Title: Metabolic Pathways for Gamma-Ray Bursts

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Abstract: There is now a consensus that gamma-ray bursts involve extraordinary power outputs, and highly relativistic dynamics. The trigger is probably a binary merger or collapse involving compact objects. The most plausible progenitors, ranging from NS-NS mergers to various hypernova-like scenarios, eventually lead to the formation of a black hole with a debris torus around it. The various modes of energy extraction from such systems are discussed.

Metabolic Pathways of Gamma-Ray Bursts

Enrico Ramirez-Ruiz (UCSC)

PI, 2011

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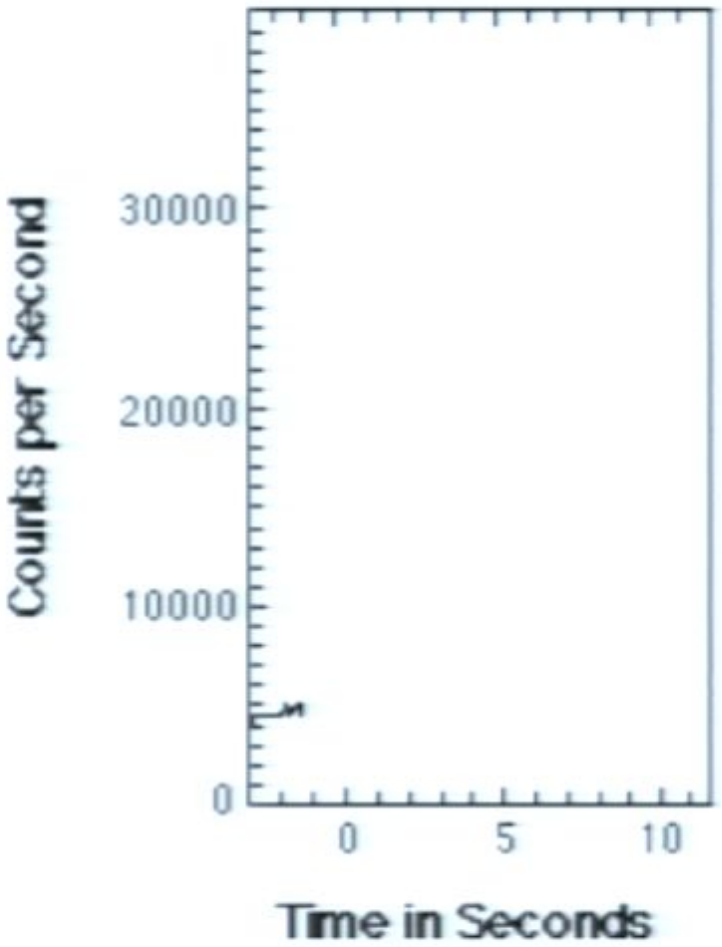

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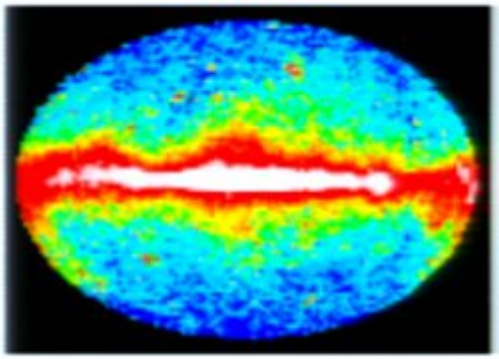

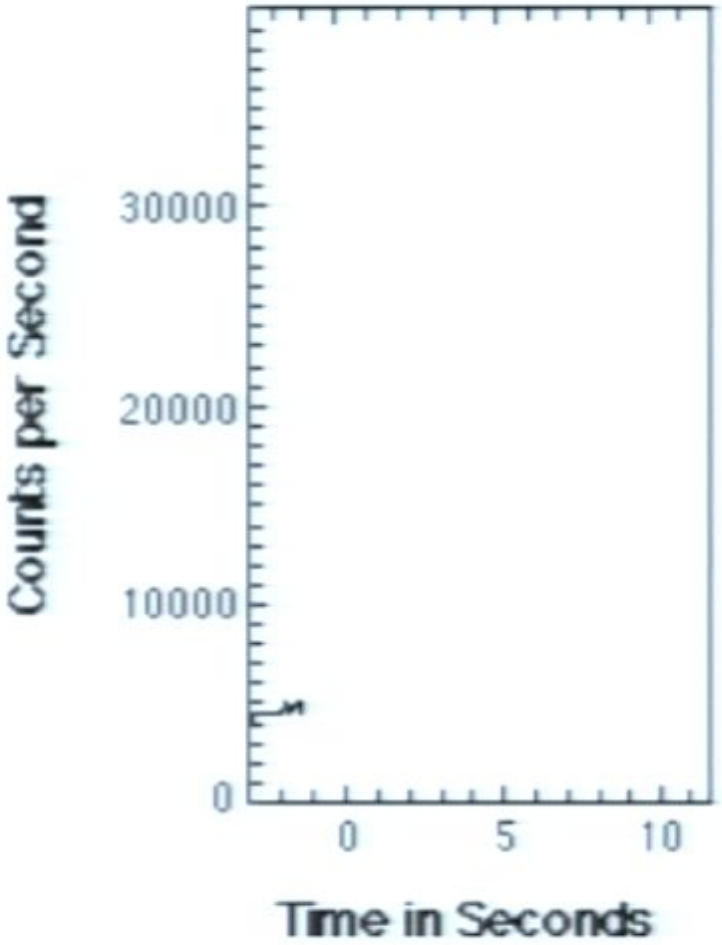

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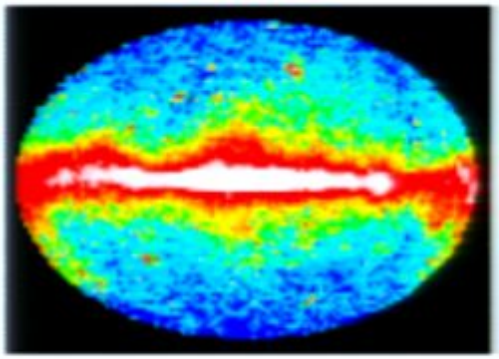

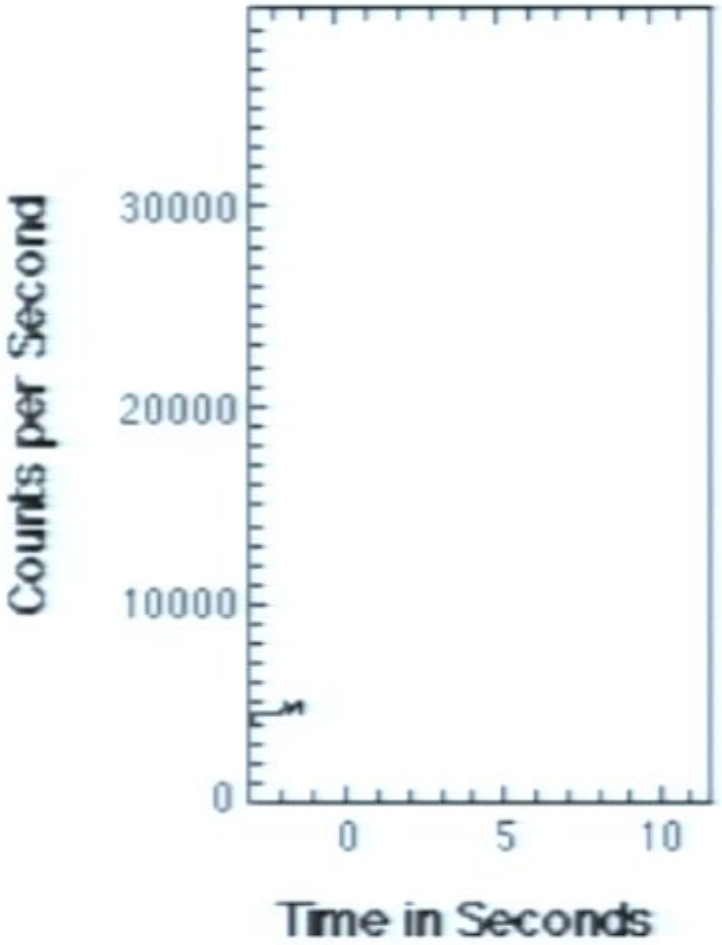

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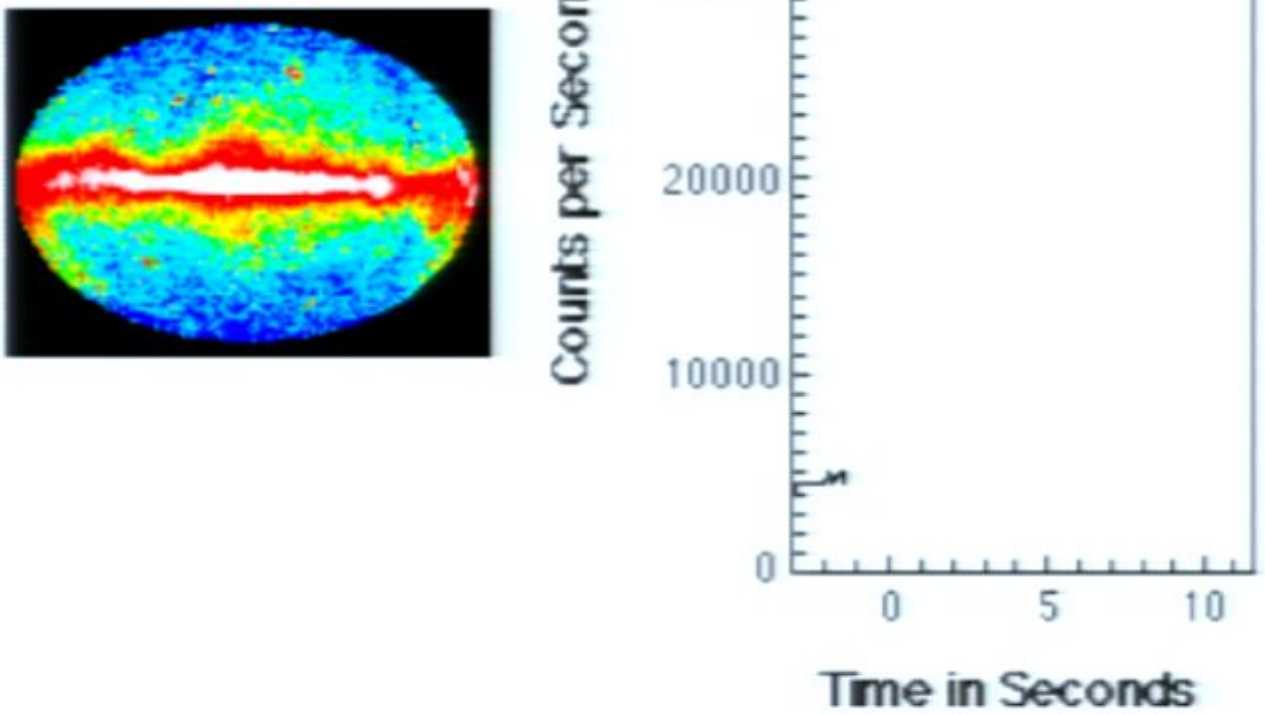

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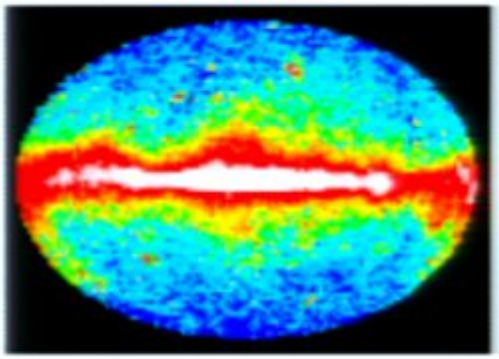

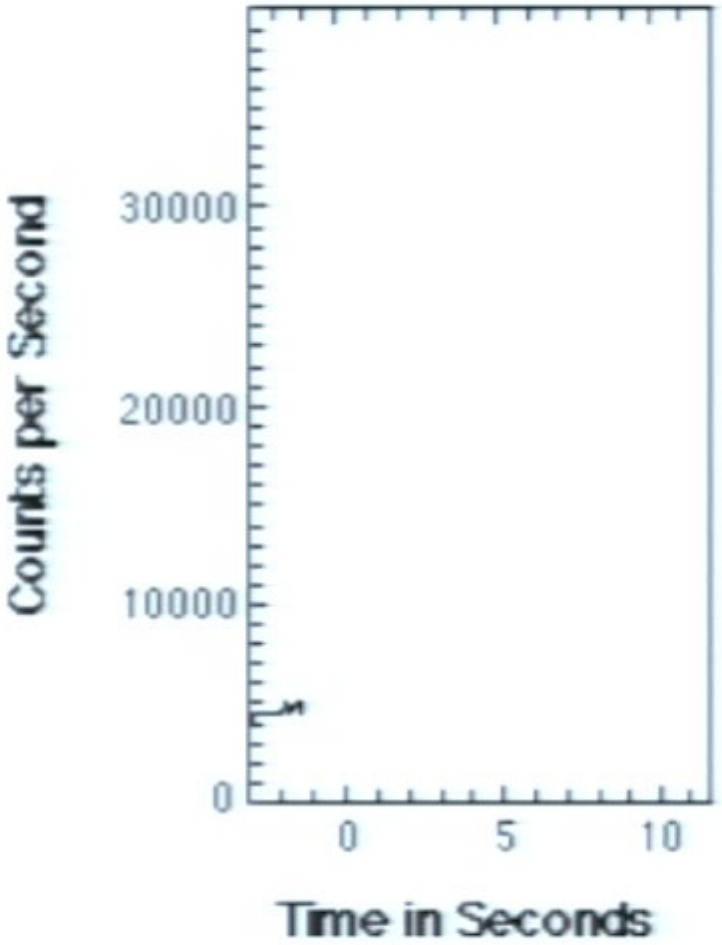

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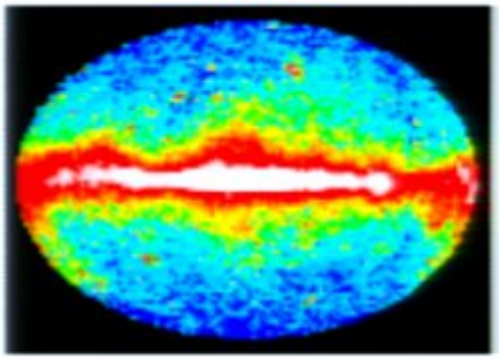
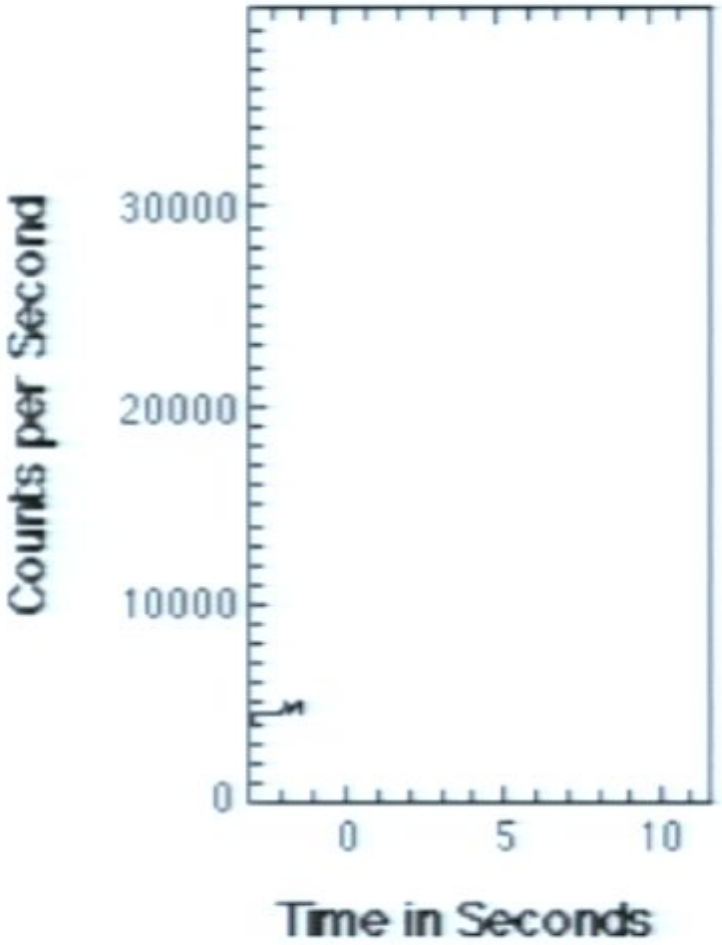
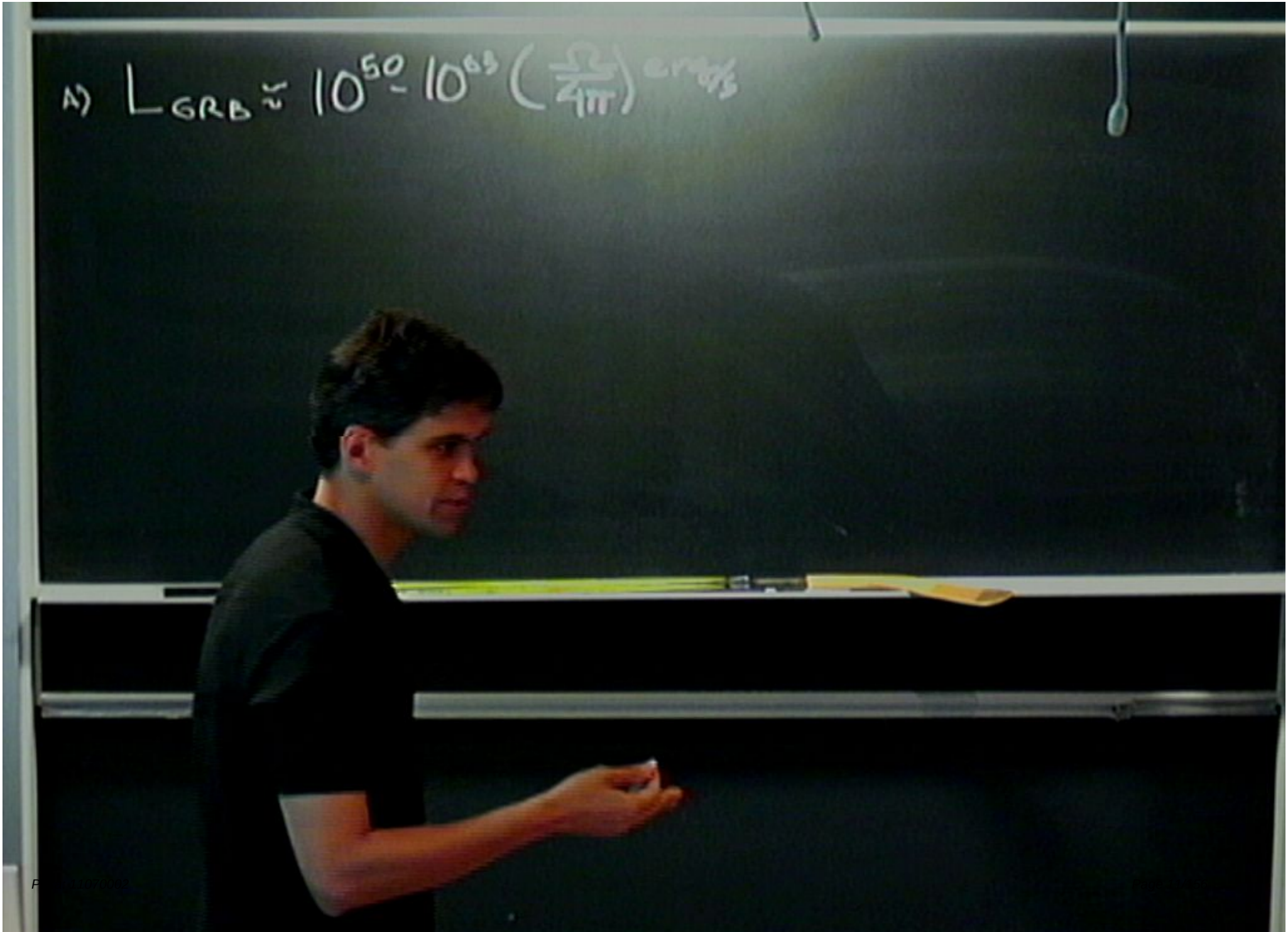
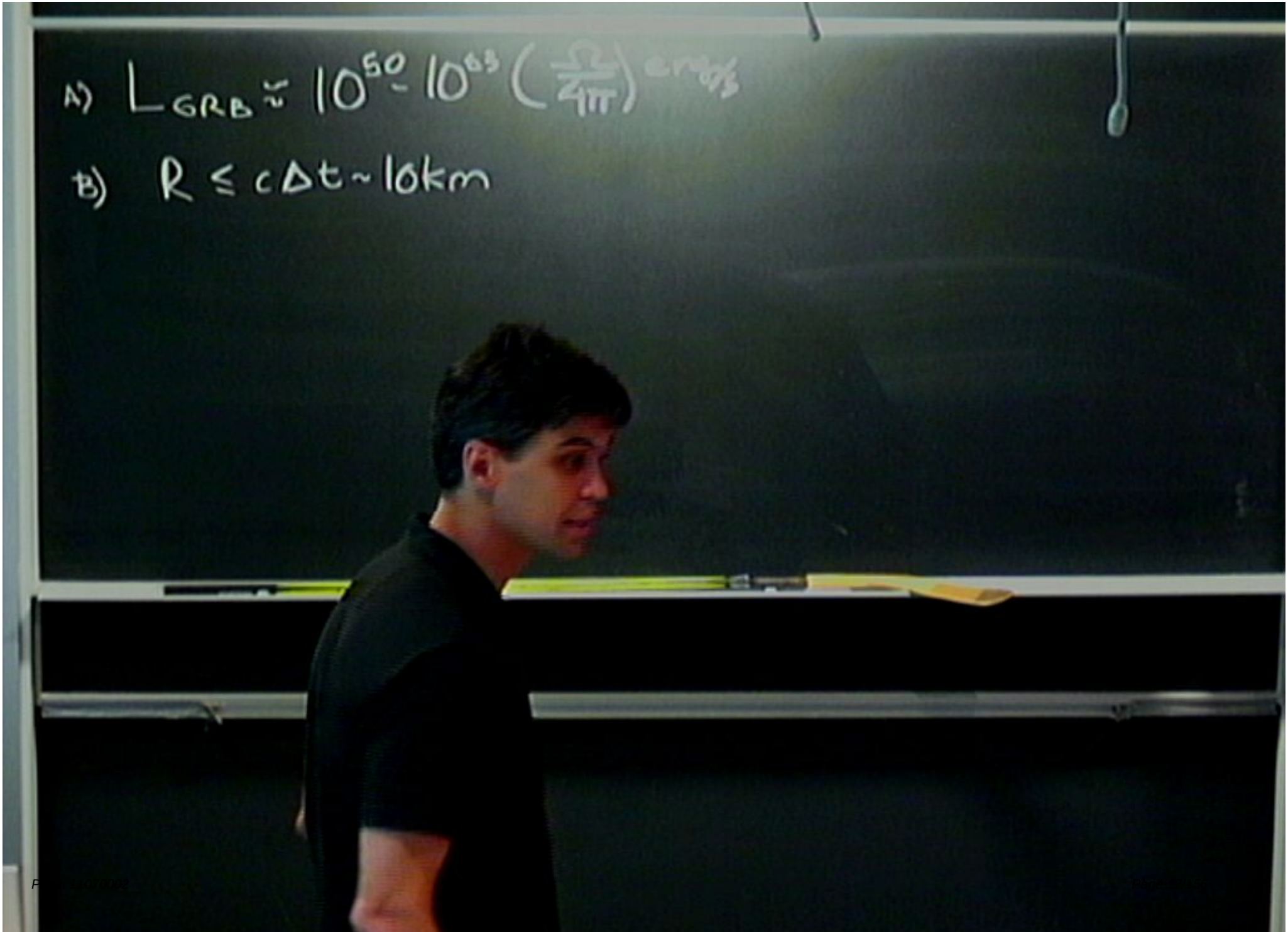
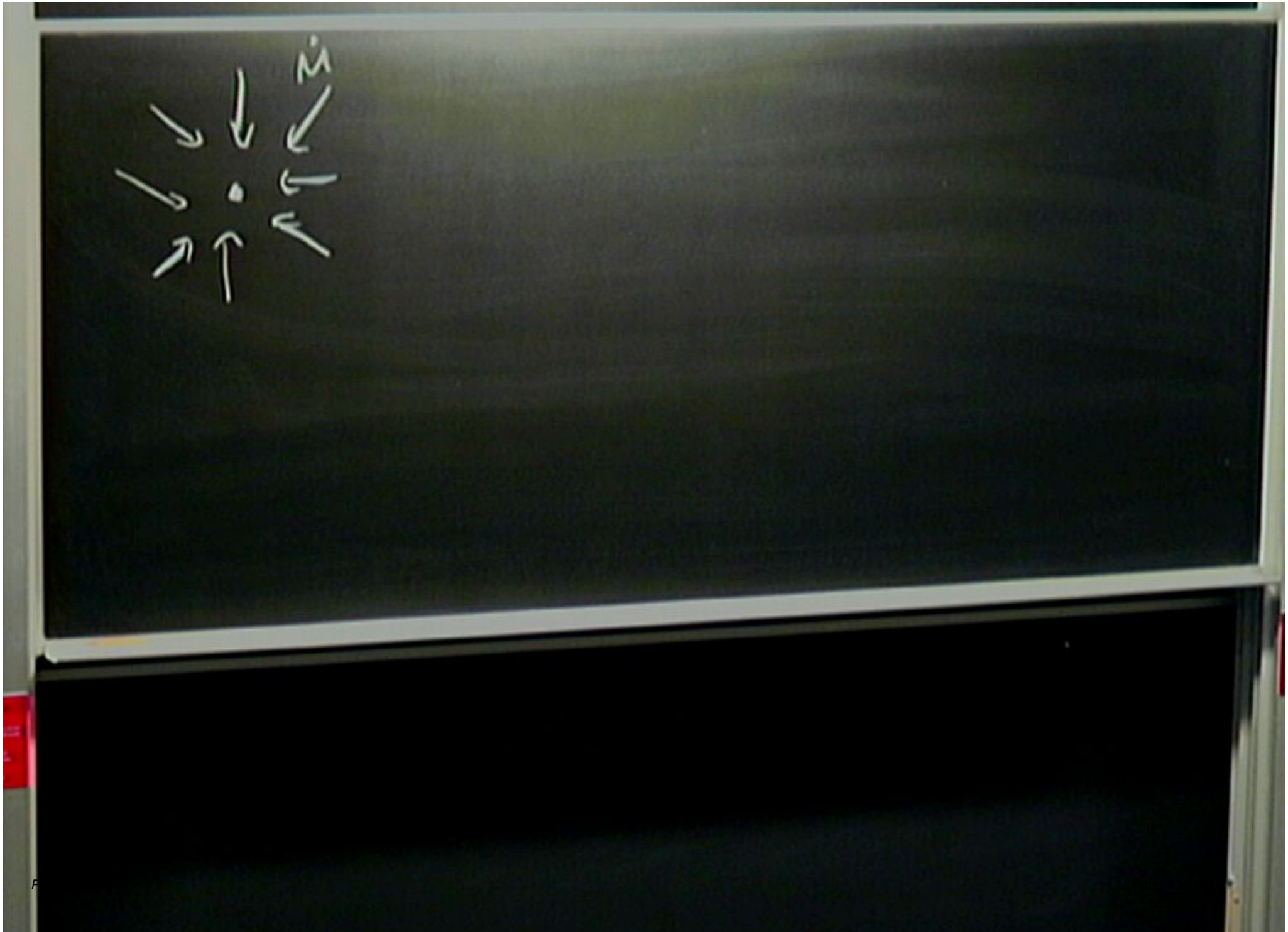
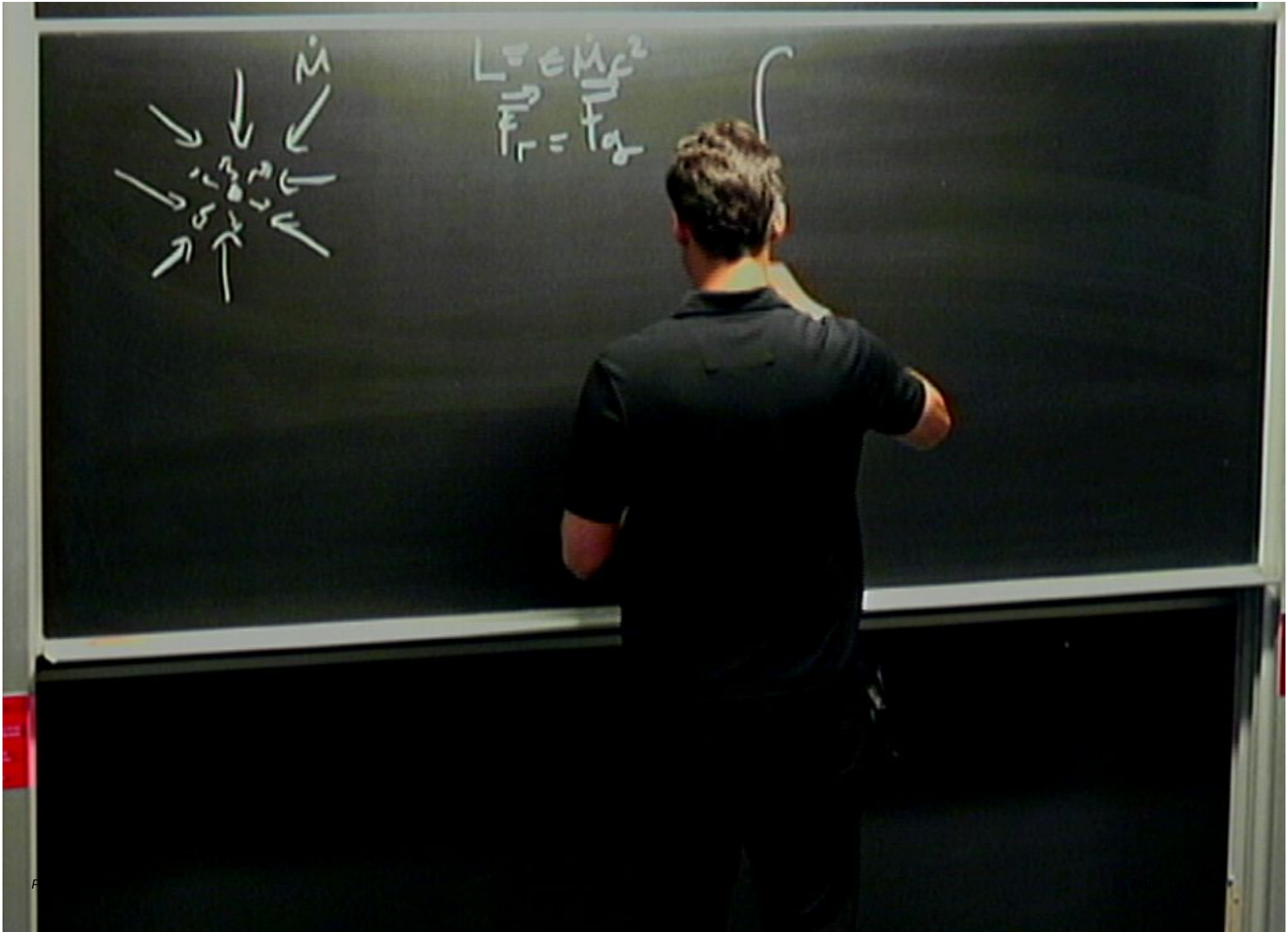


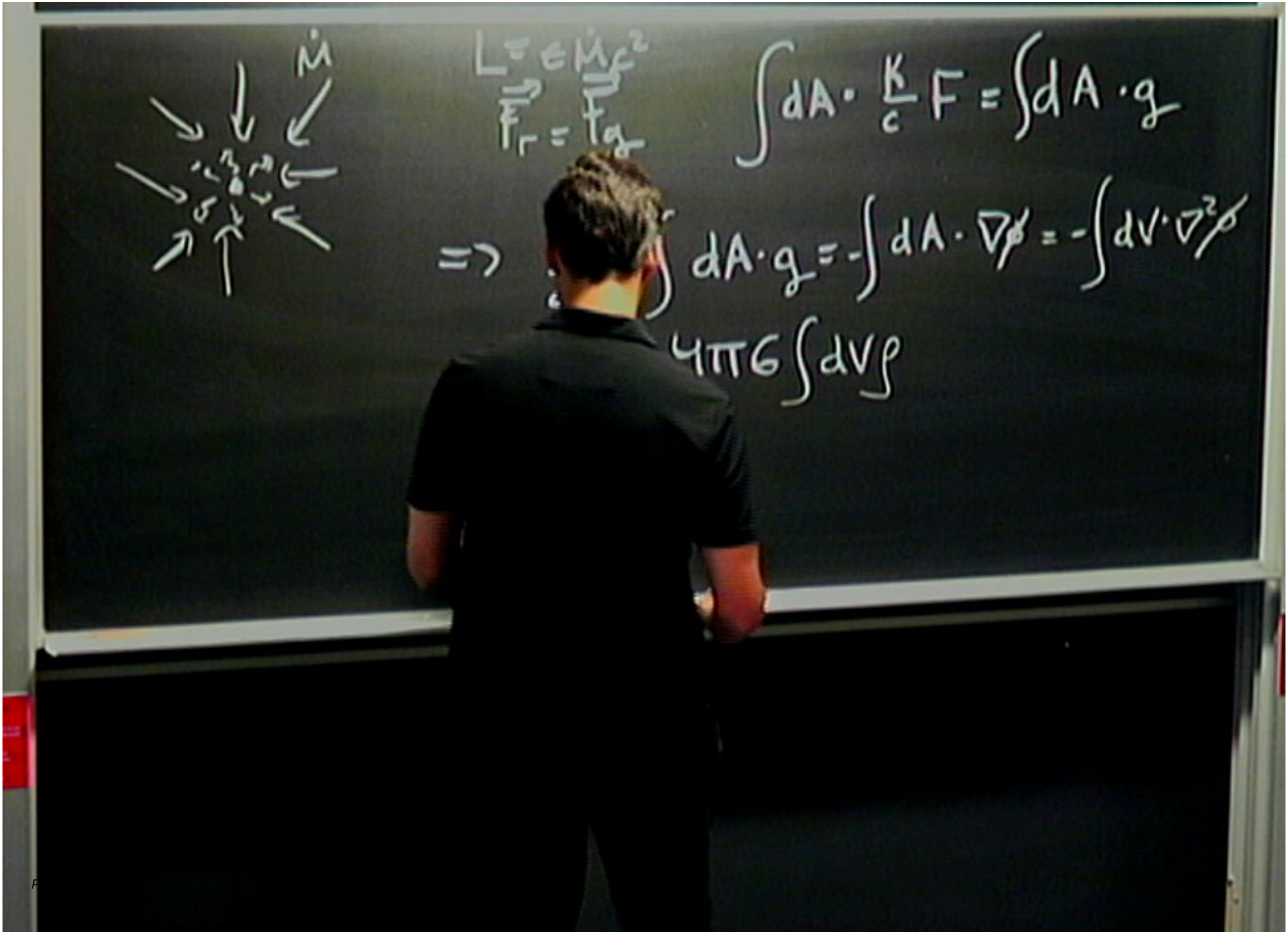



A) $L_{GRB} \sim 10^{50} - 10^{53} \left(\frac{\Omega}{4\pi}\right)$ erg/s

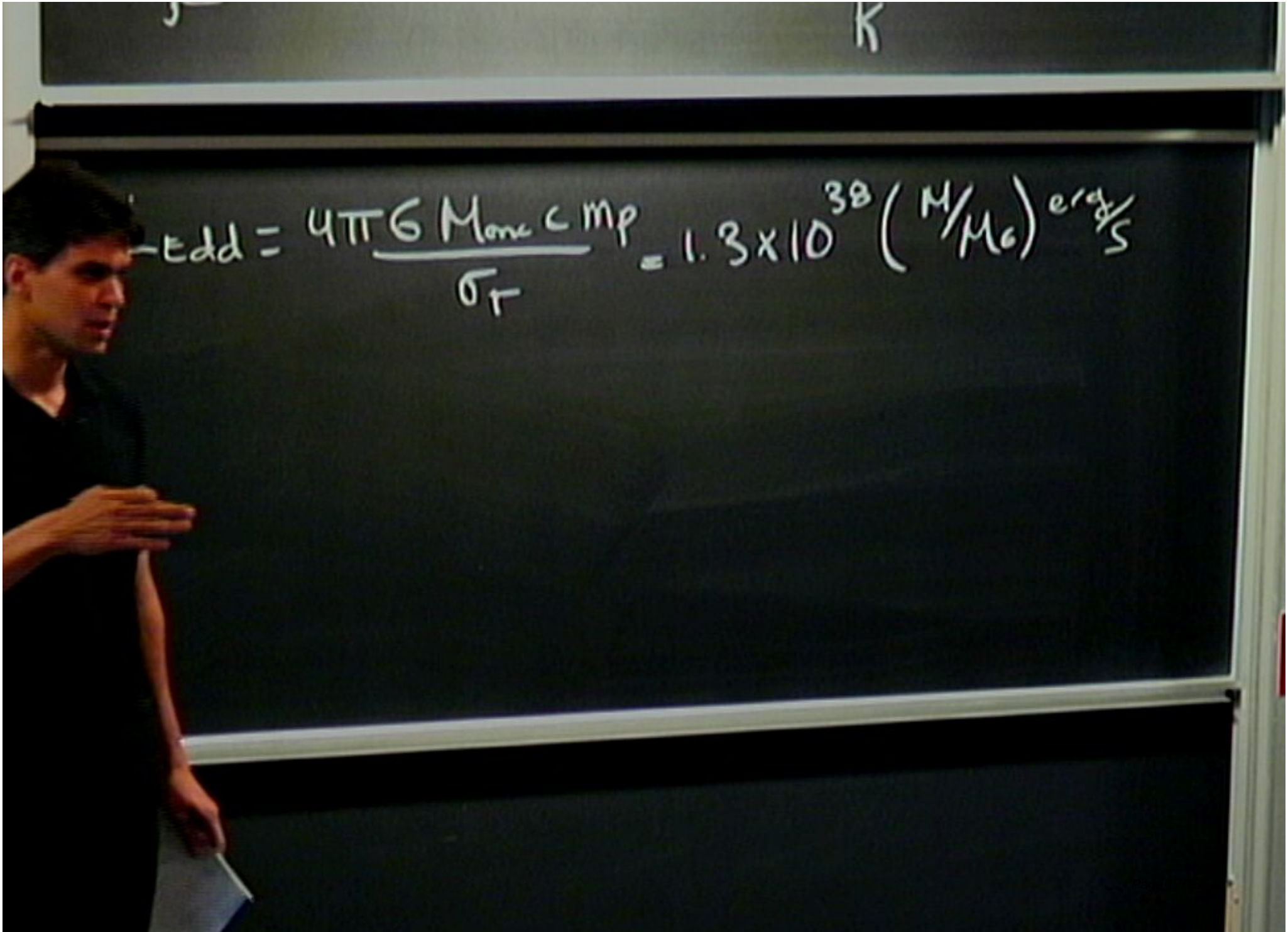

A) $L_{GRB} \simeq 10^{50} - 10^{53} \left(\frac{\Omega}{4\pi}\right)$ erg/s
B) $R \leq c\Delta t \sim 10km$

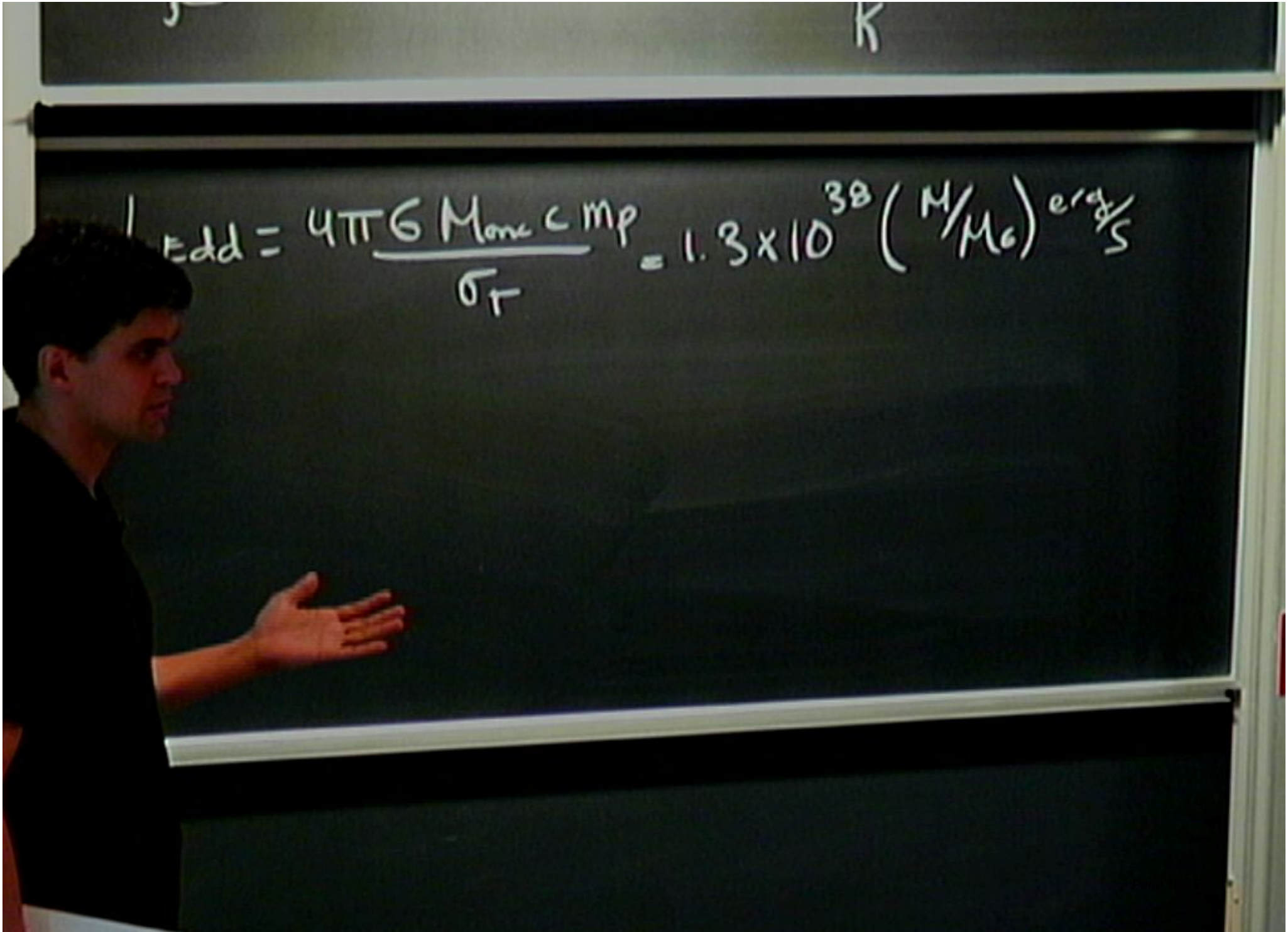

M

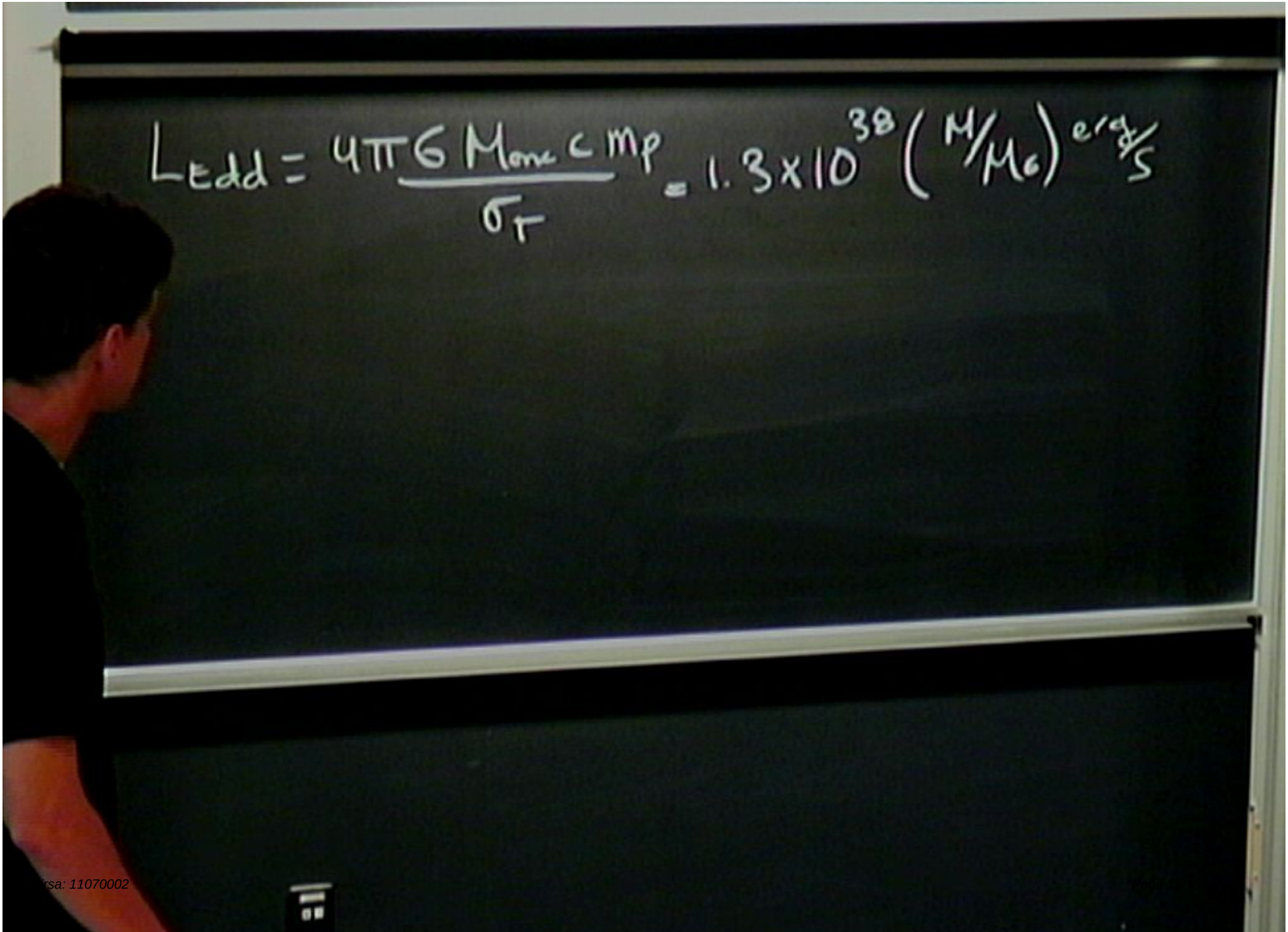

$\dot{M}$
$L = \epsilon \dot{M} c^2$
$\vec{F}_r = \vec{F}_g$

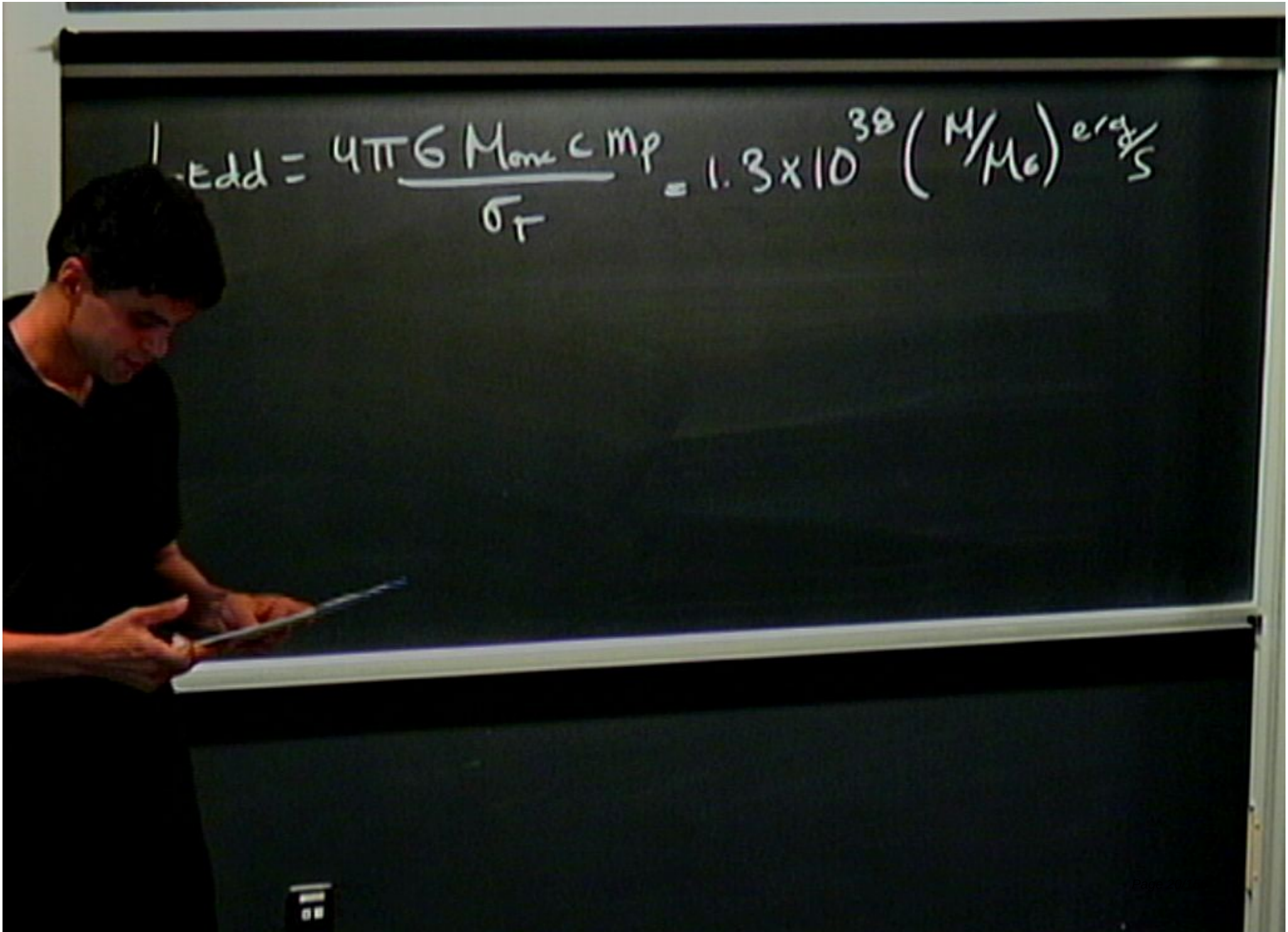

$\dot{M}$
$L = \epsilon \dot{M} c^2$
$F_r = F_g$
$\int dA \cdot \frac{K}{c} F = \int dA \cdot g$
$\Rightarrow \int dA \cdot g = -\int dA \cdot \nabla\phi = -\int dV \cdot \nabla^2\phi$
$4\pi G \int dV \rho$

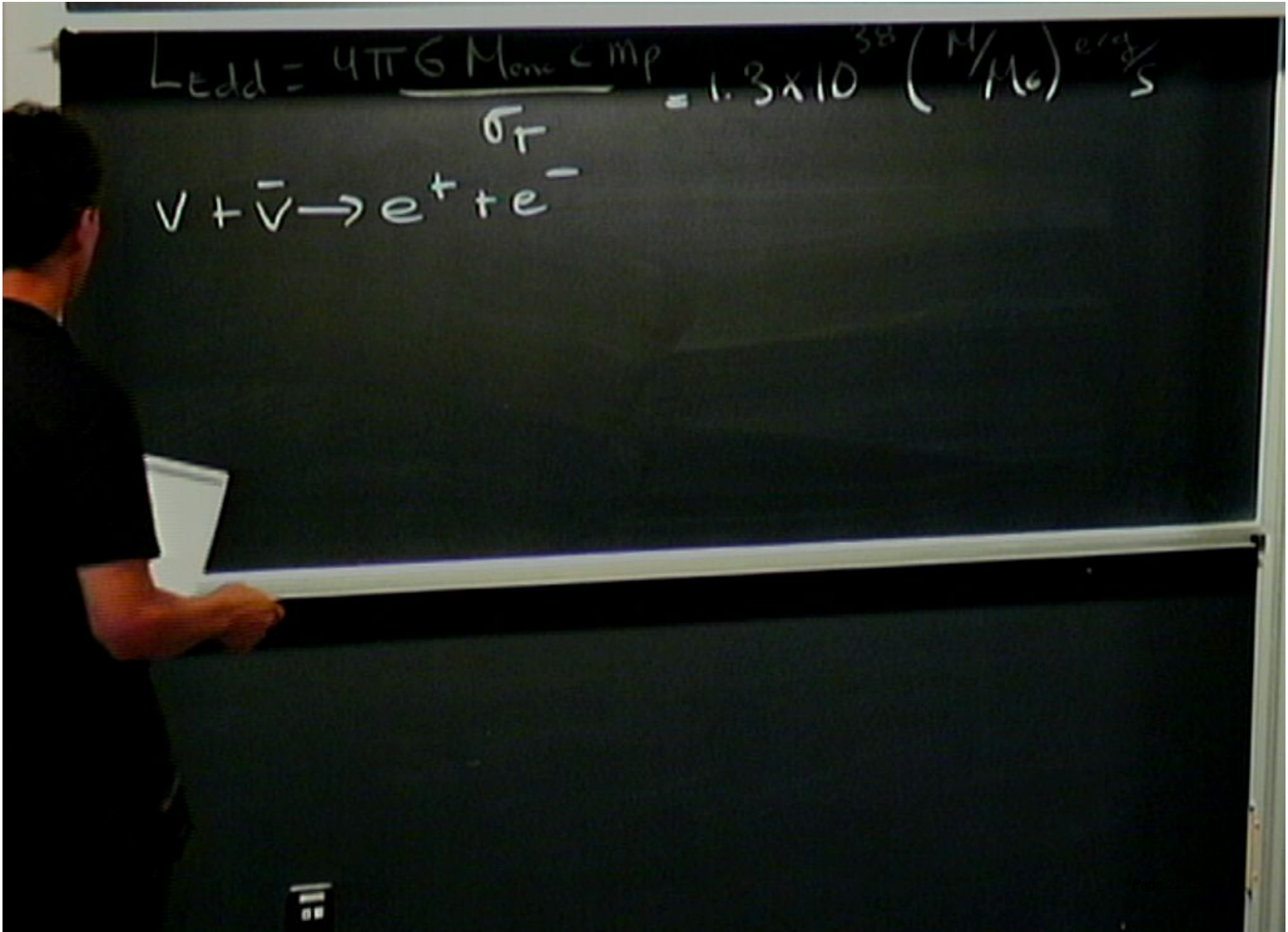
$$L_{Edd} = \frac{4\pi G M_{ons} c m_p}{\sigma_T} = 1.3 \times 10^{38} \left(M/M_\odot \right) \text{ erg/s}$$

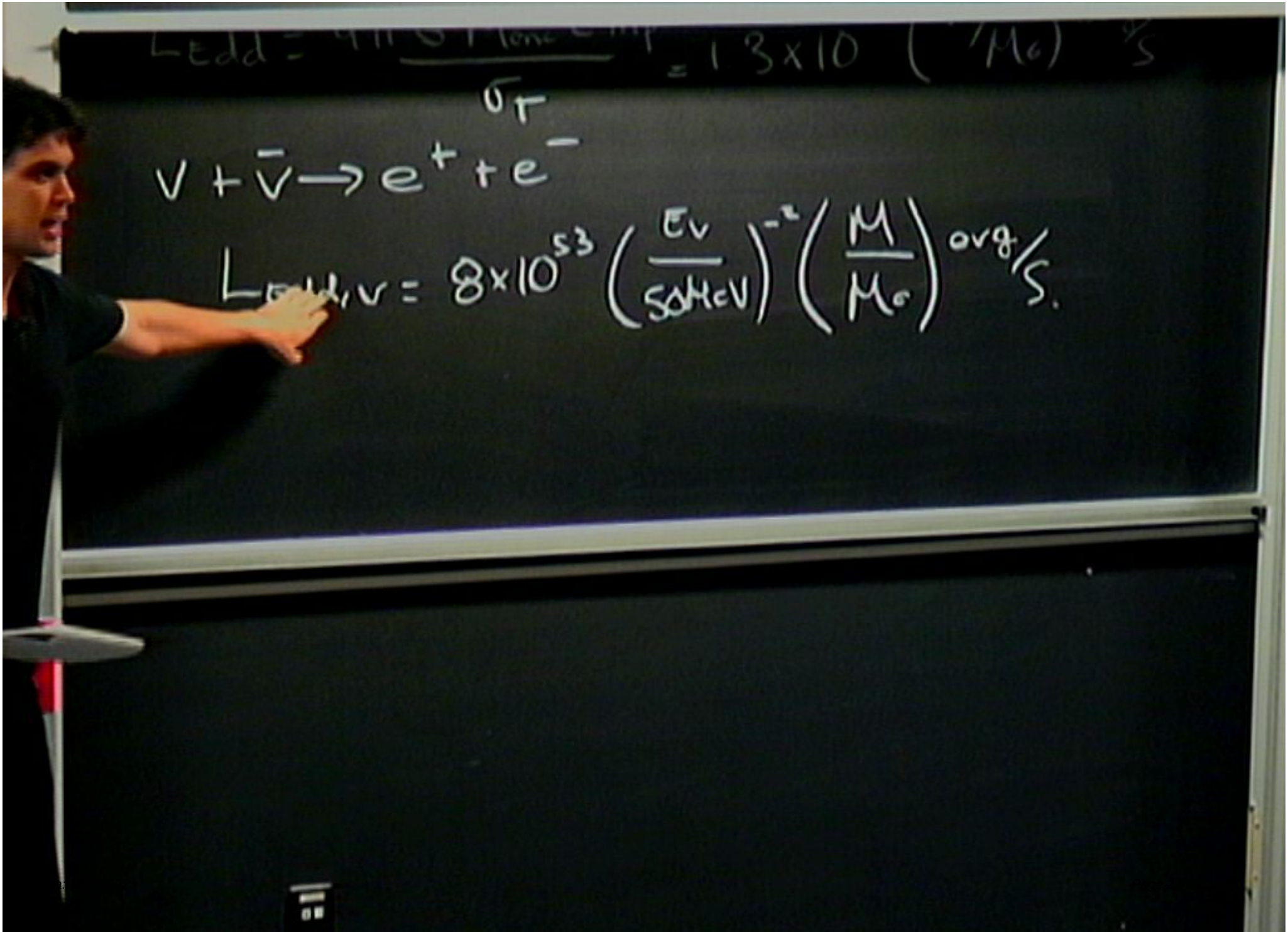

K
$L_{Edd} = \frac{4\pi G M_{one} c m_p}{\sigma_T} = 1.3 \times 10^{38} \left(M/M_\odot\right) erg/s$

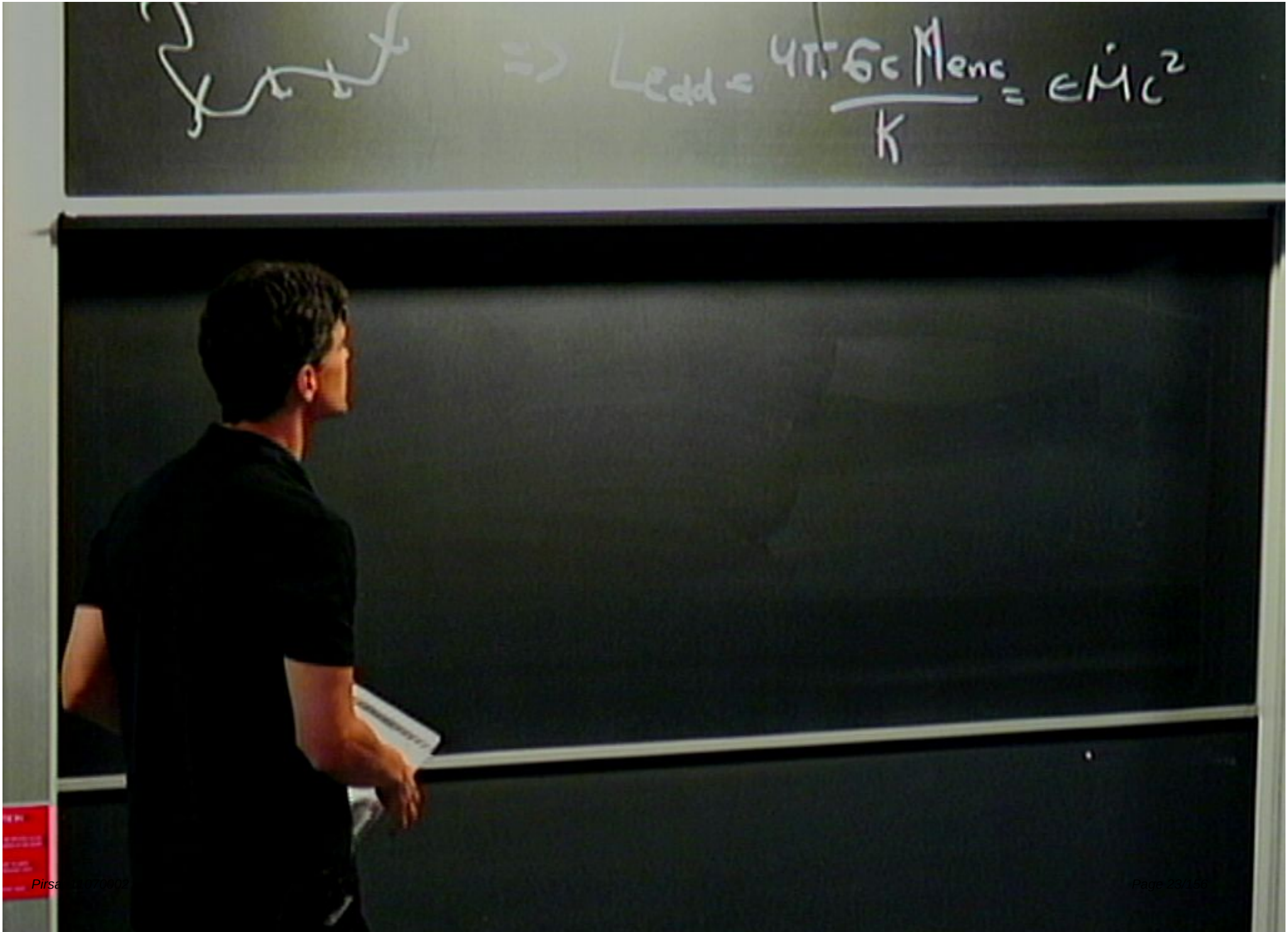

K
$L_{Edd} = \frac{4\pi G M_{ons} c m_p}{\sigma_T} = 1.3 \times 10^{38} \left(M/M_\odot\right) erg/s$

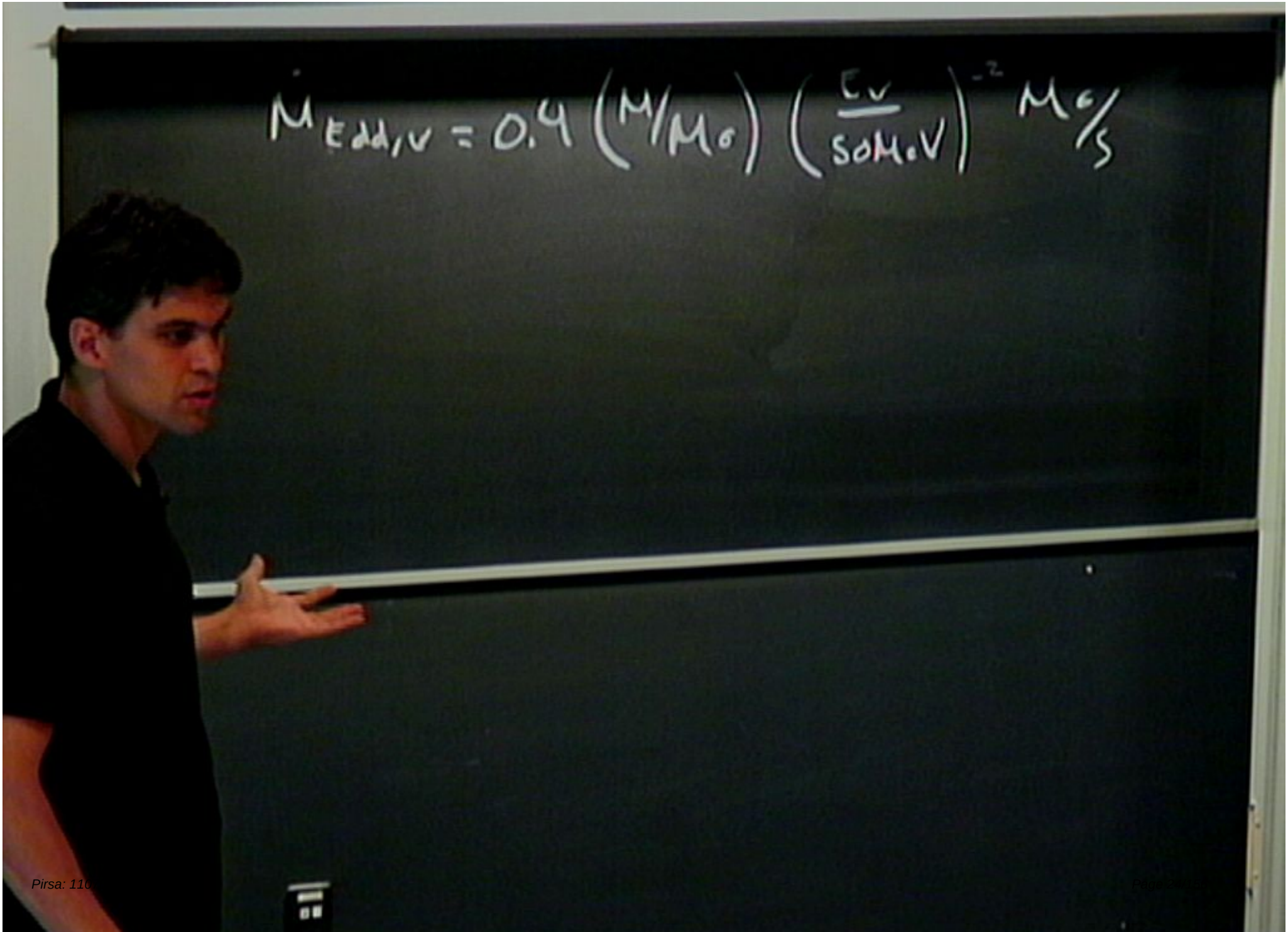

$L_{Edd} = \frac{4\pi G M_{ano} c m_p}{\sigma_T} = 1.3 \times 10^{38} \left(M/M_\odot \right) erg/s$

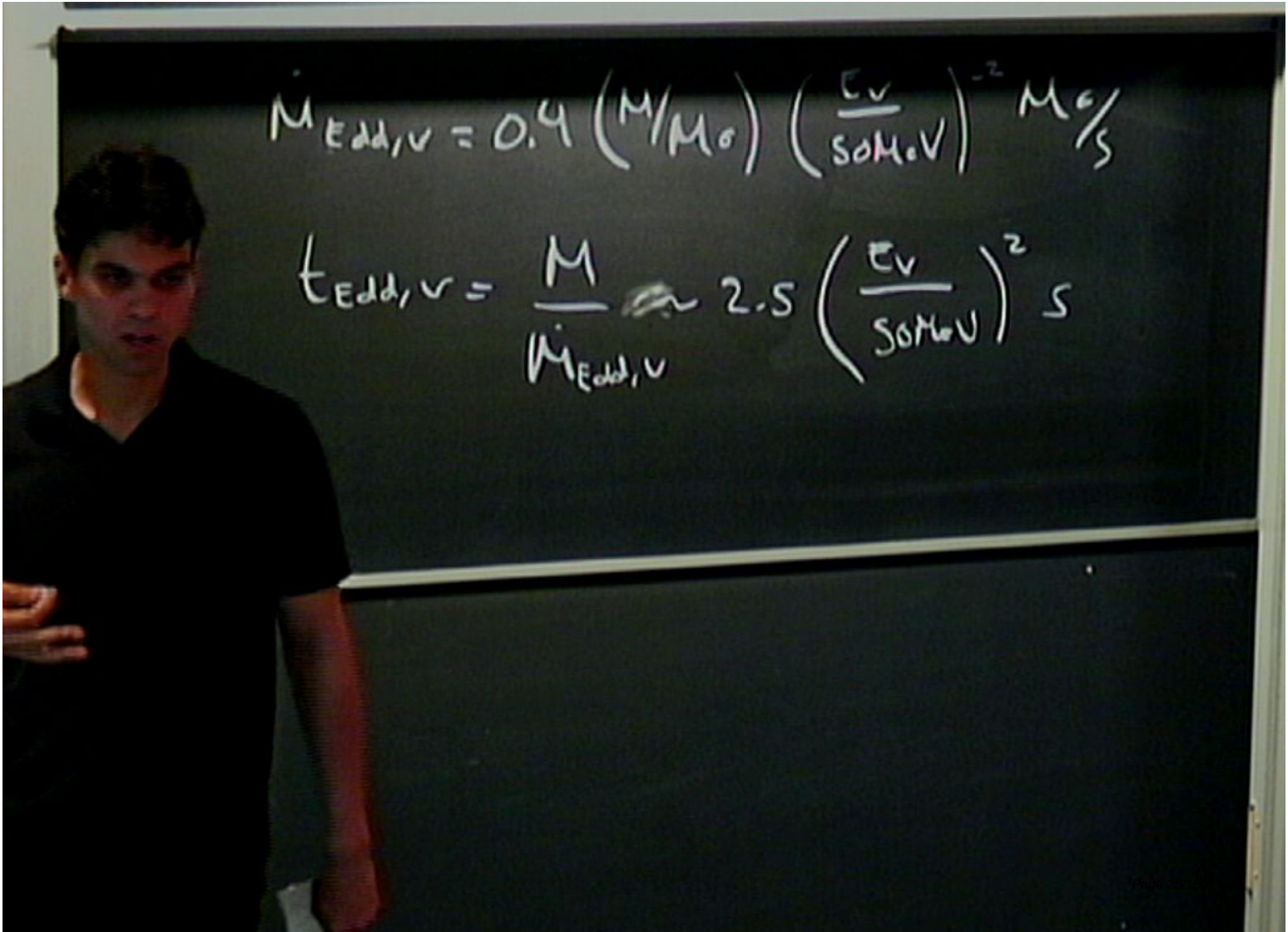

$L_{Edd} = \frac{4\pi G M_{max} c m_p}{\sigma_T} = 1.3 \times 10^{38} \left(M/M_\odot \right) erg/s$

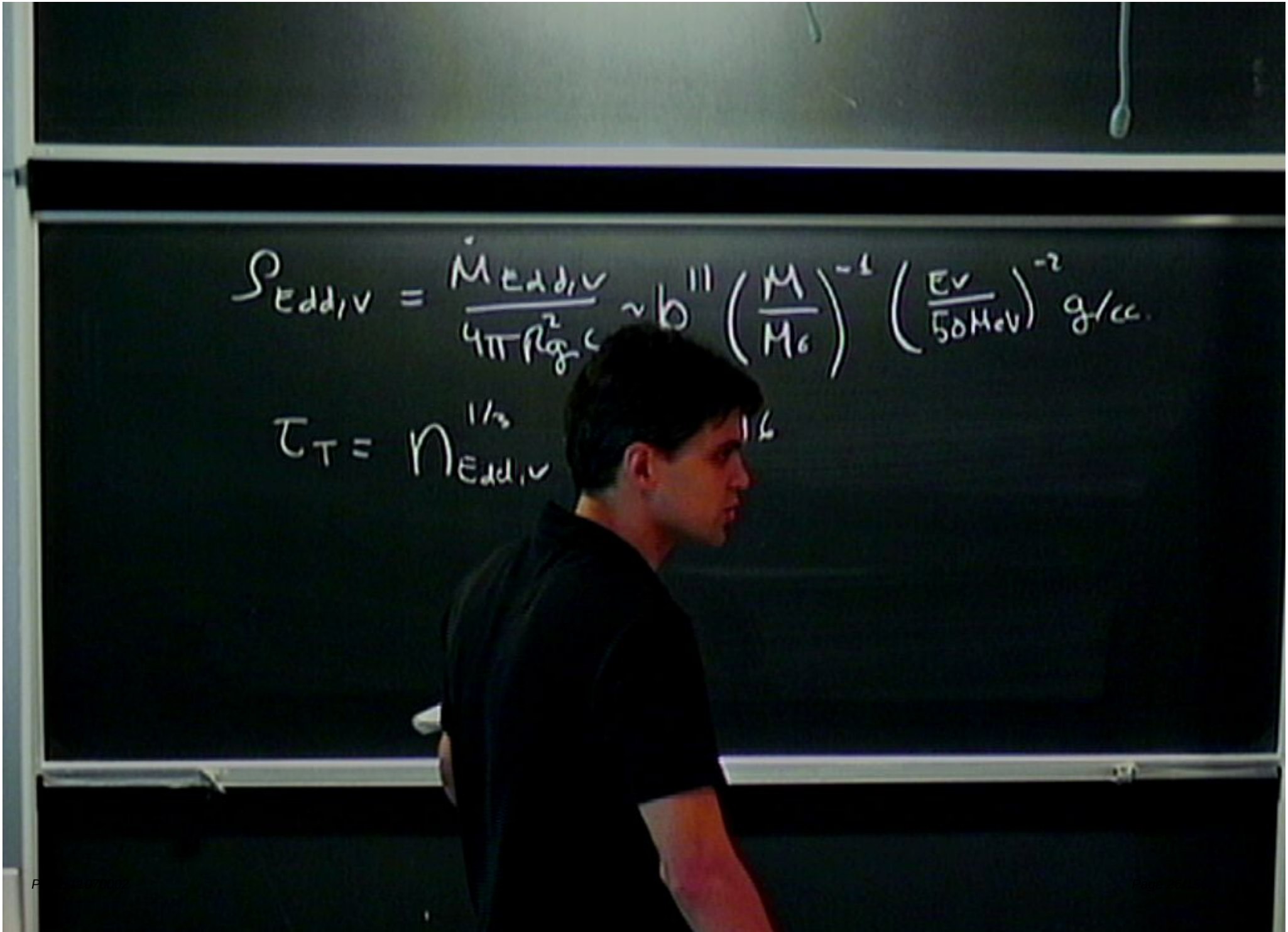

$L_{Edd} = \frac{4\pi G M_{com} c m_p}{\sigma_T} = 1.3 \times 10^{38} \left(M/M_\odot\right) erg/s$
$\nu + \bar{\nu} \rightarrow e^+ + e^-$

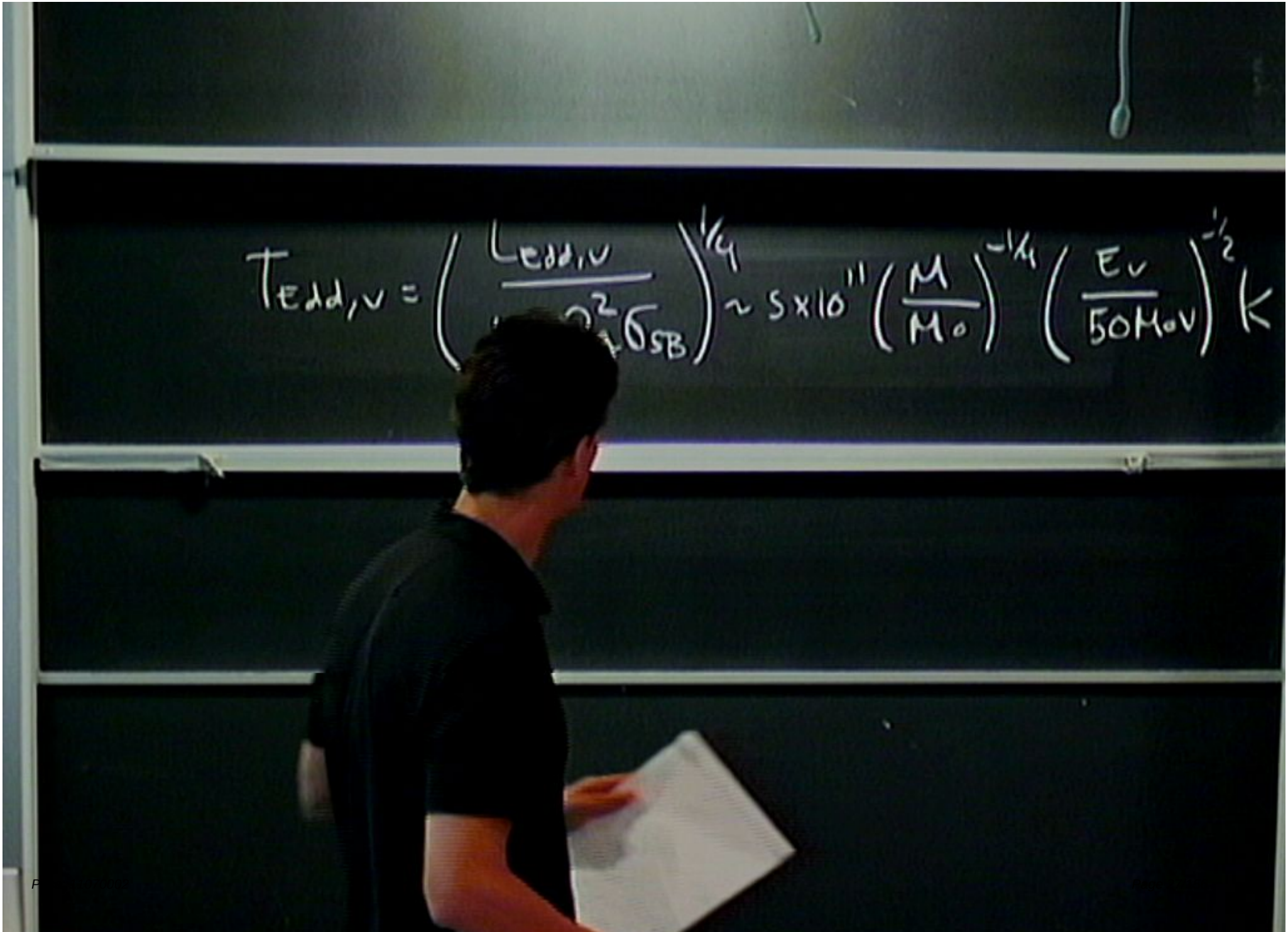

$L_{edd} = \frac{4\pi G M m_p}{\sigma_T} = 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right)$ erg/s
$\nu + \bar{\nu} \rightarrow e^+ + e^-$
$L_{\nu\bar{\nu}} = 8 \times 10^{53} \left(\frac{E_\nu}{50\,\mathrm{MeV}}\right)^{-2} \left(\frac{M}{M_\odot}\right)$ erg/s.

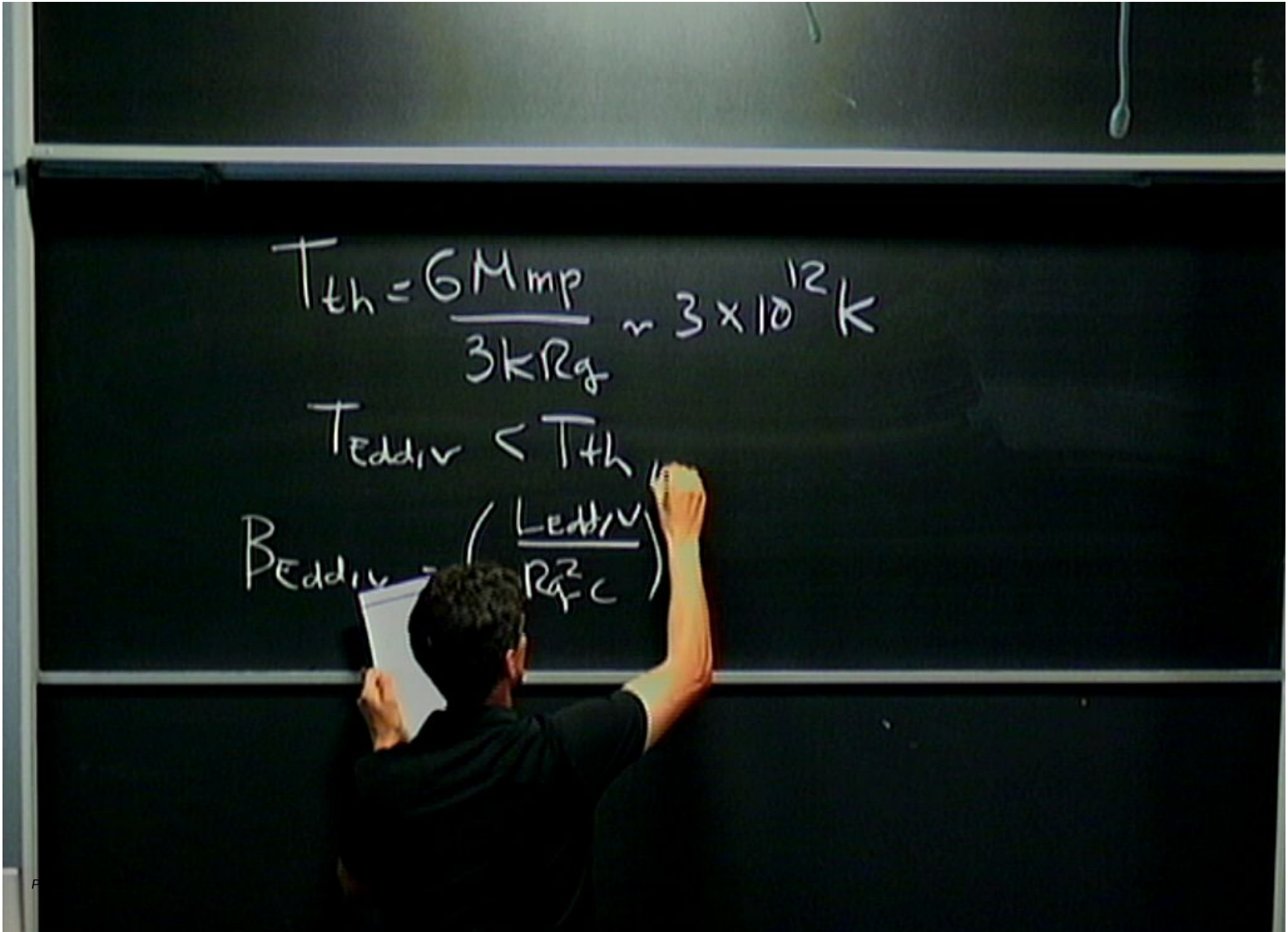

$\Rightarrow L_{edd} = \frac{4\pi G c M_{enc}}{K} = \epsilon \dot{M} c^2$

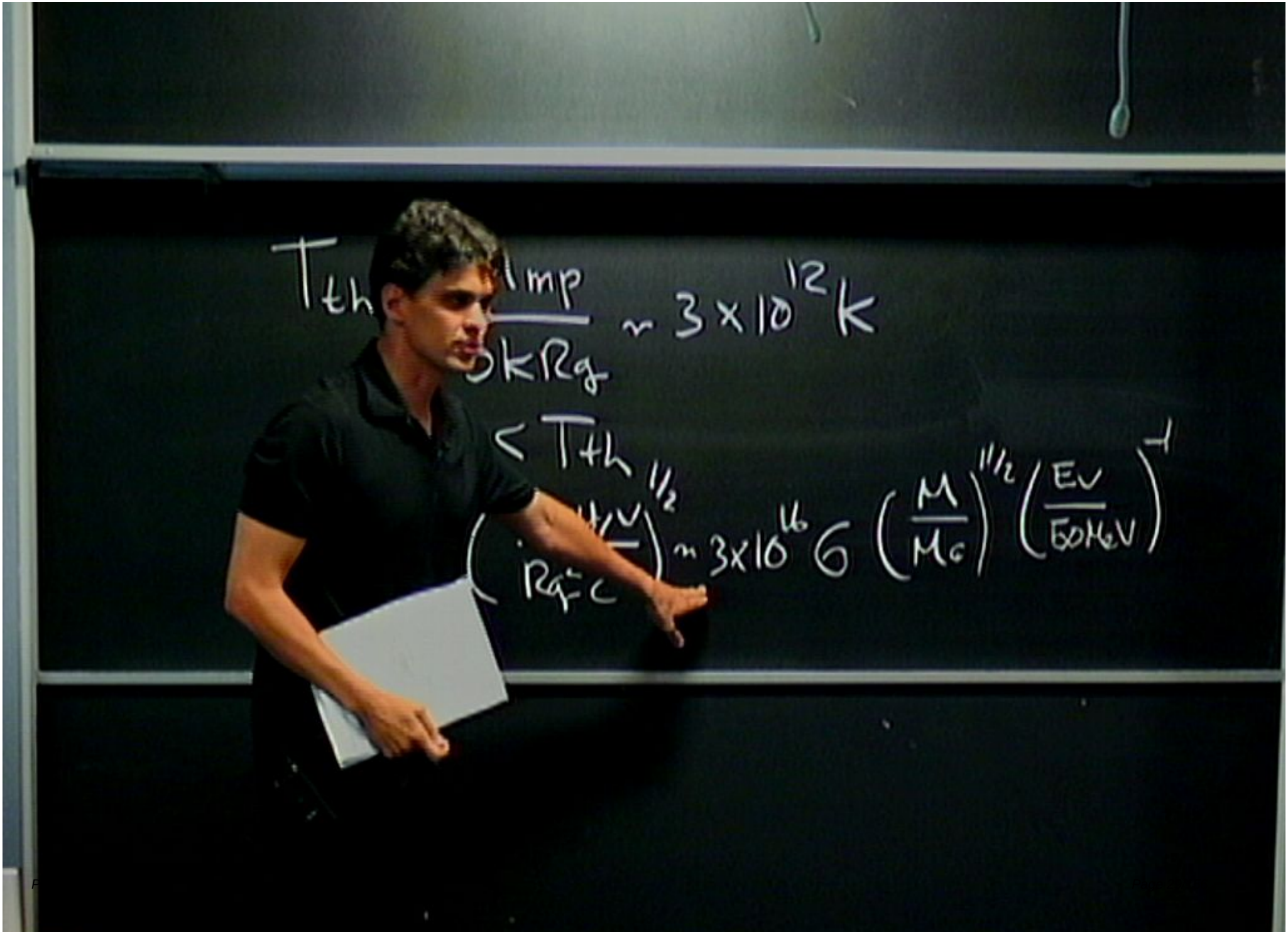

$\dot{M}_{Edd,V} = 0.4 \left(M/M_\odot\right) \left(\frac{E_V}{SoM \cdot V}\right)^{-2} M_\odot/s$


$\dot{M}_{Edd,V} = 0.4 \left(M/M_\odot\right) \left(\frac{E_V}{50 M_\odot V}\right)^{-2} M_\odot/s$
$t_{Edd,V} = \frac{M}{\dot{M}_{Edd,V}} \sim 2.5 \left(\frac{E_V}{50 M_\odot V}\right)^2 s$


$\rho_{Edd,\nu} = \frac{\dot{M}_{Edd,\nu}}{4\pi R_g^2 c} \sim 10^{11} \left(\frac{M}{M_\odot}\right)^{-1} \left(\frac{E_\nu}{50\,MeV}\right)^{-2}$ g/cc.
$\tau_T = n_{Edd,\nu}^{1/3}$


$T_{Edd,\nu} = \left(\frac{L_{Edd,\nu}}{\pi r^2 \sigma_{SB}} \right)^{1/4} \sim 5 \times 10^{11} \left(\frac{M}{M_\odot} \right)^{-1/4} \left(\frac{E_\nu}{50 MeV} \right)^{-1/2} K$


$T_{th} = \frac{GMm_p}{3kR_g} \sim 3 \times 10^{12} K$
$T_{eddiv} < T_{th}$
$B_{eddiv} \sim \left(\frac{L_{eddiv}}{R_g^2 c} \right)$

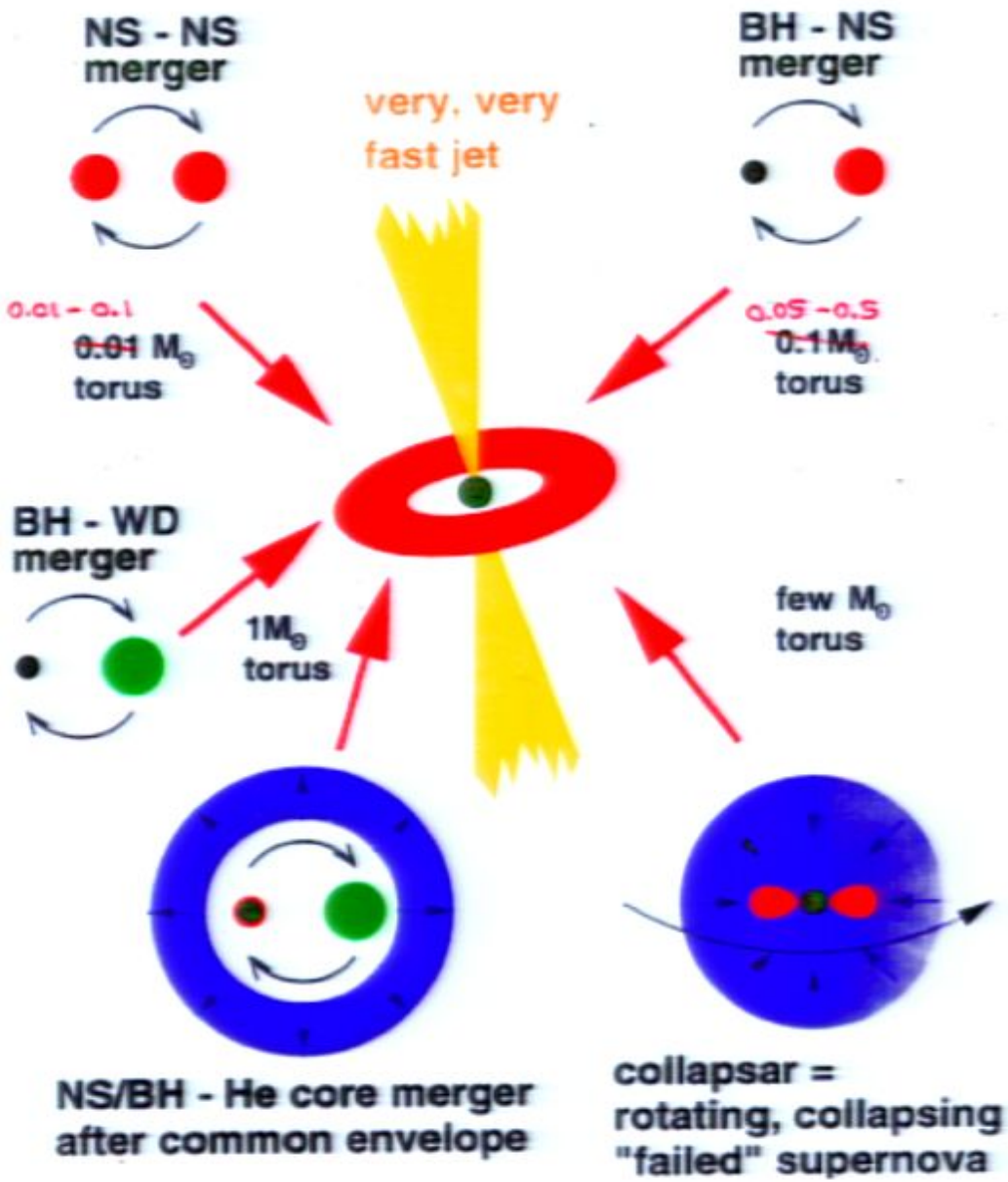

$T_{th} \sim \frac{mp}{5kR_g} \sim 3\times10^{12}\,K$
$< T_{th}$
$\left(\frac{}{R_g c}\right) \sim 3\times10^{16}\, G \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{E_V}{60\,MeV}\right)^{-1}$

$$\dot{M}_{Edd,V} = 0.4 \left(M/M_\odot\right) \left(\frac{E_V}{50 M_\odot V}\right)^{-2} M_\odot/s$$

$$t_{Edd,V} = \frac{M}{\dot{M}_{Edd,V}} \sim 2.5 \left(\frac{E_V}{50 M_\odot V}\right)^2 s$$

$$t_{dyn} \sim R_g/c$$

*Hyper*Accreting Compact Objects



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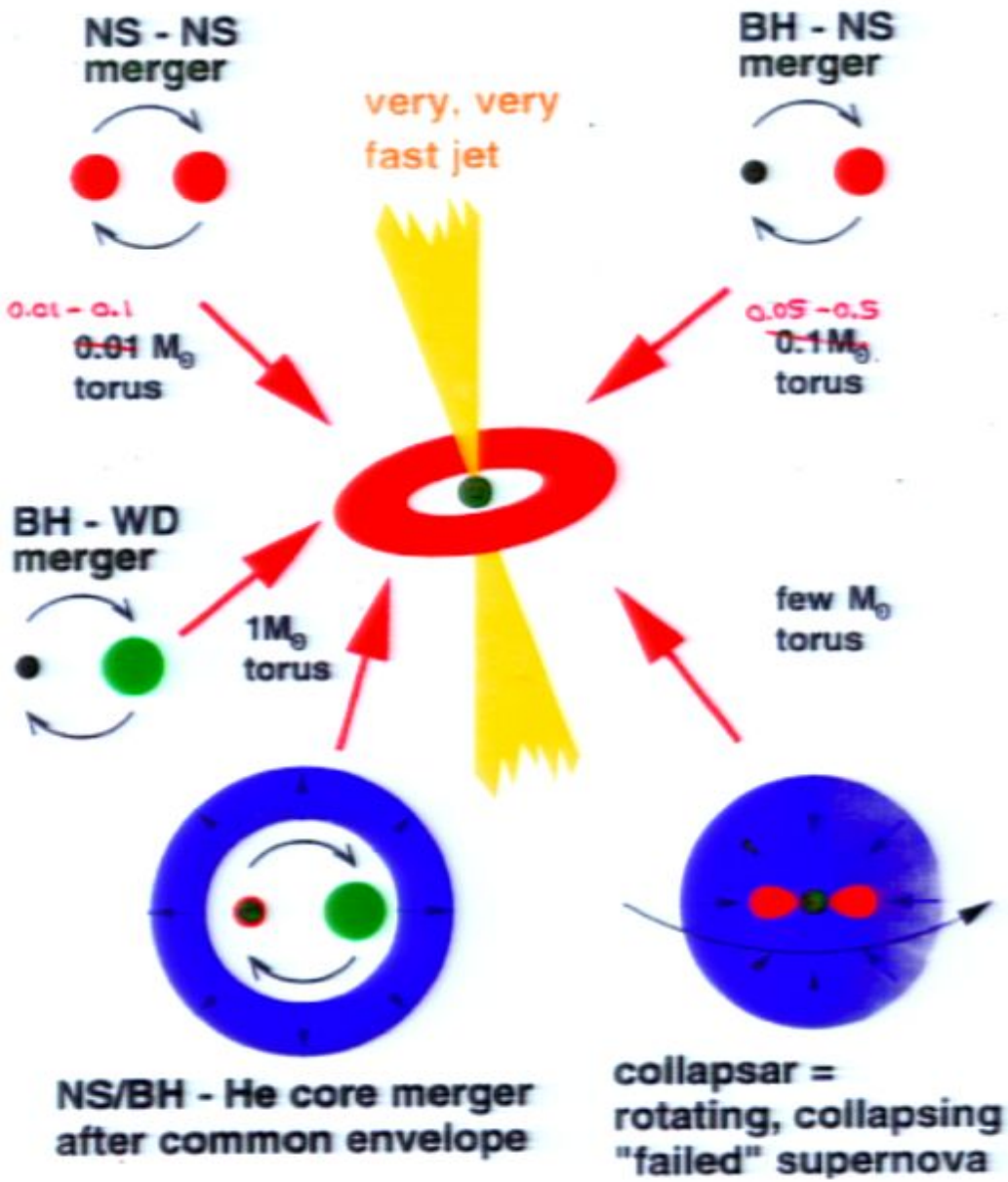
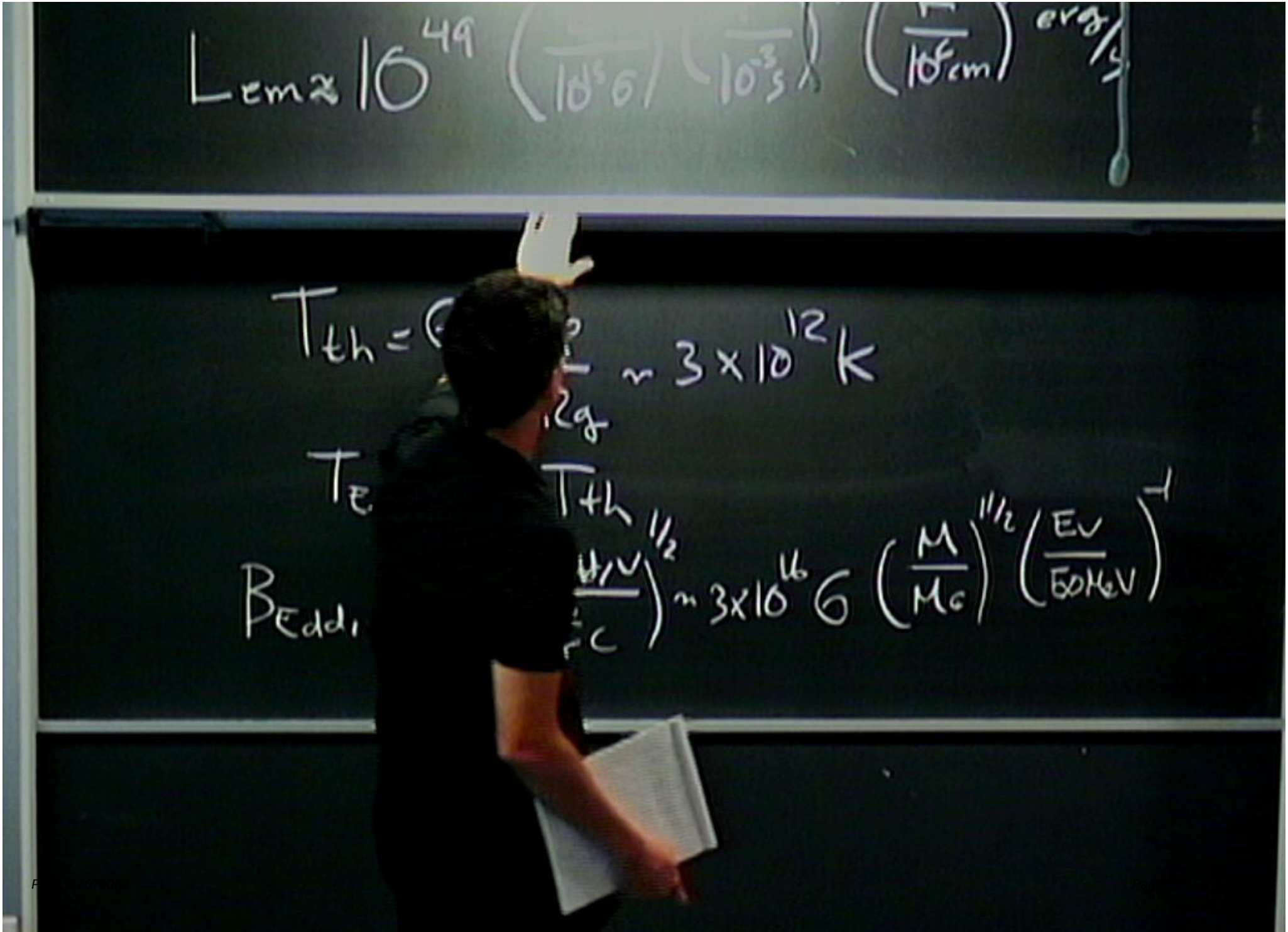
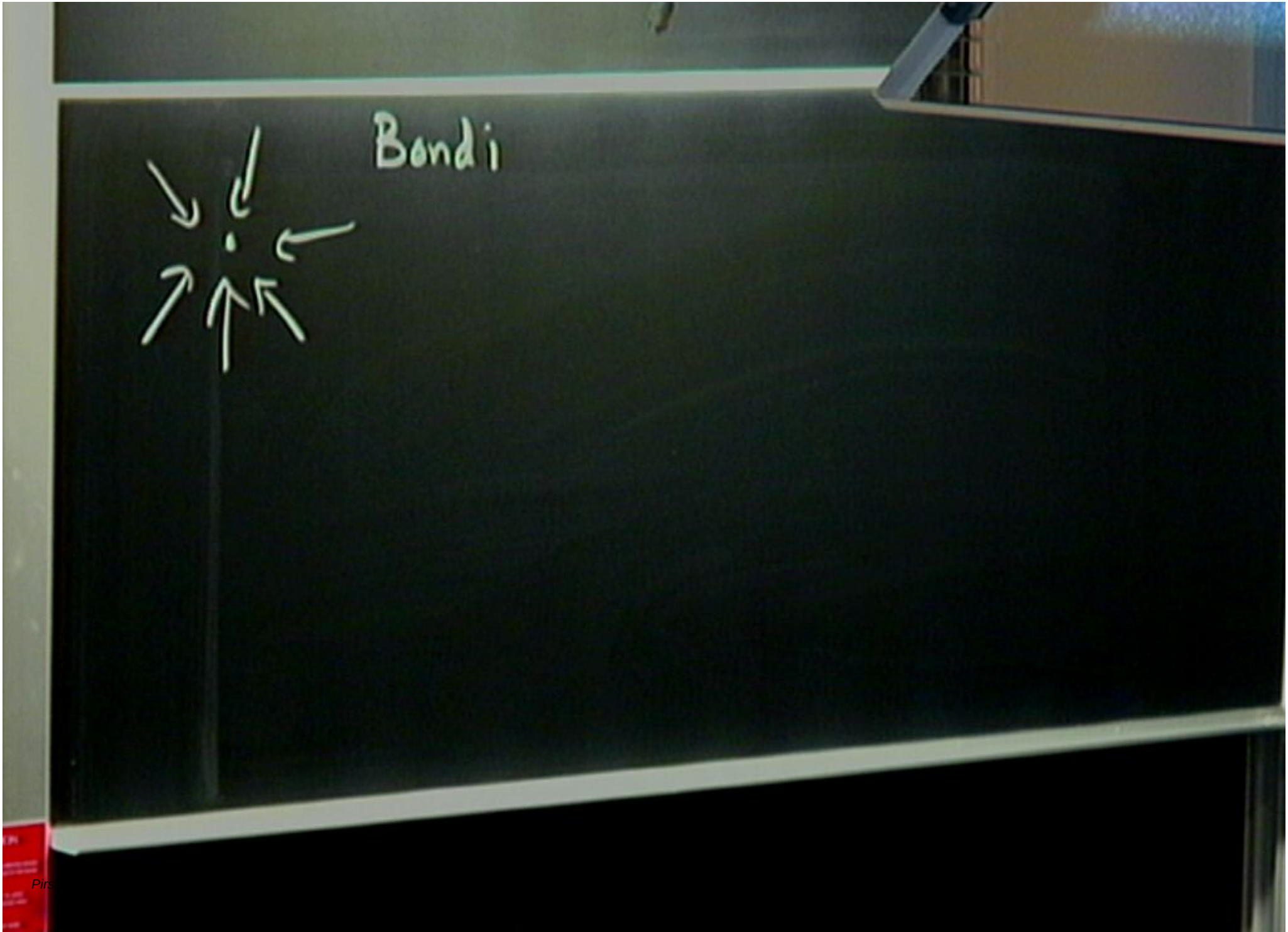
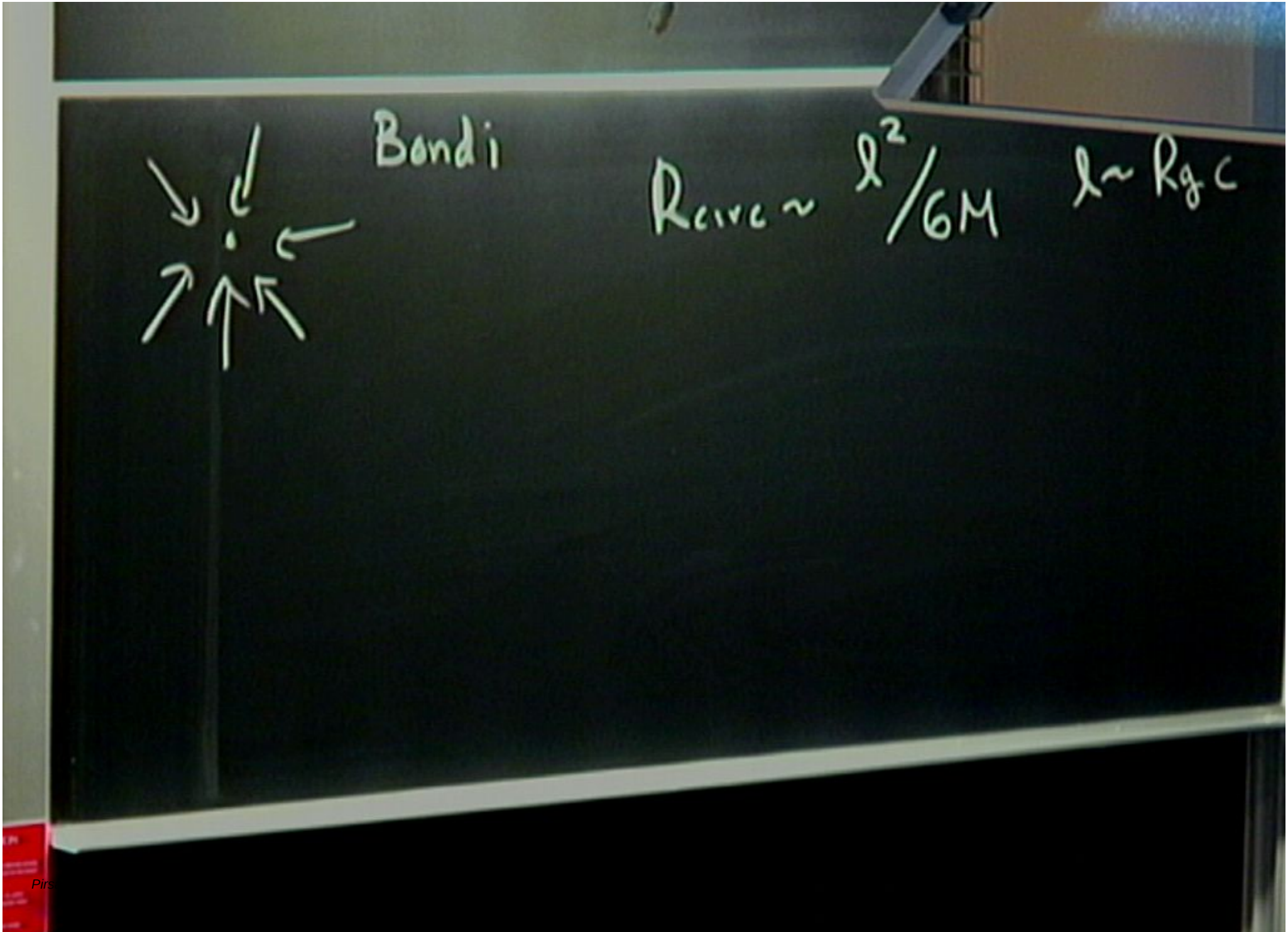
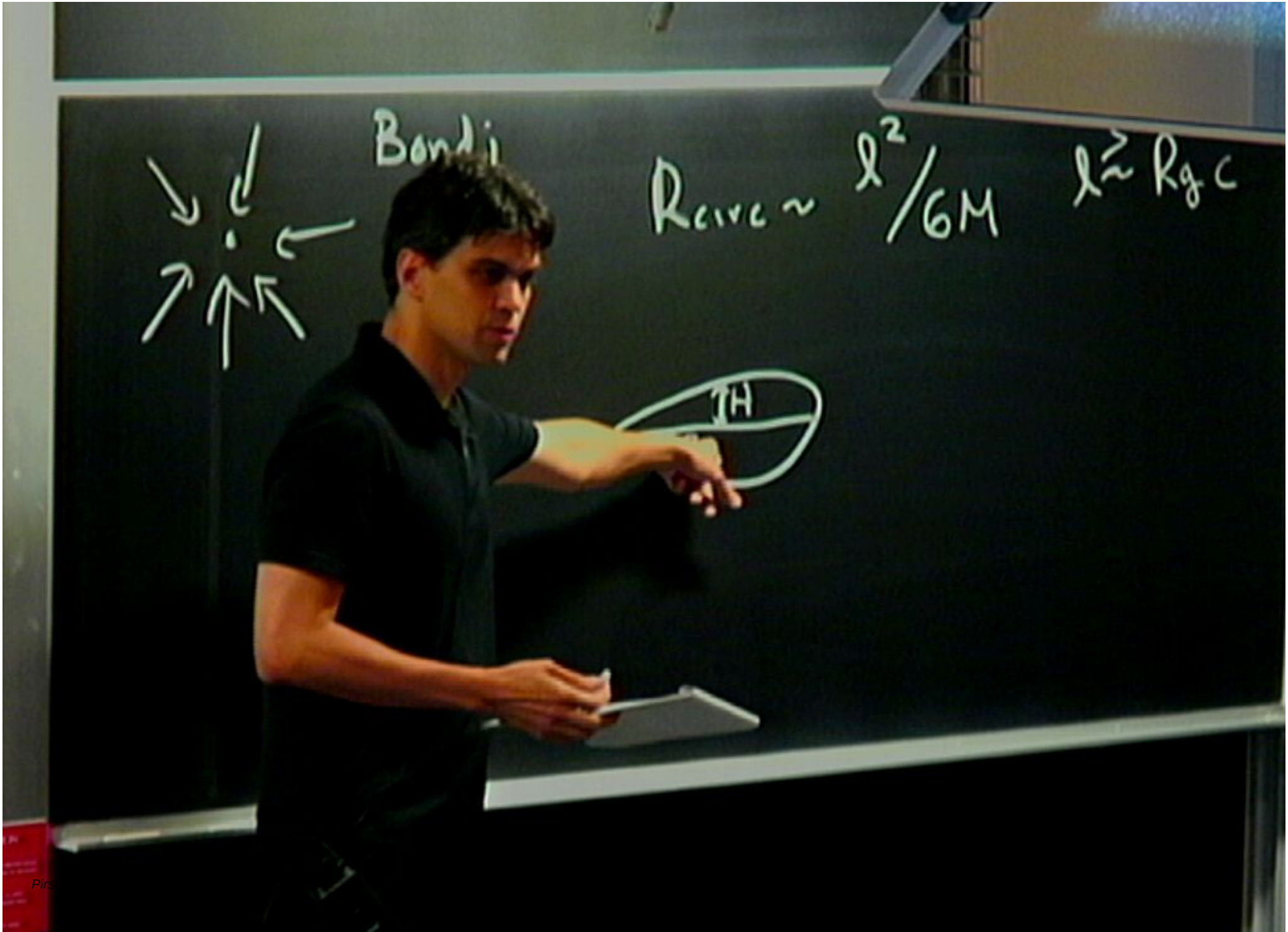
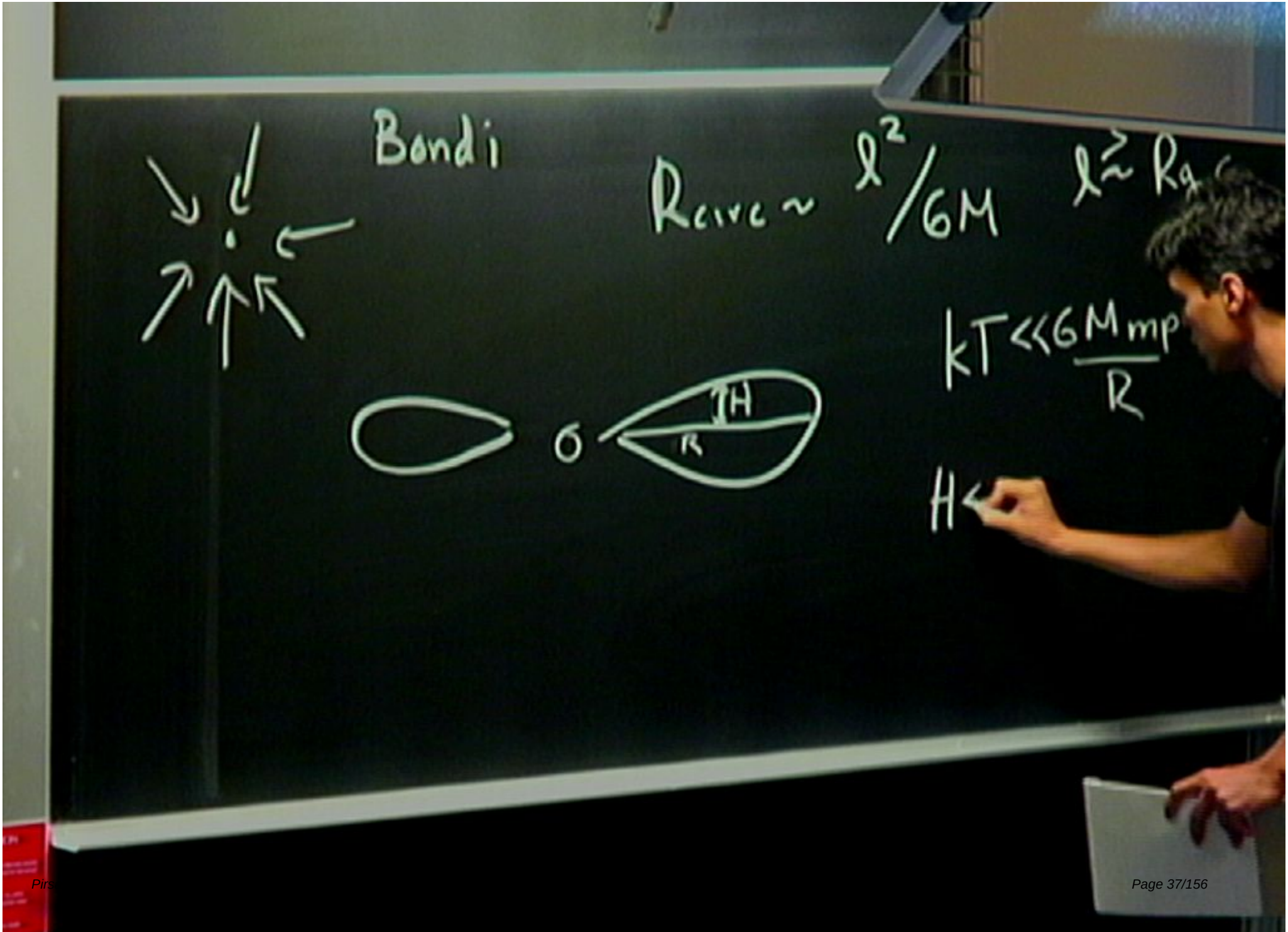


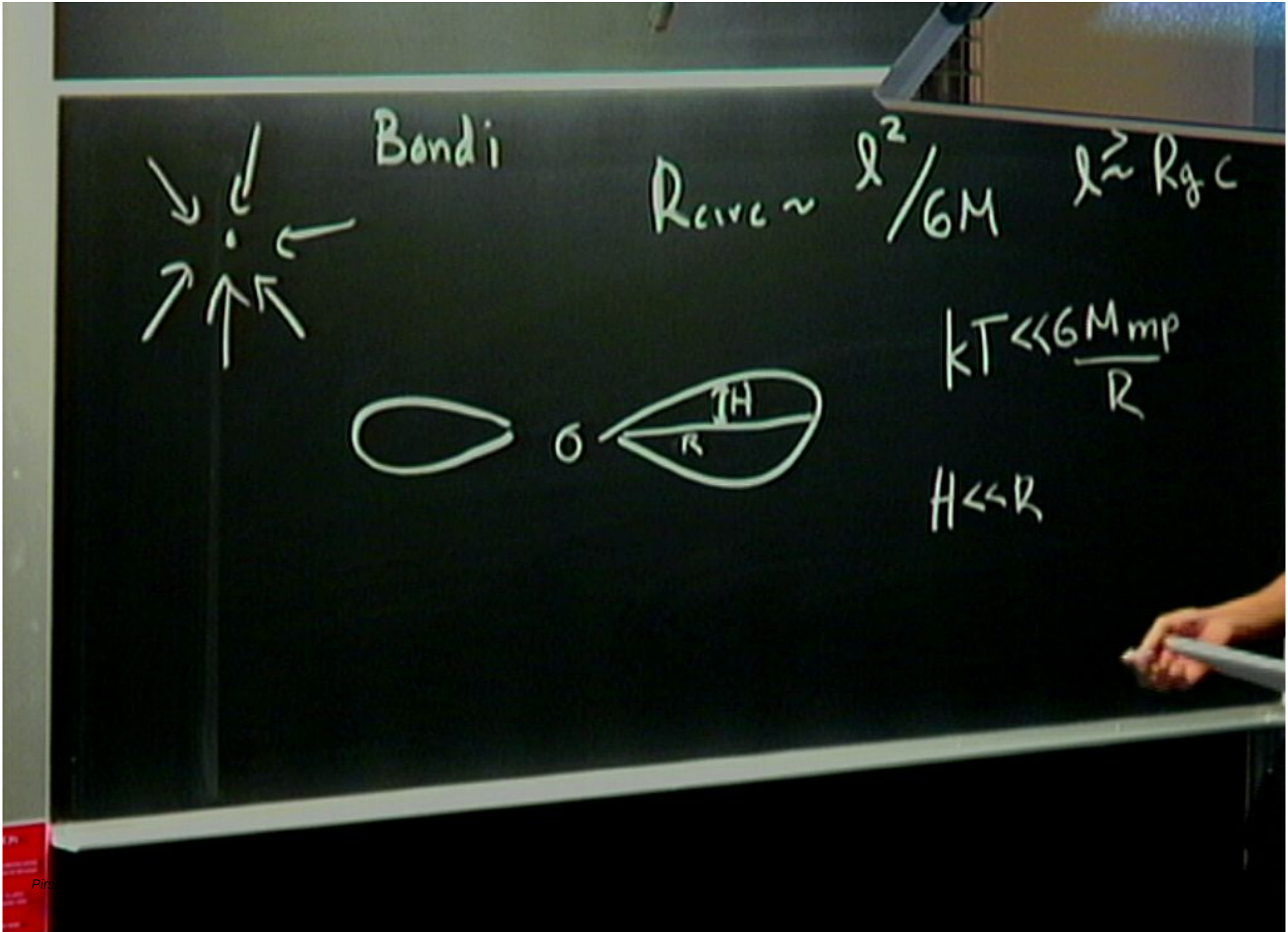

$L_{em} \approx 10^{49}$
$T_{th} \sim 3 \times 10^{12}$ K
T_e
T_{th}
B_{Edd}
$\sim 3 \times 10^{16}$ G $\left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{E_V}{50\,\mathrm{MeV}}\right)^{-1}$

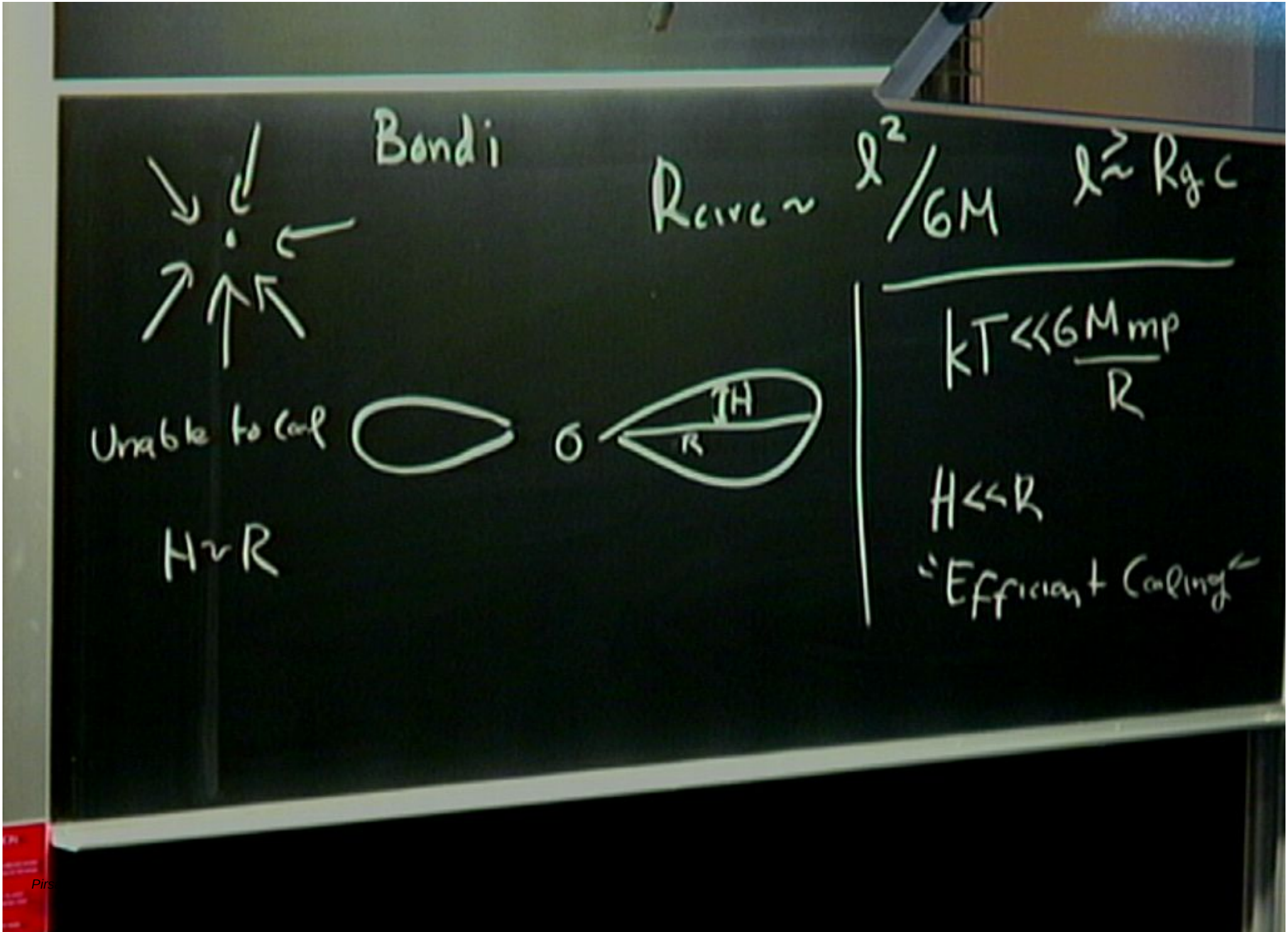

Bondi


Bondi
$R_{circ} \sim \ell^2/6M$
$\ell \sim R_g c$


Bondi
$R_{caus} \sim \ell^2/6M$
$\ell \gtrsim R_g c$
TH


Bondi
$R_{circ} \sim \ell^2/GM$
$\ell \gtrsim R_g c$
$kT \ll \frac{GM m_p}{R}$
H
R
$H < R$


Bondi
$R_{circ} \sim \ell^2/GM$
$\ell \gtrsim R_g c$
$kT \ll \frac{GM m_p}{R}$
H
R
$H \ll R$

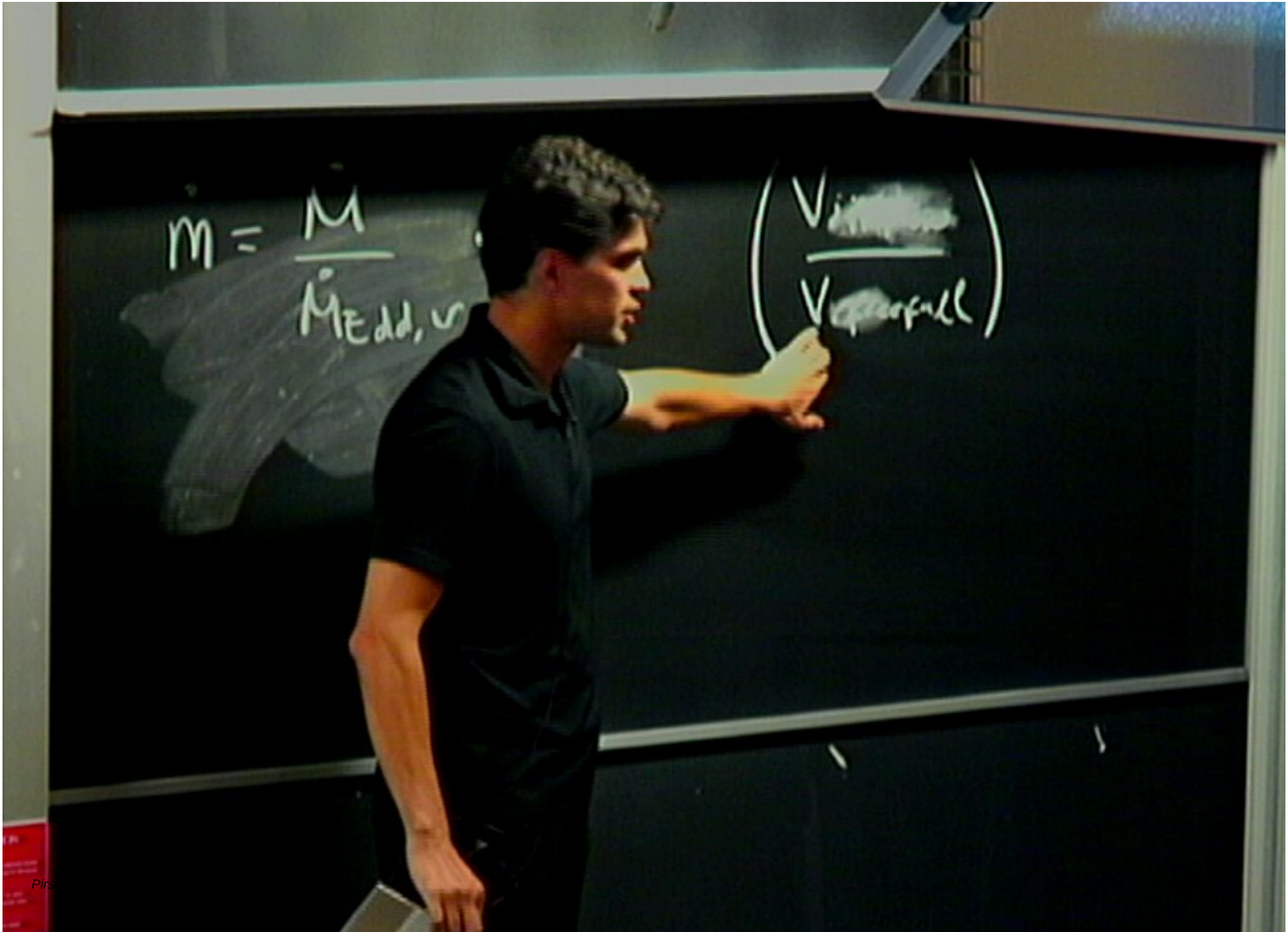

Bondi
$R_{circ} \sim \ell^2/GM$
$\ell \gtrsim R_g c$
Unable to cool
H
R
$H \sim R$
$kT \ll \frac{GM m_p}{R}$
$H \ll R$
"Efficient Cooling"

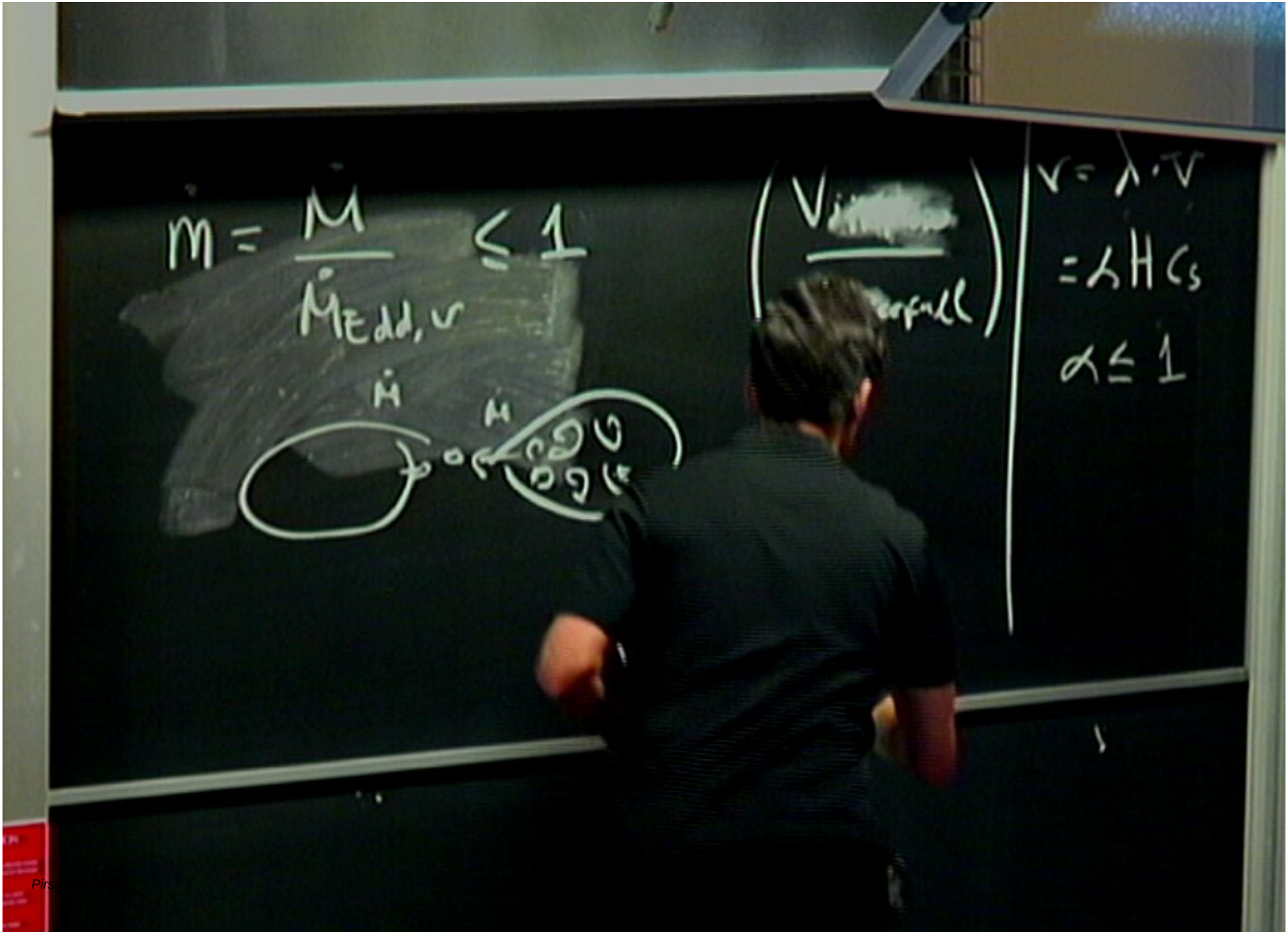
Requirements for an Engine: *Formation Rates*

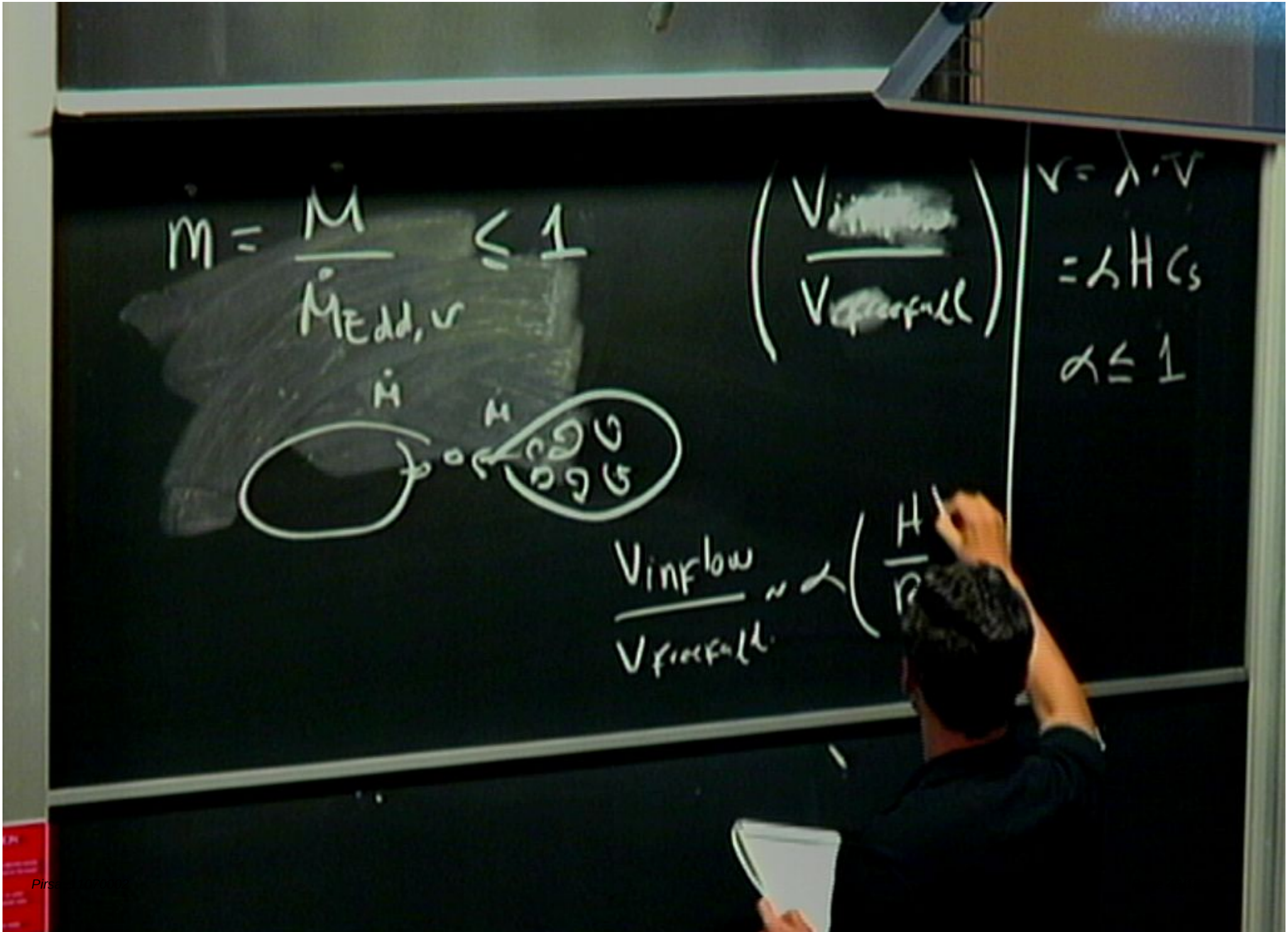
- Estimated rates for GRBs $1 - 10\ (4\pi/\Omega)\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$.

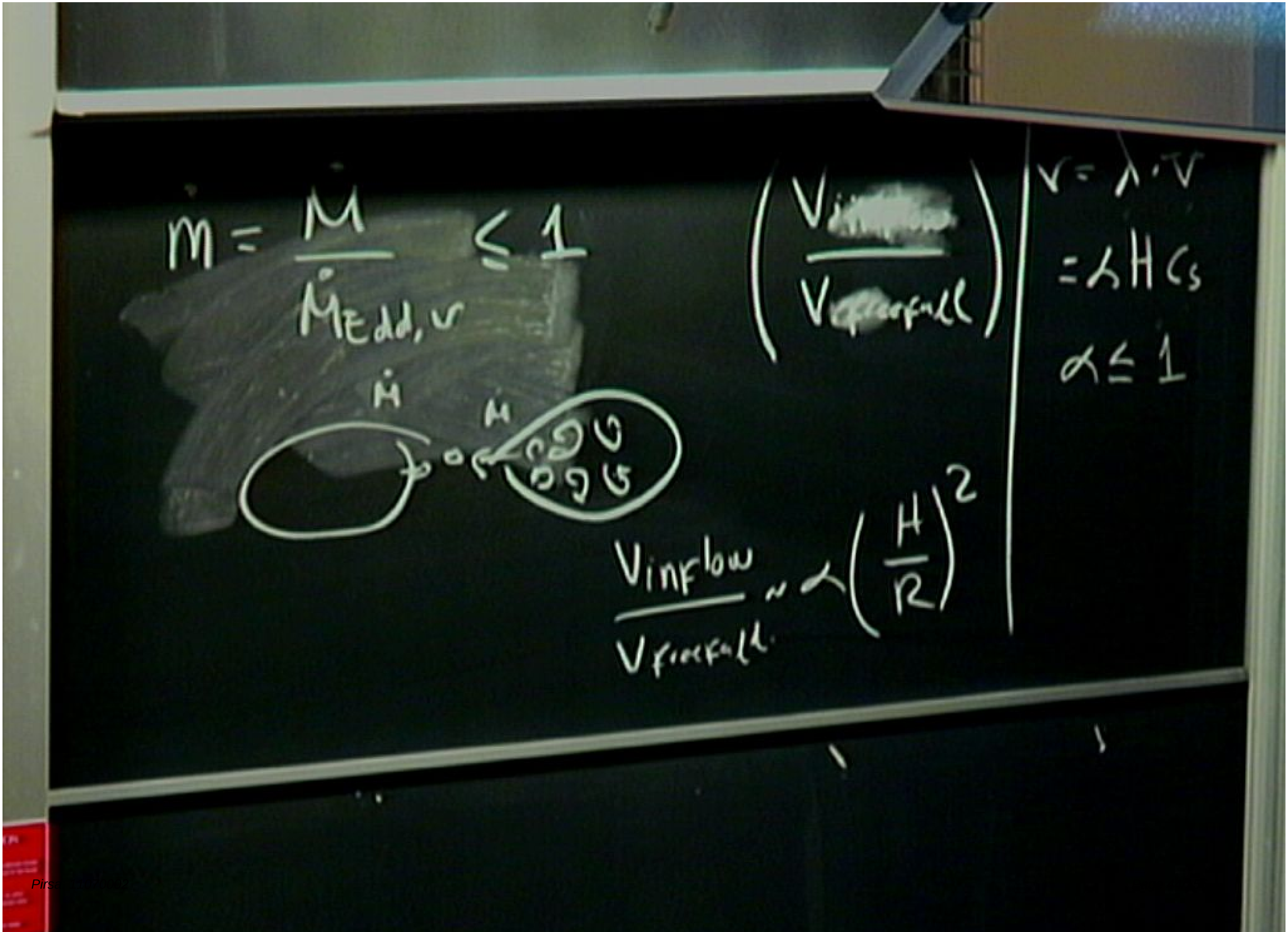
Progenitor	Rate $(z = 0)$
NS–NS	1-800
BH–NS	0.1–1000
BH–WD	0.01-100
NS AIC	0.1 - 100
WD-WD	3000
SN Ib/c	60000
SN Ia	150000

Schmidt (2000); Fryer+(1999); Levan+(2005), Izzard+(2006); Phinney (1994); Belczynski+ (2001)


$\dot{m} = \frac{\dot{M}}{\dot{M}_{Edd,\epsilon}} \cdot \left(\frac{v_{\phi}}{v_{freefall}} \right)$


$\dot{m} = \frac{\dot{M}}{\dot{M}_{Edd,\nu}} \leq 1$
$\dot{M}$
$\dot{M}$
$\left(\frac{V_{\ldots}}{\ldots}\right)$
$r = \lambda \cdot r$
$= \lambda H c_s$
$\alpha \leq 1$


$\dot{m} = \frac{\dot{M}}{\dot{M}_{Edd,\epsilon}} \leq 1$
$\dot{M}$
$\dot{M}$
$\frac{V_{inflow}}{V_{freefall}} \sim \alpha \left(\frac{H}{R} \right.$
$v = \lambda \cdot V$
$= \lambda H c_s$
$\alpha \leq 1$


ṁ = Ṁ / Ṁ Edd,ν ≤ 1
V / V freefall
ν = λ·V
= α H cs
α ≤ 1
Ṁ
Ṁ
Vinflow / Vfreefall ~ α (H / R)2

$$\rho \sim \dot{m} \left(R/R_g\right)^{-3/2} \left(\frac{v_{inflow}}{v_{freefall}}\right) \rho_{Eddiv}$$

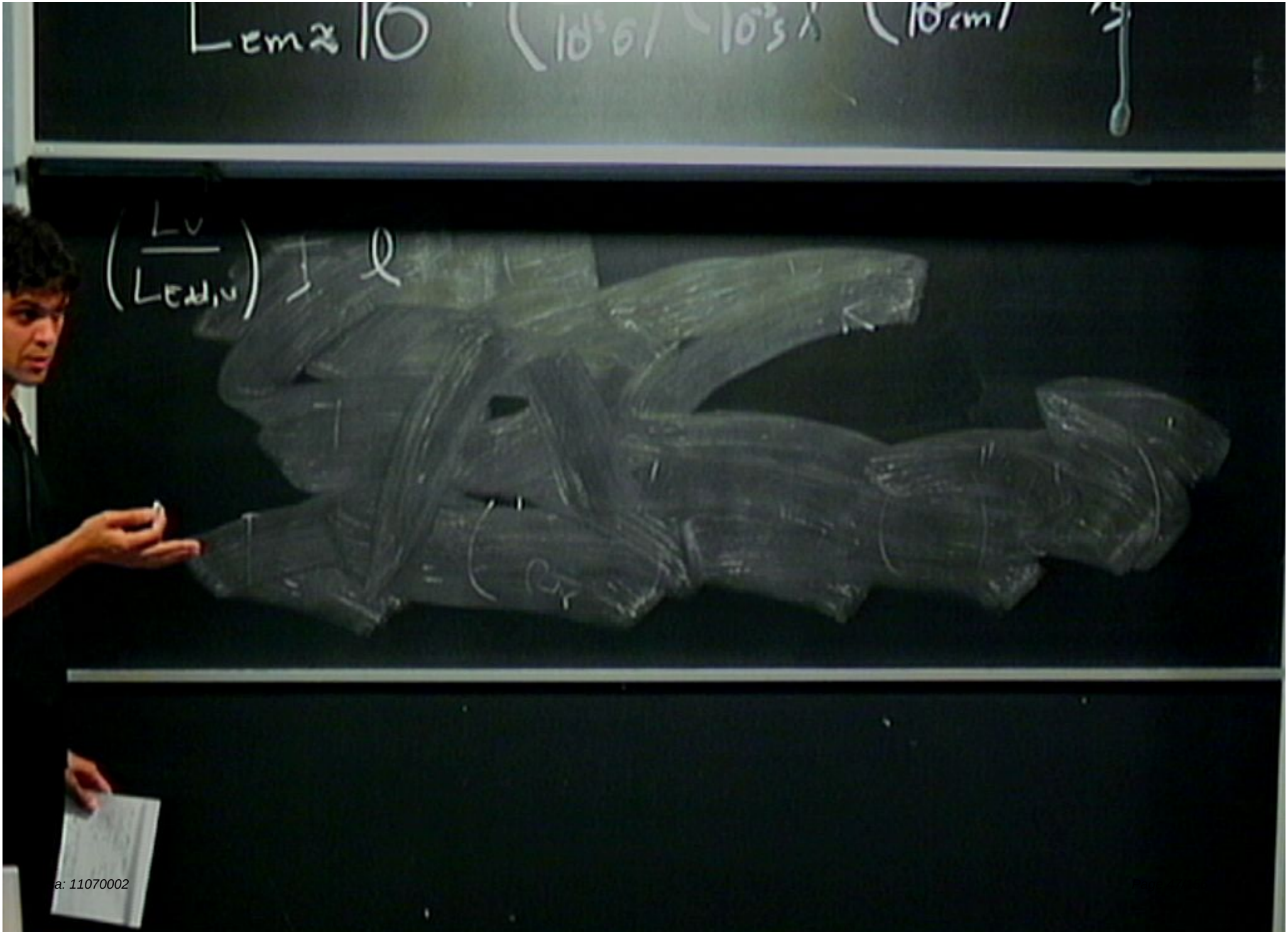
$$B_{eq} \sim \dot{m}^{1/2} \left(R/R_g\right)^{-5/4} \left(\frac{v_{inflow}}{v_{freefall}}\right)^{1/2} B_{Eddiv}.$$

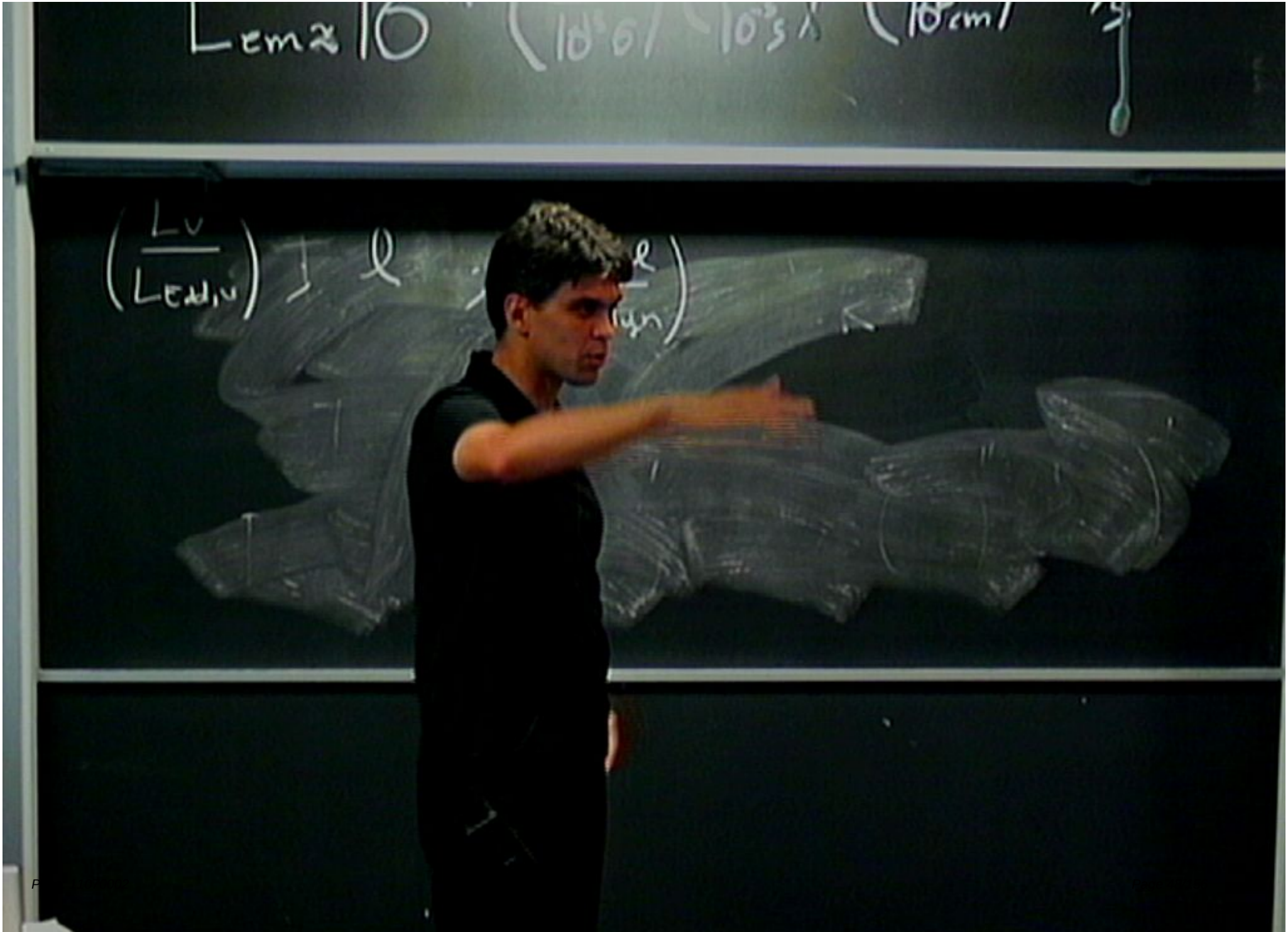
$$kT_{Eddiv} < T_{vir} \approx m_p c^2 \left(R/R_g\right)$$

$$\rho \sim \dot{m} \left(R/R_g\right)^{-3/2} \left(\frac{v_{inflow}}{v_{freefall}}\right) \rho_{Eddiv}$$

$$B_{eq} \sim \dot{m}^{1/2} \left(R/R_g\right)^{-5/4} \left(\frac{v_{inflow}}{v_{freefall}}\right)^{1/2} B_{Eddiv}.$$

$$kT_{Eddiv} < T_{vir} \approx m_p c^2 \left(R/R_g\right)$$

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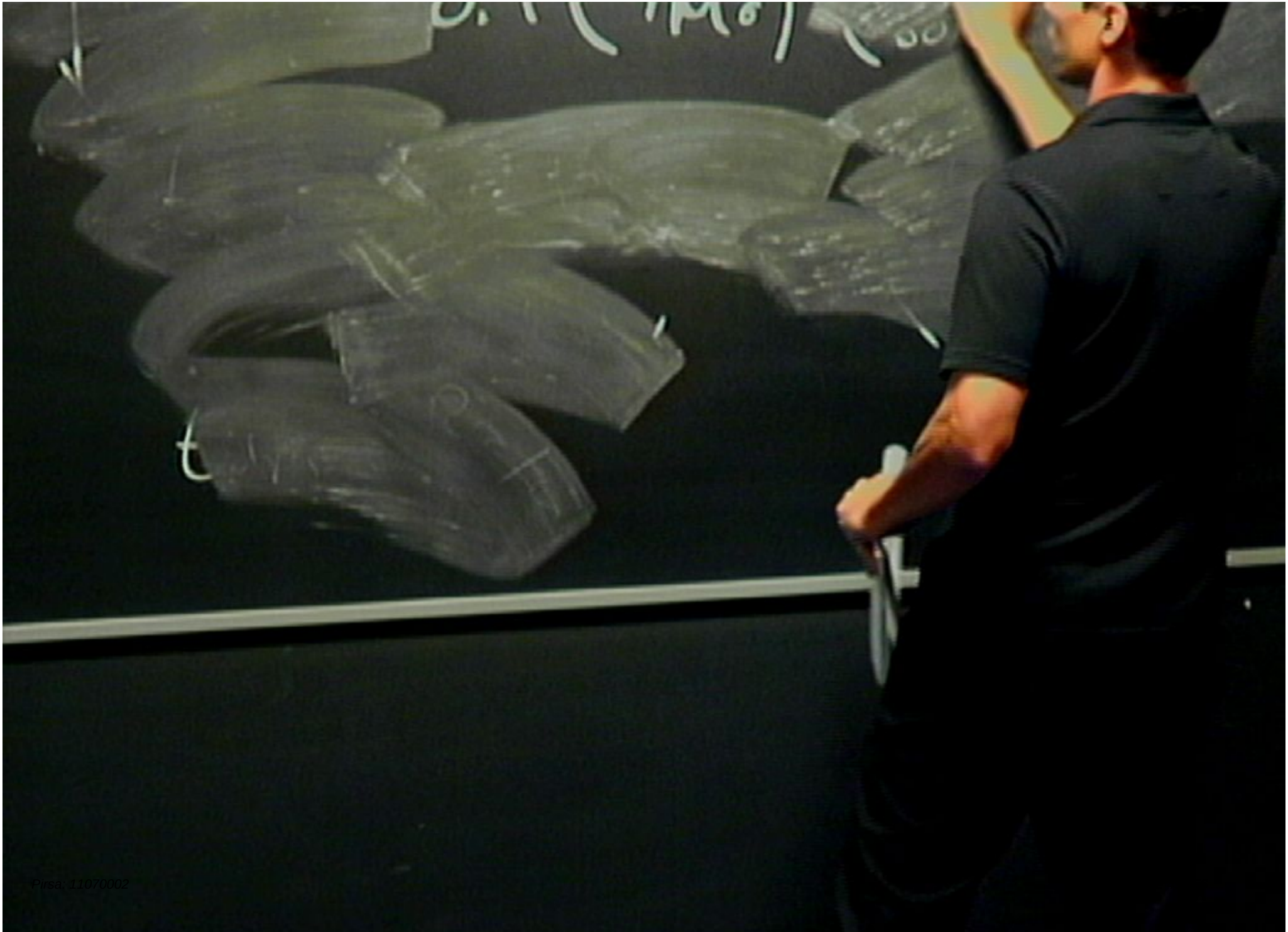

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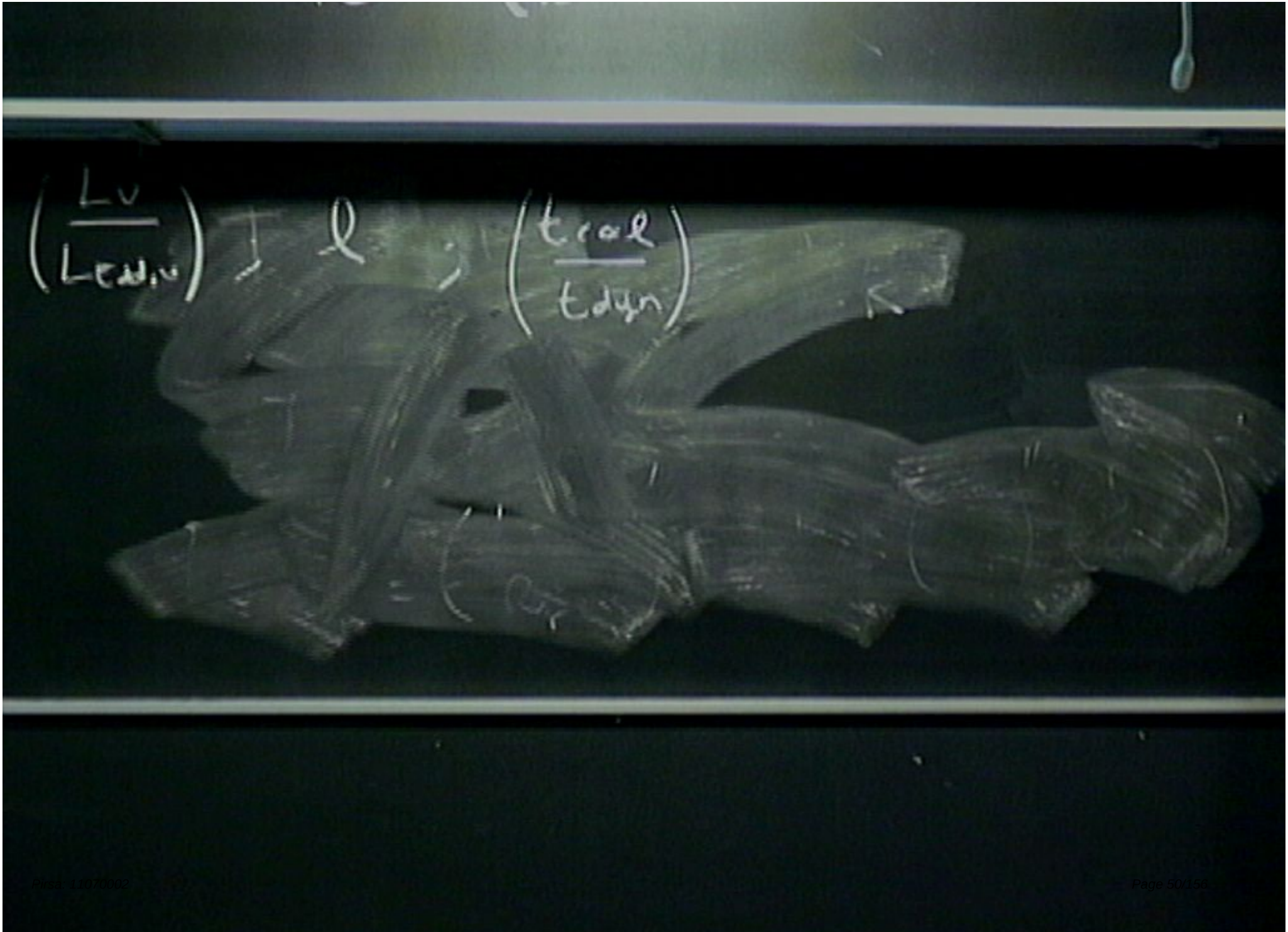
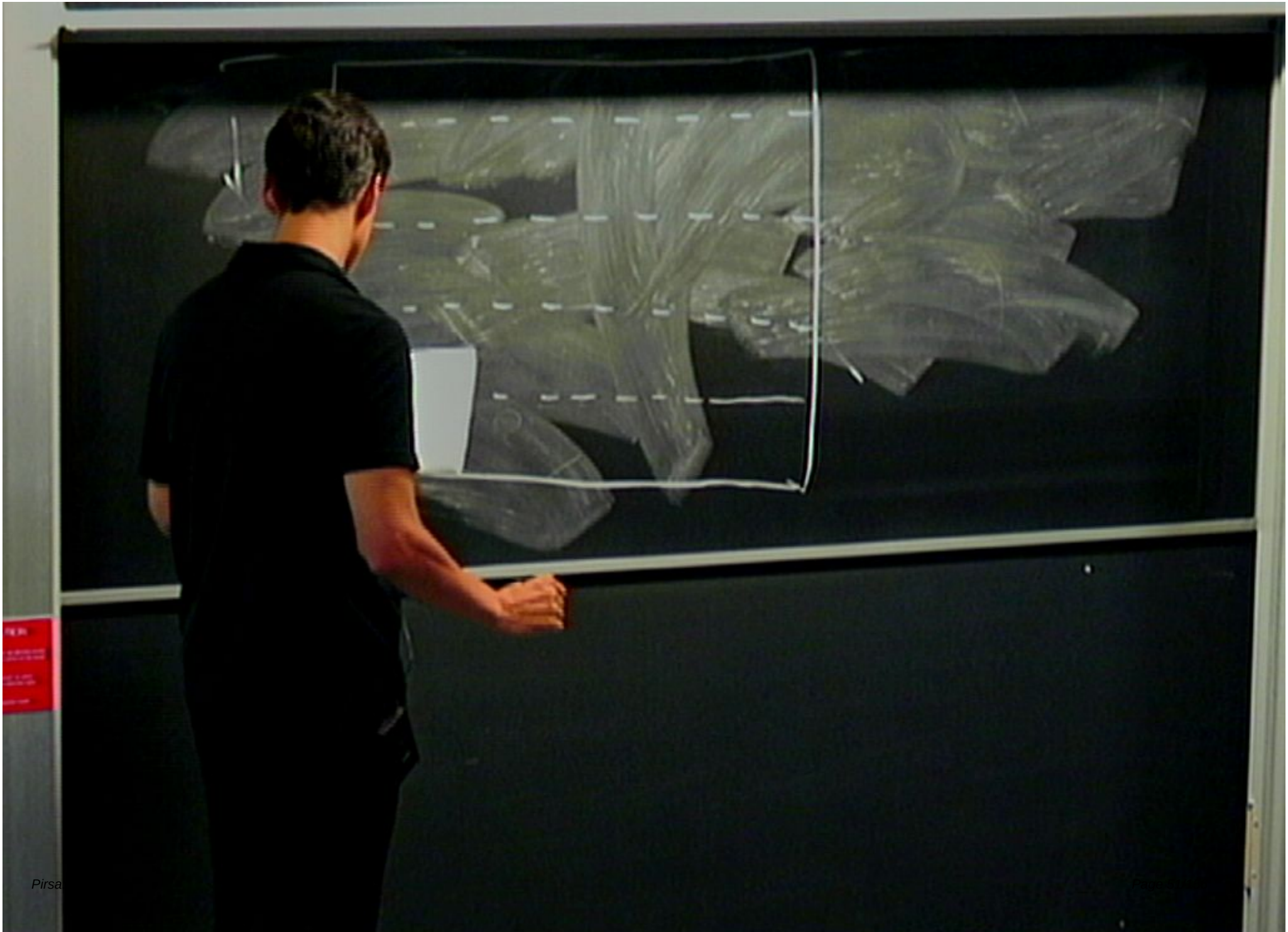
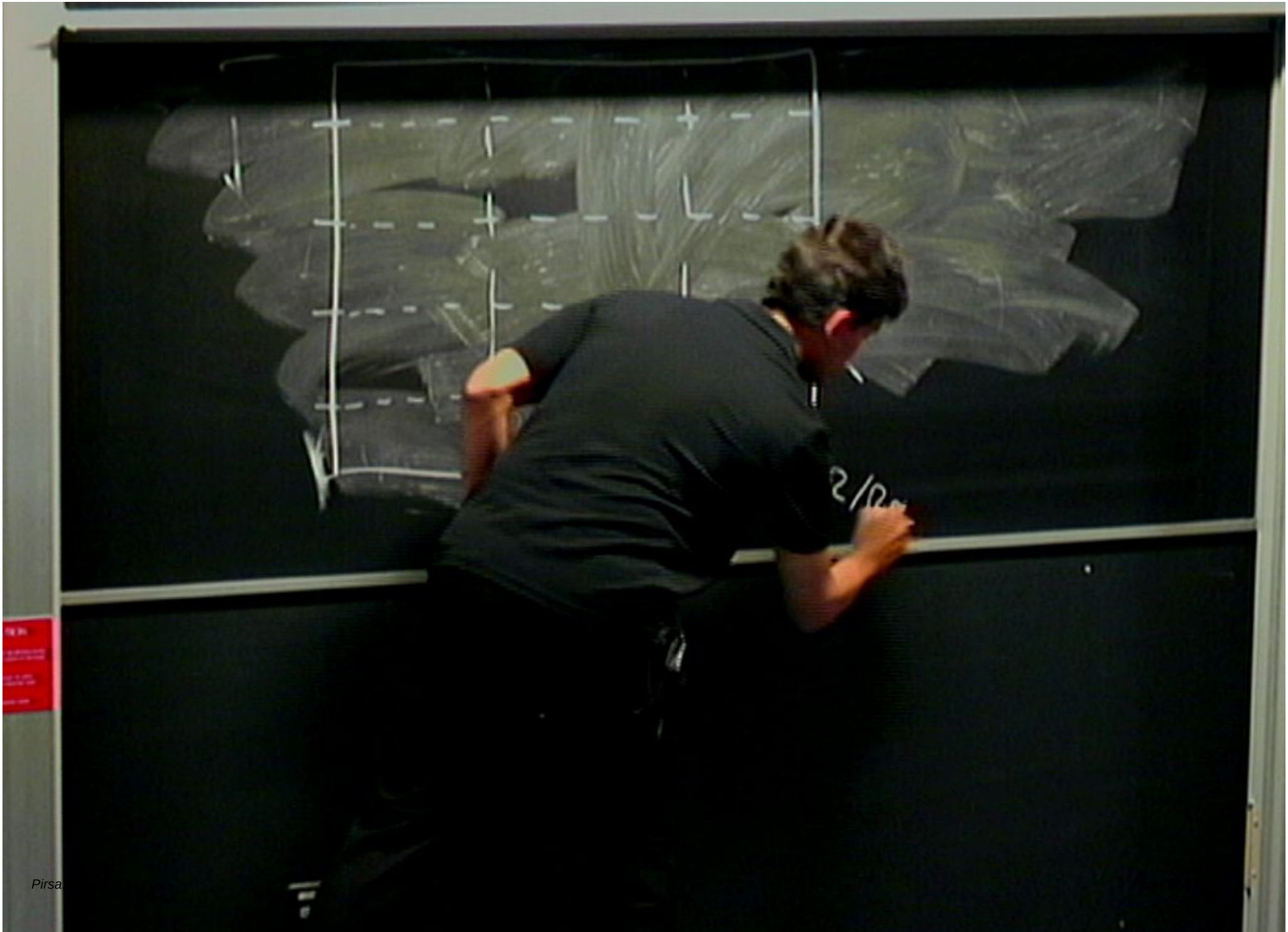
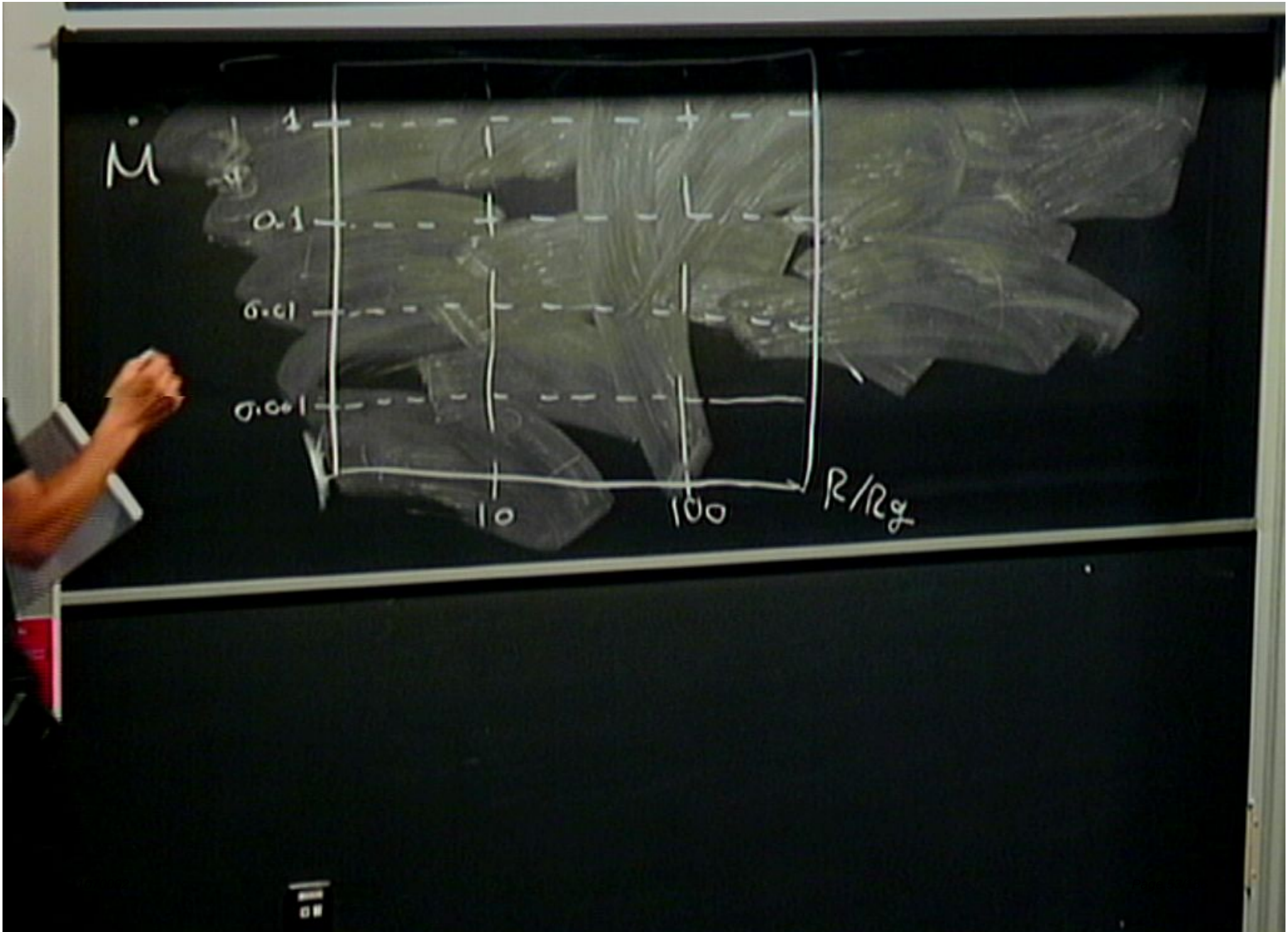
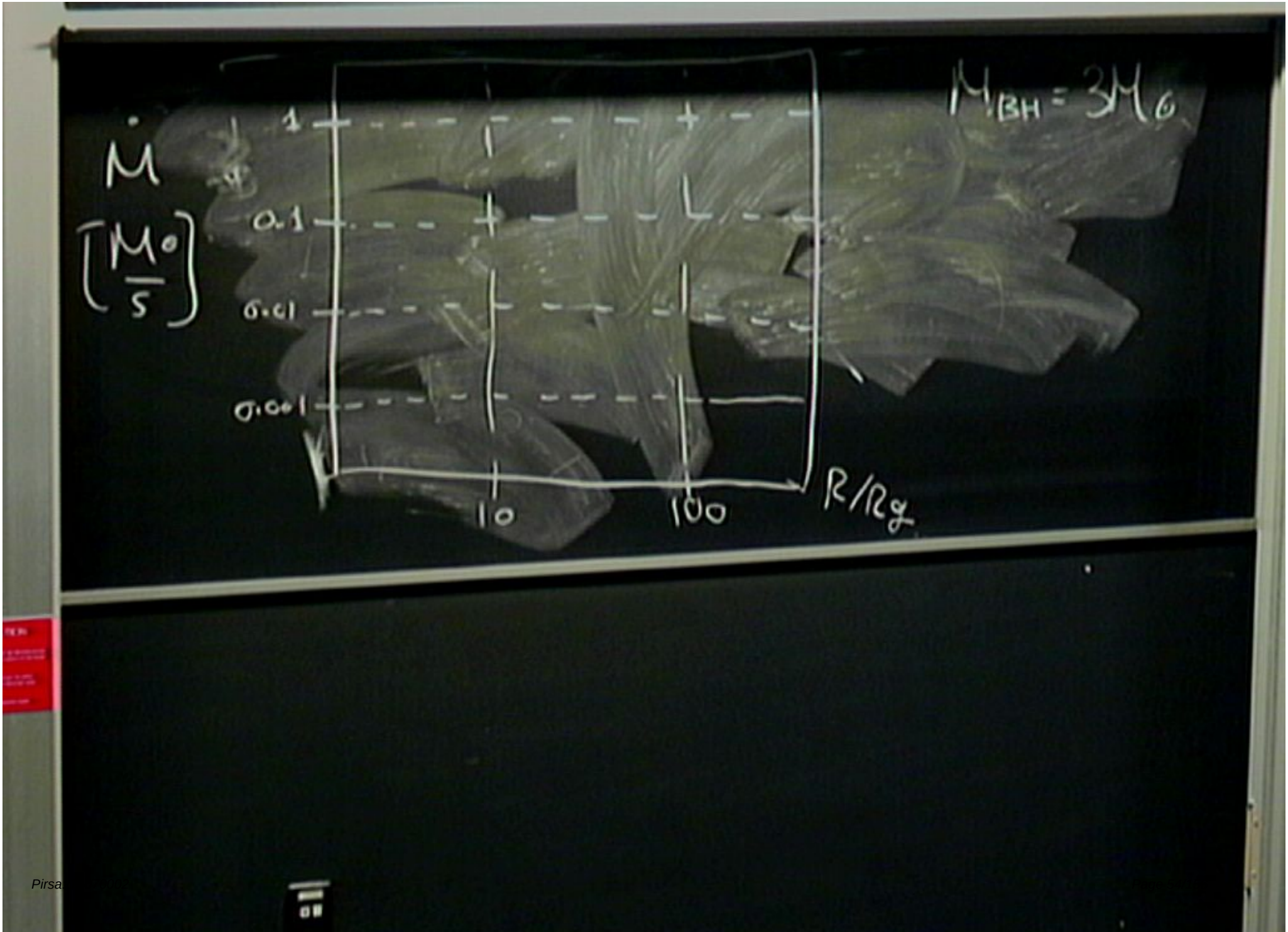

$\left(\frac{Lv}{L_{eddy}}\right)^{-1} \propto l^{-\frac{1}{3}} \propto \left(\frac{t_{real}}{t_{dyn}}\right)$

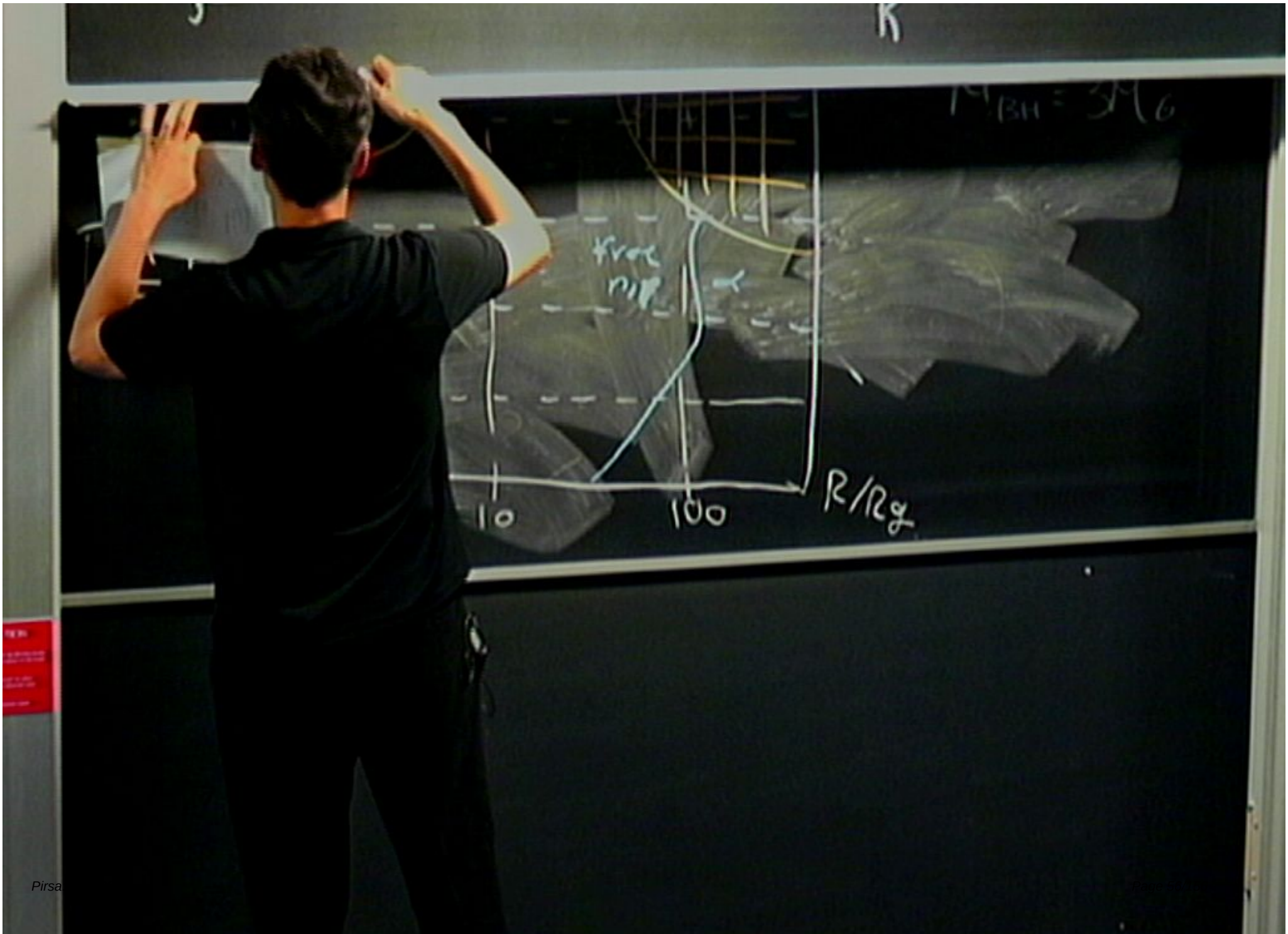


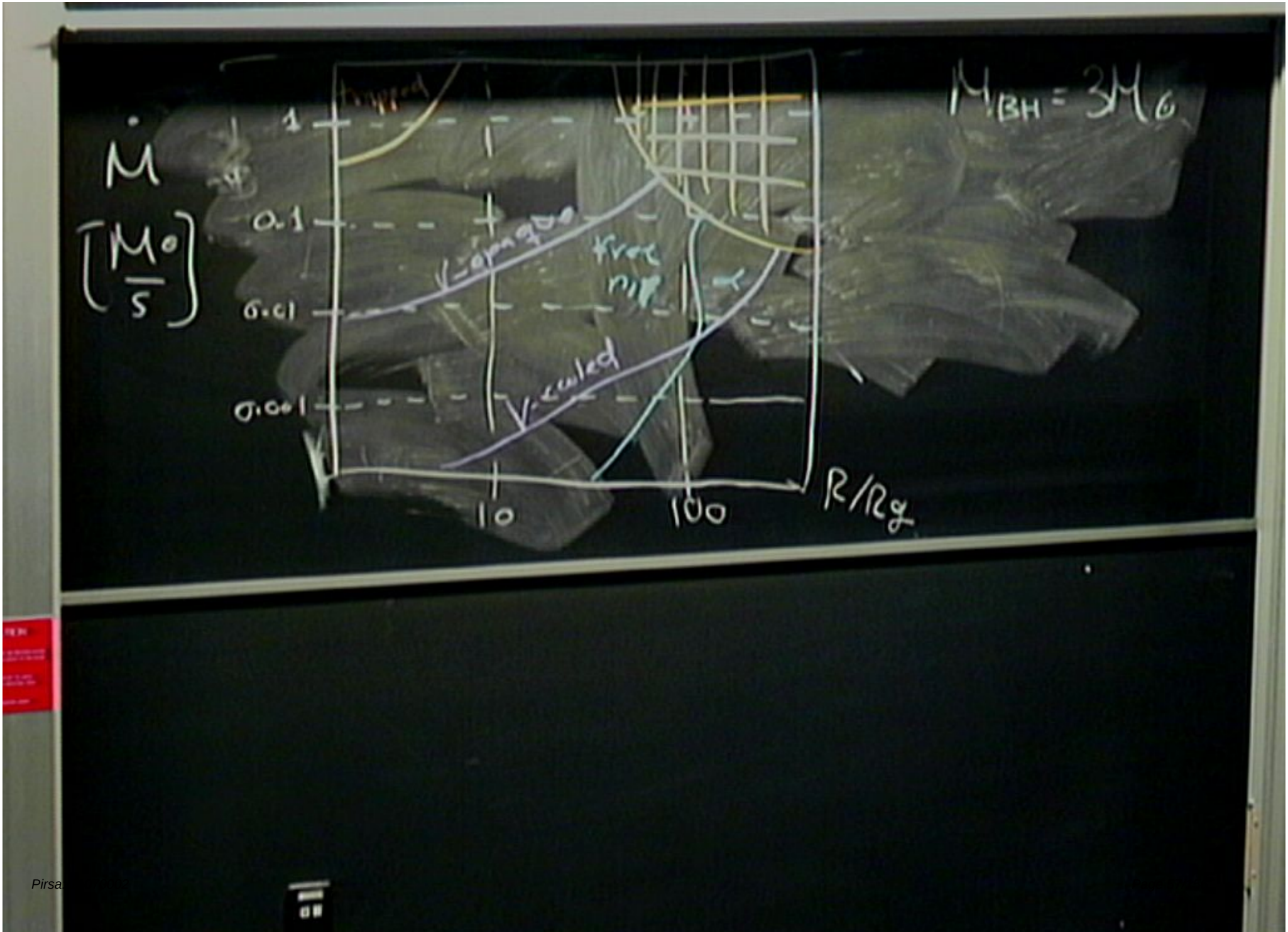



Ṁ
1
0.1
0.01
0.001
10
100
R/Rg


$\dot{M}$
$\left[\frac{M_\odot}{5}\right]$
1
0.1
0.01
0.001
10
100
R/Rg
$M_{BH} = 3M_\odot$


$\dot{M}$
$\left[\frac{M_\odot}{s}\right]$
1
0.1
0.01
0.001
$M_{BH} = 3M_\odot$
R/Rg


K
10
100
R/Rg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1
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R/Rg
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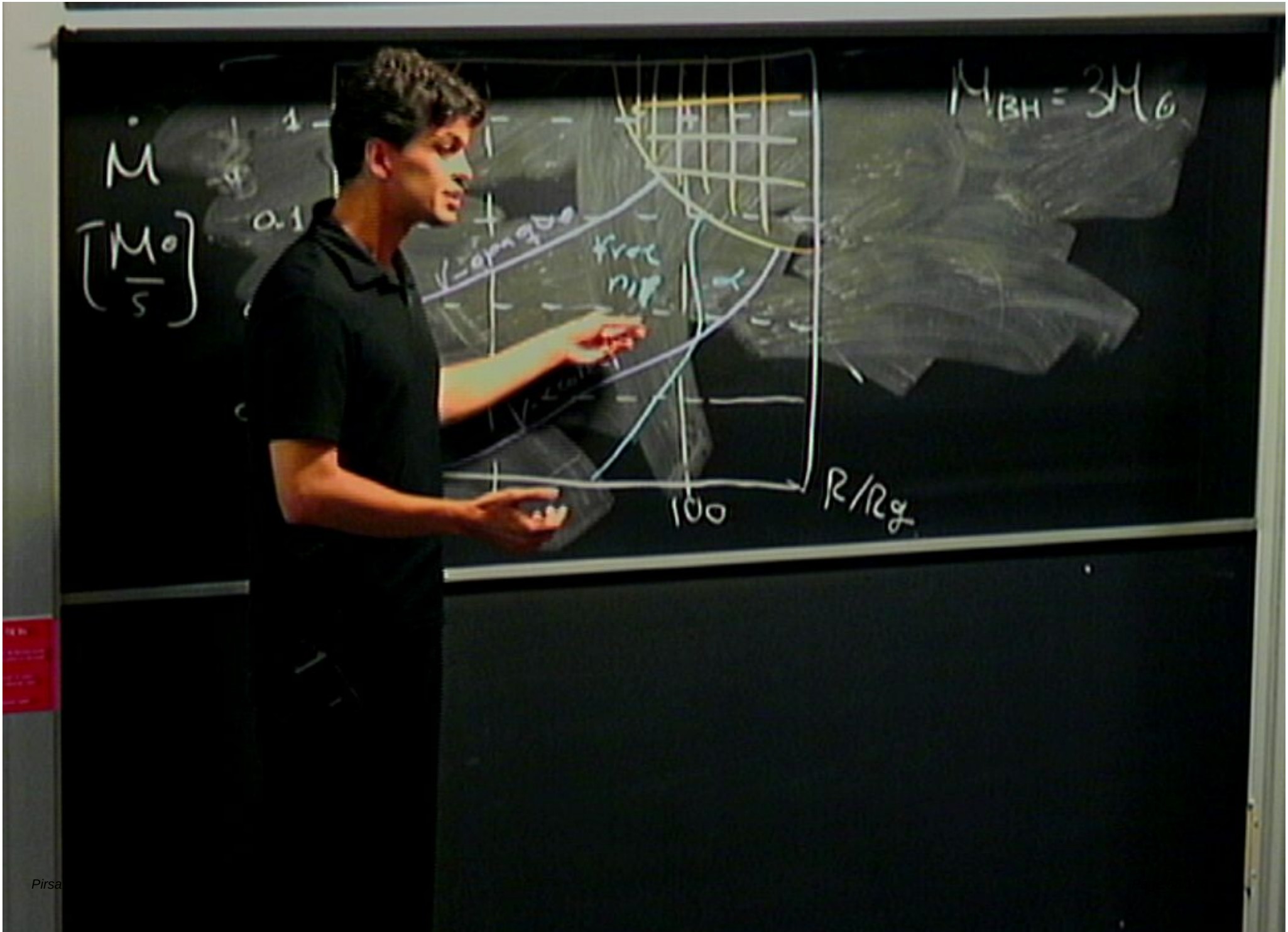
$\dot{M}$
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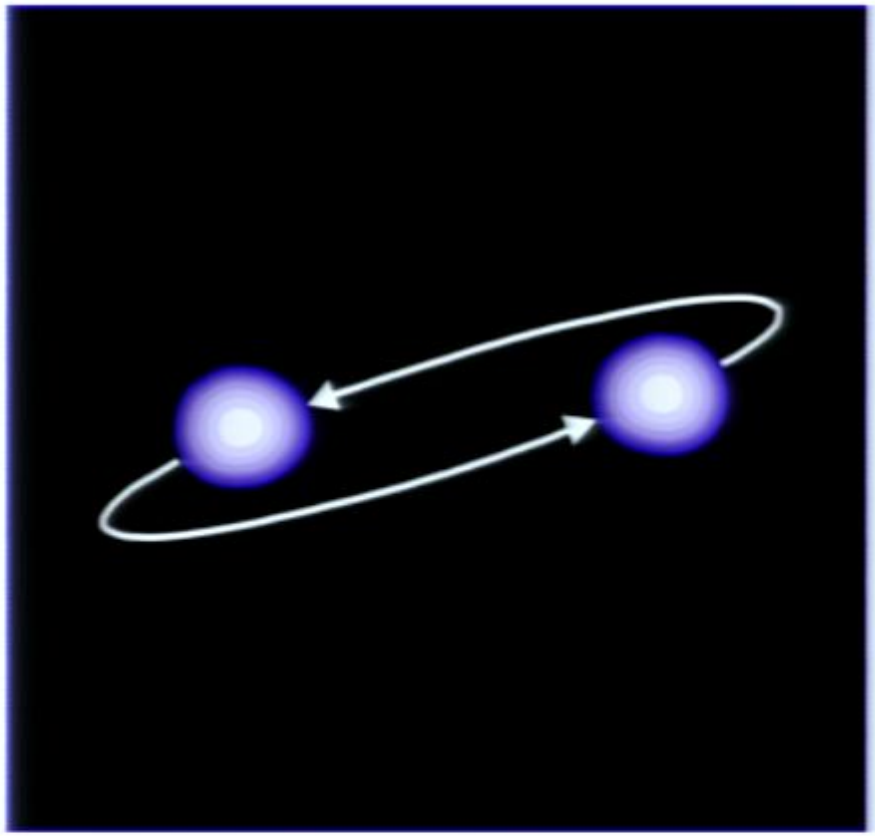
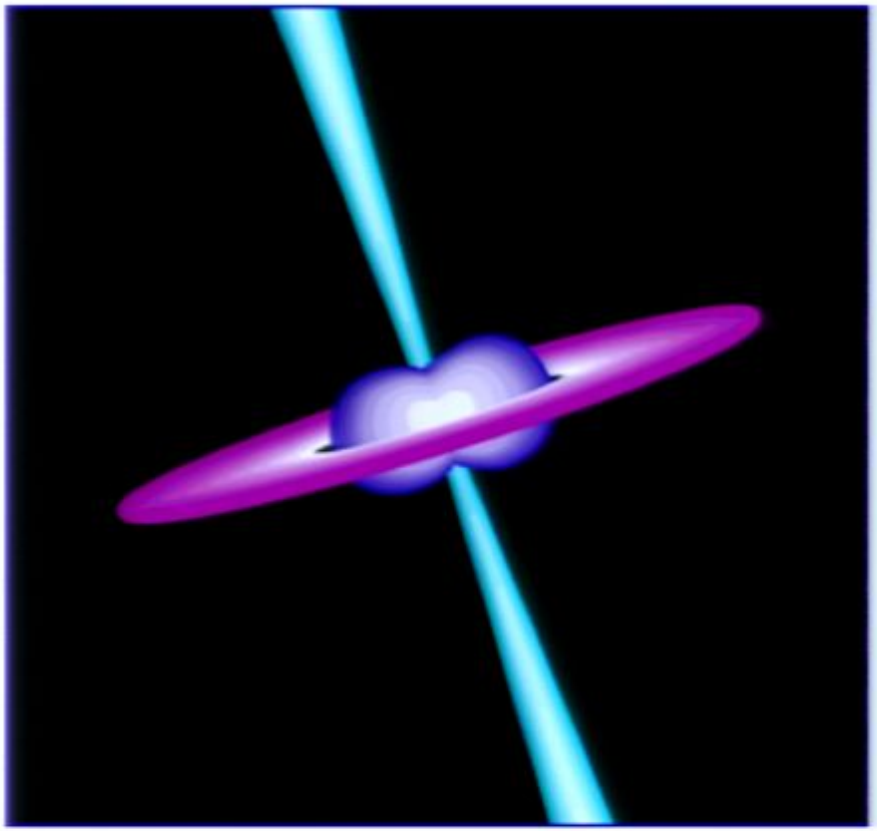
1
0.1
100
R/Rg
$M_{BH} = 3M_\odot$

Merging Compact Objects: *Short GRBs?*



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$\dot{M}$
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1
0.1
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10
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R/Rg

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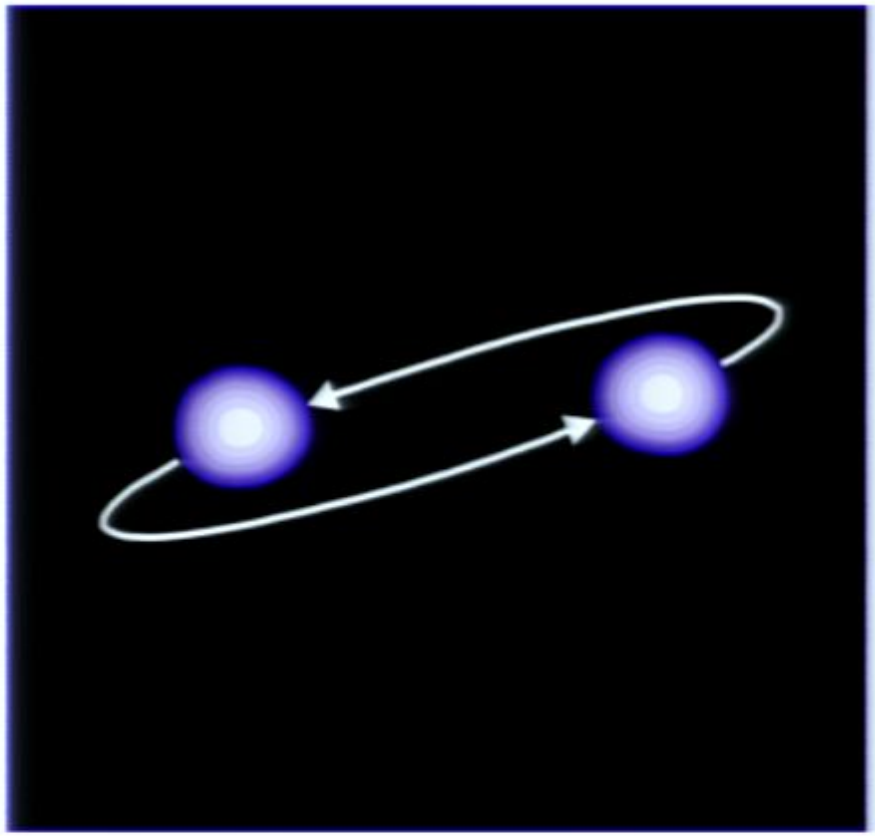

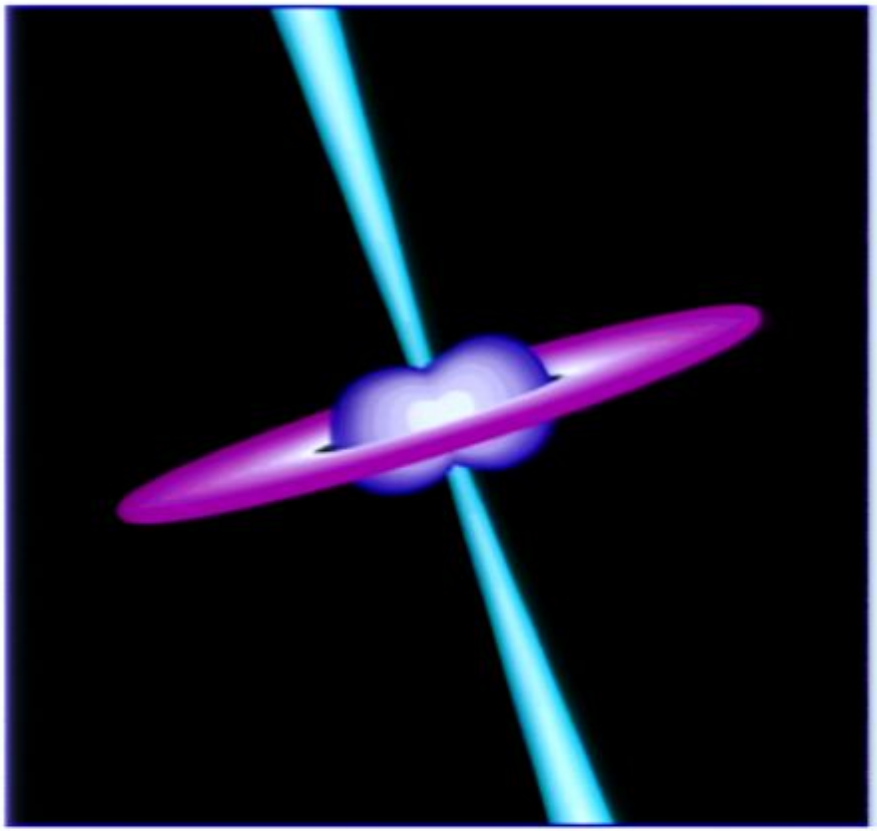

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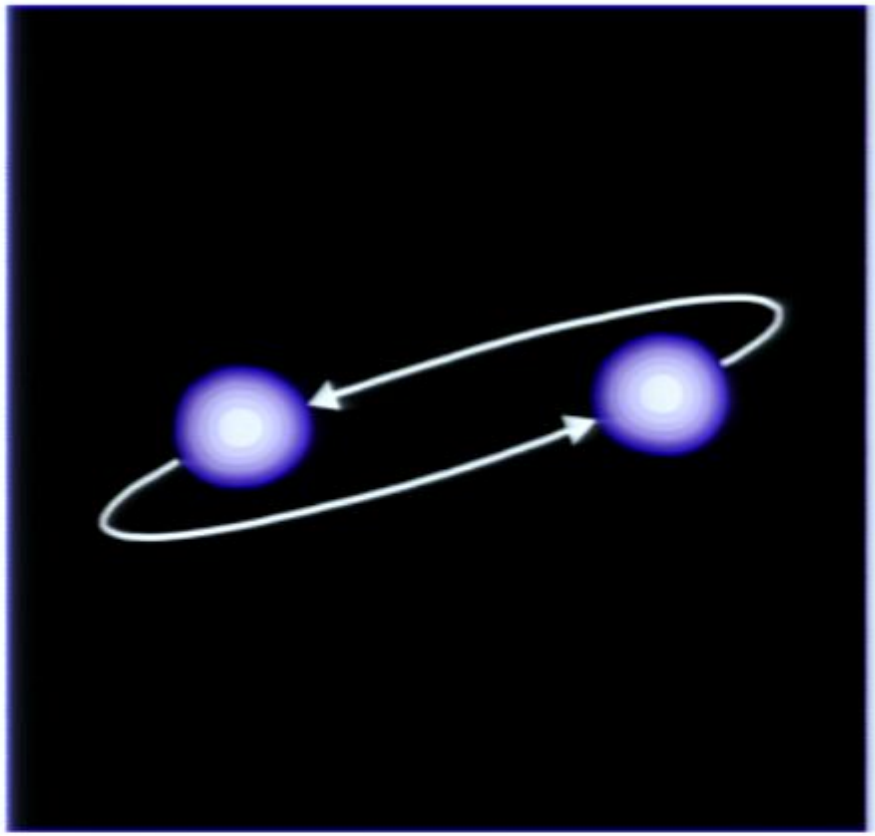
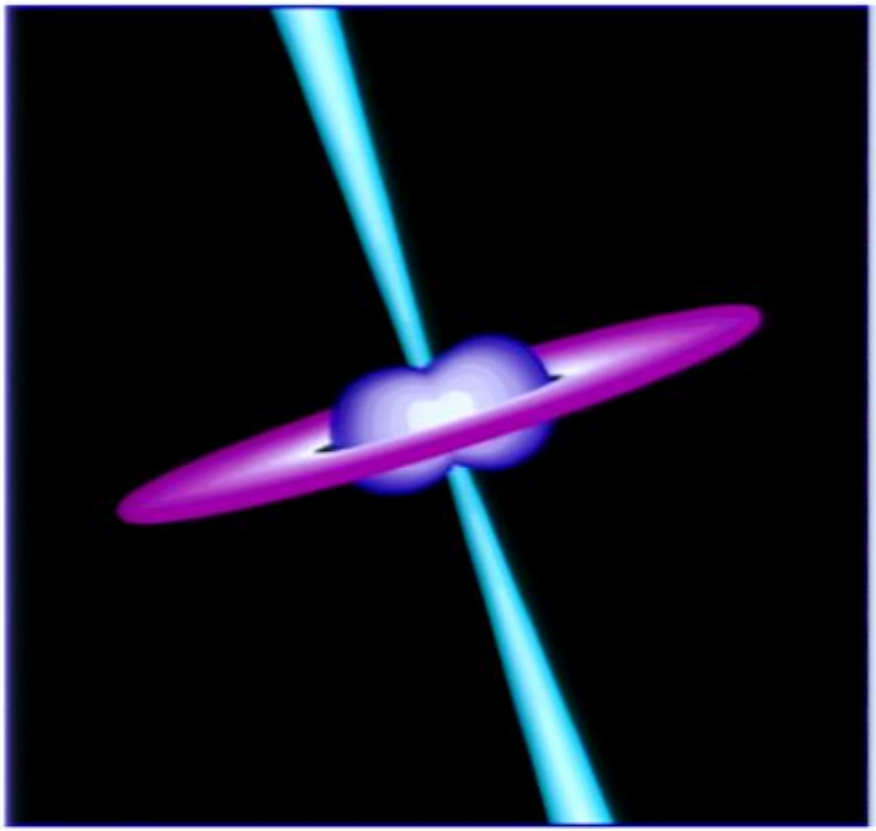
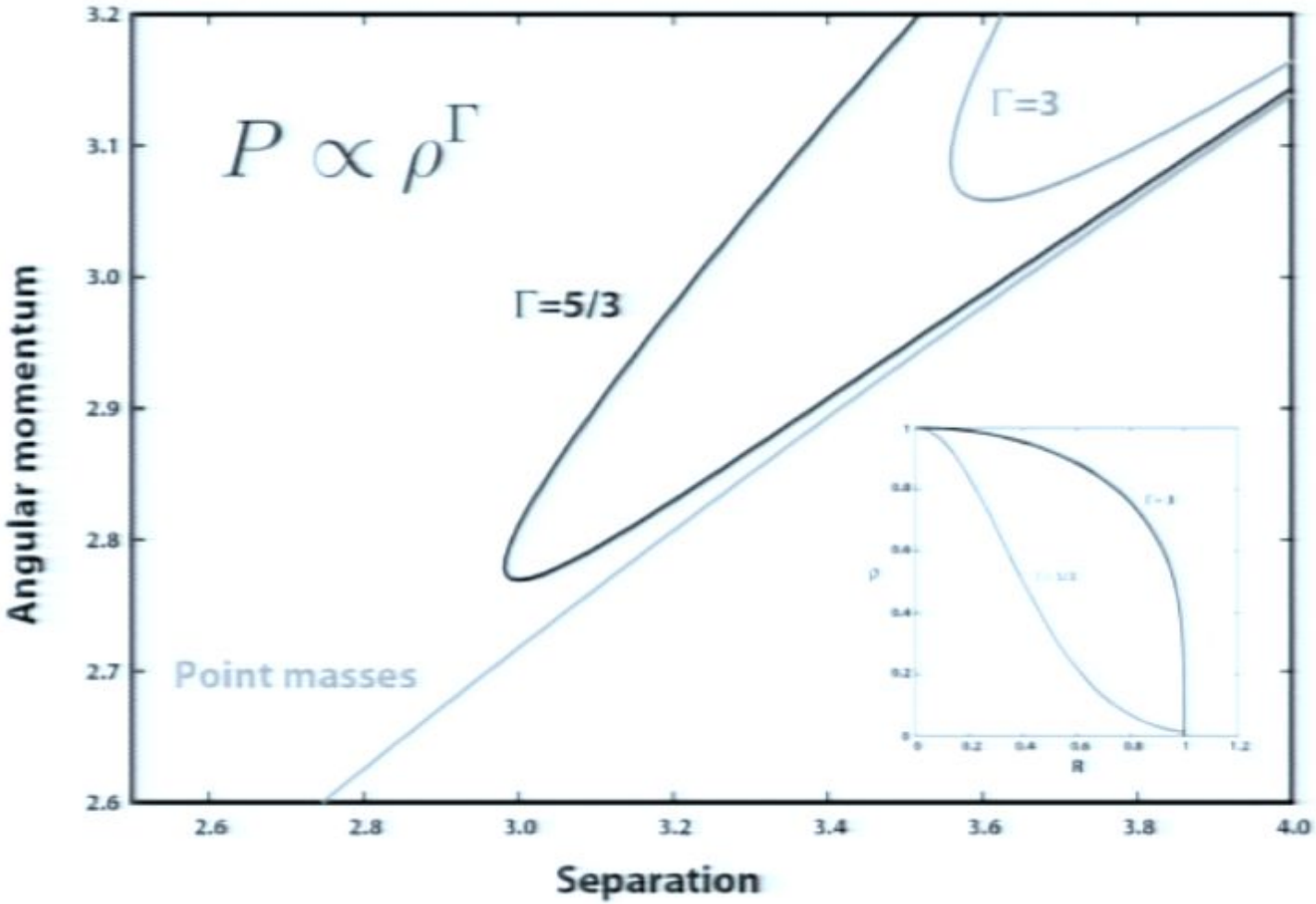


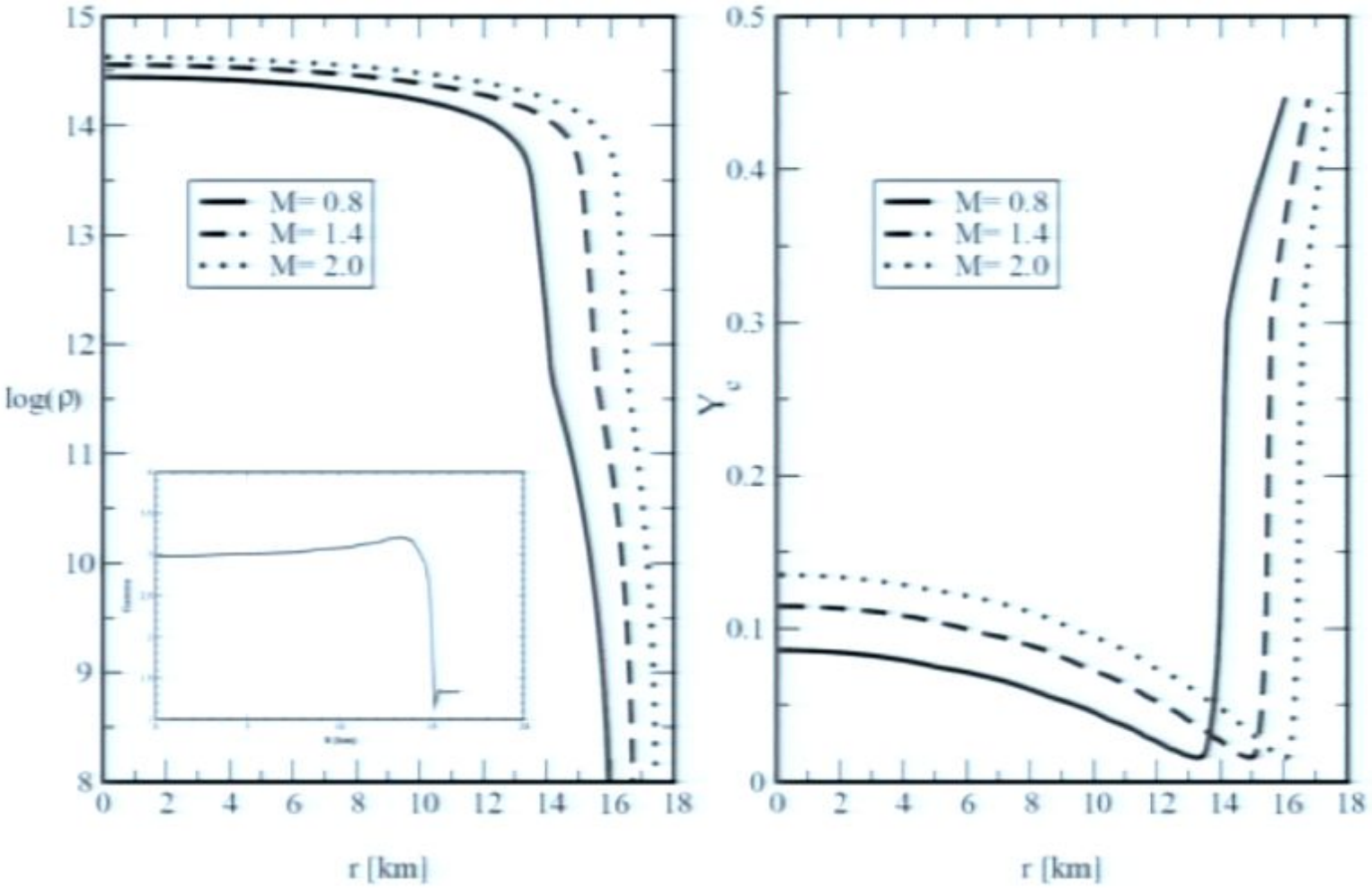


Merging Compact Objects: *Stability*

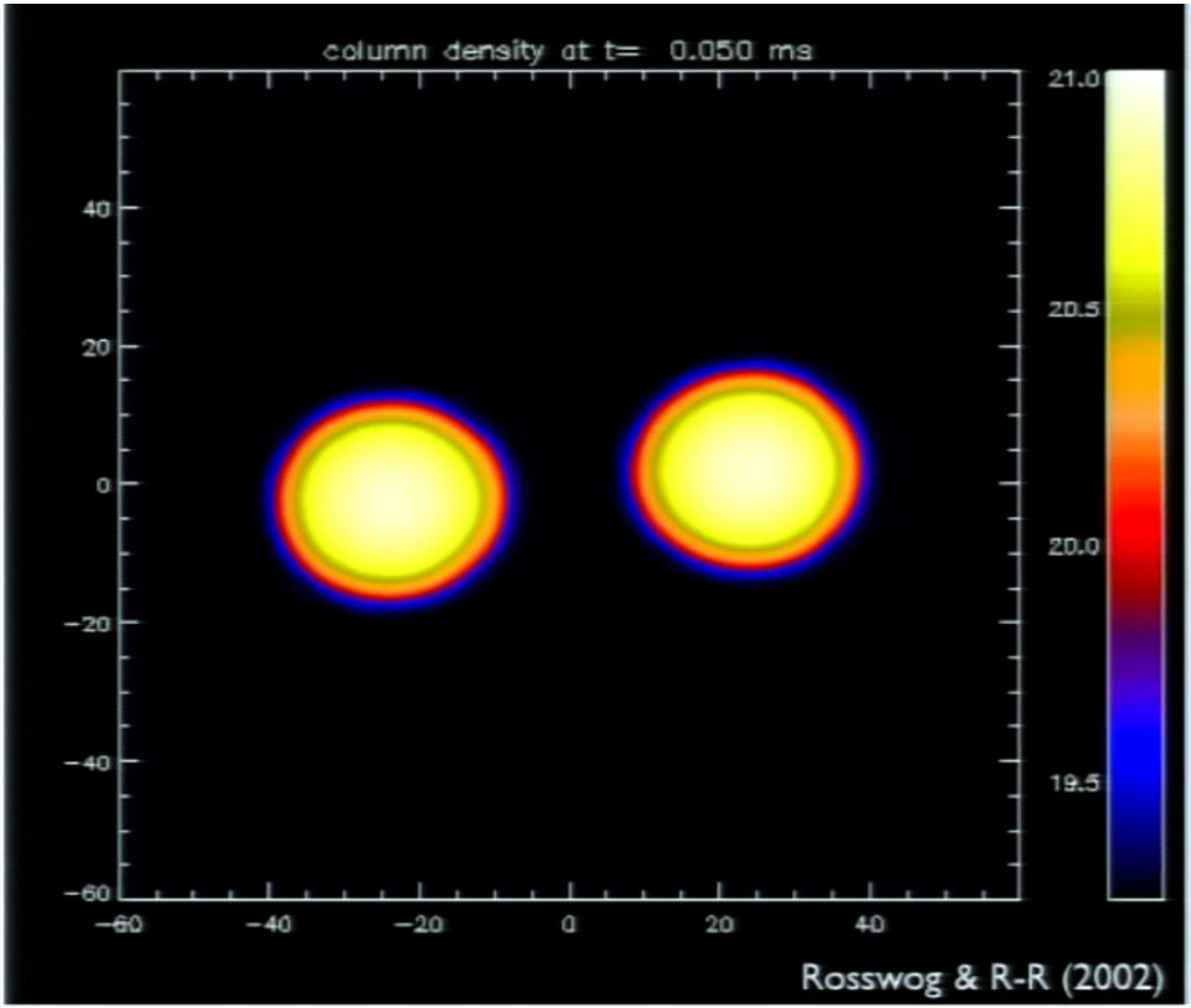


•Tidal effects increase the steepness of the effective interaction potential and produce a minimum in $J_{eq}(R)$, indicating the onset of a dynamical instability (Lai+1994).

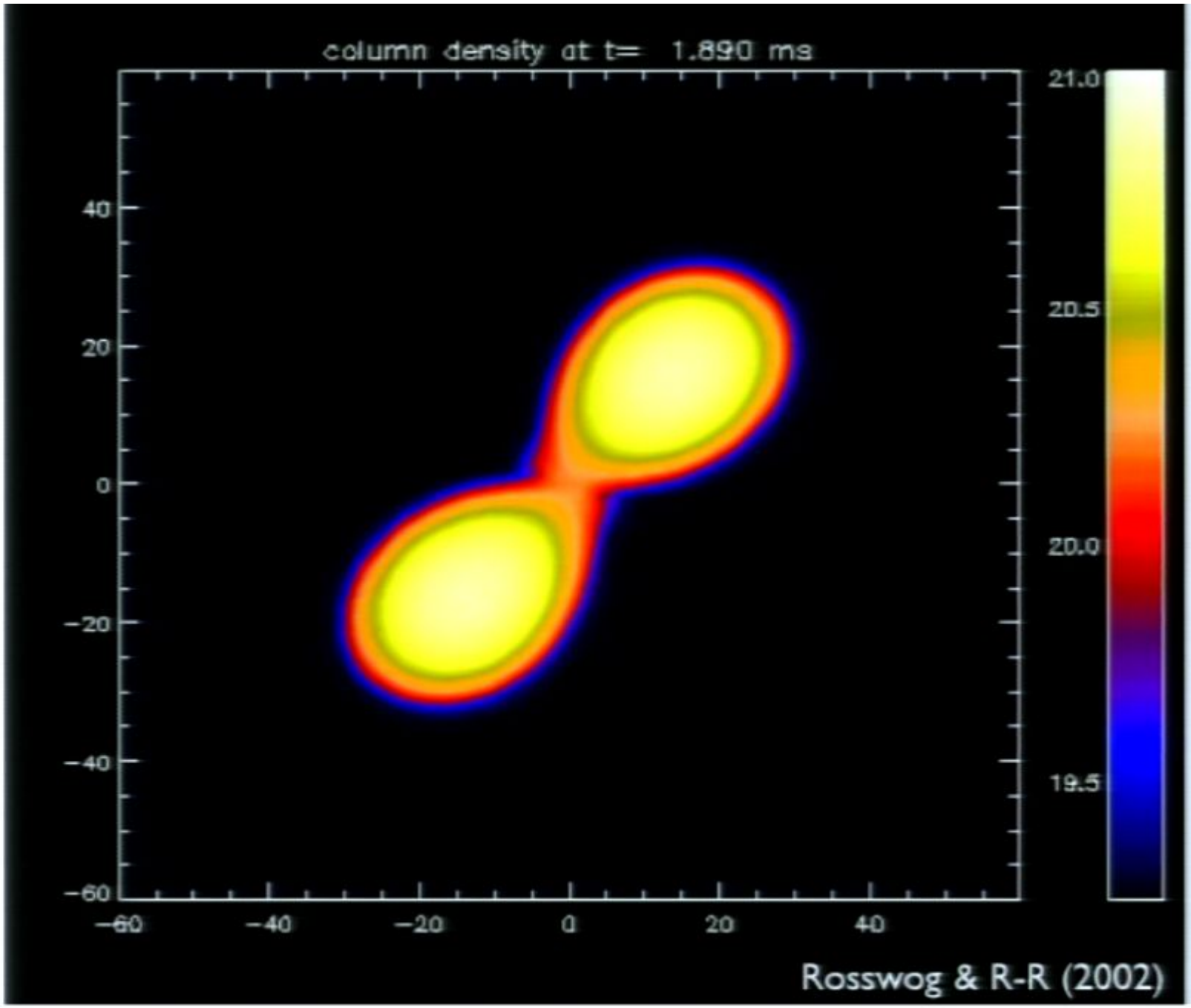
Merging Compact Objects: *Initial Conditions*



•Profiles of matter density and electron fraction of the initial neutron star models (masses in solar units).



- The equations of hydrodynamics are solved using SPH method with a realistic equation of state for hot, dense nuclear matter (Shen+1998)



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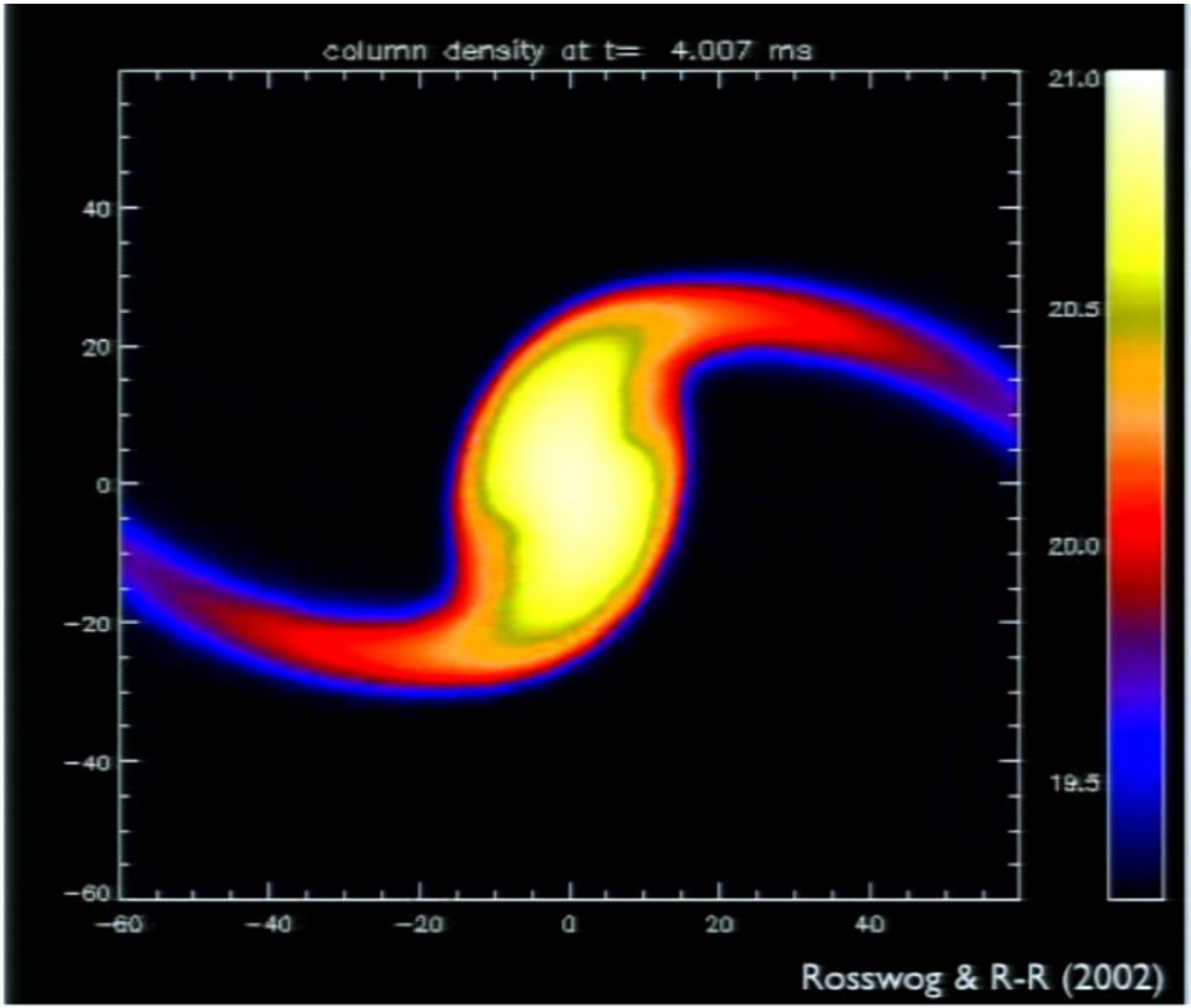

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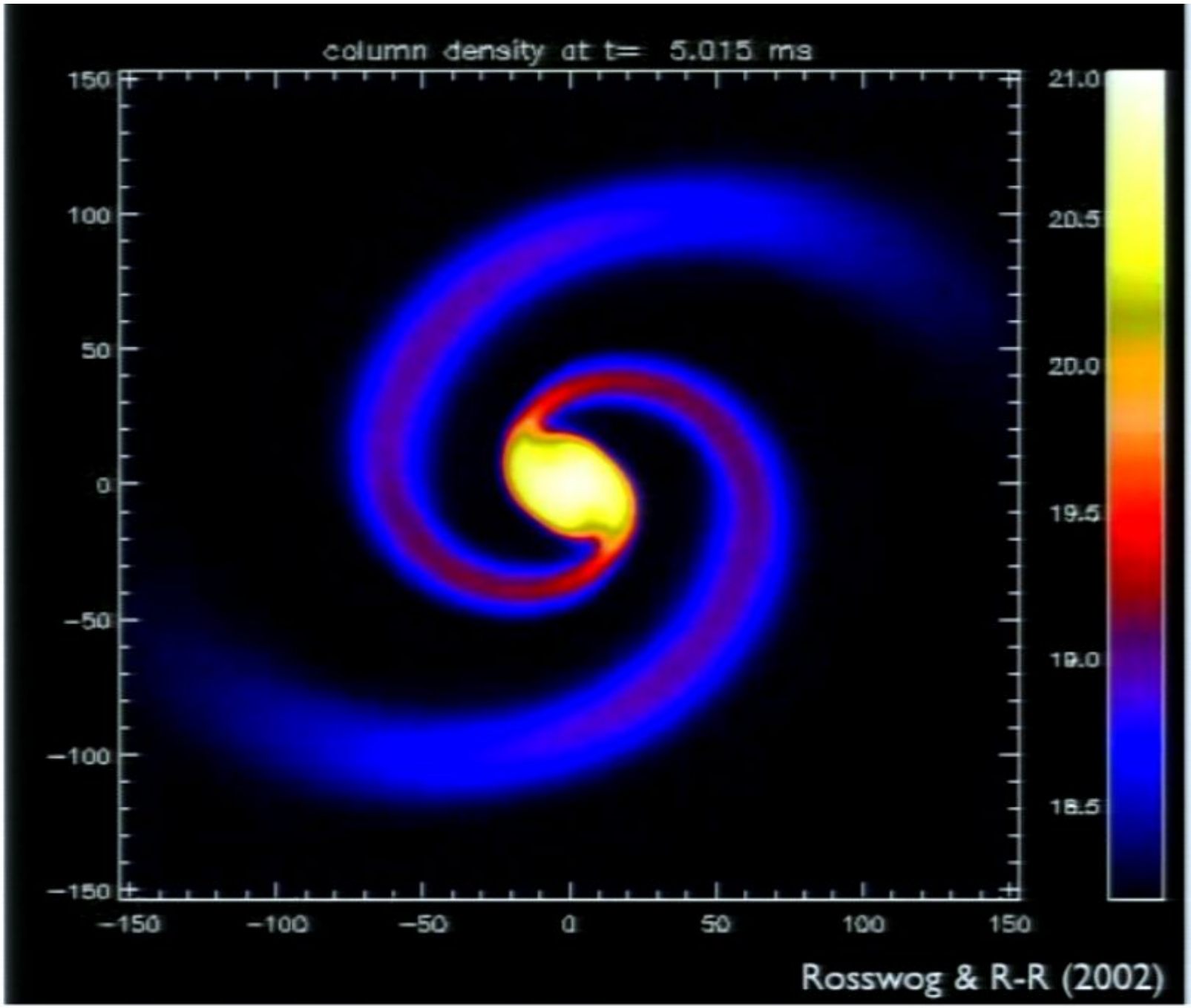

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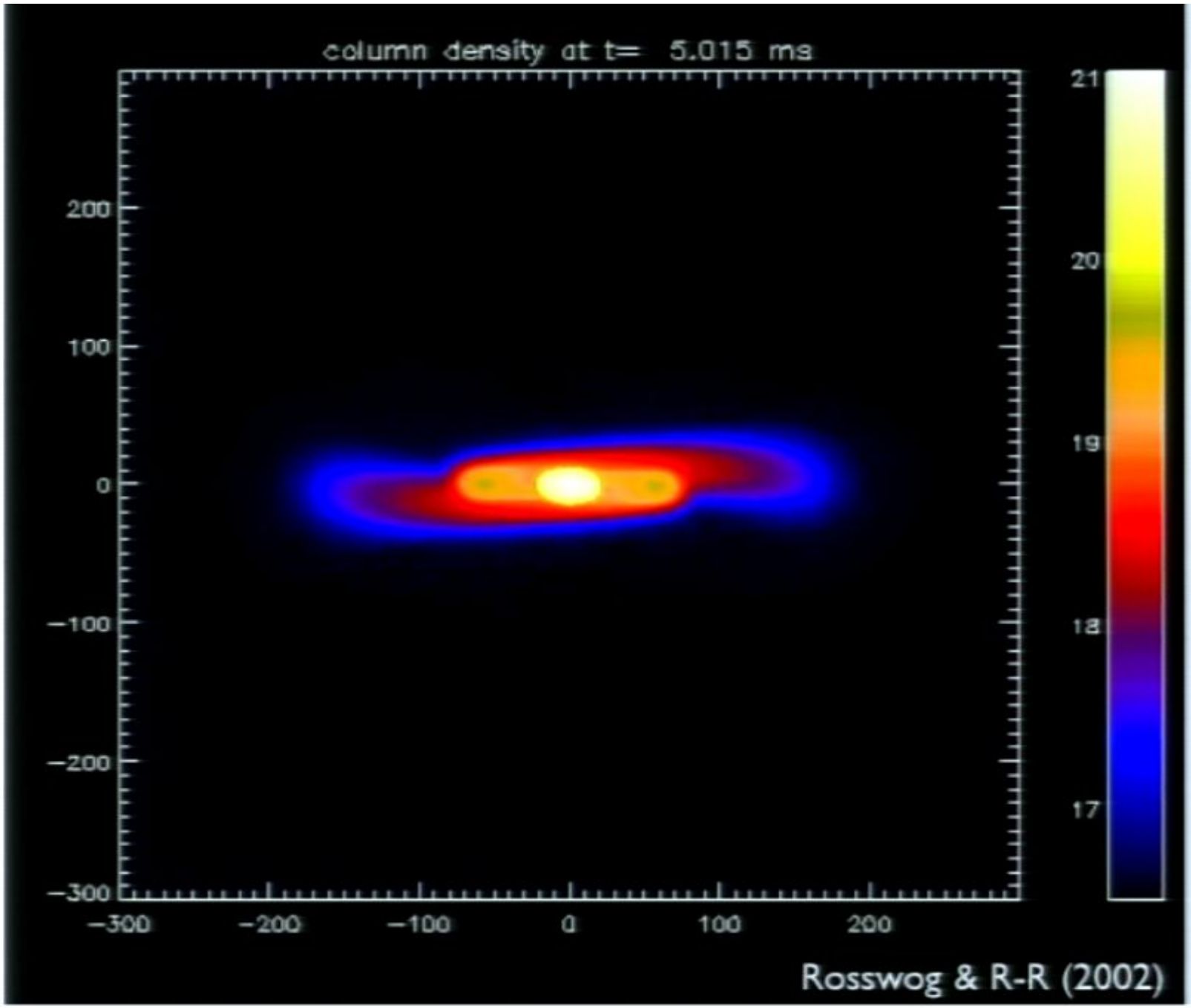

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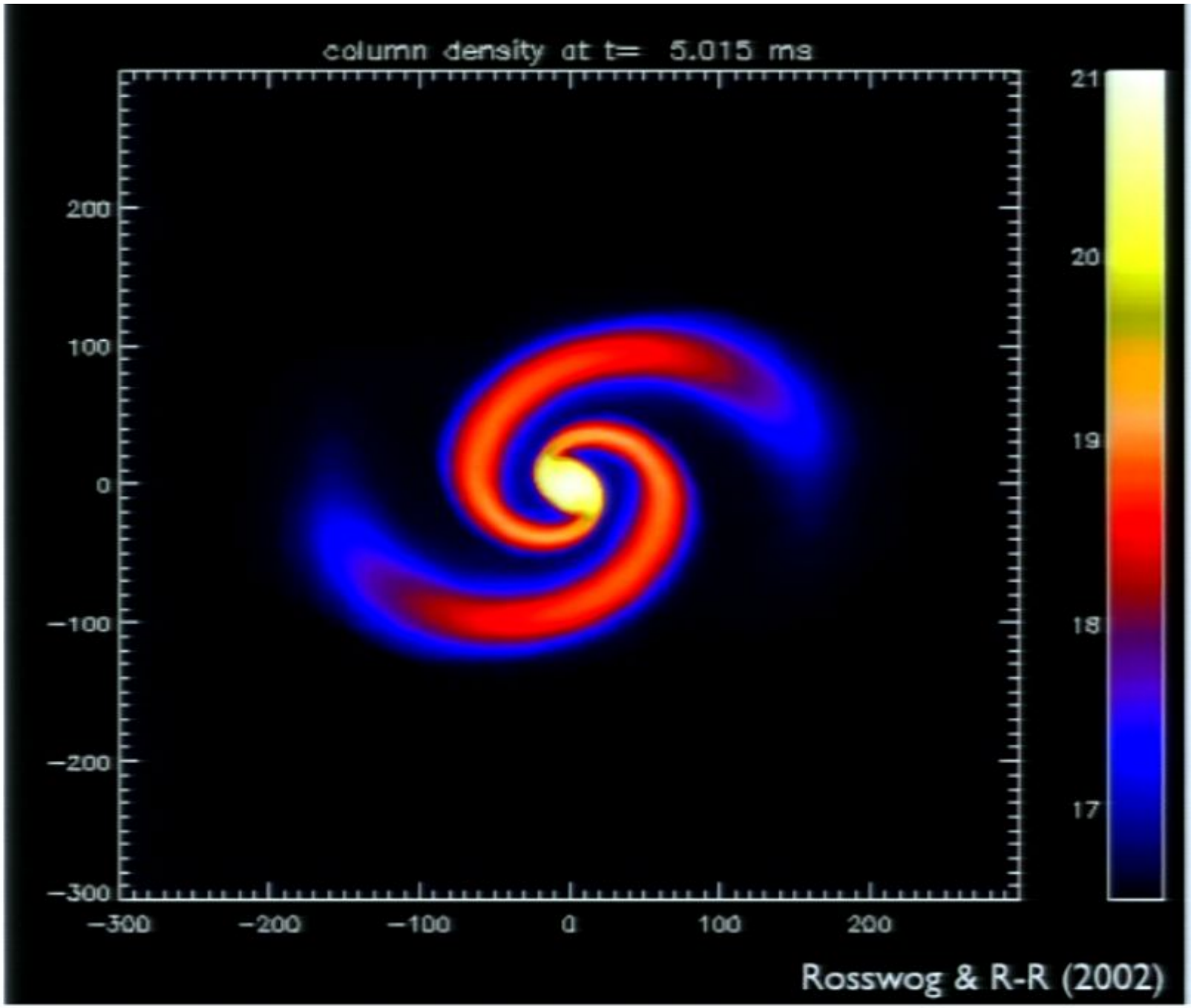

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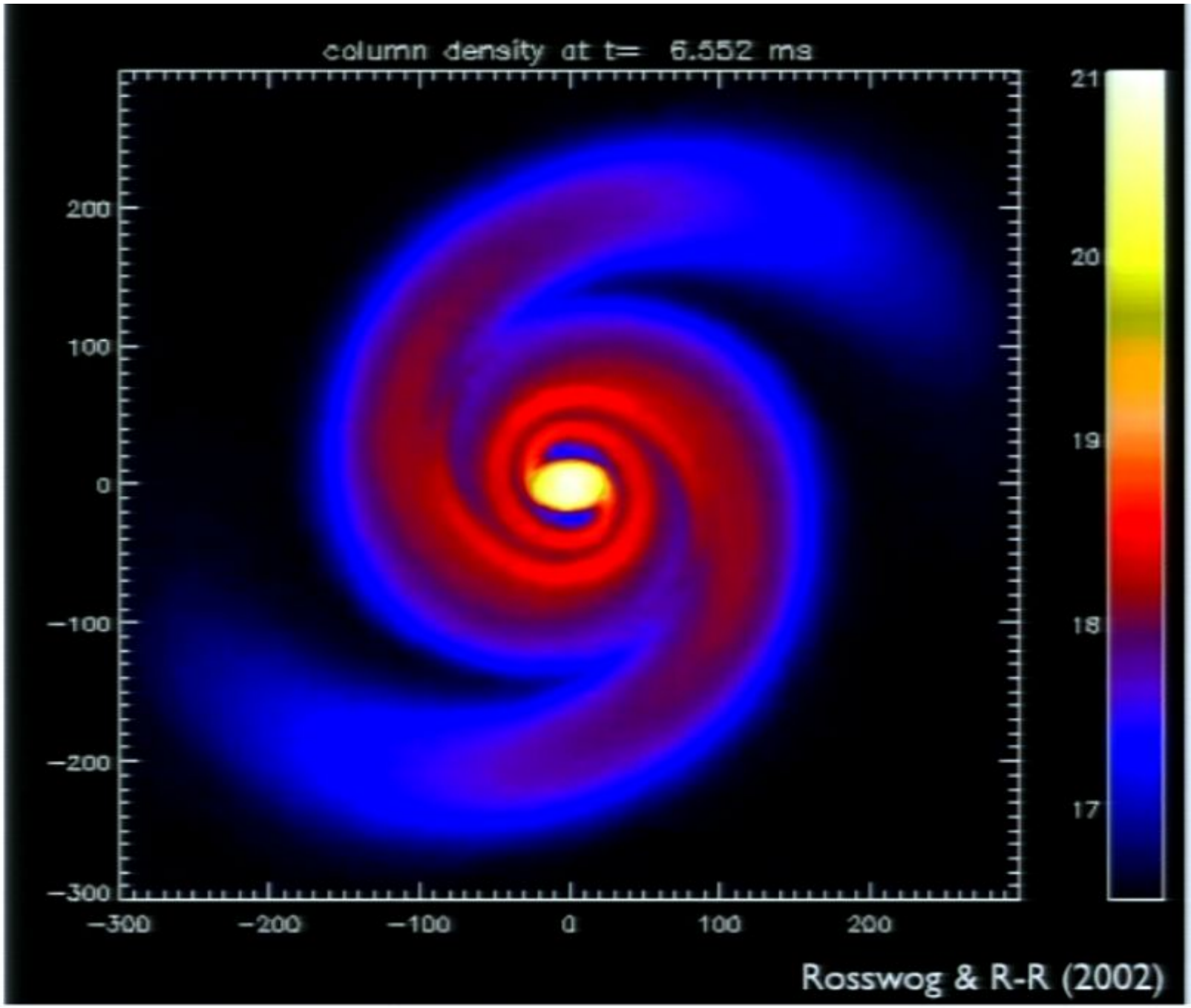

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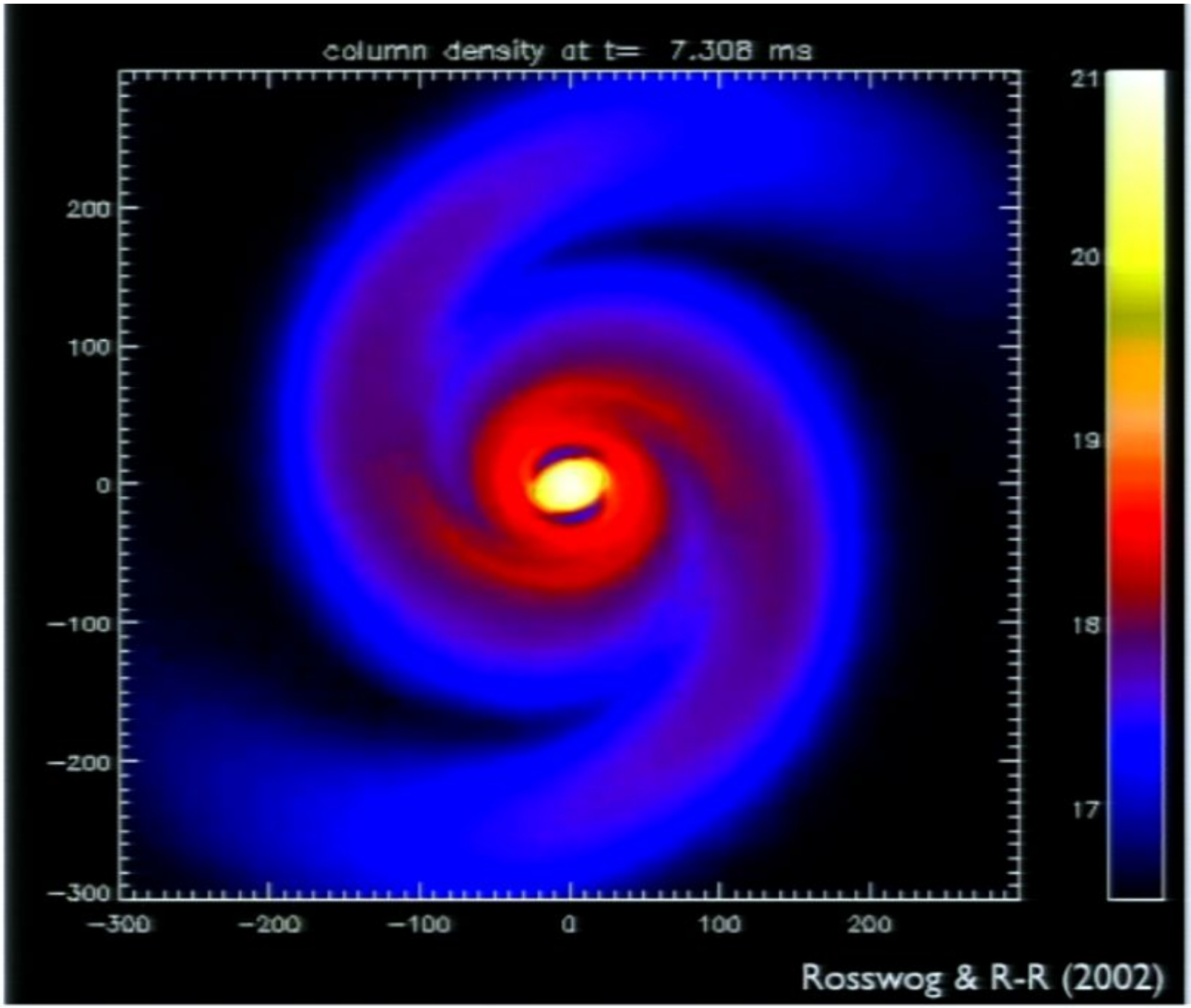

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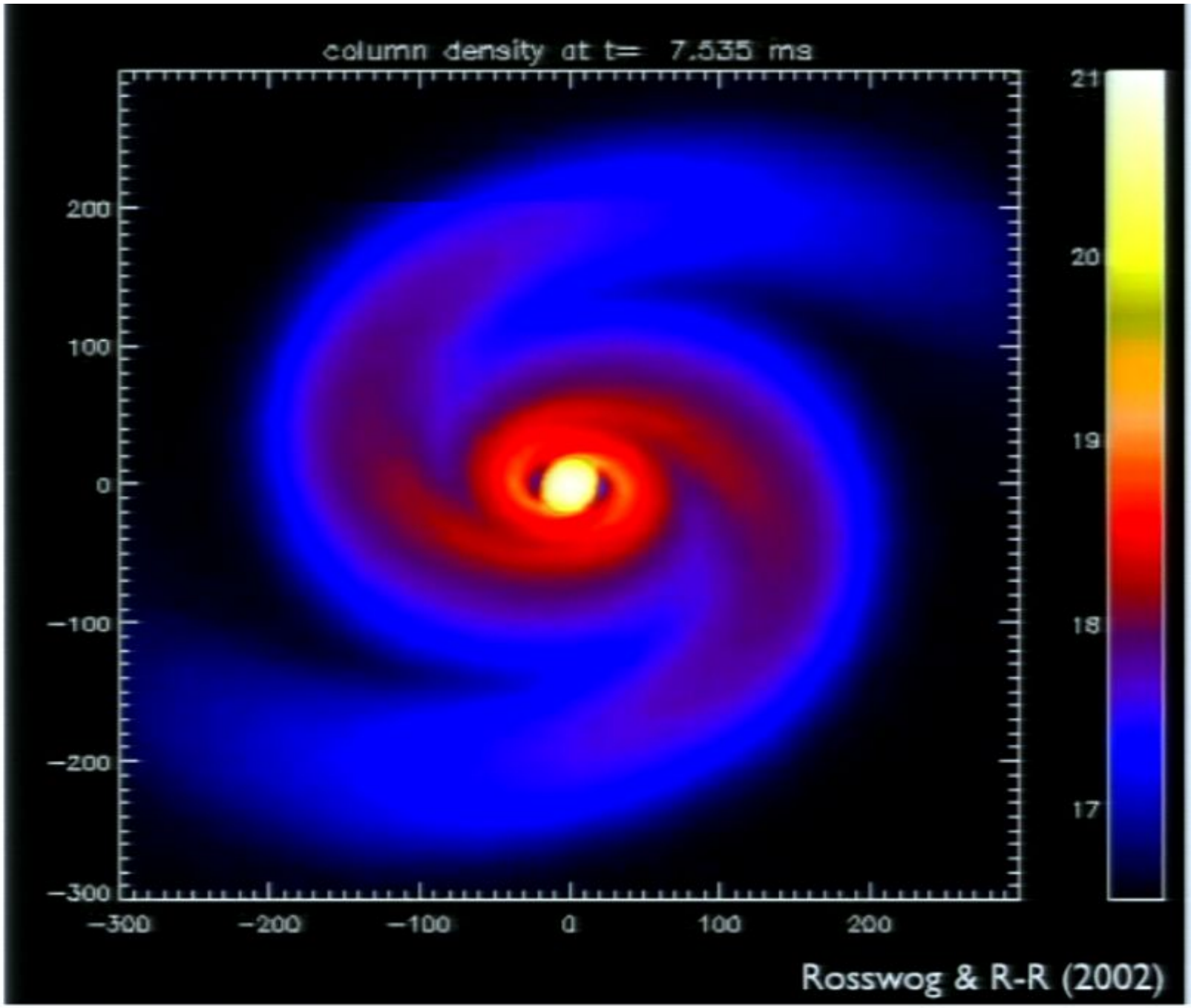

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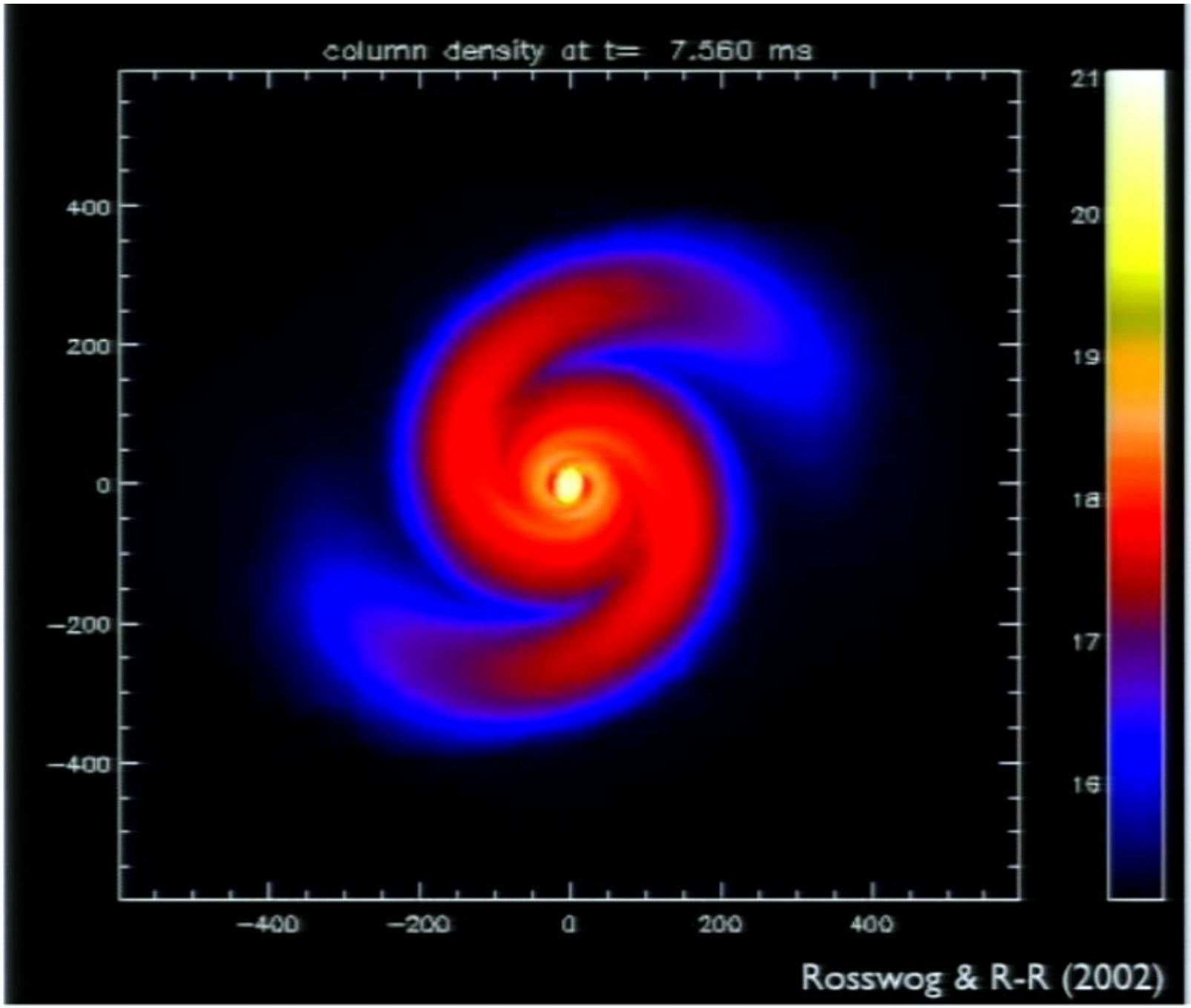

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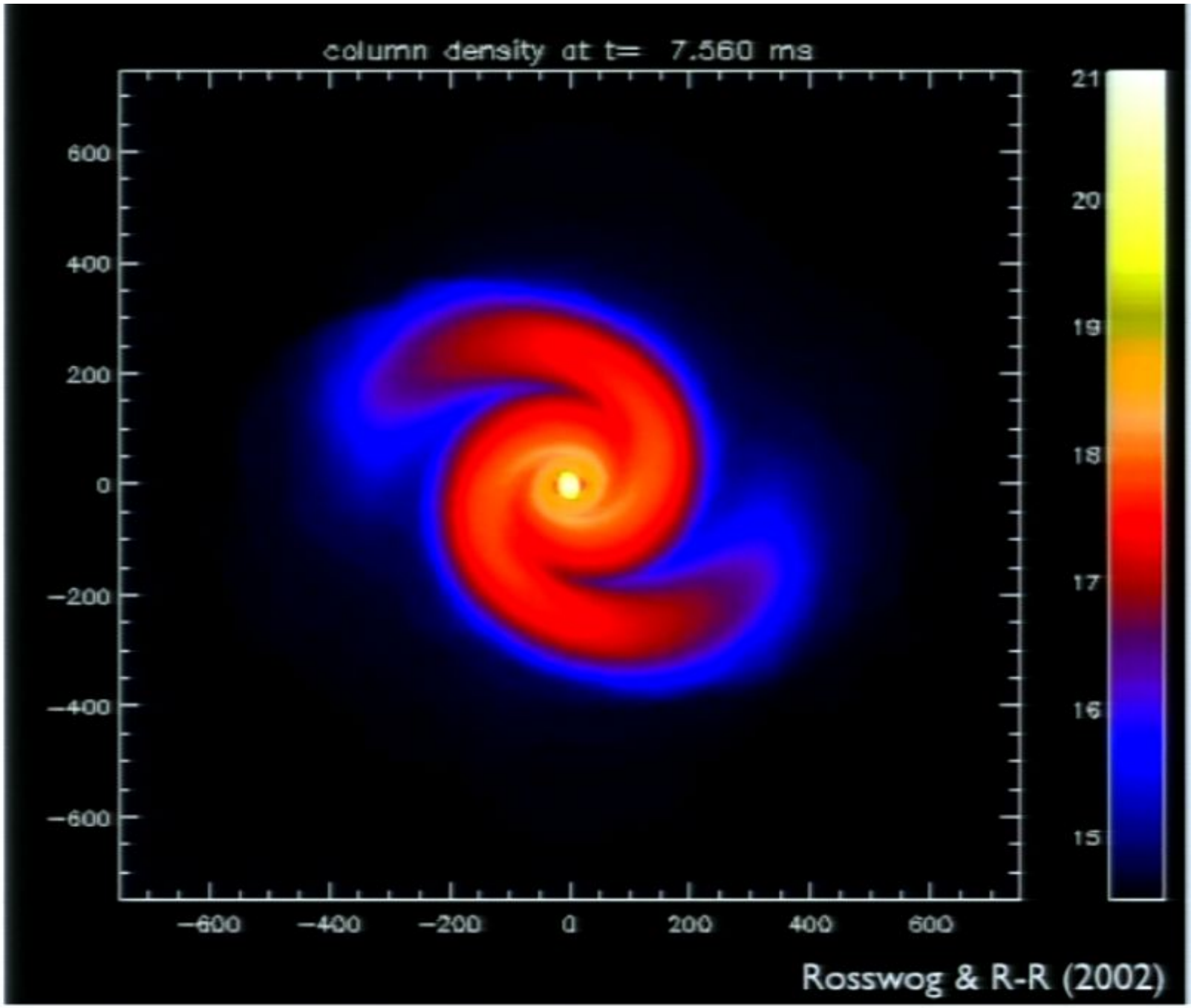

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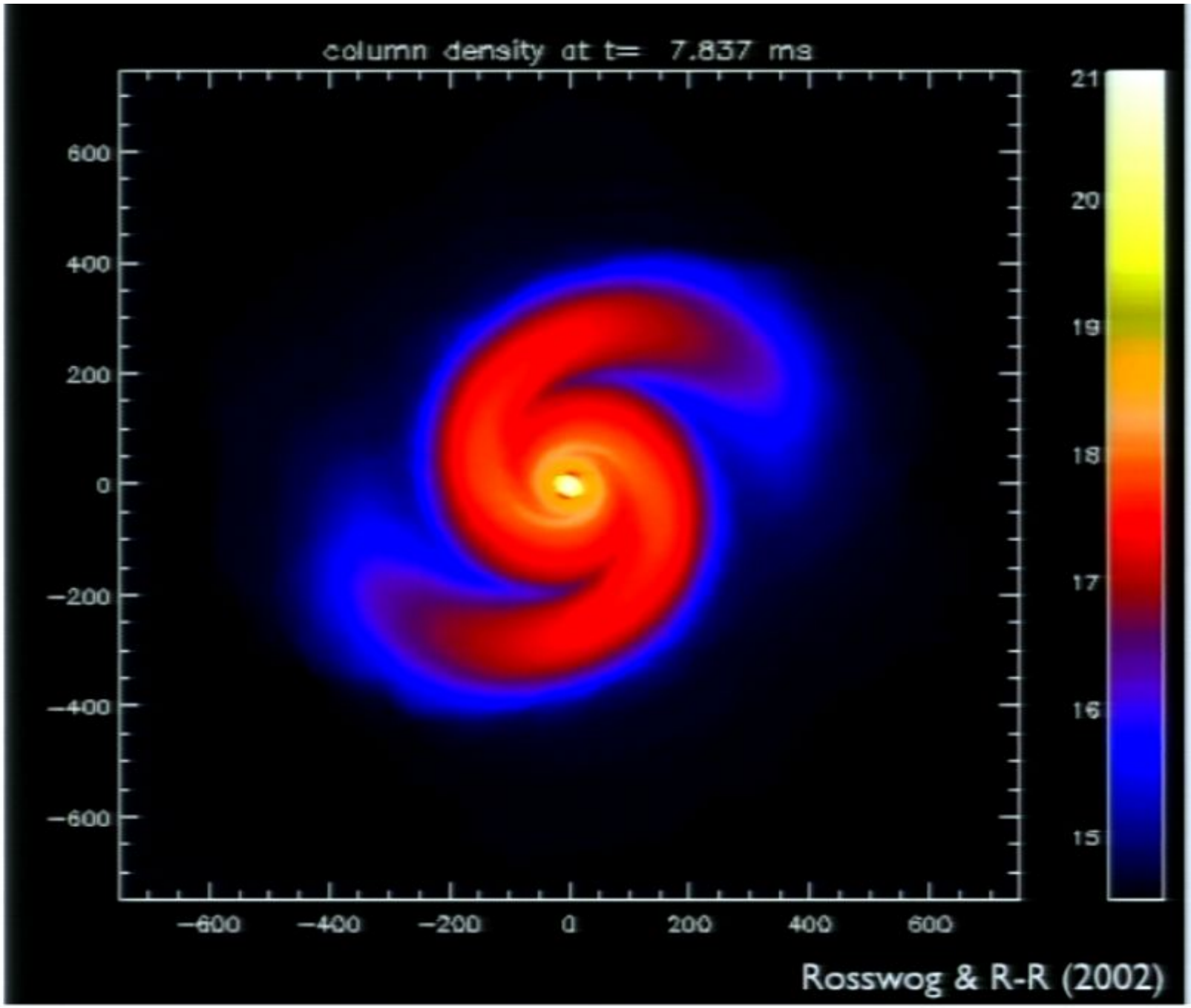

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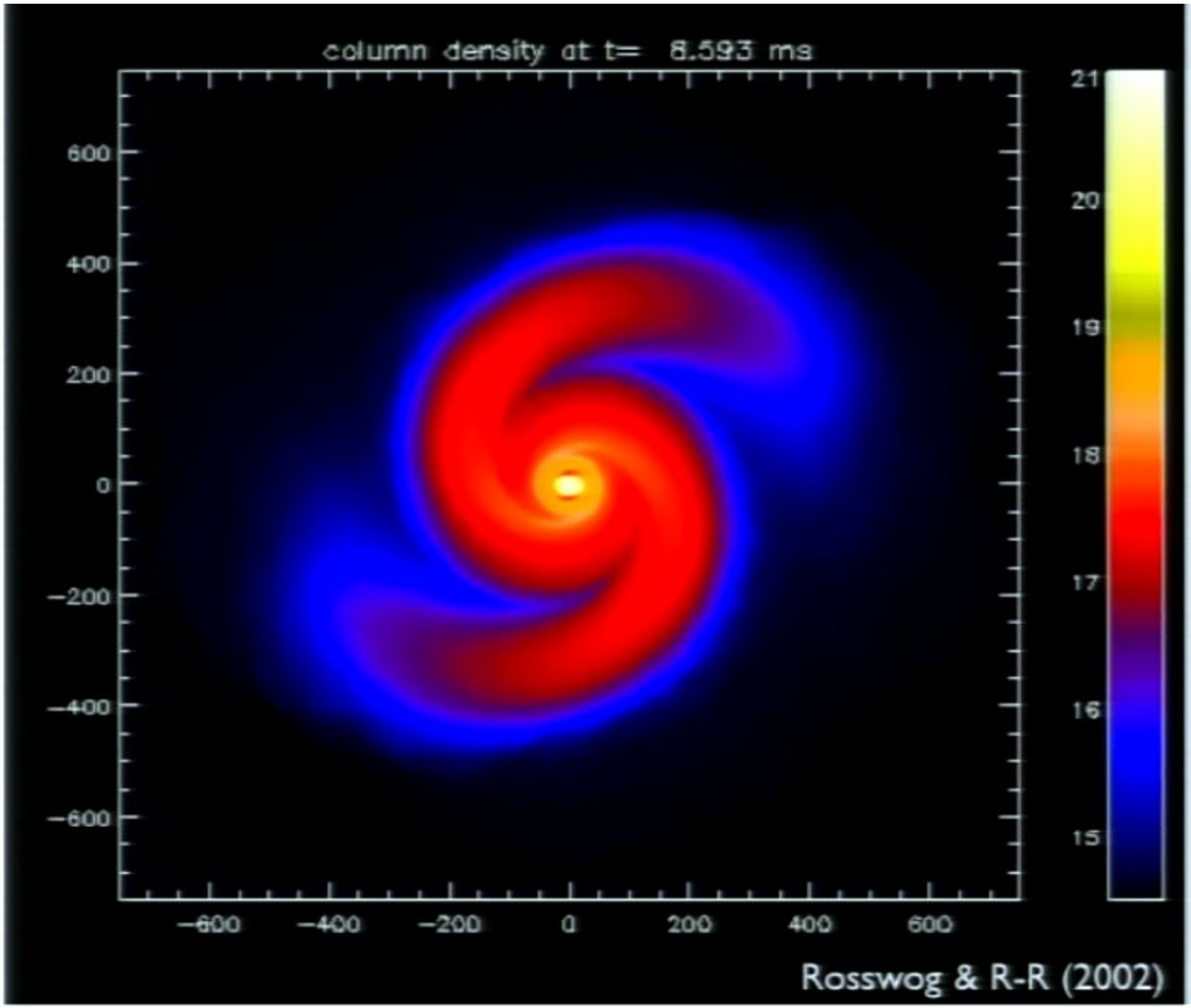

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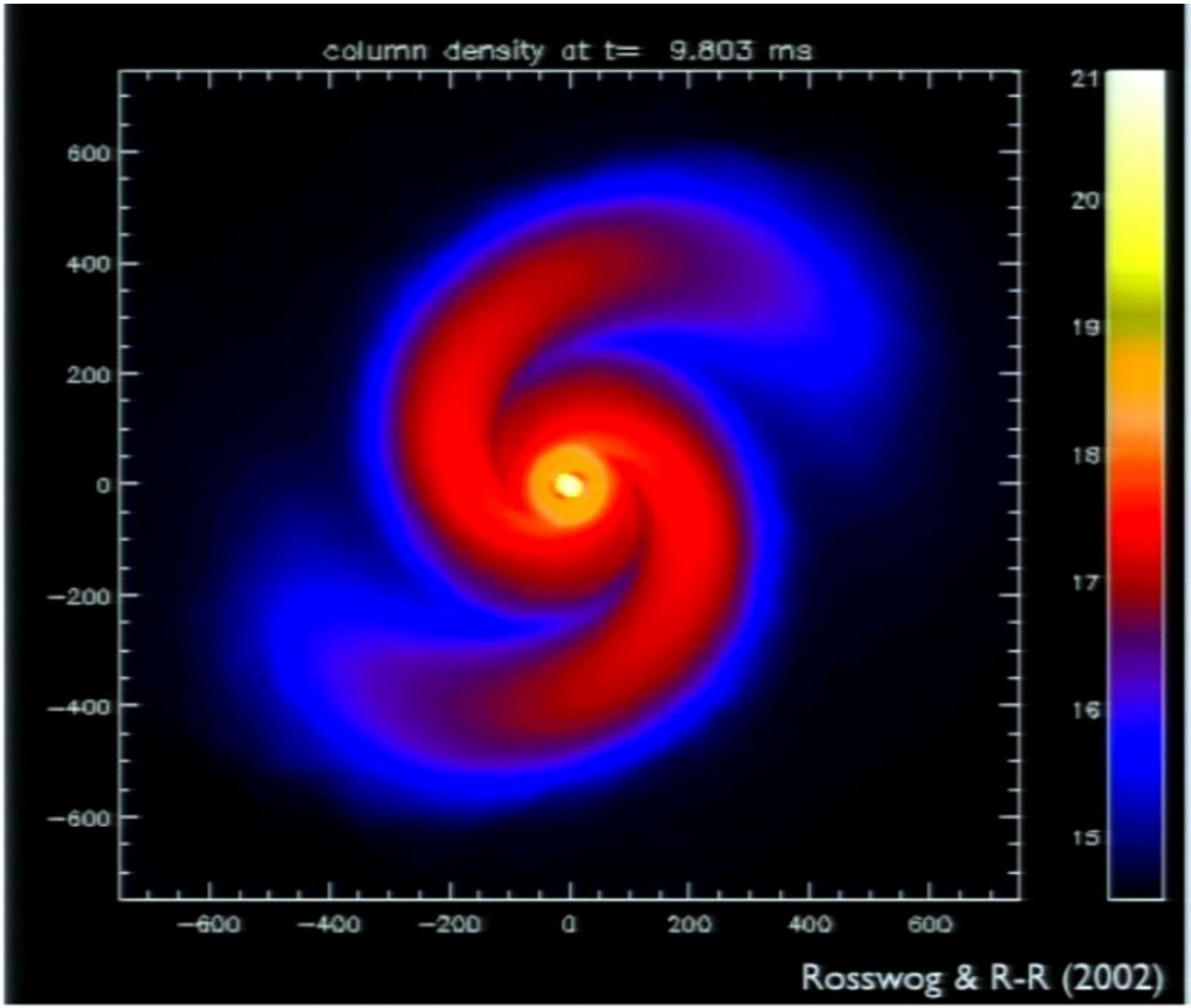

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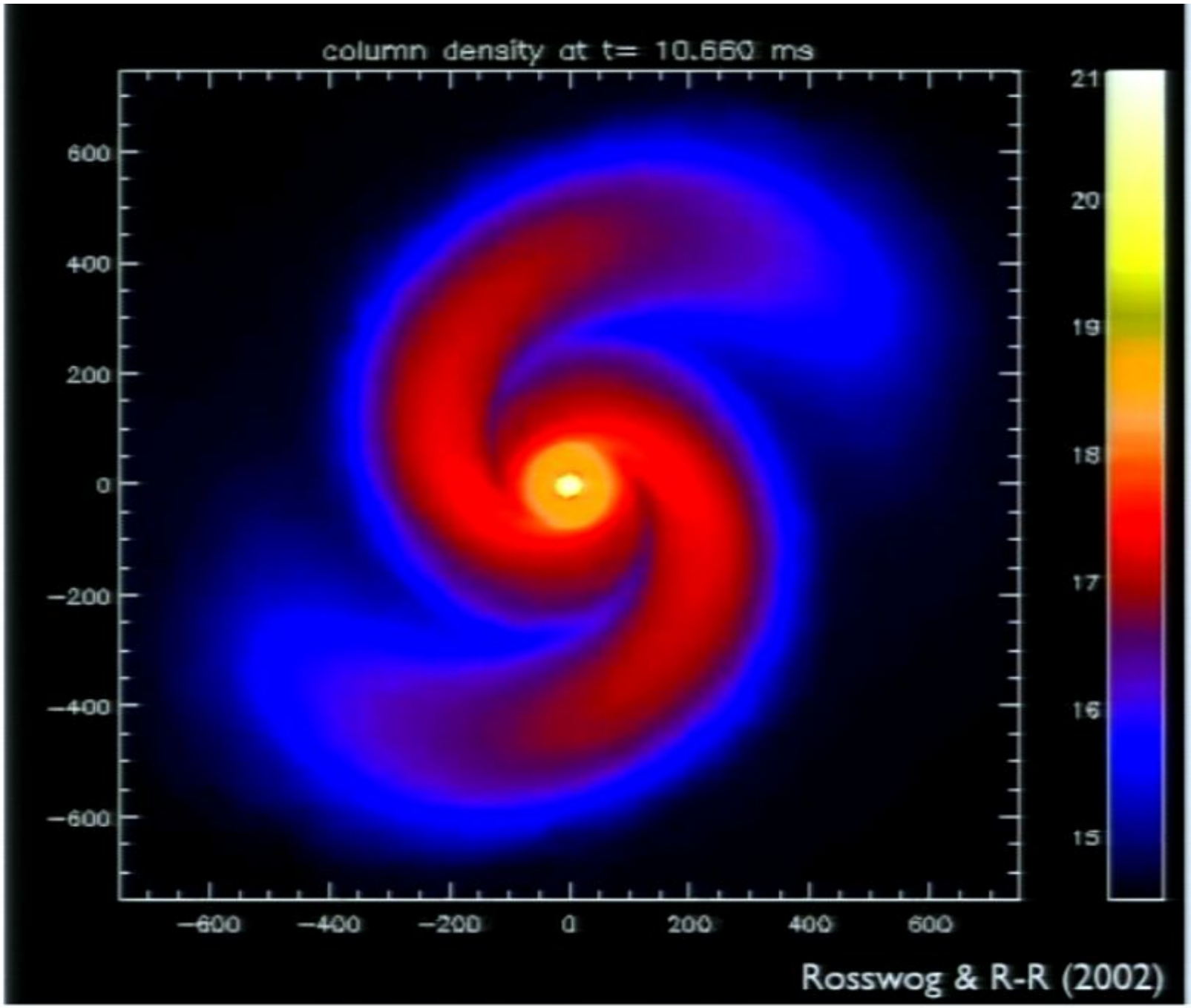

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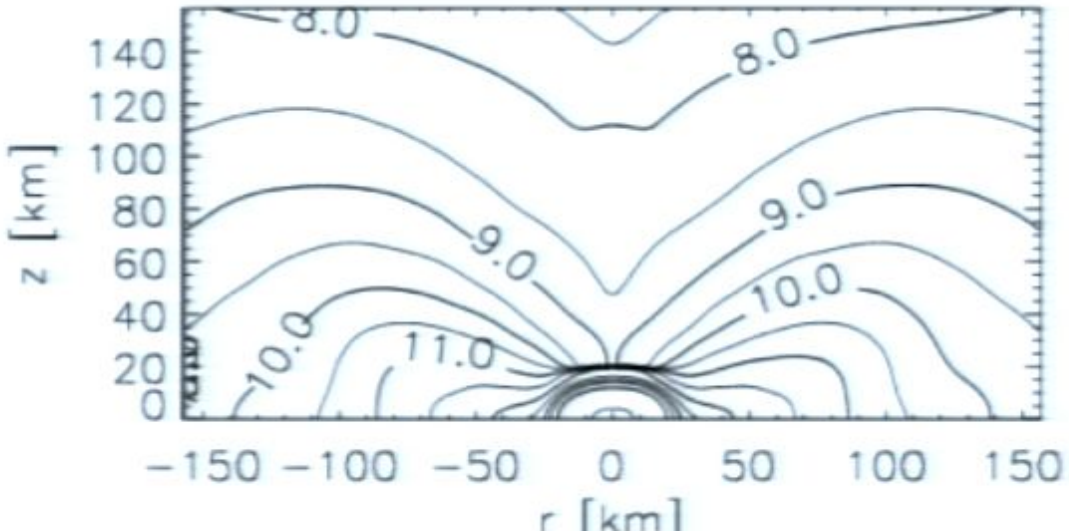
Merging Compact Objects: Initial Conditions

Prog.	$M_{\rm disk}/M_\odot$	Gravity & Method	Eq. of State
BH/NS	0.1-0.3	N, SPH	Polytropes
BH/NS	0.03-0.04	PW, SPH	Polytropes
BH/NS	0.26-0.67	N, Grid	LS[252]
BH/NS	0.001-.01	PW, SPH	Shen[253]
BH/NS	0.001-0.01	GR, SPH	Polytropes
NS/NS	0.2-0.5	N	SPH, Polytropes
NS/NS	0.4	N, SPH	Polytropes
NS/NS	0.01-0.25	N, Grid	LS[252]
NS/NS	0.25-0.55	N, SPH	LS[252], Shen[253]
NS/NS	0.05-0.26	GR, SPH	Shen[253]

Remnant Properties

	central object	debris
masses	$\sim 2.5\ M_\odot$	$\sim 0.2\ M_\odot$
densities	$\sim 3 \cdot 10^{14}\ \mathrm{gcm}^{-3}$	$\sim 10^{12}\ \mathrm{gcm}^{-3}$
temperatures	~ 15 MeV	~ 3 MeV



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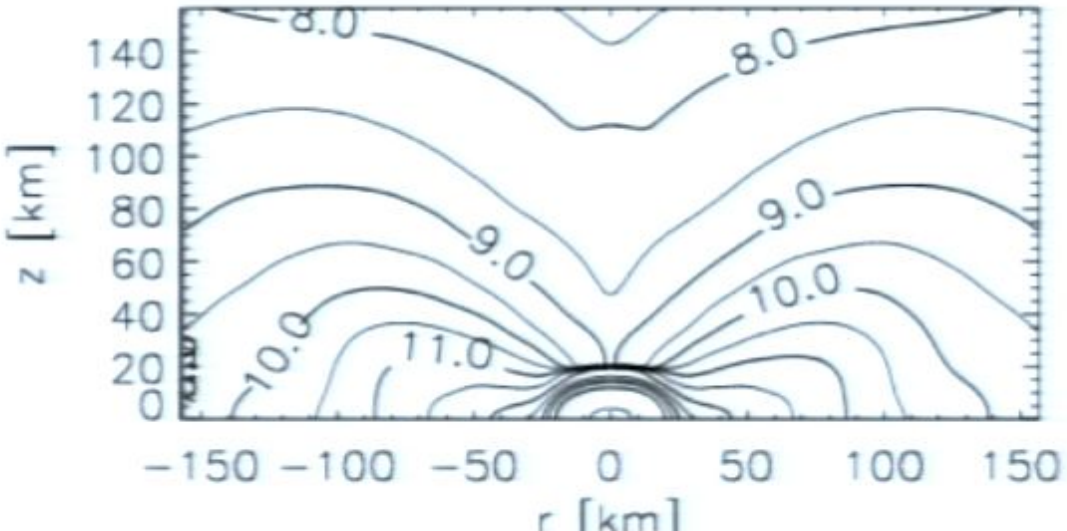


Neutrino Emission

- Temperatures of several MeV and densities ~ 10^{12} g cm $^{-3}$ → ν are emitted copiously
- They provide the most efficient cooling mechanism for the neutron star debris.
- In addition, the related weak interactions determine the compositional evolution.

The dominant neutrino processes:

- Lepton capture reactions on nucleons

$$e^- + p \rightarrow n + \nu_e \quad \text{(EC)}$$

$$e^+ + n \rightarrow p + \bar{\nu}_e, \quad \text{(PC)}$$

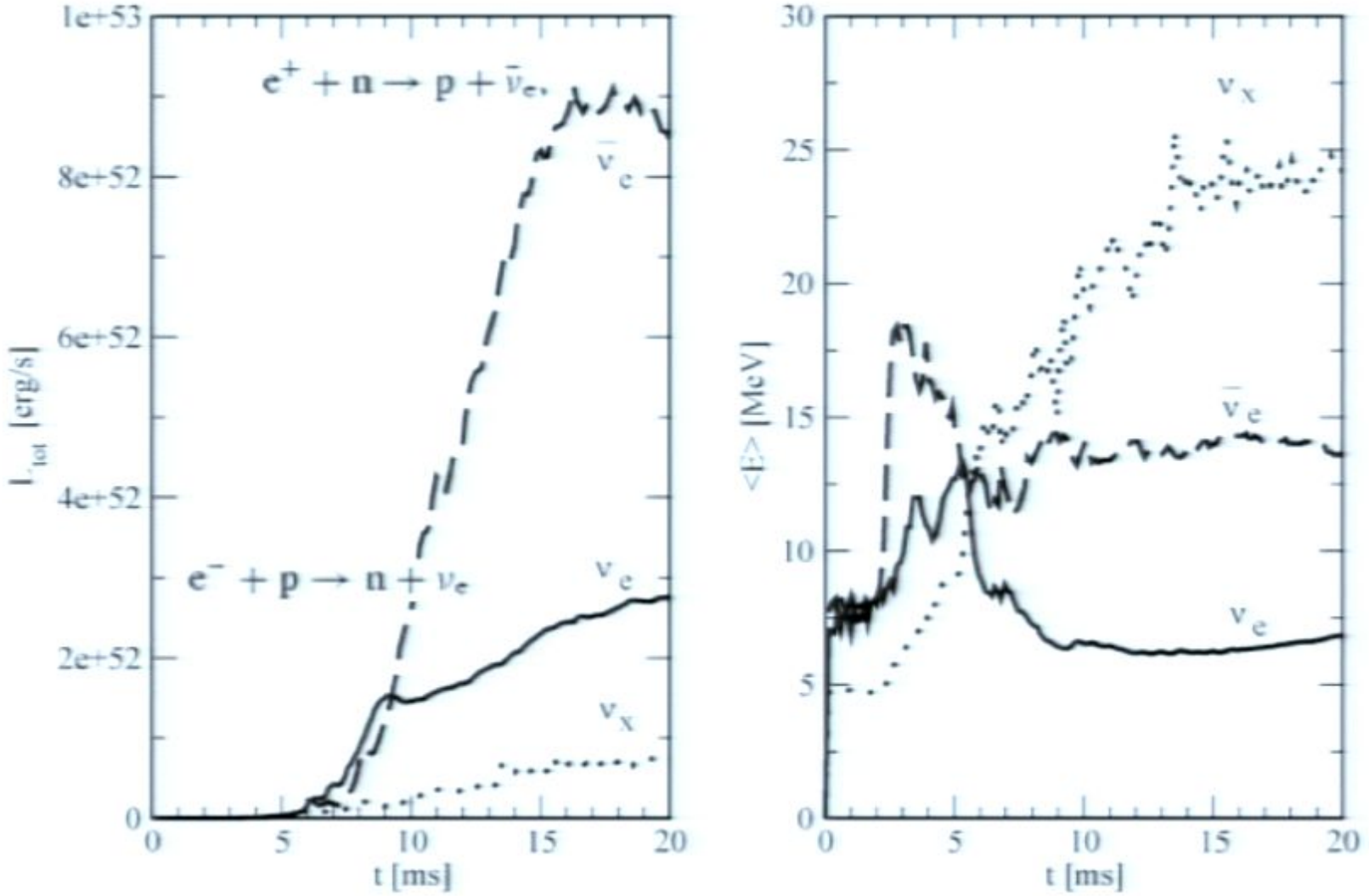
- Pair annihilation

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

- Plasmon decay

$$\gamma \rightarrow \nu_i + \bar{\nu}_i,$$

Neutrino Emission



- The average neutrino energies are similar to those in SN, but contrary to the latter, the luminosities are dominated by electron-type antineutrinos.

Neutrino Opacity

•To determine the number and energy diffusion rates based on neutrino opacities, we take into account :

• Scattering off nucleons

$$\nu_i + \{\mathrm{n}, \mathrm{p}\} \rightarrow \nu_i + \{\mathrm{n}, \mathrm{p}\},$$

•Coherent neutrino nucleus scattering

$$\nu_i + \mathrm{A} \rightarrow \nu_i + \mathrm{A},$$

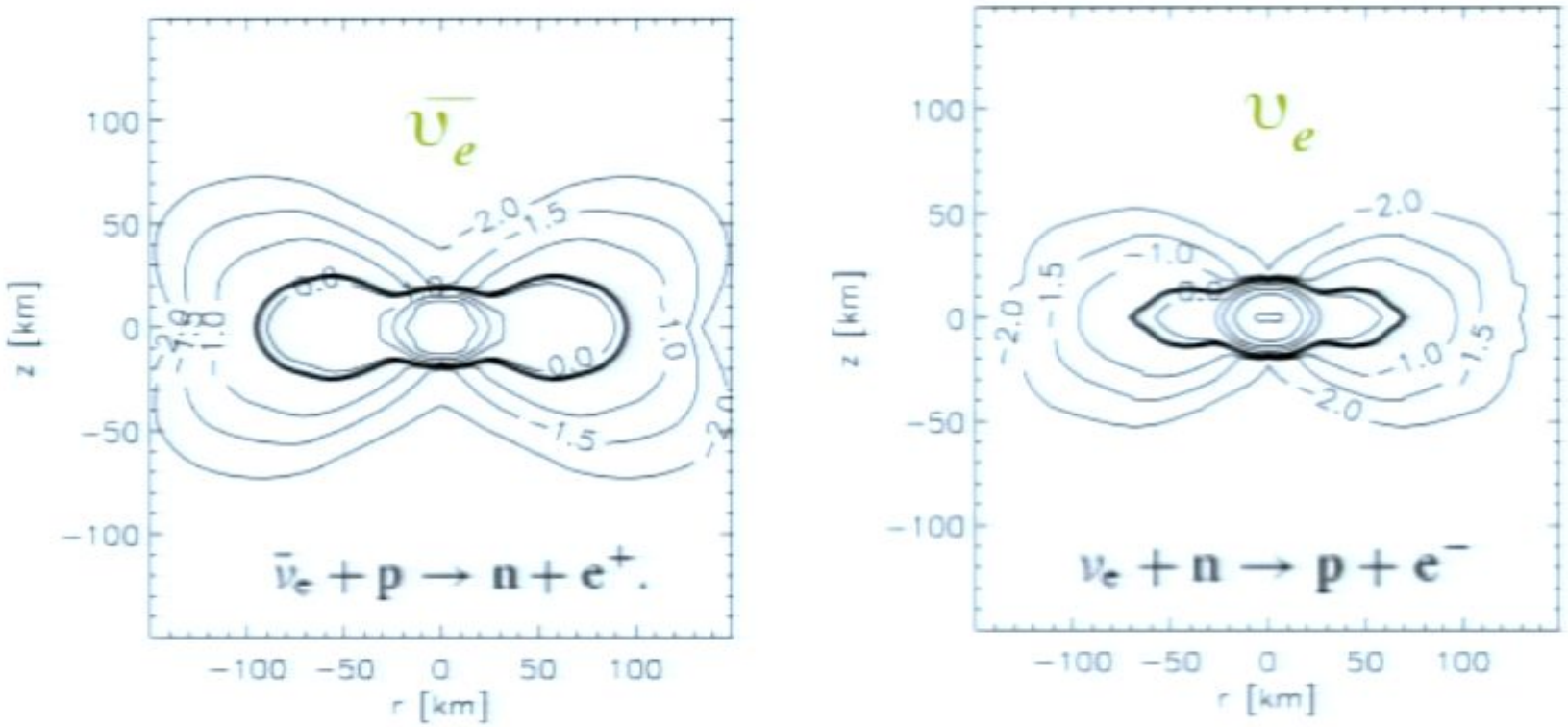
•Neutrino absorption by free nucleons

$$\nu_e + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-$$

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+.$$

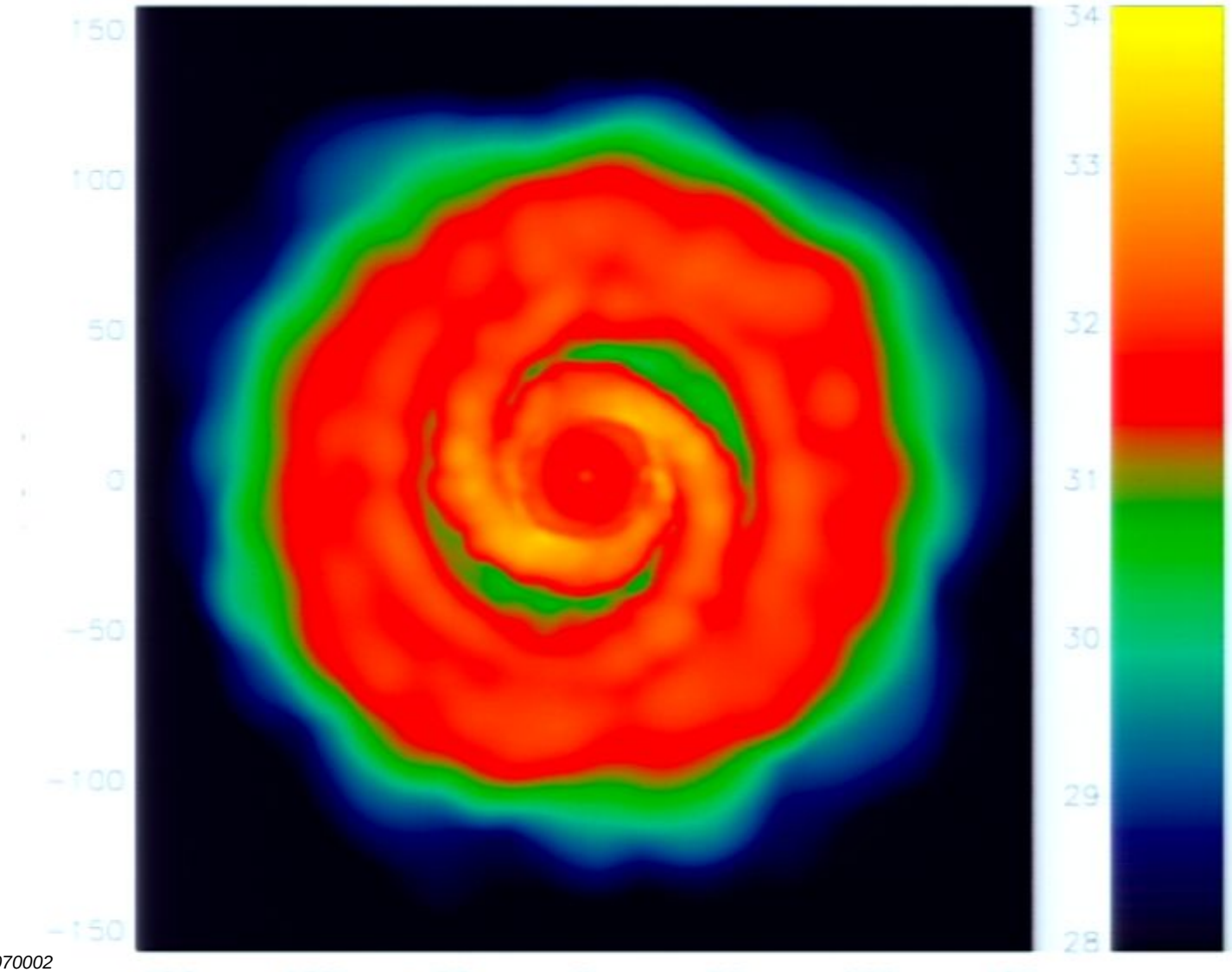
Neutrino "Spheres"

$$\tau_{\upsilon_i} = 2/3$$



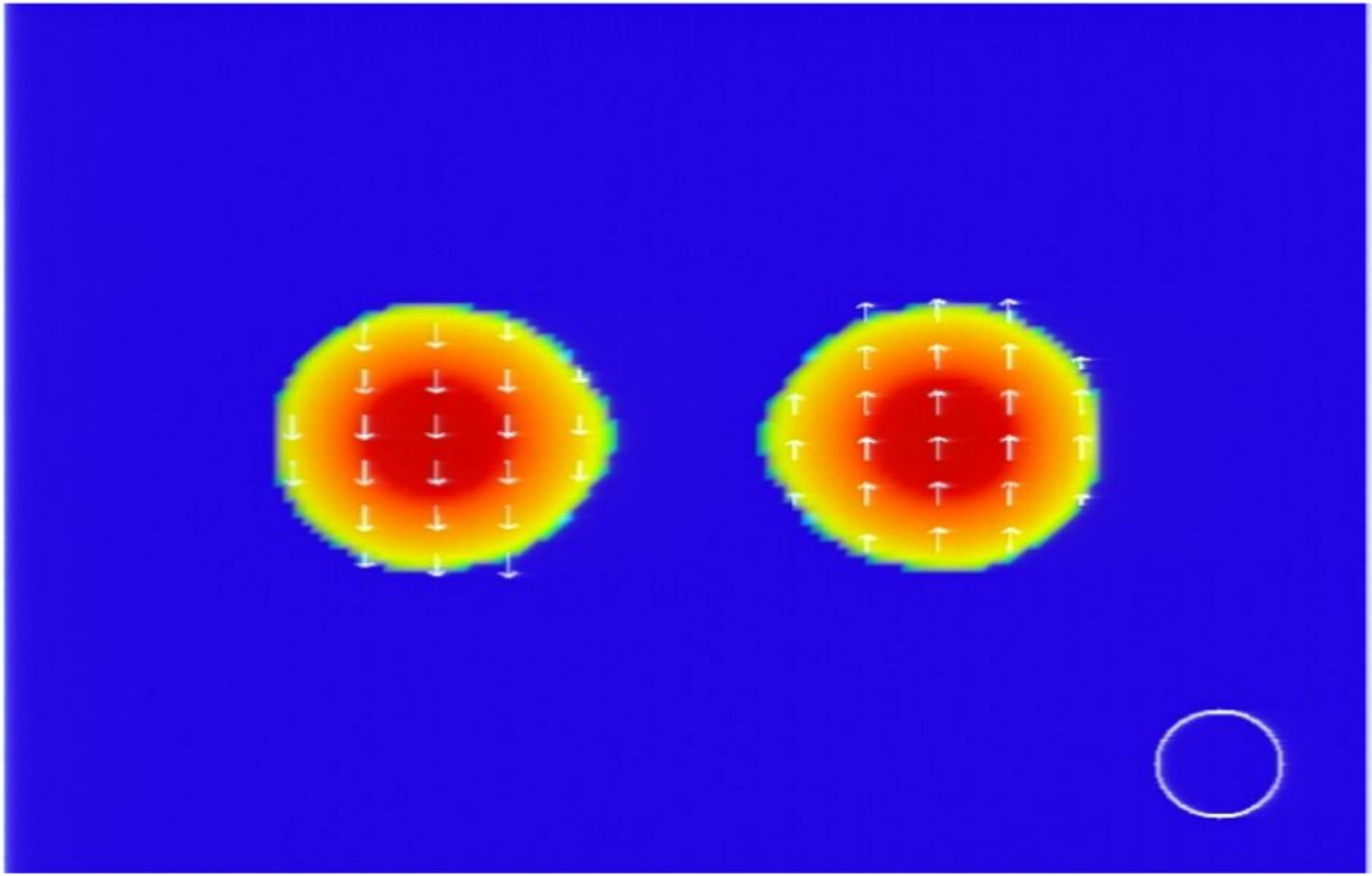
- The thick lines give the locus of the "neutrino sphere" which is essentially the distance at which the neutrinos decouple from the debris.

•Total neutrino energy per time and volume in the orbital plane (erg/ ccm /s)



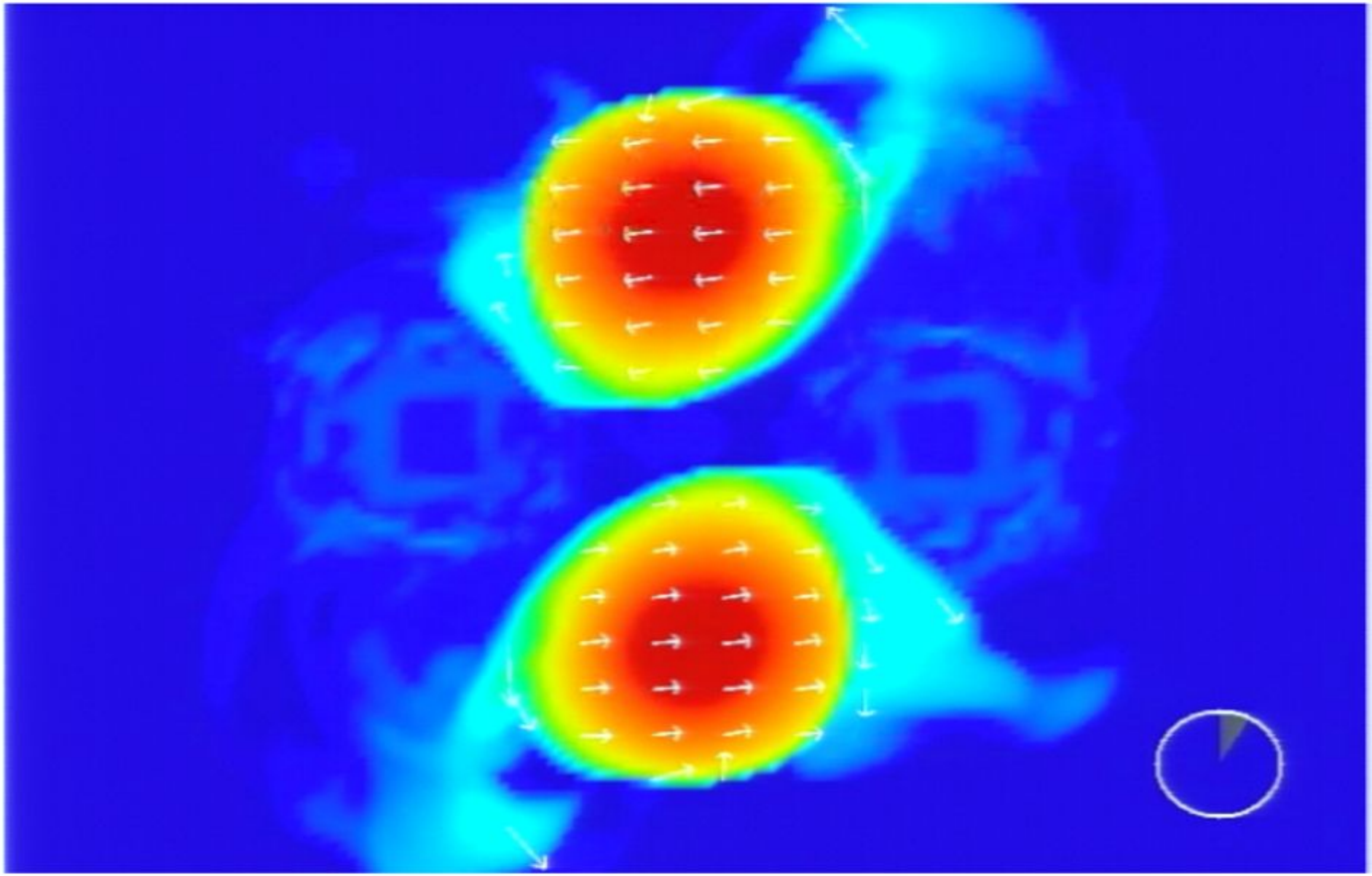
Rosswog & R-R (2003)

Black Hole Formation and Disk Assembly



[Courtesy of S. Shapiro]

Black Hole Formation and Disk Assembly



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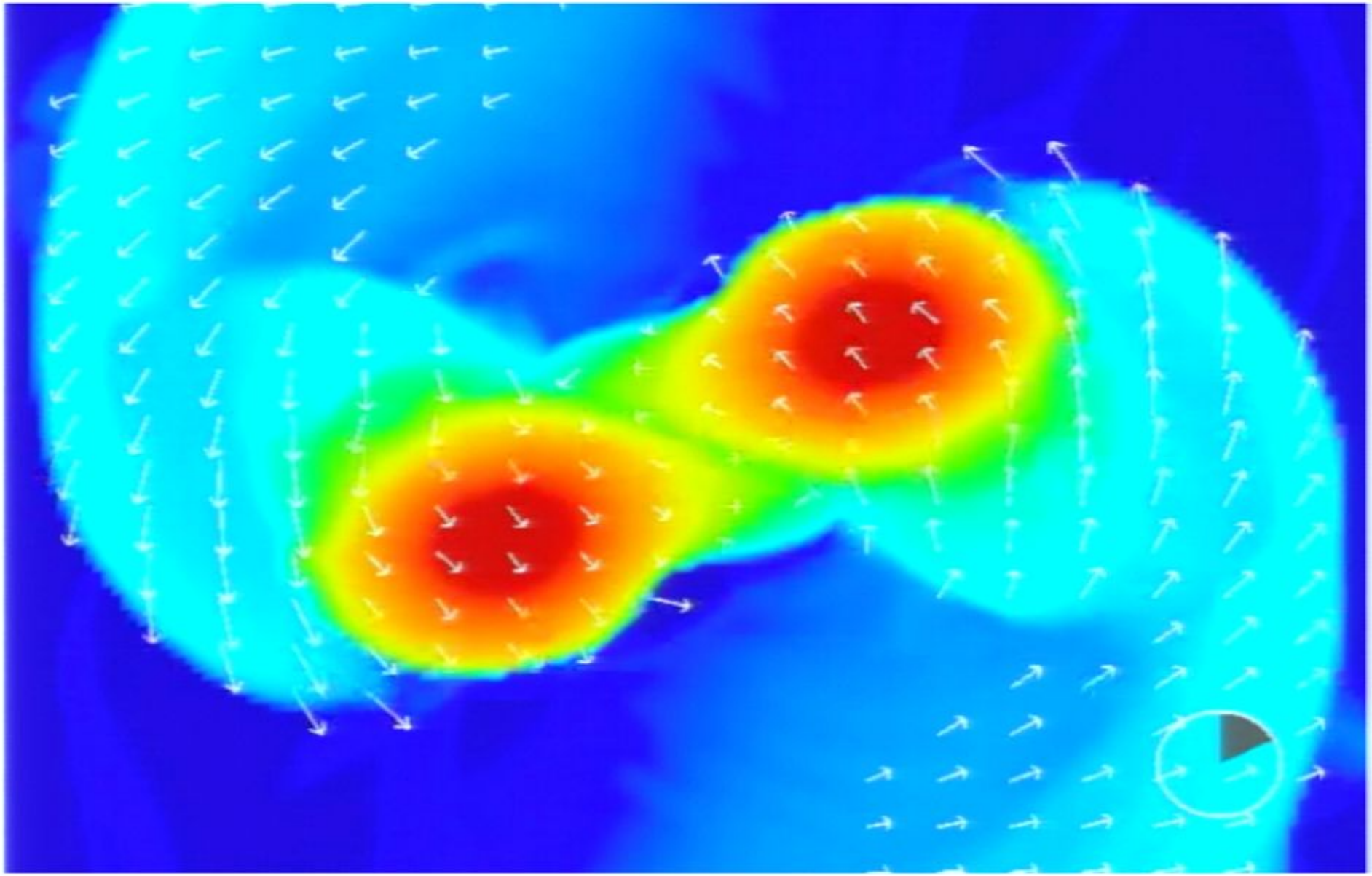

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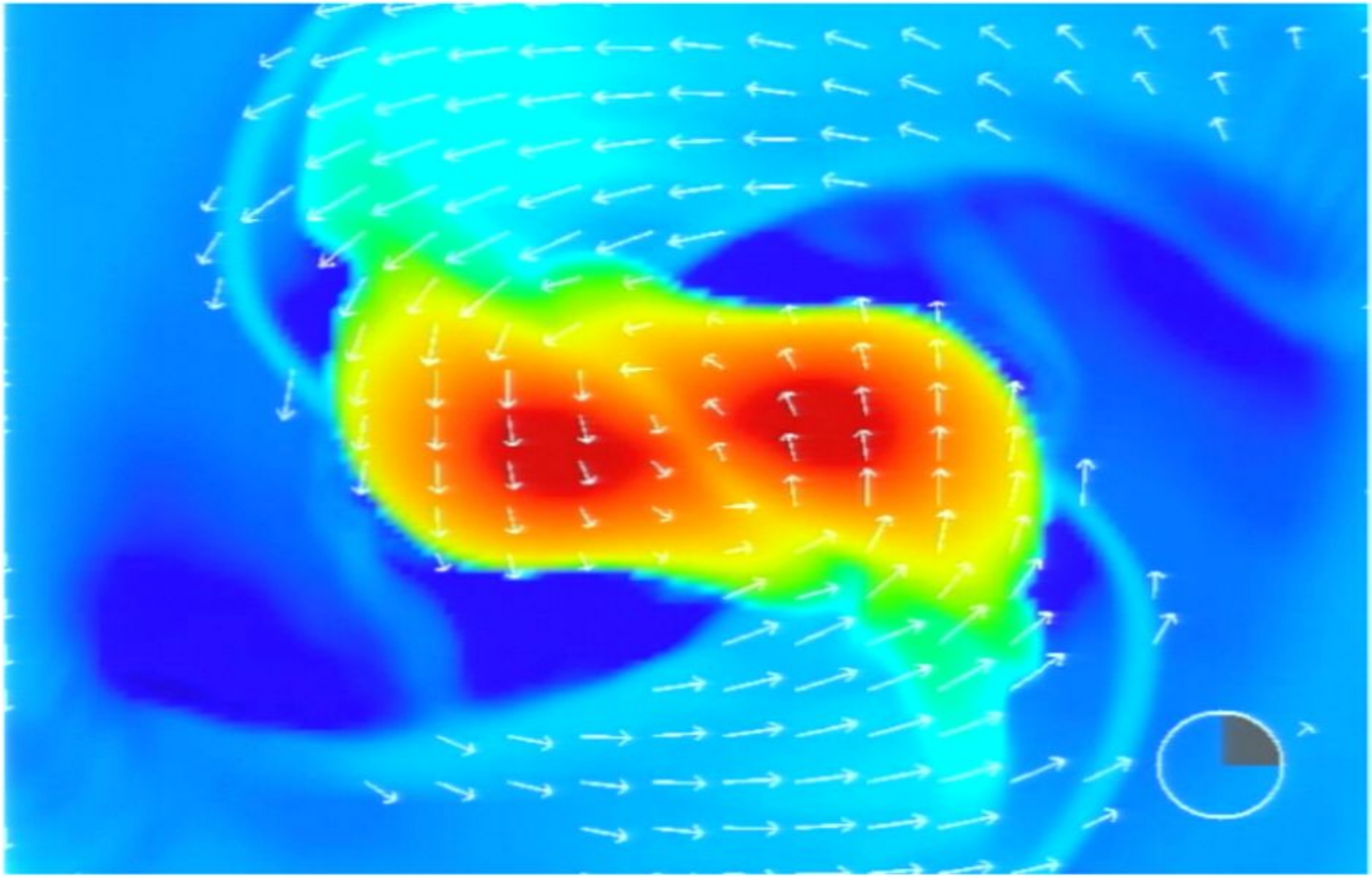

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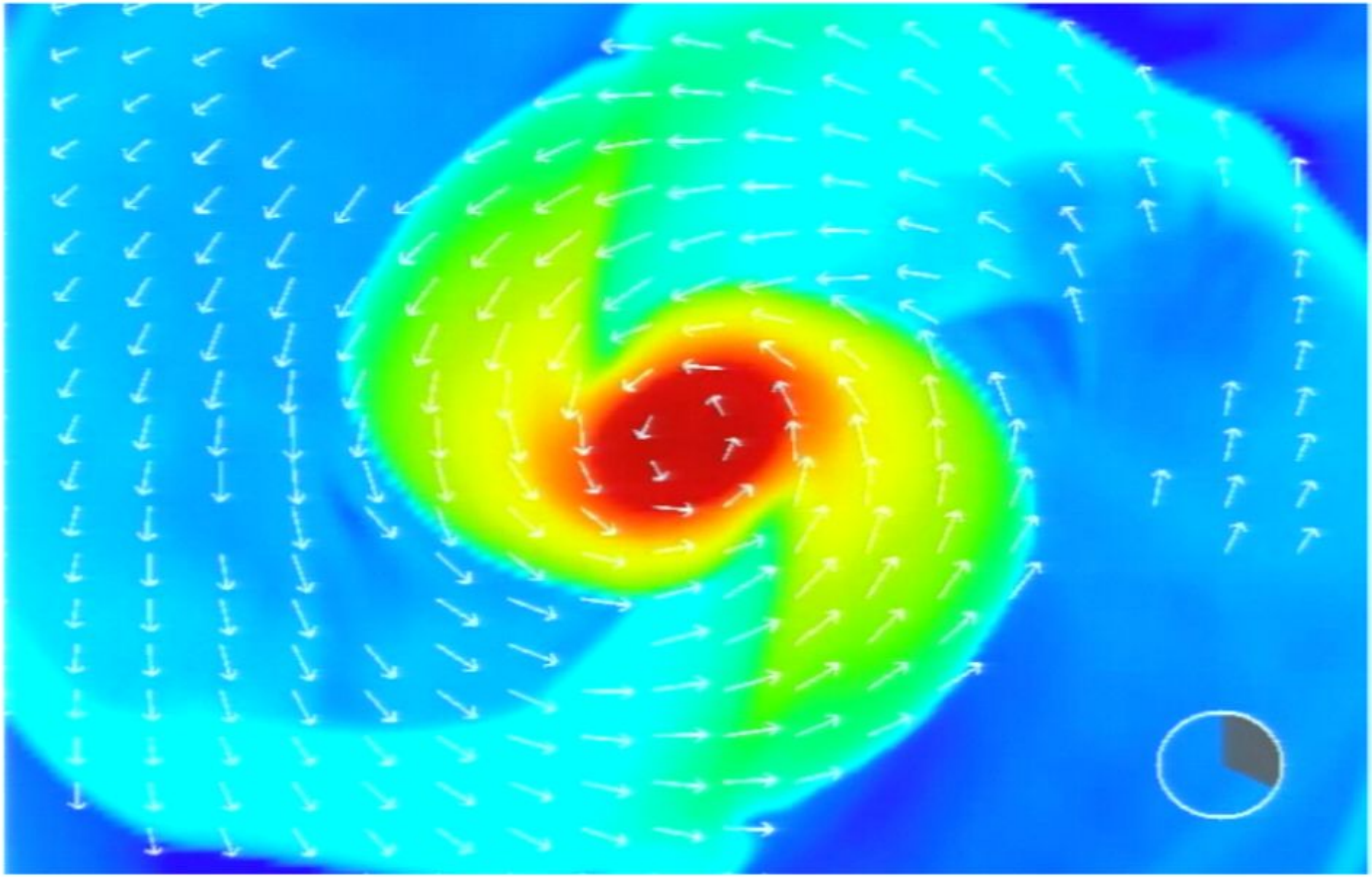
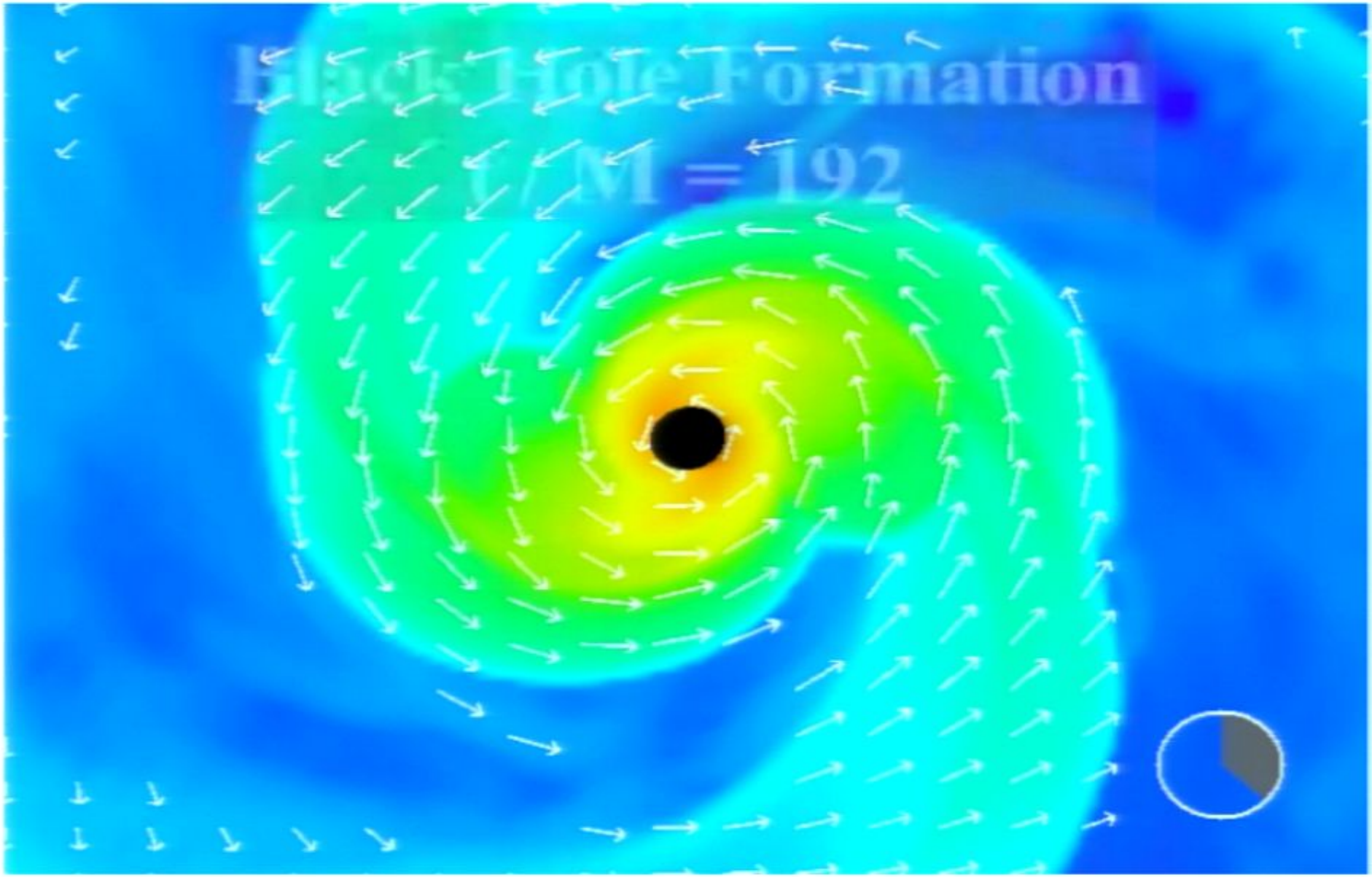


[Courtesy of S. Shapiro]

Black Hole Formation and Disk Assembly



[Courtesy of S. Shapiro]

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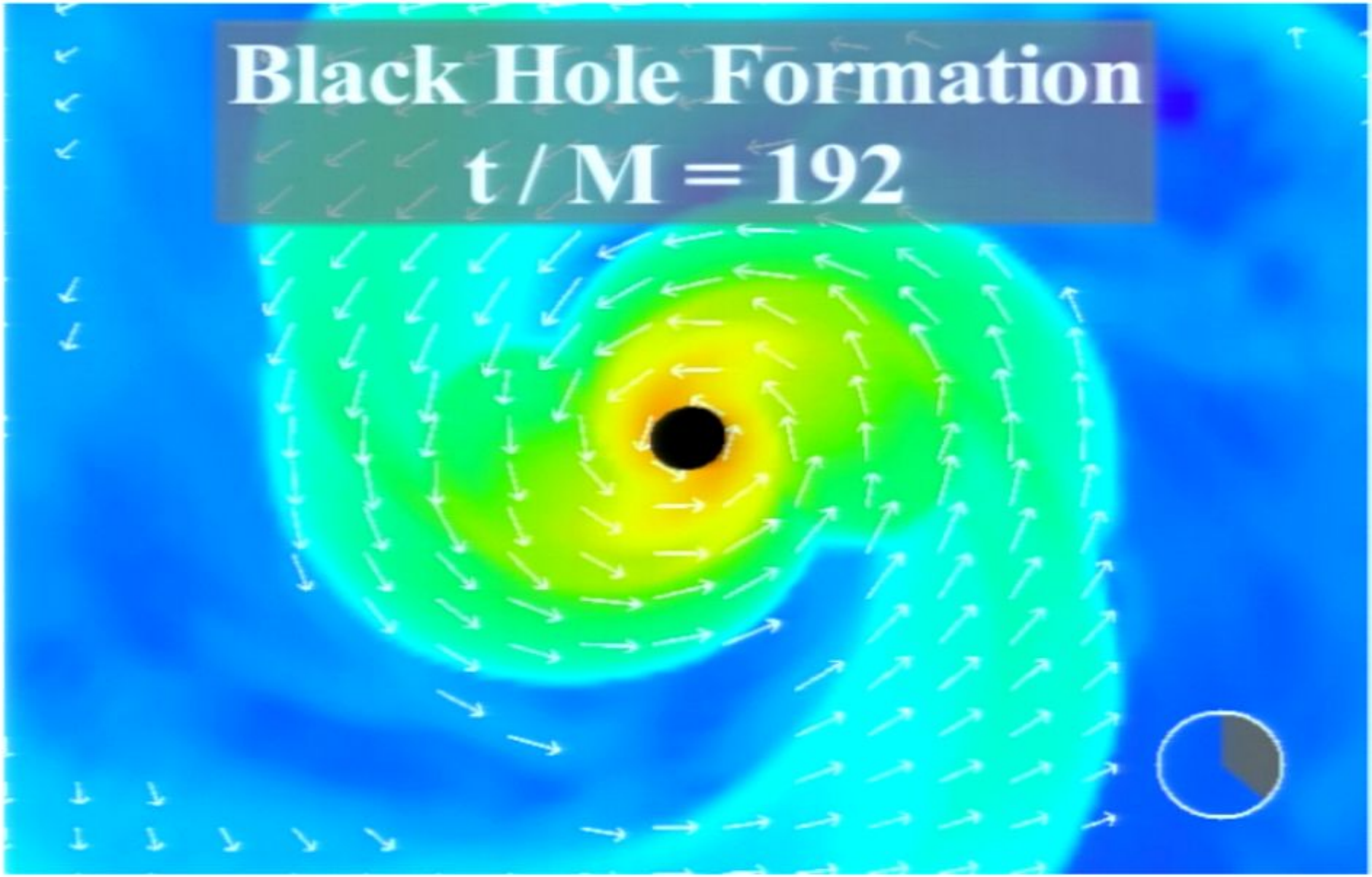

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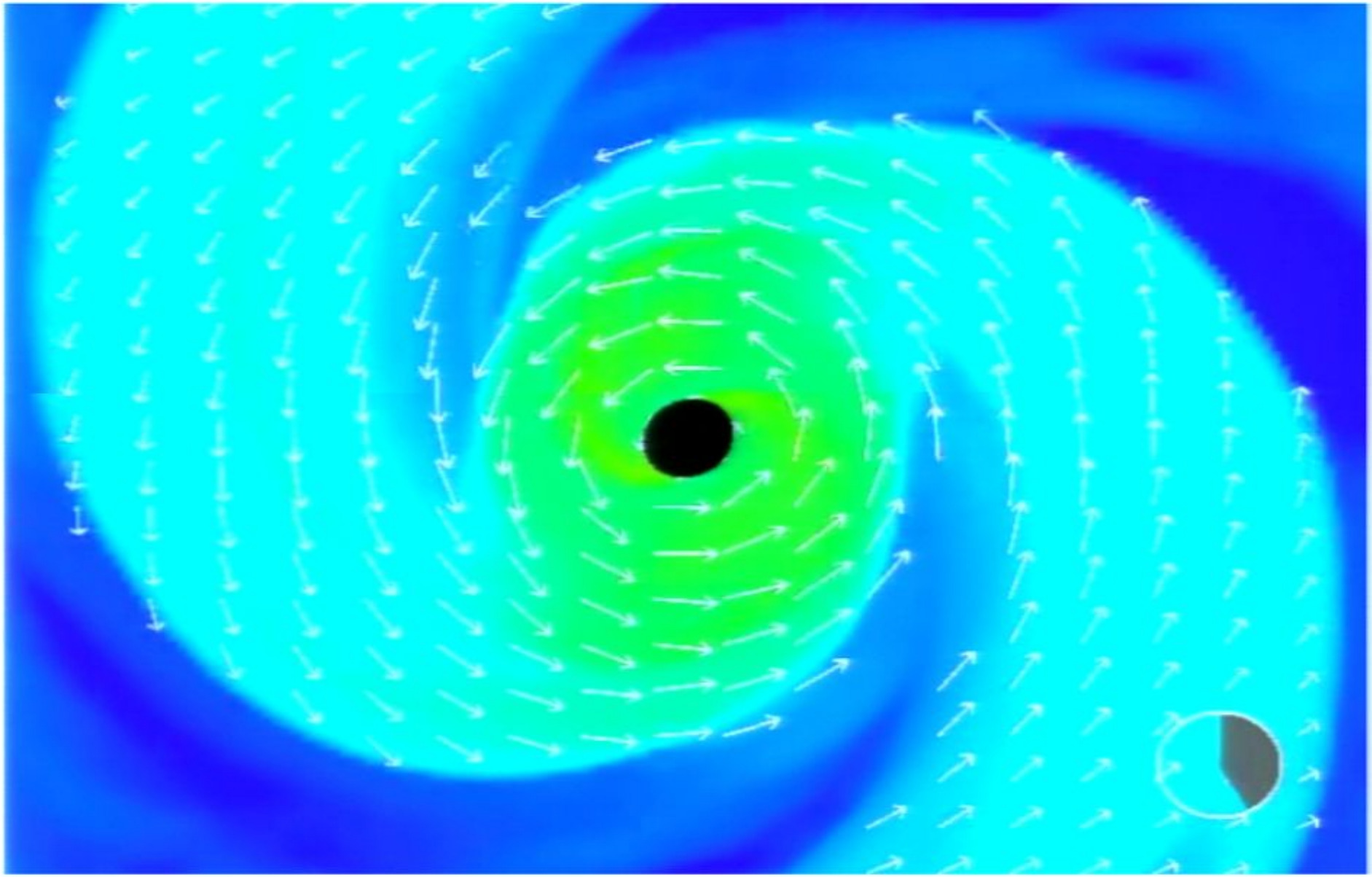

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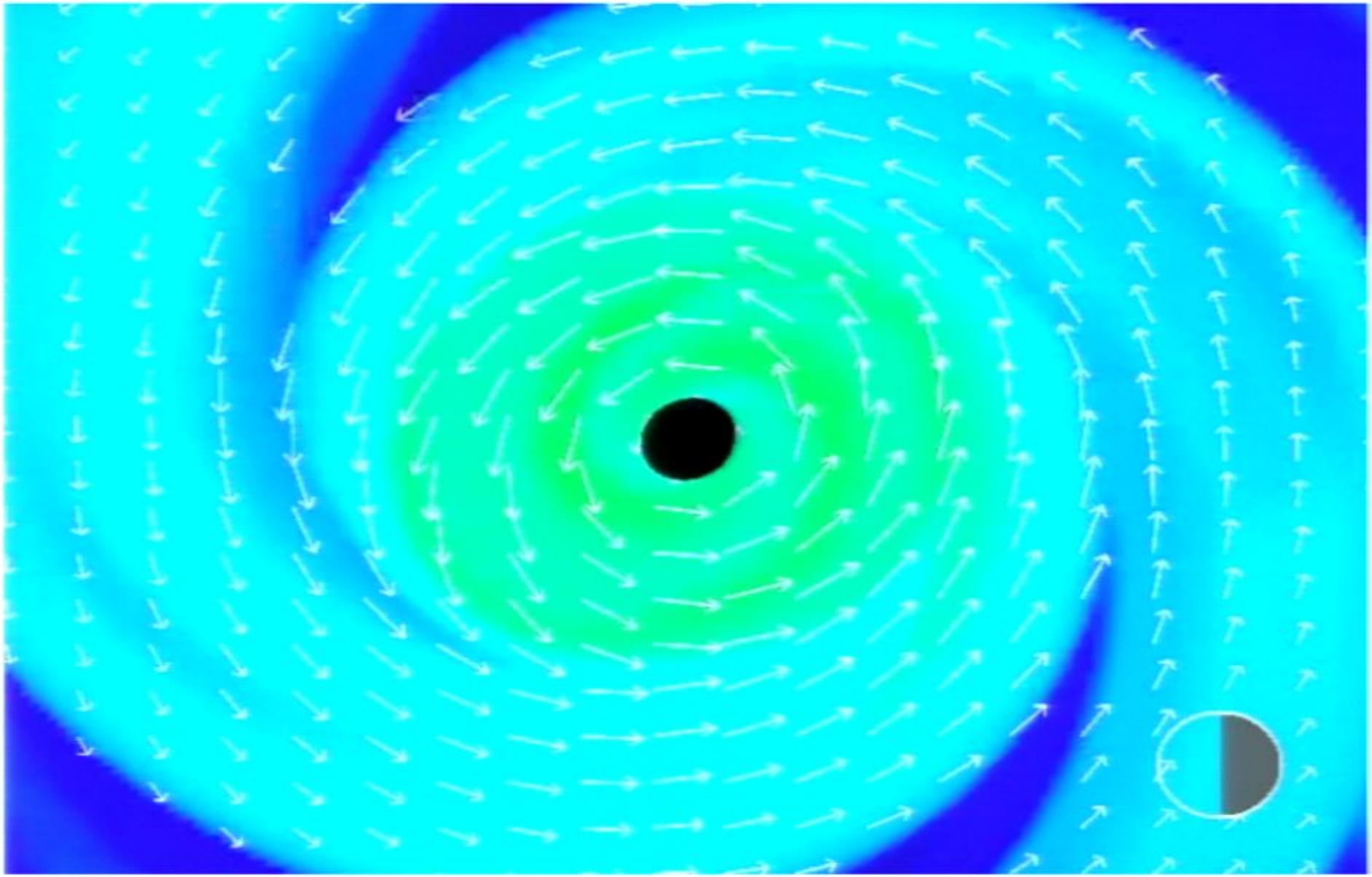
Black Hole Formation and Disk Assembly



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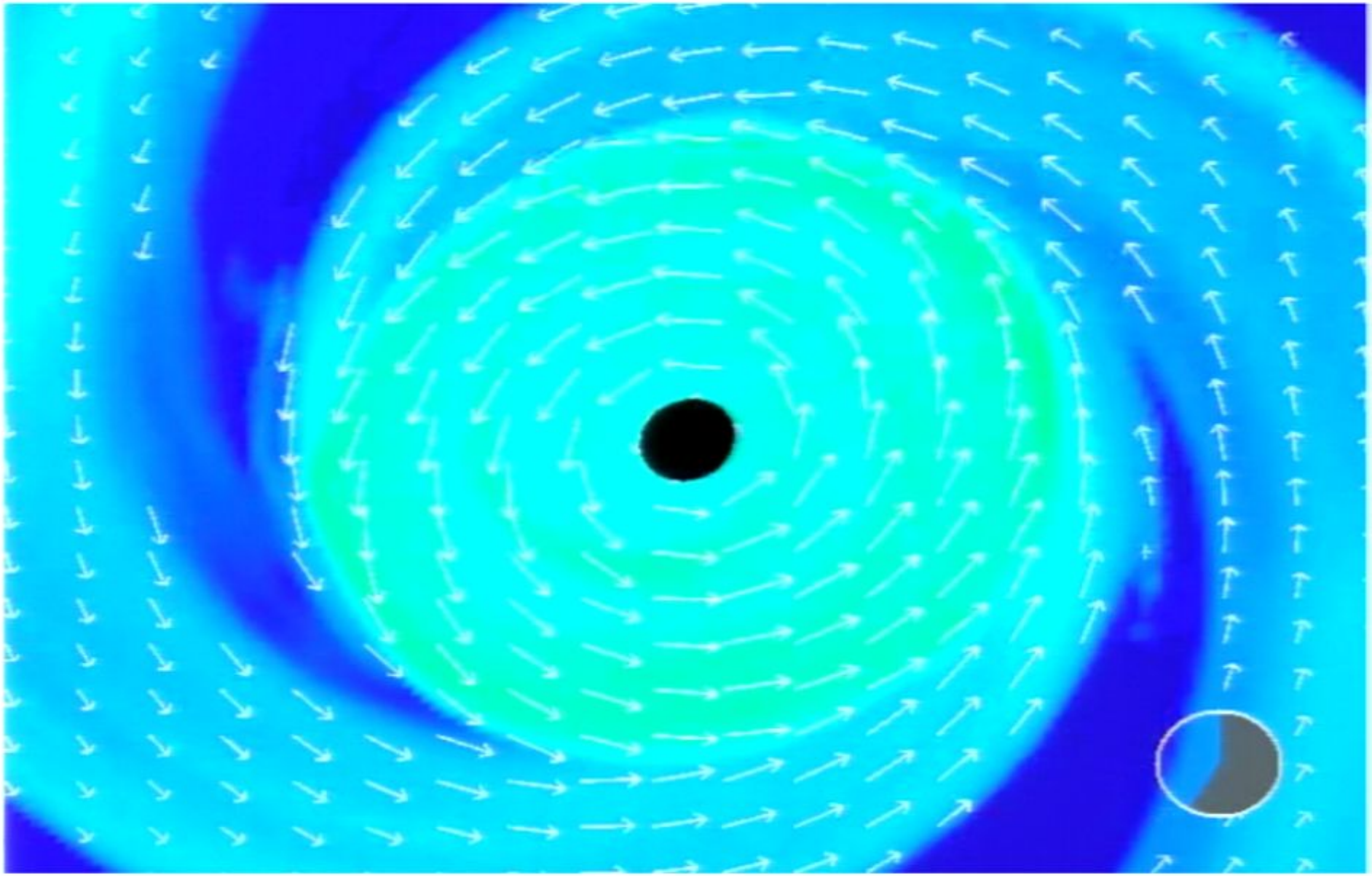
Black Hole Formation and Disk Assembly



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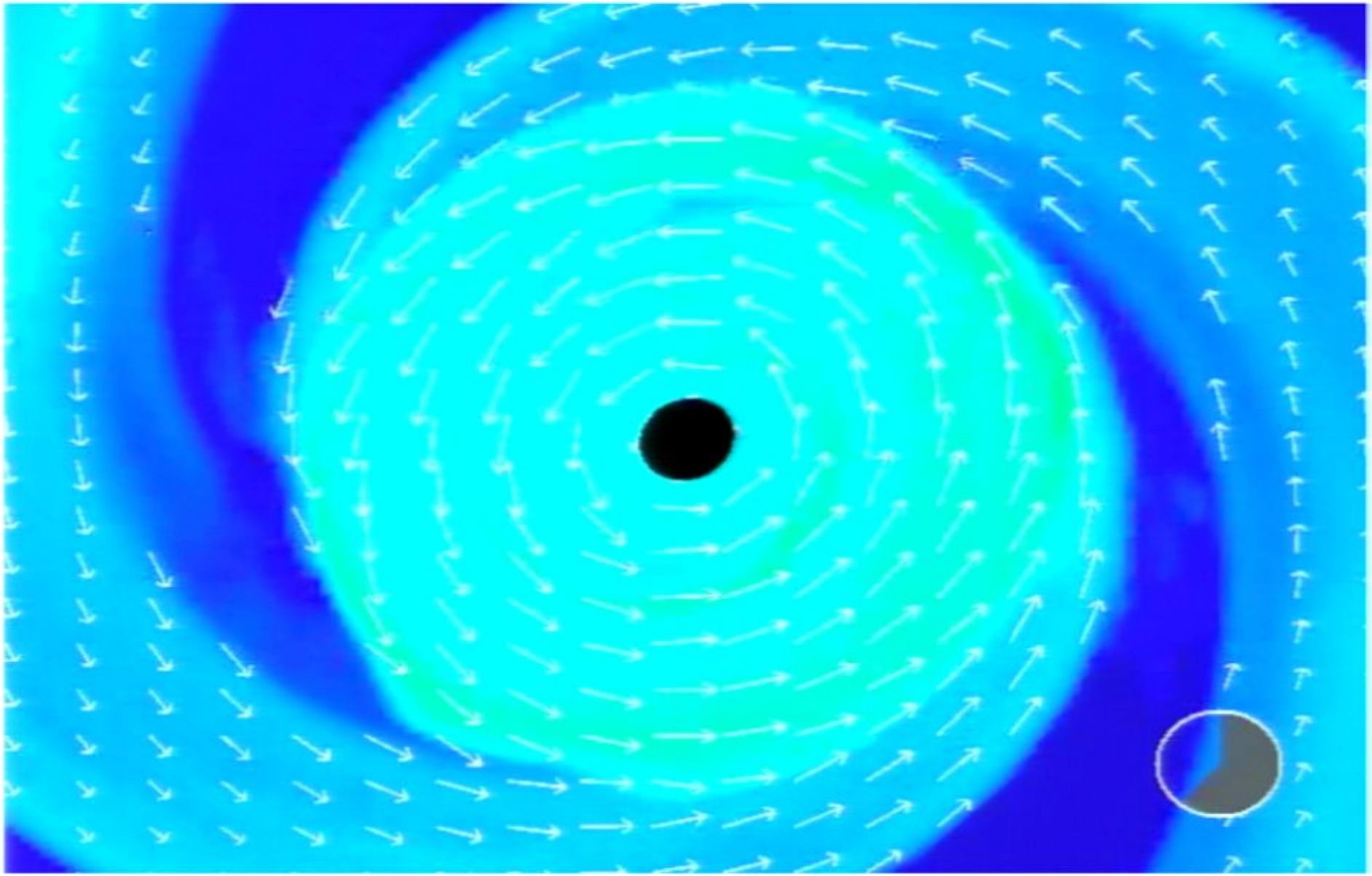
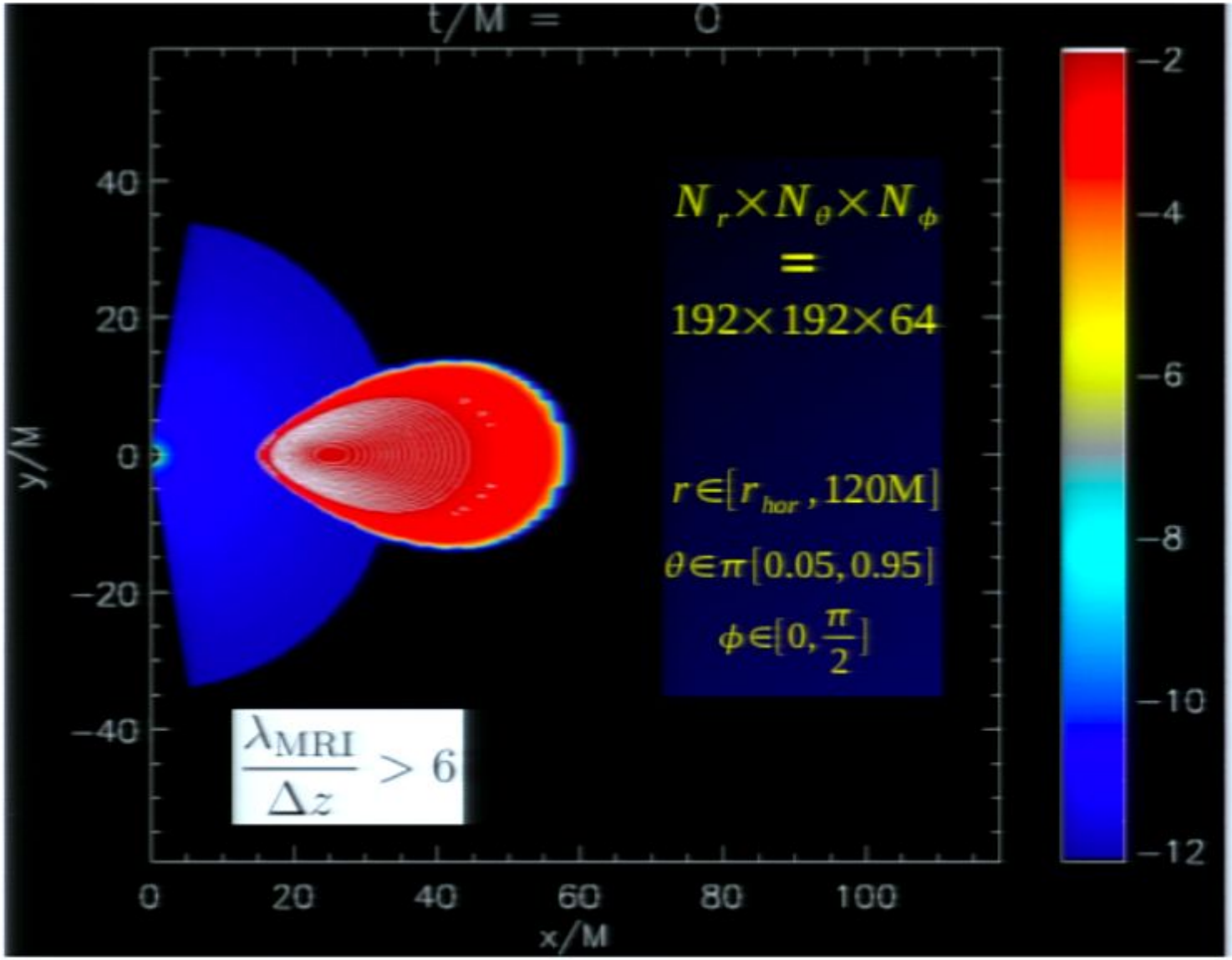
Black Hole Formation and Disk Assembly



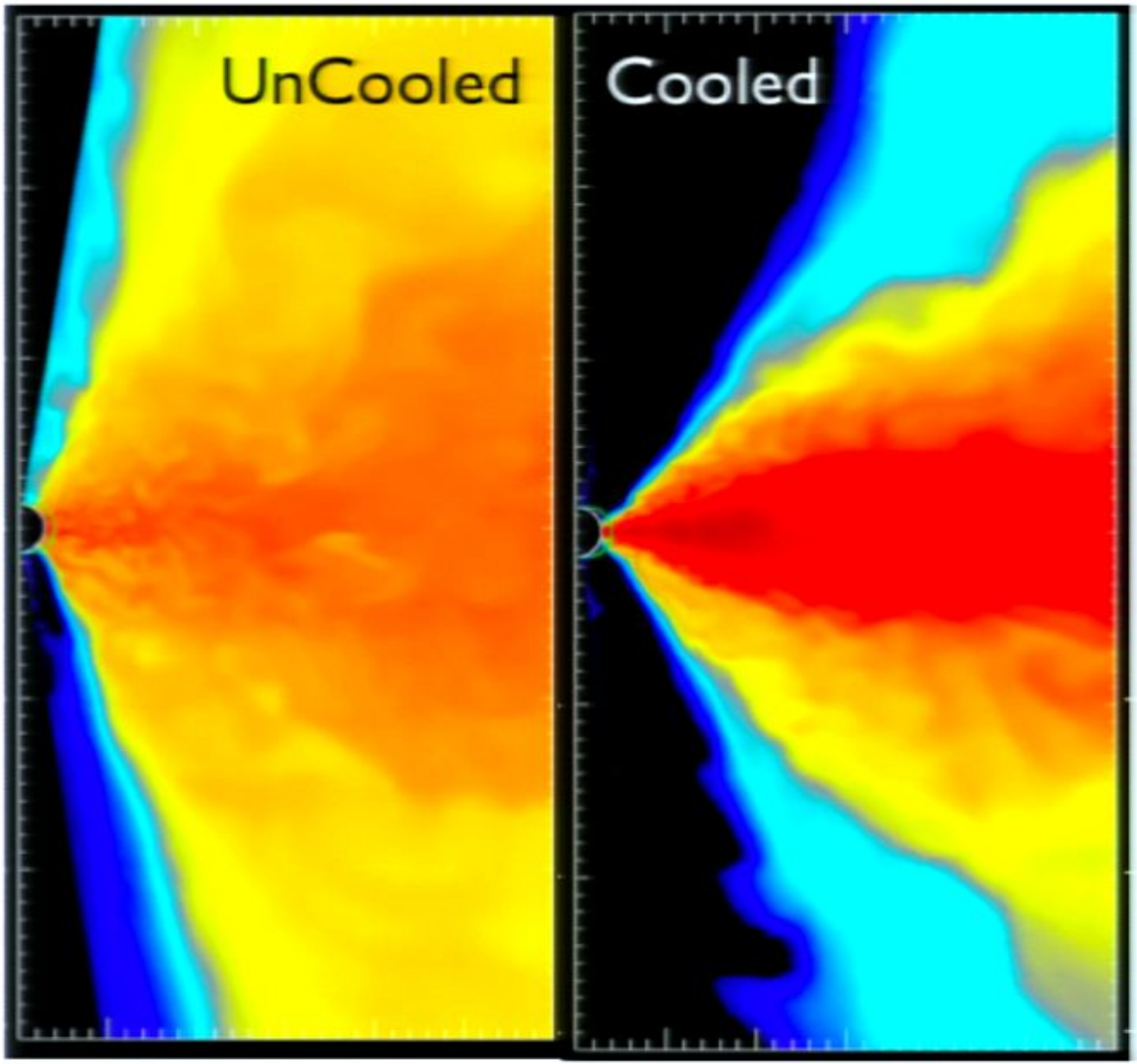
[Courtesy of S. Shapiro]

GRMHD Calculations



- The equations of hydrodynamics are solved using HARM3D with passive radiation

Evolution of Neutrino Cooled Disks



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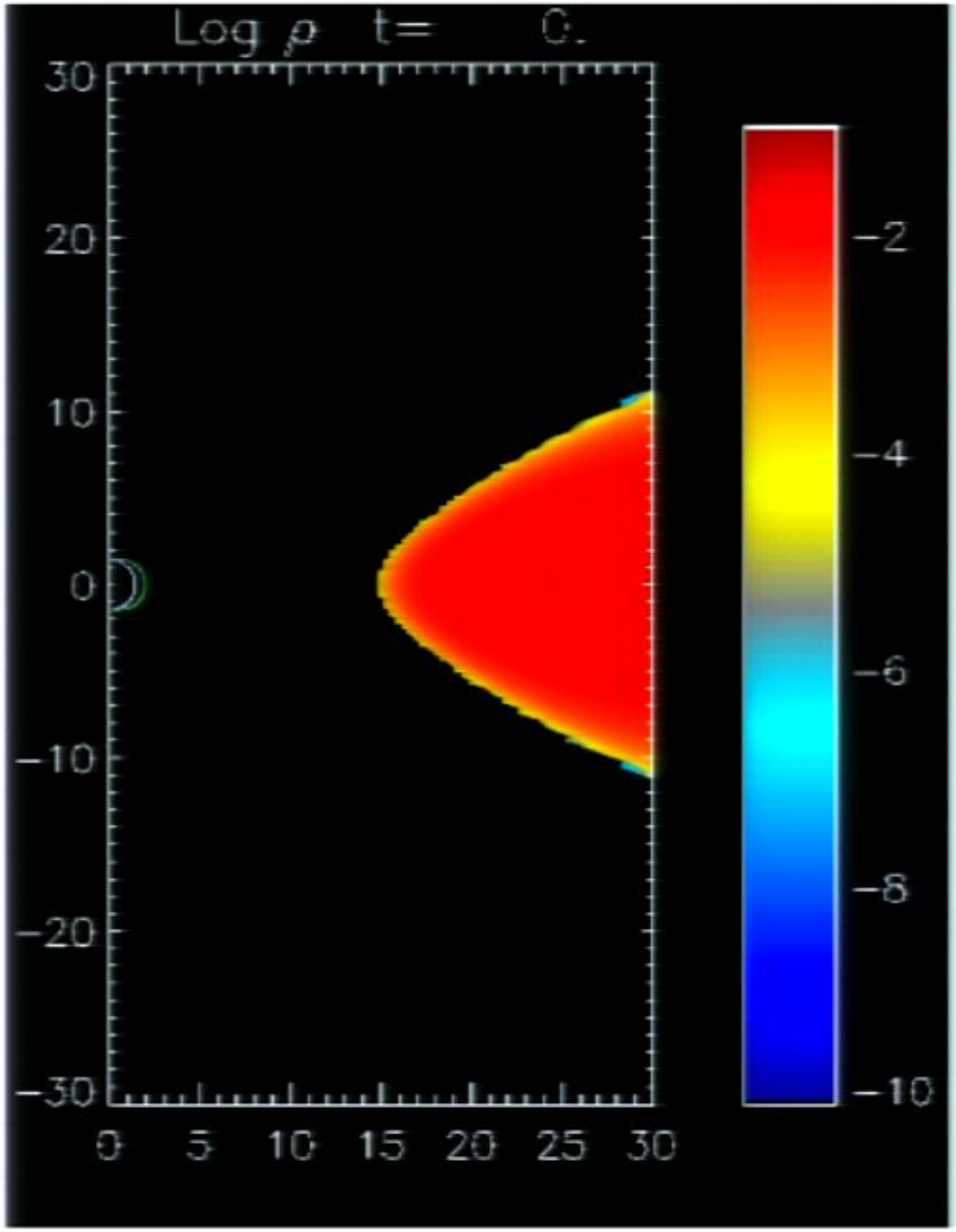
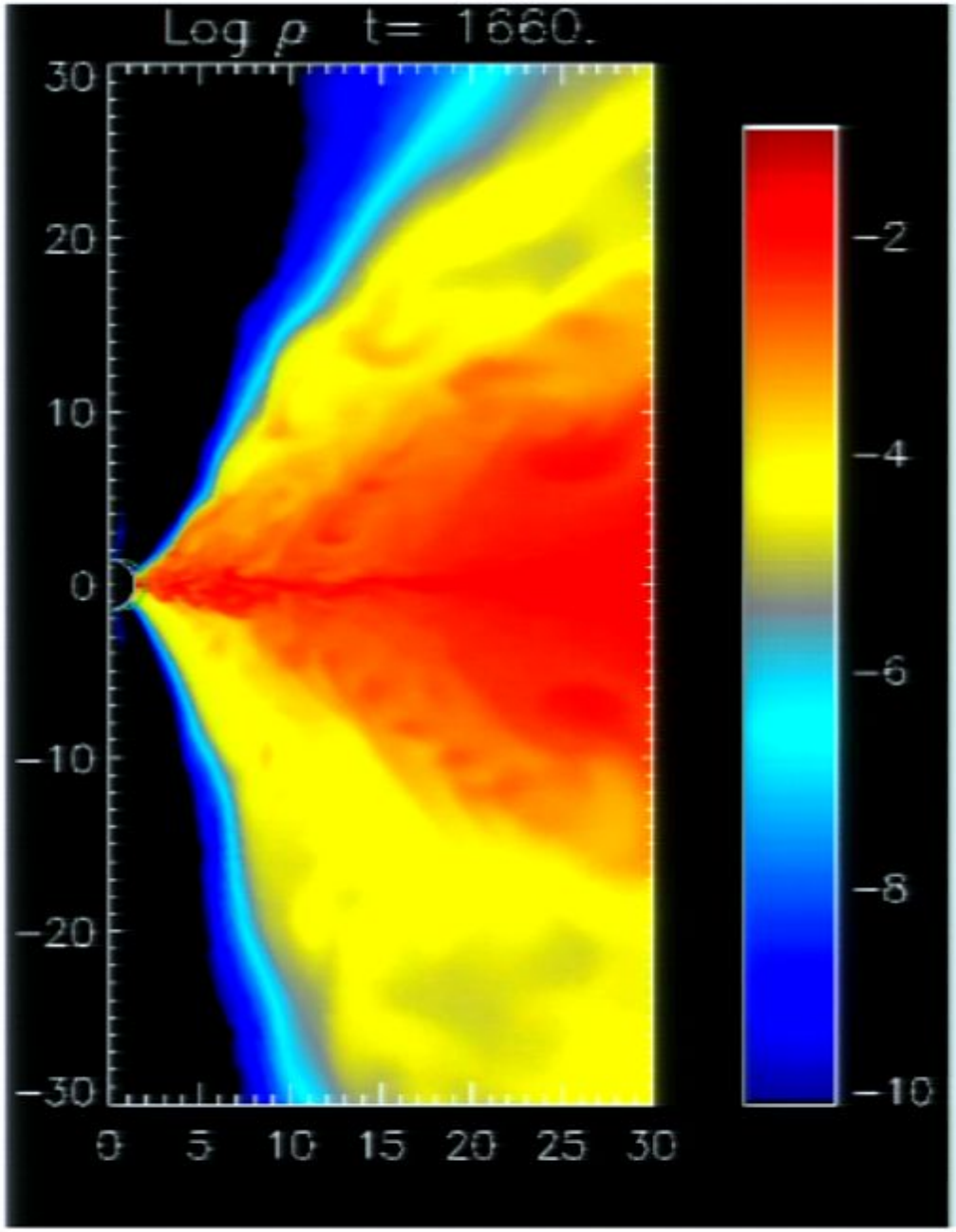


$$\frac{\lambda_{\mathrm{MRI}}}{\Delta z} > 6$$

Evolution of Neutrino Cooled Disks



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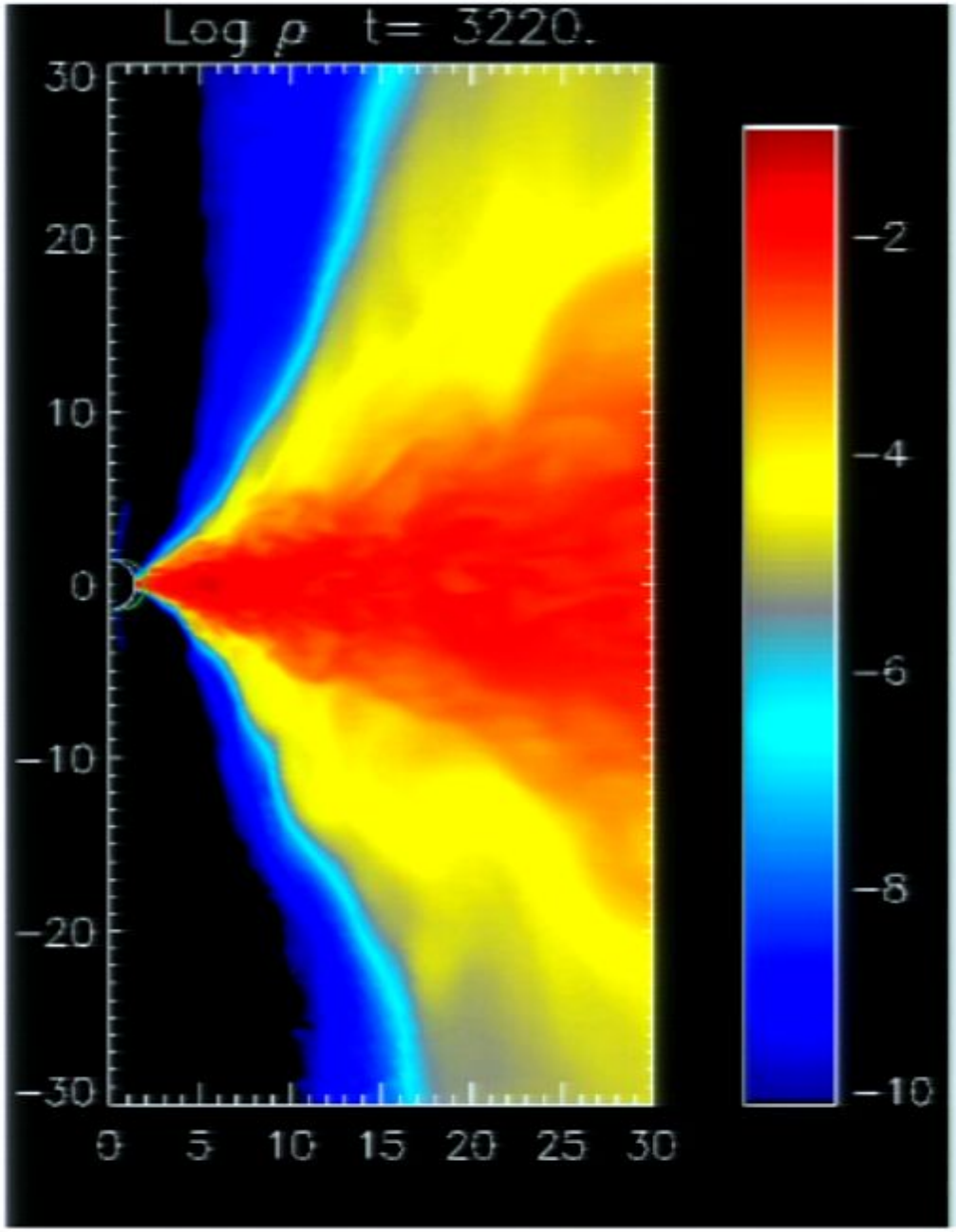

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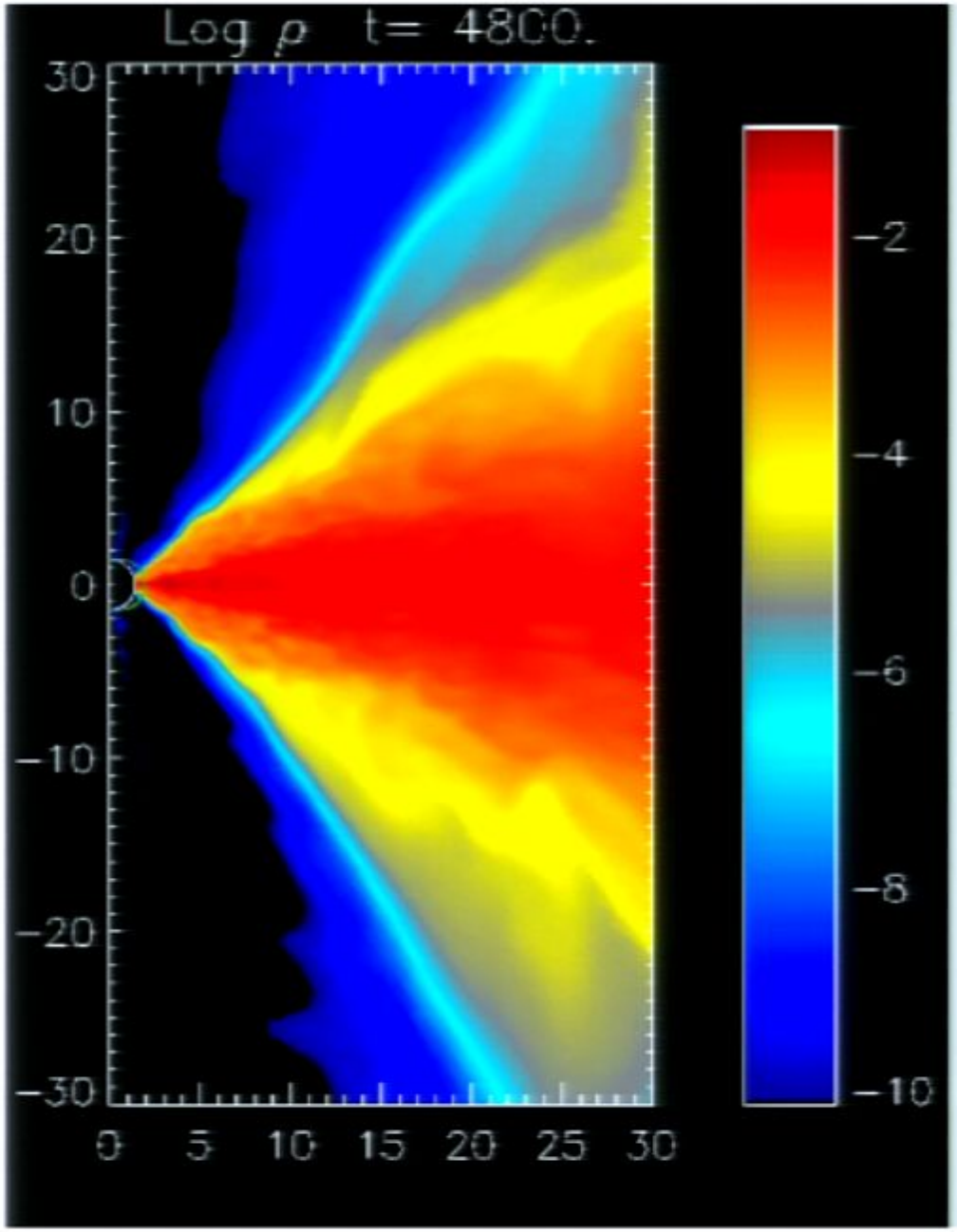

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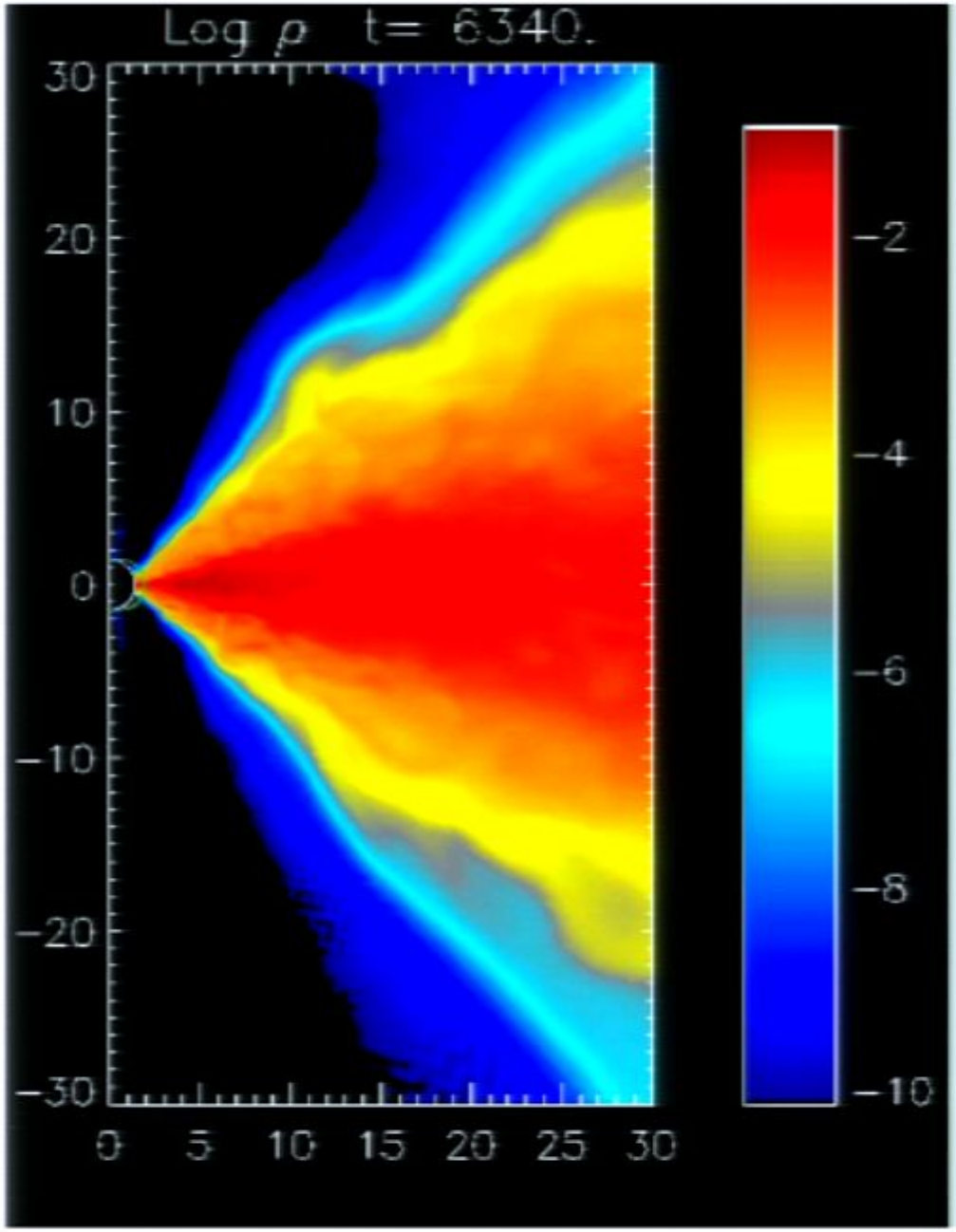

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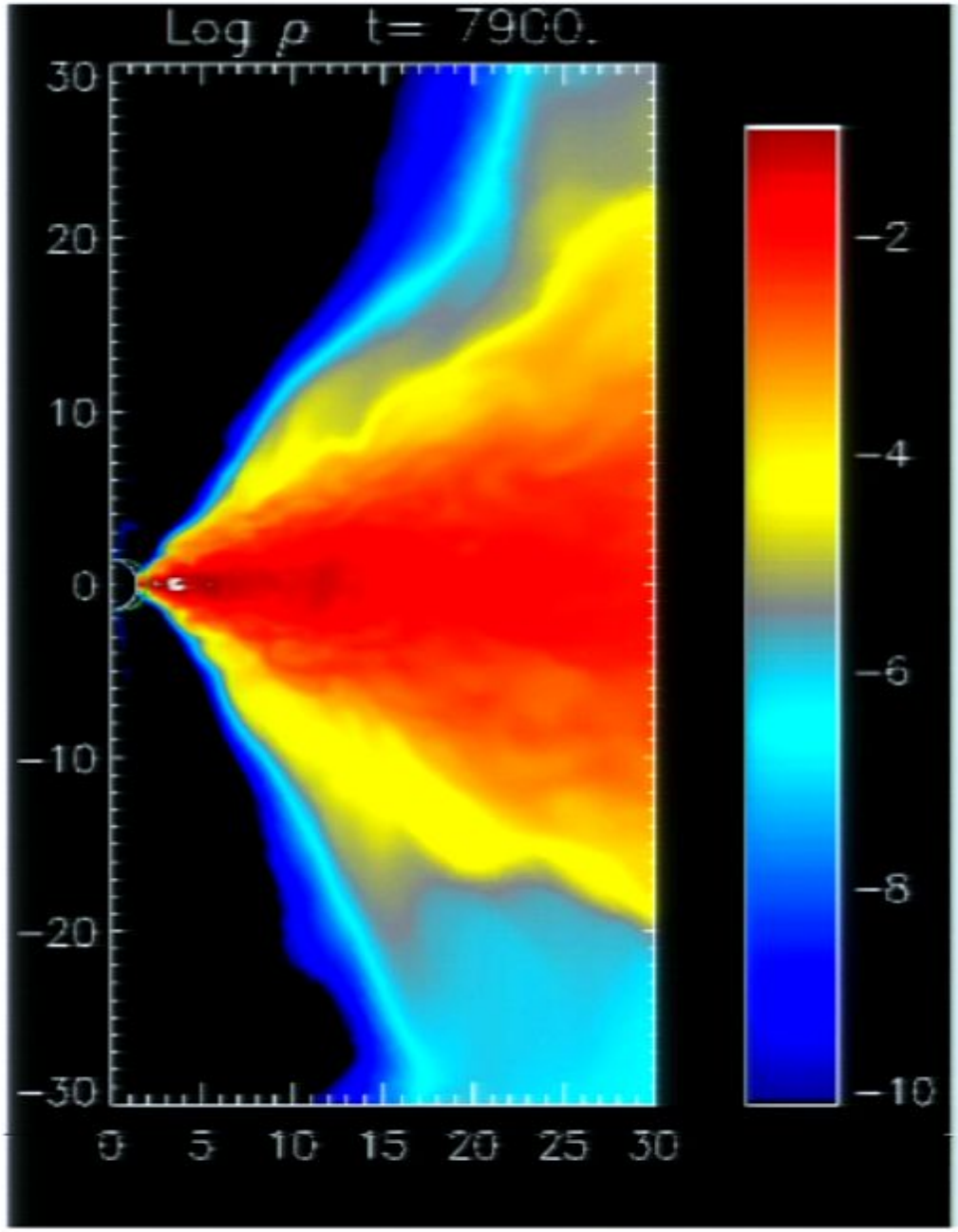

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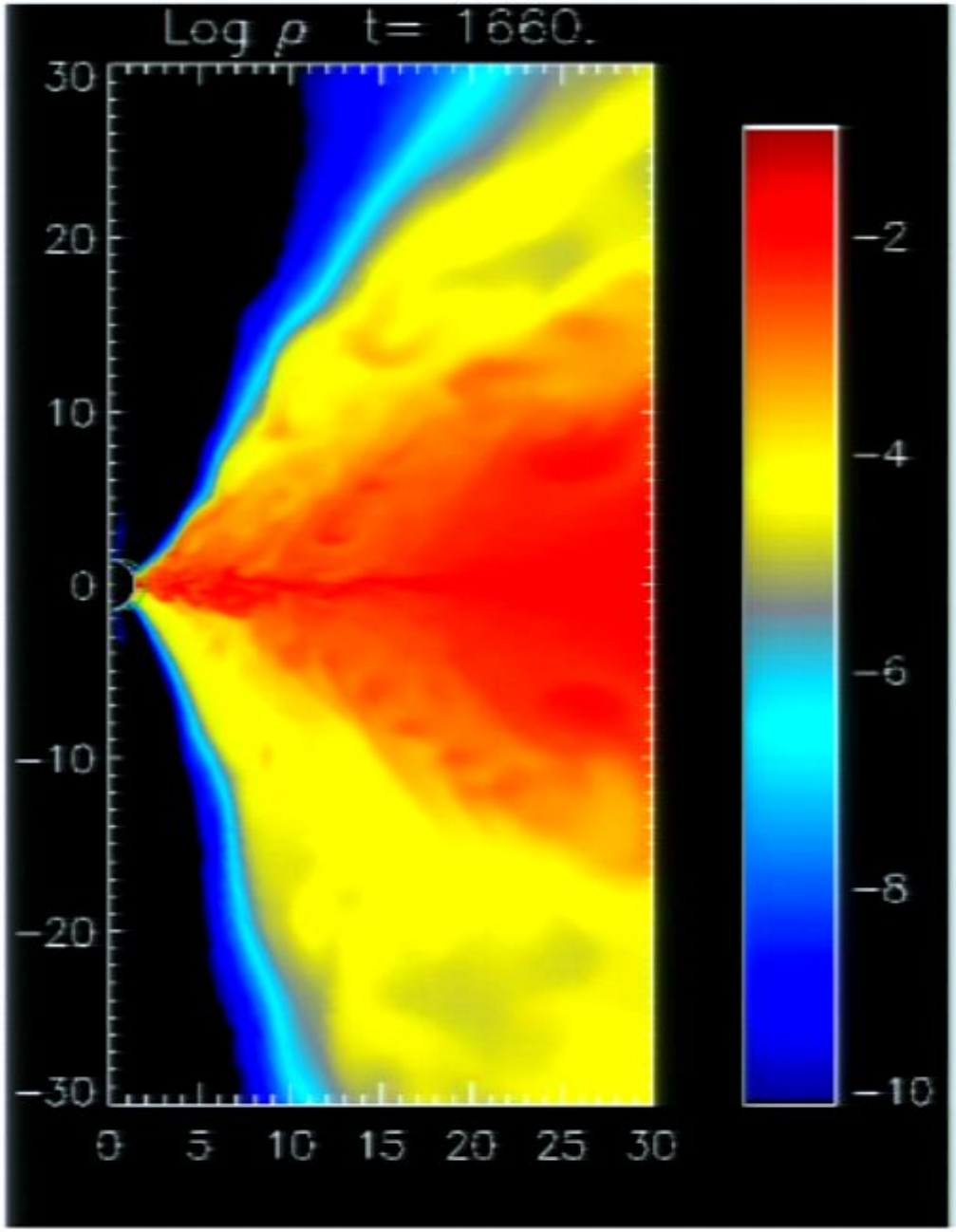

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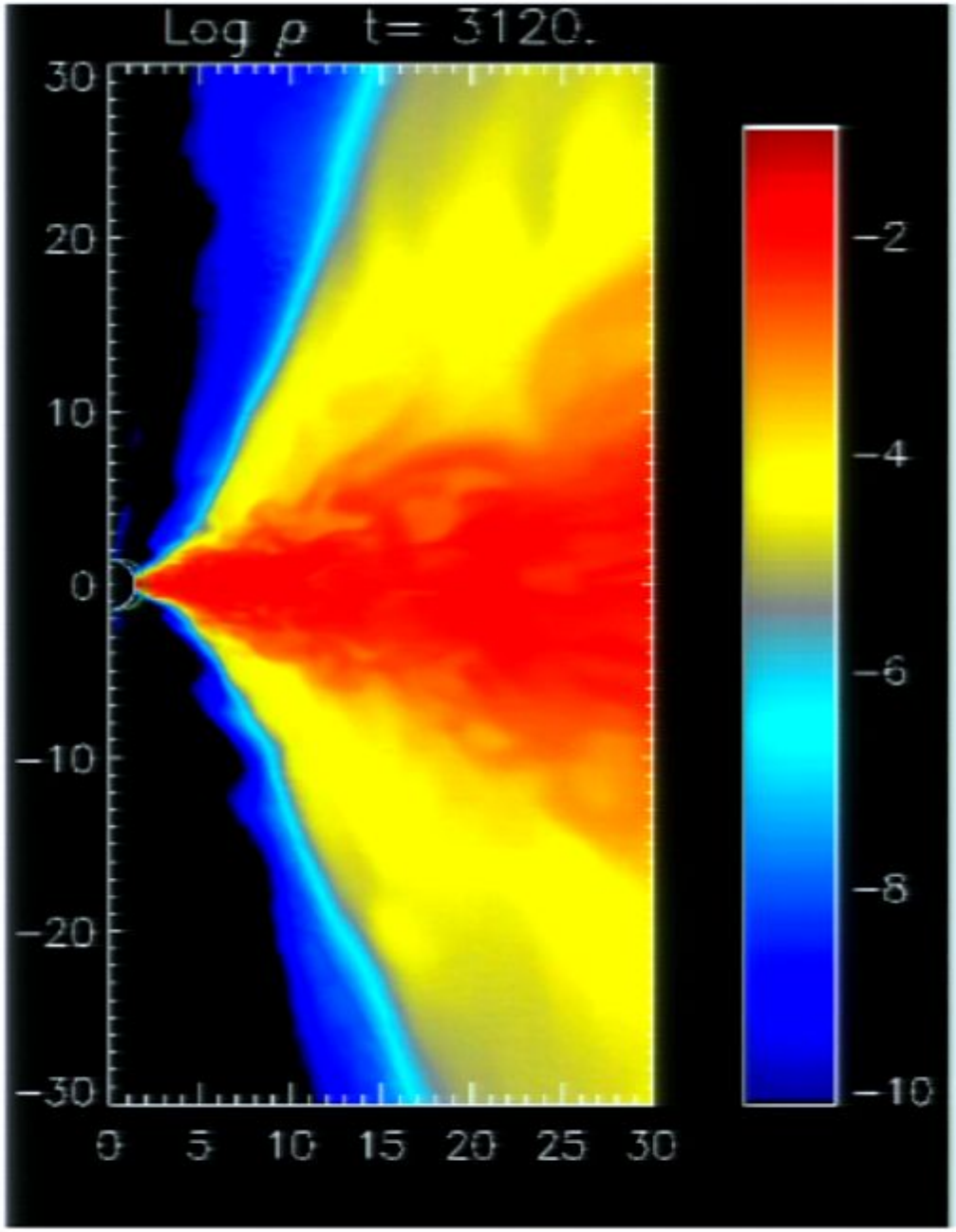

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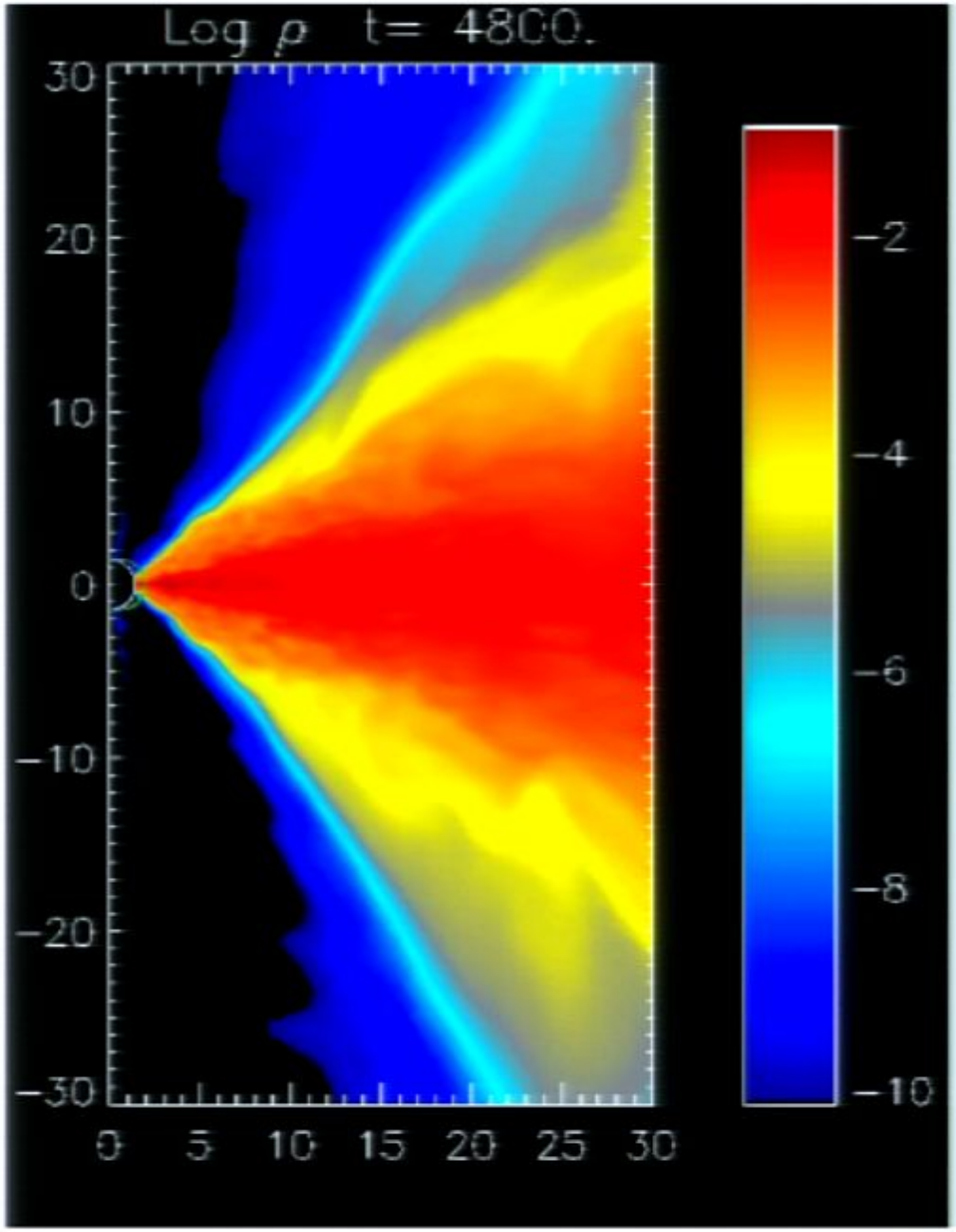

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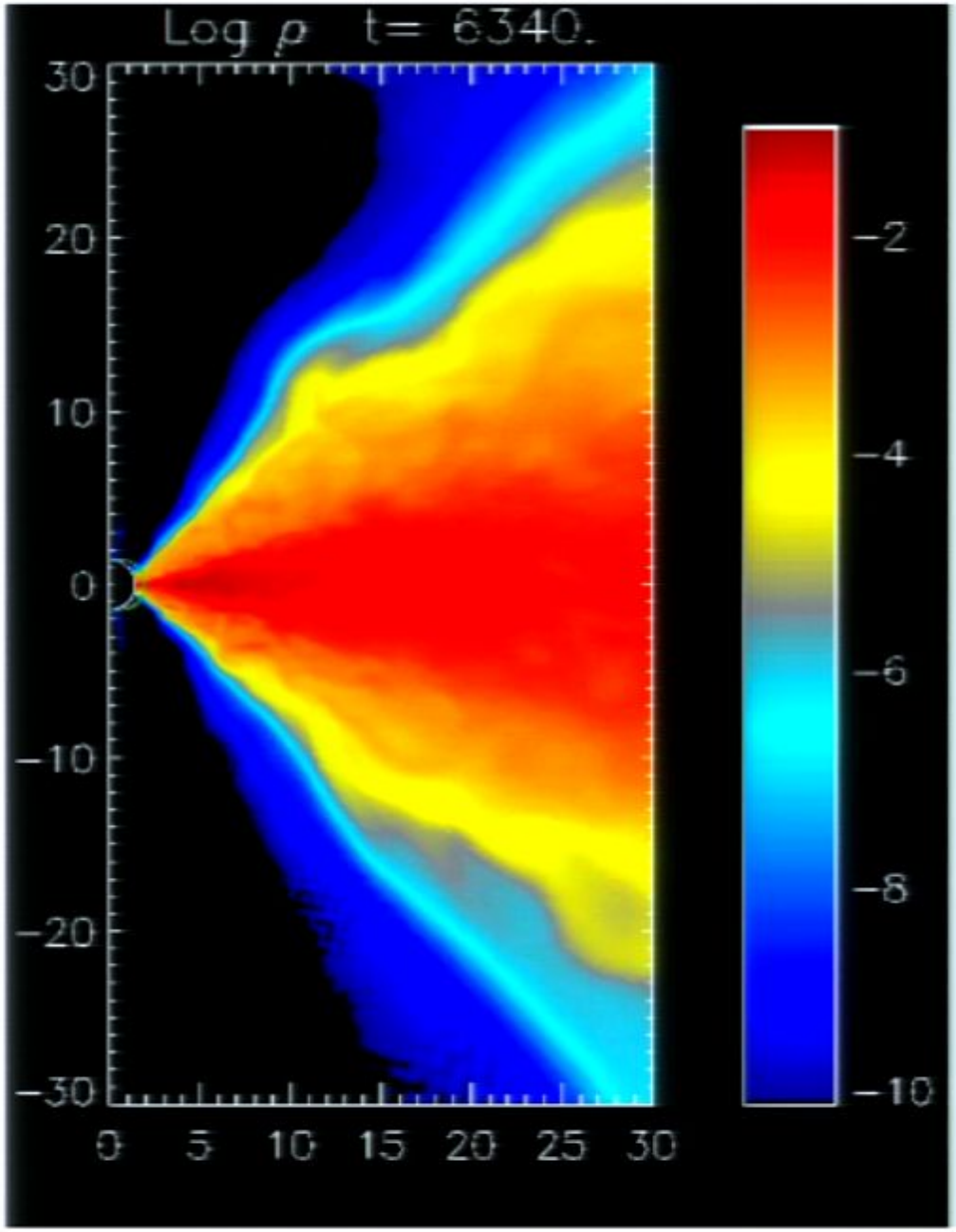

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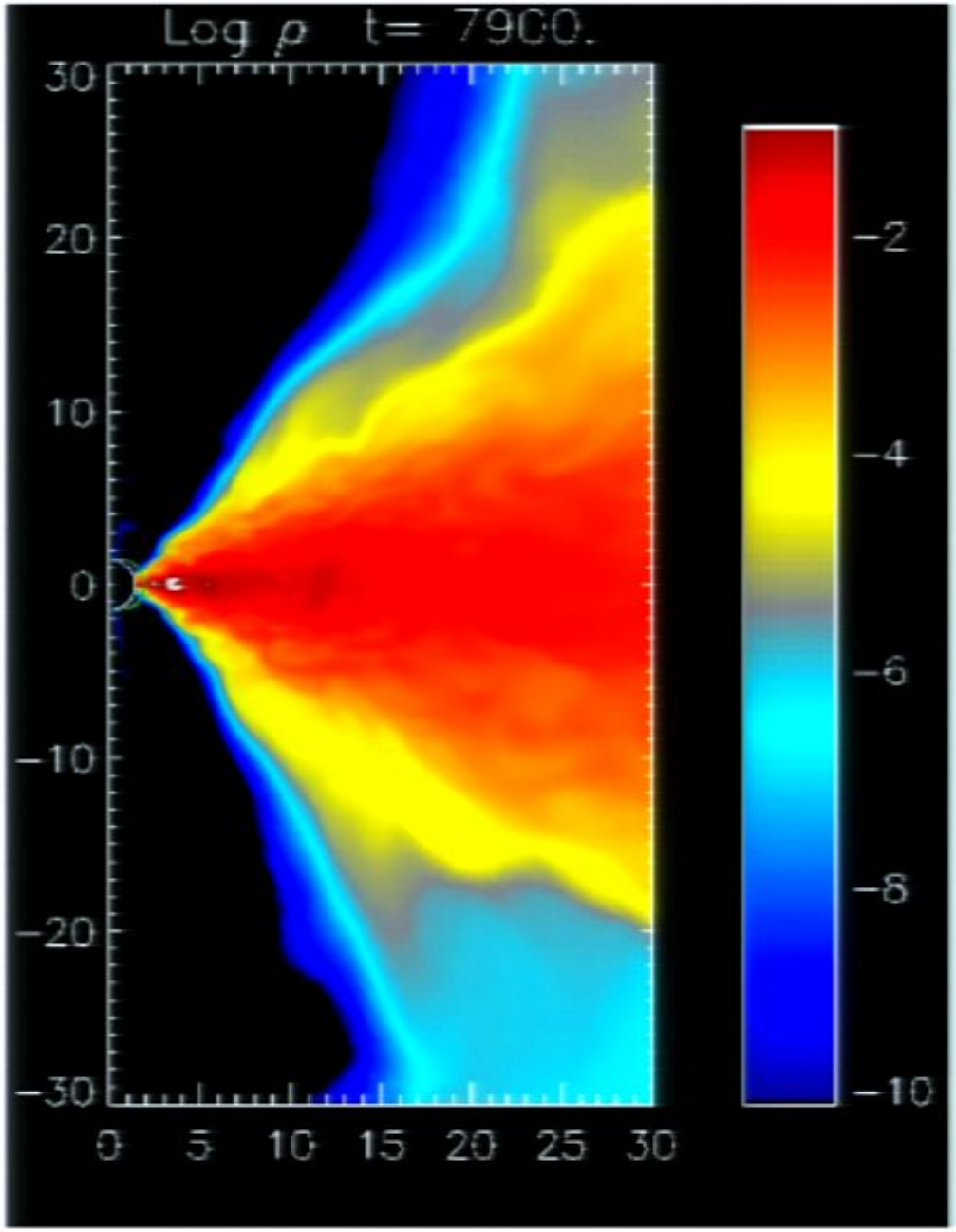

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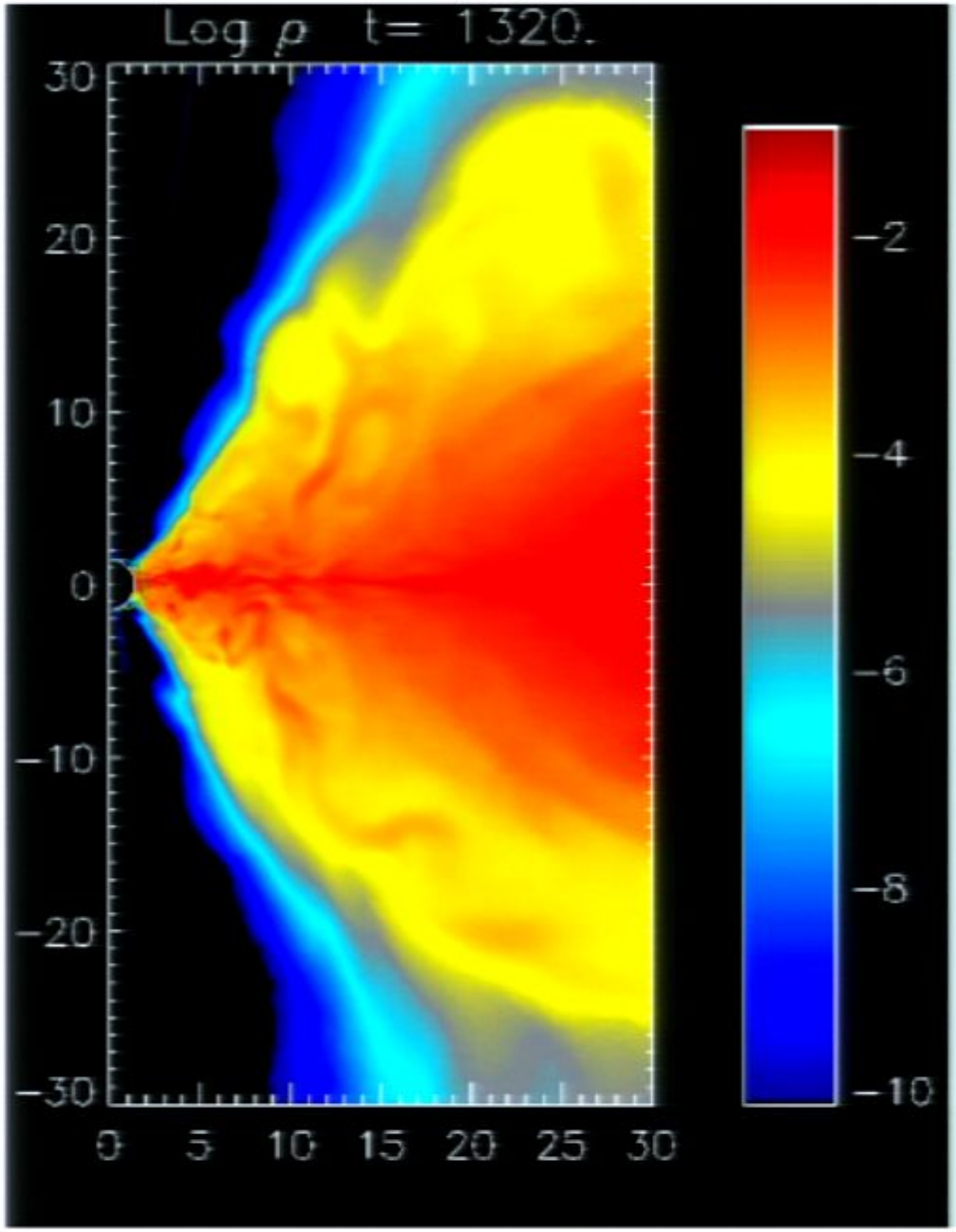

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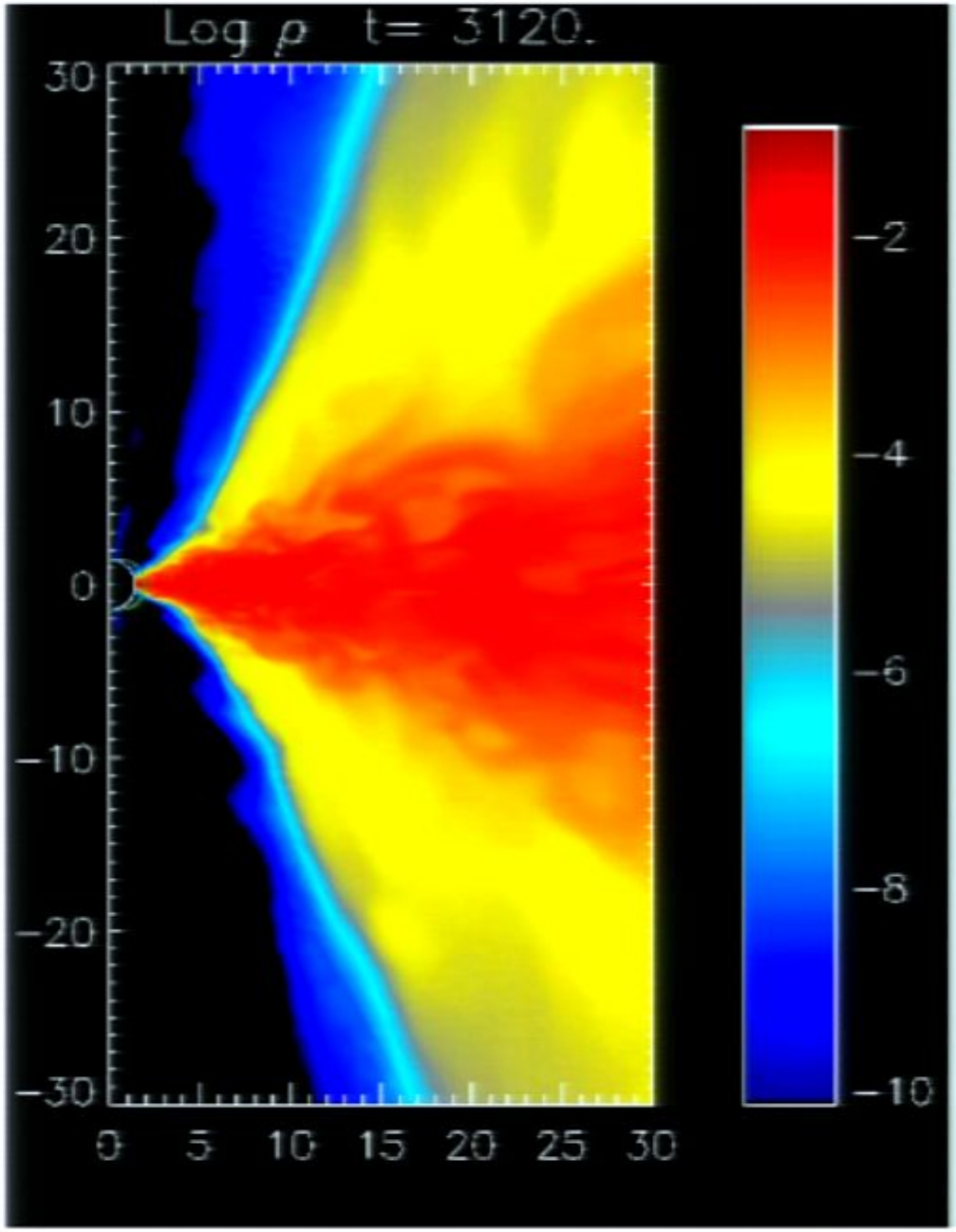

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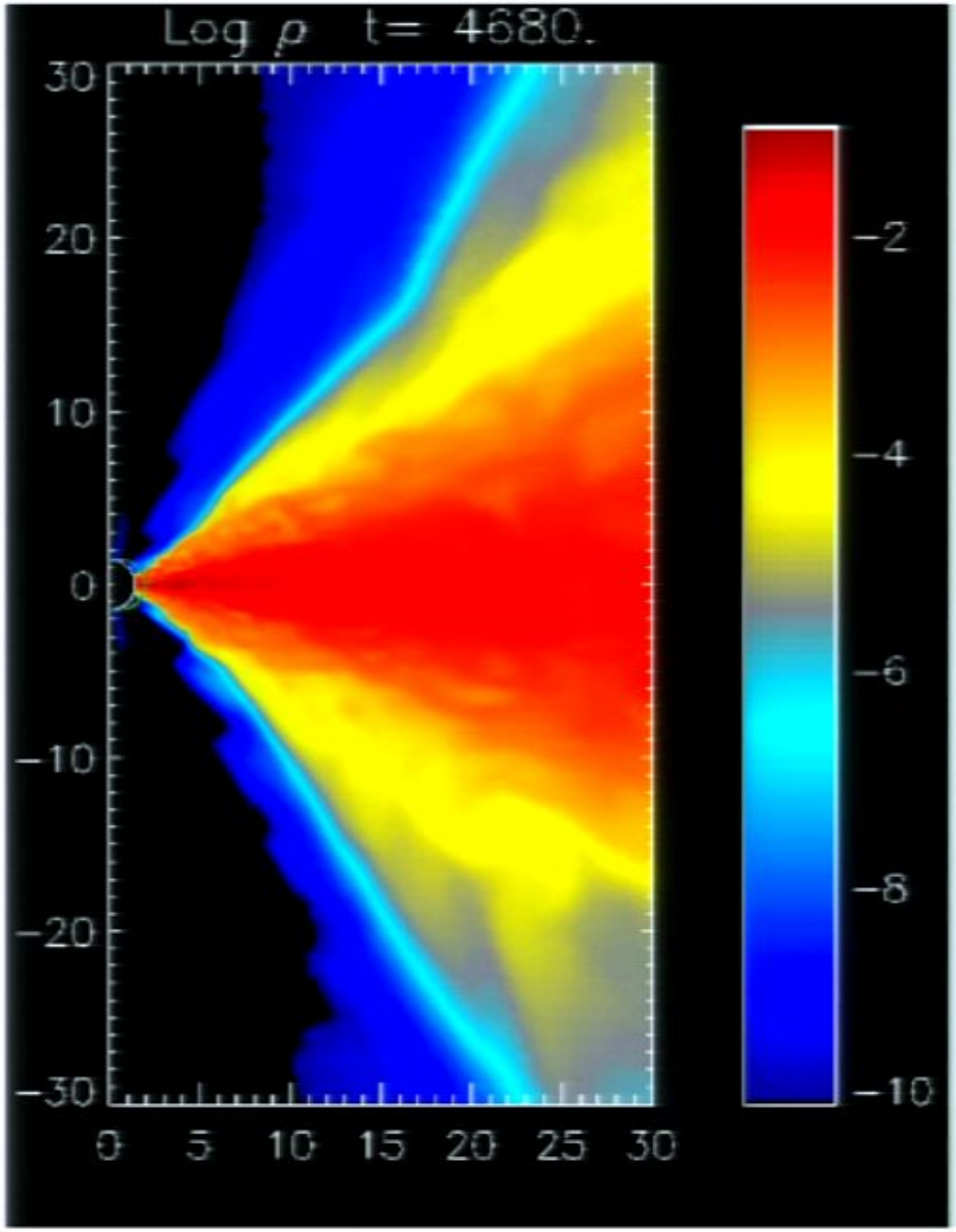

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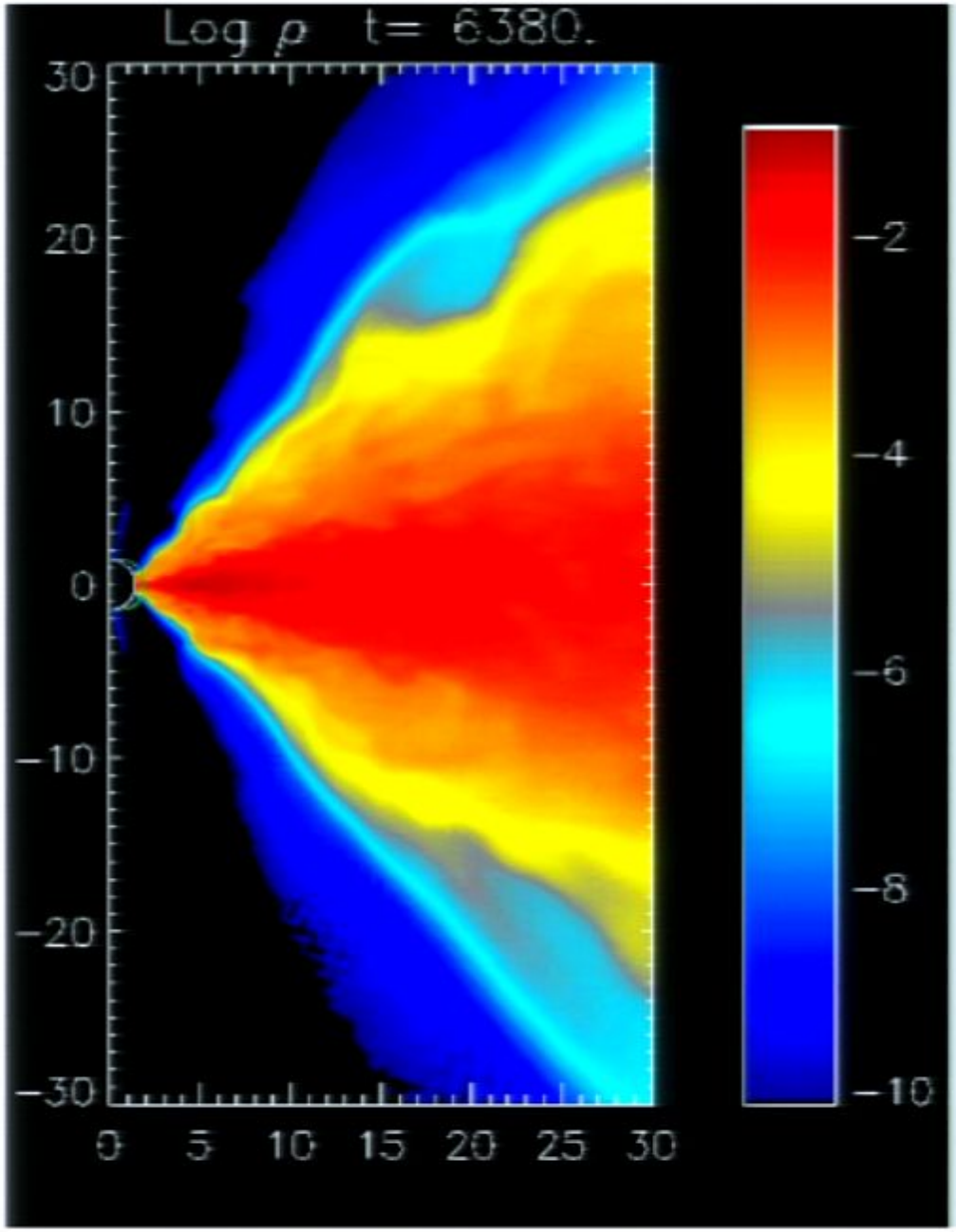

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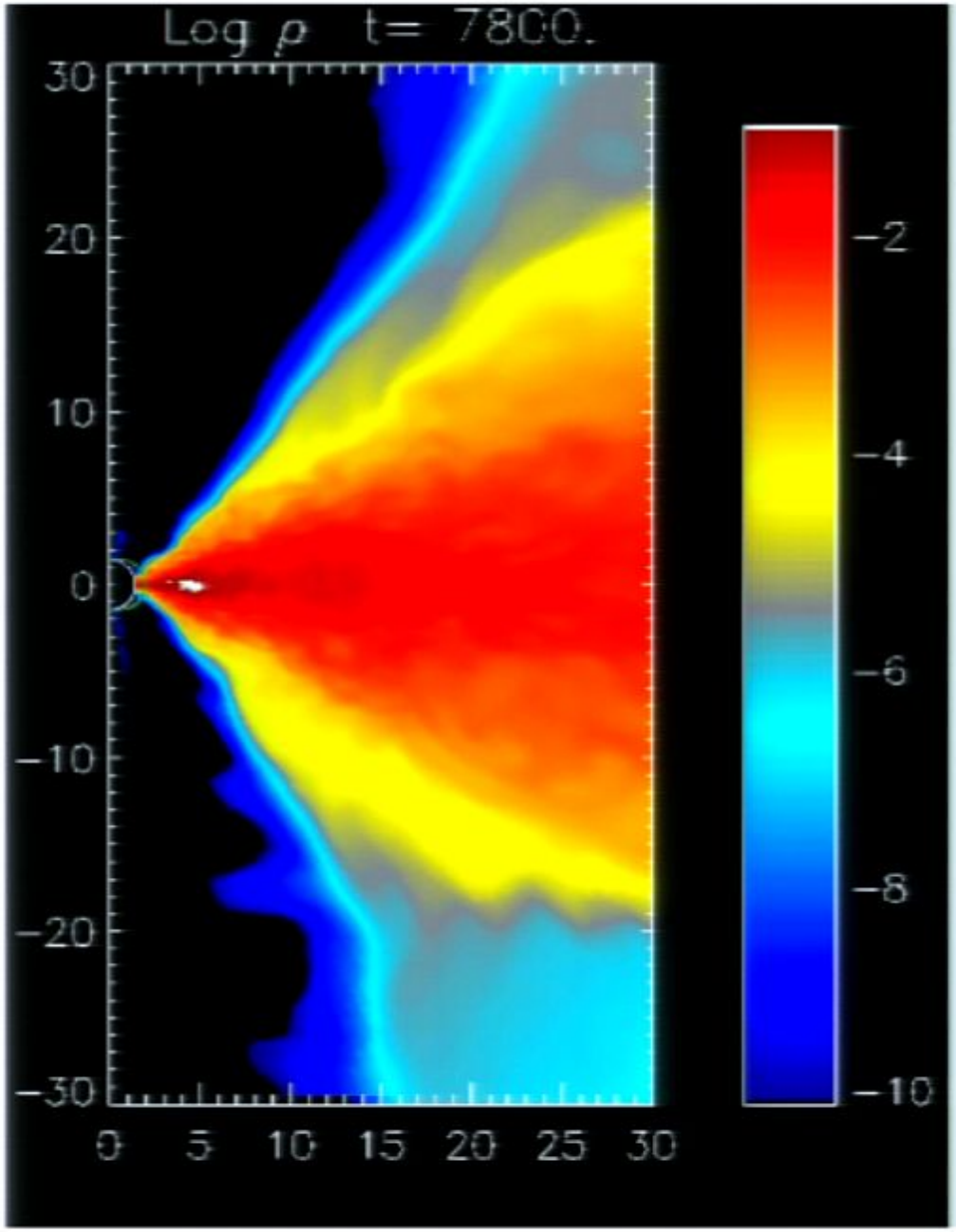

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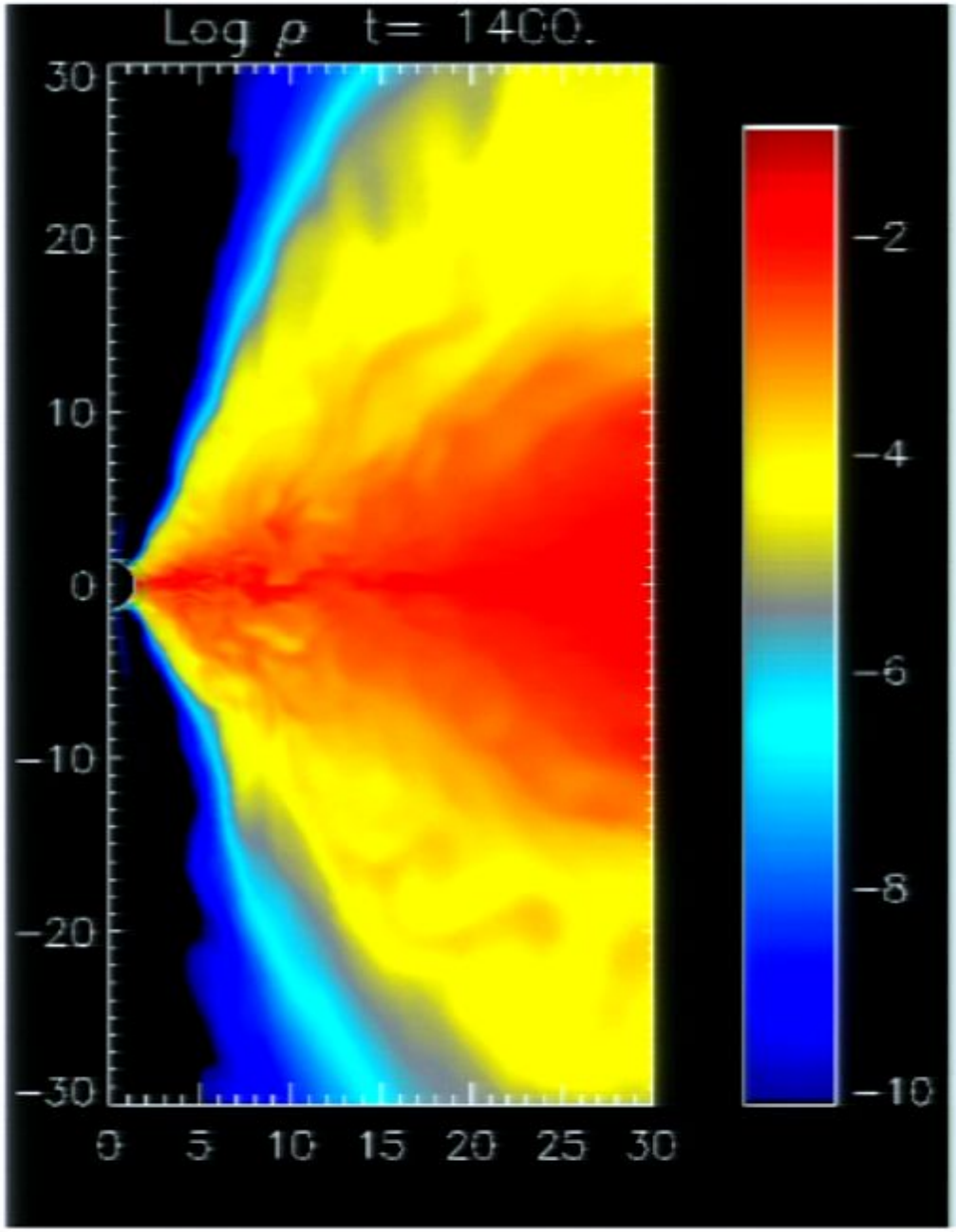

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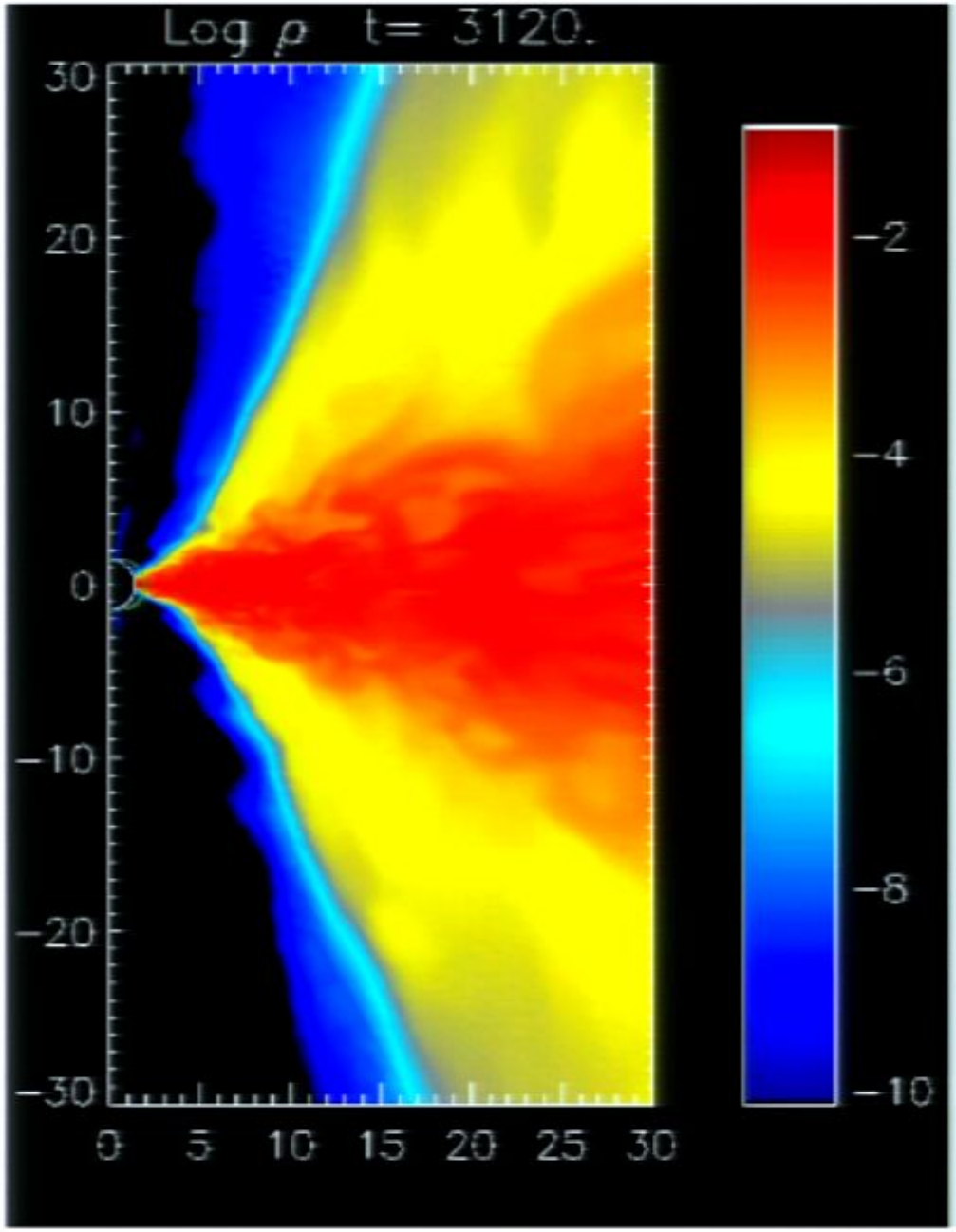

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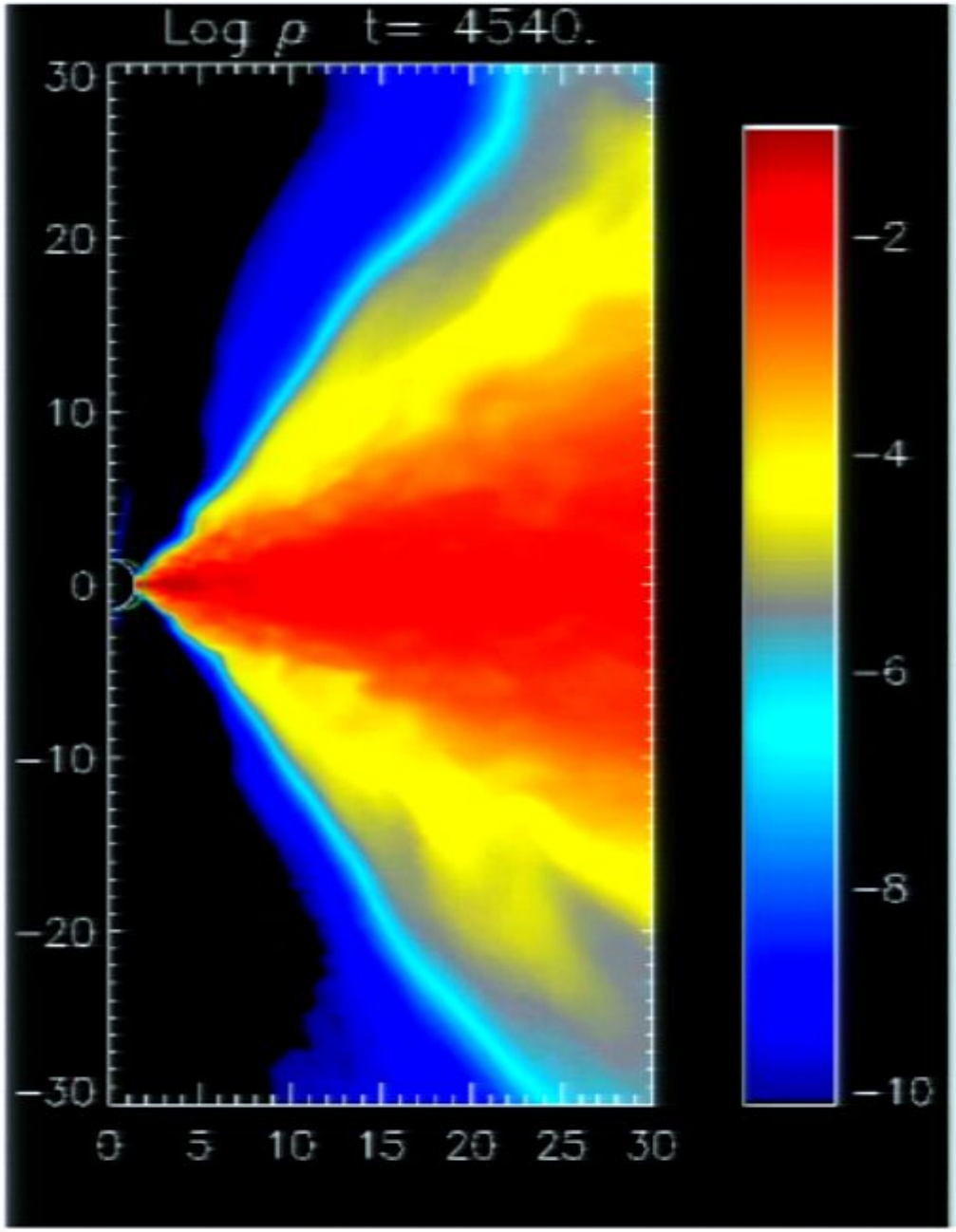

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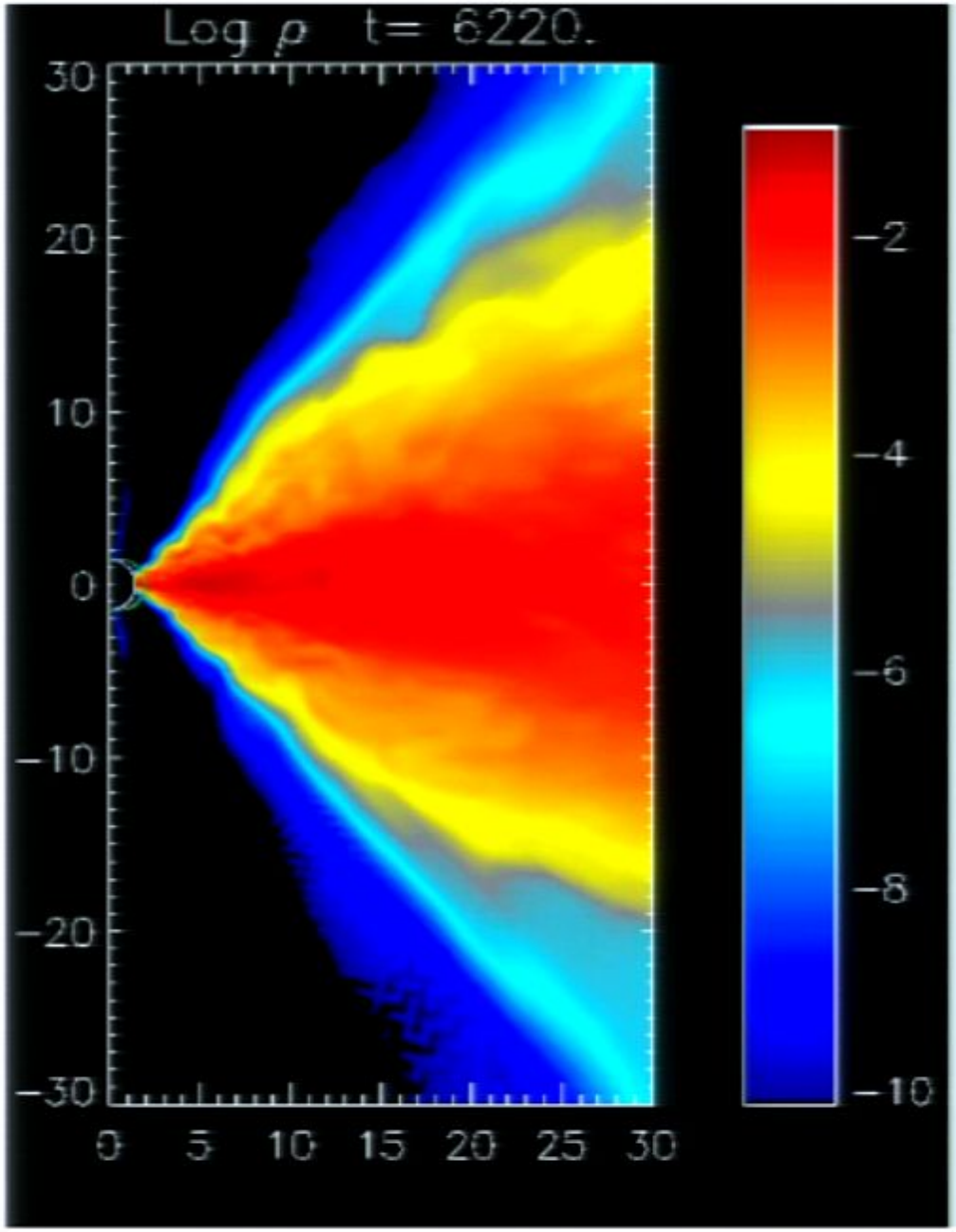

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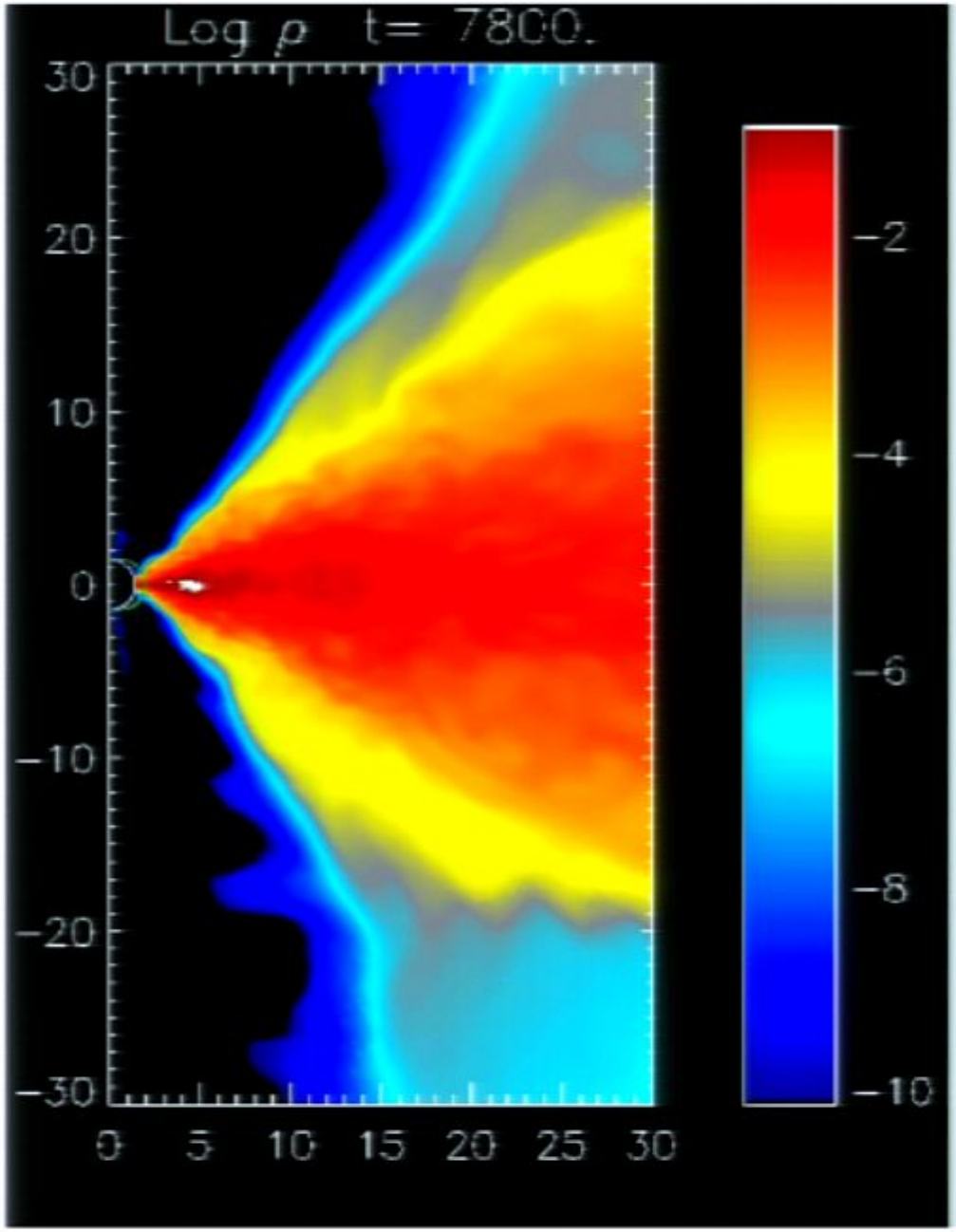

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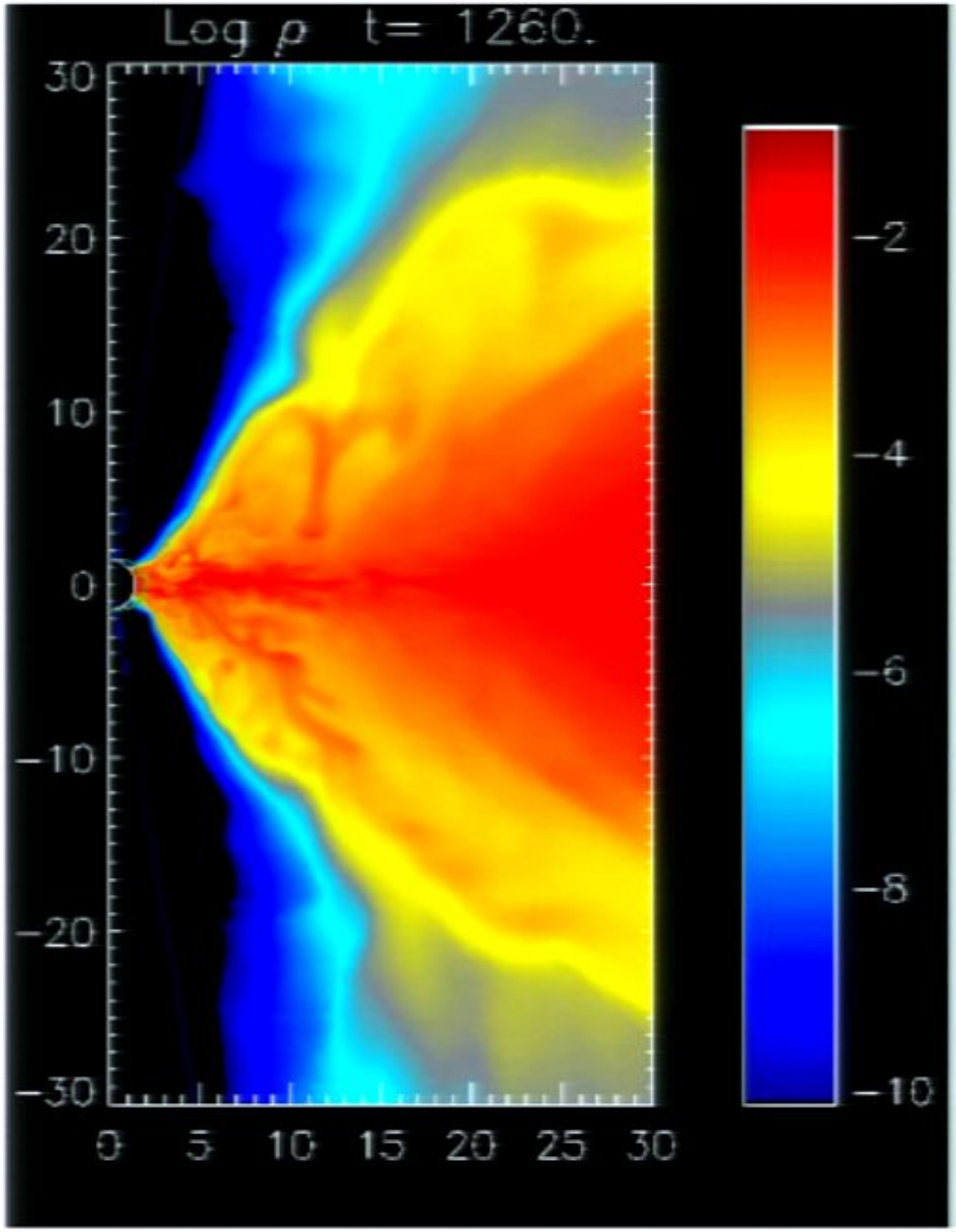

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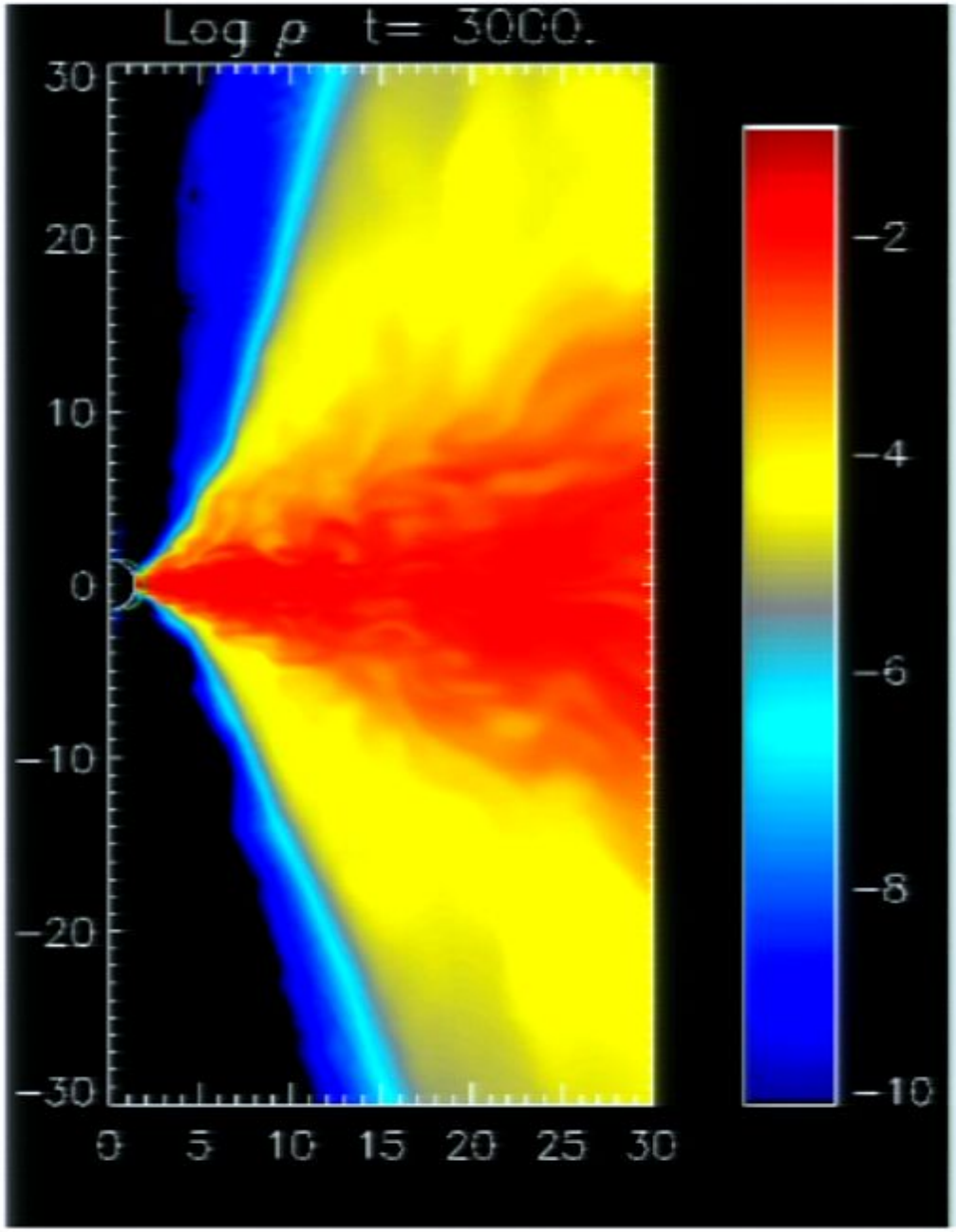

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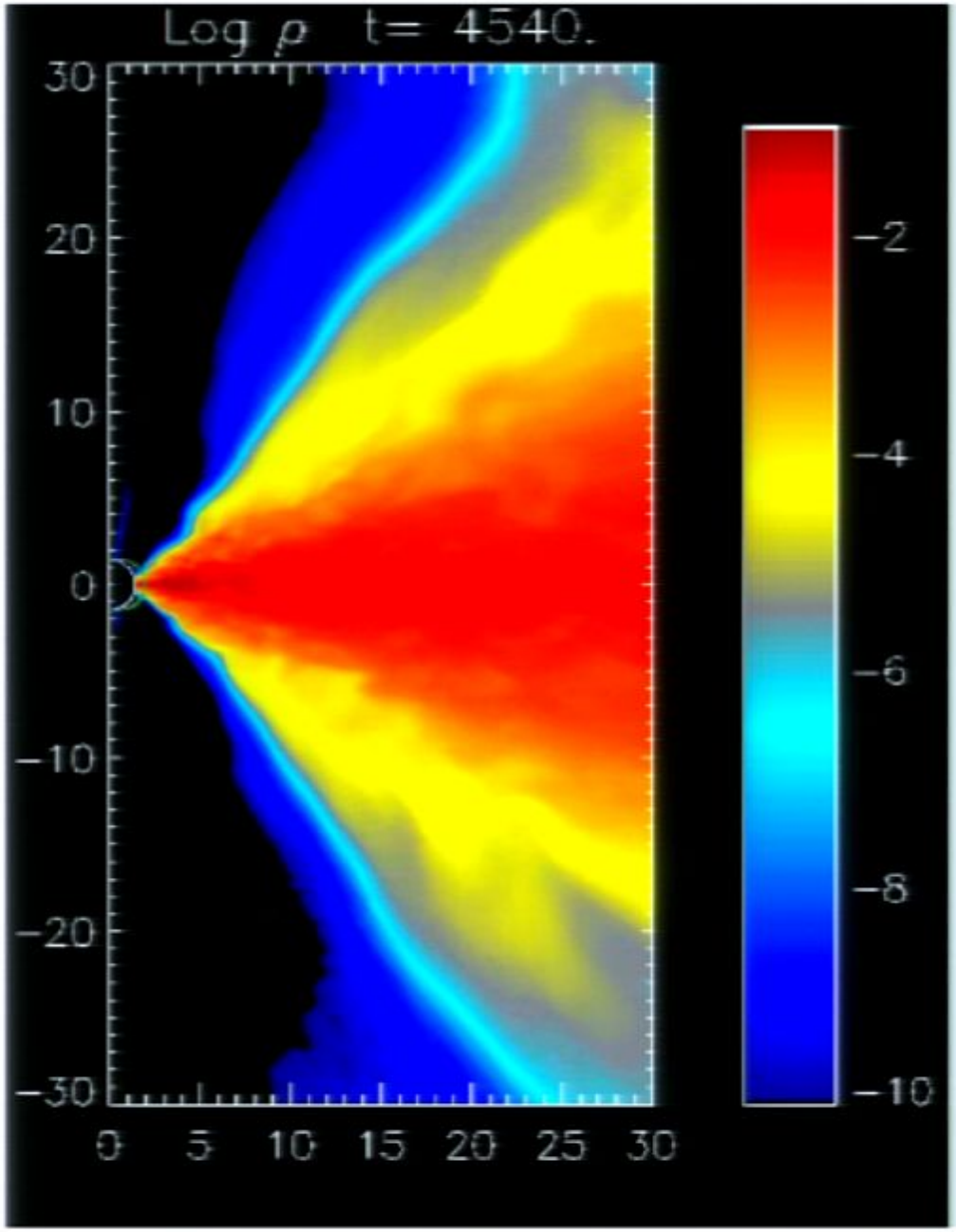

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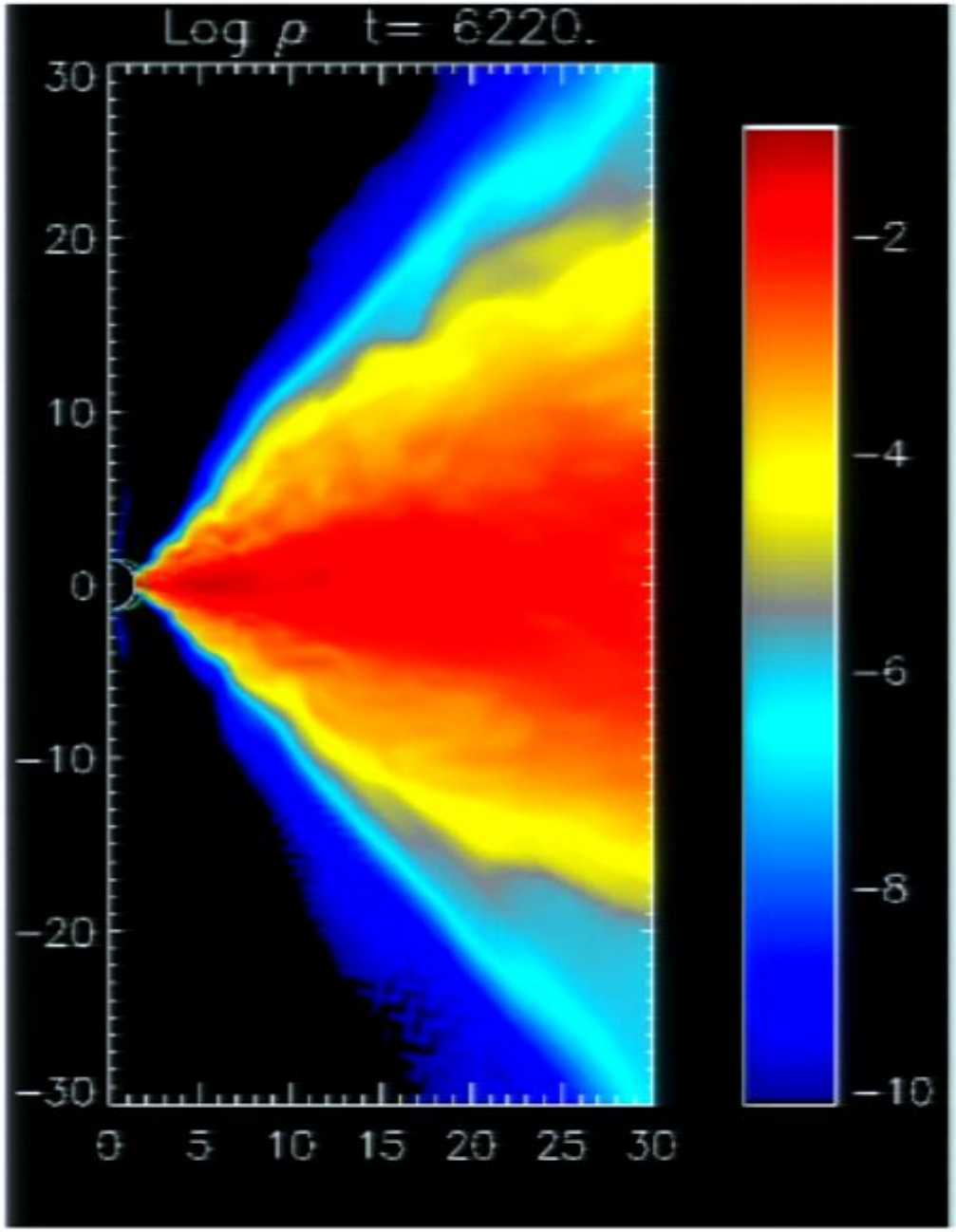

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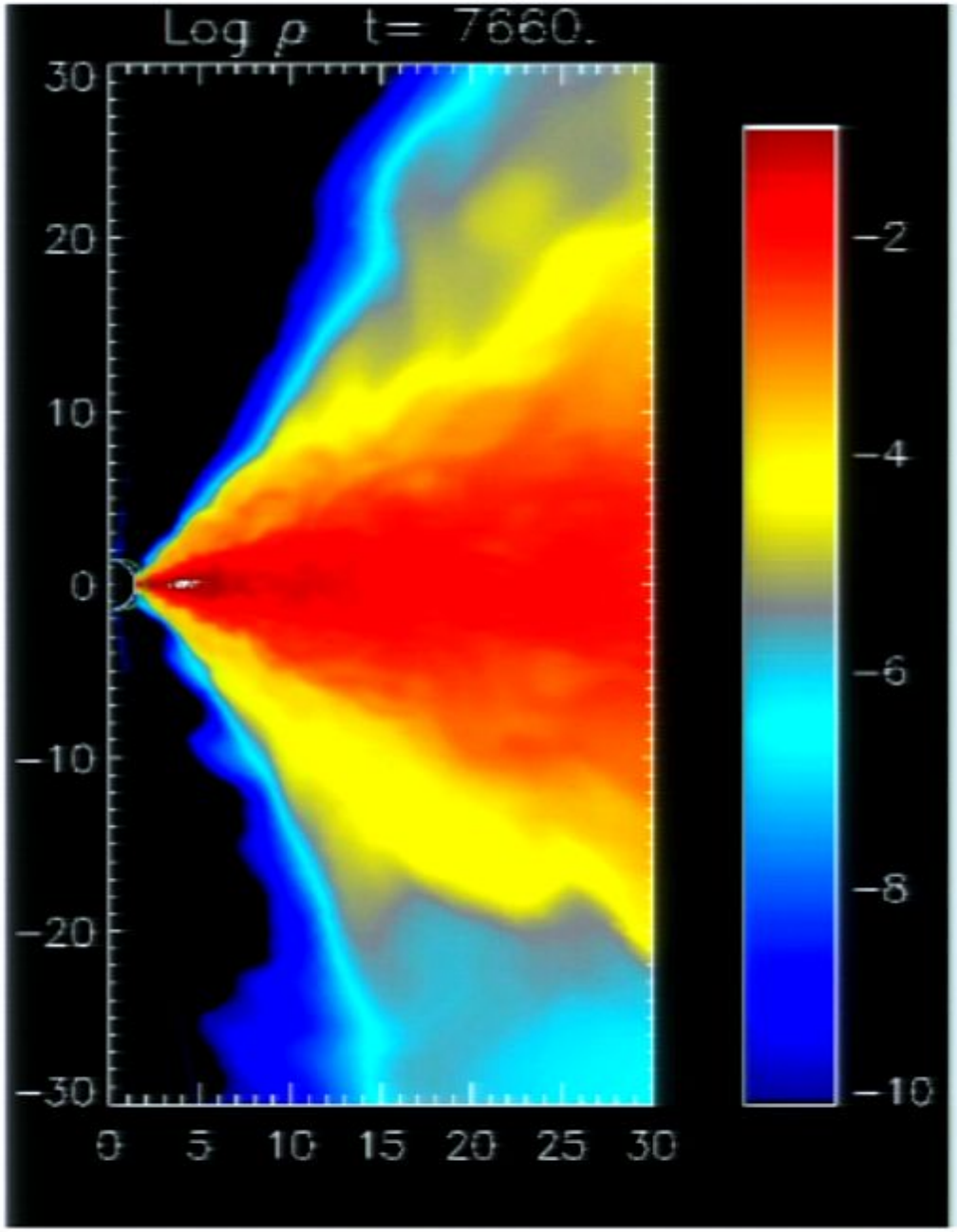

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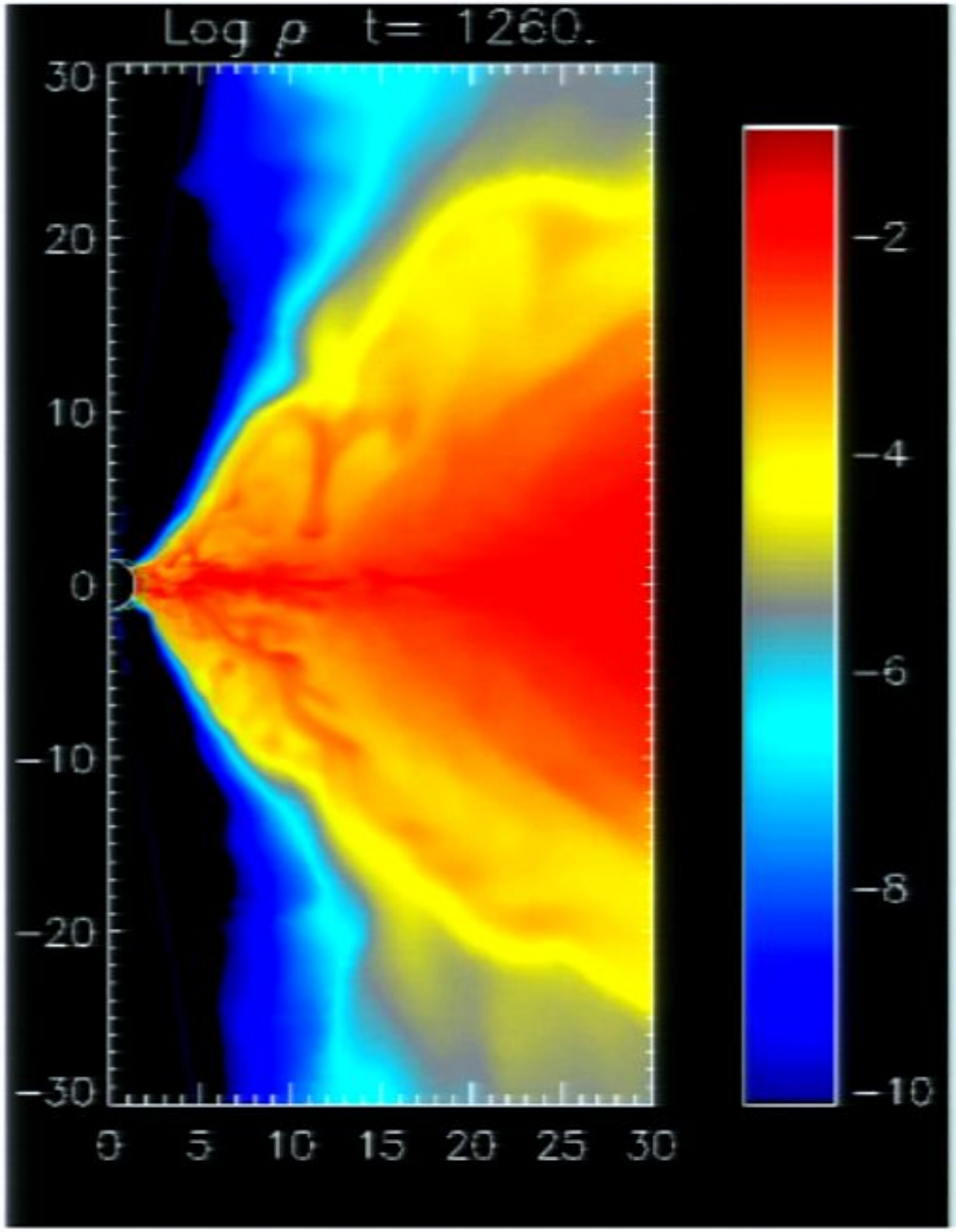

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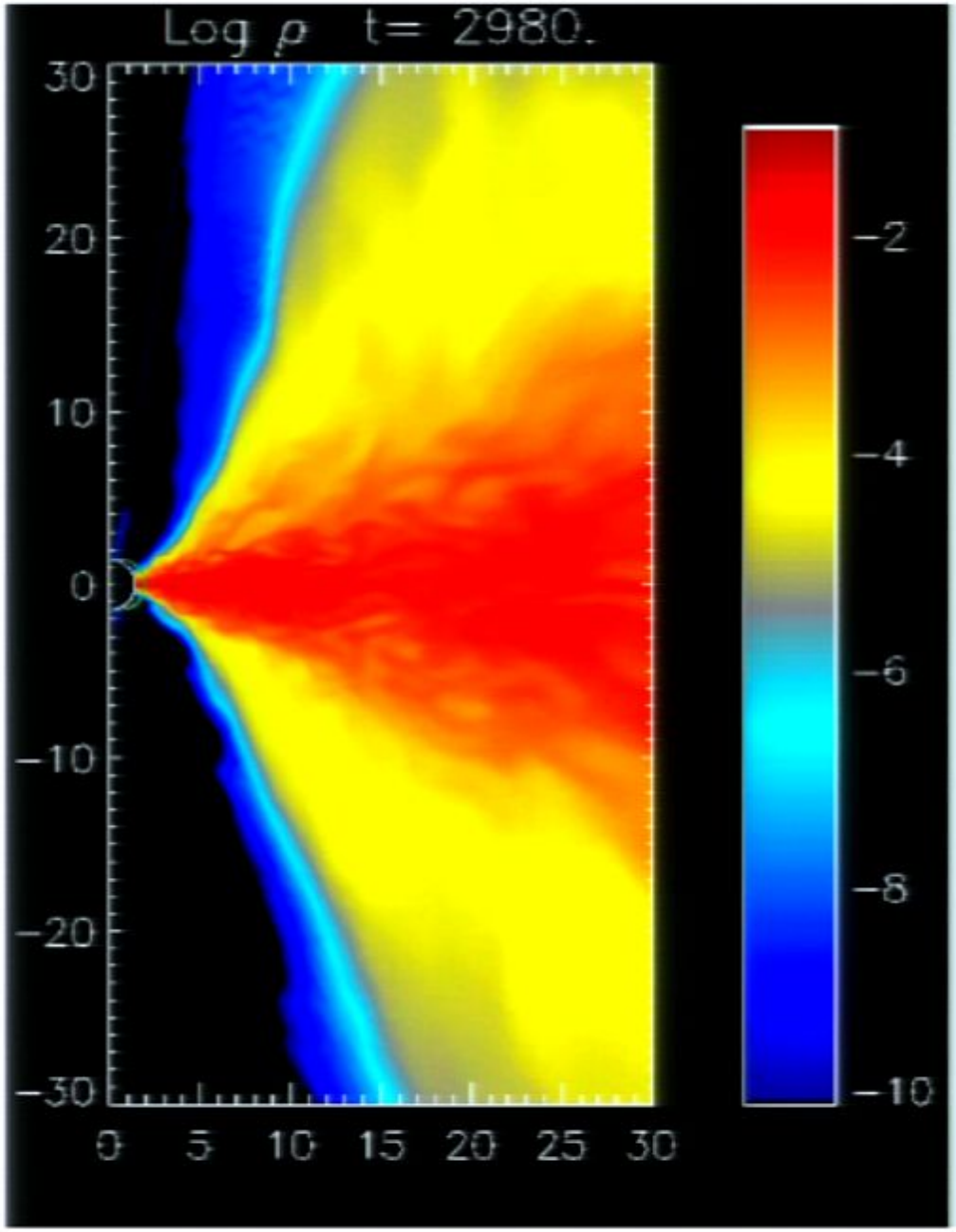

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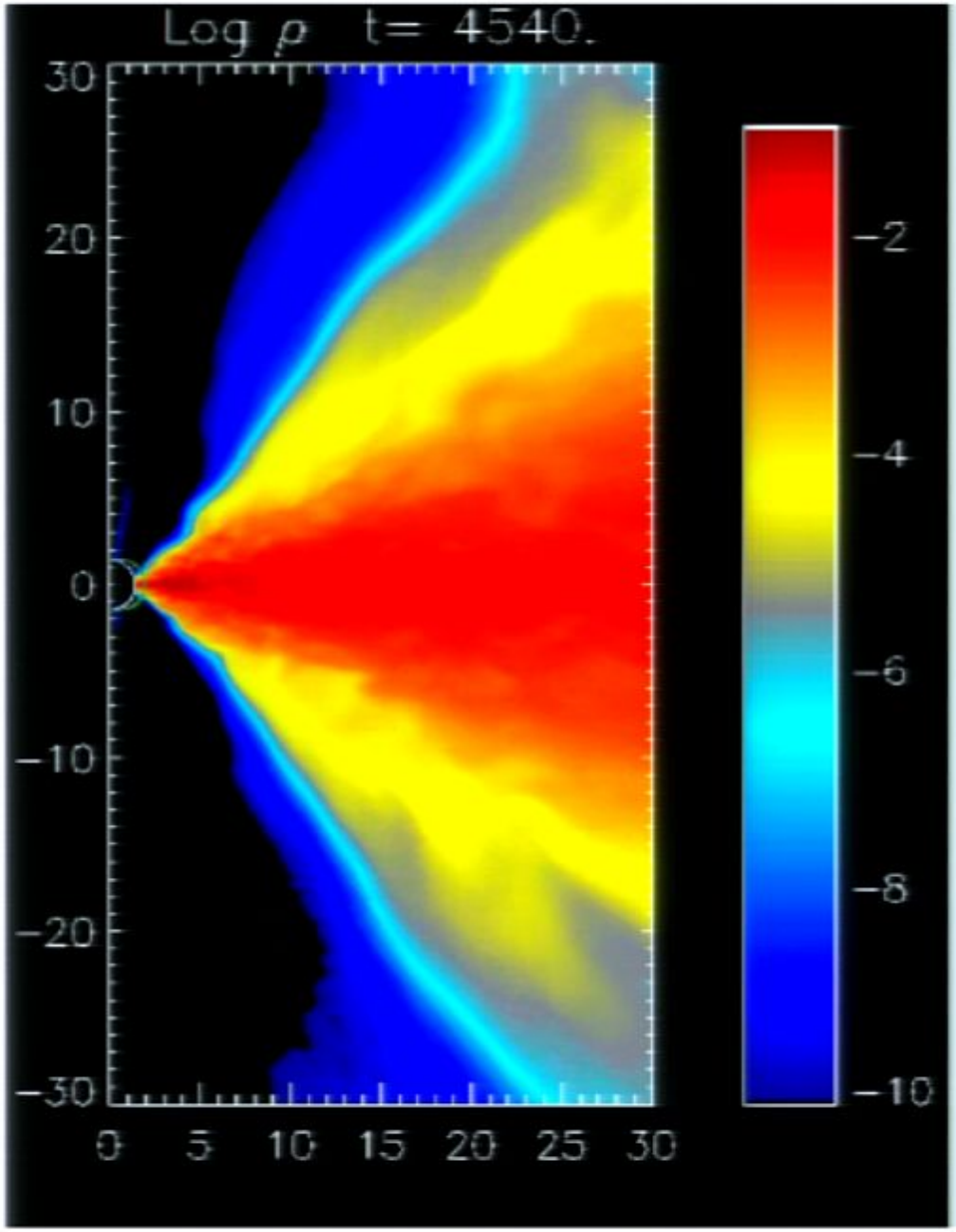

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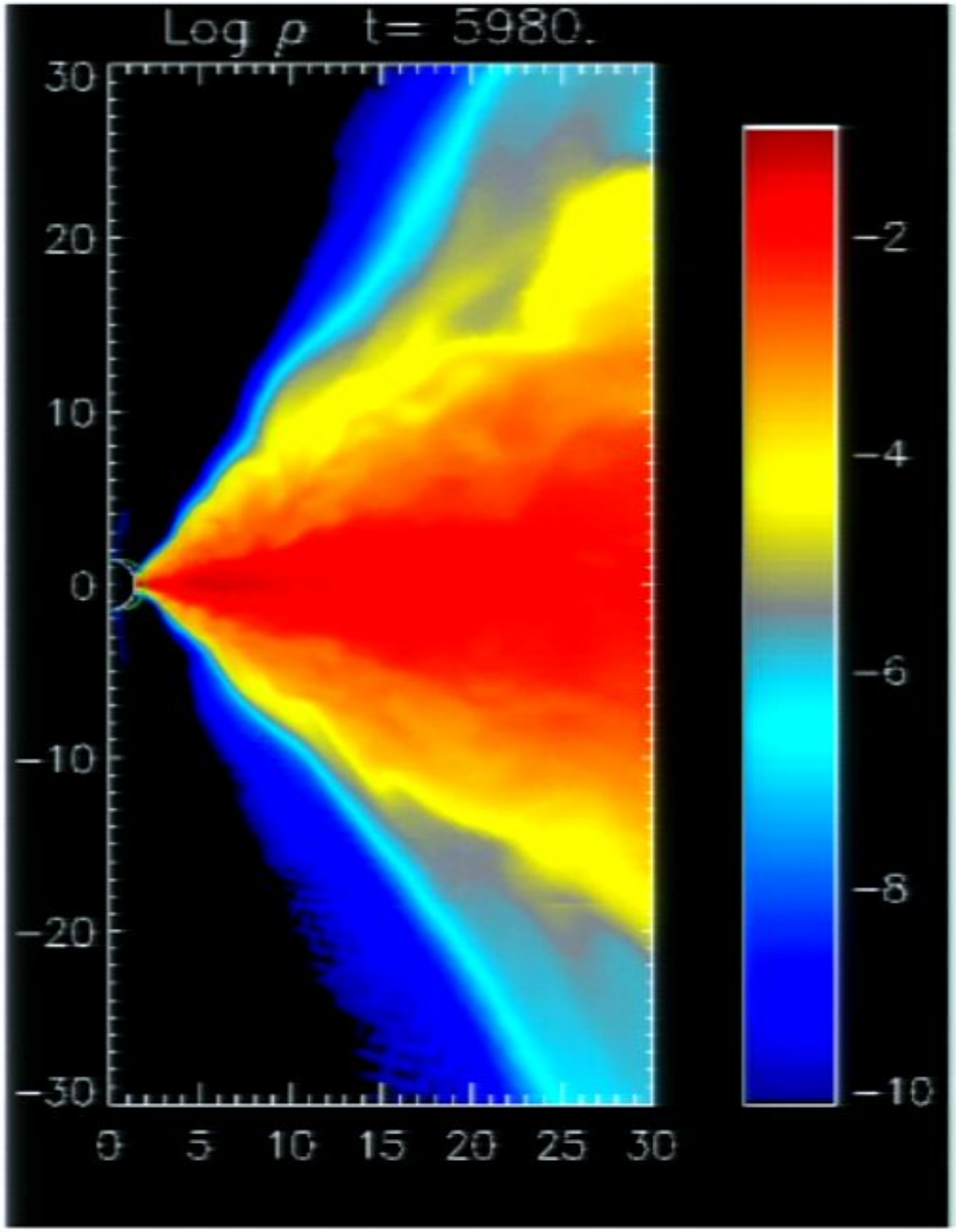

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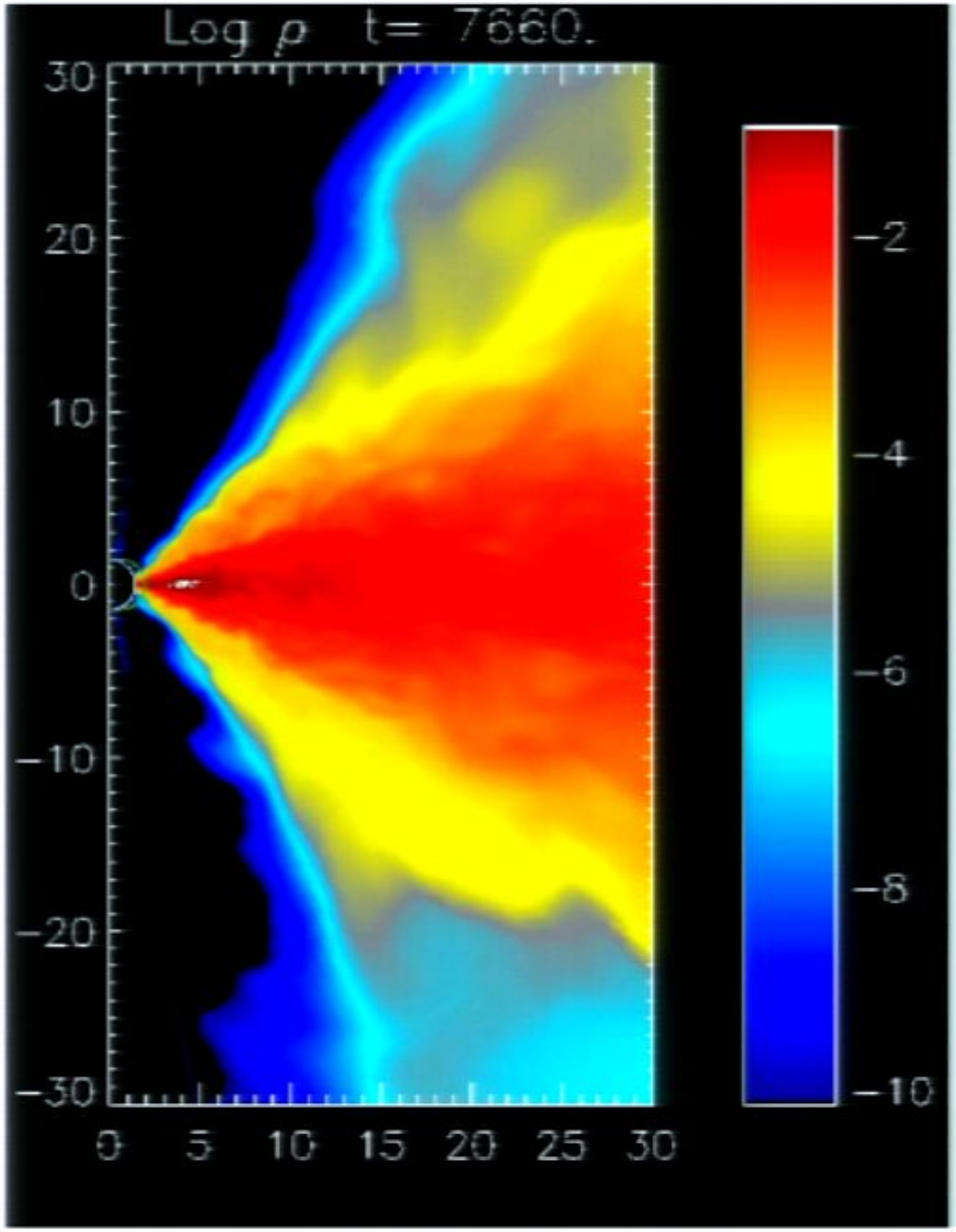

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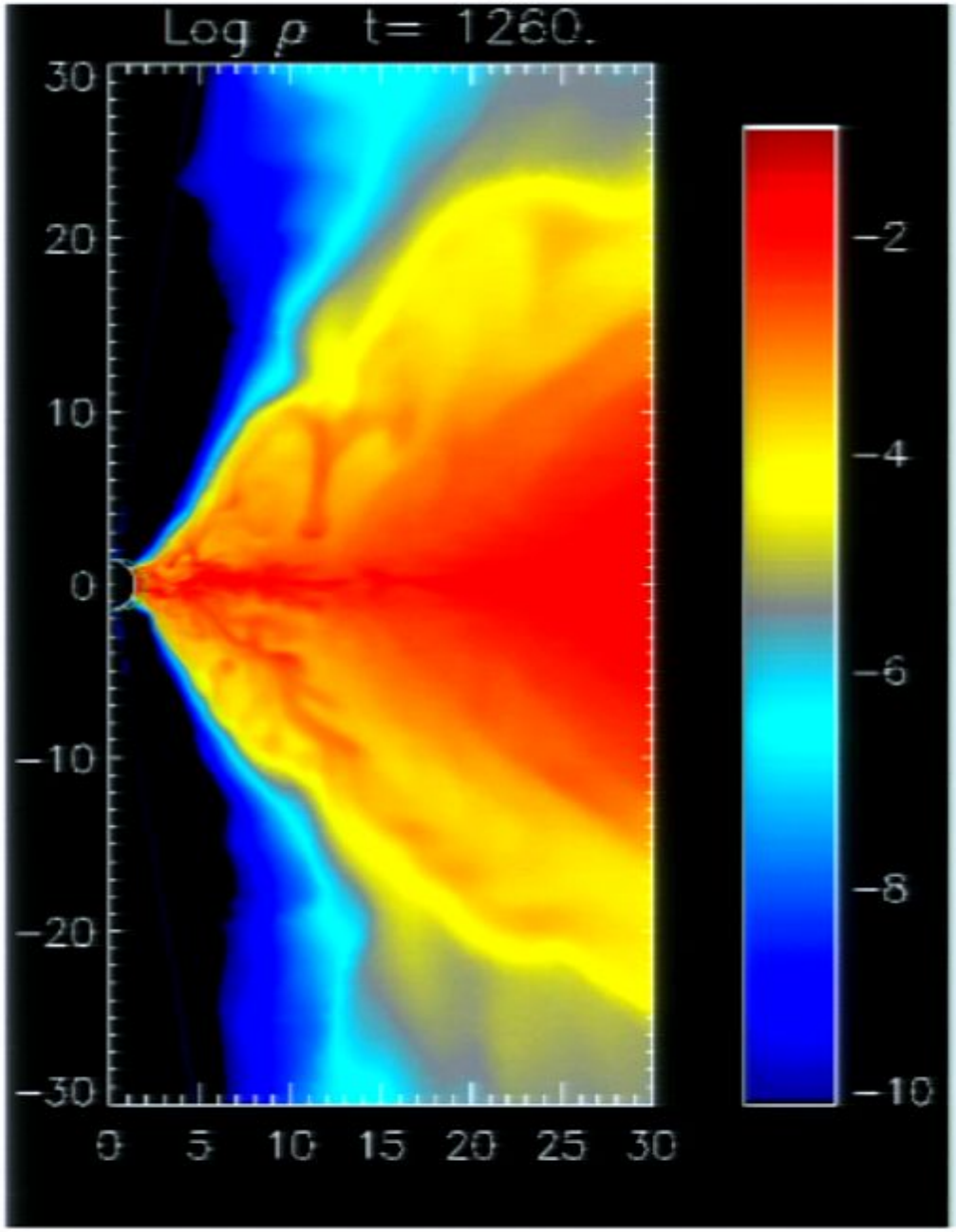

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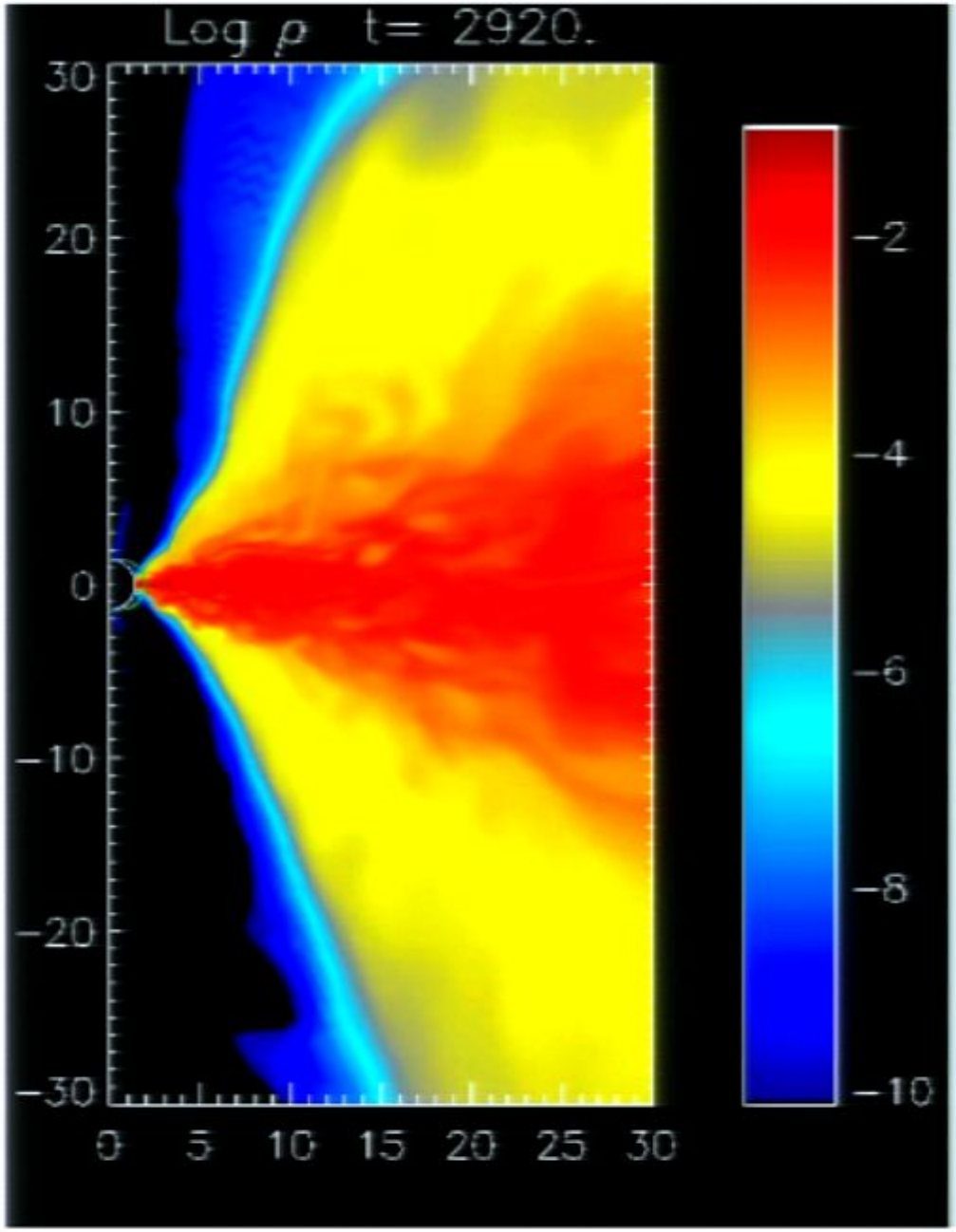

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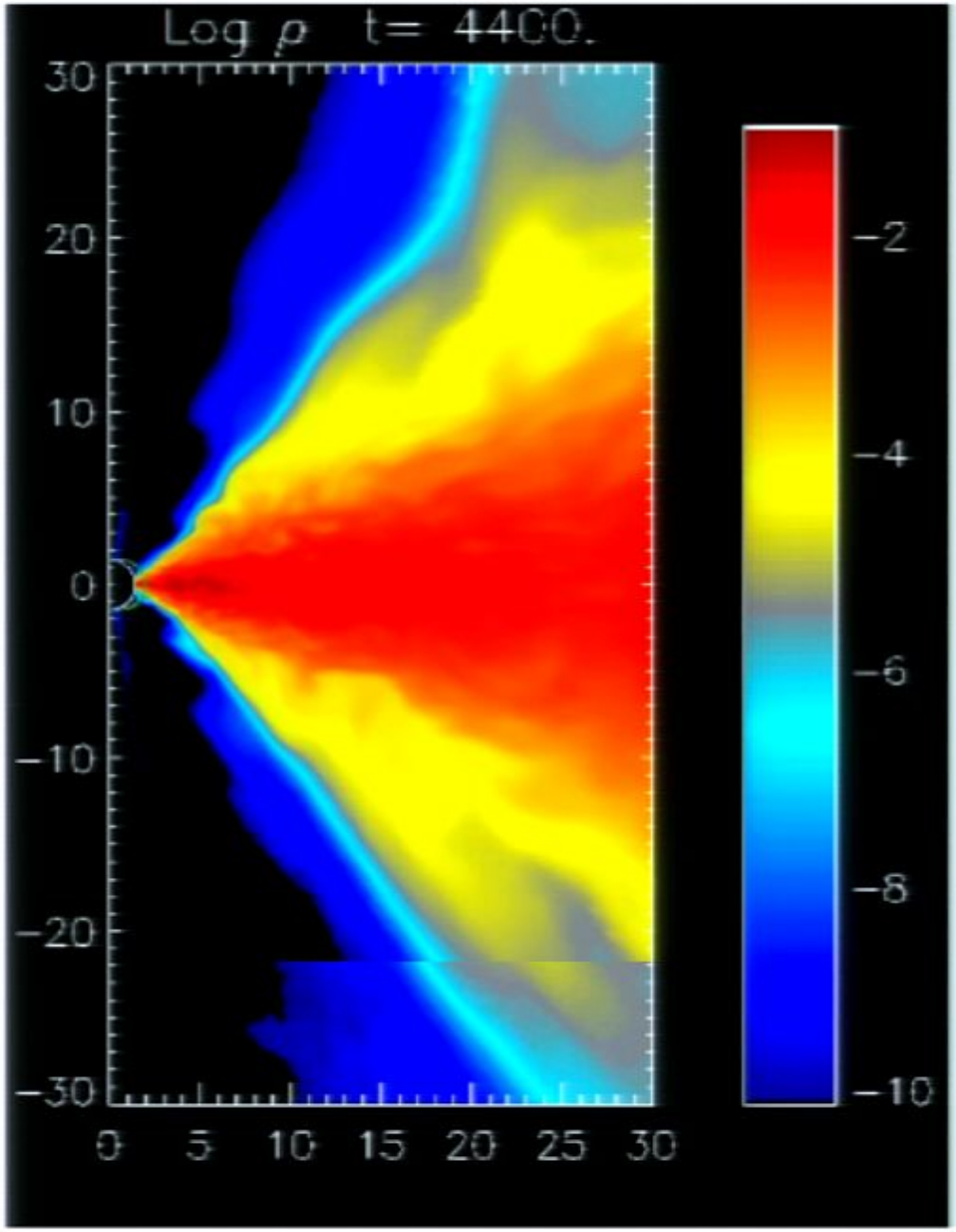

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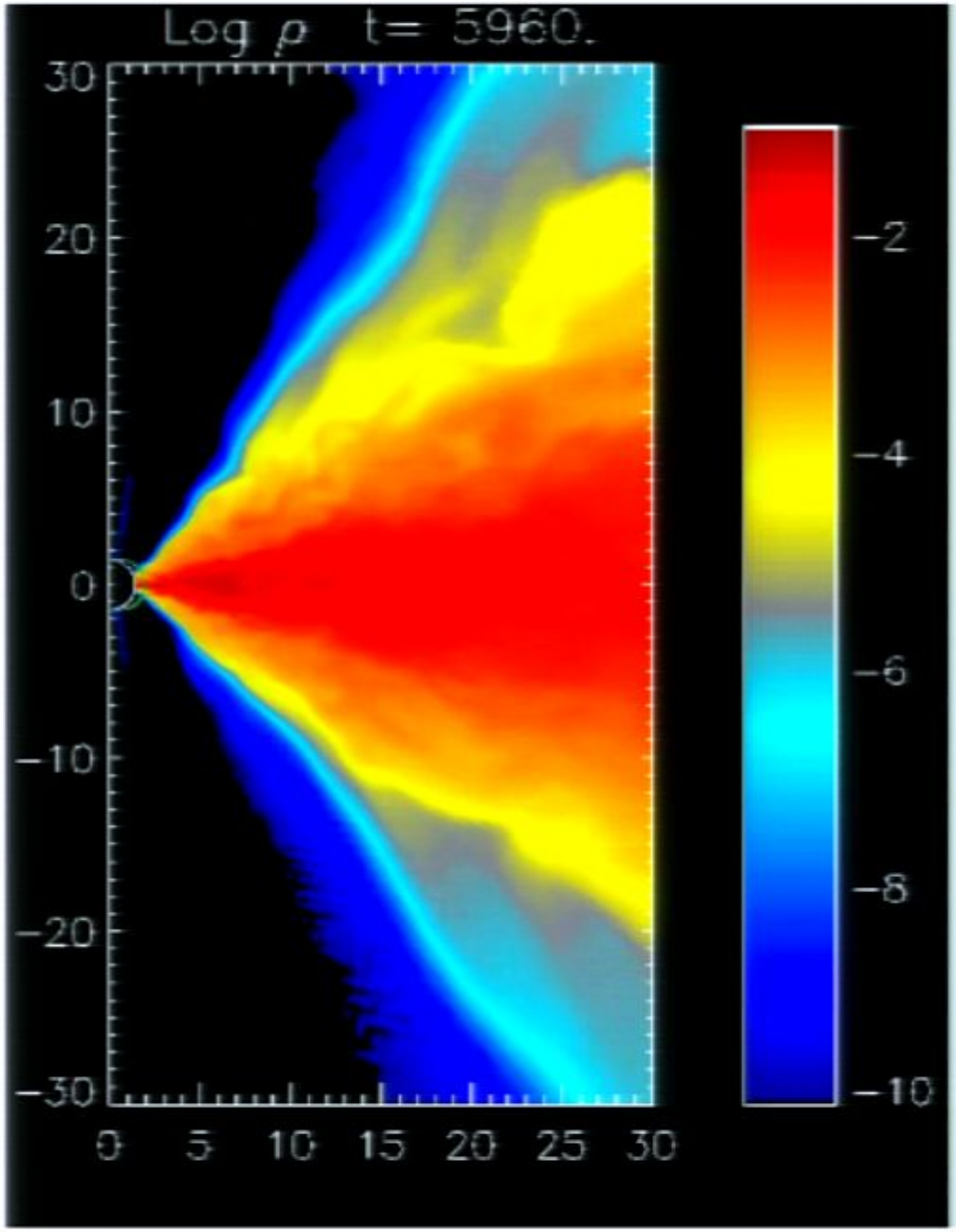

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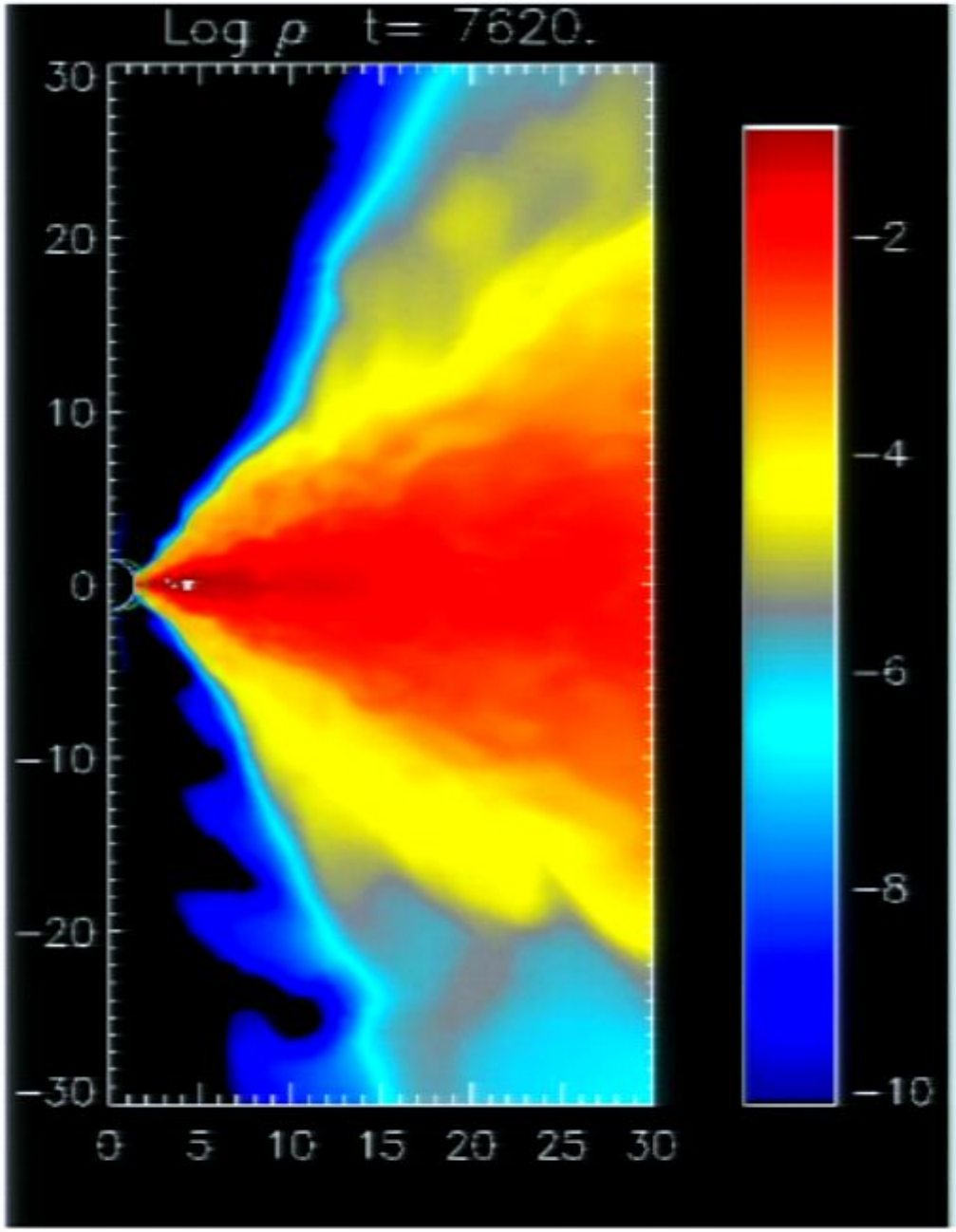

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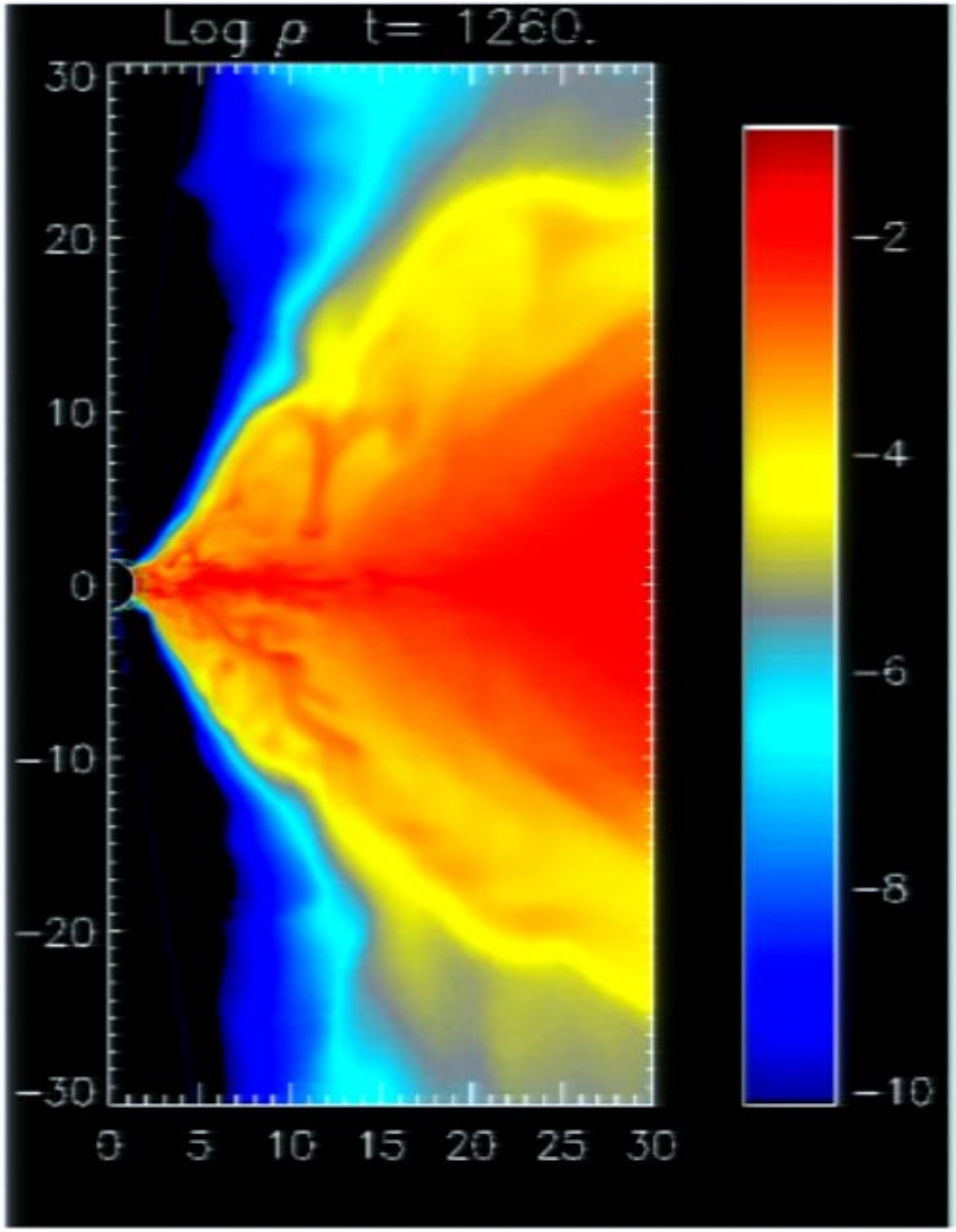

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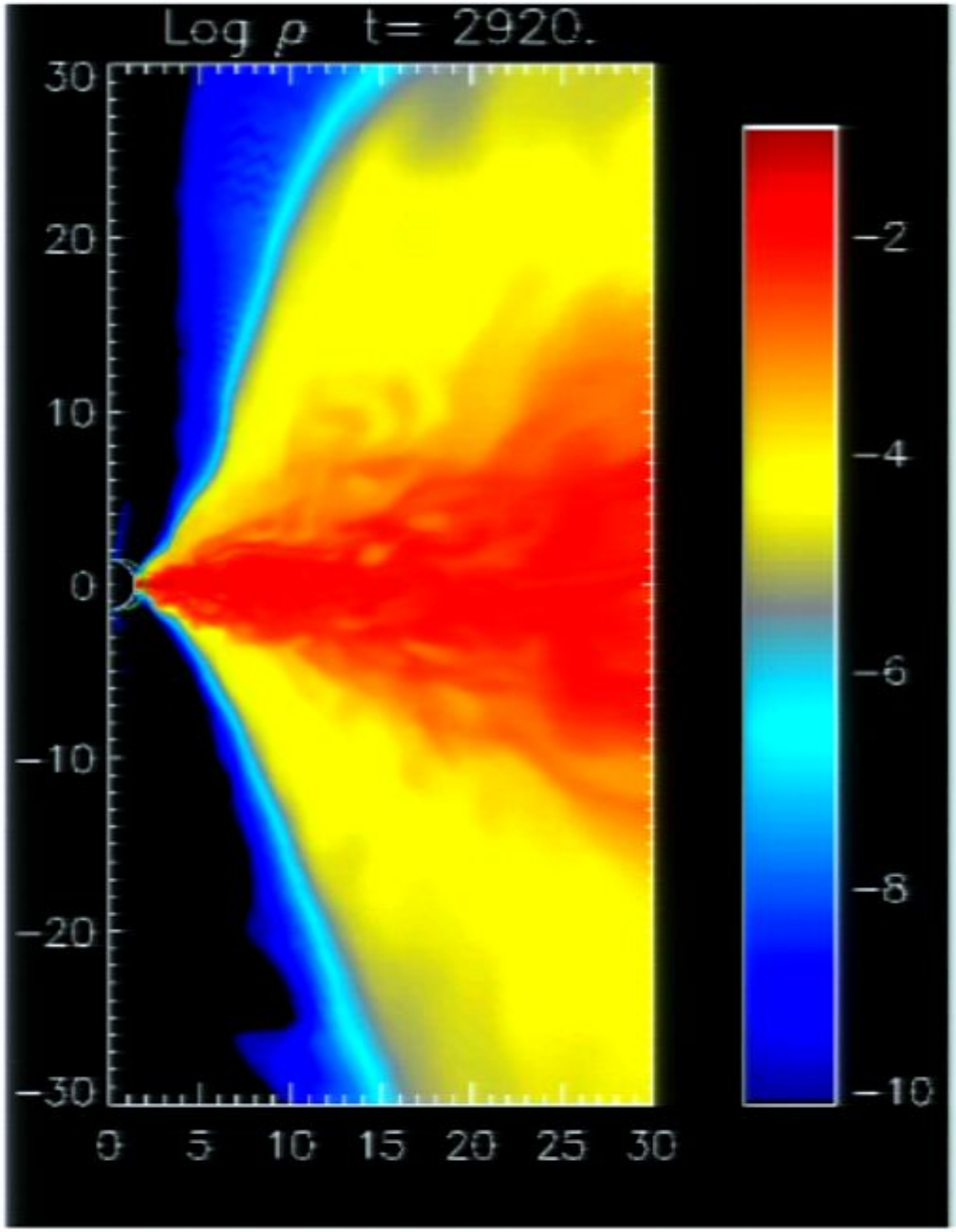

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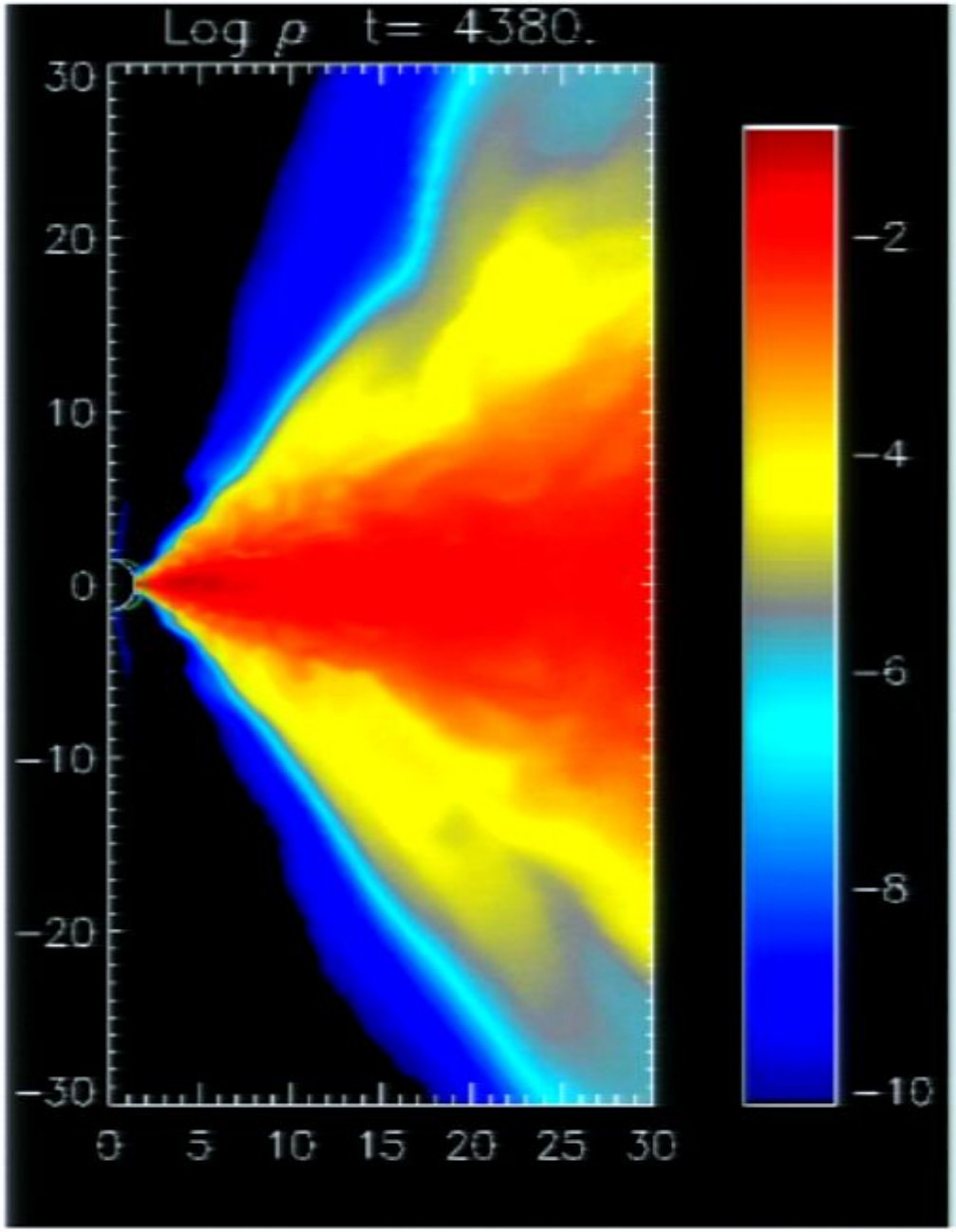

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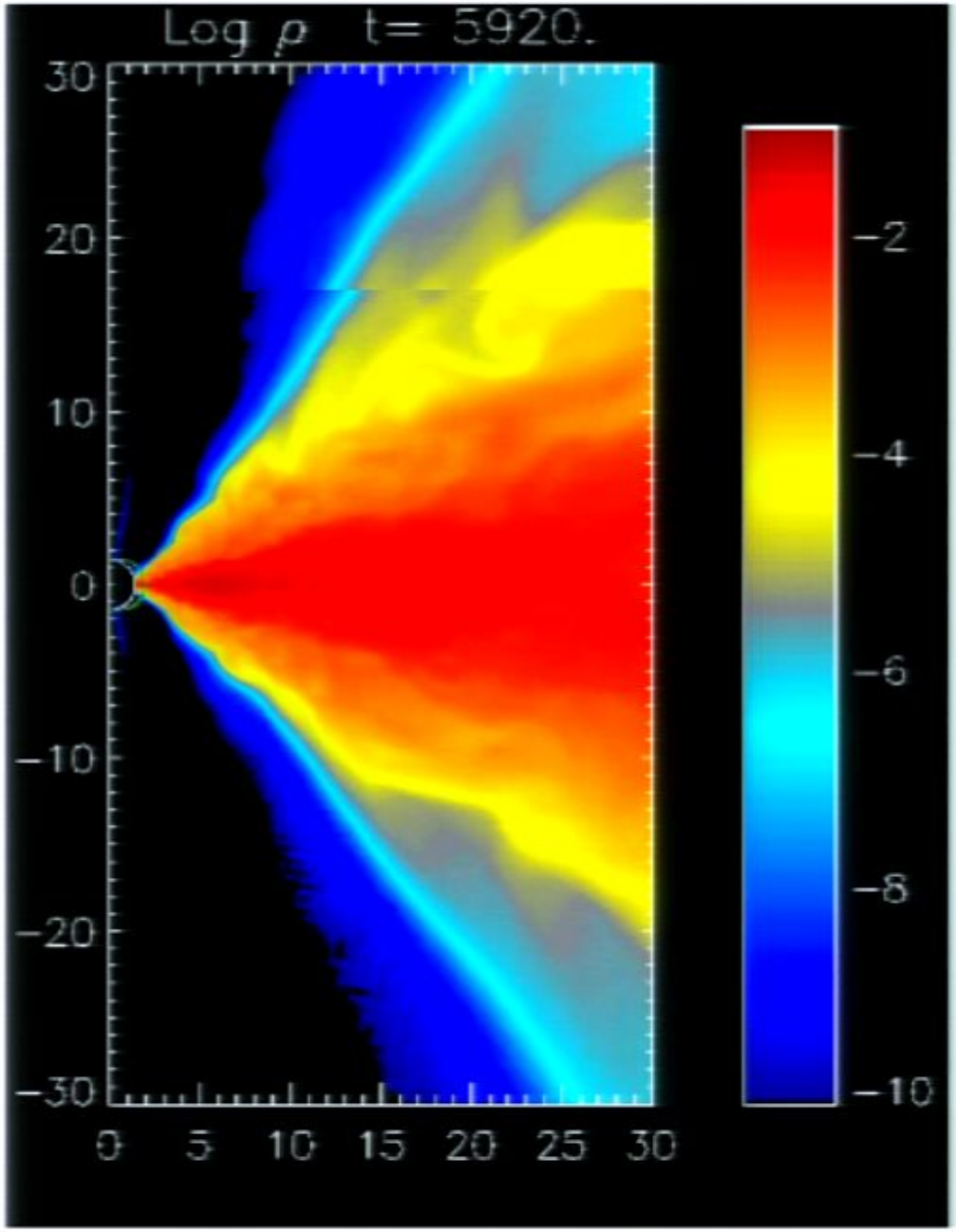

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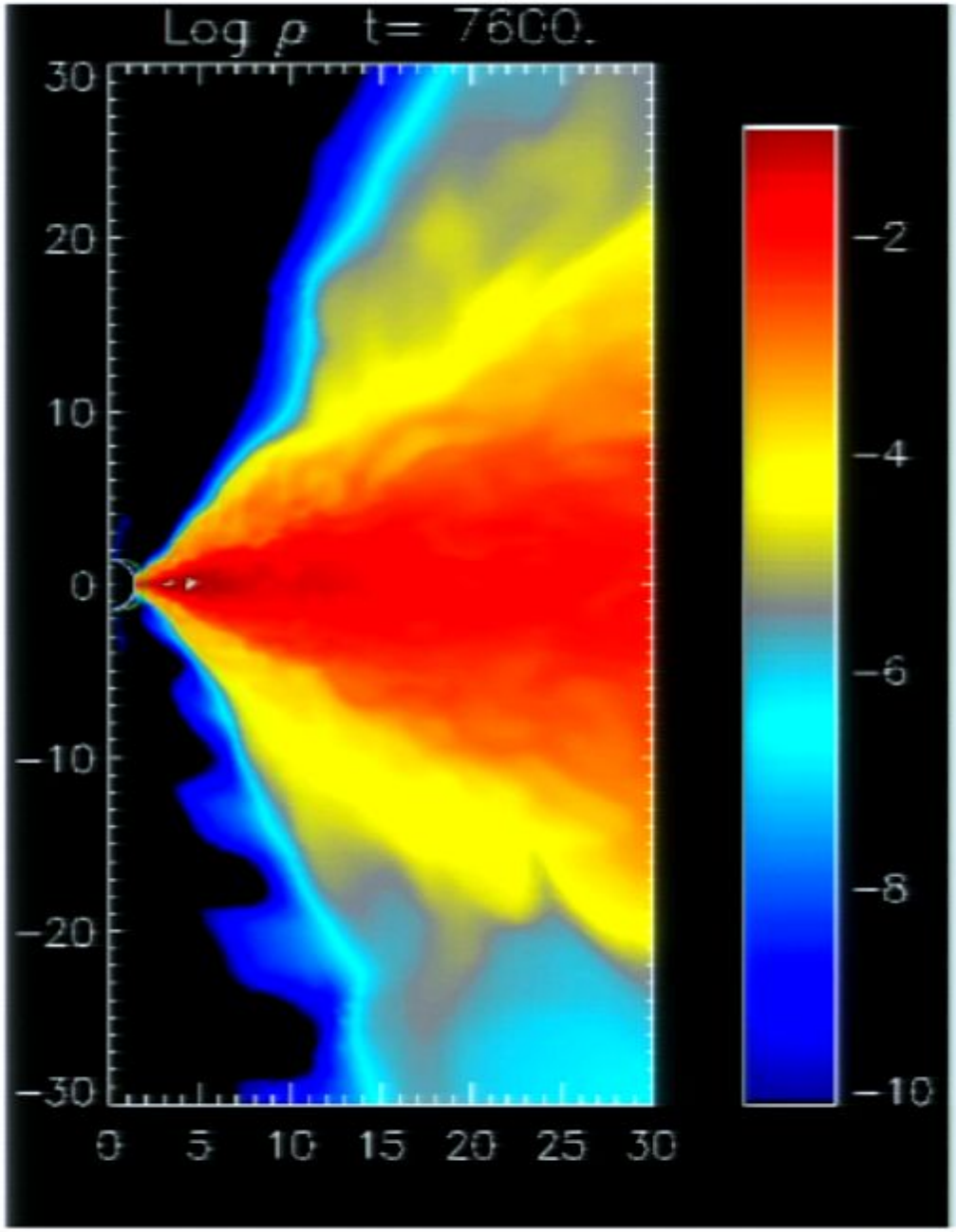

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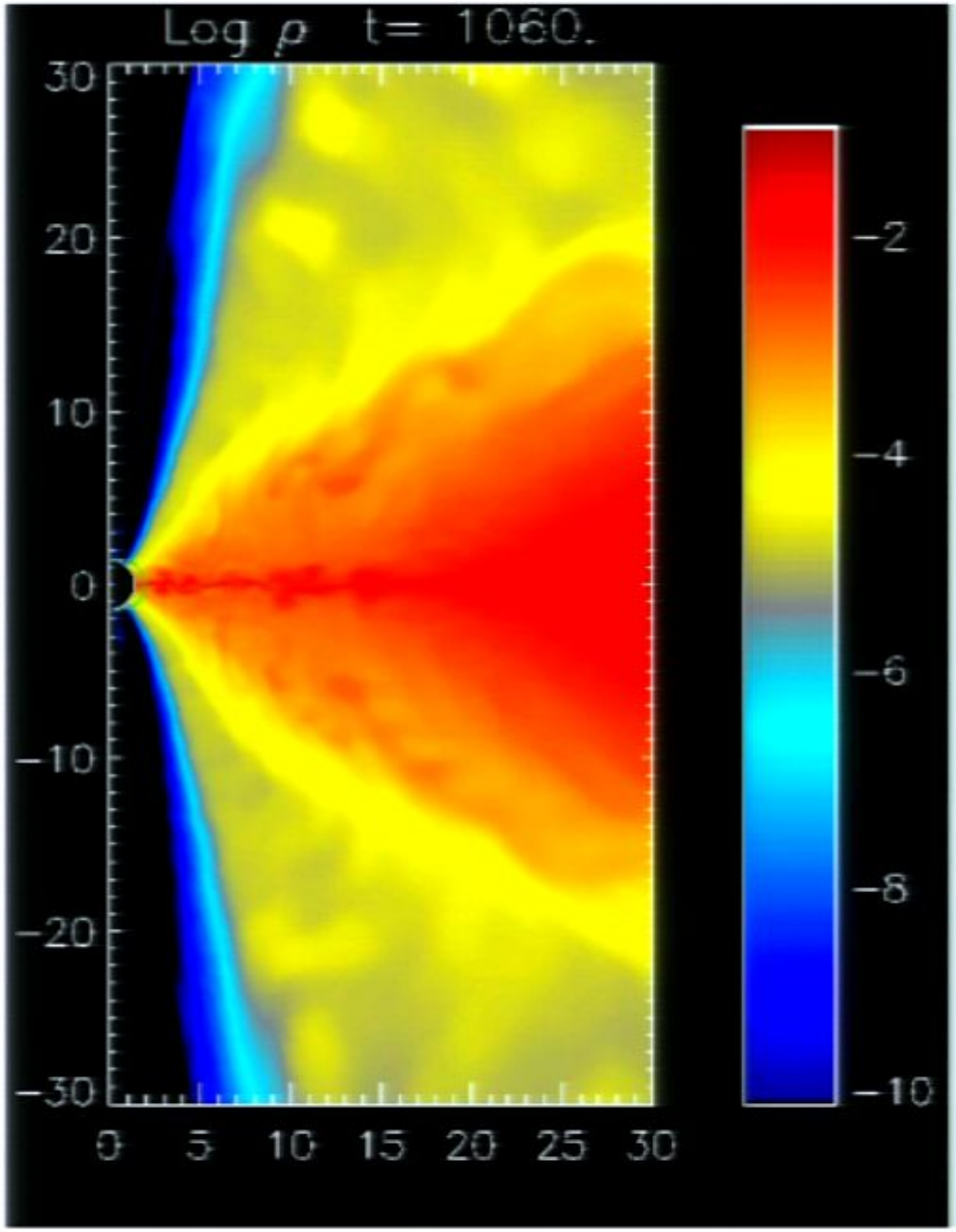

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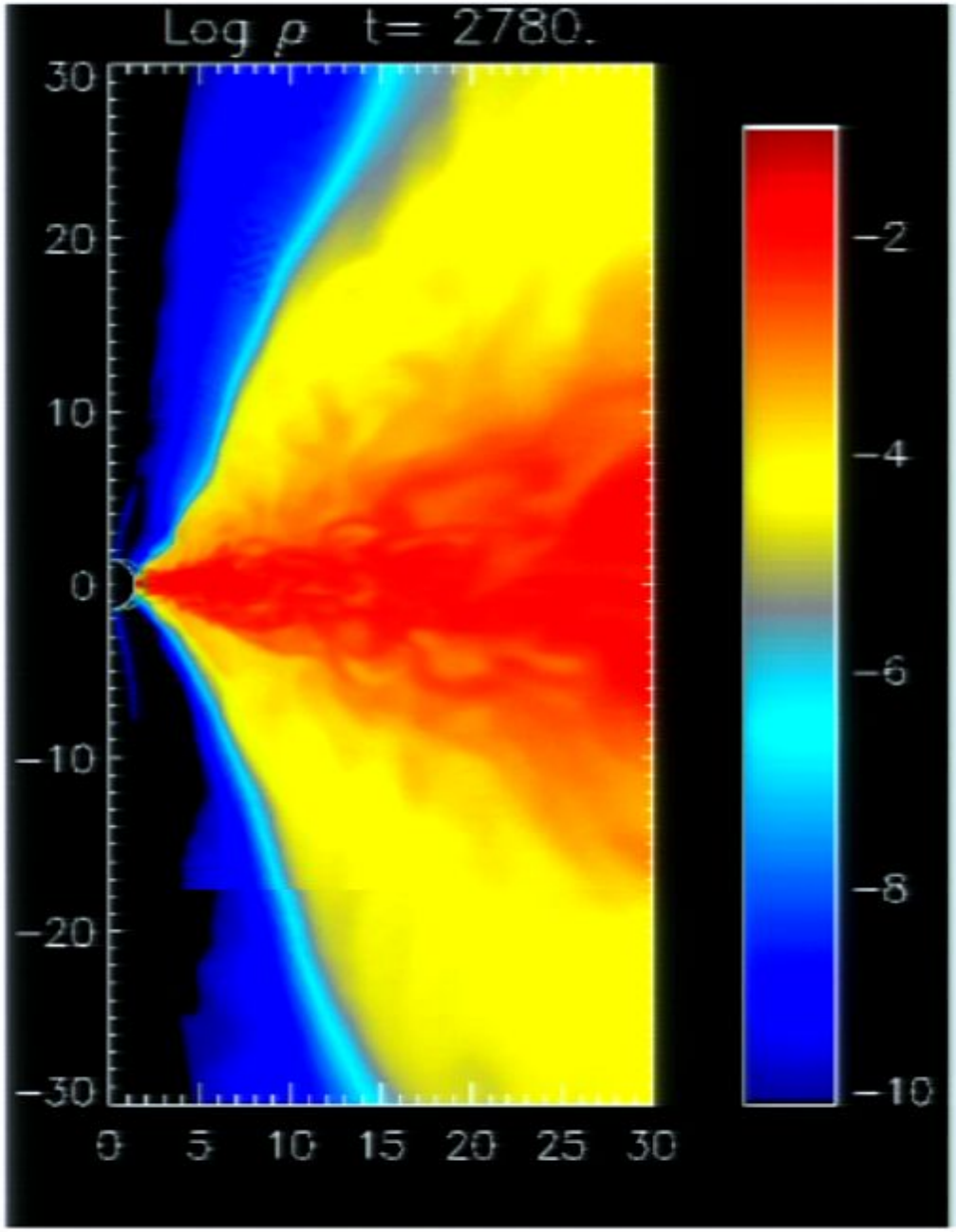

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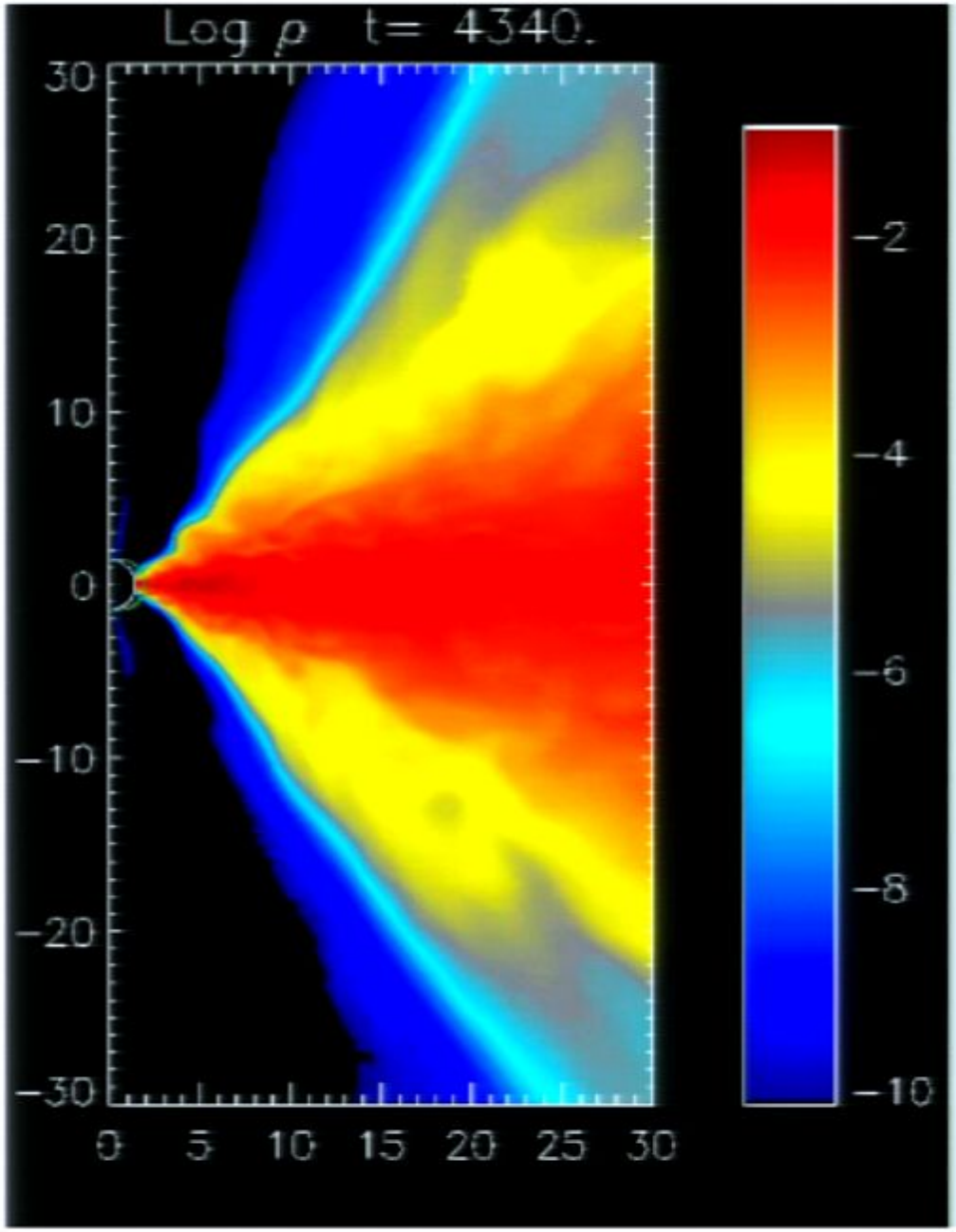

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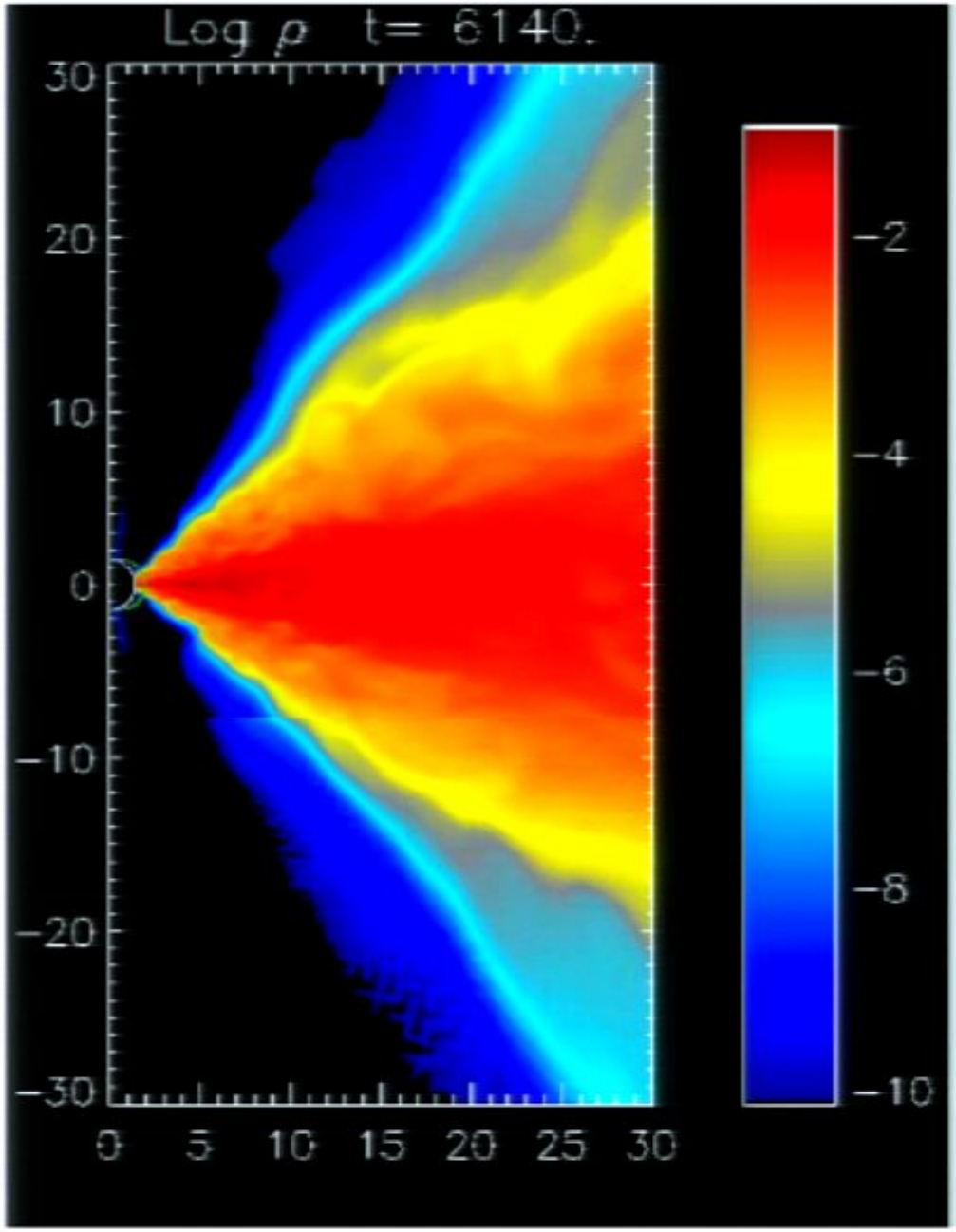
Evolution of Neutrino Cooled Disks



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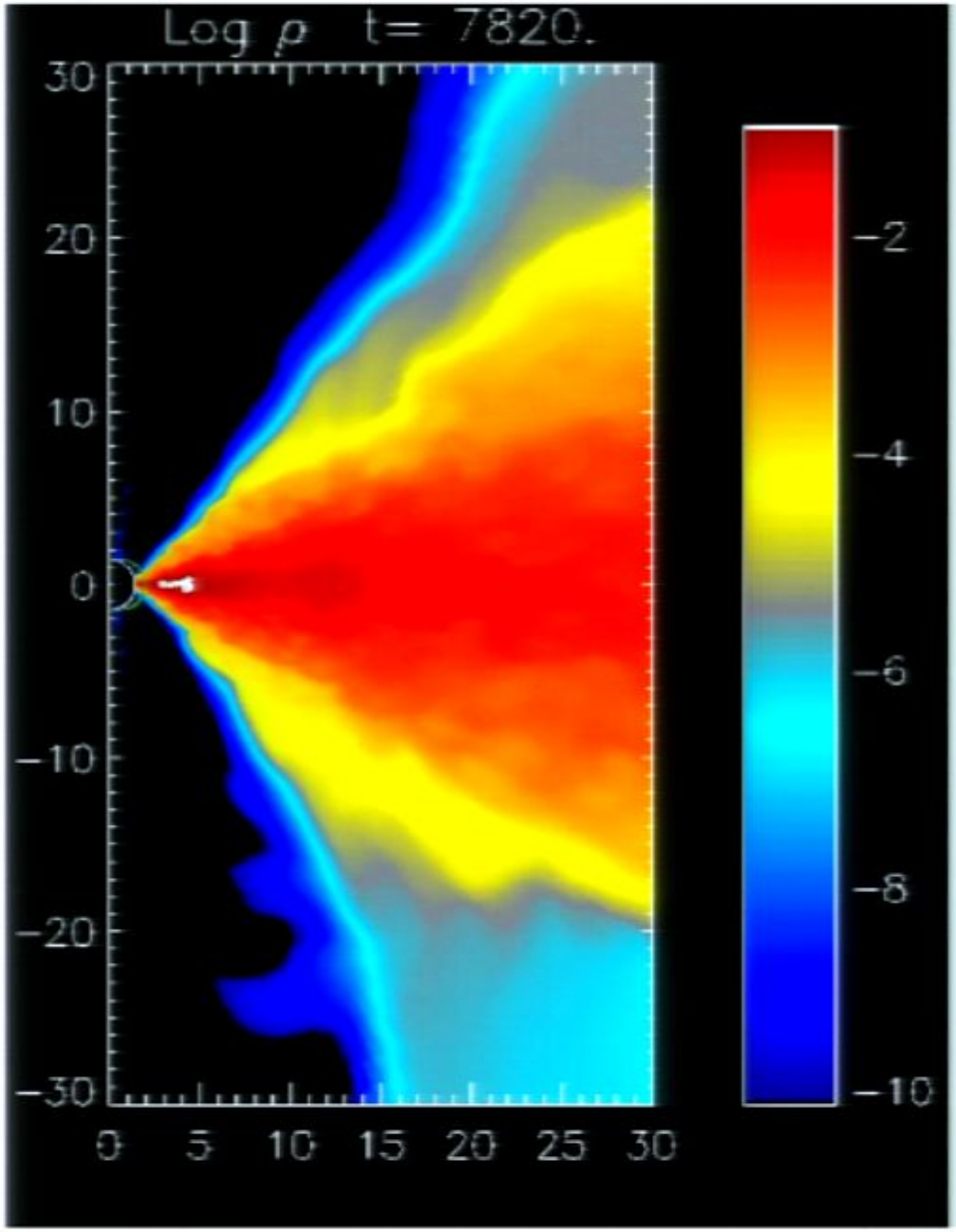

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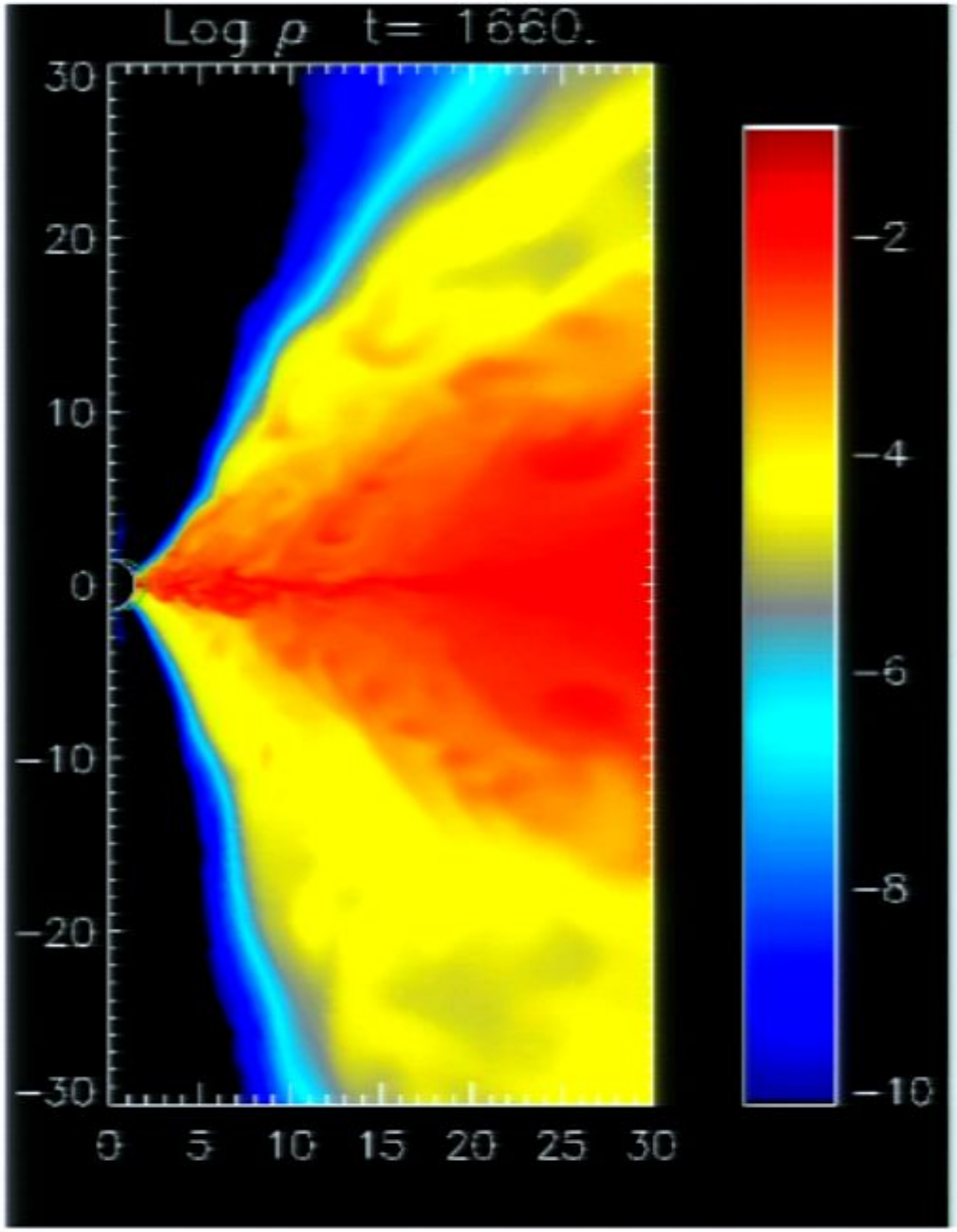

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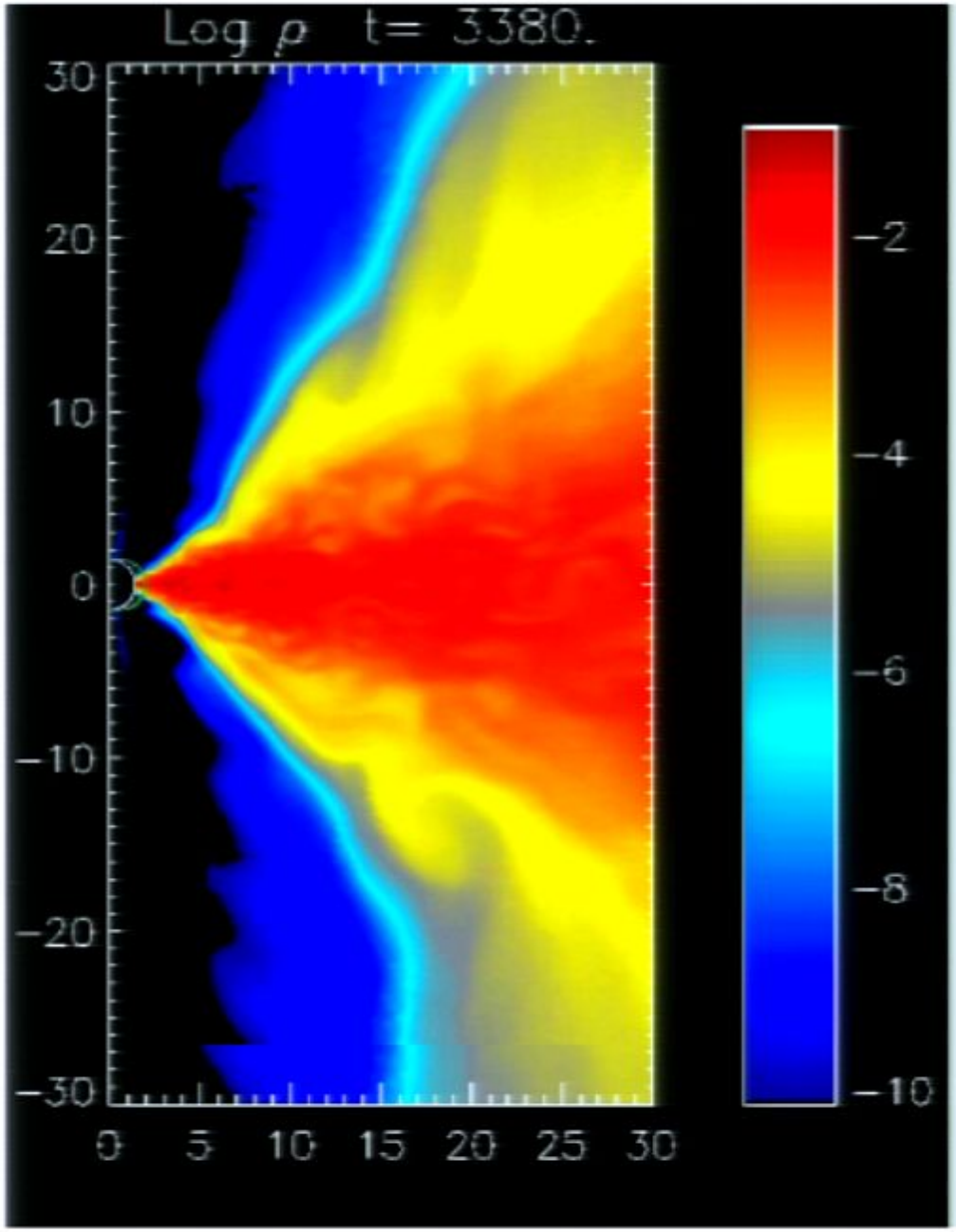

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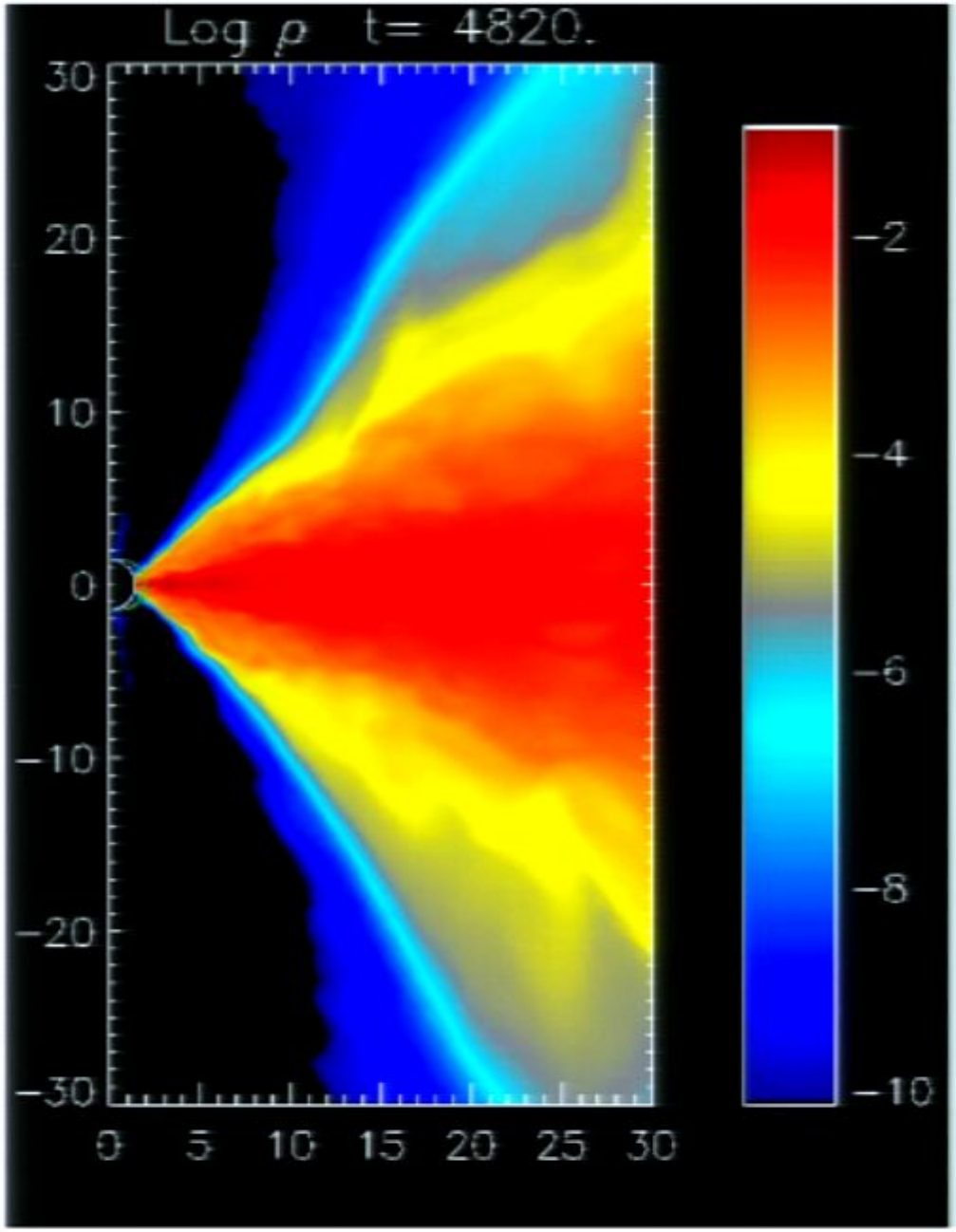

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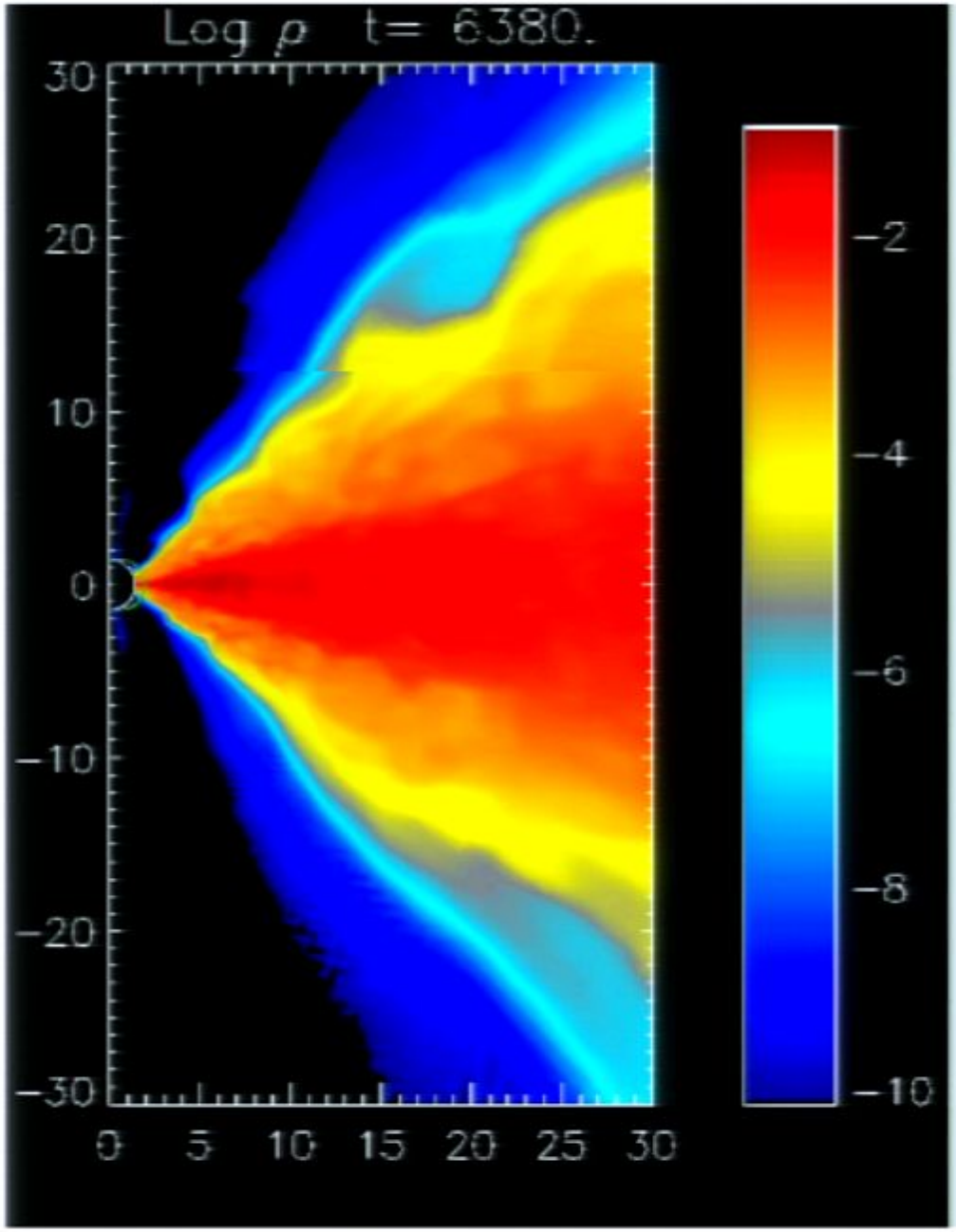
Evolution of Neutrino Cooled Disks



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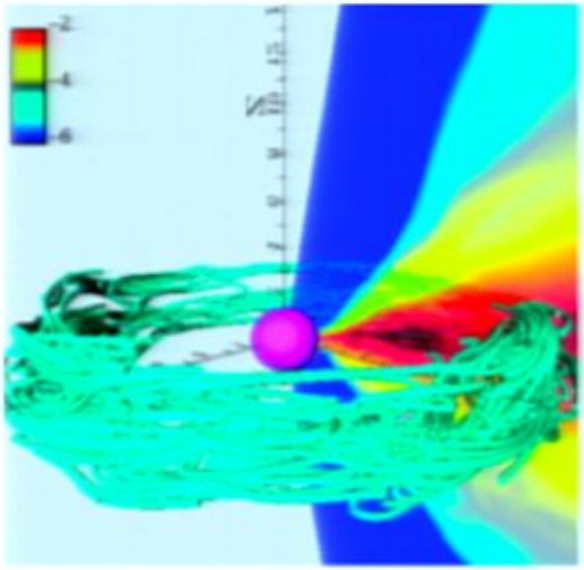
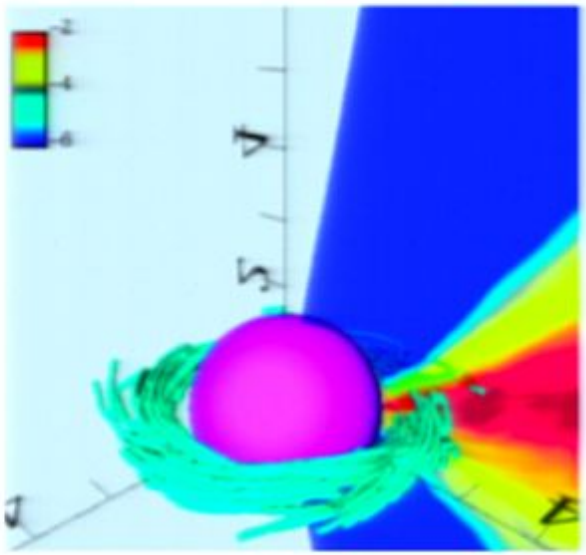
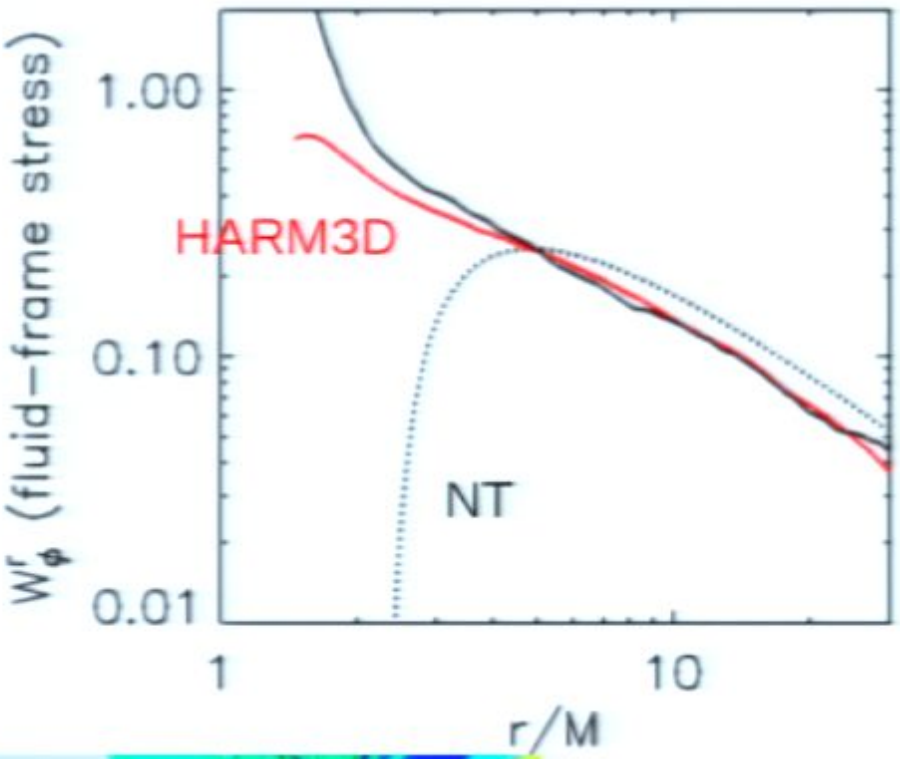
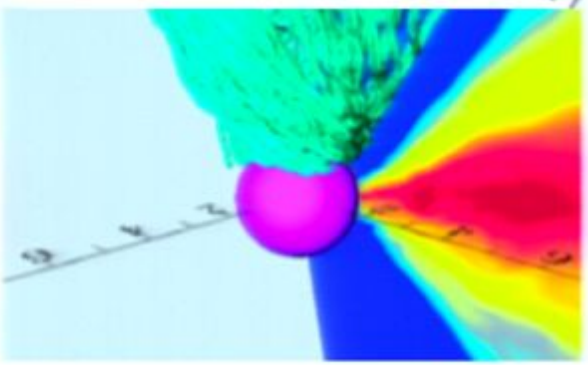
Dynamical Global Disk Models





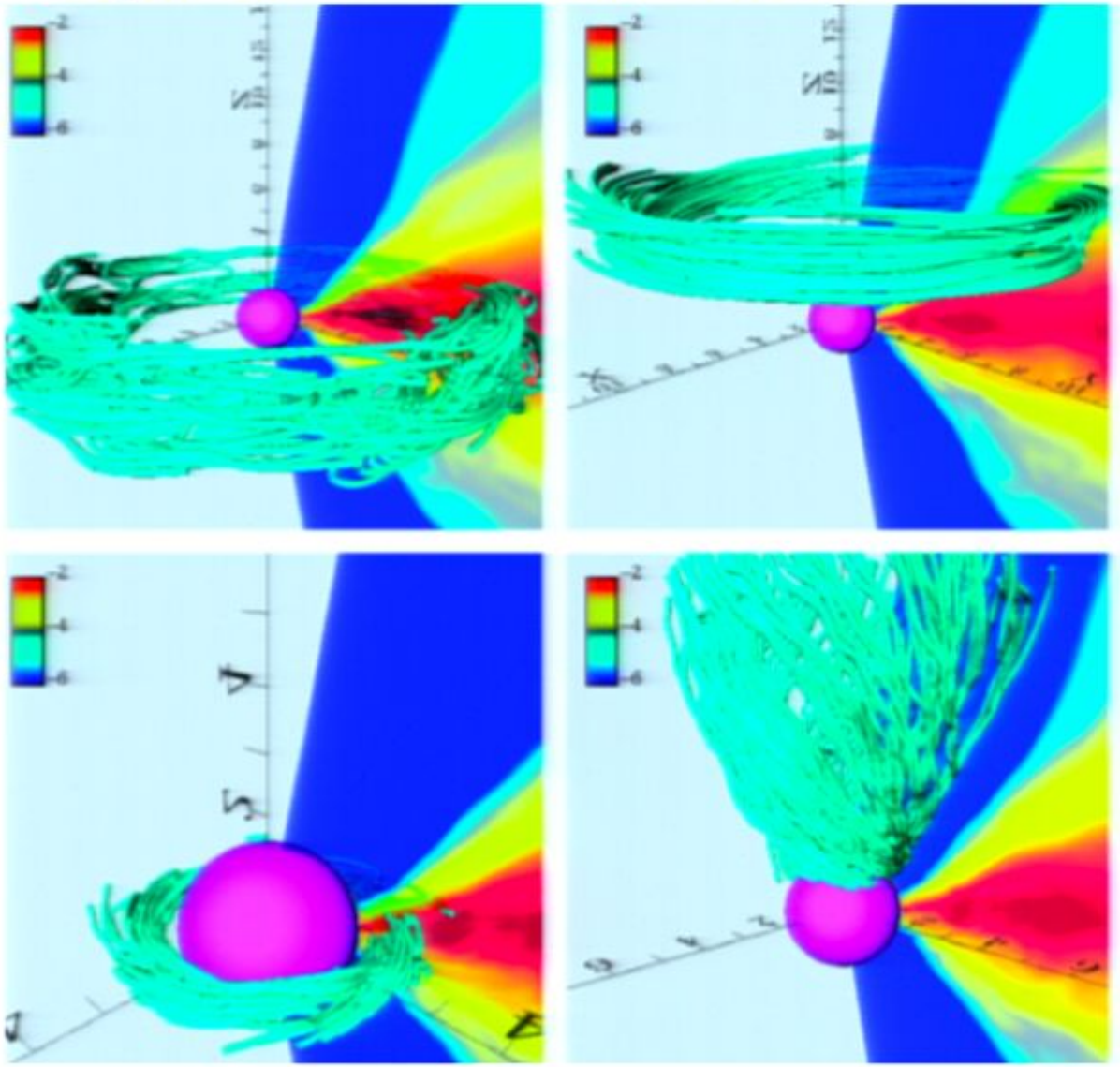




[Courtesy of D. Villiers]

- MRI develops from weak initial field
- Significant field within ISCO up to the horizon

Dynamical Global Disk Models



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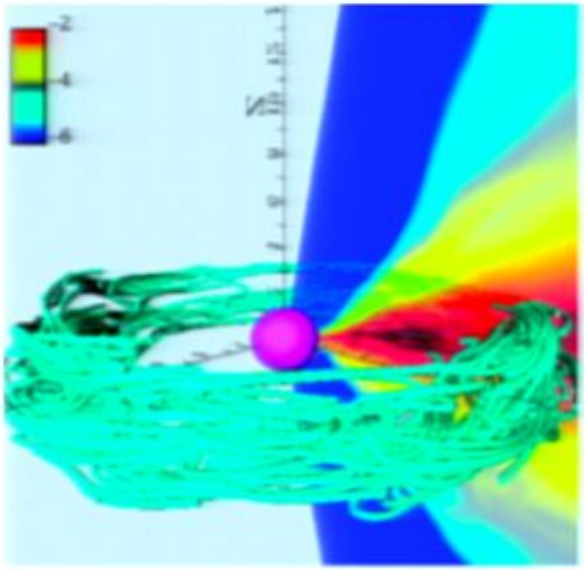
Prospects: *Central Engine*

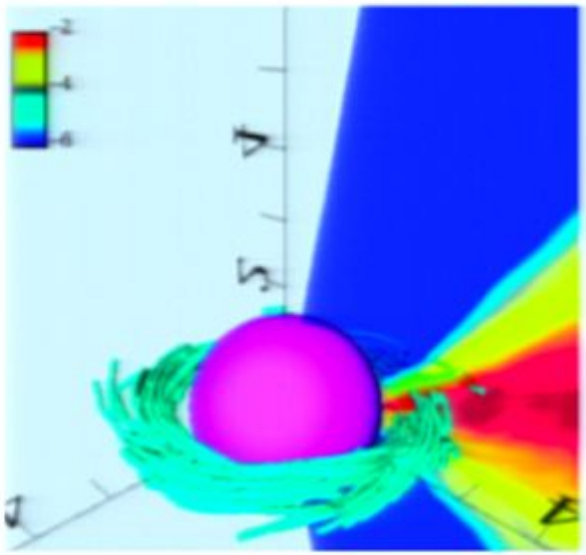
•An understanding of the nature of these sources is thus inextricably linked to the "metabolic pathways" through which gravity, spin, and energy can combine to form collimated, ultra-relativistic outflows.

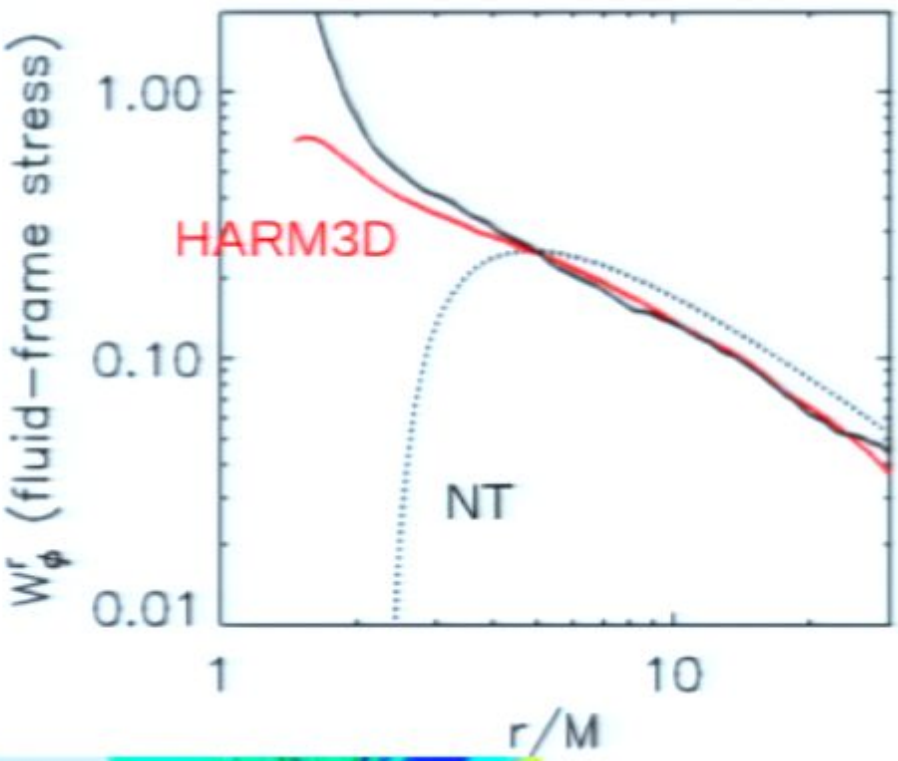
• Our eventual aim must be to understand the overall flow pattern around a central compact object, involving accretion, rotation, and directional outflow, but we are still far from achieving this.

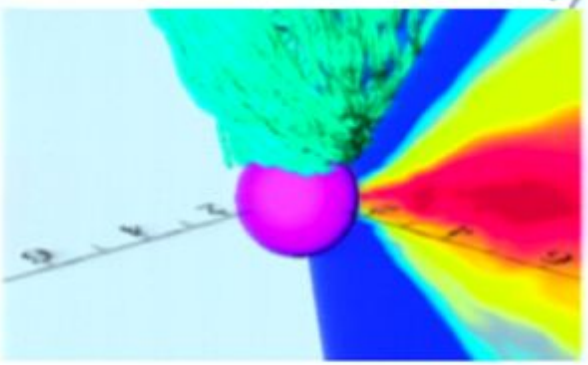
•A self-consistent model incorporating outflow and inflow must explain why some fraction of the matter can acquire a disproportionate share of energy.

Dynamical Global Disk Models









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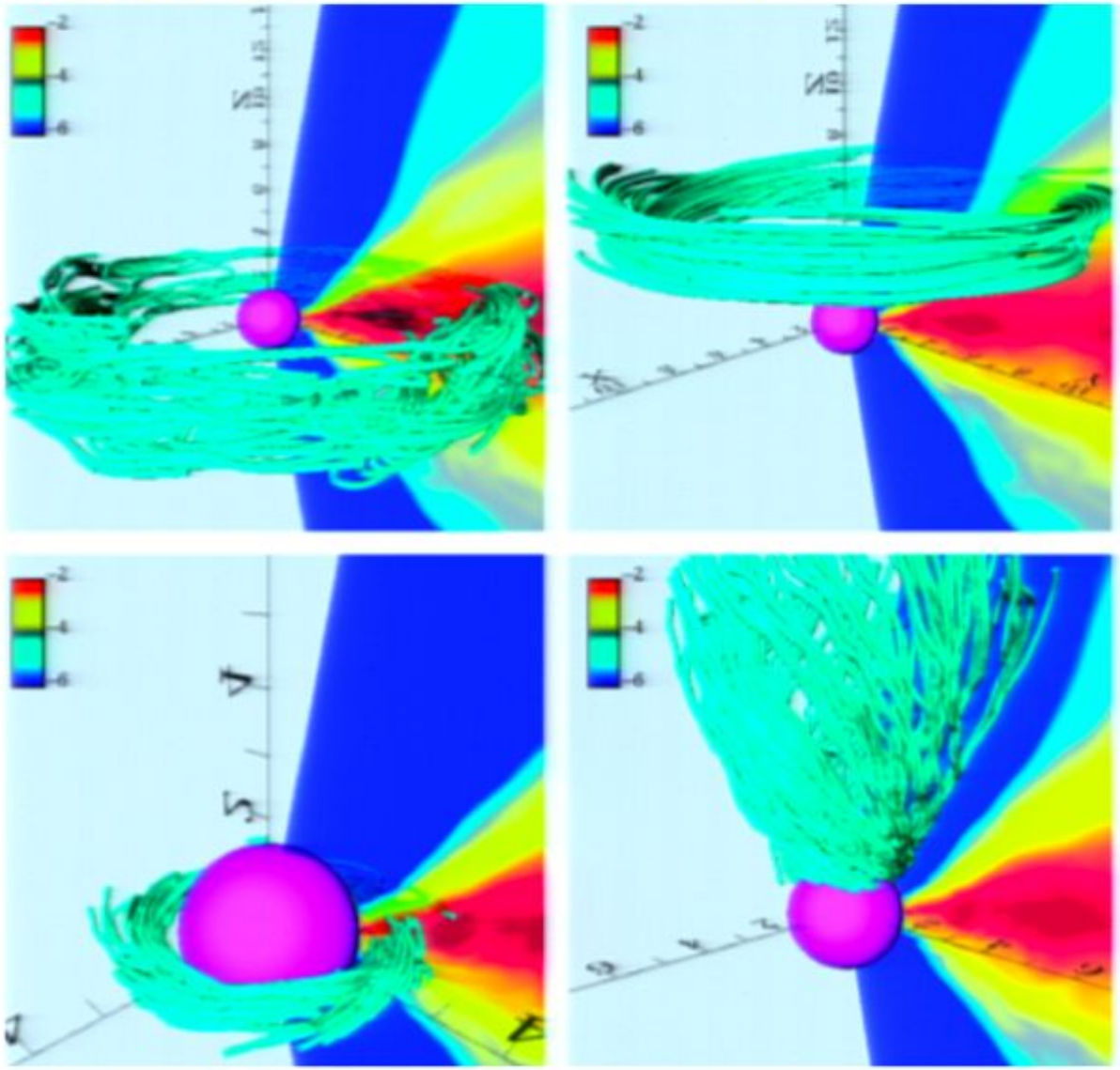

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