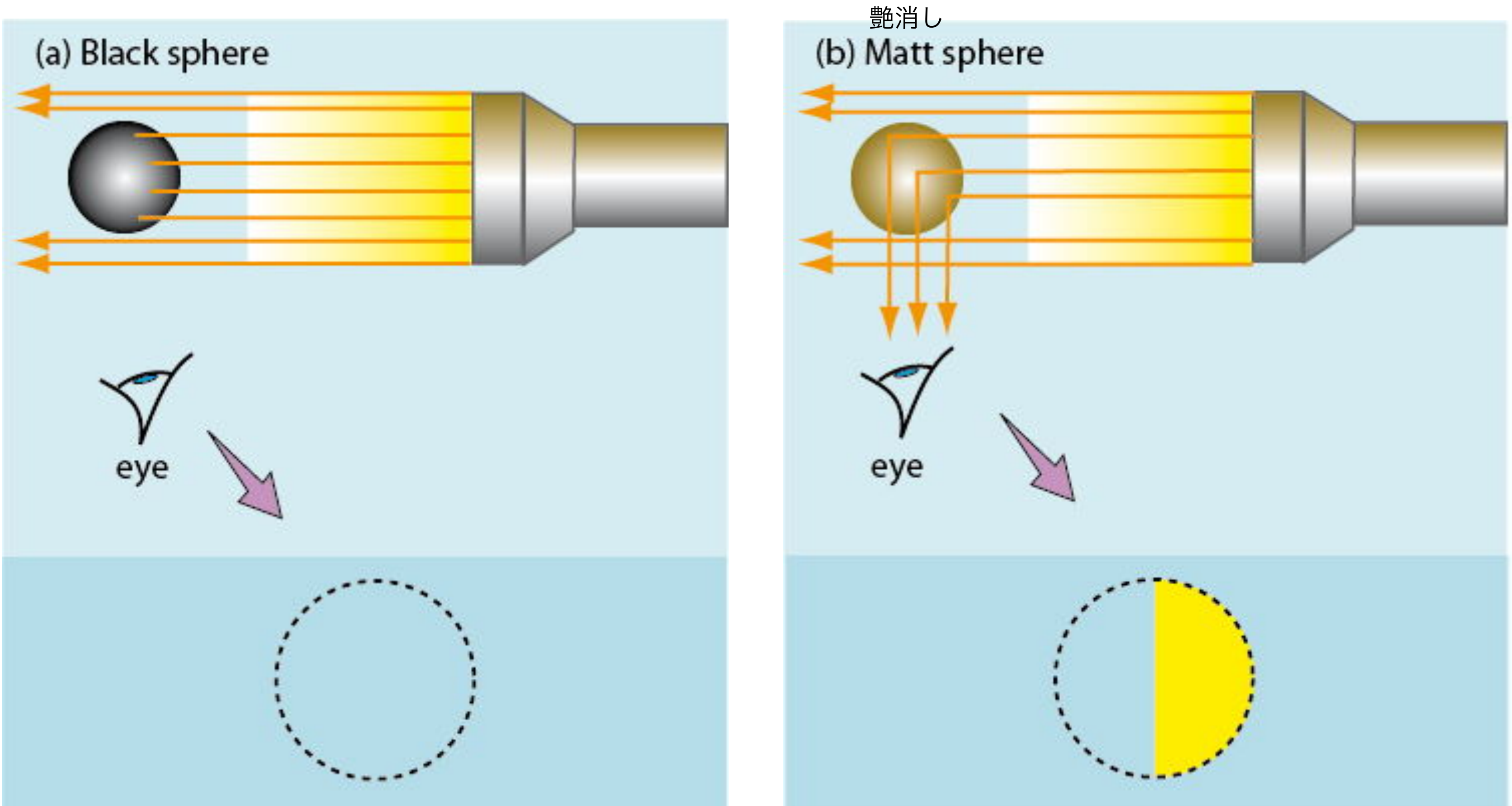


(c) Akiyama

What is the photon-ring ?

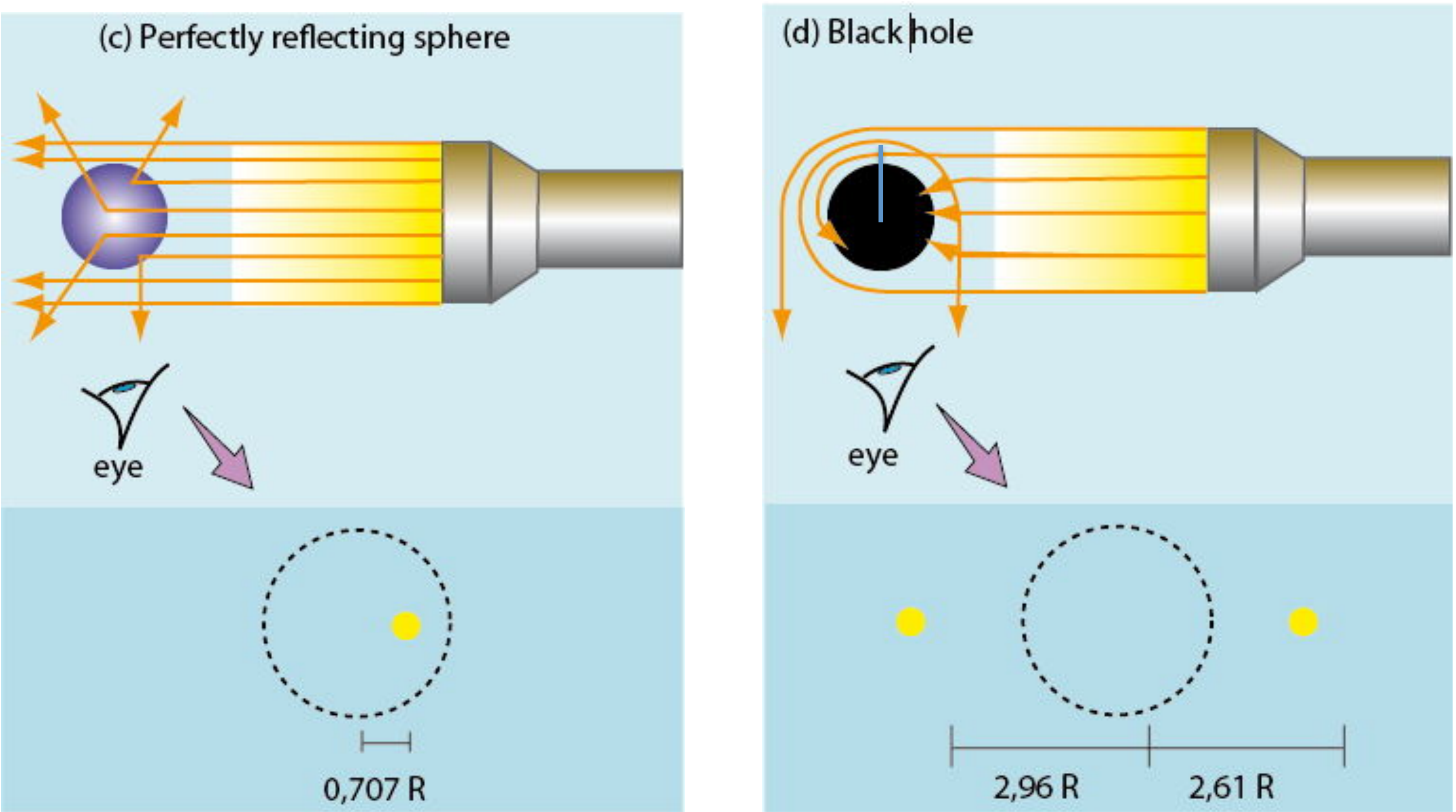
Bardeen 73, Luminet 79

reflected light



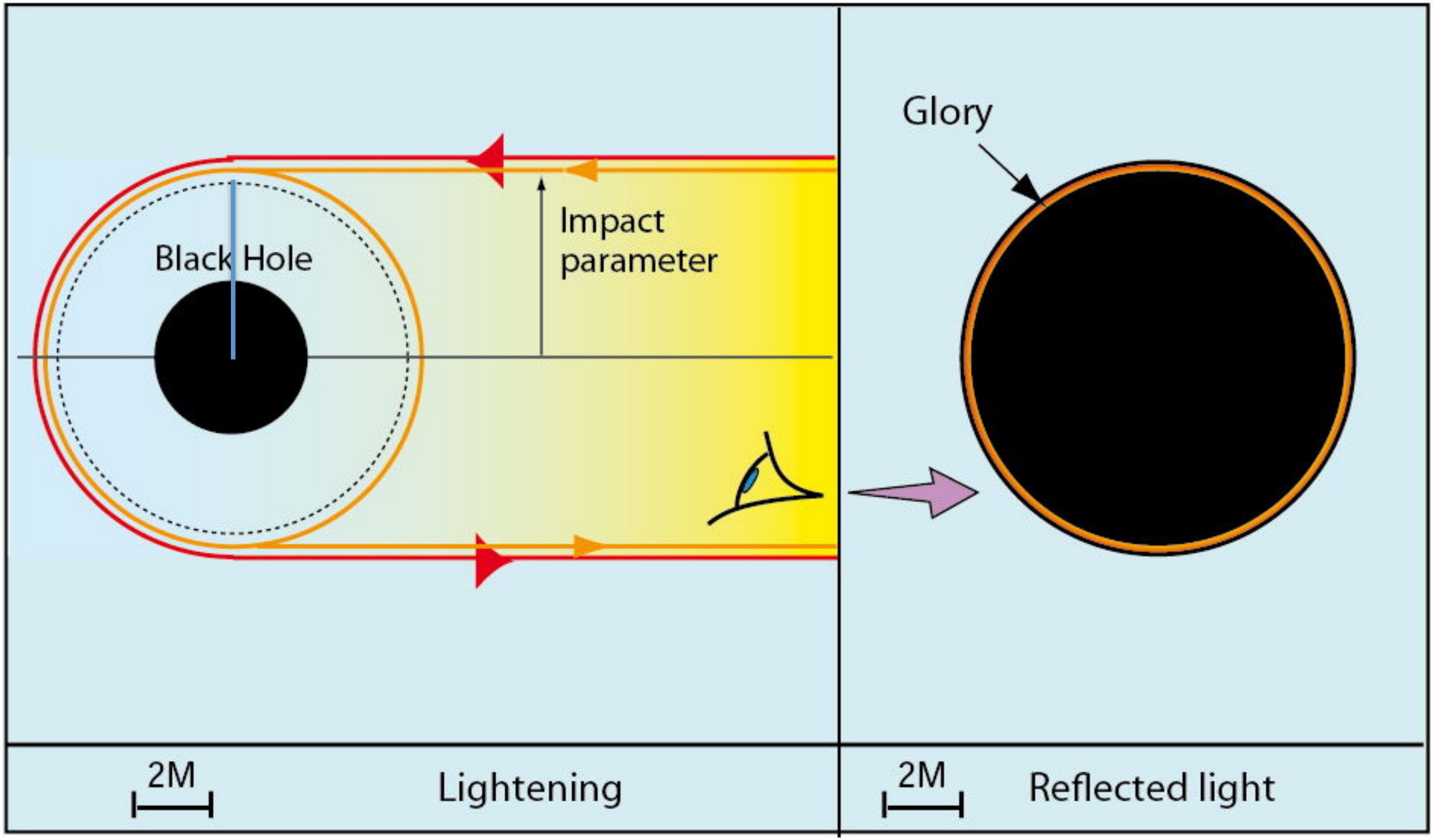
courtesy: Luminet

reflected light



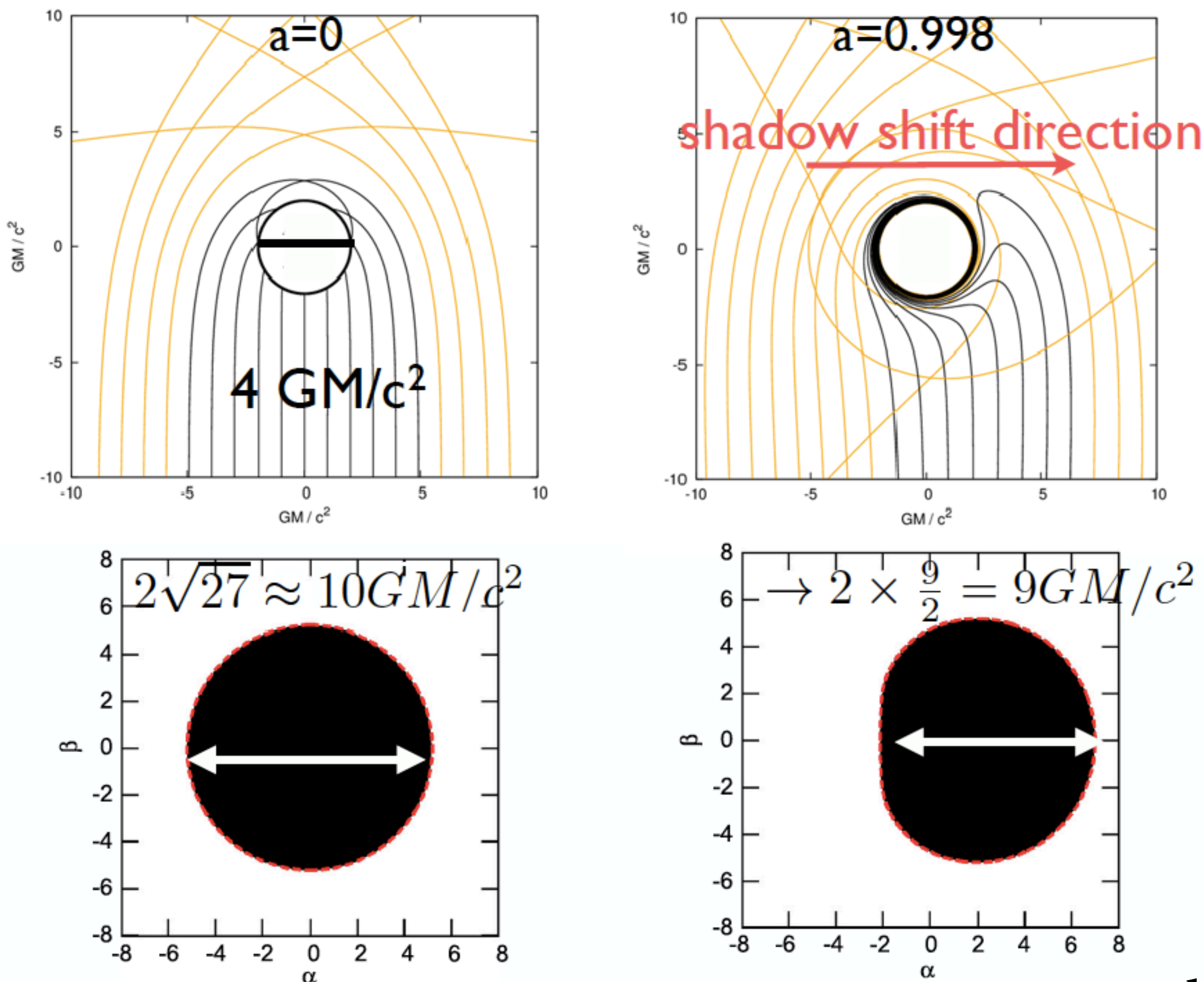
courtesy: Luminet

photon ring!



courtesy: Luminet

photon-ring (~BH-shadow) w/o and w/ spin



slide by Pu HY

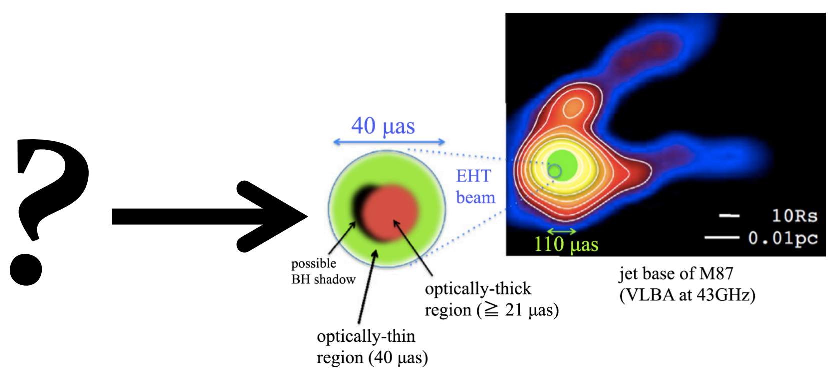
BH shadow + τ_{ssa} = ?

Kawashima, MK *in prep*

Arising question: R_photon-ring vs R_ISCO

- For higher BH-spin, R_photon-ring (~5 Rs) > R_ISCO realizes. Then, the **photon-ring would be partly smeared out due to SSA**.

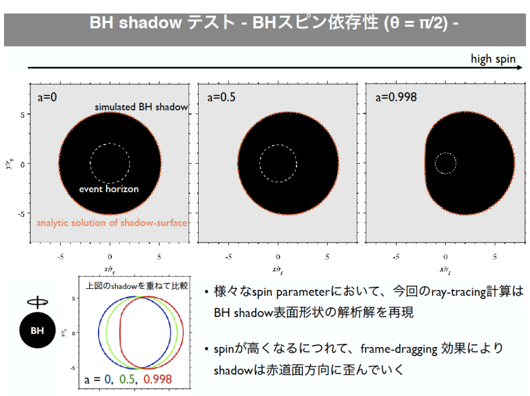
- Most of previous work seems to focus **on fully SSA-thin case at 230GHz (e.g., Brodelick & Loeb 09). It may not be the case for M87 (Kino+15).**

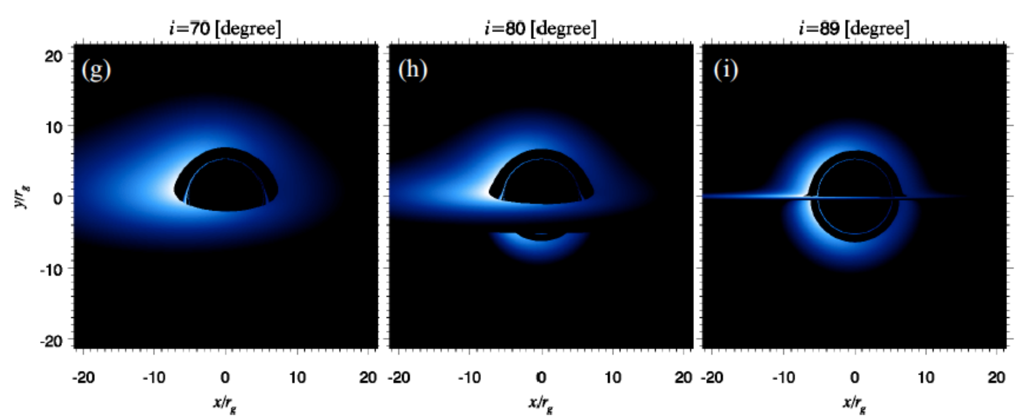


GR radiative transfer code by Kawashima-san

- Basic Scheme:
  - Ray-tracing: based on Schnittman & Krorik 13, solving r, θ, ϕ, p_r, p_θ.
  - Radiative transfer: based on Dolence+09, Monte-Carlo method for IC
- Kerr Metric w/ Boyer-Lindquist coordinate

Test runs are well consistent with previous work (Bardeen 73, Luminet+77, Chan+12 and Pu+16).





Setting (1/2)

- As a first step, we go with a simple disk model **without jet** to avoid “jet contamination” in BH-shadow images.

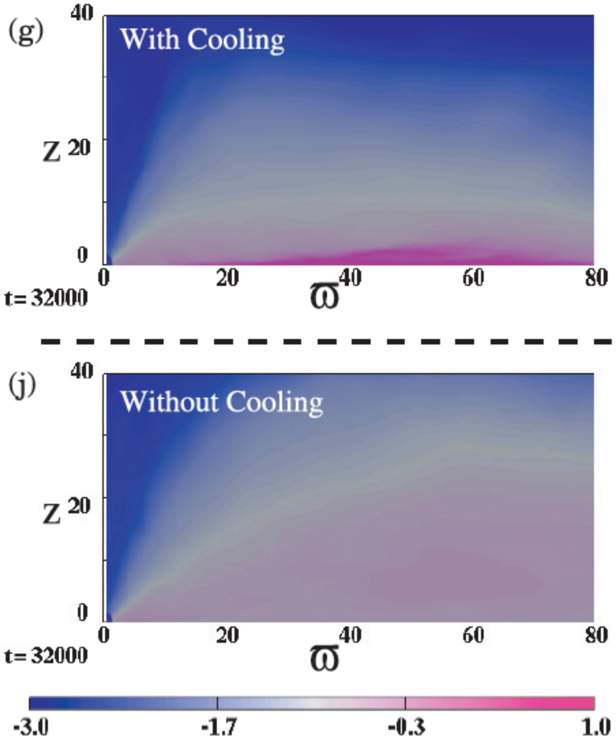
- disk thickness:

  h = H/R = 0.1

(H: scale height, R: cylindrical radius)

We mimic fast cooling.

geometrically-thin disk
w/ cooling
Machida+ (2006)



Setting (2/2)

- ρe and Te ∝ r^{-p}
  For ρe: p = 1.1
  For Te: p = 0.84
  (e.g., Pu+2016)

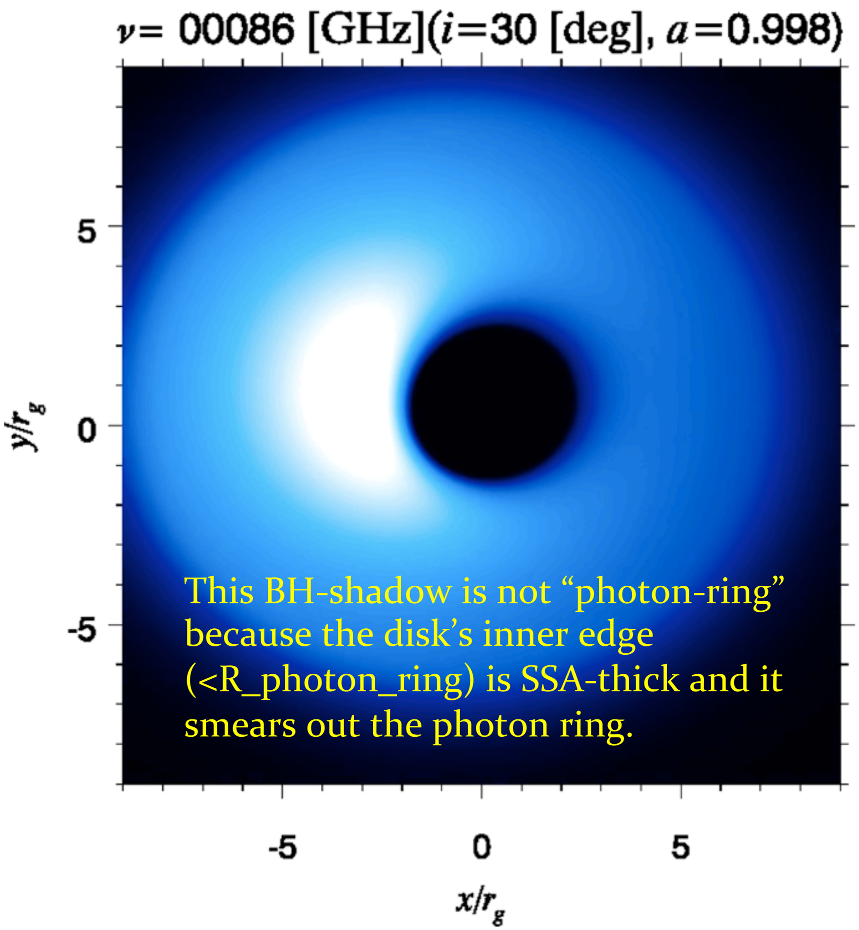
- plasma beta = 0.1

- r_out = 500 GM/c^2

- high BH-spin: a=0.998

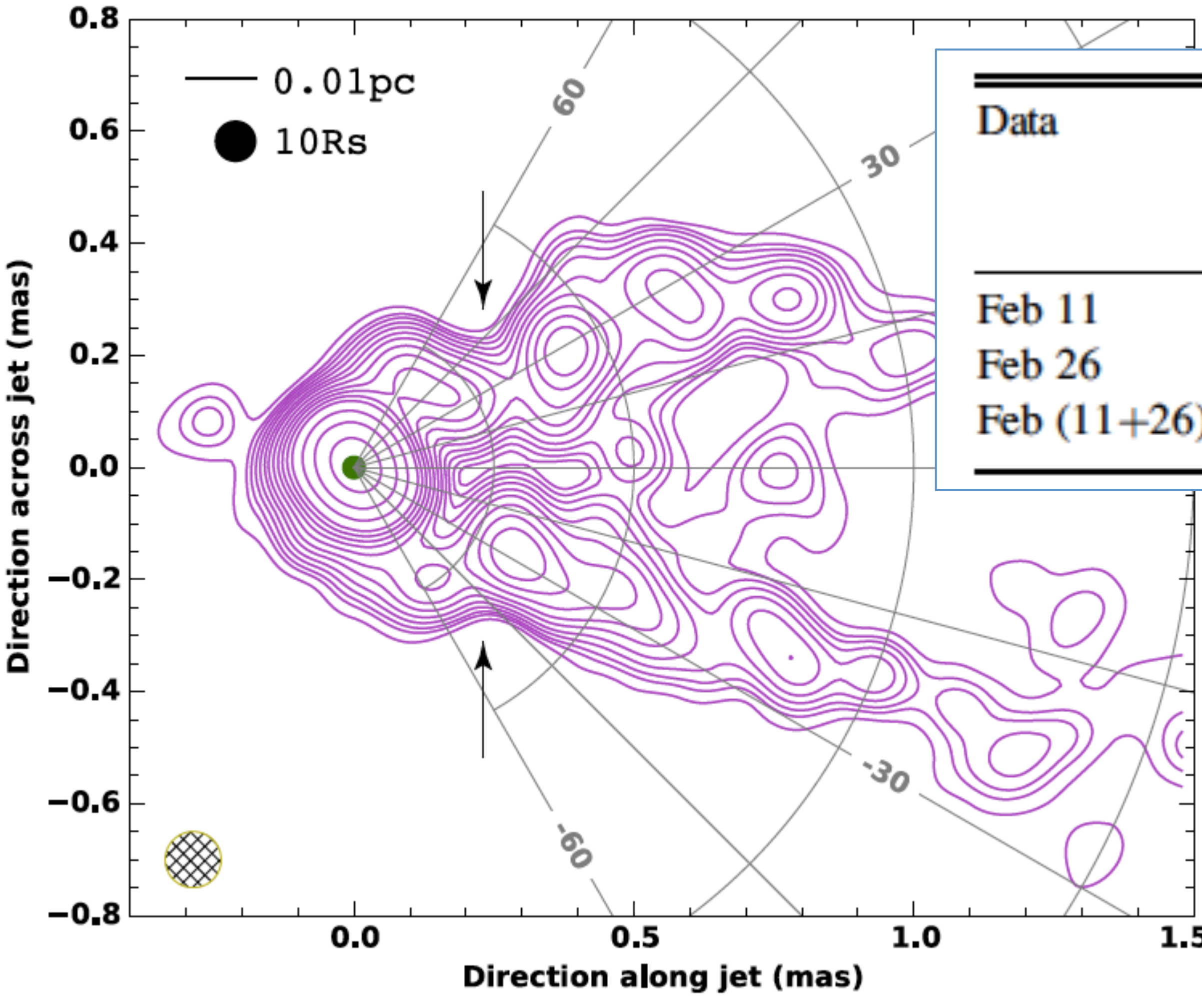
Kawashima, MK in prep

BH shadow in M87 at 86 GHz



Hada, MK, Doi+ (2016) ApJ

Actual VLBA+GBT obs. at 86GHz: measured core size (θ_{maj}, θ_{min})

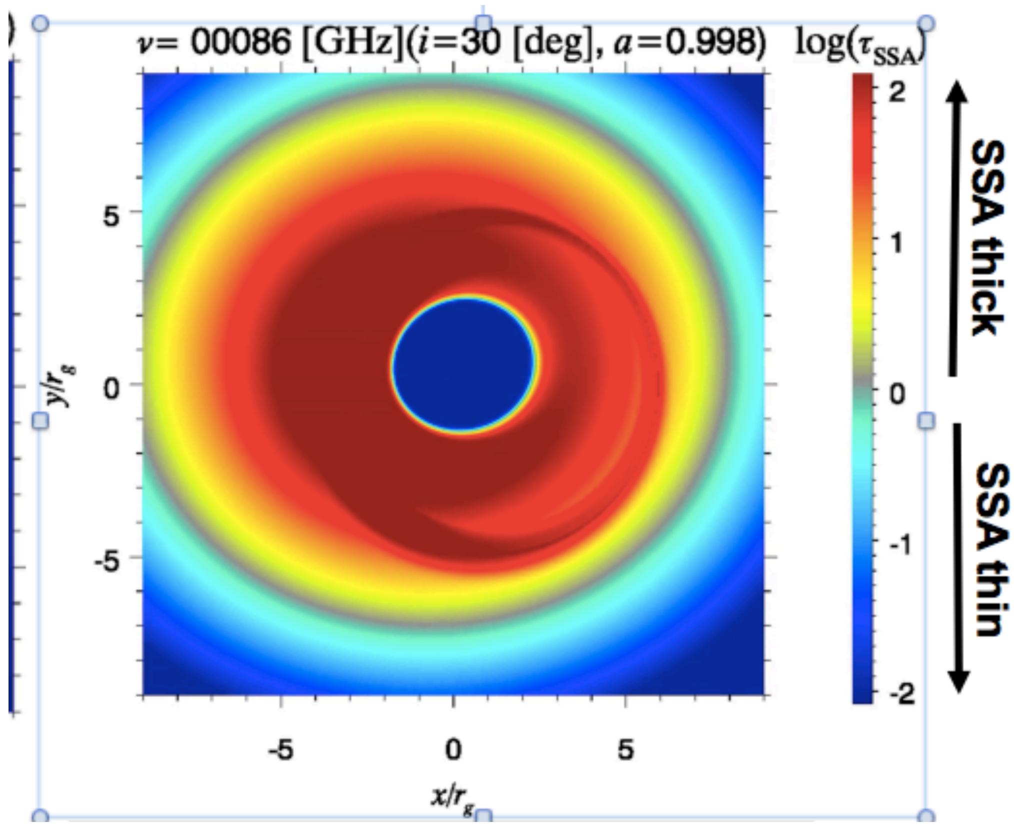


Data	θ_{maj} (μas) (a)	θ_{min} (μas) (b)
Feb 11	81 ± 4	62 ± 10
Feb 26	82 ± 3	81 ± 7
Feb (11+26)[c]	83 ± 6	76 ± 4

Many thanks to GBT!

Kawashima, MK in prep

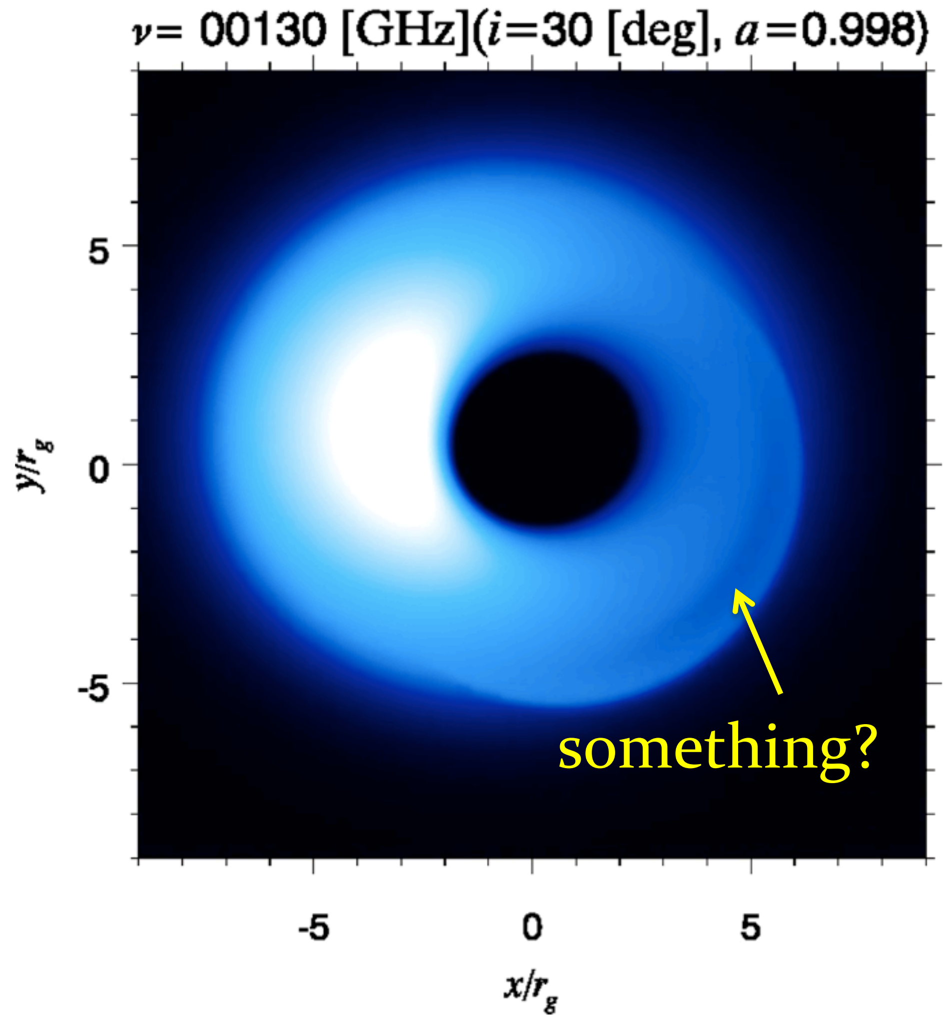
τ_{ssa} distribution at 86 GHz!



Diameter of tau_ssa=1 (narrow gray region) is ~ 20 Rg ~ 70 μas well agrees the size of radio core at 86GHz!

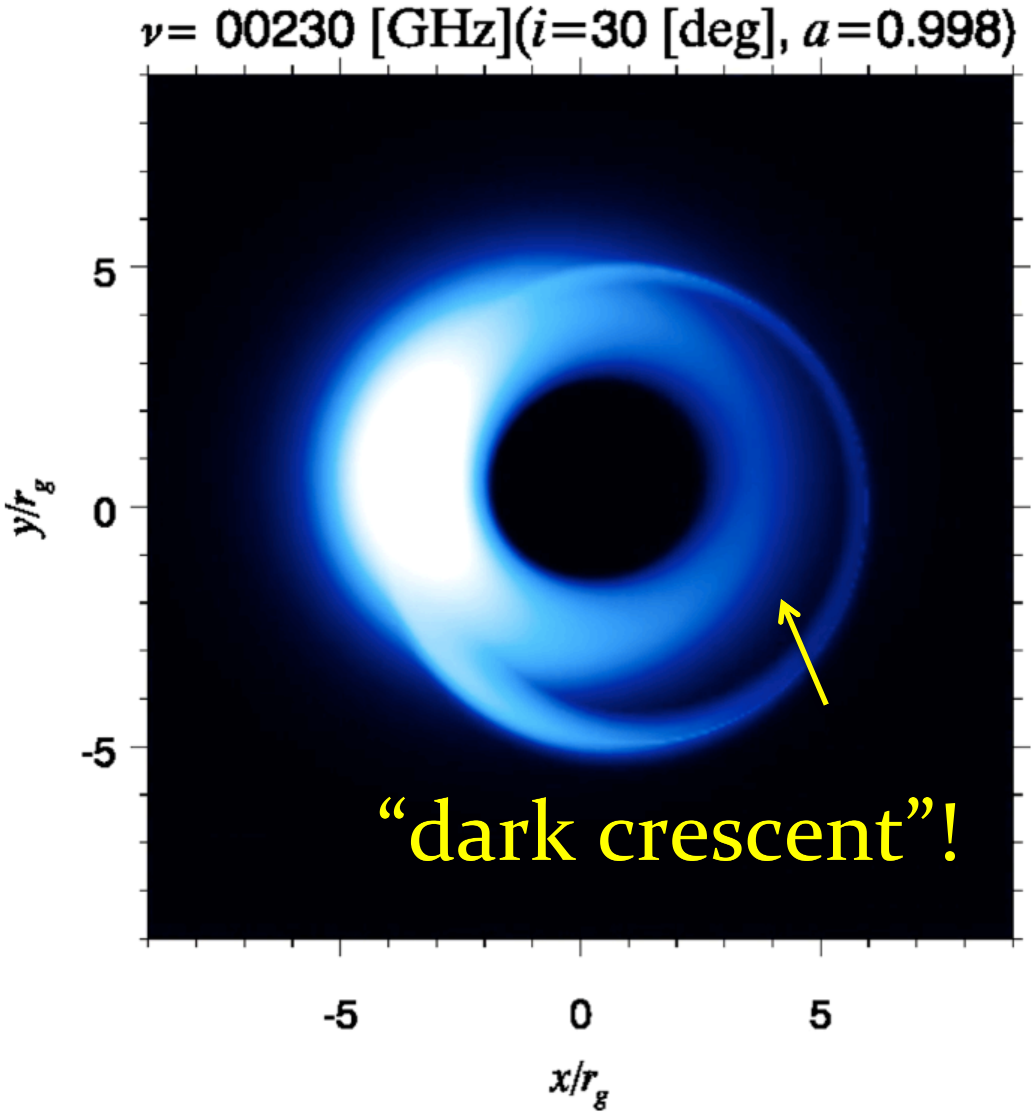
Kawashima, MK in prep

Something at 130 GHz?



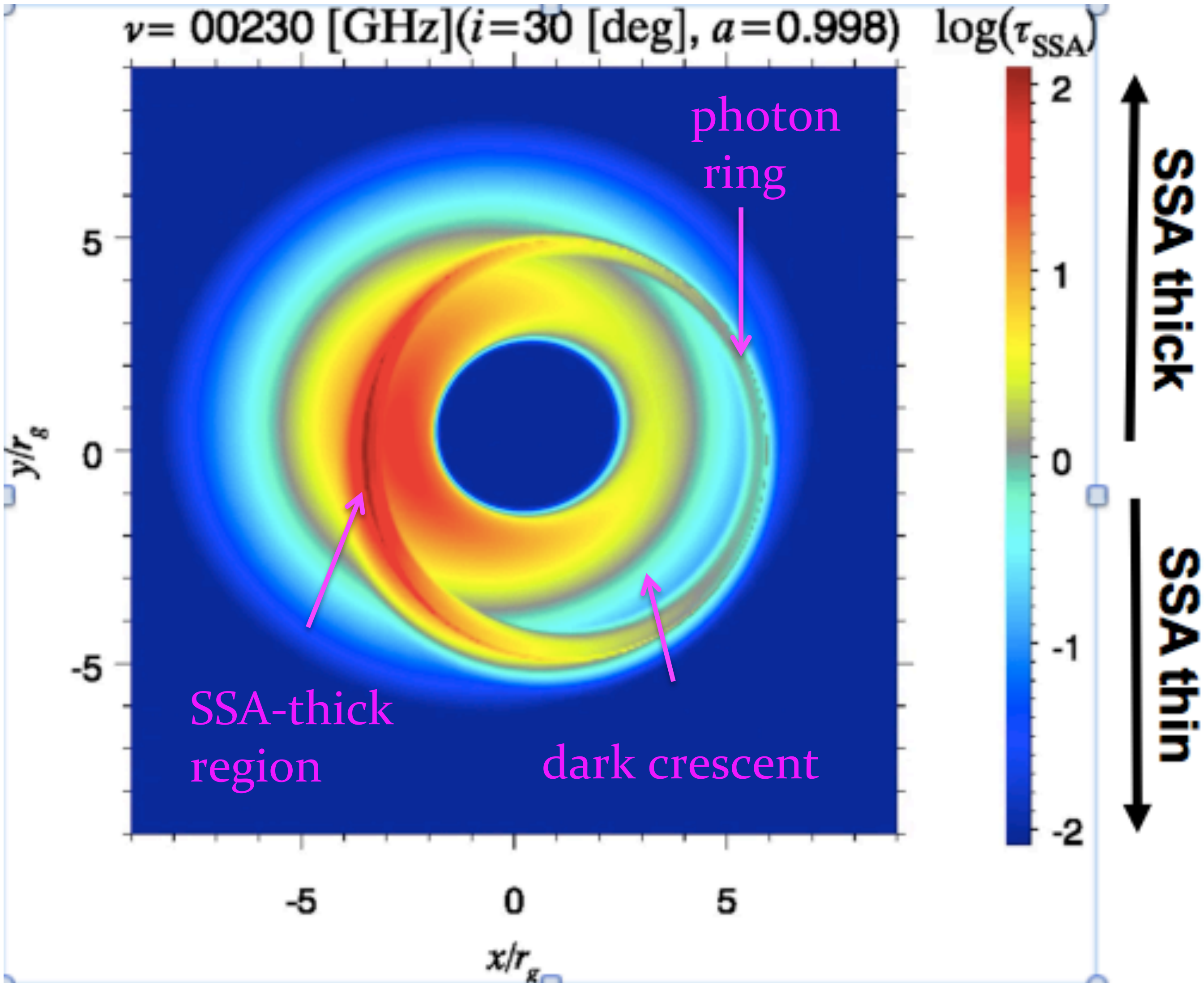
Kawashima, MK in prep

New structure at 230 GHz "dark crescent"!

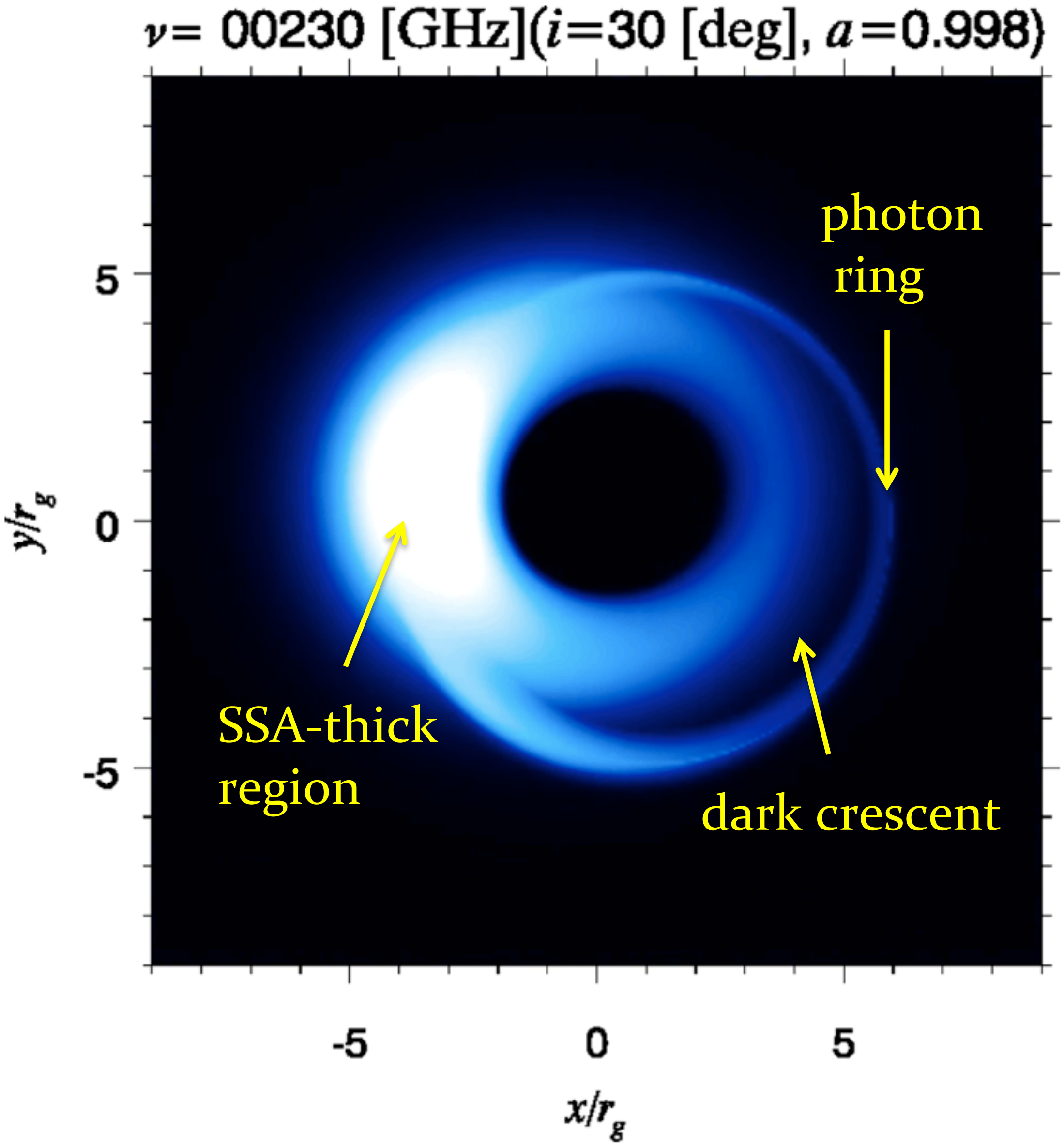


Kawashima, MK in prep

τ_{ssa} distribution at 230 GHz!



Kawashima, MK in prep



A new manifestation of high BH-spin!

Summary

Clarifying energetic of "central engine" is essential to resolve BH-jet formation mechanism.

- U_B dominance in one-zone SSA-thick region (MK+15).
- We start beyond-one zone description via BH-shadow.
    - Inclusion of SSA and GR predict a dark crescent in BH-shadow when high BH-spin. (Kawashima, MK *in prep*)