Dynamo processes in accretion disks and applications to AGN variabilities

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Transient Phenomena and Physical Processes Around Supermassive Black Holes
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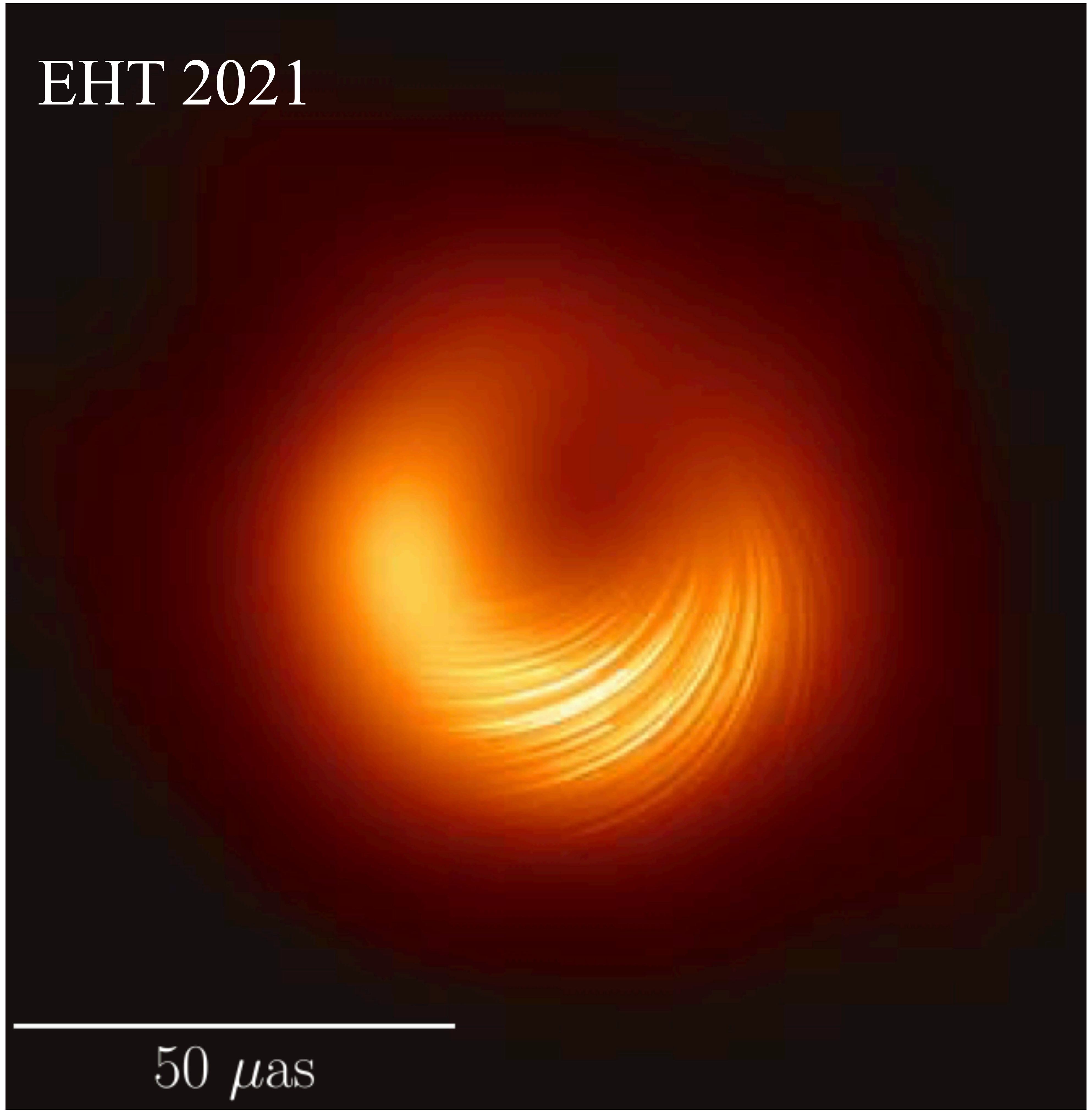
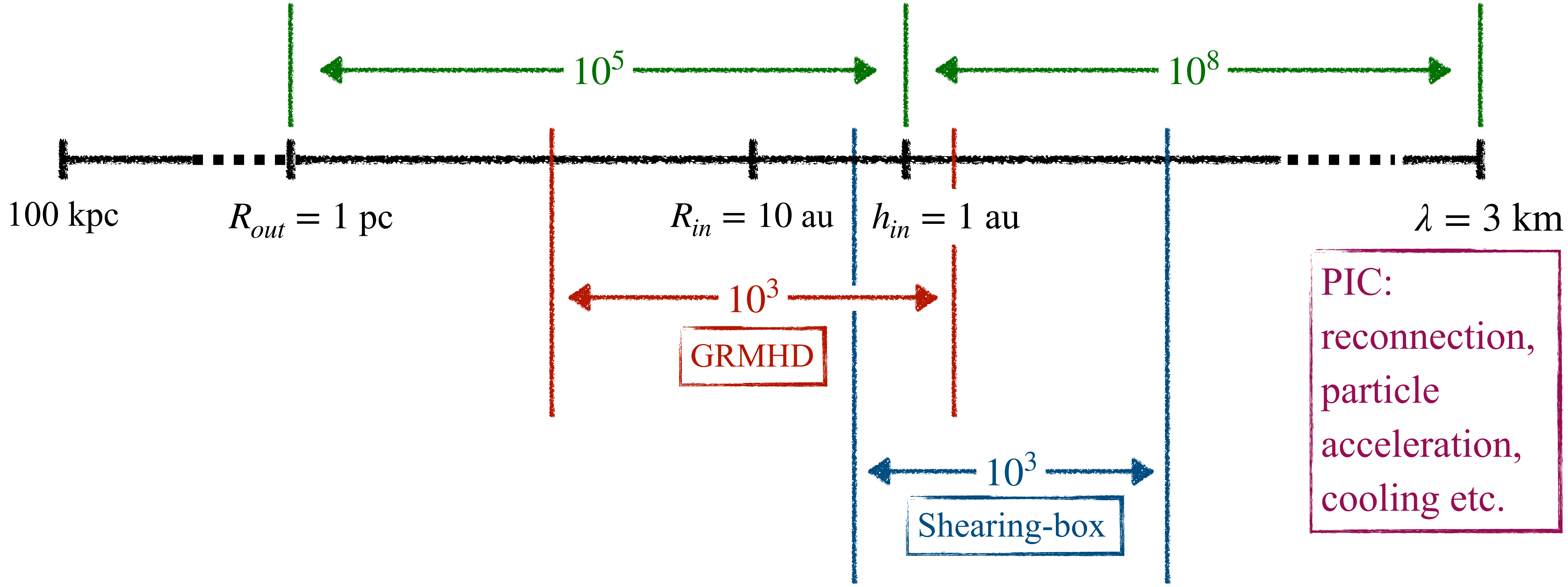
Coherent magnetic fields around SMBHs



Key questions

- Source: advected / *in situ*
- Long-term coevolution with accretion flow
- Observational consequences--jets, particle acceleration, polarization, ...

Ratios of scales in thin disks and difficulties in simulations



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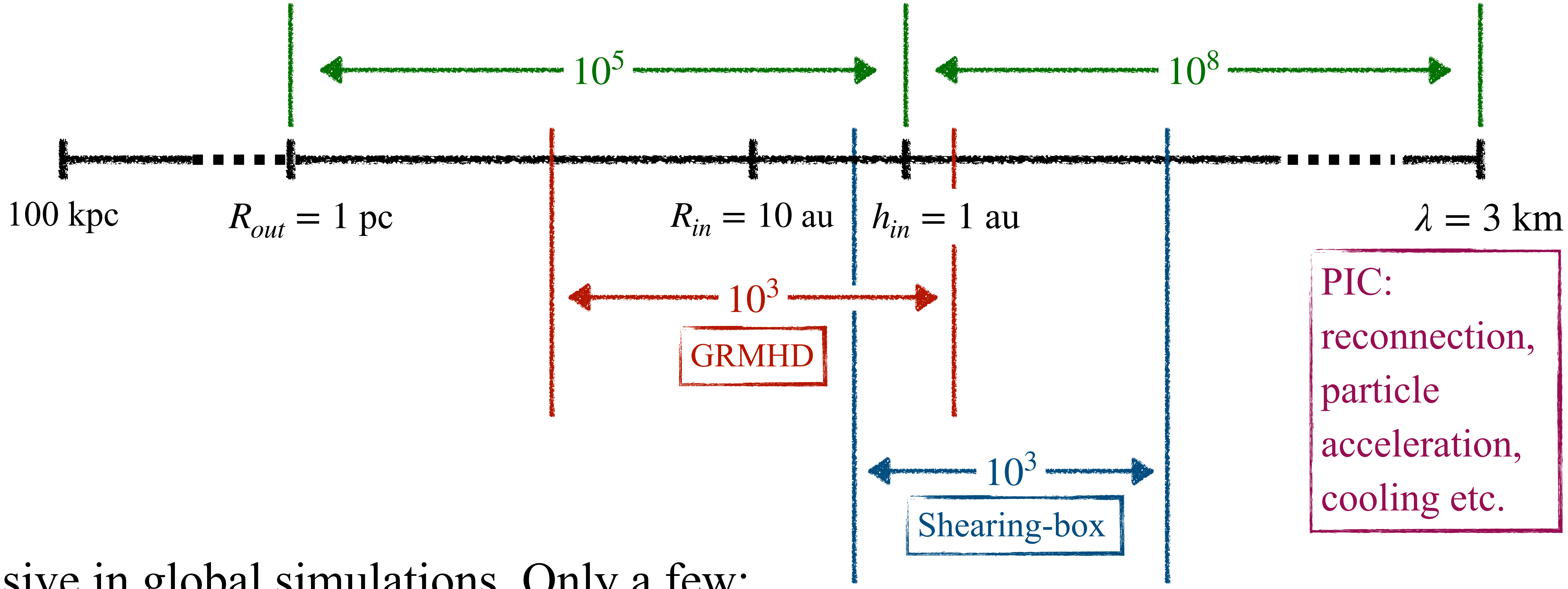

Expensive in global simulations. Only a few:

Hogg+Reynolds 16 (Newtonian), Rodman+Reynolds 24 (pseudo-Newtonian), Liska+20 (GR)

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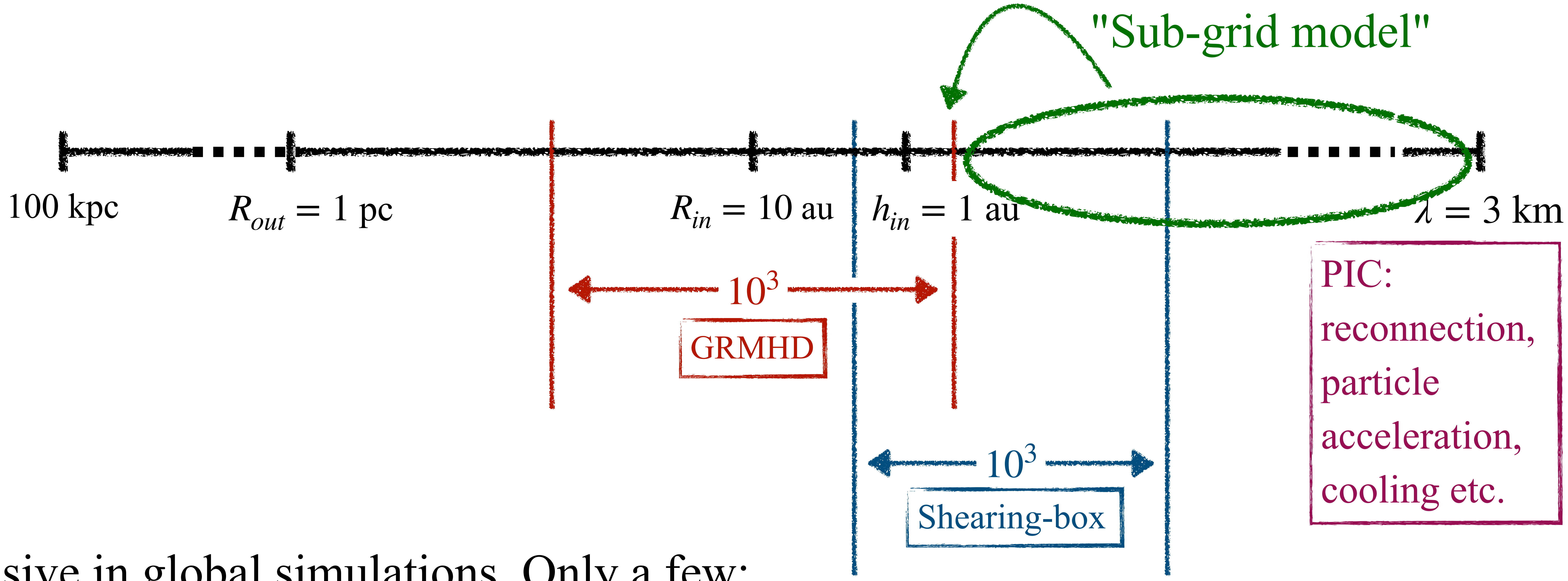

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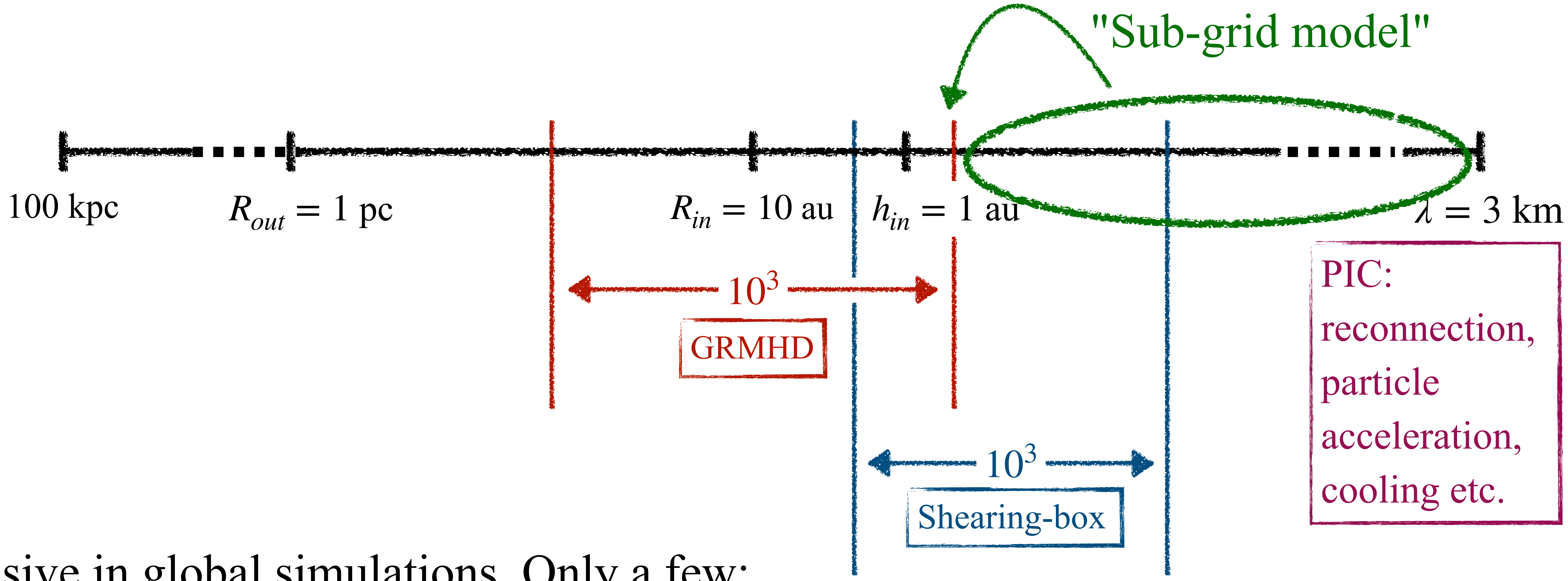

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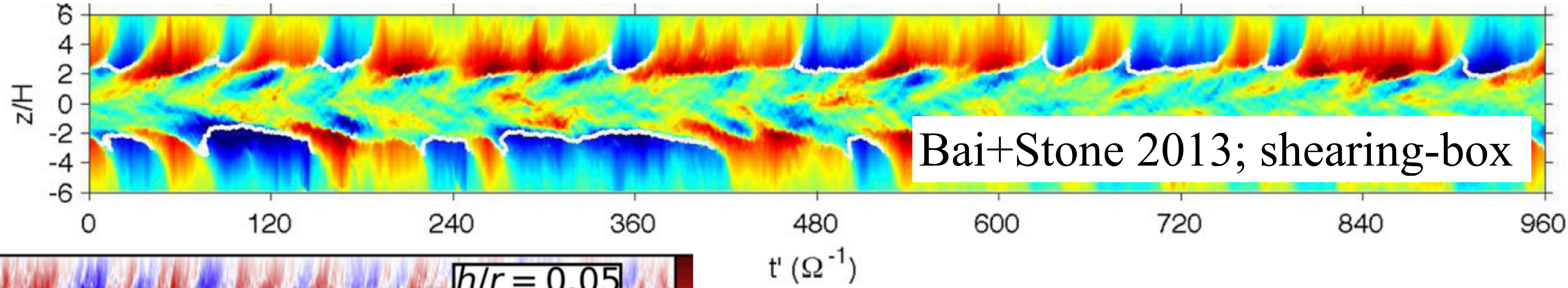
Hybrid approach uses shearing-box results as sub-grid models:

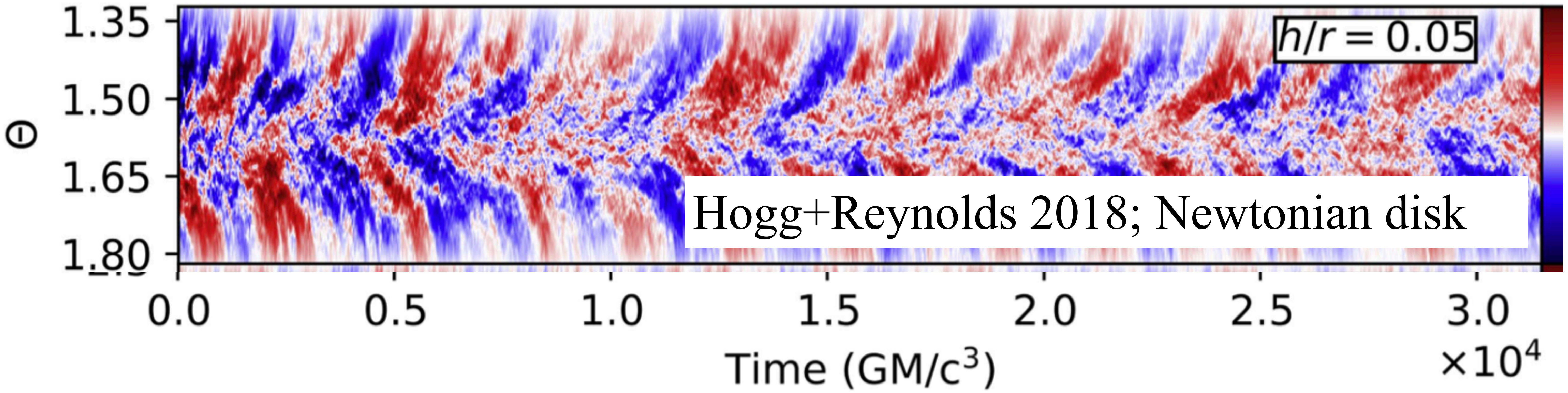
von Rekowski+03, Bucciantini+Del Zanna13, Bugli+14, Stepanovs+14, Sadowski+15, Dyda+18, Fendt+Gaßmann18, Tomei+20, Vourellis+Fendt21

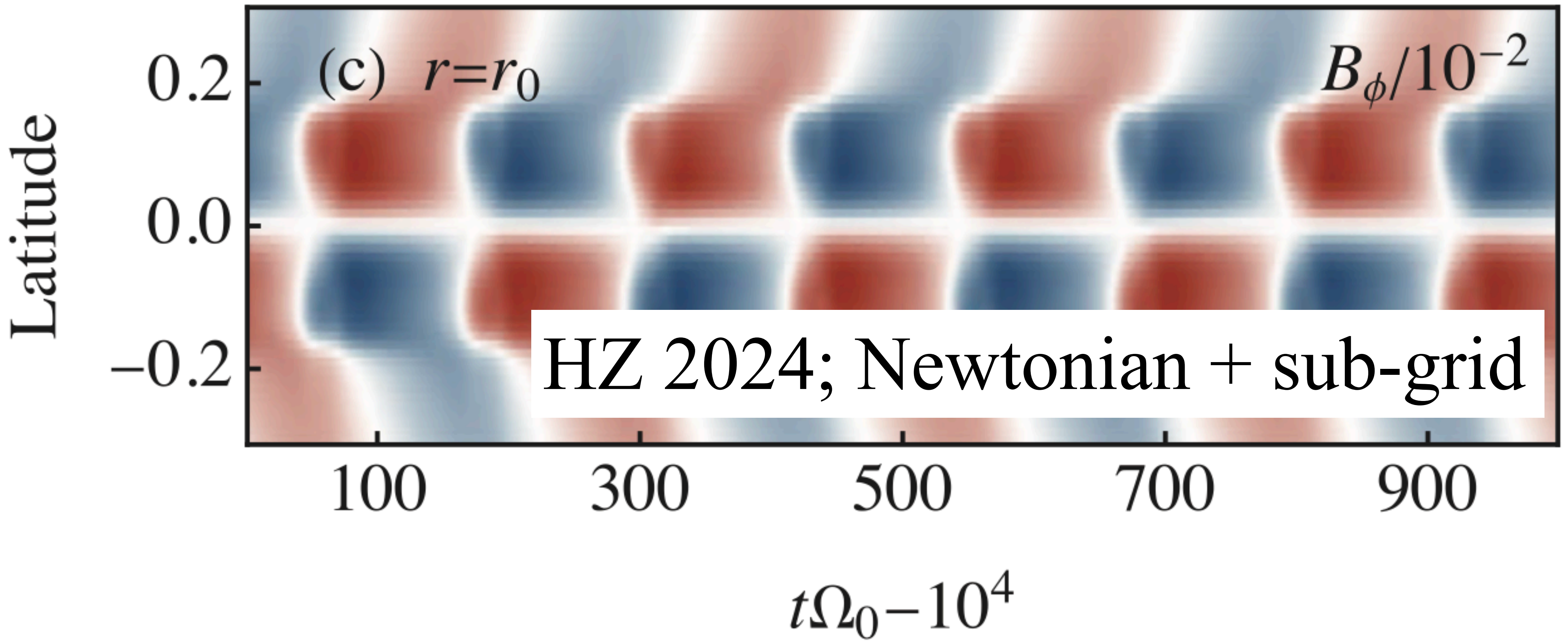
... and with self-consistent saturation: **HZ24**

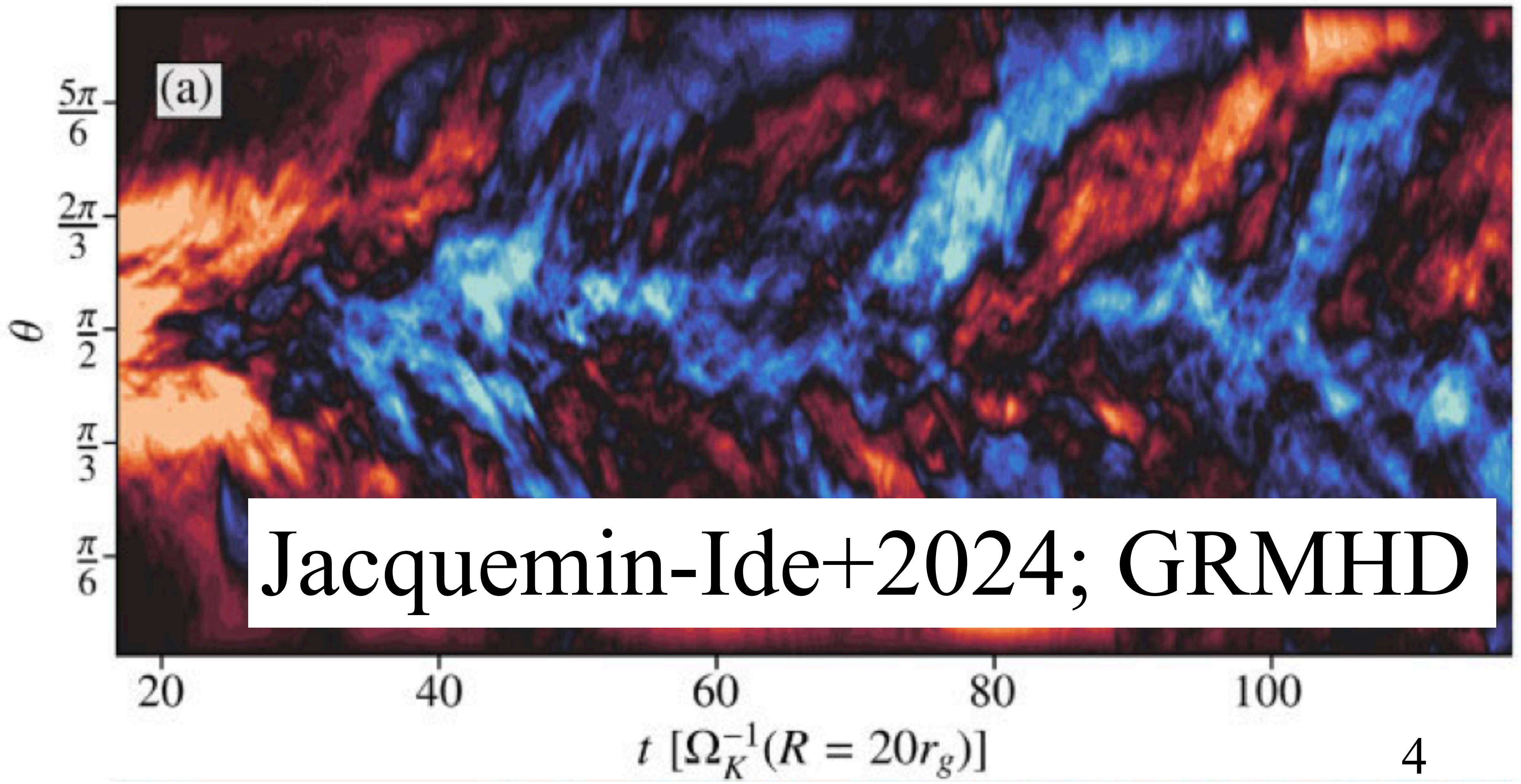
Large-scale magnetic fields from simulations

- At given radius, $B_\phi(t, z)$



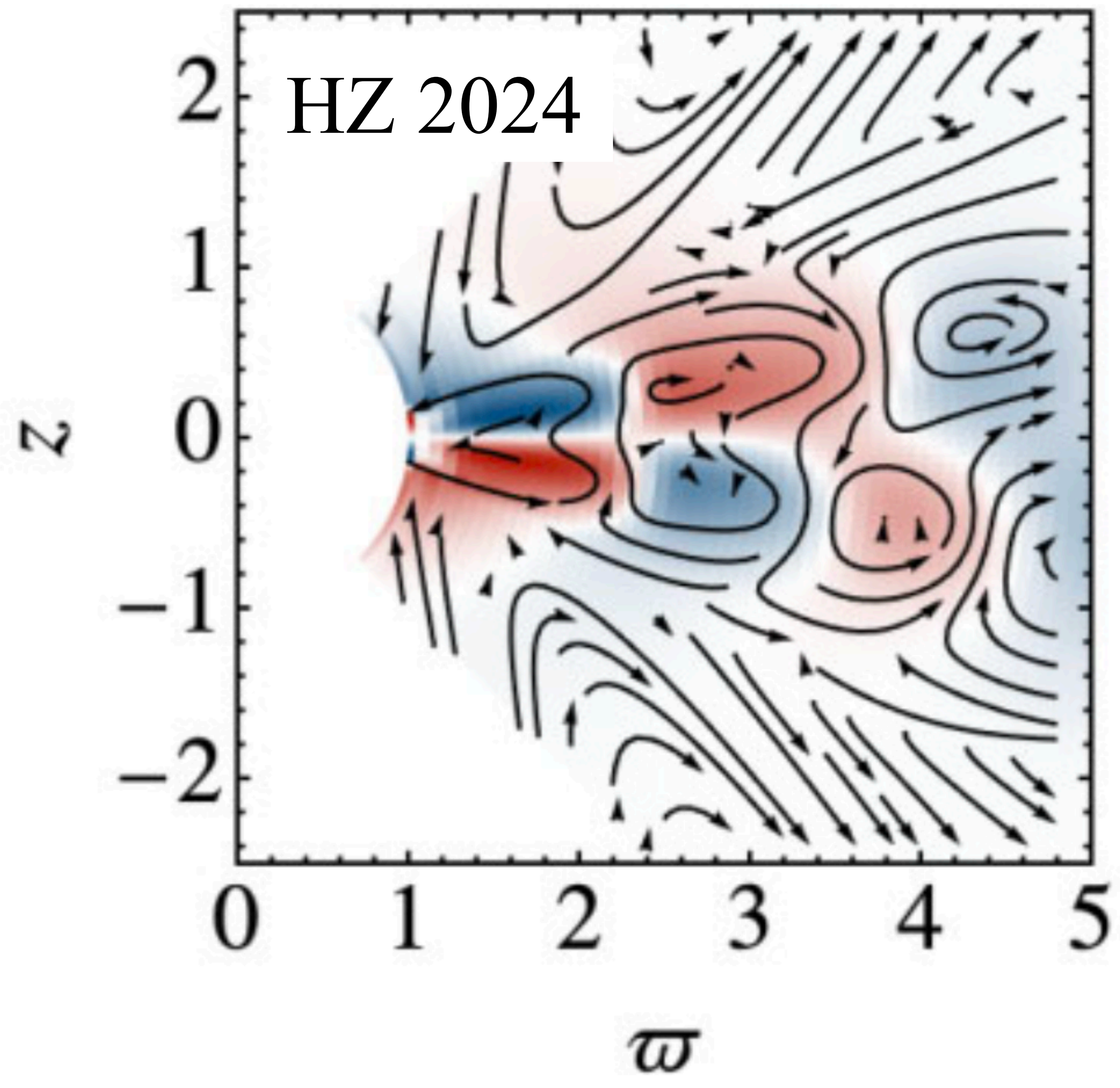


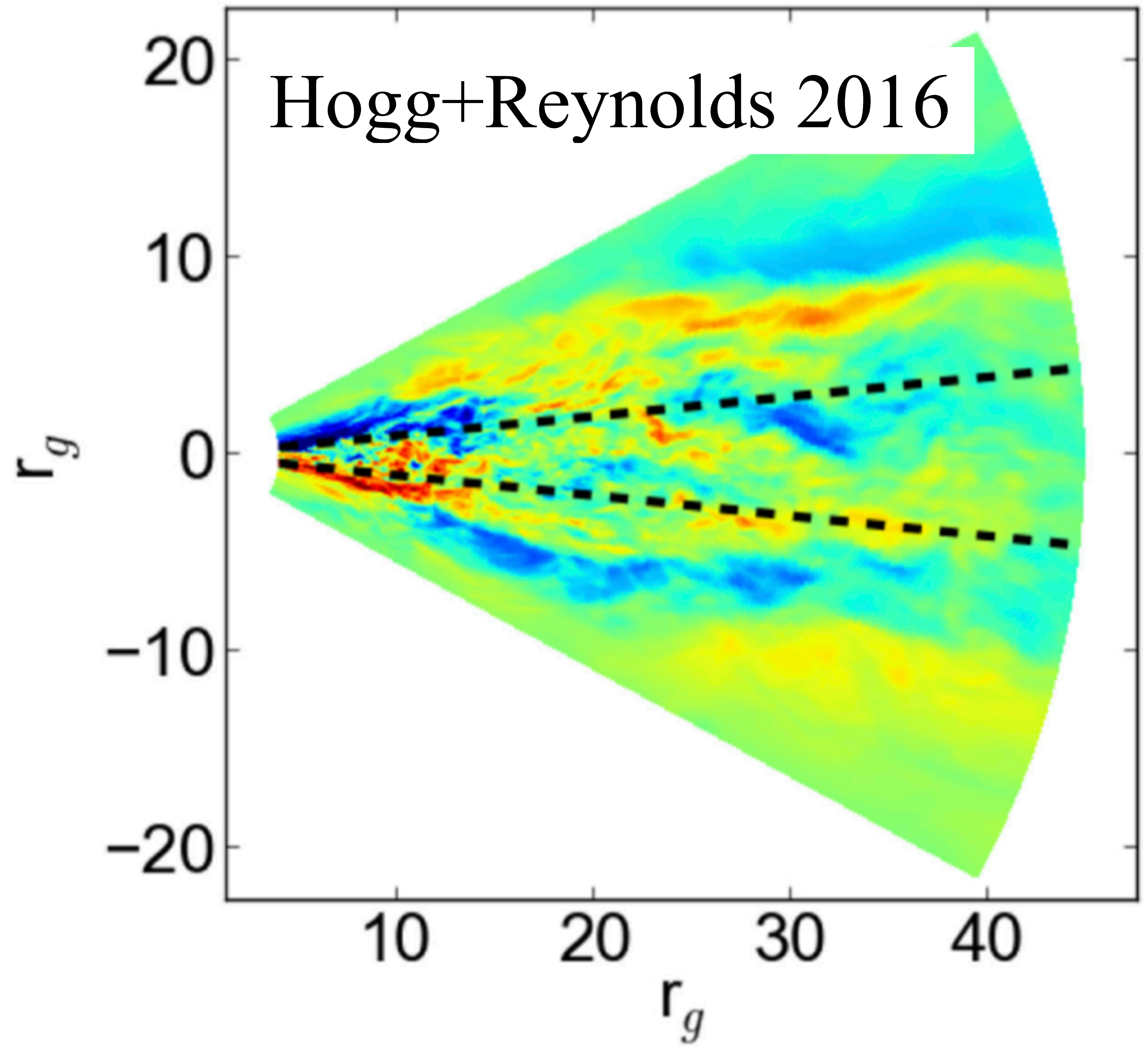


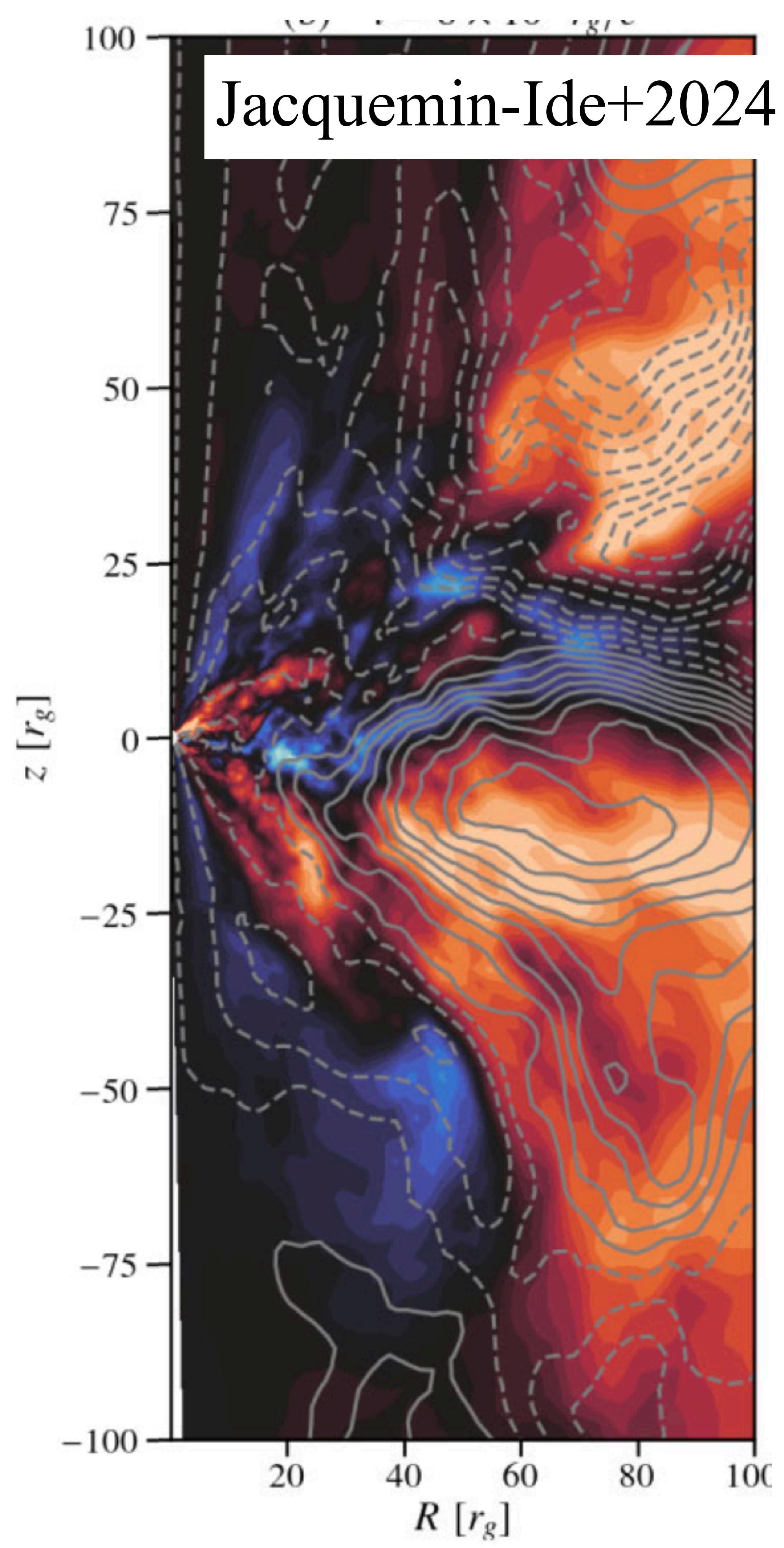


Large-scale magnetic fields from simulations

- At given snapshot, $B_\phi(r,\theta)$







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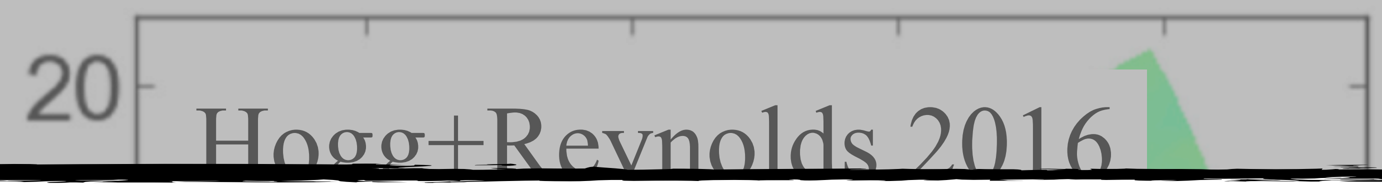
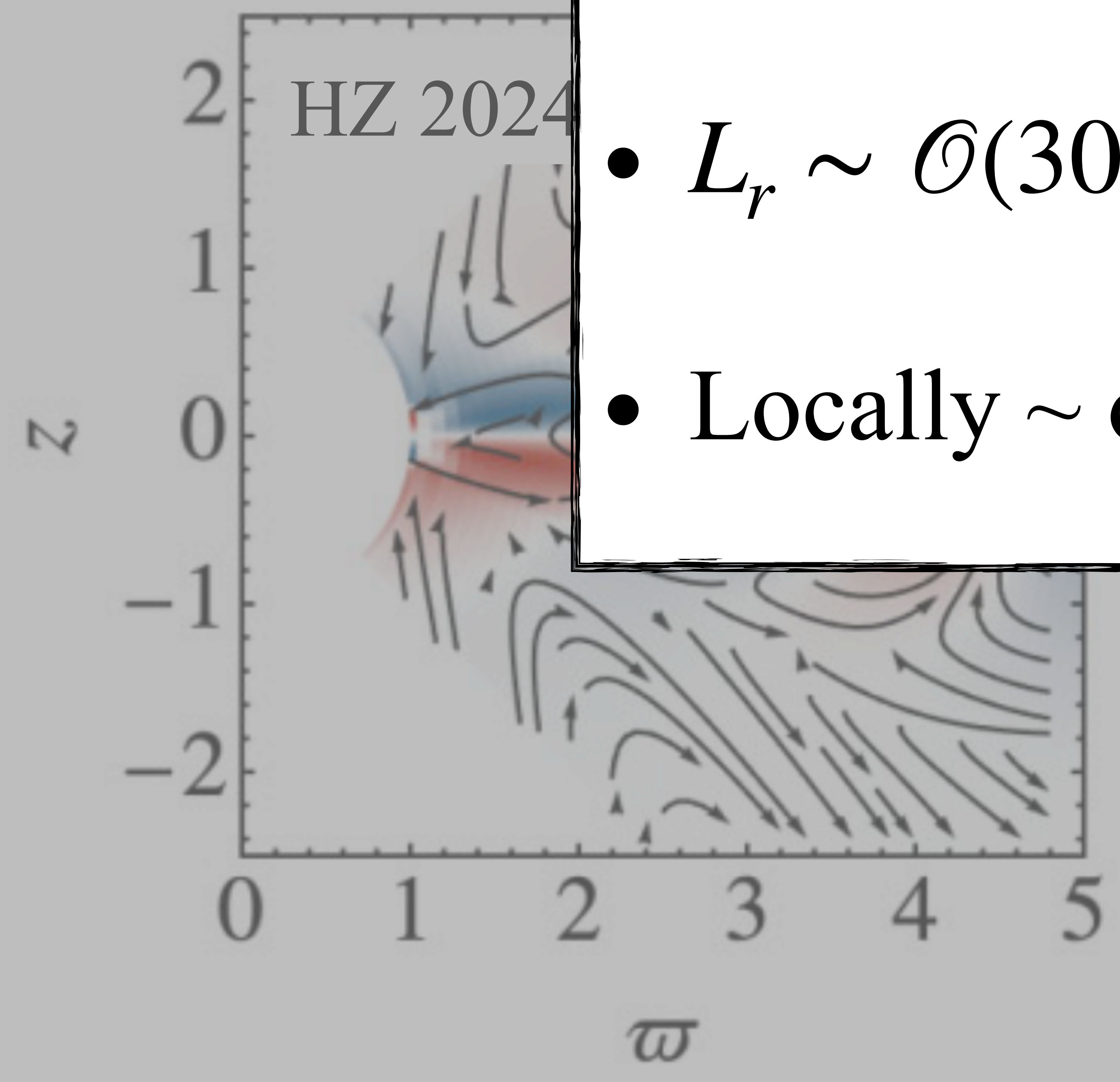
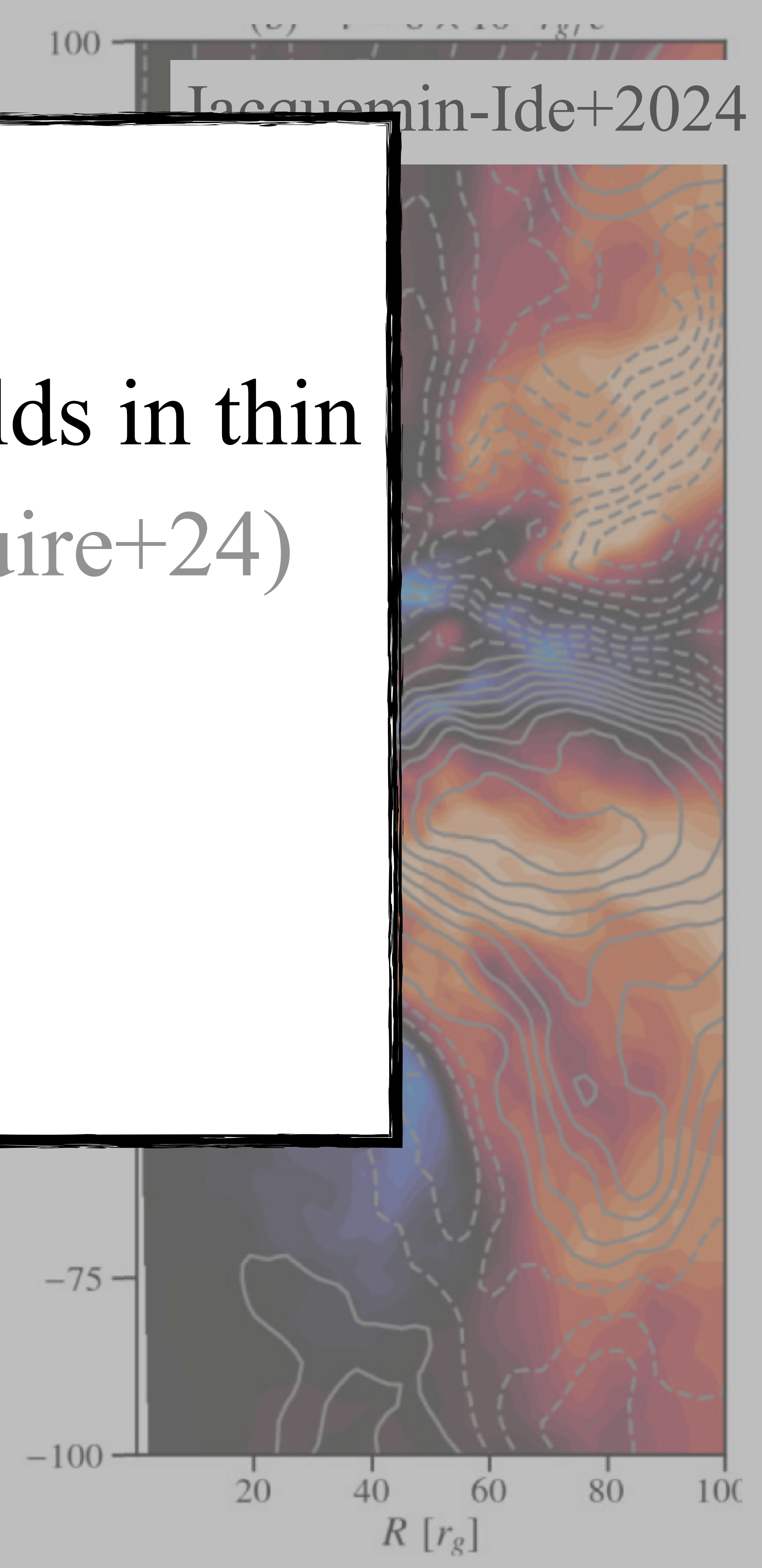




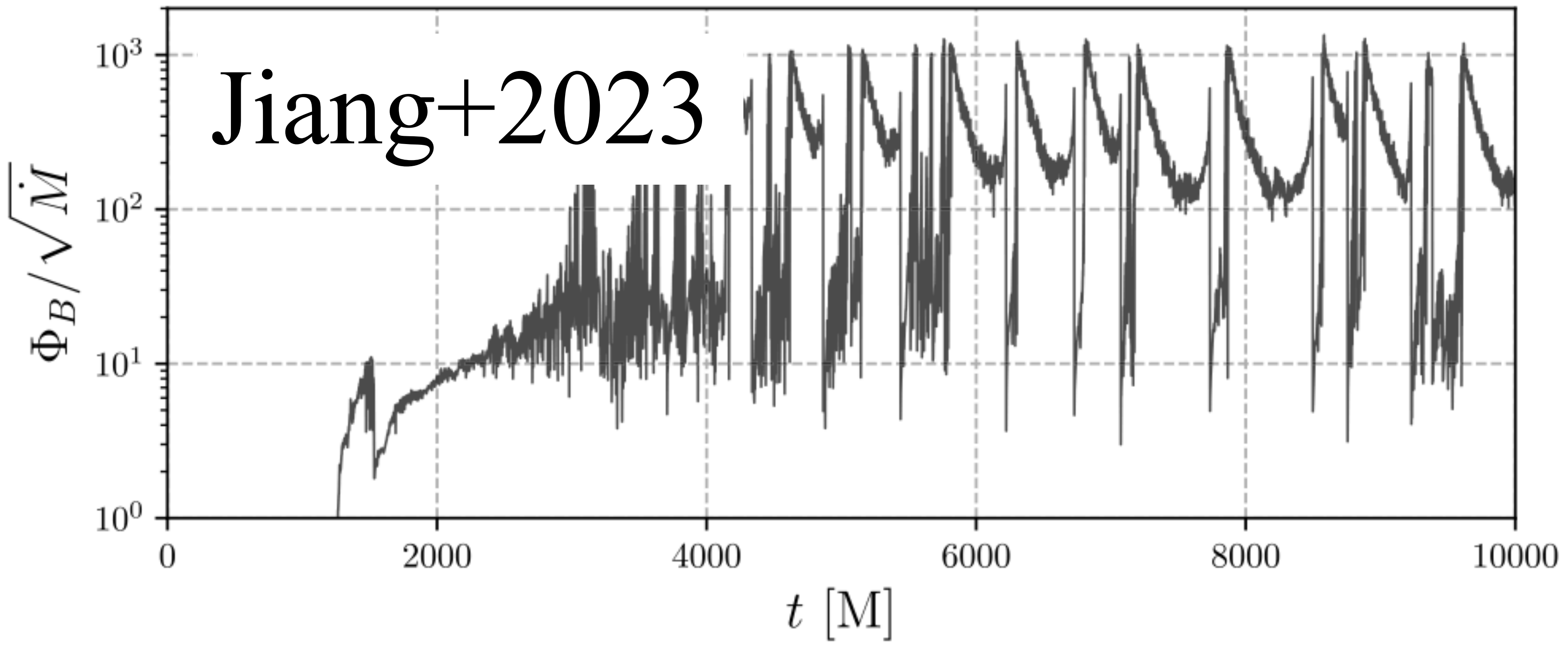


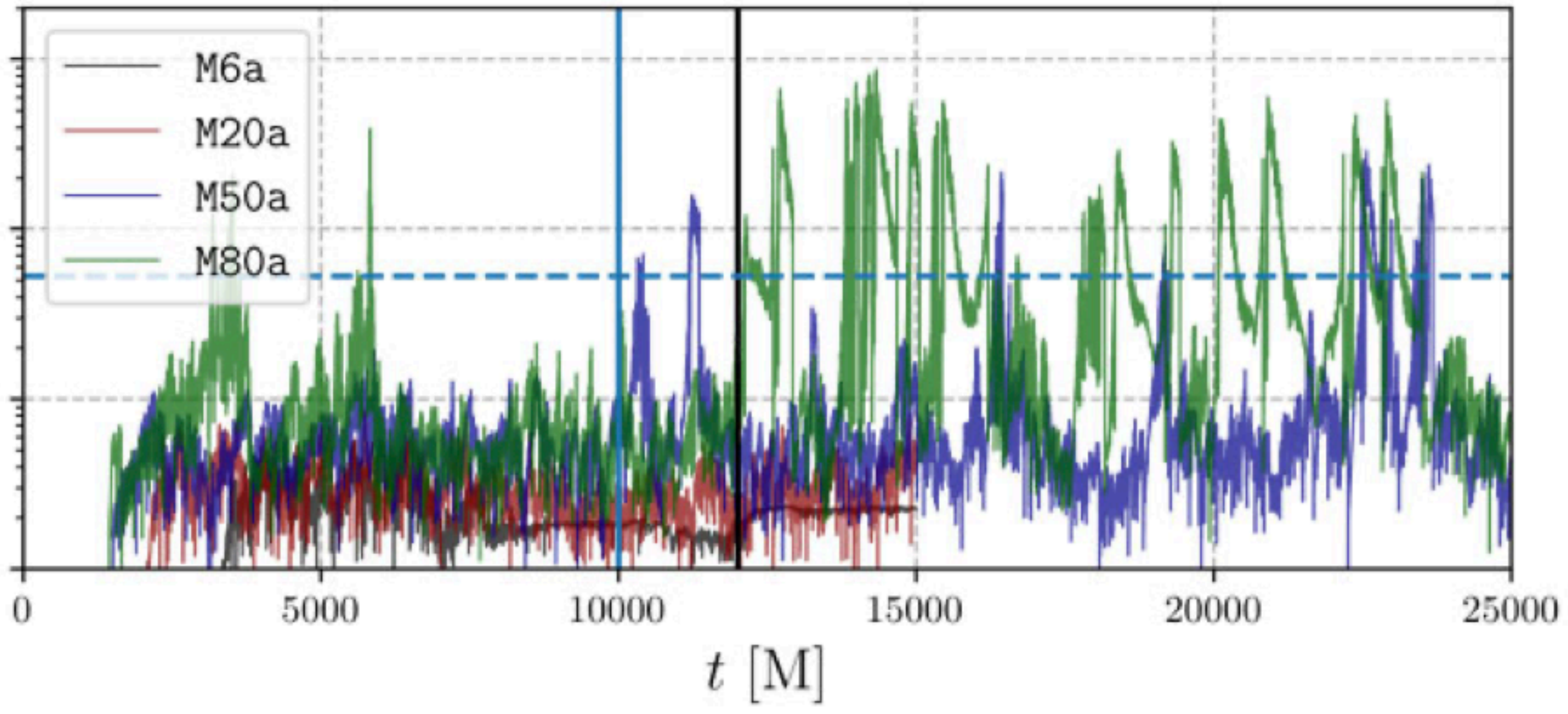
<u>What do we learn:</u>

- MRI turbulence is able to produce large-scale fields in thin disks with **<u>alternating polarities</u>** (thick disk: Squire+24)
- $L_r \sim \mathcal{O}(30h)$, $L_h \sim h$, $P \sim \mathcal{O}(30\Omega^{-1})$
- Locally ~ outgoing waves, $B \sim \sin(t/P - r/L_r)$

Consequences of quasi-periodic large-scale magnetic fields

- Jet launching -- accumulation of net flux?



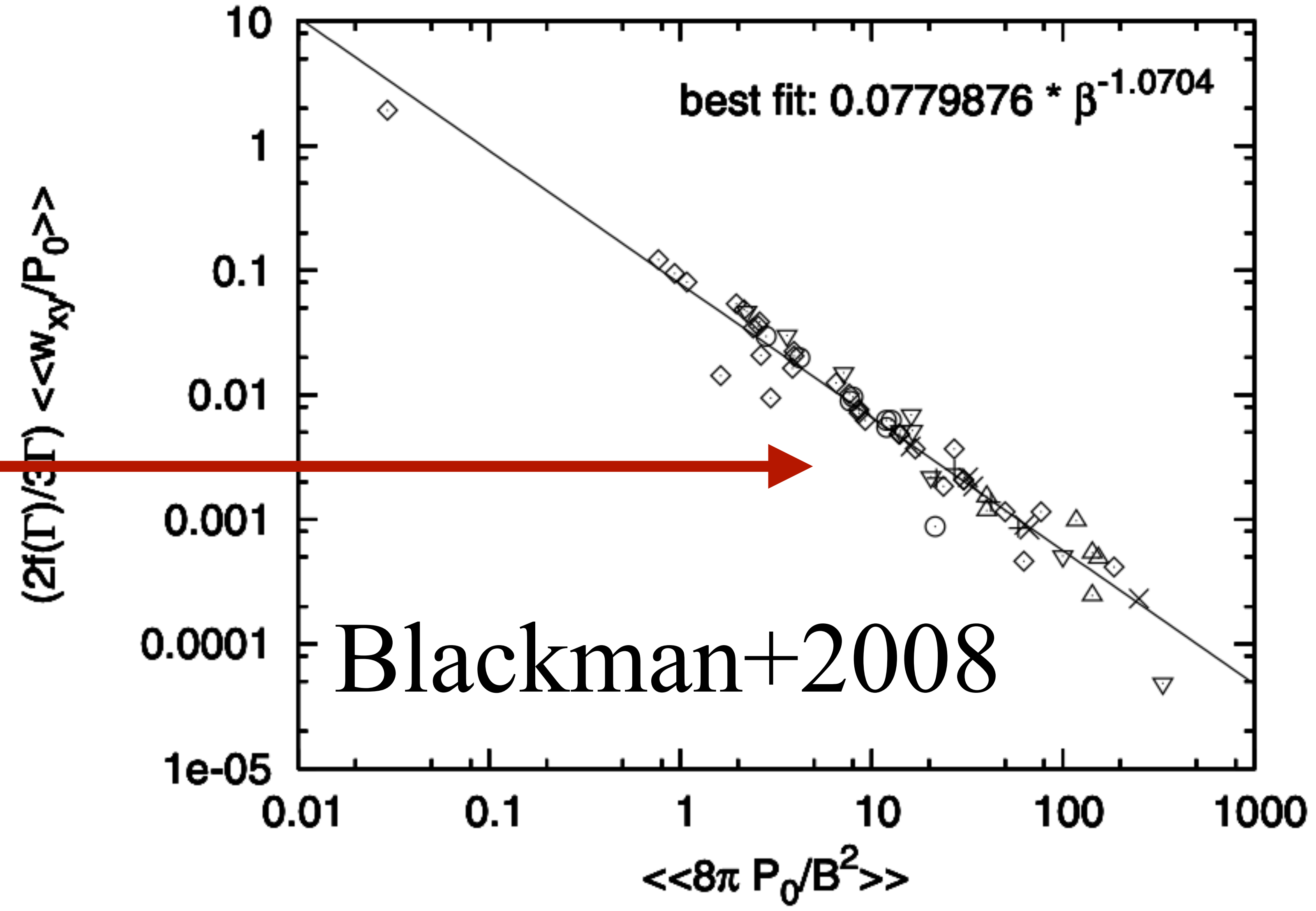


Different init. cond.: Uniform polarity → MAD Alternating polarity → SANE

- **<u>Inducing variability in $\dot{M}$?</u>** (HZ+Lai *in prep.*)

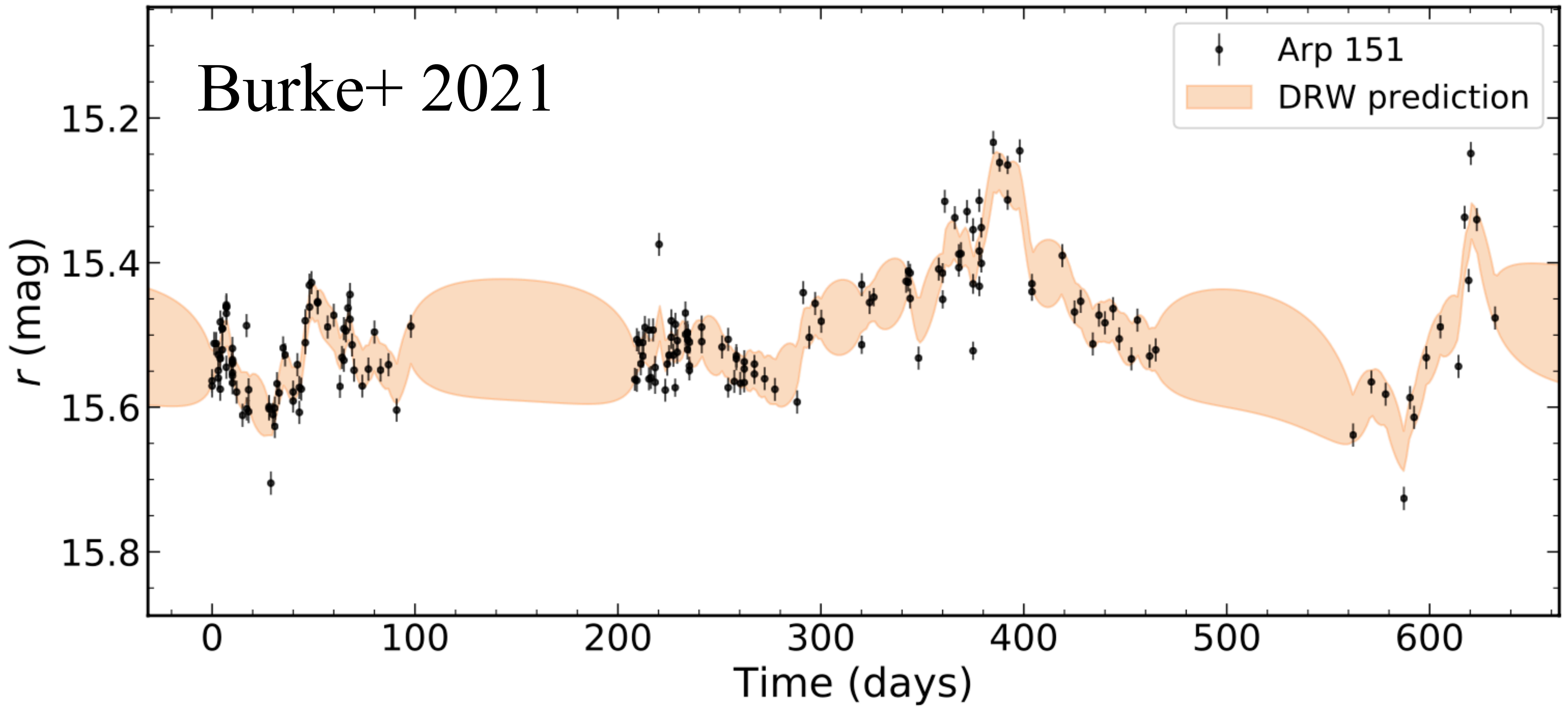
Empirical relation from shearing boxes:

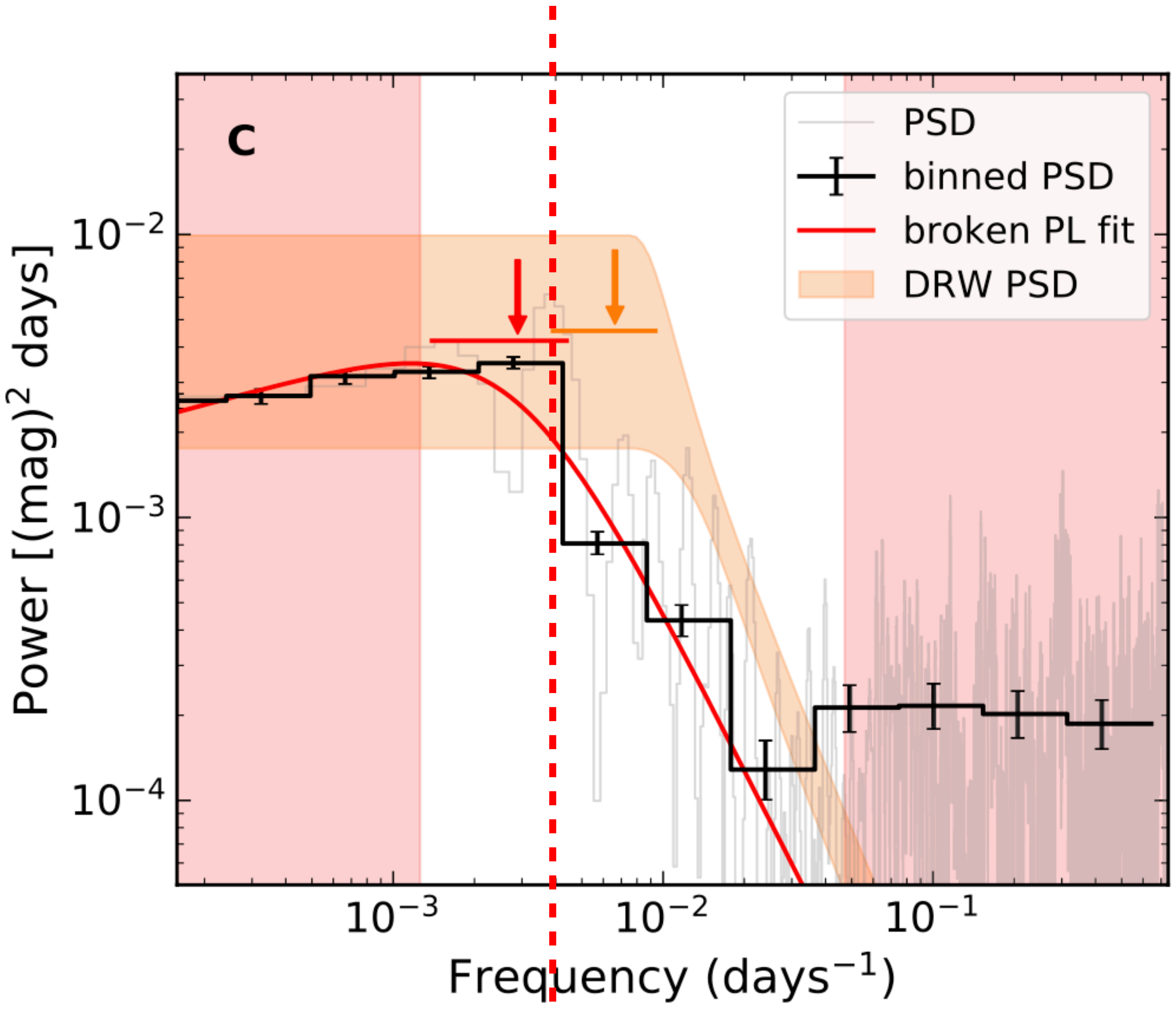
$\alpha \propto \beta_{sat}^{-1}$



*turbulent viscosity $\nu_T = \alpha c_s h$

AGN UV/optical variabilities - light curve & PSD





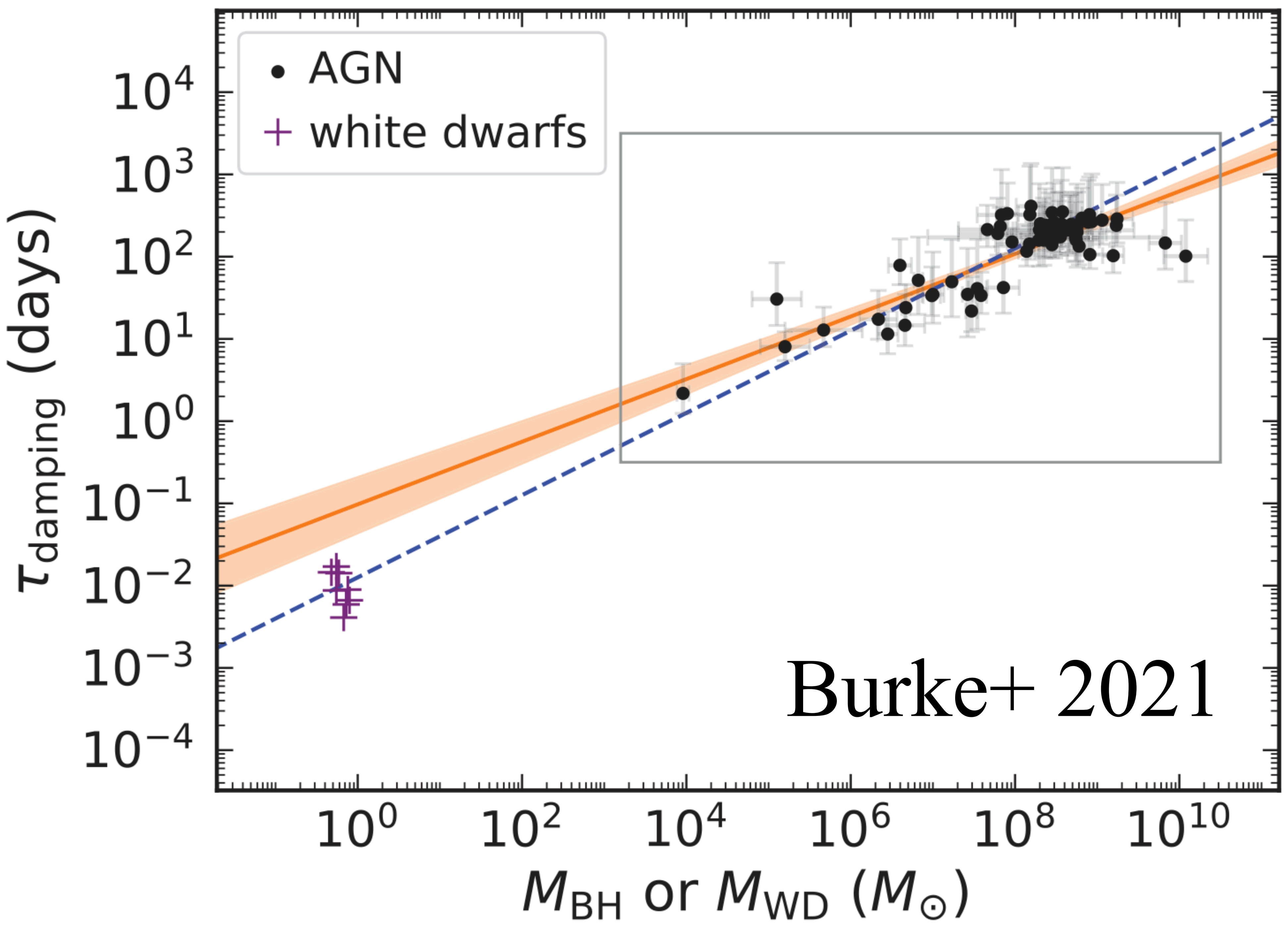
Well fitted by a

<u>"damped random walk" (**DRW**)</u>

process [e.g., $\partial_t F$ = (random walk...) $-F/\tau_d$]

$f_{crit} = 1/\tau_d$

AGN UV/optical variabilities - Scalings



- $\tau_d \propto L^a (1+z)^b \lambda^c M_{BH}^d$

  a, b: consistent with 0 (MacLeod+2010)

  $c = 0.17 \pm 0.02$ (MacLeod+2010)

  $d = 0.38^{+0.05}_{-0.04}$ (Burke+2021)

- **Caveat**: too short baselines underestimates τ_d

  Unbiased sample gives $\tau_d \propto L^{0.72} \lambda^{1.19}$ (Ren+24)

- Scalings not well-understood. Hints:

  (i) $\sim \propto M^{0.5}$ even for sBHs, WDs, YSOs →

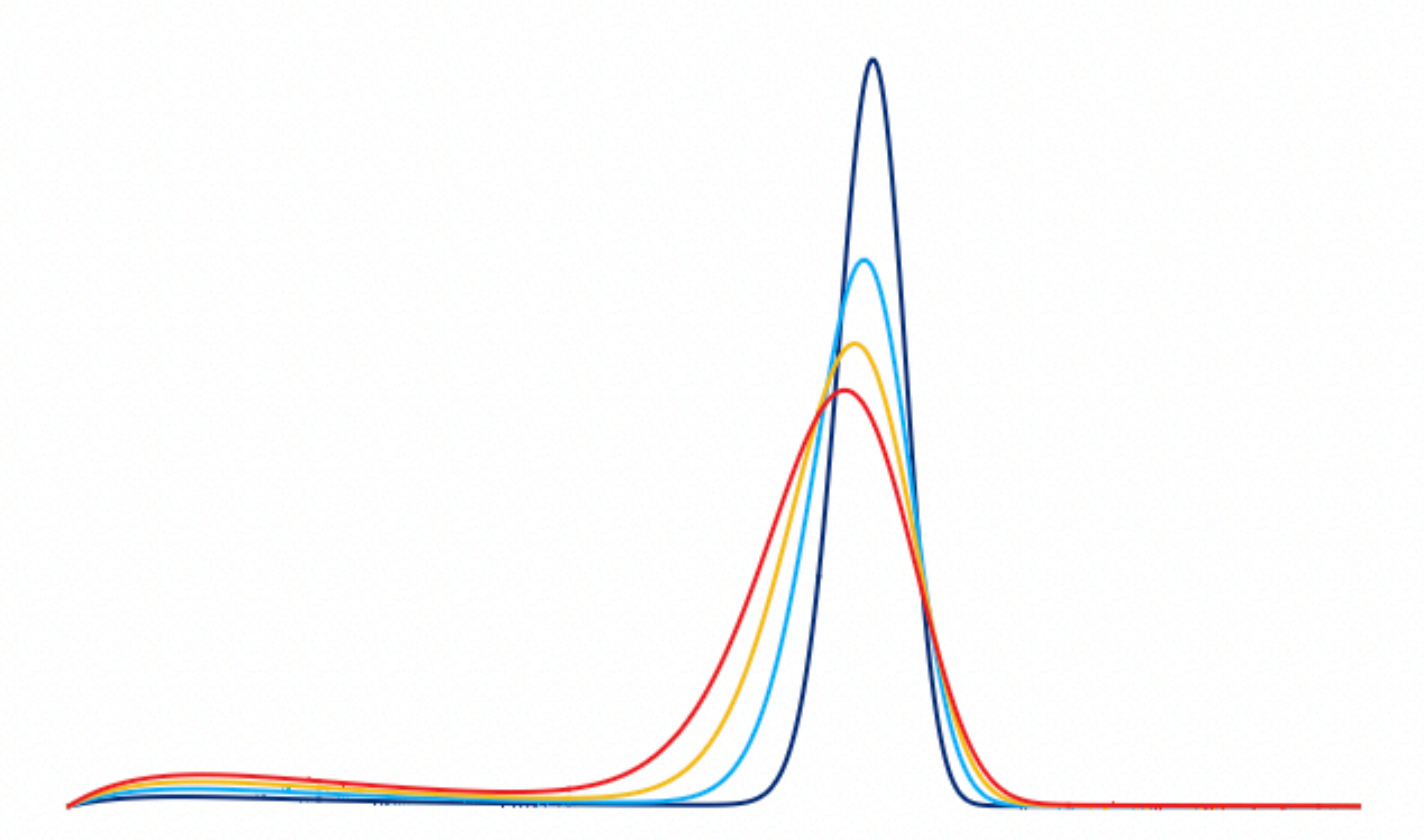
  universal, from disks & non-GR

  (ii) DRW also in sub-mm & X ray →

  magnetic activity?

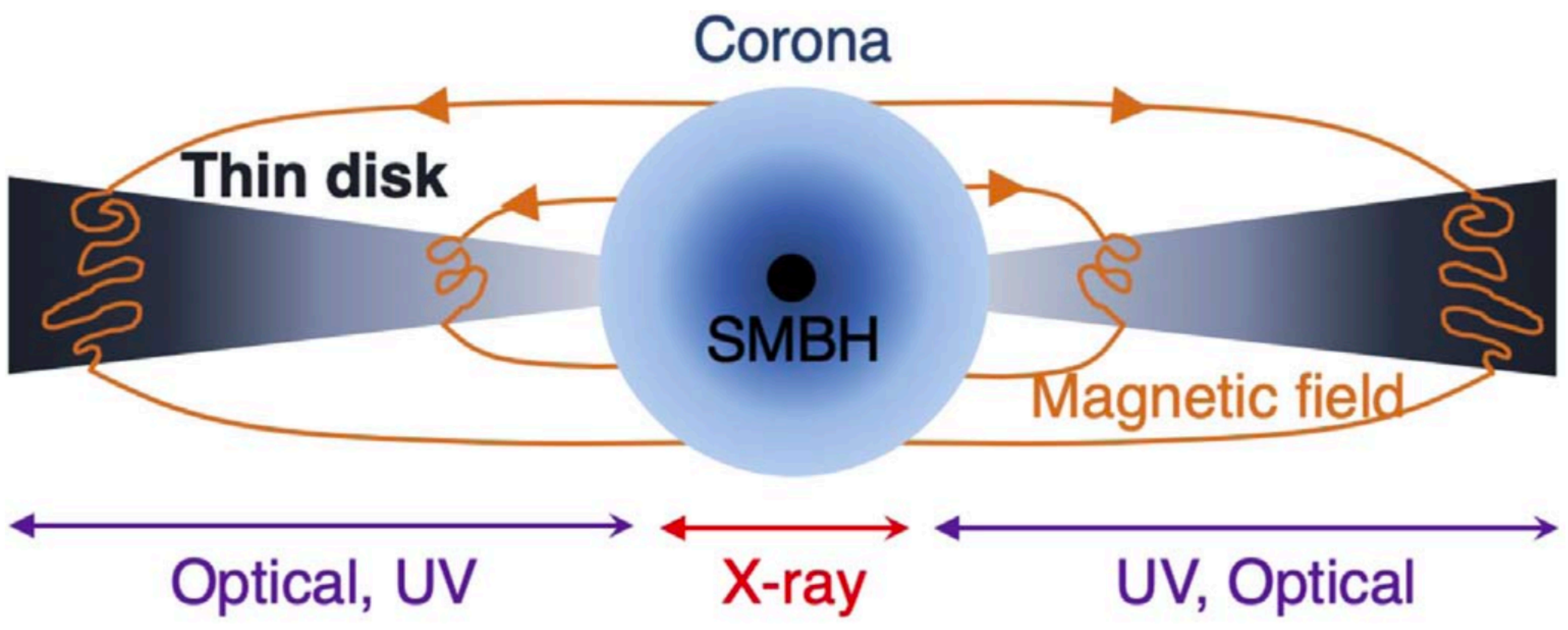
AGN UV/optical variabilities - Models

- Photon at λ comes from a single ring:
  Since $\lambda \propto T^{-1} \propto (M\dot{M}/r_\lambda/r_\lambda^2)^{-1/4} \Rightarrow \tau_d \propto \tau_{Kep}(r_\lambda) \propto \dot{M}^{1/2}\lambda$
  $\rightarrow$ c.f. $M^{0.38}\lambda^{0.17,1.19}$



- Lyubarskii 1997: spatially uncorrelated fluctuations.
  Propagation & accumulation $\rightarrow$ PSD($\dot{M}$) ~ $1/f$

- Corona-Heated Accretion-disk Reprocessing (CHAR, Sun+2020):
  disk heated by variabilities of corona
  (<u>assumed</u> to ~ $1/f$)

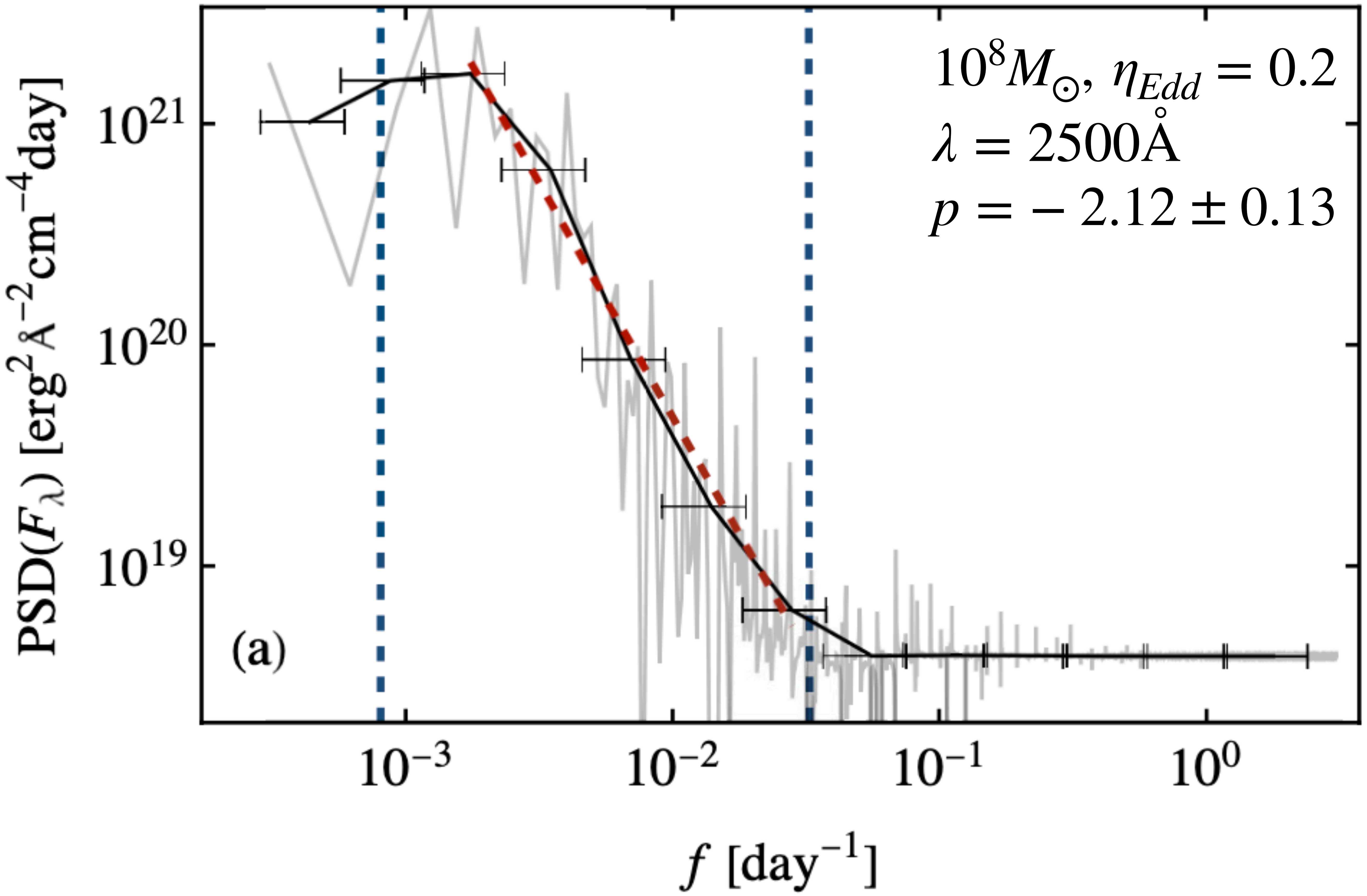


Brief overview of our model...

- **Input physics:** periodic dynamo fields inducing α perturbations
- **Method**: 1D geometrically thin optically thick disk
- **Output:** DRW-like PSDs of $\dot{M}$ and thermal emission
- **What we can explain:** weak dependence of τ_d v.s. λ, partially τ_d v.s. M
- **What we cannot explain:** soft lag, τ_d v.s. M at $M \lesssim 10^6 M_\odot$
- **What we further need:** + reprocessing models

Providing DRW-process fluctuations ($\dot{M}$) with non-DRW physics (dynamo)

Reproducing DRW-like PSDs

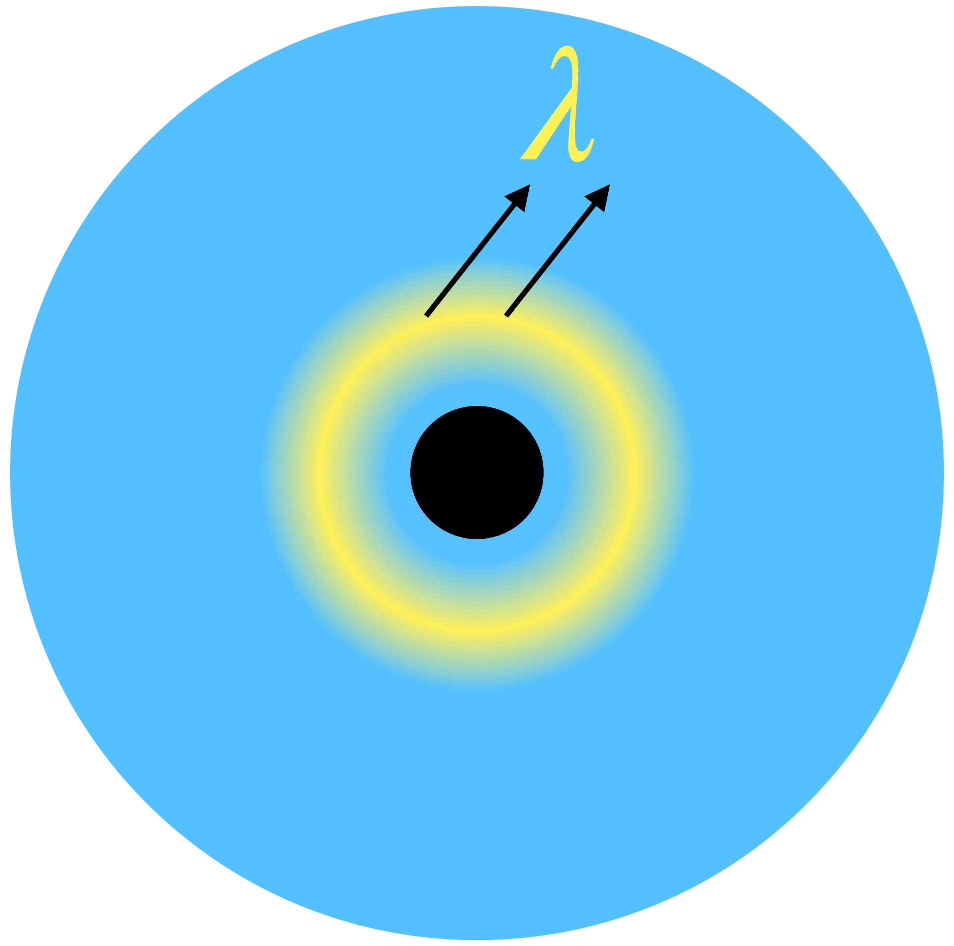


Wave-like fluctuations yield **DRW-like** variability

Understanding:

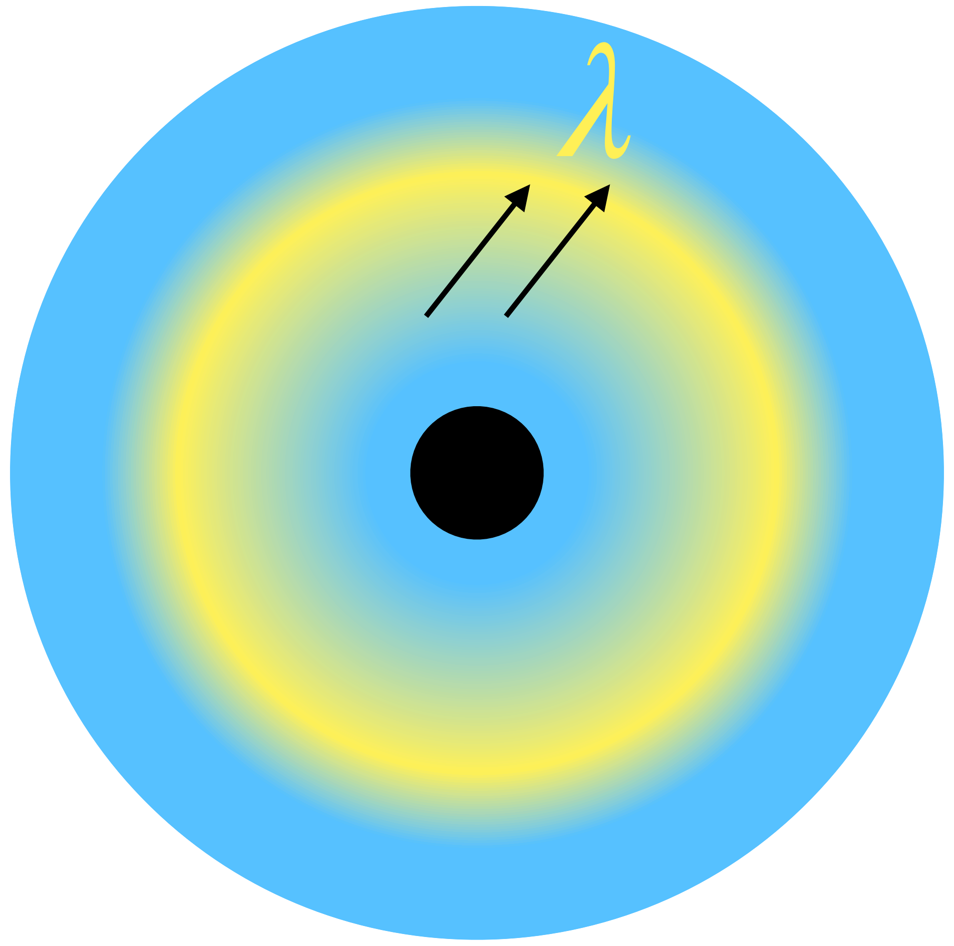
- flat low-f: multiplicative fluc.
- -2 slope high-f: random walk?
- τ_{damp}: inner radius of the emitting region

Understanding λ dependence



Short-λ from rings:

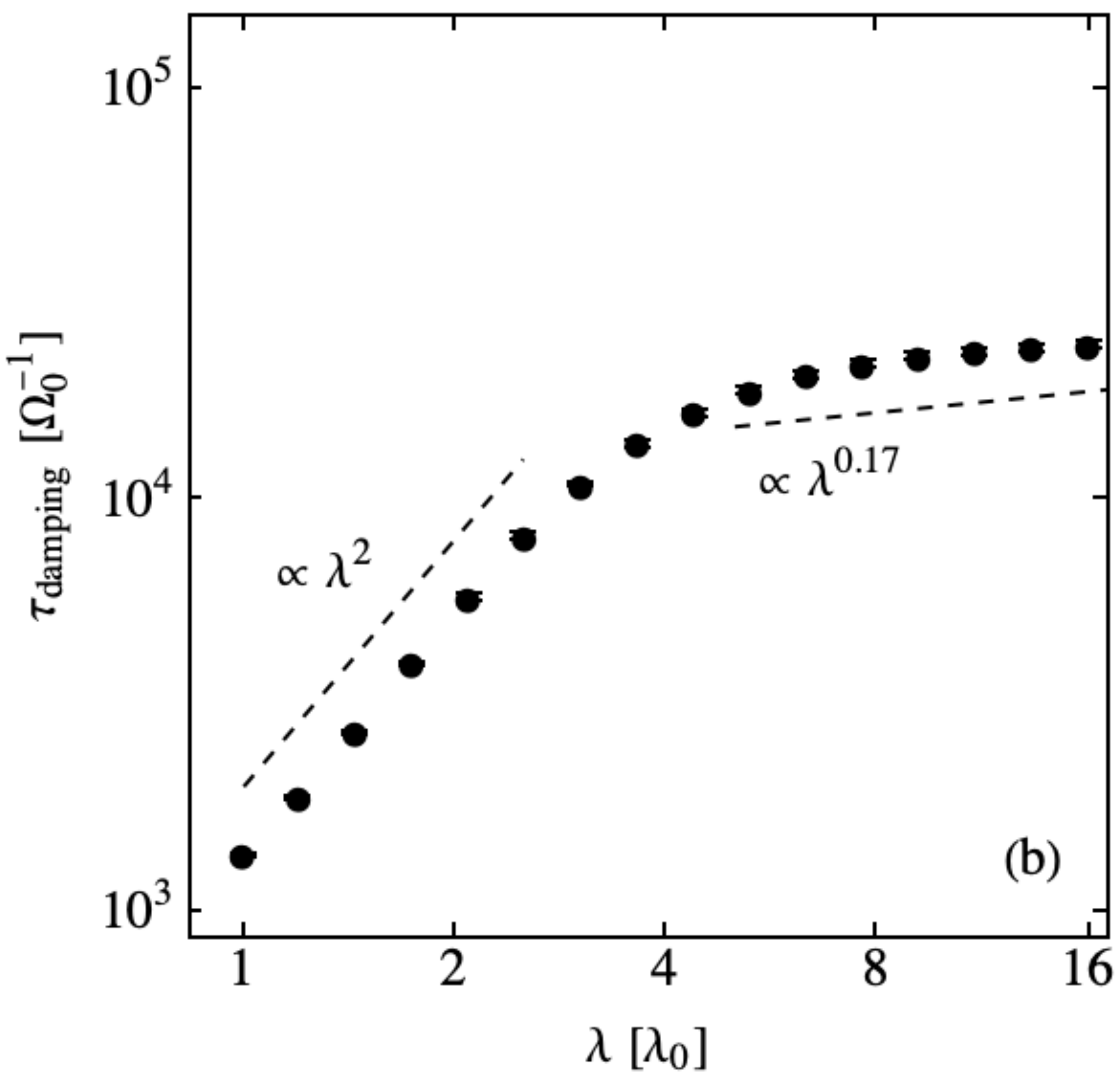
$\tau \propto \tau_{Kep}(R_\lambda) \propto \lambda^2$

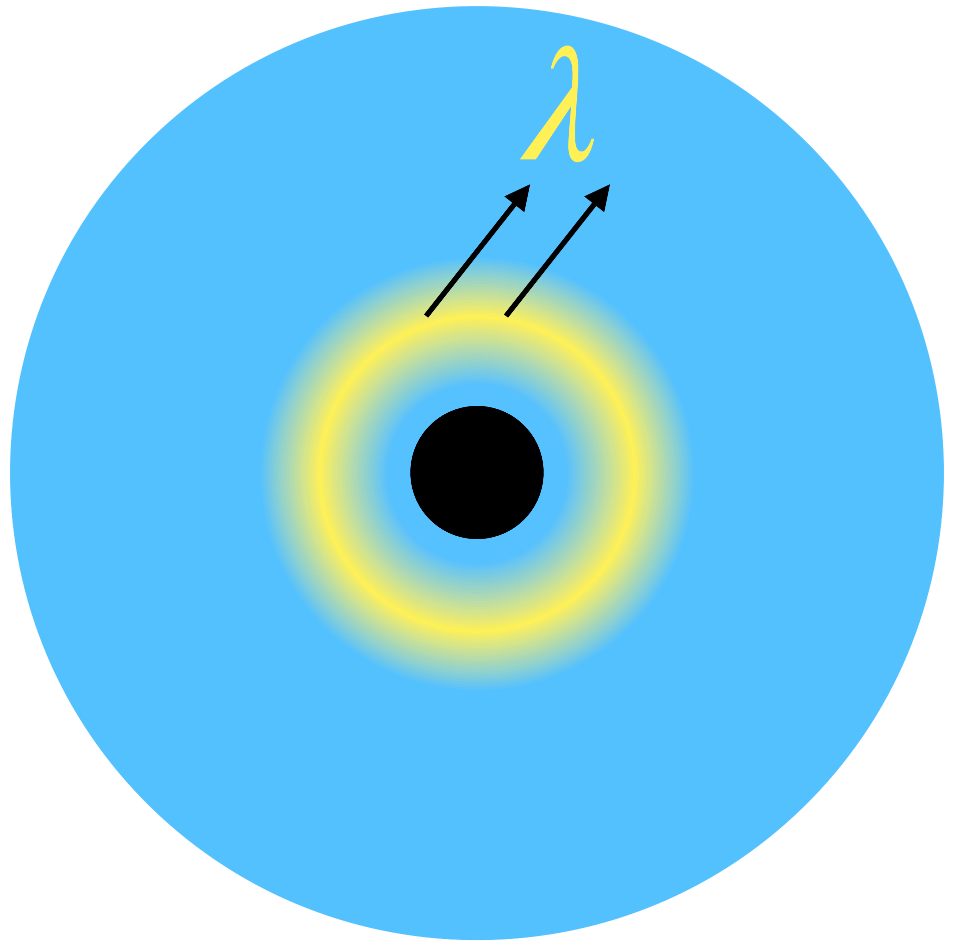


Long-λ also from inner disk:

$\tau < \tau_{Kep}(R_\lambda) \propto \lambda^2$

Understanding λ dependence





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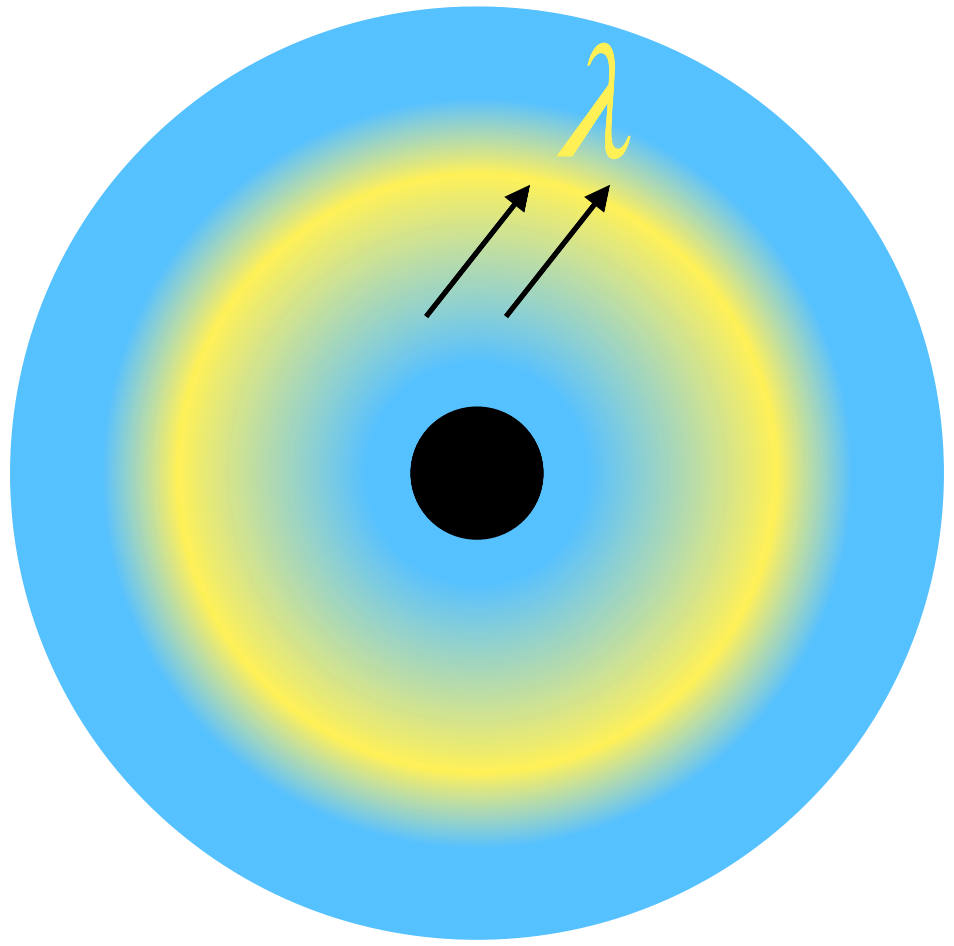

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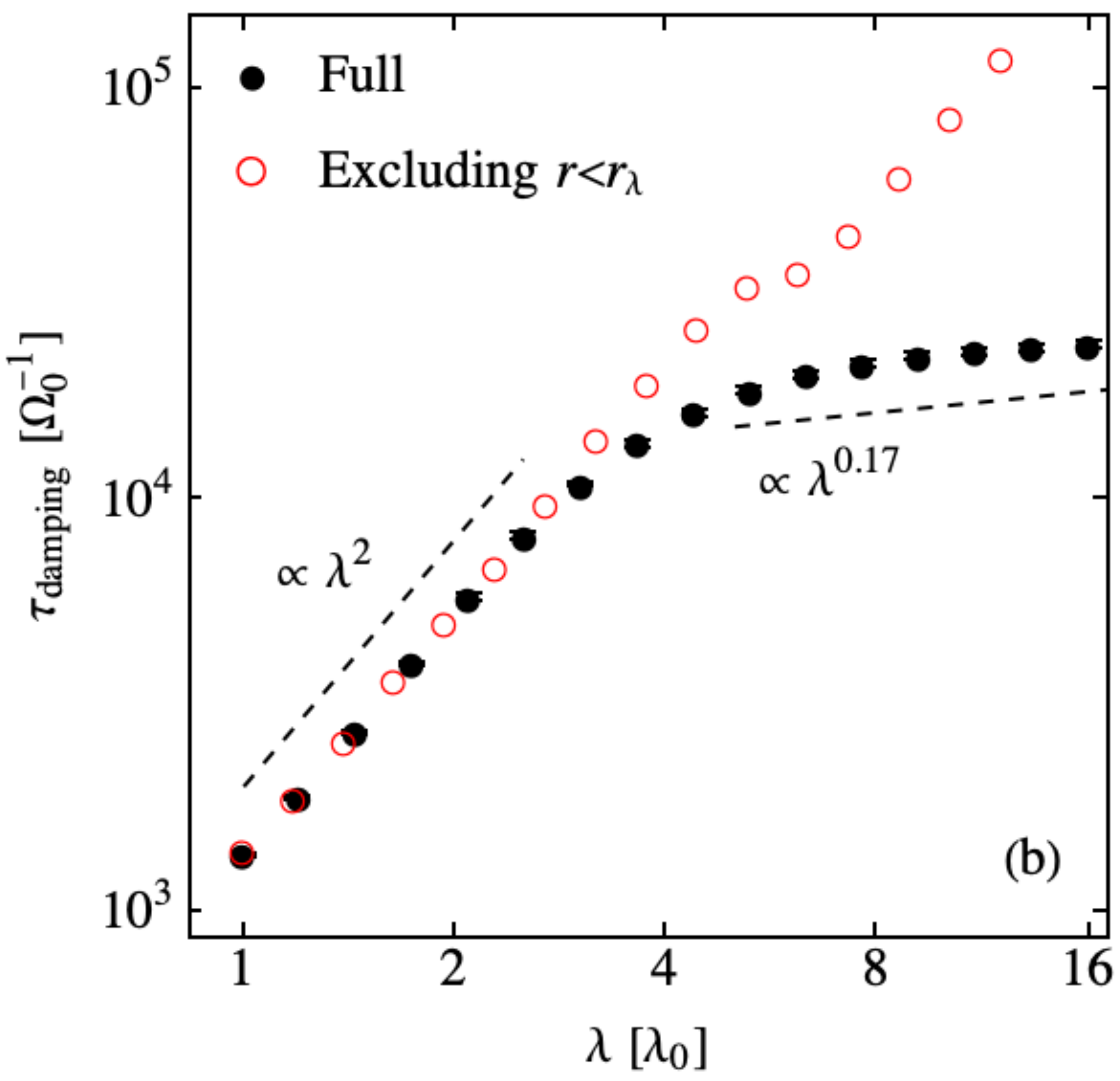

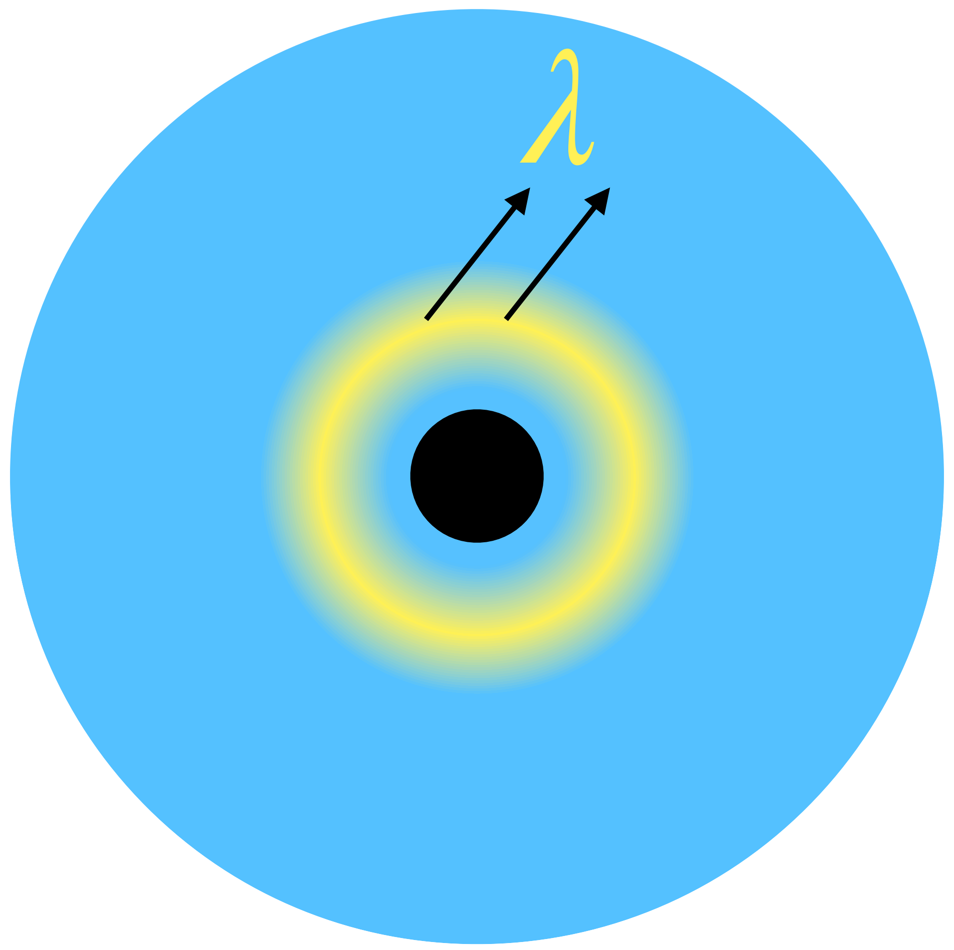

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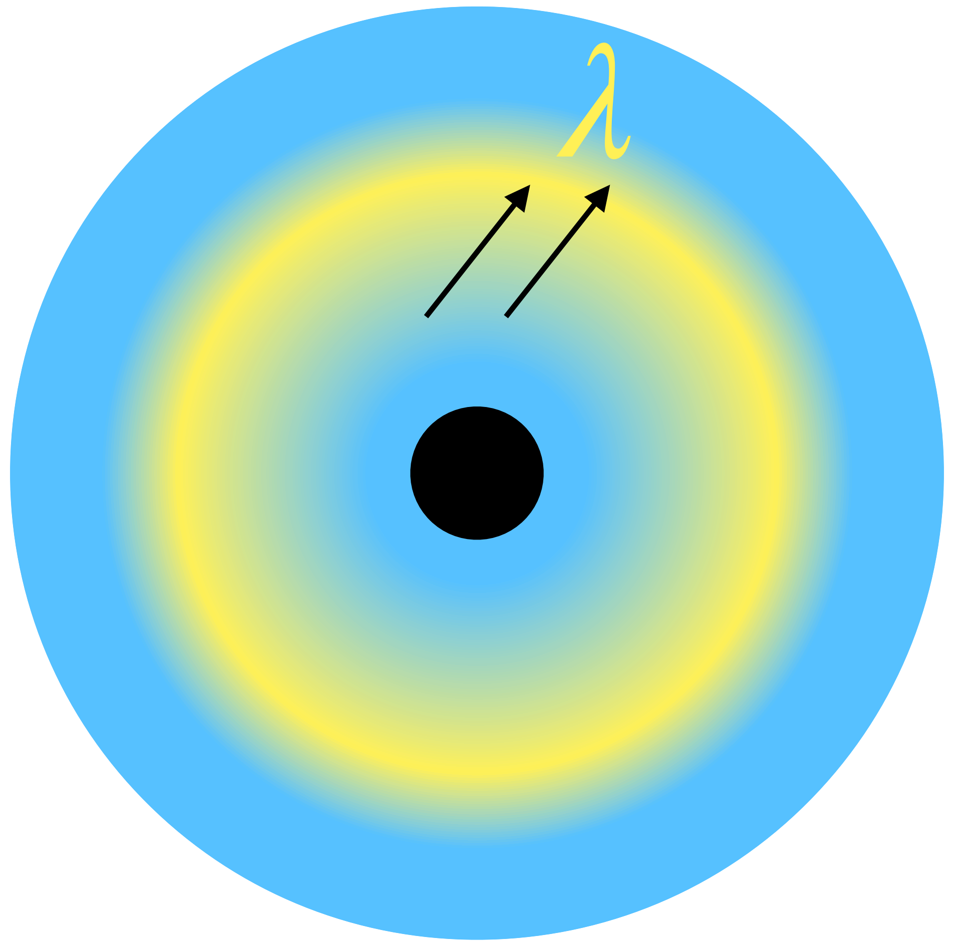

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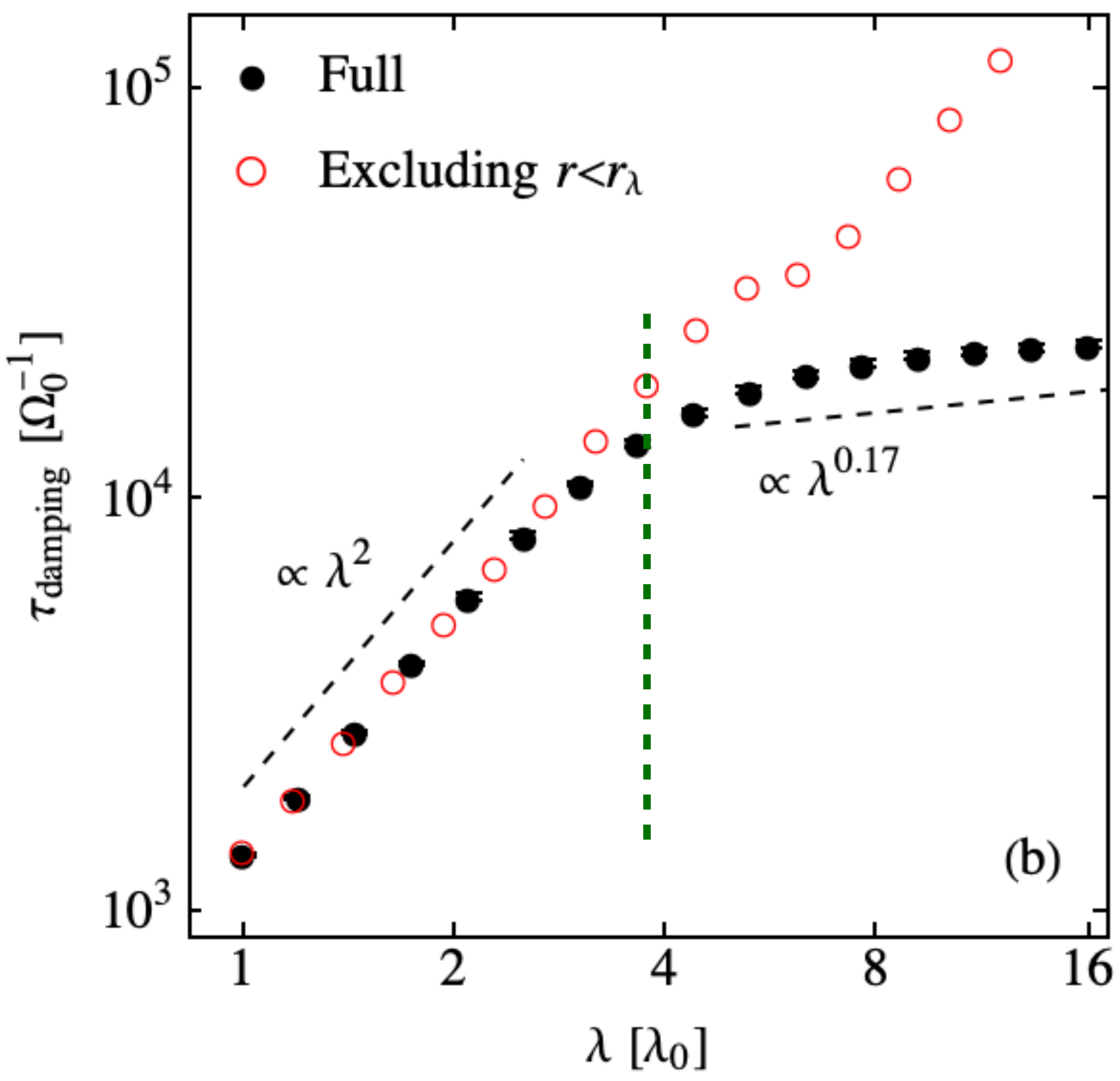

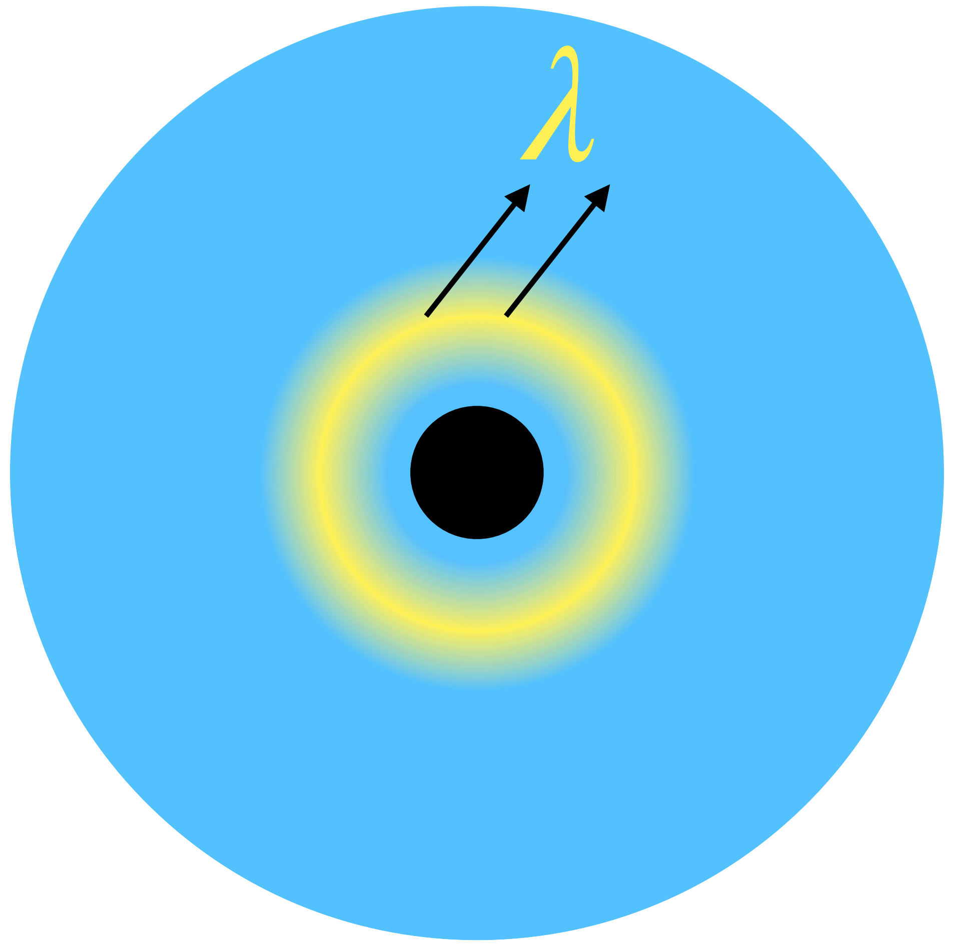

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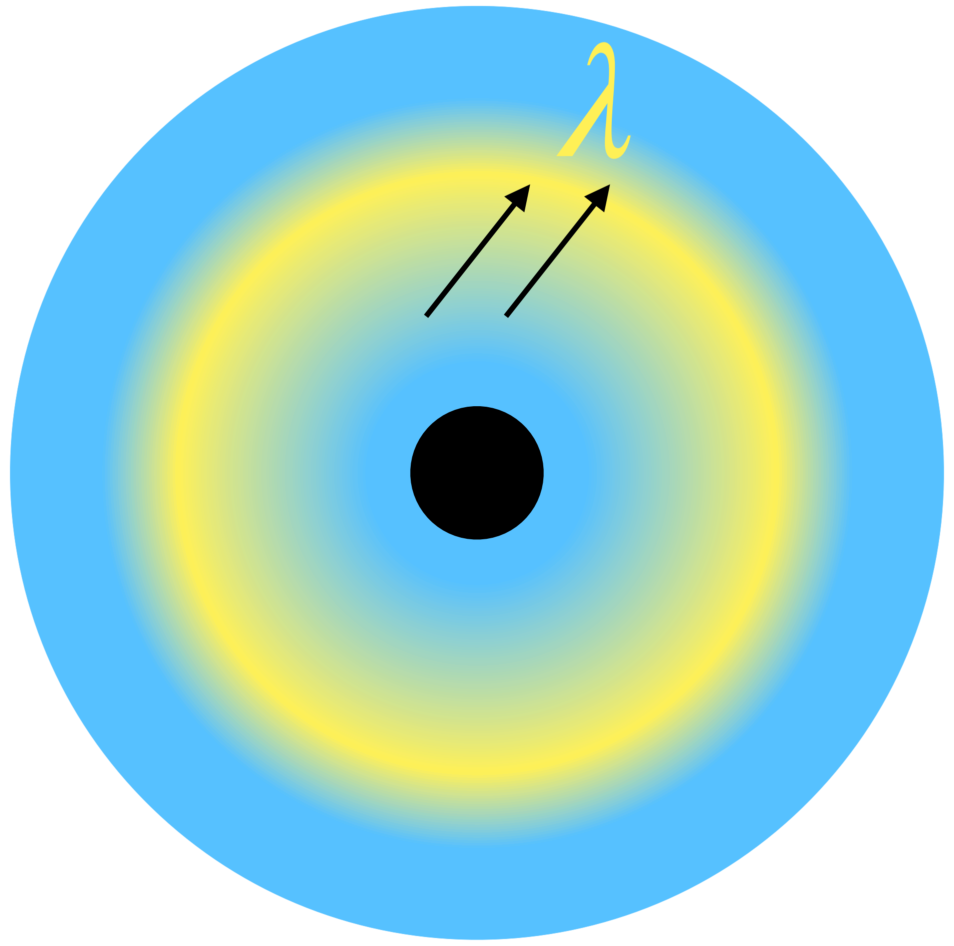

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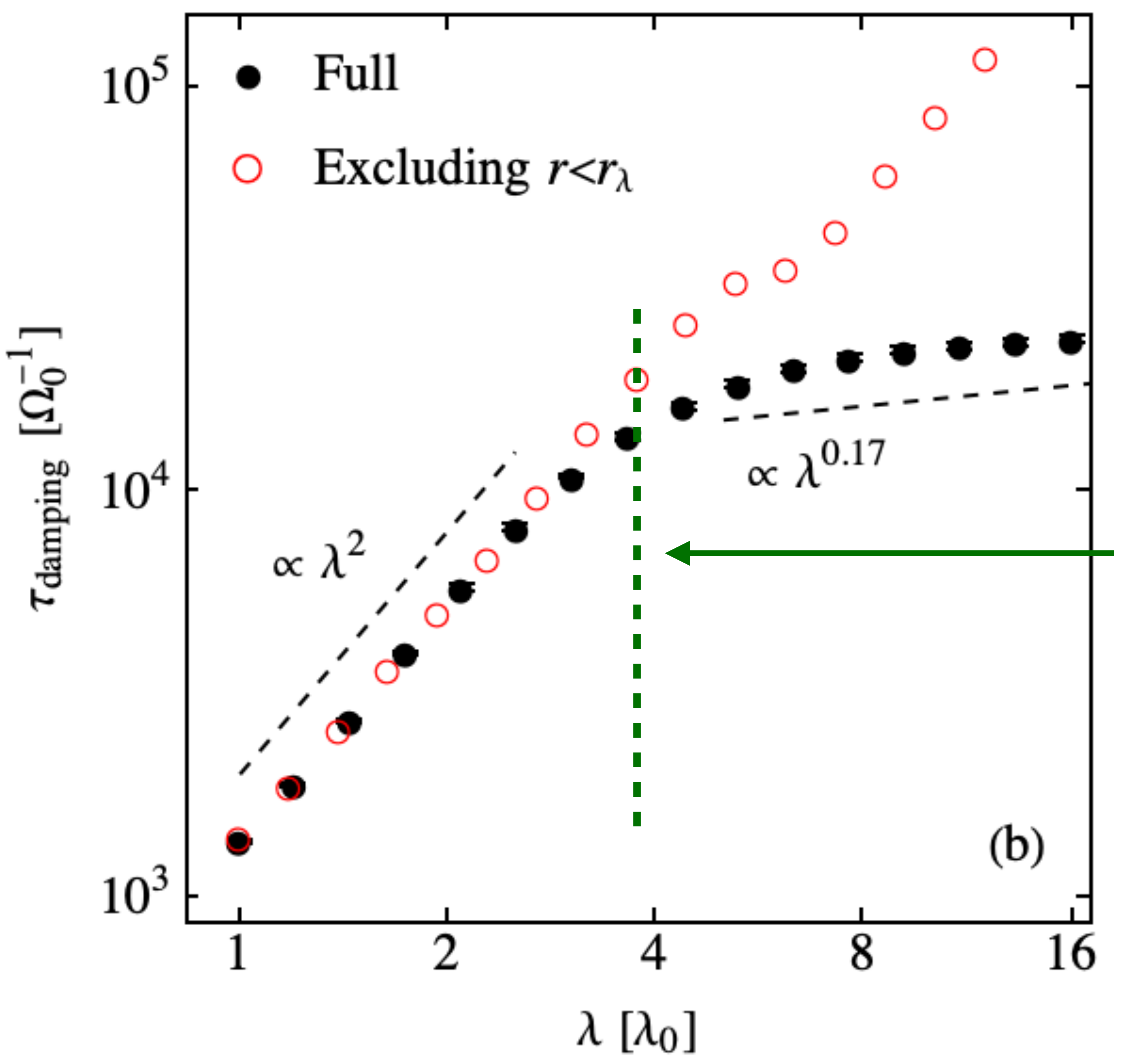
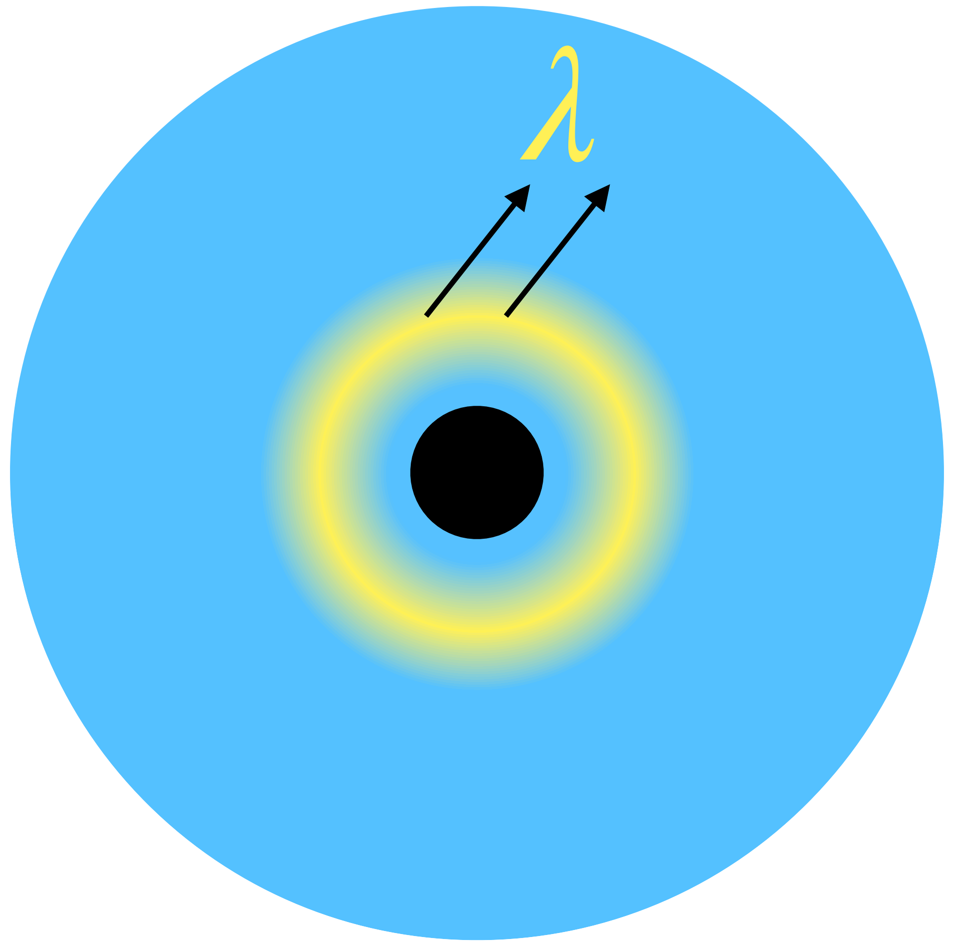


$$\lambda_c \simeq 3000\text{Å}\ m_8^{-1/2}\eta_{0.2}^{-1/4}$$



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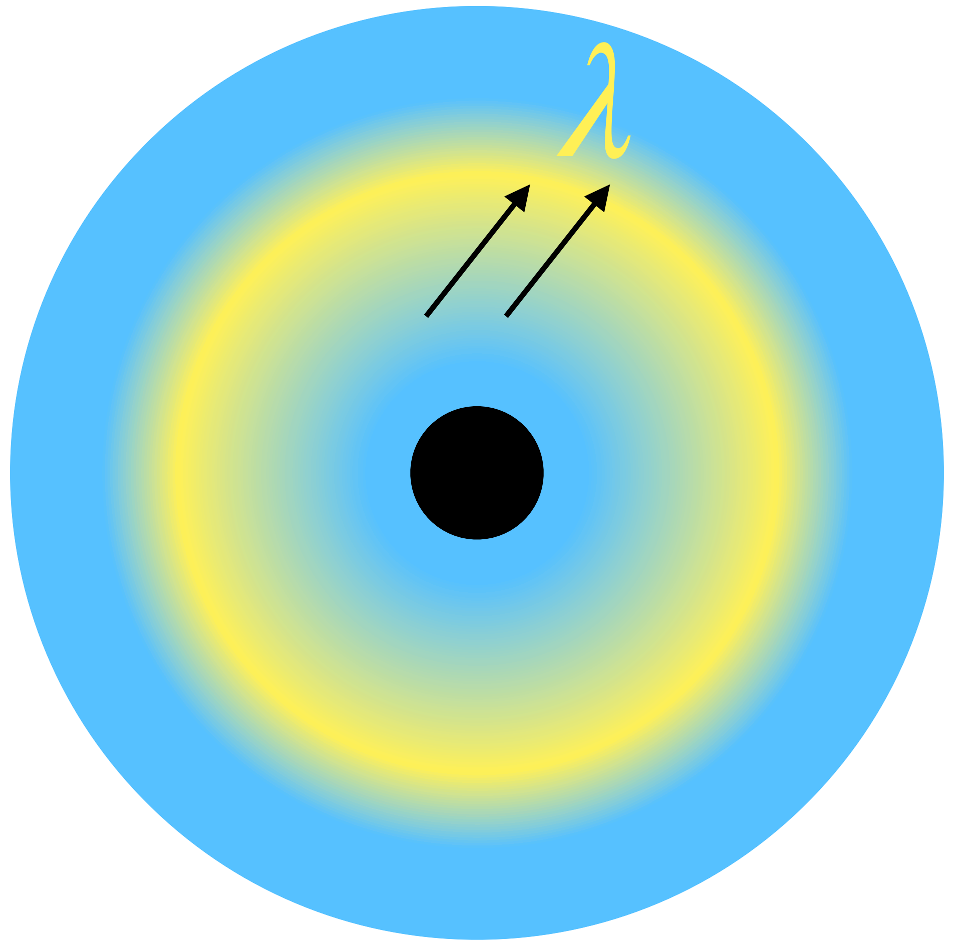

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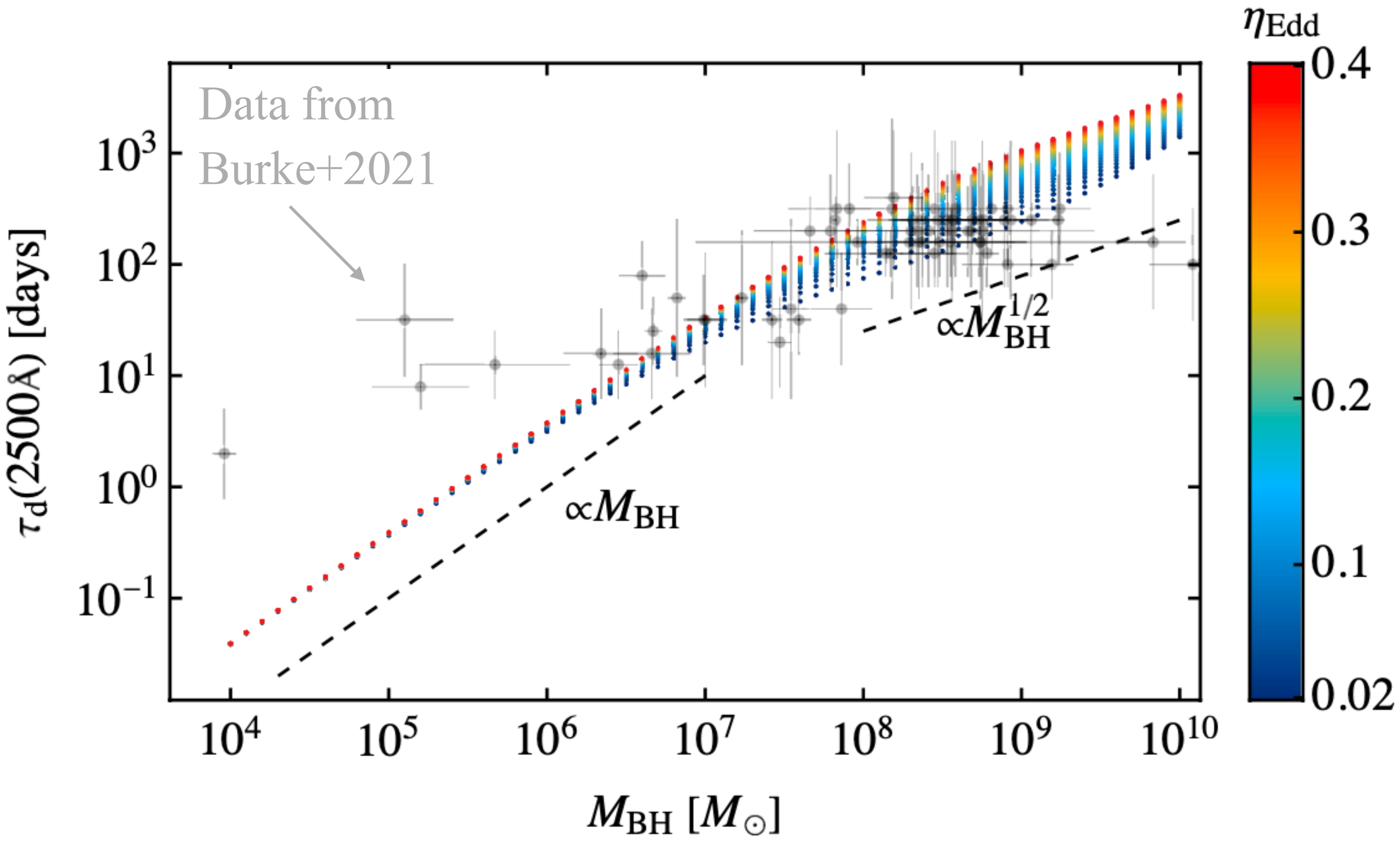
M_{BH} dependence



Reproducing $M_{BH}^{1/2}$ law for $M_{BH} \gtrsim 10^{6-7} M_\odot$

Low-M_{BH} end:

M_{BH}- and $\dot{M}$-dependence of dynamos?

Take-home messages

- Local/global simulations suggest amplification of large-scale magnetic fields.
  Outgoing dynamo waves, with $L \sim \mathcal{O}(30h)$, $P \sim \mathcal{O}(30\Omega^{-1})$ (HZ 2024)

- Wave-like viscosity parameter varies along with B,
  producing DRW-like PSDs of disk thermal emission (HZ+Lai *in prep.*)

Unknowns & Reach-outs

- Properties of large-scale B fields (geometry, periodicity) v.s. accretion parameters
  → to be solved in GRMHD + sub-grid simulations
  → inverting: can we infer dynamo properties from AGN variabilities?

- Integration with reprocessing models

- Explain also sub-mm and X-ray bands? → Bridging disk, corona & jet activities