A Multi-Scale Approach to MHD Turbulence in Accretion Disks

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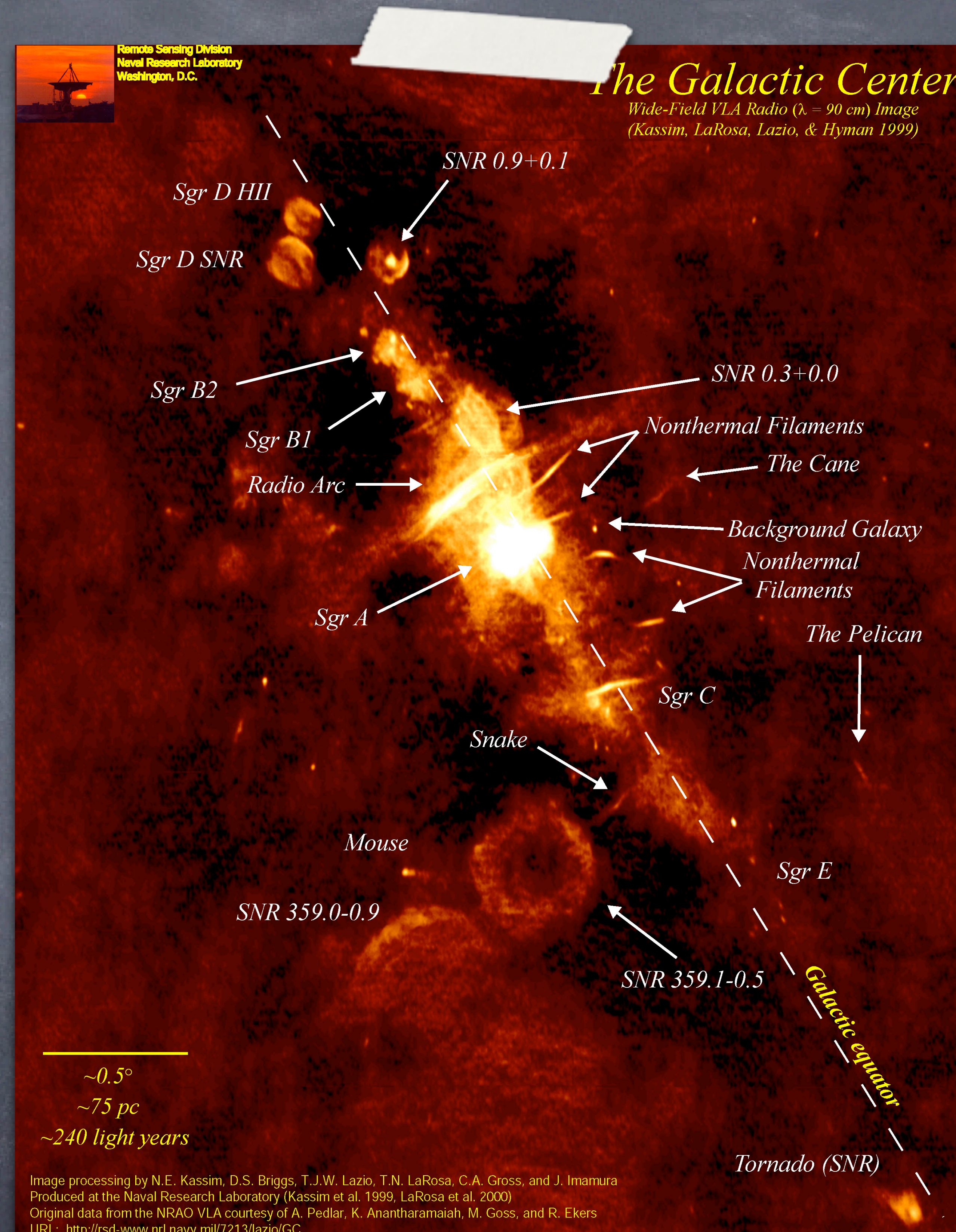
Thank: D. Psaltis (Arizona), M. Pessah (IAS);
R. Narayan (CfA), R. Shcherbakov (CfA); S. Succi (CNR)

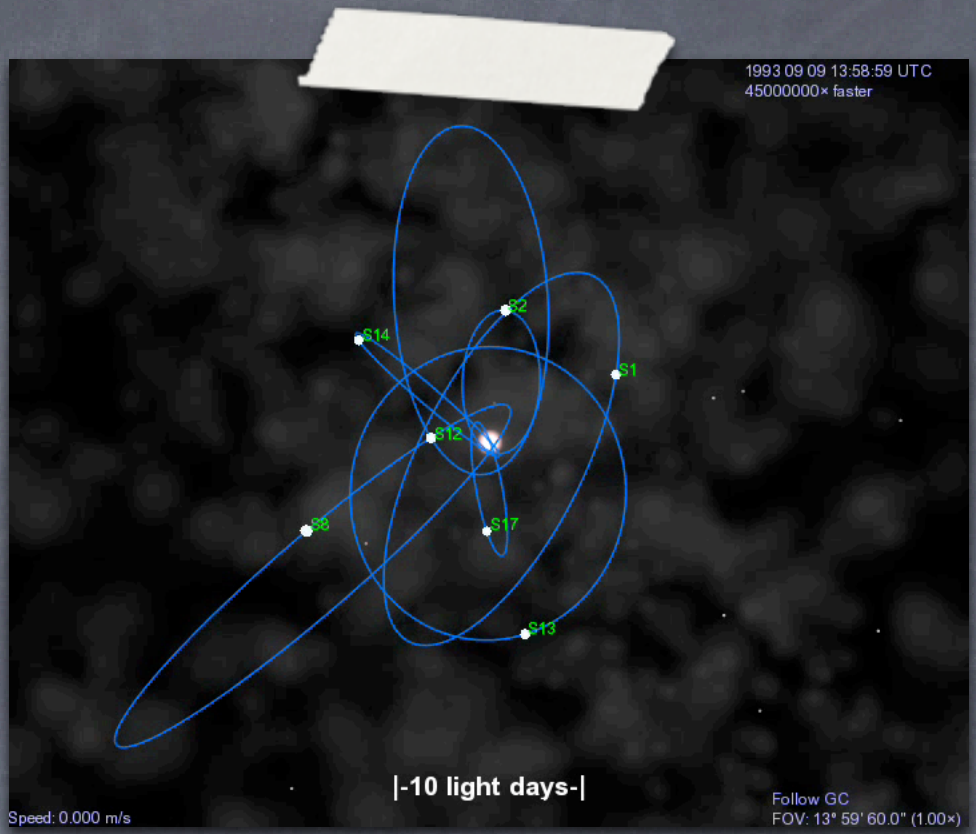
Case Study: Galactic Center

Chan, Liu, Fryer, Psaltis, Ozel, Rockefeller, Melia (2008)

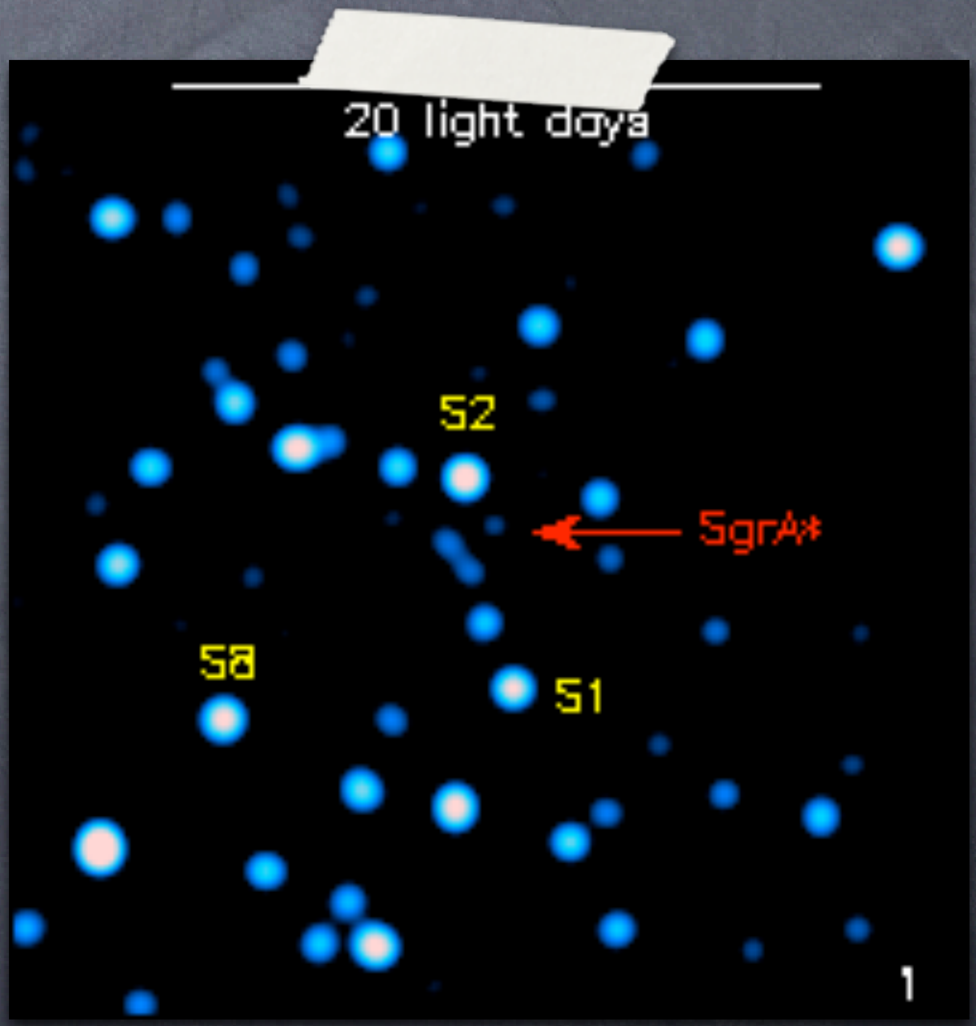


Wide-Field VLA Radio Image (Kassim, LaRosa, Lazio, & Hyman 1999) http://rsd-www.nrl.navy.mil/7213/lazio/GC

- Supermassive black hole
- Radiatively inefficient accretion disk
- Flares seen once a day
- Quasi-periodic signals observed during flares

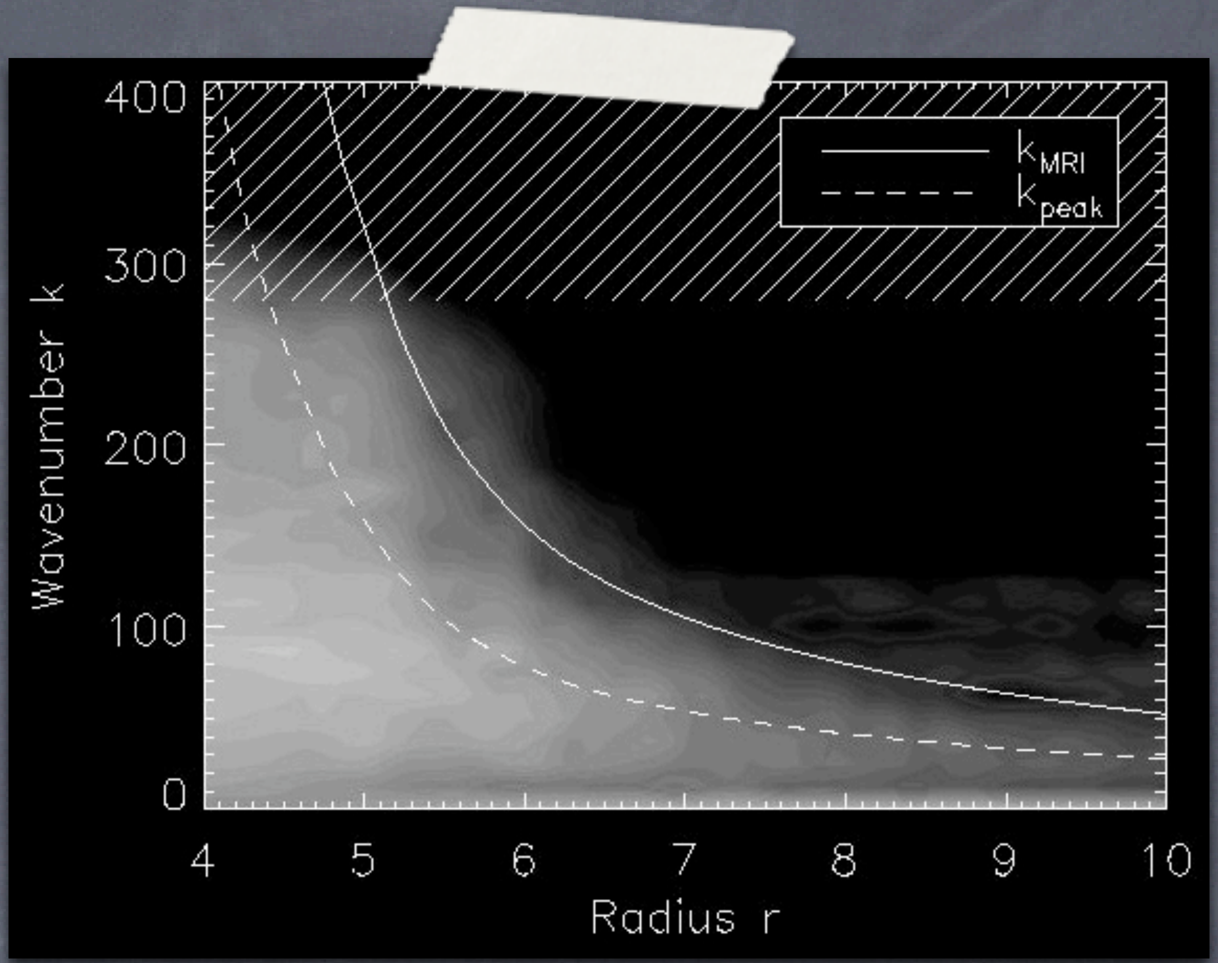


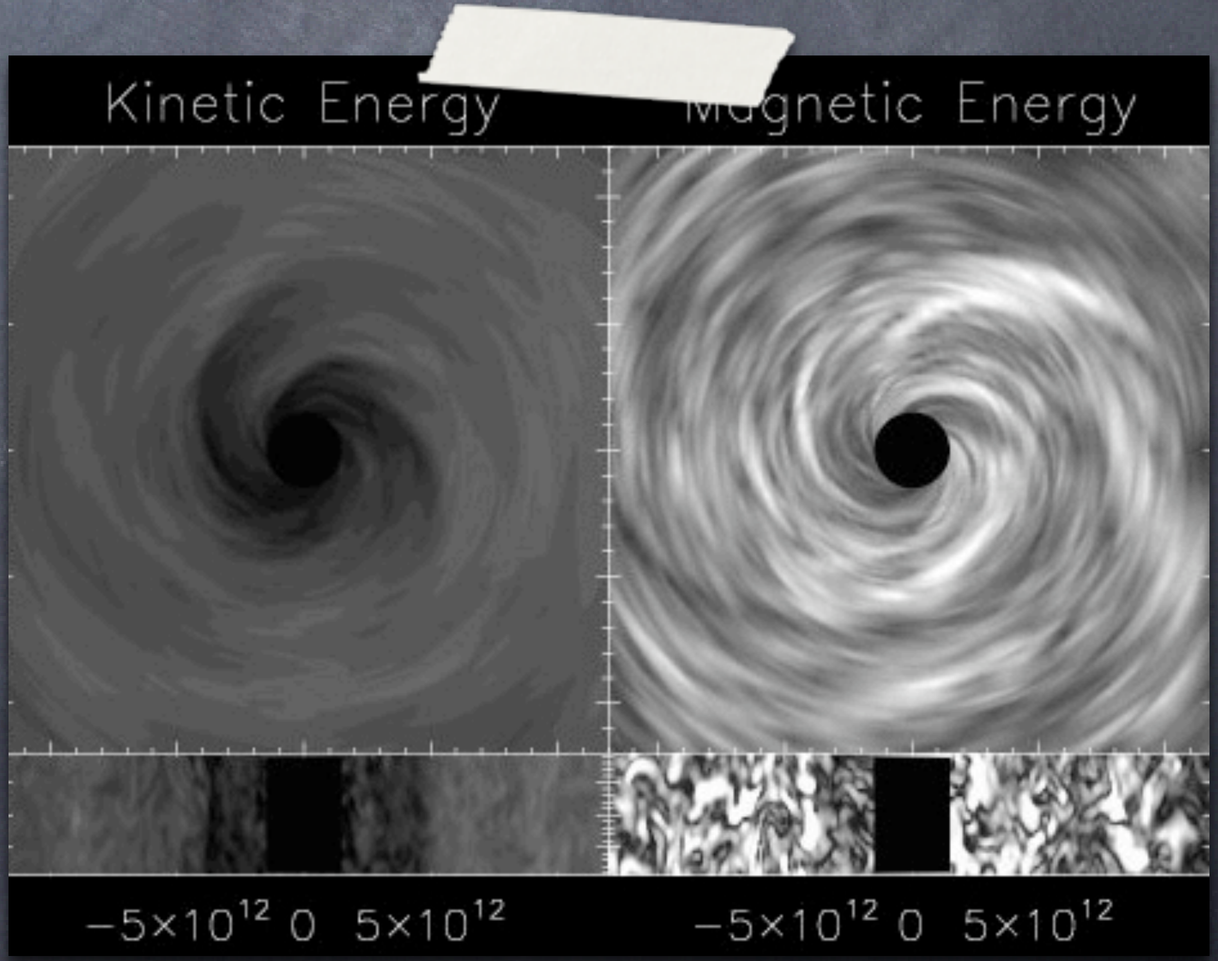
Stellar Orbits (Schödel et al 2003)



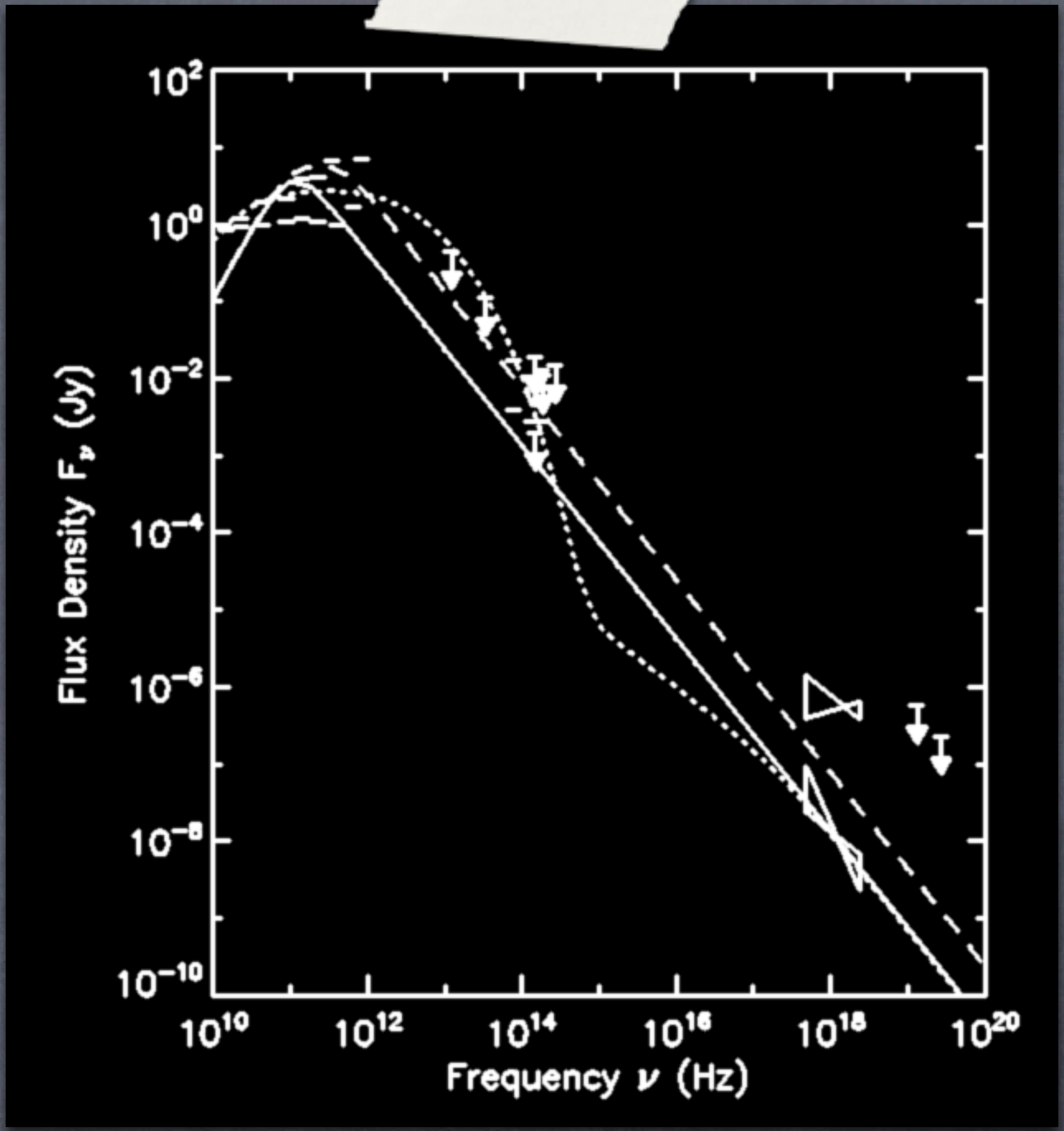
Near-Infrared Flare (Genzel et al 2003)

- Pseudo-spectral code with super-vanish viscosity
- Vector potential for magnetic field
- Pseudo-Newtonian gravity
- Properties of linear growth agrees with the MRI

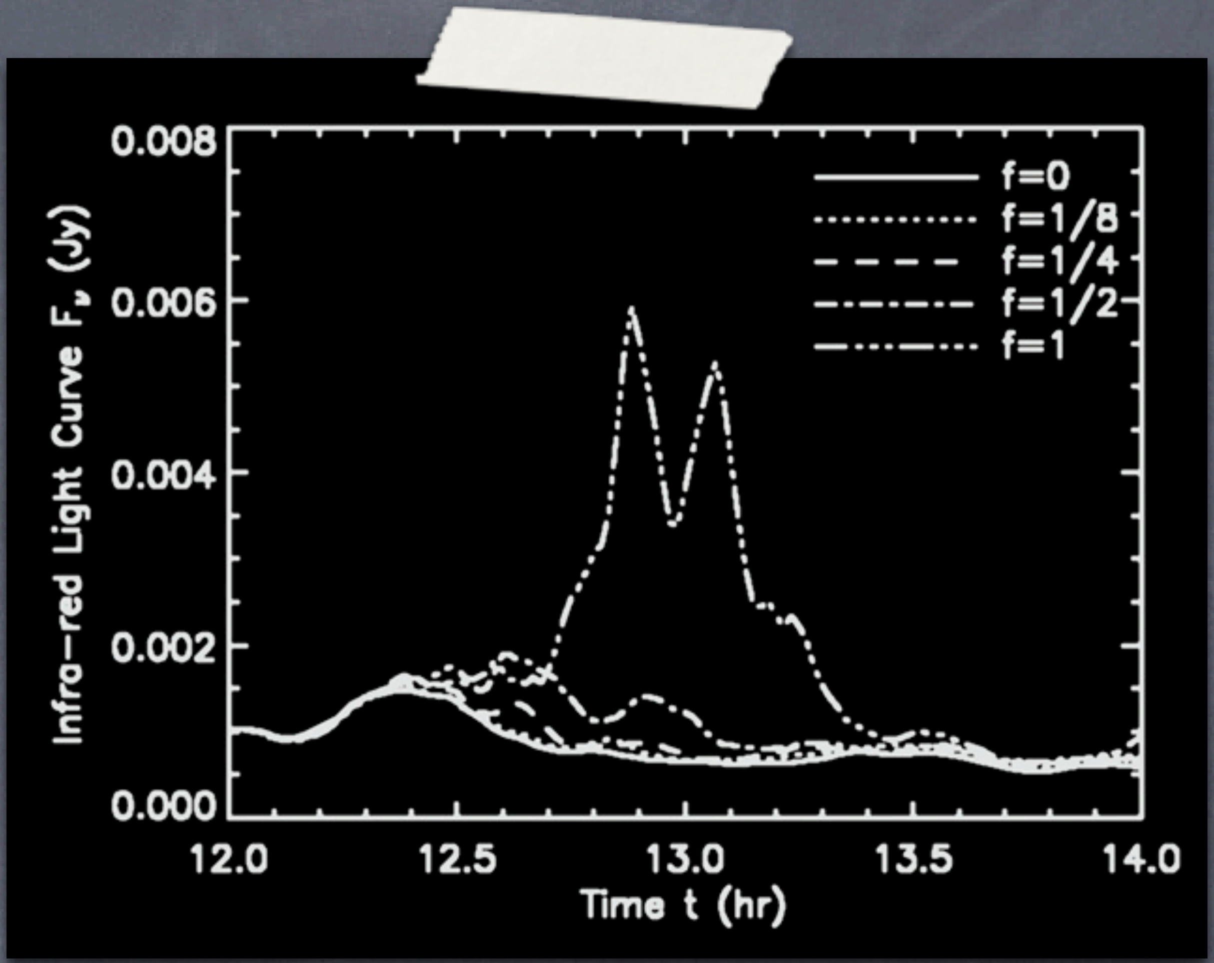


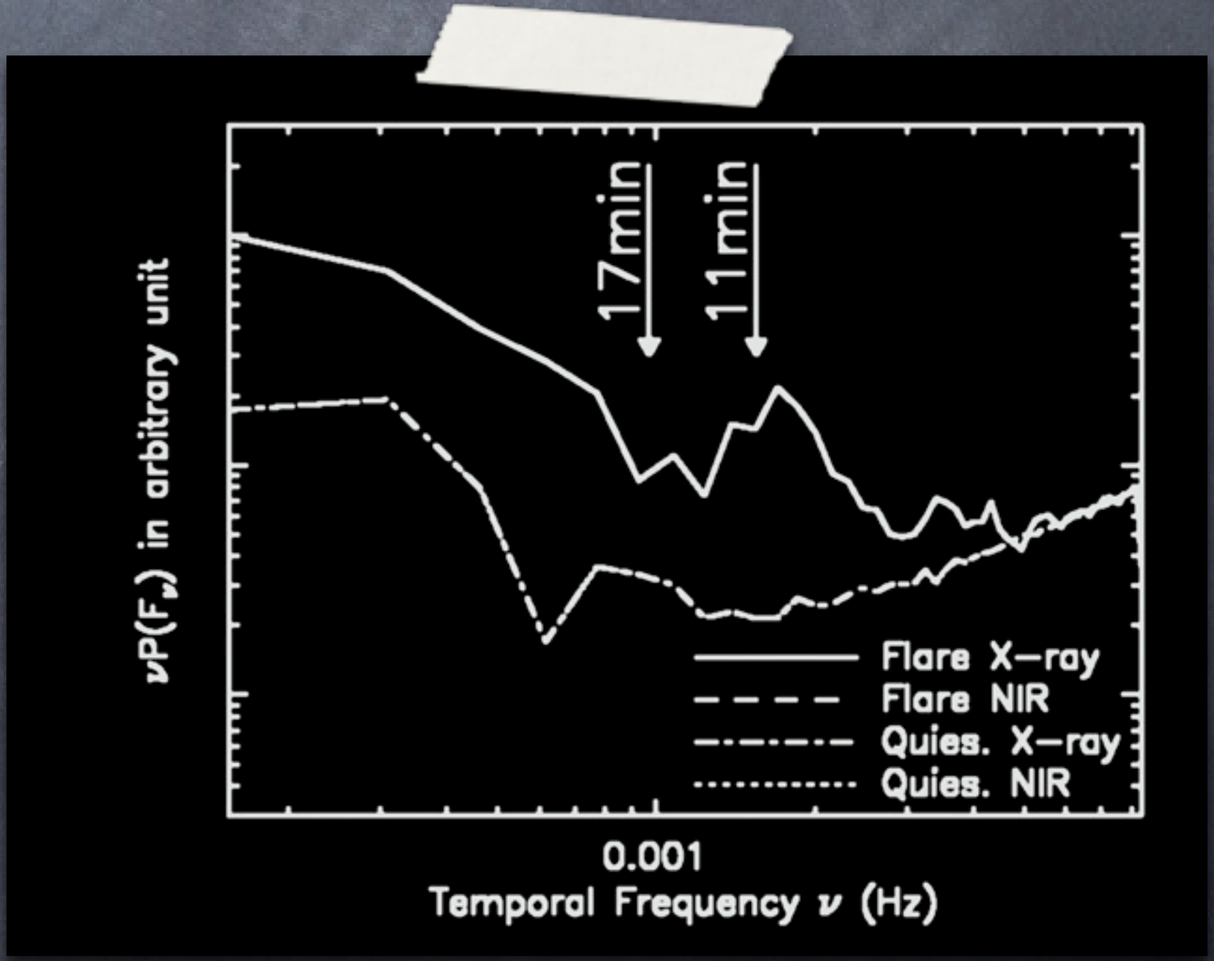


- No radiation feedback
- Synchrotron radiation as post-process
- Assume hybrid thermal-nonthermal electron distribution (Ozel & Narayan 2000)
- Use quiescent spectrum to fit electron distribution
- Study flares



- Parameter study of clumpy material falling onto the Galactic black hole
- Flares depend very nonlinearly of the perturbation
- Quasi-periodic oscillations associate with magneto-sonic point at 2.4 r_S instead of ISCO (3 r_S)

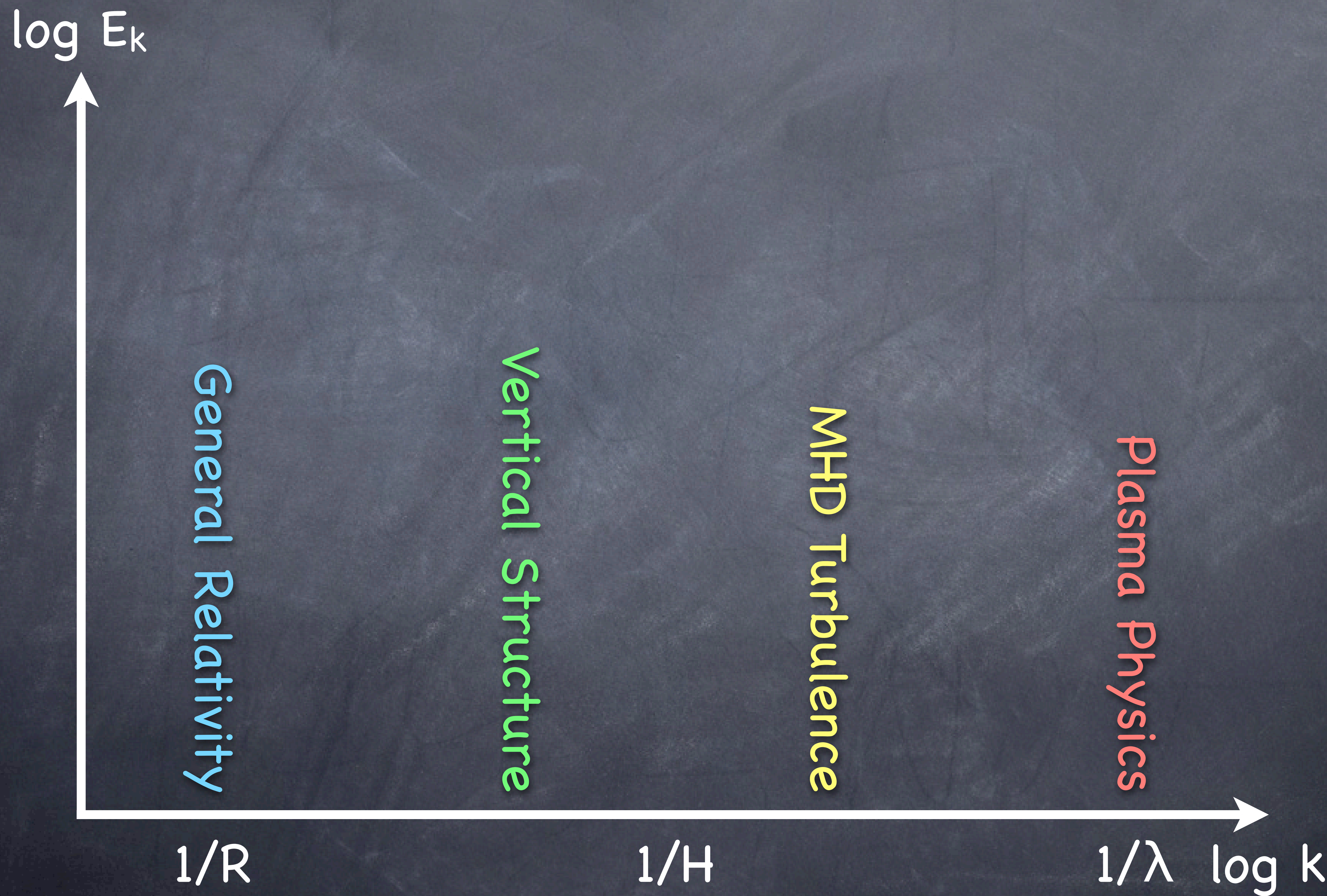




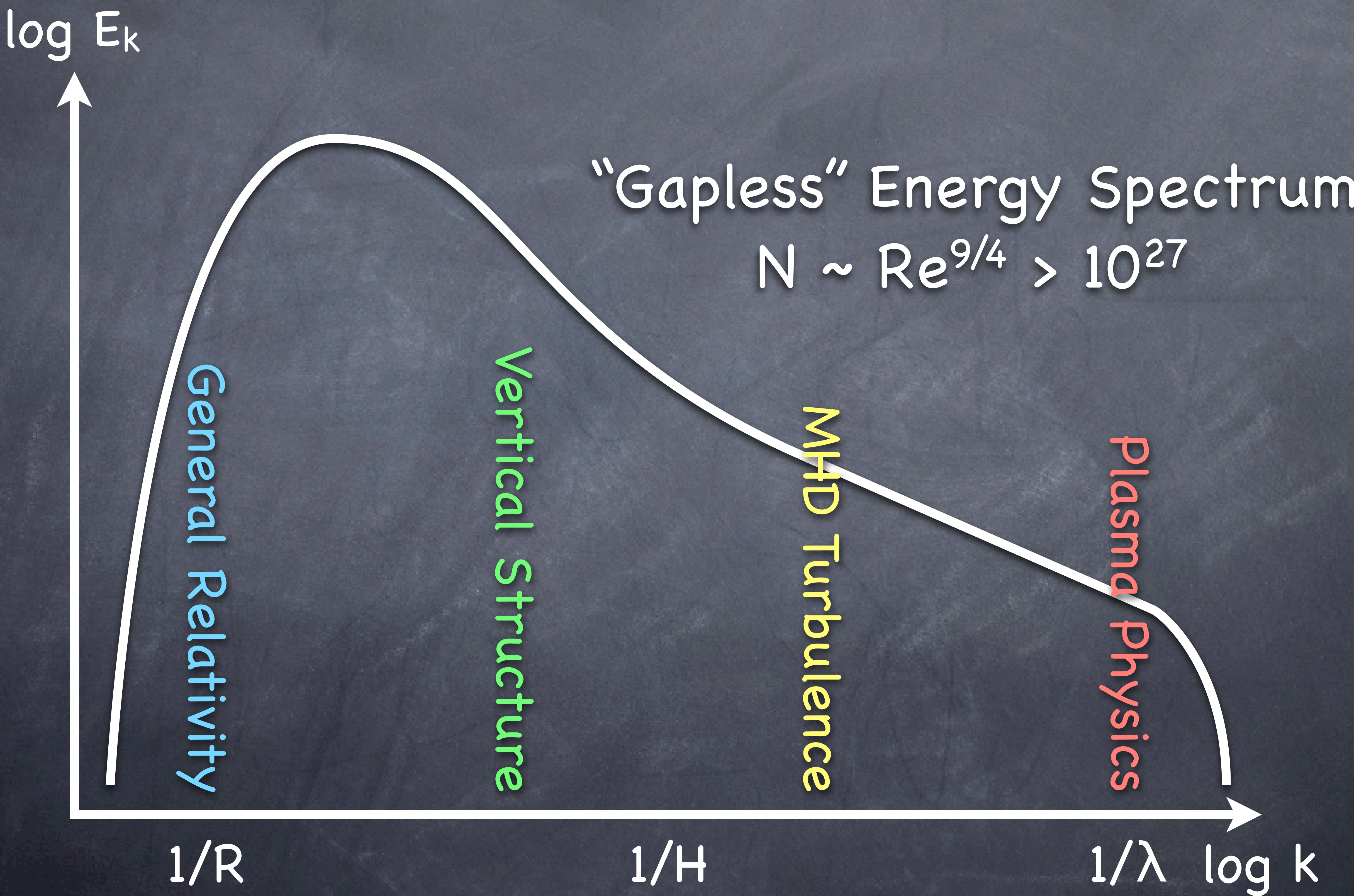
Limitations

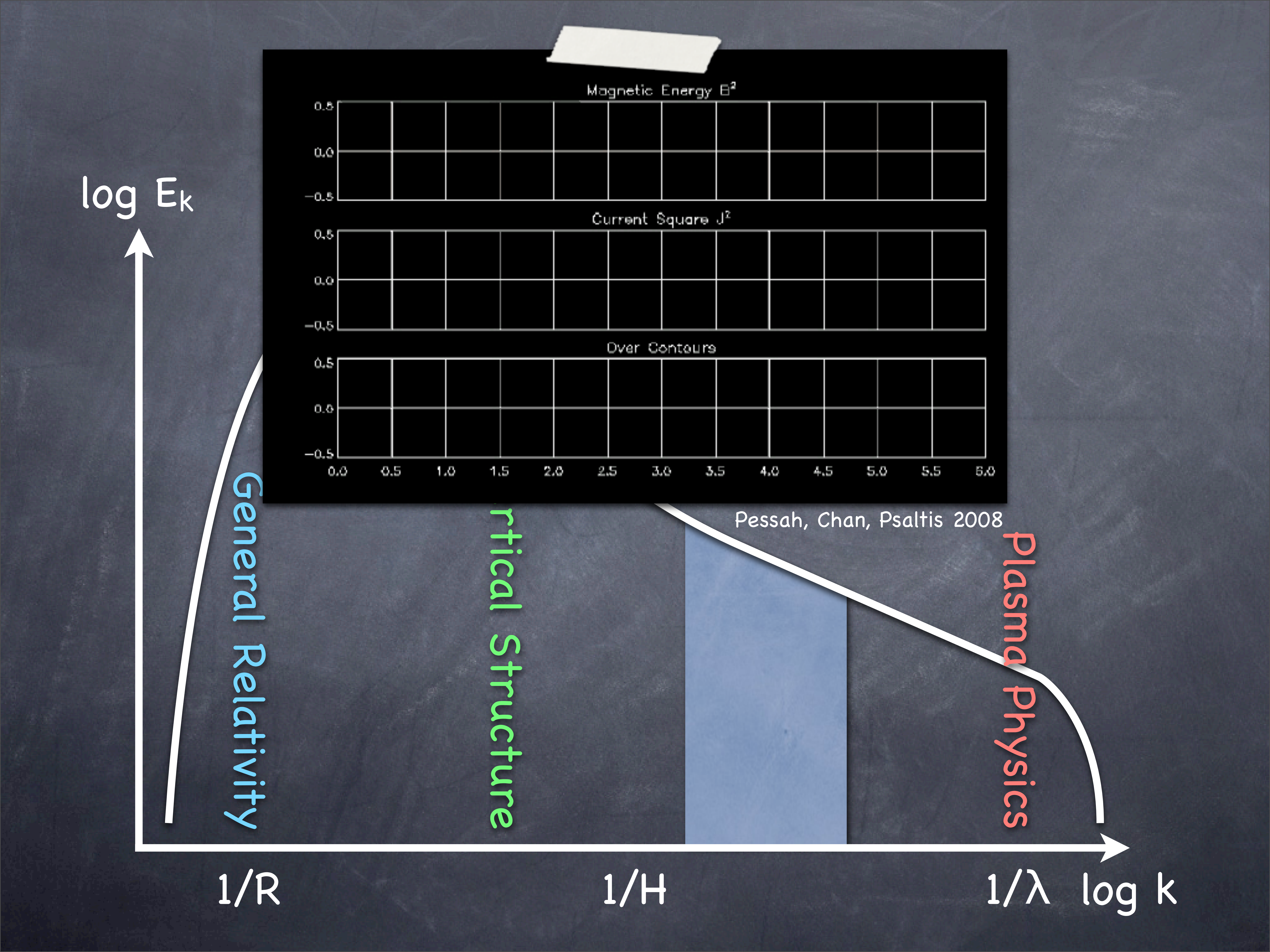
- Need General Relativity
- Need Vertical Structure
- Need Plasma Physics

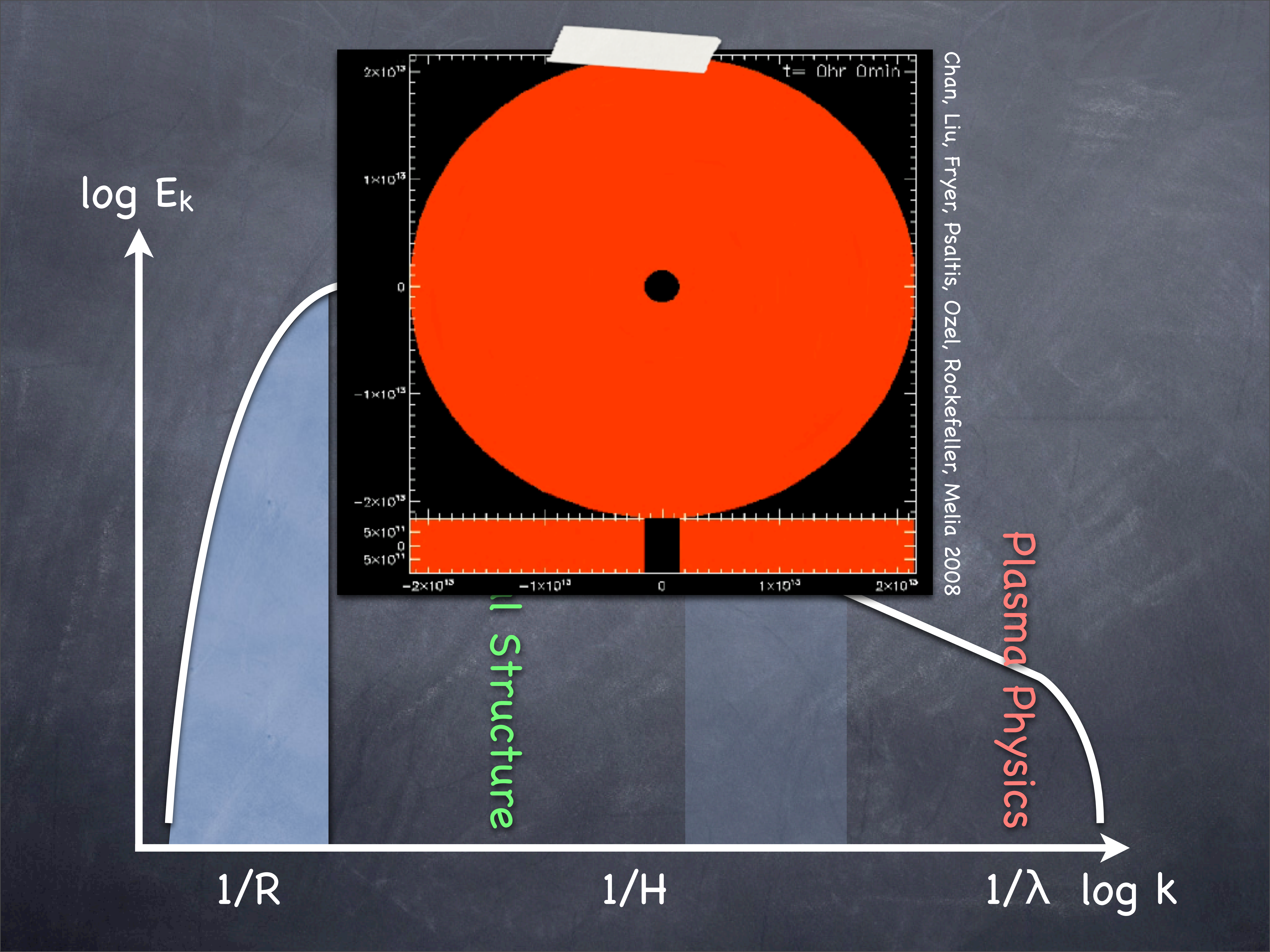
Limitations



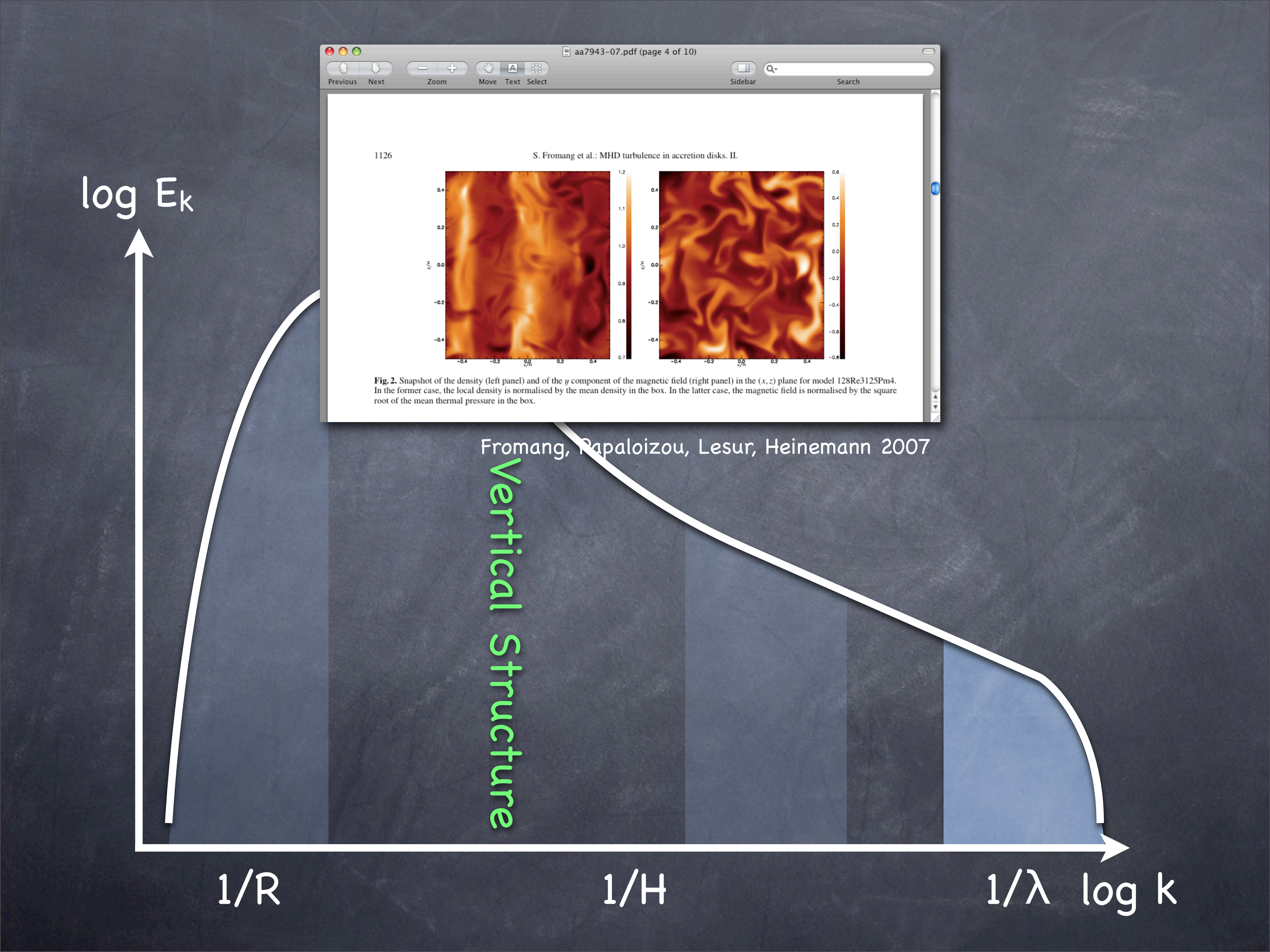
Multi-Scale Problem




log E_k
Magnetic Energy B^2
0.5
0.0
−0.5
Current Square J^2
0.5
0.0
−0.5
Over Contours
0.5
0.0
−0.5
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
General Relativity
rtical Structure
Plasma Physics
Pessah, Chan, Psaltis 2008
1/R
1/H
1/λ
log k



log Eₖ
t= 0hr 0min
2×10¹³
1×10¹³
0
−1×10¹³
−2×10¹³
5×10¹¹
0
5×10¹¹
−2×10¹³
−1×10¹³
0
1×10¹³
2×10¹³
Chan, Liu, Fryer, Psaltis, Ozel, Rockefeller, Melia 2008
l Structure
Plasma Physics
1/R
1/H
1/λ
log k



log E_k
aa7943-07.pdf (page 4 of 10)
Previous
Next
Zoom
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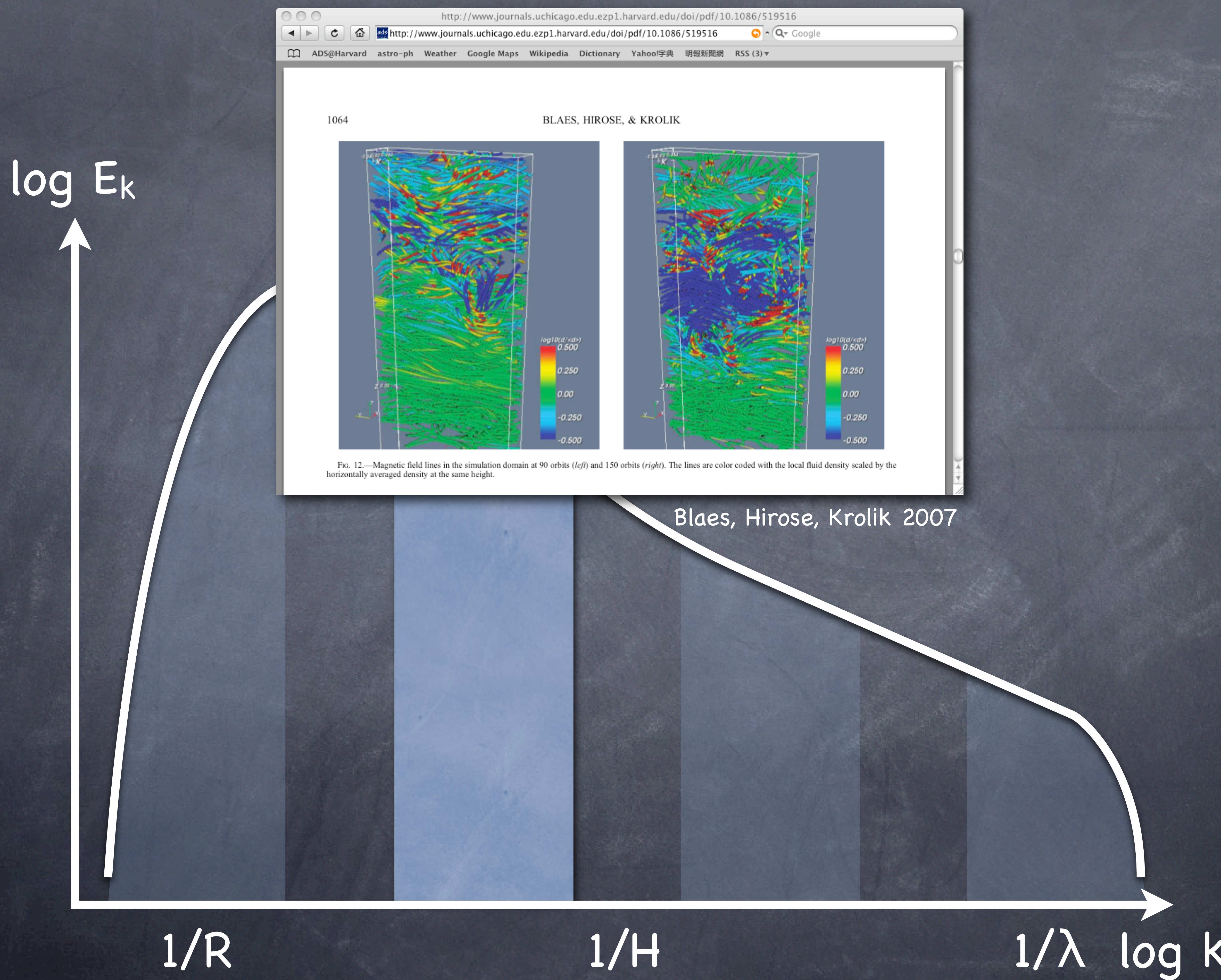
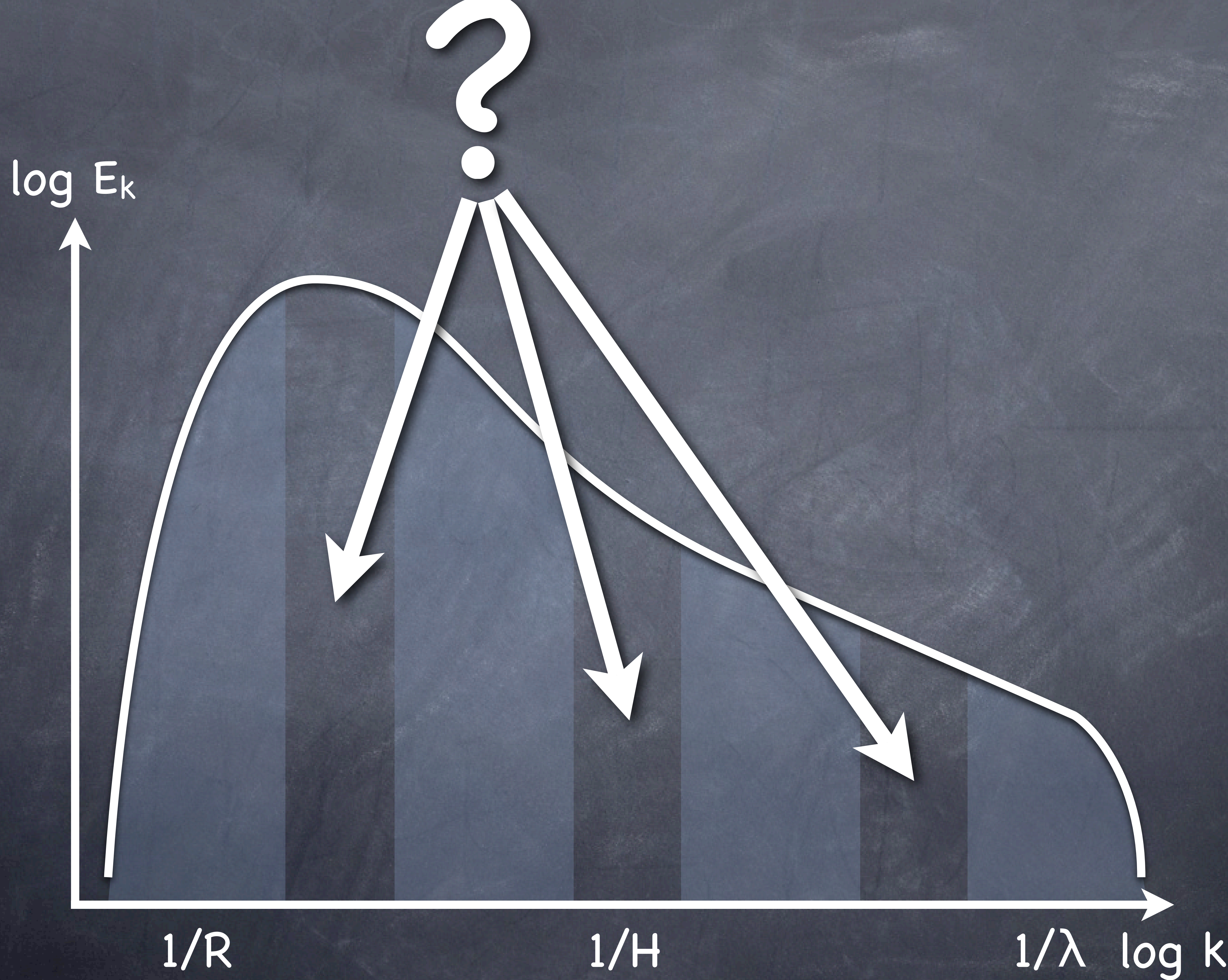
1126
S. Fromang et al.: MHD turbulence in accretion disks. II.
Fig. 2. Snapshot of the density (left panel) and of the y component of the magnetic field (right panel) in the (x, z) plane for model 128Re3125Pm4. In the former case, the local density is normalised by the mean density in the box. In the latter case, the magnetic field is normalised by the square root of the mean thermal pressure in the box.
Fromang, Papaloizou, Lesur, Heinemann 2007
Vertical Structure
1/R
1/H
1/λ
log k

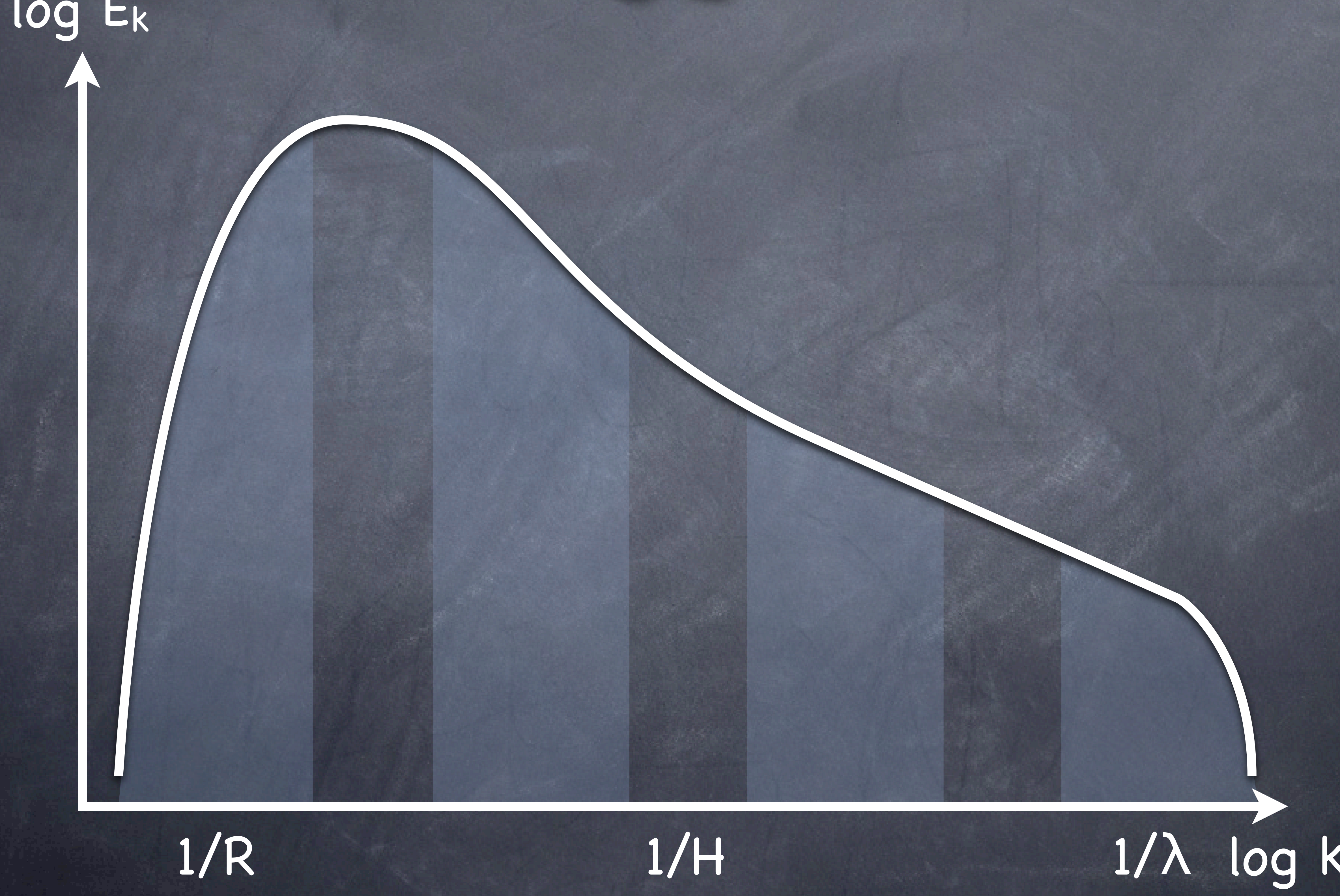


log E_k
http://www.journals.uchicago.edu.ezp1.harvard.edu/doi/pdf/10.1086/519516
ADS@Harvard astro-ph Weather Google Maps Wikipedia Dictionary Yahoo!字典 明報新聞網 RSS (3)
1064
BLAES, HIROSE, & KROLIK
log10(d/<d>)
0.500
0.250
0.00
-0.250
-0.500
FIG. 12.—Magnetic field lines in the simulation domain at 90 orbits (left) and 150 orbits (right). The lines are color coded with the local fluid density scaled by the horizontally averaged density at the same height.
Blaes, Hirose, Krolik 2007
1/R
1/H
1/λ
log k

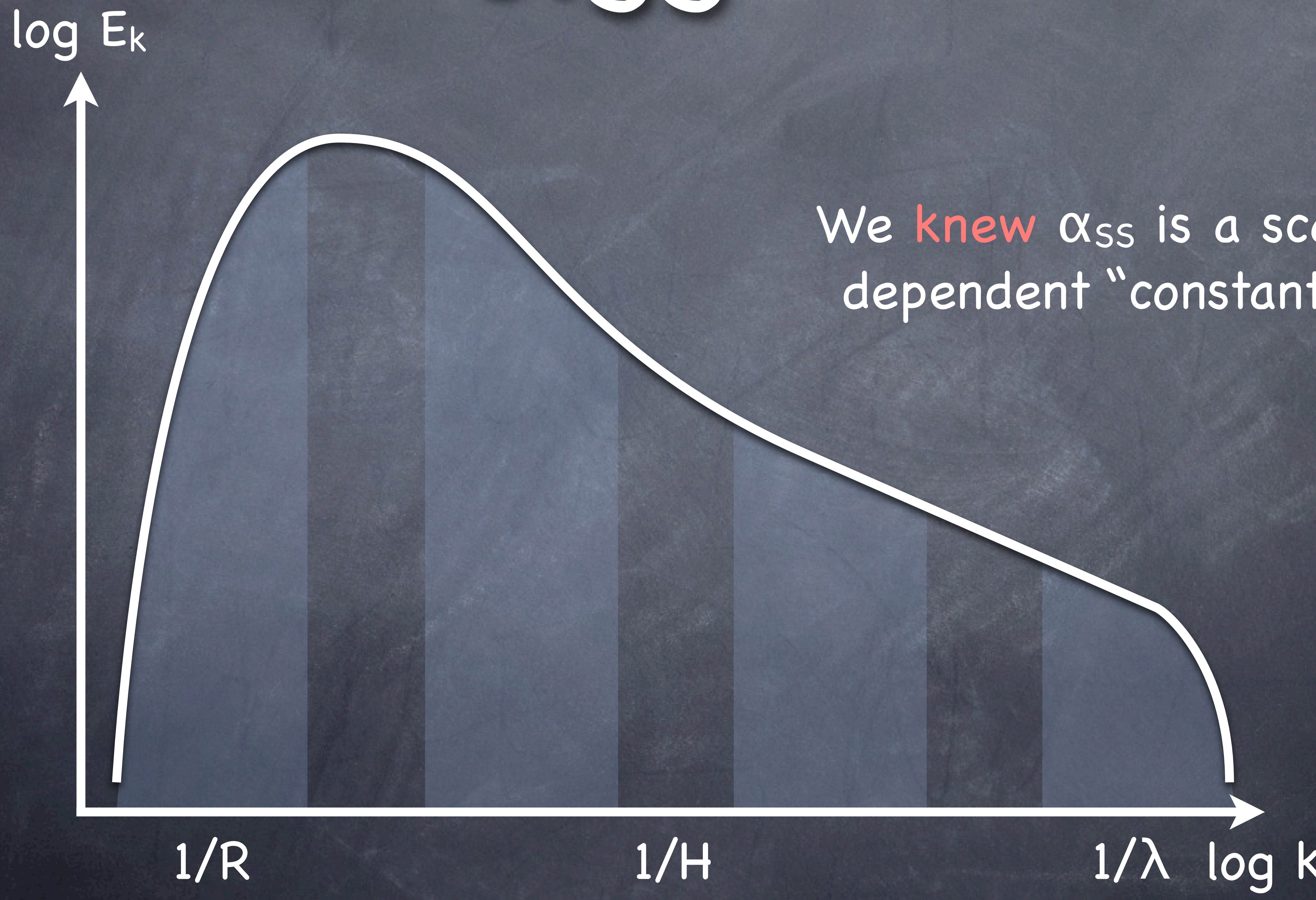


?
log Eₖ
1/R
1/H
1/λ
log k

$$\alpha_{SS} \sim T_{xy}/P$$

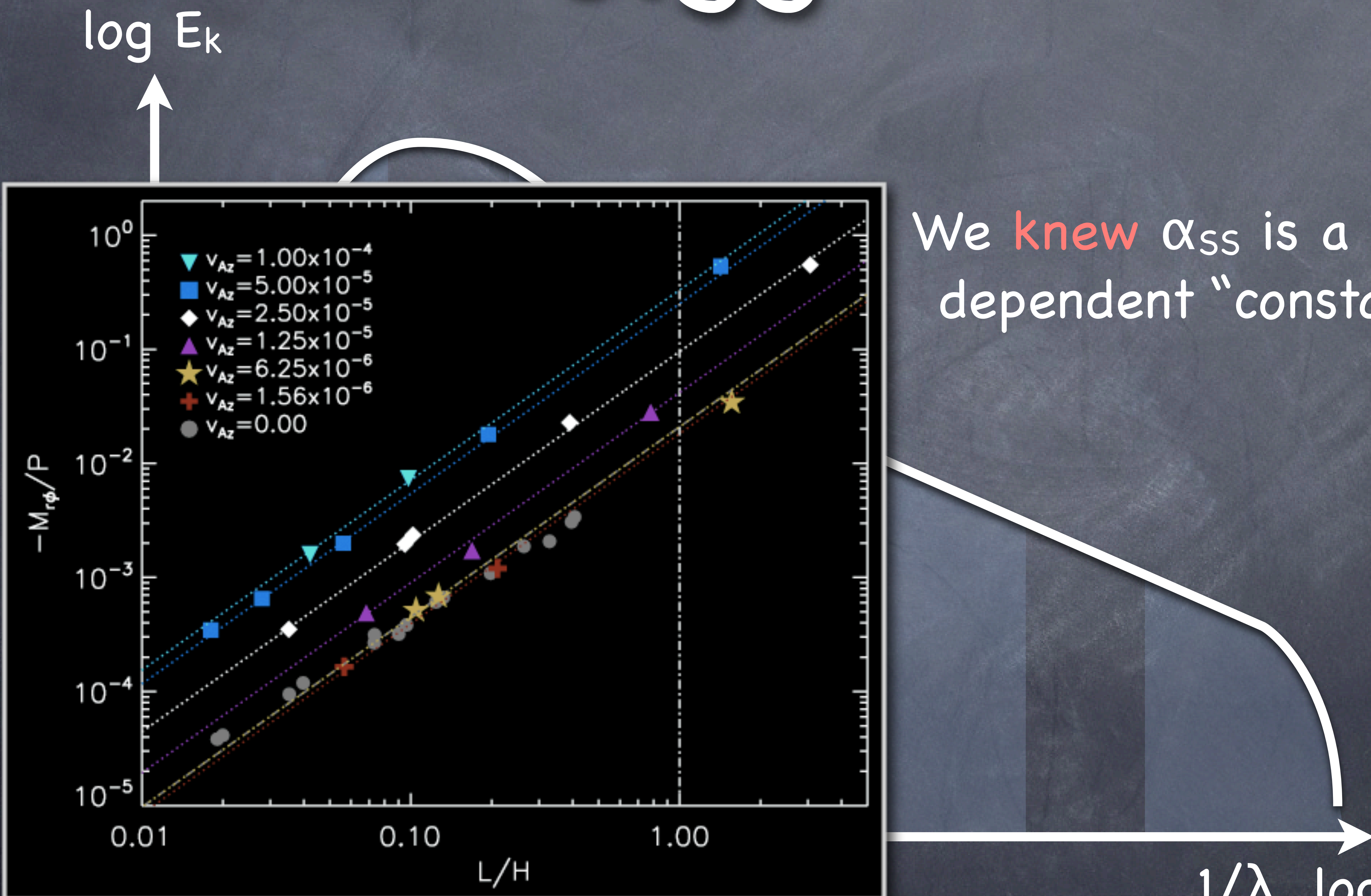


$\alpha_{SS} \sim \int b_x b_y^* d^3k/P$



We knew α_{SS} is a scale dependent "constant"

$\alpha_{SS} \sim \int b_x b_y^* d^3k/P$



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Pessah, Chan, Psaltis 2007, data by Sano, Inutsuka, Turner, Stone 2004

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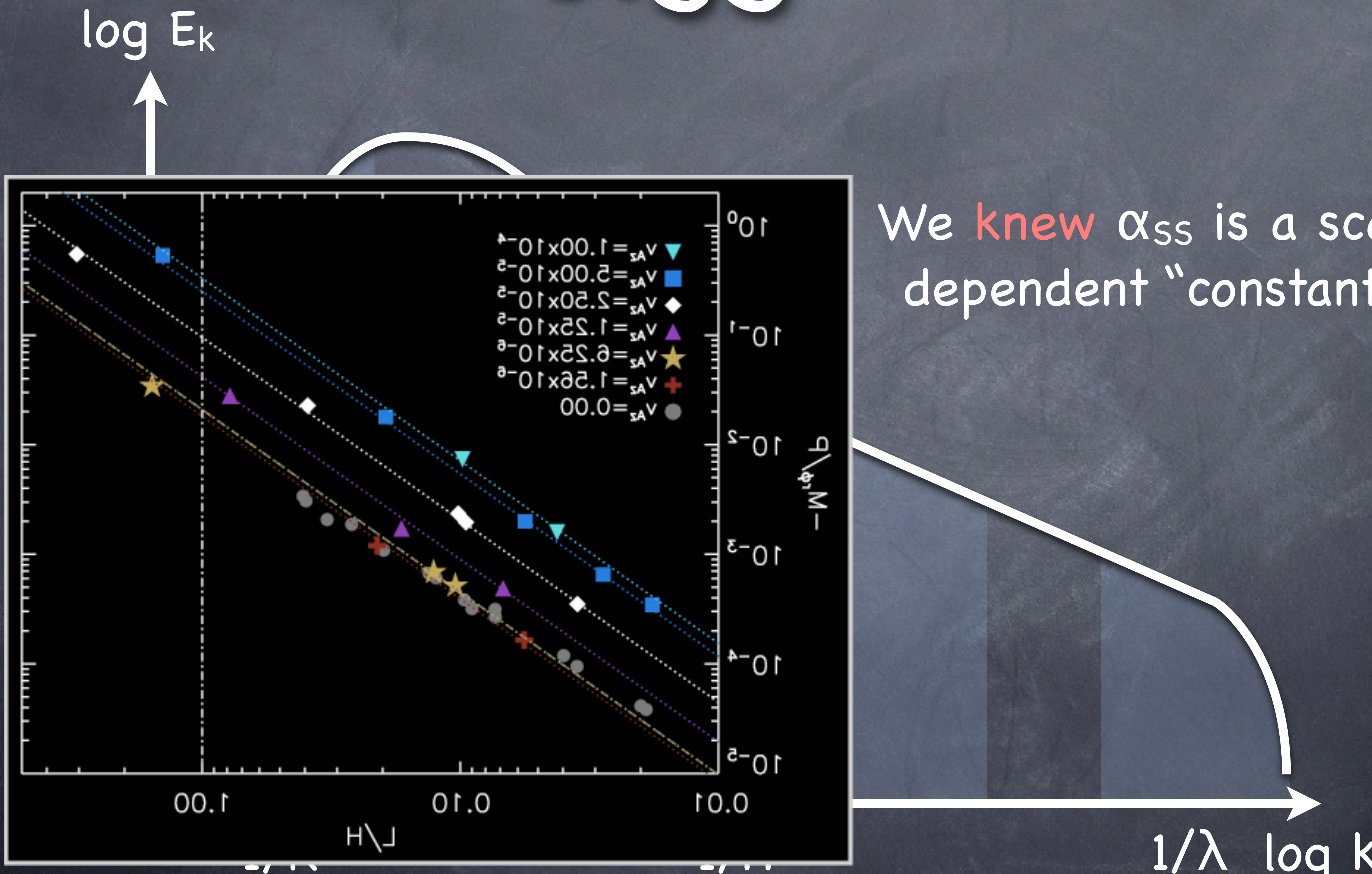

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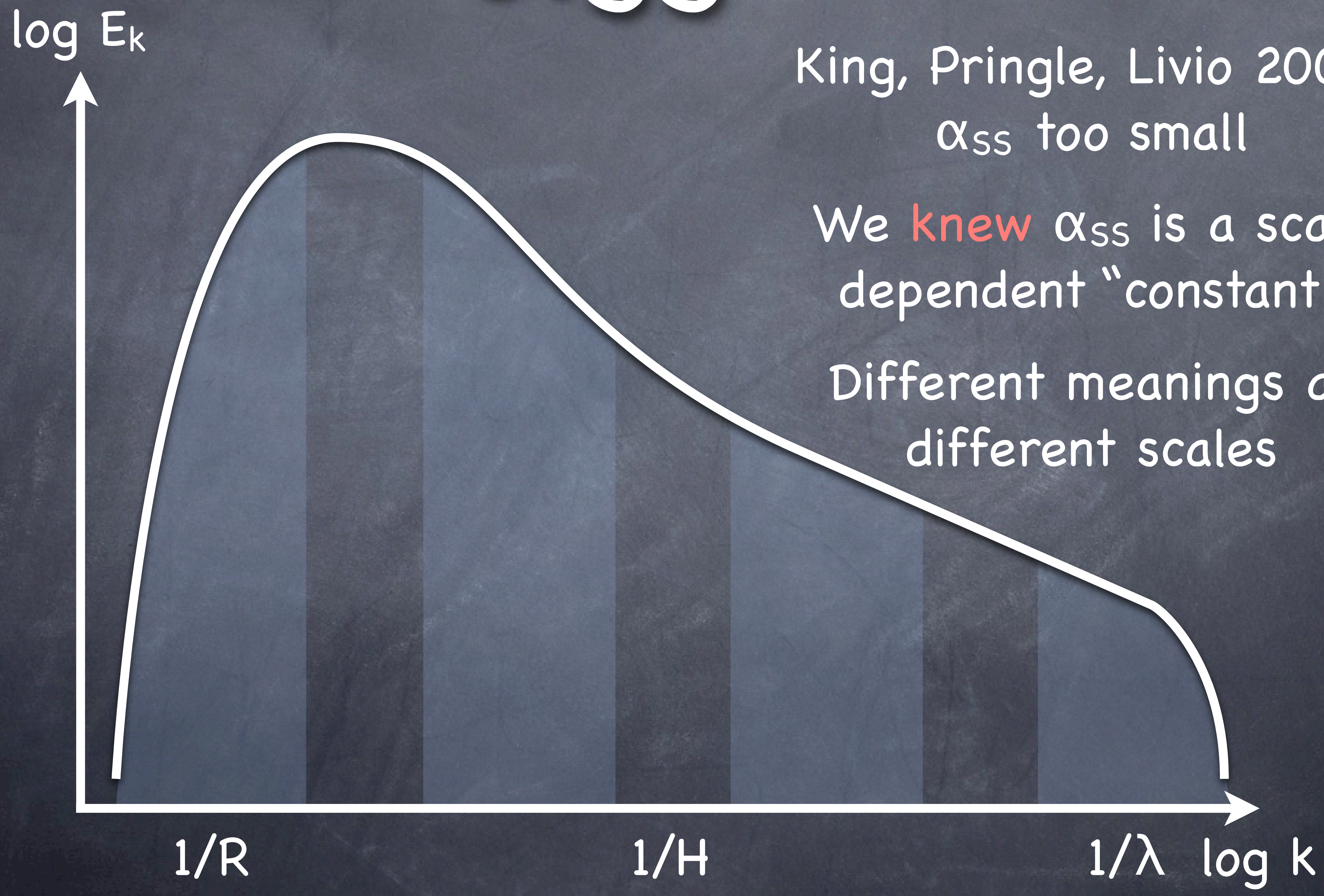
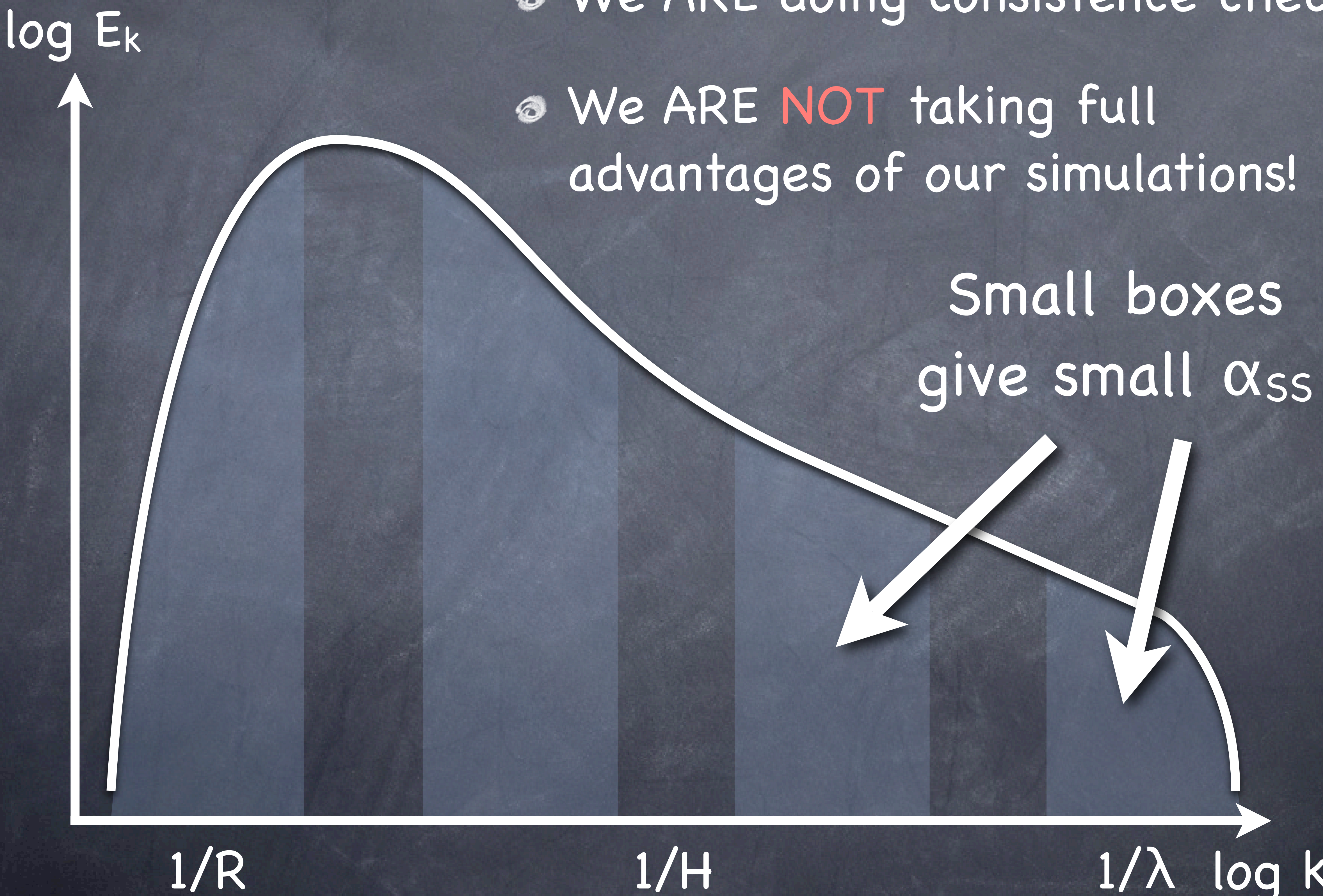


King, Pringle, Livio 2007: α_{SS} too small

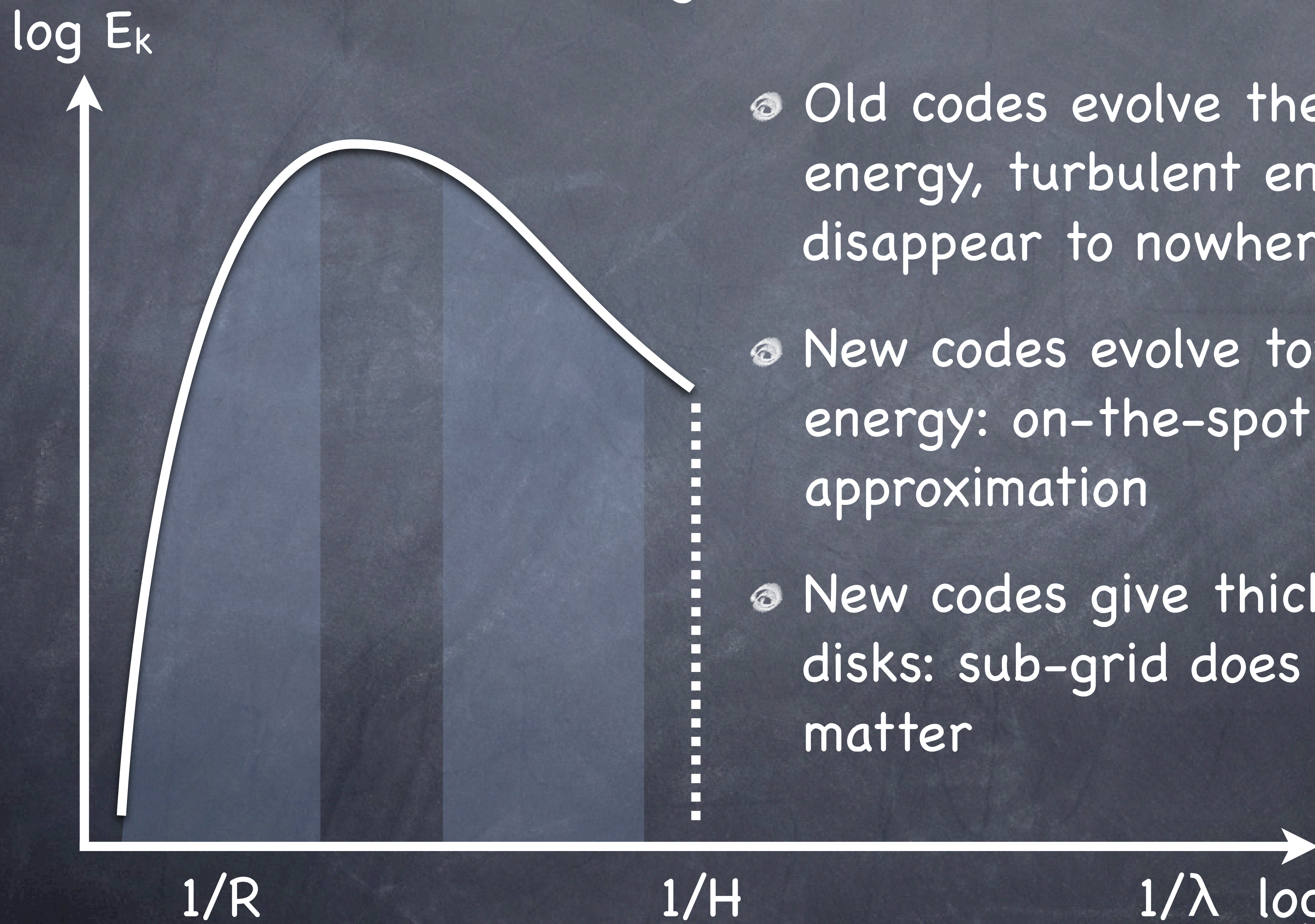
We knew α_{SS} is a scale dependent "constant"

Different meanings at different scales

- We ARE doing multi-scale studies
- We ARE doing consistence check
- We ARE NOT taking full advantages of our simulations!



- Maybe study large scales only? Forget about small scales?



- Old codes evolve thermal energy, turbulent energy disappear to nowhere
- New codes evolve total energy: on-the-spot approximation
- New codes give thicker disks: sub-grid does matter

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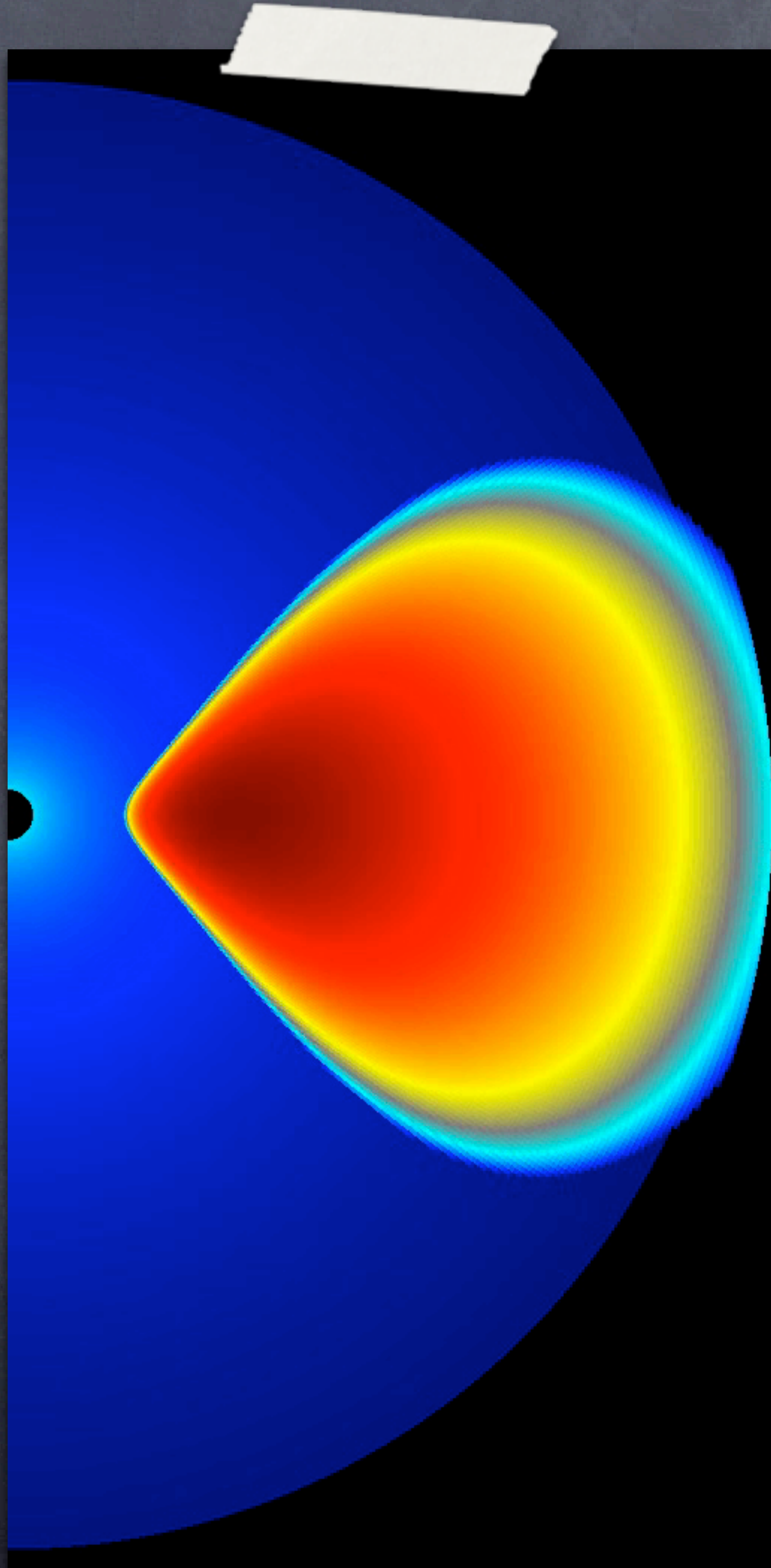

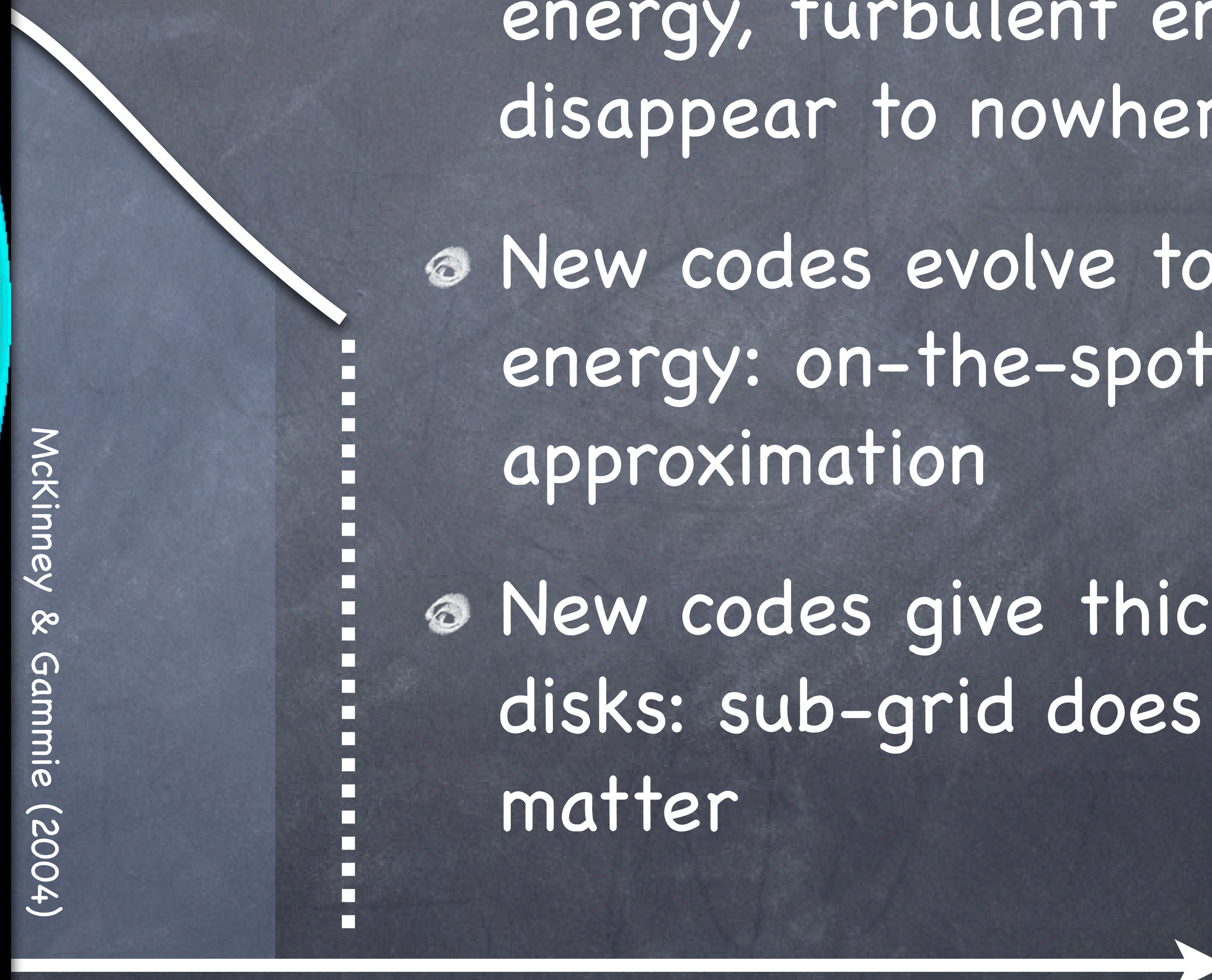

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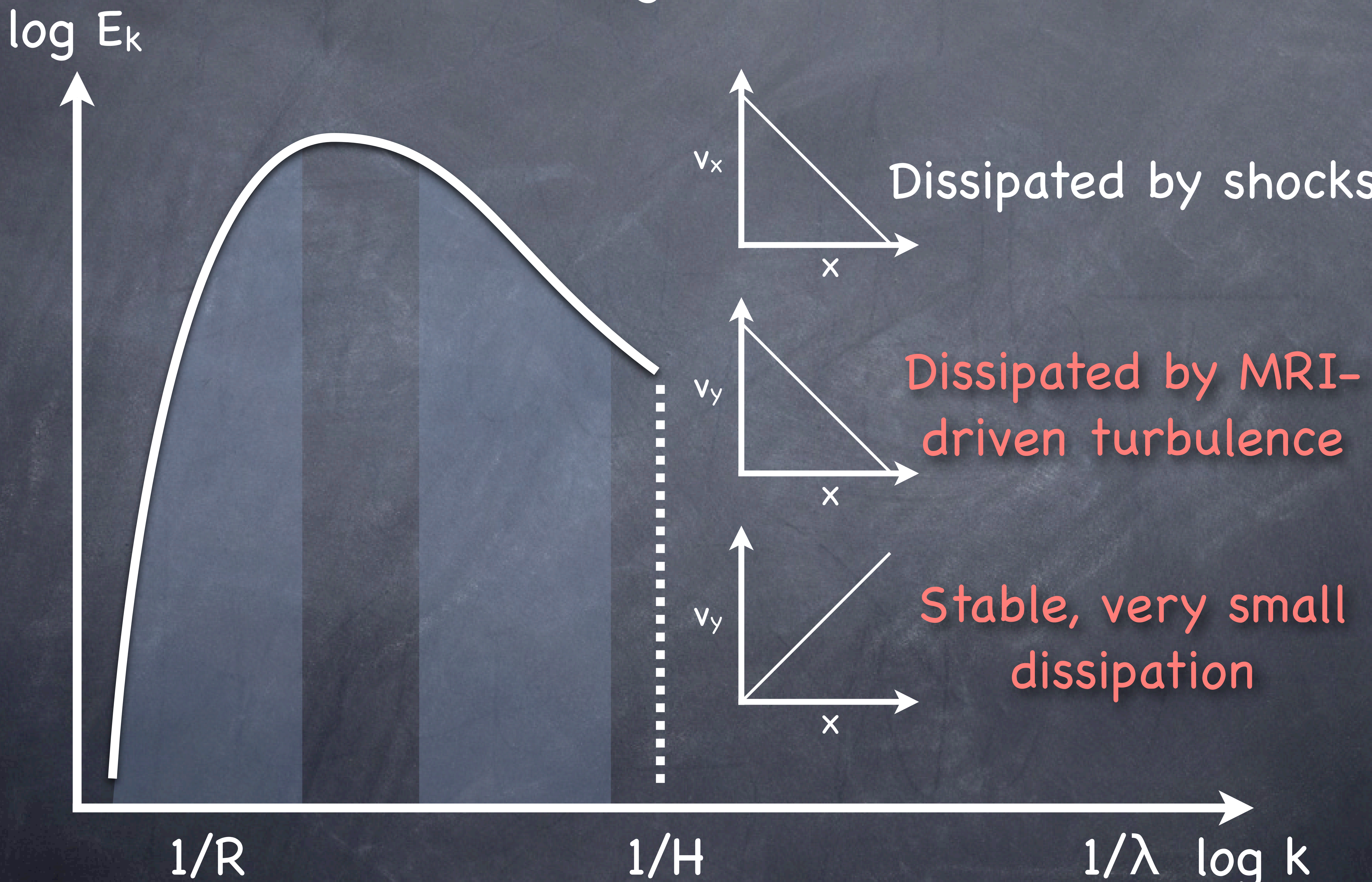
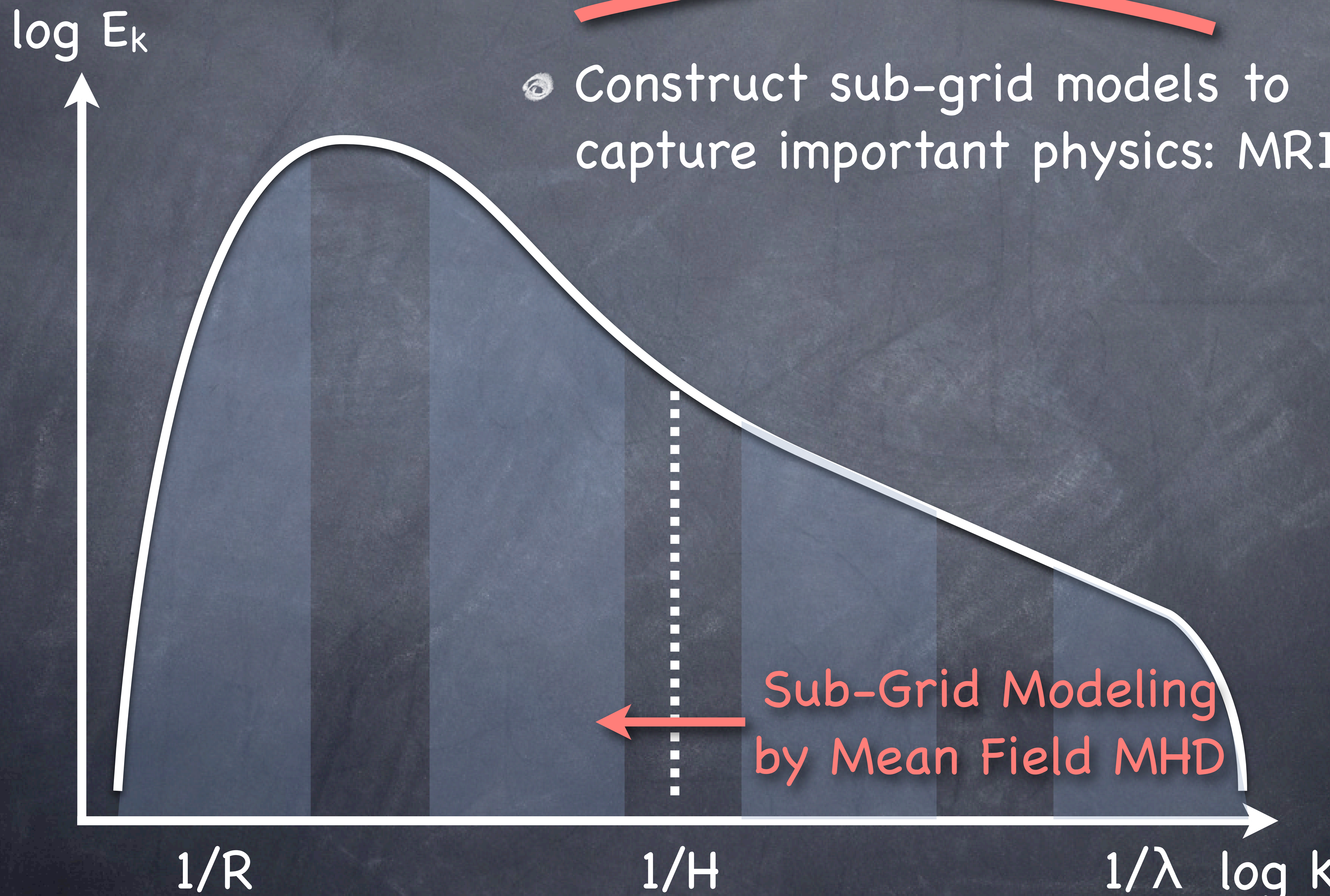


- ~~Maybe study large scales only? Forget about small scales?~~
- Construct sub-grid models to capture important physics: MRI



- Sub-grid modeling by mean field MHD: average over MHD equations

- Mean turbulent stress:

$$T_{ij} \equiv R_{ij} - M_{ij} \equiv \langle v'_i v'_j \rangle - \langle b'_i b'_j \rangle$$

- Mean turbulent EMF:

$$\mathcal{E}_i \equiv \langle u' \times b' \rangle_i$$

- Ideallly, measure T_{ij} and $\mathcal{E}_i$ from simulations, find transport coefficients, feed them back to simulations!

Dynamo people care about this

Engineers care about this

Accretion people care about this

A Model for MRI-Driven Turb.

- Use our knowledge of MRI to construct a minimal turbulence model (Pessah, Chan, & Psaltis 2006)
- Minimal equations containing MRI

$$\partial_t \begin{bmatrix} v_x \\ v_y \\ b_x \\ b_y \end{bmatrix} = \begin{bmatrix} 0 & 2 & ik & 0 \\ -(2-q) & 0 & 0 & ik \\ ik & 0 & 0 & 0 \\ 0 & ik & -q & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ b_x \\ b_y \end{bmatrix}$$

- Derive dynamic equations for 2nd order correlations

$$\tfrac{1}{2}\partial_t \langle b_x b_x \rangle = \langle ik b_x v_x \rangle$$

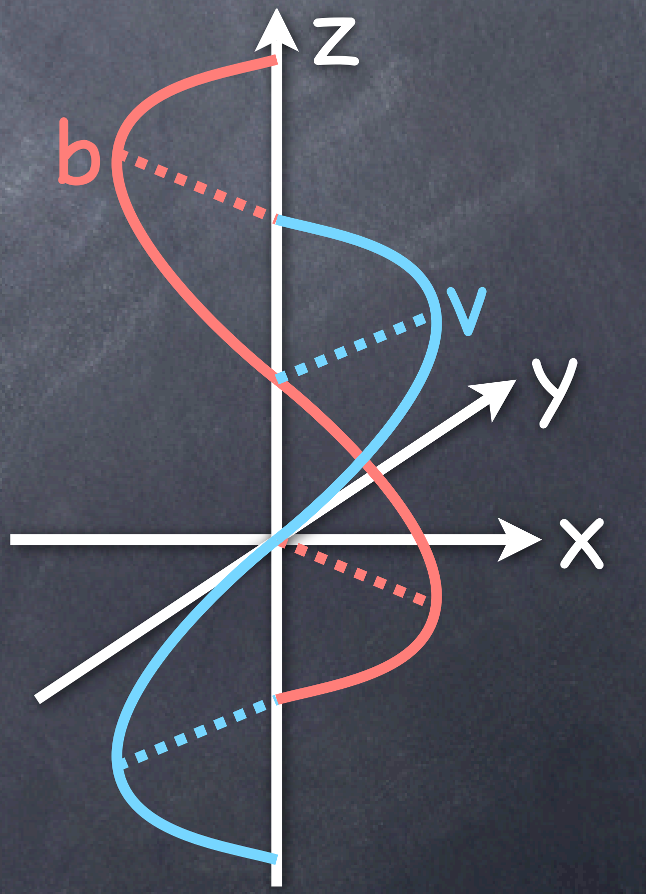
- How to model $\langle ik b_x v_x \rangle$?

$$\langle ik b_x v_x \rangle \equiv iK \langle b_x v_x \rangle$$

- Won't work, because (unstable) fluctuations are out of phase, $\langle b_i v_j \rangle$ always small!
- Define

$$W_{xy} \equiv - \langle ik b_x v_x \rangle \equiv \langle b_x \omega_y \rangle$$

- Treat it as new dynamic variable, closure at "second moment" in ik



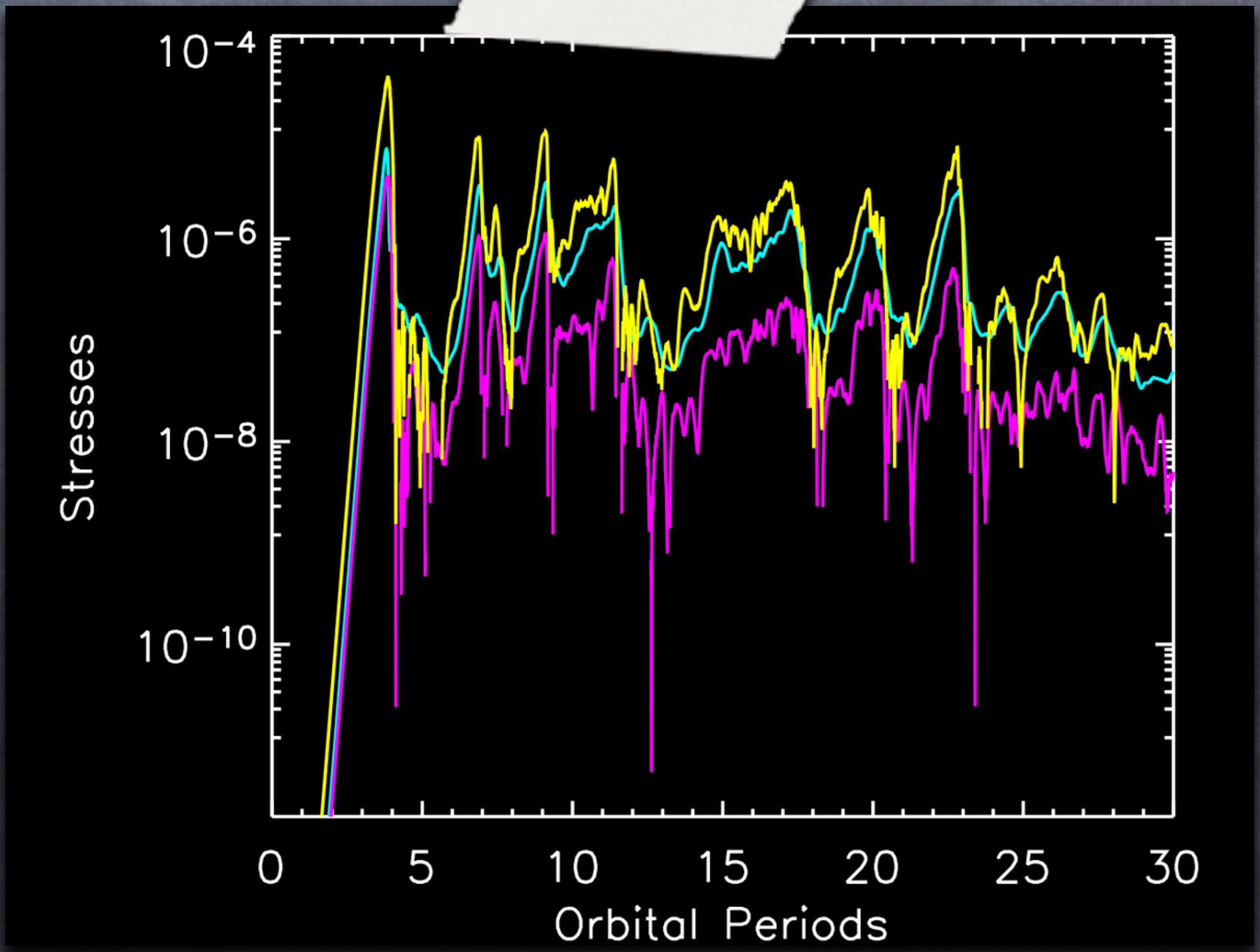
- R_{ij}, M_{ij}, and W_{ij}, 12 dynamic equations, e.g.,

$$\partial_t R_{xx} = 4R_{xy} + 2W_{xy}$$

$$\partial_t W_{xy} = 2W_{yy} - K^2 R_{xx} + K^2 M_{xx}$$

$$\partial_t M_{xx} = -\ 2W_{xy}$$

- $K^2 \equiv \langle k^2 v_i v_j \rangle / R_{ij} \approx \langle k^2 b_i b_j \rangle / M_{ij}$



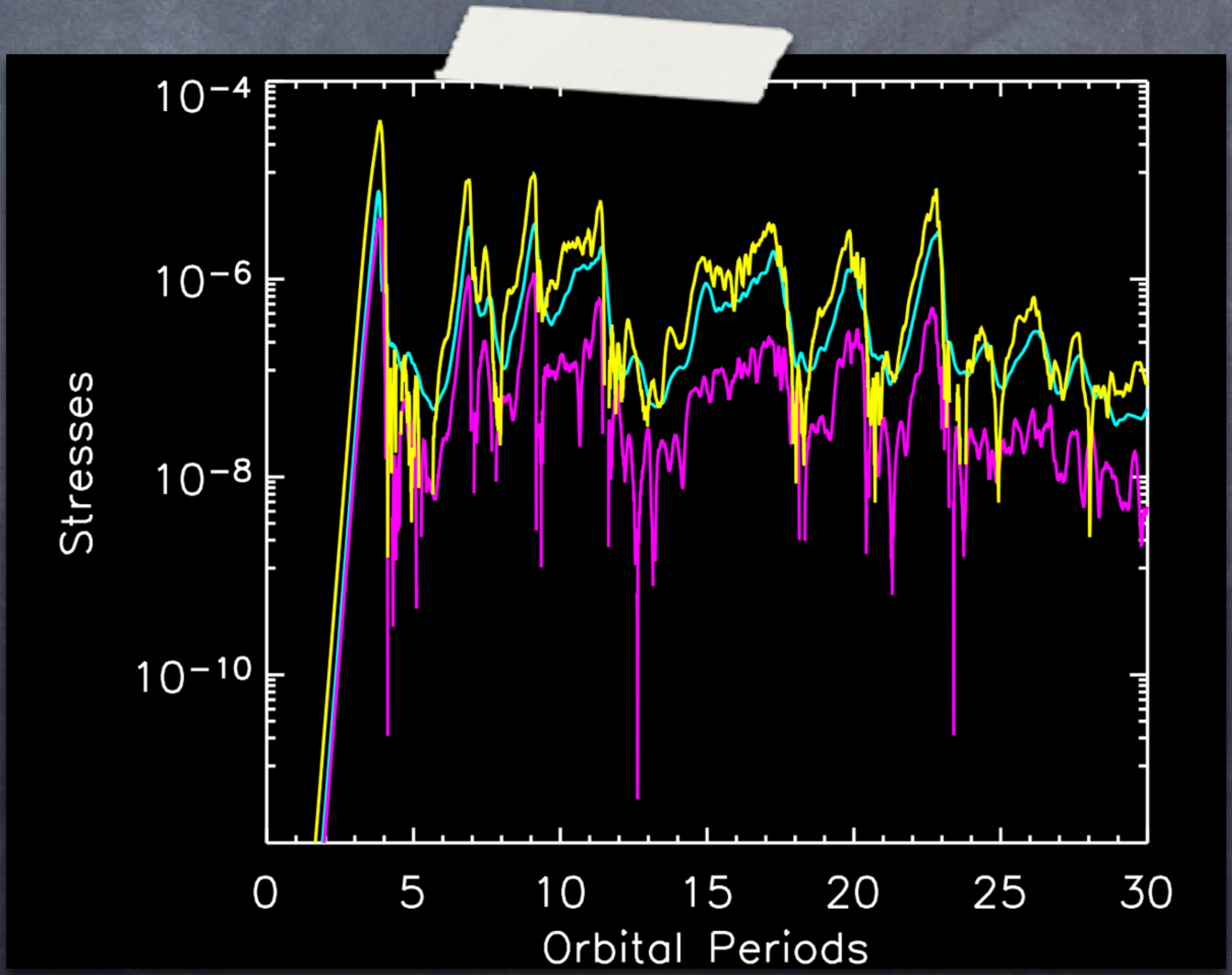
- Very simple nonlinear saturation term

$$\partial_t R_{xx} = 4R_{xy} + 2W_{xy} - \sqrt{M/M_0}\, R_{xx}$$

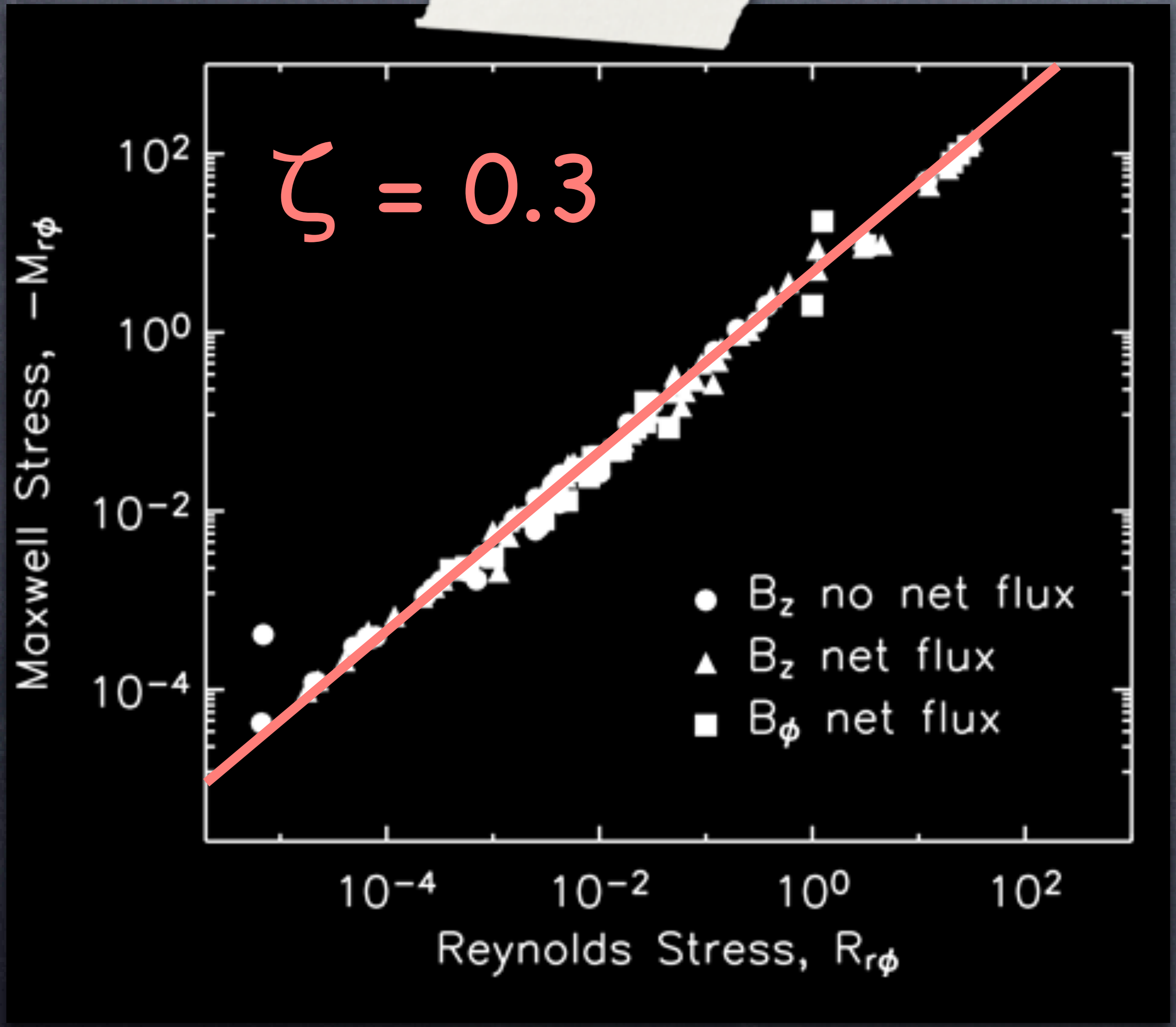
$$\partial_t W_{xy} = 2W_{yy} - K^2 R_{xx} + K^2 M_{xx} - \sqrt{M/M_0}\, W_{xy}$$

$$\partial_t M_{xx} = -\, 2W_{xy} - \sqrt{M/M_0}\, M_{xx}$$

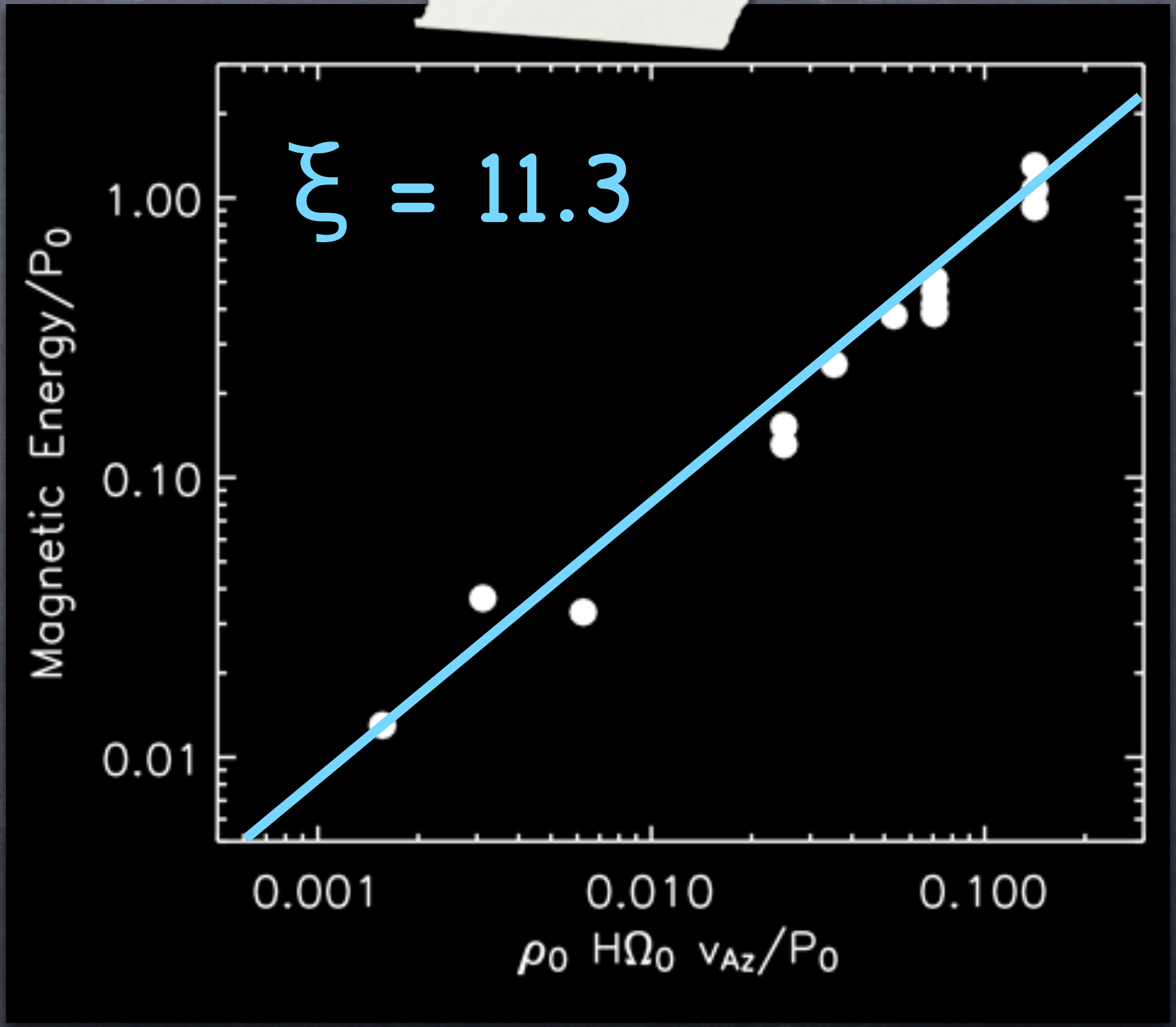
- $M \equiv M_{xx} + M_{yy}$, $M_0/2$ = saturated magnetic energy



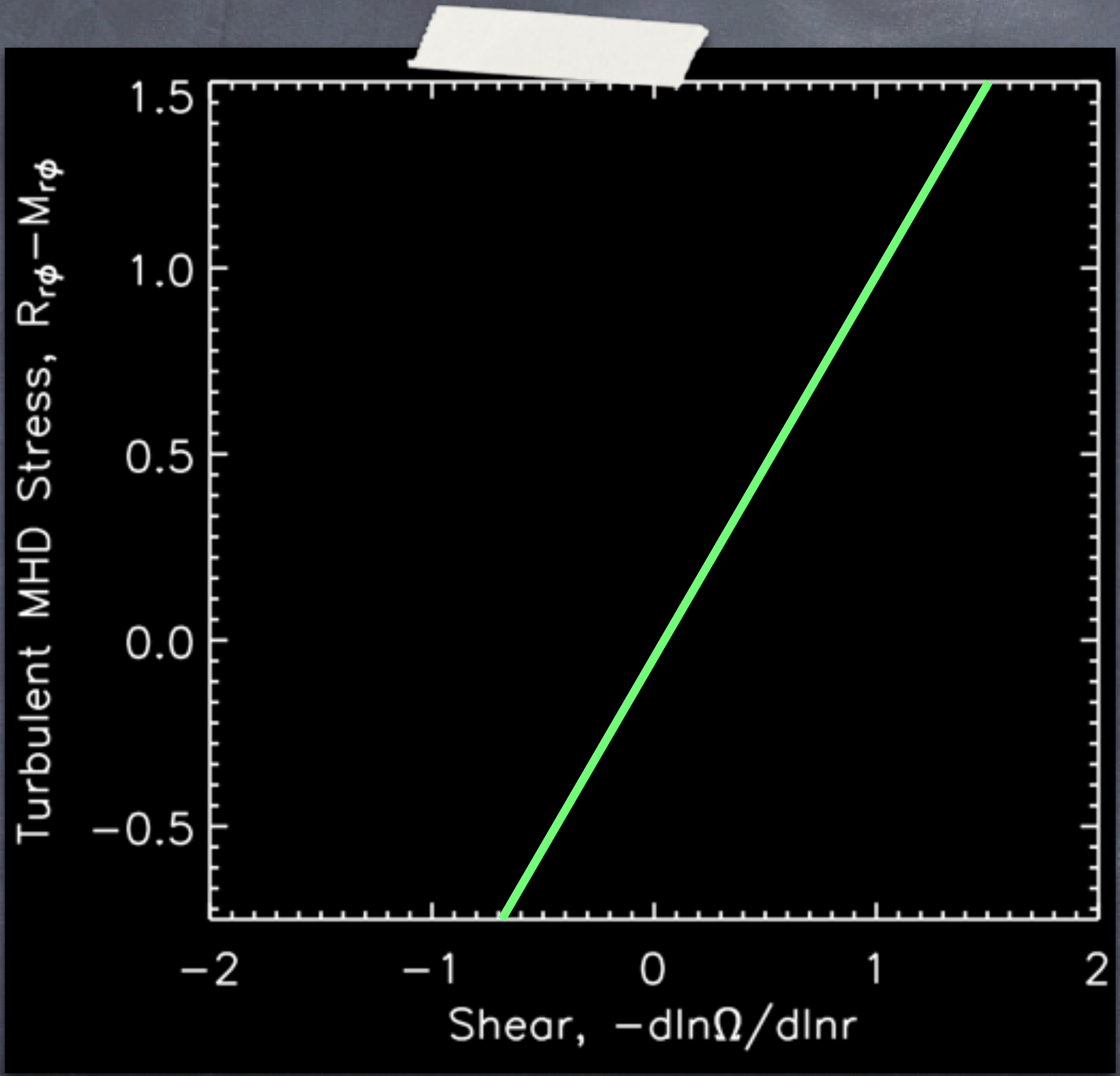
- Two parameters ζ and ξ:
  - $K = \zeta k_{max}$
  - $M_0 = 2\xi \rho_0 H \Omega_0 b_z$



Pessah, Chan, Psaltis 2006a

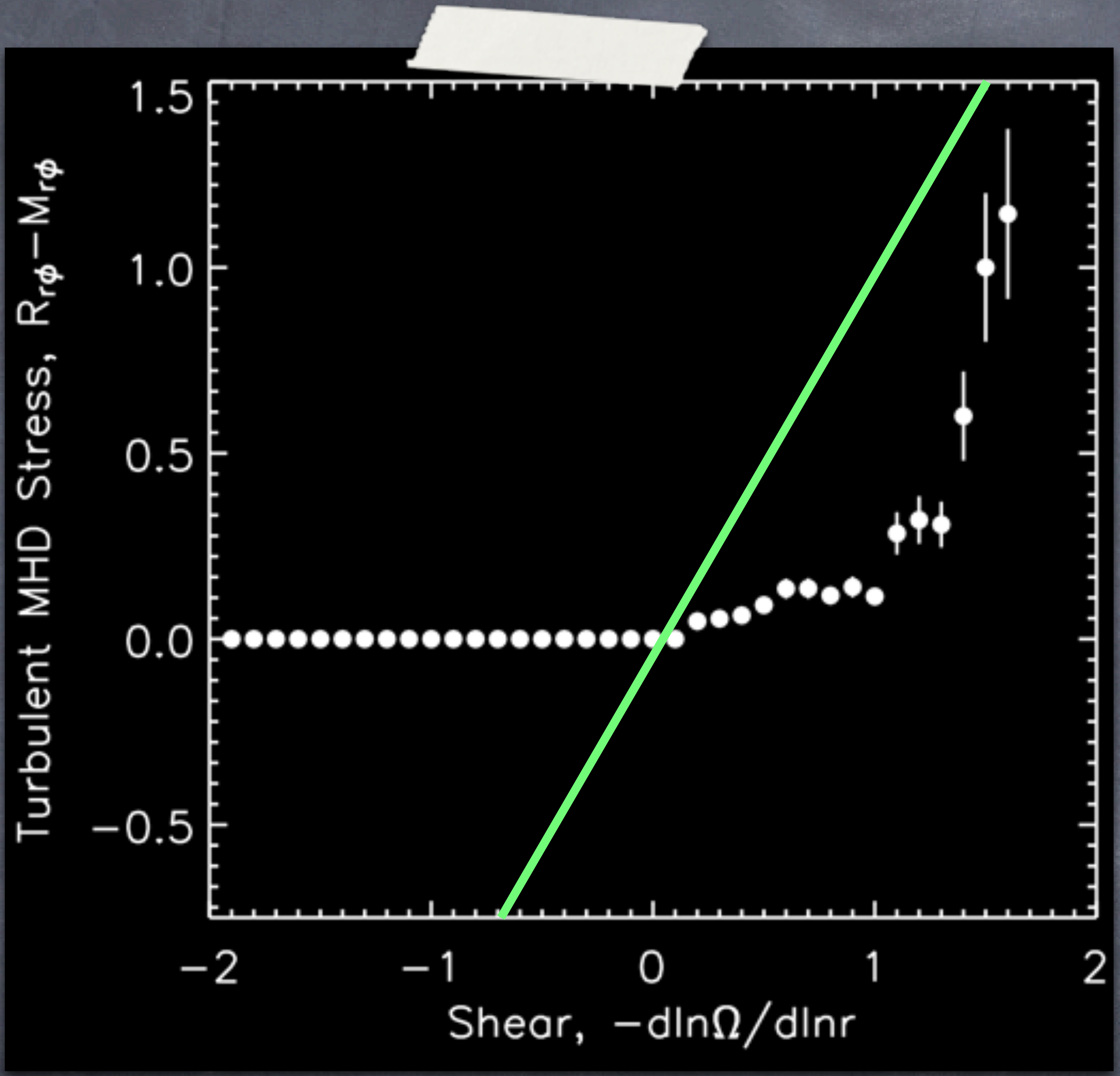


Pessah, Chan, Psaltis 2006b, data from Hawley et al 1995



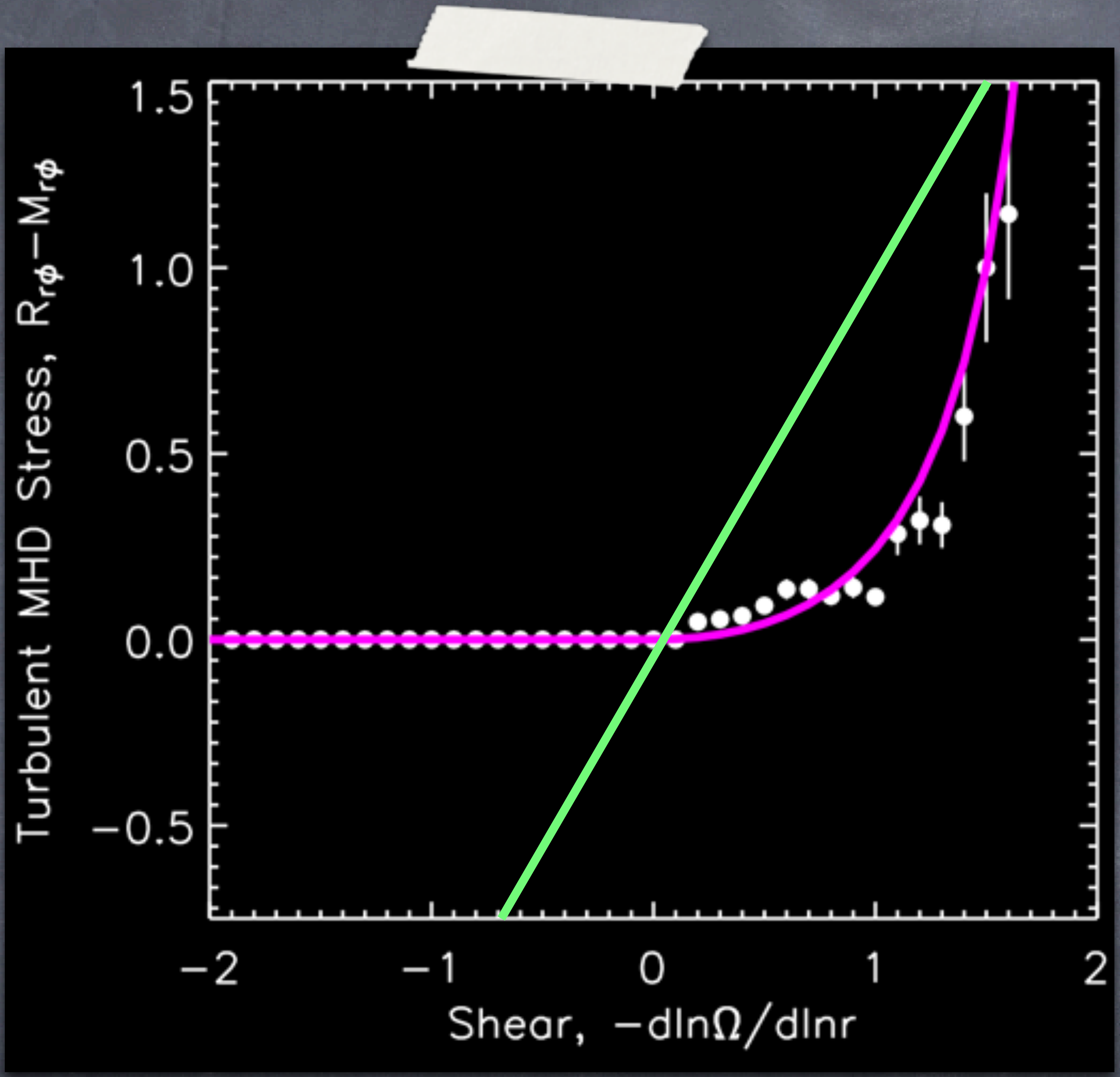
Pessah, Chan, Psaltis 2006b

α_{SS}-model is Newtonian



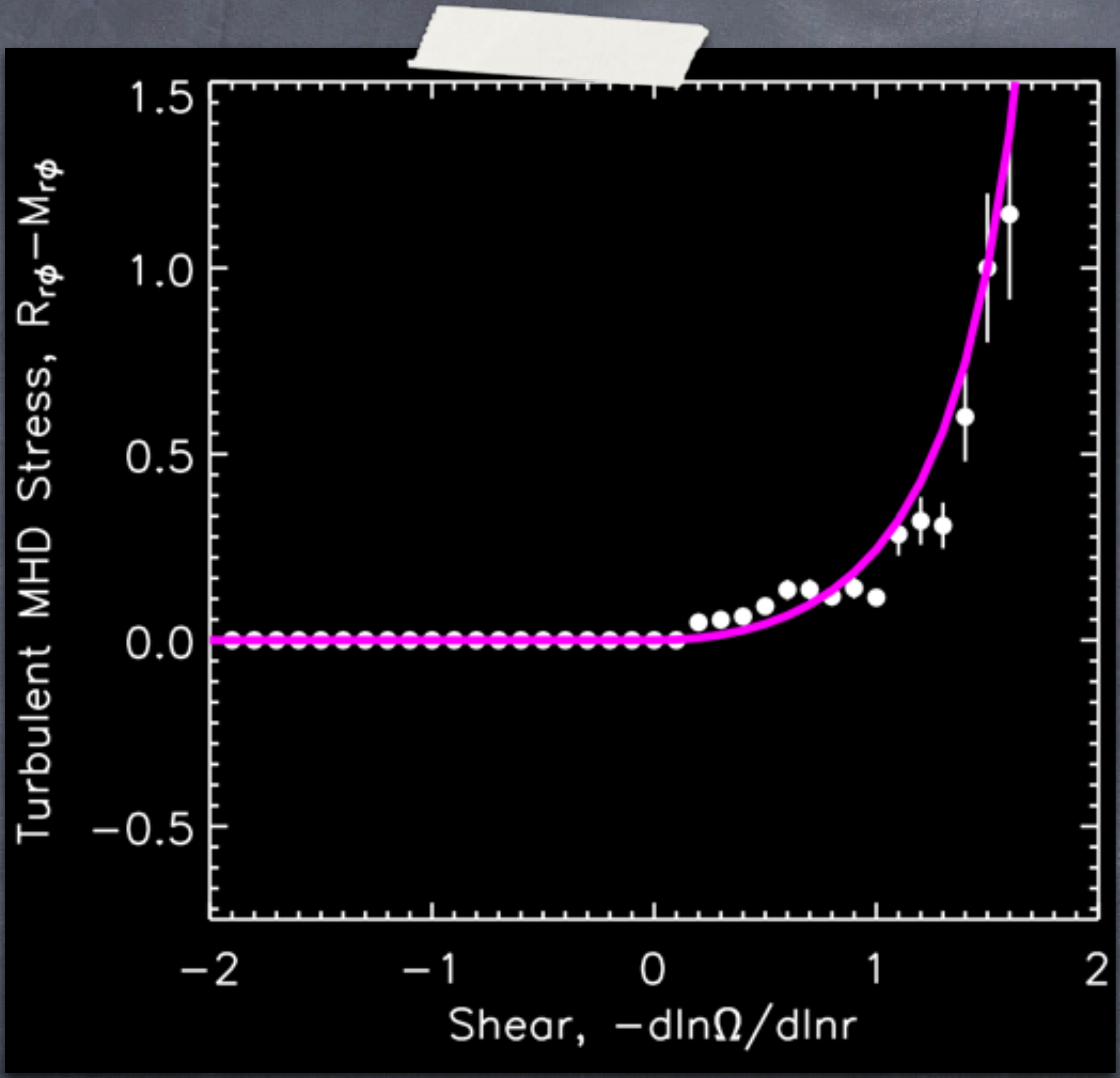
Pessah, Chan, Psaltis 2006b

MRI-driven turbulent stress from shearing boxes



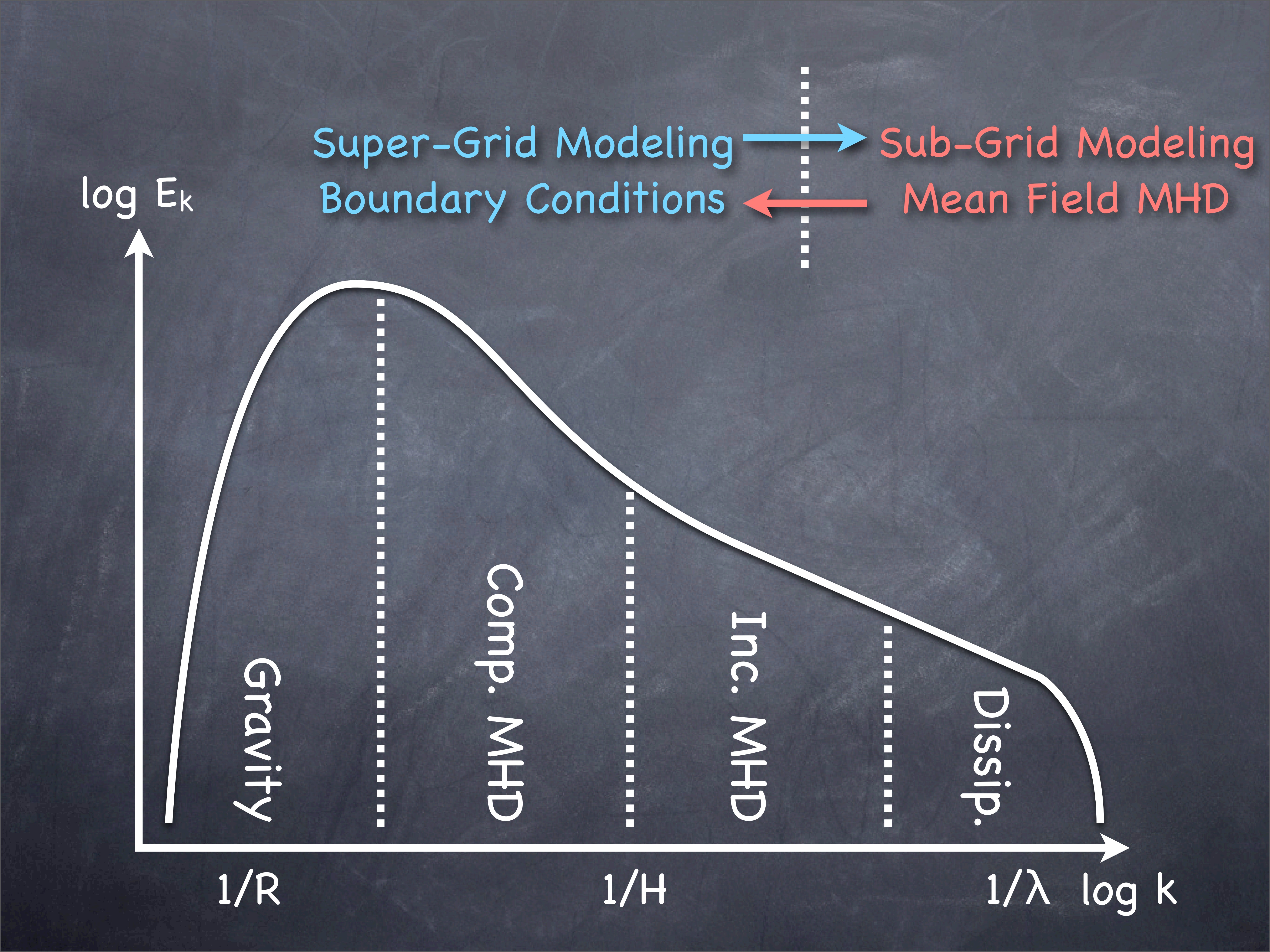
Pessah, Chan, Psaltis 2006b

Parameters fit by Keperian shearing boxes



Pessah, Chan, Psaltis 2006b

A simple turbulence model that can capture MRI


Super-Grid Modeling
Sub-Grid Modeling
Boundary Conditions
Mean Field MHD
log Ek
Gravity
Comp. MHD
Inc. MHD
Dissip.
1/R
1/H
1/λ
log k

Global simulations tell local simulations how to shear; while local simulations tell global simulations how to transport