Multiscale relativistic jets modelling with FLASH-HARM joint simulations.

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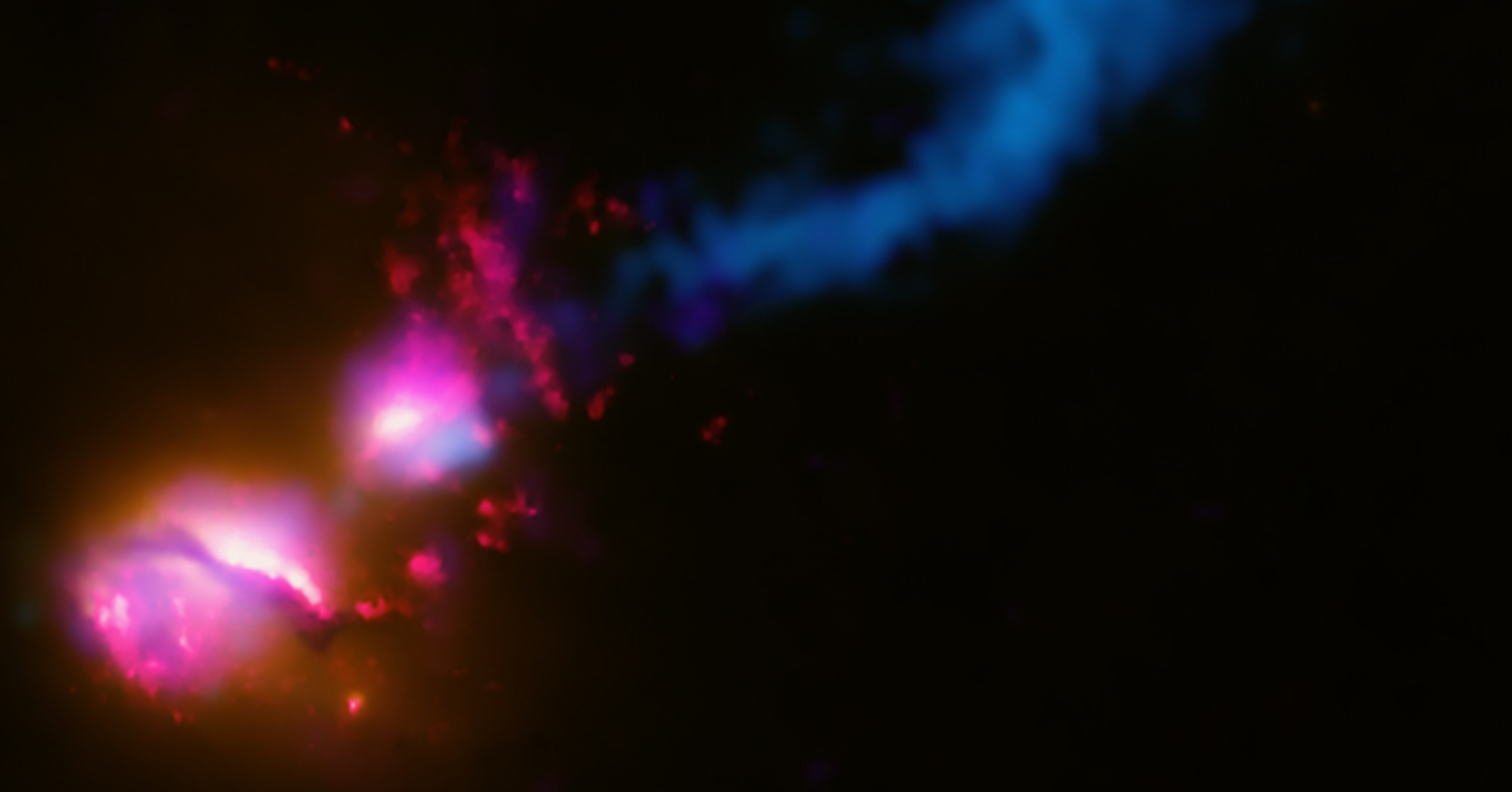

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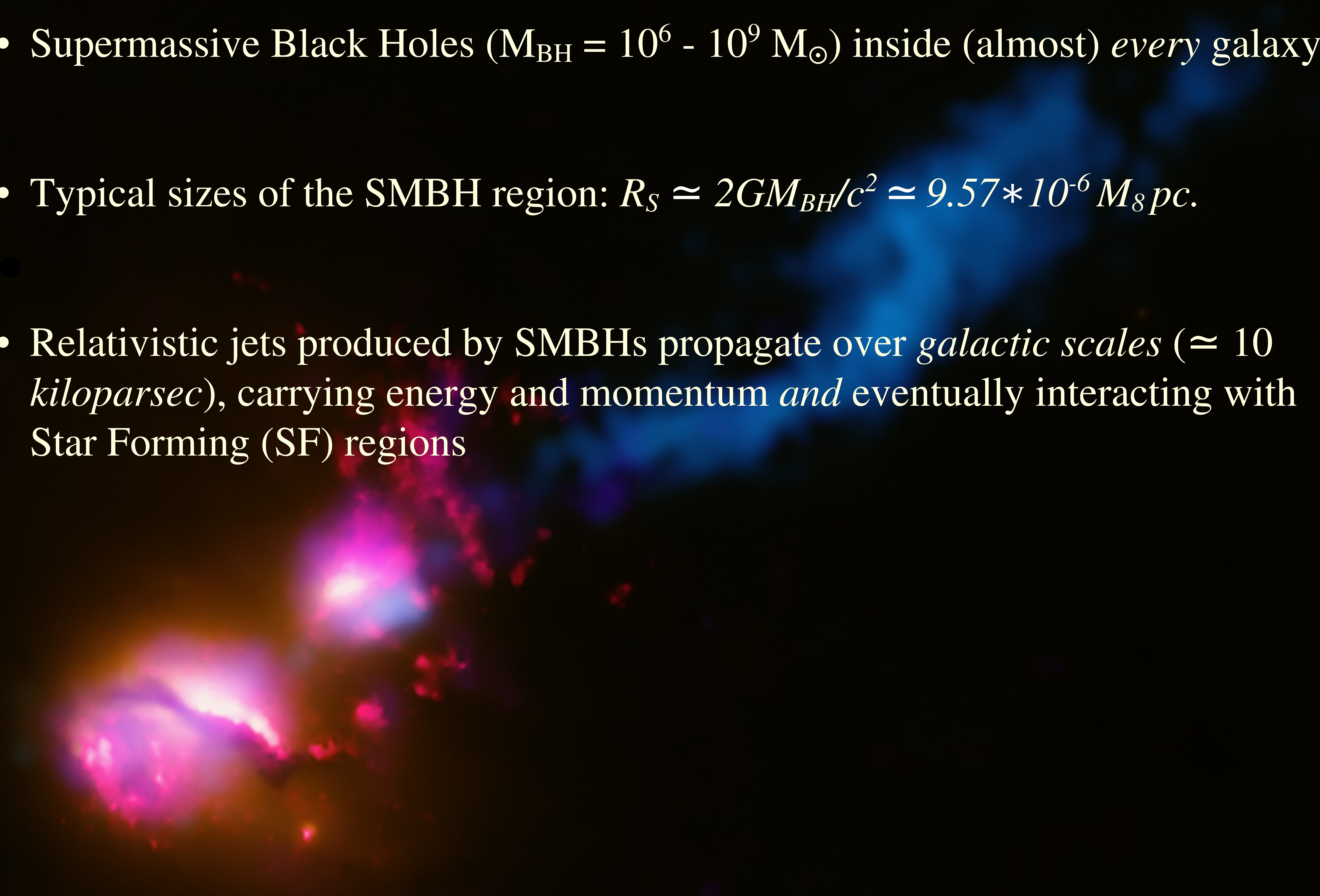

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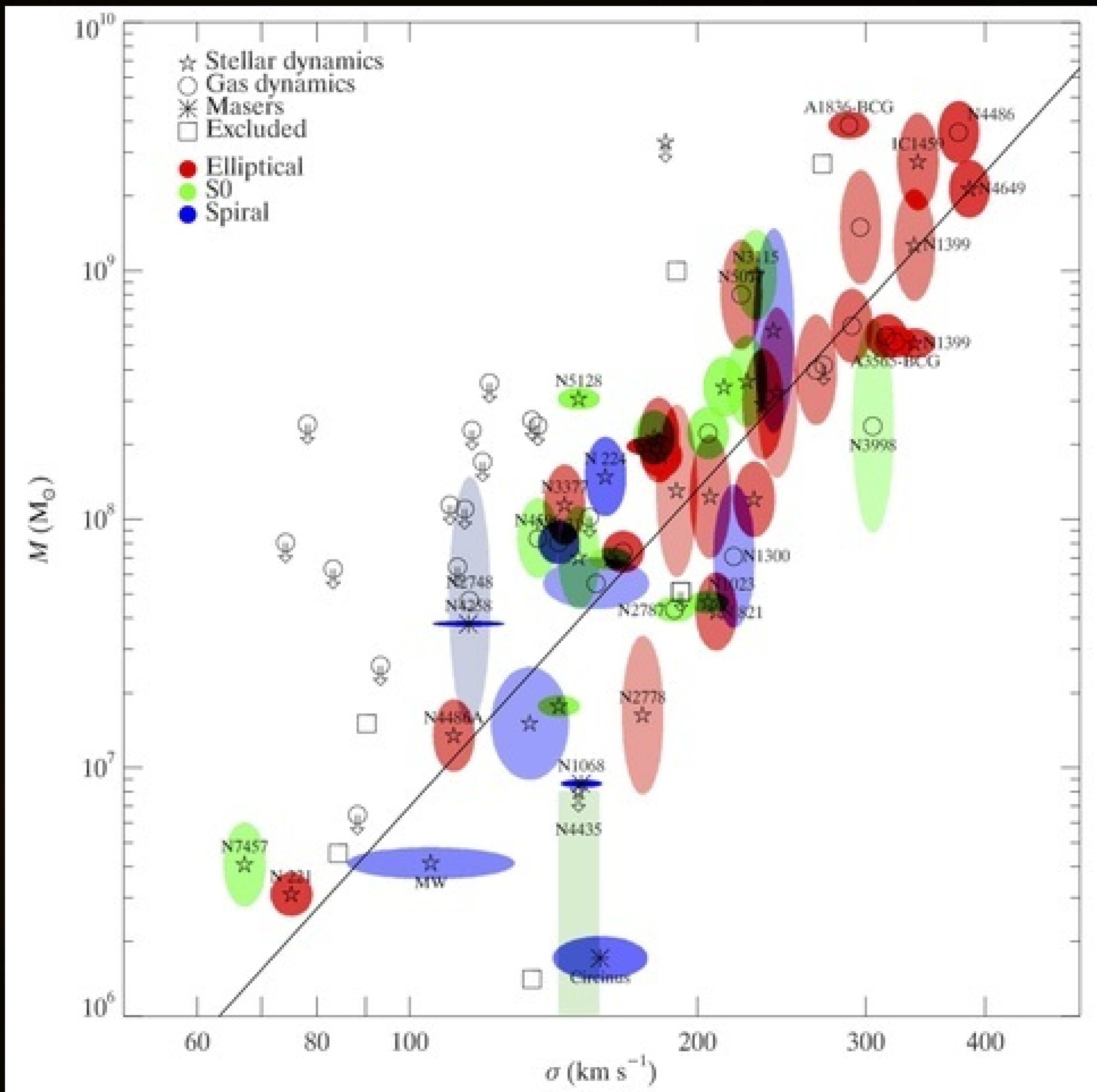
- $\sigma_g = \langle v_*^2 \rangle \propto GM/R_g$ (a *proxy* for total [stellar+dark matter] mass within R_g .



- SMBHs mass is phenomenologically tightly connected to those of their host galaxies.
  <u>Yet</u>, $R_{BH} = 2GM_{BH}/c^2 \approx 9.57{*}10^{-8}\, M_6$ pc $\ll R_g \approx 10^4$ pc

How can be possible that such a tight correlation arises when the spatial (and temporal) scales of SMBHs and stellar formation processes are so different?

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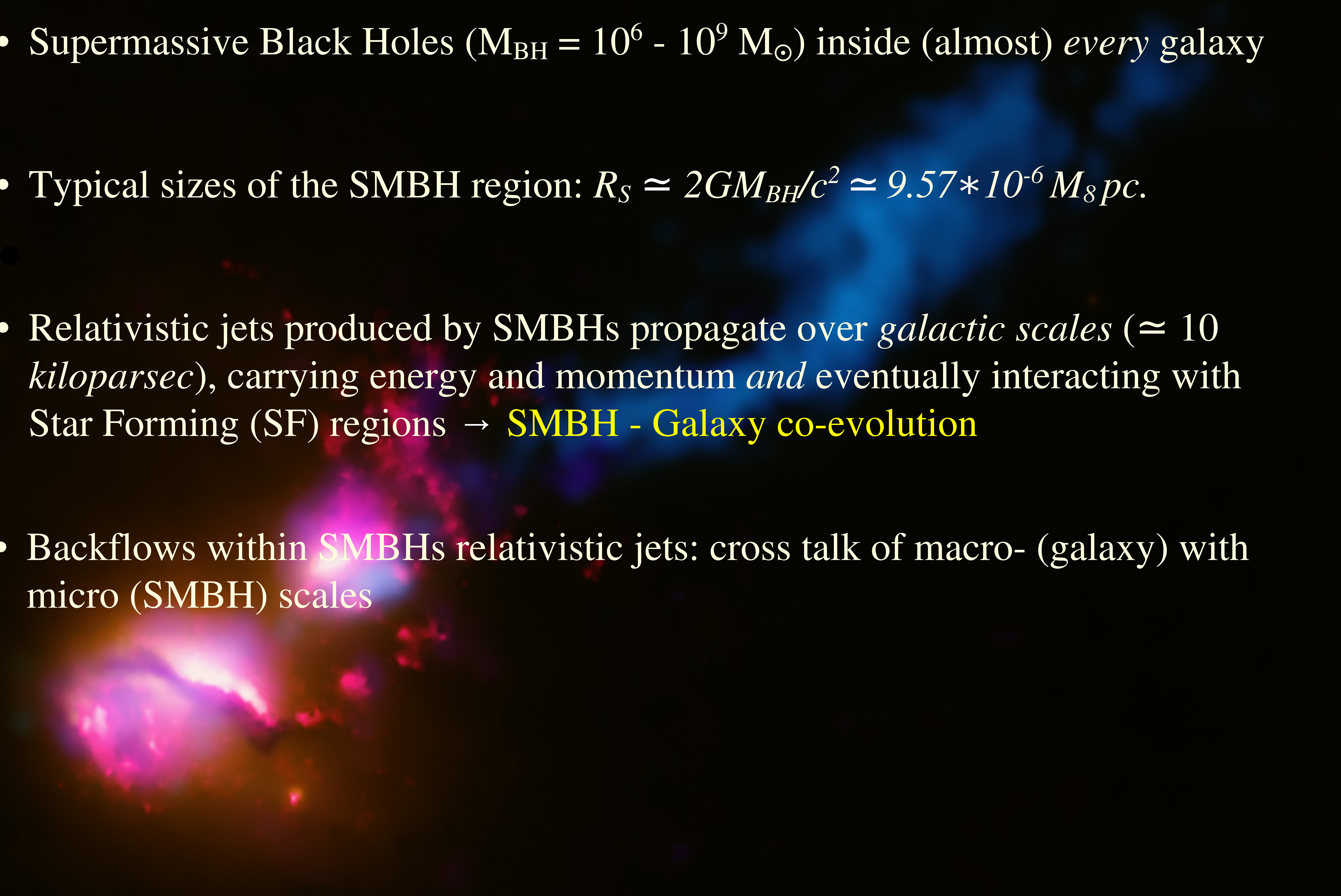

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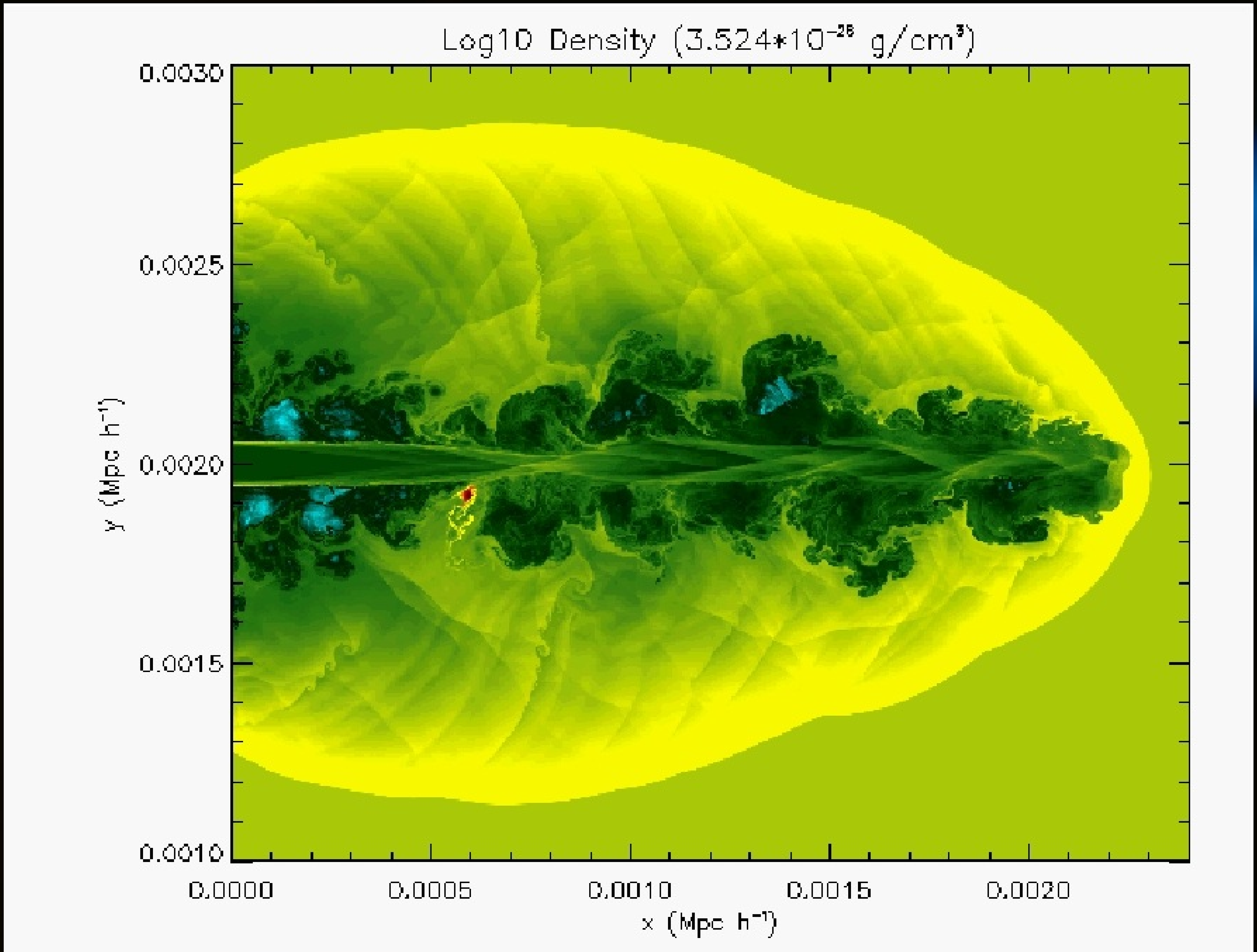
- Backflows within SMBHs relativistic jets: cross talk of macro- (galaxy) with micro (SMBH) scales

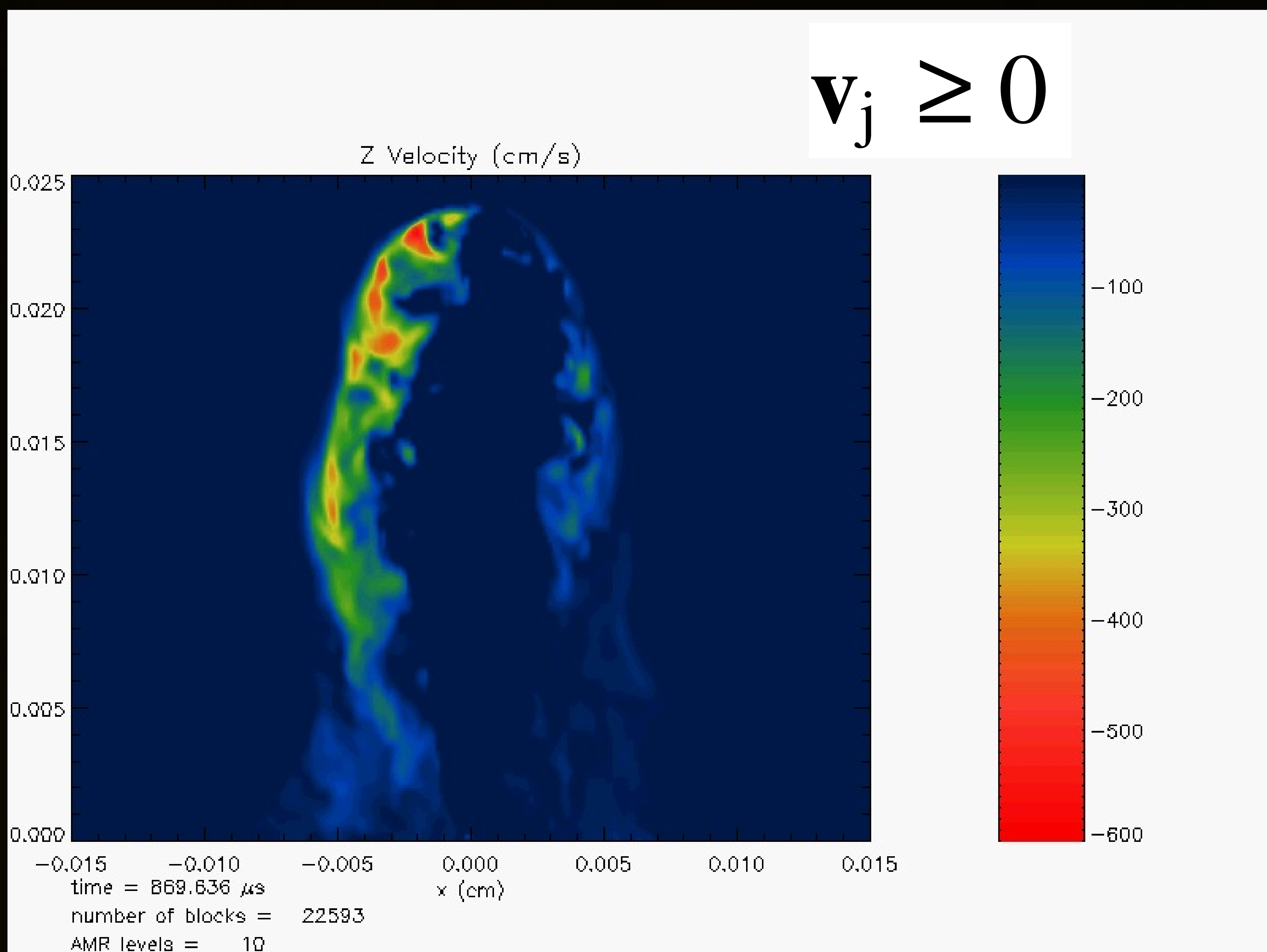
Jet propagation on galactic scales (FLASH)

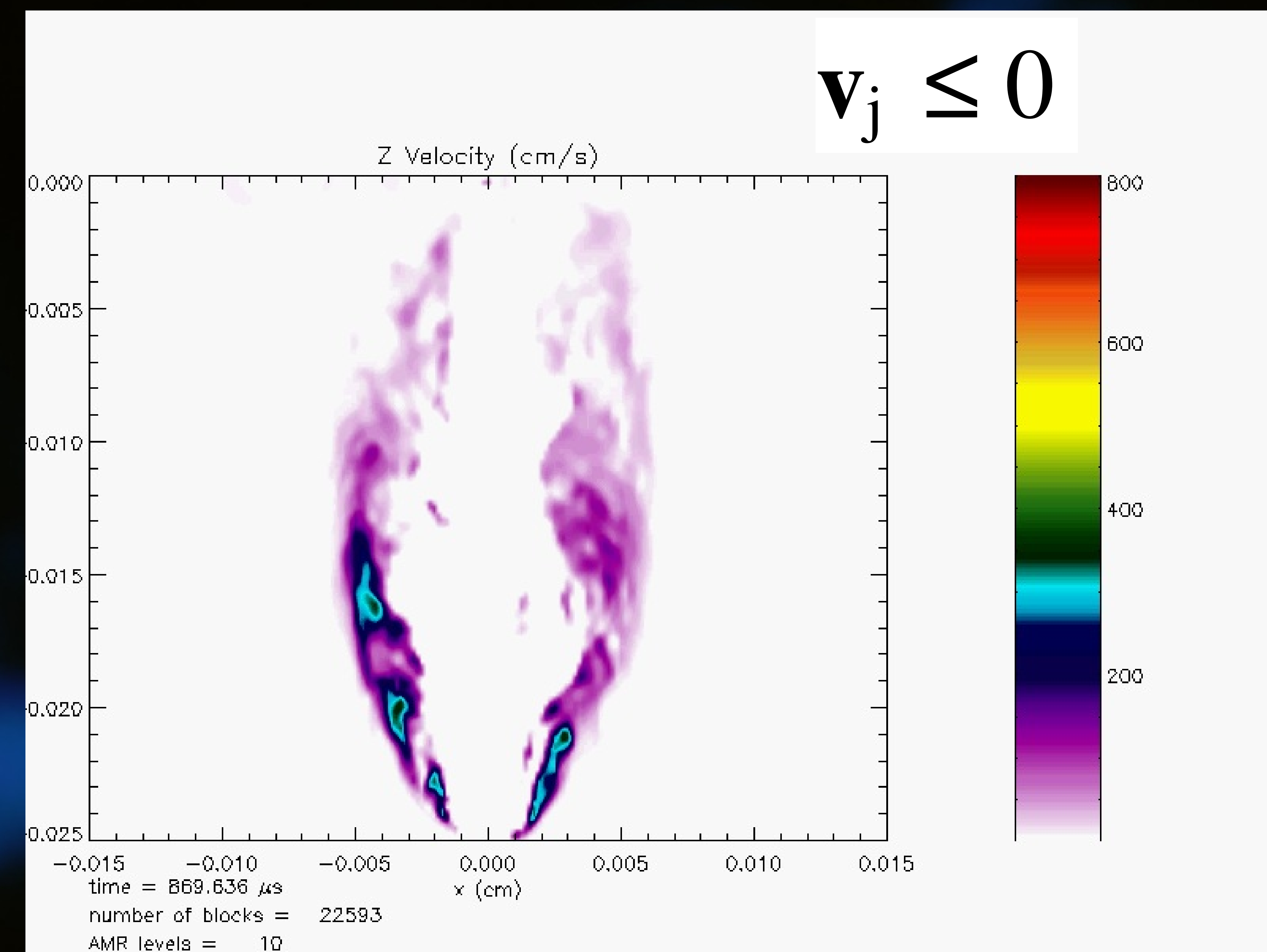


- Jets carve large cavities (*cocoons*) within the Interstellar Medium of the host galaxy, filling it with *hot* (10^6 - $10^{8.7}$ K), *low density* (10^{-1} - 10^{-6} e^- cm^{-3}) plasma → SF clouds (red) shocked and evaporated (*negative feedback*)

- Backflows (not visible here) develop

Backflows: gas flowing opposite to the main jet





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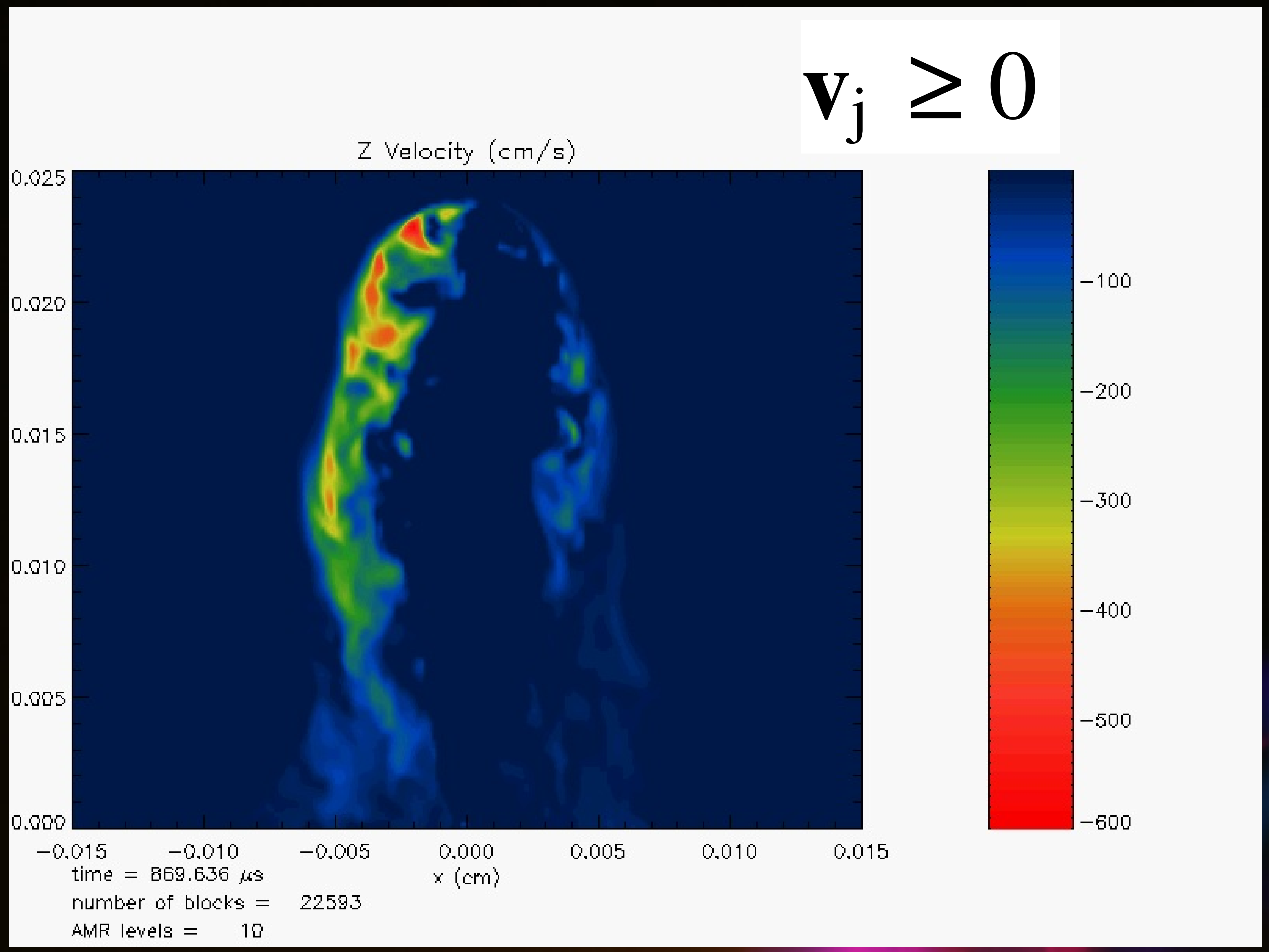

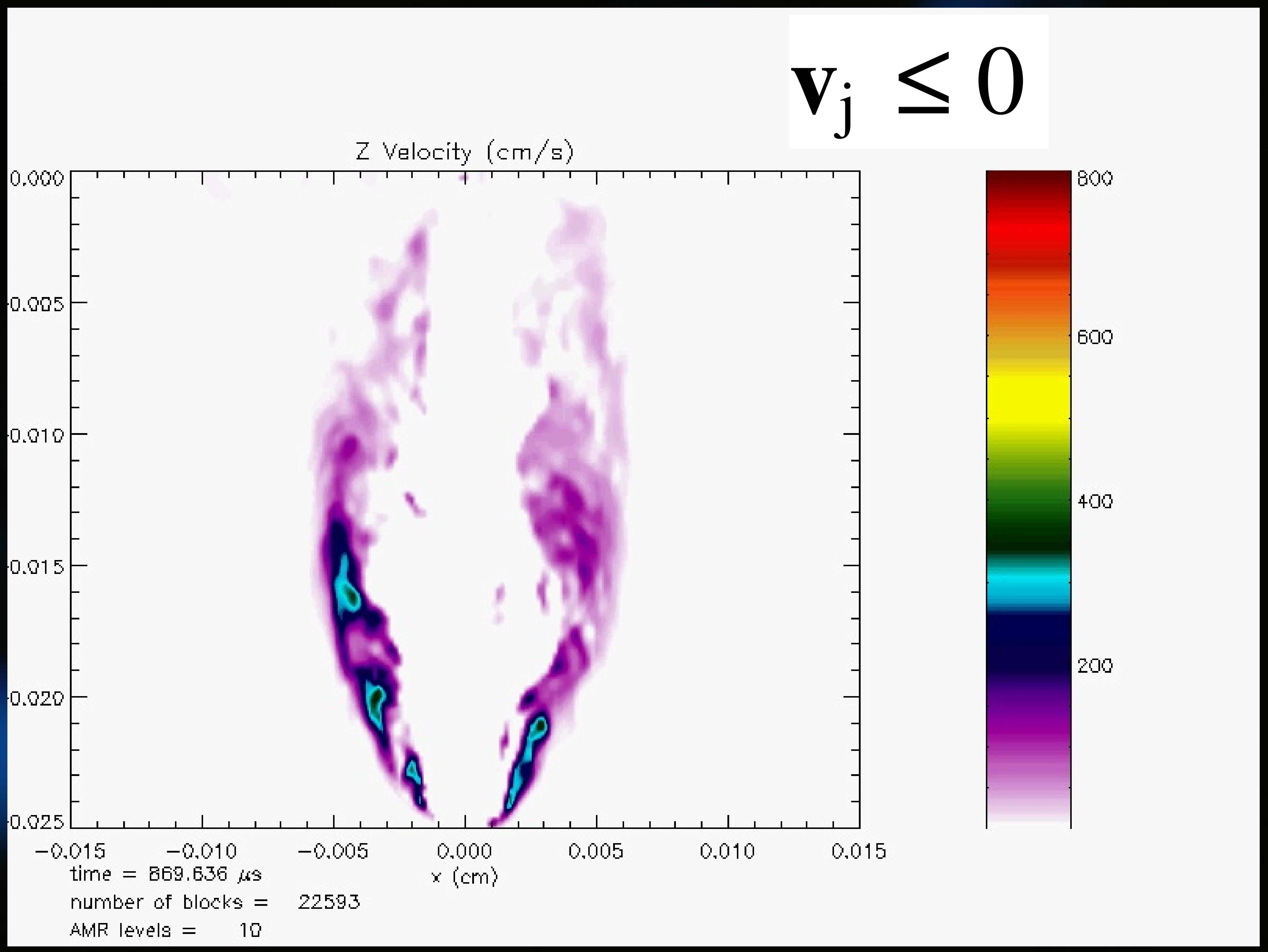

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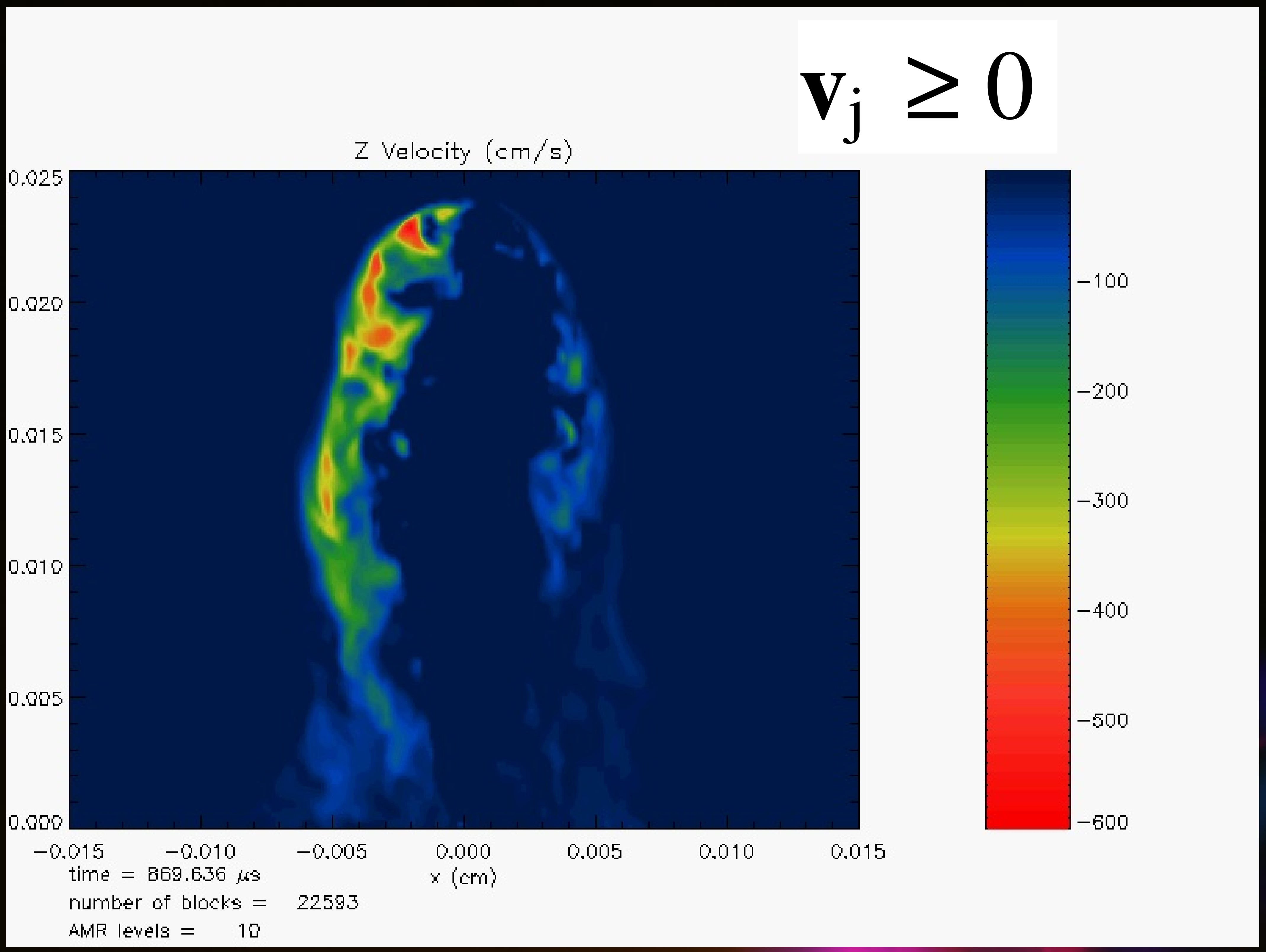

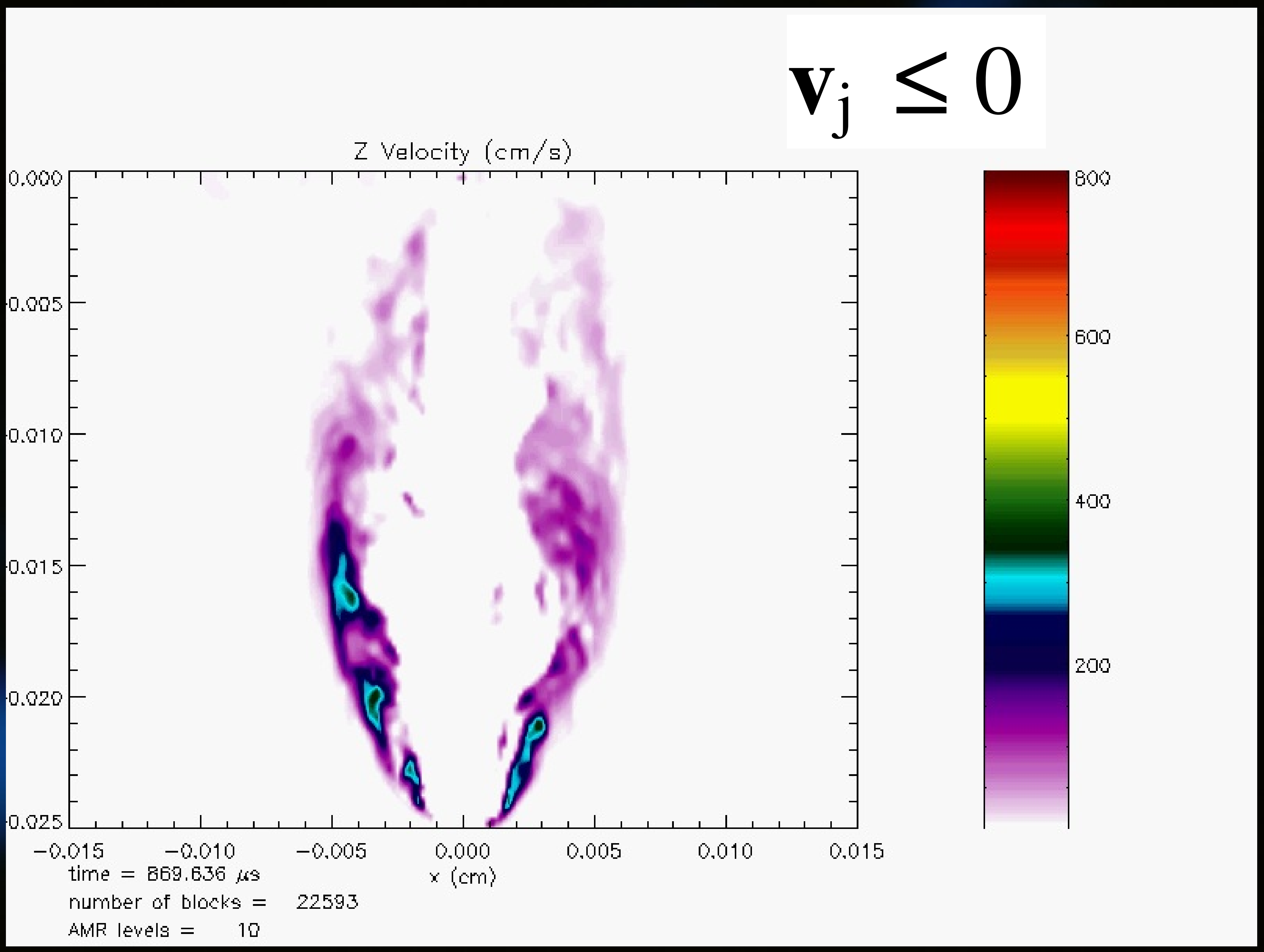

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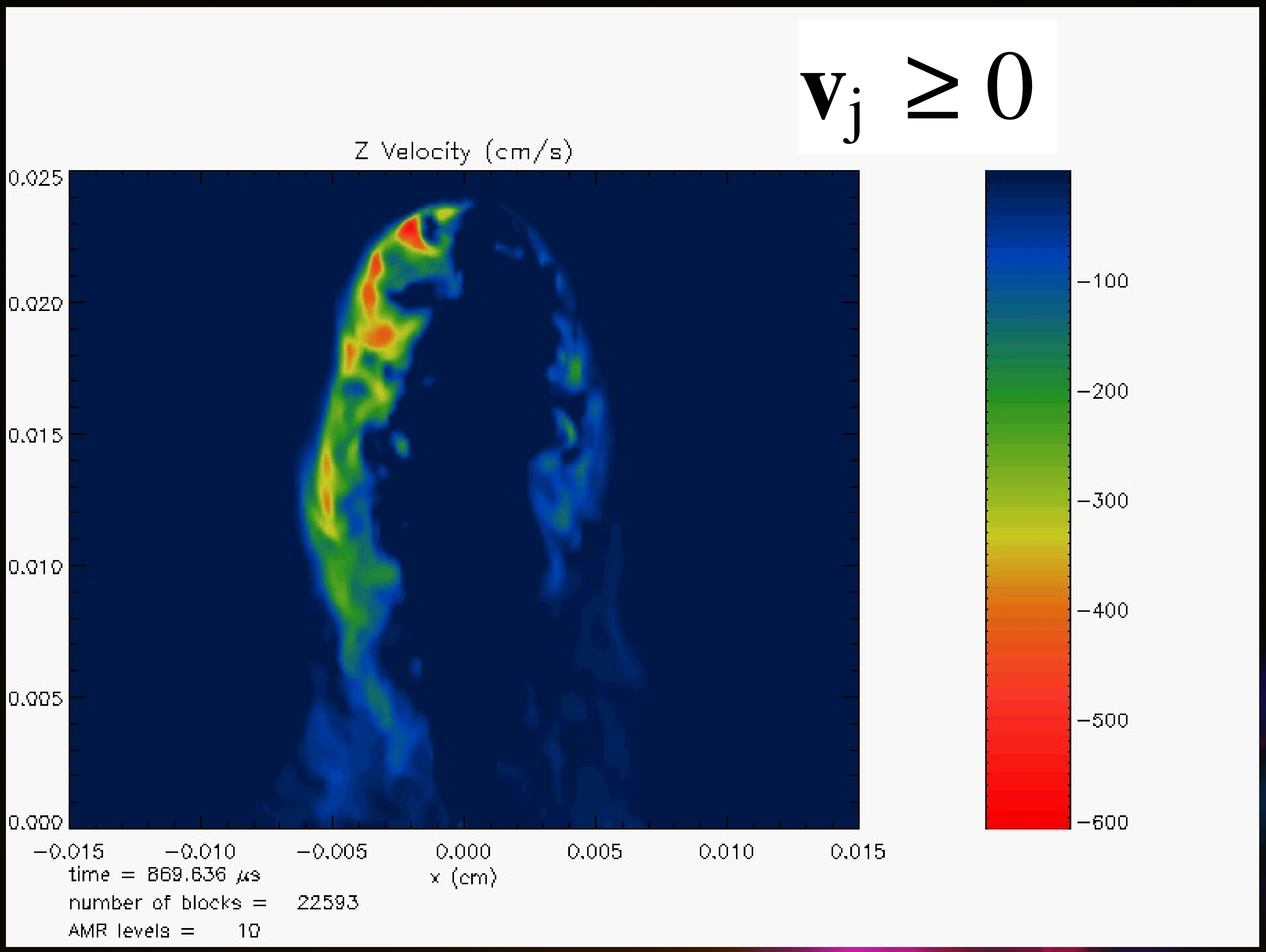

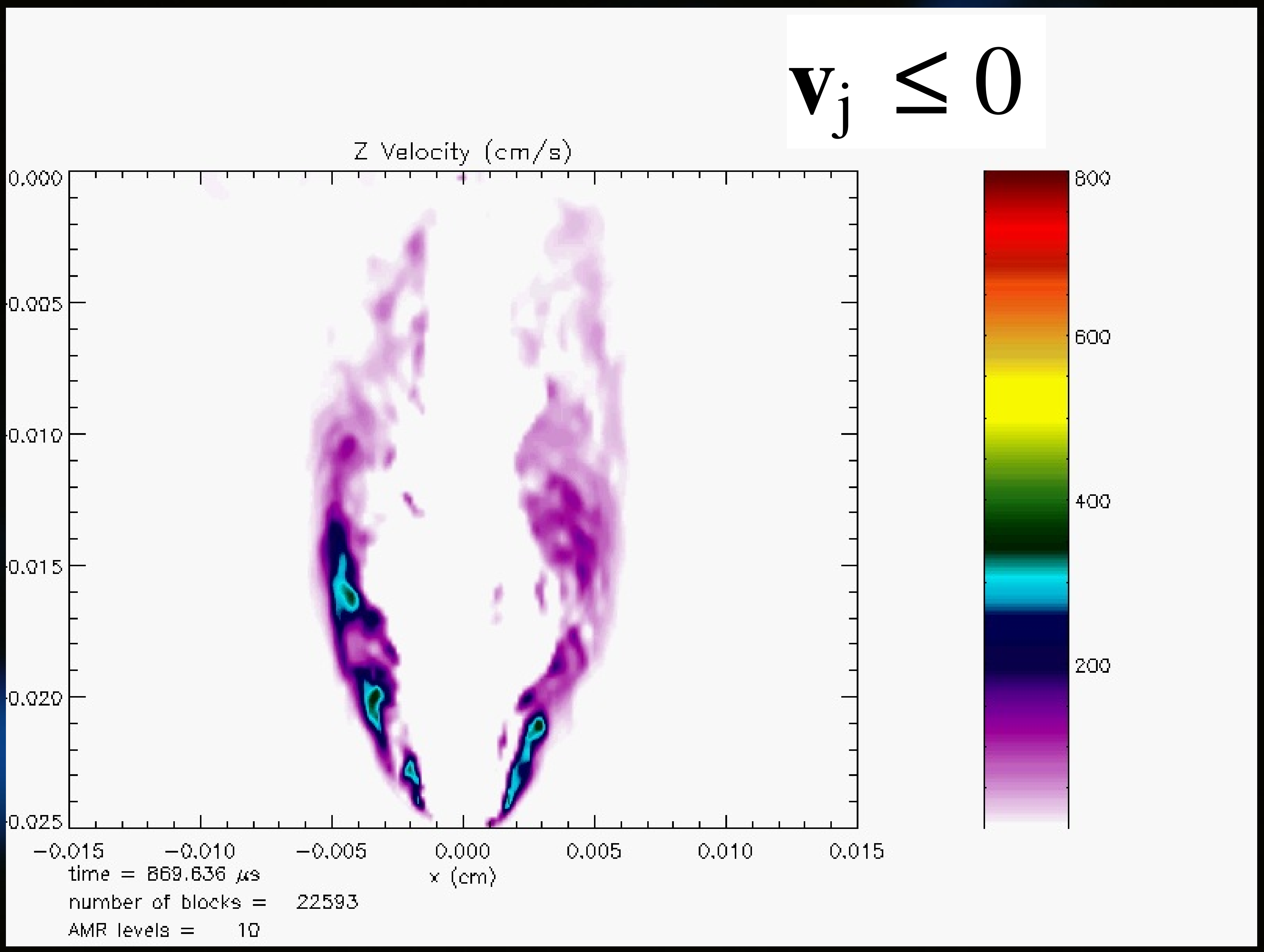

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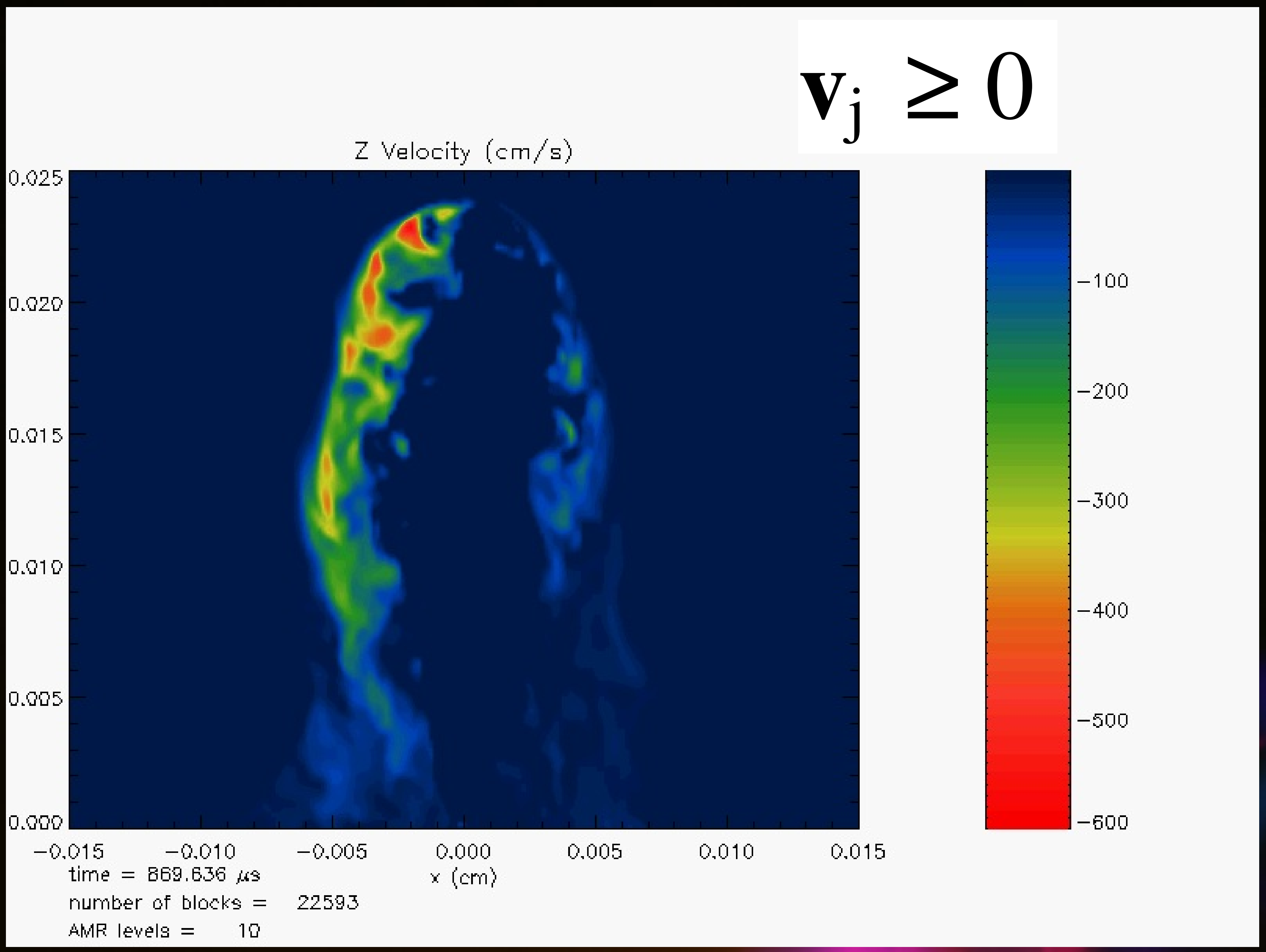

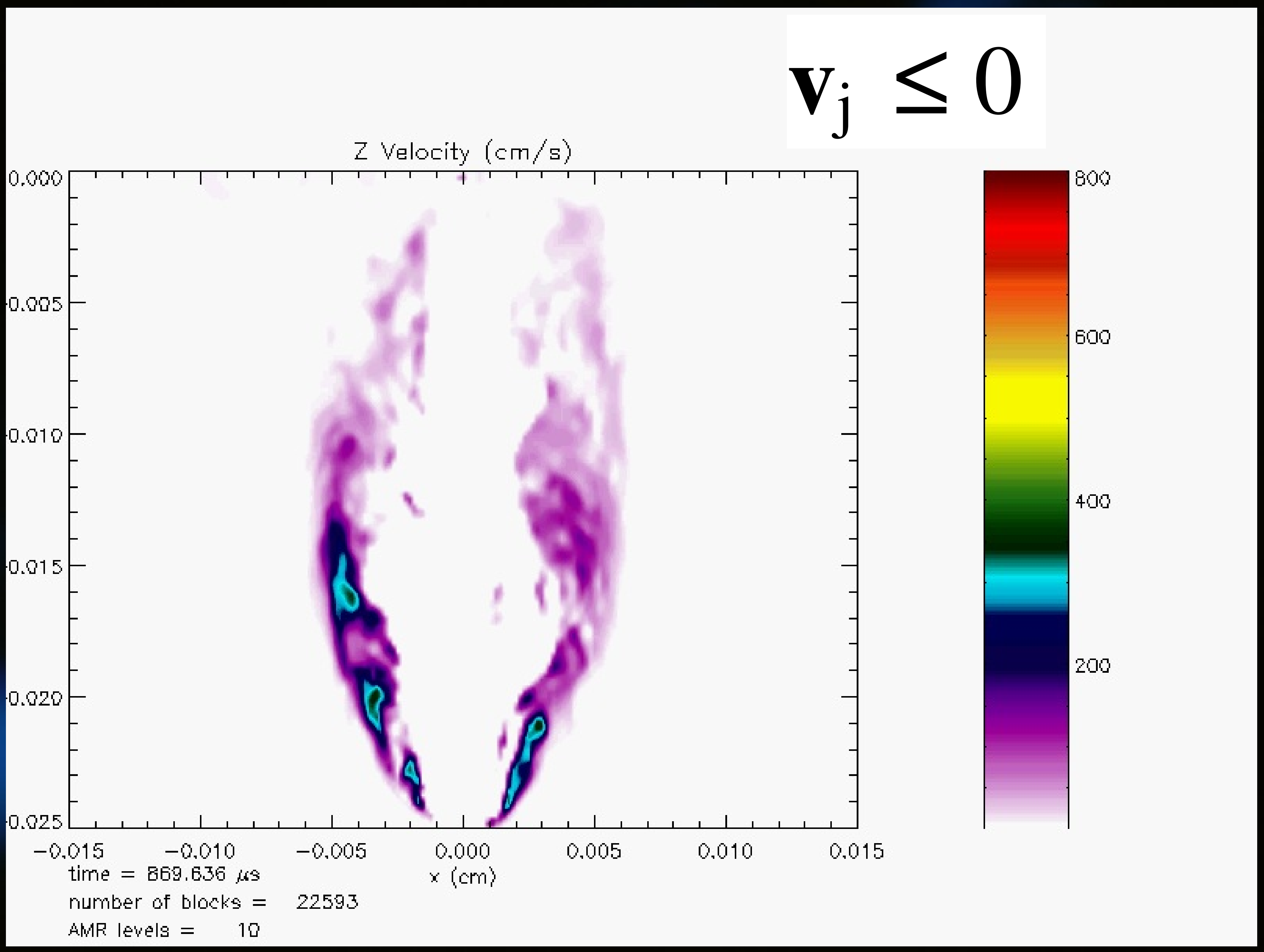

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  3) Spatial resolution of FLASH not sufficiently high to resolve the flows down to SMBH scale ☹

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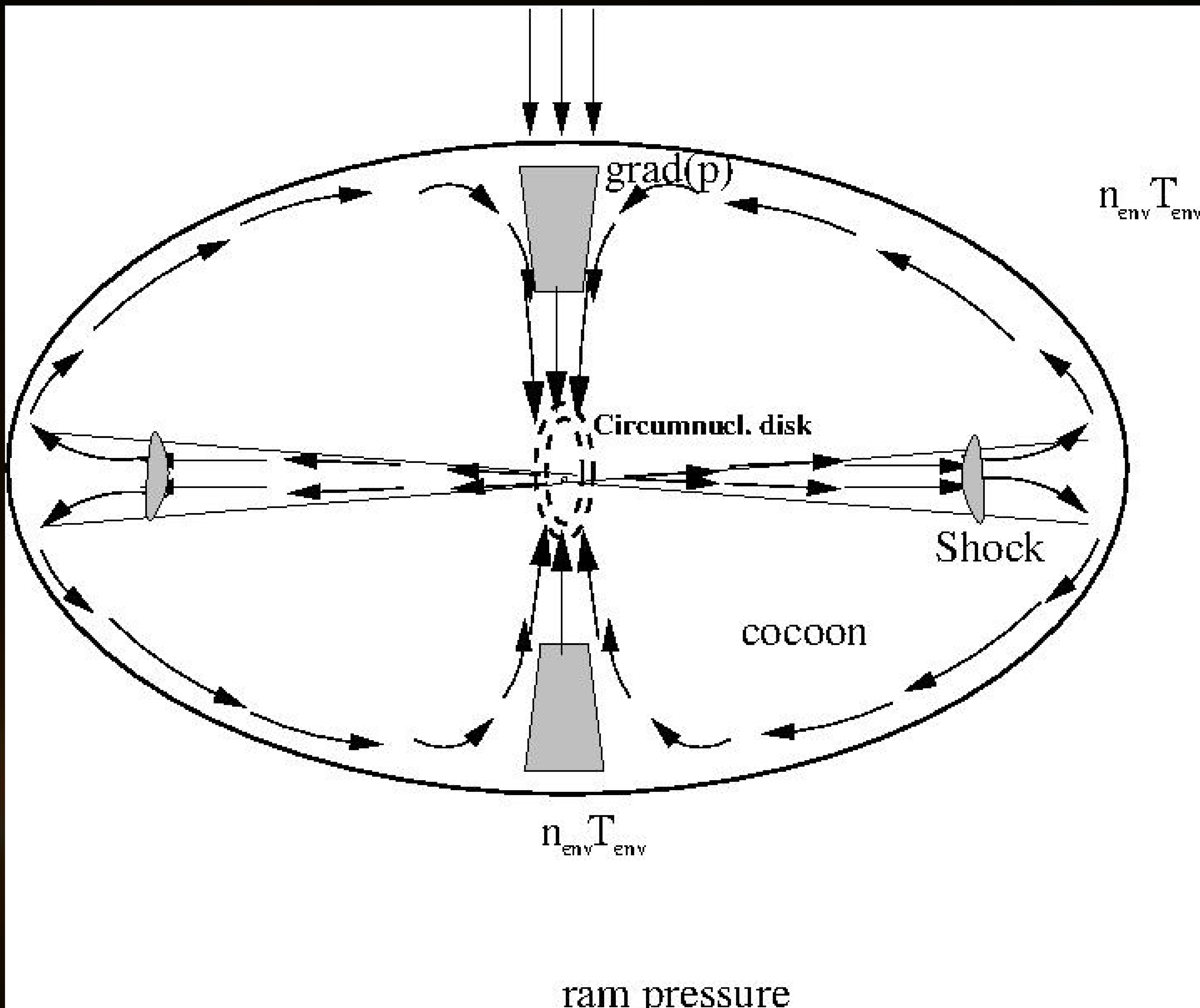

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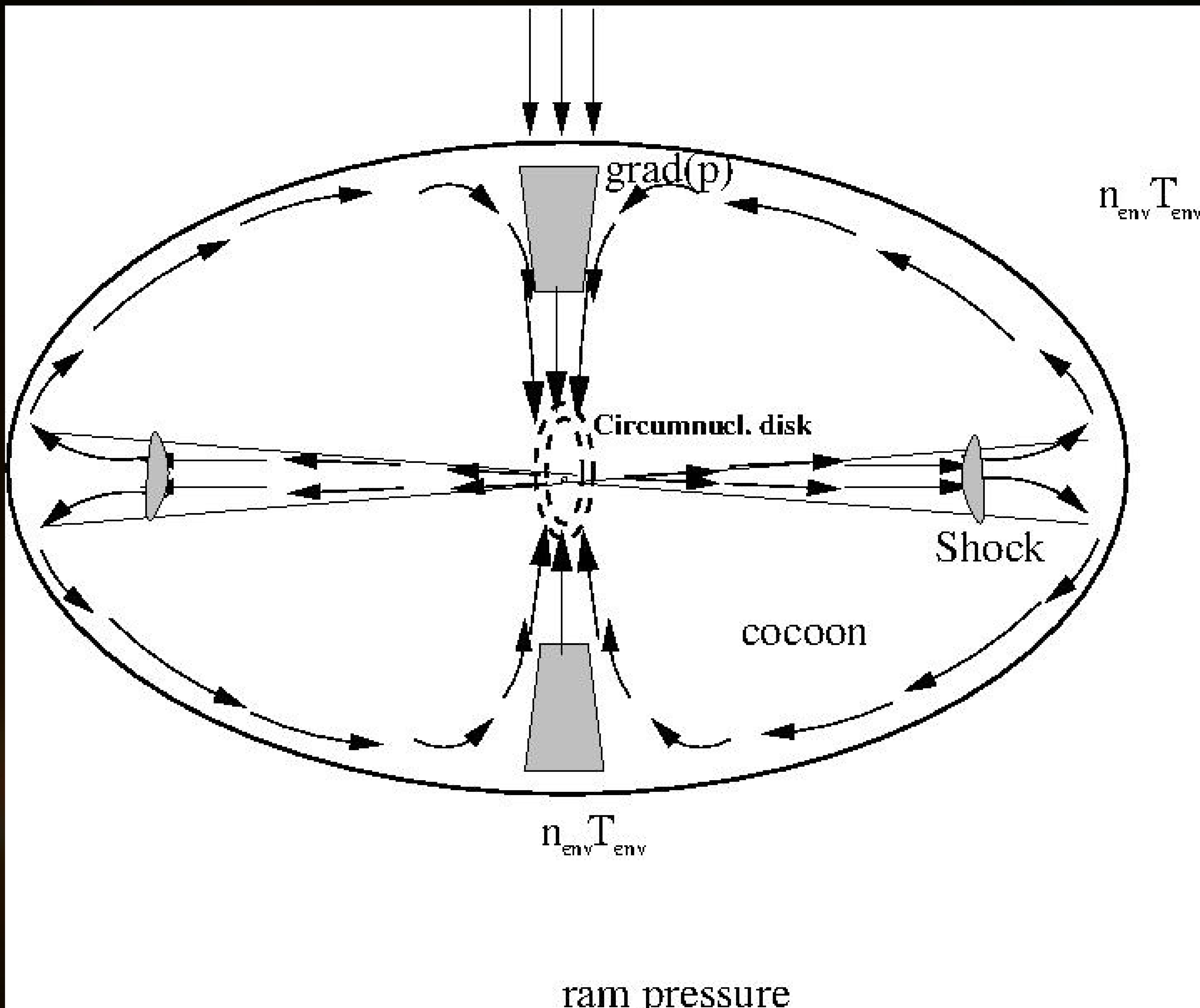

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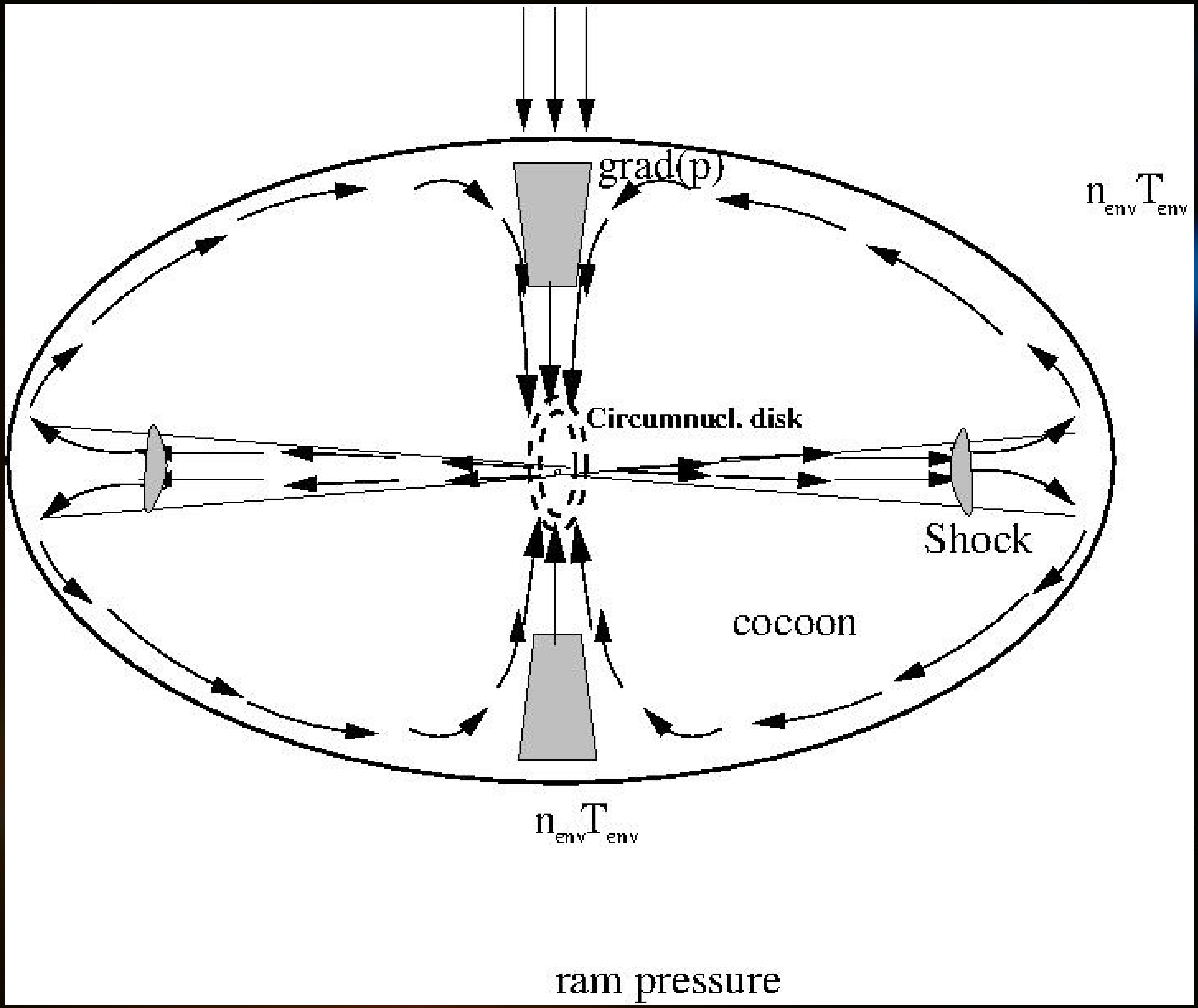

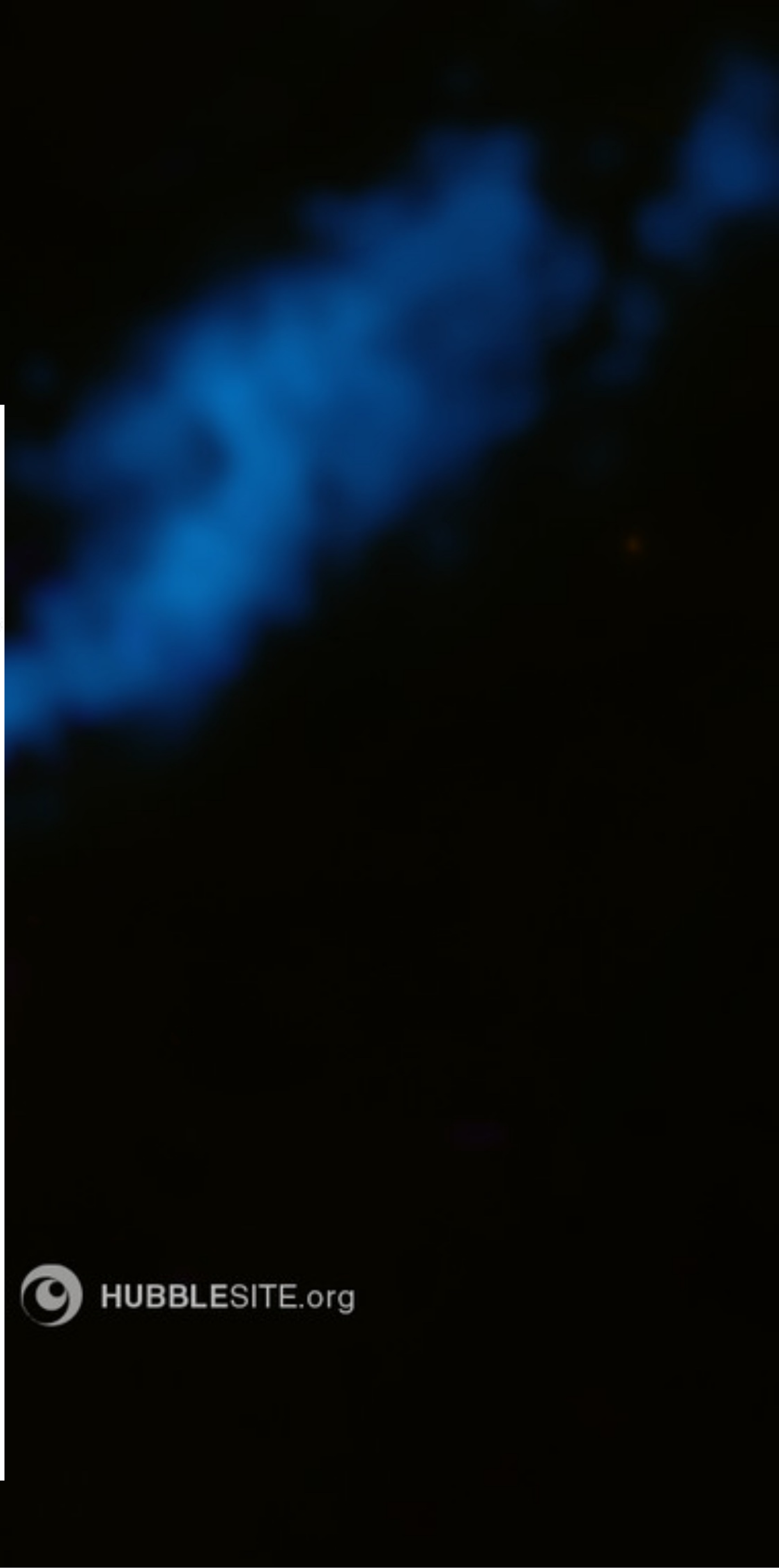

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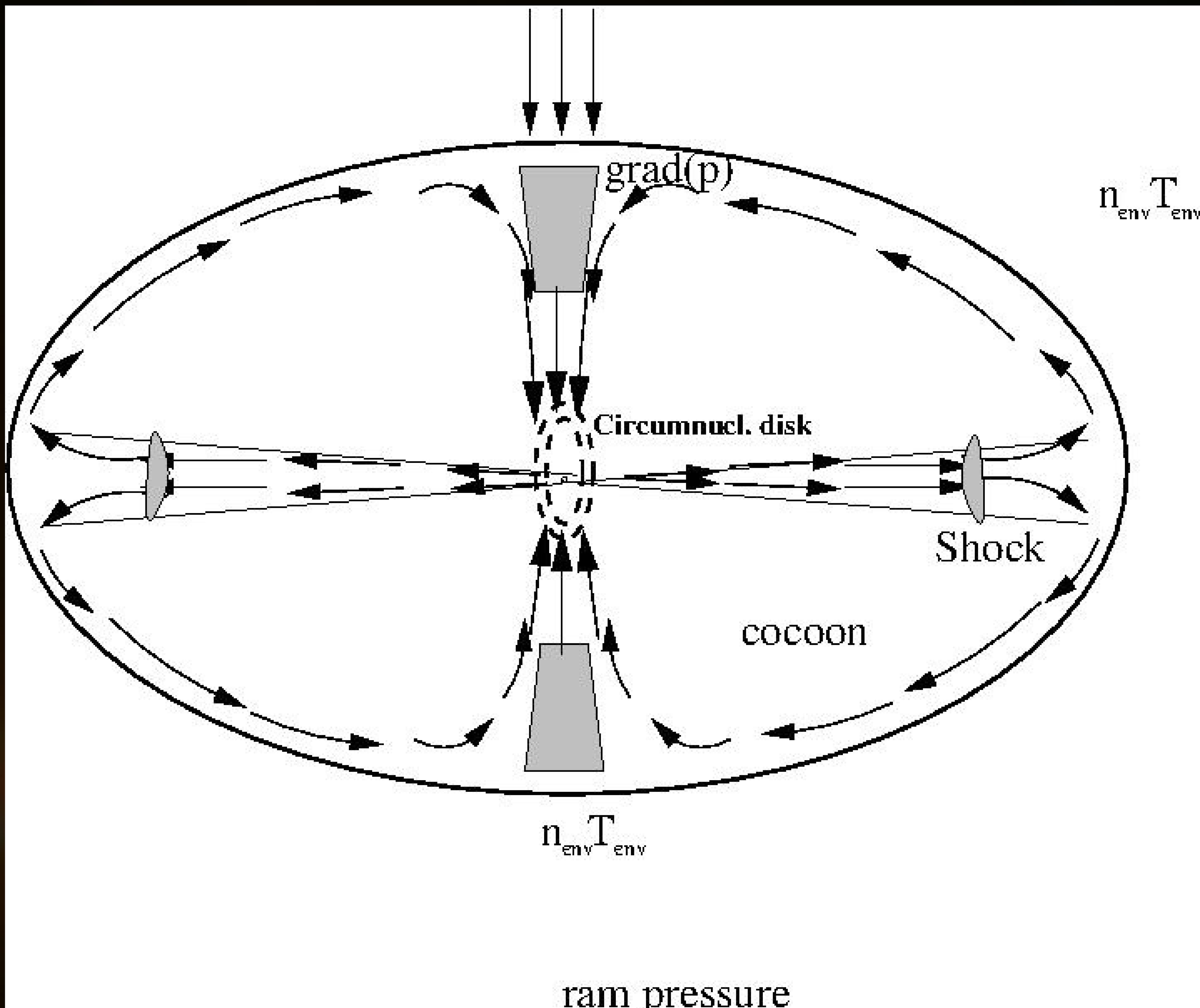

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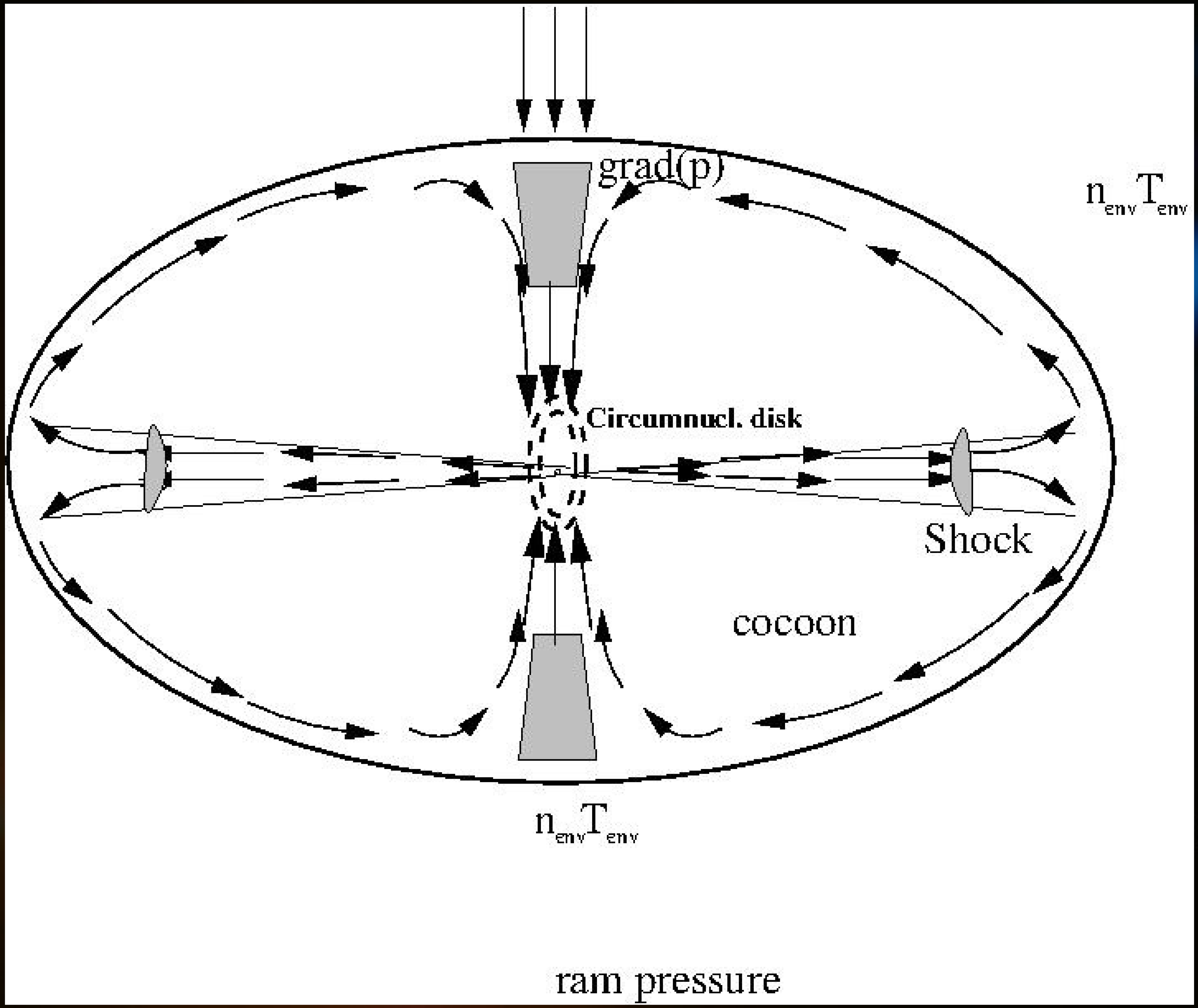

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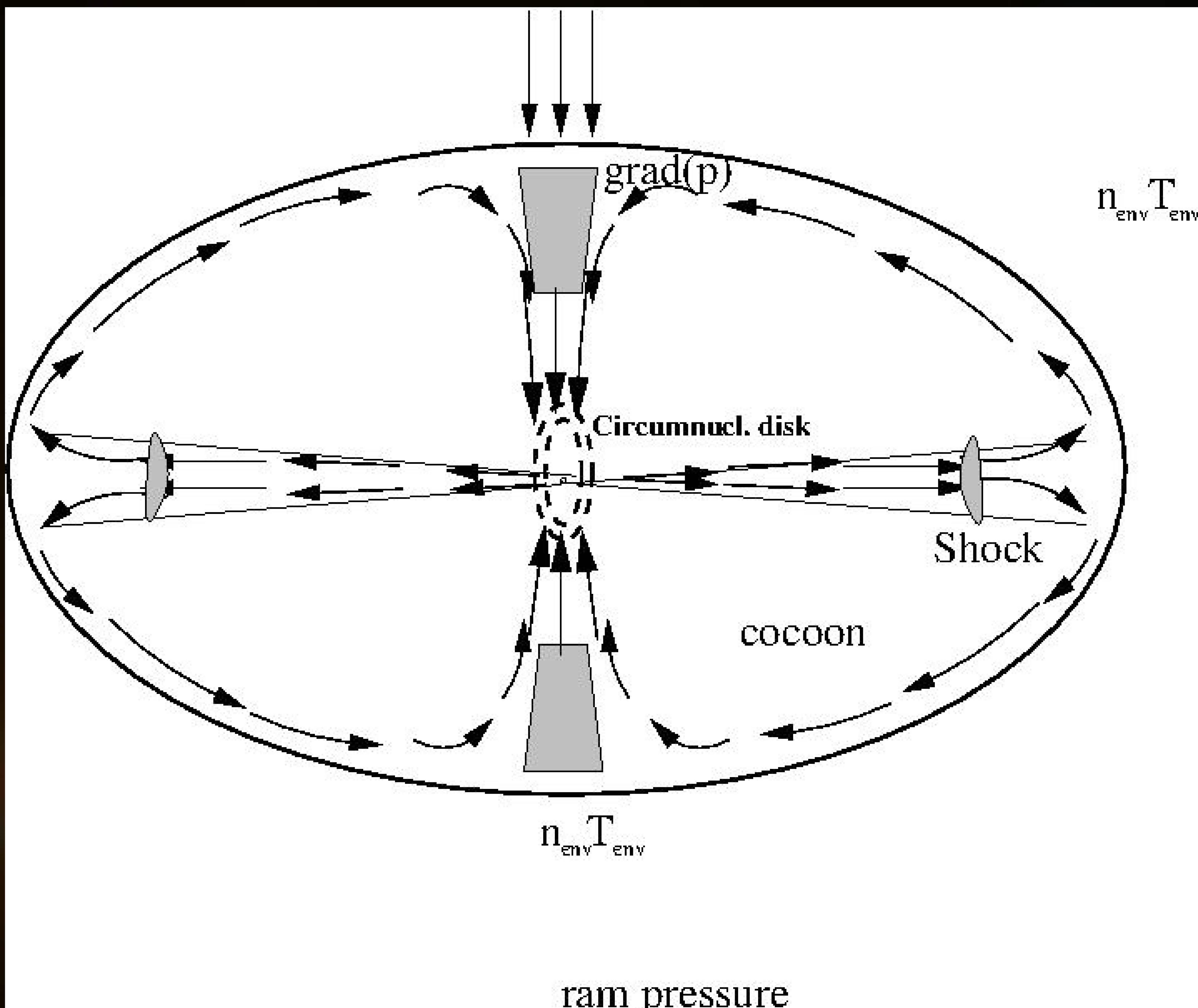

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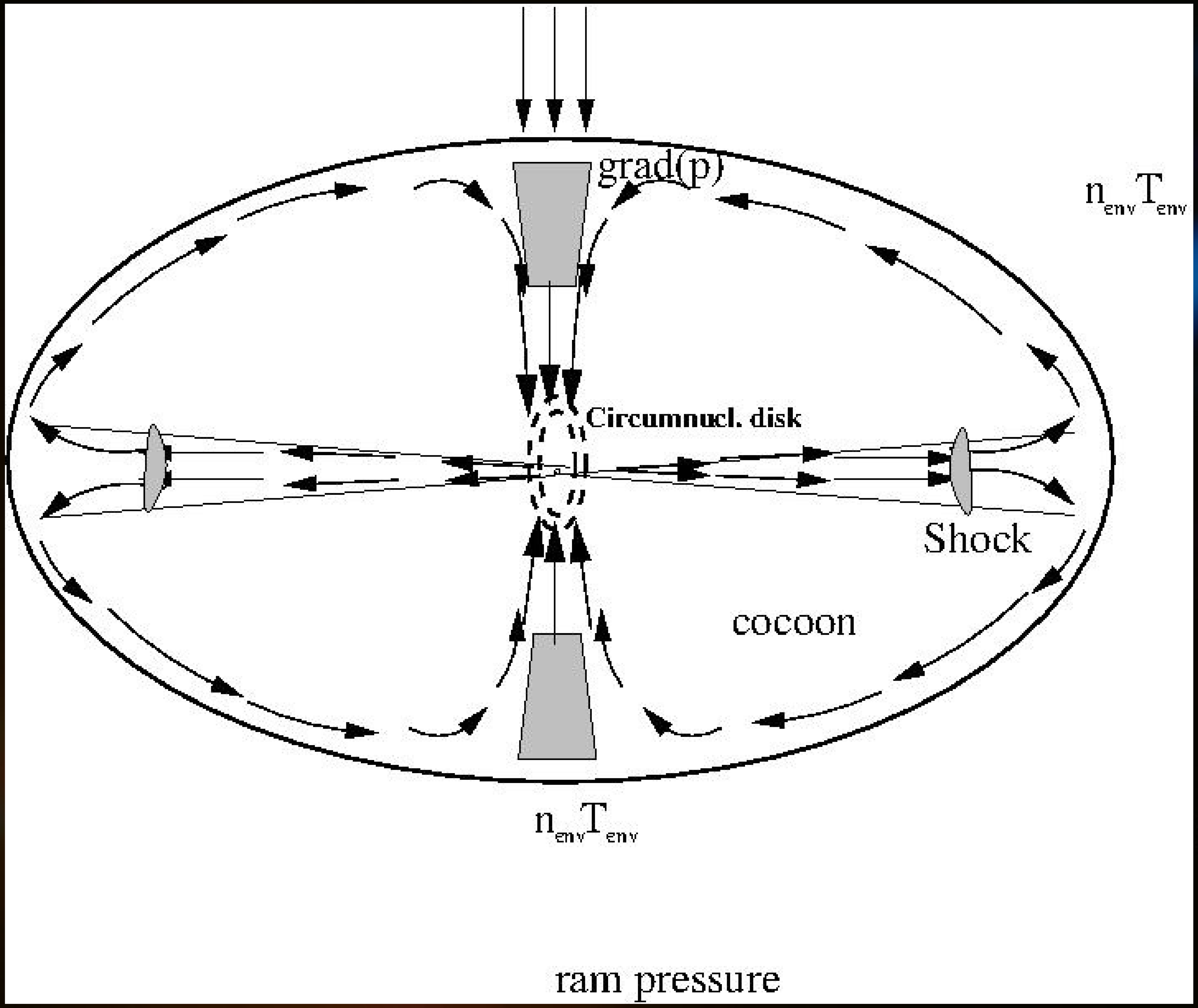

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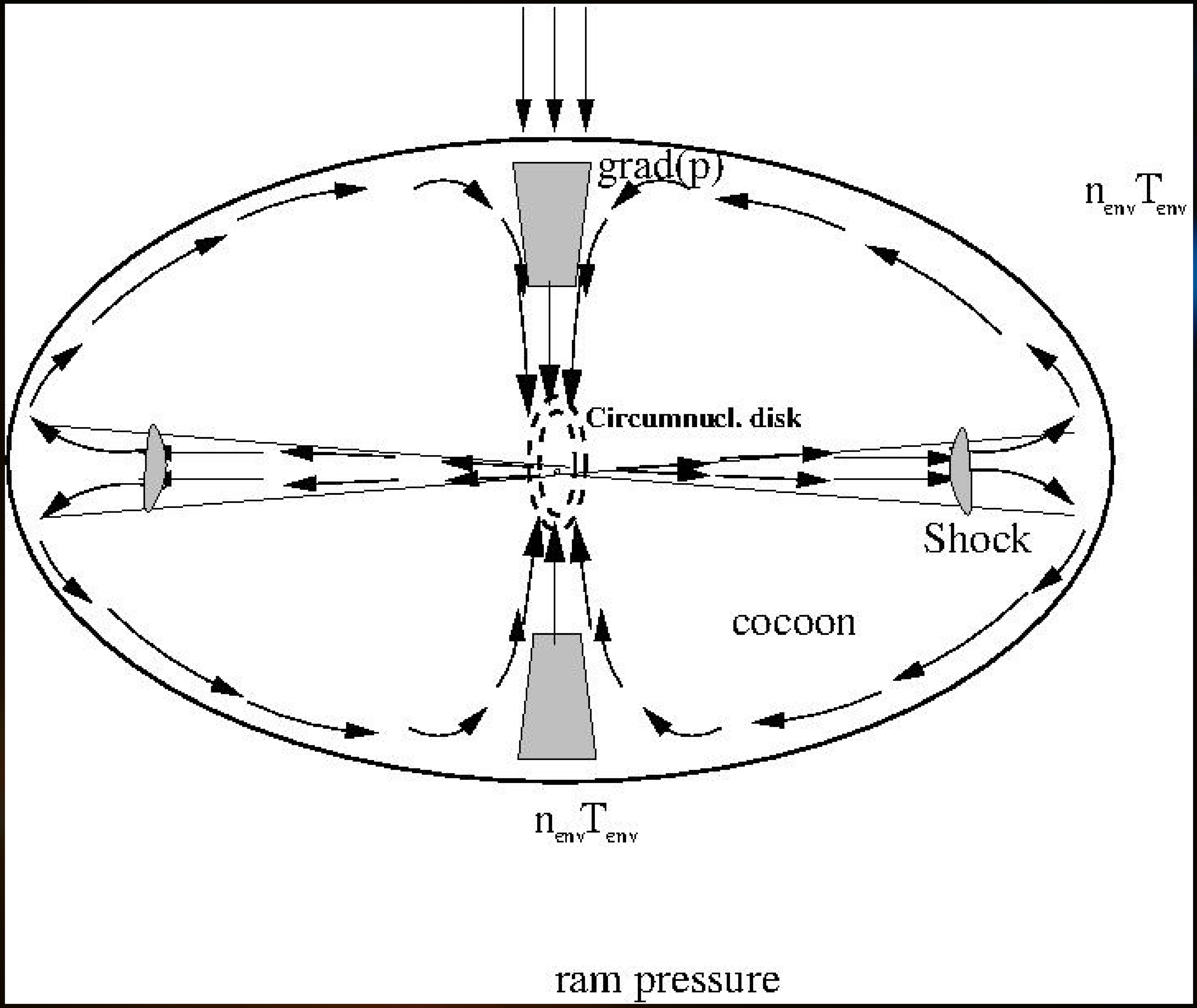

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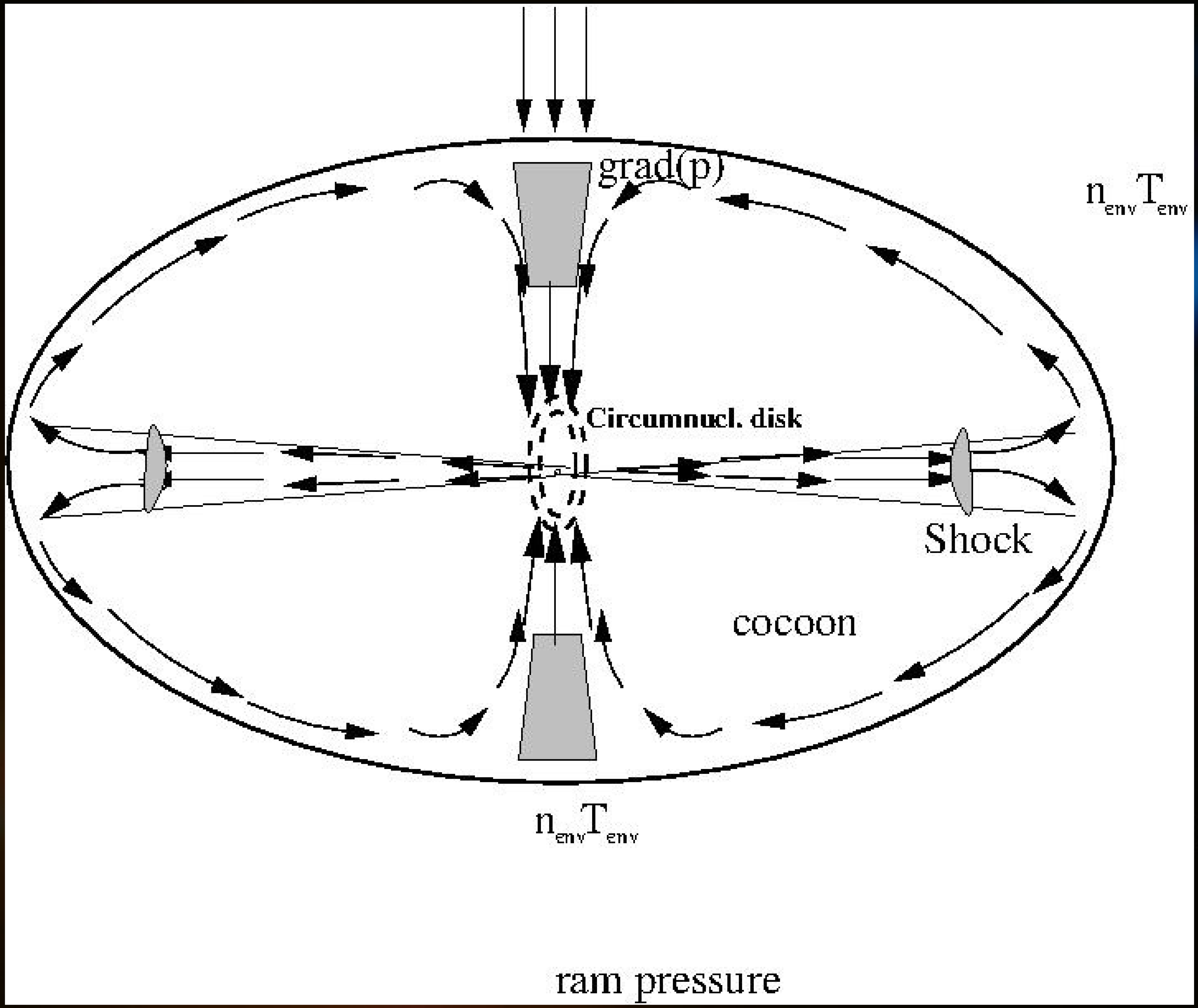

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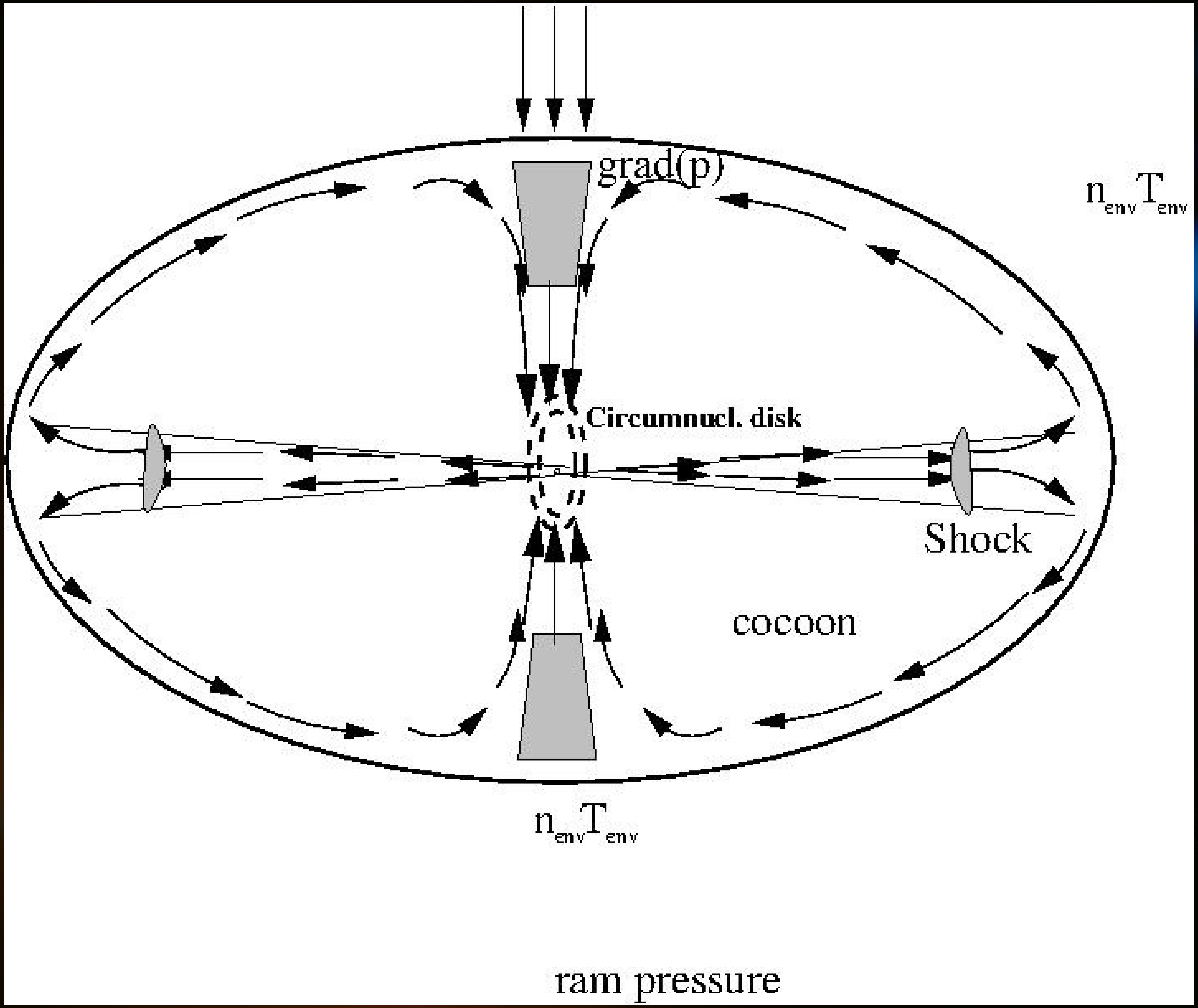

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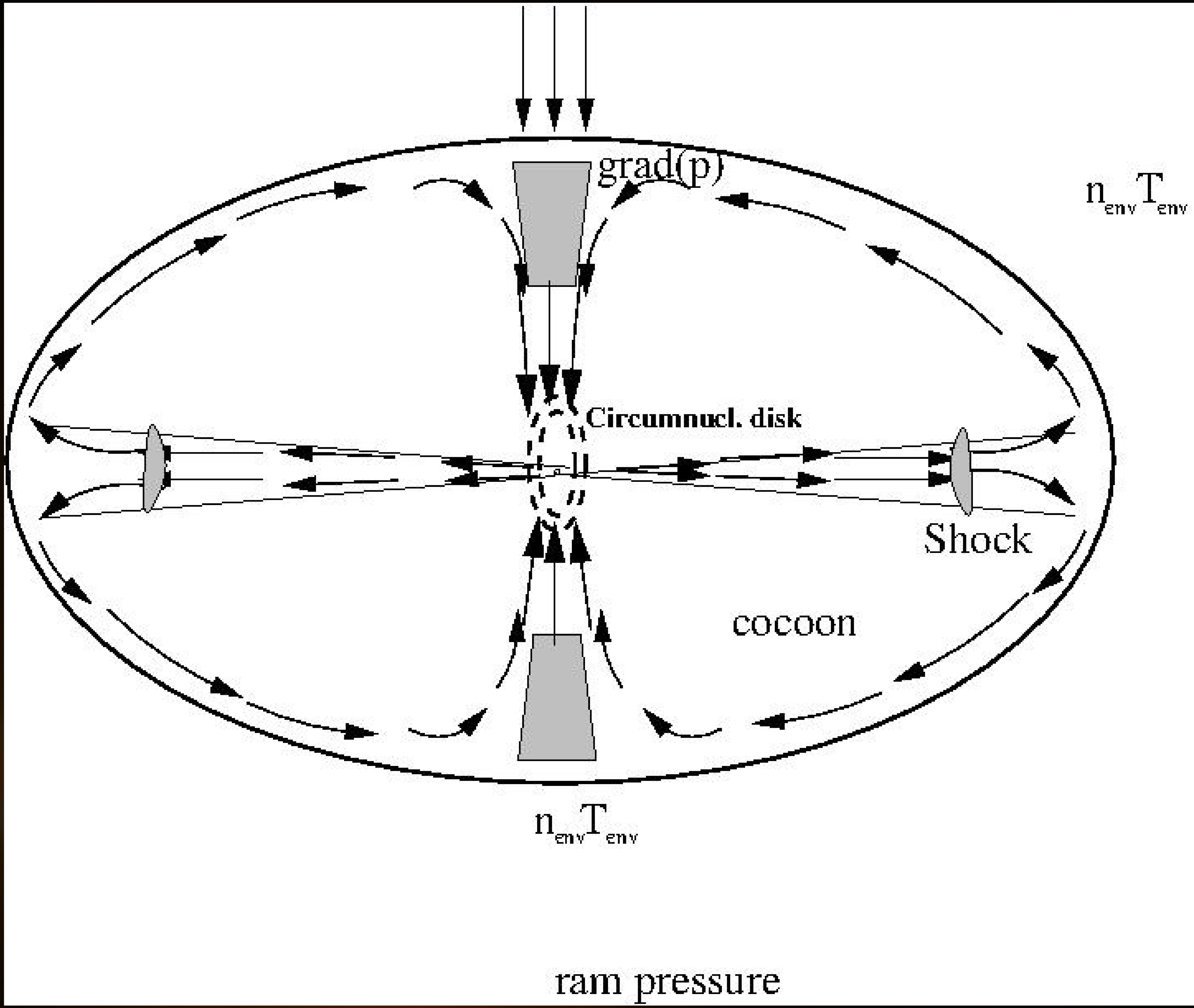

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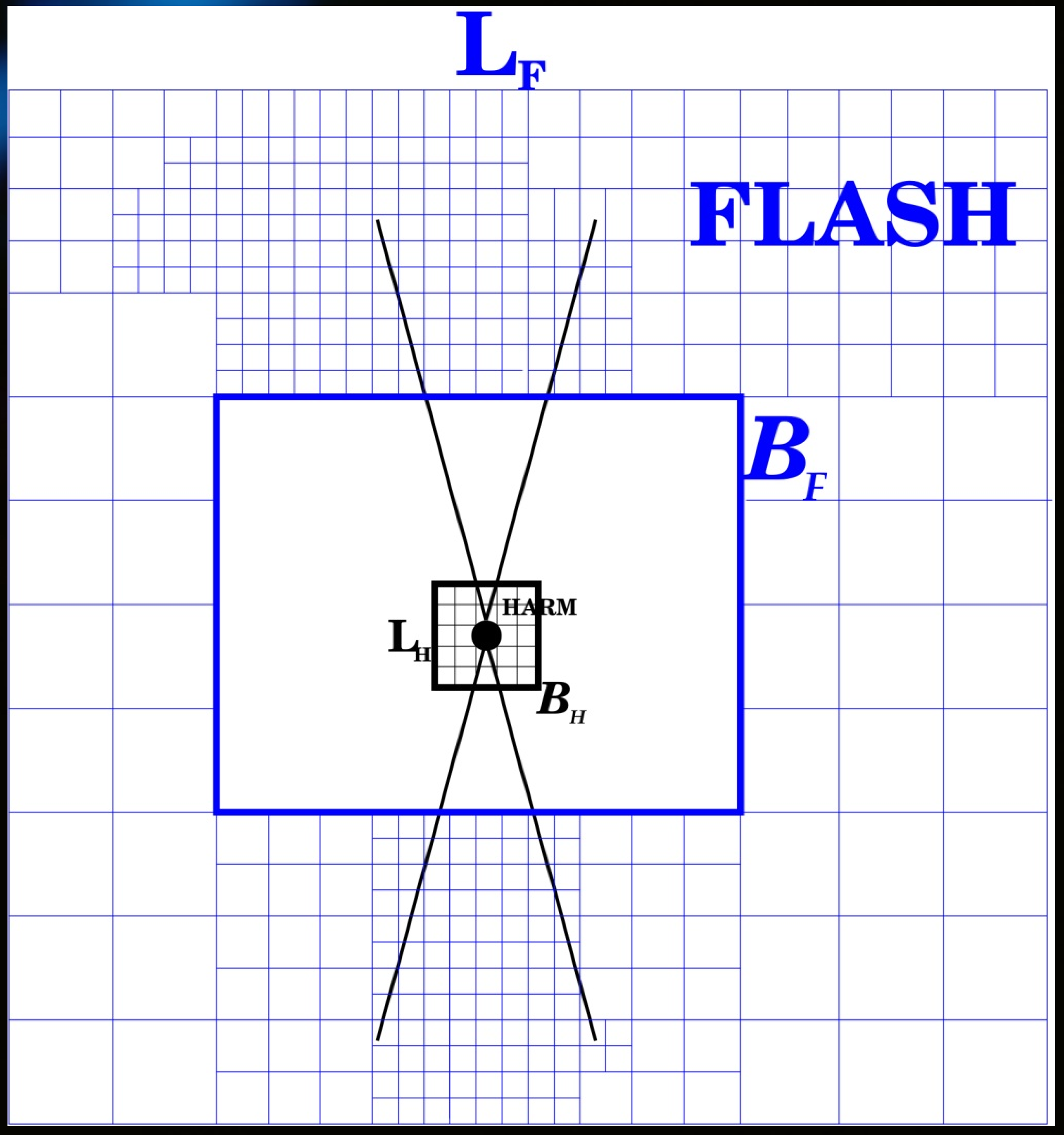

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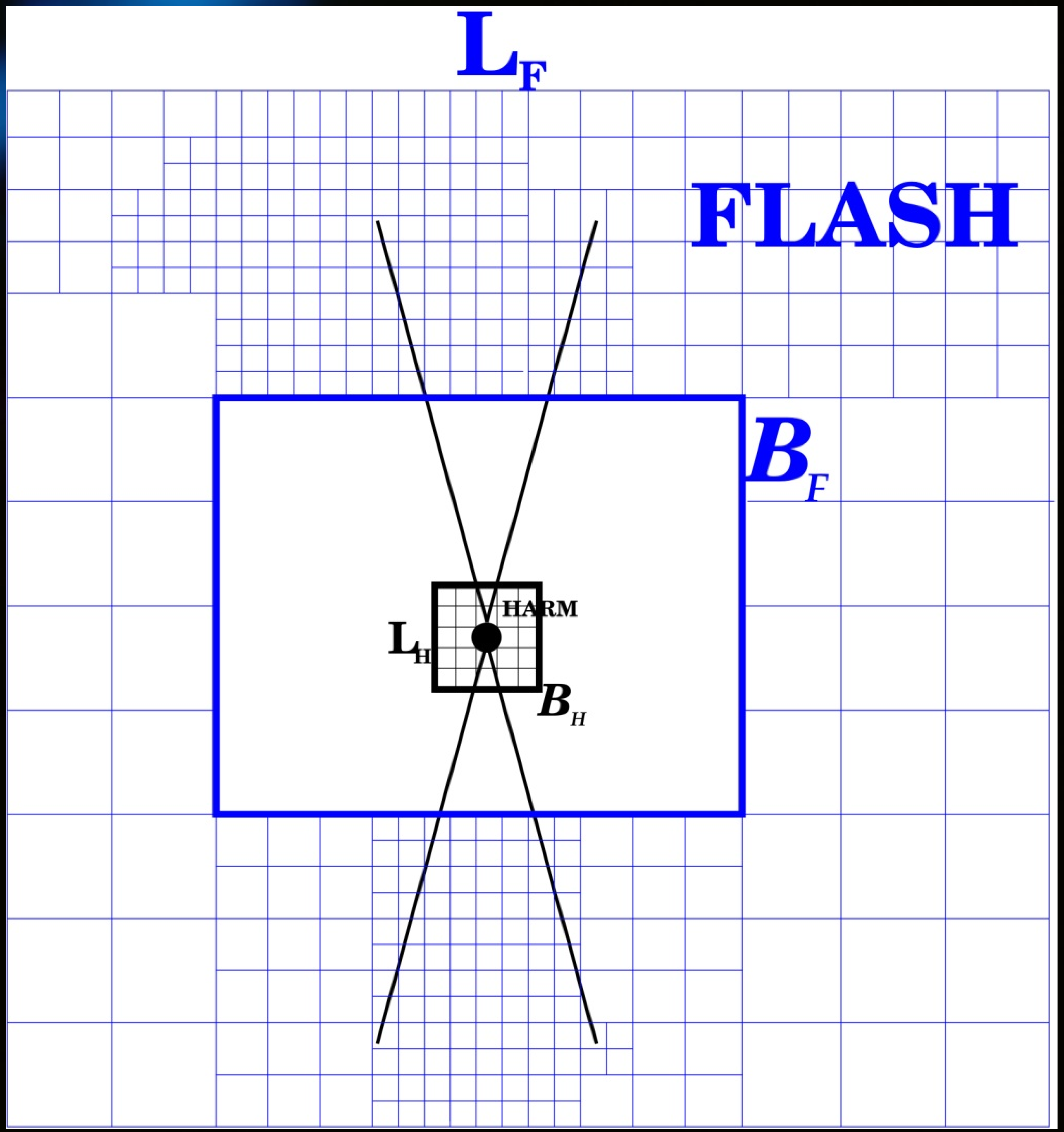

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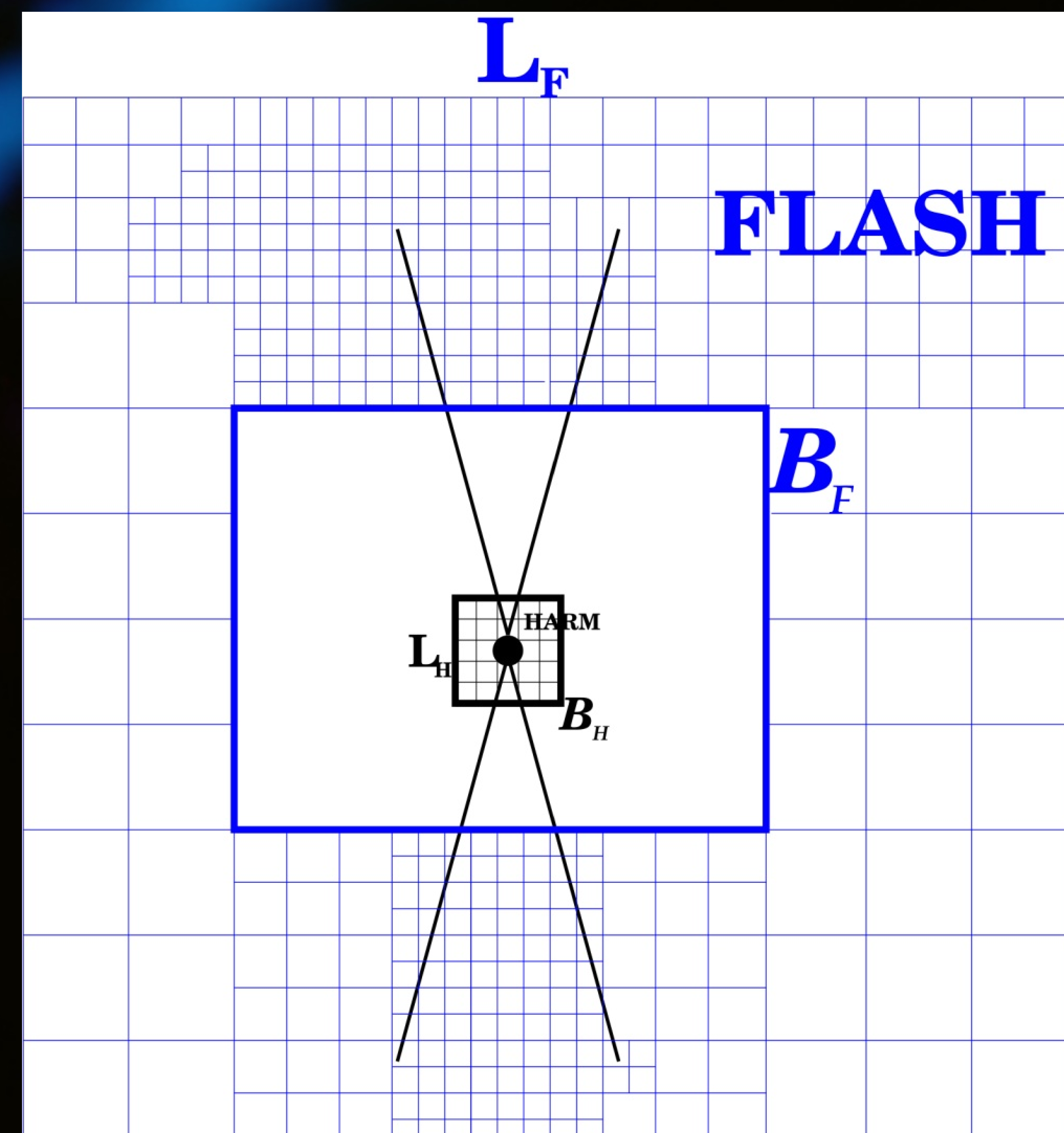

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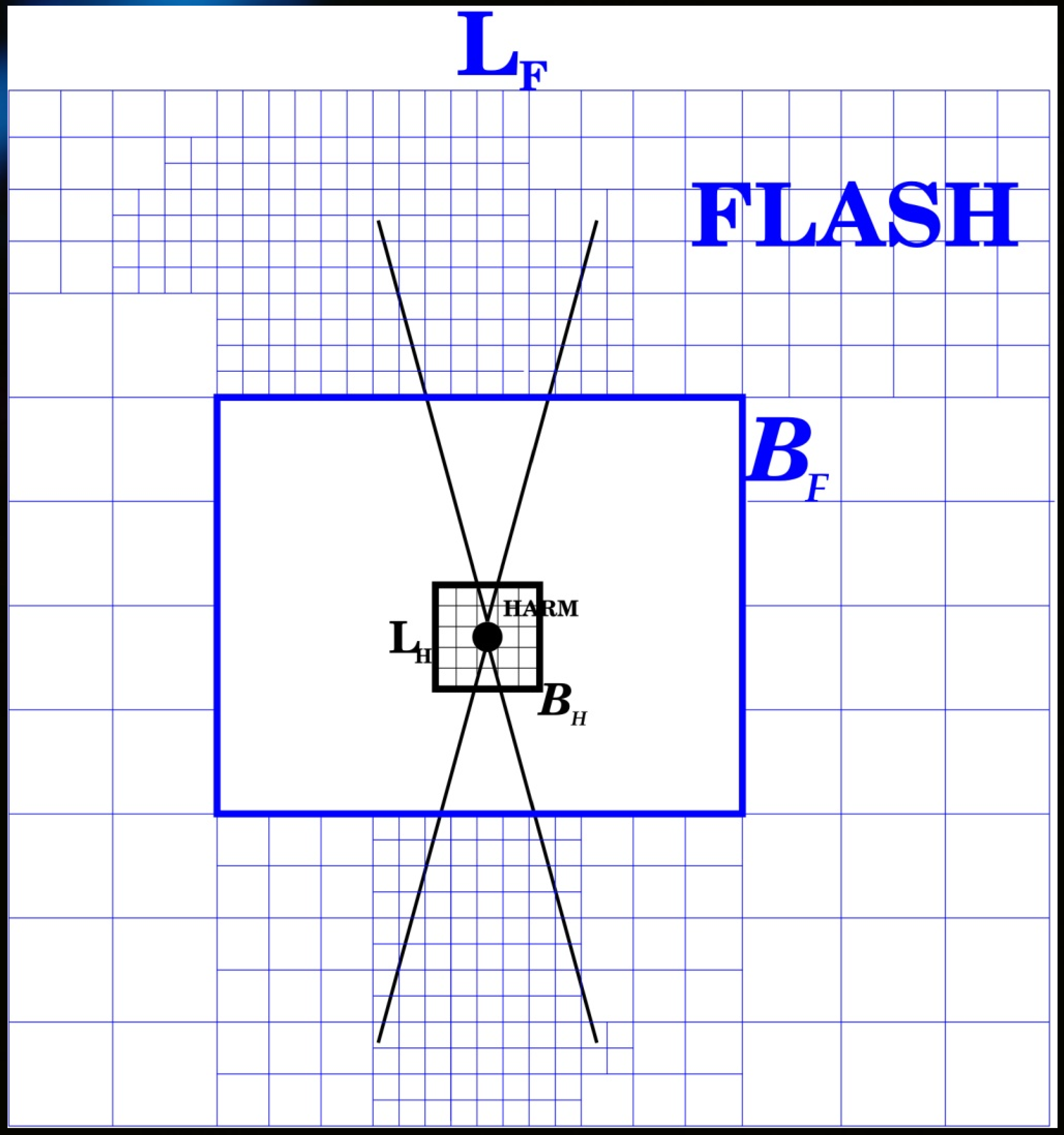

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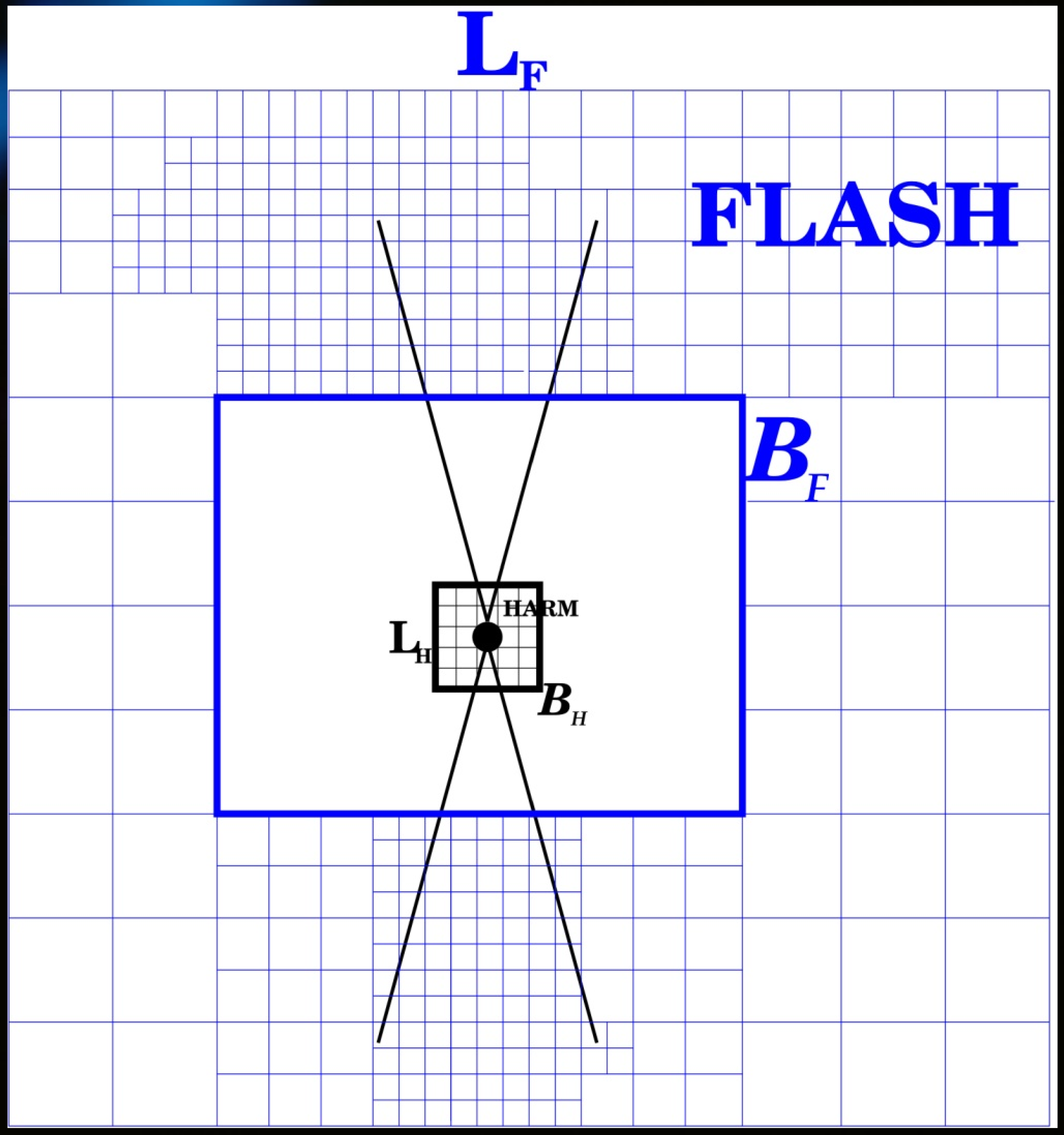

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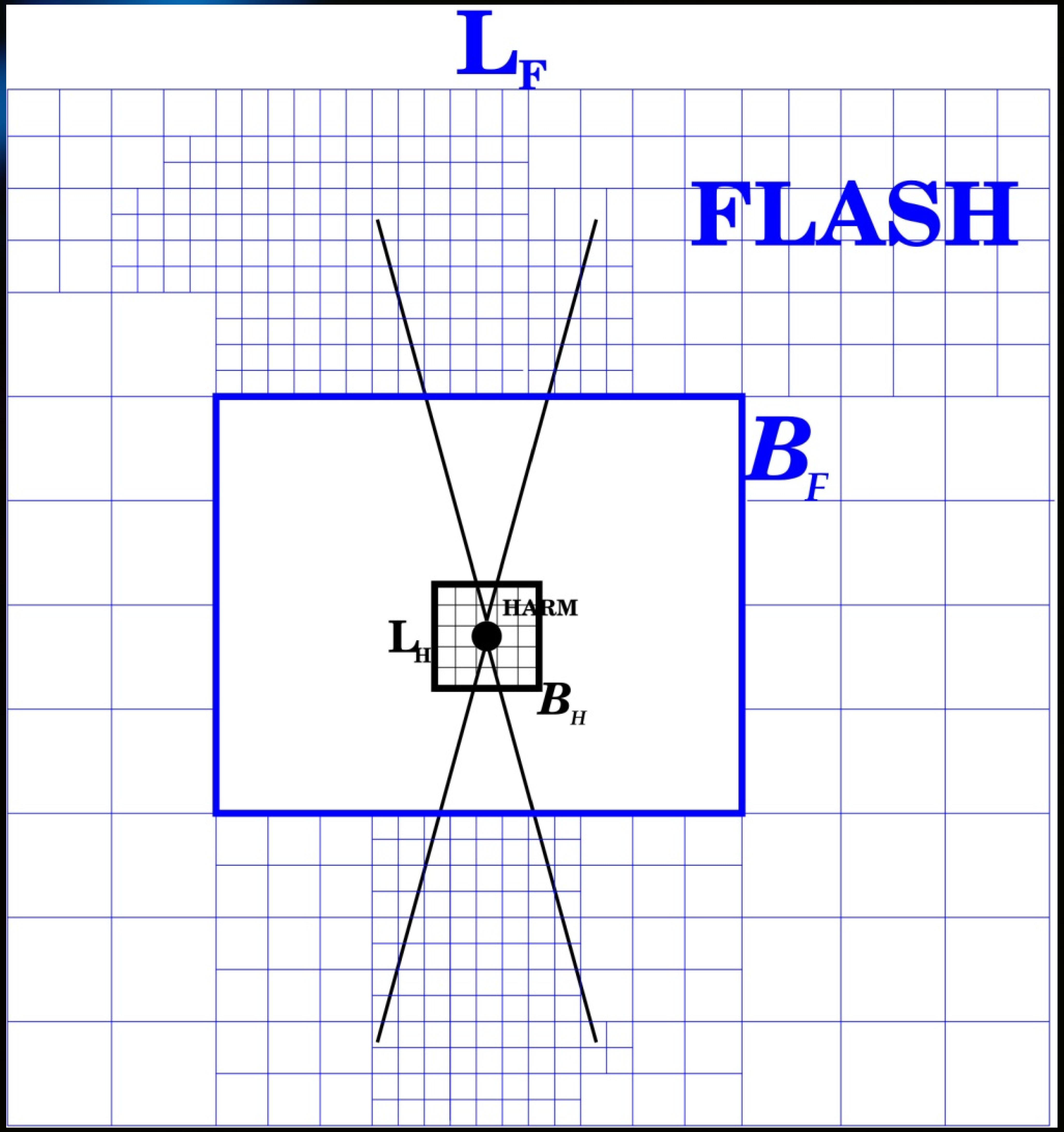

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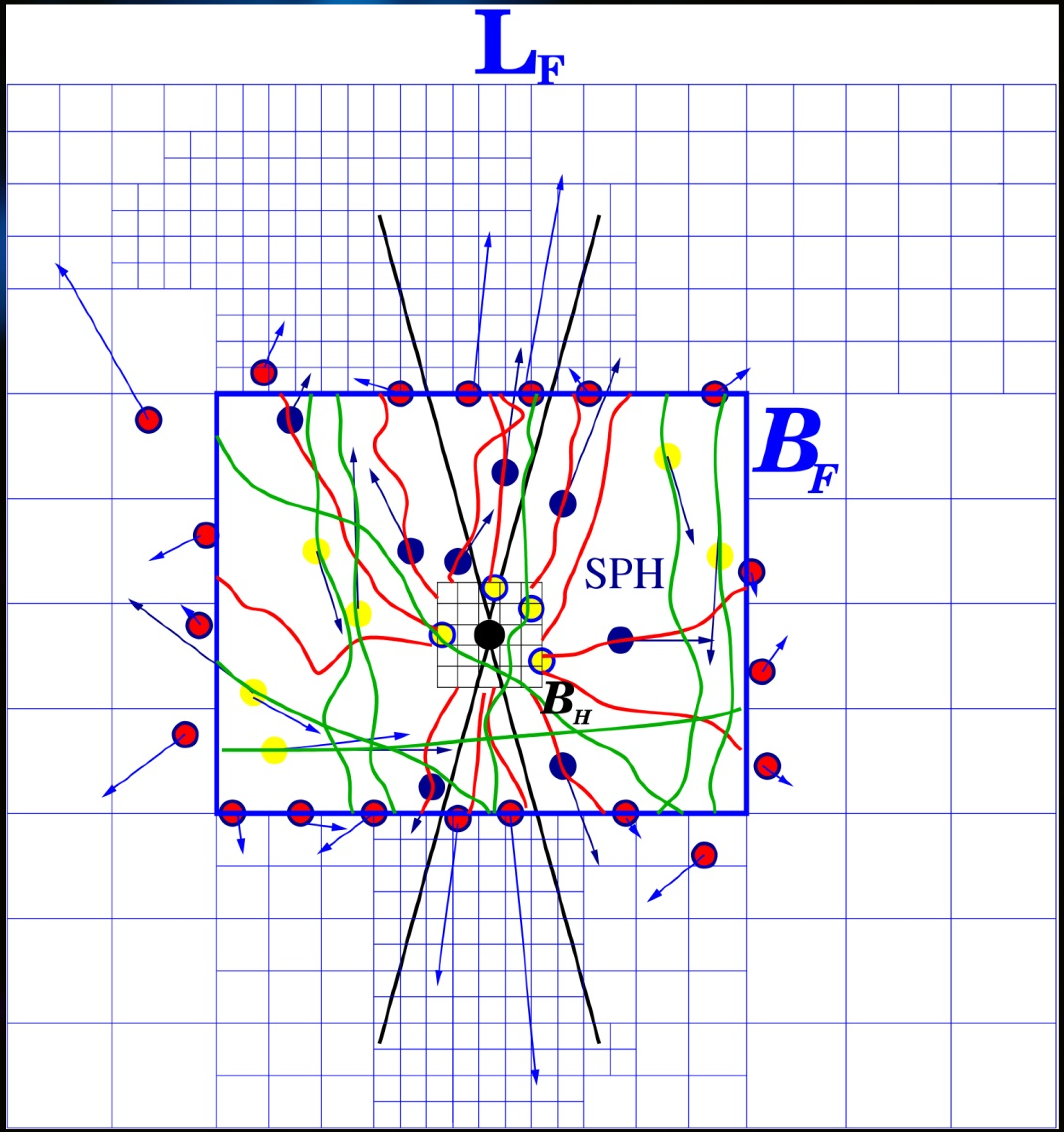

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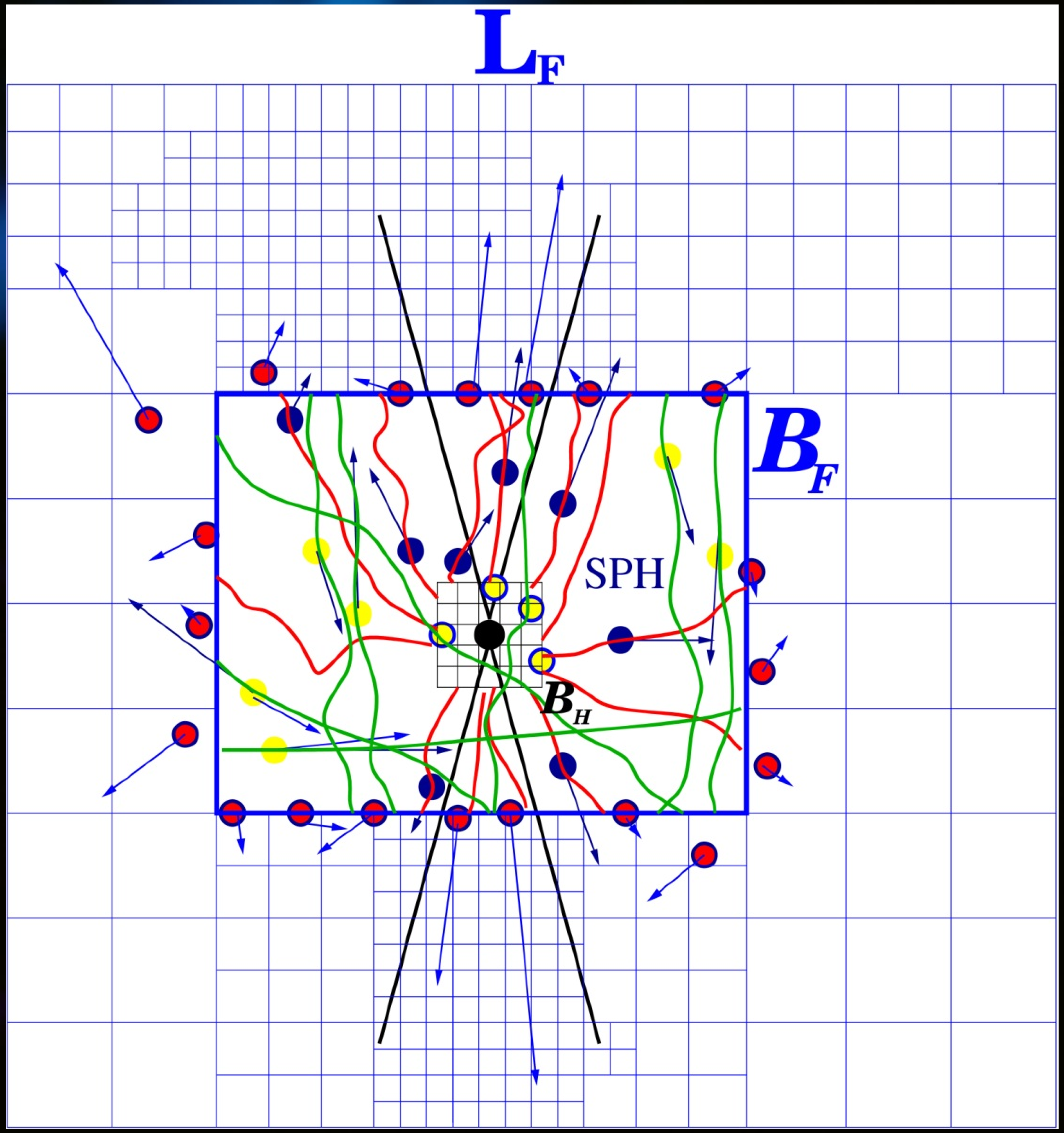

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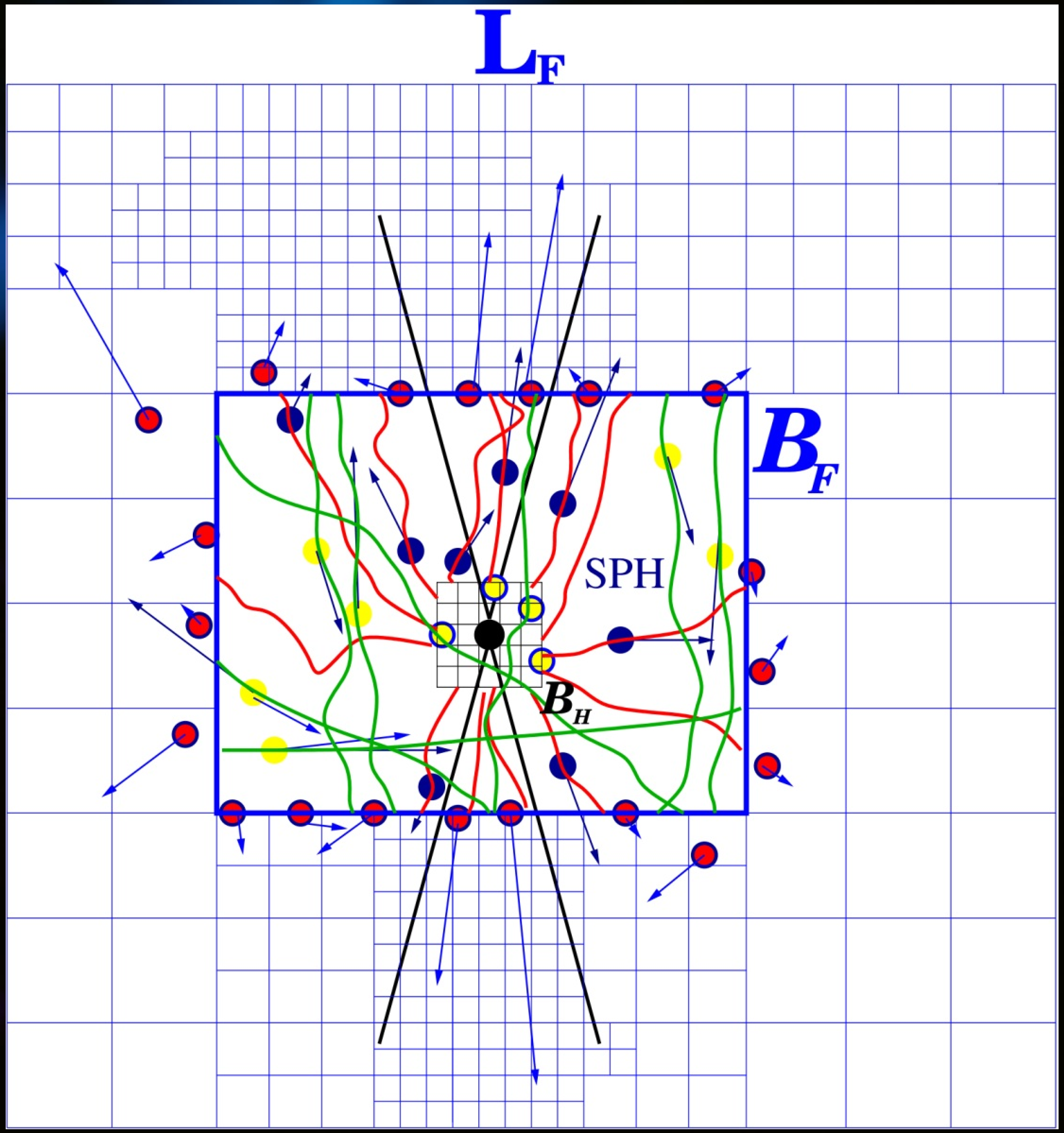

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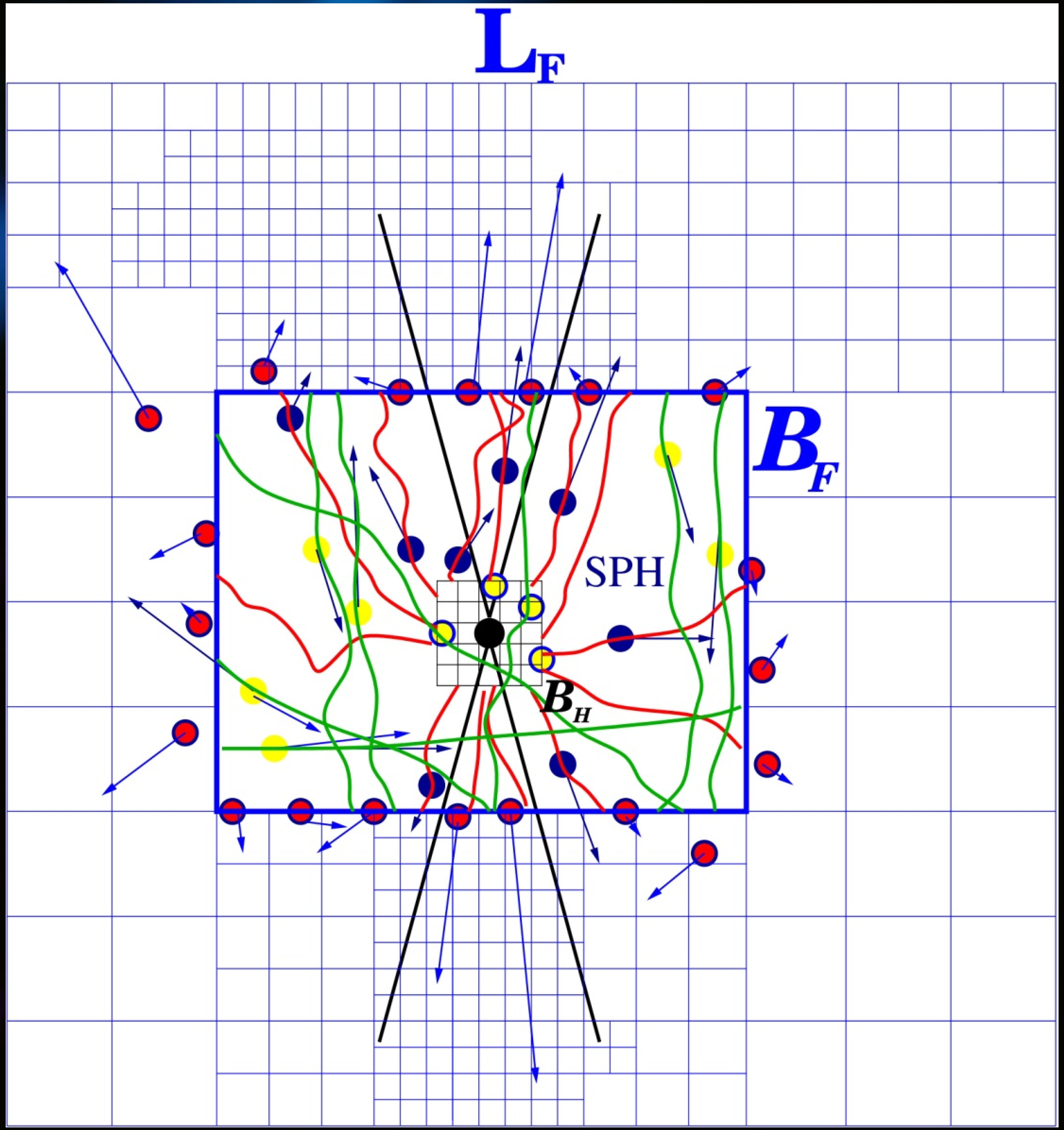

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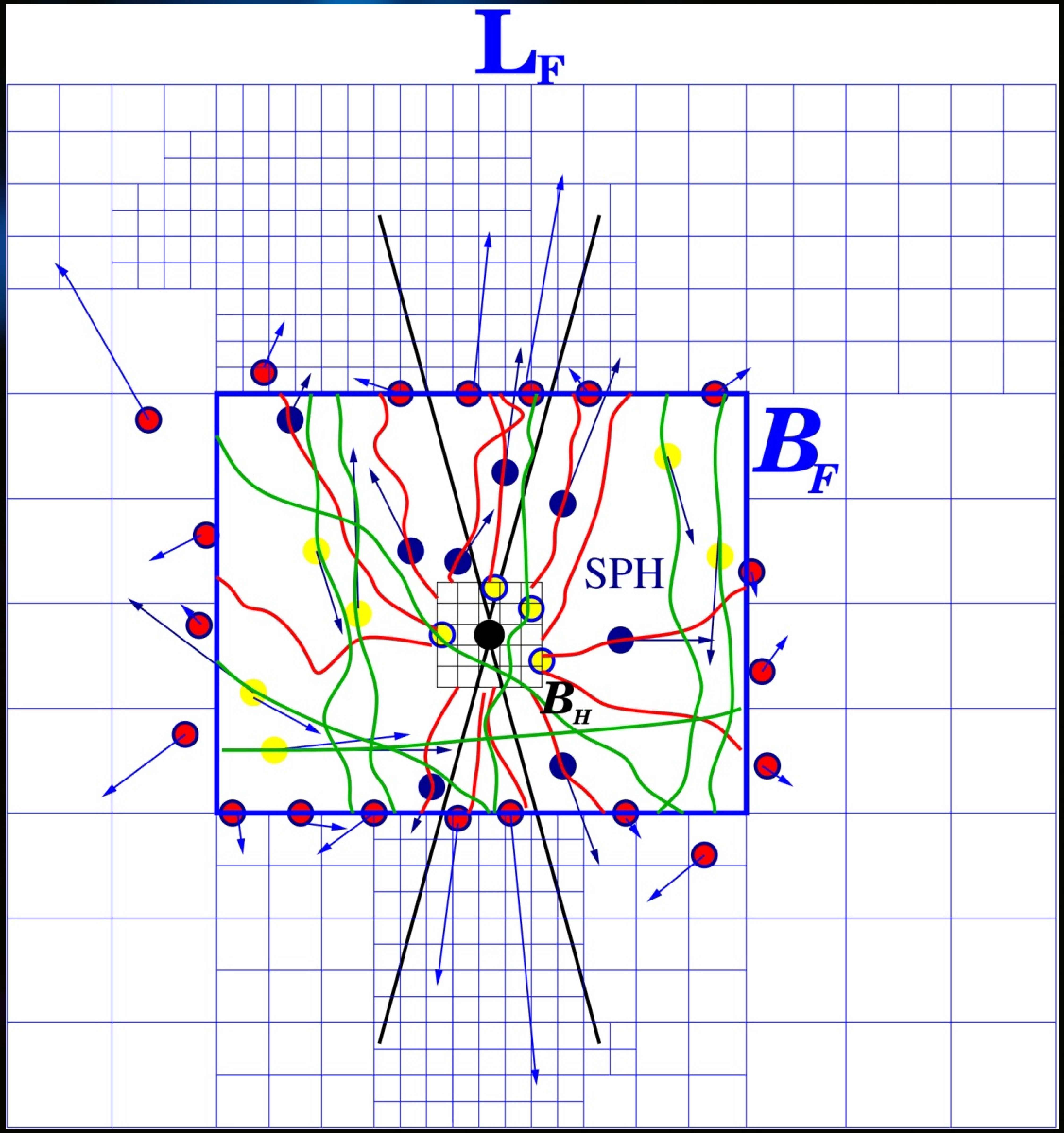

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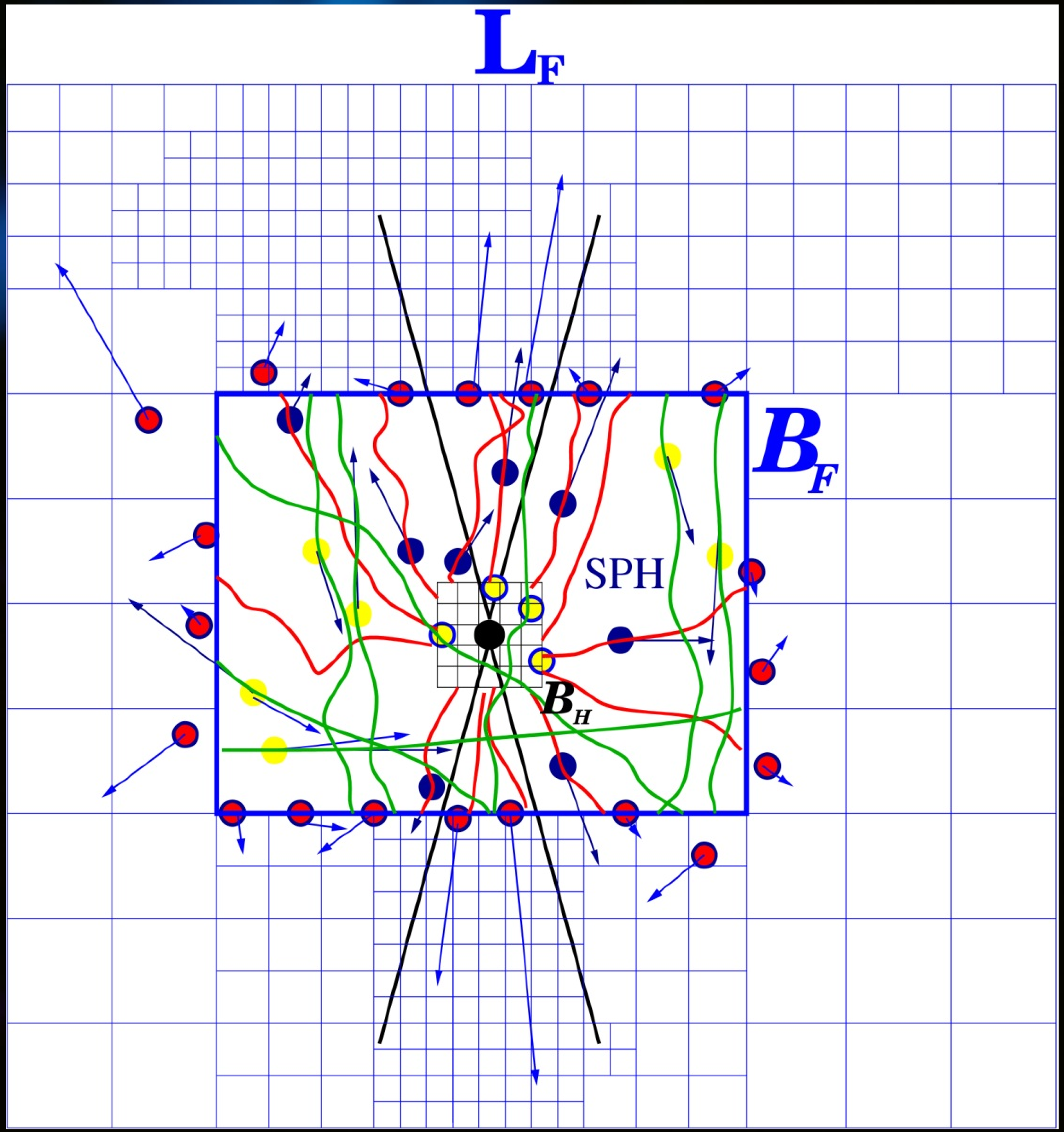

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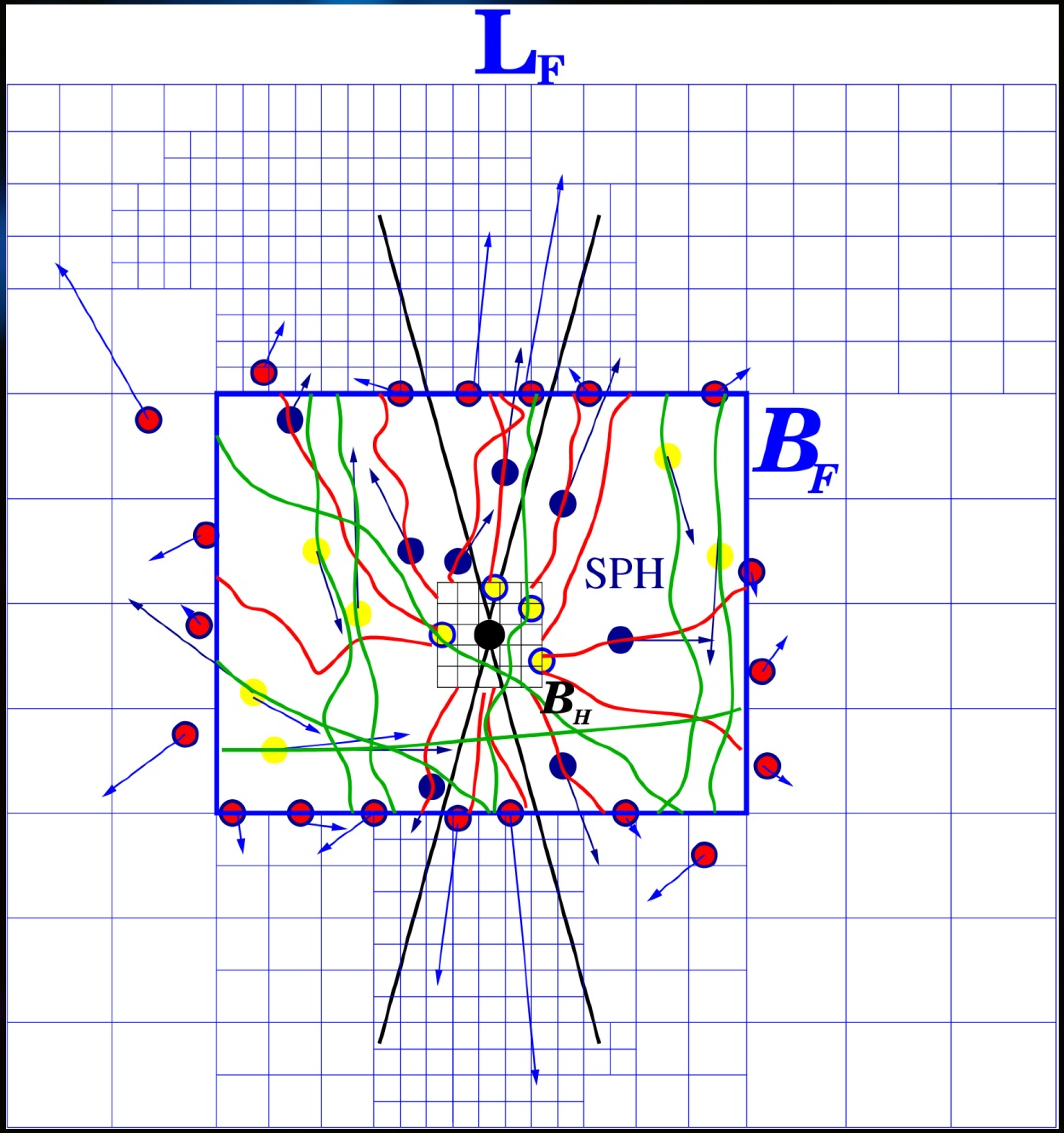

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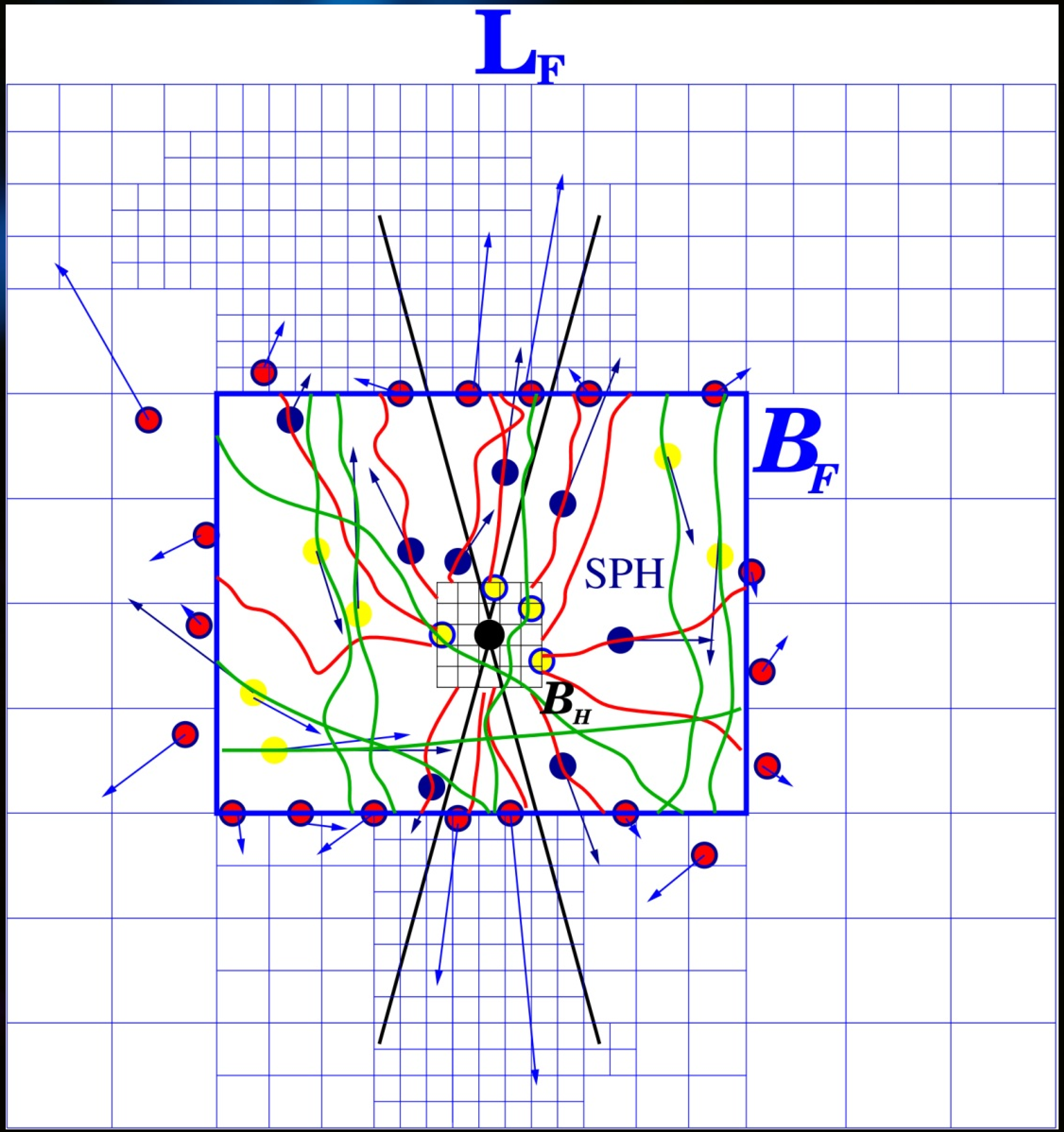

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  a. Flow resolution depends on the number of SPH within the interface.

Results: Backflow converges to the central SMBH

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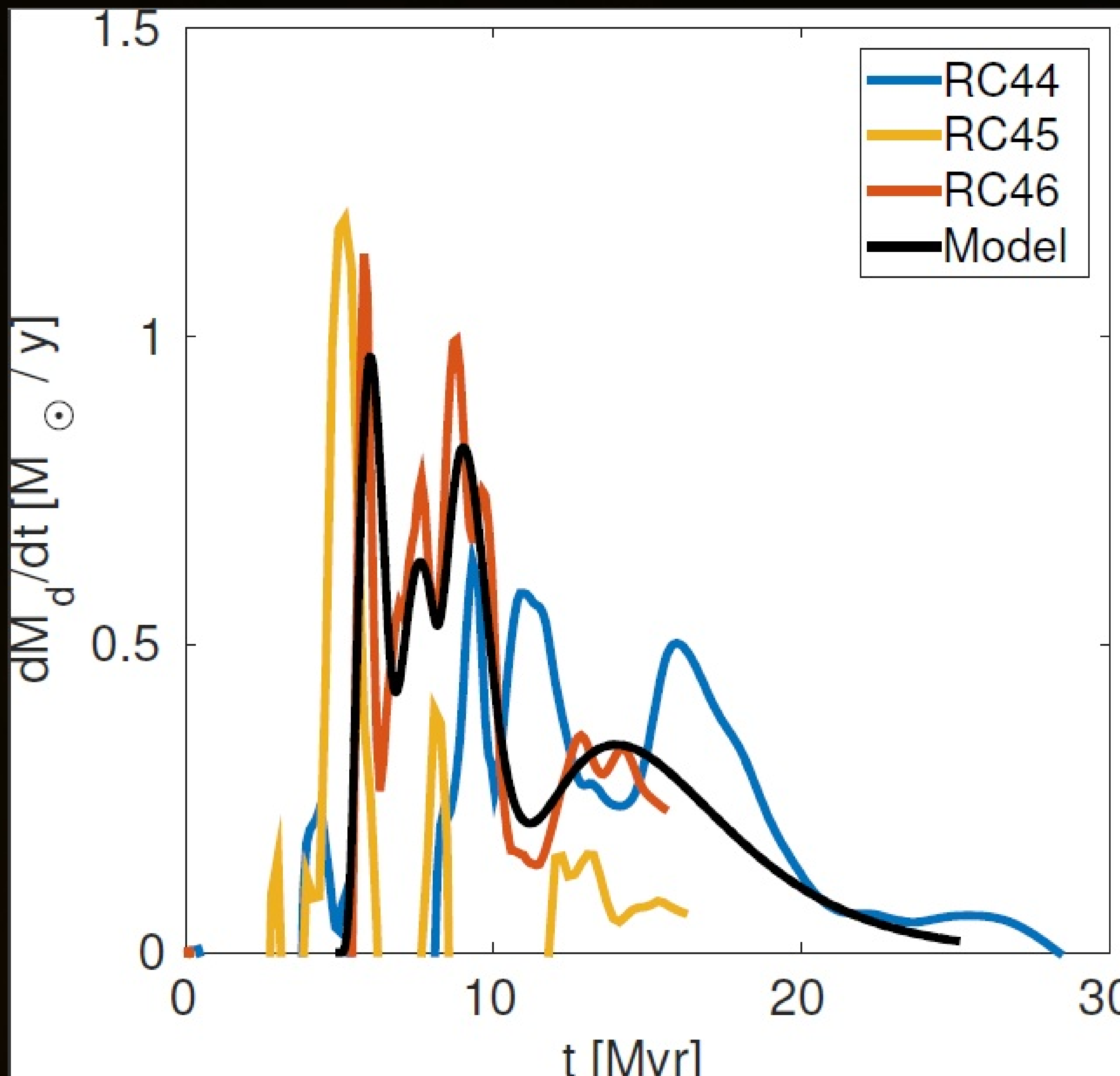
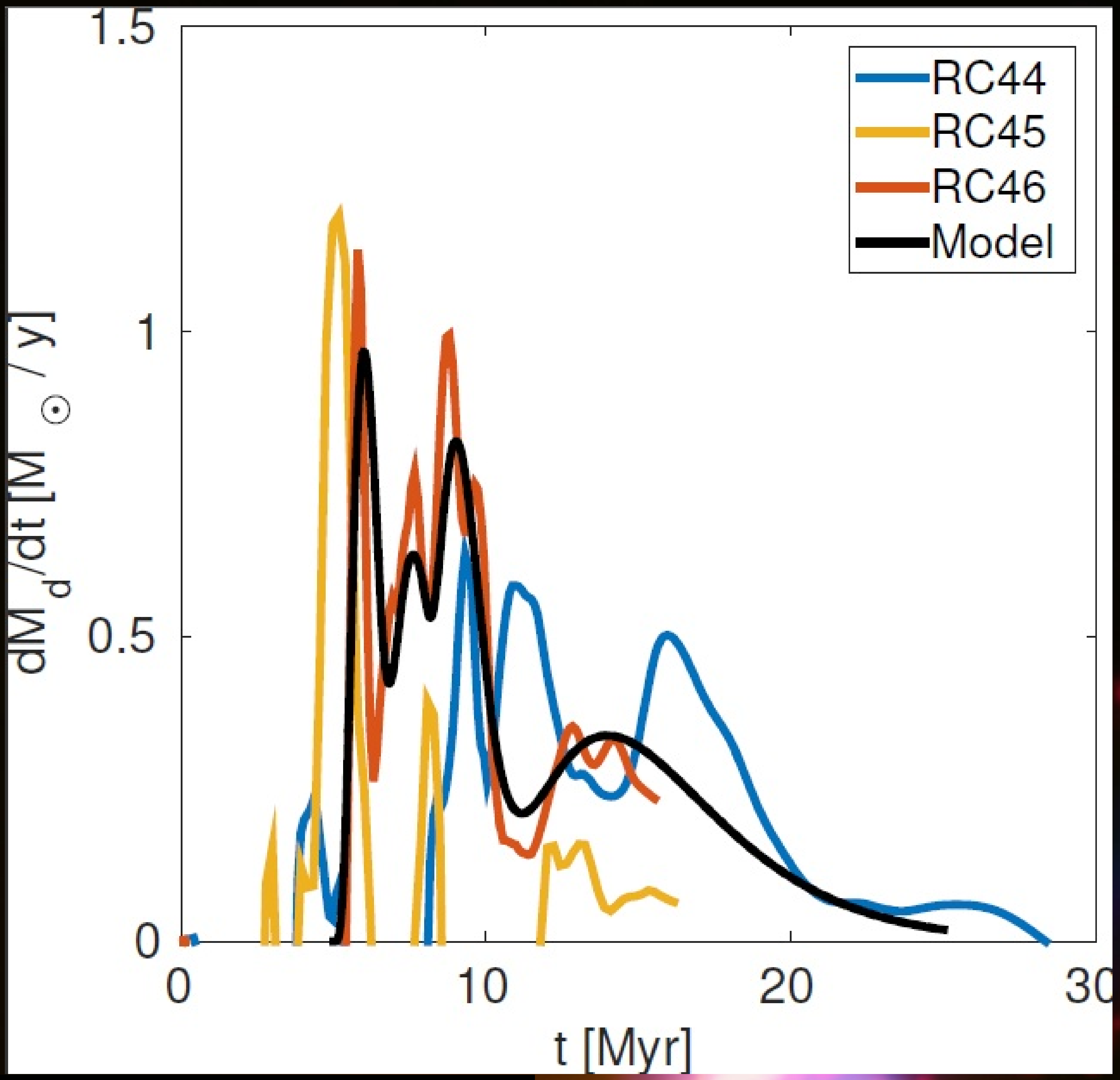
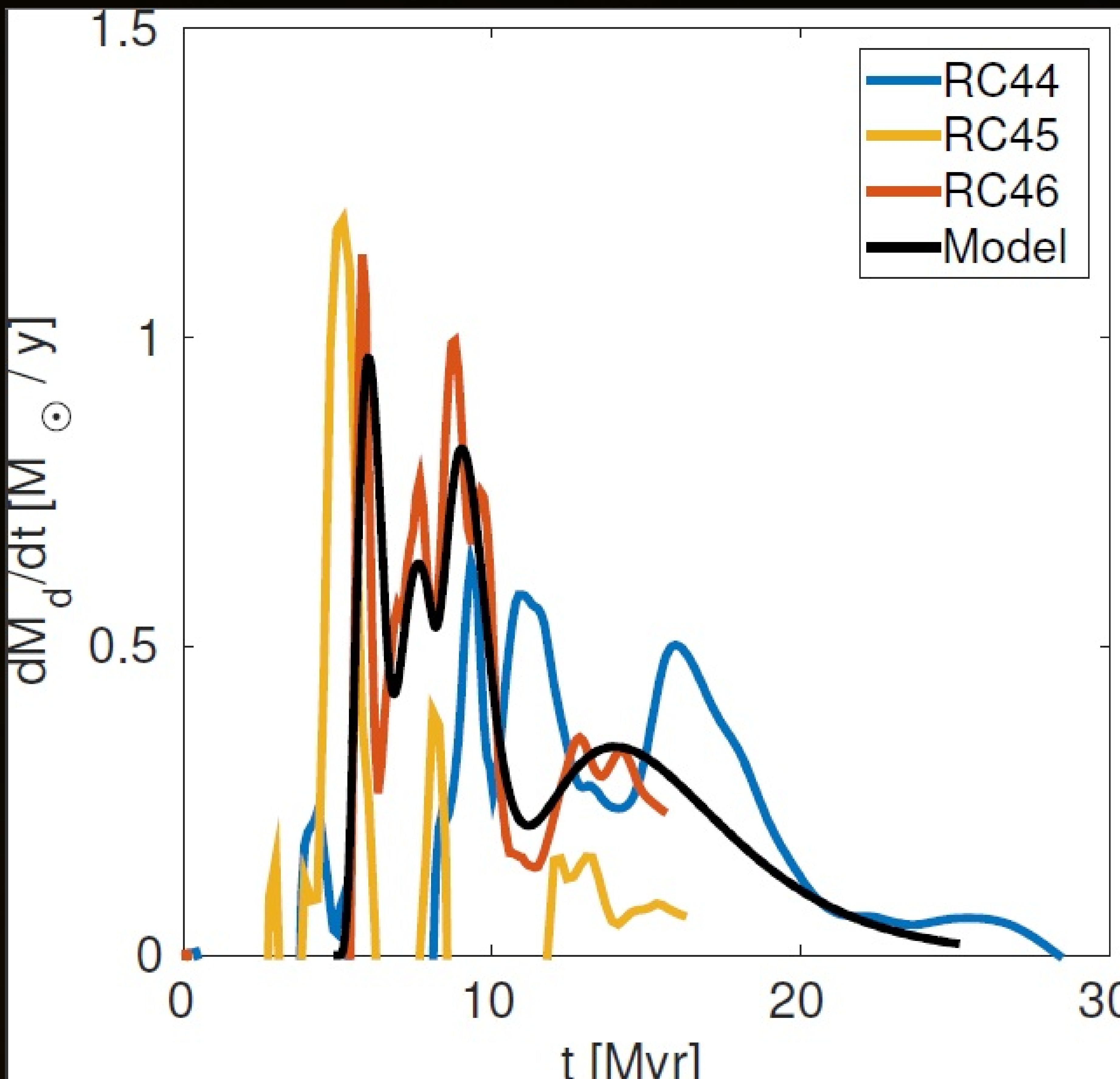


Results: Backflow converges to the central SMBH

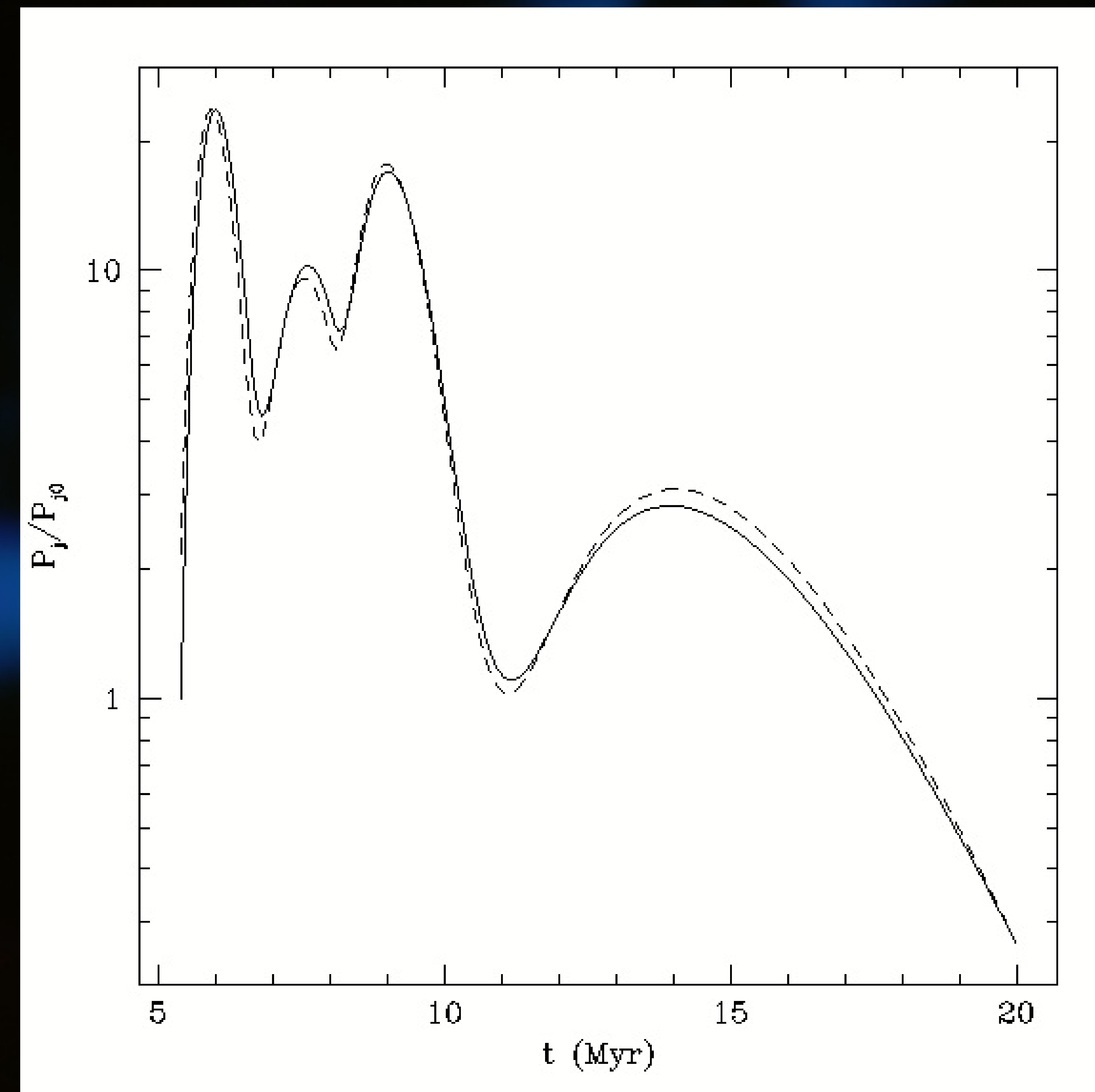


The backflow compression enhances dM_{BH}/dt up to a factor ~10

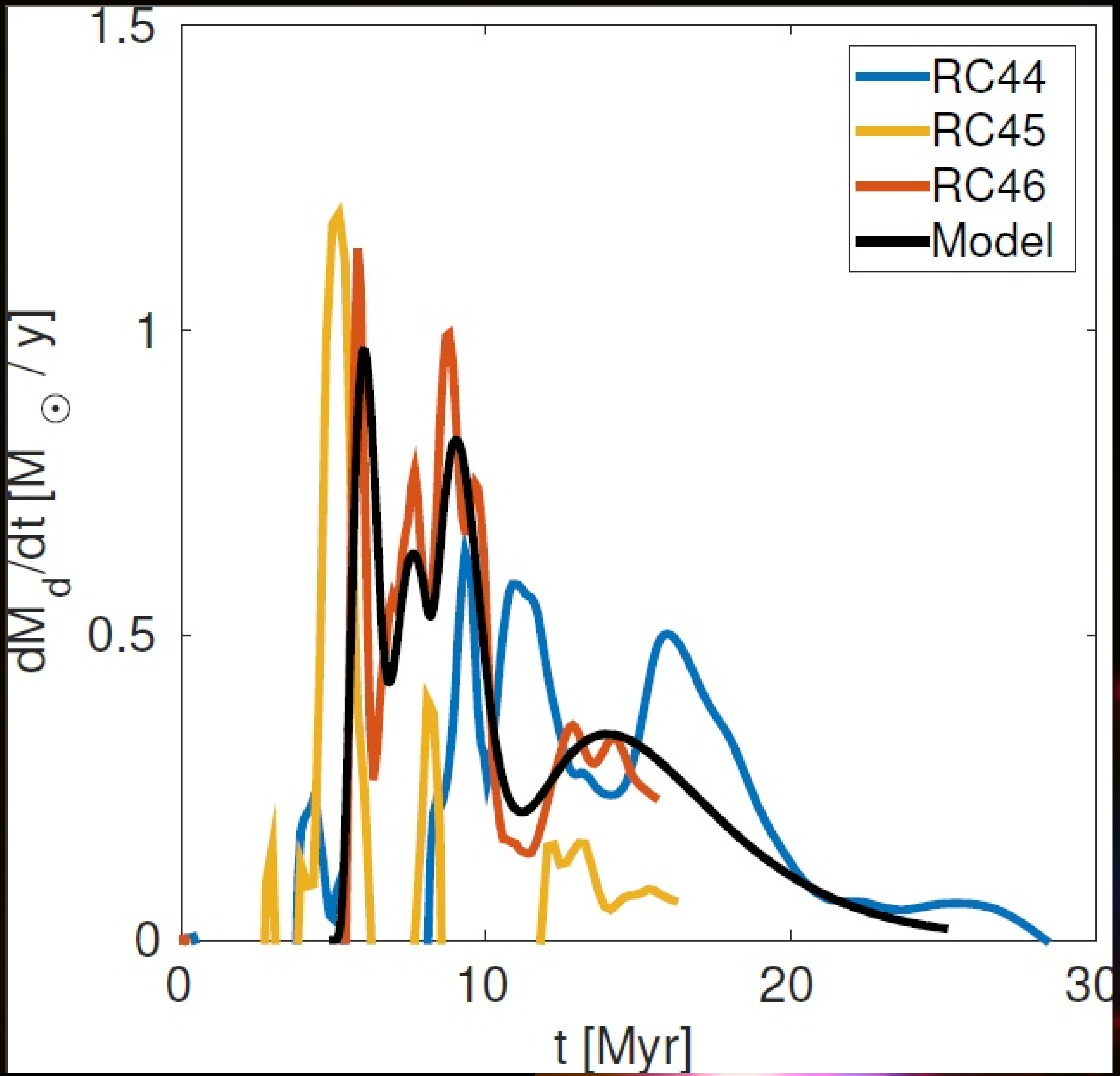
Results: Backflow converges to the central SMBH



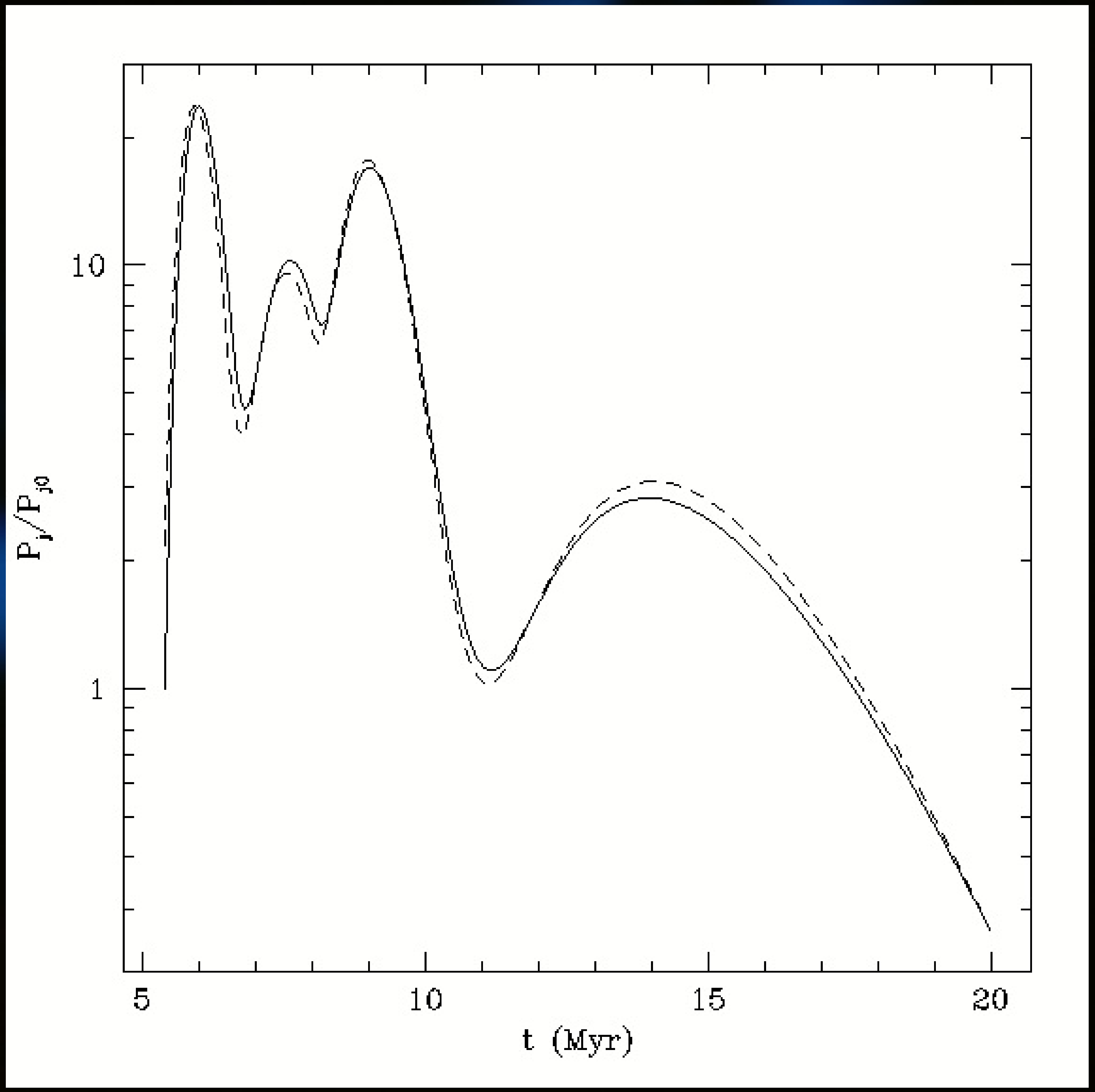
The backflow compression enhances dM_{BH}/dt up to a factor ~10



Results: Backflow converges to the central SMBH



The backflow compression enhances dM_{BH}/dt up to a factor ~10



- P_{jet} enhanced by a factor ~ 10 on $t \lesssim 10$ Myrs.

α⊥ β γ δ ε ζ η θ κ λ μ ν ξ ο π ρ ς σ τ υ φ χ ψ ω
Γ Δ Θ Λ Ξ Ρ Σ Φ Ω

→ ≃ ∾ ∝ ≤ ≥ ⊙ ≲ ≳ ∅ ∑ ± ∓ ∊ ∈ ∄ ∀ ≫ ≪ ≡ ≄ ≠ ∗ Δ ∂ ∫ ∮ ∇ Å ⊥ ∥
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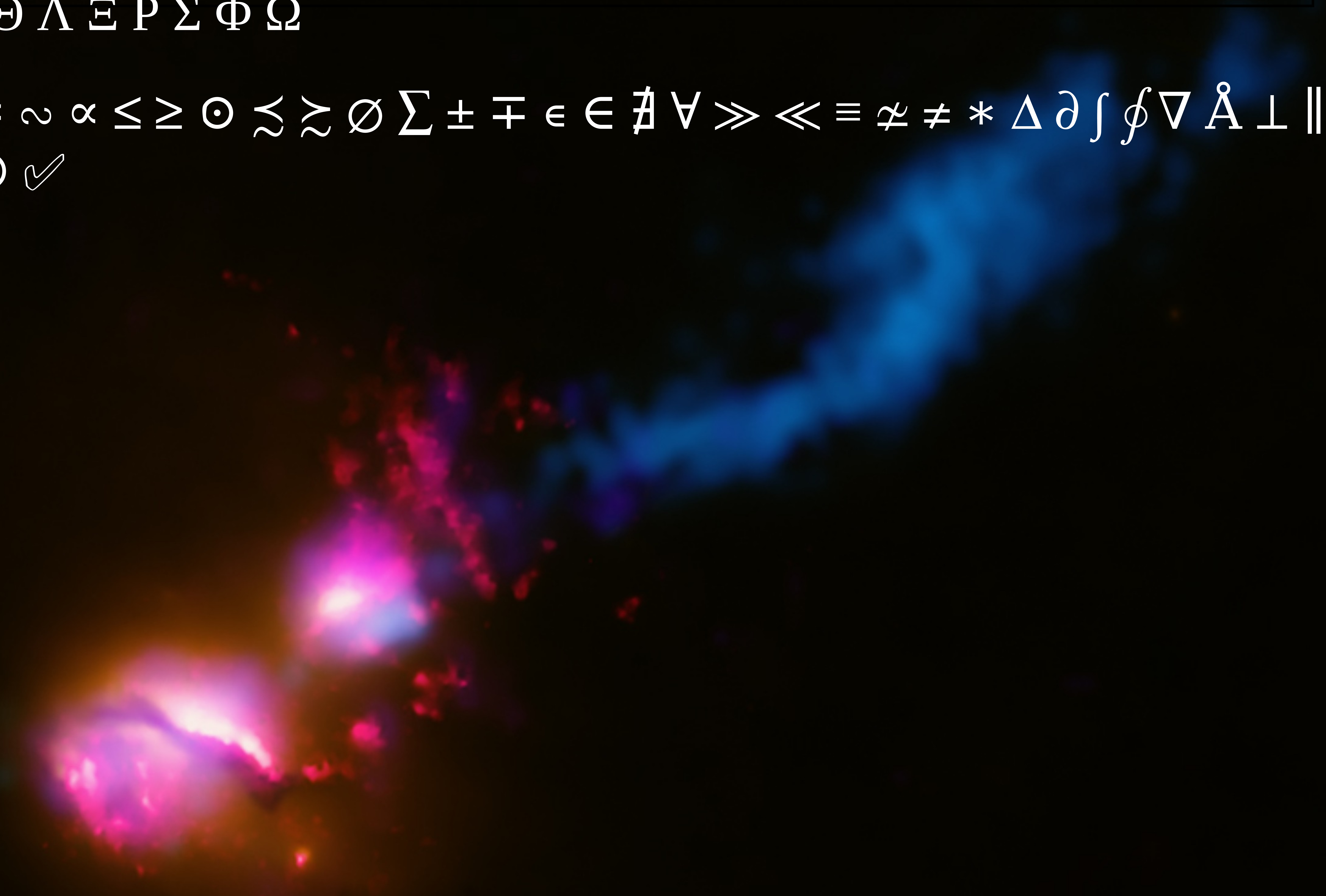


Moran, J. M., ASP Conf.Ser. 395, 87 (2008)

Efficiency factor ε:

From observed luminosities and mass:

$$\dot{m} = \frac{L}{\epsilon c^2} \approx 0.18 \frac{1}{\epsilon} \left(\frac{L}{10^{46}\,\mathrm{erg/s}} \right) \left(\frac{M_\odot}{1\,\mathrm{yr}} \right)$$

→ even for modest values of $\dot{m}$ one gets very high values of the mass-radiation energy conversion factor ε.

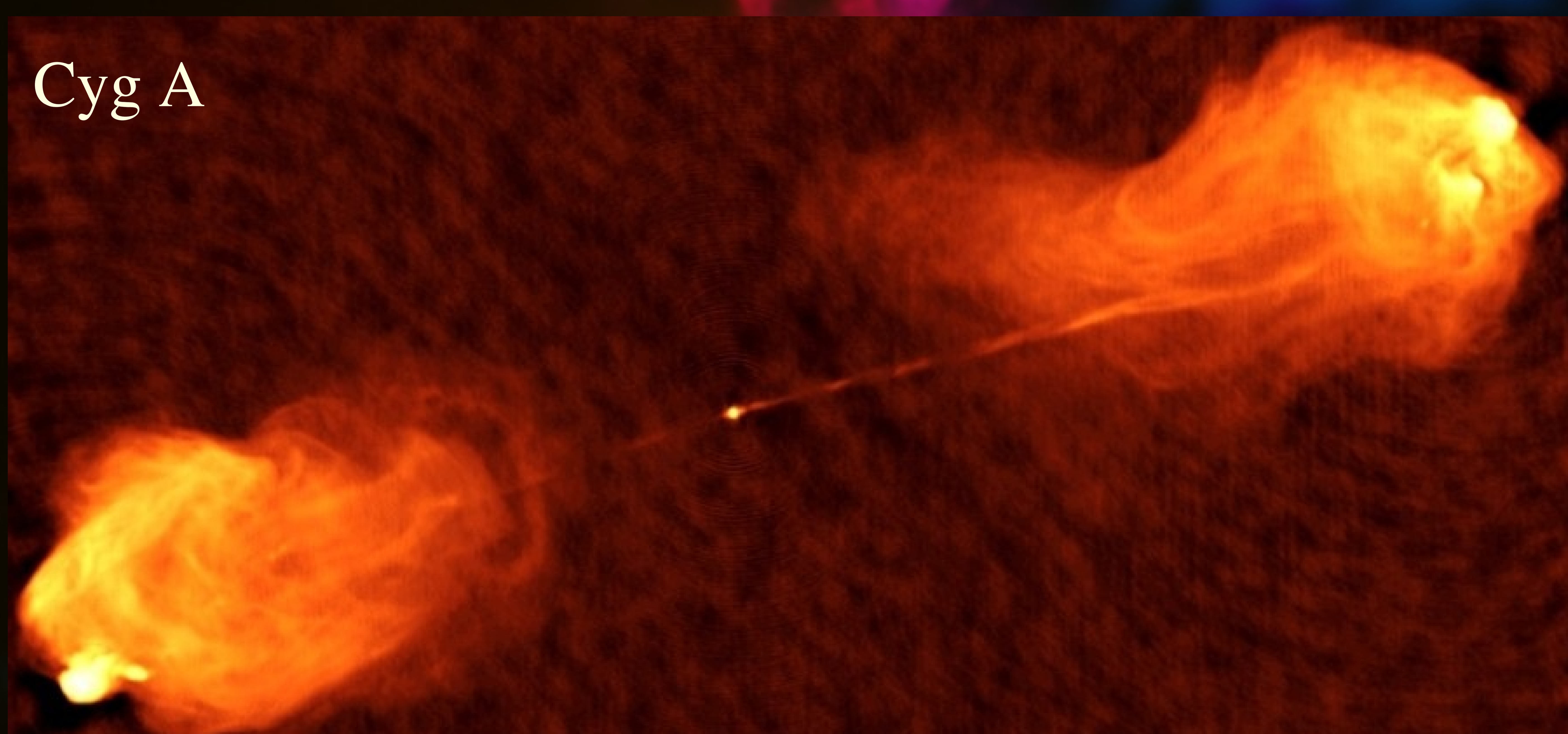
Recall that nuclear fusion conversion factors: $\varepsilon_{nuc} \lesssim 7 * 10^{-3}$

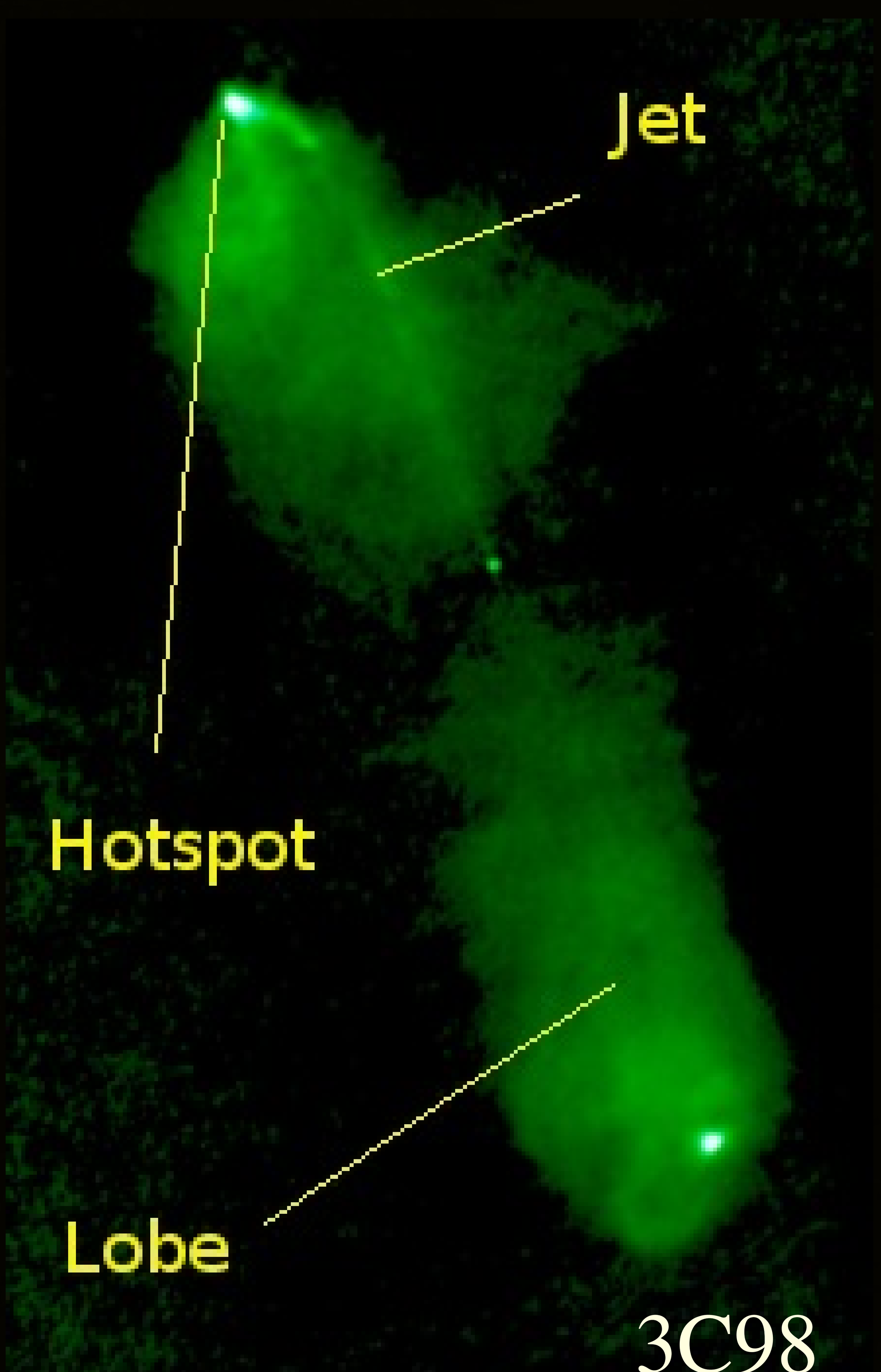
SMBHs are the most efficient *engines* to convert mass-energy into radiation and mechanical power (relativistic jets).

AGNs/QSO feedback: current paradigm

"Quasar" mode: powerful ($L \simeq 10^{46}$-10^{47} erg s^{-1}) radio emission from the subparsec accretion region around the central SMBH → $L \geq L_{Edd}$ → powerful outflows blow away the host galaxy's ISM → quick *inhibition of star formation* (**negative** feedback)

"Radio" mode: a relativistic jet from the accretion region conveys energy (and little momentum) into the host galaxy's ISM → inflates a *cocoon* of hot ($T_c \simeq 10^{8\text{-}9.5}$ K) low density ($n_e \simeq 10^{-4}$-10^{-1} cm^{-3}) high β plasma





Quasar vs. Radio: **isotropic** vs. **directional** feedback

BH feedback: how BHs *inhibit* star formation in their host galaxies.

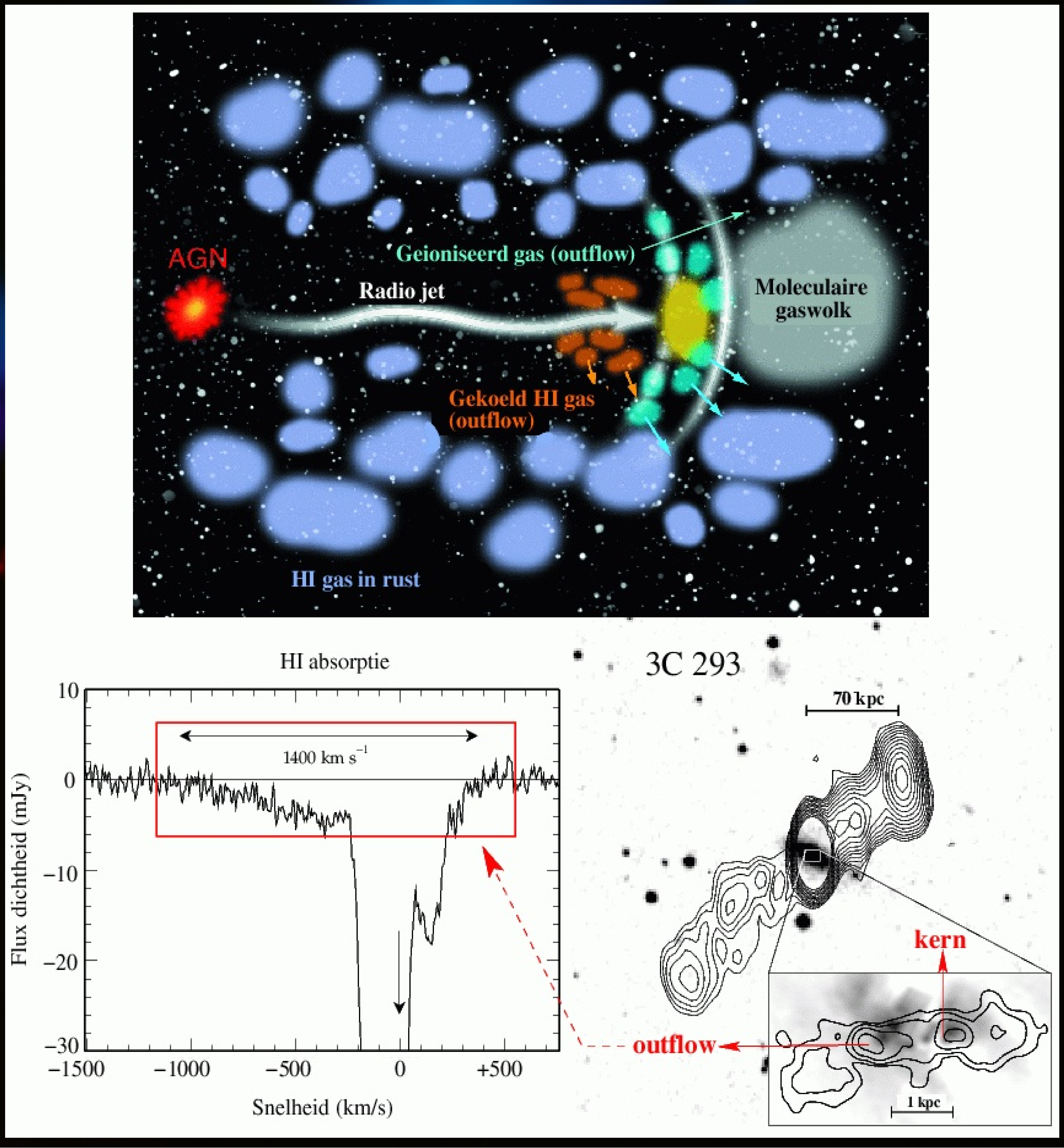
Relativistic jets emitted by AGNs enter the Interstellar, star-forming gas of their host galaxies.

- SF Clouds are shocked and heated up.
- Critical mass for Star formation (Bonnor-Ebert mass):

$$M_{\rm max} \simeq 1.14 \frac{c_{\rm is}^2}{G^{3/2} p_0^{1/2}}$$

c_{is} : sound speed within the cloud
p_0: pressure of the confining warm phase

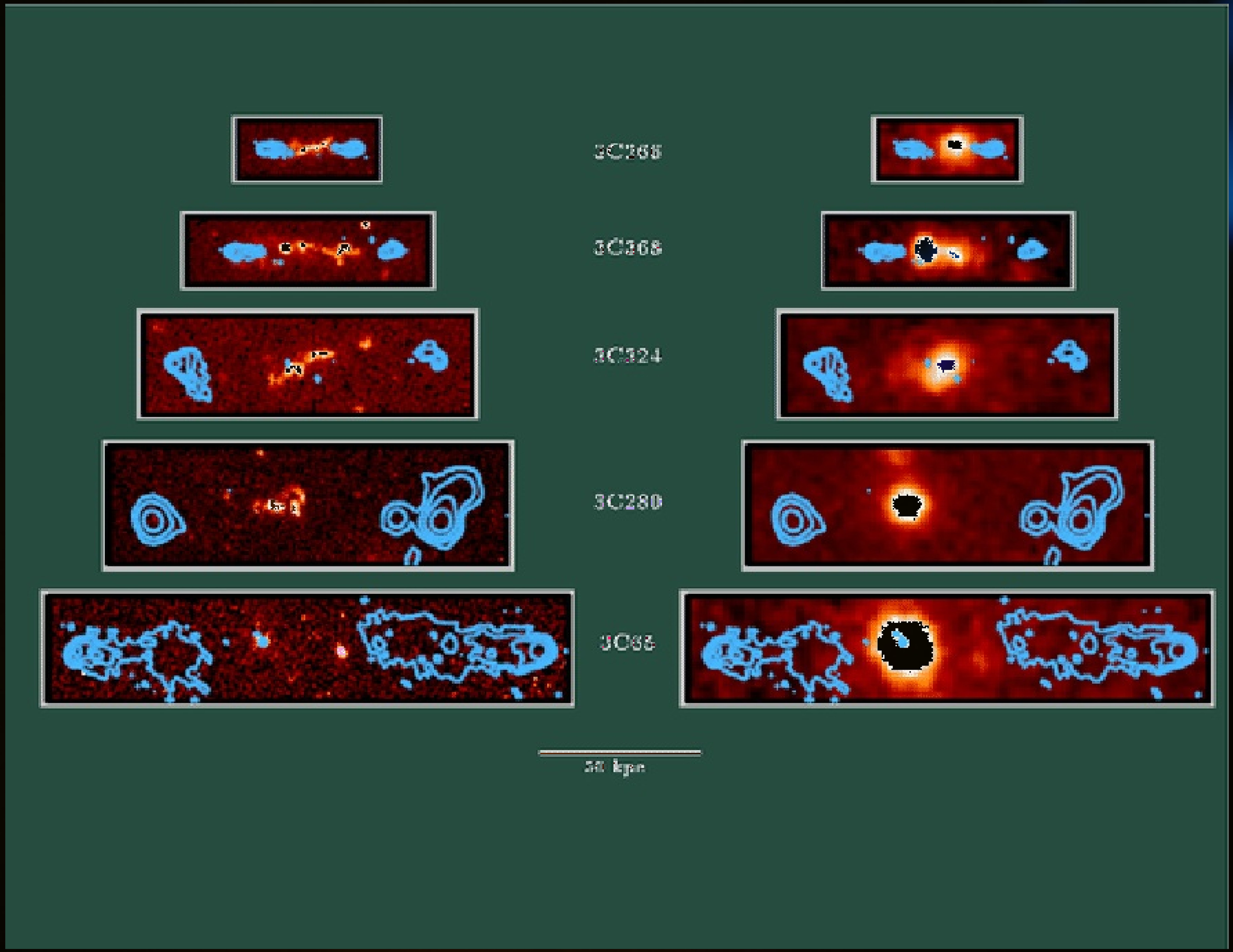
- Larger T_c → Larger M_{max} → Supernovae → Winds blow out clouds → No more Star Form.



Positive feedback (?): the Radio/optical alignment in RGs

IR (star formation) and radio (jet) emission contours tend to be aligned in high-z radio galaxies.

Best, Longair and Rottgering (1996): 28 HzRG, FRII with both HST (optical), IRCAM (2.2 μm) and radio (1.8 GHz) contour maps.



- Radio lobes extending from 300 to 1200 Kpc
- All these galaxies are E's : yet regions of *recent star formation* (optical, colour isocontours) are aligned with the jets
- Redshift selection ($1 \lesssim z \lesssim 1.3$) ensures similar intrinsic $P_{1.8}$ → hom. sample
- Similar for *small* RGs sample

Numerical experiment of jet propagation and feedback

A&A 617, A58 (2018)
https://doi.org/10.1051/0004-6361/201832582

Astronomy & Astrophysics

Feedback from reorienting AGN jets

I. Jet–ICM coupling, cavity properties and global energetics*

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Jet propagation in galaxies

Numerical experiments provide a quantitative framework to describe how feedback connects the small accretion, sub-parsec scale to the large, kiloparsec galaxy scale.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla p_* = \rho \mathbf{g} + \nabla \cdot \tau$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\mathbf{v}(\rho E + p_*) - \mathbf{B}(\mathbf{v} \cdot \mathbf{B})) = \rho \mathbf{g} \cdot \mathbf{v} + \nabla \cdot (\mathbf{v} \cdot \tau + \sigma \nabla T) + \nabla \cdot (\mathbf{B} \times (\eta \nabla \times \mathbf{B})$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = -\nabla \times (\eta \nabla \times \mathbf{B})$$

where

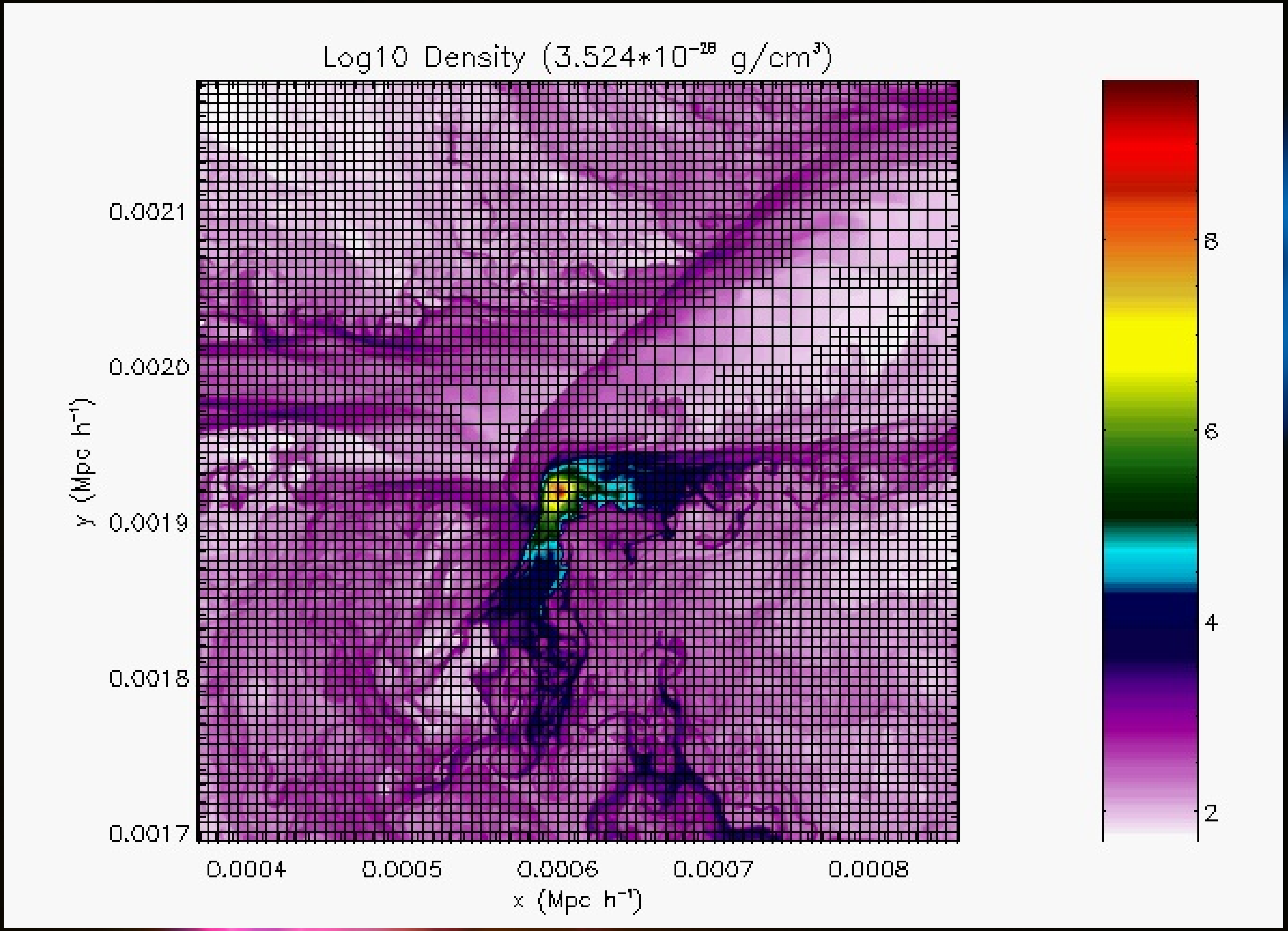
$$p_* = p + \frac{B^2}{2},$$

$$E = \frac{1}{2} v^2 + \epsilon + \frac{1}{2}\frac{B^2}{\rho},$$

$$\tau = \mu \left((\nabla \mathbf{v}) + (\nabla \mathbf{v})^{\mathrm{T}} - \frac{2}{3}(\nabla \cdot \mathbf{v})\mathbf{I} \right)$$

We actually solve a *discretized version* of this system → convergence issues e.g. under *shock collisions* are not *analytically* (numerical analysis) really clear....

Multiple shocks and their downstream acoustic waves are natural by-products of jet propagation in the Interstellar Medium (ISM) of its host galaxy.



- *Shock-capturing* centered discretization schemes strongly <u>limit numerical diffusion</u> and provide a *reliable* tool to a quantitative study of the rich thermodynamic phenomenology inside the cocoons.
- *Jet-(cold) cloud* interactions are resolved to a <u>quantifiable accuracy</u> through *Adaptive Mesh Refinement* discretization.

Jet propagation in galaxies

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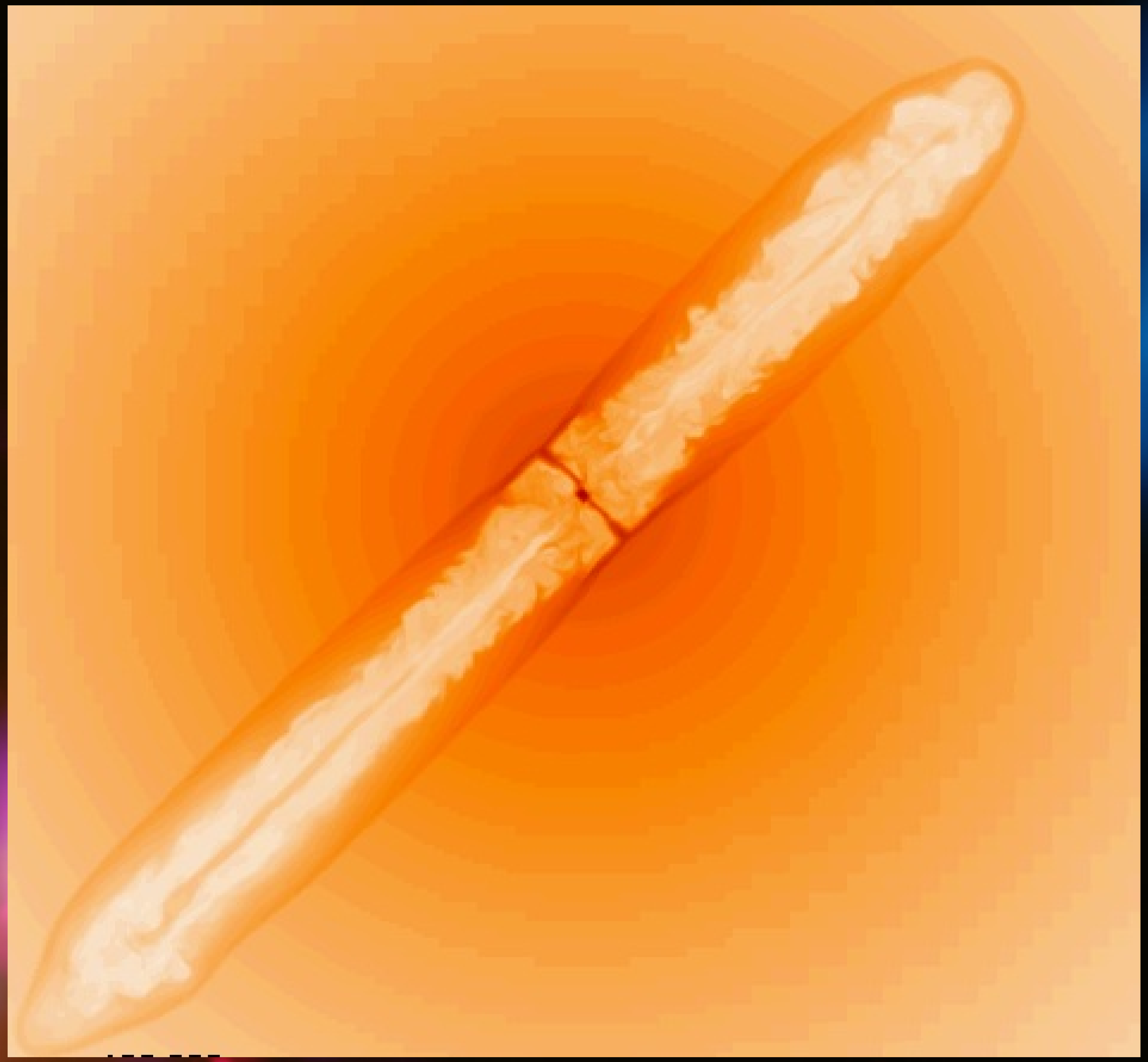


- Cocoon: turbulence, expansion, slowing down due to ISM's ram pressure
- Is there a feedback also from the ISM down to the very small central accretion scale?
- Can this feedback promote a self-regulation of AGNs activity?
- Could the environment play a role in self-regulation of AGN's activity?

Backflows in jet-powered AGNs

Standard model of jet propagating into the ISM of its host galaxy (Alexander, 1980):
Jet carves a *cocoon*

$n_c \ll n_{env}$, $T_c \gg T_{env}$ but: $p_c = n_c T_c \gg n_{env} T_{env}$ → cocoon (initially) expands

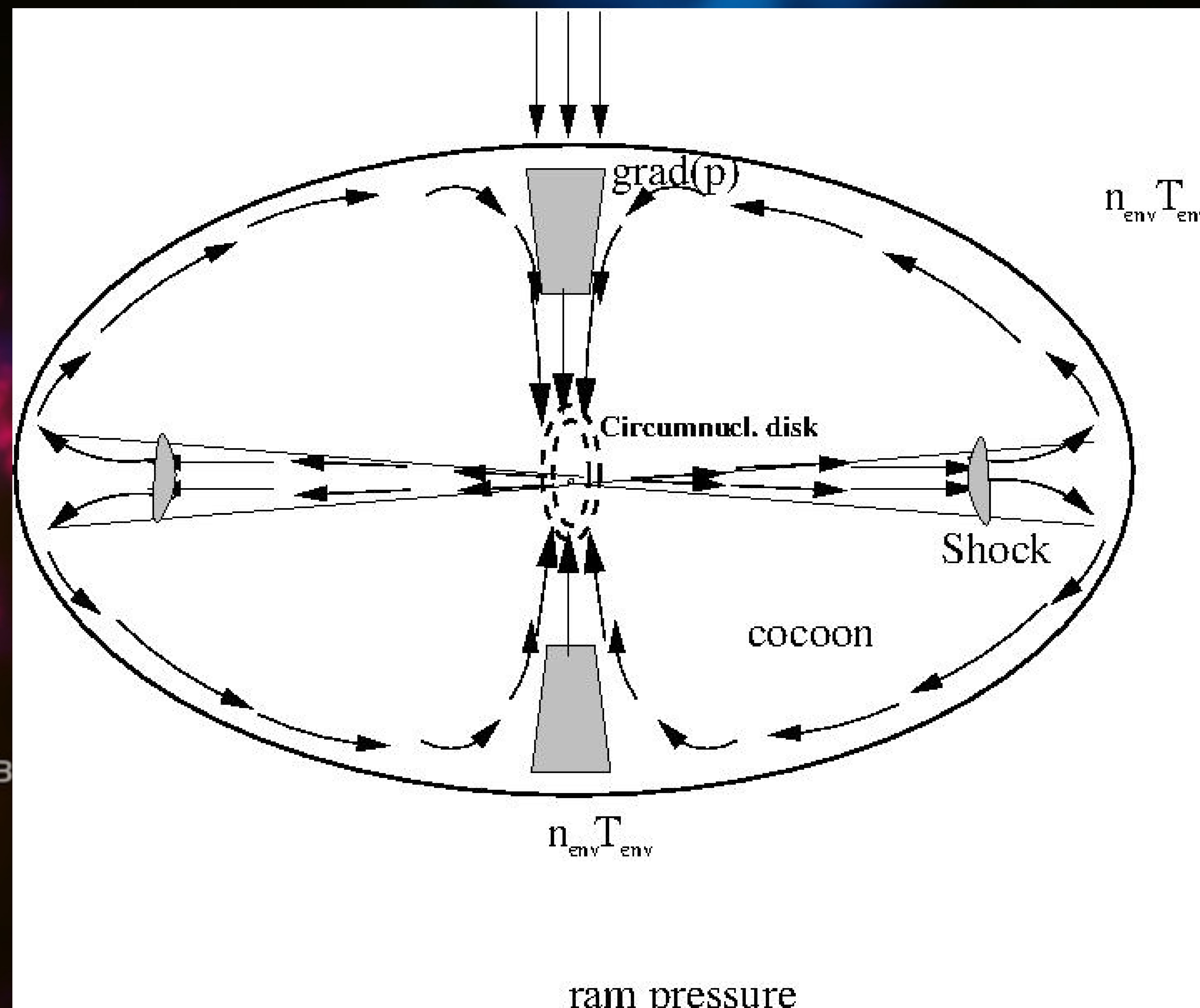
In FRII: $V_{jet} \gg c_s \gtrsim V_c$ →
Shock

What is the fate of the shocked gas?

1. $V_{ps} \simeq 0$ → thermalization
2. $\nabla x V \neq 0$ → *backflow*

BOTH these take place.
On the meridional plane $\nabla p \neq 0$

Powerful Jet from a Supermassive B

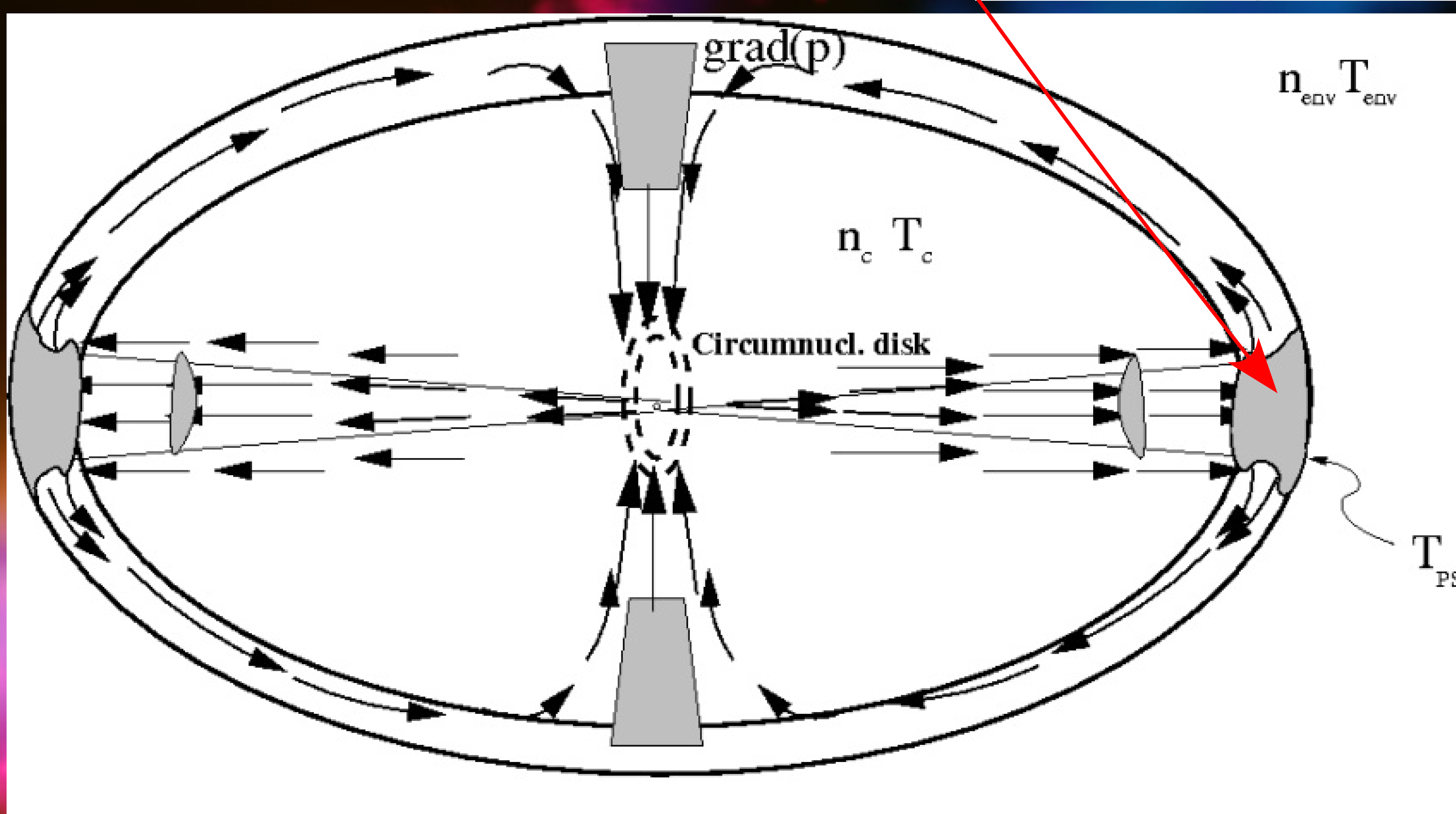


Backflows from first principles hydrodynamics

- Crocco's theorem: vorticity arises from *curved shock fronts* (ZAMM 17, 1, 1937)
- Origin is *thermodynamical* : vorticity is produced from discontinuities in h and S before the Hot Spot

$$\vec{v} \times \mathrm{curl}\,\vec{v} = \nabla h - T\nabla S.$$

$$h = U + \frac{p}{\rho} + \frac{1}{2}v^2$$



- Random curvature fluctuations → non-Markov turbulence
- Macroscopic curvature → backflow

- Backflow is *temporally persistent* but *spatially incoherent* and *not axisymmetric* all way down to the central accretion region

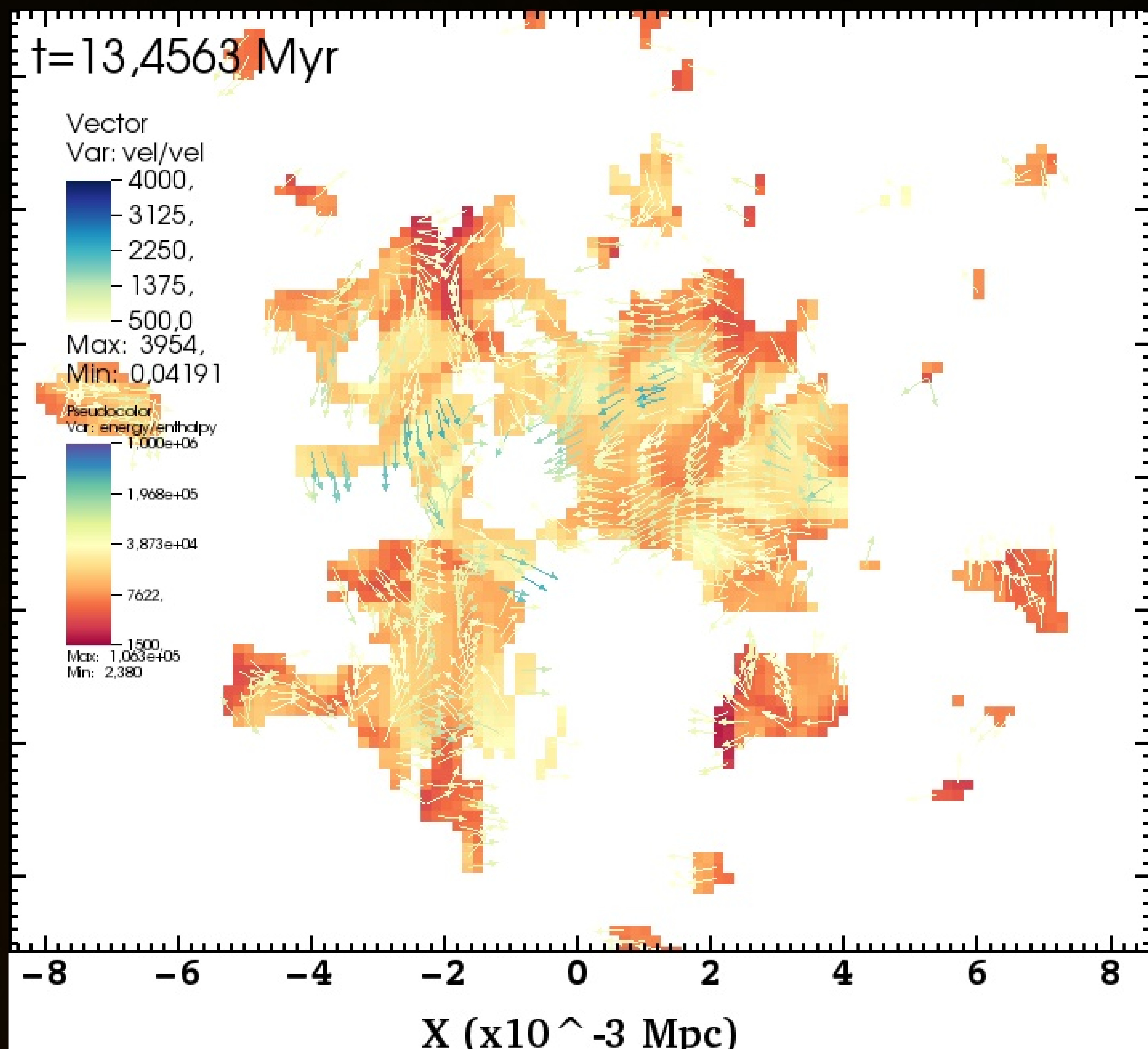
Numerical experiments

Name	Simulation Resolution [pc]	t_{max} [Myr]	Halo M_{200} [$M_\odot$]	$t_{cool,0}$ [yr]	Jet P_{jet} [erg/s]	$\mathcal{M}_{jet}$	Δt_{jet} [Myr]	Backflowing mass (at given time) *Tot in cavity* [$M_\odot$]	*Central 2 kpcdisk* [$M_\odot$]
Elongated Cavity series									
EC42	156.25	473	1.7×10^{12}	6×10^8	10^{42}	5	79	4.84×10^5 (20 Myr)	1.28×10^4 (20 Myr)
EC43	156.25	140	1.7×10^{12}	6×10^8	10^{43}	5	42	4.69×10^5 (10 Myr)	7.11×10^3 (10 Myr)
EC44	156.25	115	1.7×10^{12}	6×10^8	10^{44}	5	21	9.92×10^5 (10 Myr)	1.9×10^4 (7 Myr)
Round Cavity series									
RC44	156.25	23.1	2.6×10^{12}	4×10^8	1.12×10^{44}	5	23.1	6.90×10^4 (10 Myr)	1.04×10^5 (10 Myr)
RC45	156.25	22.2	2.6×10^{12}	4×10^8	1.12×10^{45}	5	22.2	4.84×10^4 (8 Myr)	6.80×10^4 (8 Myr)
RC46	156.25	22.2	2.6×10^{12}	4×10^8	1.12×10^{46}	5	22.2	2.71×10^5 (7 Myr)	4.34×10^4 (7 Myr)

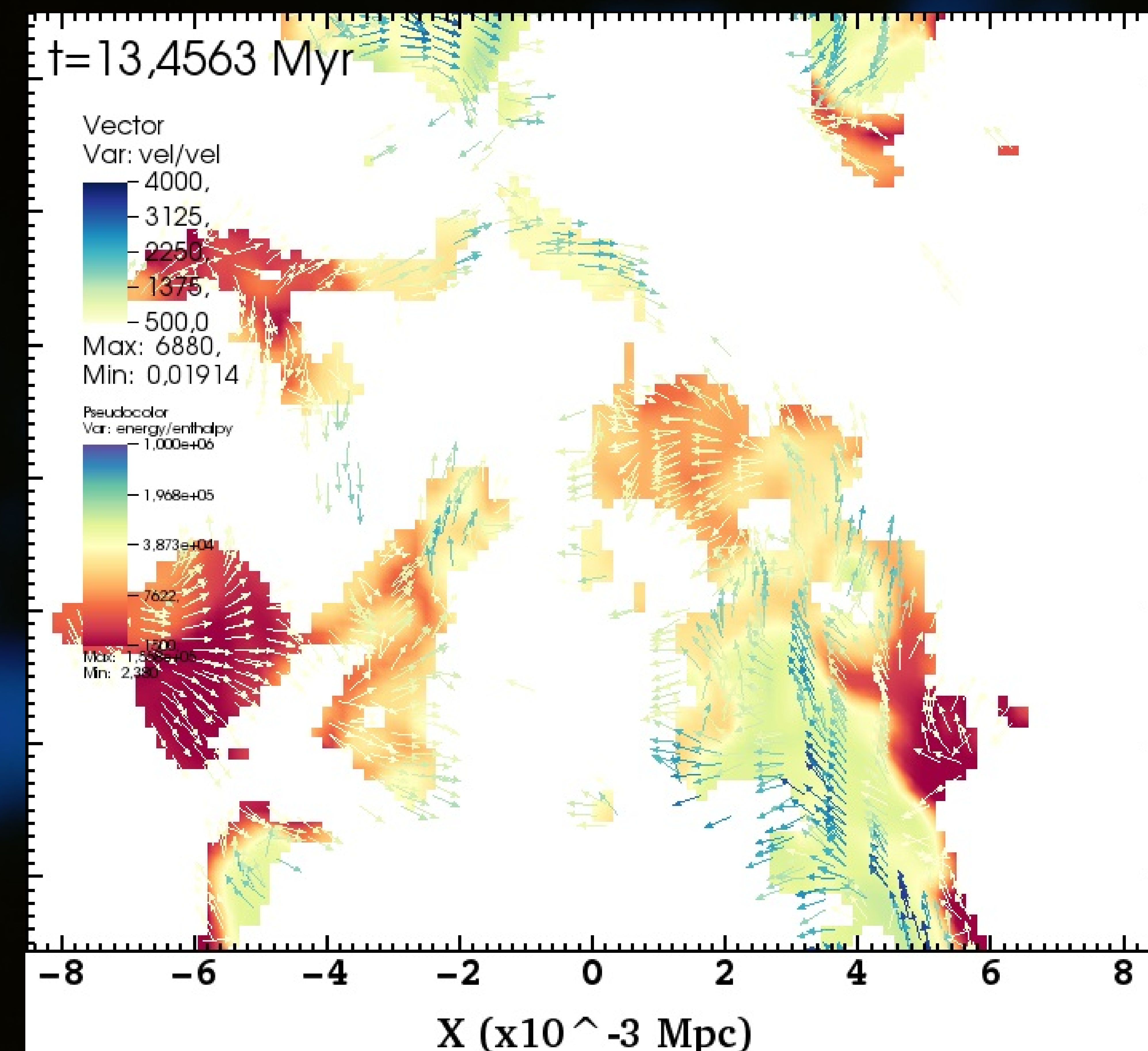
Table 1. Parameters, timings and bubbles' characteristics. All simulation parameters: run specifications (name, smallest cell side, simulation time), halo parameters (mass, central cooling time), jet parameters (power of each of the two jets, Mach number, time of activity) and total backflow gas mass at the given time (i.e. the total mass in the backflowing region isolated in Figures 1 to 4).

Here we consider only the FRII (with hotspot) series RC44-46.

Crocco mechanism at work



y=0



z=0

- Converging, patchy, intermittent flows feed the central accretion region
- Large-scale backflow *is bent in the meridional plane* and *shows intermittent spiral features*

Observational evidence for backflows

- Scattering from CMB on backflows: linear polarization

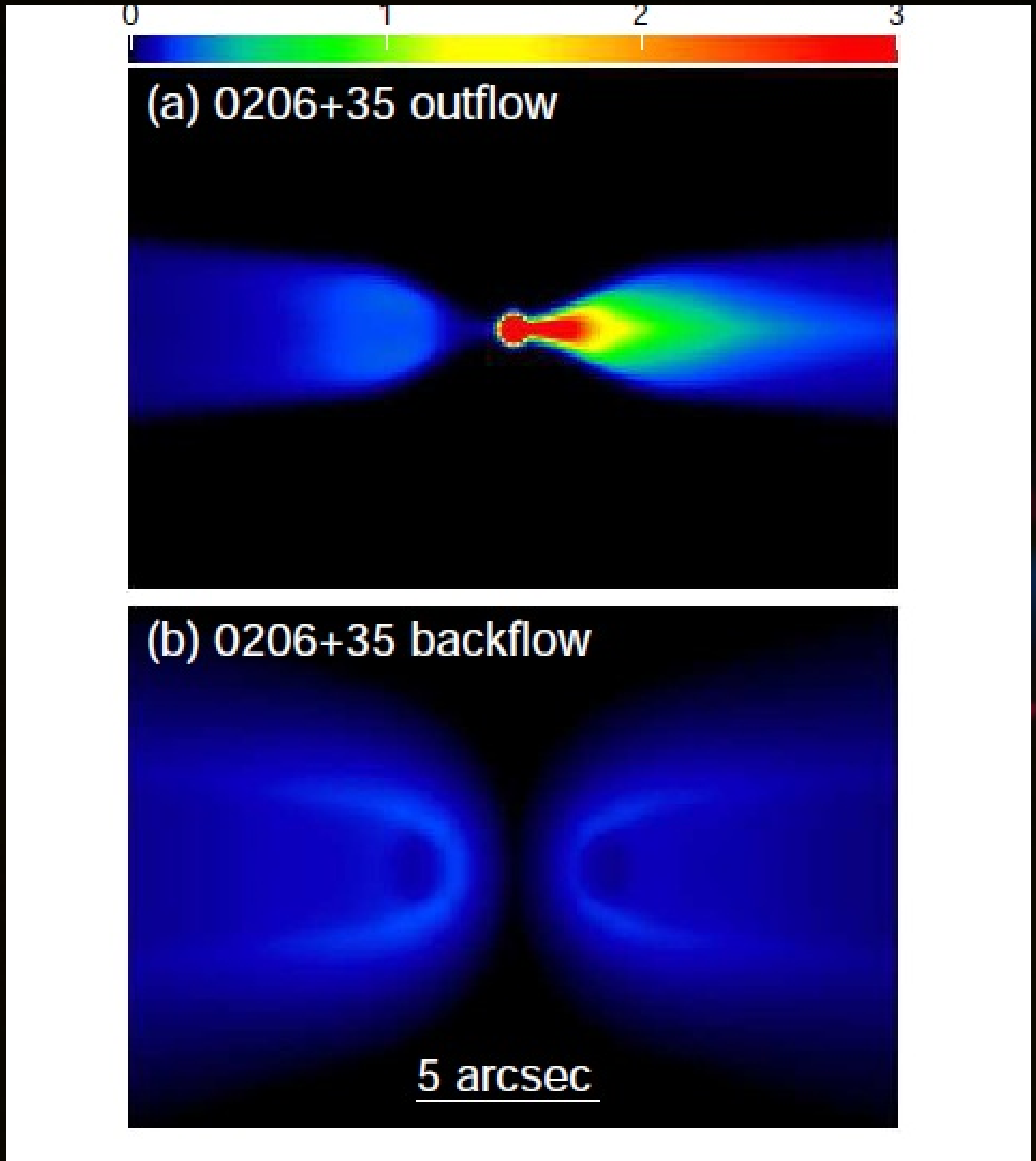
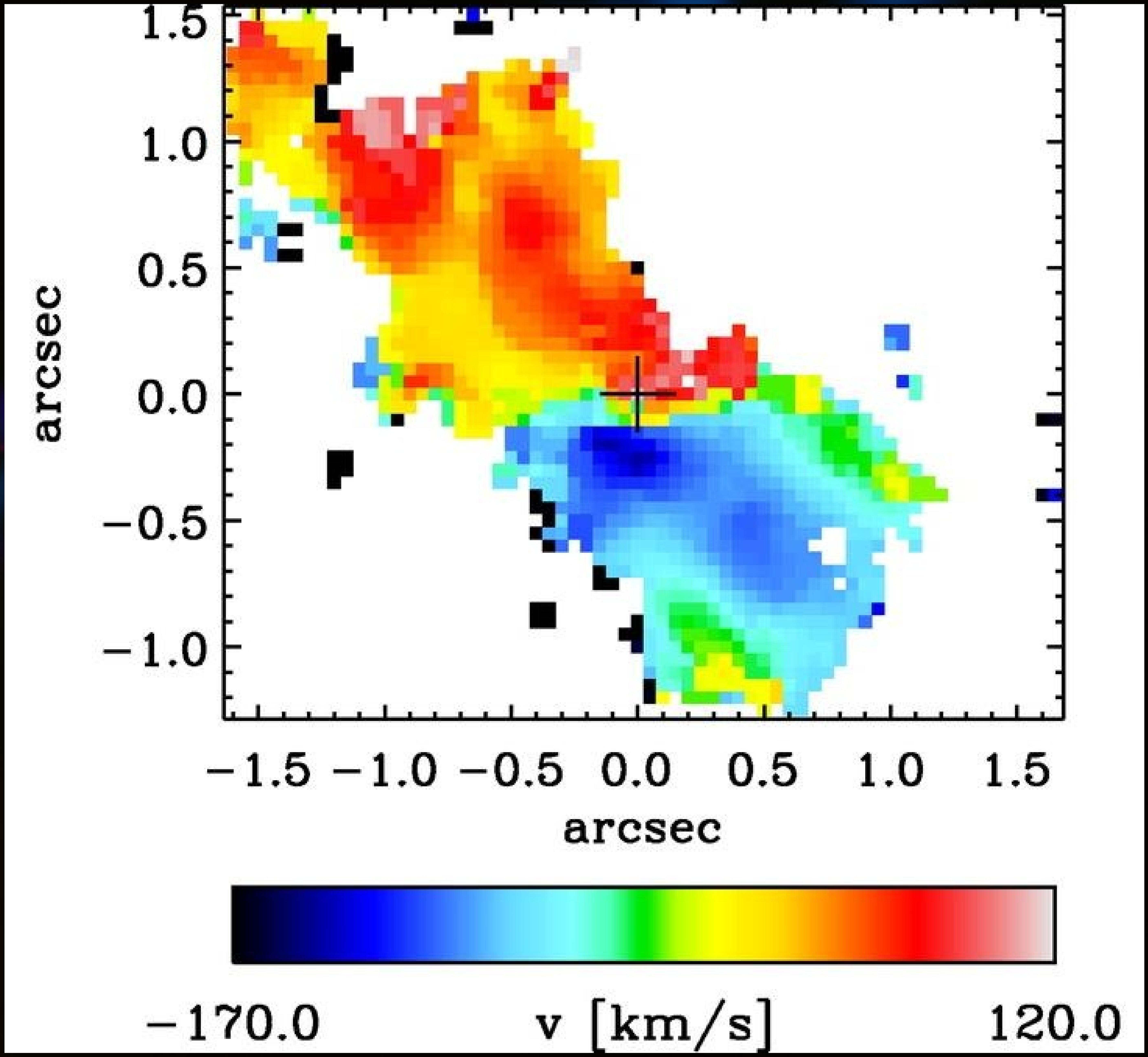


Figure 9. Predicted brightness distributions for the outflowing and back-flowing parts of the model for 0206+35. (a) outflow; (b) backflow.



Laing & Bridle, 2012: FRI, mildly relativistic velocities

Neumayer et al, 2007: CEN A

Deeper analysis with MUSE: Hamer et al., 2015

AGN backflows:
a self-regulation mechanism of growth and feedback

Mon. Not. R. Astron. Soc. 000, 1–13 (2016) Printed 21 July 2016 (MN LaTeX style file v2.2)

Backflows by AGN jets: Global properties and their influence on SMBH accretion

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[4] *Department of Physics and Astronomy, The Johns Hopkins University Homewood Campus, Baltimore, MD 21218, USA*

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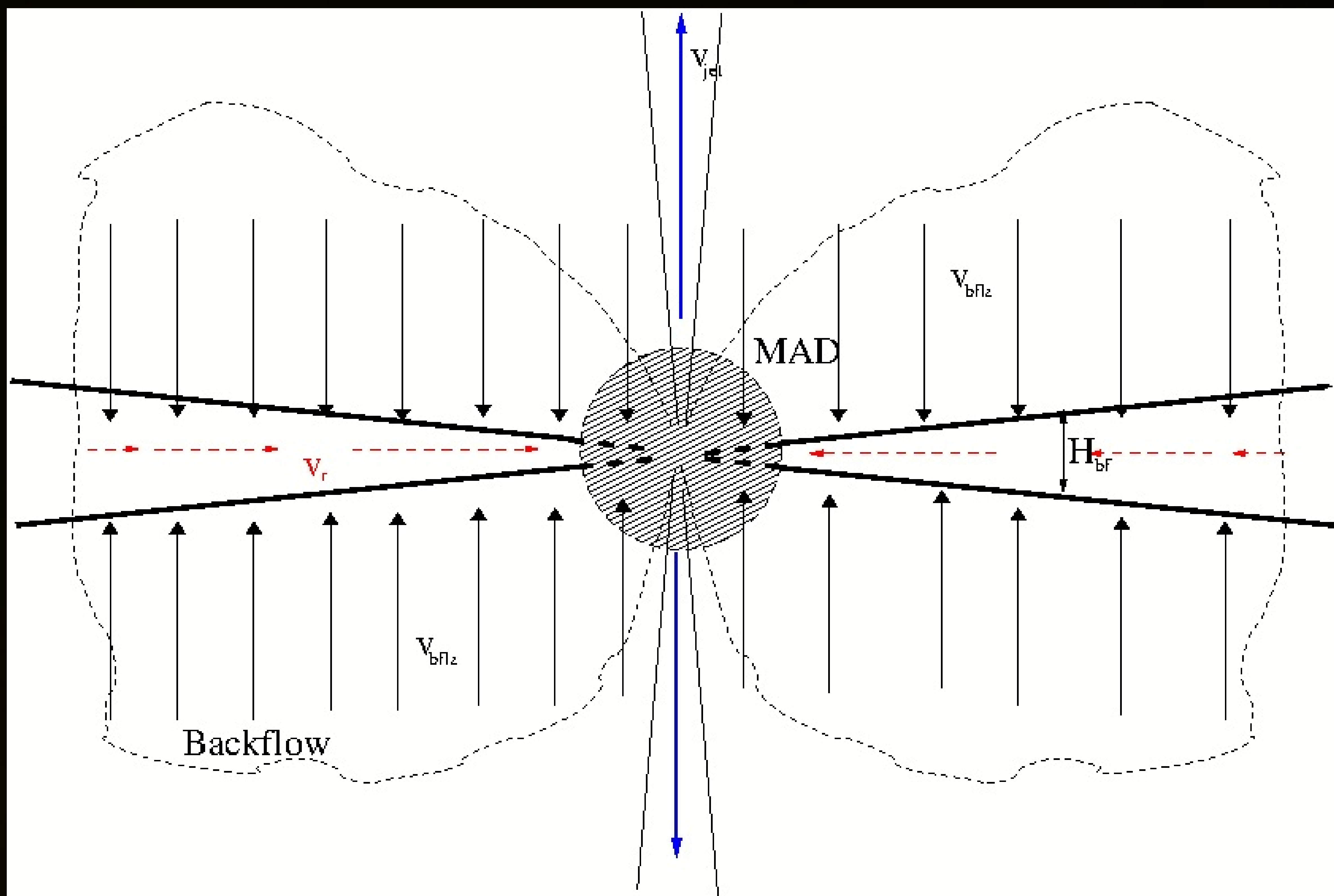
Self-regulation of accretion:
How compressive backflow enhances accretion



- A ***Magnetically Arrested Disc*** is compressed by the backflow → Time-varying surface density

Initial disc: Kaburaki (1986) magnetised disc profile:

$$\Sigma_0\left(r\right) = \sigma_0 \frac{r_0}{r}$$

Assume

$$v_r = -\frac{\beta A(t)}{r}$$

$$\frac{\partial \Sigma}{\partial t} + v_r \frac{\partial \Sigma}{\partial r} + \frac{\Sigma}{r}\frac{\partial}{\partial r}\left(r v_r\right) = -2\rho_{bf} v_{bf|z}\,|_{z=H/2} \equiv A(t)$$

<u>**EXACT**</u> solution:

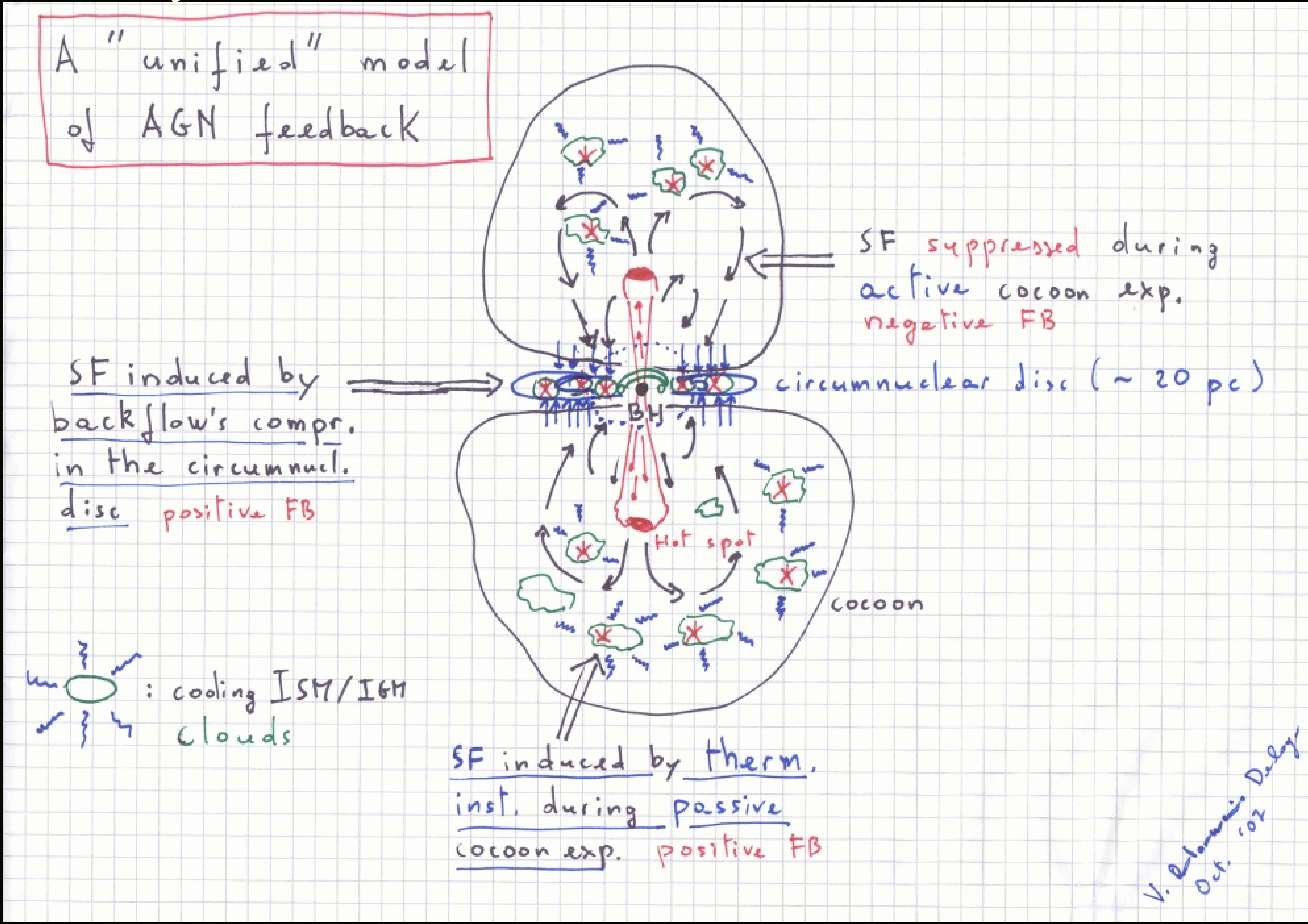
$$\Sigma(r,t) = \int_0^t d\tau A\left(\tau\right) + \Sigma_0\left(\sqrt{r^2 + 2\beta\int_0^t d\tau A\left(\tau\right)}\right)$$

Comments and drawbacks

Both 3D CFD simulations and models predict backflows as the only global feedback mechanism acting to regulate SMBH jet emission and accretion.

- Implicit assumption: all the accreted gas within MAD enhances P_{jet}. **But** some will be *accreted* by the SMBH.....
- Fate of gas after entering MAD ?
- Backflow changes accretion on short ($t \lesssim$ 2-5 Myrs) - it has never been taken into account in accretion and jet powering models so far.
- Next paper: model predicts a correlaton between EUV ($\lambda \lesssim 1100$ Å) with GHz synchr. for RLQ

My "unified" mechanical AGN feedback model



The self-similar model of jet-cocoon systems

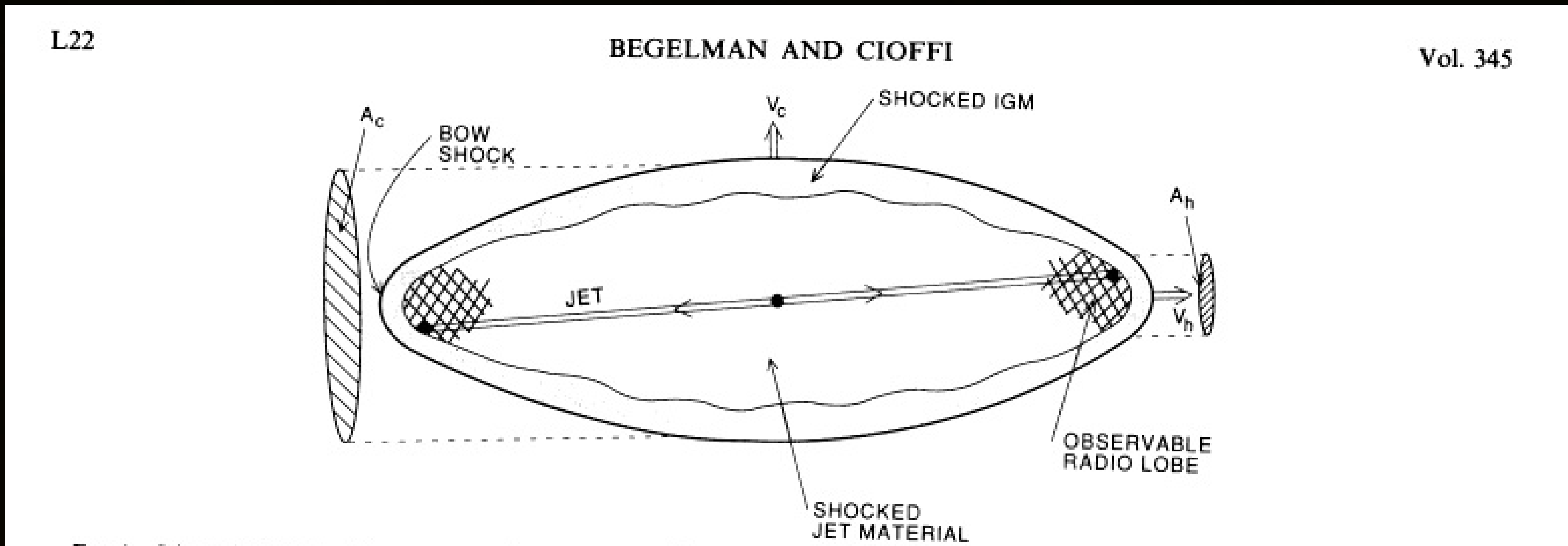
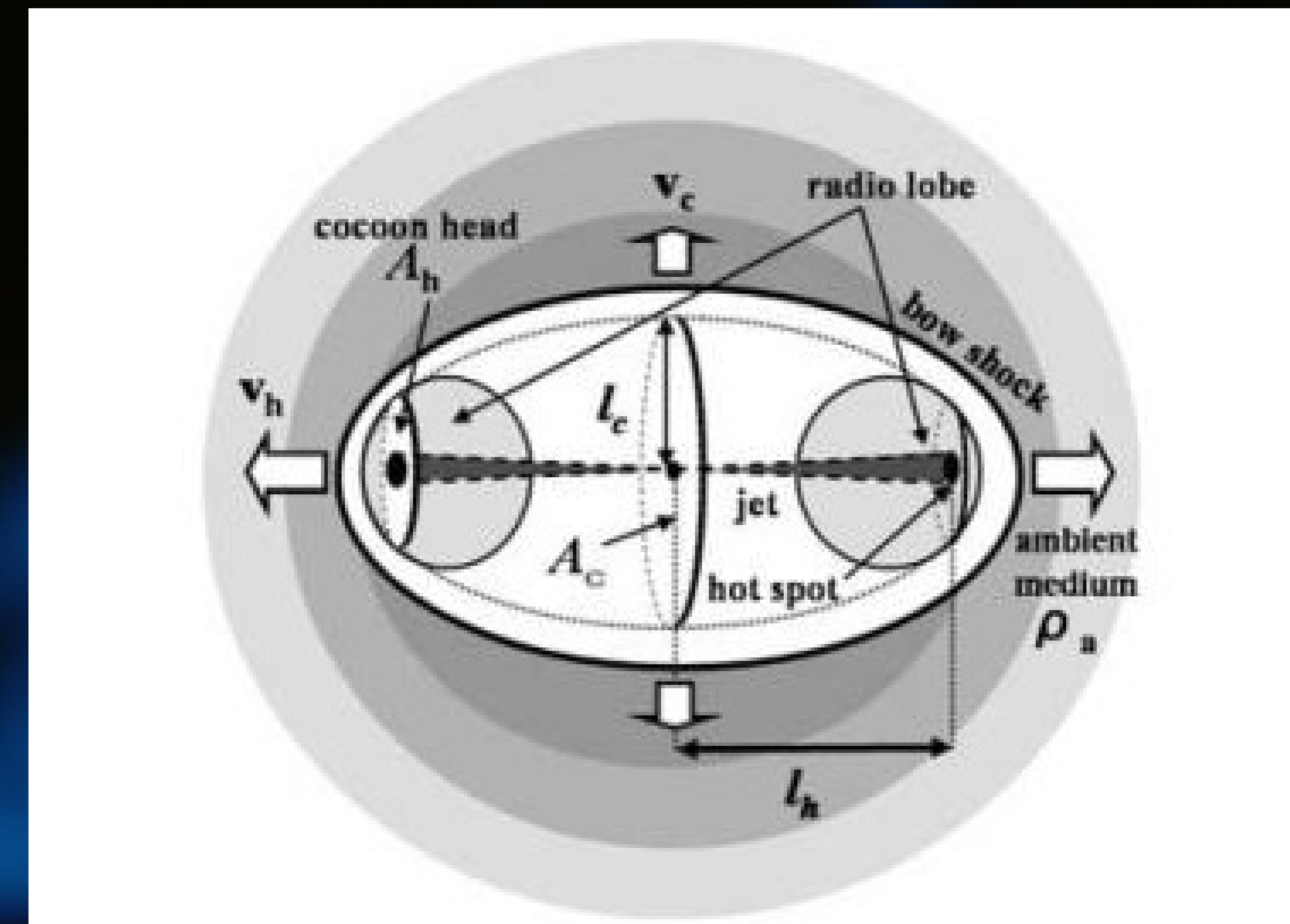


FIG. 1.—Schematic diagram of the overpressured cocoon surrounding a powerful double radio source. The shock bounding the cocoon expands into the IGM with speed v_h along the mean jet axis and $\sim v_c$ in orthogonal dirctions. The observable radio lobes constitute only a small fraction of the cocoon's volume near the ends of the jets, and the mean cross sectional area of the cocoon, A_c, is much larger than the area of the bow shock, A_h. Due to fluctuations in the jet directon, momentum is deposited over a much wider area than the instantaneous jet cross section. For Cygnus A, we estimate $A_h \sim 28$ kpc^2; the total projected length of the cocoon is ~ 120 kpc (for $H_0 = 75$ km s^{-1} Mpc^{-1}). In the multiphase IGM proposed for high-z radio galaxies, clouds could penetrate into the region of shocked jet material and star formation could occur throughout the interior of the cocoon.

Begelman & Cioffi, 1989



Kino & Kawakatu, 2006

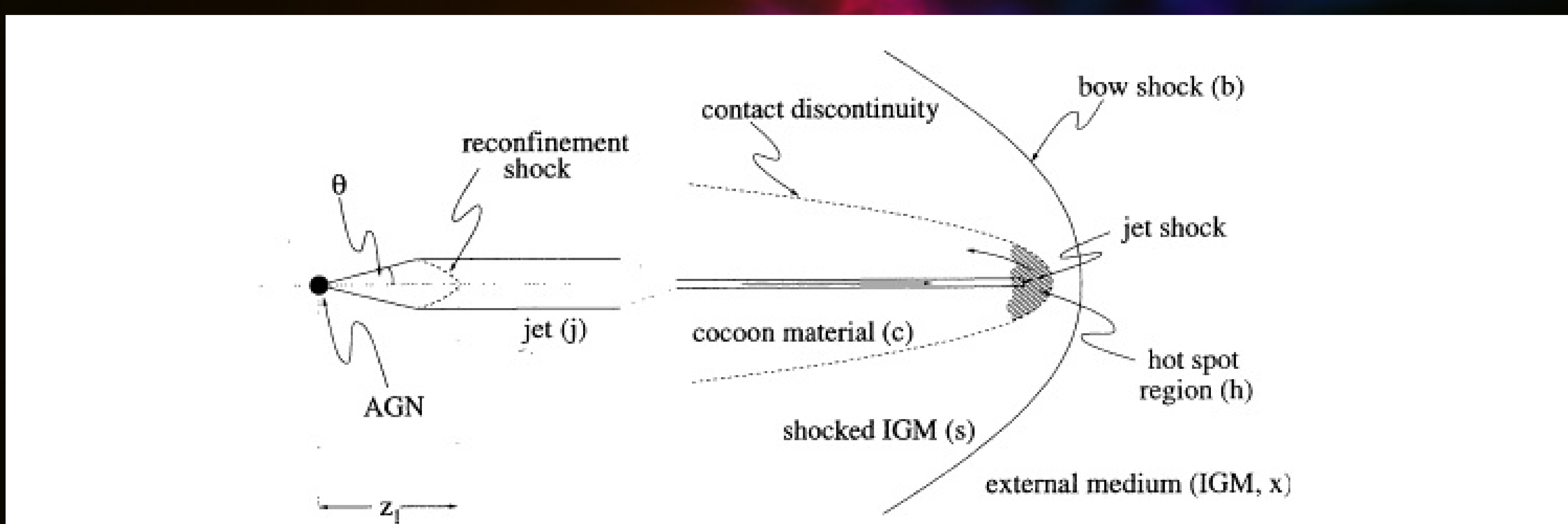


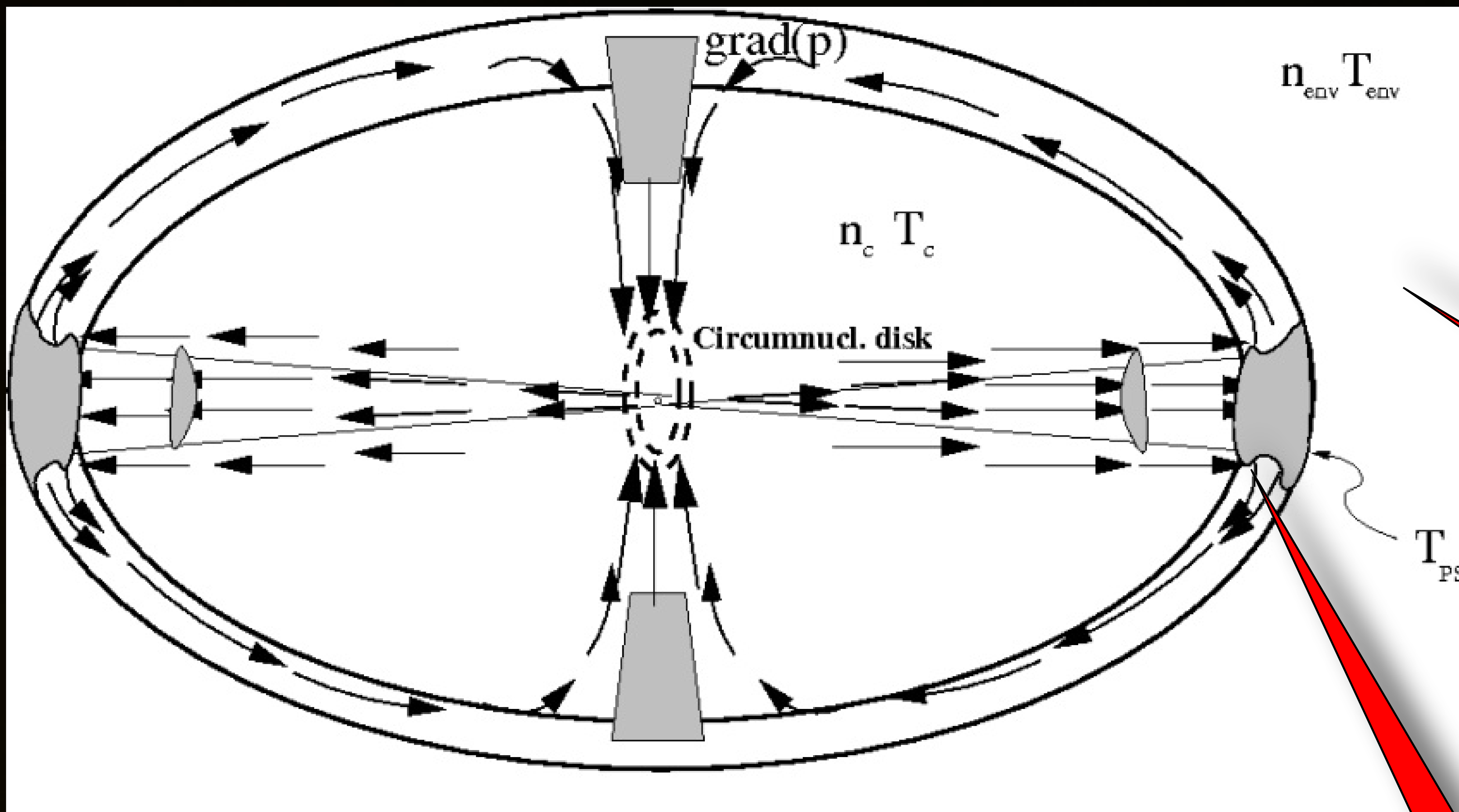
Figure 1. Basic elements of a radio source. The letters in brackets are the indices used for quantities in the indicated regions.

© 1997 RAS, MNRAS **286**, 215–222

Kaiser & Alexander, 1997

- Falle (1991), Alexander (1997): Self-similar expansion, a/b constant, a(t) from: $p_{hs} * A_{hs} = m_{hs} dv_{hs}/dt$
- No cooling → adiabatic expansion of cocoon NO backflow is predicted within the SSM

Backflow's origin is <u>*thermodynamical*</u>



- Shock dissipation → Δh ≠ 0 → gradients in specific enthalpy across a shock
- Crocco's theorem (1937):

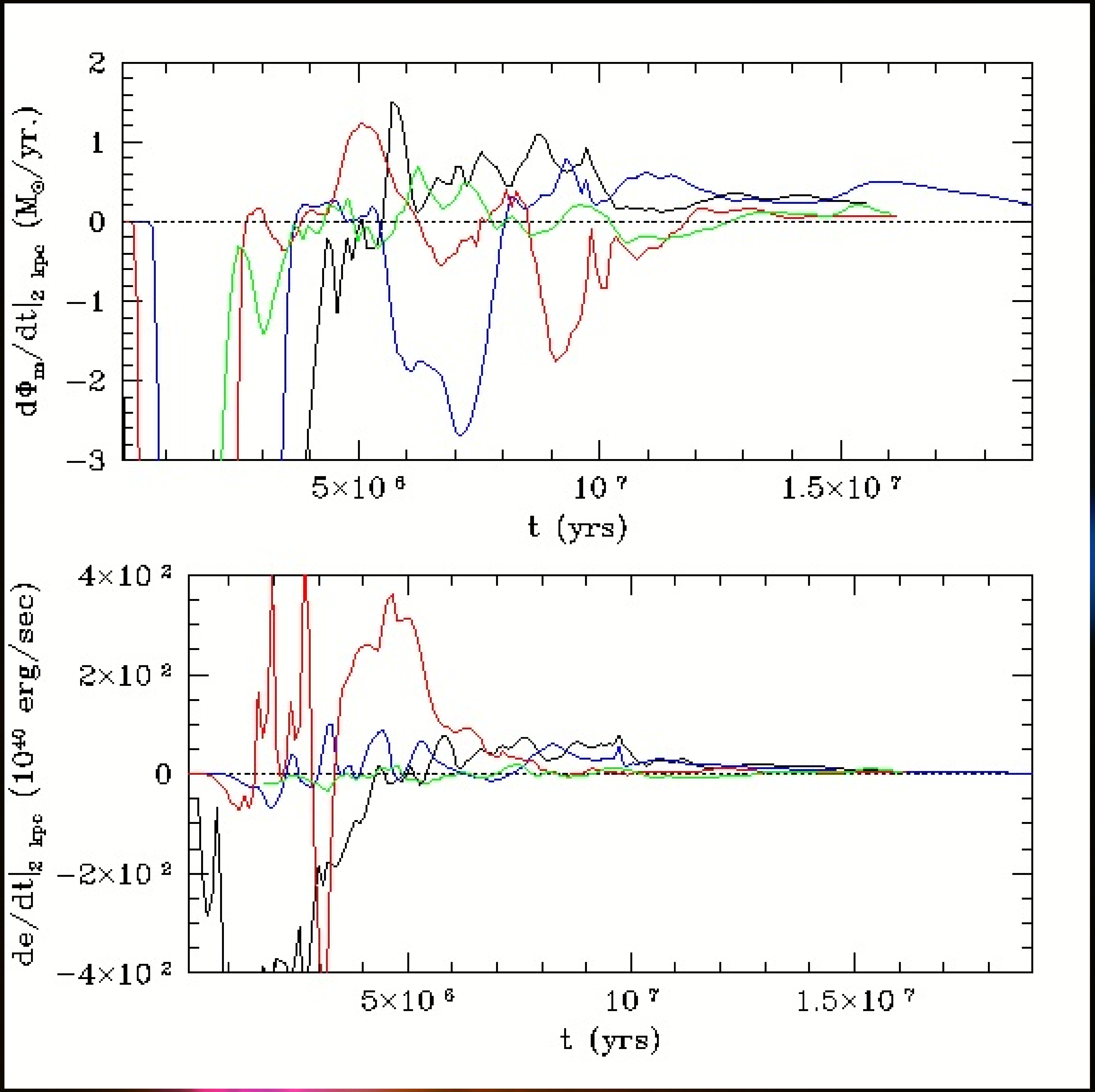
$$\vec{v} \times \mathrm{curl}\,\vec{v} = \nabla h - T \nabla S.$$

Circulation is <u>created</u> by discontinuities in *h* <u>and/or</u> entropy *S*

$$h = U + \frac{p}{\rho} + \frac{1}{2} v^2.$$

- **At least two regions** in a bi-jet/cocoon system where Δh ≠ 0: Hot spot and on the meridional symmetry plane

Mass and energy flux

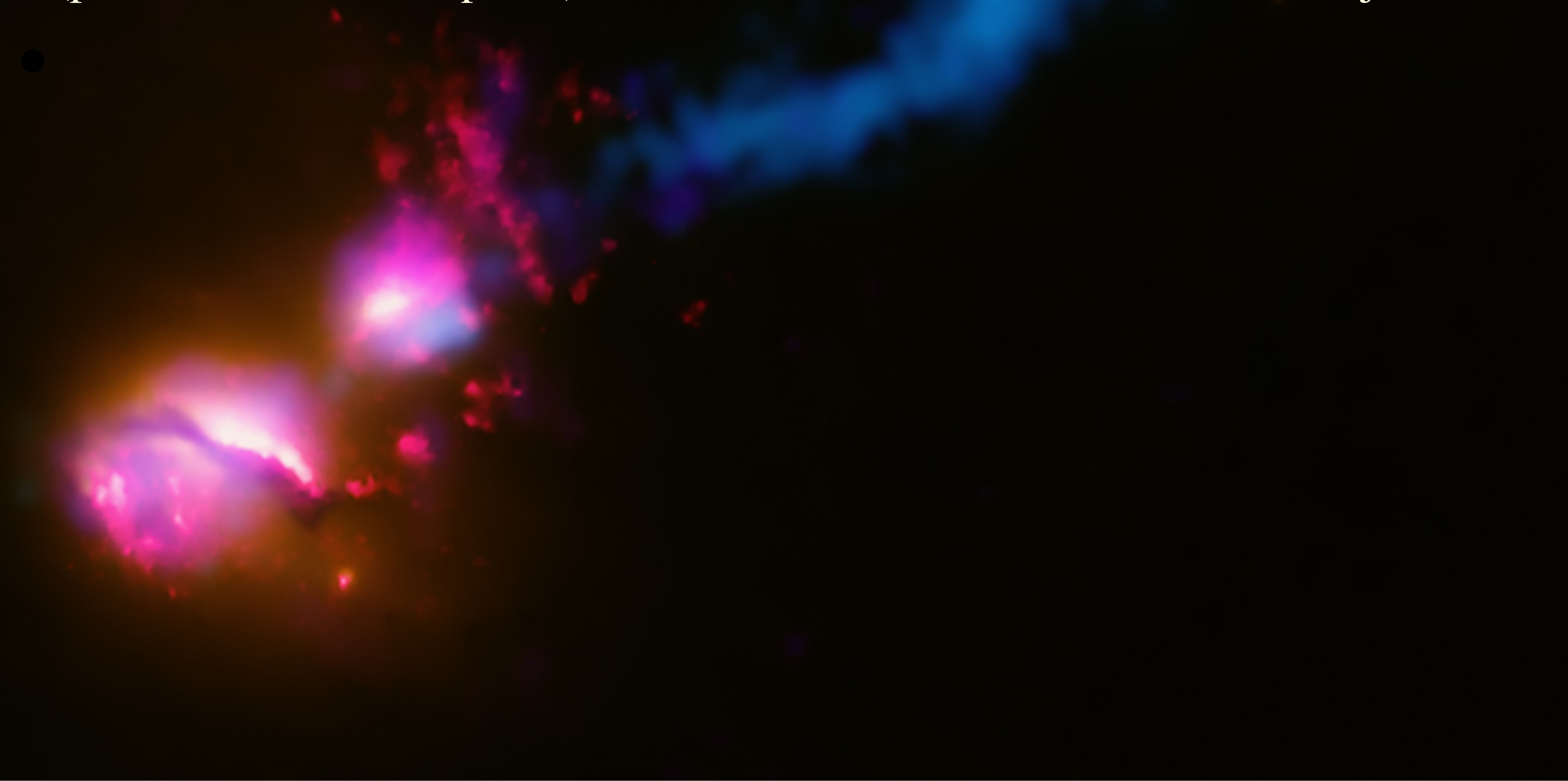


- dM/dt and de/dt @ r=2 kpc around central SMBH
- After t ≃ 6 - 10 Myrs. constant <u>positive</u> inflows → total mass and energy are advected
- $M(t_{acc} \simeq 2x10^7$ Myr.) ≃ $10^{6-6.7}\ M_\odot$
- Independent of P_{jet}

- This <u>low angular momentum gas</u> can feed the SMBH ↔ self regulation mechanism

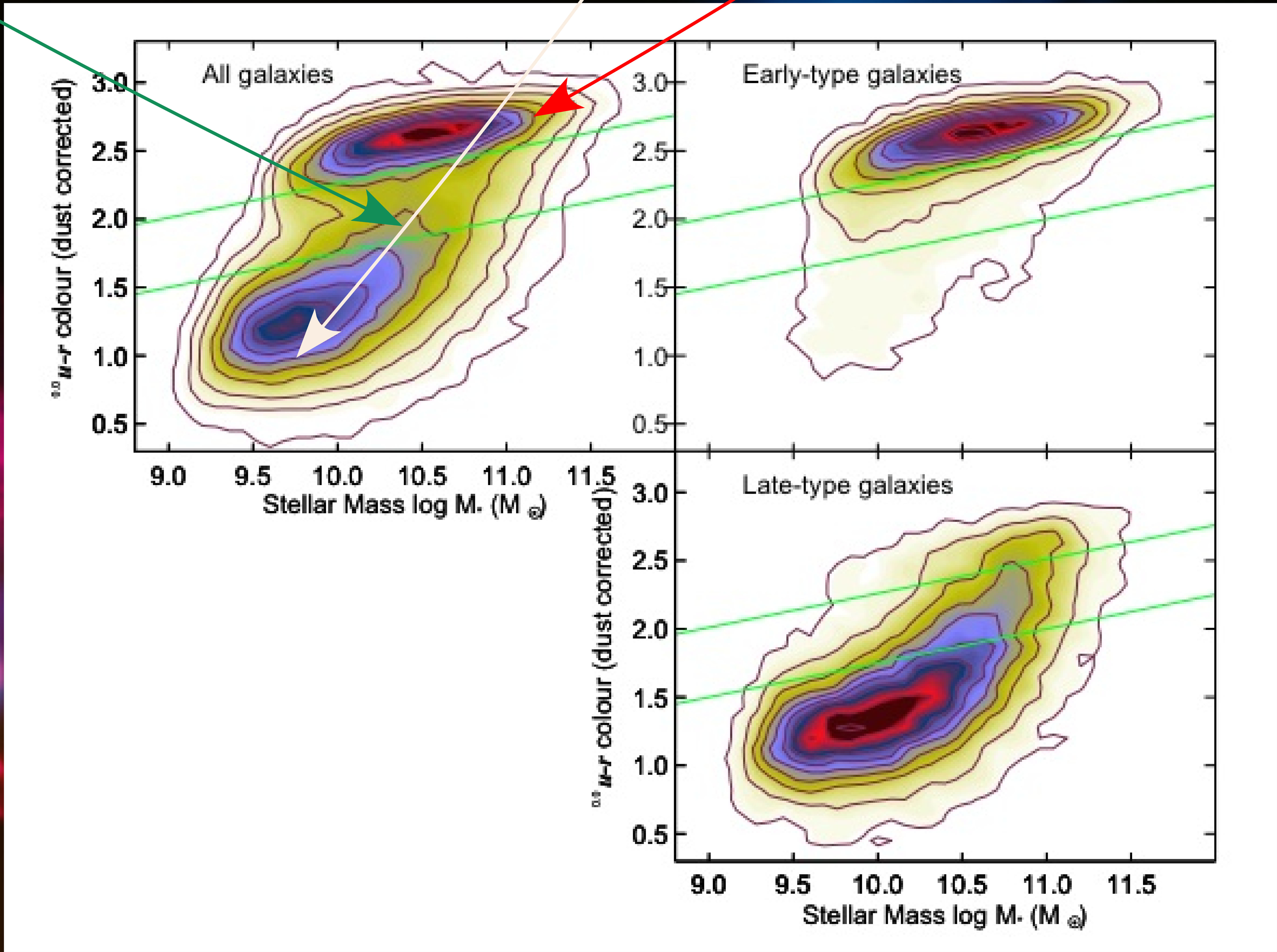
AGNs/QSO feedback: what is it?

- RGs: low z () and high z (radio alignment effect, see: https://ned.ipac.caltech.edu/level5/Sept08/Miley/Miley4.html)
- Feedback - Blue cloud/Red valley migration . Evidence for AGN negative feedback (quote also Romeo's paper)
- Positive feedback: why is needed - History: Rees & Silk - Gaibler et al's paper (posiive feedback in spirals) - Evidence in CenA, M87, Minkowski object



AGNs/QSO feedback: what is *negative feedback?*

- The Colour-Magnitude diagram of galaxies: *Blue Cloud*, *Red Sequence* and *Green Valley*

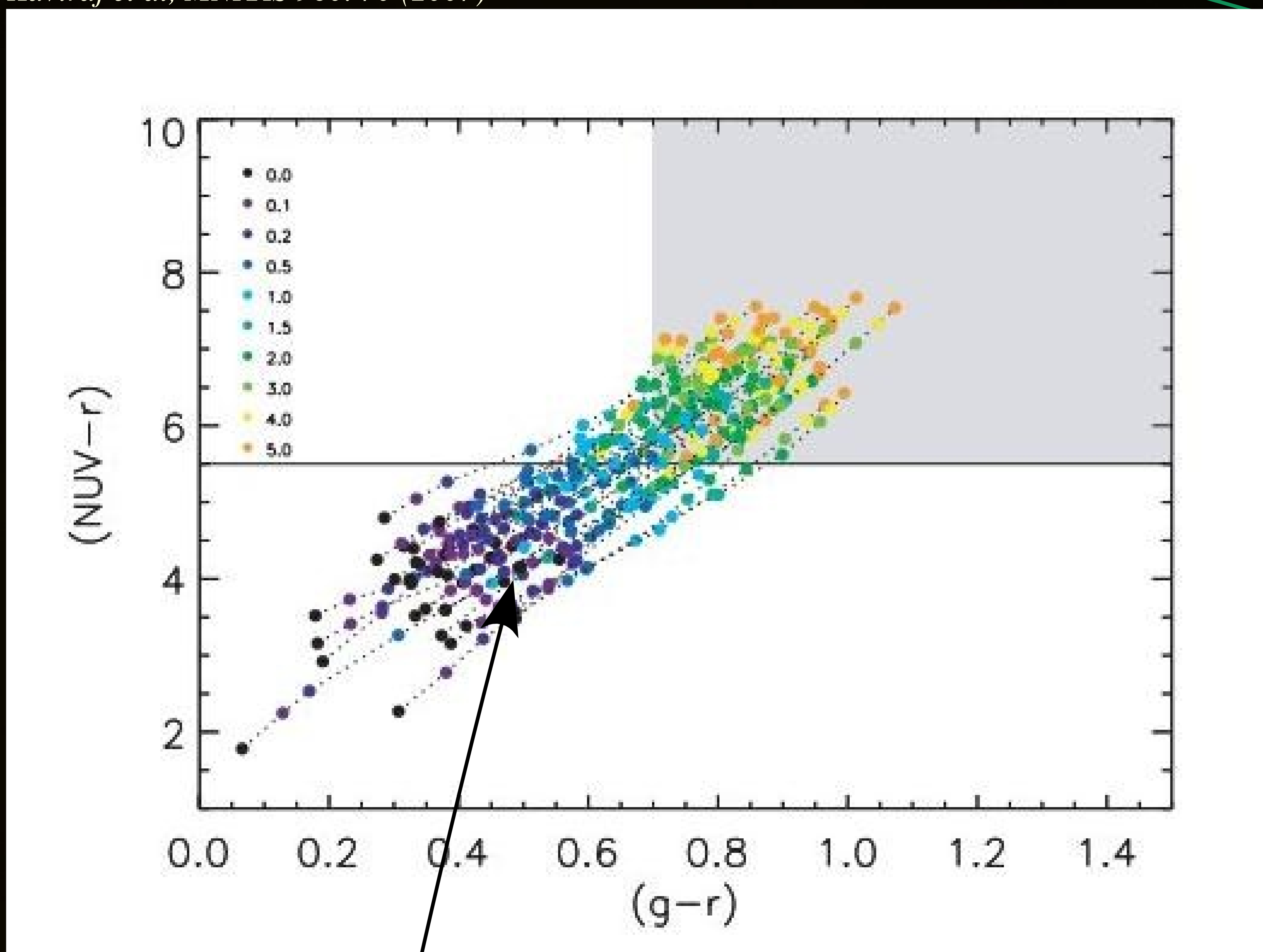


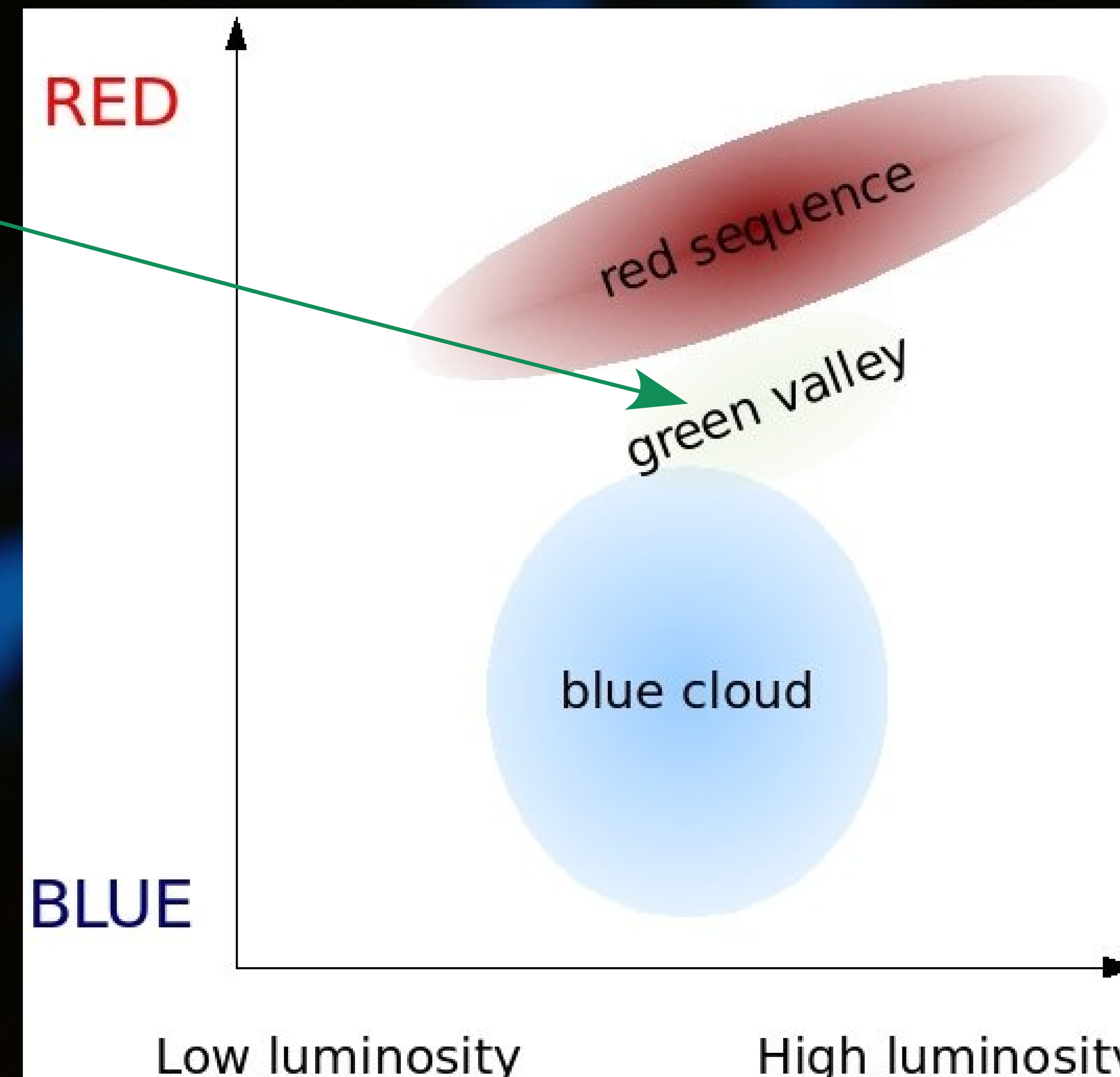
- Colours → stellar populations
- Early-type galaxies today host ~ 80% of all the stars in the local Universe → How can stellar populations have evolved so fast from *Blue Cloud* to *Red Sequence*?
- A stellar evolutionary question.

AGNs/QSO feedback acts quickly

All these galaxies host a (sometimes active) AGN, e.g. most late-type in the *Green Valley* are Seyfert 1

Kaviraj et al, MNRAS 960. 70 (2007)





AGNs can *quickly* ($\lesssim$ 2-3 Gyrs) and *heavily* damps star formation promoting migration from the *Blue Cloud* to the *Red Sequence* (Silk & Rees 1998)