Neutrino-Dominated Accretion Flows as the Central Engine of Gamma-Ray Bursts

NK & Mineshige 2007
Masada, NK, Sano & Shibata 2007
NK, Piran & Krolik 2013
NK & Masada in prep.
NK & Kohri 2012
NK, Mineshige & Piran 2013
Liu, Gu, NK & Li 2015
Kimura, Mineshige & NK 2015

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Jet and Shock Breakouts in Cosmic Transients @ YITP, Kyoto
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Outline

1. Introduction: What is an NDAF?

2. Structure and Luminosity of NDAFs

3. Stability of NDAFs: the origin of short-term variability in GRBs
   - the effects of neutrino diffusion
   - the effects of viscosity/resistivity

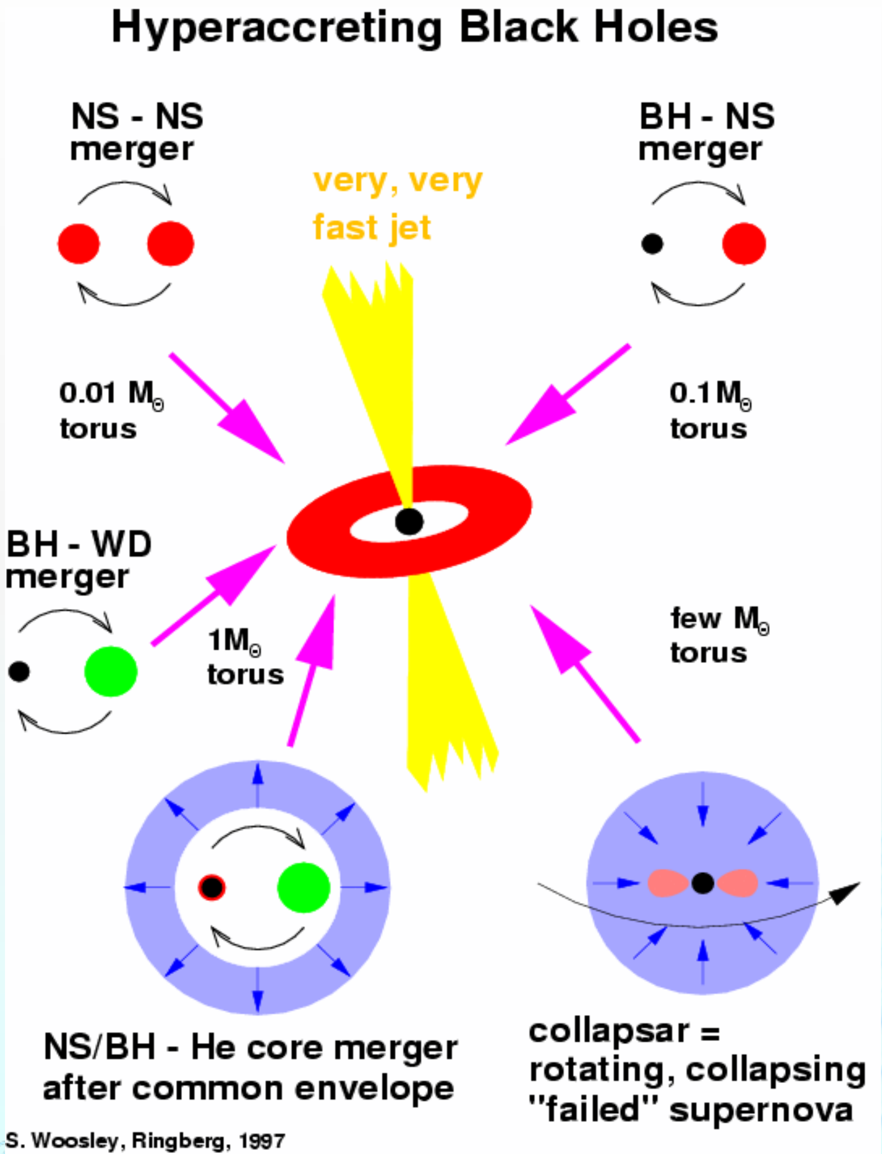
1. Introduction

Central Engine of Gamma-ray Bursts

- total energy ~ 10^{51} erg/ compact/relativistic jet/…
- most likely : a massive accretion disk around a stellar-mass black hole
- the outcome of the collapse of a massive star or a merger of compact objects

$$\boxed{\dot{M} \approx 0.01 - 1 M_{\mathrm{sun}}\ \mathrm{s}^{-1}}$$

- Photons are trapped in the accretion flow (Advection-Dominated Accretion Flow; ADAF).
- When $\dot{M}$ is large enough, neutrino emission becomes efficient.



Neutrino-Dominated Accretion Flow (NDAF)

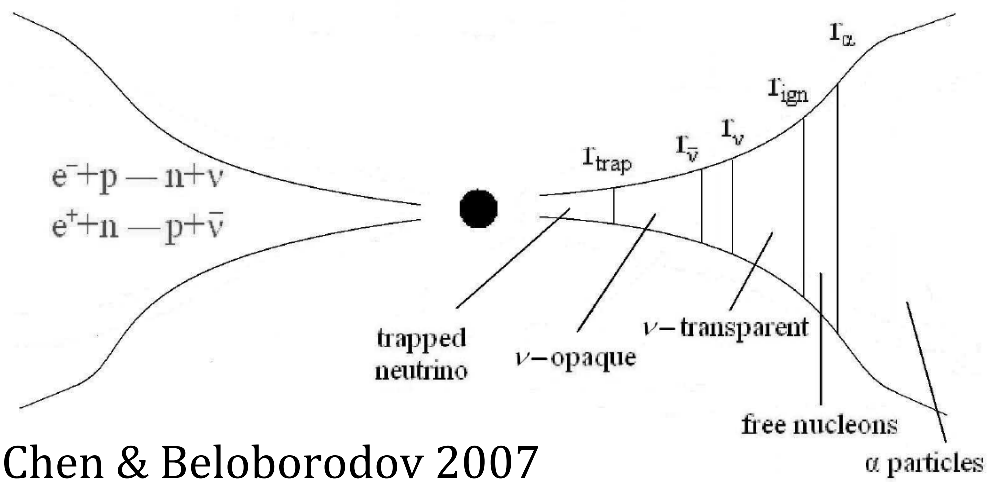
- <u>cools via neutrino emission</u>
- appears above ~0.01$M_{\rm sun}$ s^{-1}; $\rho \sim 10^{9\text{-}11}$ g cm^{-3}, $T \sim 10^{10\text{-}11}$ K
- URCA processes ($e^- + p \rightarrow n + \nu_e$ / $e^+ + n \rightarrow p + \bar{\nu}_e$) are dominant

Analytical studies

Popham+ 99; Narayan+ 01; Kohri & Mineshige 02, Di Matteo+ 03; Kohri+ 05; Chen & Beloborodov 07; NK & Mineshige 07; Masada, NK+07; Liu+ 07; NK & Kohri 12; NK, Piran & Krolik 13; NK, Mineshige & Piran 13; Liu, Gu, NK & Liu 15; Kimura, Mineshige & NK 15 etc.

Simulation studies

Lee & Ramirez-Ruiz 02; Lee+ 03; Setiawan+ 04; Shibata+07; Metzger+ 08; Sekiguchi & Shibata 11; Siegel & Metzger 17; Kyutoku+ 18 etc.



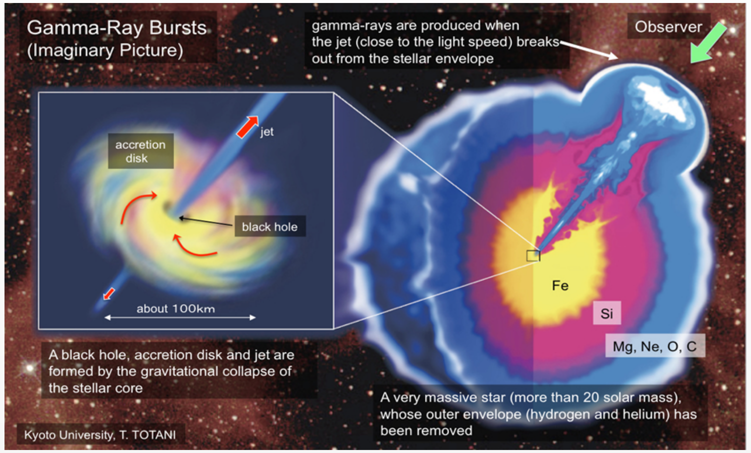
Chen & Beloborodov 2007

Problems to be solved

- Jet launching mechanism

Compactness problem
→ ultrarelativistic jet

How can the NDAF drive a powerful jet?

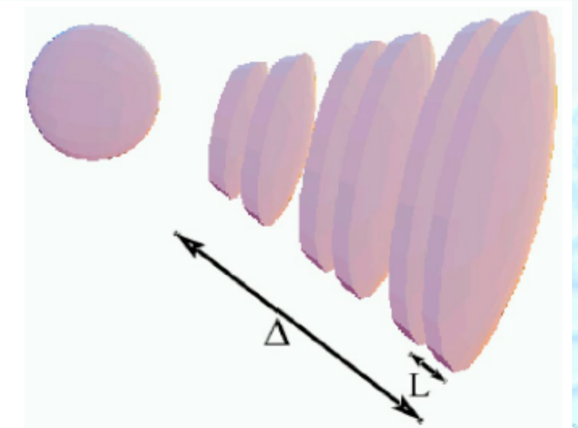


From T.Totani's website

- Origin of short-term variability

internal shock model
… a jet ejected from the NDAF
should be spatially inhomogeneous

What mechanism makes a highly variable jet?



2. Structure and Luminosity of NDAFs

Important Physics

- neutrino emission

URCA process (dominant) $e^- + p \rightarrow n + \nu_e, e^+ + n \rightarrow p + \bar{\nu}_e$

e± pair annihilation $e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i$

nucleon bremsstrahlung $n + n \rightarrow n + n + \nu_i + \bar{\nu}_i$

plasmon decay $\tilde{\gamma} \rightarrow \nu_e + \bar{\nu}_e$ etc.

- pressure source

gas/radiation/degenerated electrons/neutrinos

- composition

photodissociation of nuclei around $\sim 100 R_g$

- neutrino trapping

When mass accretion rate is very large, the disk would be optically-thick with respect to neutrinos

Fundamental Equations of an NDAF

$$\dot{M} = -2\pi R \Sigma \upsilon_R$$

mass conservation

$$2\alpha p_{\mathrm{disk}} H = \frac{\dot{M}\Omega}{2\pi}$$

ang. mom. conservation
(α−viscosity)

$$Q^+_{\mathrm{vis}} = Q^- \left(= Q^-_{\mathrm{adv}} + Q^-_{\nu}\right)$$

energy balance
(Q^-_{adv}:advection, Q^-_{ν}:neutrino)

$$\frac{p_{\mathrm{disk}}}{\rho} = \Omega^2 H^2$$

hydrostatic balance

$$p_{\mathrm{disk}} = \frac{\rho k_{\mathrm{B}} T}{m_p} + \frac{11}{12} a T^4 + \frac{2\pi hc}{3} \left(\frac{3}{8\pi m_p} \right)^{4/3} \left(Y_e \rho \right)^{4/3} + \frac{u_\nu}{3}$$

EoS

One can evaluate ρ, T, v_R, H, and p_{disk} as functions of R, $\dot{M}$, M_{BH}, α

Innermost region of an NDAF

(NK, Piran & Krolik 2013 etc.)

Depending on mass accretion rate, the dominant cooling process and pressure source would change

$\dot{M}$ ↓

1. Advection-dominated (ADAF/photons are trapped)

   neutrino cooling is not efficient $\dot{M} / M_{\mathrm{sun}}\mathrm{s}^{-1} \leq 0.018$

   $p_{\mathrm{disk}} \sim (11/12)aT^4$

2. "optically thin" NDAF $0.018 \leq \dot{M} / M_{\mathrm{sun}}\mathrm{s}^{-1} \leq 0.045$

   e^-/e^+ captures onto $p/n \rightarrow \nu / \bar{\nu}$

   $p_{\mathrm{disk}} \sim \rho k_{\mathrm{B}} T/m_p$

3. "optically thick" NDAF $0.045 \leq \dot{M} / M_{\mathrm{sun}}\mathrm{s}^{-1} \leq 4.1$

   $\tau_\nu >\sim 1 \rightarrow Q^- \propto U_\nu / \tau_\nu$

   $p_{\mathrm{disk}} \sim \rho k_{\mathrm{B}} T/m_p$

4. Advection-dominated (ADAF/neutrinos are trapped)

   $p_{\mathrm{disk}} \sim 11/12aT^4 + u_\nu/3$ $4.1 \leq \dot{M} / M_{\mathrm{sun}}\mathrm{s}^{-1}$

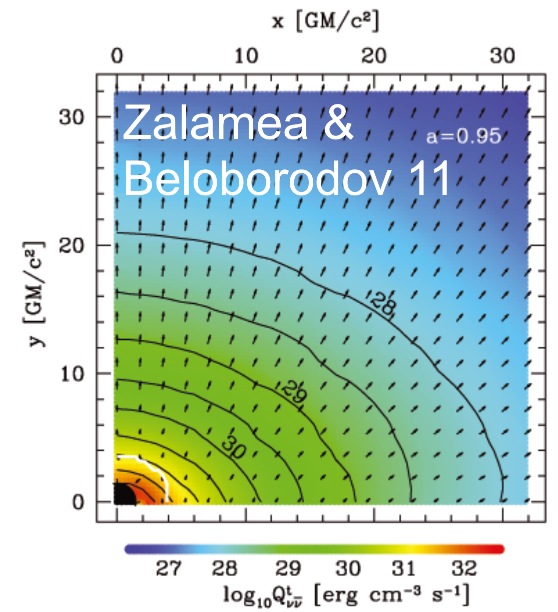
How is the relativistic jet launched?

- neutrino pair annihilation

$\nu\bar{\nu} \rightarrow e^{+}e^{-}$ above the disk

→ fireball formation?

(Eichler+ 89; Asano & Fukuyama 00, 01; Birkl+ 07; Zalamea & Beloborodov 11 etc.)

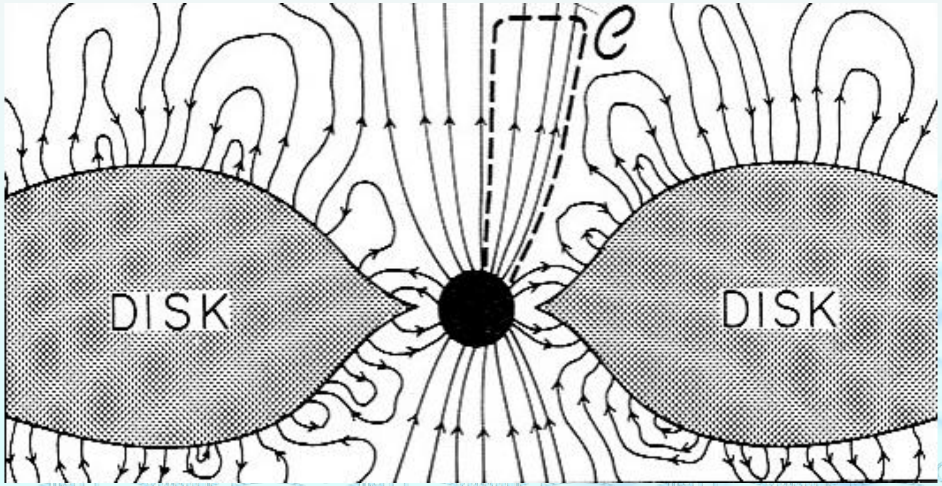

Zalamea & Beloborodov 11

- MHD mechanism (e.g. Blandford-Znajek process)

energy extraction from a rotating BH via magnetic field

→ Poynting-dominated jet

Q: How powerful is the jet and how does it depend on the mass accretion rate and other properties?



How to Estimate the Poyinting Jet Luminosity

$$L_{\mathrm{jet}} \sim c\left(\frac{B^2}{8\pi}\right)R_g^2 f\left(a/M_{\mathrm{BH}}\right)$$

B: poloidal magnetic field strength on the BH horizon
$f(a/M_{\mathrm{BH}})$: increasing function of $|a/M_{\mathrm{BH}}|$; $\sim O(1)$ if $a/M_{\mathrm{BH}} \sim 1$ and the poloidal field is dominant (Hawley & Krolik 06)

Assumption:

The magnetic pressure near the horizon is limited by the inner disk pressure: $B^2/8\pi \sim p_{\mathrm{disk}}$ (Beckwith+09)

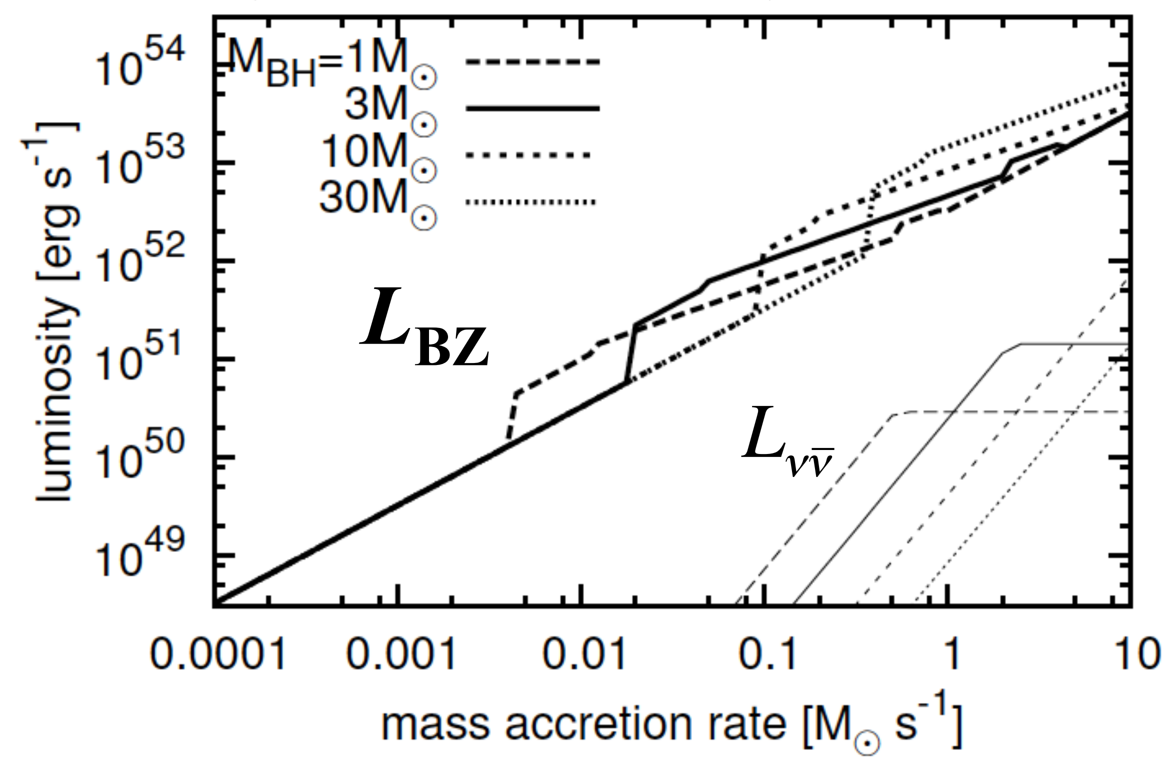
→ $L_{\mathrm{jet}} \sim c p_{\mathrm{disk}}(R_{\mathrm{in}}) R_g^2 f(a/M_{\mathrm{BH}})$

Need to evaluate $p_{\mathrm{disk}}(R_{\mathrm{in}})$ as a function of mass accretion rate, BH mass, etc.

Jet Luminosity from a Hyperaccretion flow

$\alpha=0.1,\ R_{\mathrm{in}}=6GM_{\mathrm{BH}}/c^2,$

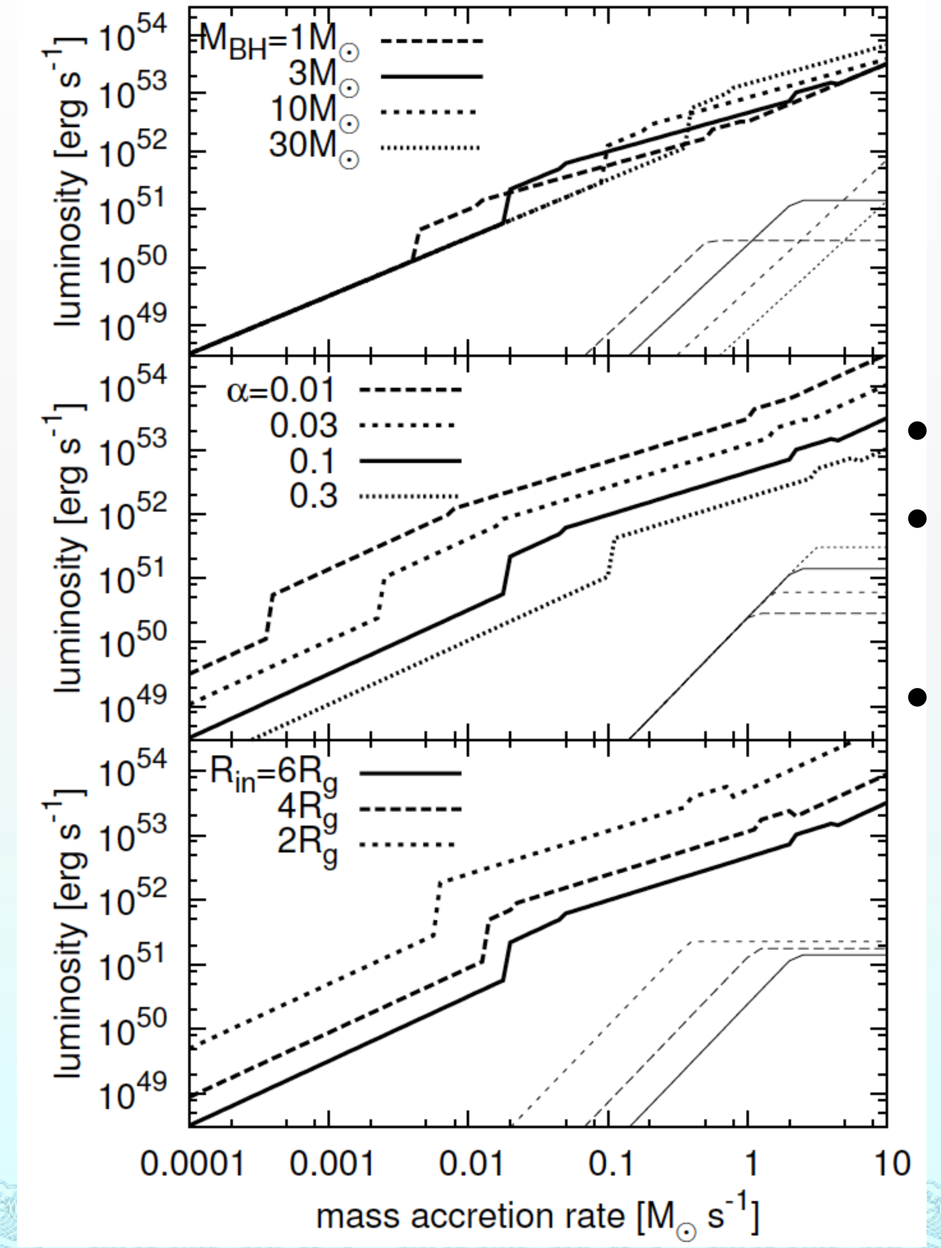
(Newtonian calculation)



NK, Piran & Krolik 2013

- simple estimates of Blandford-Znajek luminosity L_{BZ} and $\nu\bar{\nu}$ annihilation luminosity $L_{\nu\bar{\nu}}$
- **a discontinuity at a certain mass acc. rate** $\left(\dot{M}_{\mathrm{ign}}\right)$
- corresponds to the transition between ADAF and NDAF

Results (Jet luminosity vs accretion rate)



thick: BZ luminosity
thin: ν annihilation luminosity

solid lines:
$M_{\rm BH}=3M_{\rm sun}$, $\alpha=0.1$, $R_{\rm in}=6GM/c^2$

- $L_{\rm jet}$ at $\dot{M}_{\rm ign}$: ~$10^{50\text{-}51}$erg/s
- similar to the jet luminosity inferred from observed GRBs
- the drop in $L_{\rm jet}$ (a factor of ~5) at $\dot{M}_{\rm ign}$ may lead to the variability observed in the prompt emissions or the steep decay in the afterglows

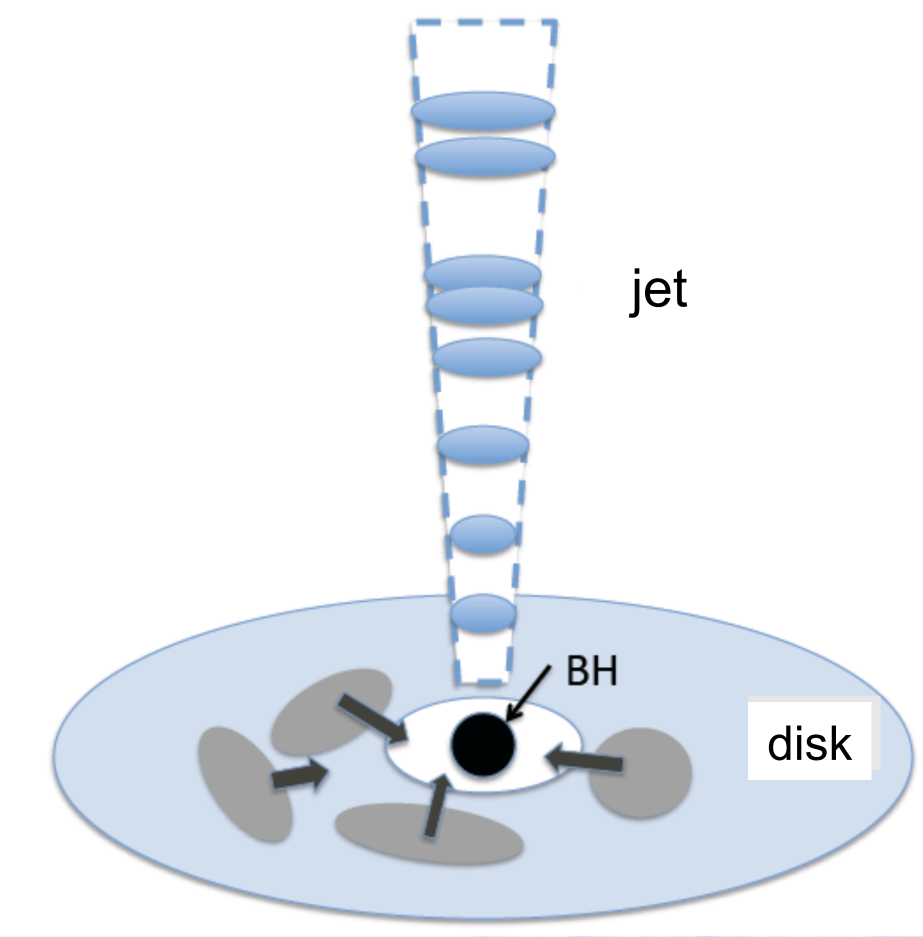
NK et al. (2013a)

3. Stability of NDAFs

Origin of short-term variability in GRBs?

- The disk instability may drive the intermittent mass accretion
  → inhomogeneous jet?
- often discussed in the context of X-ray binaries (Lightman & Eardley 74; Shibazaki & Hōshi 75; Shakura & Sunyaev 76; Piran 78)
- Some instabilities of NDAFs have been found

thermal instability: Janiuk+07
viscous instability: Masada, NK +07; NK & Kohri 12; NK+ 13b; Kimura, Mineshige & NK 15; NK & Masada in prep.



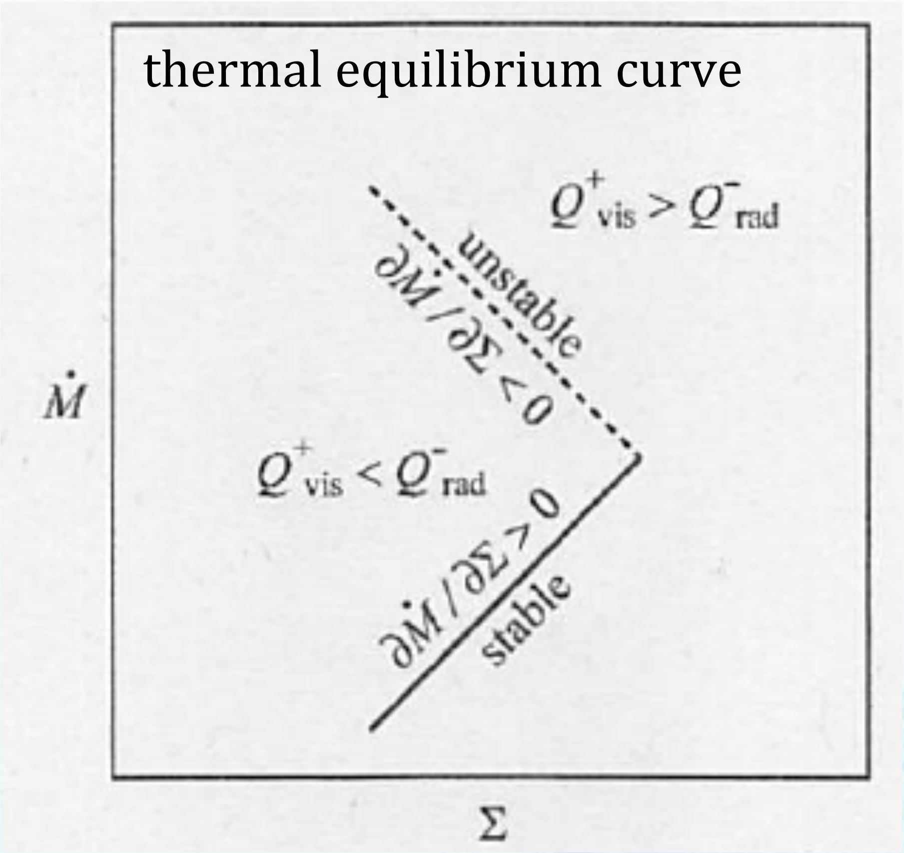
Viscous Instability (Secular Instability)

$\dot{M}$: mass accretion rate
Σ : surface density of a disk

unstable condition

$$\boxed{\left(\frac{\partial \dot{M}}{\partial \Sigma}\right)_{\text{equilibrium, fixed } r} < 0}$$

∵ $\Sigma(r)$ grows
→ less inward mass accretion
→ $\Sigma(r)$ grows further
→ unstable, clump formation
→ intermittent mass accretion



Kato, Fukue & Mineshige 2008

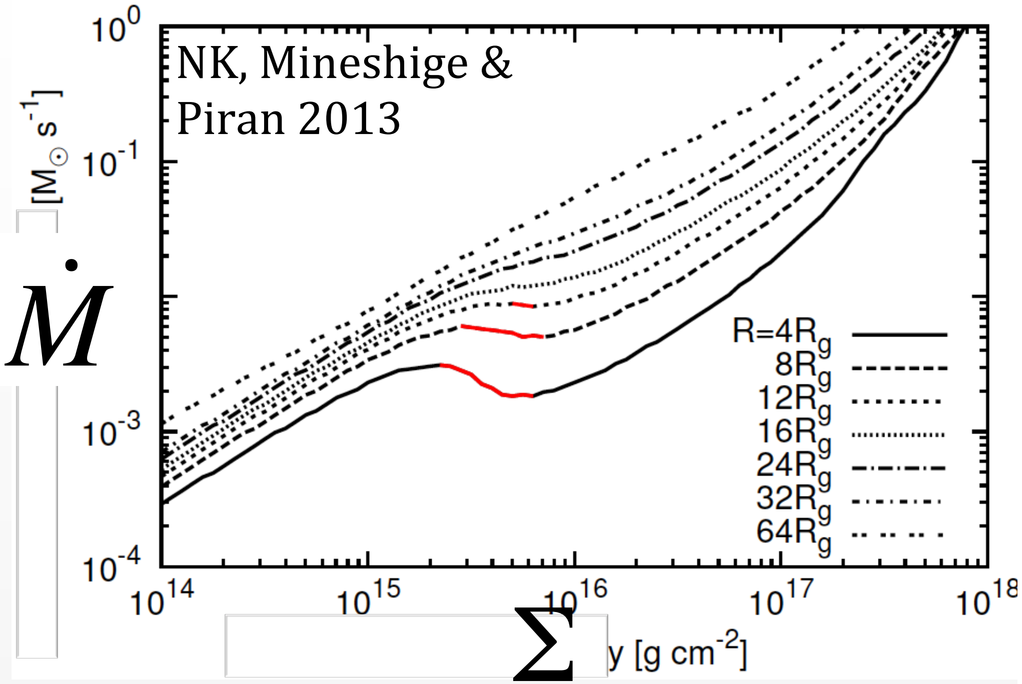
Constant α−viscosity

$$\left.\frac{\partial \dot{M}}{\partial \Sigma}\right|_{\text{equilibrium}} < 0$$

in the inner disk region

→ secularly unstable

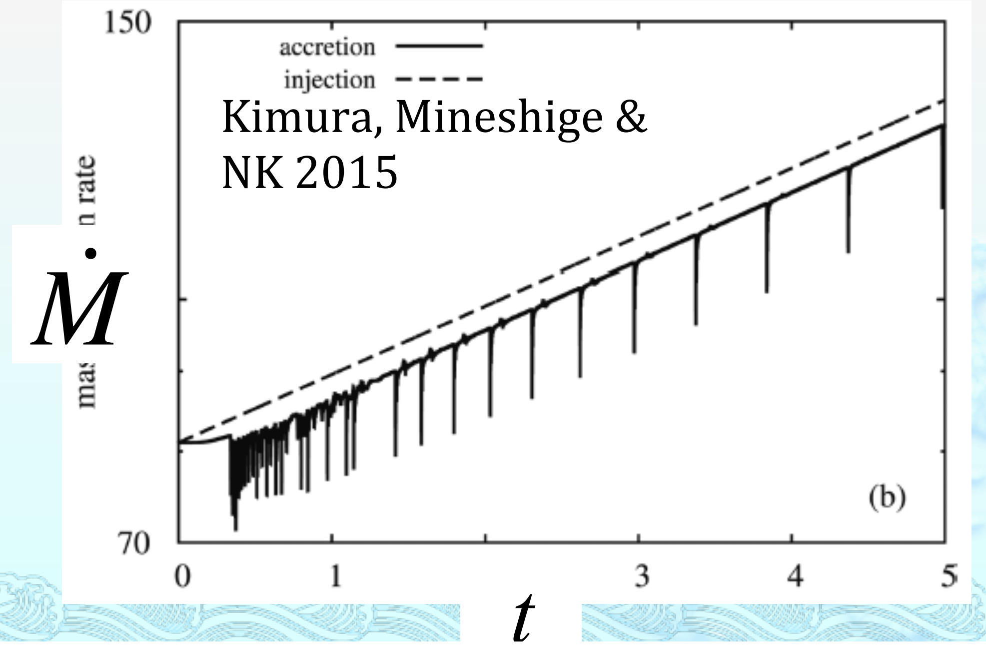
(NK et al. 2013b)



NK, Mineshige & Piran 2013

intermittent mass accretion

(Kimura, Mineshige & NK 2015)



Kimura, Mineshige & NK 2015

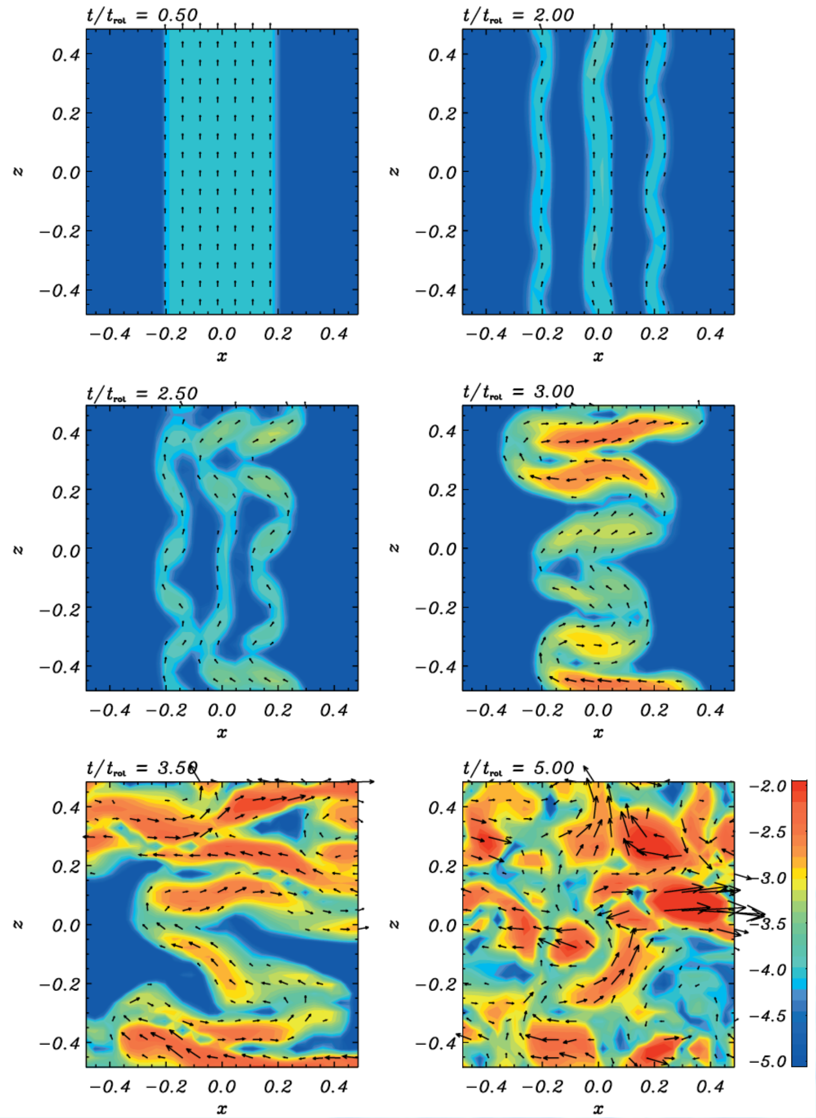
Q. Is the α-viscosity parameter always constant in an NDAF?

A. No!

Origin of shear viscosity in an accretion disk

… turbulence driven by MagnetoRotational Instability (MRI) → α-prescription (Shakura & Sunyaev 1973)

∴ If the growth of MRI is boosted (suppressed), α becomes larger (smaller).



Sano et al. 2004

The growth of MRI in an NDAF can be affected by

(1) neutrino diffusion (Masada et al. 2007)

(2) e^- viscosity/resistivity (NK & Masada in prep.)

MRI in a ν-thick NDAF?

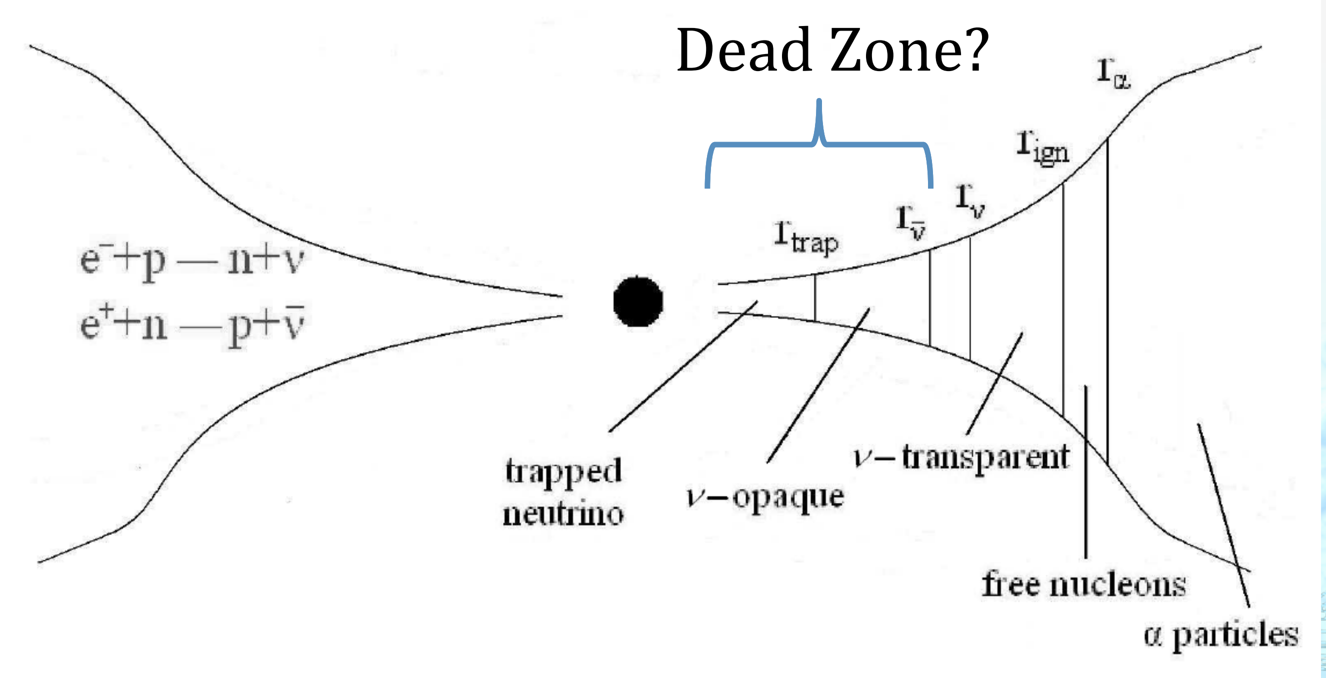
Masada, NK, Sano & Shibata 2007

$$\dot{M} \geq 0.1 - 1 M_{\odot} \mathrm{s}^{-1}$$

→ innermost region may be neutrino-opaque

→ energy/momentum transport due to neutrino diffusion is effective

→ The growth of MRI would be suppressed



Order Estimate

The fastest growing mode of MRI: $\lambda \sim v_A/\Omega$

The growth timescale of MRI $\sim \lambda/v_A$

The damping timescale due to the viscosity $\sim \lambda^2/\nu$

→ MRI can grow only when

$$\mathrm{Re} \equiv \frac{LU}{\nu} = \frac{v_{\mathrm{A}}^2}{\nu\Omega} \gtrsim 1,$$

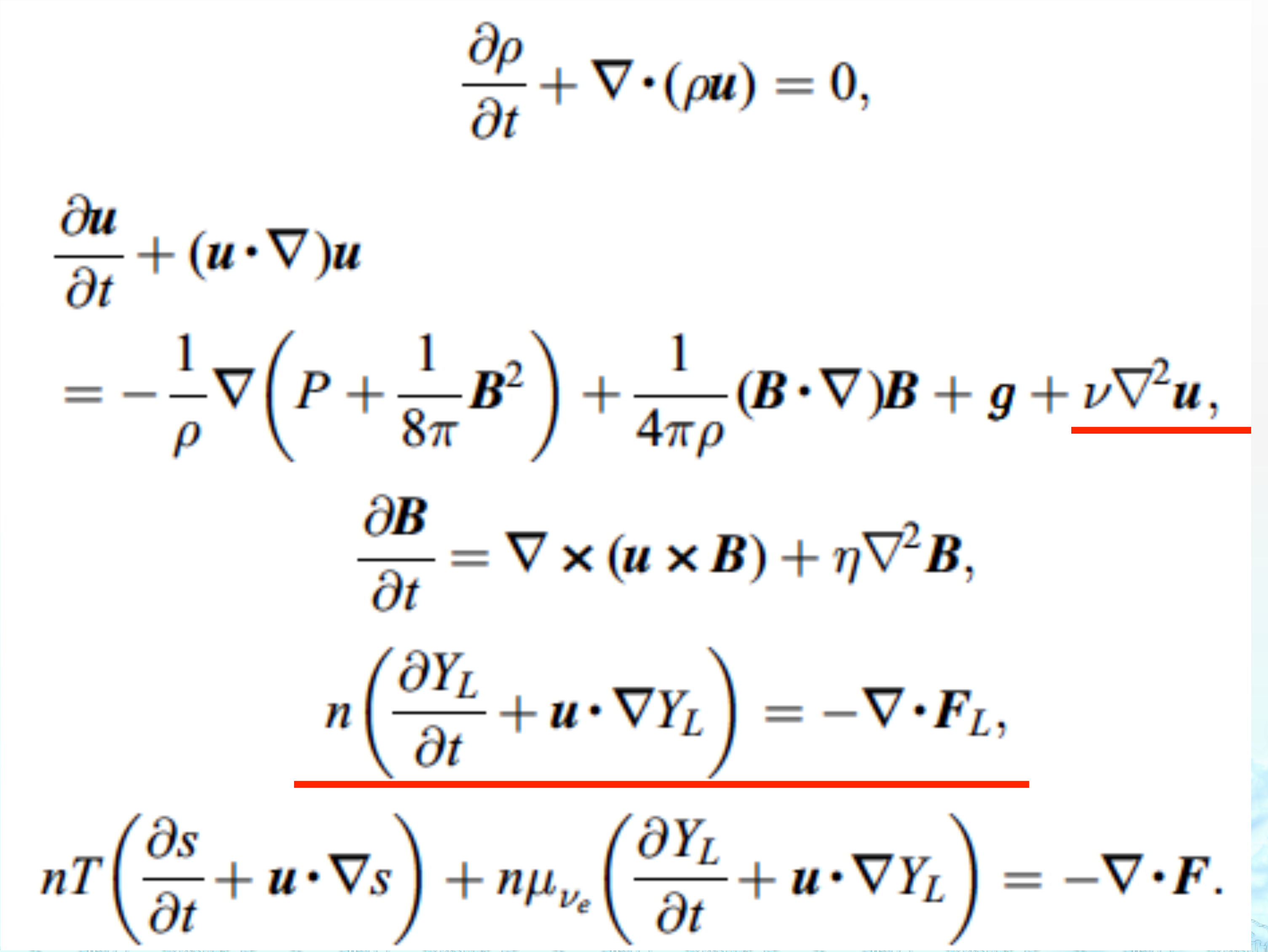
Neutrino viscosity:

$$\nu = \frac{4}{15}\frac{U_\nu}{\rho c}\langle\lambda\rangle \approx 5.2\times10^{12} T^2 \rho^{-2}\ \mathrm{cm}^2\ \mathrm{s}^{-1},$$

➡ $\mathrm{Re} \approx 3.4\times10^{-7} B_{11}\rho_{11}T_{11}^{-2}\left(M/3M_\odot\right)\left(r/3r_S\right)^{3/2}$

Neutrino Diffusion Effect on MHD eqs.

Masada, Sano & Shibata (2007)



$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0,$$

$$\frac{\partial\boldsymbol{u}}{\partial t}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}$$

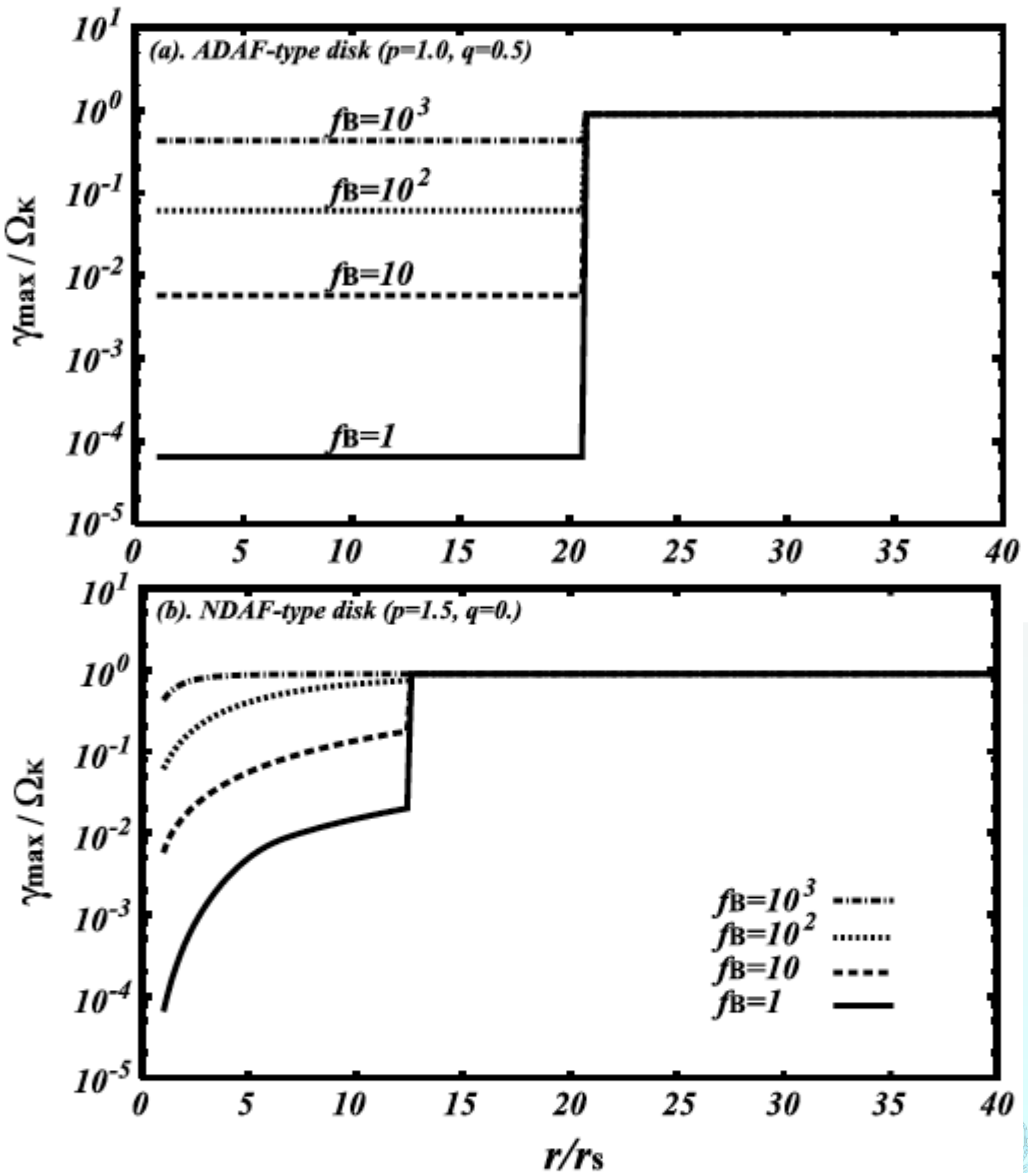
$$=-\frac{1}{\rho}\nabla\left(P+\frac{1}{8\pi}\boldsymbol{B}^2\right)+\frac{1}{4\pi\rho}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}+\boldsymbol{g}+\underline{\nu\nabla^2\boldsymbol{u},}$$

$$\frac{\partial\boldsymbol{B}}{\partial t}=\nabla\times(\boldsymbol{u}\times\boldsymbol{B})+\eta\nabla^2\boldsymbol{B},$$

$$\underline{n\left(\frac{\partial Y_L}{\partial t}+\boldsymbol{u}\cdot\nabla Y_L\right)=-\nabla\cdot\boldsymbol{F}_L,}$$

$$nT\left(\frac{\partial s}{\partial t}+\boldsymbol{u}\cdot\nabla s\right)+n\mu_{\nu_e}\left(\frac{\partial Y_L}{\partial t}+\boldsymbol{u}\cdot\nabla Y_L\right)=-\nabla\cdot\boldsymbol{F}.$$

Maximum growth rate



MRI would be suppressed in the inner region (neutrino-opaque)
→ Angular momentum transport would be taken by neutrinos, which would be weaker than that in the outer region (neutrino-thin)

Evolution scenario of an NDAF

α-parameter by neutrino viscosity

$$\alpha_\nu = \frac{\nu\Omega_{\rm K}}{c_s^2} = 5.2\times10^{-5} f_\Sigma^2 f_T^2 M_3^{-2} \hat{r}^{-2(p-q)+3/2}.$$

Mass accretion rate from the MRI-dead zone:

$$\dot{M}_{\rm out} = 4\pi r\rho H v_r \simeq 7.2\times10^{-4}\left(\frac{\alpha_\nu}{10^{-4}}\right) f_\Sigma f_T M_3 \dot{M}_\odot,$$

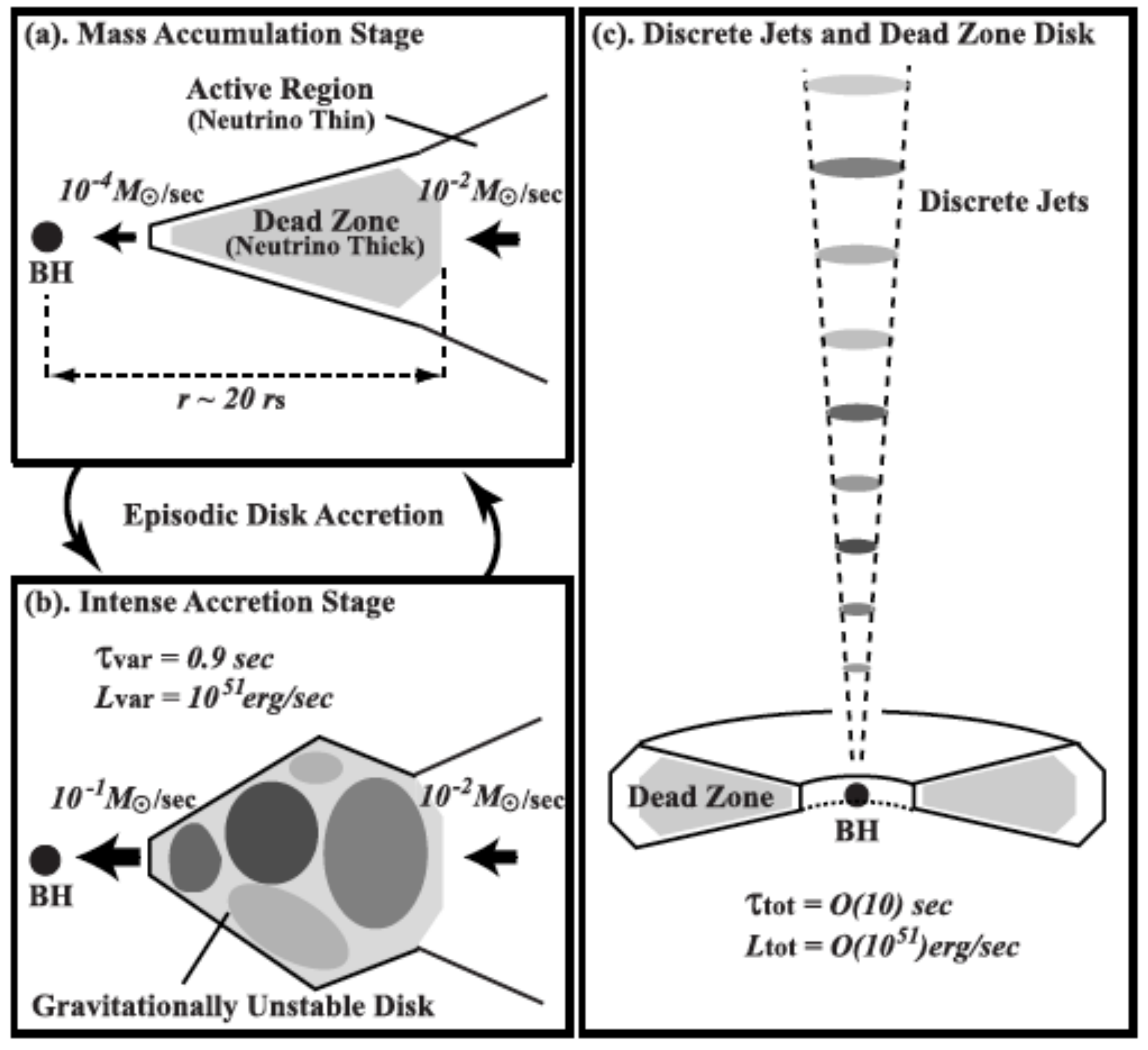
Mass accretion from the outer (MRI-active) zone:

$$\dot{M}_{\rm in} \simeq 7.2\times10^{-2}\left(\frac{\alpha_t}{10^{-2}}\right) f_\Sigma f_T M_3 \dot{M}_\odot. \quad >> \dot{M}_{\rm out}$$

Matter would be accumulated into the dead zone → Gravitationally unstable!

$f_\Sigma, f_T \sim O(1)$

Schematic picture



The growth of MRI in an NDAF can be affected by
(1) neutrino diffusion (Masada et al. 2007)
(2) e^- viscosity/resistivity (NK & Masada in prep.)

e^- viscosity can affect the MRI efficiency

Magnetic Prandtl number P_m could influence the saturated state of the MRI turbulence

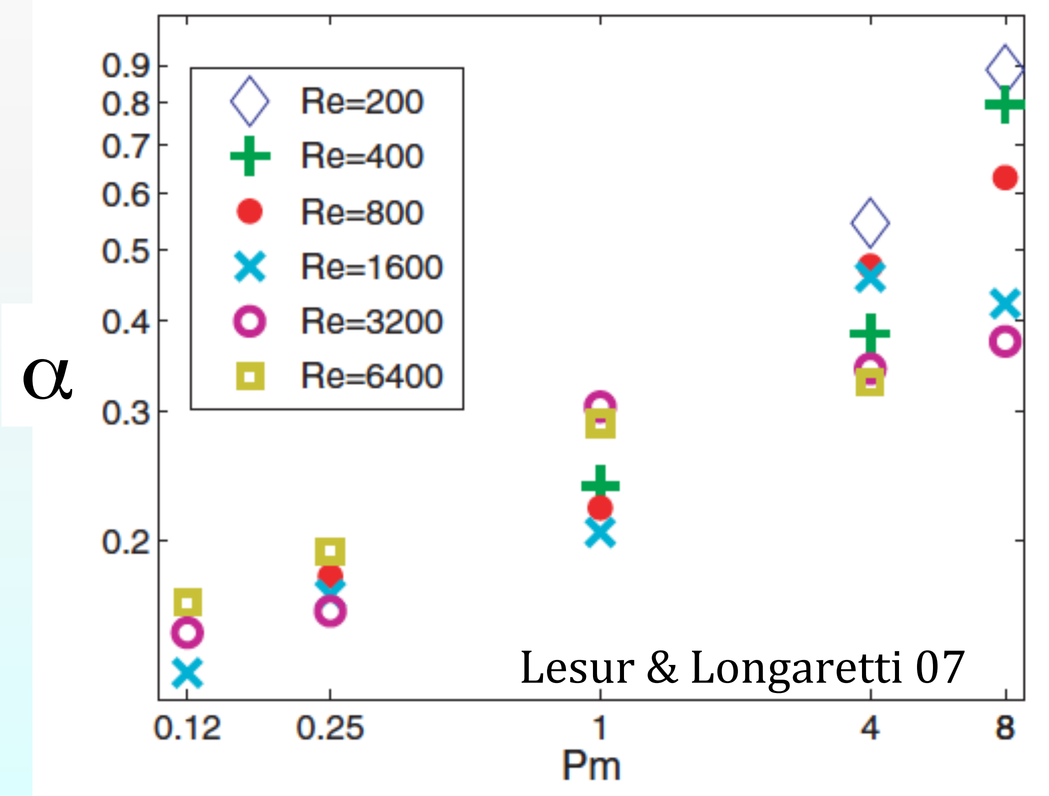
(Fromang et al. 2007; Lesur & Longaretti 2007; Simon & Hawley 2009 etc.)

$$\mathrm{Pm} = \frac{\nu}{\eta} = \frac{\mathrm{Re_M}}{\mathrm{Re}}$$

ν: viscosity

η: resistivity

$$\alpha \propto P_m^{\delta} \ ?$$



Lesur & Longaretti 07

Disk instability induced by varying α

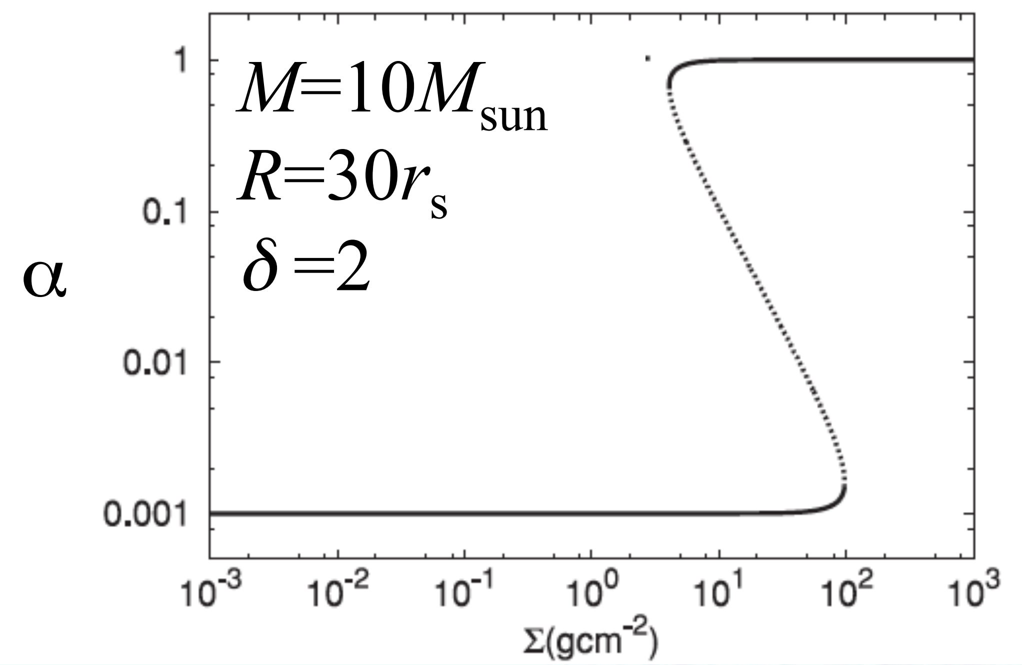
Takahashi & Masada 2011
Potter & Balbus 2014

e.g. accretion disks in X-ray binaries

Cooling: photon

viscosity, resistivity: Coulomb scattering of electrons

➡ $P_m(T, \rho)$



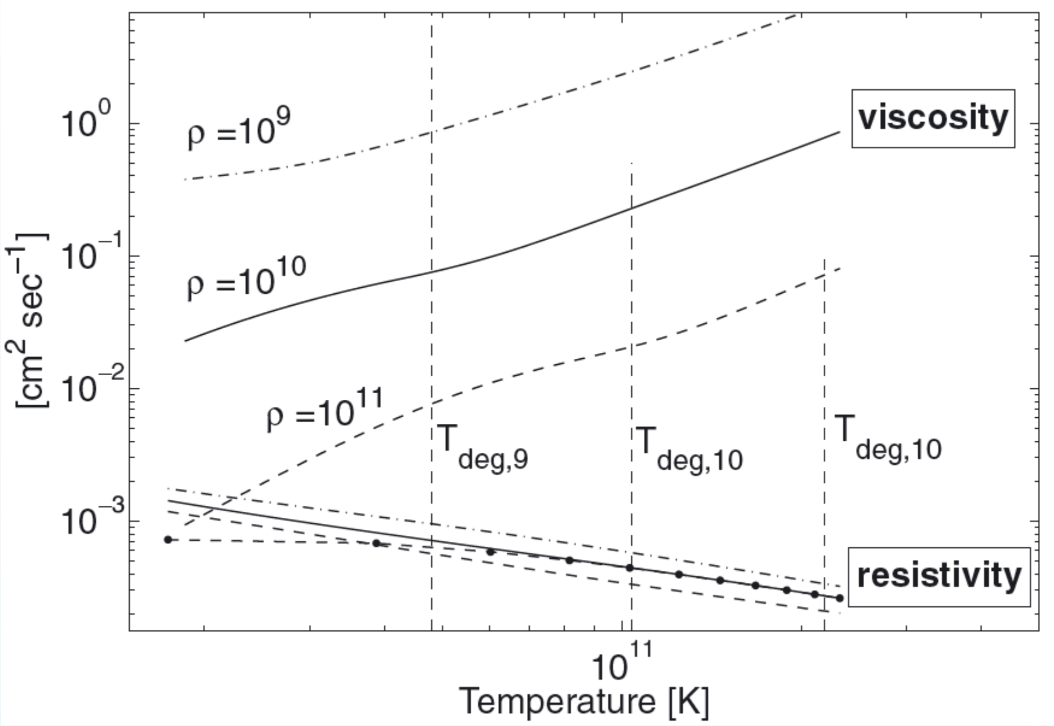
Potter & Balbus 2014

Assuming $\alpha \propto P_m^{\ \delta}$, an accretion disk can be unstable when $\delta > 2/3$

How about an NDAF?

Cooling: neutrino

viscosity, resistivity: Coulomb scattering of relativistically degenerate electrons



Rossi et al. 2008

$$\mathrm{Pm} \simeq 5.74 \left(\frac{T}{10^{10}\ \mathrm{K}}\right)^{3/2} \left(\frac{\rho}{10^{11}\ \mathrm{g\ cm^{-3}}}\right)^{-1}$$

instability criterion

NK & Masada in prep.

When $\dot{M} \sim 0.01 - 0.1 M_{\odot} \mathrm{s}^{-1}$ (ν-thin cooling regime),

an NDAF becomes viscously unstable if

$$\frac{\partial \dot{M}}{\partial \Sigma} < 0 \xrightarrow[\text{gas pressure}]{\nu\text{-cooling}} \frac{\partial \left(\alpha^{6/5} \Sigma \right)}{\partial \Sigma} < 0$$

Assuming $\alpha \propto \mathrm{P}_{\mathrm{m}}^{\delta}$

$$\boxed{\frac{5}{8} < \delta < \frac{5}{2}}$$

1-d simulation of an NDAF

NK & Masada in prep.

Equation for the surface density

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right]$$

$\Sigma(r,t)$: surface density

$\nu = \alpha c_s H$: kinetic viscosity

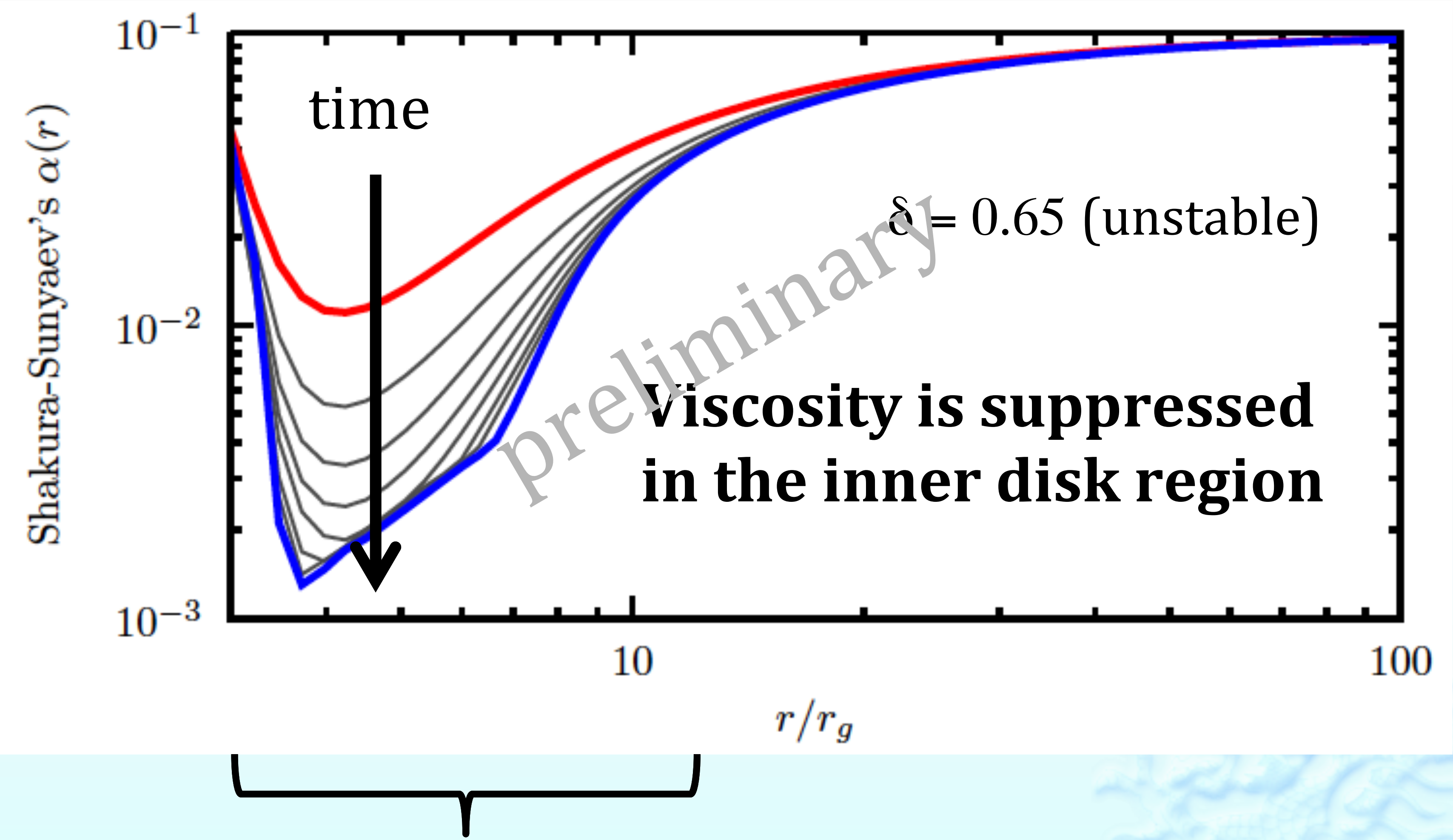
parameter

Assumption: $\alpha = \alpha_{\min} + (\alpha_{\max} - \alpha_{\min})\left(\frac{\mathrm{Pm}^{\bigcirc\!\!\!\!\delta}}{\mathrm{Pm}^{\delta} + 1}\right)$

$\alpha_{\min}=0.01$, $\alpha_{\max}=10$

time variation of α-viscosity

NK & Masada in prep.

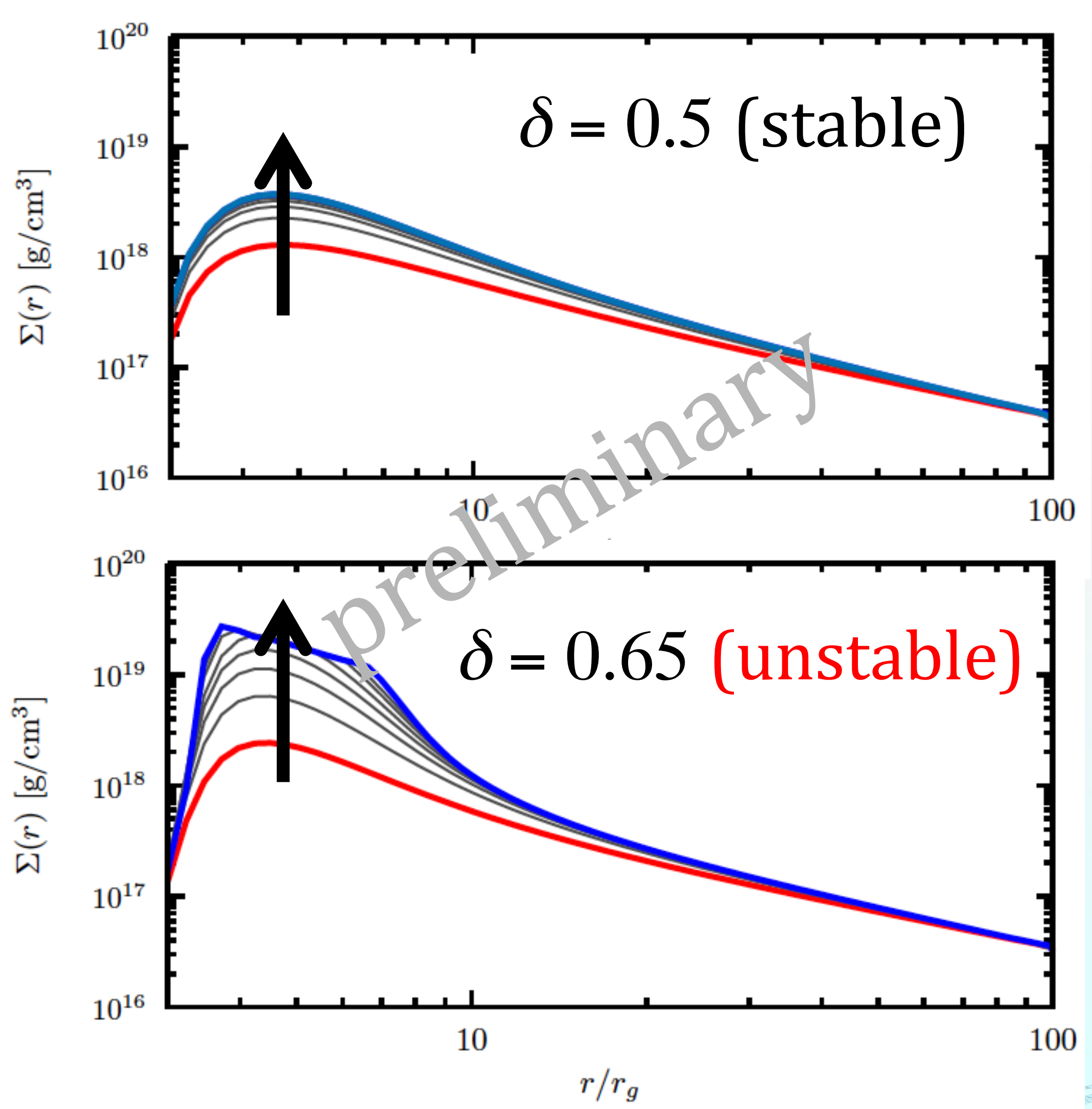


Viscosity is suppressed in the inner disk region

ν-thin cooling region

Evolution of the surface density

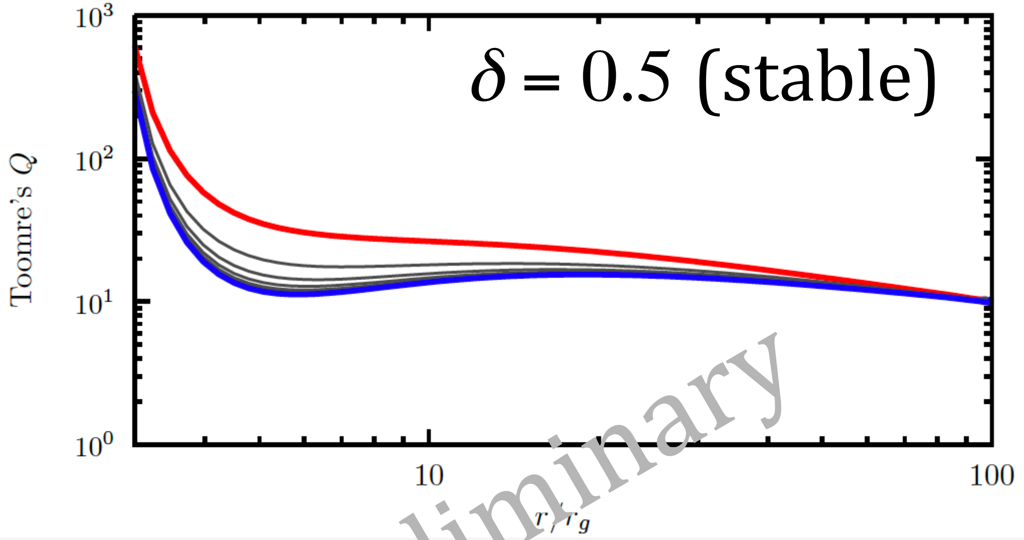
NK & Masada in prep.

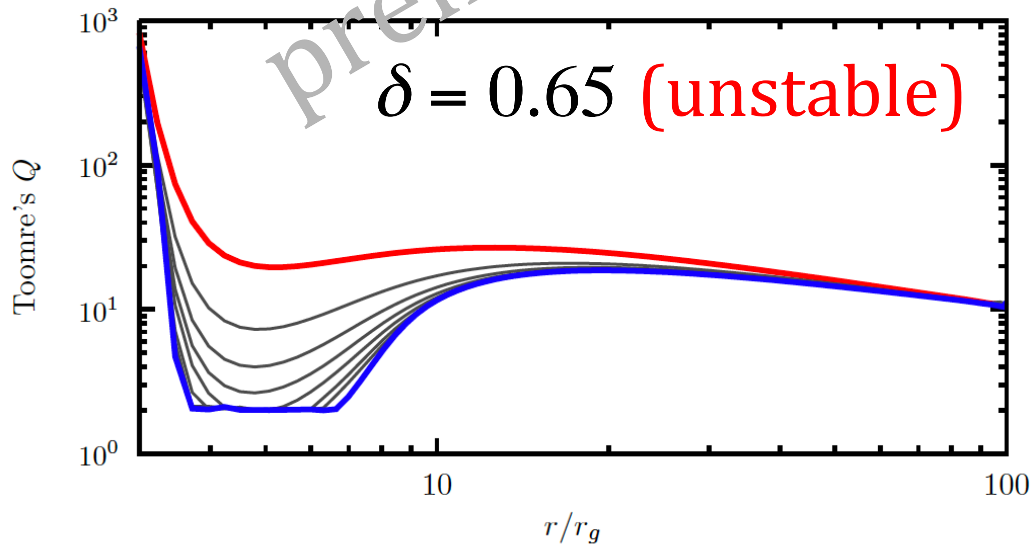


Viscosity is suppressed
→ Infalling matter is accumulated in the small-α region

Toomre's Q

NK & Masada in prep.





$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma}$$

When $Q < Q_{\rm crit}=2$, the disk becomes gravitationally unstable

→ non-axisymmetric patterns

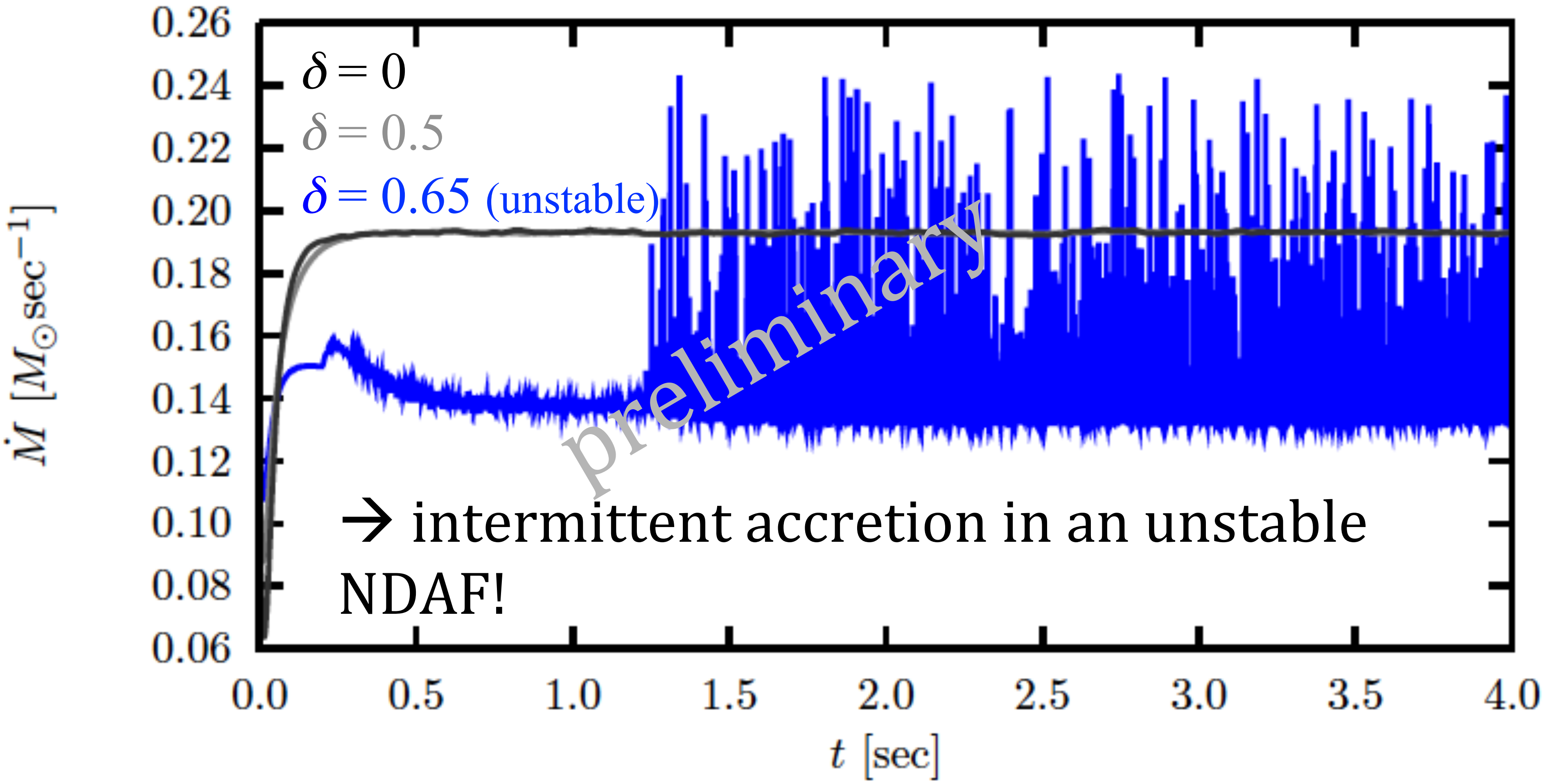
→ Outward angular momentum transport

→ Intense mass accretion

Assumption: $\alpha_{\rm grav} = 0.1\left(\frac{Q_{\rm crit}^2}{Q^2} - 1\right)$

mass accretion variability

NK & Masada in prep.



→ intermittent accretion in an unstable NDAF!

Summary

- Hyperaccretion flows as a central engine of GRBs

→ Neutrino-Dominated Accretion Flow (NDAF)

- A powerful jet may be driven by the MHD process resembling Blandford-Znajek mechanism when an accretion flow is efficiently cooled by neutrinos.
- Viscous instability: the origin of the short-term variability of GRBs?
- α-parameter is not always constant in an NDAF.
- An NDAF may become viscously unstable and mass accretion may be highly variable when it is neutrino thick (due to neutrino diffusion) or thin (due to degenerate electrons' viscosity/resistivity).