Extragalactic Cosmic Rays and Magnetic Fields
Facts & Fiction

Torsten Enßlin

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Thanks: Corina Vogt, Christoph Pfrommer, Klaus Dolag, Tracy Clarke, Phil Kronberg, Peter Biermann, Francesco Miniati, Gopal–Krishna, Uli Klein, Huub Rottgering, Sebastian Heinz, Marcus Brueggen, Eugene Churazov, Larry Rudnick, ...

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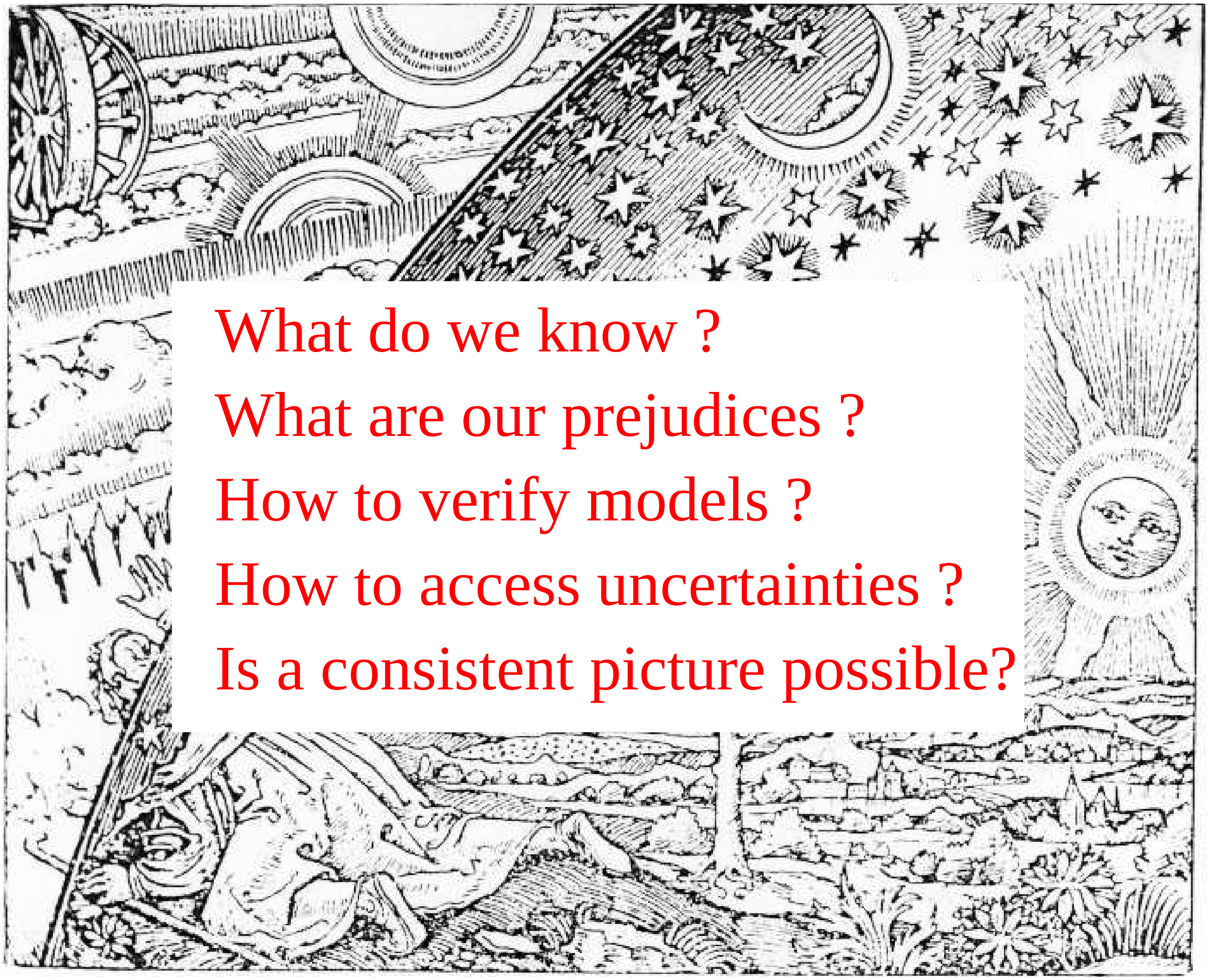
Facts & Fiction



What do we know ?

What are our prejudices ?

How to verify models ?

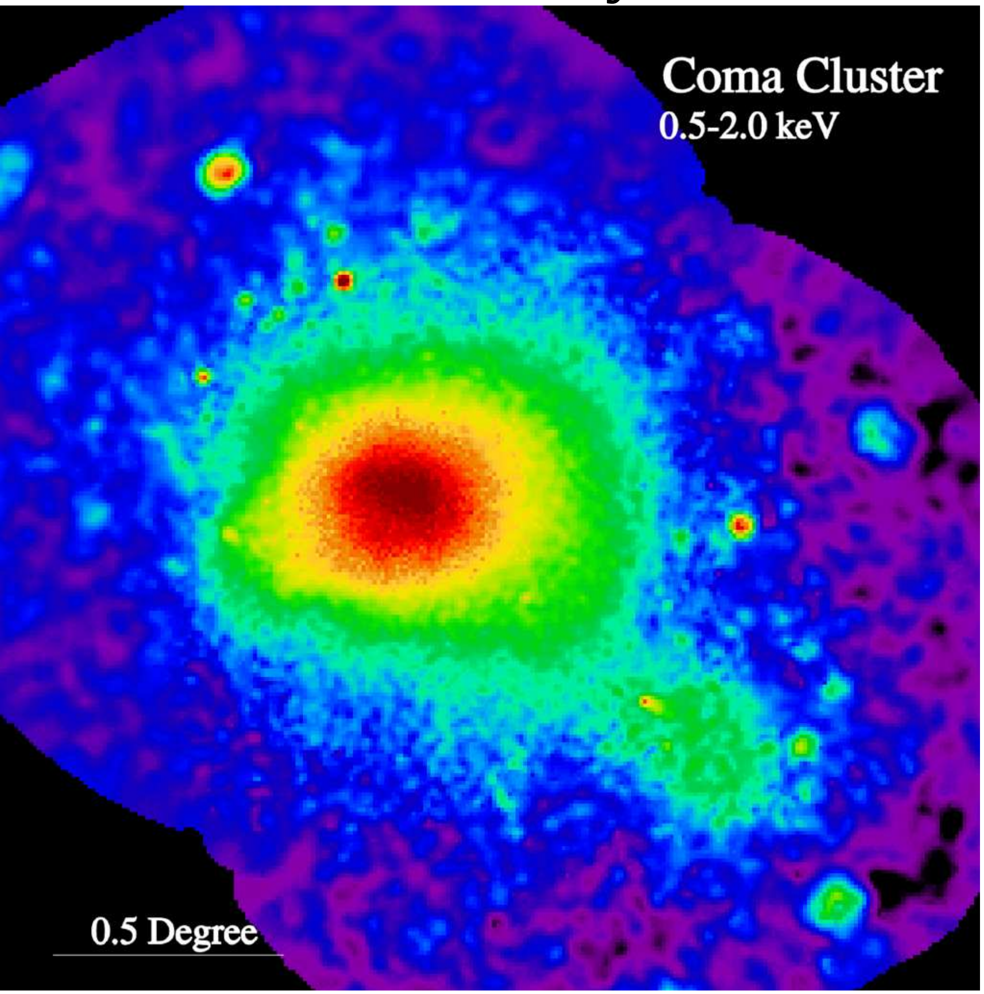
How to access uncertainties ?

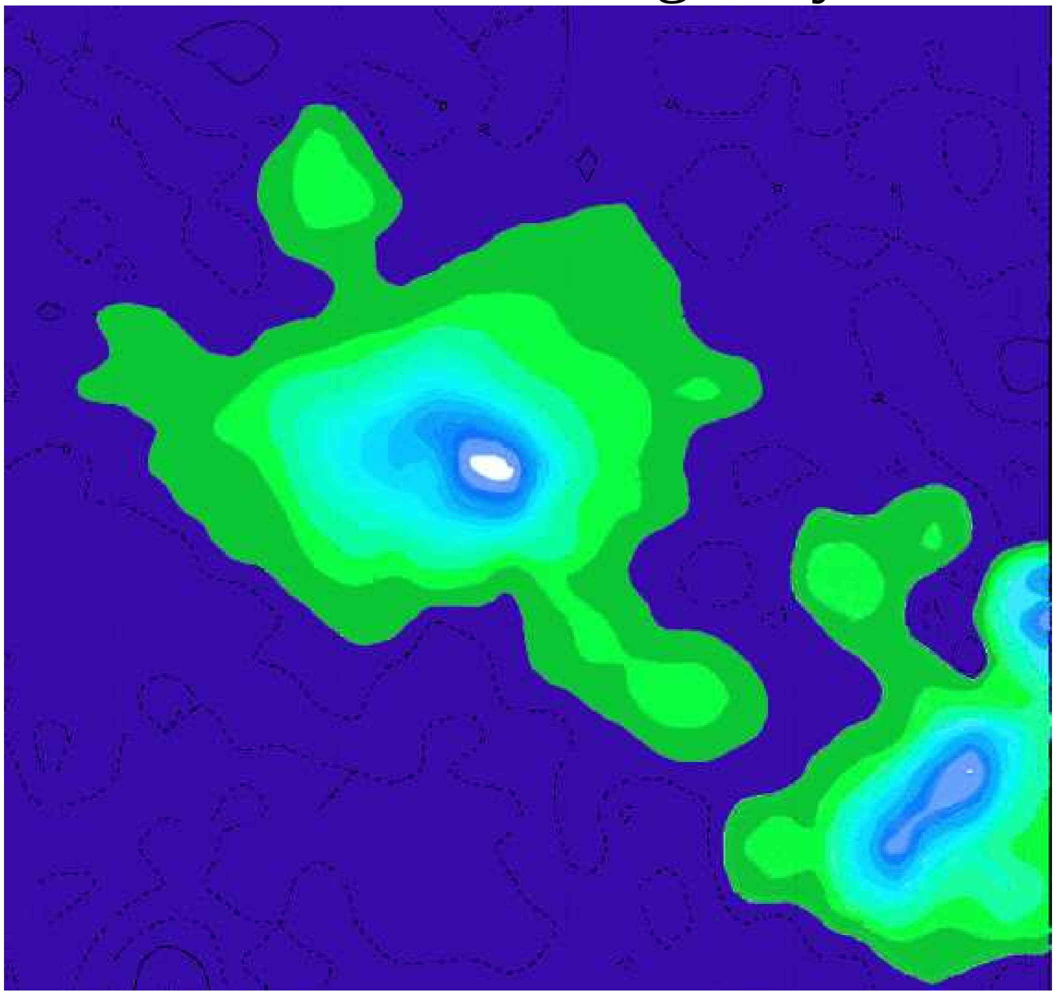
Is a consistent picture possible?

What do we know ?

cosmic ray electrons (CRe) and magnetic fields exist !

Radio synchrotron emission from the Coma galaxy cluster





ROSAT−PSPC: 2.7° x 2.5°

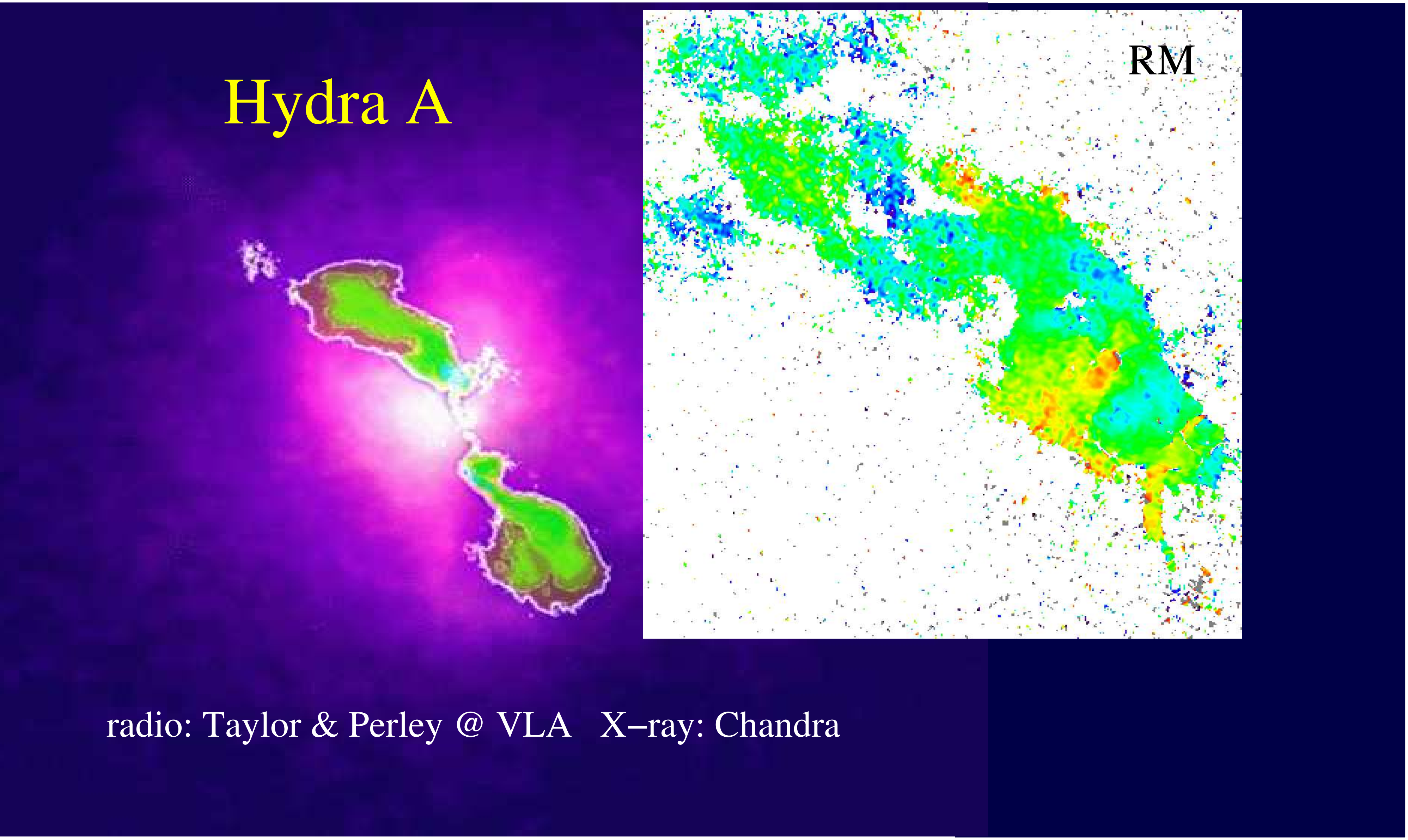
Credit: ROSAT/MPE/Snowden

Radio halo, 1.4 GHz: 2.5° x 2.0°

Credit: B.Deiss/Effelsberg

What do we know ?

Faraday rotation reveals turbulent magnetic field structures (Corna Vogt's talk)



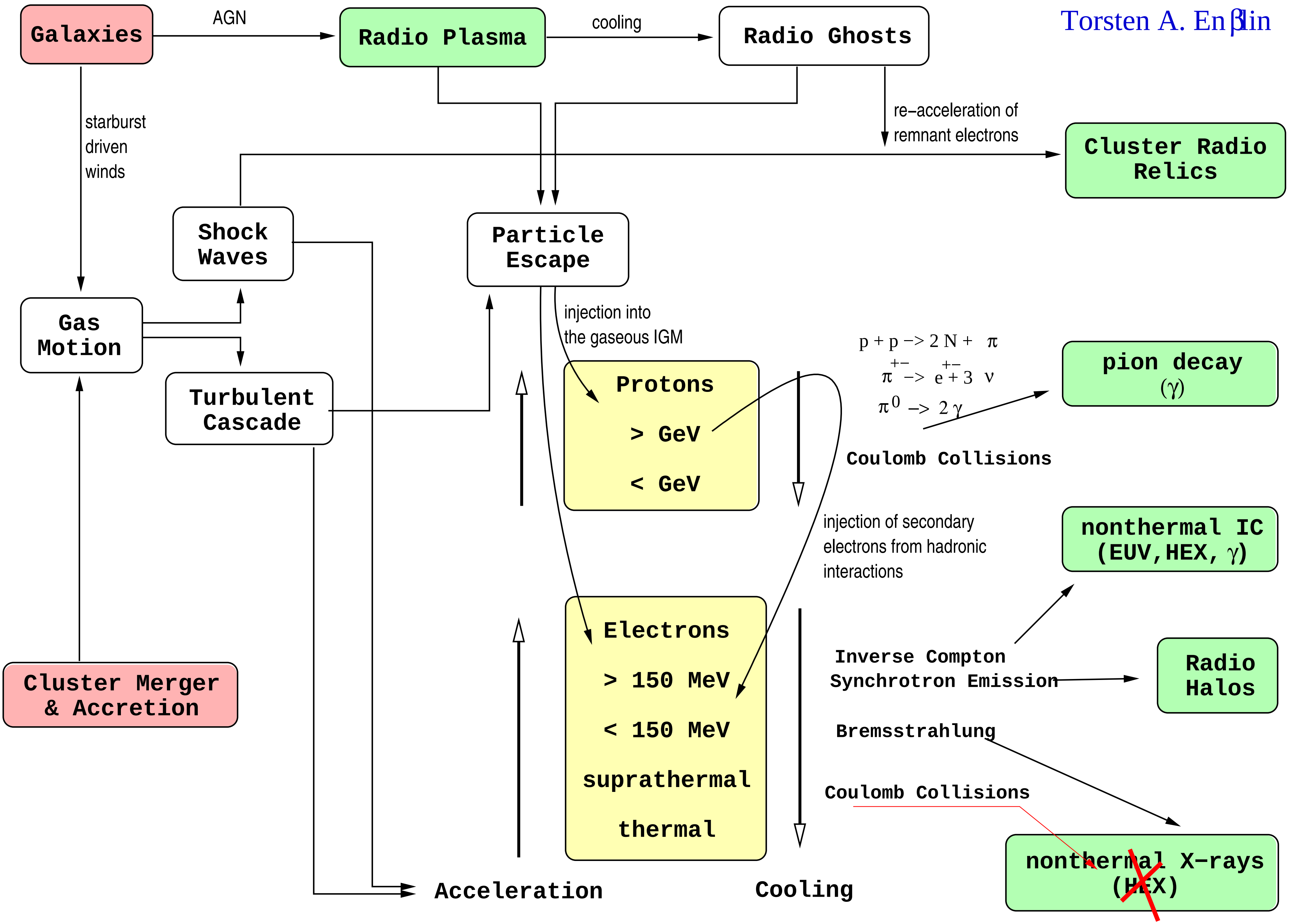
What do we know ?

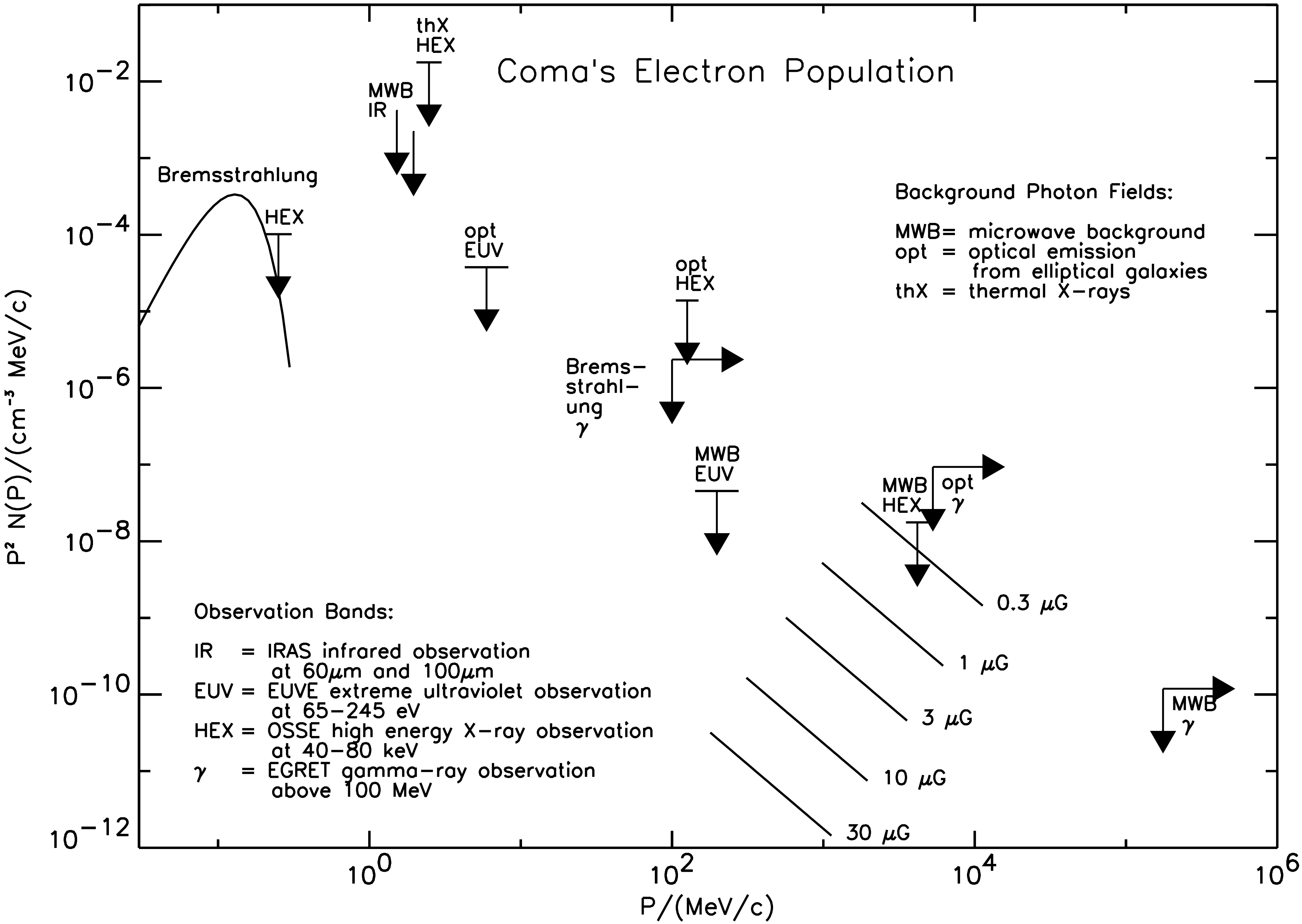
Sufficient energy sources are present in clusters:

– cluster merger: shock waves and turbulence
– accretion shocks
– AGNs
– SNR
– galactic wakes
– decaying/annihilating dark matter particles ???

Basic understanding of physical processes exist:

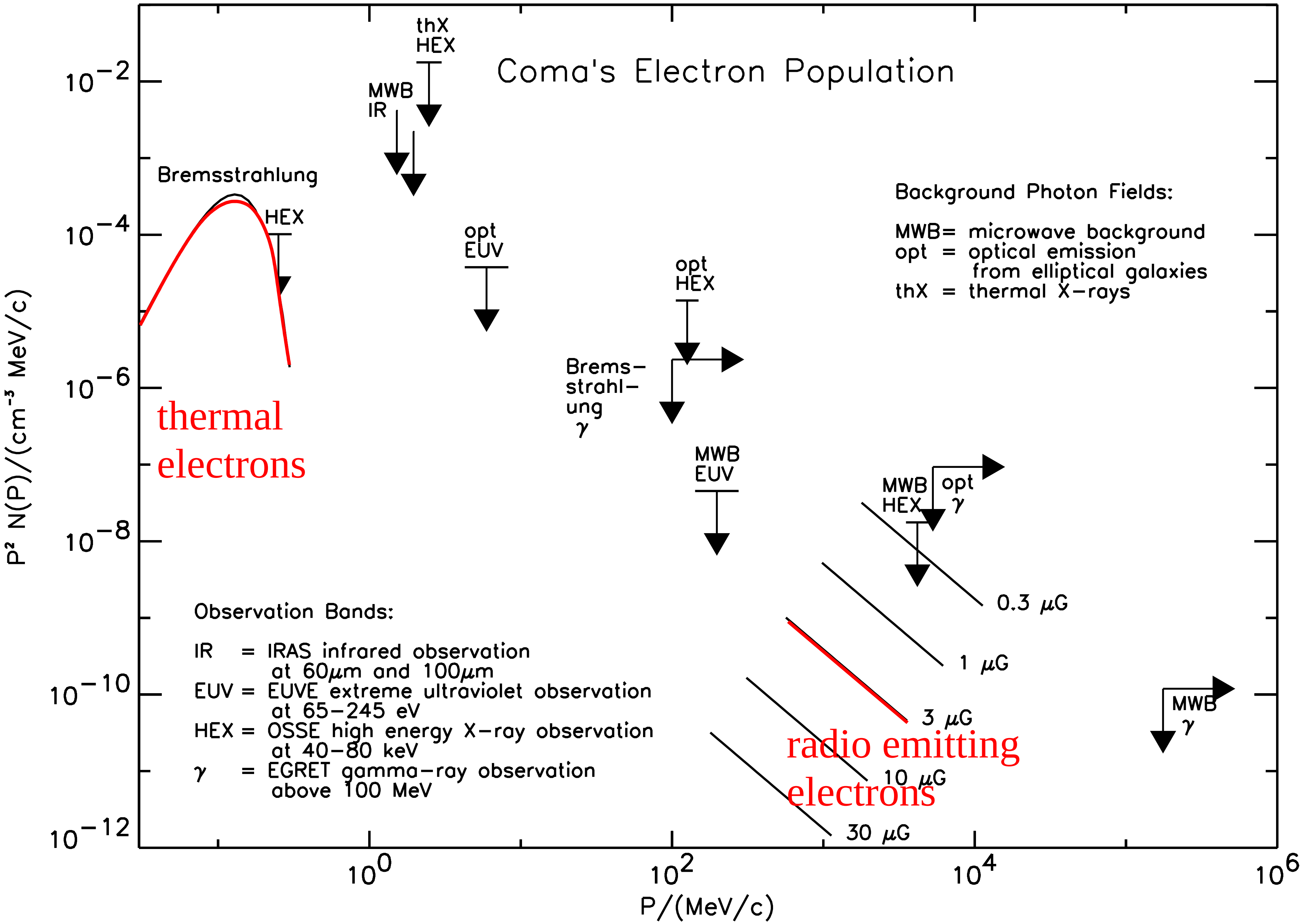
– particle cooling/radiation mechanisms
– particle acceleration by shocks and turnbulence
– magneto–hydrodynamics


Torsten A. Enßlin
Galaxies
AGN
Radio Plasma
cooling
Radio Ghosts
re−acceleration of
remnant electrons
Cluster Radio Relics
starburst
driven
winds
Shock Waves
Particle Escape
Gas Motion
Turbulent Cascade
injection into
the gaseous IGM
Protons
> GeV
< GeV
p + p −> 2 N + π
π+− −> e+− + 3 ν
π0 −> 2 γ
pion decay
(γ)
Coulomb Collisions
injection of secondary
electrons from hadronic
interactions
nonthermal IC
(EUV,HEX, γ)
Electrons
> 150 MeV
< 150 MeV
suprathermal
thermal
Inverse Compton
Synchrotron Emission
Radio Halos
Bremsstrahlung
Coulomb Collisions
nonthermal X−rays
(HEX)
Cluster Merger
& Accretion
Acceleration
Cooling

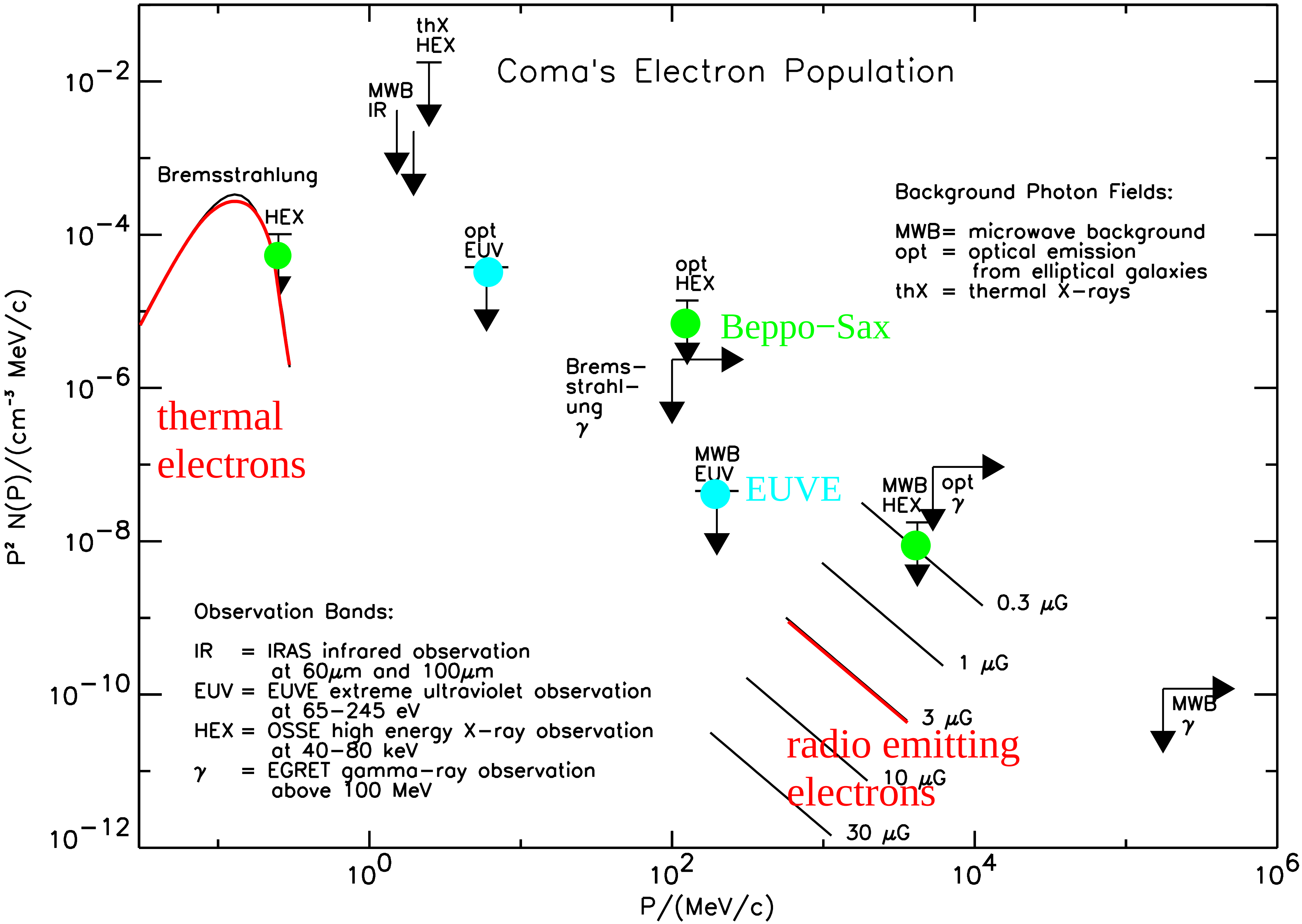


Enβlin & Biermann 1998

electron momentum →



Enβlin & Biermann 1998



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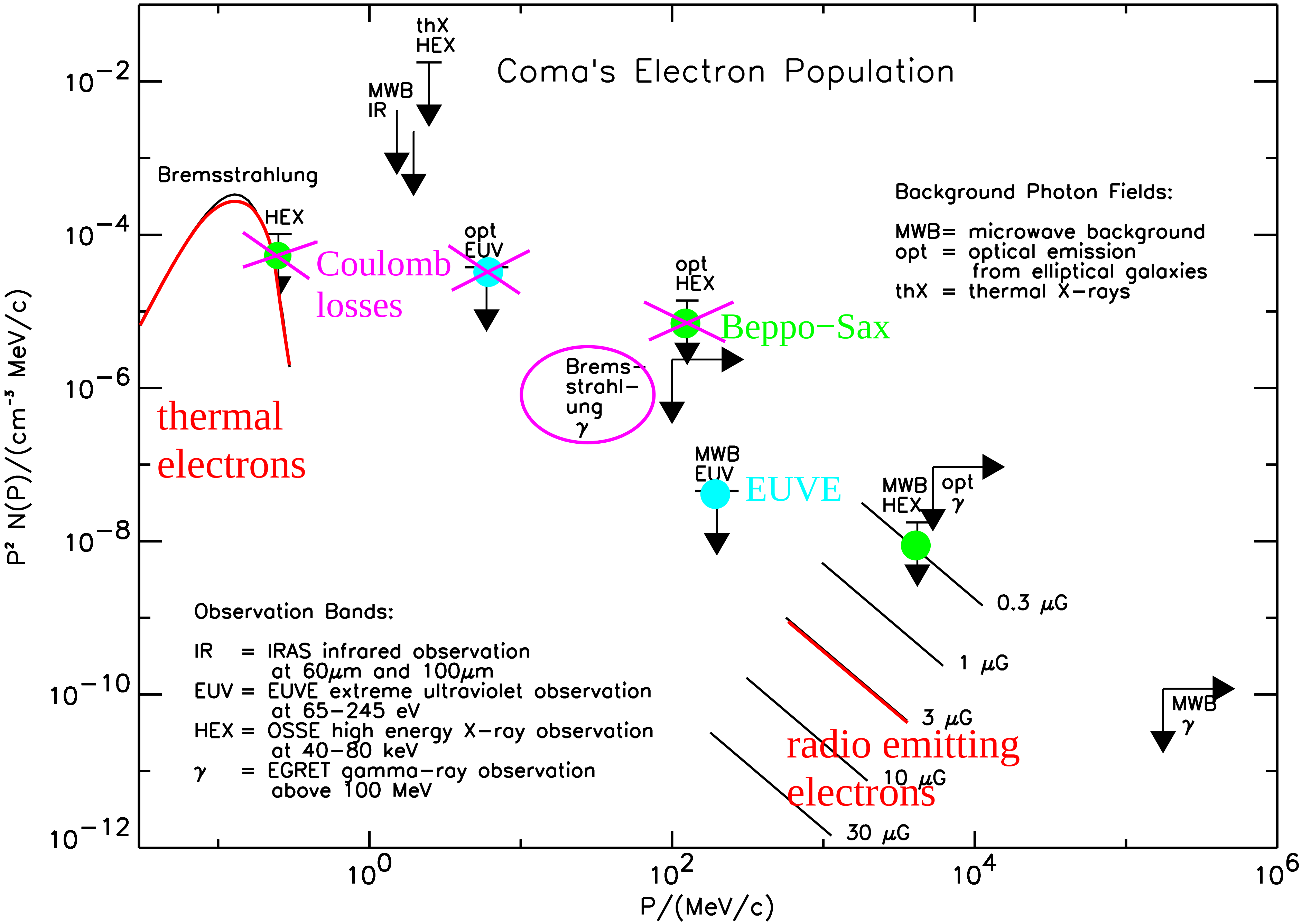

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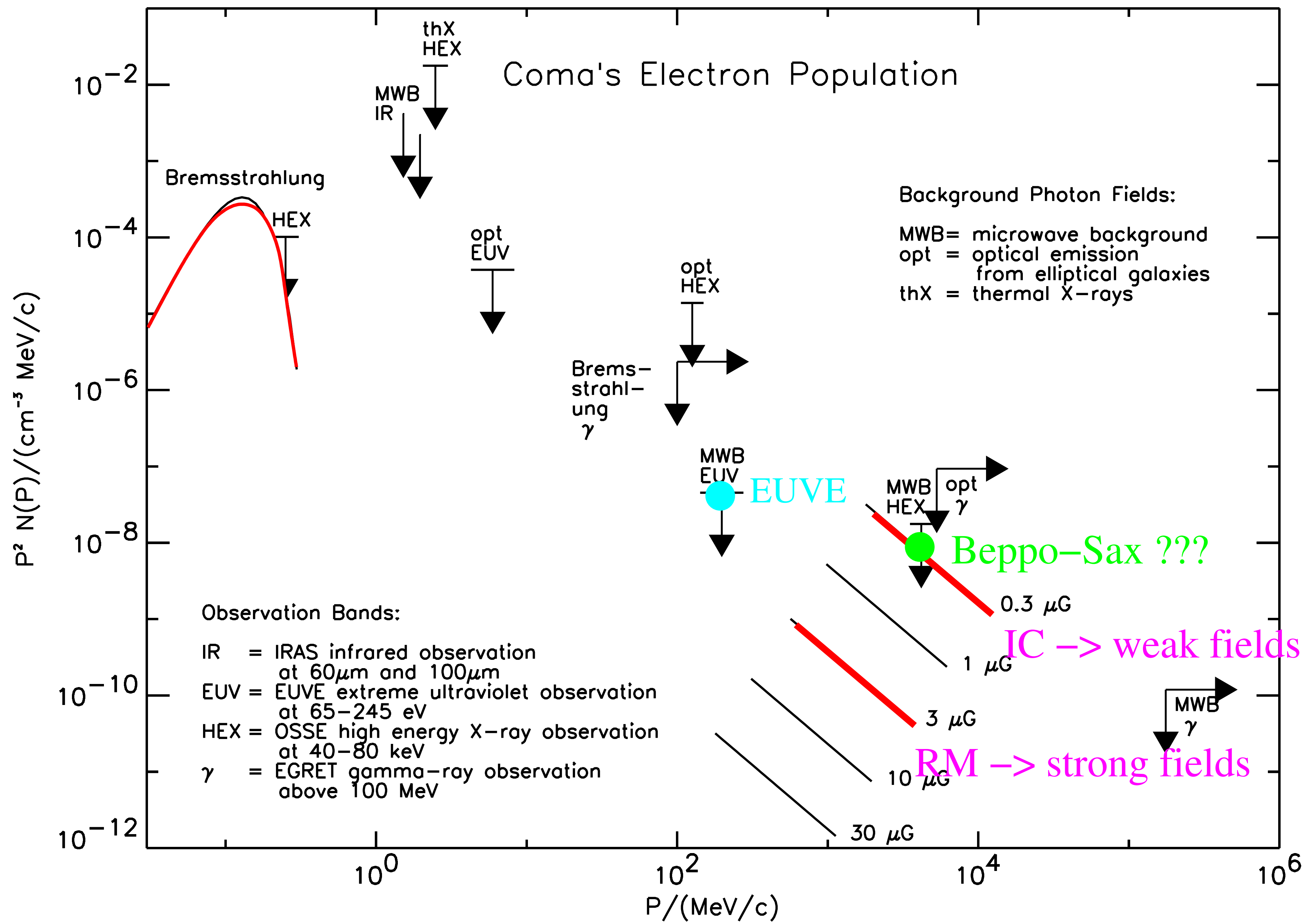

Enβlin & Biermann 1998

What are our prejudices ?

Depending on whom one asks:

CRe are due to (re–)acceleration
"There is growing evidence ... " (Brunetti et al.)
radio spectral bending/variations are easily explained

CRe are secondaries from hadronic CRp–p interactions
only few CRp necessary for radio halos
  ––> Christoph Pfrommer's talk
theory tells us that CRp are easier to accelerate than CRe
  ––> secondary CRe seem to be unavoidable

Inverse Compton fluxes –> magnetic fields are weak

Faraday rotation –> magnetic fields are strong

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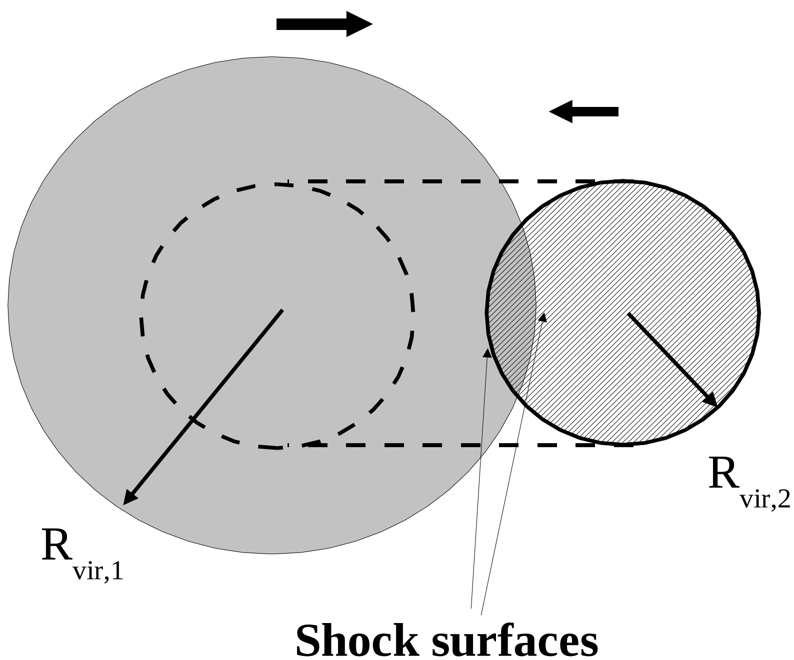
Don't expect unbiased arguments !

What are our prejudices ?

hadronic halo model:
cluster merger/accretion shock waves must have accelerated a CRp population

semi−analytic cluster merger description (Gabici & Blasi):
only weak shocks in large cluster merger possible
−−> not sufficient CRp accumulation



similarly sized clusters:

$M = v/c_s$
$c_s \sim T_{vir}^{1/2}$
$v \sim v_{vir} \sim T_{vir}^{1/2}$
$M \sim 1$

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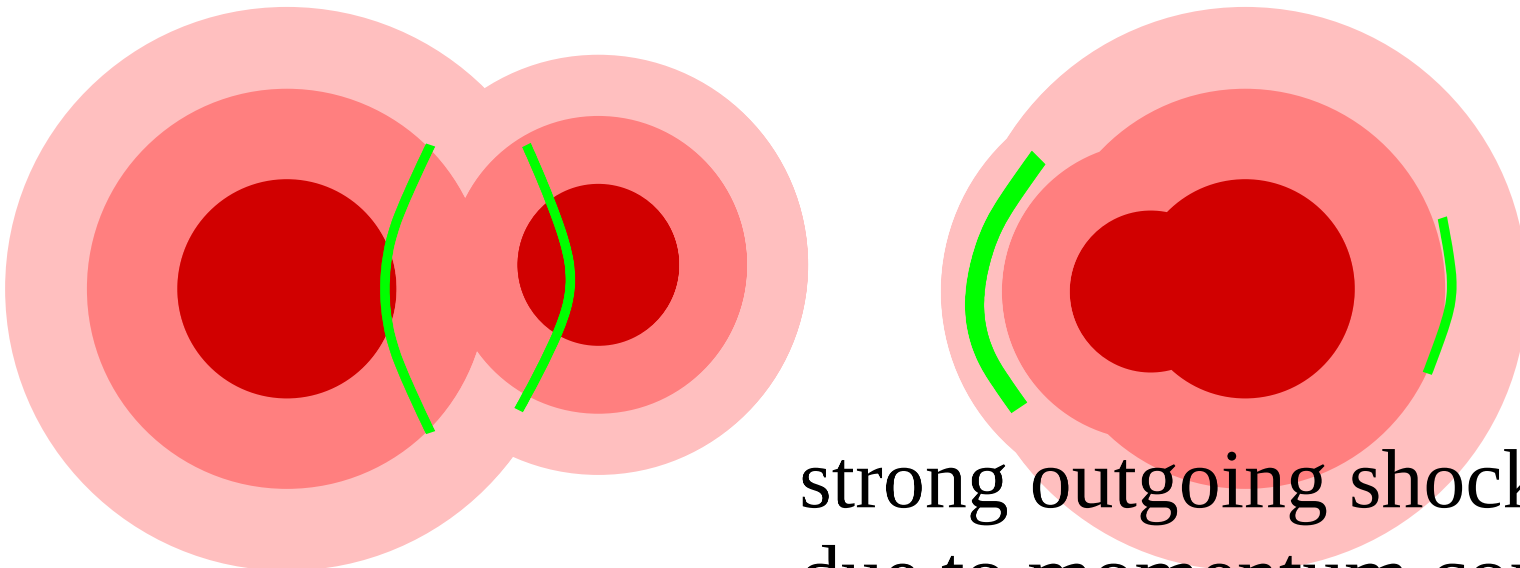
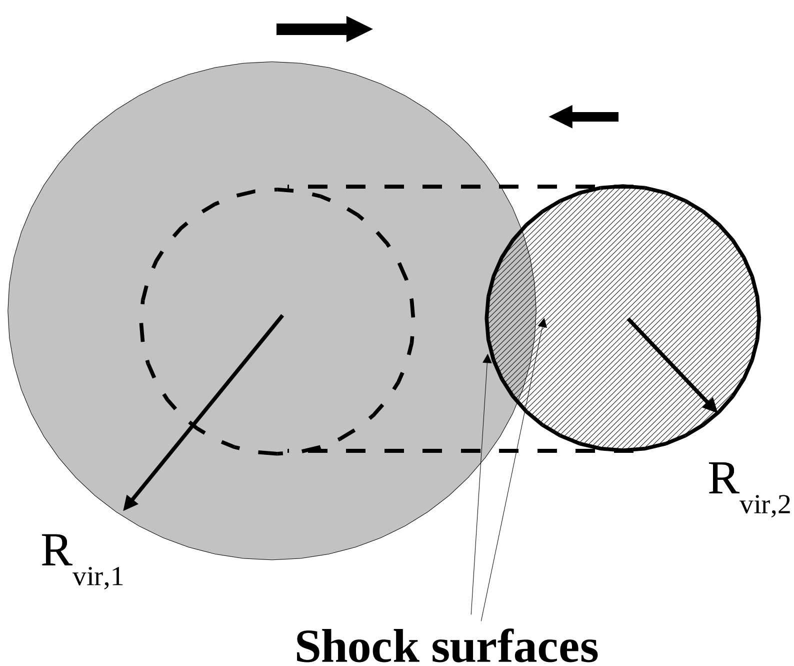


strong outgoing shock waves
due to momentum conservation



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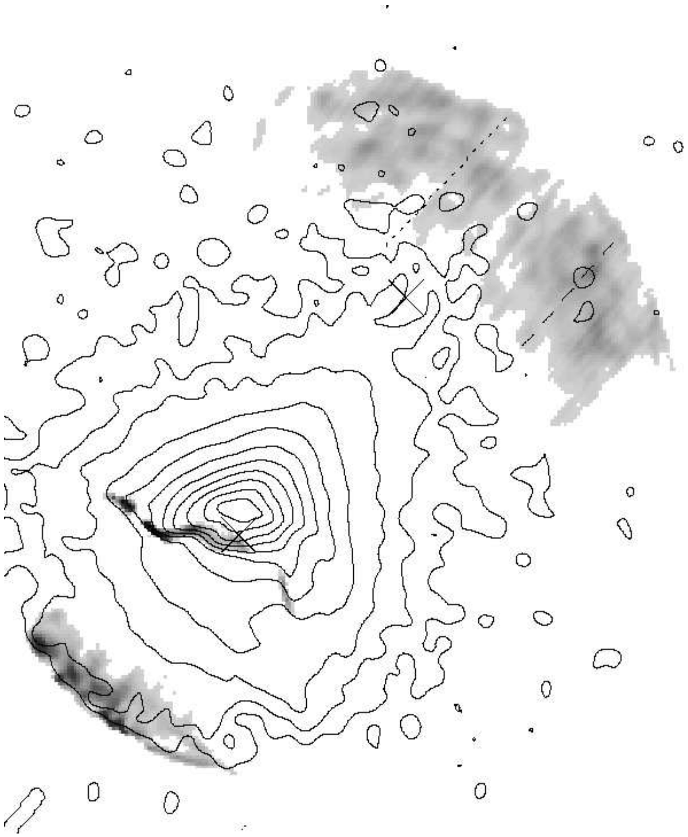
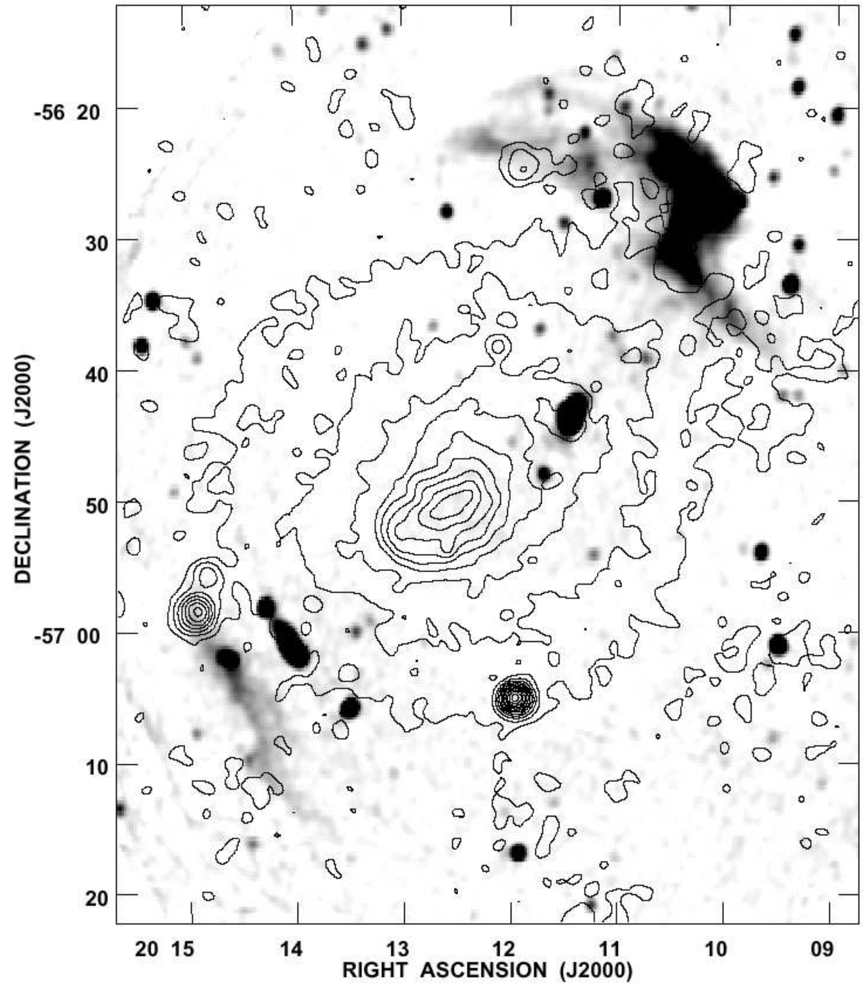
What are our prejudices ?

hydrodynamical simulated merger incl. CRe shock acc.



Roettinger et al.

A3667: real merger showing radio relics as shock tracer (Ensslin et al.)

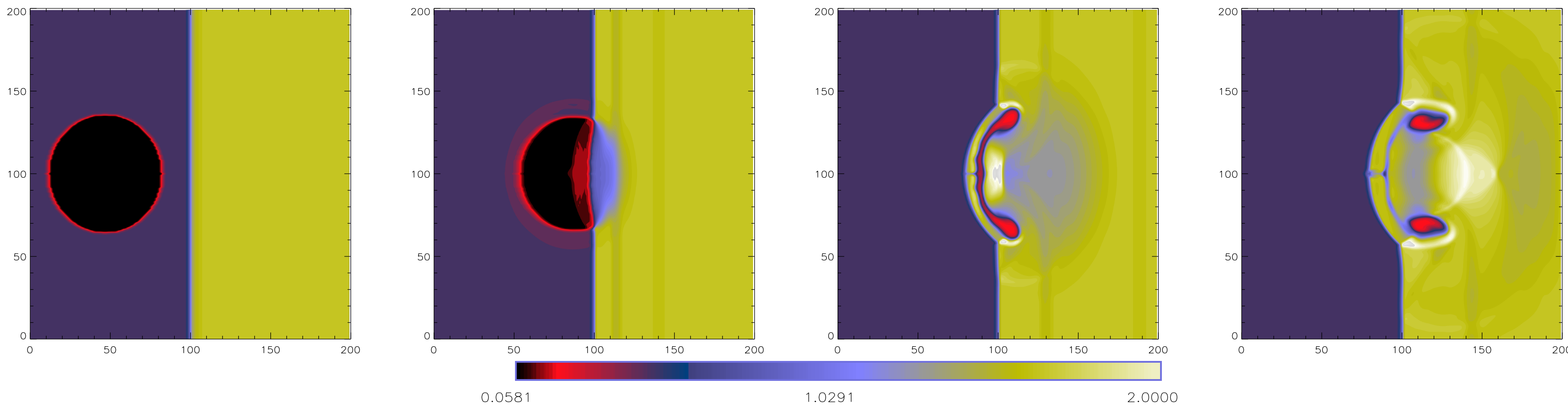


Roettgering et al.

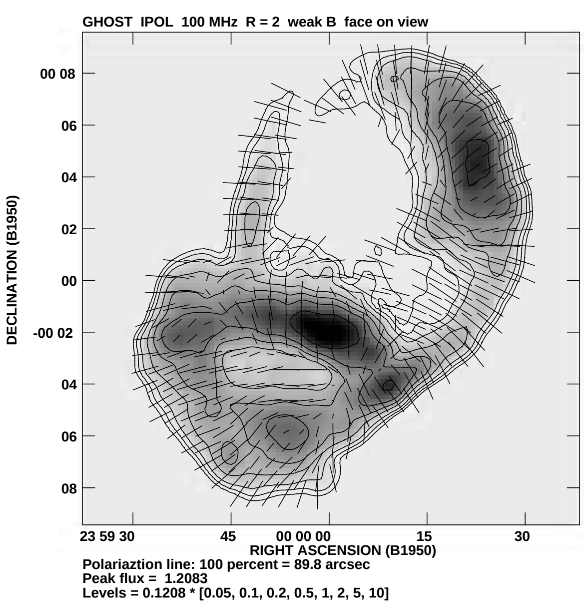
Shock passage of an old radio coccon

Enβlin & Brüggen 2002

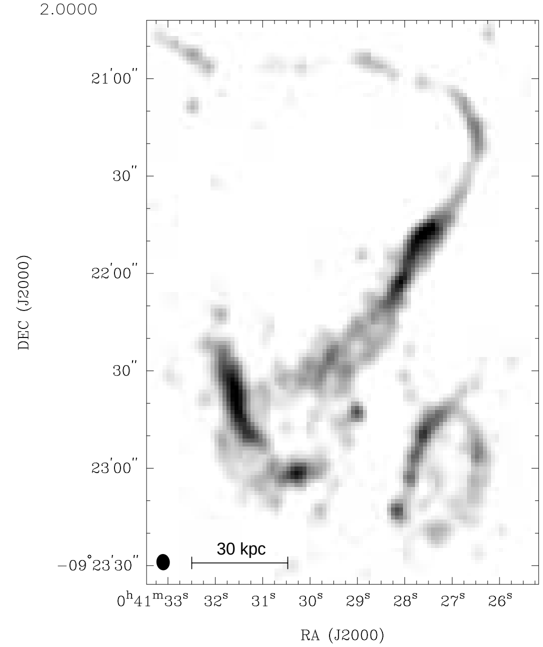
temporal evolution of the gas density



simulated radio map of shock processed radio ghost



observed radio map of cluster radio relic in Abell 85



How to verify models ?

Theories can only be falsified. To be a scientific theory, it has to be falsifiable (Popper). This means, it must be possible to derive from it unambigious predictions for doable experiments such that, were contrary results be found, at least one premise of the theory would have proven not to apply to nature.

hadronic model: prediction of gamma and neutrino fluxes

1) gammas should be detectable with GLAST

--> Christoph Pfrommer's and Olaf Reimer's talks

2) model can not explain very strong spectral bending

3) necessary energy budget can exceed available energy sources

(re–)acceleration model: seem to be able to fit any yet reported radio profile & spectra. Distinctive predictions are not known, or ?

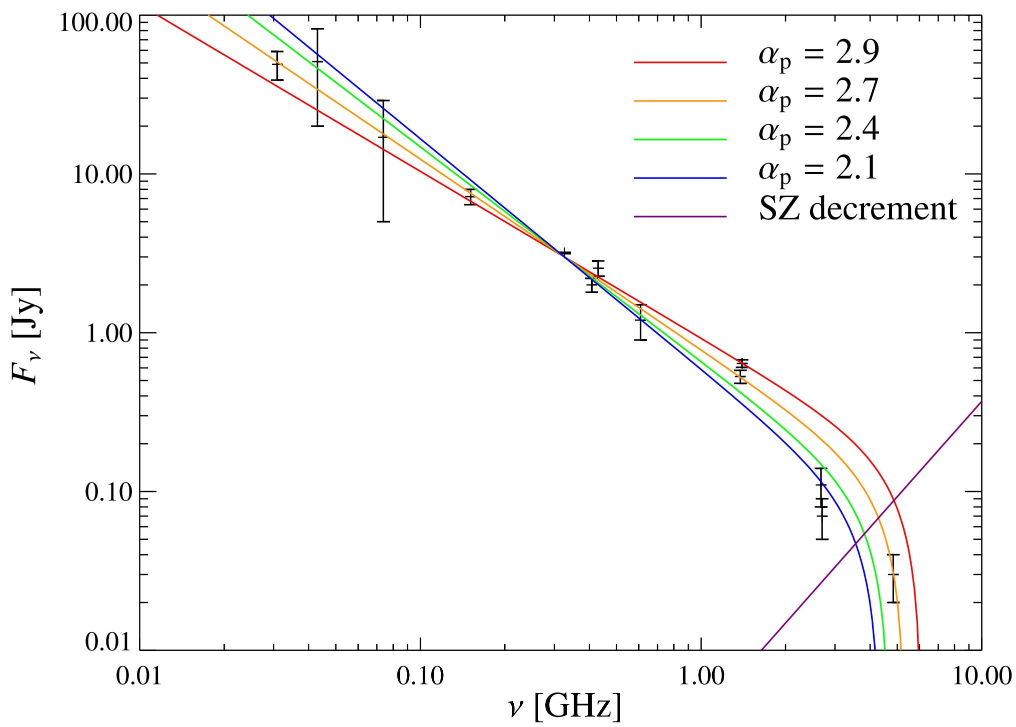
How to acess uncertainties ?

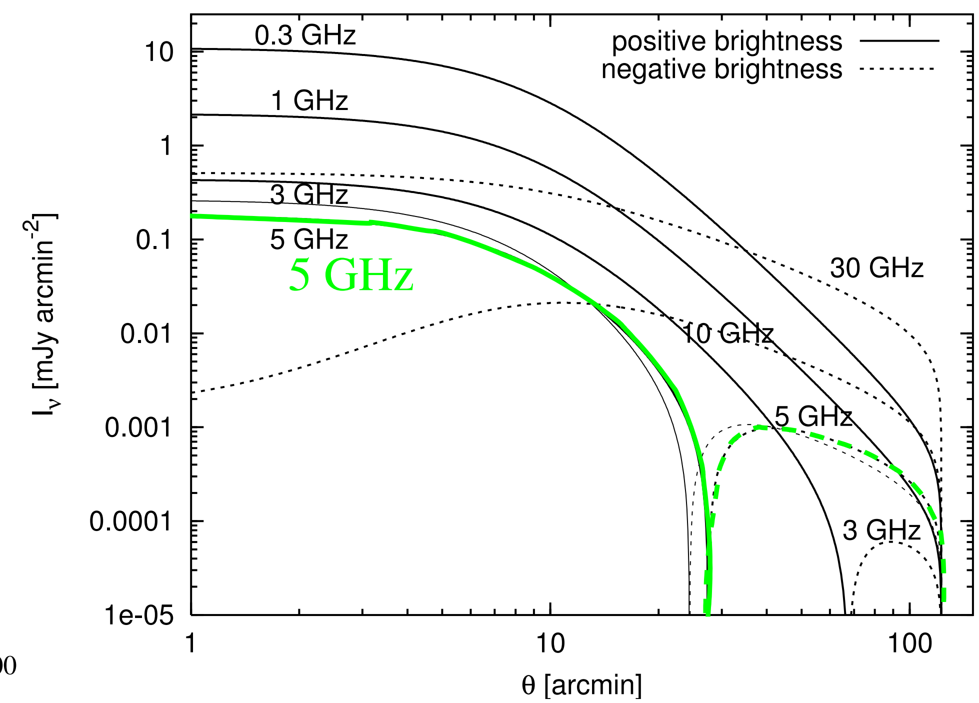
Many of the used datasets in non−thermal cluster physics suffer from systematic and selection effects.
−> Danger to fit/explain observational artefacts.

Required: Detailed understanding of these effects.

How to acess uncertainties ?

Example: reported spectral steepening of radio halos could falsify the hadronic model, if real. But steepening could be easily observational artefact or SZ–effect contamination.

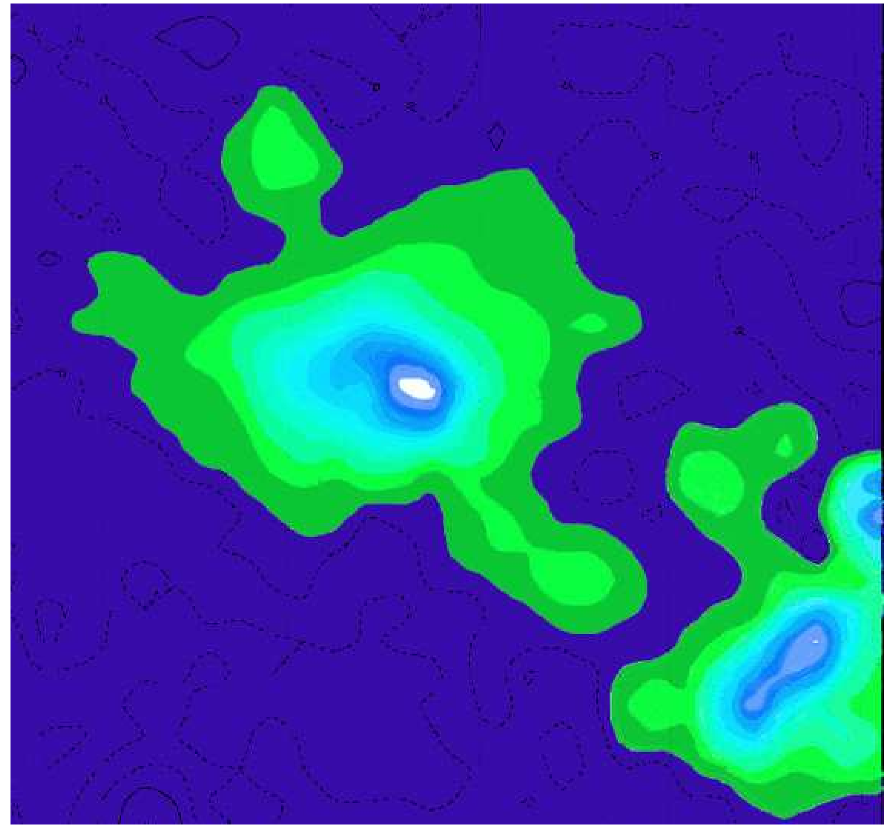




How to acess uncertainties ?

Radio astronomy is an art !

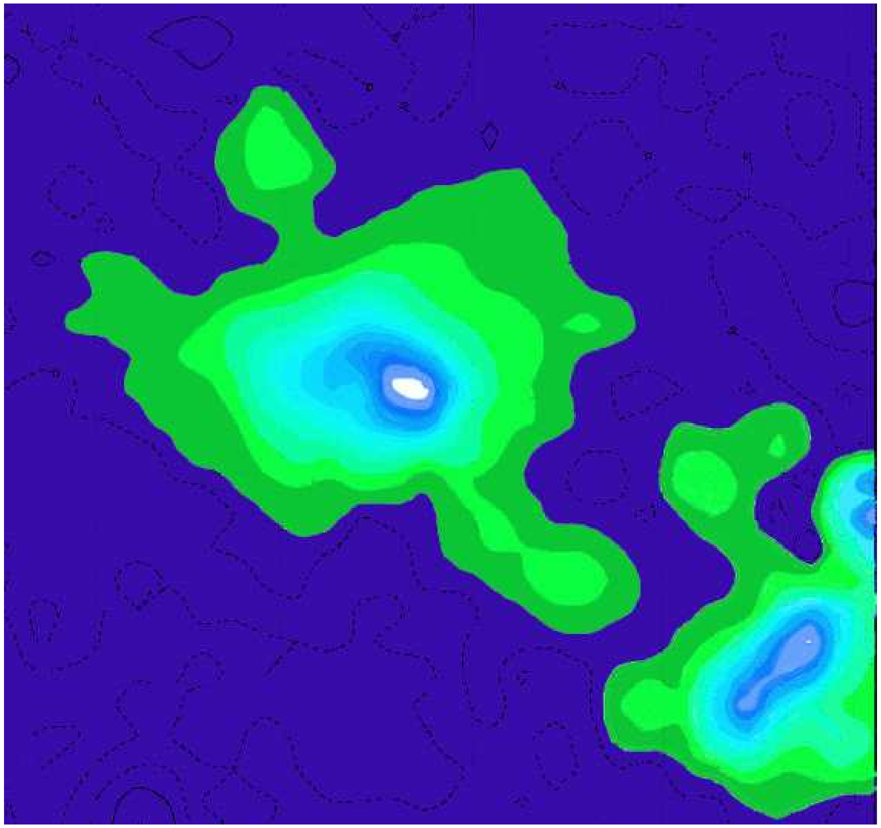
How to acess uncertainties ?



To understand the meaning and significance of features & spectra we need an end–to–end analysis of the data reduction process. From detector signal, through (self–)calibration to map making.

Radio astronomy is an art !

How to acess uncertainties ?



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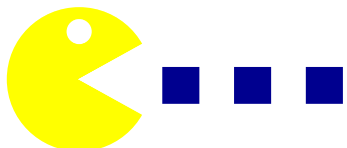
Radio astronomy is an art !

How to acess uncertainties ?

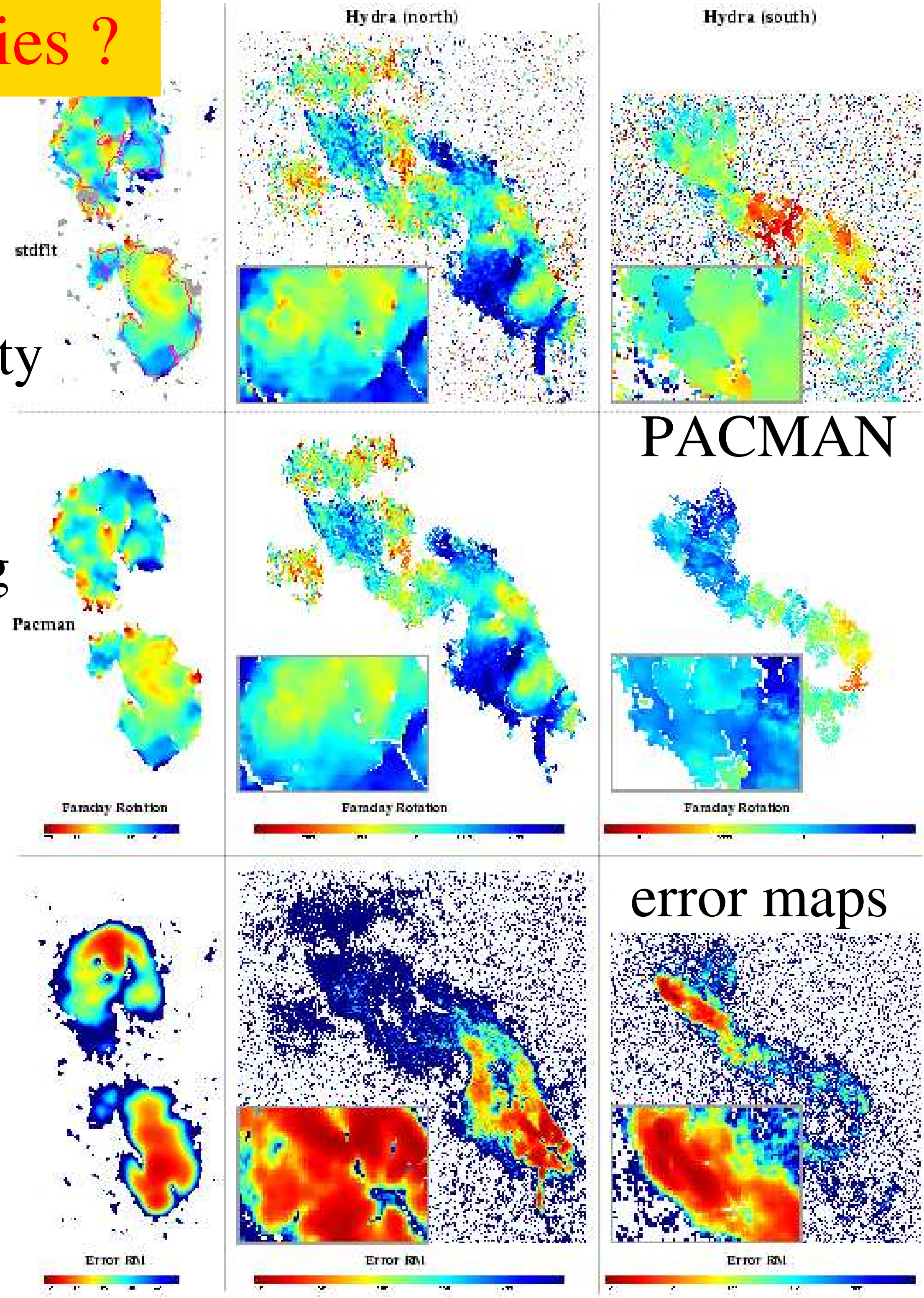
Magnetic power spectra measurements from RM maps require high map quality

PACMAN

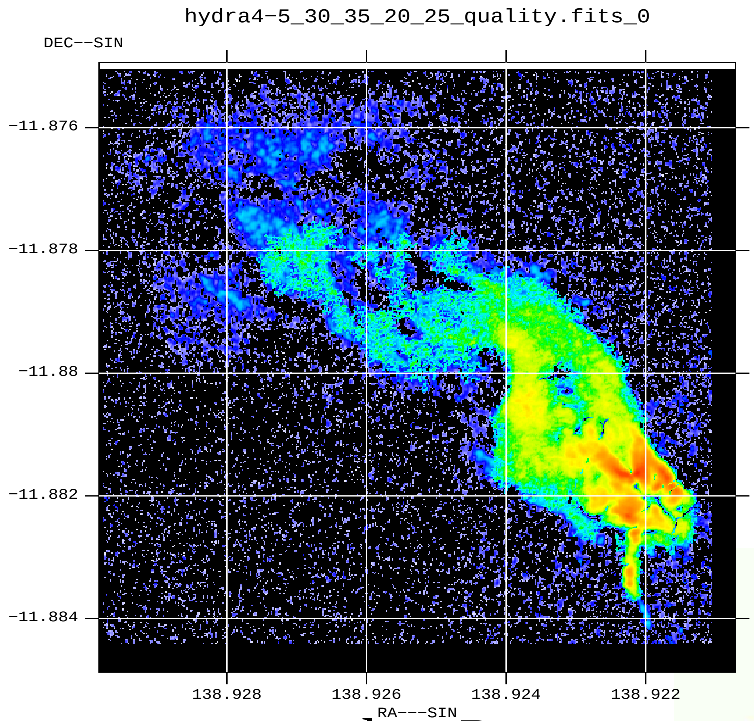


Polarisation Angle Correcting rotation Measure ANalysis

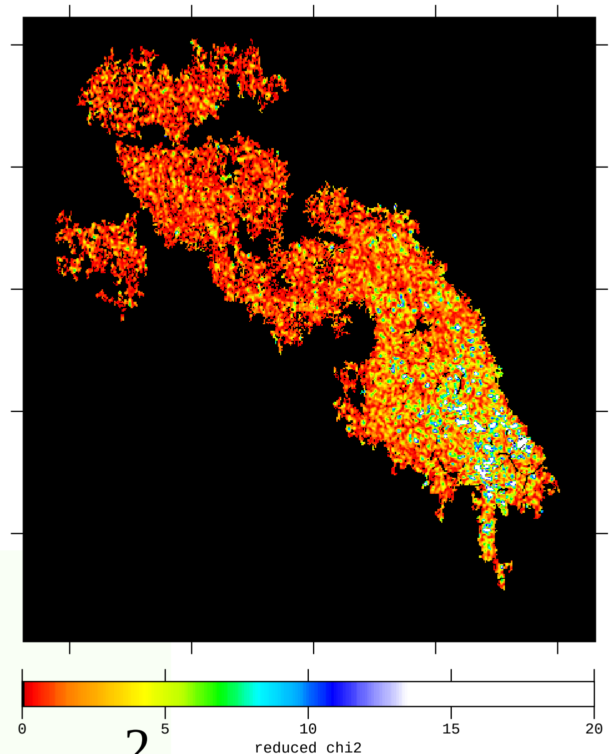
non−local RM mapping to solve n−pi amiguities
+ error weighted fitting



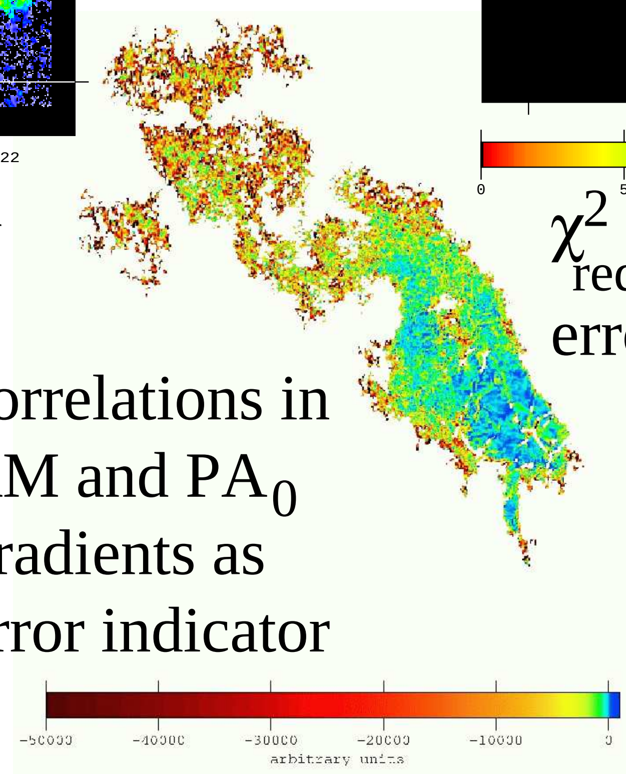
Understanding the RM−error map of Hydra North



error map by Pacman

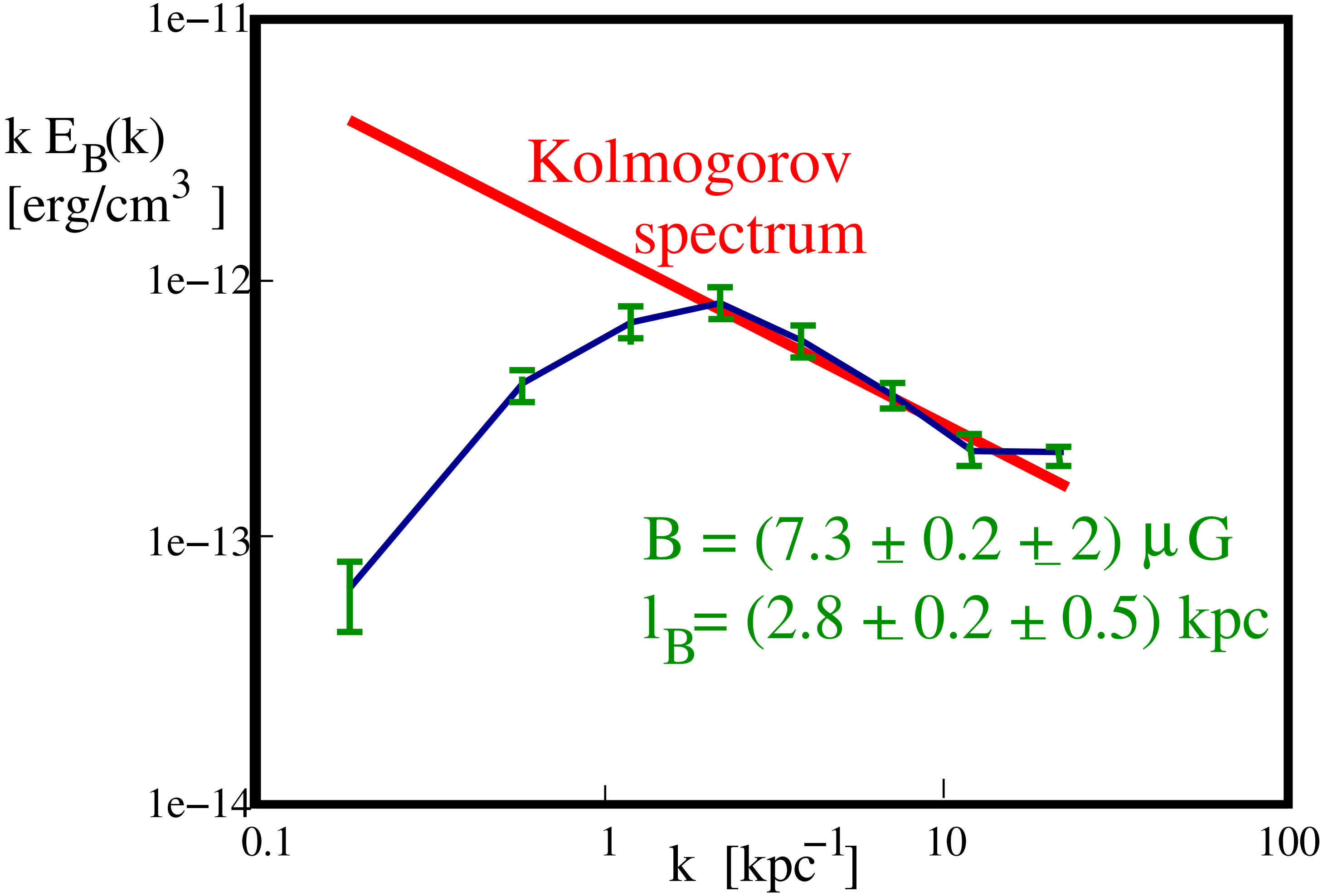


χ^2_{red} map indicating error underestimations



correlations in RM and PA_0 gradients as error indicator

Magnetic power spectrum in cool core region of Hydra A cluster (Corina Vogt's talk)



Is a consistent picture possible?

Is a consistent picture possible?

Fiction !

Is a consistent picture possible?

Observational data:

RM map in Hydra: indication of 7 μG fields, 3 kpc correlation length
RM maps of non–cooling flow clusters: somewhat weaker fields,
larger correlation length, but requires further studies ...

radio halo synchrotron emission: $< \text{CRe times } B^2 >_{vol}$

Inverse Compton emission (EUVE, HEXE): $< \text{CRe} >_{vol}$

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$$< B^2 >_{CRe} = \frac{< \text{CRe times } B^2 >_{vol}}{< \text{CRe} >_{vol}}$$

~ 0.3 μG (HEXE ???)
~ 1.3 μG (EUVE)

$$< B^2 >_{vol} = 3 - 10 \ \mu G$$

Is a consistent picture possible?

Required:

1) Inhomogeneous magnetic field strength
2) Inhomogeneous CRe populations
3) Anti–correlation between CRe and B

$$< B^2 >_{\mathrm{CRe}} = \frac{< \mathrm{CRe\ times\ } B^2 >_{\mathrm{vol}}}{< \mathrm{CRe} >_{\mathrm{vol}}} \sim 0.3\ \mu\mathrm{G}$$

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Required:

physical mechanisms to ...

a) ... creat inhomogeneous field strengthes
b) ... to anti−correlate the CRe with B

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Synchrotron cooling can easily produce an anticorrelation, if the CRe injection is not correlated with magnetic fields.

hadronic model: Yes, no correlated injection expected.
reacceleration model: correlated injection is expected, or ???

Is a consistent picture possible?

Required:

1) Inhomogeneous magnetic field strength
2) Inhomogeneous CRe populations
3) Anti−correlation between CRe and B

Required:

physical mechanisms to ...

a) ... creat inhomogeneous field strengthes
b) ... to anti−correlate the CRe with B √ (hadronic model)

Magnetic fields seem to be shaped by turbulence.

What does MHD theory predict ?

What does turbulent dynamo theory predicts ?

Non–helical turbulent dynamo (Gaussian closure), with short turbulent correlation time (tau–approximation), and with a simplified description of magnetic backreaction (K. Subramanian) saturates in a state with a characteristic magnetic field spectrum.

The effective magnetic Reynolds number (incl. magnetic field decay due to back reactions) reaches a 'critical' value of Rc ~ 60

What does turbulent dynamo theory predicts ?

Predictions (K. Subramanian, Pune):

A) magnetic fluctuation are concentrated on scale $l \sim L \; Rc^{-1/2}$

B) Correlations exist up to scale L, turn into an anti–correlation and decay quickly on larger scales

C) This can be understood in Zeldovich's flux rope model, in which magnetic ropes with diameter l are bent on a scale L

D) Within flux ropes, magnetic field can be near equipartition with the turbulent energy density

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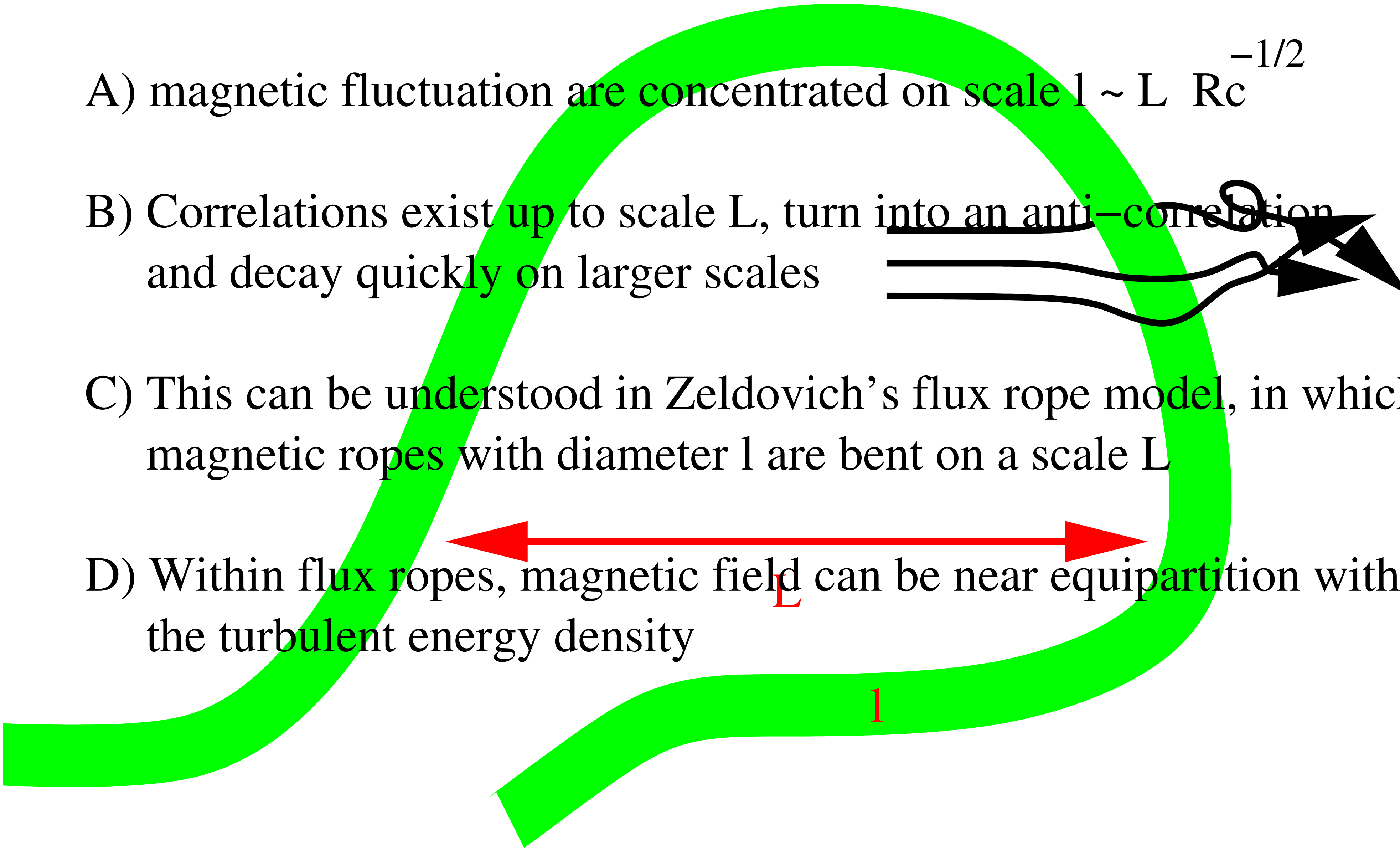

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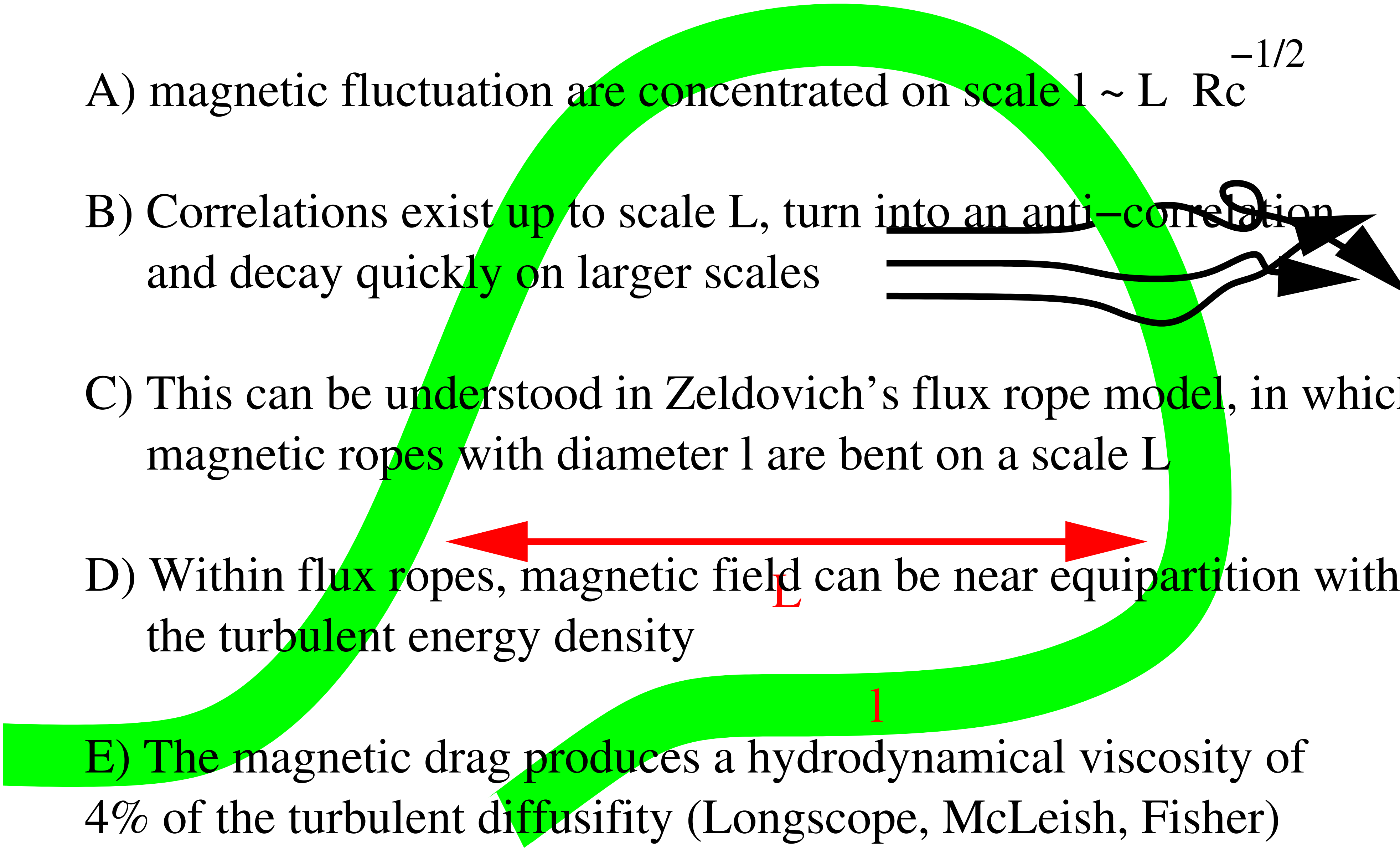
E) The magnetic drag produces a hydrodynamical viscosity of
4% of the turbulent diffusifity (Longscope, McLeish, Fisher)



What does turbulent dynamo theory predicts ?

Confronting predictions with observations:

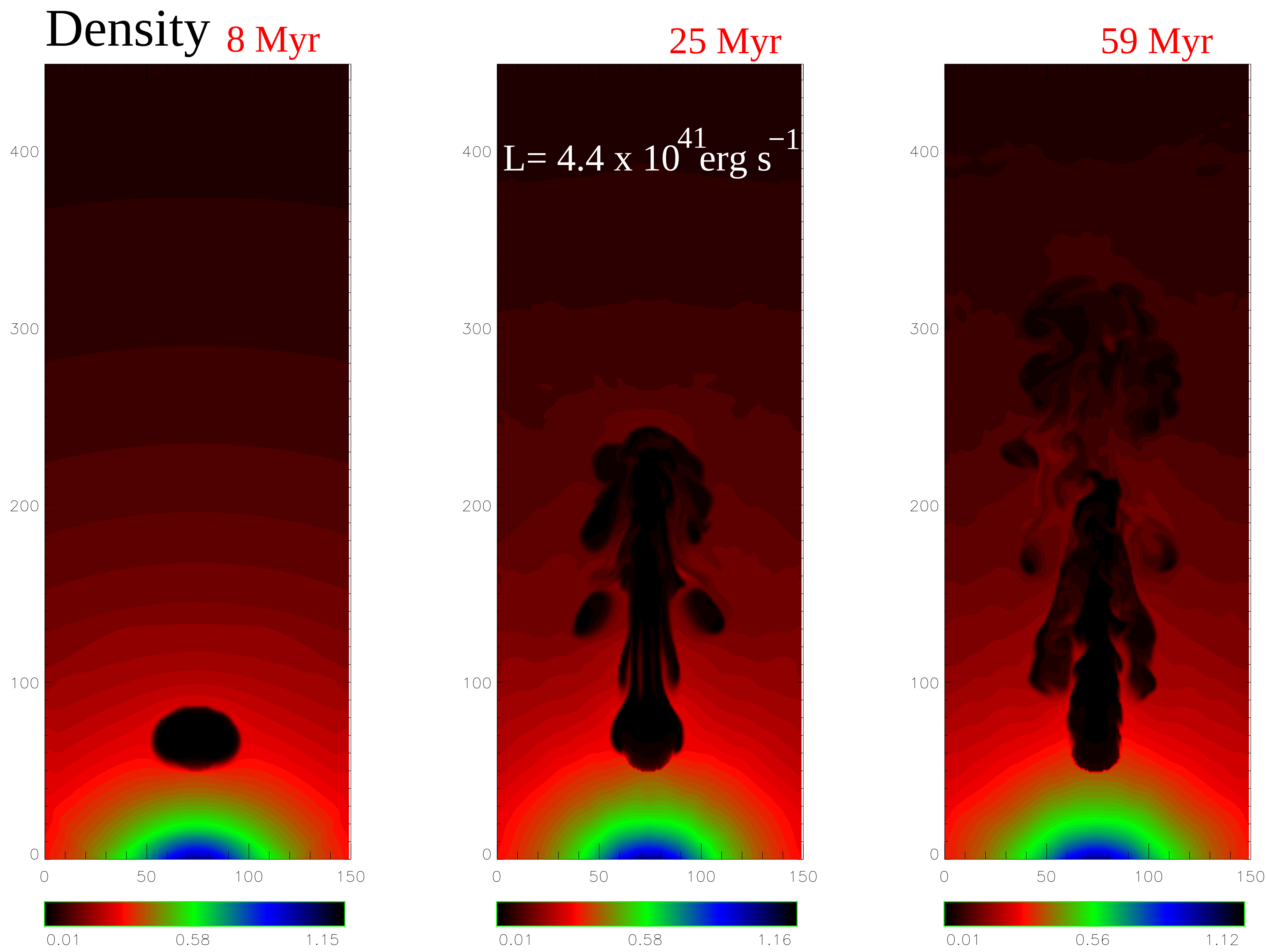
A) magnetic fluctuation are concentrated on scale $l \sim L\ Rc^{-1/2}$

Hydra A: $l \sim 3$ kpc

=> $L \sim 25$ kpc

expected turbulent injection scale due to stiring by buoyand radio plasma

possible explanation on why the radio source is conveniently sized to allow RM studies of the peak of magnetic turbulence



Brueggen, Kaiser, Churazov, Ensslin 2002

What does turbulent dynamo theory predicts ?

Confronting predictions with observations:

B) Correlations exist up to scale L, turn into an anti−correlation and decay quickly on larger scales

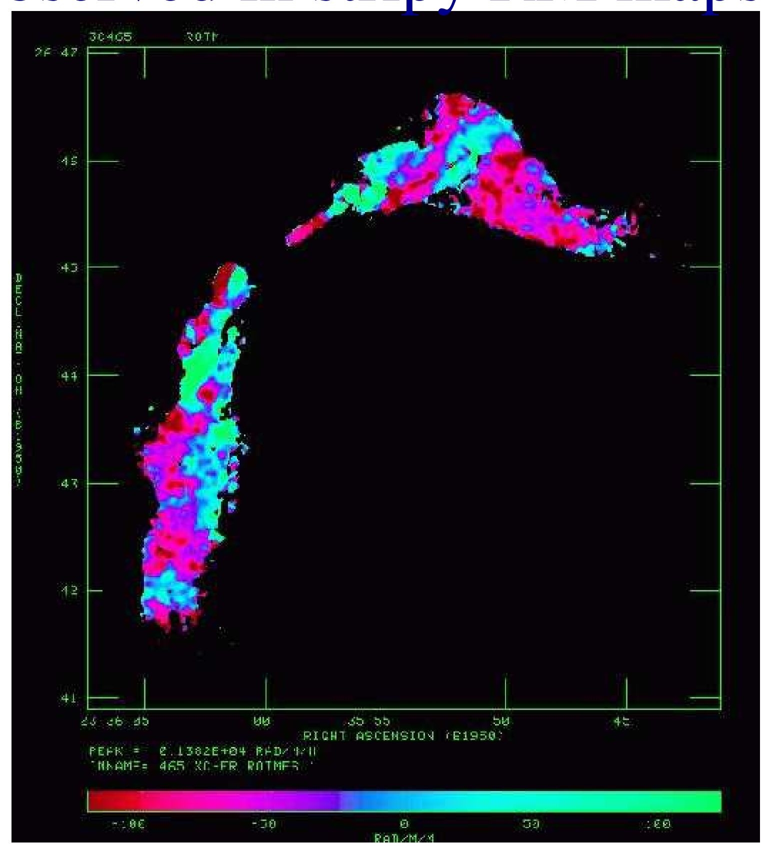
Measured large scale turn around in magnetic spectrum is consistent with this.

What does turbulent dynamo theory predicts ?

Confronting predictions with observations:

C) This can be understood in Zeldovich’s flux rope model, in which magnetic ropes with diameter l are bent on a scale L

Magnetic intermittency might be observed in stripy RM maps (Eilek & Owen).



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Confronting predictions with observations:

D) Within flux ropes, magnetic field can be near equipartition with the turbulent energy density

Hydra A cluster:

$E_{turb} \sim < E_B >_{vol} Rc \sim 10^{-10} erg \quad cm^{-3}$

$v_{turb} \sim$ 500 km/sec

of the order of the expected speed of buoyant radio bubbles (e.g. Ensslin & Heinz)

What does turbulent dynamo theory predicts ?

Confronting predictions with observations:

E) The magnetic drag produces a hydrodynamical viscosity of 4% of the turbulent diffusifity (Longscope, McLeish, Fisher)

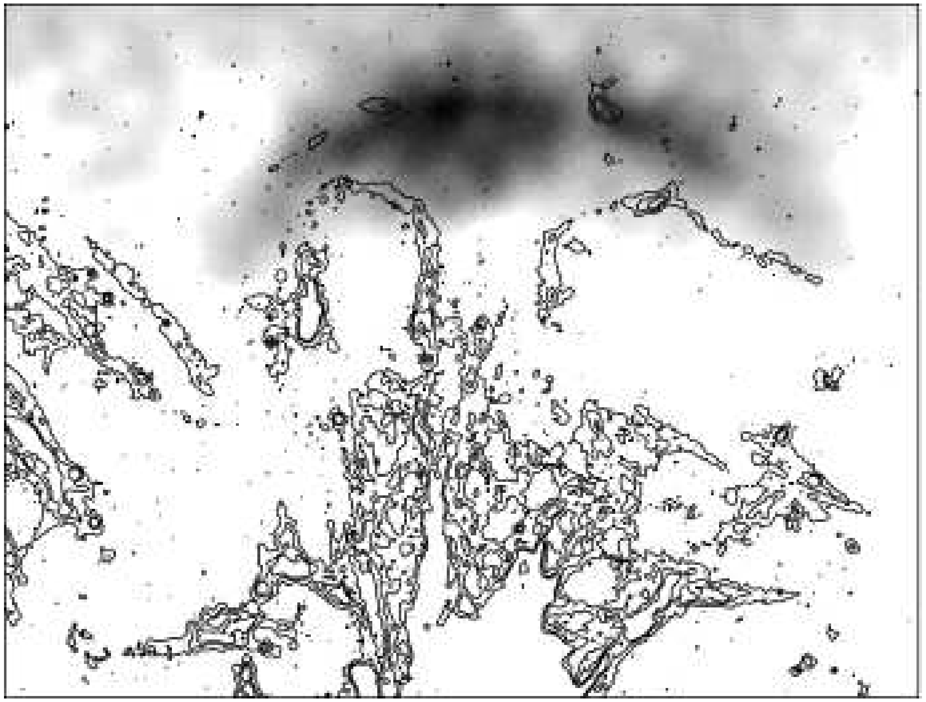
viscosity for large scale flows (larger than typical flux rope distance)

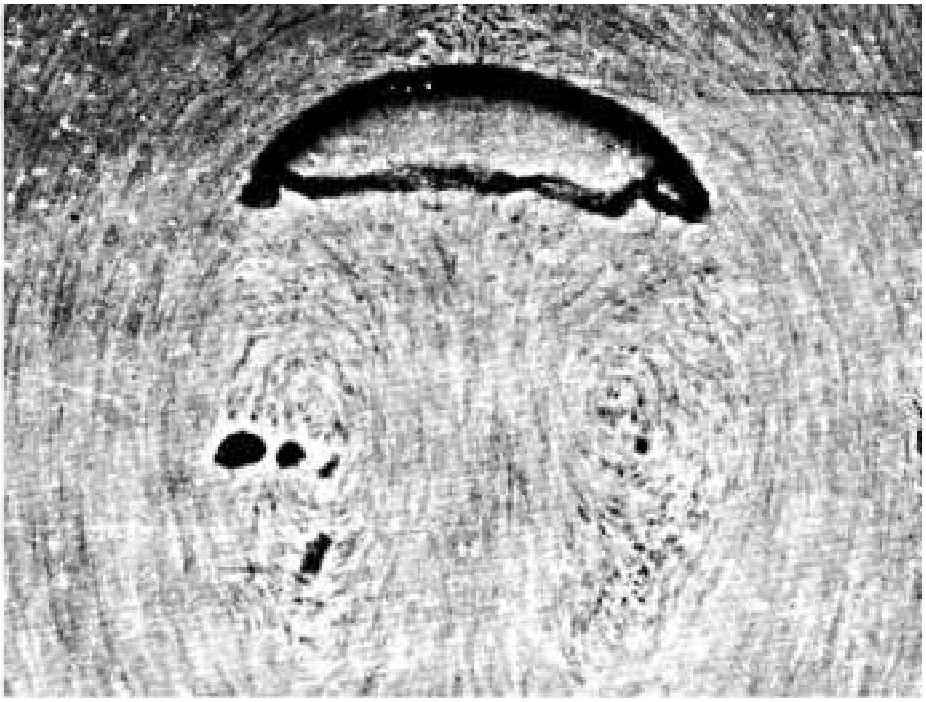
viscosity ~ 4 % 1/3 $v_{turb}L$ ~ 4 10^{28} cm /sec

What does turbulent dynamo theory predicts ?

viscosity ~ 4 % 1/3 $v_{turb}L$ ~ 4 10^{28} cm^2/sec

Perseus cluster: buoyant radio bubble (grey) and Ha filaments (Fabian et al.





required viscosity for laminar large scale flow: 4 10^{27} cm^2/ sec

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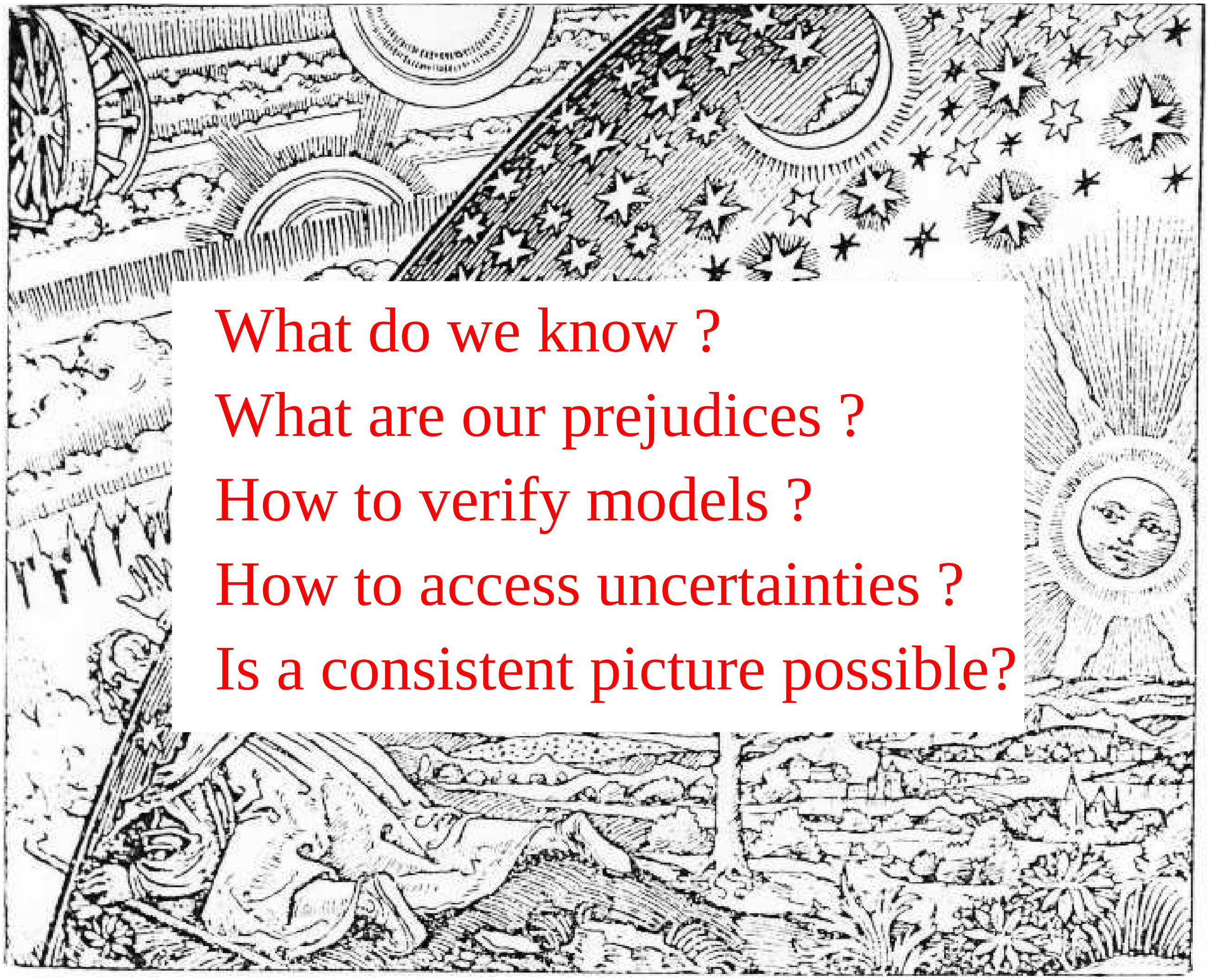

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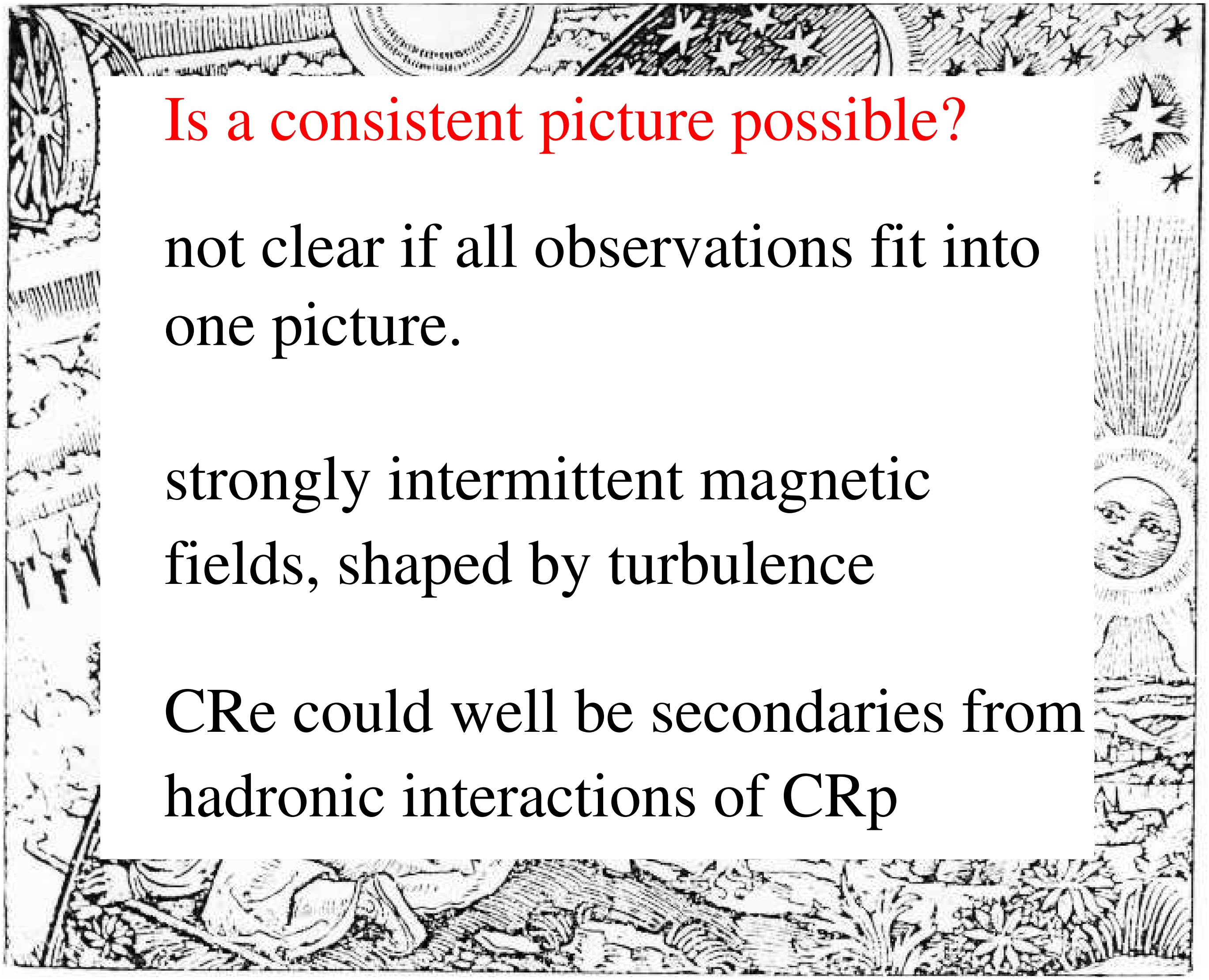

Is a consistent picture possible?

not clear if all observations fit into one picture.

strongly intermittent magnetic fields, shaped by turbulence

CRe could well be secondaries from hadronic interactions of CRp

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Thank you !