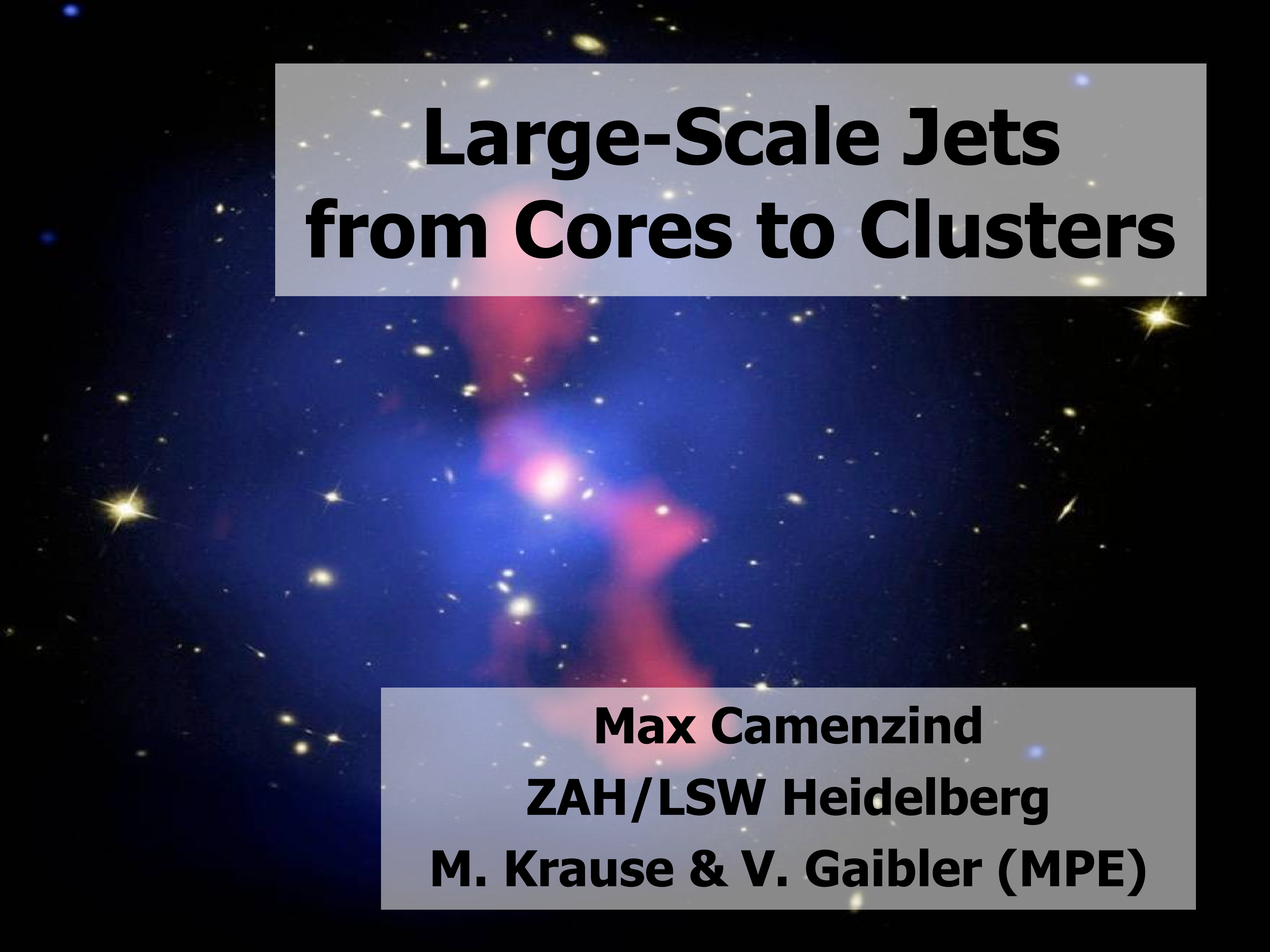


Large-Scale Jets from Cores to Clusters

Max Camenzind
ZAH/LSW Heidelberg
M. Krause & V. Gaibler (MPE)

The non-Thermal Physics of Clusters

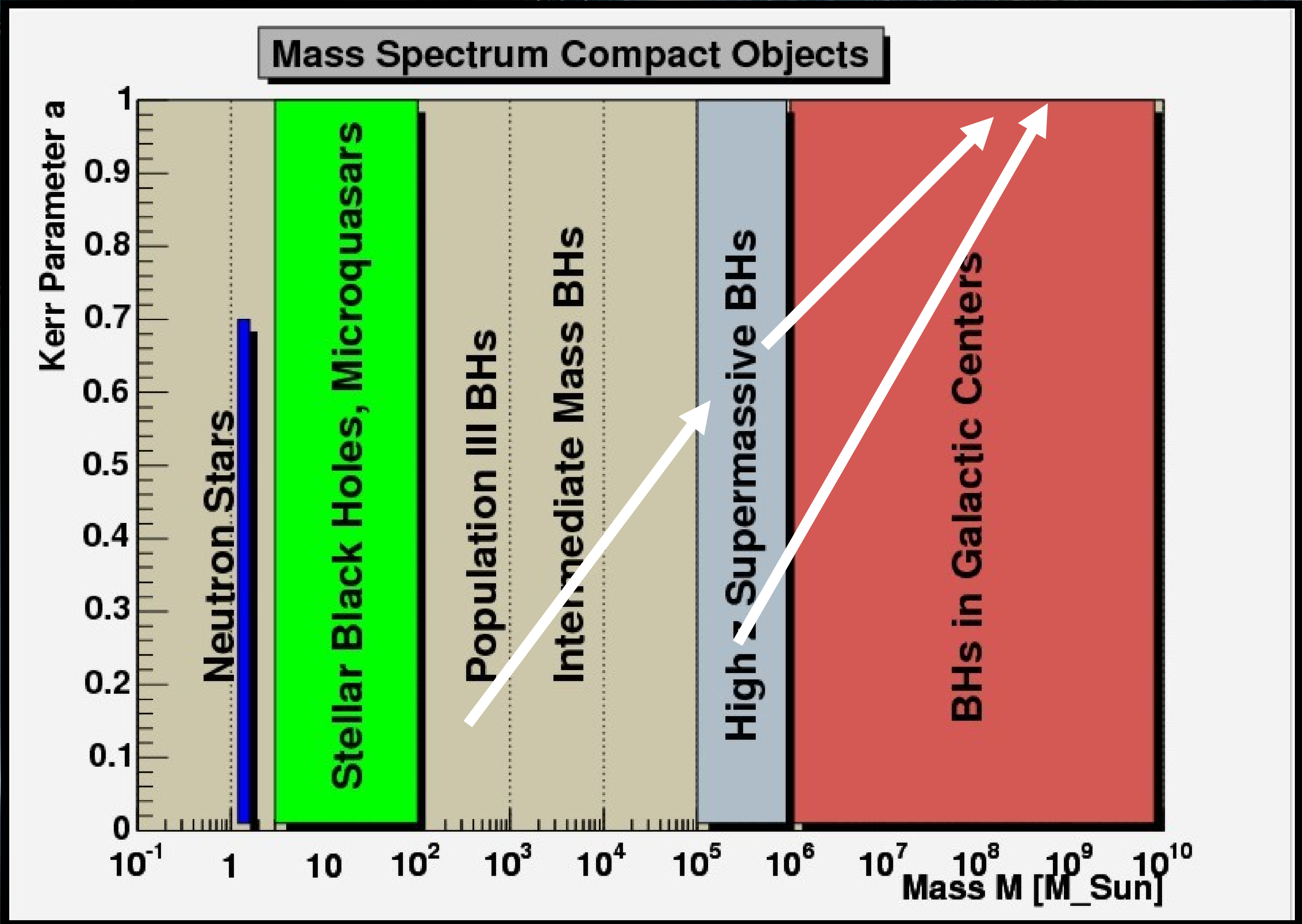
- **Clusters of galaxies** have long been used as cosmological probes, provided gas is mostly in hydrostatic equilibrium. ➔ attention has to be devoted to **magneto-dynamical processes within the ICM.**
- Chandra and XMM-Newton have however shown a much richer and more complex picture of the ICM ➔ many cluster centers seem to have a **self-regulated energy feed-back**.
- This feed-back results from activity of the **Black Holes** residing in cluster centers.

- **Radio galaxies** pinpoint the sites of AGN that contain the most massive BHs in the Universe. Their Jets enrich the ICM with thermal energy, relativistic particles (CRs), magnetic fields and drive **turbulence** in the cluster medium.
- **Halo merging (LCDM)** may however also dissipate gravitational energy in enormous shock waves. A fraction of this energy could also be used for accelerating relativistic particles, amplifying magnetic fields and injecting MHD turbulence.

Topics

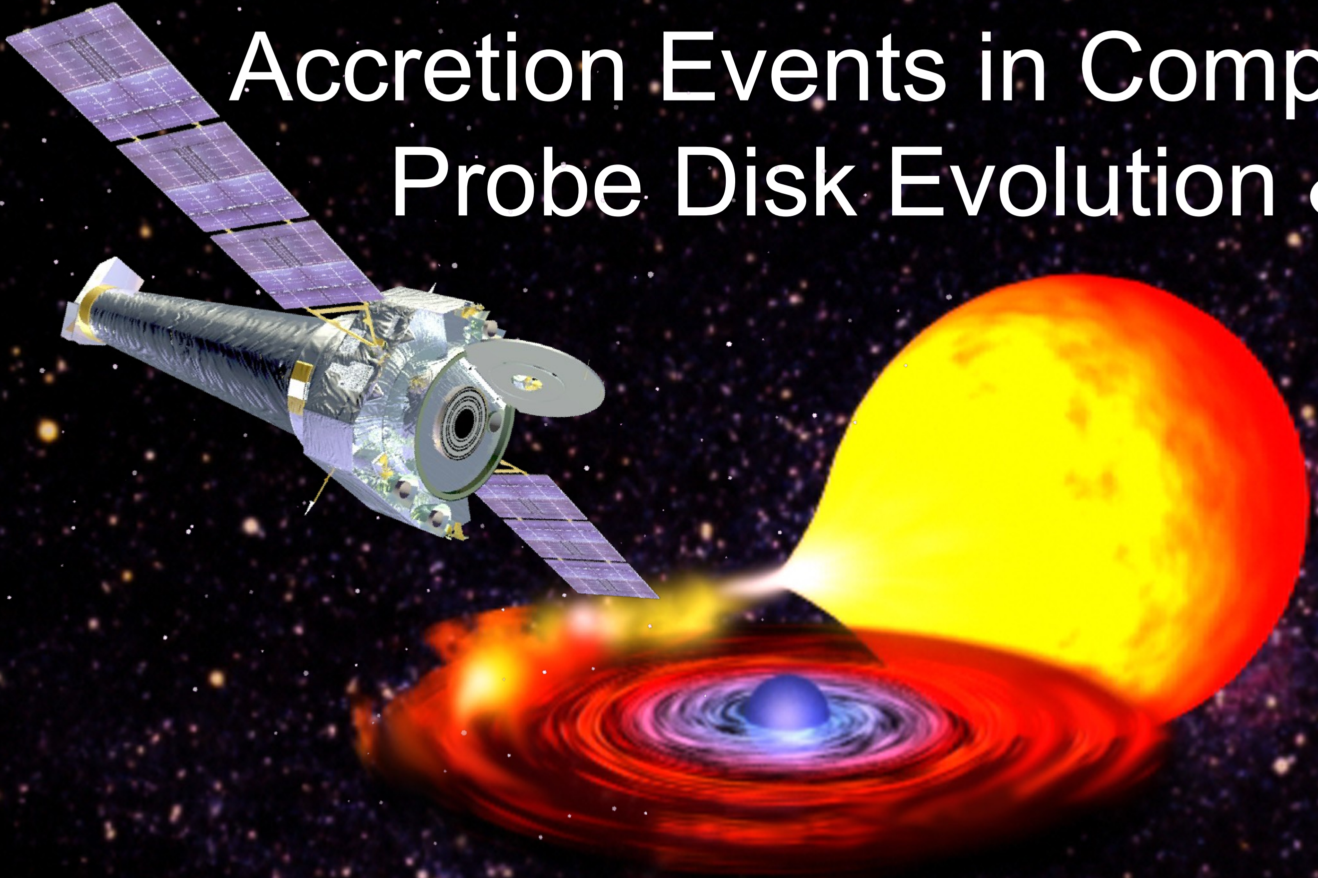
- **Black Holes at Work**: Jets come from Black Holes ➔ Accretion Events in Stellar Black Hole Binaries – a clue towards understanding jet generation ➔ Jets only generated for **dotM < 0.1**.
- Jet – Accretion Links – is there a **spin-regulated feedback ?** (…., McNamara 2009).
- Jet Interactions with Hot Atmospheres in Galaxies and Clusters ➔ generate turbulence for **η < 0.01**
- **Simulations** ➔ Large-Scale Jet Morphology and its understanding in terms of hot ICM
- How to **gauge Energetics**? ➔ Look at X-Ray Cavities and radio bubbles.

„Black Holes have Mass & Spin“



Camenzind 2006

Accretion Events in Compact Binaries Probe Disk Evolution & Outflows



A plethora of observations with Chandra, XMM, **RXTE**, Suzaku, …

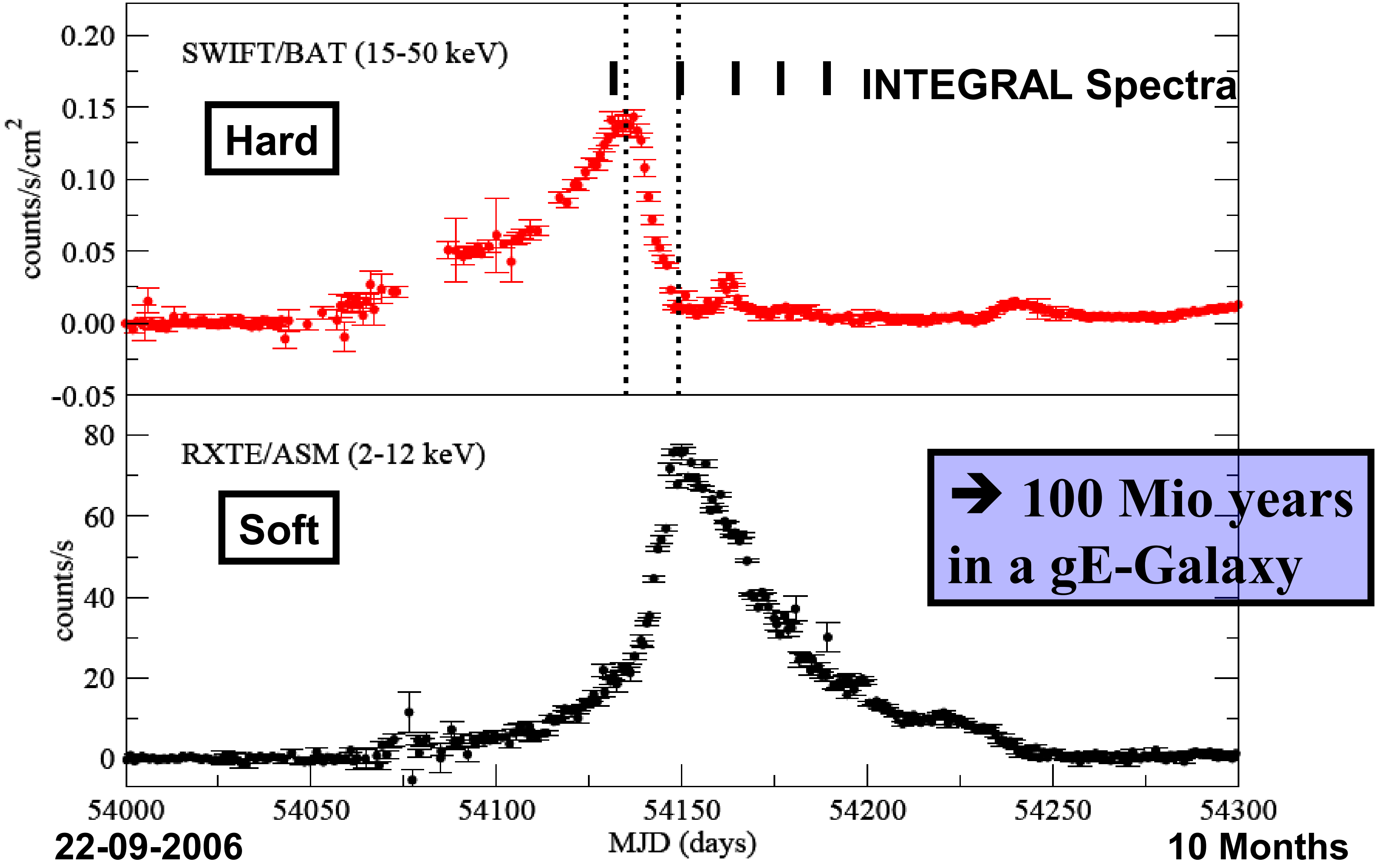
- ➔ When are Jets generated in Accretion events
- ➔ Low-state jet luminosity
- ➔ Question of global evolution (Spin-Evolution, Accretion History)

BH Masses and Spins µQuasars

Source Name	BH Mass ($M_{\odot}$)	BH Spin (a_*)
LMC X-1	9.0 – 11.6	0.88 – 0.92
LMC X-3	5.9 -- 9.2	~ 0.25
XTE J1550-564	8.4 -- 10.8	~ 0.5
GRO J1655-40	6.0 -- 6.6	0.7 ± 0.05
M33 X-7	14.2 - 17.1	0.77 ± 0.05
4U1543-47	7.4 -- 11.4	0.8 ± 0.05
GRS 1915+105	10 -- 18	0.98 – 0.99

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Steiner et al. (unpublished); Gou et al. (unpublished); Miller et al. (2009); Reis et al. (2009)

GX 339-4 Accretion Event 2007



INTEGRAL Spectra

Hard

Soft

➔ 100 Mio years in a gE-Galaxy

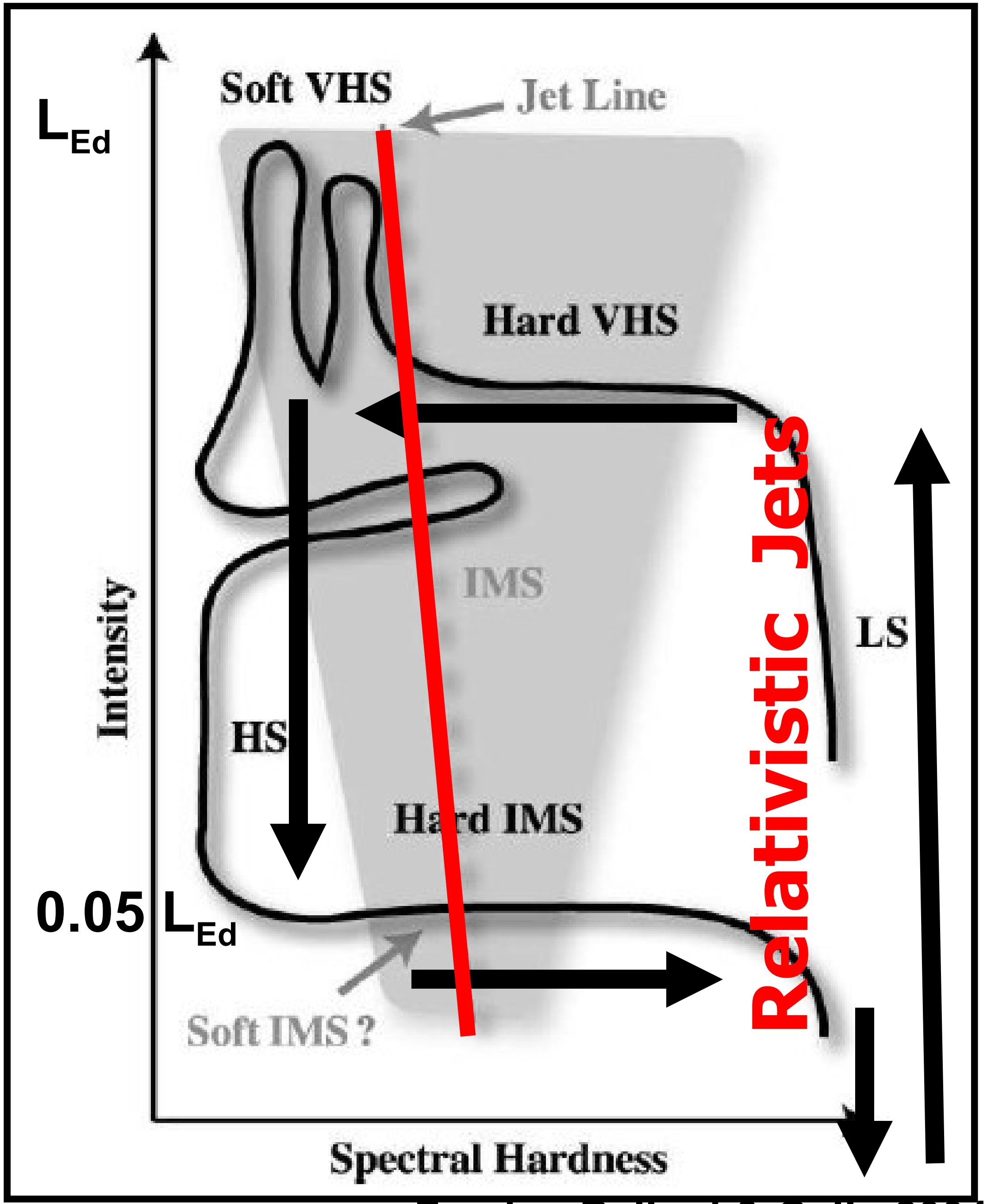
22-09-2006

10 Months

Accretion States µQuasars

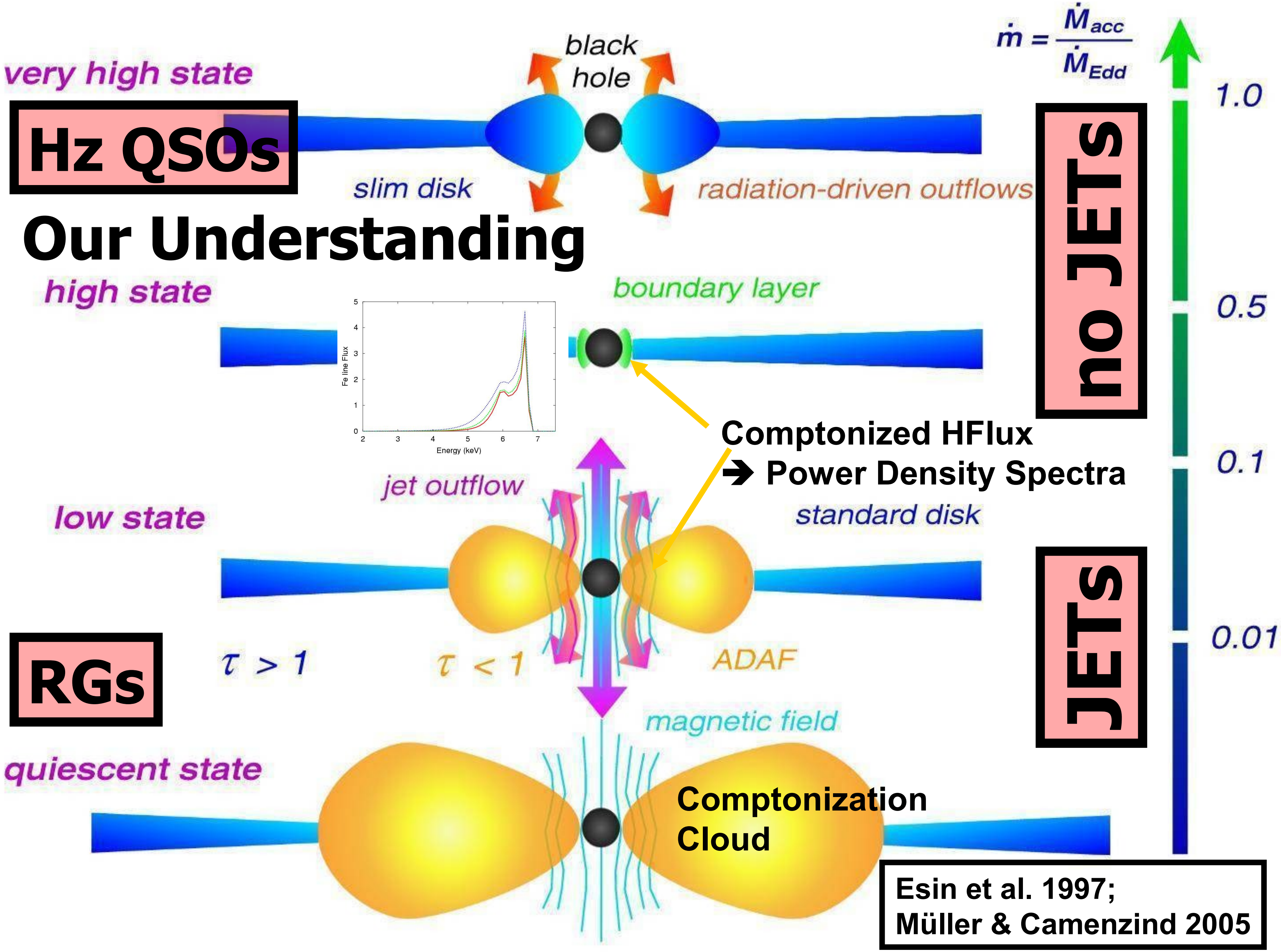
➔

Hysteresis in Intensity and Hardness for accretion events



Fender, Belloni & Gallo 2004

Our Understanding



Hz QSOs

no JETS

Comptonized HFlux

➔ Power Density Spectra

JETS

RGs

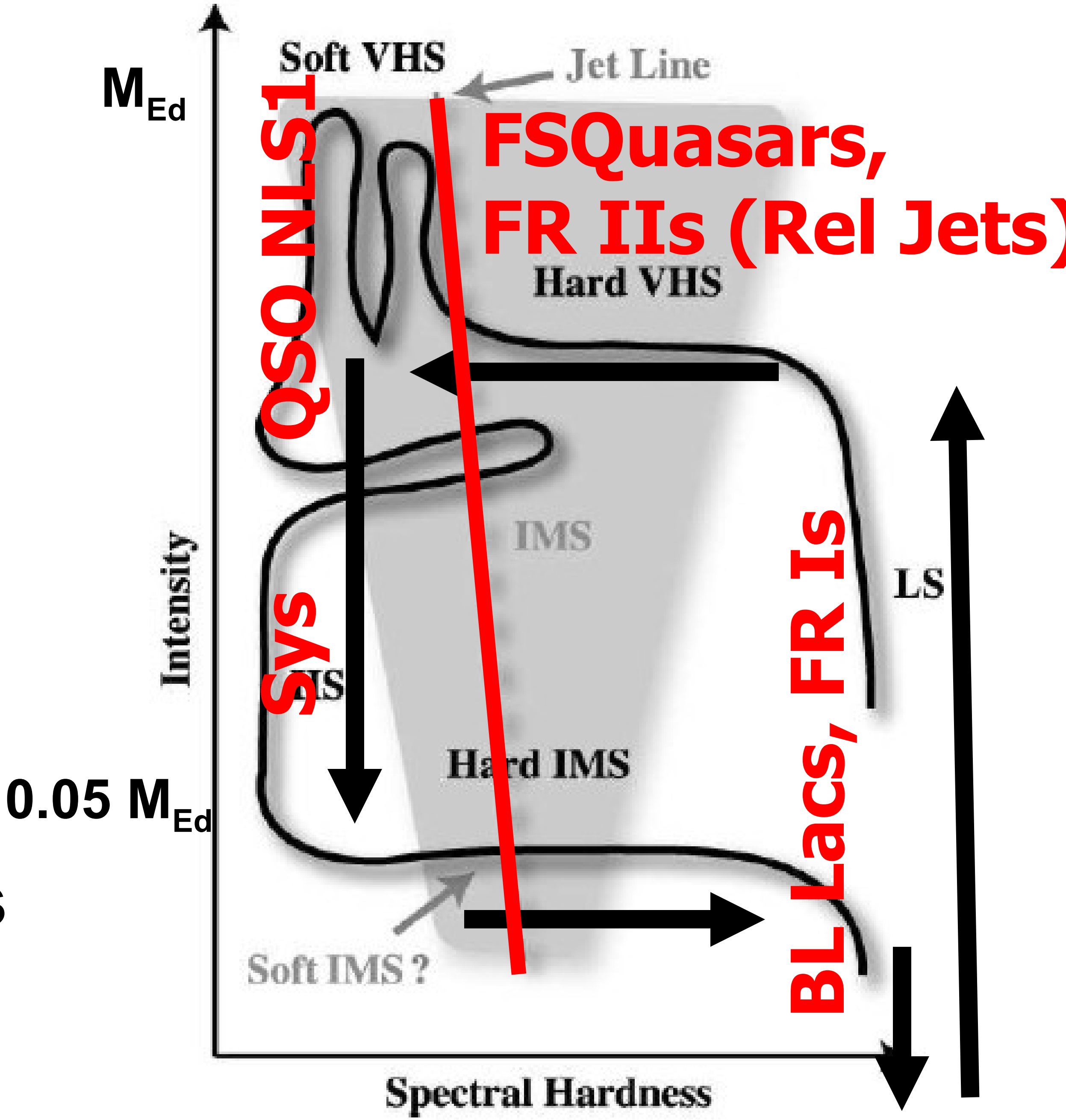
Comptonization Cloud

Esin et al. 1997;
Müller & Camenzind 2005

Extension to Accretion States of AGN

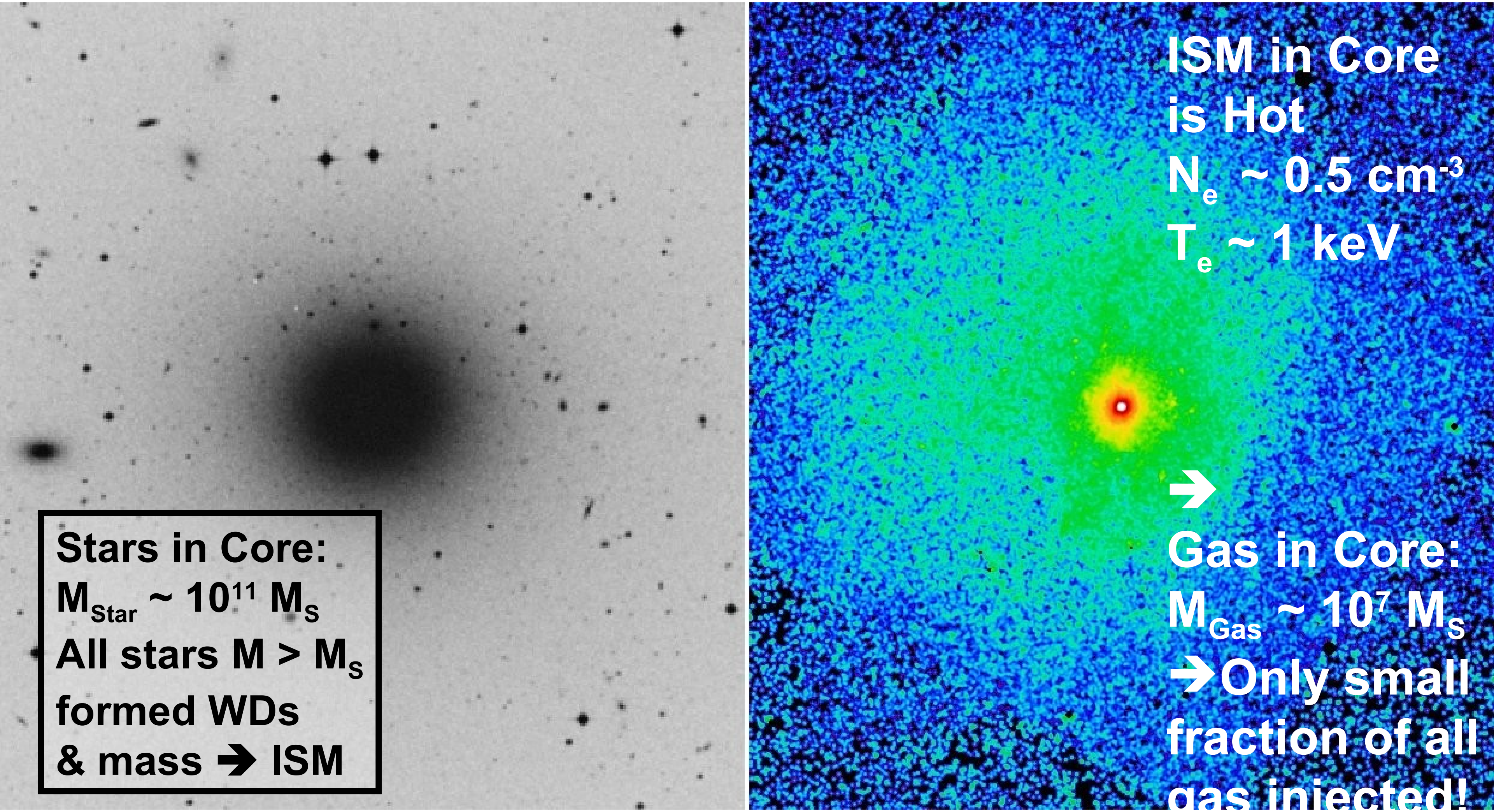
-

Hysteresis in Intensity and Hardness for accretion events



Koerding et al. 2006; …. ; Camenzind 2008

Fuel-Source - ISM in Core-Ellipticals



Stars in Core:
$M_{Star} \sim 10^{11}\ M_S$
All stars $M > M_S$
formed WDs
& mass → ISM

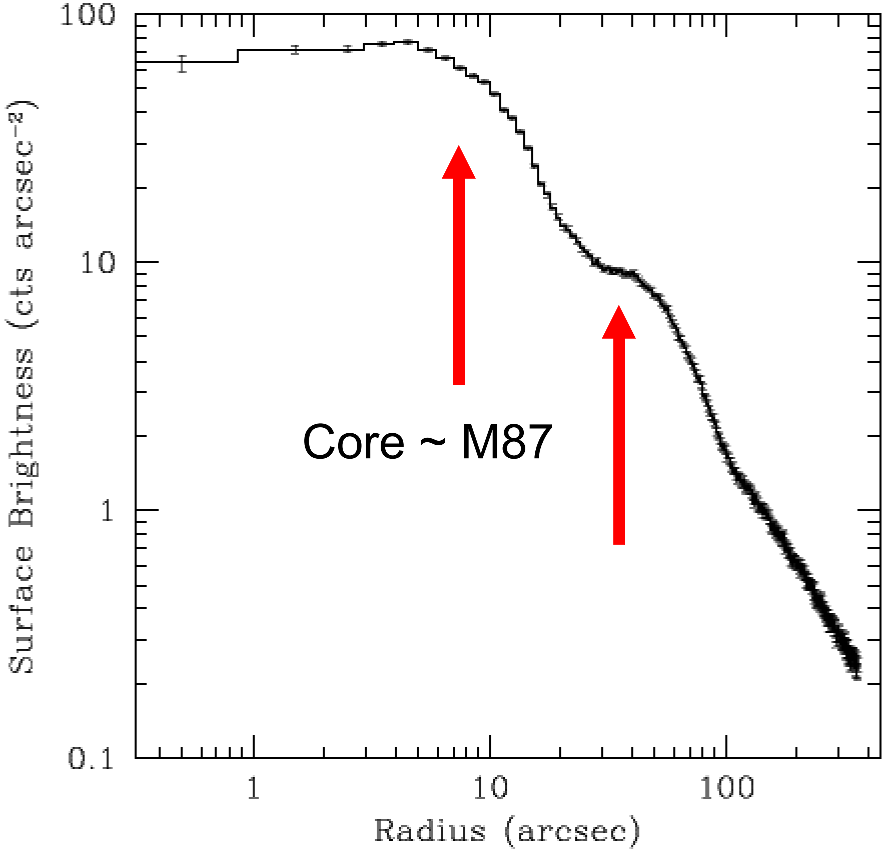
ISM in Core
is Hot
$N_e \sim 0.5\ \mathrm{cm}^{-3}$
$T_e \sim 1$ keV

→
Gas in Core:
$M_{Gas} \sim 10^7\ M_S$
→Only small
fraction of all
gas injected!

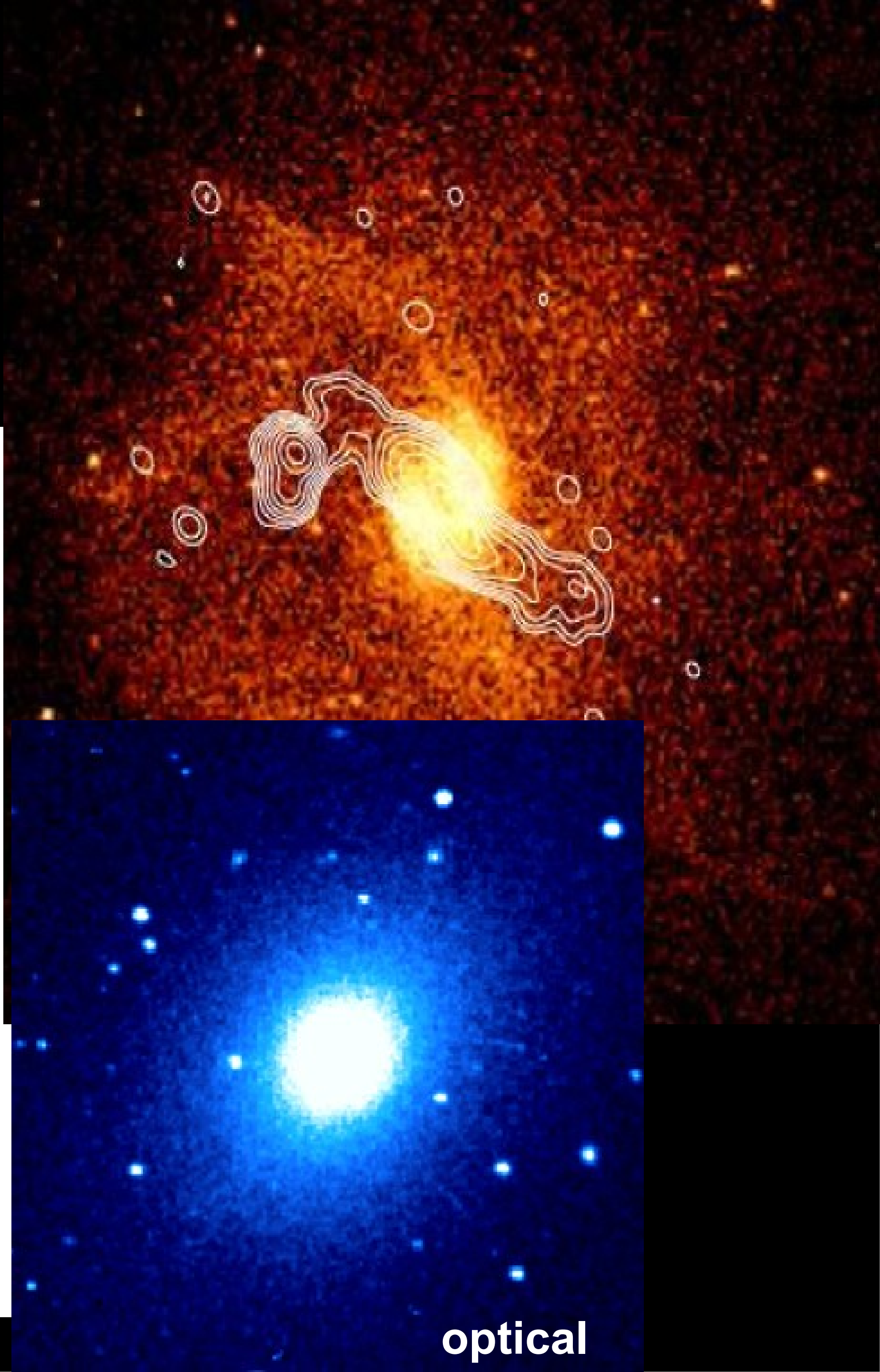
Optical (left) and X-ray (right) images of elliptical galaxy NGC1399 (central galaxy in the Fornax cluster) [Churazov et al. 2008]

NGC 4636

Baldi et al. 2009



Core ~ M87


optical

2 Stage Accretion

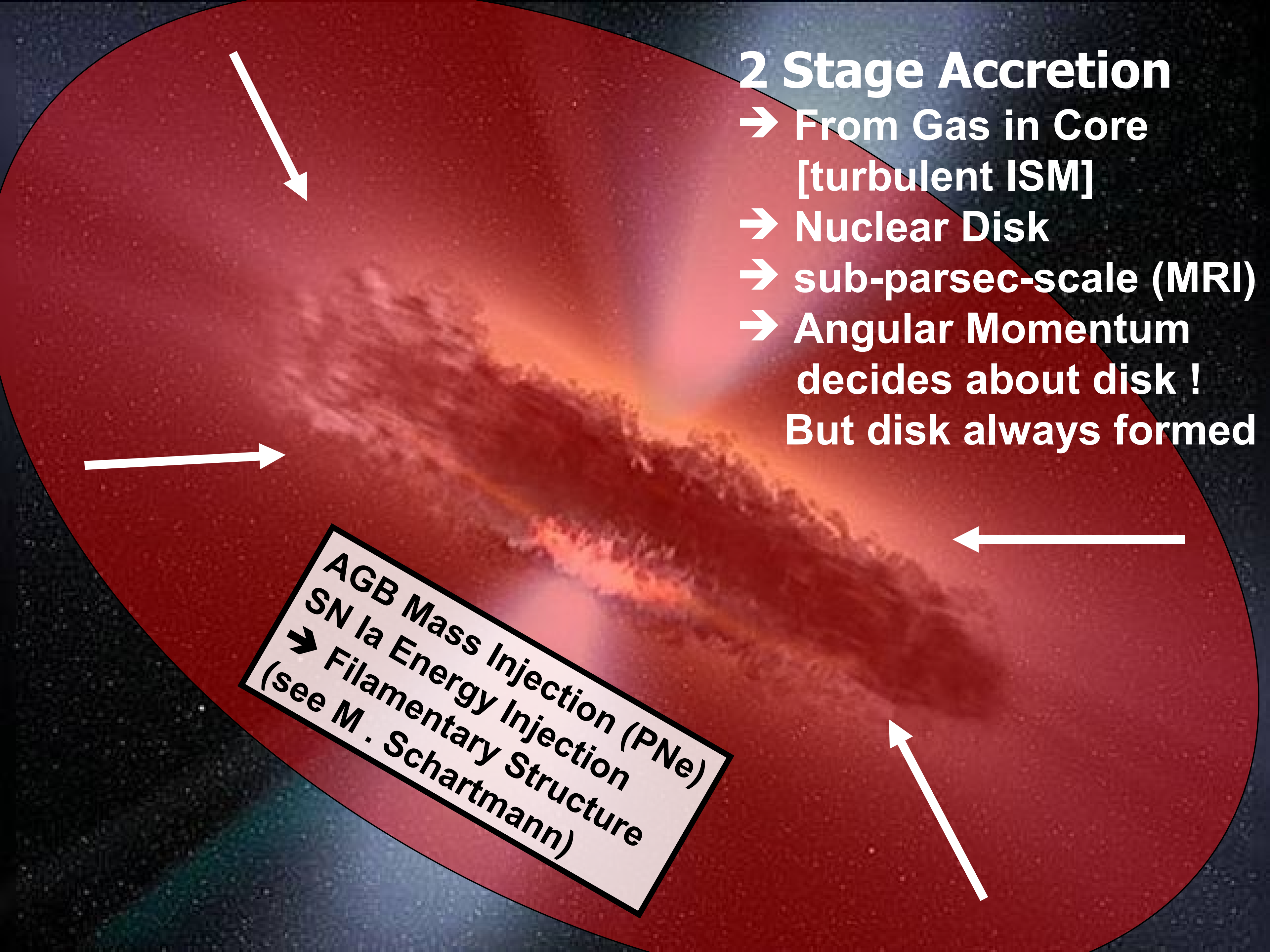
→ From Gas in Core [turbulent ISM]

→ Nuclear Disk

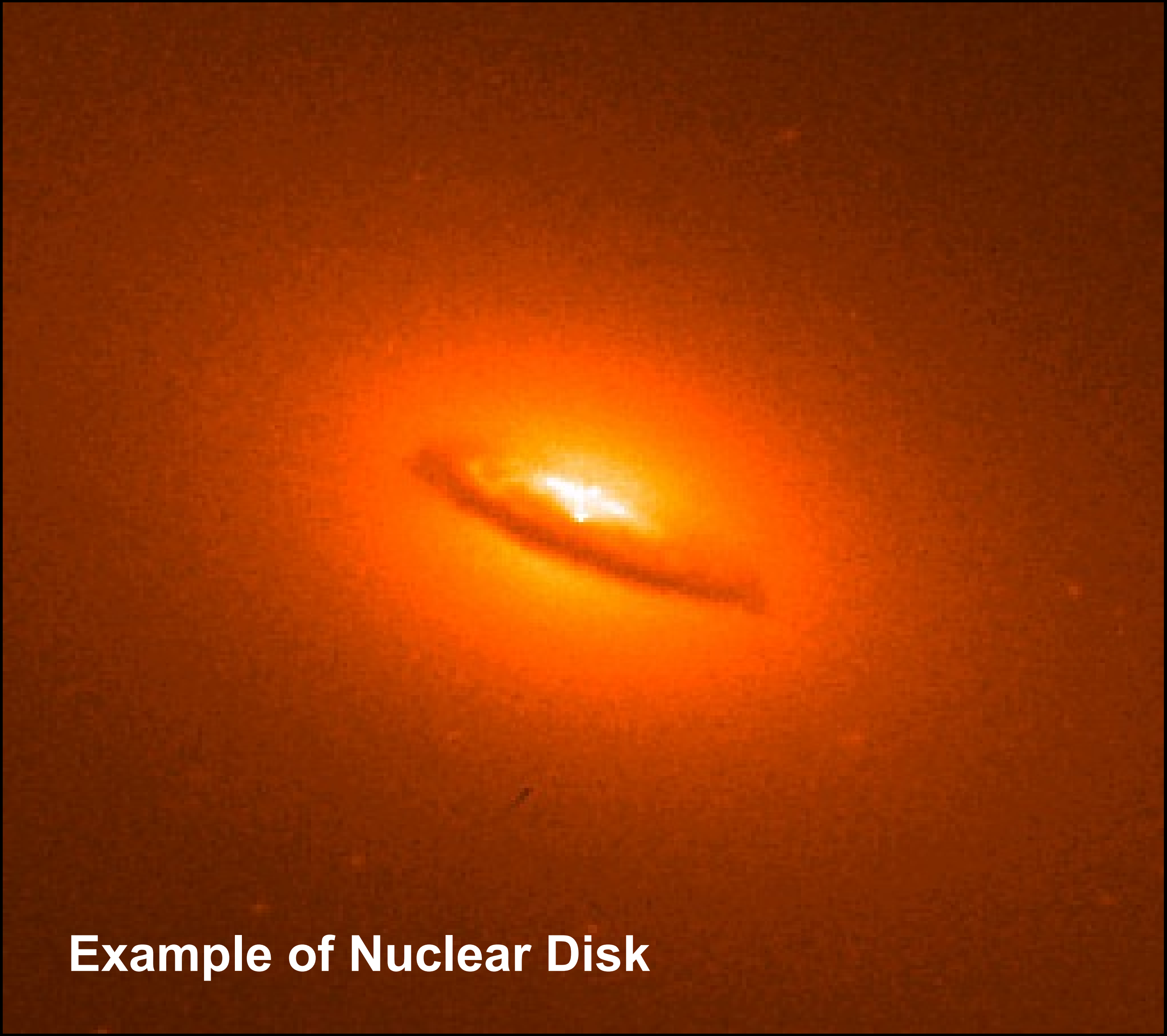
→ sub-parsec-scale (MRI)

→ Angular Momentum decides about disk !

But disk always formed



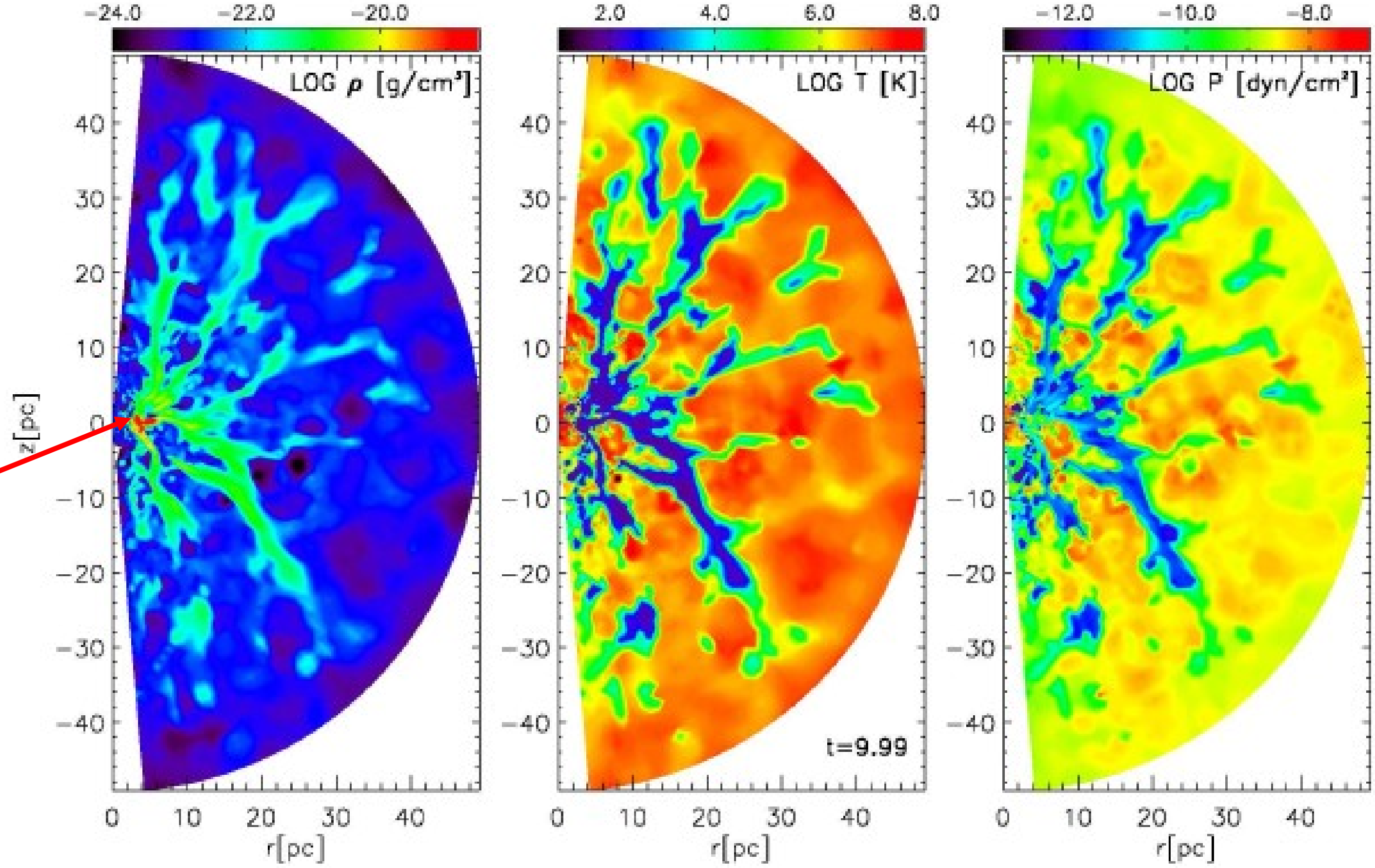
AGB Mass Injection (PNe)
SN Ia Energy Injection
→ Filamentary Structure
(see M. Schartmann)



Example of Nuclear Disk

Schartmann: Turbulent AGN tori

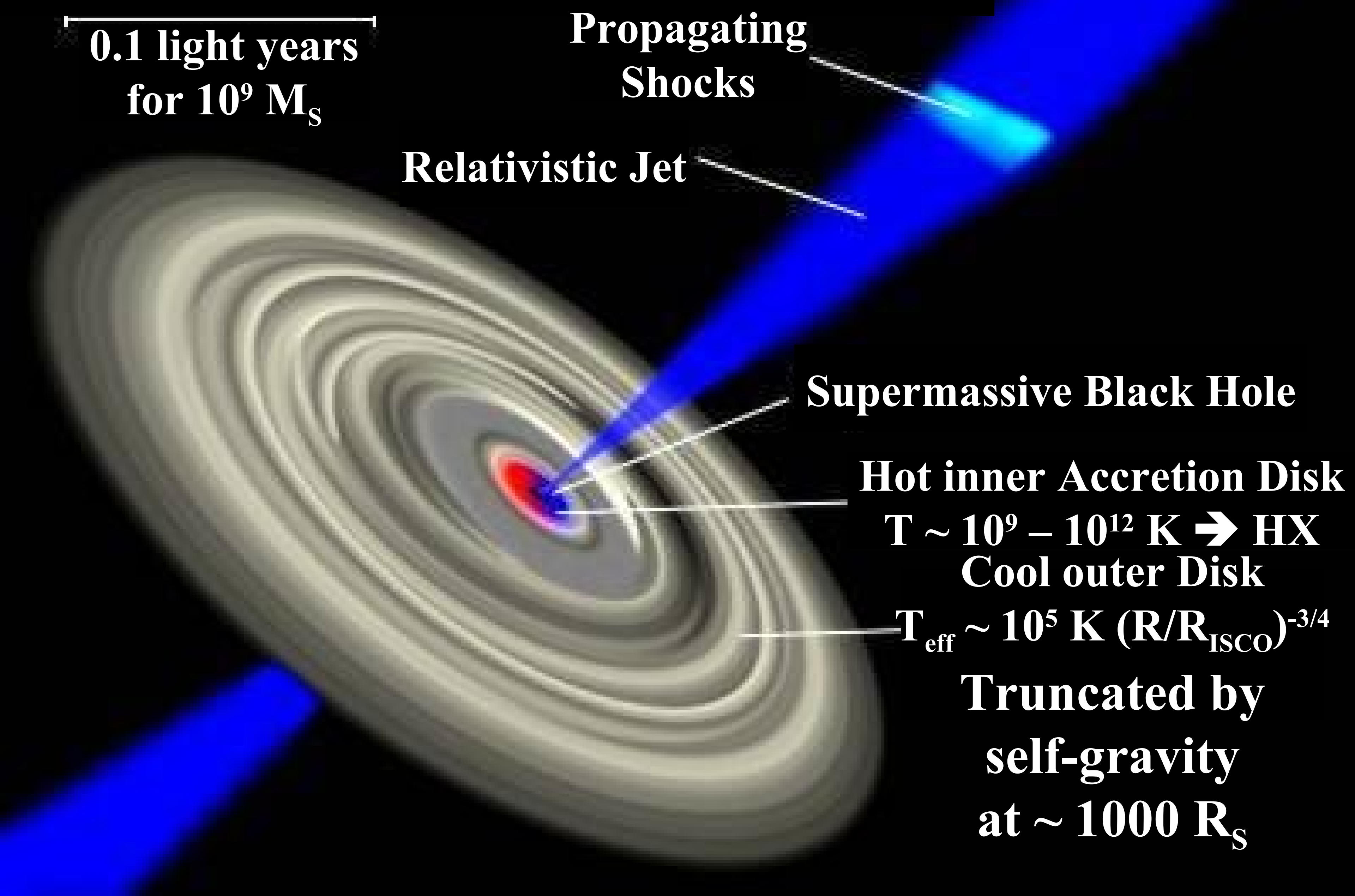
Disk is formed by inflowing filaments



Age > 1 Giga years

Parameter	Value	Parameter	Value	Parameter	Value
M_{BH}	$6.6 \cdot 10^{7}\ M_{\odot}$	R_{T}	5 pc	T_{ini}	$2.0 \cdot 10^{6}$ K
M_{Rc}	$6.7 \cdot 10^{8}\ M_{\odot}$	σ_{*}	165 km/s	$\dot{M}_{\mathrm{n}}$	$6.0 \cdot 10^{-9}\ M_{\odot}/(yr\ M_{\odot})$
$M_{\mathrm{gas}}^{\mathrm{ini}}$	$1.2 \cdot 10^{4}\ M_{\odot}$	α	0.5	M_{PN}	$2.2\ M_{\odot}$
R_{c}	25 pc	Γ	5/3	SNR	10^{-10} SNe/(yr $M_{\odot}$)

Inner Disk in Galactic Nuclei



0.1 light years for $10^9\ M_S$

Propagating Shocks

Relativistic Jet

Supermassive Black Hole

Hot inner Accretion Disk

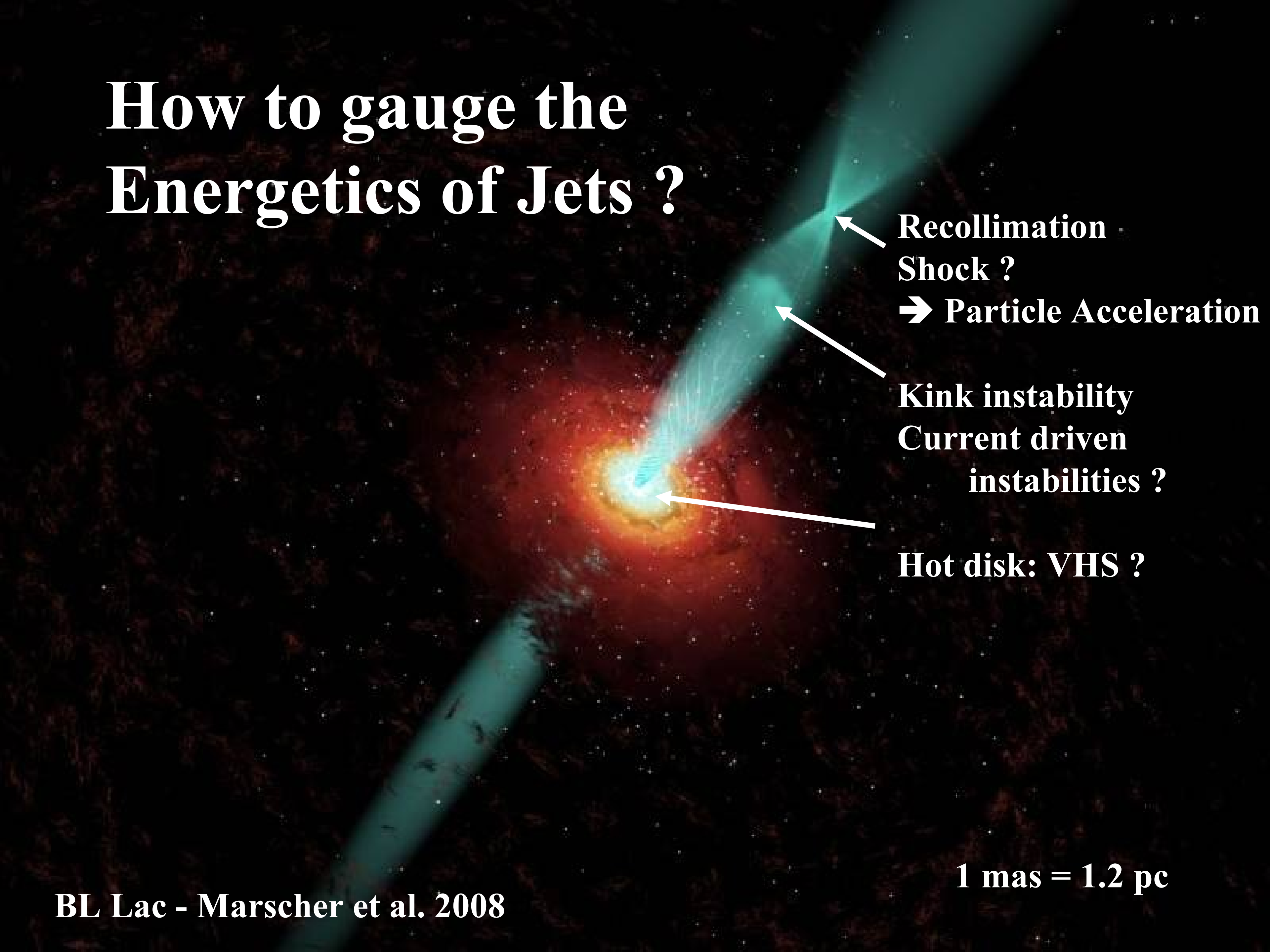
$T \sim 10^9 – 10^{12}$ K ➔ HX

Cool outer Disk

$T_{eff} \sim 10^5\ K\ (R/R_{ISCO})^{-3/4}$

Truncated by self-gravity at $\sim 1000\ R_S$

How to gauge the Energetics of Jets ?



Recollimation
Shock ?
➔ Particle Acceleration

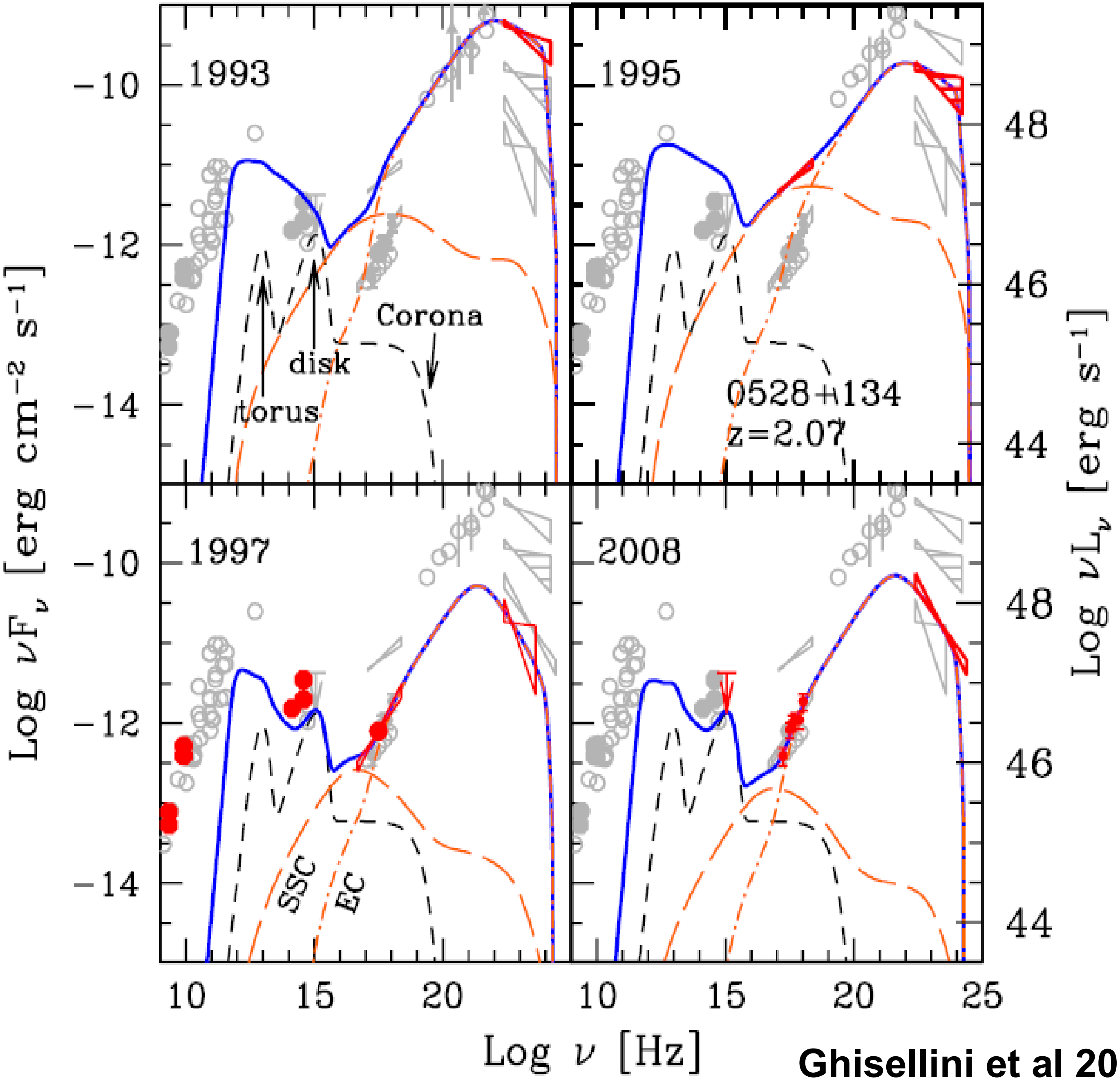
Kink instability
Current driven
instabilities ?

Hot disk: VHS ?

1 mas = 1.2 pc

BL Lac - Marscher et al. 2008

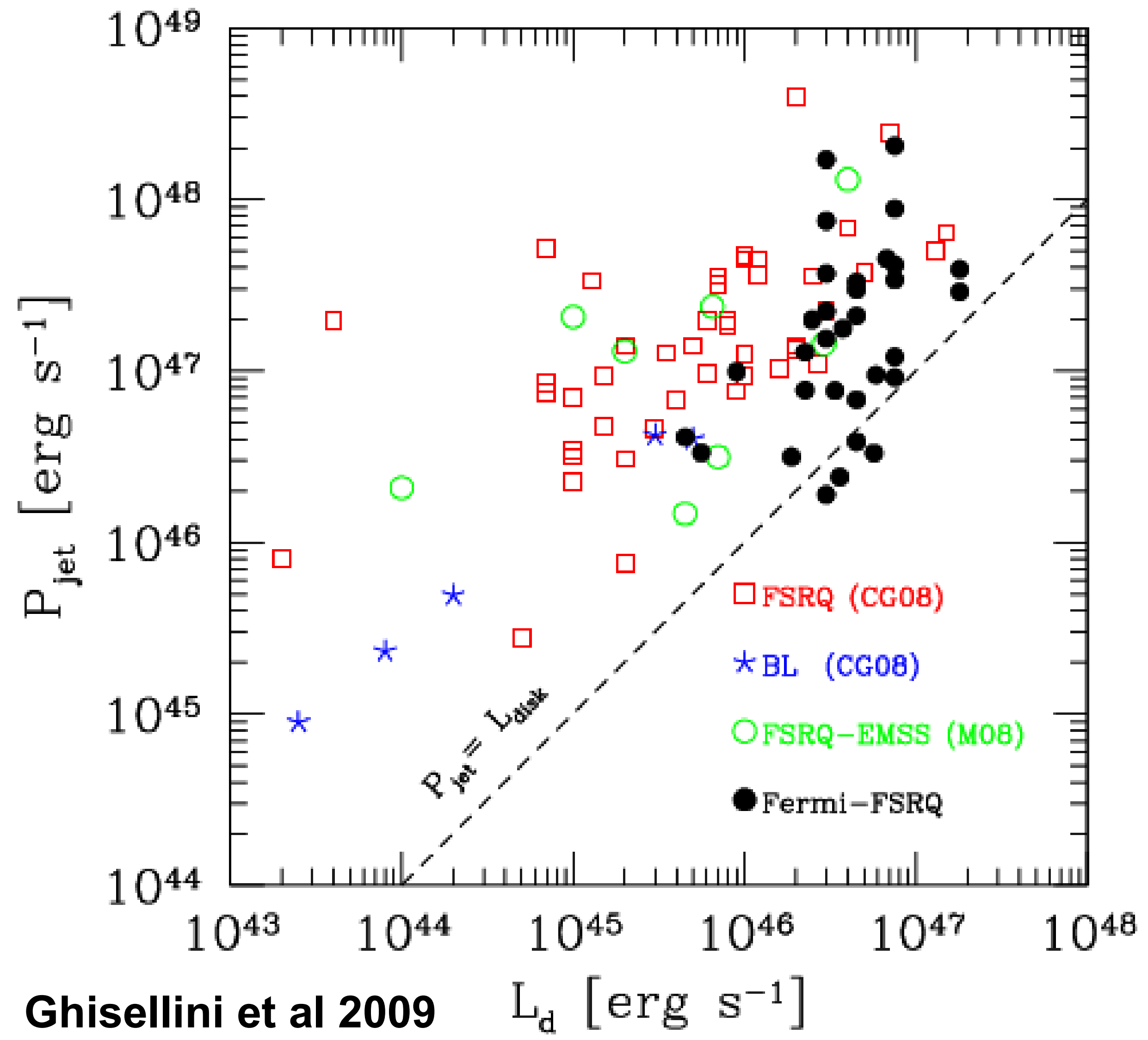
Use Energetics of Fermi Blazars



Ghisellini et al 2009

Power of Fermi Blazars

→ Jet Power exceeds Disk Lum



Ghisellini et al 2009

Black Holes ➔ The Spin Paradigm

- Binding energy of ISCO ➔ tapped by accretion **ε_H(a, dotm).**
- Rotational energy ➔ tapped by magnetic fields, similar to rotating neutron stars (BZM).

$$L_{Rot} = E_{Rot}/t_{brake}$$
$$\sim 10^{45}\ \mathrm{erg/s}\ (M_H/10^9\ M_S)\ (t_H/t_{brake})$$

$$L_{Rot} = E_{Rot}/t_{brake}$$
$$\sim 10^{37}\ \mathrm{erg/s}\ (M_H/10\ M_S)\ (t_H/t_{brake})$$

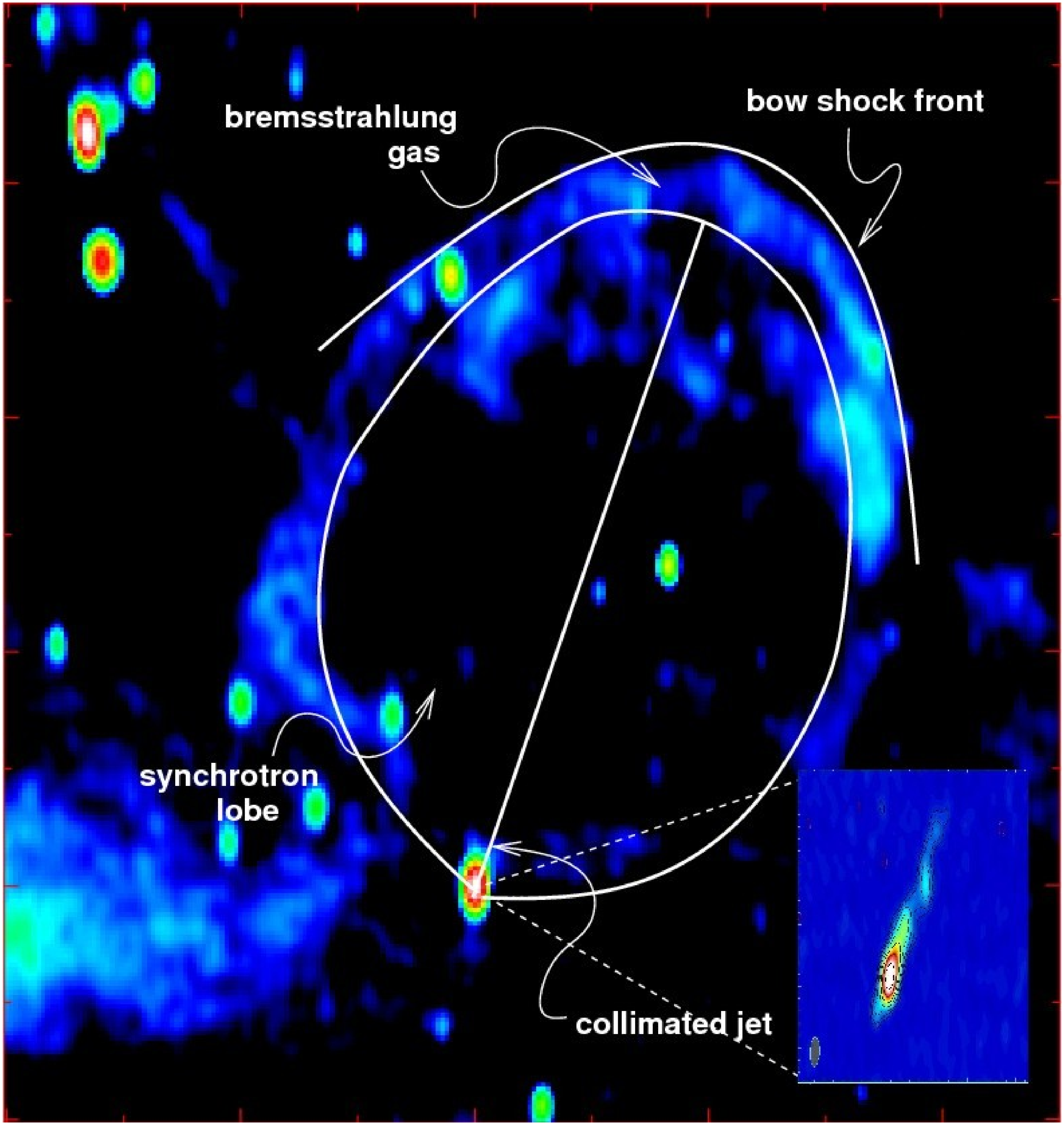
t_{brake} = f (a, B,...)   [BZ 1977, ...]

Cyg X-1 Jet-Bubble

→ Jet Power ~10^{37} erg/s

~ 100 times L_{Radio}

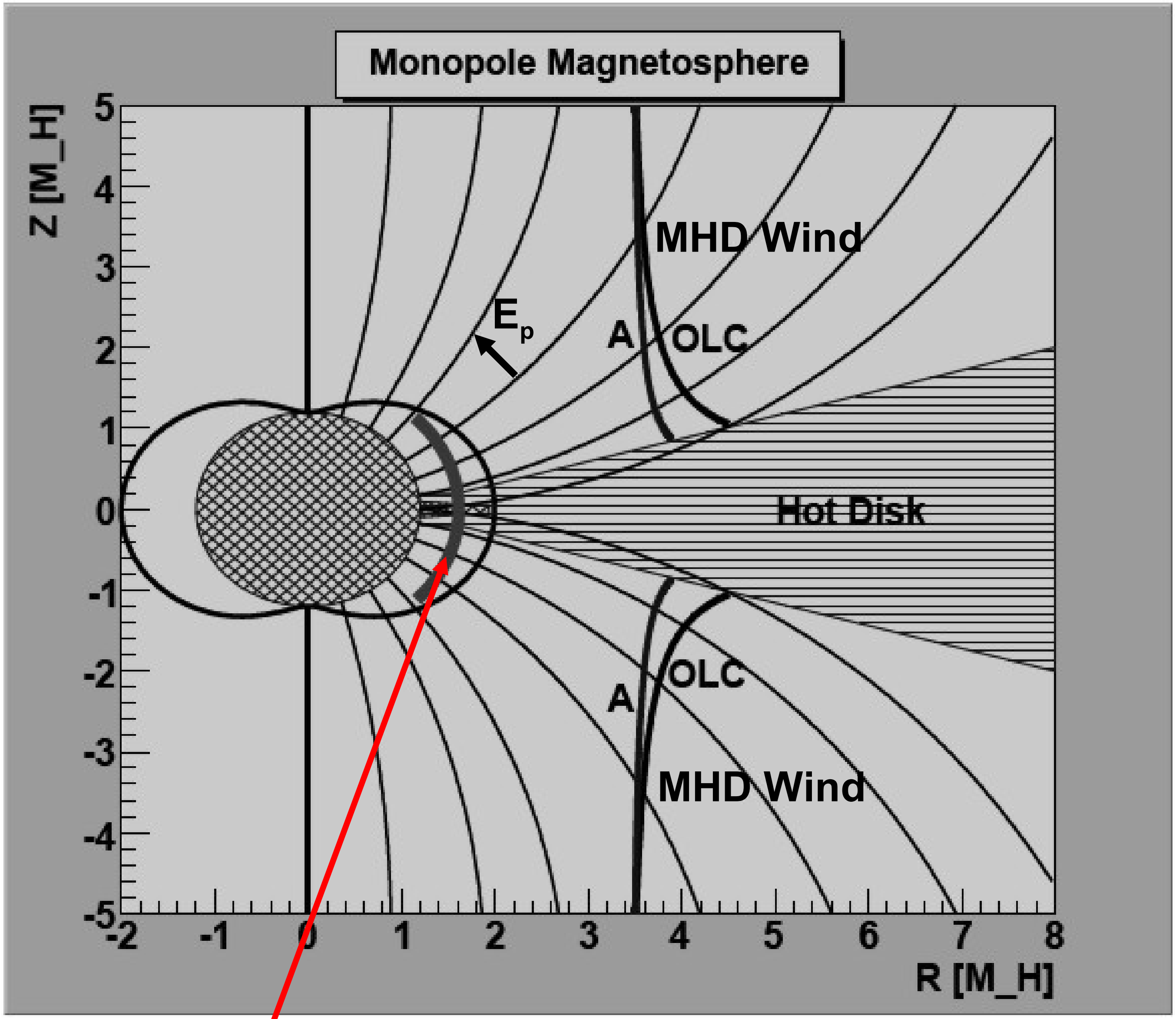
BH Rotational Energy ?



Gallo 2005
(60 hours WSRT)

DIP Magnetosphere of Black Holes ➔ Jets

A: Alfven surface; OLC: outer light surface c/Ω_F



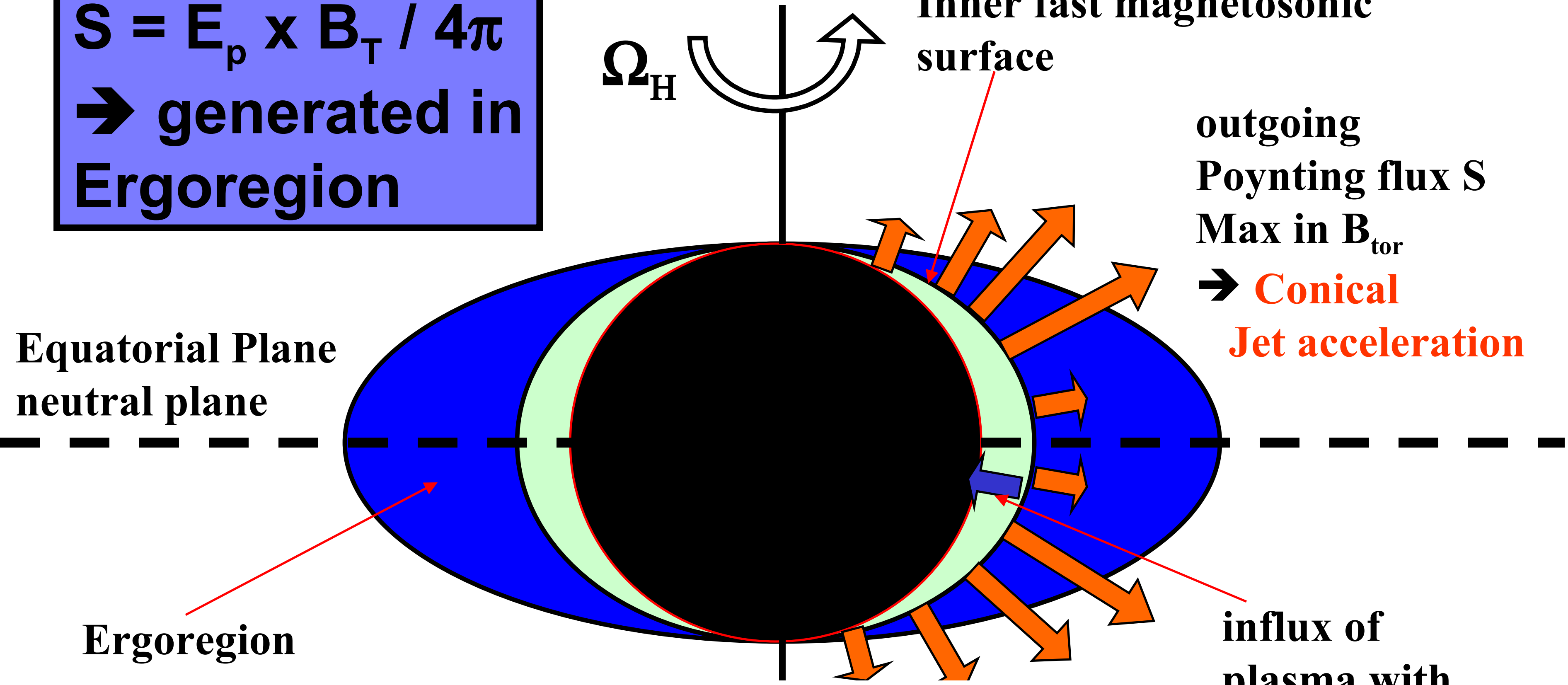
Plasma injection around ISCO

Camenzind 2007

BZ Poynting Flux – Dipole Geometry

$S = E_p \times B_T / 4\pi$

→ generated in Ergoregion



Ω_H

Inner fast magnetosonic surface

outgoing
Poynting flux S
Max in B_{tor}
→ Conical
Jet acceleration

Equatorial Plane
neutral plane

Ergoregion

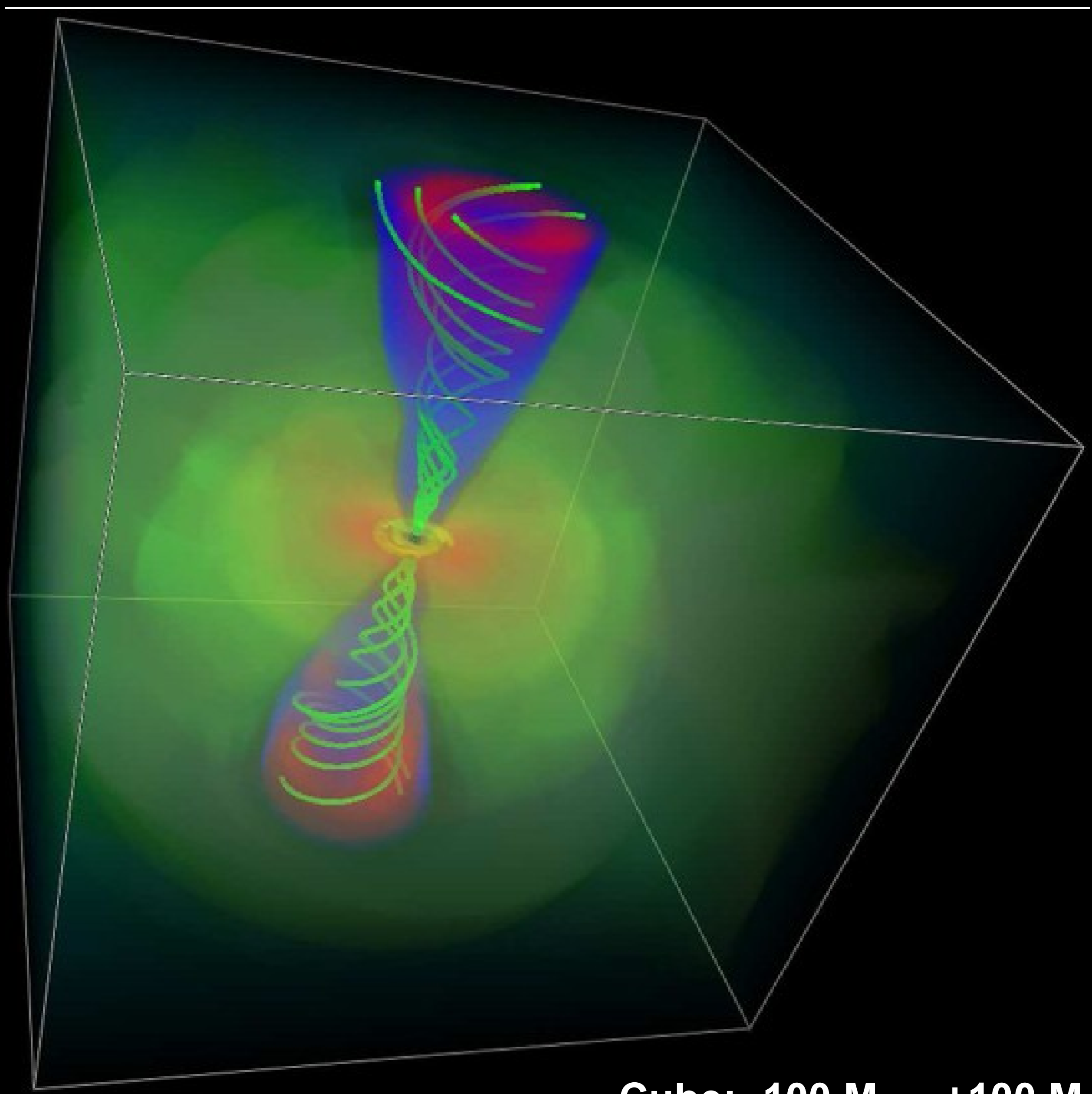
influx of
plasma with
negative energy

$$\frac{\partial T}{\partial t} + \alpha(\boldsymbol{v}_p \cdot \nabla)T - \alpha\tilde{\omega}^2 \nabla \cdot \left(\frac{T}{\tilde{\omega}^2}\boldsymbol{v}_p\right) - \alpha\tilde{\omega}^2 \nabla \cdot \left(\frac{\eta}{\gamma\tilde{\omega}^2}\nabla T\right) = \alpha\tilde{\omega}^2 \boldsymbol{B}_p \cdot \nabla\Omega + \alpha\tilde{\omega}\, \boldsymbol{e}_\phi \cdot \nabla \times \left(\frac{\eta}{\gamma}\frac{\partial \boldsymbol{E}_p}{\partial t}\right) .$$

$T \sim RB_\phi$

Camenzind 2007

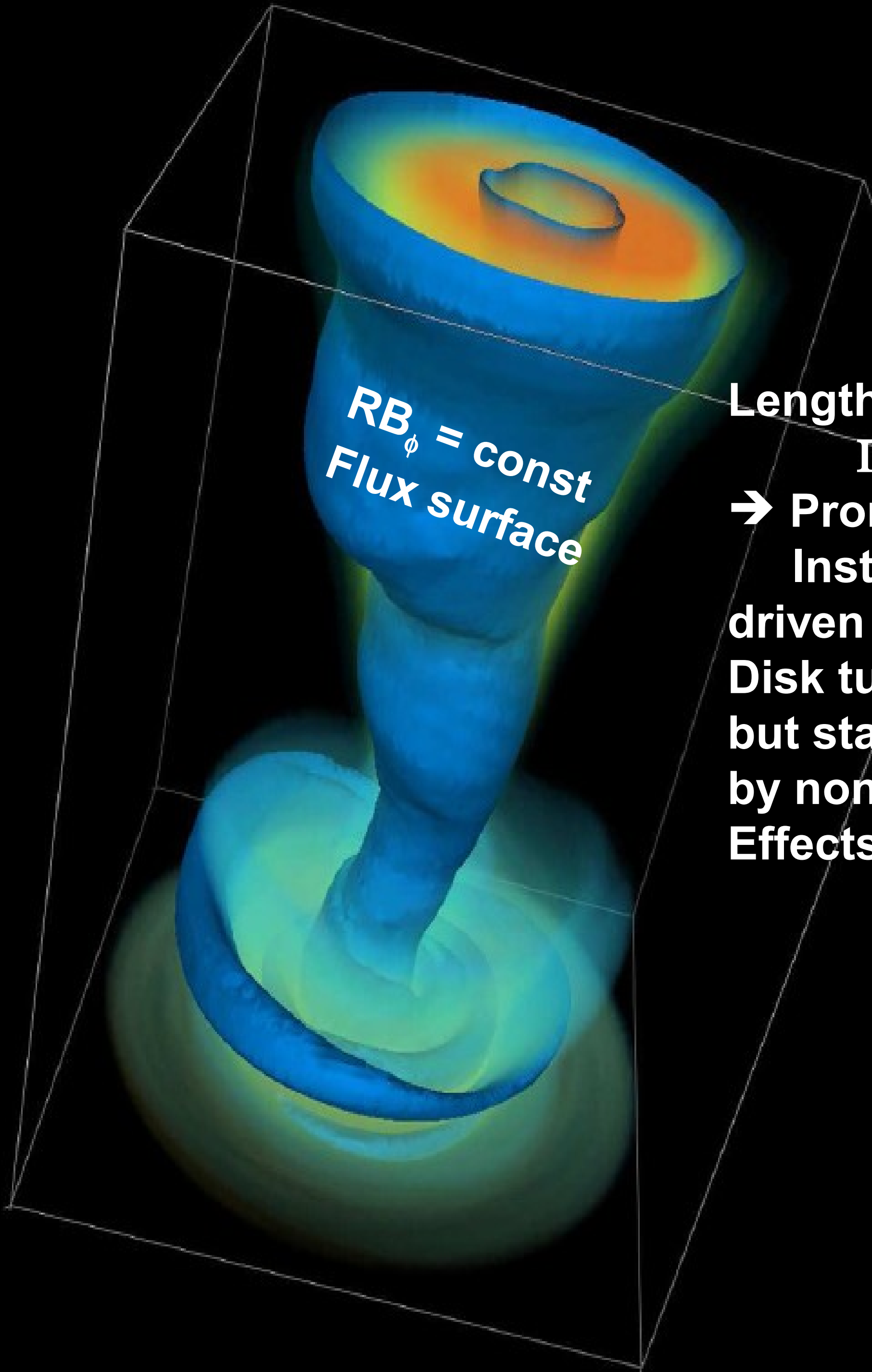
BH Driven DIP Jets



McKinney 2008
3D HARM GRMHD
[see also Beckwith et al.]

Cube: -100 M … +100 M

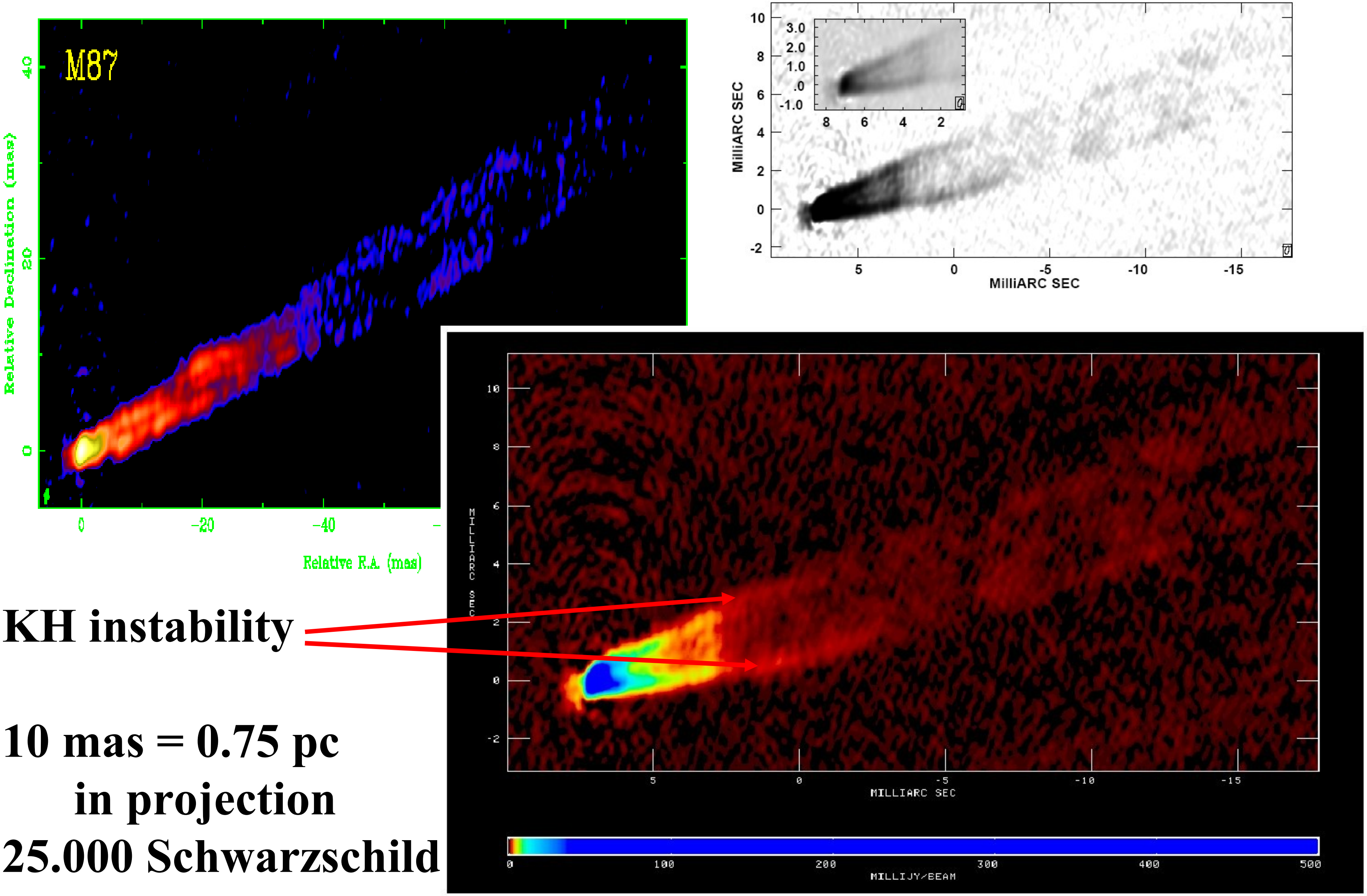
BH Driven DIP Jets
➔ Kink Stable (m=1)



Length: 1000 M
$\Gamma = 10$ Jet
➔ Prone to Kink Instabilities driven by Disk turbulence, but stabilized by non-linear Effects

McKinney 2008
3D HARM GRMHD

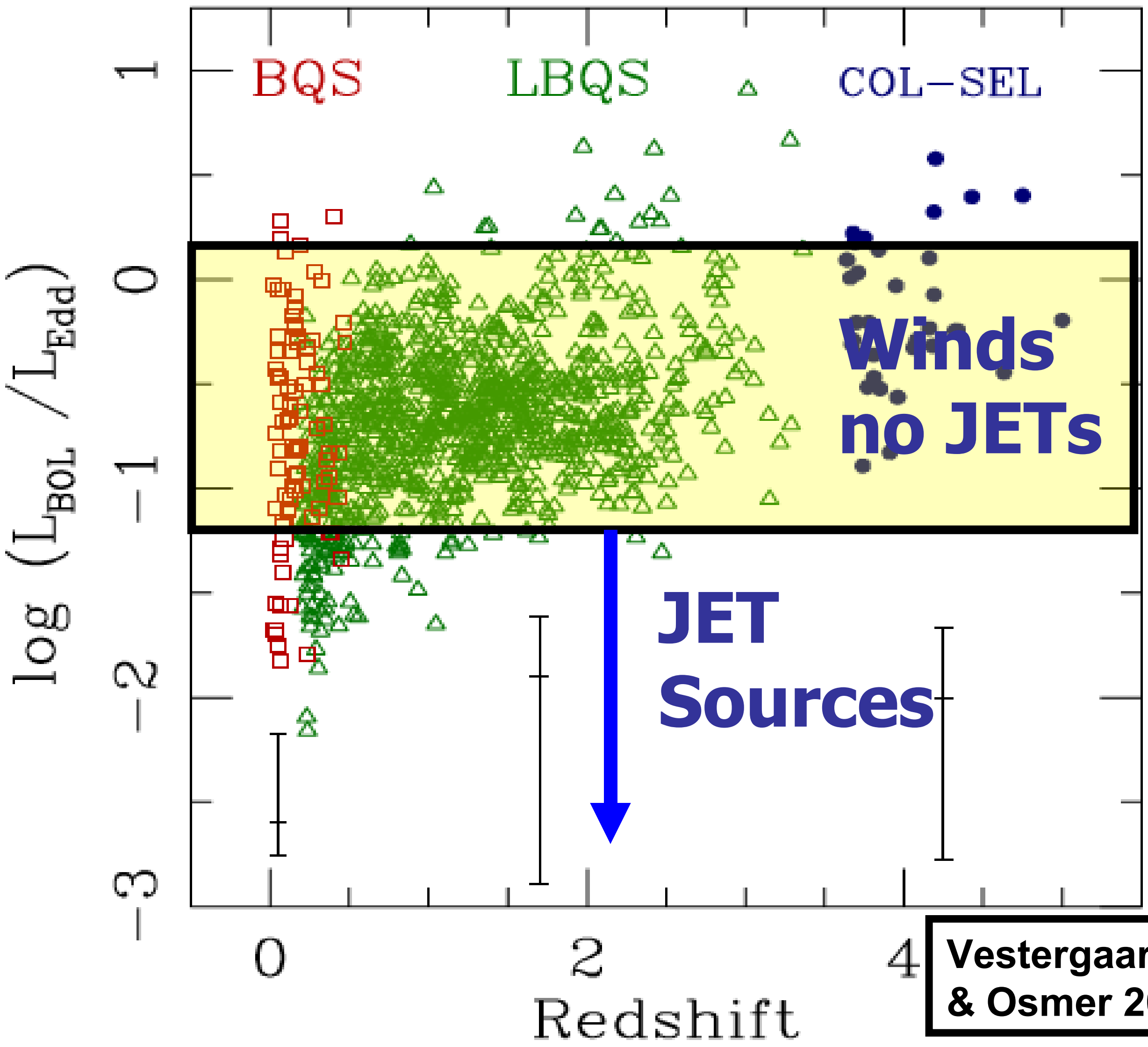
M87 – 5 GHz / 43 GHz VLBA



KH instability

10 mas = 0.75 pc
in projection
25.000 Schwarzschild

RQs Quasars are too High-Accretors



Winds no JETs

JET Sources

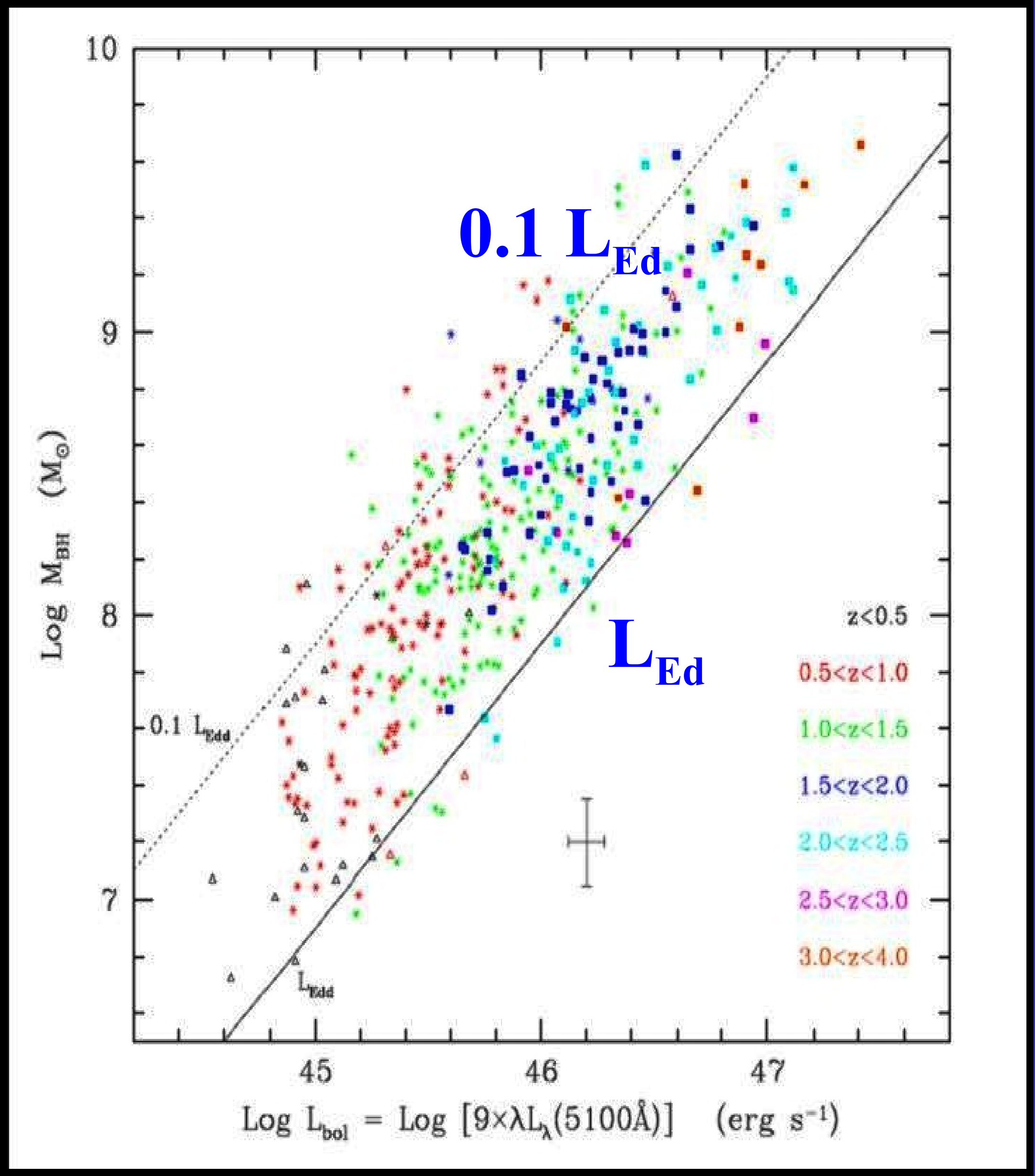
Vestergaard & Osmer 2009

Quasars High Accretors

- For z > 0.5:

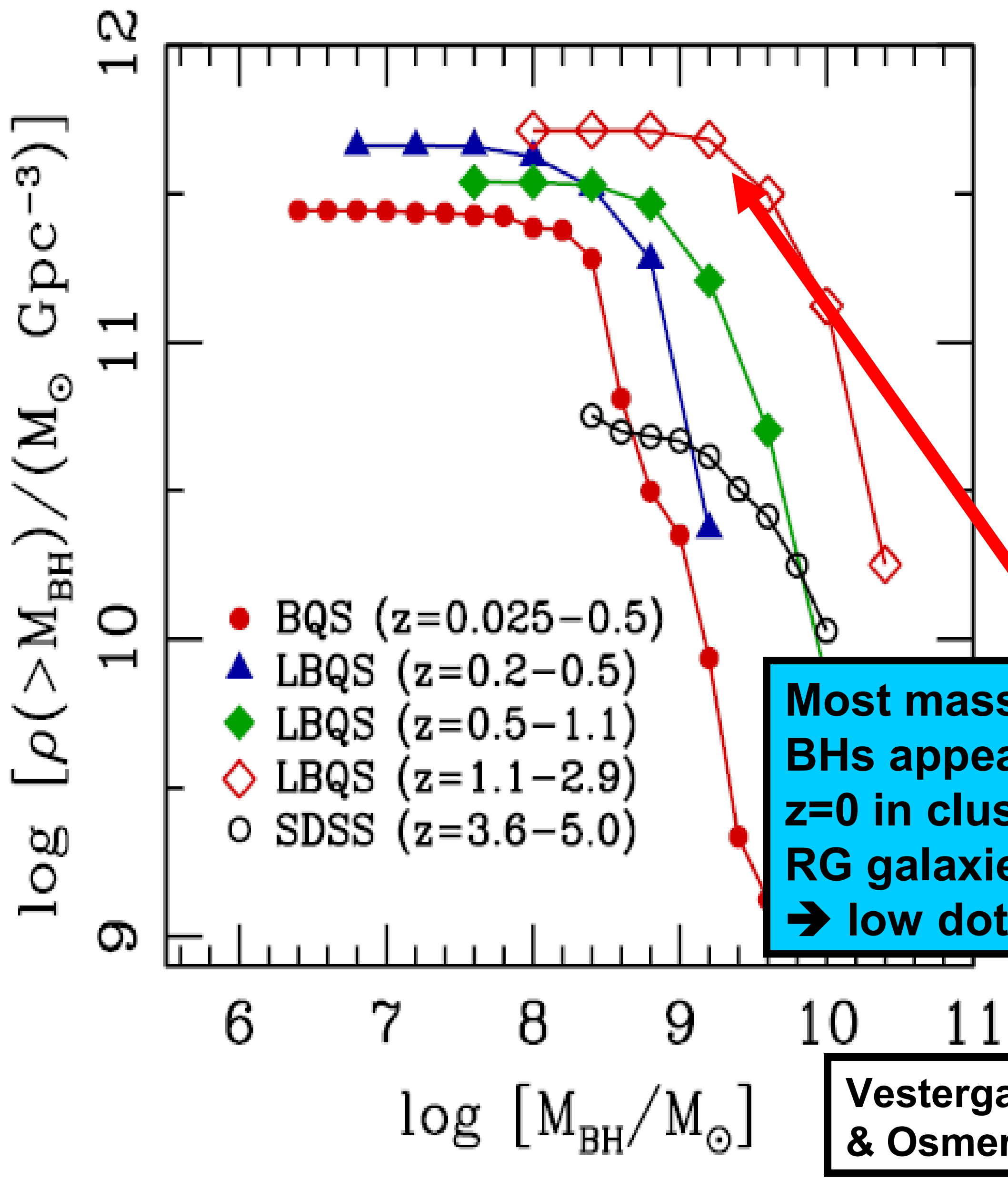
L_{Bol}/L_{Ed} ~ ¼

➔ Distribution is strongly peaked



Kollmeier et al. 2007

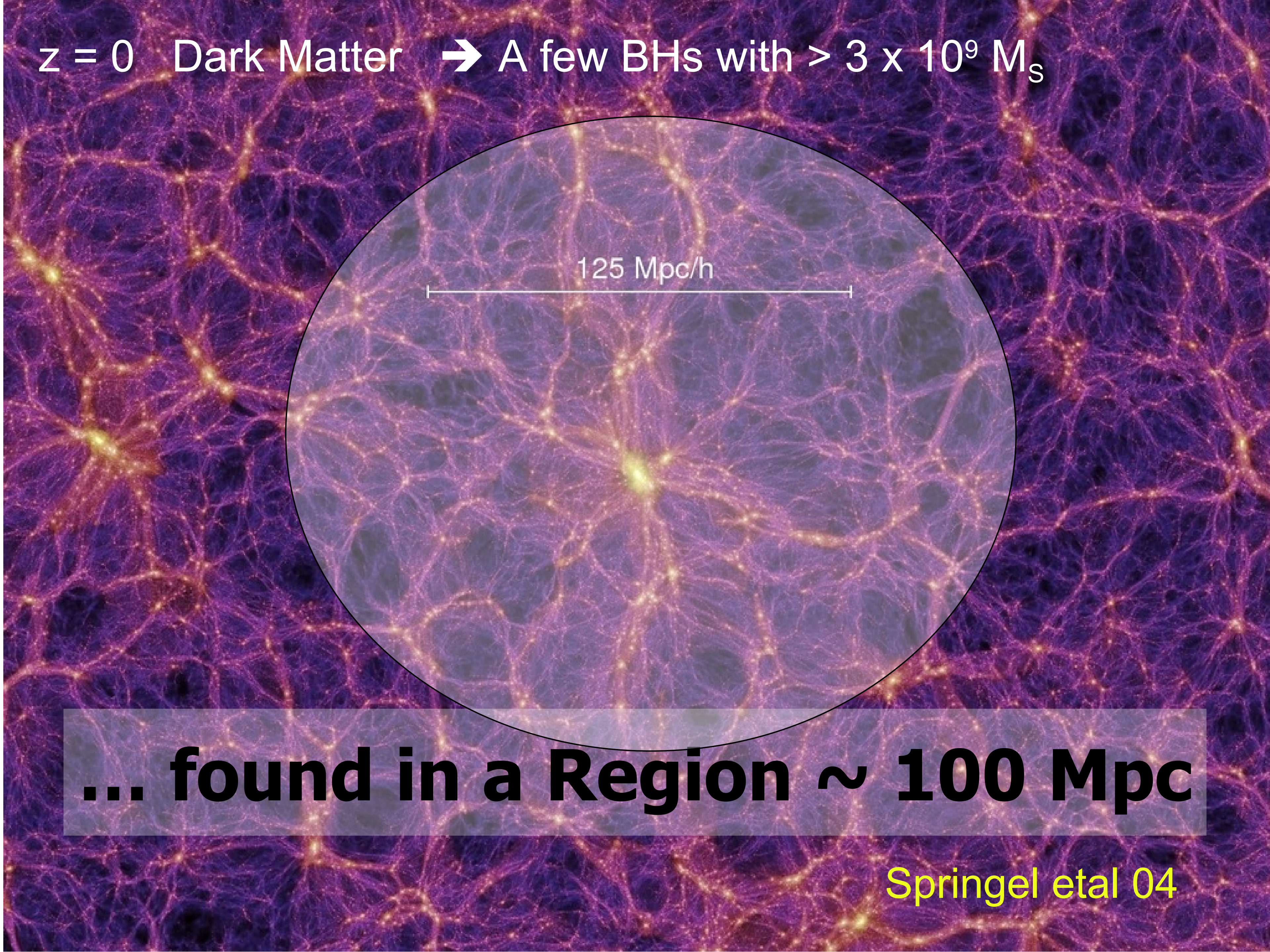
High-z Quasars are very Massive ~ 10^9 M_s but very rare ➔ Cluster



Most massive BHs appear @ z=0 in cluster RG galaxies ➔ low dotM !

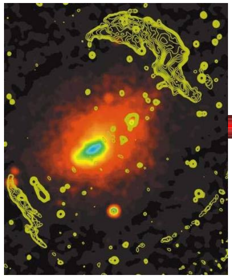
Vestergaard & Osmer 2009

z = 0 Dark Matter ➔ A few BHs with $> 3 \text{ x } 10^9 M_S$



… found in a Region ~ 100 Mpc

Springel etal 04



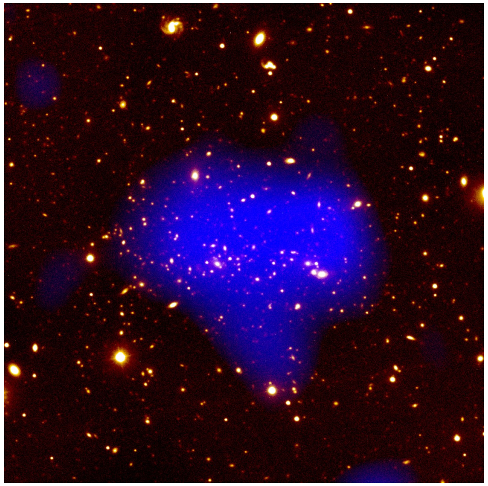
What is a Cluster made of ?

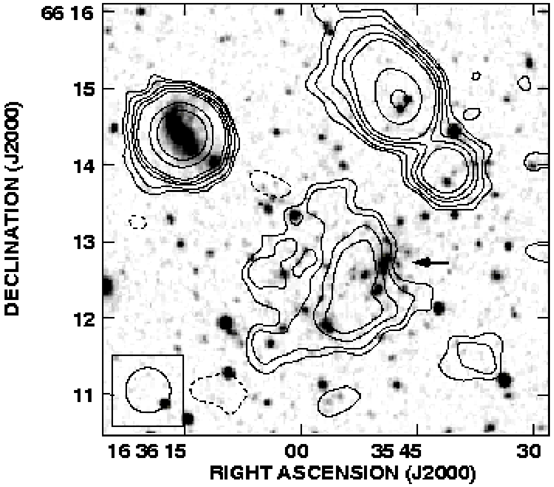
Galaxy clusters are the largest (~ Mpc size) laboratories for (particle) - astrophysics.

Baryons
(Gas + Stars)

Dark Matter
(WIMPs)

Relativistic particles
(Radio halos/relics)

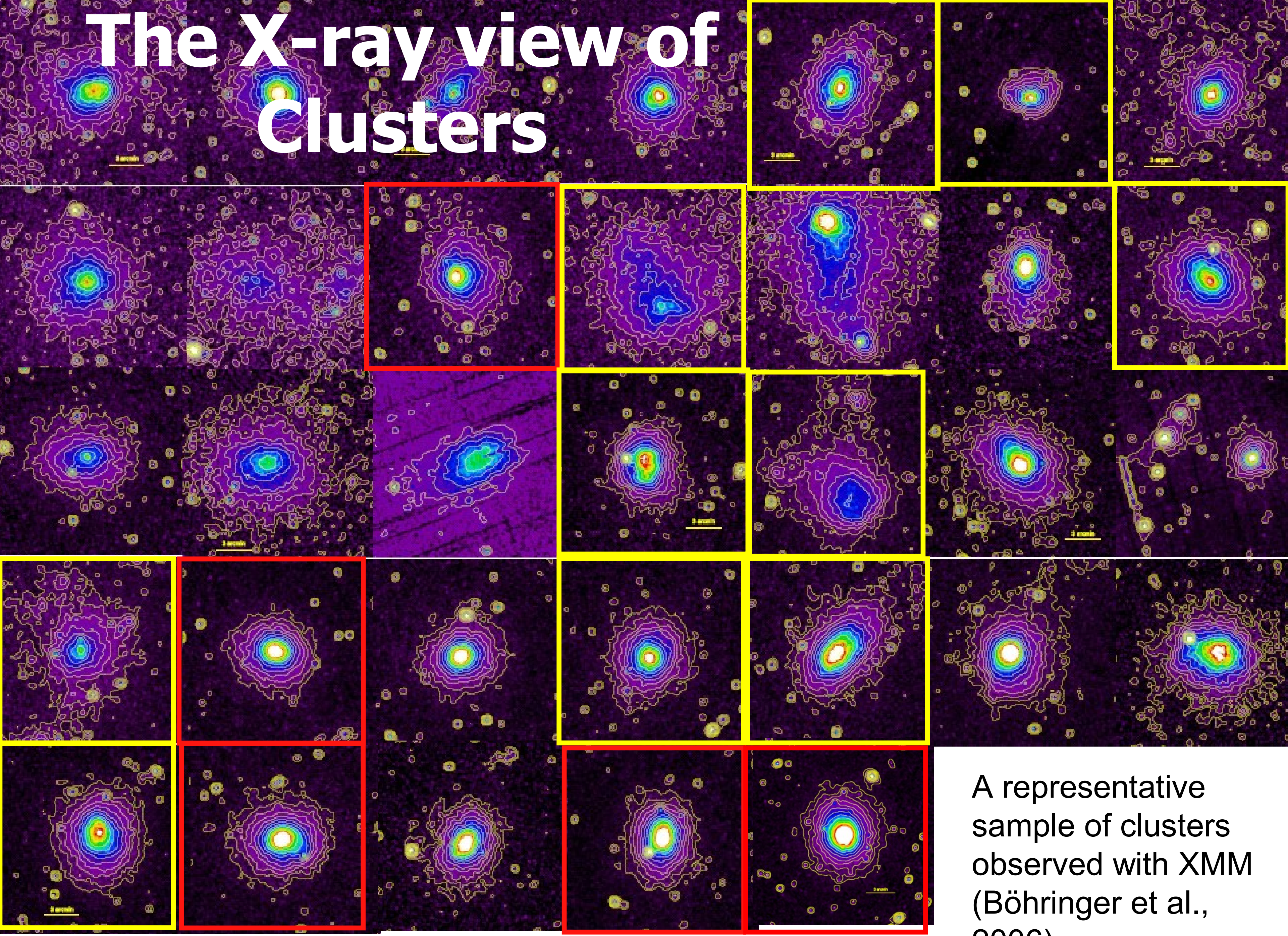




The X-ray View of Clusters

- Clusters of galaxies contain hot gas
- Dense: $n \sim 0.01\ \mathrm{cm}^{-3}$, $k_B T \sim$ few keV
- Conditions for efficient radiation by thermal bremstralung and inner-shell recombination
- Luminous X-ray sources,“easily” observed by satellite missions (XMM, Chandra, …)
- “easy” to measure density, pressure and hence total mass and baryon mass

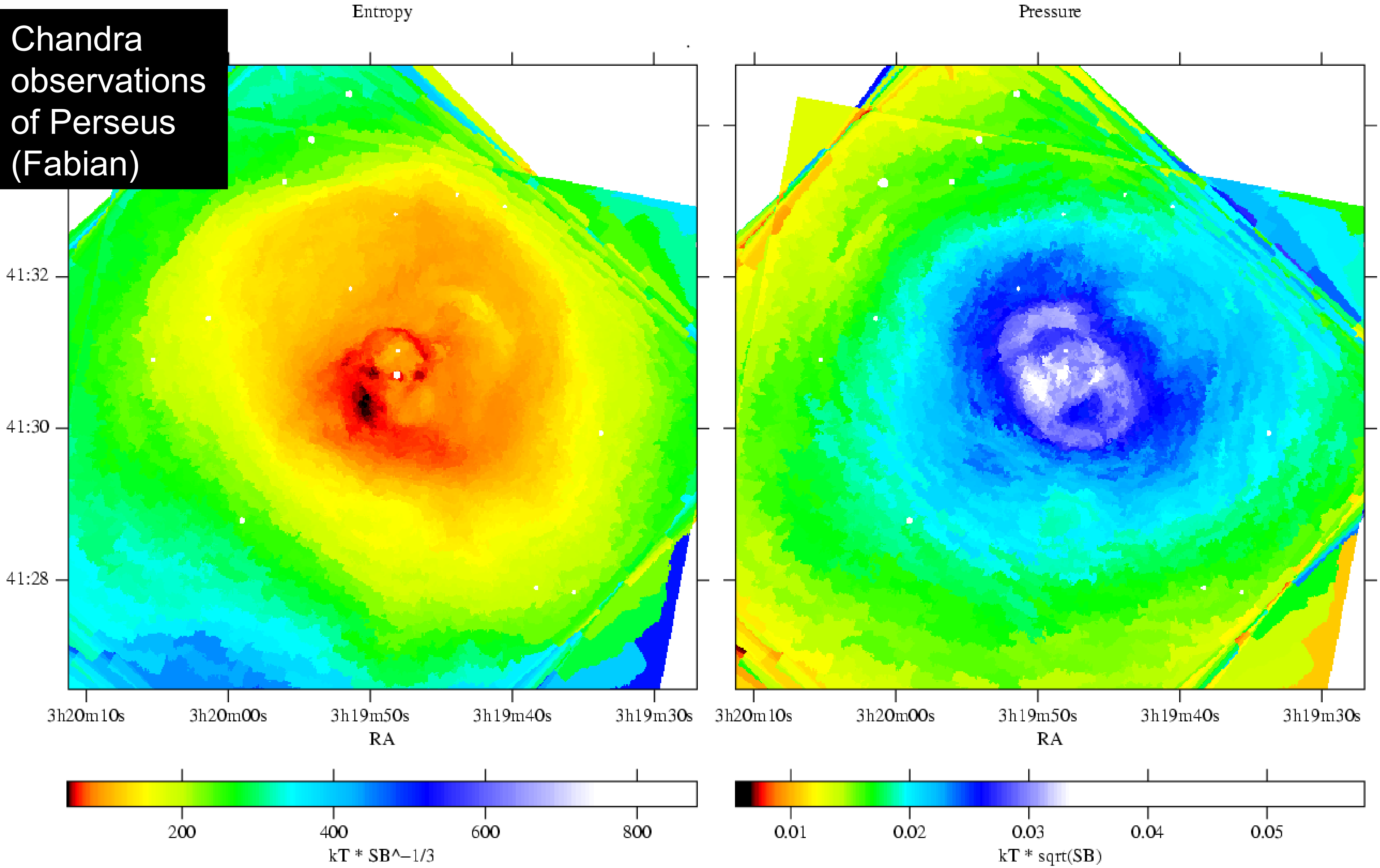
The X-ray view of Clusters

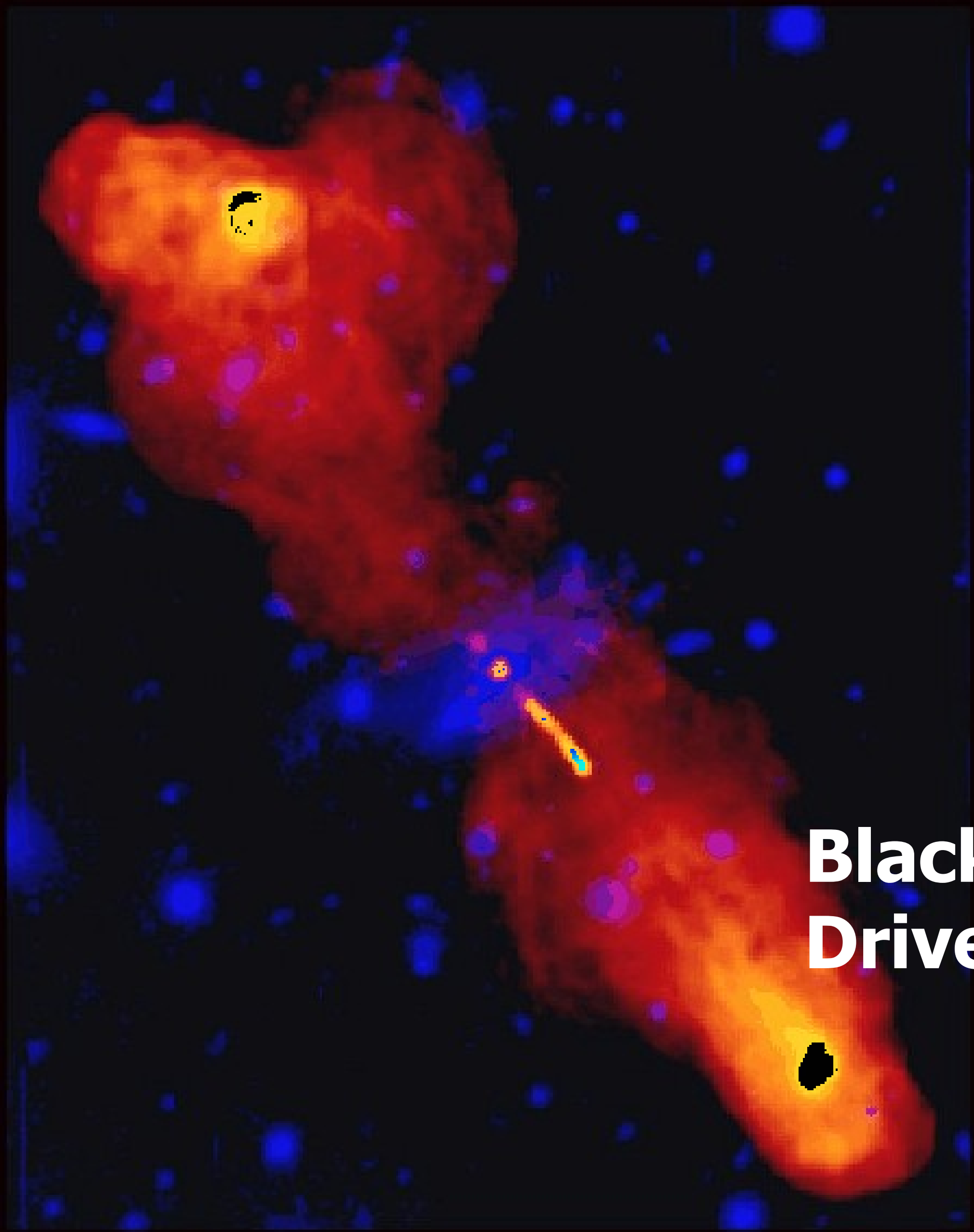


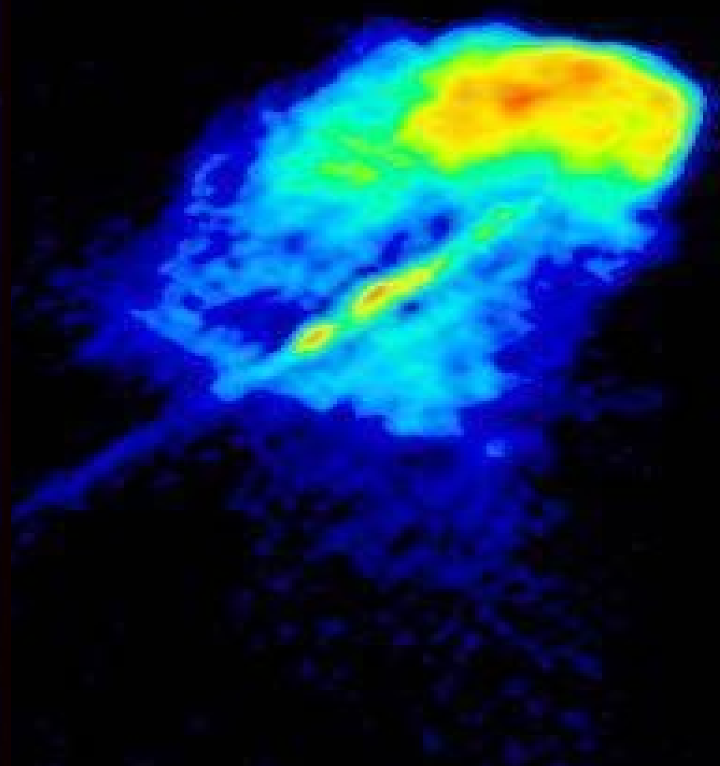
A representative sample of clusters observed with XMM (Böhringer et al., 2006)

Cluster Centers are often Disturbed
Entropy and Pressure

Chandra observations of Perseus (Fabian)

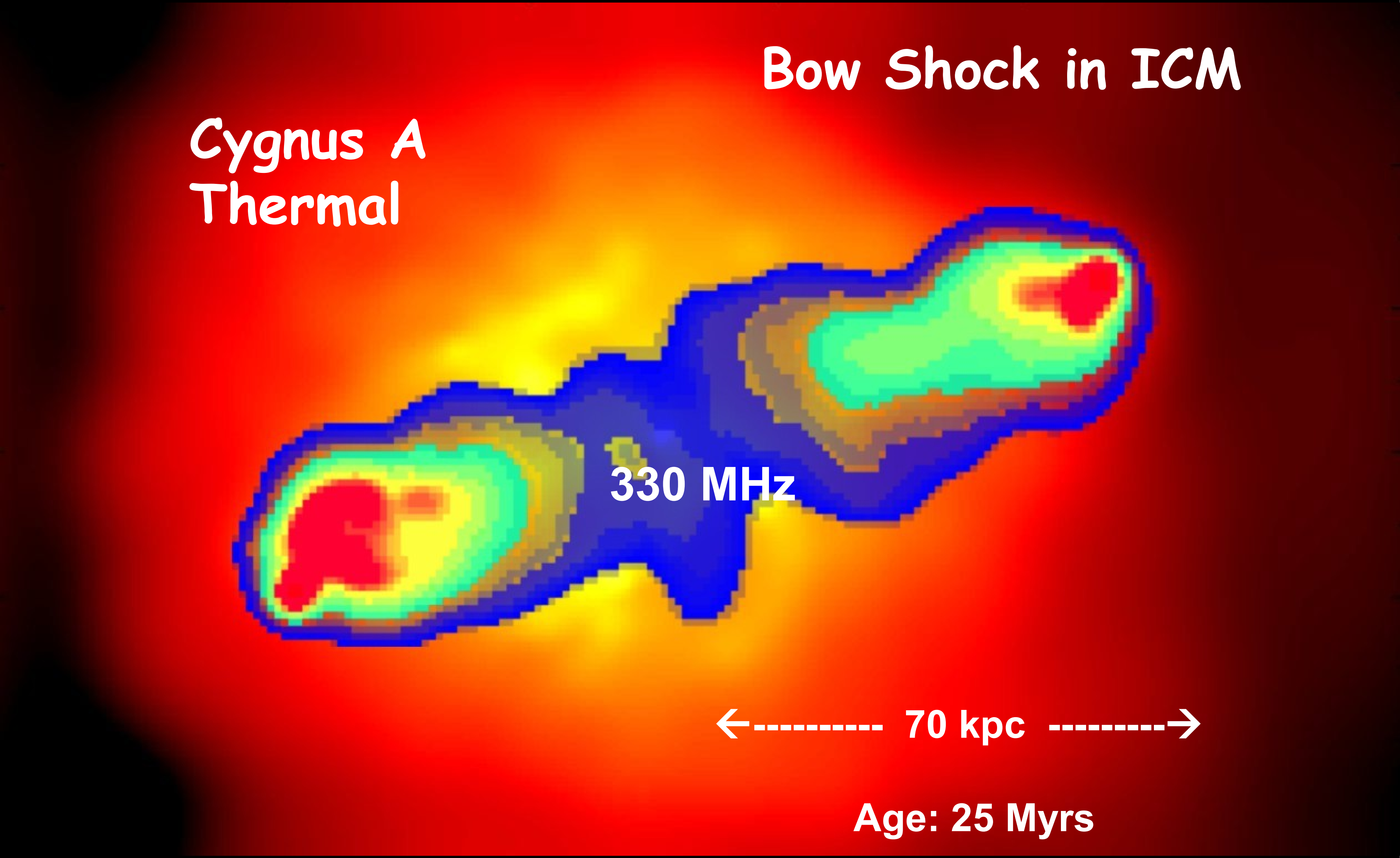






Black Holes in gE-Galaxies Drive Jets into Cluster Gas

Cygnus A (VLA)
3C 219 (VLA)



Bow Shock in ICM

Cygnus A
Thermal

330 MHz

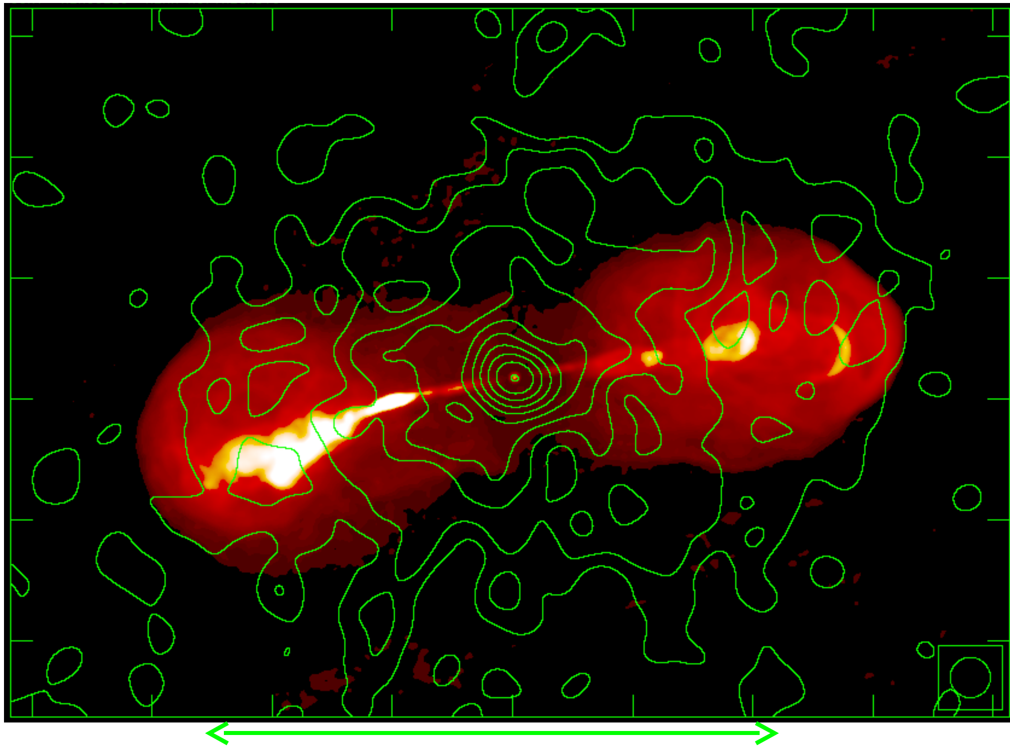
←---------- 70 kpc ---------→

Age: 25 Myrs

Chandra/VLA

Dying Jet: Hercules A

- **Powerful DRAGN in cluster-dominating galaxy at z= 0.154.**
- **X-ray parameters typical of Abell clusters.**
- **Cluster elongated along radio axis.**
- **Age: 100 Mio yrs**



Gizani & Leahy 2005

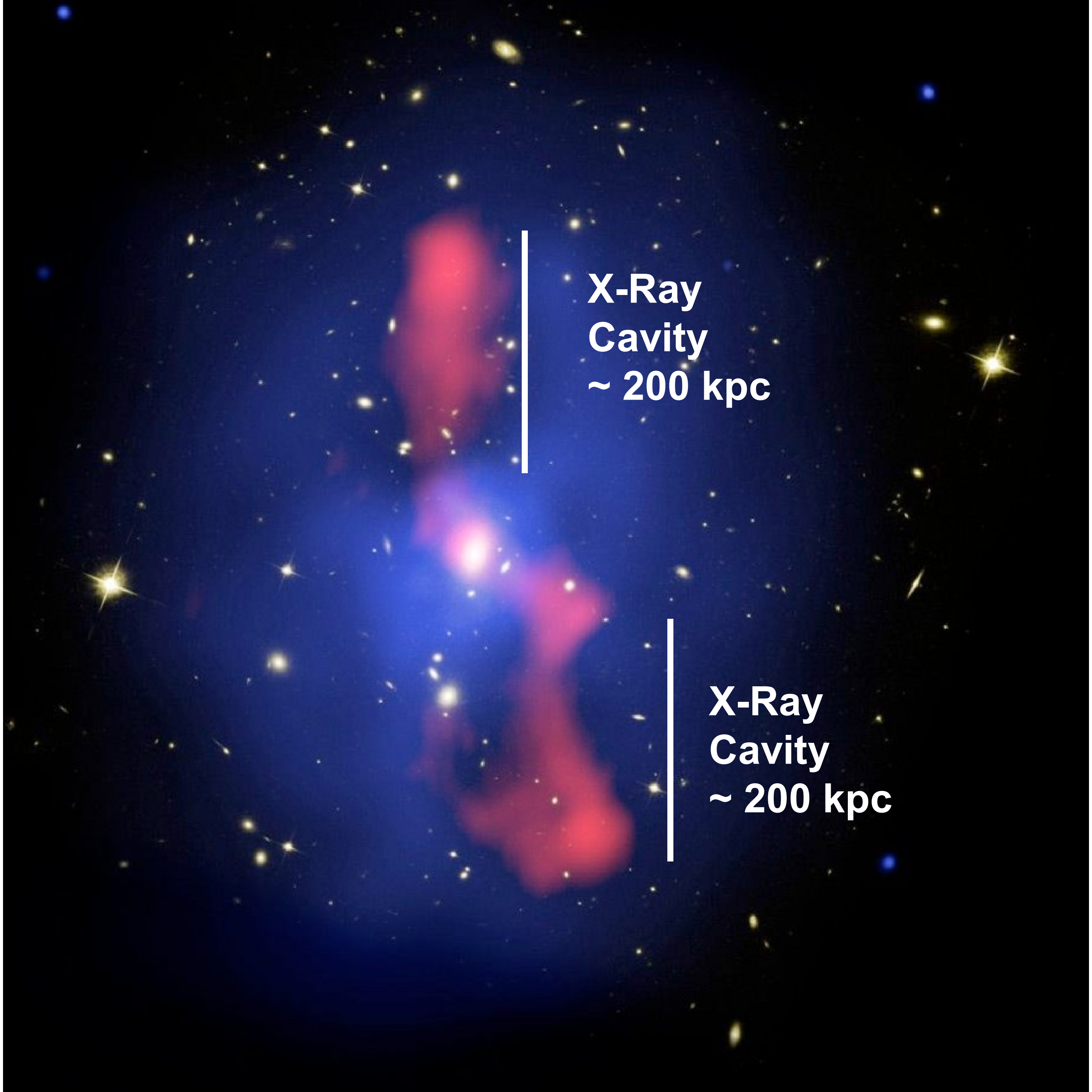
Before dying → Repeated Injection

VLA B+C+D
λ3.6 cm
0.74″ beam

MS 0735.6+7421

Chandra + VLA 330 MHz

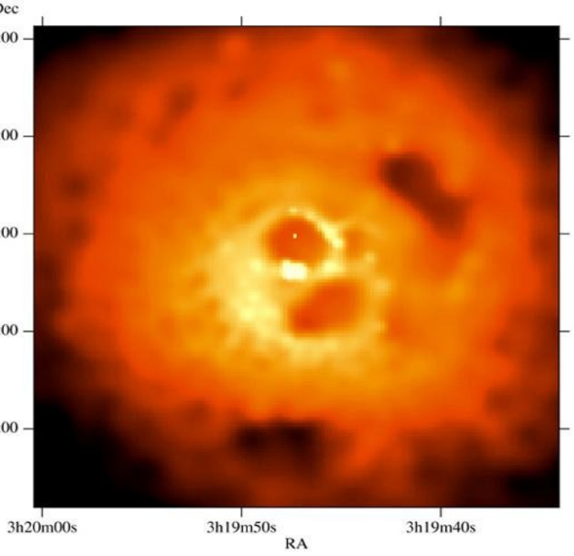
Age: 100 Mio yrs



McNamara & Nulsen 2007

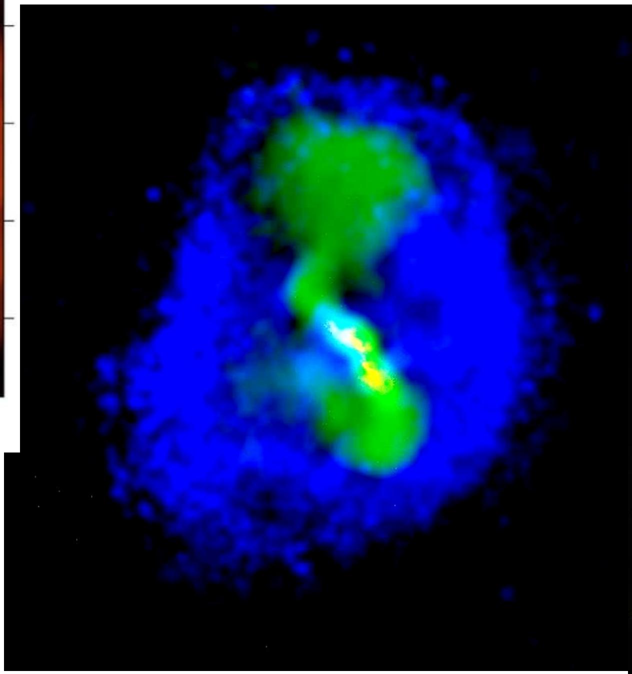
Jets and Lobes in Galaxy Clusters : The most Extreme Examples → Different Outburst Energies

Perseus (Fabian et al.)



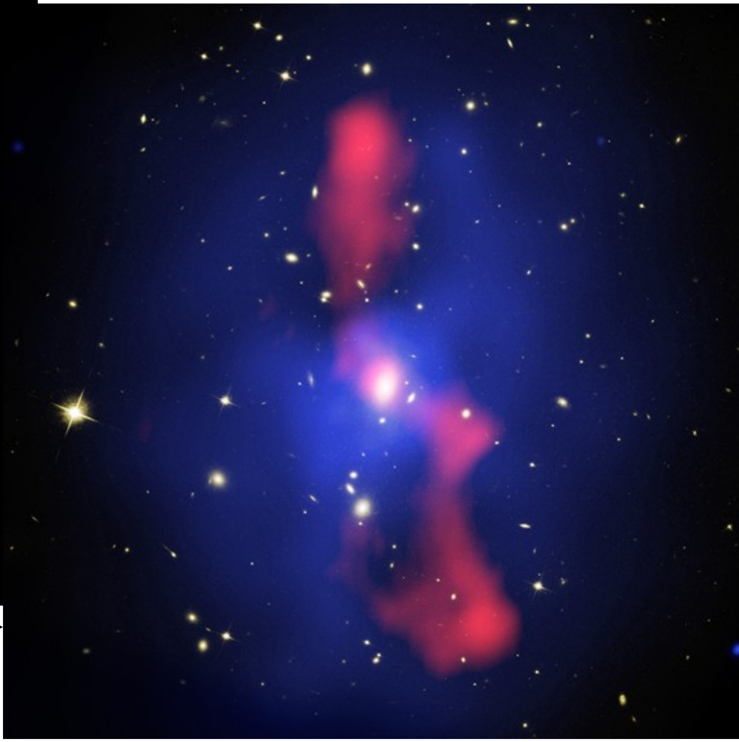
~ 250 kpc

Hydra A (Wise et al.)



~ 400 kpc

MS0735.6+7421 (McNamara et al.)

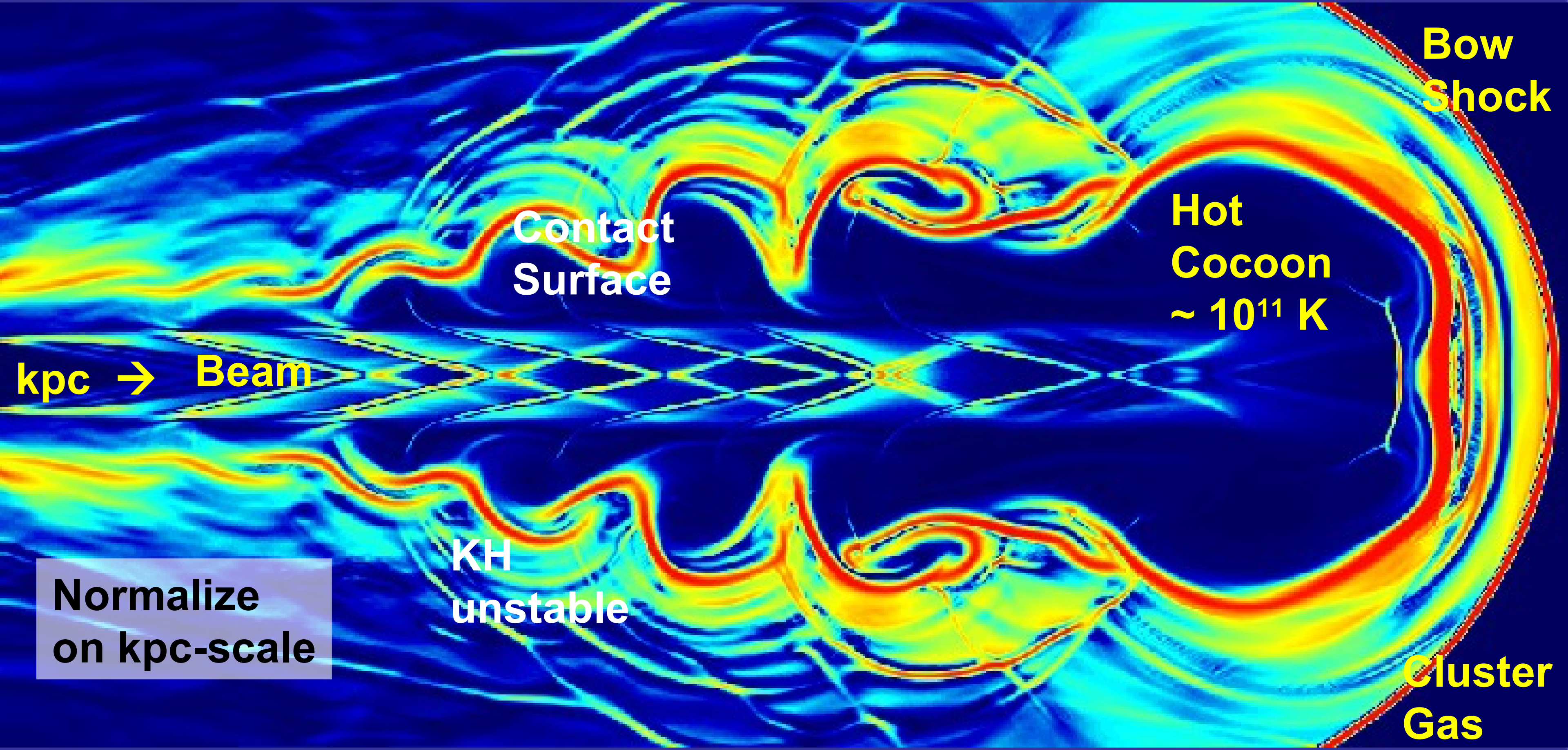


~ 1 Mpc

The Current View on Clusters

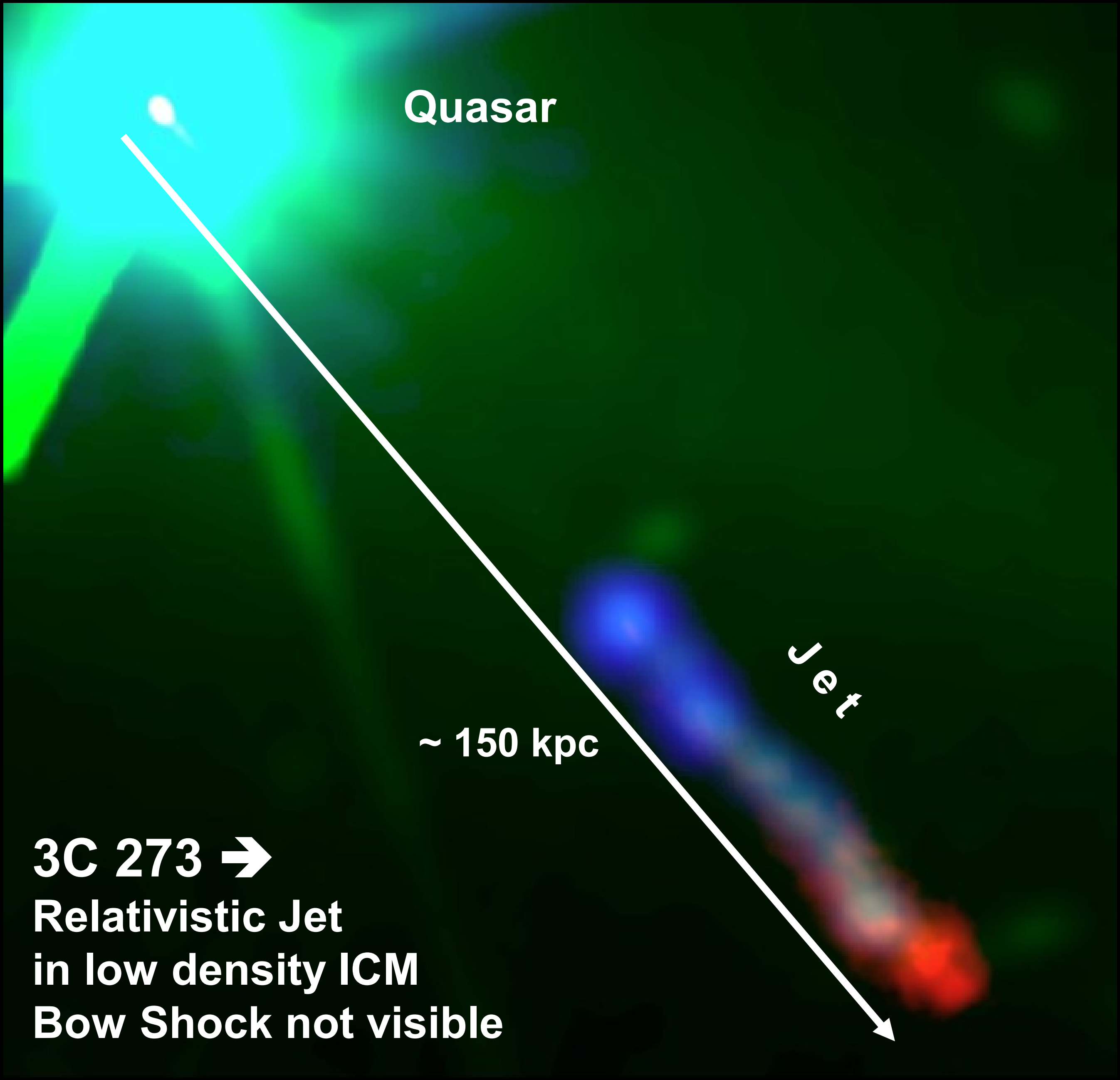
- **Jets affect the ICM:**
  - Heating by bubbles and cavities
  - **Inflated by radio jets**
- **How is the heat distributed?**
  - Shock waves?
  - Viscosity?
  - **Turbulence ~ old SN-remnant (t>100 Myrs)**
- **How is the power source regulated?**
  - Accretion from ISM in Core
  - **Energy probably driven by spin of BH**

Early Understanding of Jets (Heavy Jet → Quasar 3C 273)



→ in fact, cluster jets are much lighter

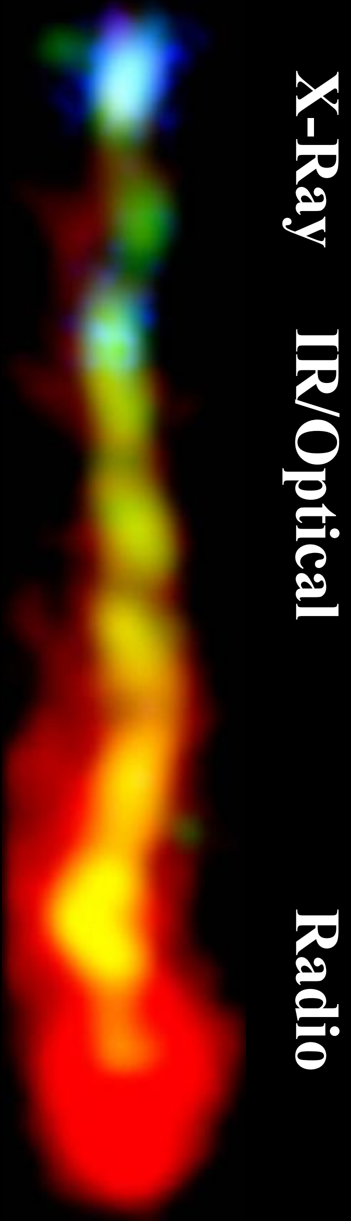
Lorentz factor = 1.04, v_B = 0.28 c, Mach = 6
[Hughes 1996] 6 ppb



3C 273 ➔

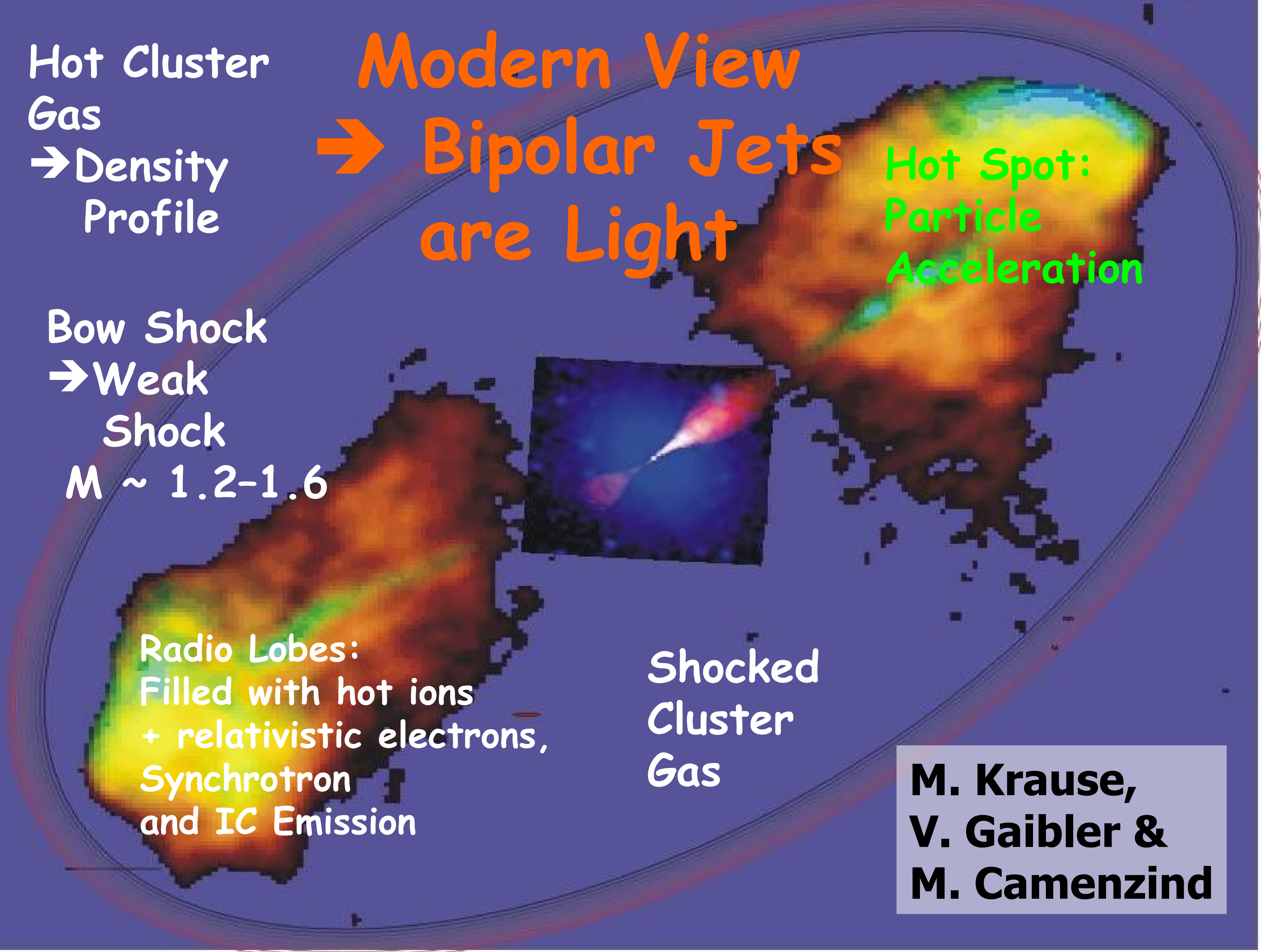
Relativistic Jet
in low density ICM
Bow Shock not visible

Uchiyama et al. 2006



➔Cocoon Plasma

Modern View → Bipolar Jets are Light



Hot Cluster Gas
→Density Profile

Bow Shock
→Weak Shock
M ~ 1.2-1.6

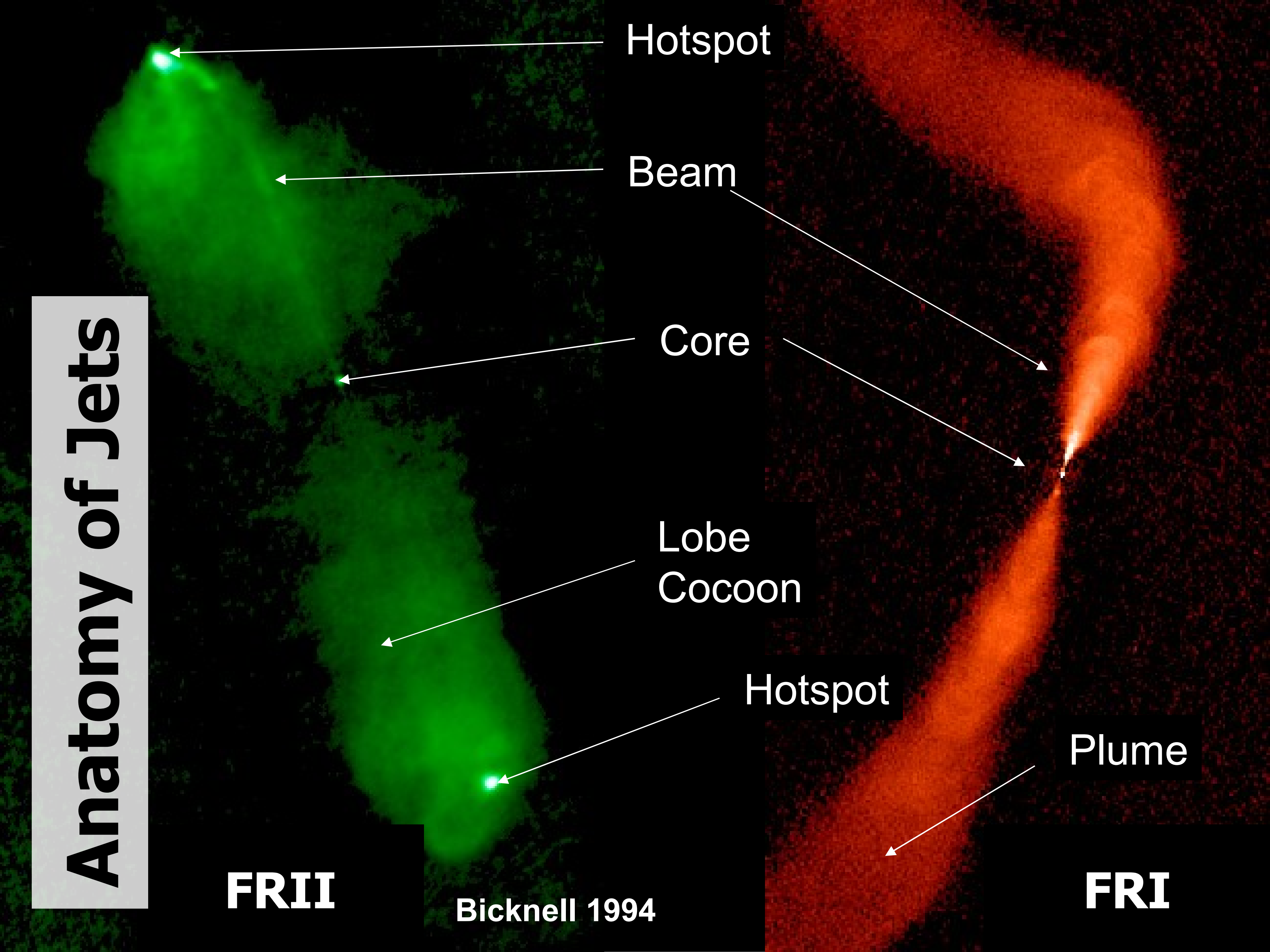
Hot Spot:
Particle Acceleration

Radio Lobes:
Filled with hot ions
+ relativistic electrons,
Synchrotron
and IC Emission

Shocked Cluster Gas

M. Krause,
V. Gaibler &
M. Camenzind

Anatomy of Jets



Hotspot

Beam

Core

Lobe
Cocoon

Hotspot

Plume

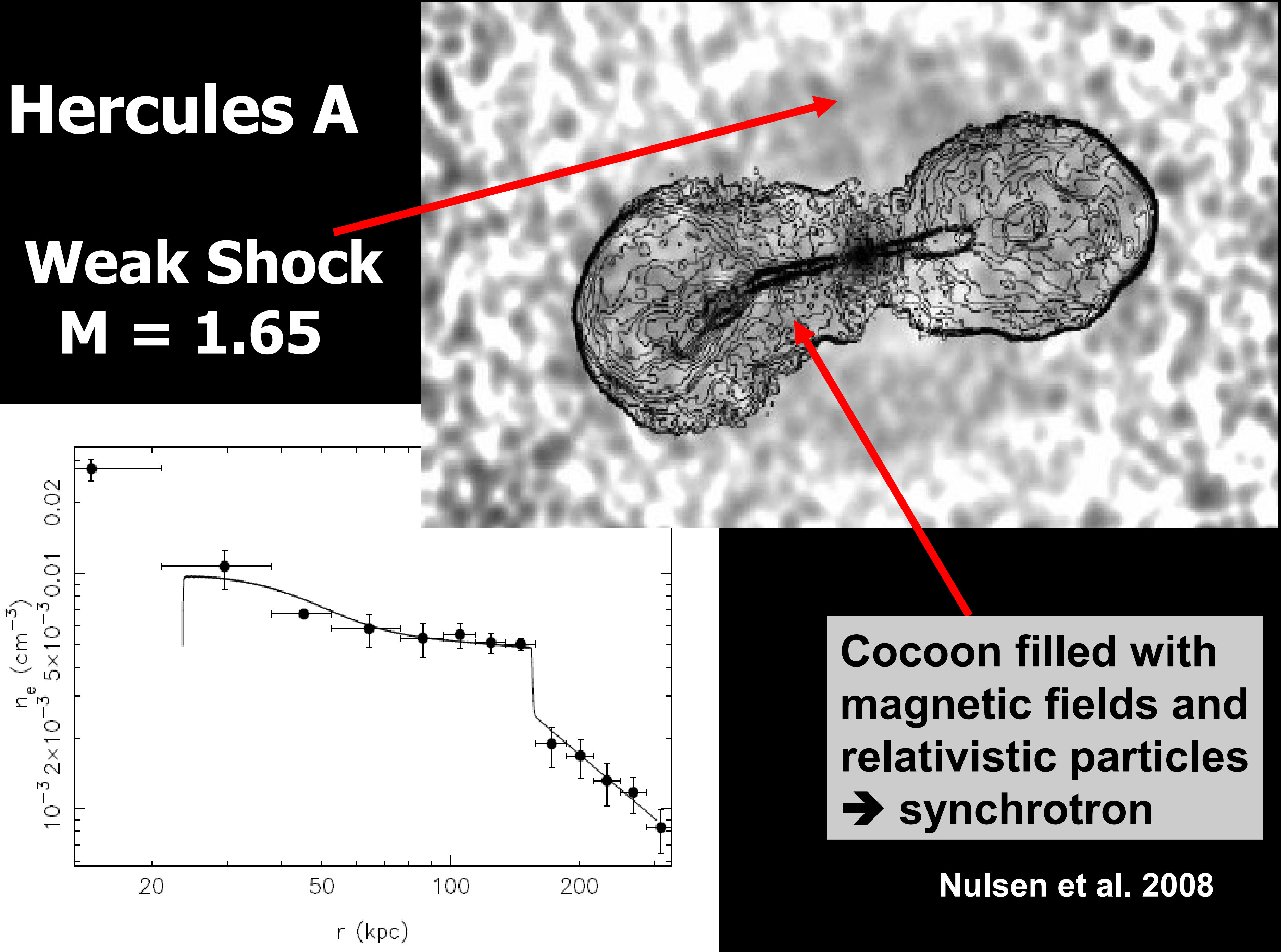
FRII

Bicknell 1994

FRI

Hercules A

Weak Shock
M = 1.65

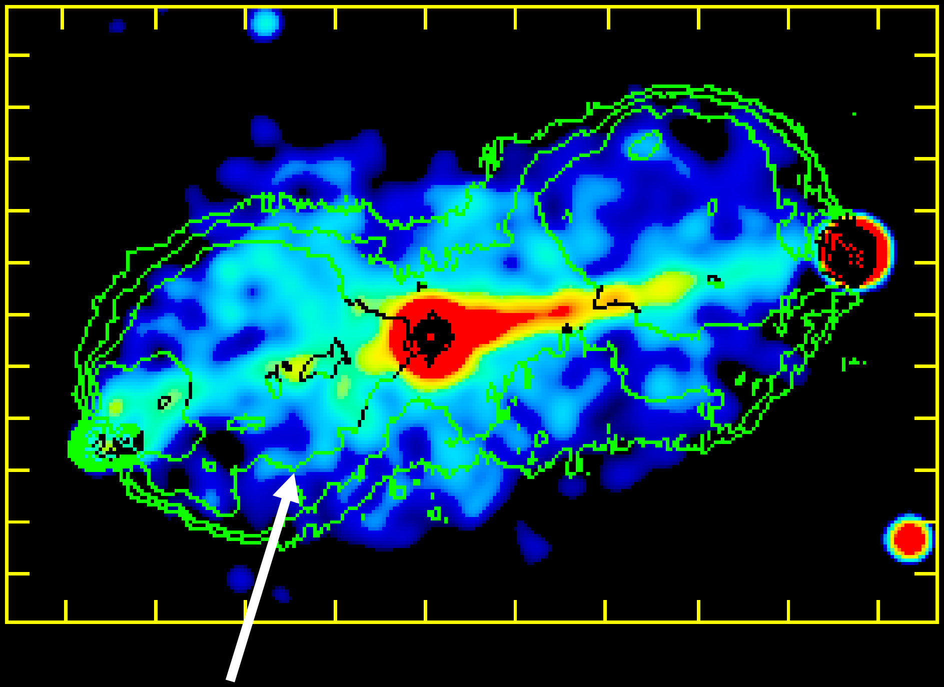


Cocoon filled with magnetic fields and relativistic particles
➔ synchrotron

Nulsen et al. 2008

Cocoon Inverse-Compton

- Detection of inverse-Compton emission in principle allows us to measure the **magnetic field strength** – and therefore electron number density, total energy etc.
- But **CMB** inverse-Compton X-rays at 1 keV come from electrons with γ ~ 1000, radiating at 10s of MHz in a B-field of 0.3 nT.



Inverse-Compton emission from the lobes of Pictor A

(MJ Hardcastle + Croston 2005)

Hot Spot Advance Speed

The evolution of hot spot is tightly linked to that of cocoon.

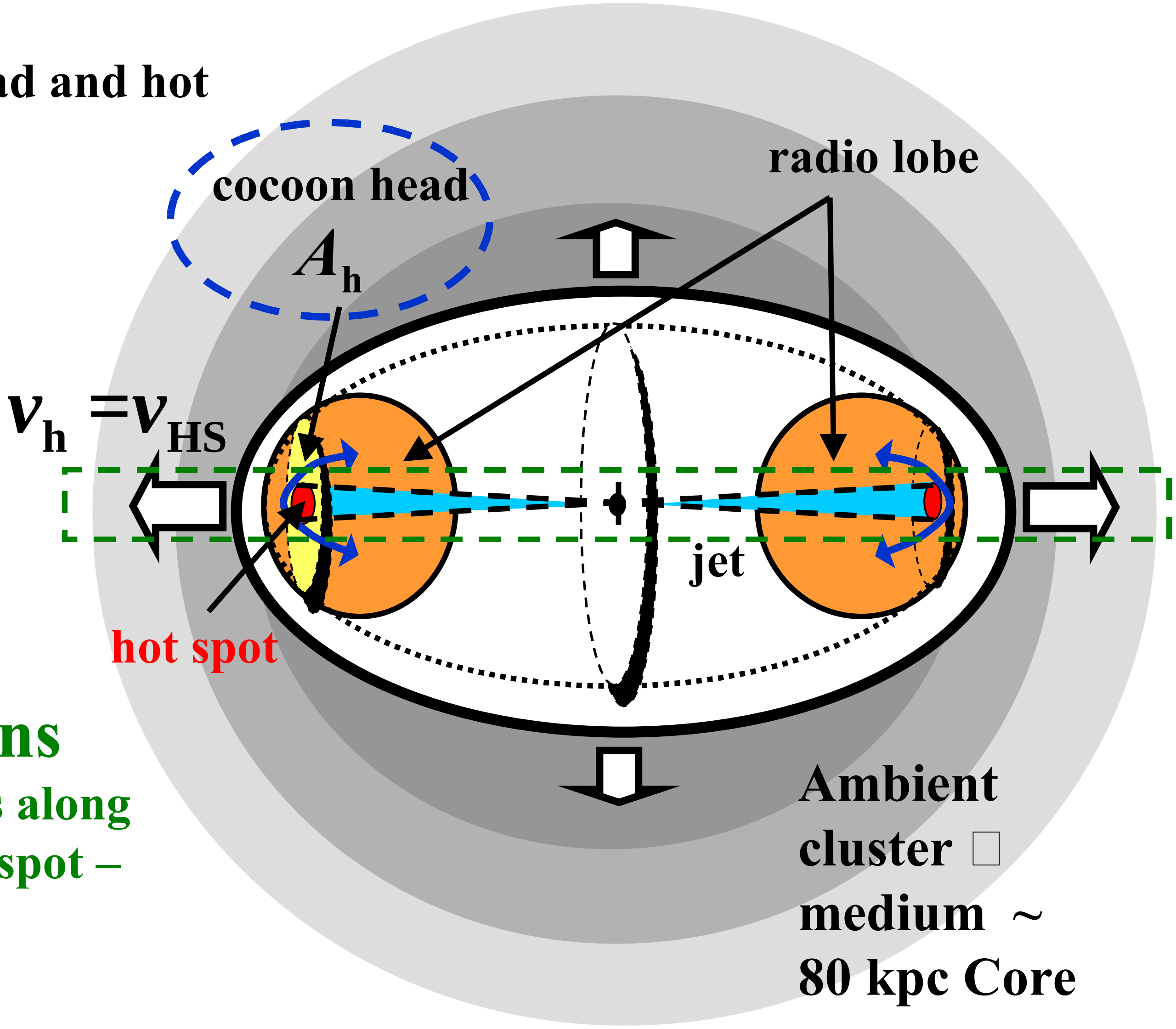
The velocity of cocoon head and hot spot is determined by

effective working surface A_h (> A_j)

- Sideways escape
- vortex via shocks
- Jittering of jet
- etc…

1D shock conditions

(to connect the quantities along the jet axis, i.e., jet – hot spot – ambient medium) □



$$V_{\mathrm{Head}} = V_{\mathrm{Beam}} \frac{\sqrt{\eta \in}}{1 + \sqrt{\eta \in}} \;\; ; \;\; M >> 1$$

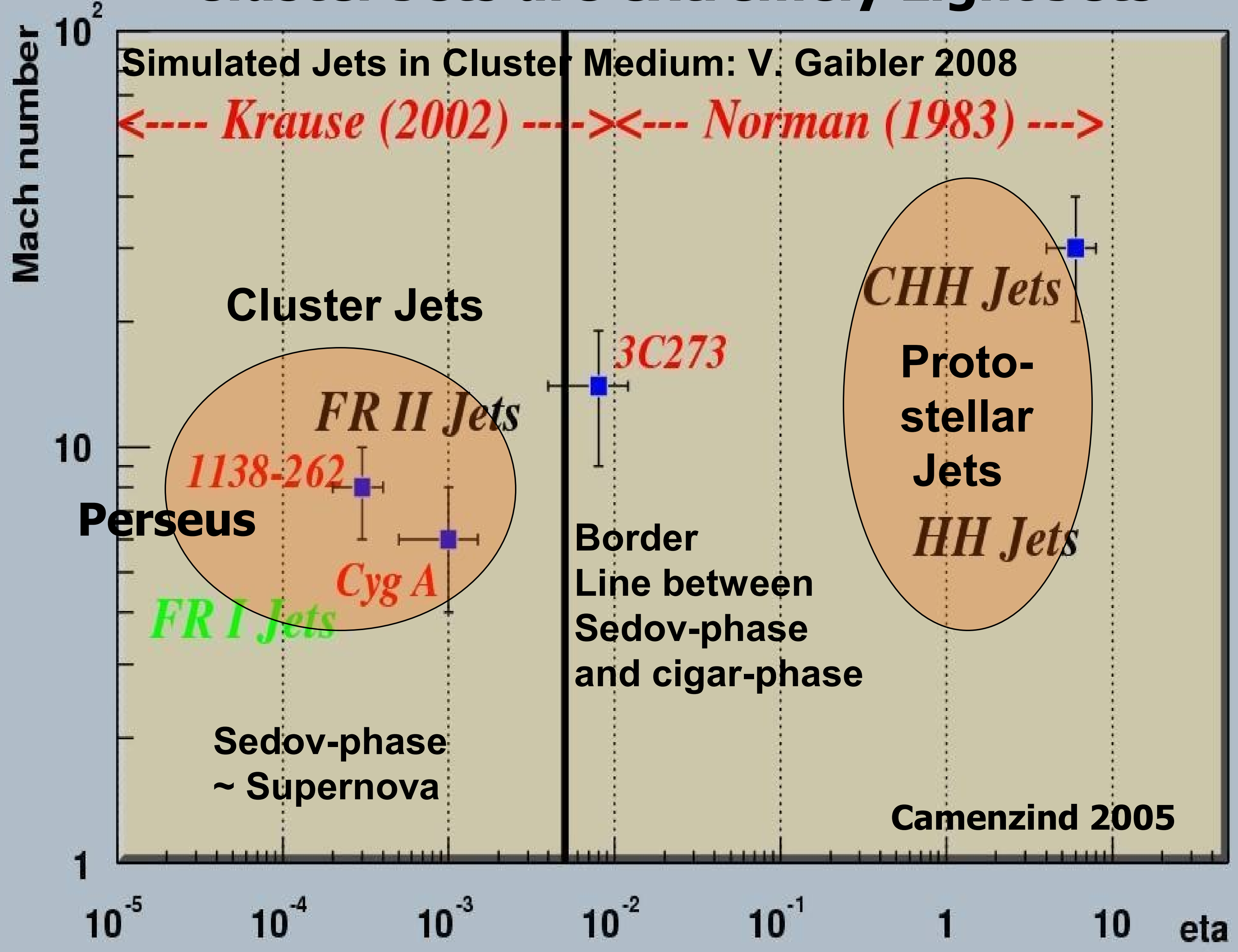
$$\eta = \rho_{B} h_{B} \Gamma_{B}^{2} / \rho_{G}$$: density contrast

Normalize on kpc-scale

$$V_{\mathrm{Beam}} = 100 \, \frac{\mathrm{kpc}}{\mathrm{Myr}} \sqrt{\frac{10^{-4}}{\eta \in}} \, \frac{V_{\mathrm{Head}}}{\mathrm{kpc/Myr}}$$

$$c = 307 \ \mathrm{kpc/Myr} \ ; \ c_{S,\mathrm{Gas}} = 0.6 \ \mathrm{kpc/Myr}$$

Cluster Jets are extremely Light Jets



Simulated Jets in Cluster Medium: V. Gaibler 2008

Cluster Jets

Perseus

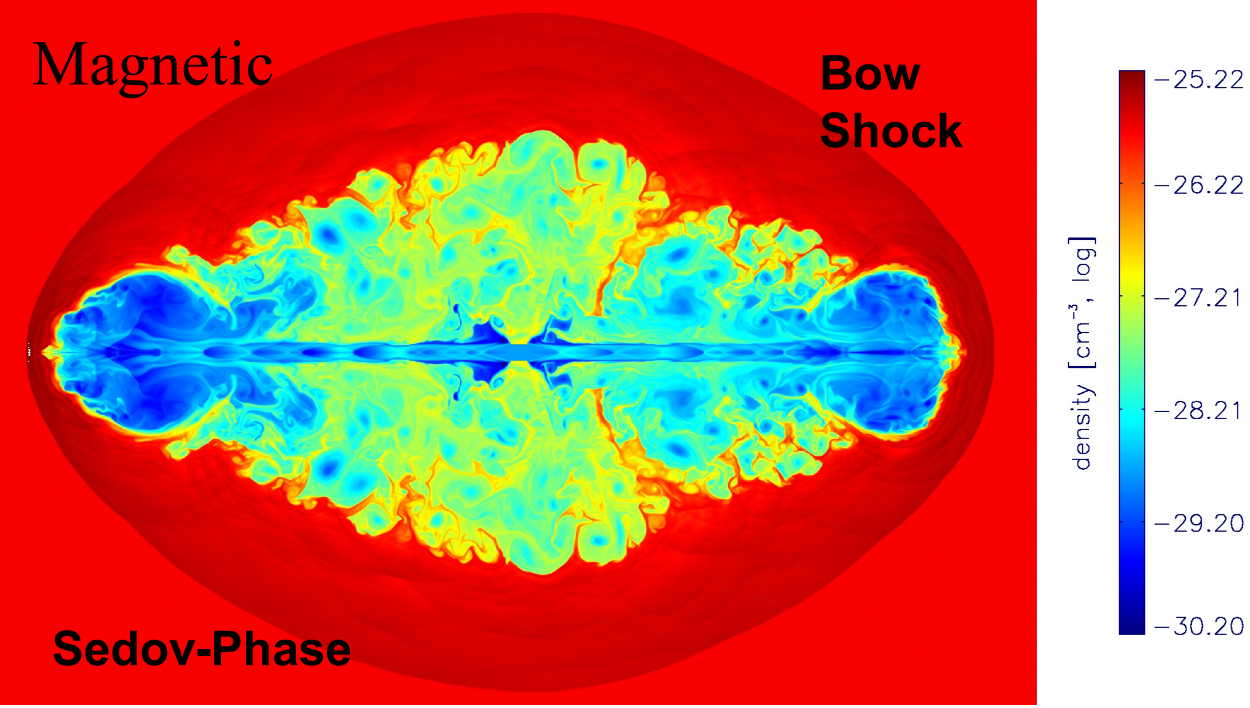
Border
Line between
Sedov-phase
and cigar-phase

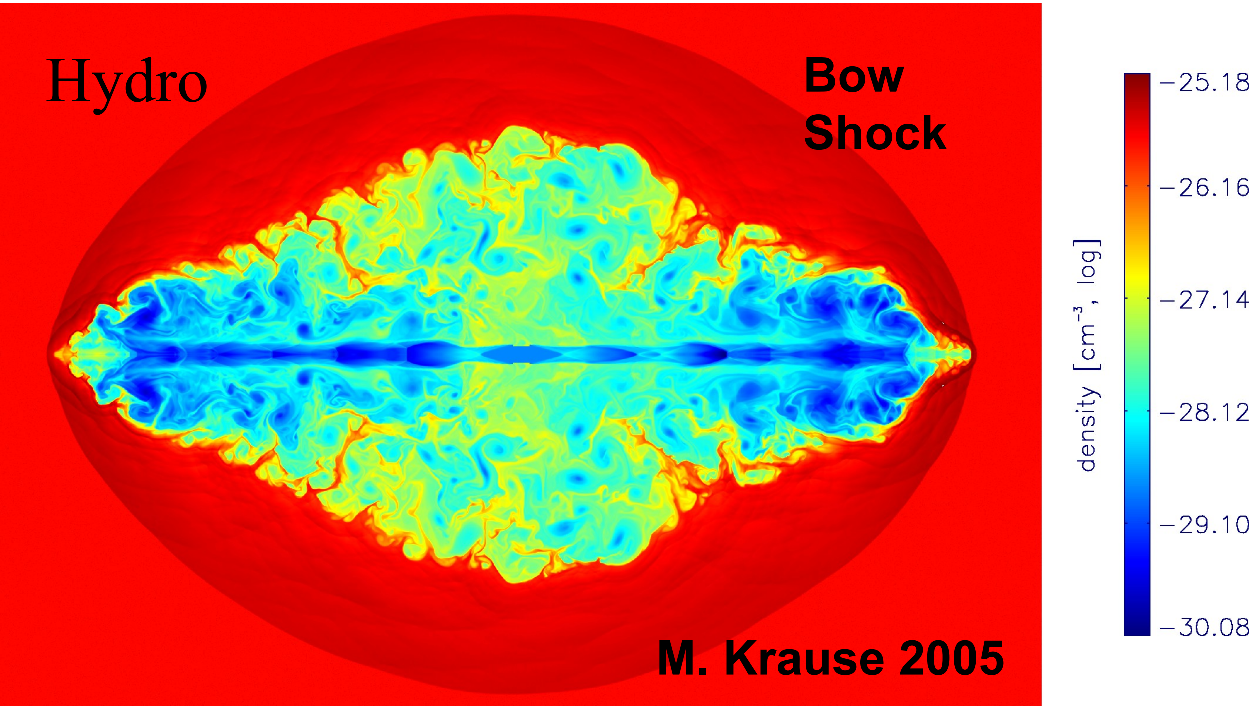
Proto-
stellar
Jets

Sedov-phase
~ Supernova

Camenzind 2005

Magnetic vs. Hydro $\eta=10^{-3}$





M. Krause 2005

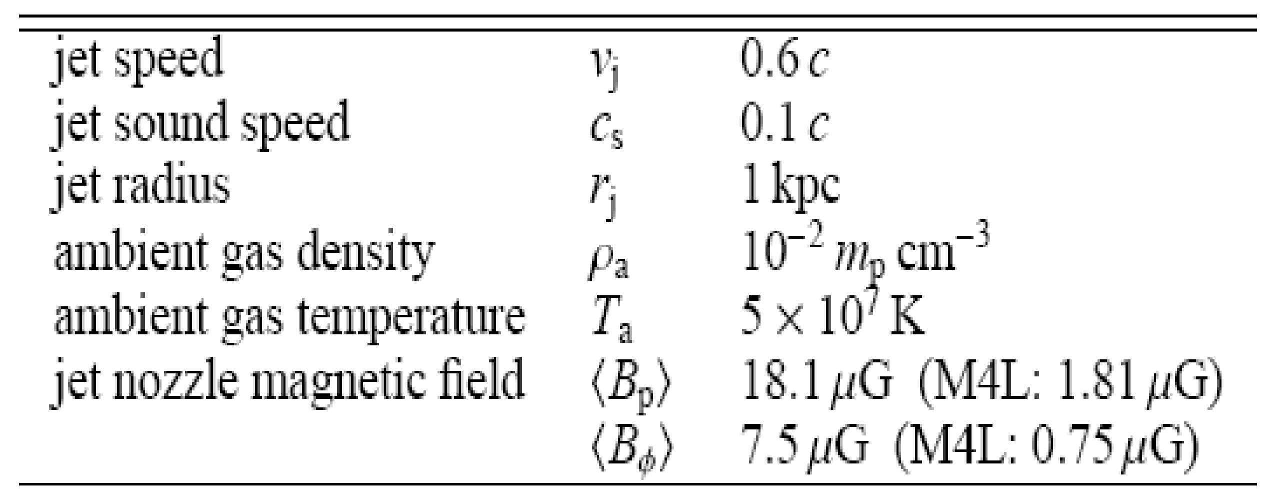
Morphology similar

KH instabilities suppressed

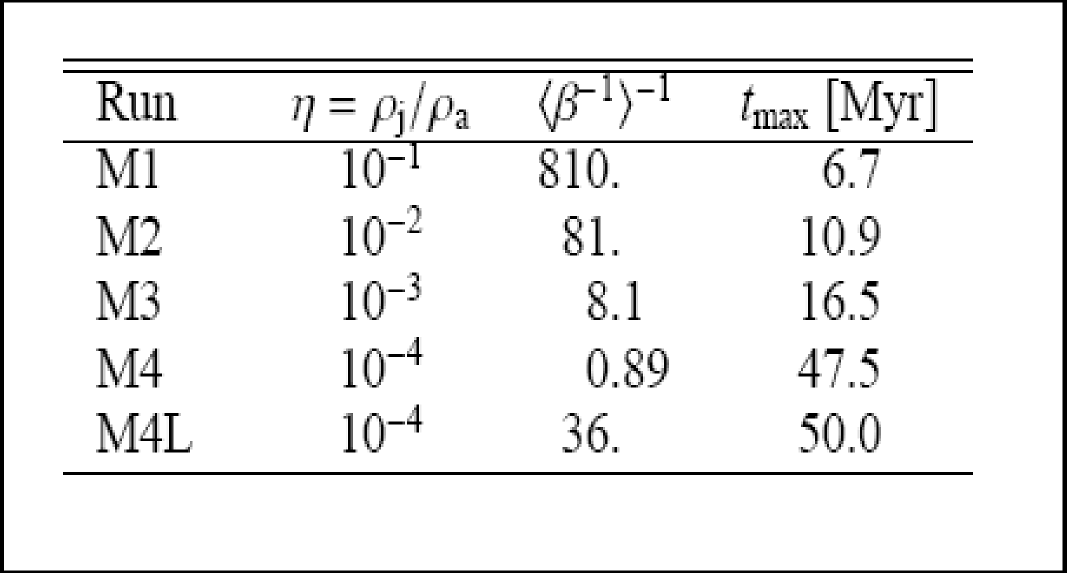
contact discontinuity in head region is more stable.

Cocoon still not cylindrical

From Light to very Light Jets
Computational Challenge



jet speed	v_j	$0.6\,c$
jet sound speed	c_s	$0.1\,c$
jet radius	r_j	1 kpc
ambient gas density	ρ_a	$10^{-2}\,m_p\,\mathrm{cm}^{-3}$
ambient gas temperature	T_a	5×10^7 K
jet nozzle magnetic field	$\langle B_p \rangle$	$18.1\,\mu$G (M4L: $1.81\,\mu$G)
	$\langle B_\phi \rangle$	$7.5\,\mu$G (M4L: $0.75\,\mu$G)

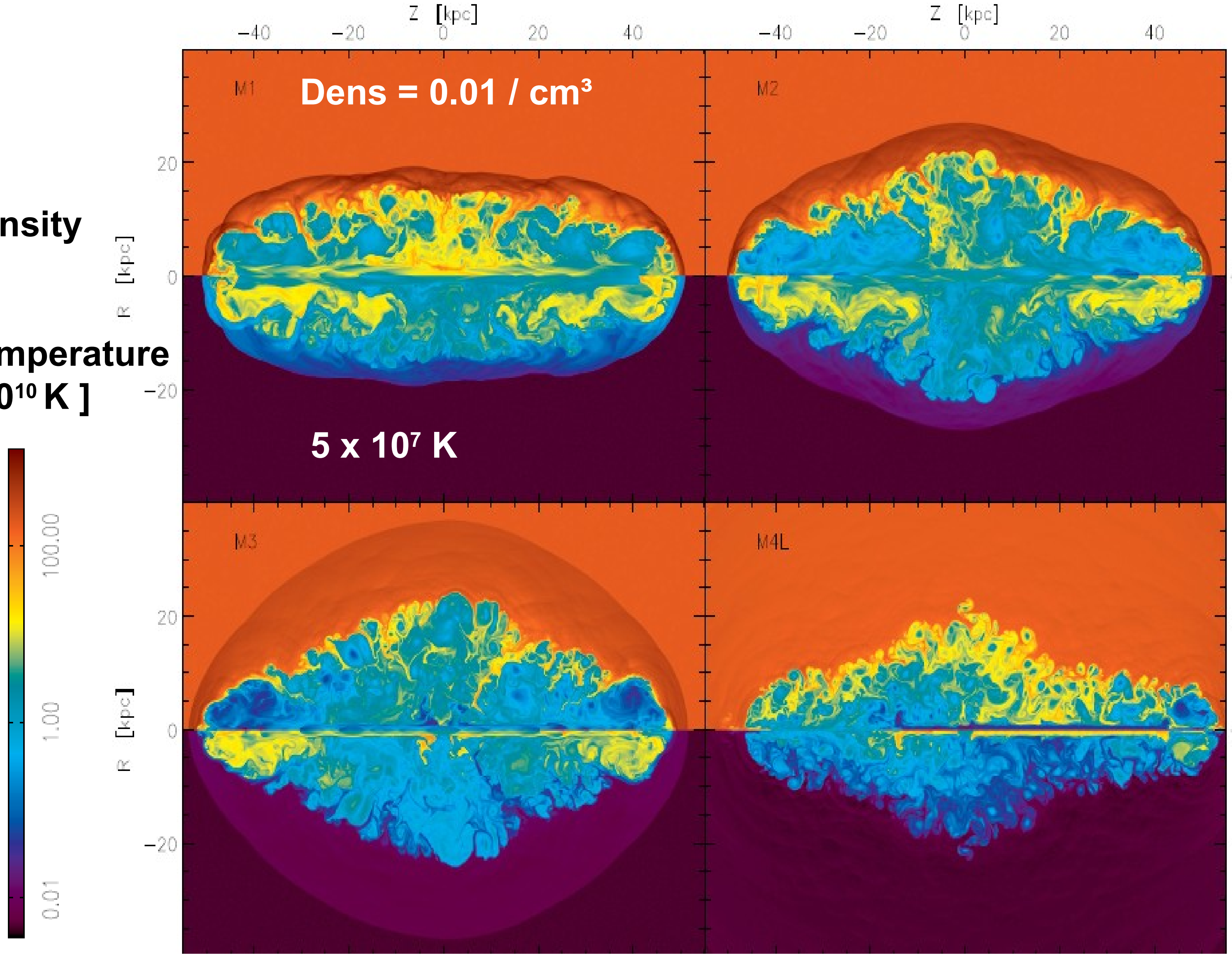


Run	$\eta = \rho_j/\rho_a$	$\langle \beta^{-1} \rangle^{-1}$	t_{max} [Myr]
M1	10^{-1}	810.	6.7
M2	10^{-2}	81.	10.9
M3	10^{-3}	8.1	16.5
M4	10^{-4}	0.89	47.5
M4L	10^{-4}	36.	50.0

V. Gaibler / LSW 2008

Density

Temperature
[10^{10} K]



Dens = 0.01 / cm³

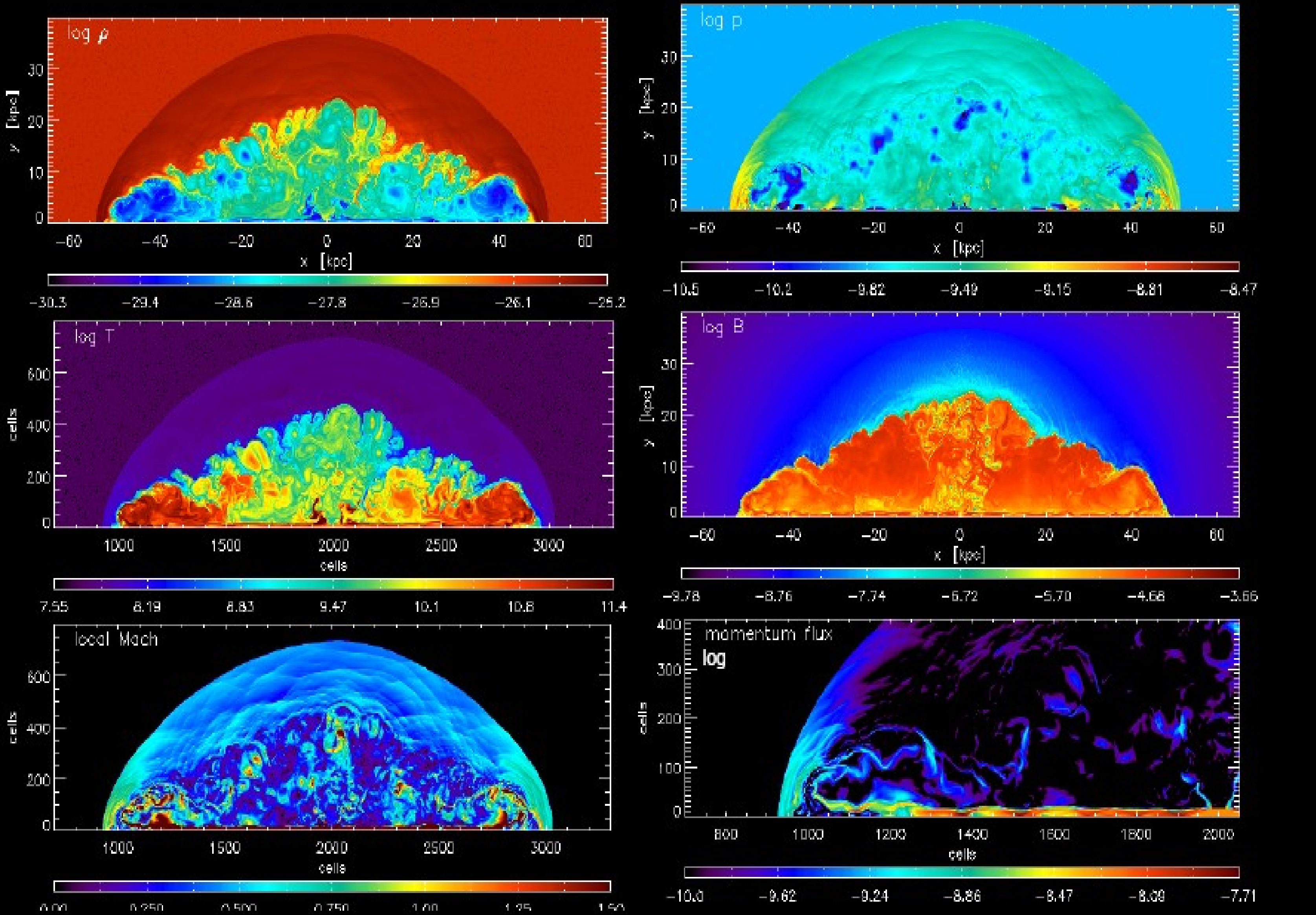
5 x 10^7 K

Volker Gaibler LSW 2008 - Propagation in Cluster Core / different dens contrast

Example

10^{-3} MHD @ 15 Myr

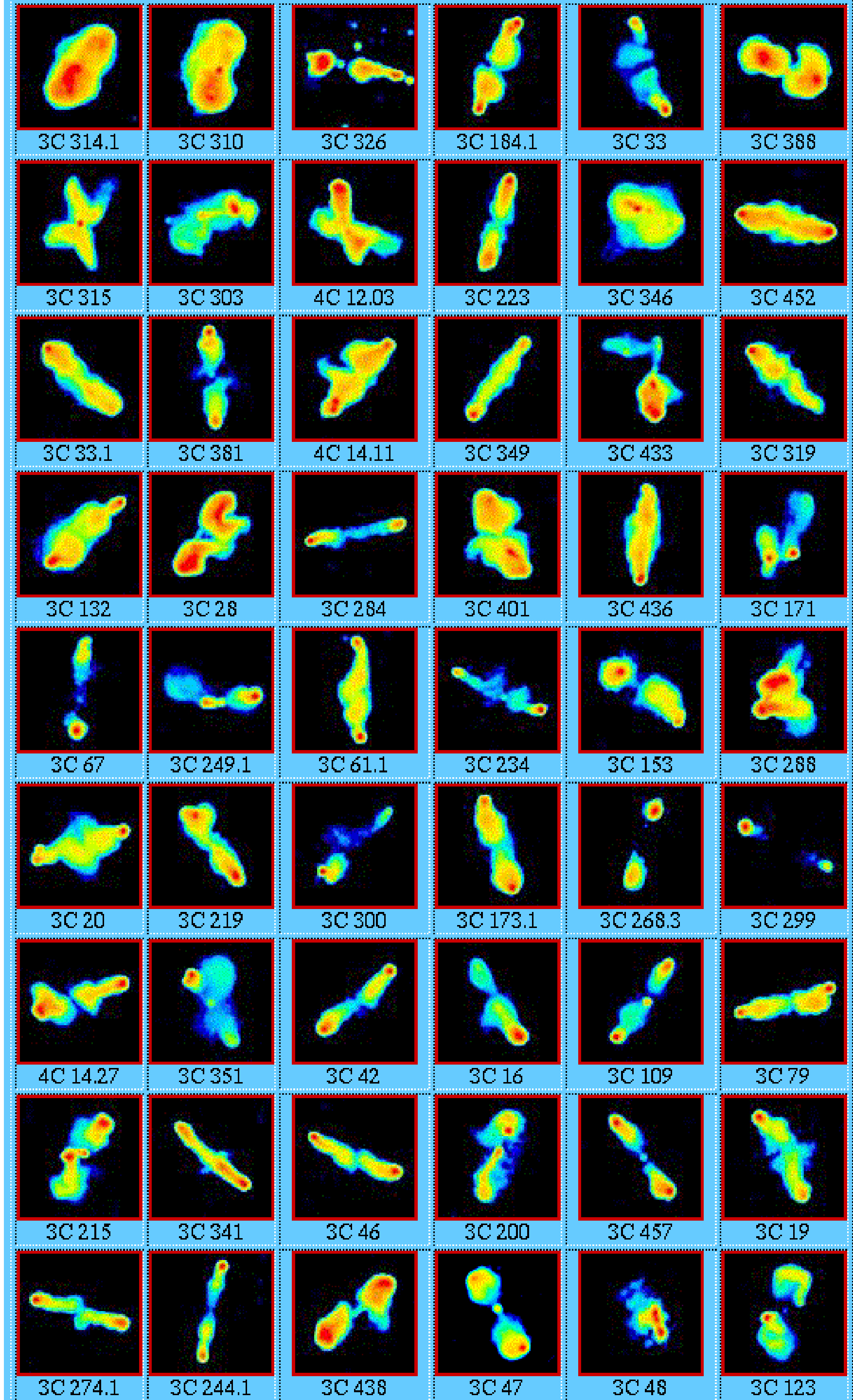
→ Talk V. Gaibler



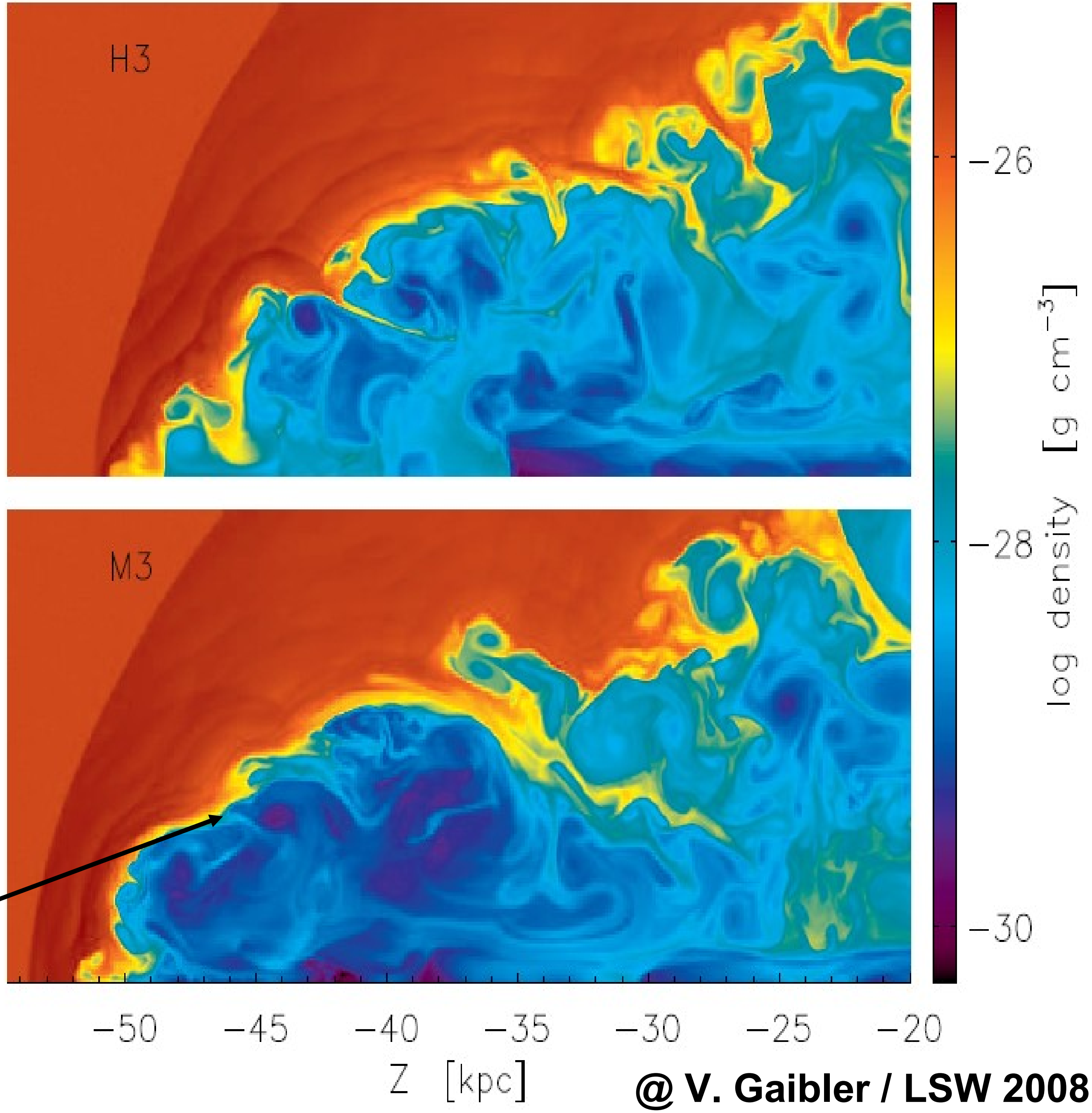
Understanding DRAGN Morphology

- Hotspots in 80-90% of lobes in powerful DRAGNs ➔ jets nearly always “on”.
- **Evolution from Sedov phase (elliptic cocoons) to cigar-shape** on time-scales ~ 100 Mio years.

From Atlas of DRAGNs (Leahy, Bridle & Strom 1996)



Kelvin-Helmholtz Instability → Turbulence

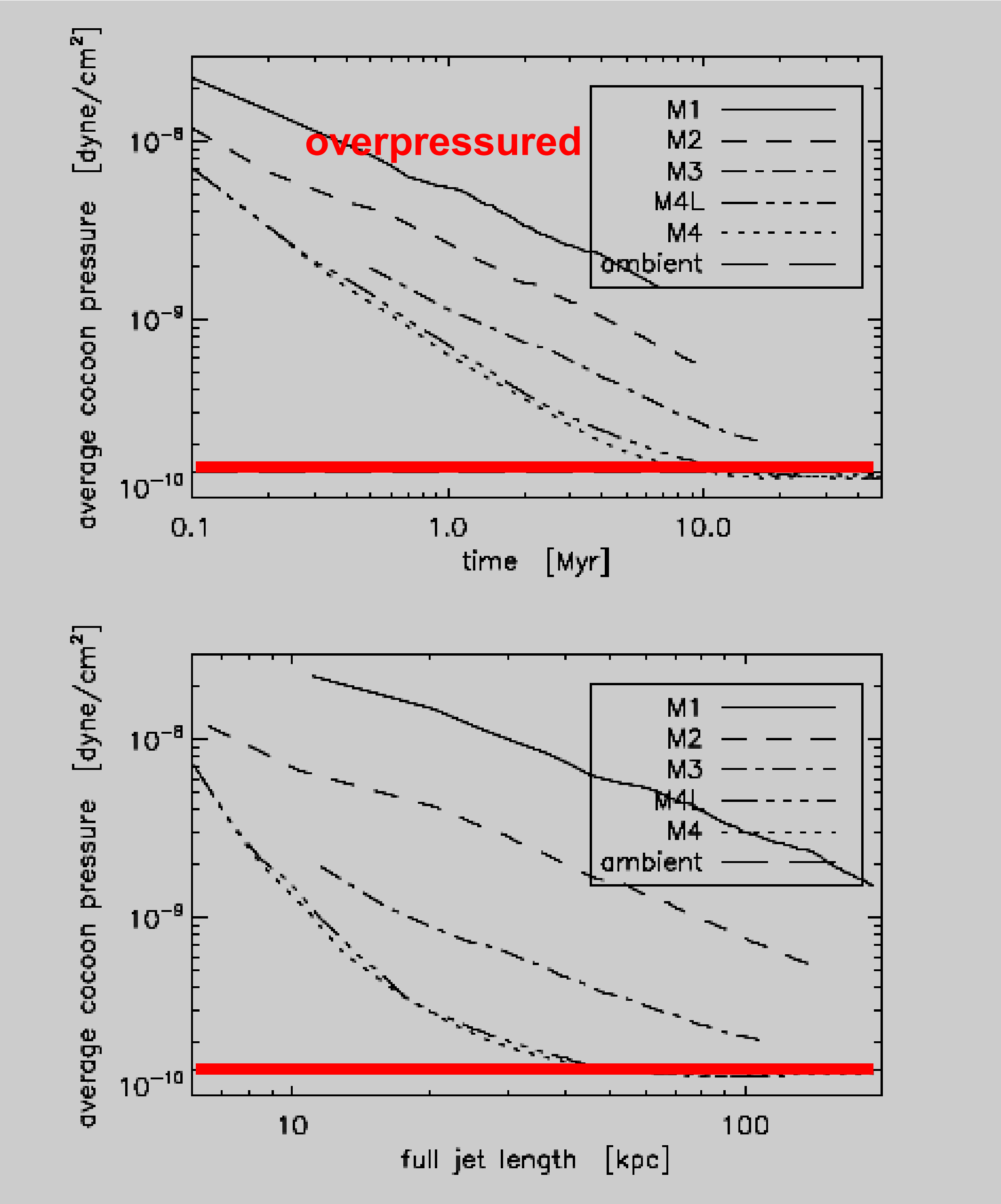


Contact surface stabilized by BFields
→In 3D all stabilized !

@ V. Gaibler / LSW 2008

Cocoon Pressure

→ For Jets > 100 kpc Cocoon no longer overpressured



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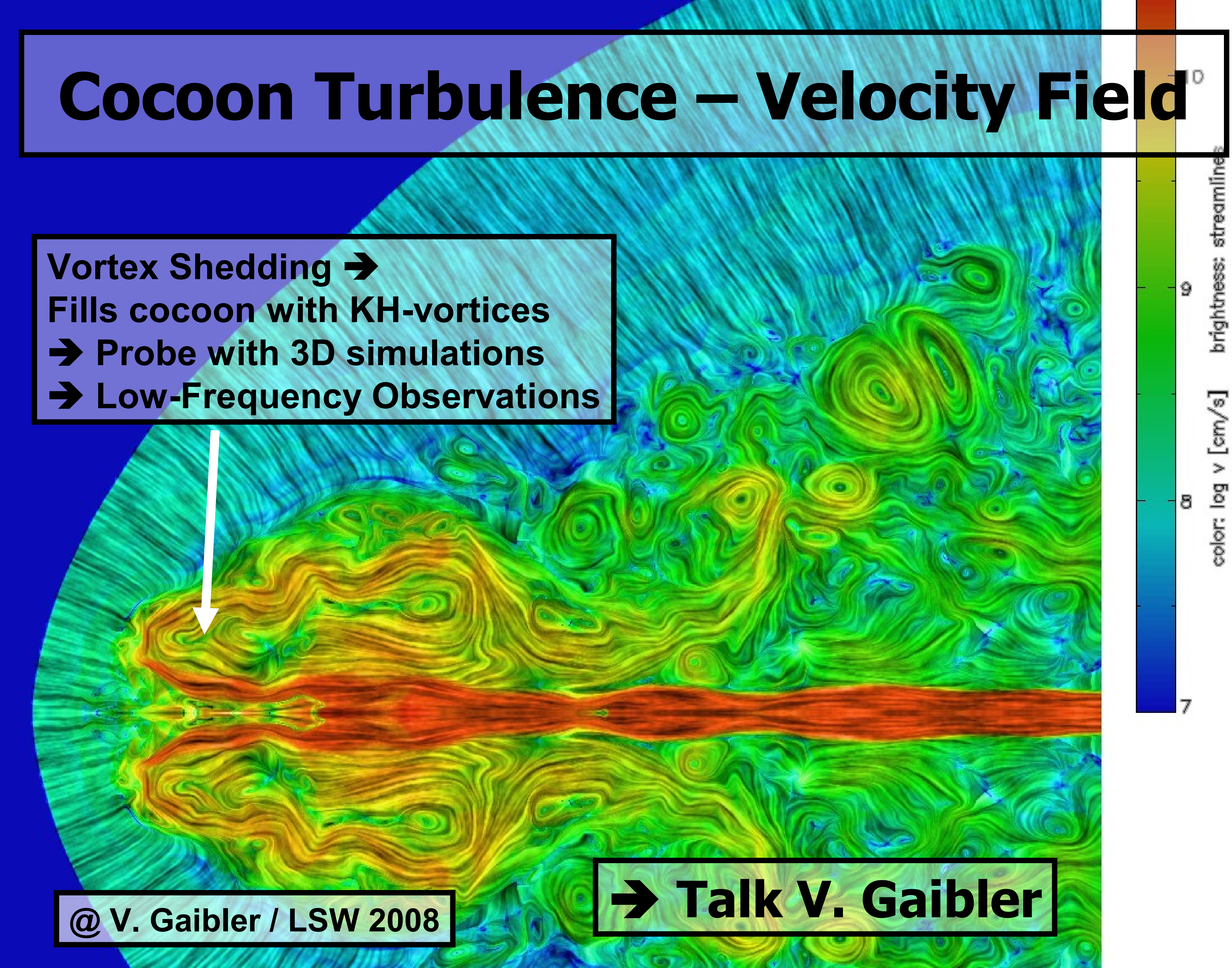
Cocoon Turbulence – Velocity Field

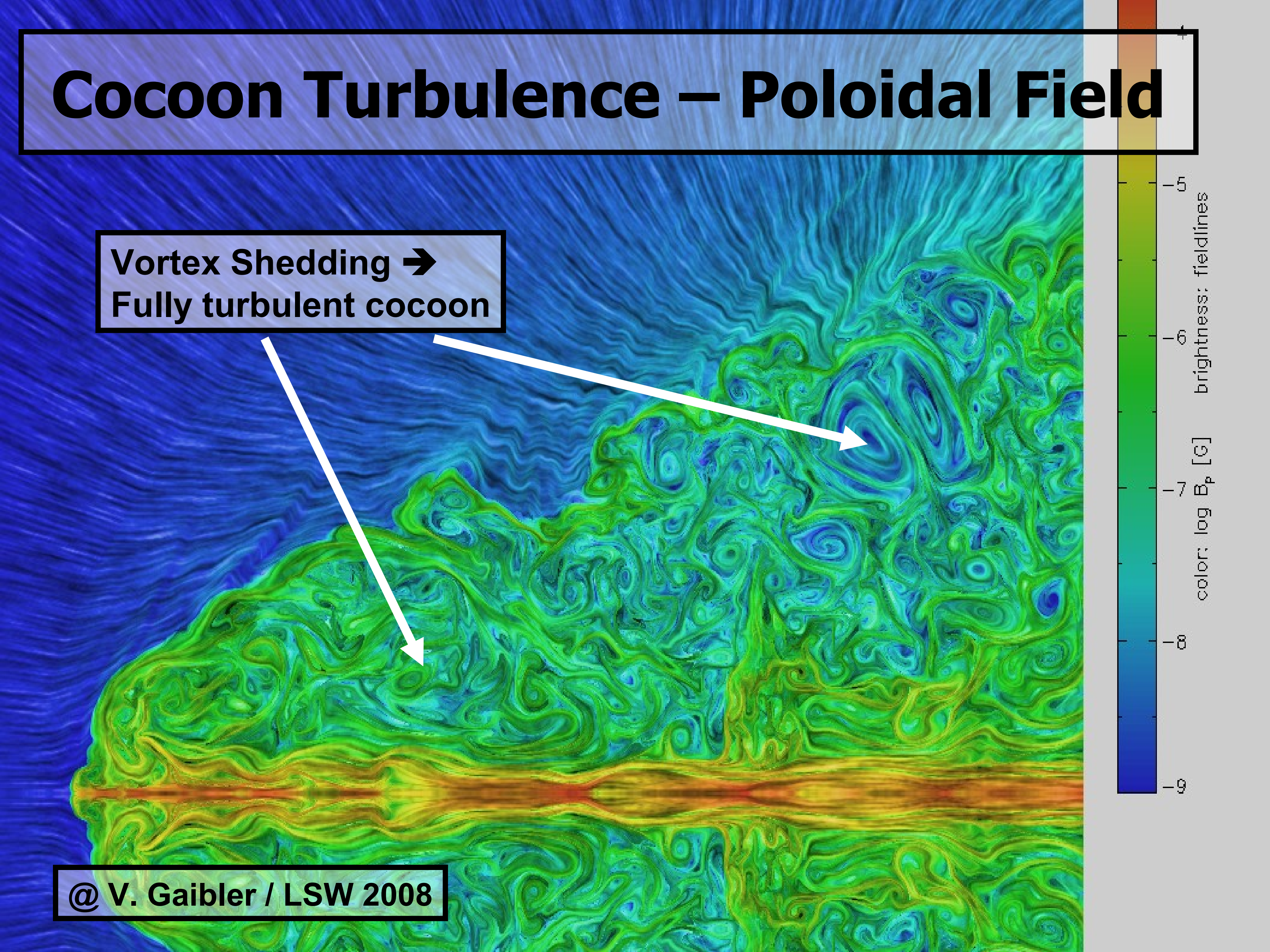


Vortex Shedding ➔
Fills cocoon with KH-vortices
➔ Probe with 3D simulations
➔ Low-Frequency Observations

@ V. Gaibler / LSW 2008

➔ Talk V. Gaibler

Cocoon Turbulence – Poloidal Field



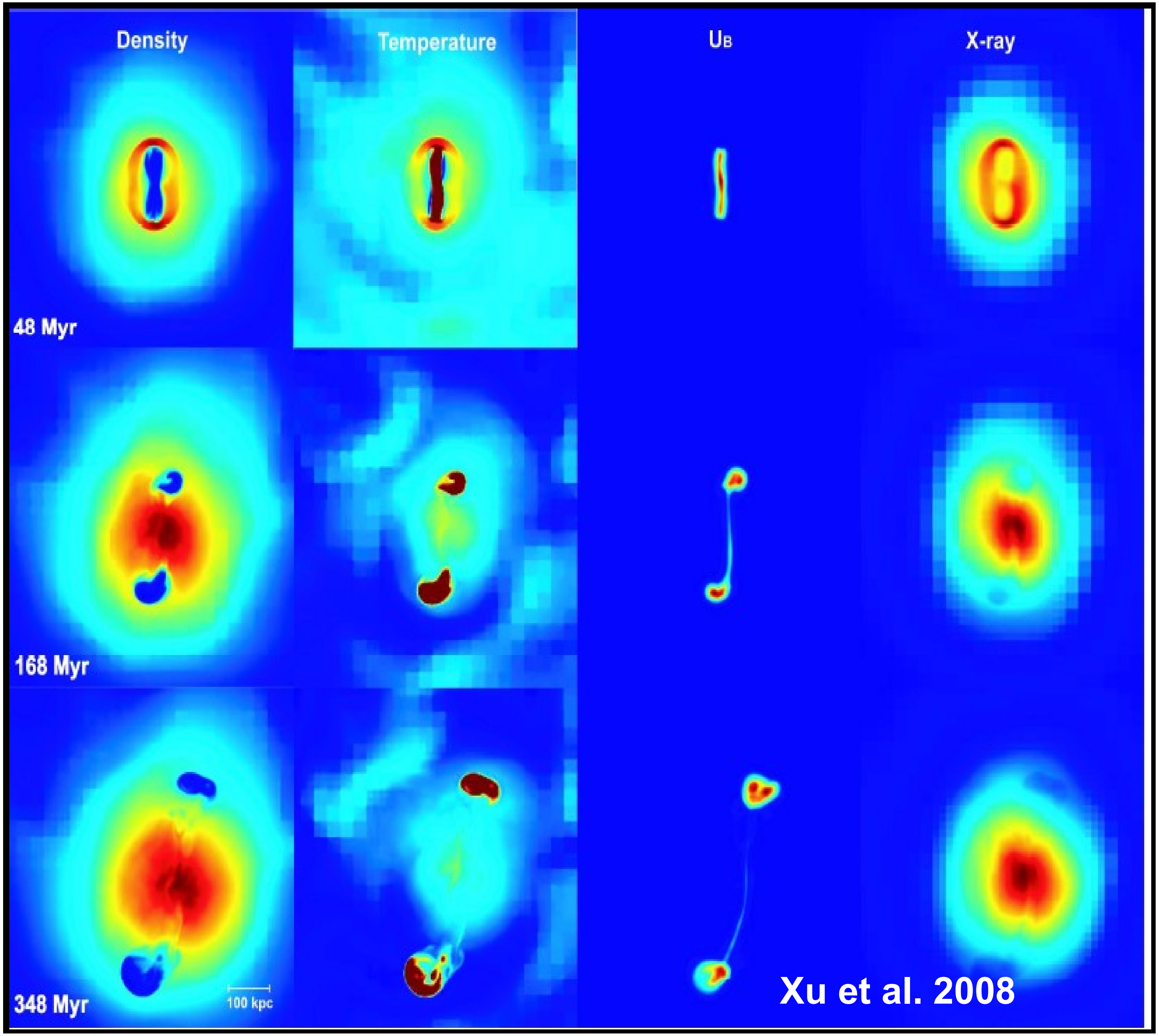
Vortex Shedding ➔
Fully turbulent cocoon

@ V. Gaibler / LSW 2008

Jets fade away on long terms > 50 Mio yrs

➔ Cluster Cavities

ENZO_MHD
Res = 2 kpc
B Inj z=0.05
for 36 Myr



Xu et al. 2008

Radiative Efficiencies are Low
Cavity Power → Mechanical Jet Power

Energy required to generate a Cavity = PV work + thermal energy

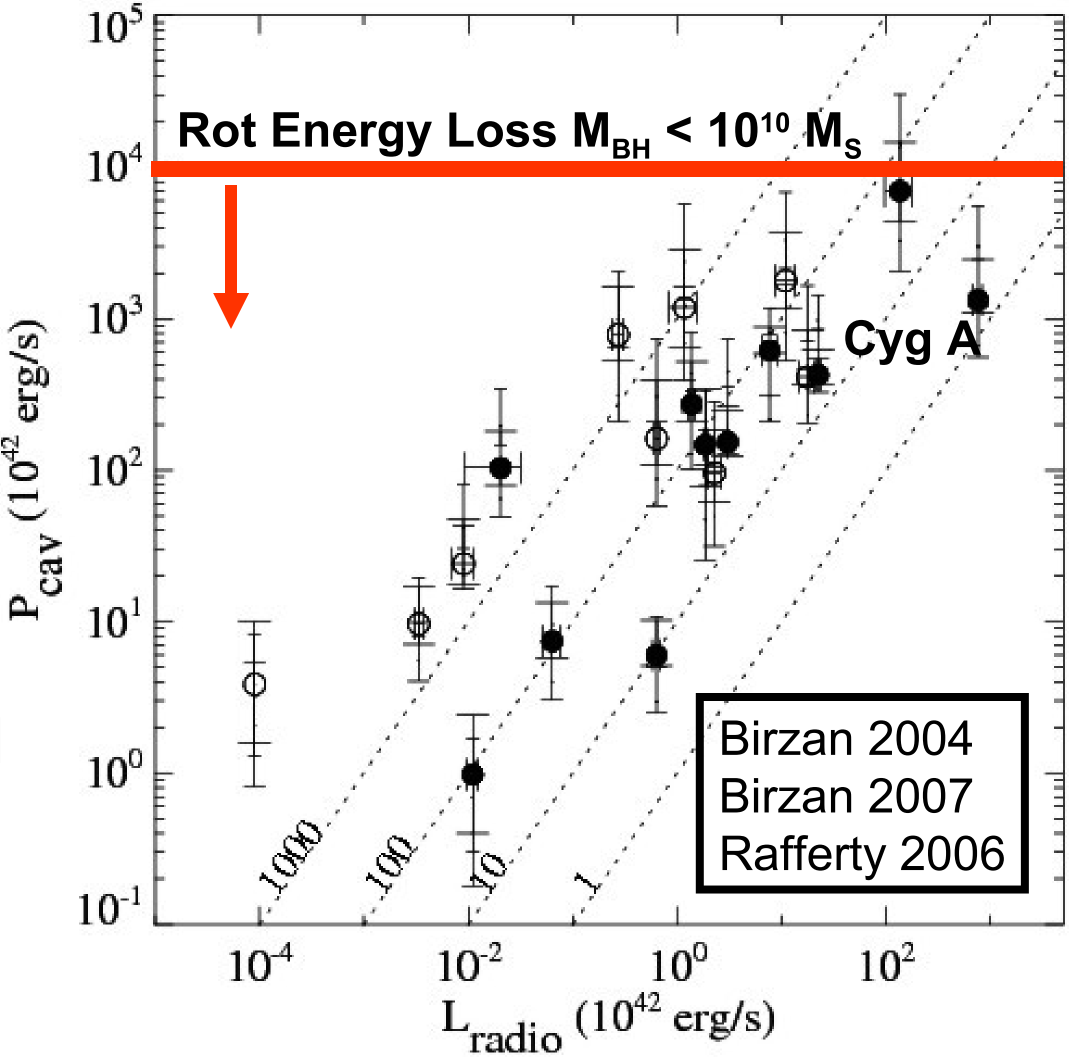
$$H = E + PV \sim 4\,PV$$

$$\rightarrow \quad P_{cav} = H / t_{age}$$

Since accretion is low

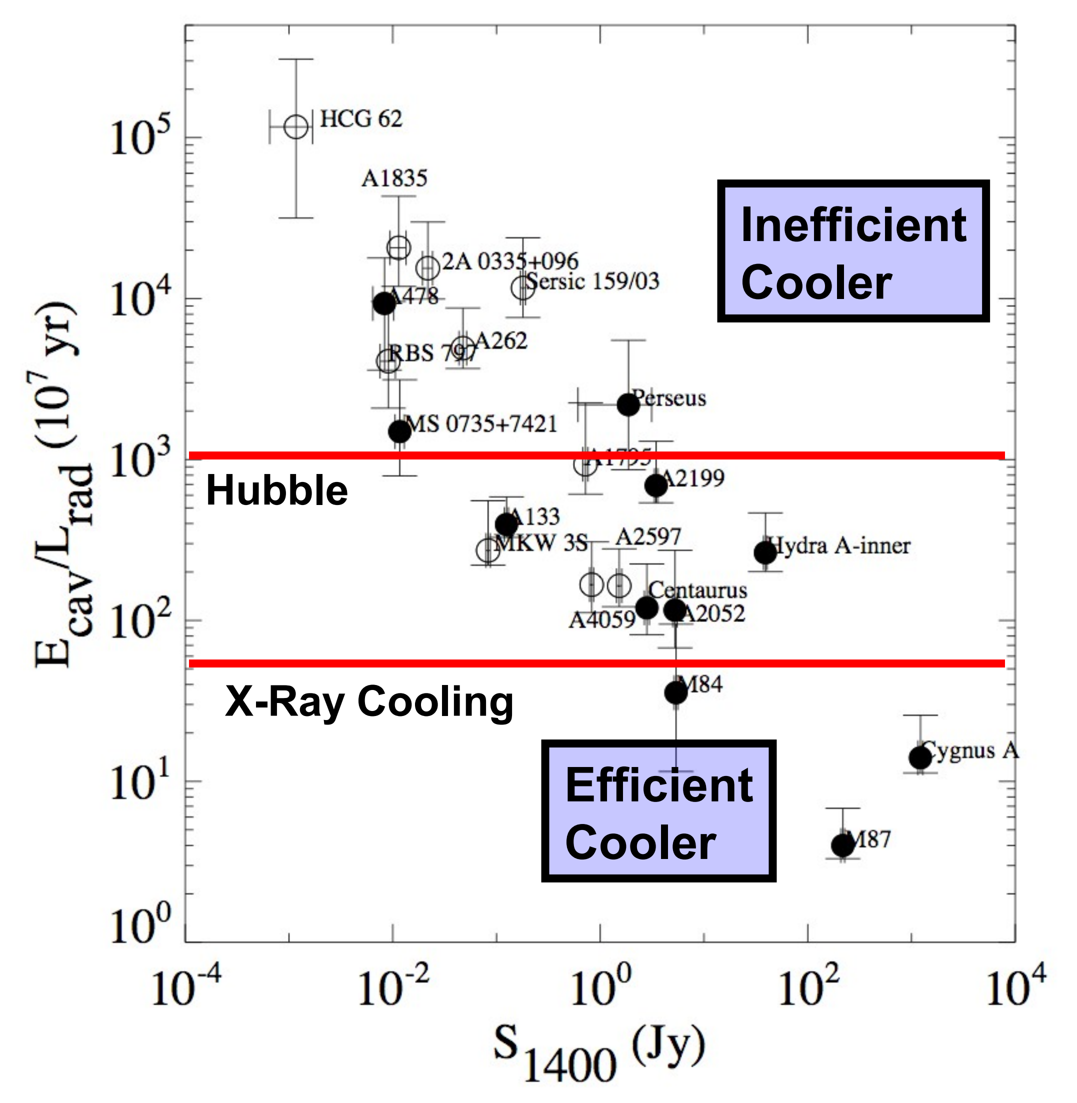
→ Jet power explained by Rotational Energy Loss of BH $M_H < 10^{10}\,M_S$

→ Small fraction is radiated away.



McNamara & Nulsen 2007

Cavity Cooling Time



$t_{radio} = E_{cav}/L_{rad}$ = radio cooling timescale

McNamara
& Nulsen 2007

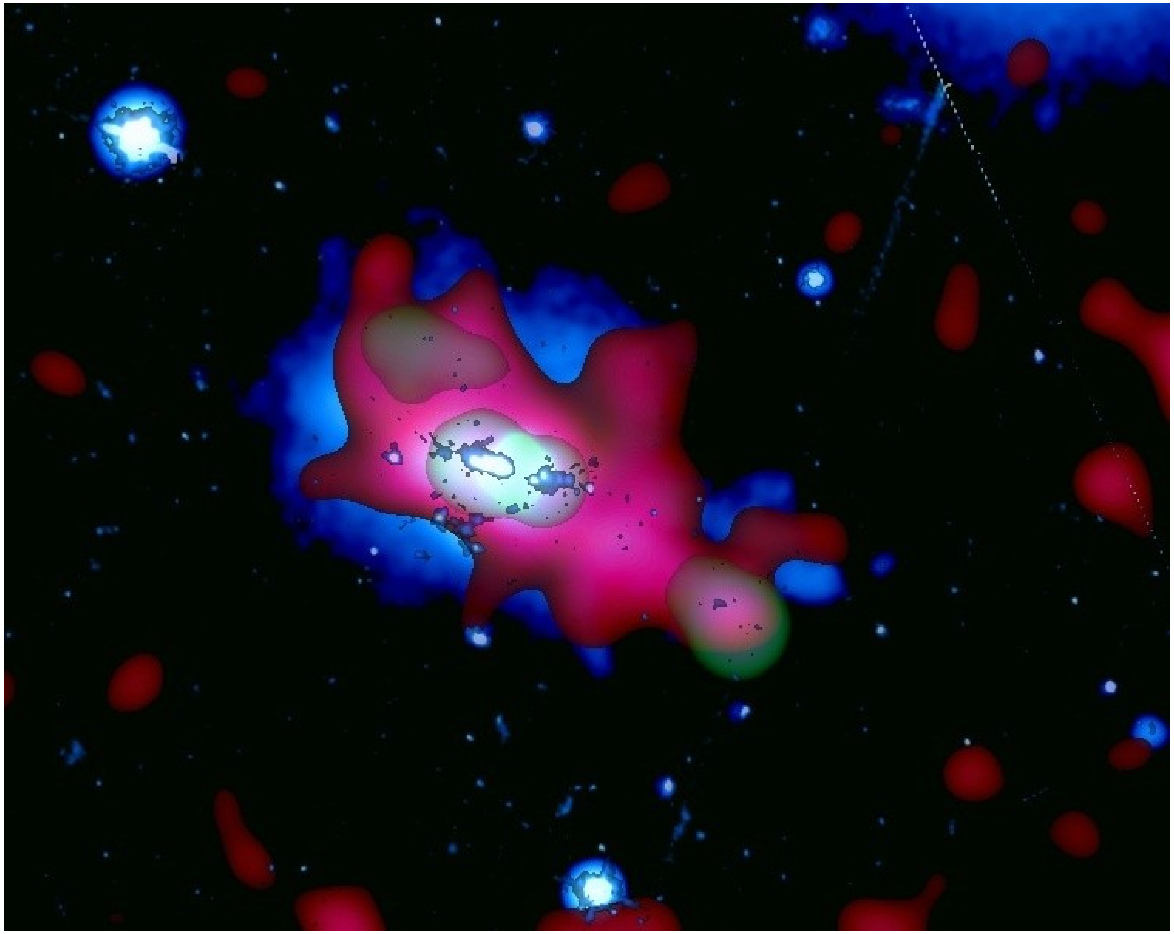
Conclusions on Jets

- Heat source (BH) is roughly of the size of solar system – heating conditions are however tuned to region ~ 10 orders of magnitude greater ➔ impossible to simula
- In low density contrast sources, we understand how energy, which is initially highly collimated, is then spread over entire region, in a quasi-spherical region.
- Weak shocks may make a transition to just sound waves (observed as ripples in Perseus cluster), travel at a speed of ~ 0.5 kpc/Myr ➔ **Outburst Cycle ~ 100 Myrs!**

Emission Line Regions in Extragalactic Jet Flows

4C 41.17, z=3.8 (Michiel Reuland)
Blue: Lyα, Green: radio, Red: X-ray

See Krause & Gaibler 2009



Giant Lyman alpha haloes

- Strongest line at high z
- up to z > 5
- Aligned X-ray: IC, highlights *cocoon* of faint, backflowing radio plasma
- Morphology: suggest ENLR = cocoon

Conclusions

- ✂➔ Jet power in µQuasars & radio galaxies in giant ellipticals is probably not driven by accretion, but by rotation of BH.
- ✂➔ Rotational energy is the ultimate jet power in gEs and cD galaxies.
- ✂➔ solves the heating problem of „cooling flows“
- ✂➔ Accretion cycles ~ 50 – 200 Mio years (➔ very many cycles over 5 Gigayears !).
- ✂➔ Cycles driven by refilling from kpc core in gEs, not from the 100 kpc cluster gas.

➔ Computational Challenges

- **Evol ISM in core-ellipticals** should be simulated on time-scales of ~ 100 Mio. years (3D filamentary structure (inflow) and hot outflowing medium).
- **GRMHD simulations of MRI disks** including jet formation, propagation, …
- **Relativistic MHD-Jet propagation** from kpc-scale to cluster scale with extremely low density contrast (**PLUTO, AMRVAC**).
- Inclusion of **non-thermal plasma** (shock acceleration, diffusion, Alfven turbulence etc; Jones et al.) **➔ 2 component MHD.**