Heating in the IGM and ICM

Peng Oh (UCSB)

Heating in the IGM: hydrogen reionization

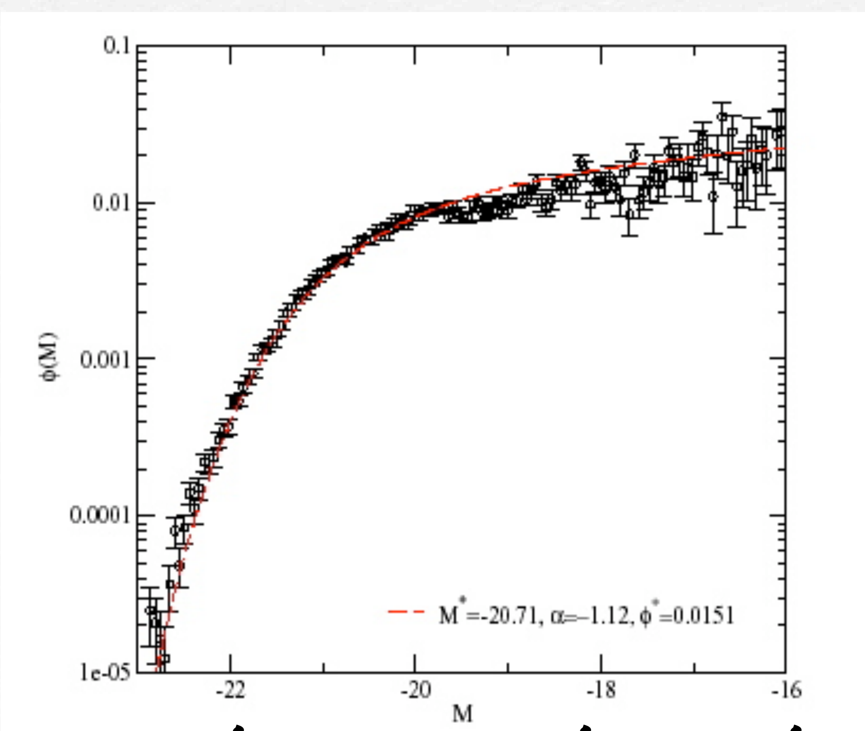
- When did it happen?
- How fast was reionization?
- What was the topology of reionization?
- What were the sources responsible?

Field is driven primarily by observations

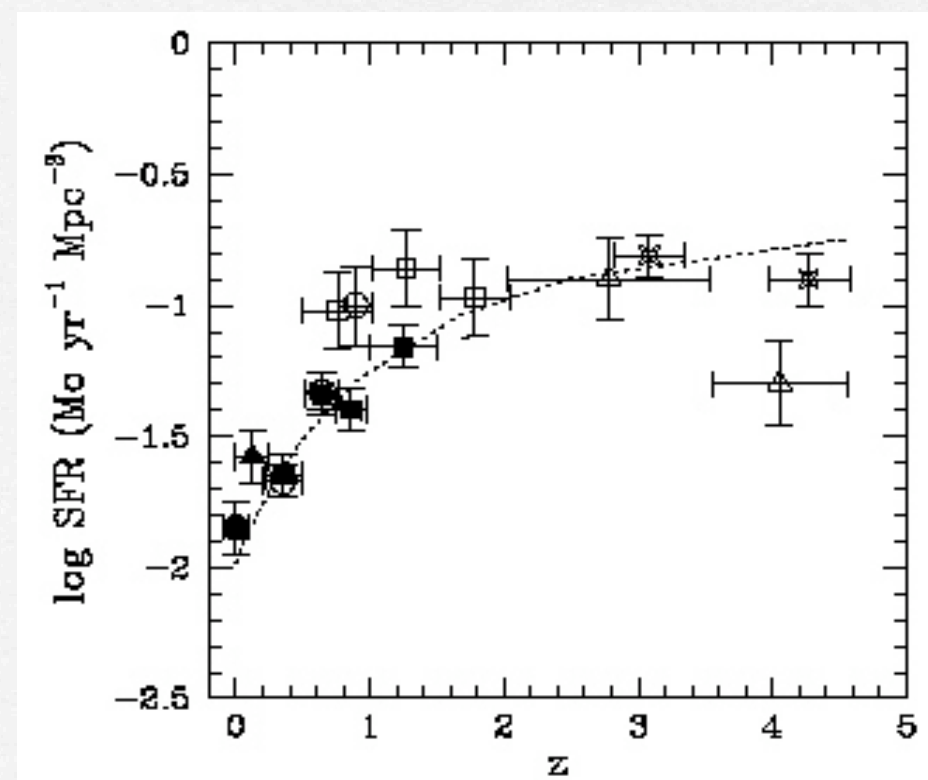
The argument from people power:
It’s the last time that baryons did anything together en masse….after that they all did their own thing.

Heating in the ICM

- How can we understand the characteristic mass scale L* for galaxies?
- Why haven't most collapsed baryons turned to stars?



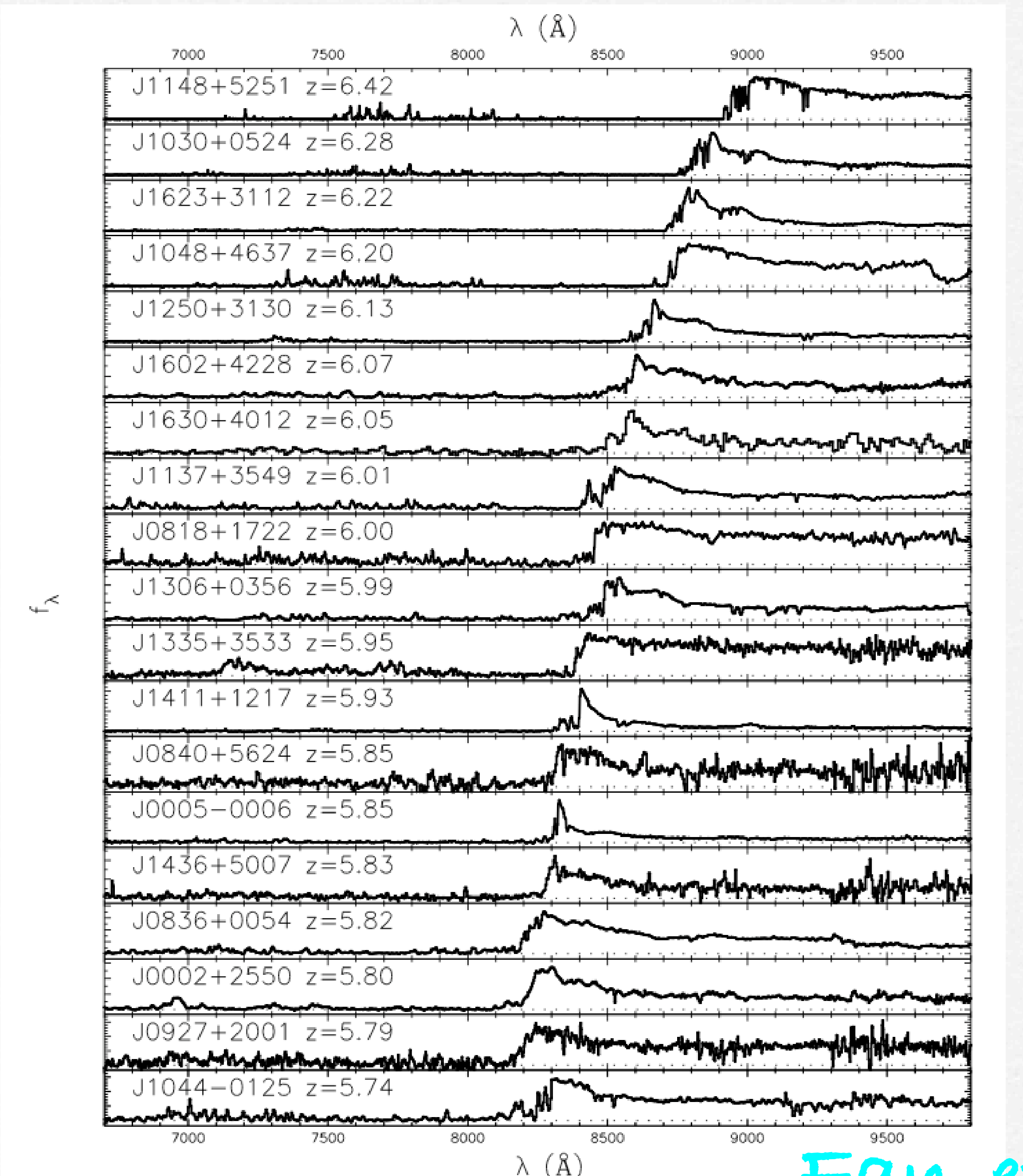
Knee in luminosity function



Downturn in comoving SFR

What do we already know about the z~6 IGM?

How neutral is the Universe at z~6?

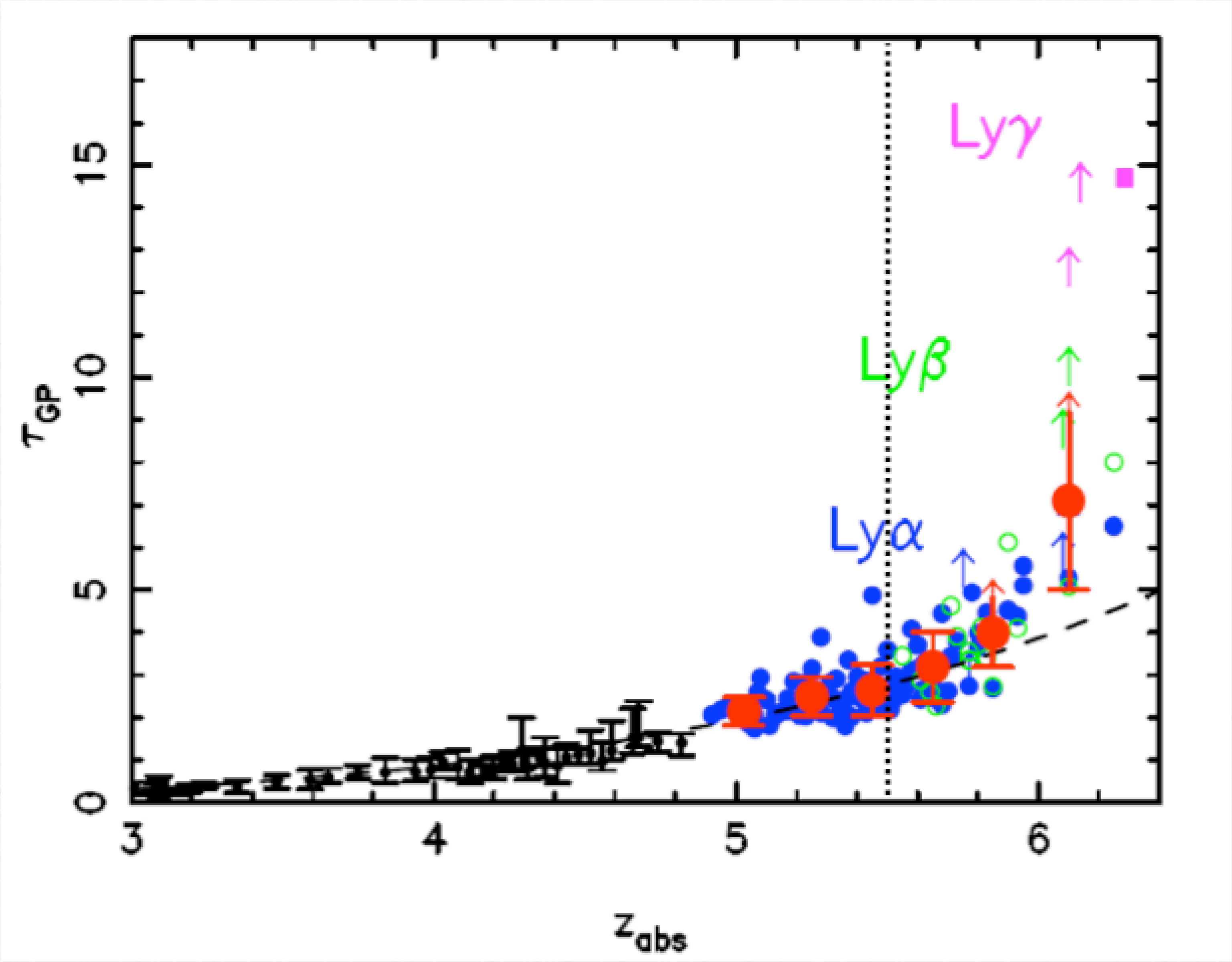


Best probe: Ly series absorption seen in 19 SDSS QSOs with $5.74 < z < 6.42$

Saturated absorper: can only probe tail end of reionization

Fan et al 2006

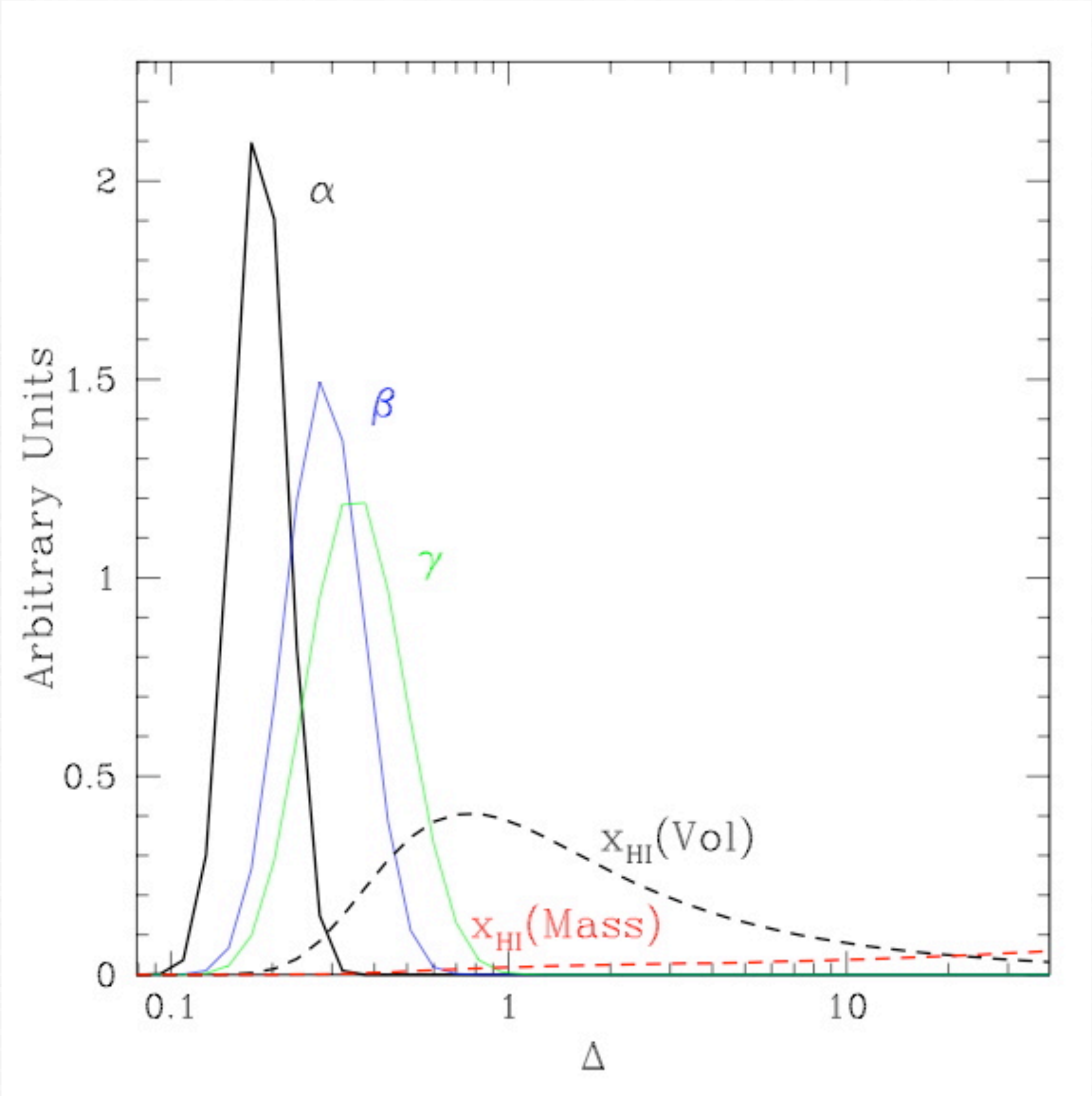
End of reionization?



Claimed sharp increase in optical depth and scatter

Fan et al 06

...but it's really hard to infer neutral fraction...



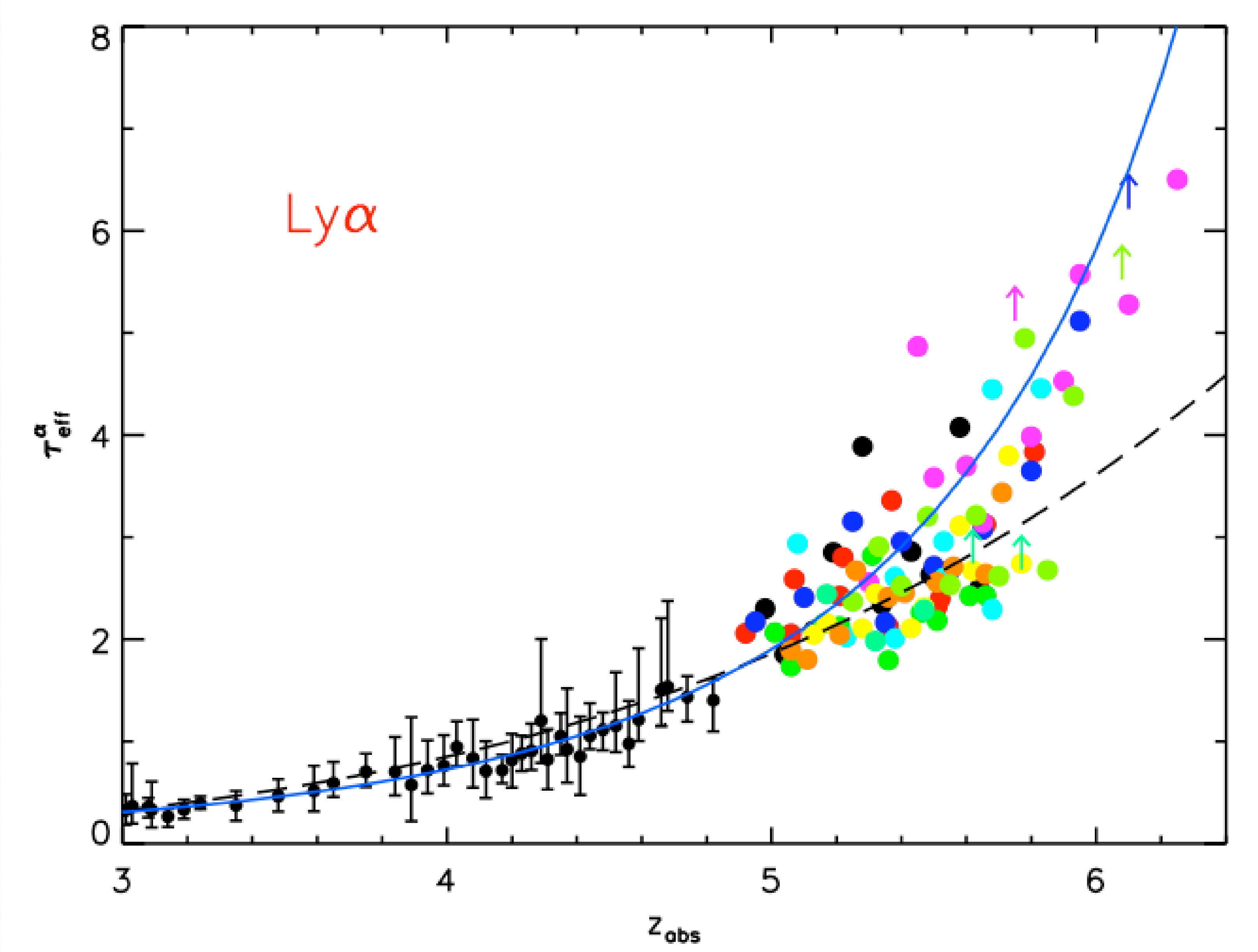
Oh & Furlanetto 2005

Transmission mainly due to rare voids

Most HI at higher overdensities

Caution: comparing different Lyman series on absolute scale is hard

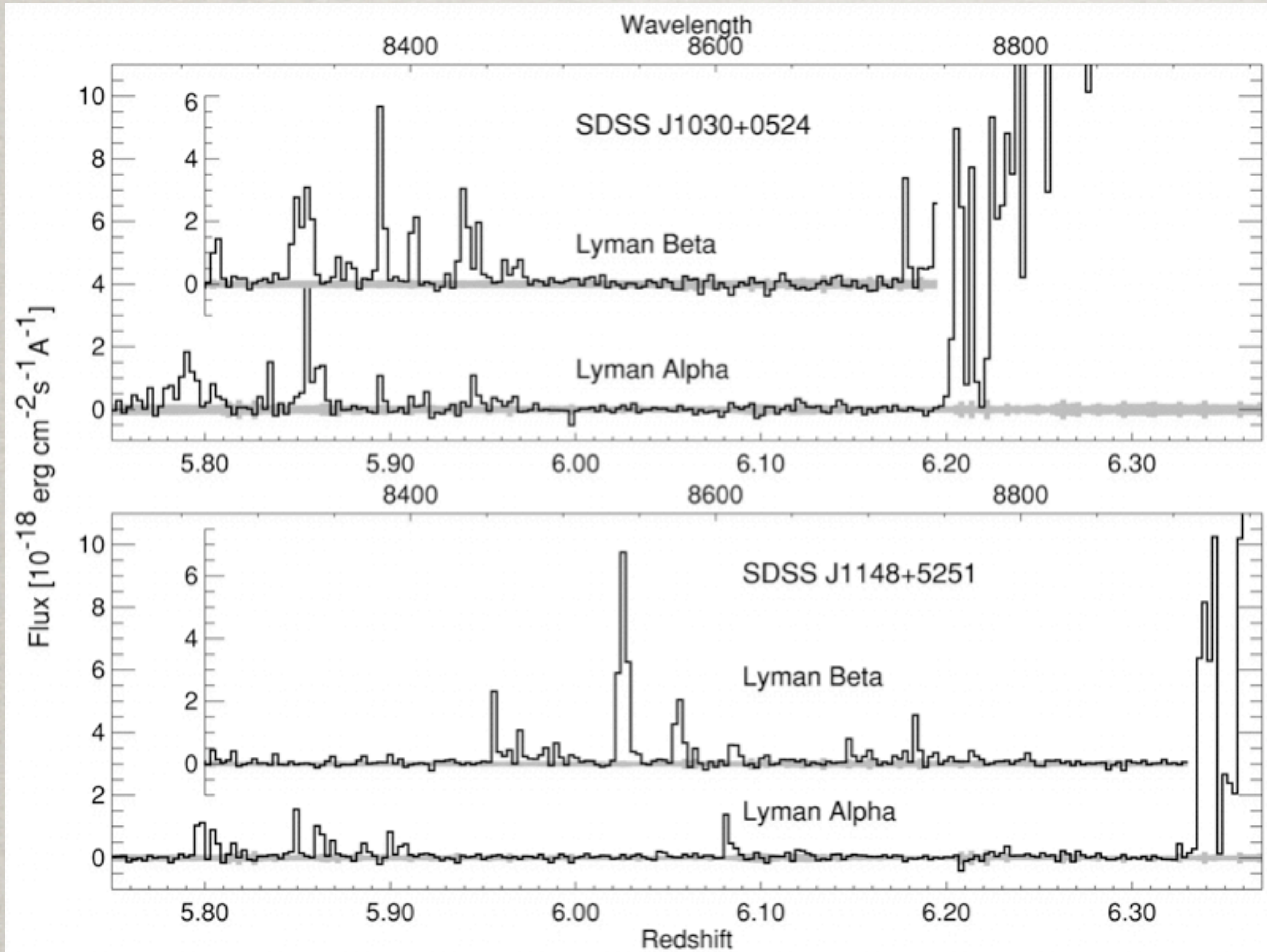
...and highly dependent on assumed density PDF



Becker, Rauch & Sargent 2006

Evolution can be explained if assume lognormal PDF

Have We Seen Patchy Reionization?



White et al 2003

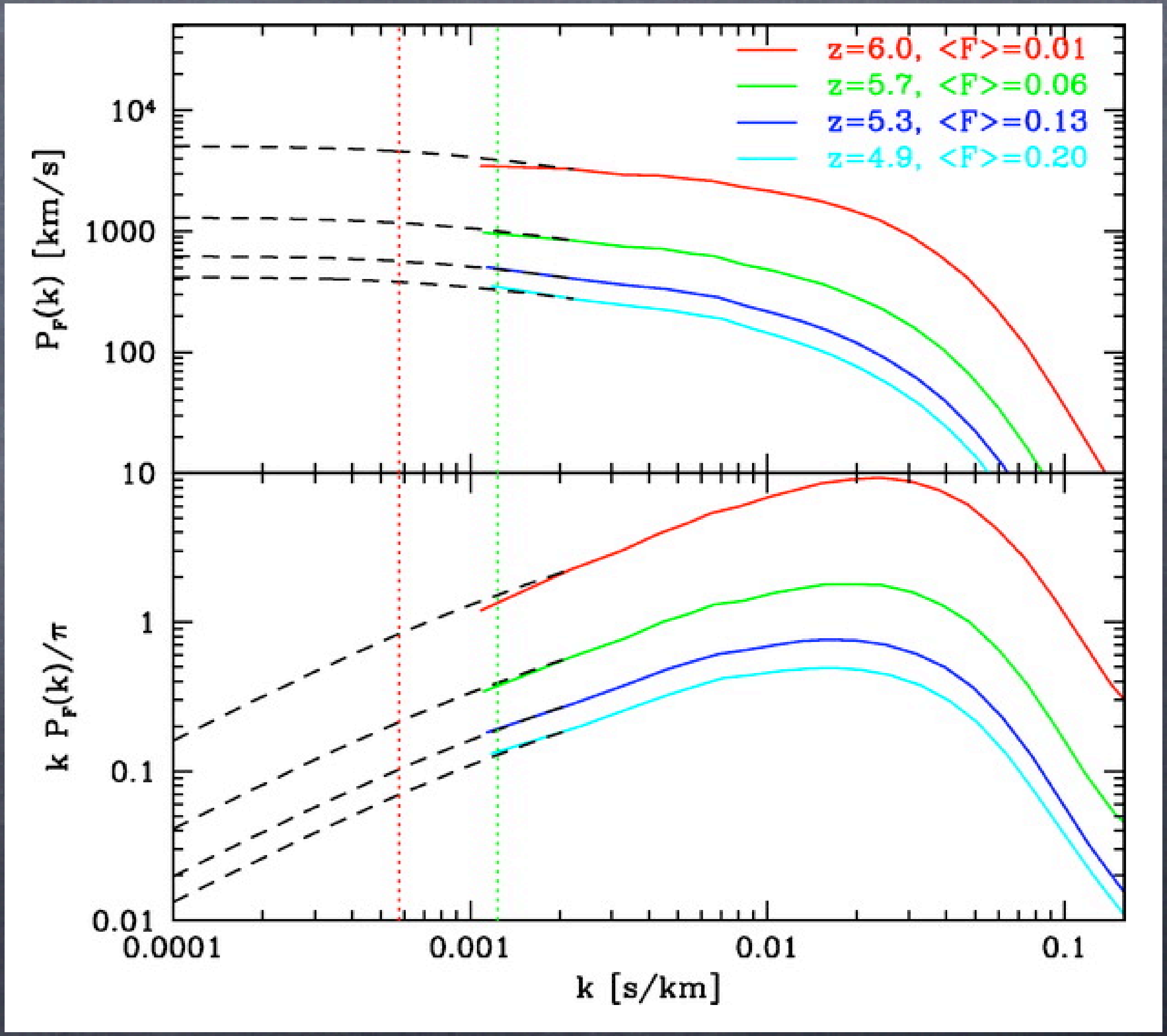
There's a lot of sight-line to sight-line scatter in QSO absorption spectra. Order unity fluctuations on LARGE (50-100 Mpc comoving) scales

But it is VERY hard to see patchy reionization...

Lidz, Oh & Furlanetto 2006

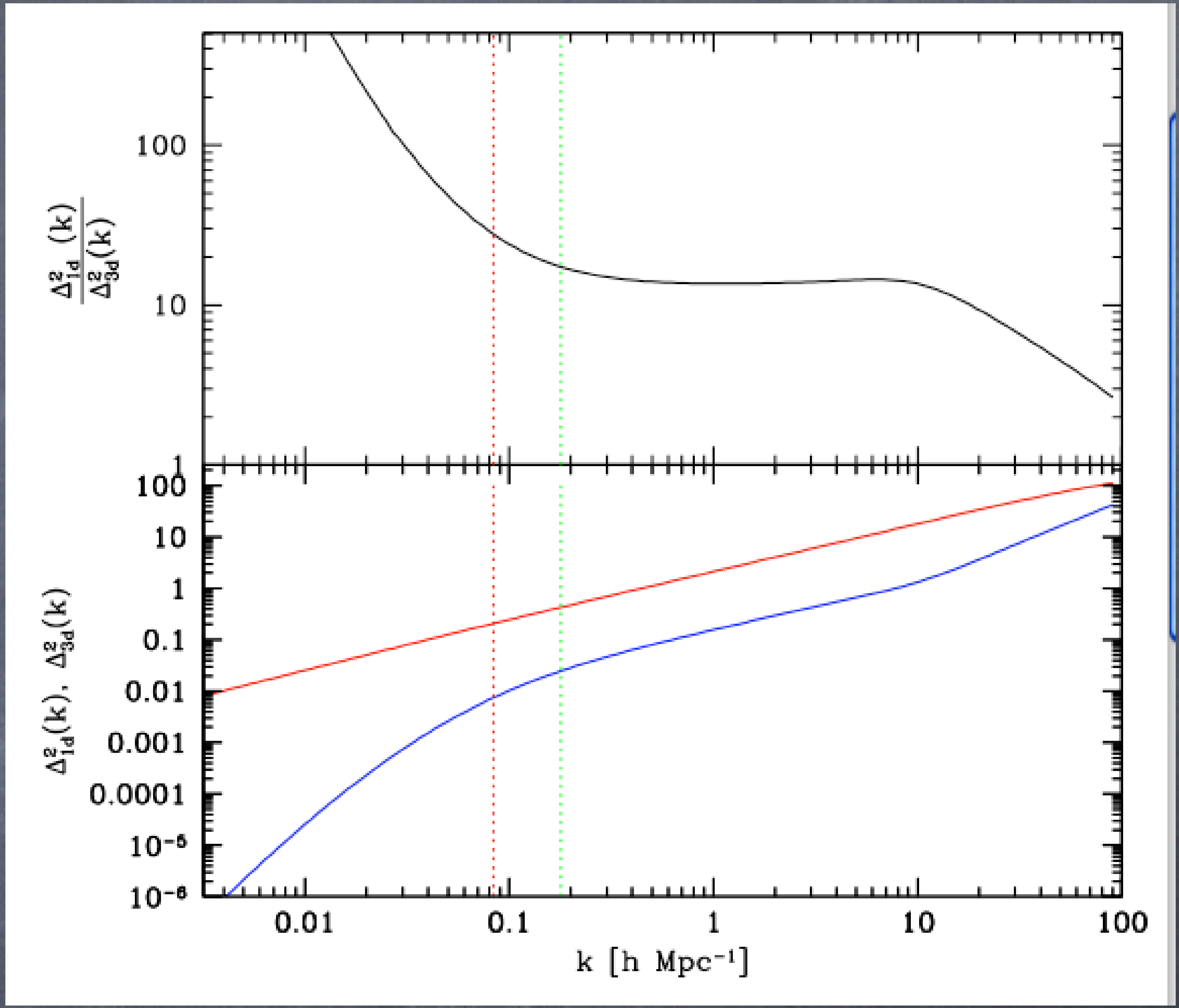
Simulate 40 Mpc h^-1 box

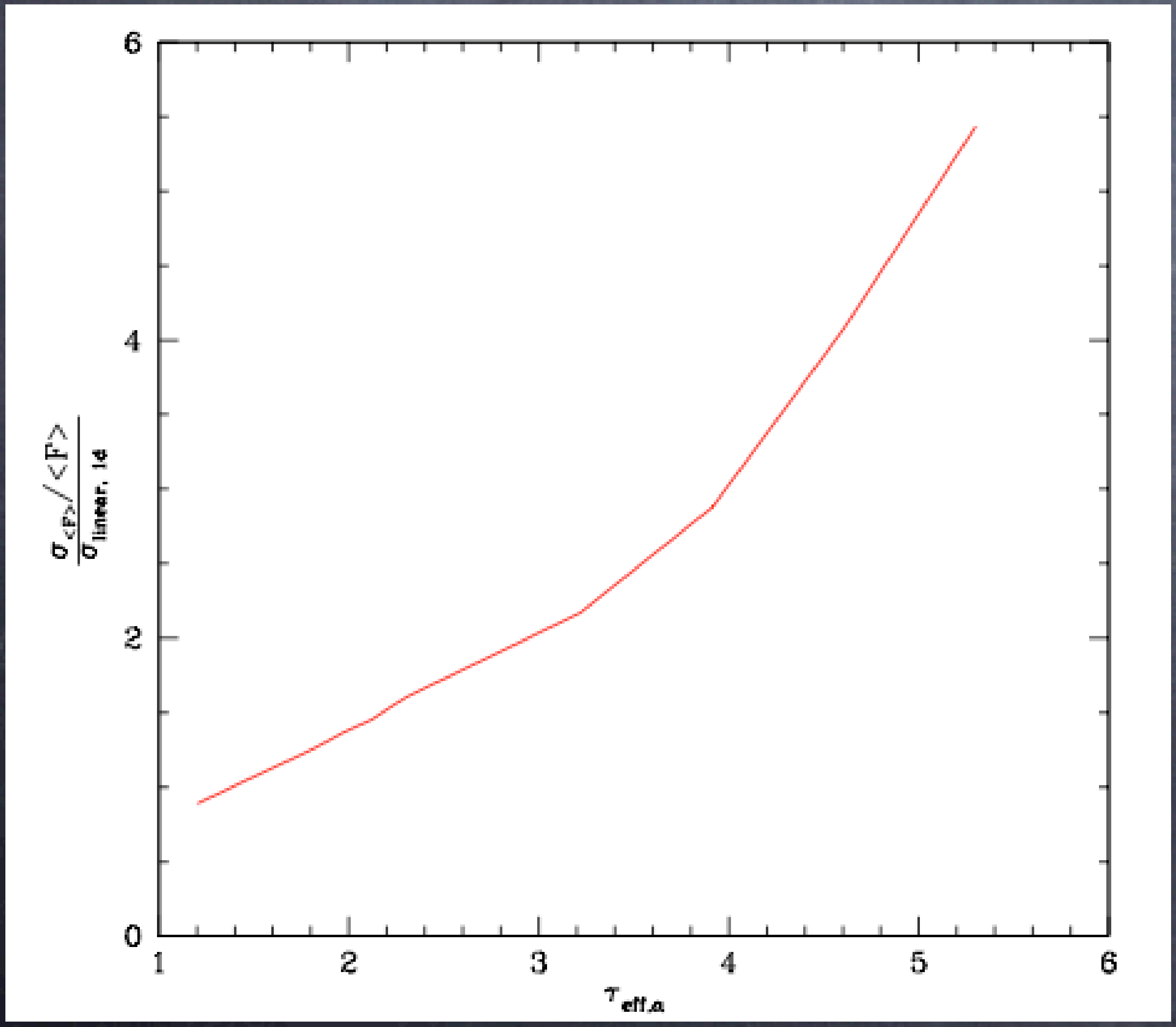
Flux power spectrum declines slowly with scale



Two effects

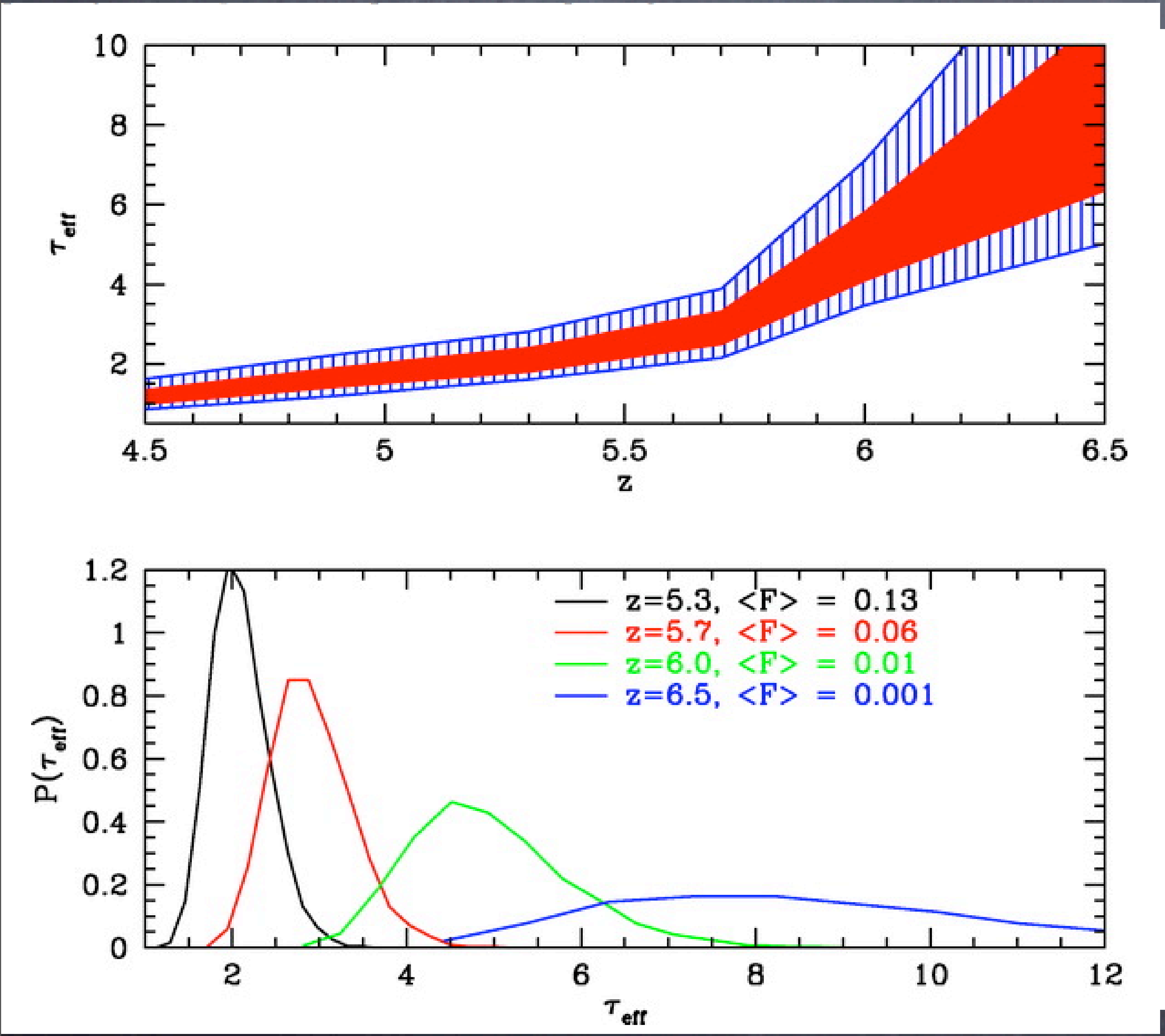
Aliasing boosts power on large scales

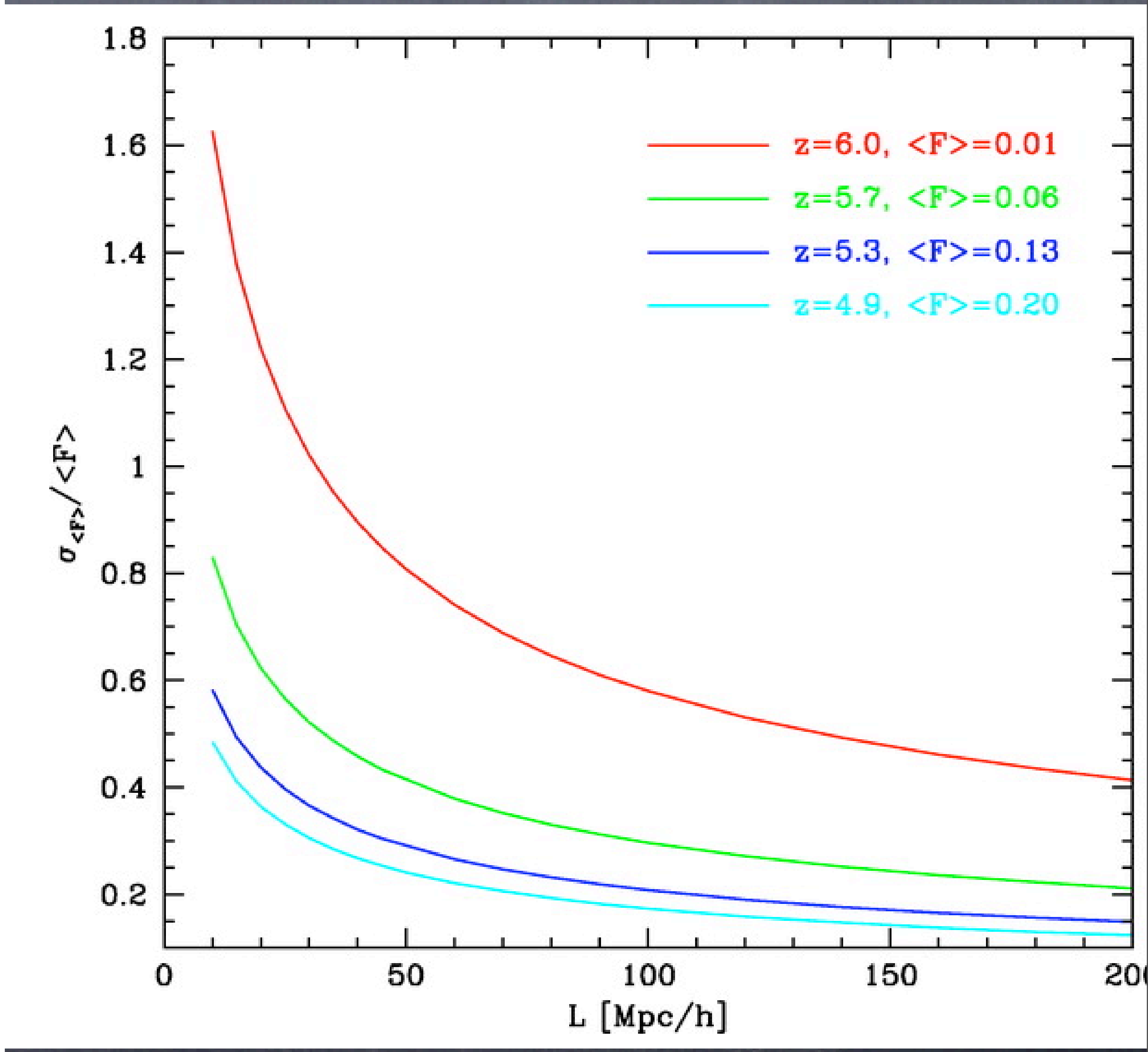




Bias increases amplitude of fluctuations

Uniform Radiation Field is consistent w/ observed scatter...



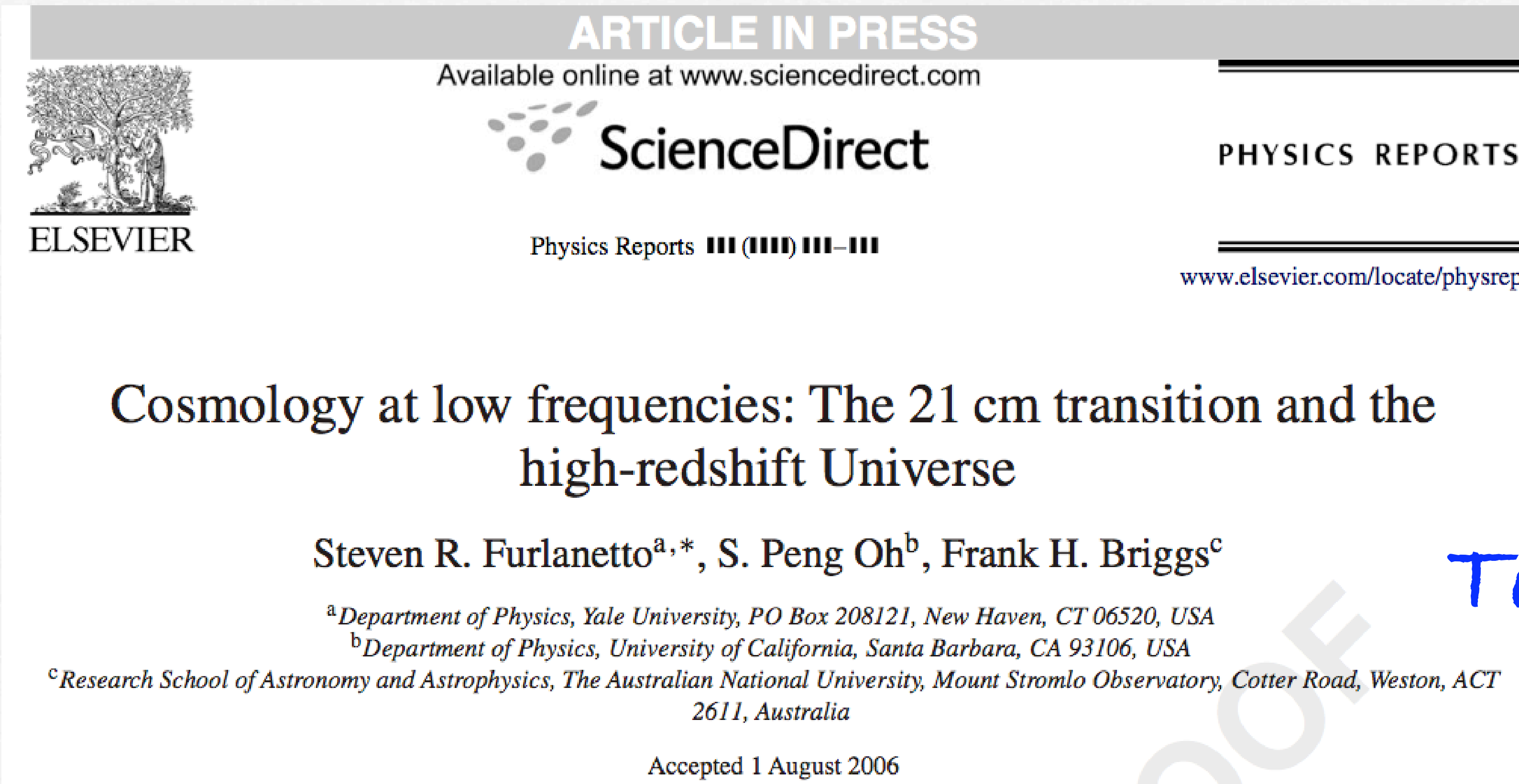


The future: 21cm observations

"There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy."

--Hamlet (Act I, Scene V)

Advertising: 21cm Review Article



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Cosmology at low frequencies: The 21 cm transition and the high-redshift Universe

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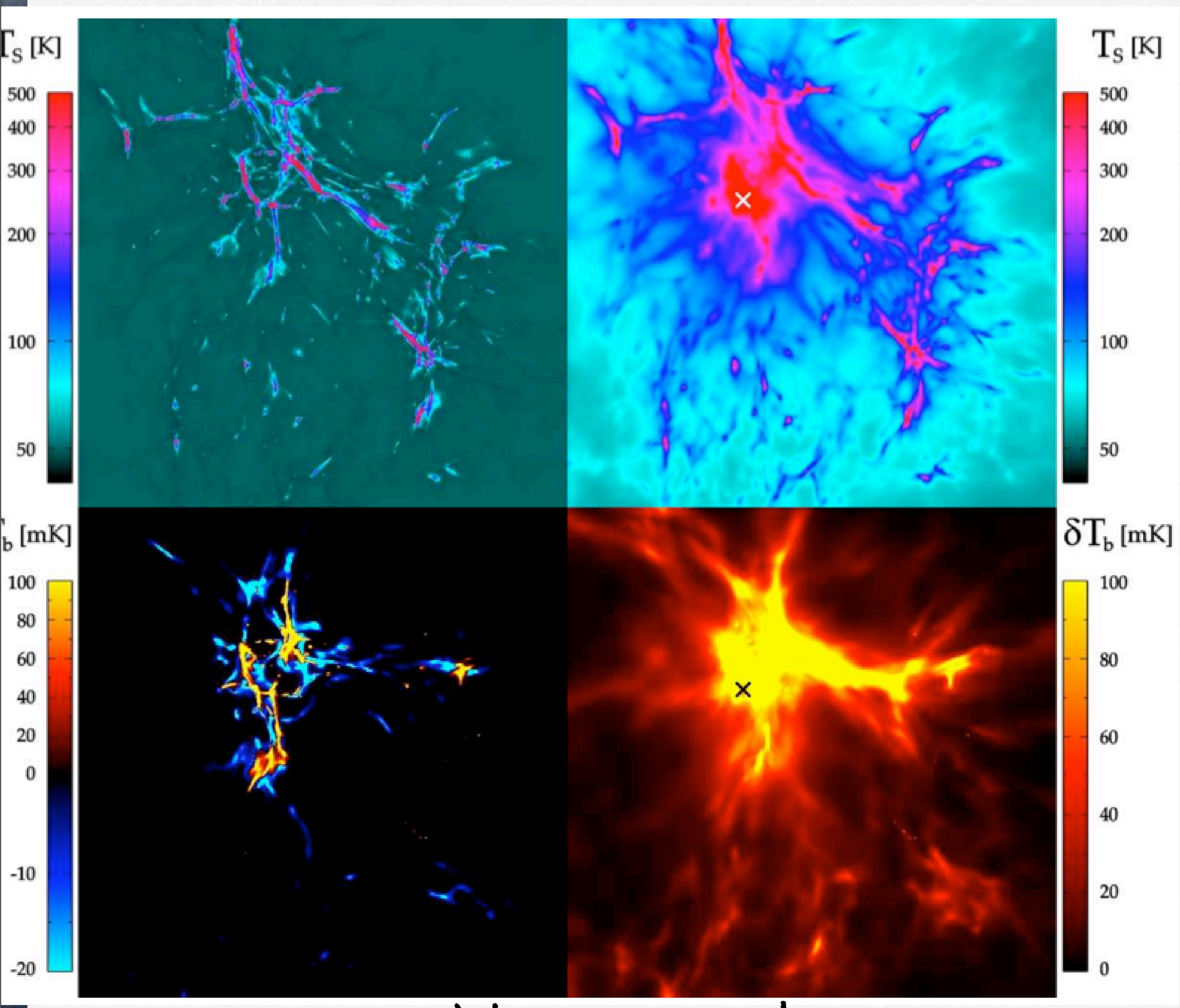
Accepted 1 August 2006

Furlanetto, Oh & Briggs 2006 (FOB06) astro-ph/0608032

Top Google hit for '21cm transition'

But if you Google '21cm line' instead you get...

21cm observations will revolutionize the field



Kuhlen & Madau 06

See 21cm emission from IGM in absorption or emission against CMB

Couple spin and kinetic temperatures by collisions or Wouthuysen-Field effect

Probe both Dark Ages and First Light

PAPER--USA/Australia

GMRT---India

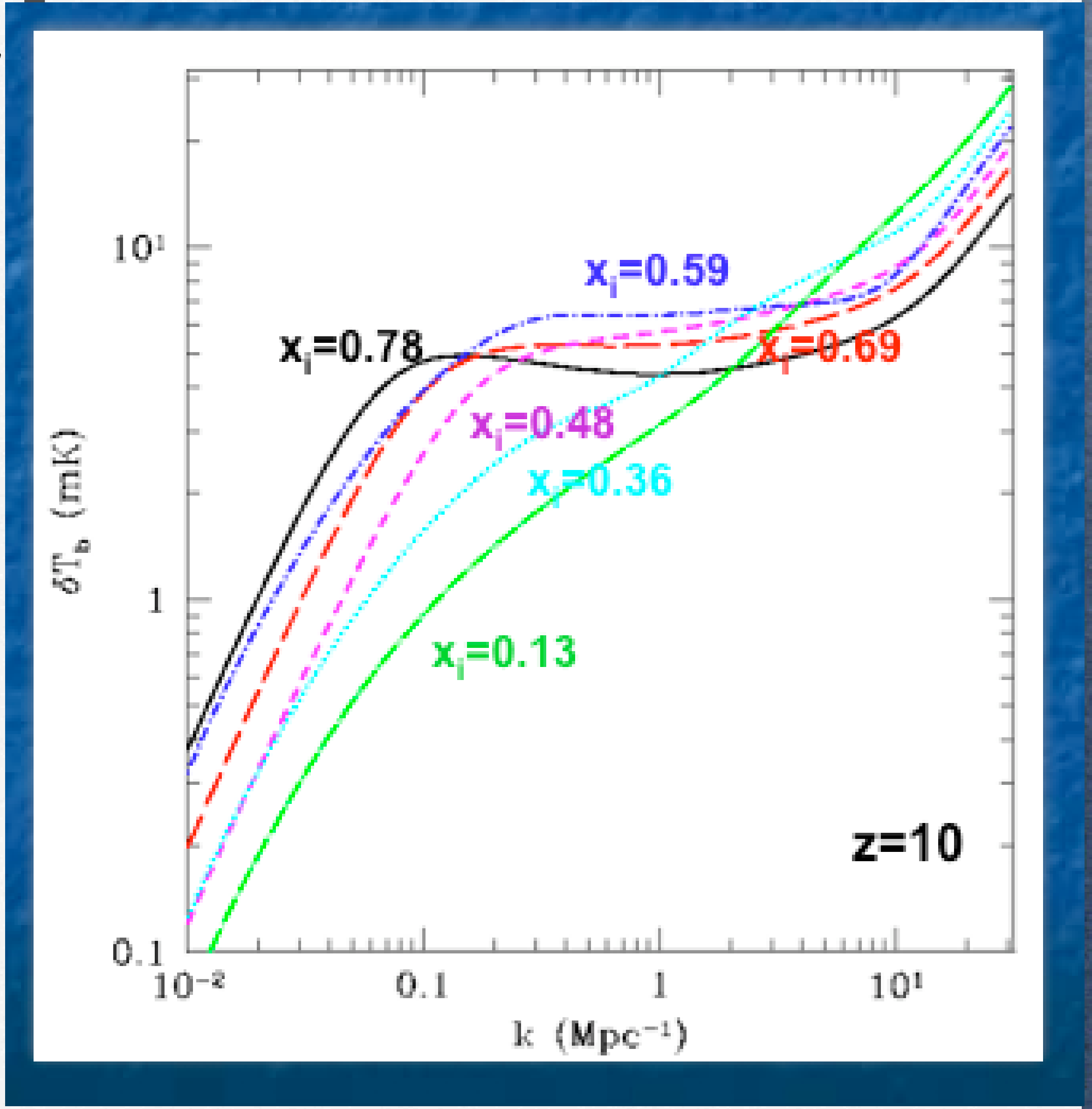
MWA---Western Australia

LOFAR--Netherlands

SKA--??

21cm Power Spectrum

- Language generally used for 21cm fluctuations
- Tools developed for CMB/ galaxy surveys
- Natural language for interferometer
- Good choice for Dark Ages, before ionizing sources turn on. But after that...

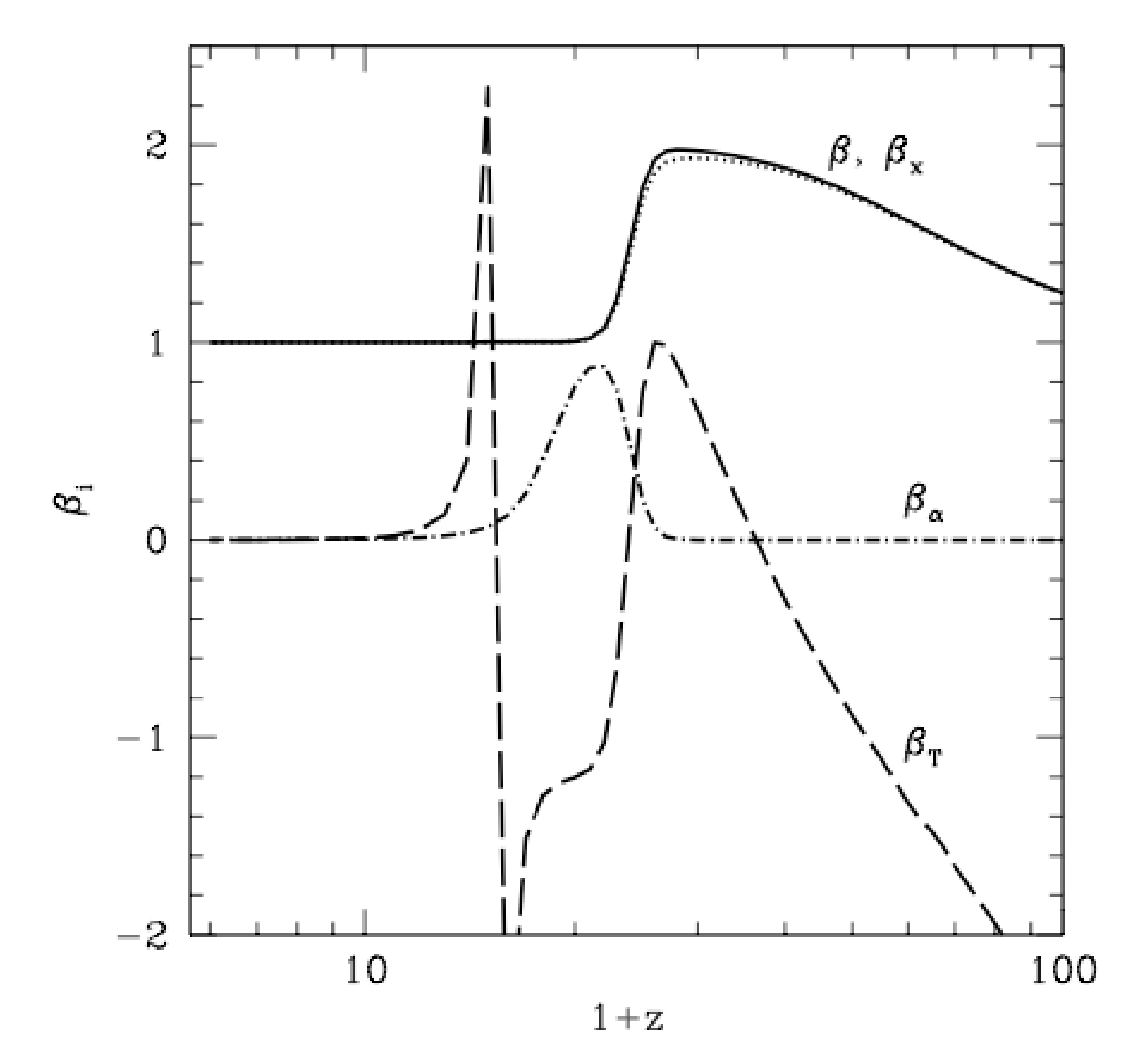


FOB06

...many effects contribute

Fluctuations in...

- ☐ density (Gaussian)
- ☐ Ly-alpha flux
- ☐ ionization state
- ☐ temperature
- ☐ velocity gradients

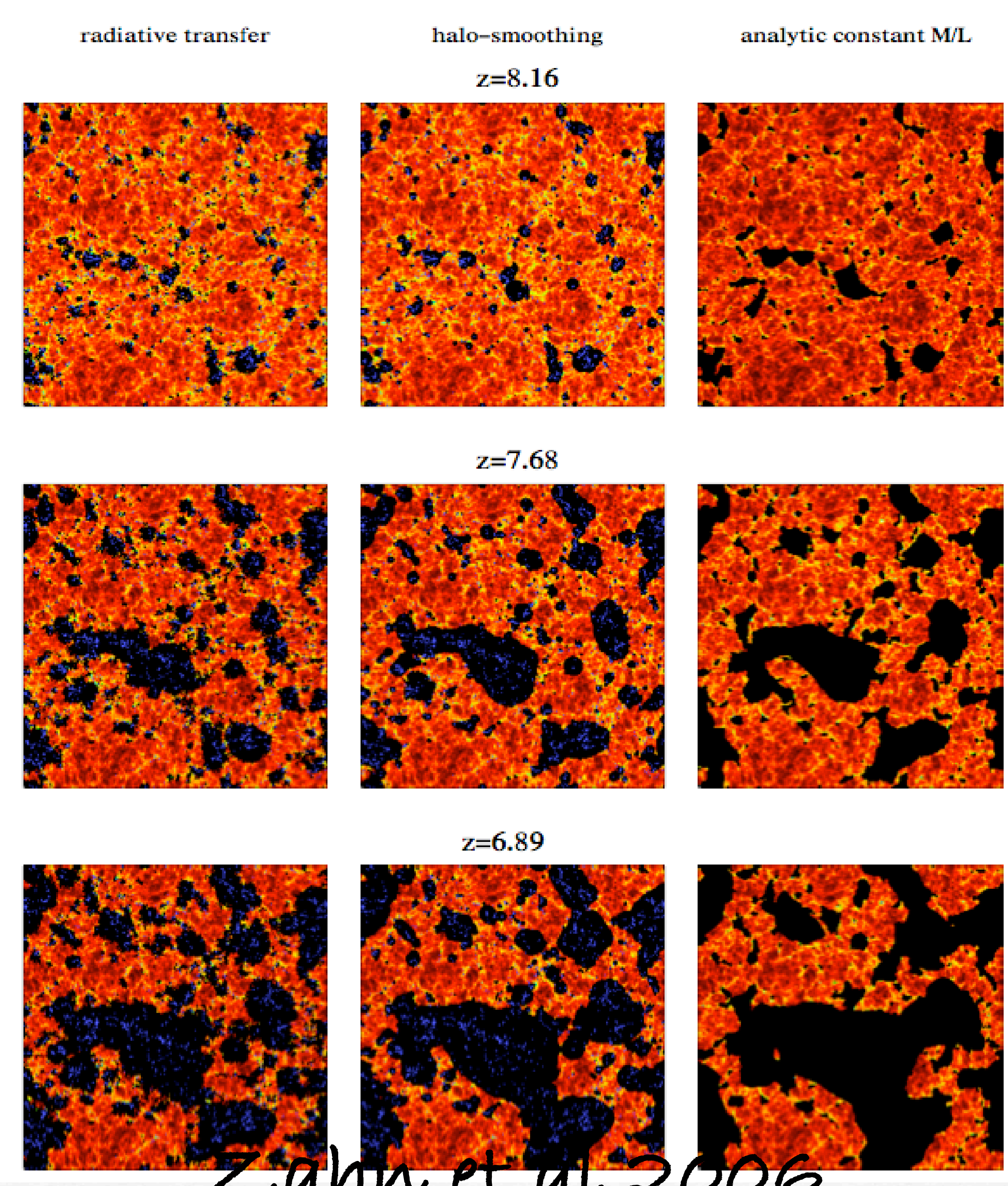


FOB06

Many likely to be correlated

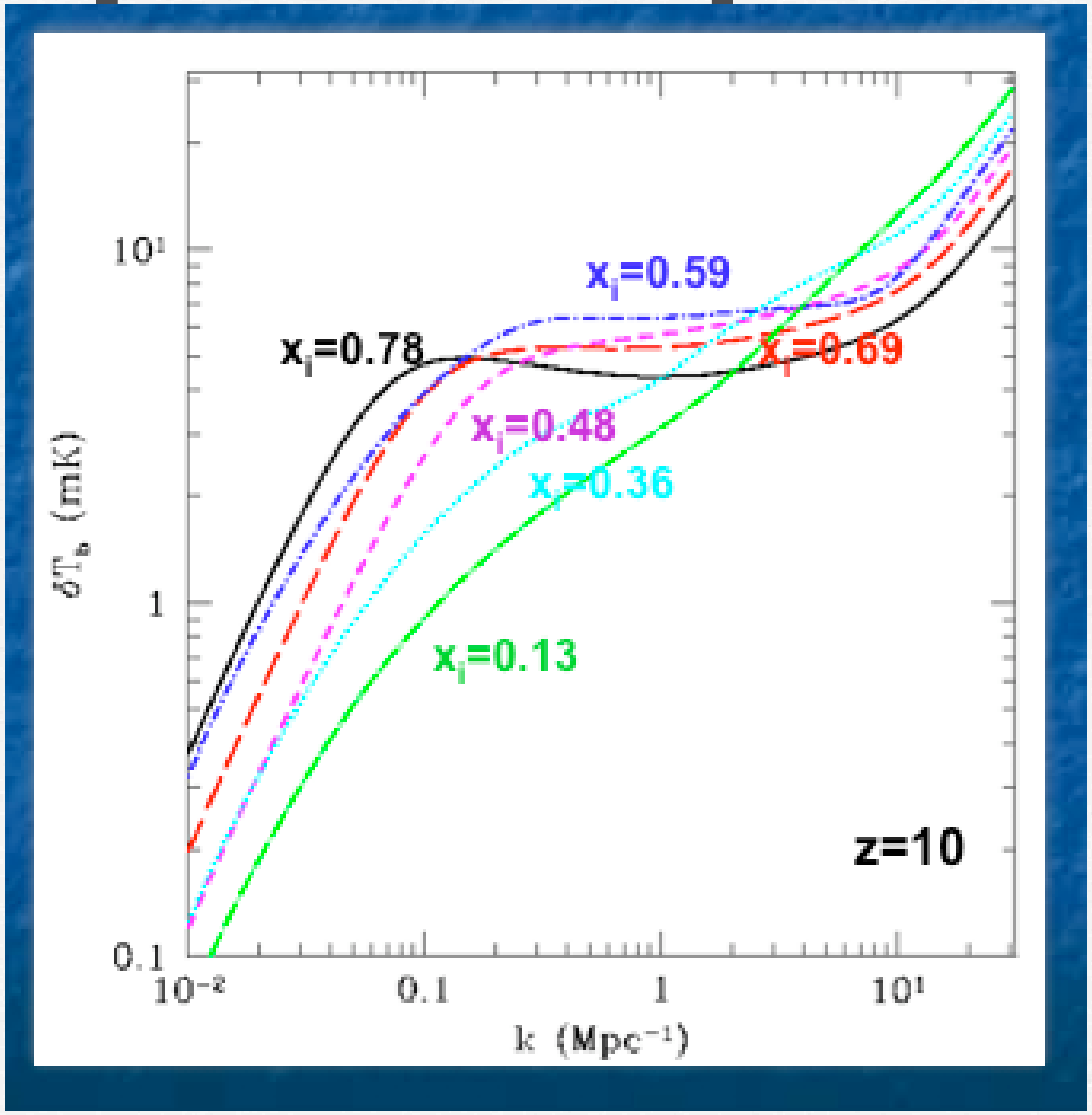
...it's a highly non-Gaussian field!

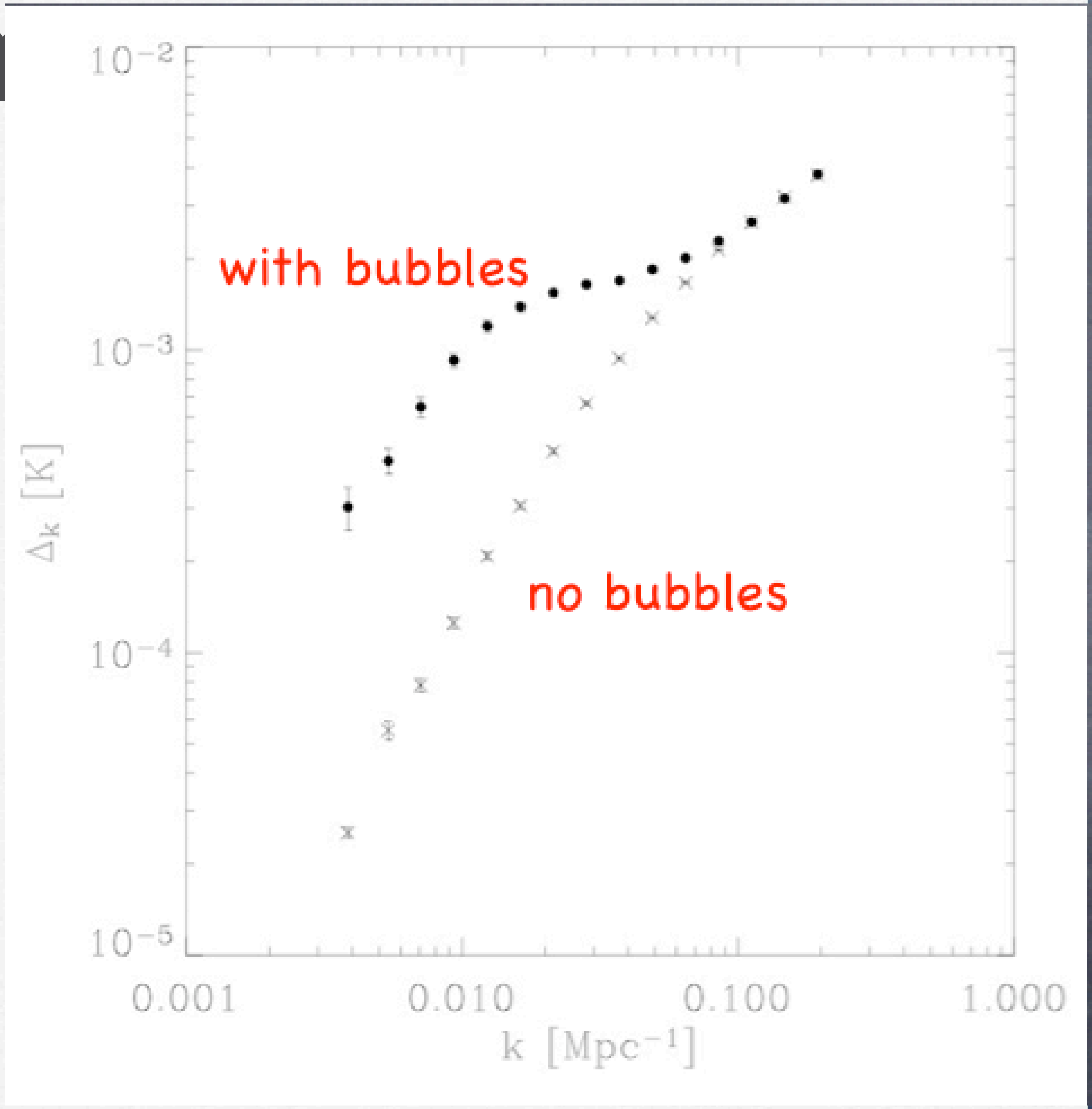
If we want to study growth and topology of reionization, we should focus on the bubbles



Zahn et al 2006

...bubbles DO strongly affect power spectrum

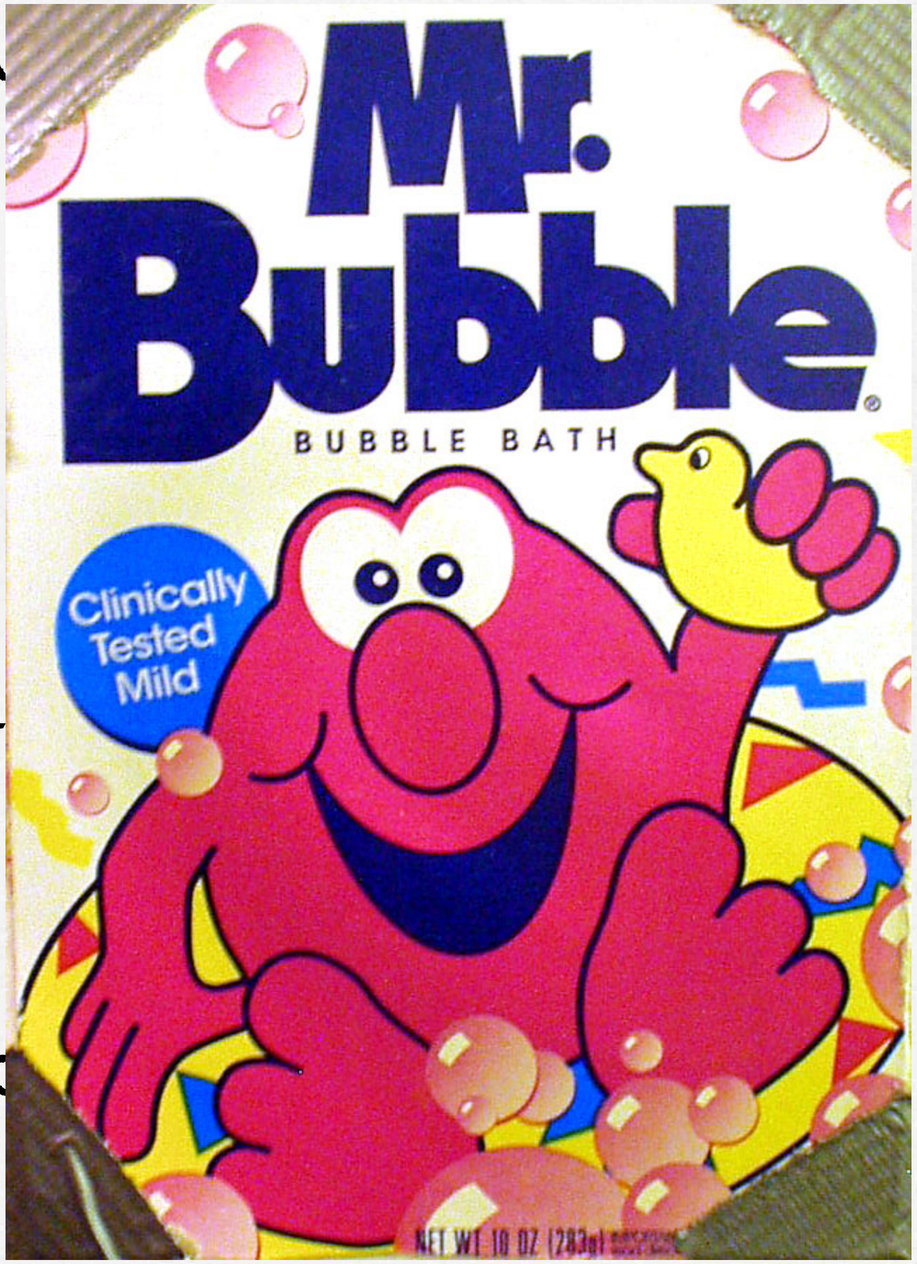




...but quantifying this will be model-dependent

Bubbles are your Friend

- Probe of ionizing source population (supposed to be big)
- Directly extract HII filling factor
- Foreground calibrator:
  - Measure mean temperature T(z)
  - Remove long wavelength artifact from foreground removal

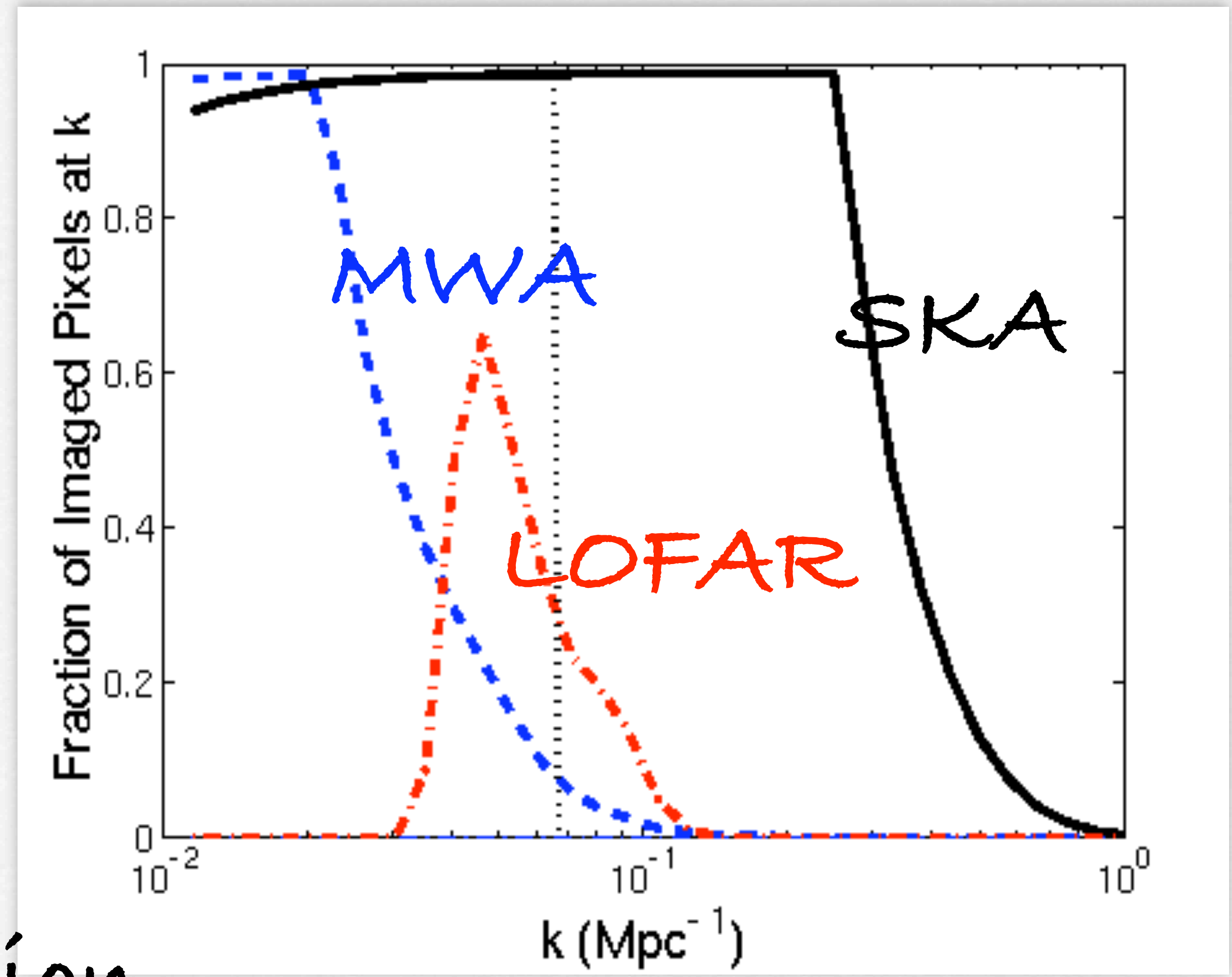


Direct Imaging

S/N high only on largest scales, need R~20 Mpc

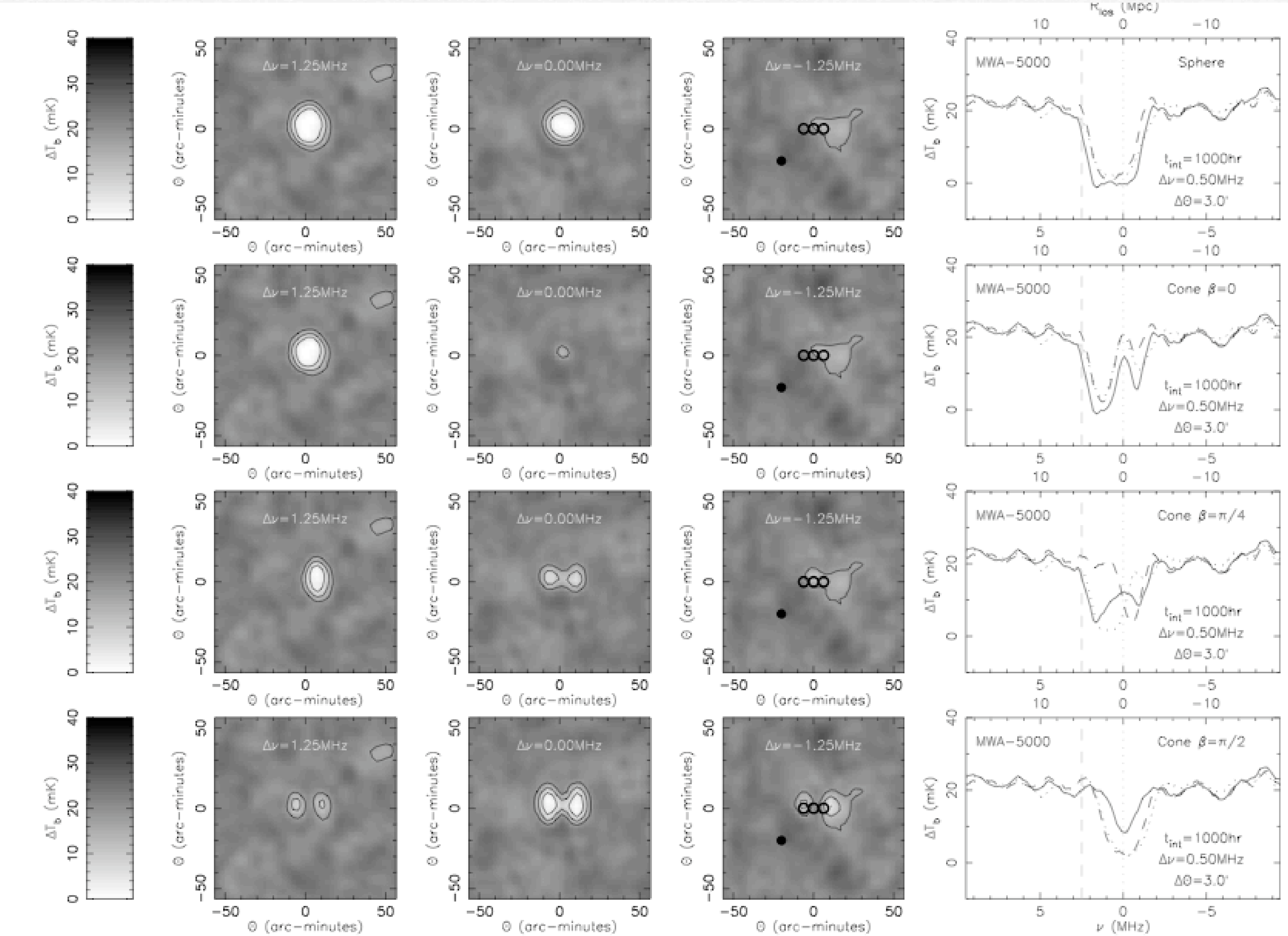
Rare bright quasars (or clustered galaxies)

BUT: survey volume is HUGE!



Expect 1 active/fossil HII region in every MWA FOV with R > (24,40) Mpc at z=7 (Wyithe, Loeb & Barnes 2004)

McQuinn et al 2006



Wyithe, Loeb & Barnes 2004

...what do we get?

- -- $\delta T_b(z)$ X-rays, fossil HII
- Foreground calibrator
- Size, shape of HII region--> QSO properties
- Discover QSOs? (though mostly their fossils)
- Try to cross-correlate with galaxy population

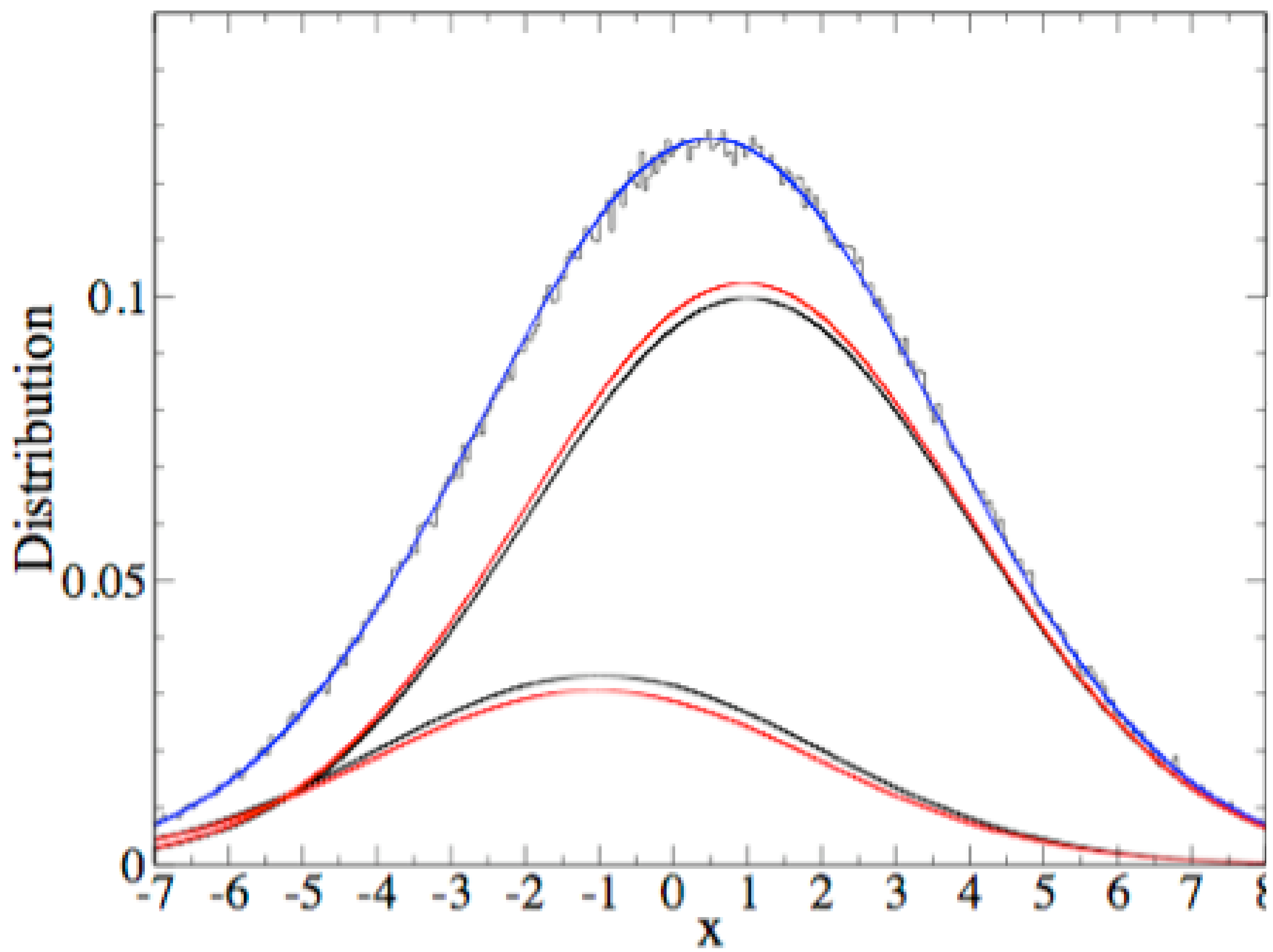
But can we see the smaller bubbles and get Q_HII(z)?

Back to Basics: One Point Statistics

Hansen, Oh & Furlanetto
(2007, in prep)

One Point Statistics

Bubbles create bimodality in the PDF



Can we pick it out?

Directly tells us Q_HII (z)!!!

DETECTING BIMODALITY IN ASTRONOMICAL DATASETS

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ABSTRACT

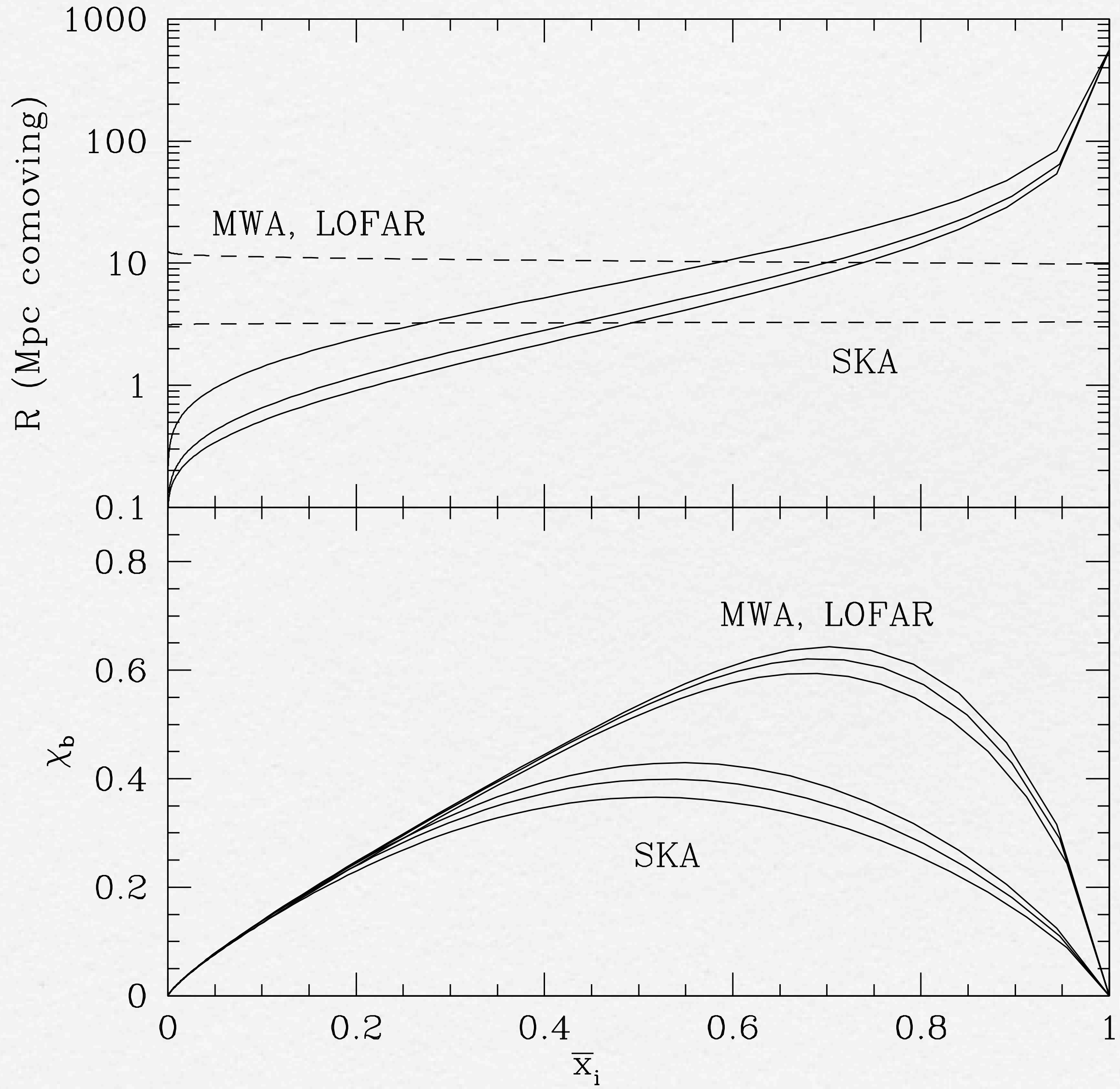
We discuss statistical techniques for detecting and quantifying bimodality in astronomical datasets. We concentrate on the KMM algorithm, which estimates the statistical significance of bimodality in such datasets and objectively partitions data into subpopulations. By simulating bimodal distributions with a range of properties we investigate the sensitivity of KMM to datasets with varying characteristics. Our results facilitate the planning of optimal observing strategies for systems where bimodality is suspected. Mixture-modeling algorithms similar to the KMM algorithm have been used in previous studies to partition the stellar population of the Milky Way into subsystems. We illustrate the broad applicability of KMM by analyzing published data on globular cluster metallicity distributions, velocity distributions of galaxies in clusters, and burst durations of gamma-ray sources. FORTRAN code for the KMM algorithm and directions for its use are available from the authors upon request.

...partially ionized boundary pixels create complications

$$f_{bd} \approx 3\frac{r_{pix}}{R_{bub}}Q_{\rm HII}$$

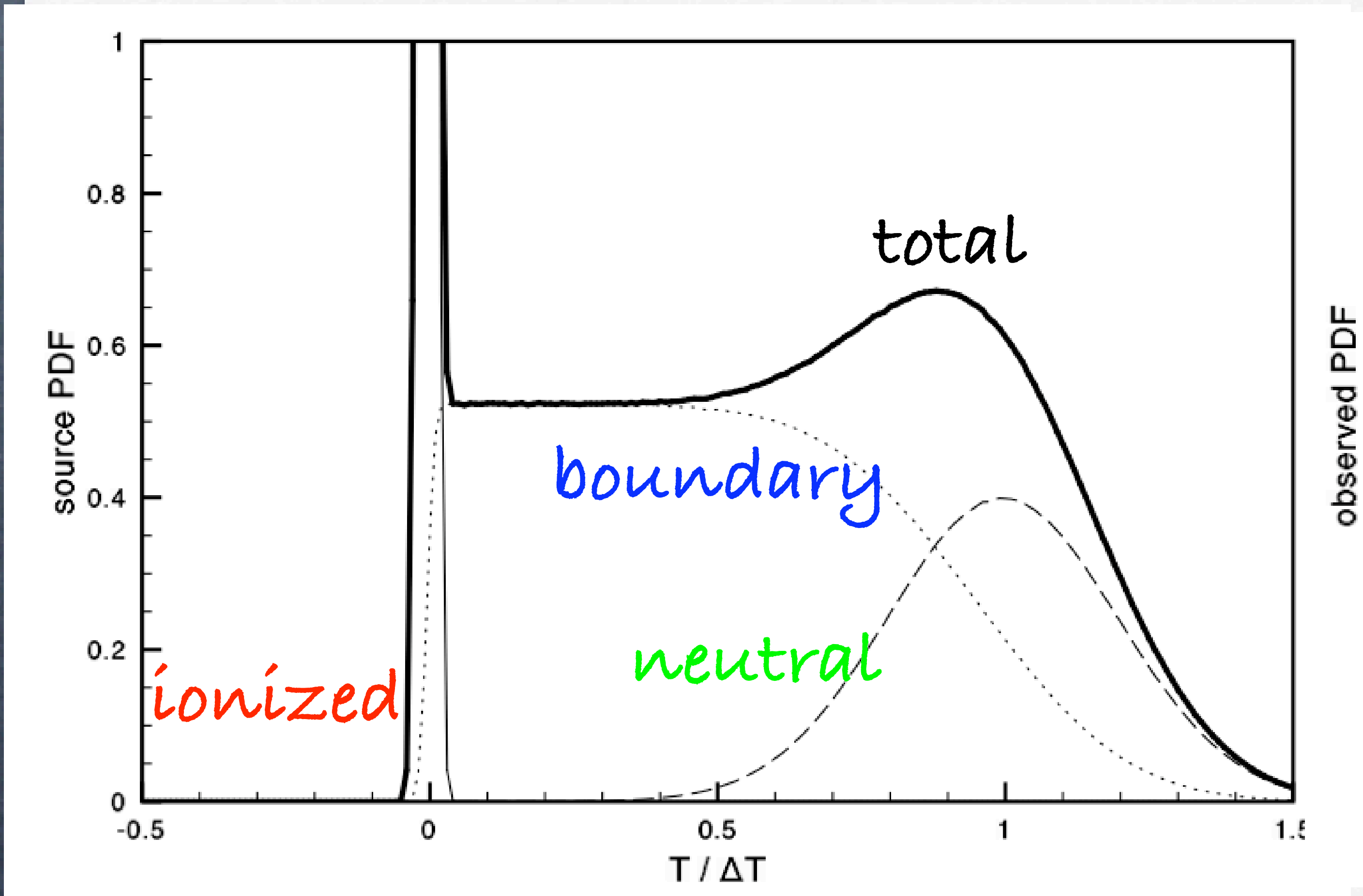
Can be ~10-70% of pixels

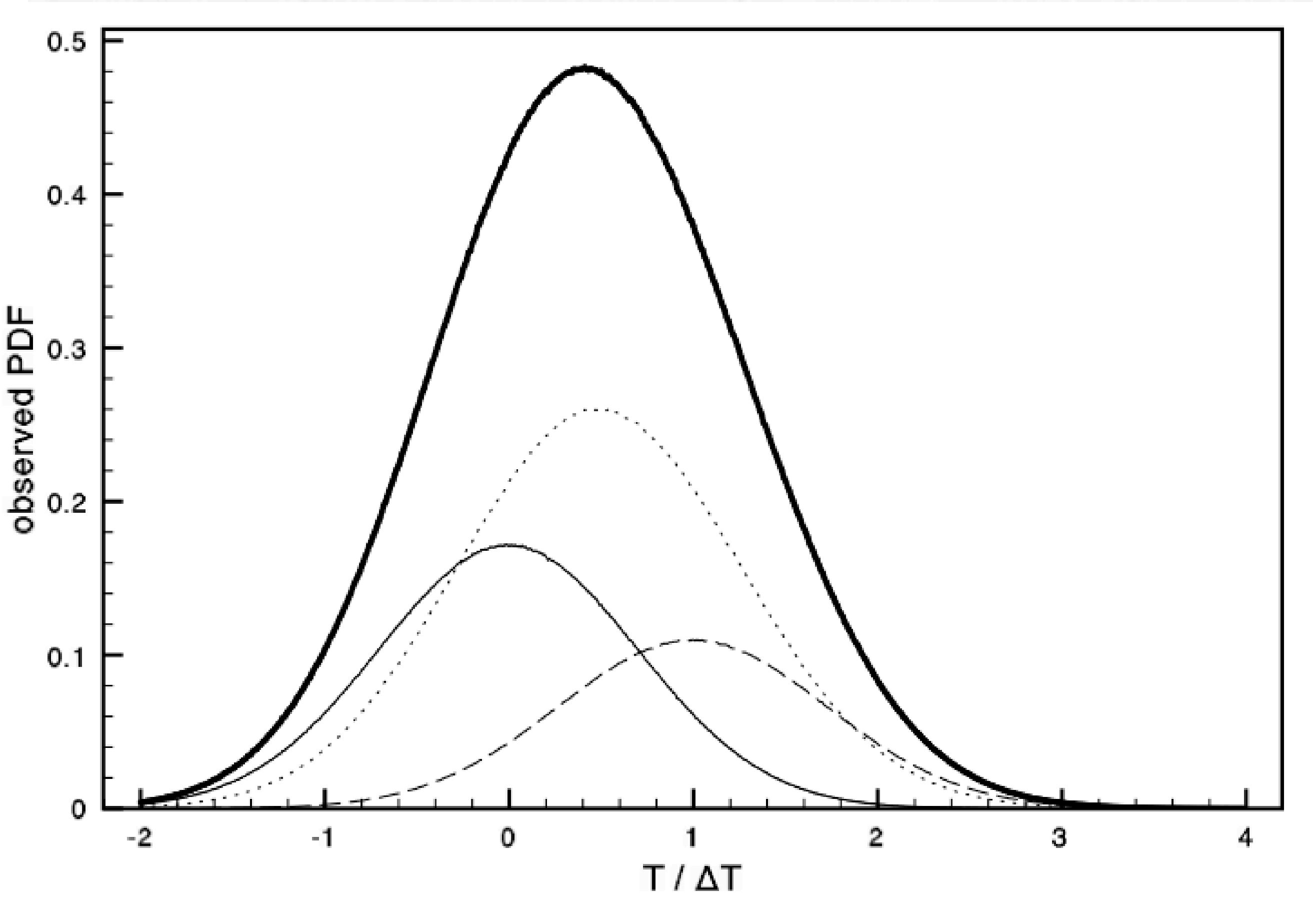
Dependent on telescope resolution+bubble size



Also partially ionized pixels from X-rays, fossil regions

...here's a more realistic PDF



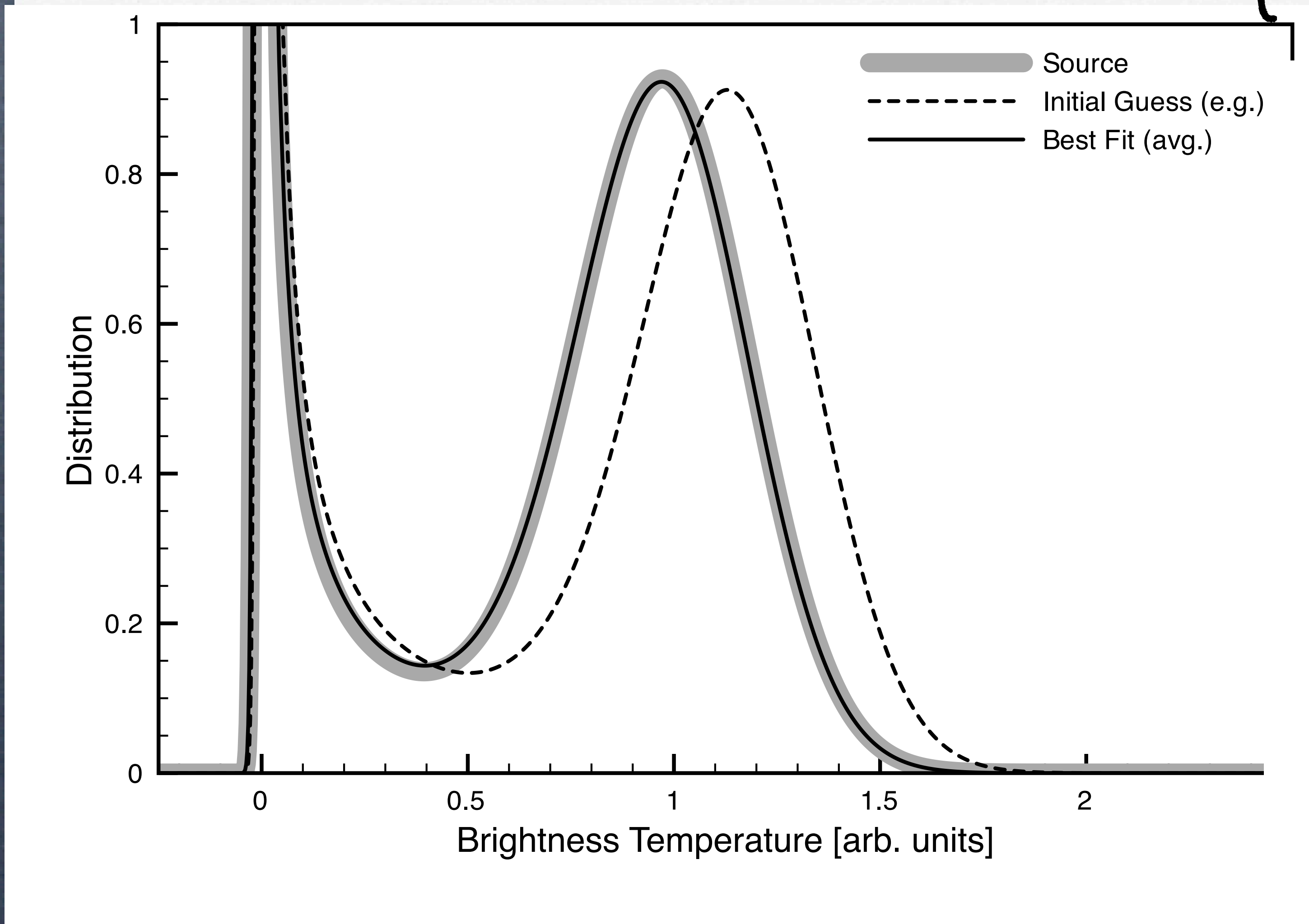


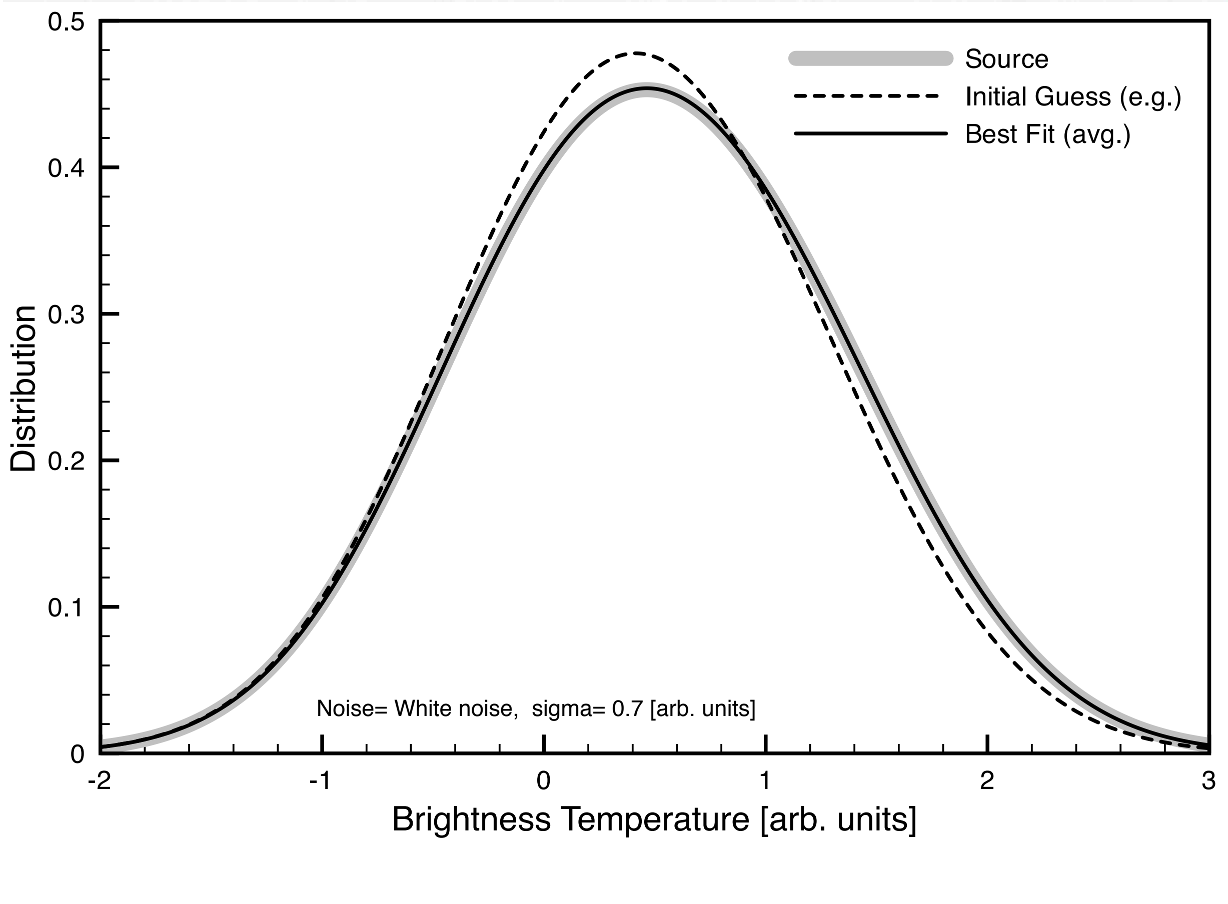
no noise

with noise

It works!

Solve for populations via iterative Max-likelihood technique



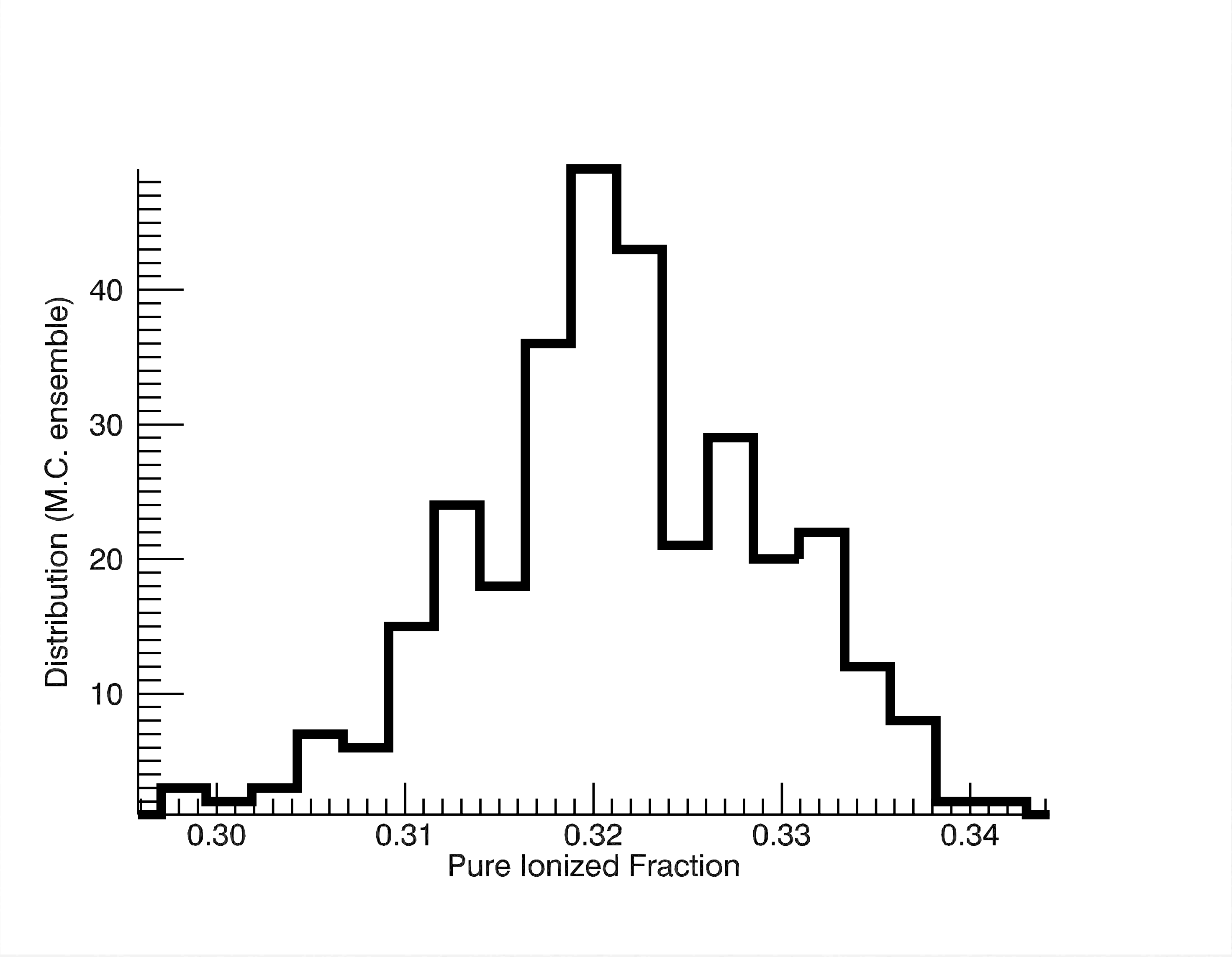


original distribution

with noise

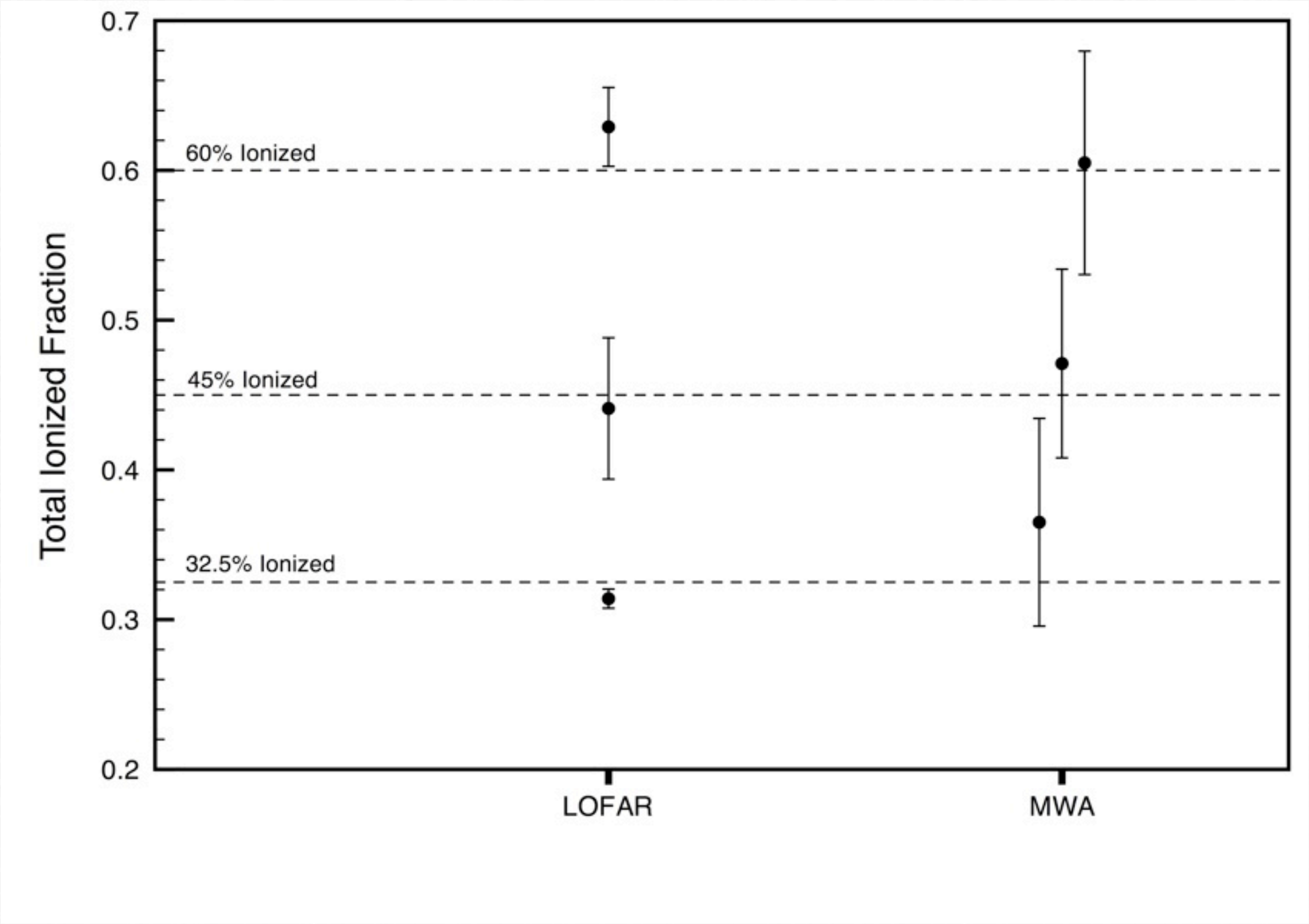
Leverage comes from having many pixels

Monte Carlo Errors agree with Fisher Matrix estimates



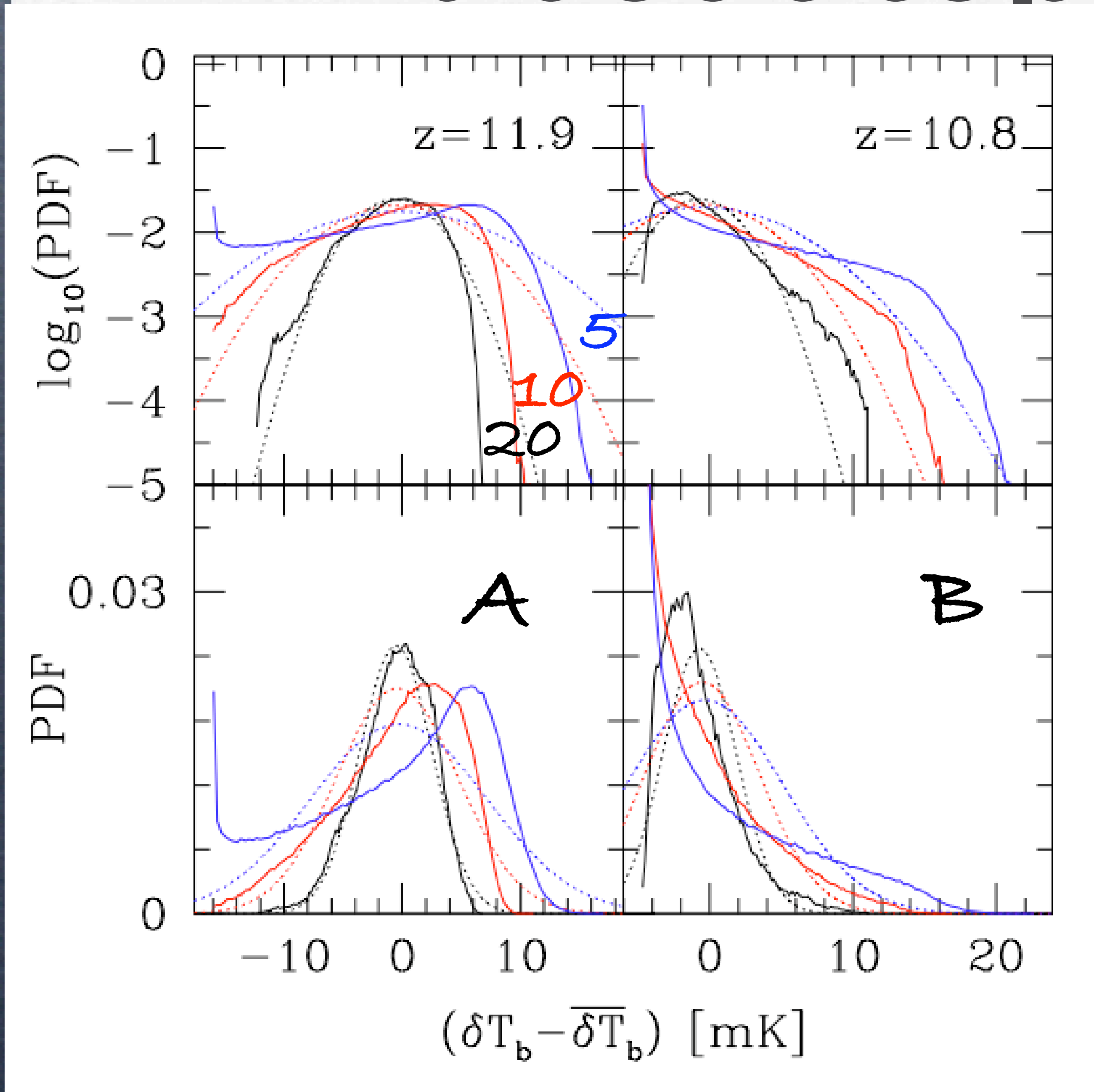
An idealized case, but results are very encouraging...

Results...



Looks promising...

In principle, PDF has info about topology too



A: Cutoff at high Tb-- inside-out reionization

B: Tail at high Tb-- islands of neutral gas inside HII regions

Note: distribution narrows as smoothing scale increases

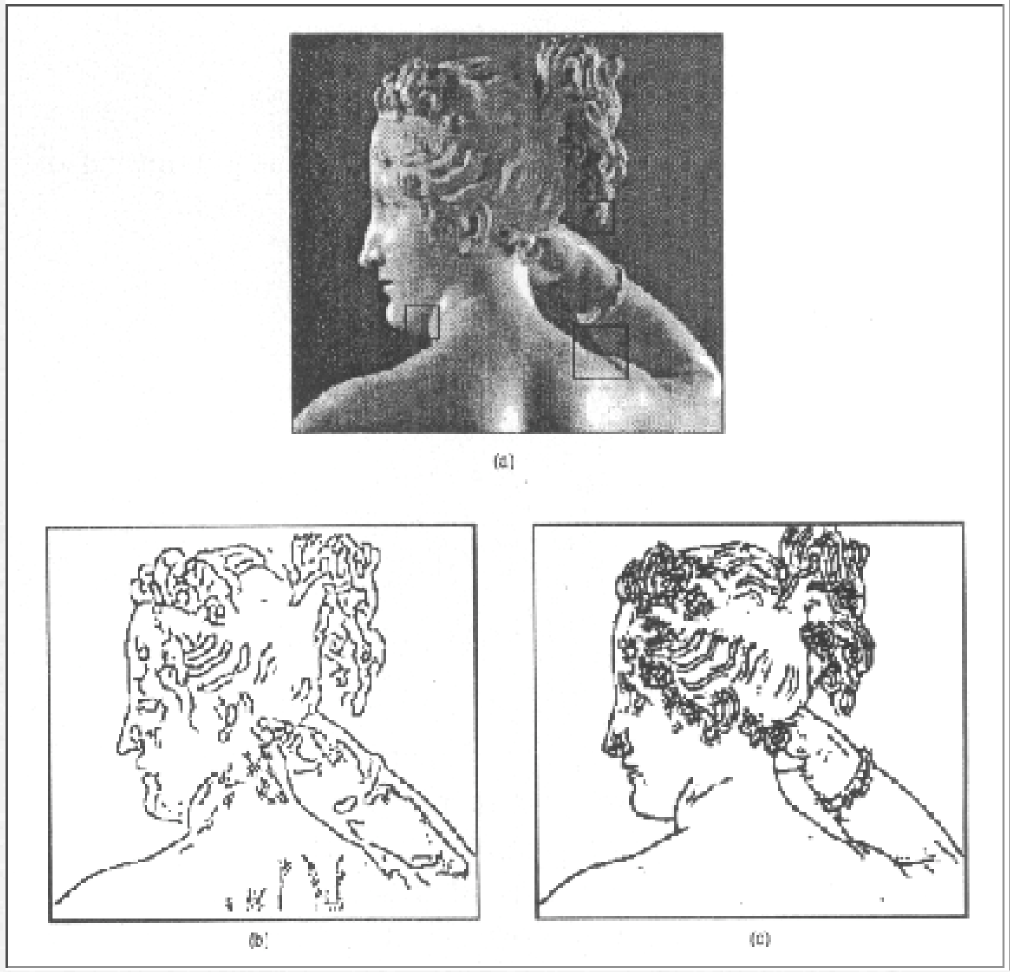
Mellema et al 2006

Direct Bubble Detection: The Canny Algorithm

Phelps et al (2007, in prep)

How to detect bubbles directly?

Look for edges in noisy background: classic image processing problem



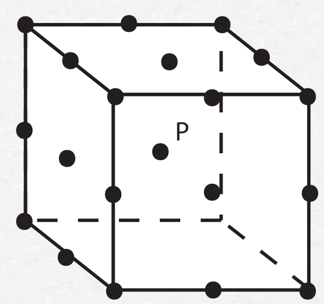
Canny Algorithm:
--optimal edge detector
--looks for maxima in derivatives of smoothed image

1. Apply Gaussian filter

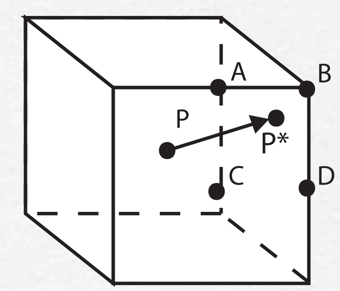
--need to do this several times at different scales

2. Find edge pixels

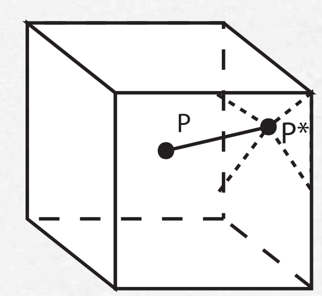
-- find maximum in 3D spatial gradient



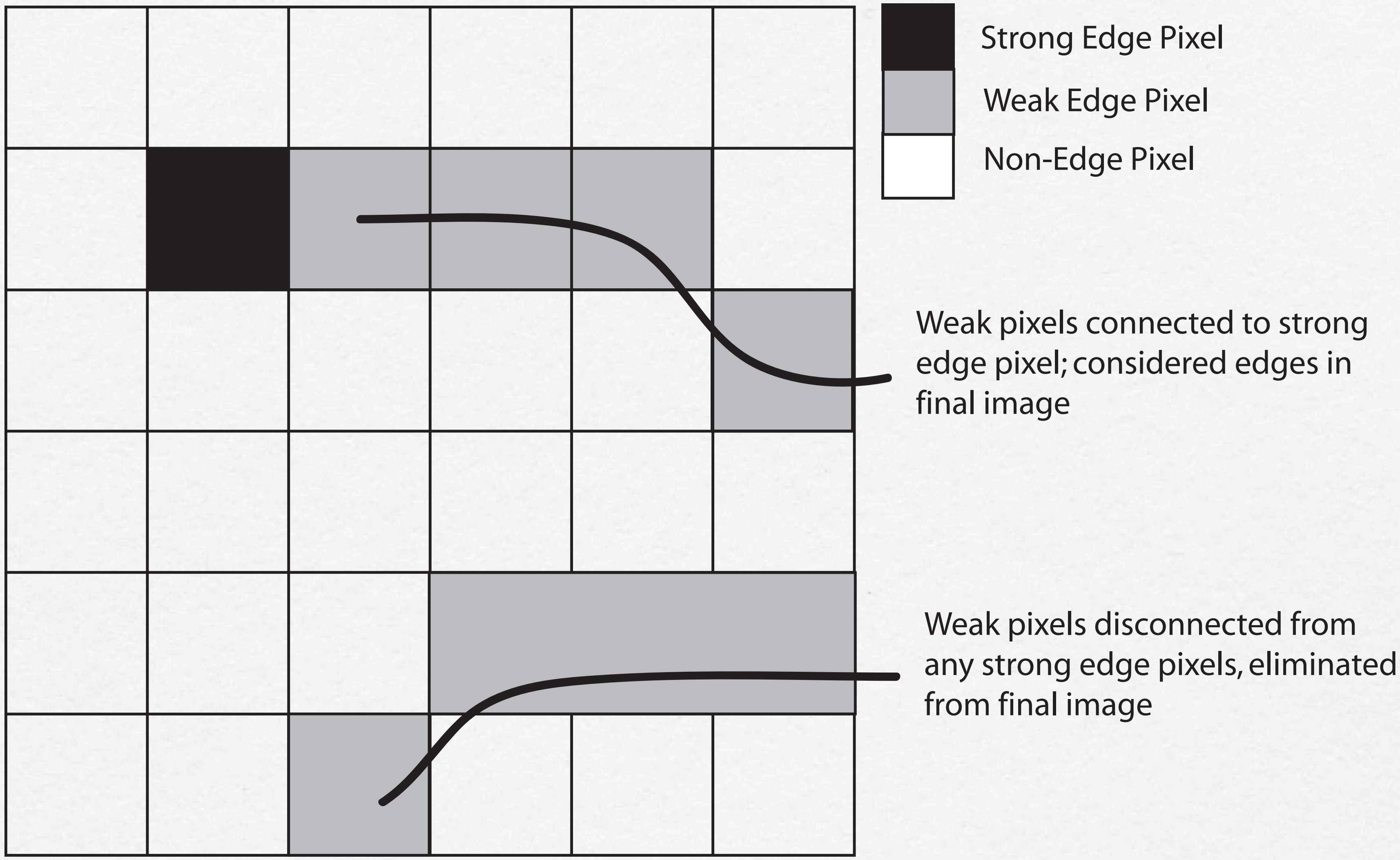
We want to determine whether pixel P (in the center of the cube) is a local maximum of the signal



By using the gradient information, we are able to determine that the gradient of P intersects the cube at point P*, which lies closest to pixels A, B, C, and D.



Interpolating the gradient magnitudes of the signal at pixels A, B, C, and D, we are able to determine the gradient magnitude of P*. If this value, and the corrolating value in the opposite direction, are less than the gradient magnitude at P*, P* is indeed a maximum.

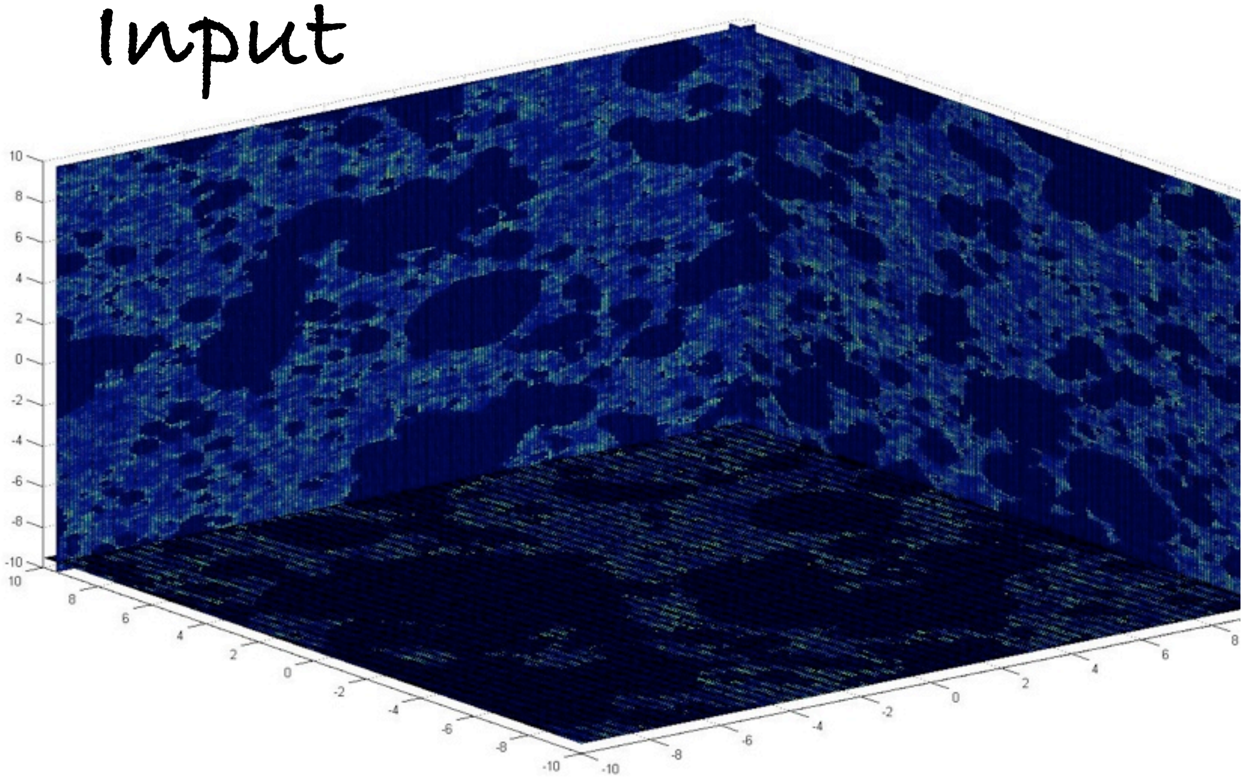


3. Apply thresholding with hysteresis

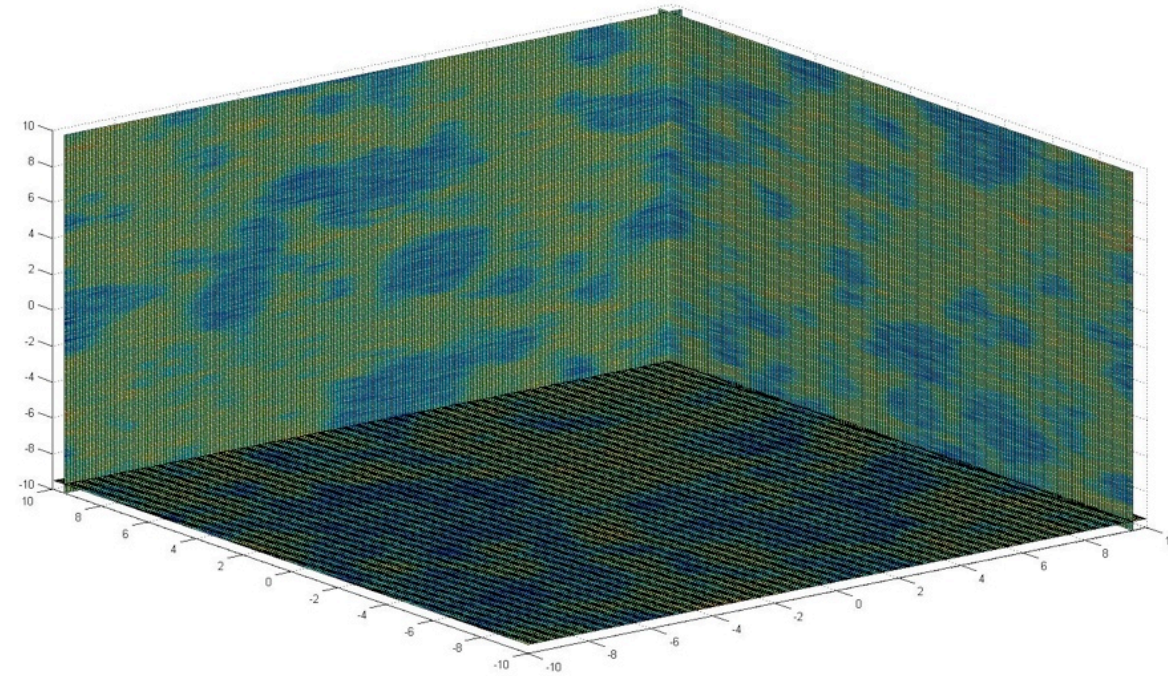
--strong pixel: automatically part of edge

--weak pixel: only part of edge if connected to strong pixel

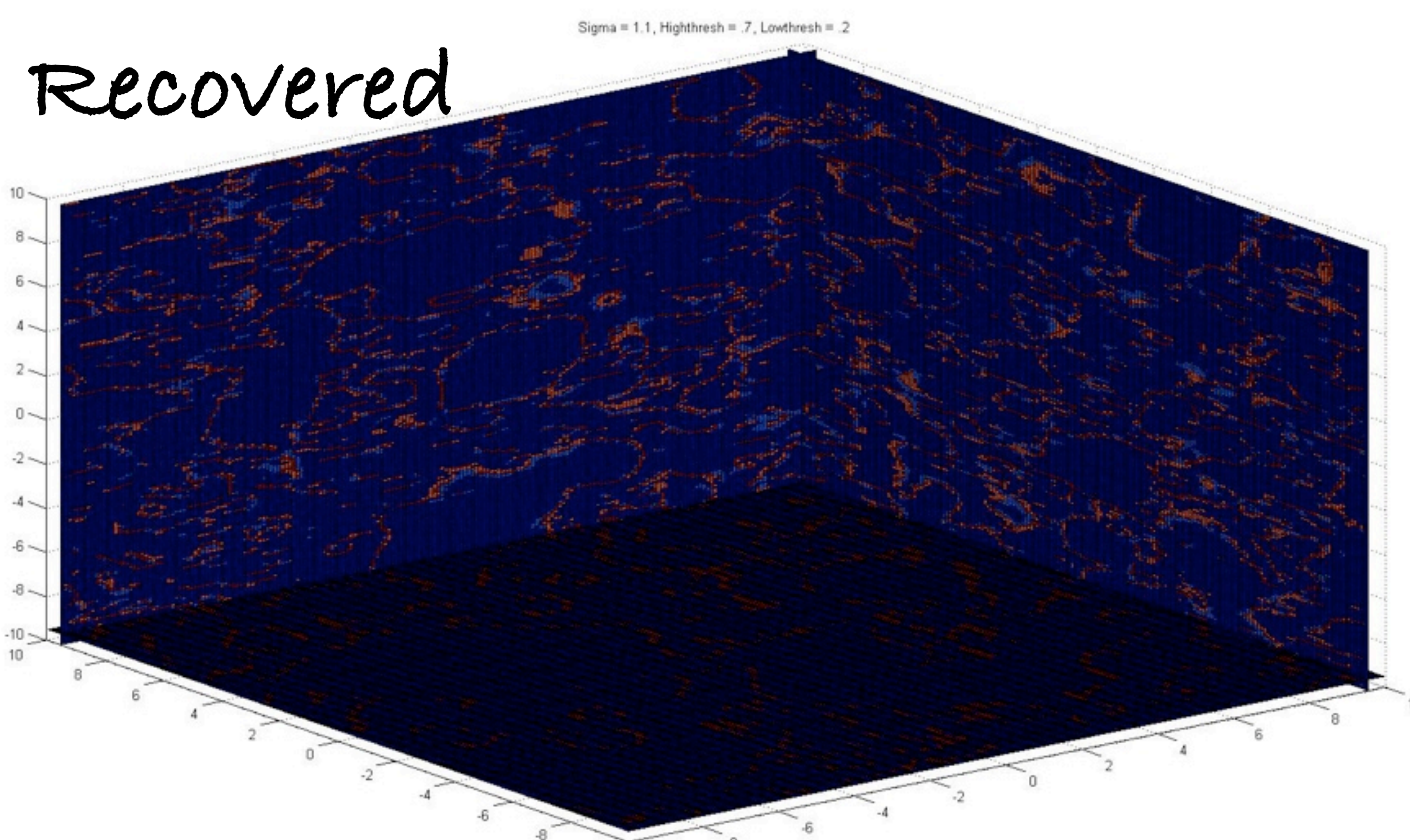
Input



with noise



Recovered



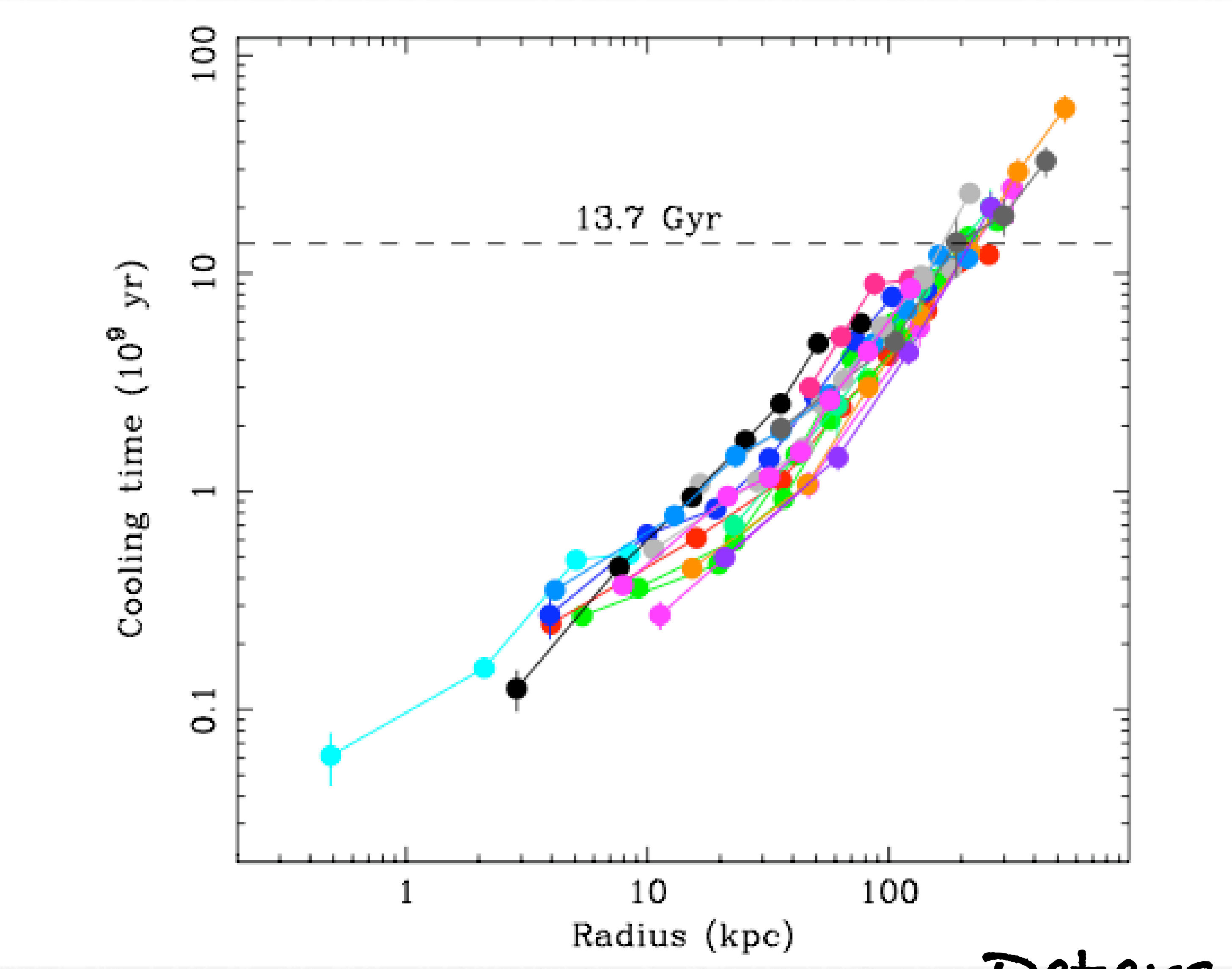
Input box from Mesinger & Furlanetto 2007

Bottom Line

- HII Bubbles are main feature (holes in 21cm emission) after first sources light up
- Much needed foreground calibrators
- Can only directly image biggest ones: sharpen detection w/ Canny algorithm
- If can detect statistically, obtain Q_HII(z)
- More work needed!

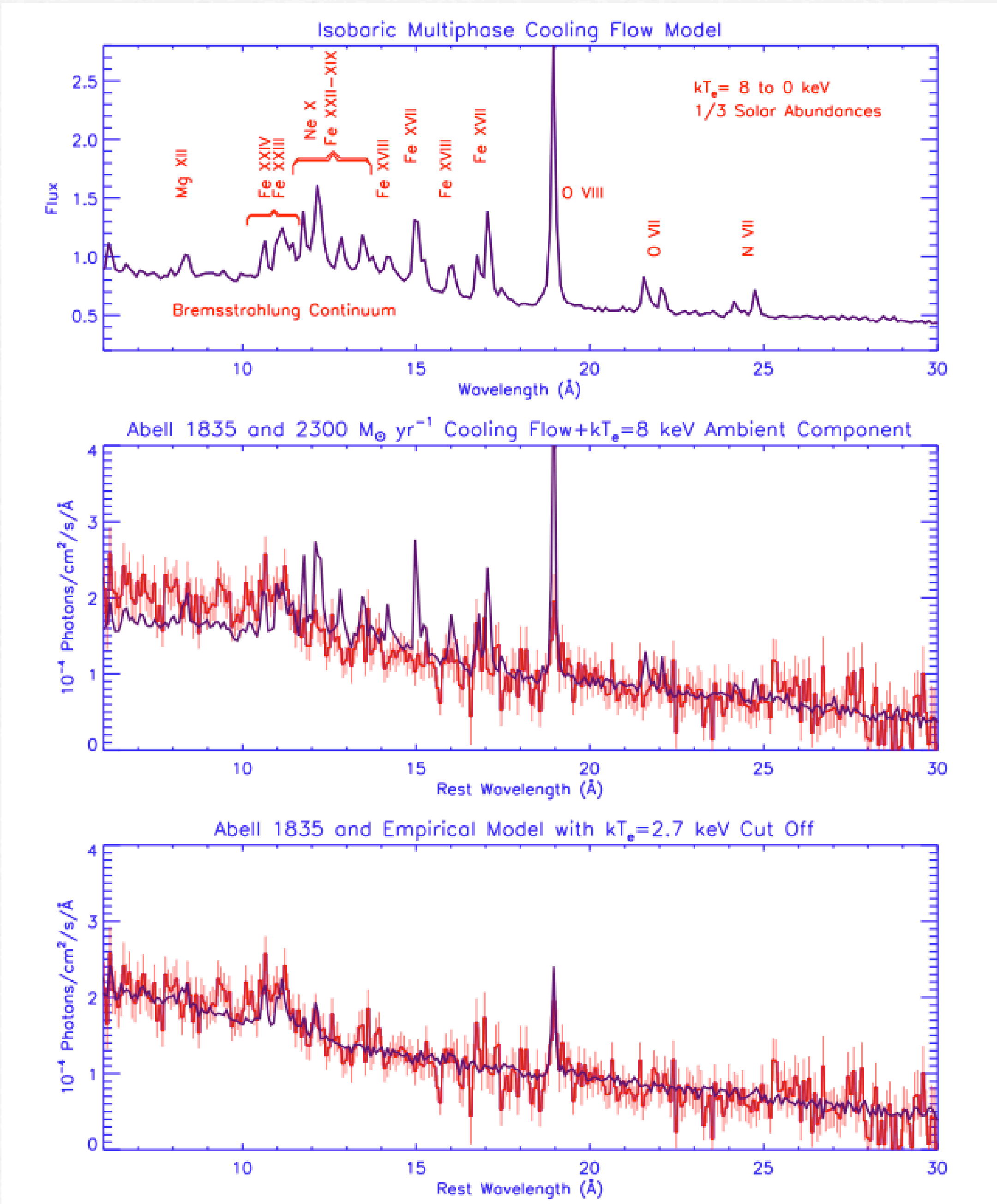
Feedback Heating in Galaxy Clusters

Although gas cooling times in clusters are short...



Peterson & Fabian (2006)

Gas does not appear to cool below ~1/3 of T_vir



Can only fit spectra if prevent gas from cooling below ~1/3 of ambient temperature

Universal across different cluster temperatures

Peterson et al (2001)

What's going on?

Plasma Physics effect? (e.g.,)

--Turbulent mixing

--non-Maxellian distribution function

Feedback heating (e.g...)

---thermal conduction

---AGN mechanical heating

--cosmic ray heating (this talk)

The Straw Man: Isobaric Cooling Flow

For a constant mass-flow rate $\dot{M}$, the power release is thus

$$\mathrm{d}\,L = \frac{5}{2}\frac{k_{\mathrm{B}}}{\mu m_{\mathrm{H}}}\dot{M}\mathrm{d}\,T. \tag{1}$$

We also have, from the definition of the cooling function Λ,

$$\begin{aligned} \mathrm{d}\,L &= n_{\mathrm{e}}n_{\mathrm{H}}\Lambda(T,Z)\mathrm{d}\,V, \\ \mathrm{d}\,L_{\nu} &= n_{\mathrm{e}}n_{\mathrm{H}}\Lambda_{\nu}(T,Z)\mathrm{d}\,V. \end{aligned} \tag{2}$$

Hence we obtain the spectral power for a steady-state flow cooling from T_{max} to T_{min}

$$L_{\nu} = \frac{5}{2}\frac{k_{\mathrm{B}}}{\mu m_{\mathrm{H}}}\dot{M}\int_{T_{\mathrm{min}}}^{T_{\mathrm{max}}}\frac{\Lambda_{\nu}(T,Z)}{\Lambda(T,Z)}\mathrm{d}\,T. \tag{3}$$

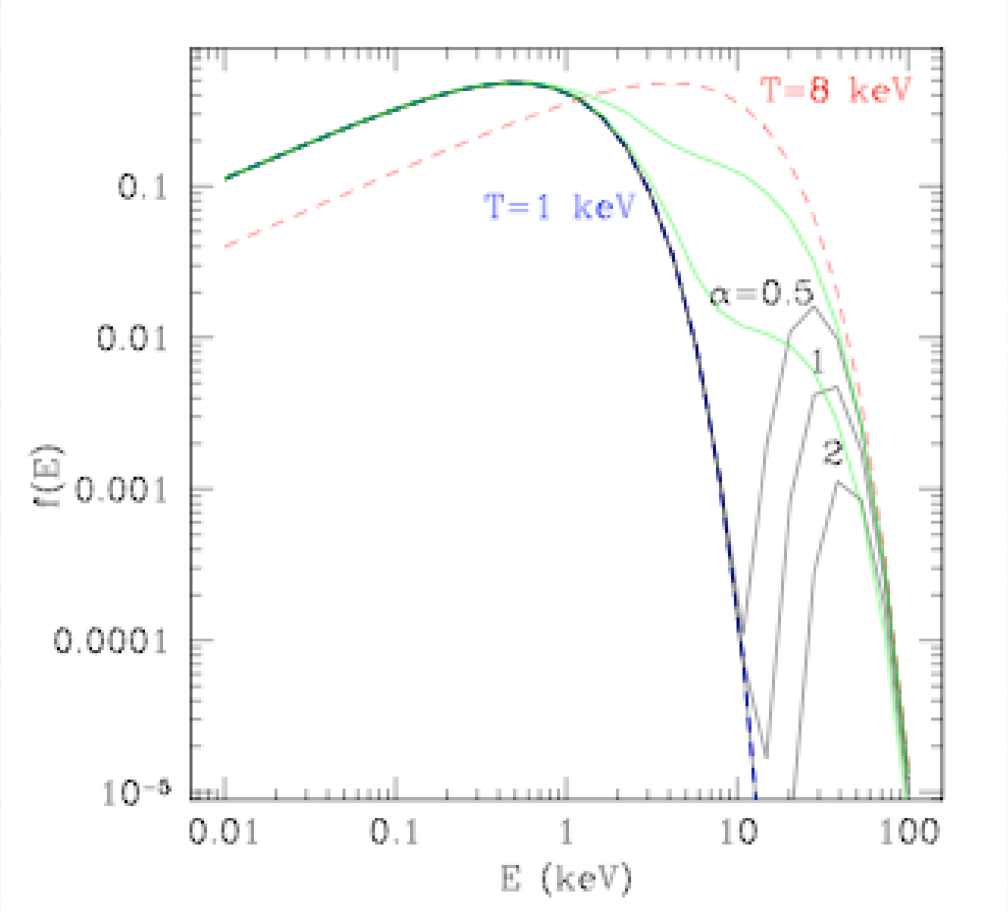
e.g. see Fabian (1994)

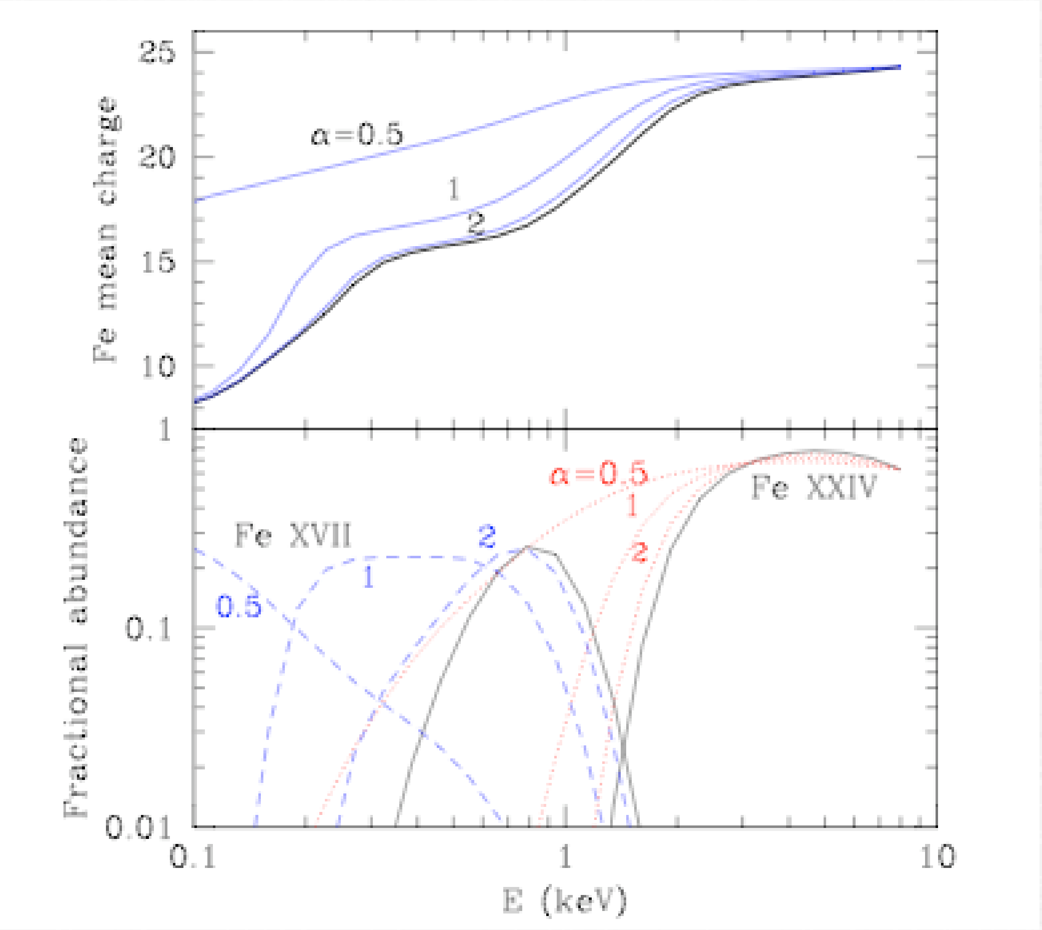
Plasma effects I:Turbulent mixing?

Gas cools non-radiatively by mixing hot and cold gas (Begelman & Fabian 1990)

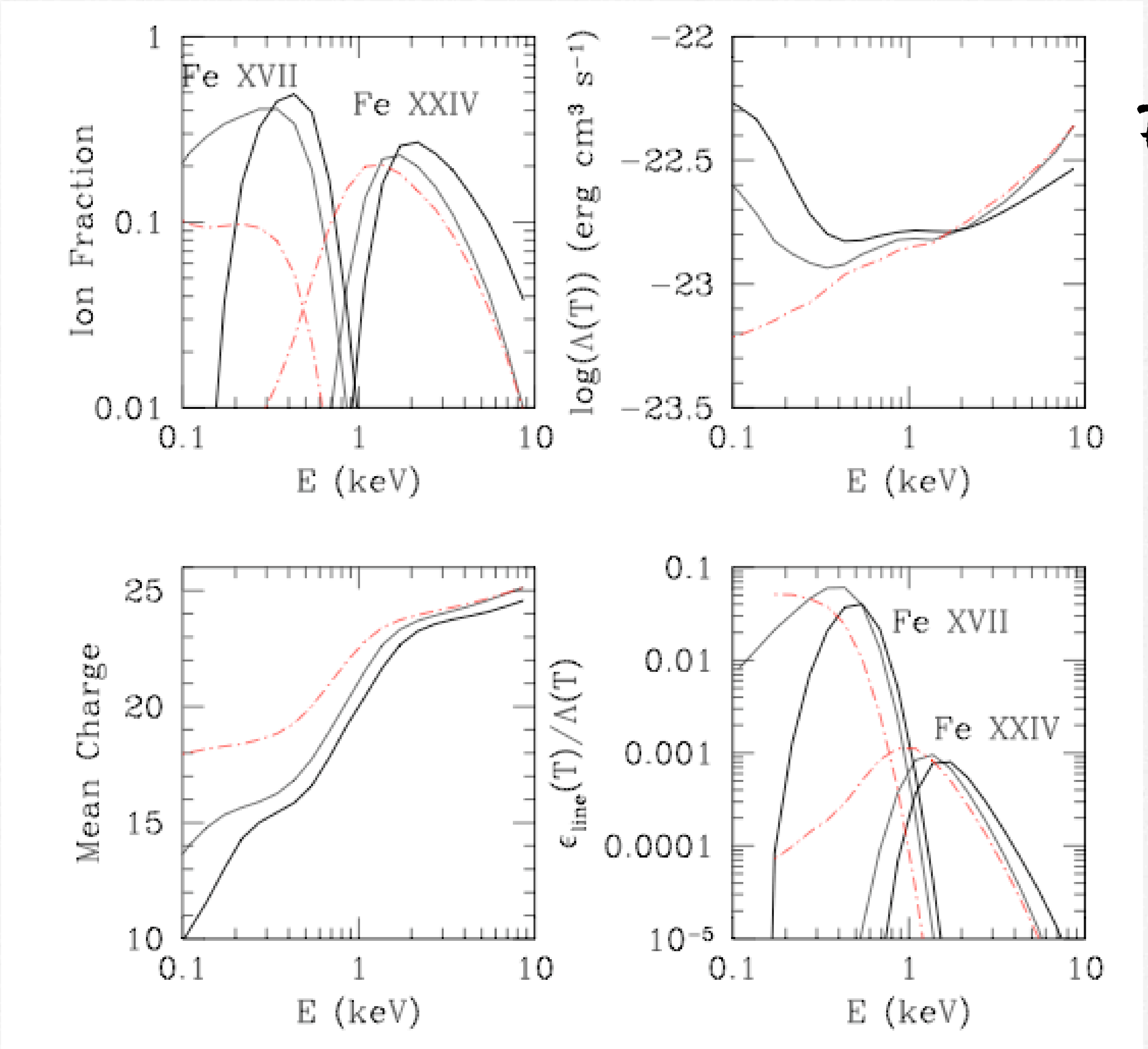
Energy eventually escapes through optical lines

Plasma Effects II: break collisional equilibrium?





Non-Maxwellian distribution function (Oh 2004)

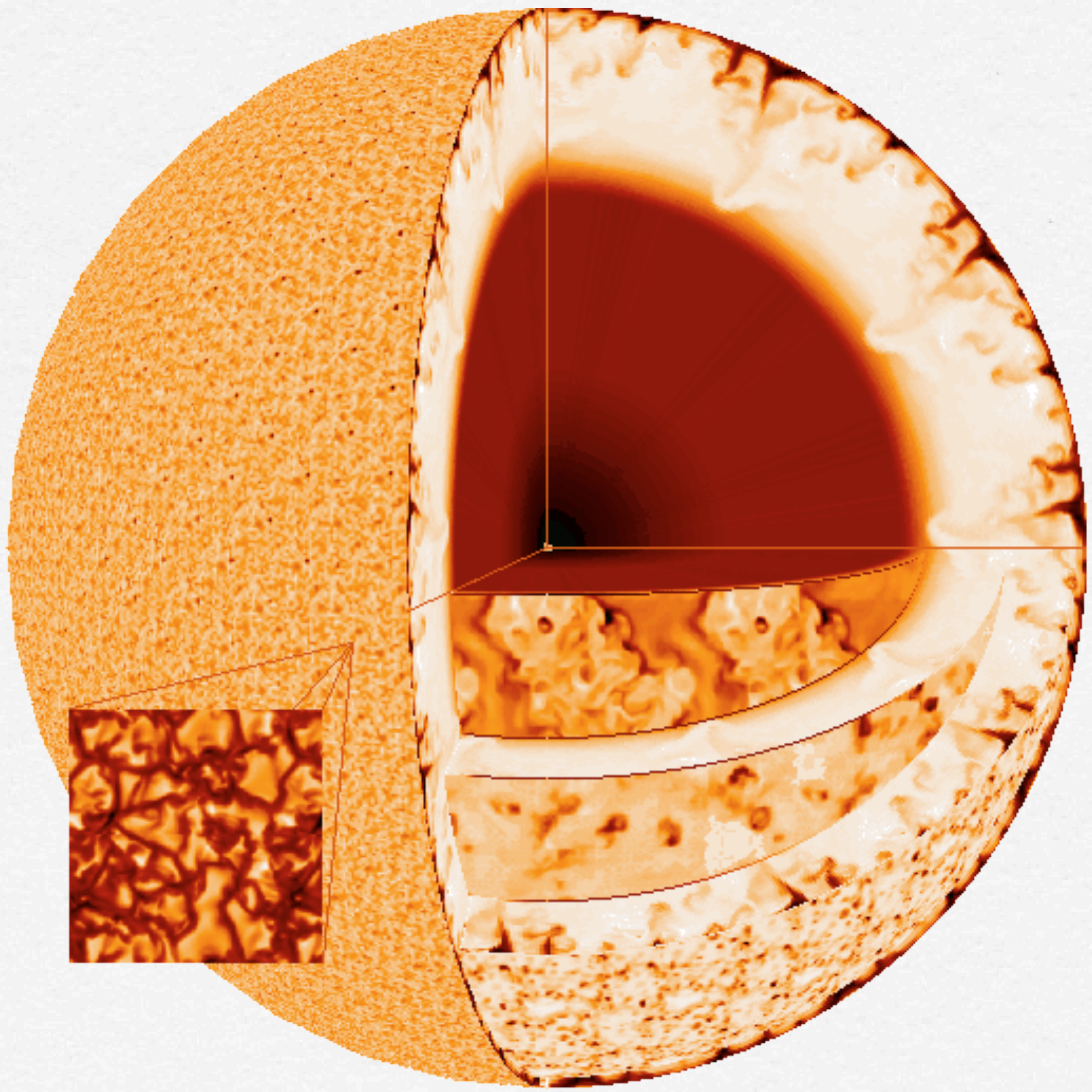


Photoionization from surrounding cluster gas or central AGN

Decreased cooling efficiency at low T: emission measure of low ionization state lines larger

Photoionization (Oh 2004)

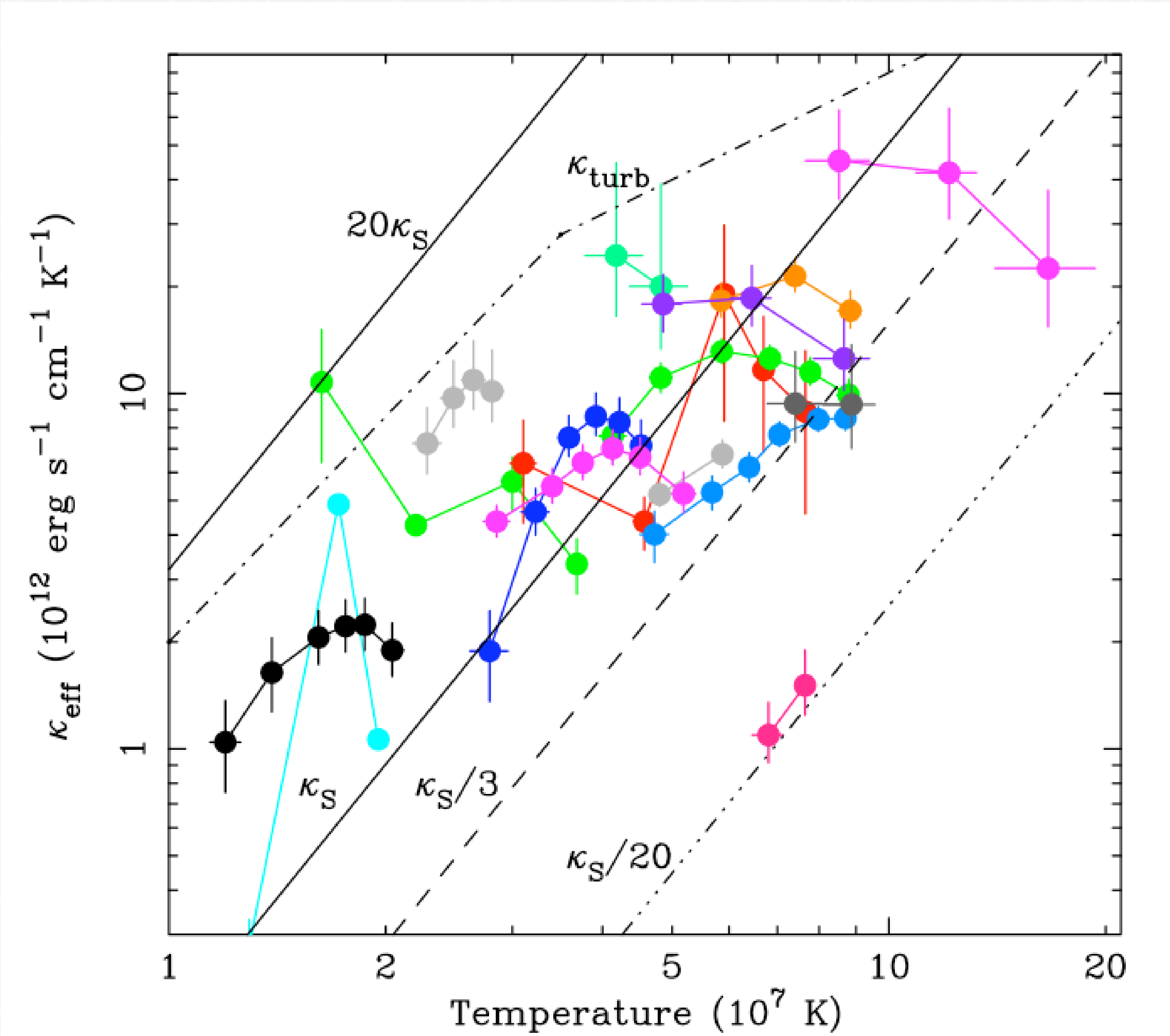
Heating is a more popular solution



Cluster sits in quasi-thermal equilibrium: just like a star!

Also explains lack of cold gas/stars

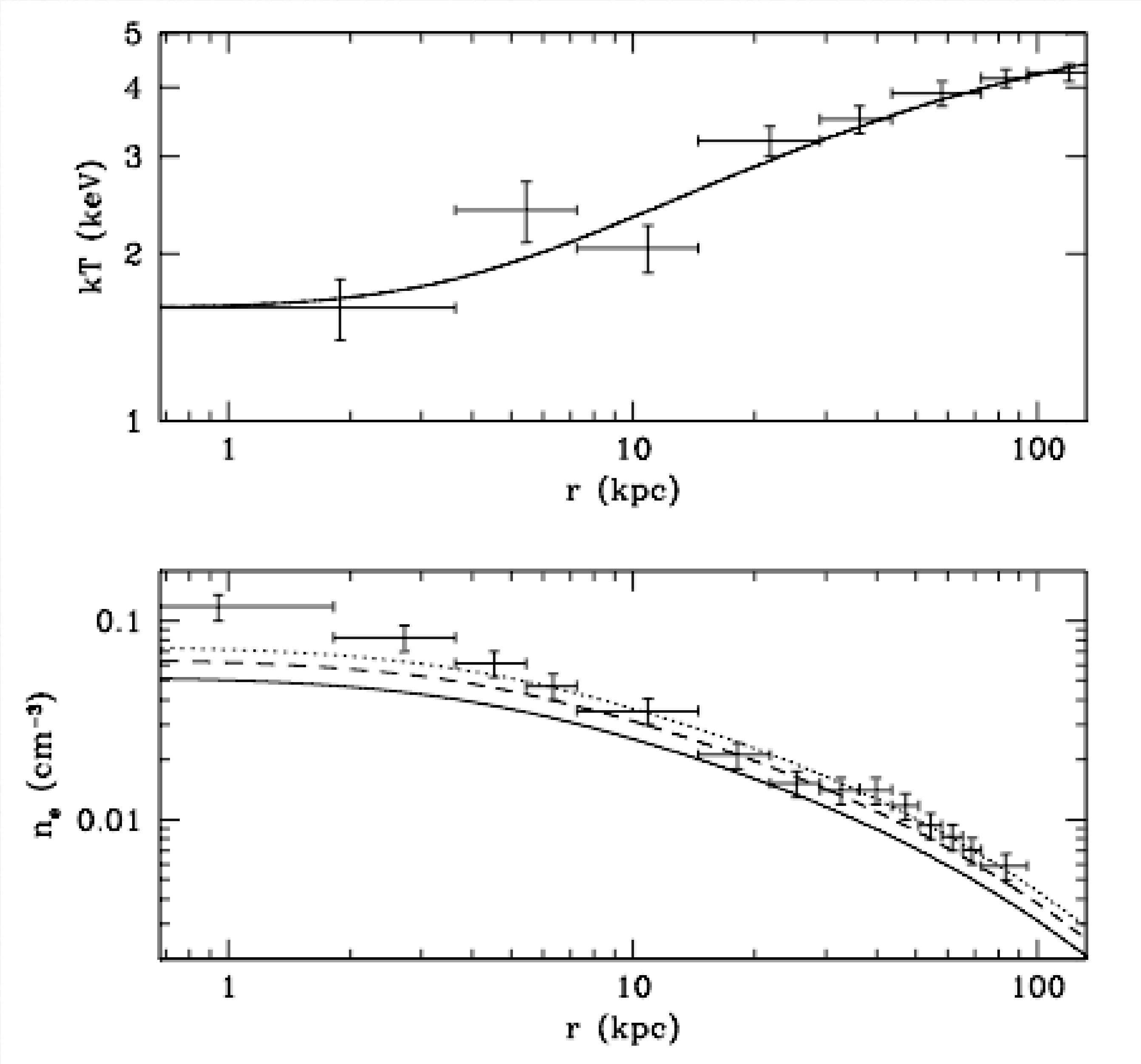
Thermal Conduction



Peterson & Fabian (2006)

Conduction at fraction of classical Spitzer value close to what's needed.

Coincidence??

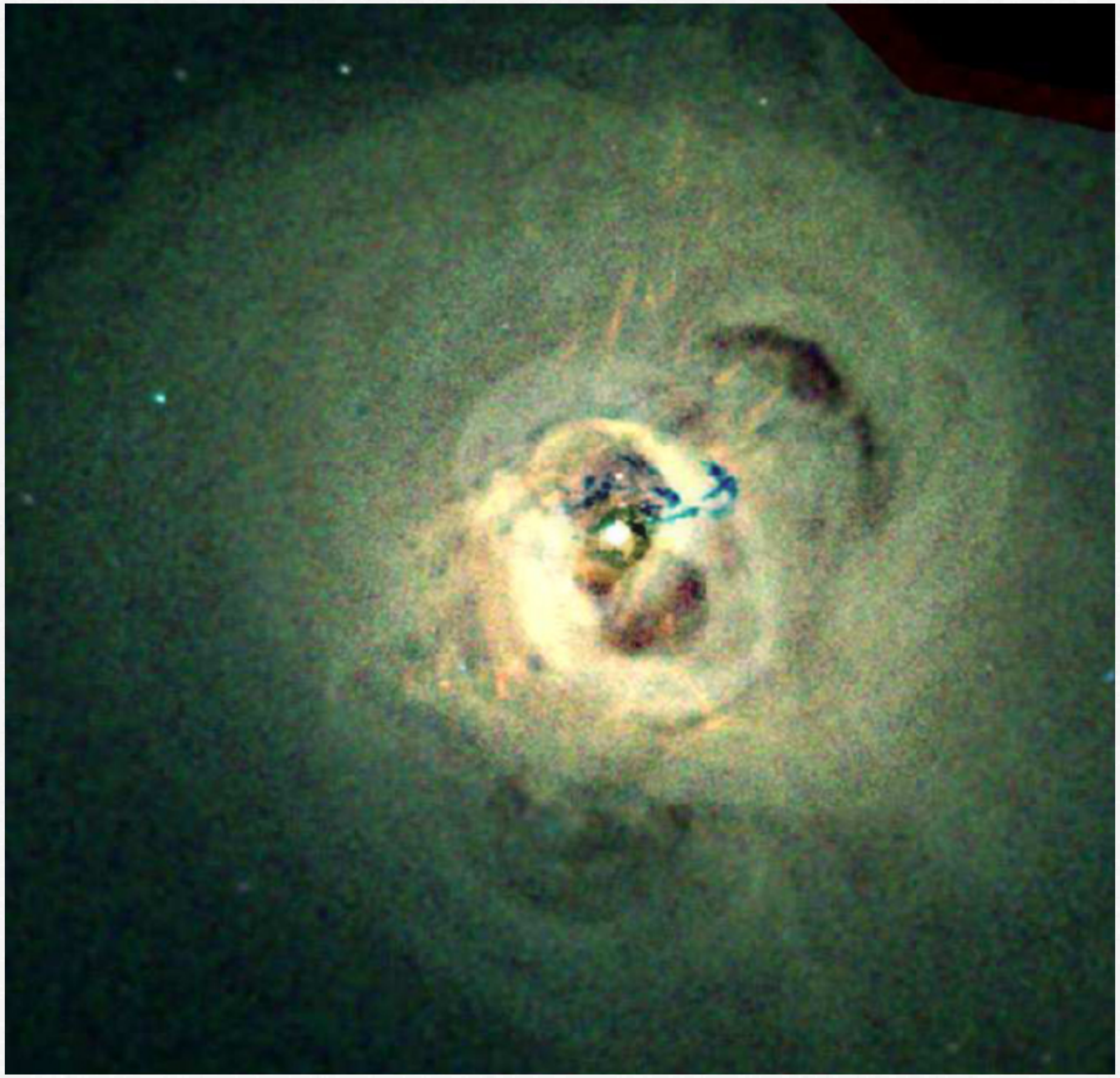


Zakamska & Narayan (2002)

Can build conduction-only models in hydrostatic and thermal equilibrium

But: suffer fine-tuning problems, tend to be globally unstable

AGN/radio galaxy heating



Chandra image, Perseus cluster

Bubbles observed in ICM, filled with hot/relativistic plasma

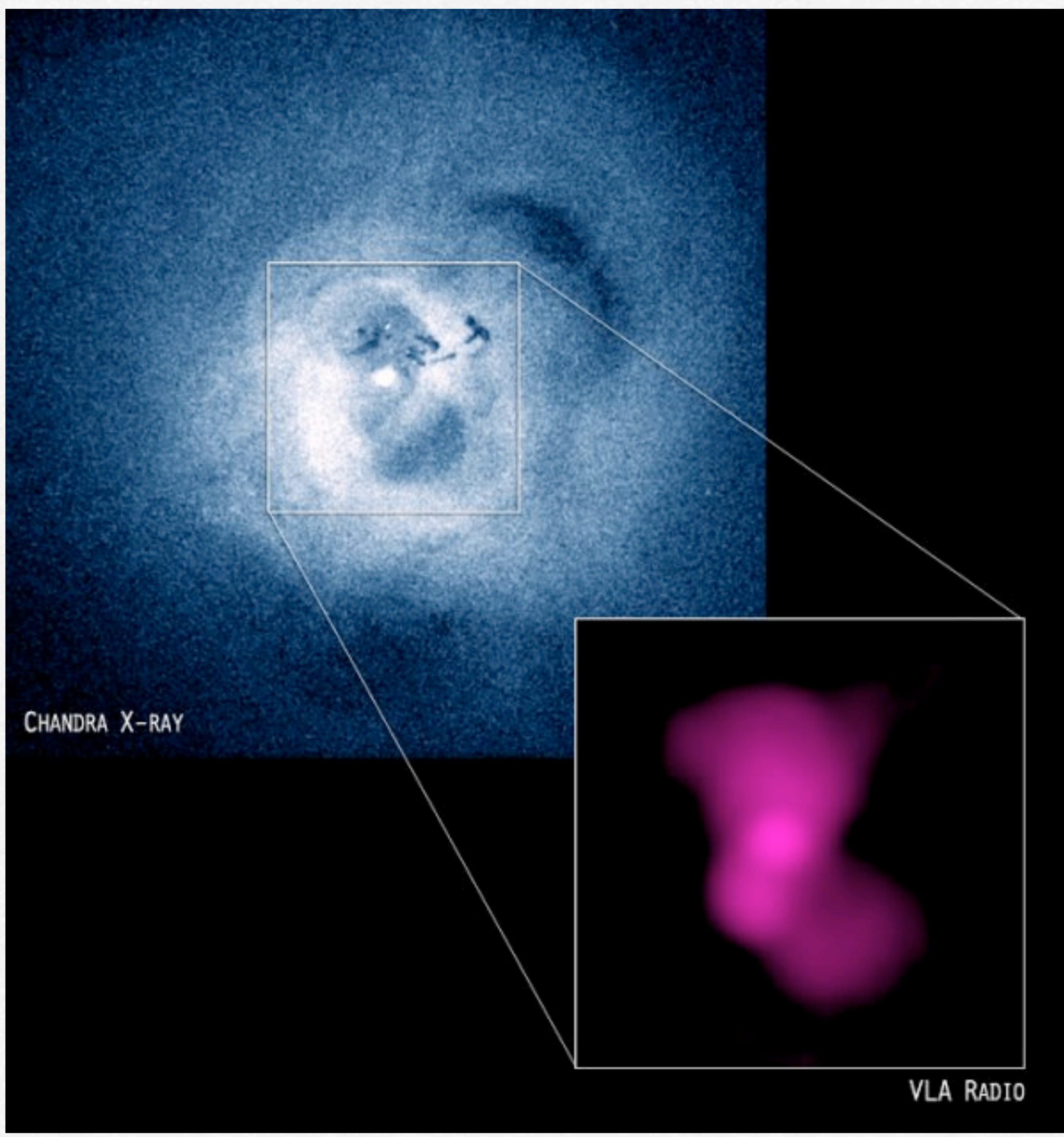
Maybe: entrain cold gas

pdV work

This talk: cosmic ray heating

(Guo & Oh 2007)

Why cosmic rays ?



We see radio synchrotron emission

Spallation products indicate CRs could be present (Nath, Madau & Silk 2005)

Many sources: jets, accretion shock, SN

Provide gentle, distributed heating

It's been tried before...

- Authors have considered dynamical and heating effects (via Coulomb, hadronic and Alfven wave interactions) (Boehringer & Morfill 1988, Loewenstein et al 1991, Repaheli & Silk 1995, Colafrancesco et al 2004, Jubelgas et al 2006, Prommer et al 2006)
- None have constructed models where CRs successfully stop cooling flow

A key problem: CR transport is slow

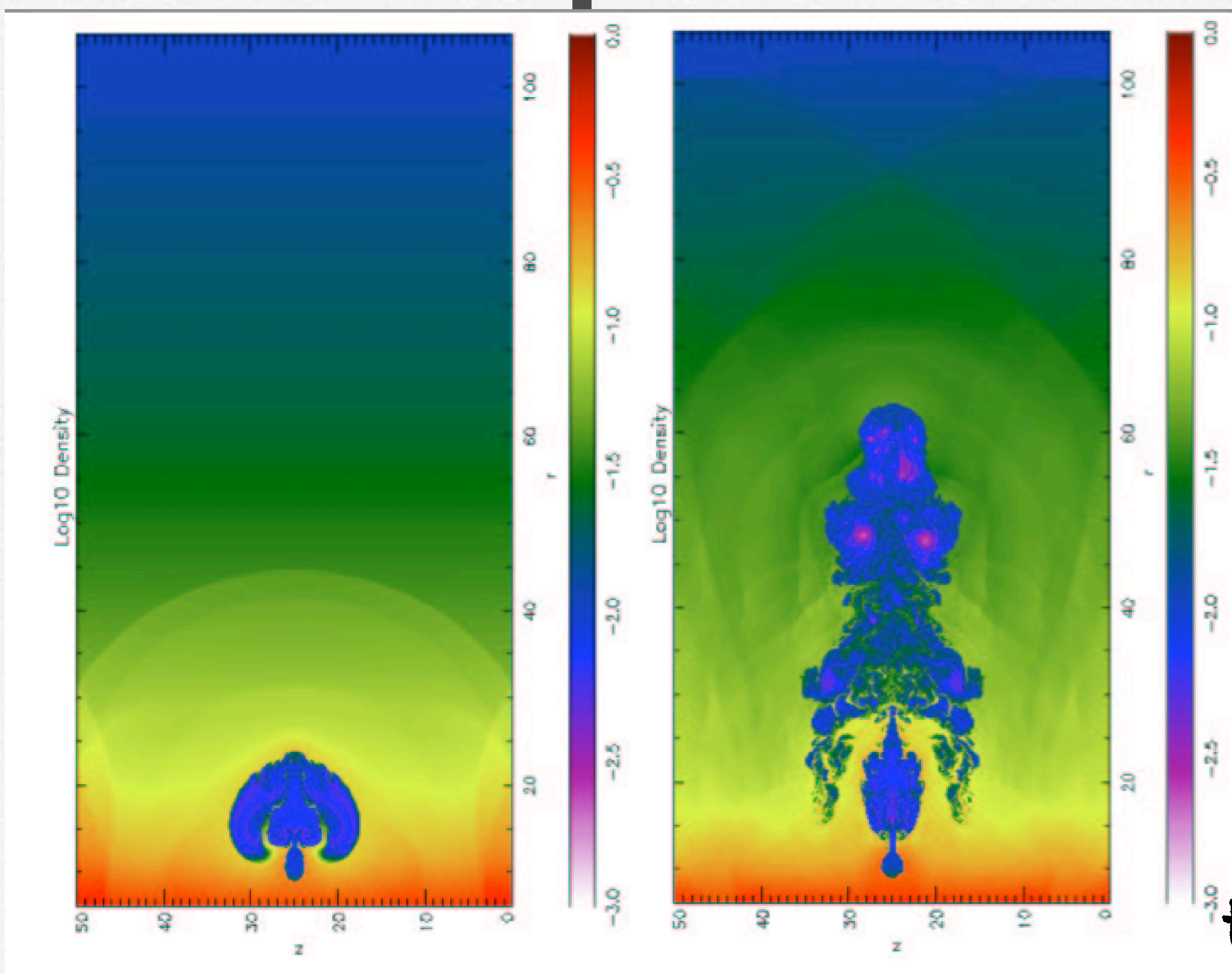
$$\boldsymbol{F}_{\rm c} = \gamma_{\rm c} E_{\rm c}(\boldsymbol{u} + \boldsymbol{v}_{\rm A}) - \boldsymbol{n}\kappa_{\rm c}(\boldsymbol{n} \cdot \boldsymbol{\nabla} E_{\rm c}), \tag{A14}$$

$$\frac{\partial E_{\rm c}}{\partial t} = (\gamma_{\rm c} - 1)(\boldsymbol{u} + \boldsymbol{v}_{\rm A}) \cdot \boldsymbol{\nabla} E_{\rm c} - \boldsymbol{\nabla} \cdot \boldsymbol{F}_{\rm c} + \bar{Q}. \tag{A15}$$

Diffusive and other CR transport timescales are long

Leads to overpressured center with insufficient heating at outskirts (though may drive turbulent convection: Chandran & collaborators)

Our model: use bubbles to transport CRs



Bruggen & Kaiser (2002)

Bubbles disrupted by Rayleigh-Taylor & Kelvin-Helmholtz instabilities as rise

(Also: CRs diffuse out)

Fast way of transporting CRs: rise time ~ sound crossing time

Method

- 1D Zeus code: solve time-dependent hydrodynamic equations + CR heating & transport equations
- calculate steady steady CR spectrum, assuming Coulomb, hadronic and Alfven-wave energy loses (latter dominates):

$$\Gamma_{wave} = v_A \frac{dP_c}{dr}$$

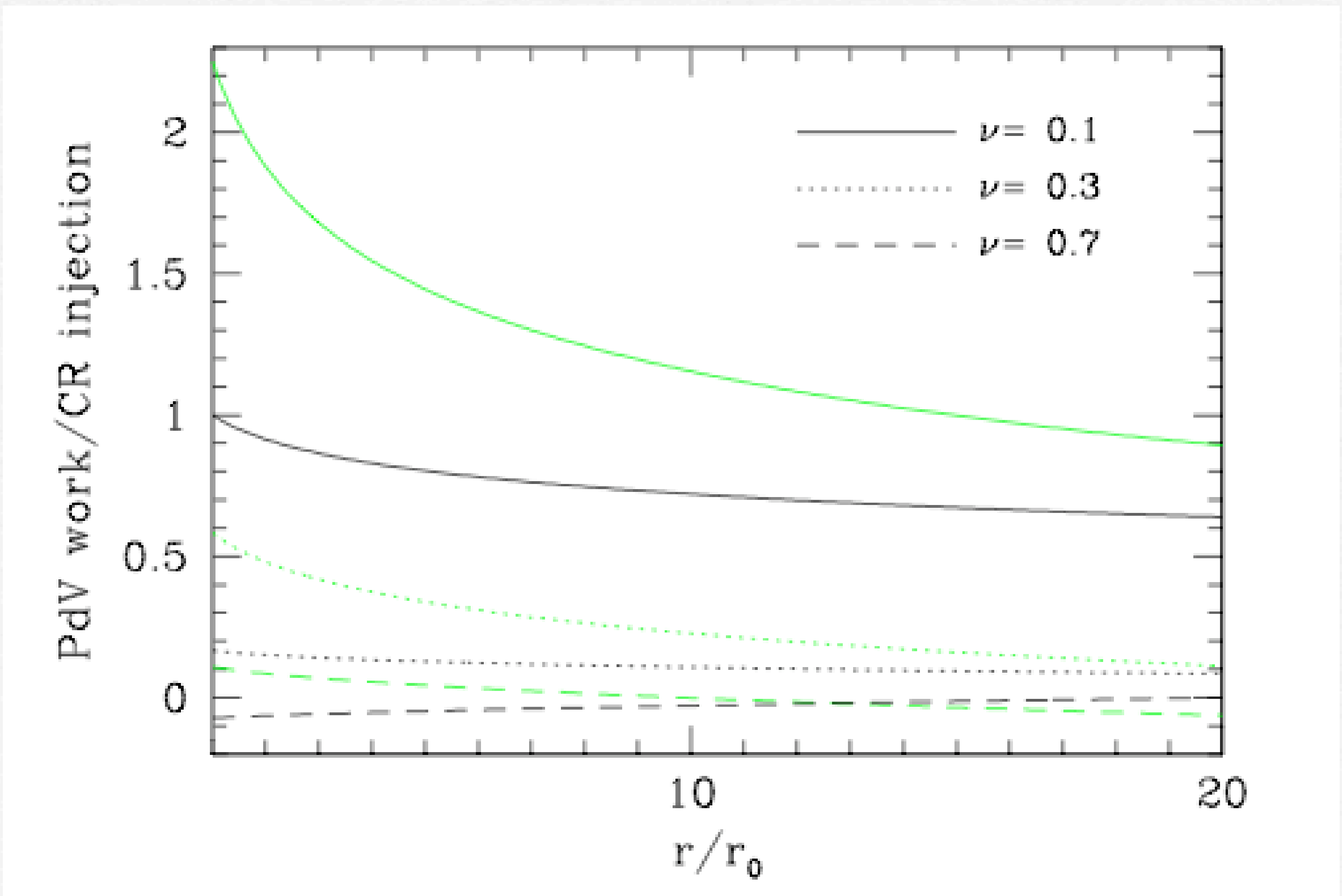
- Assume energy density in bubbles is a power-law with radius (note: CR injection rate depends on gas cooling---feedback effect)

$$L_{\rm bubble} \sim -\epsilon \dot{M}_{\rm in} c^2 \left(\frac{r}{r_0}\right)^{-\nu} \quad \text{for } r > r_0,$$

$$\begin{aligned} Q_{\rm c} = \nabla \cdot \mathbf{F}_{\rm bubble} &\sim -\frac{1}{4\pi r^2}\frac{\partial L_{\rm bubble}}{\partial r}\left[1 - e^{-(r/r_0)^2}\right] \\ &\sim -\frac{\nu \epsilon \dot{M}_{\rm in} c^2}{4\pi r_0^3}\left(\frac{r}{r_0}\right)^{-3-\nu}\left[1 - e^{-(r/r_0)^2}\right], \end{aligned} \quad (19$$

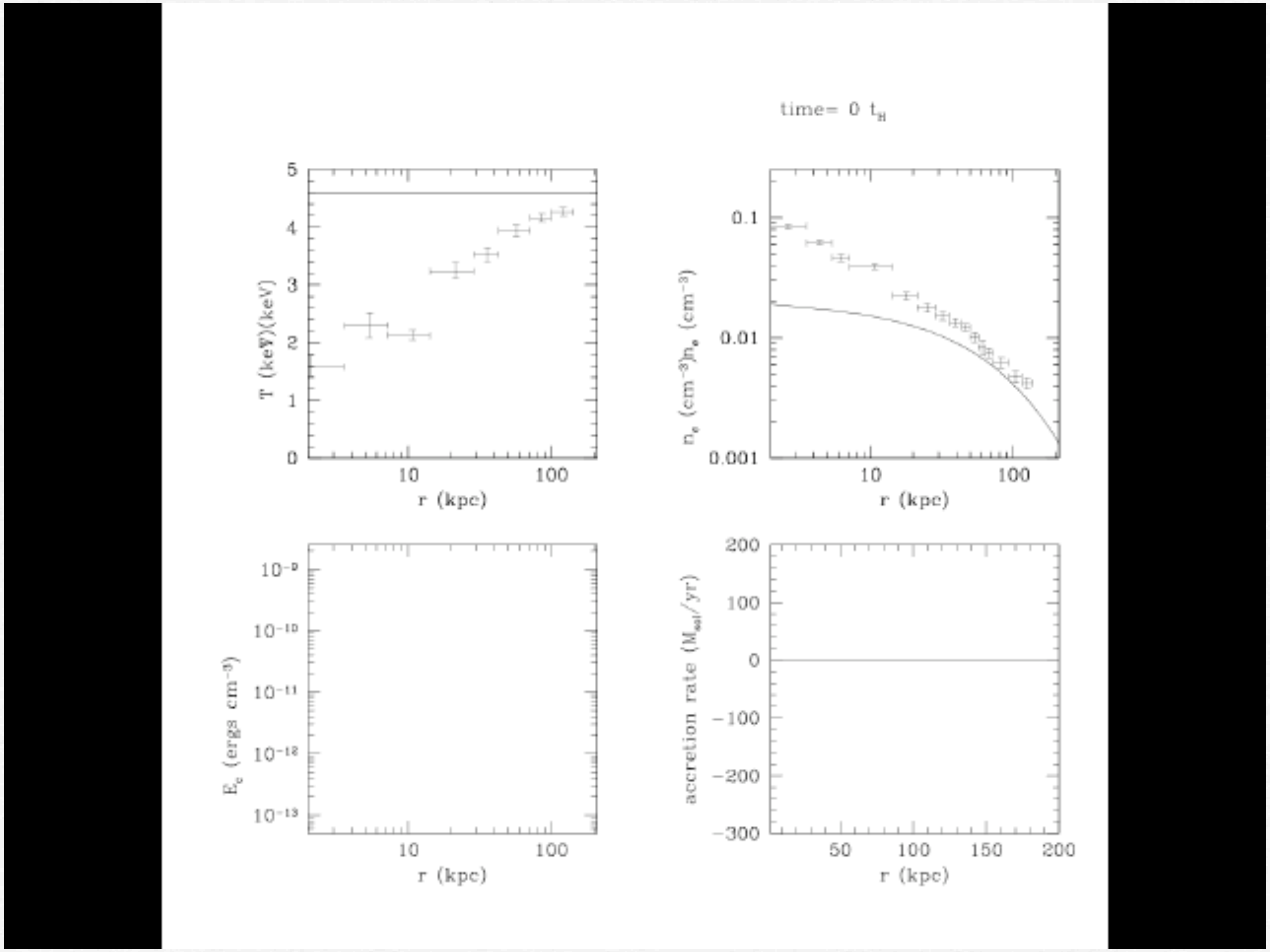
Slope is free parameter, implicitly specifies bubble disruption rate

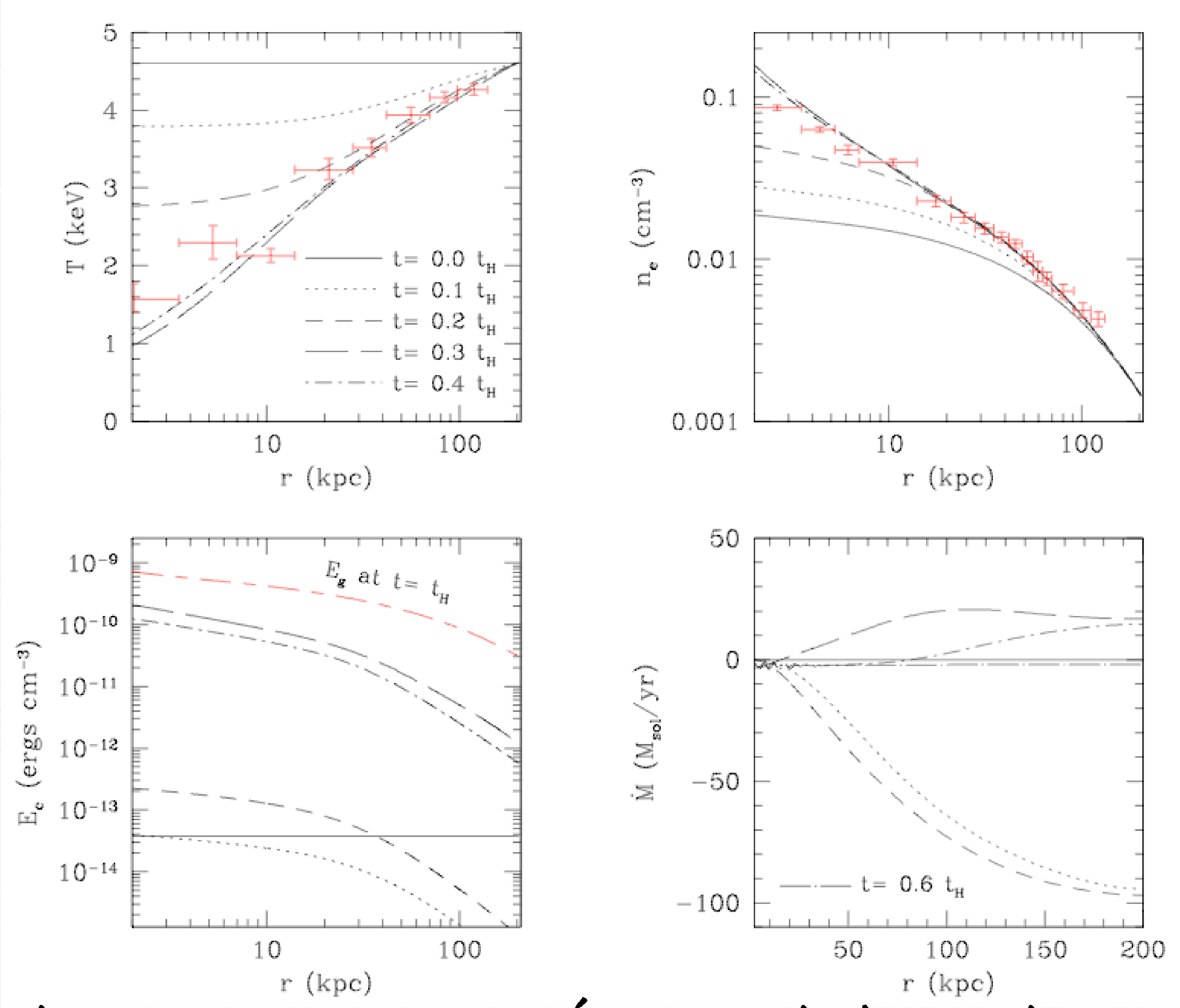
- Amount of energy lost to pdV work is small, at most comparable to the bubble disruption rate



(pdV work can also heat ICM, we ignore it)

Bottom line: it works!

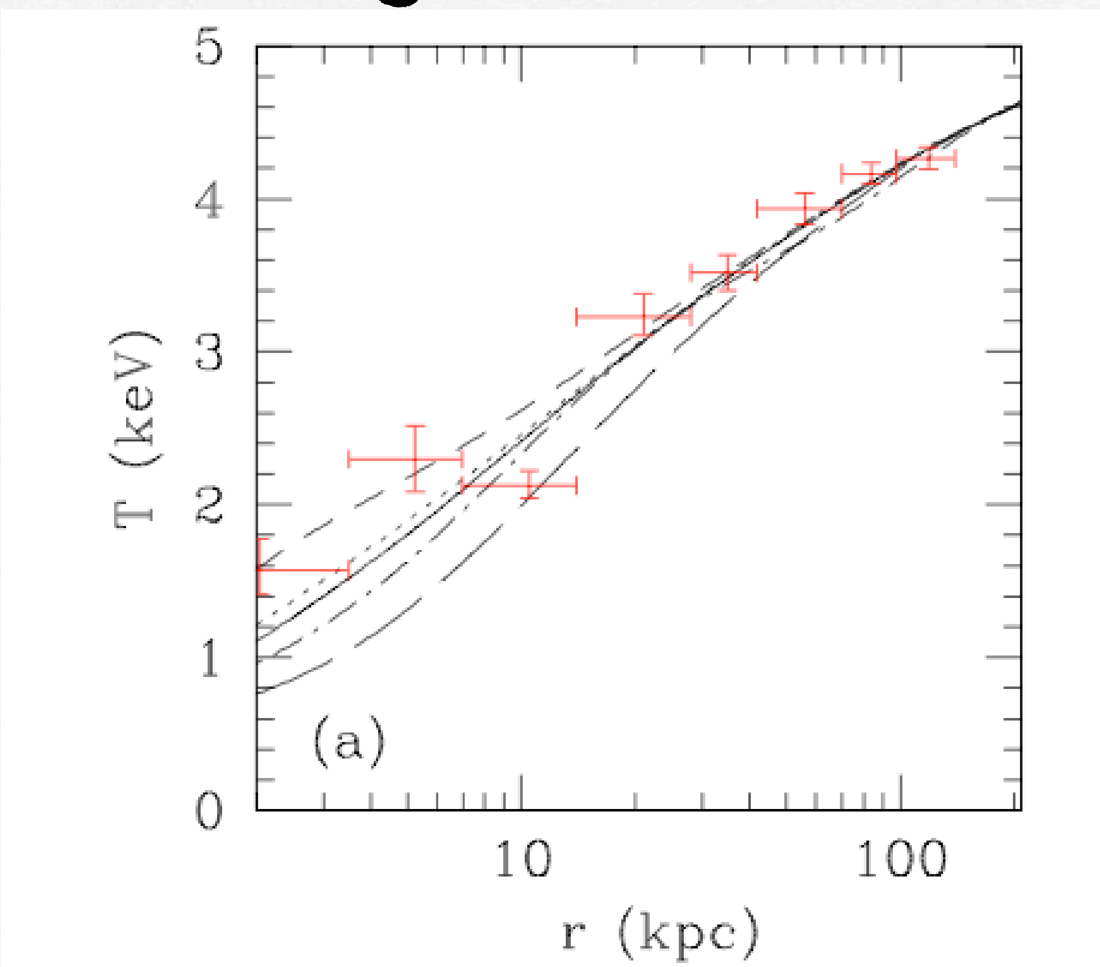




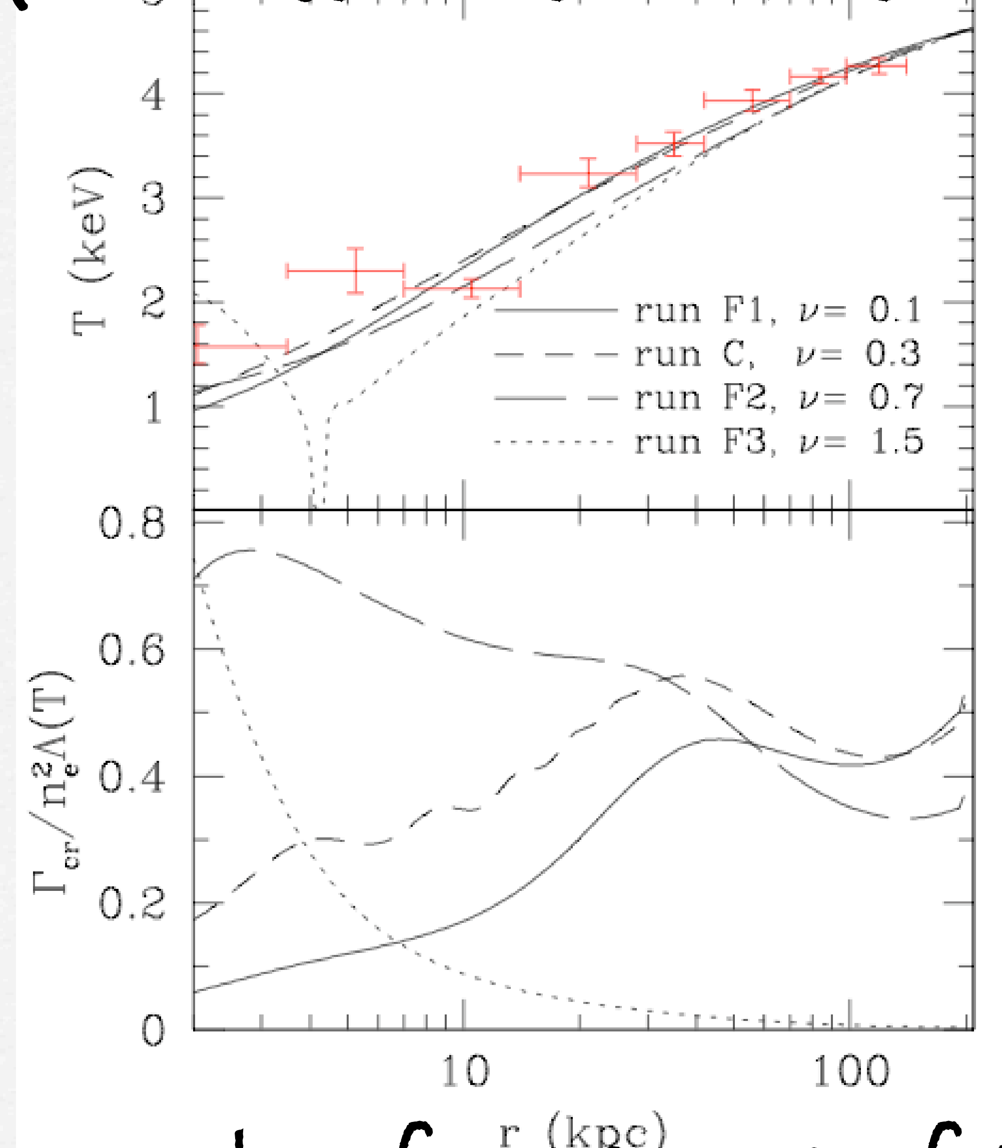
Note that CR pressure is much less than thermal pressure

No fine tuning

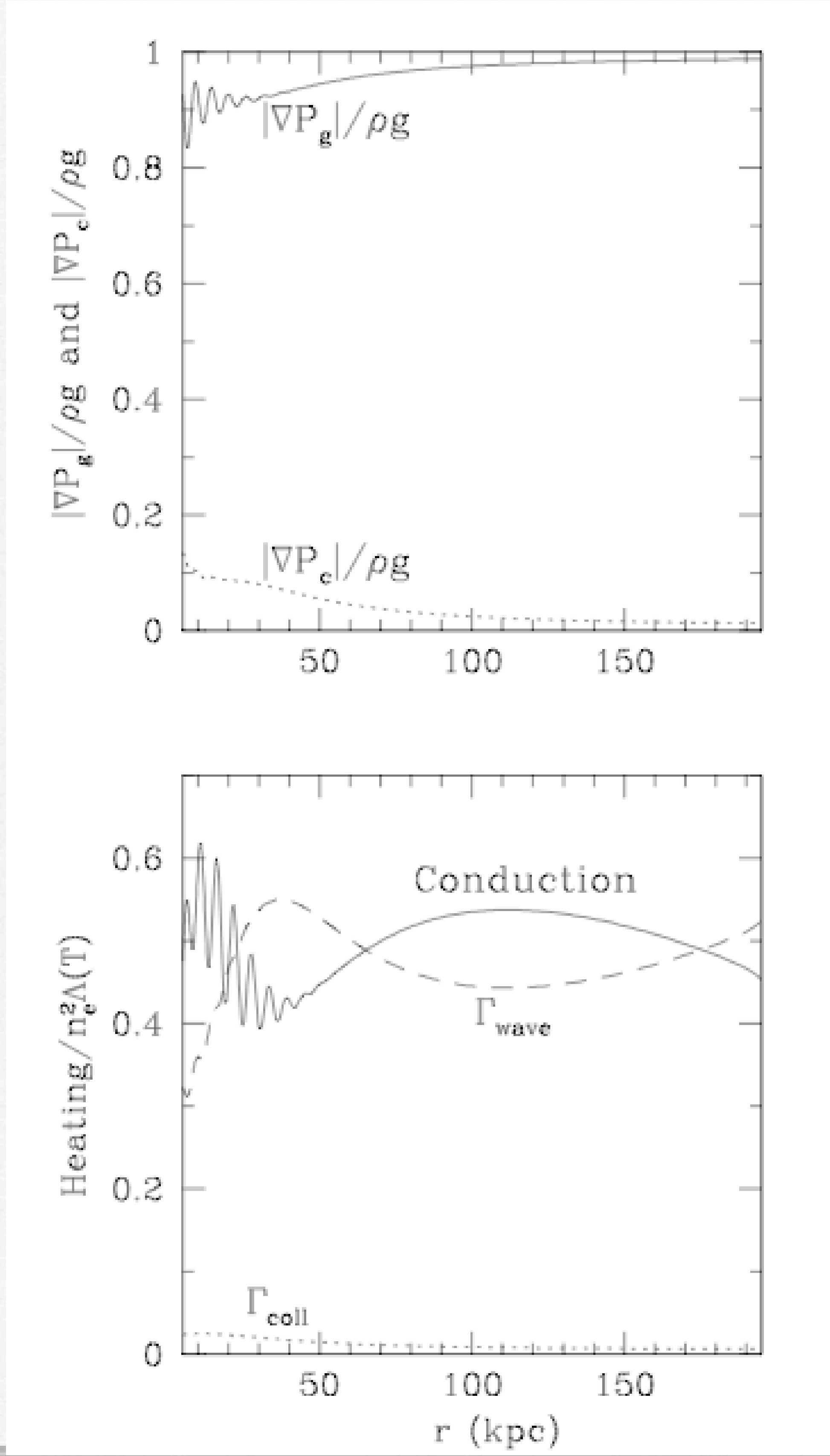
Works (i.e., no massive cooling flow) starting from arbitrary initial conditions (unlike other models...)



works for range of AGN + conduction parameters



works for range of CR profiles

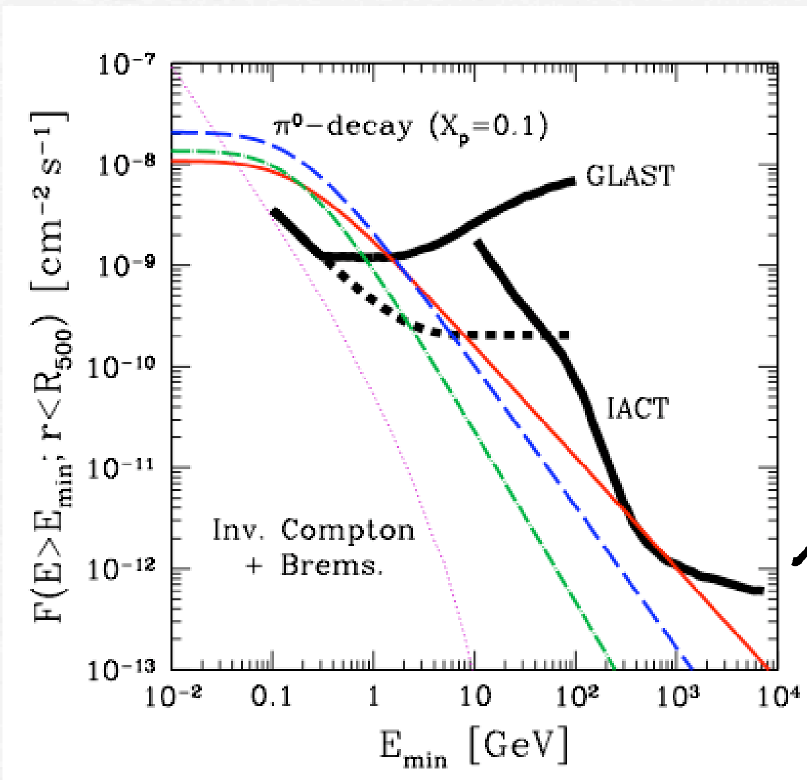


Required CR pressure gradients OK

Small fraction of thermal pressure gradient

most heating is wave heating

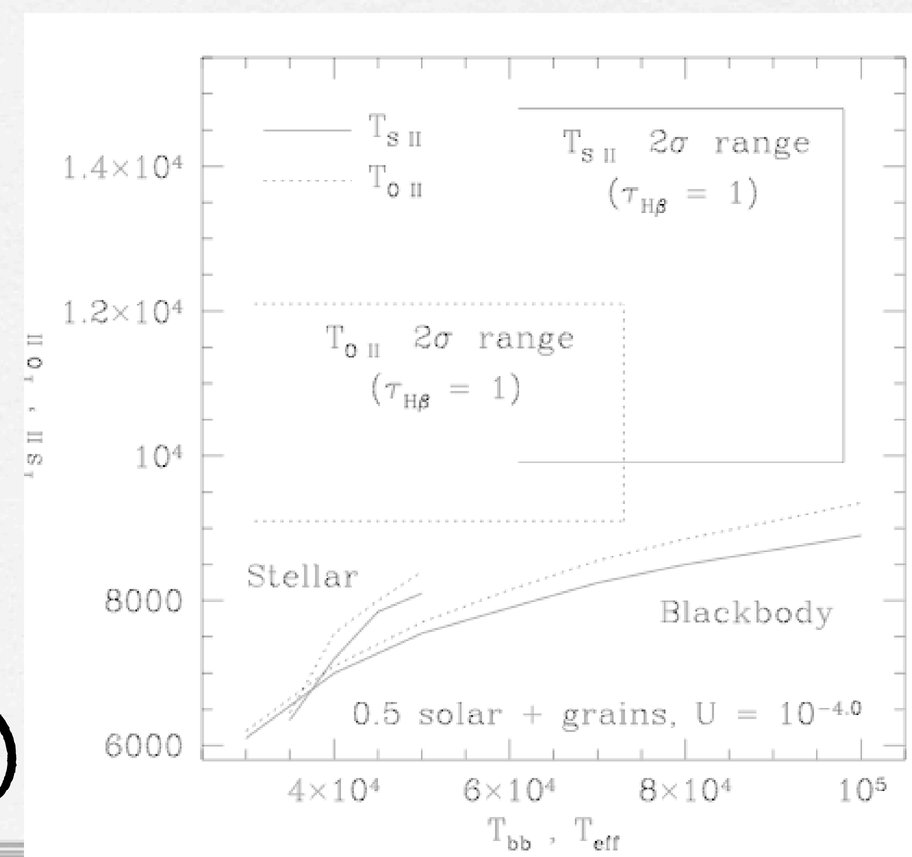
Observational tests



See gamma-rays from pion-decay with GLAST

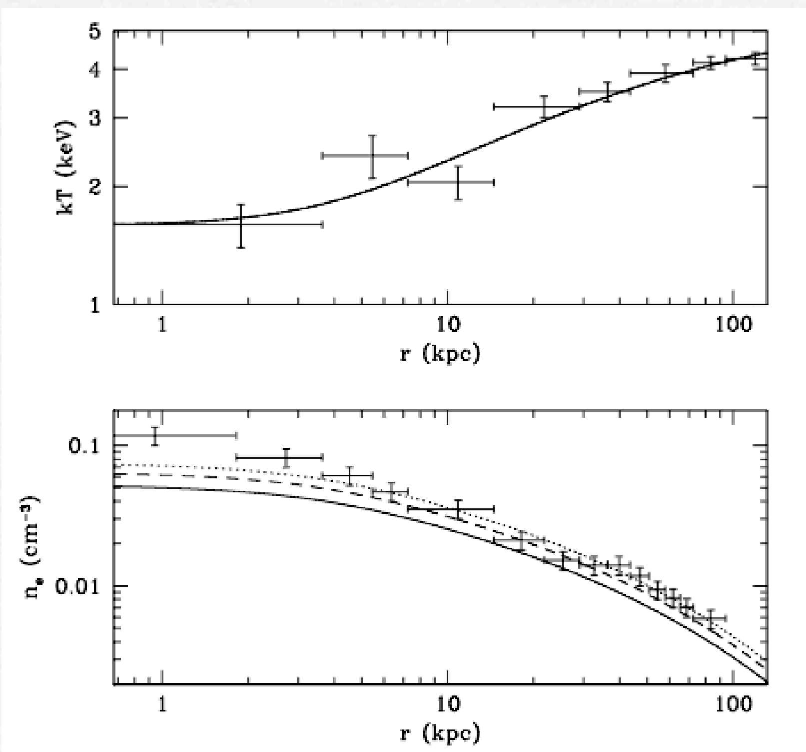
Ando & Nagai (2007)

Optical filaments: need source of anomolous heating?

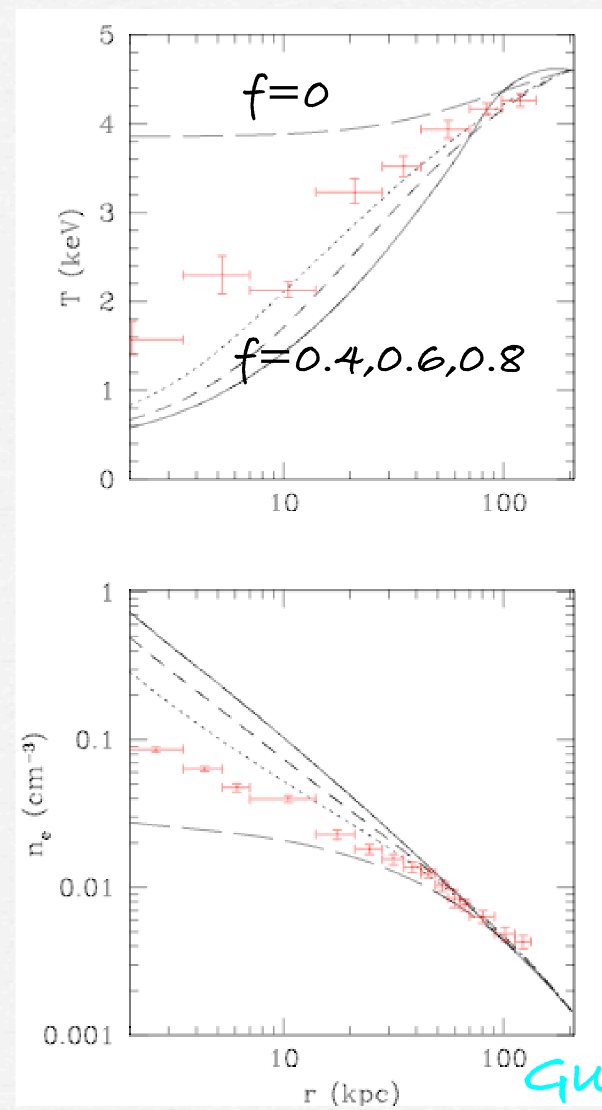


Voit & Donahue (1997)

Let's look more closely at fine-tuning issues for conduction models..



Can have equilibrium model which fits observations (solve eigenvalue problem)



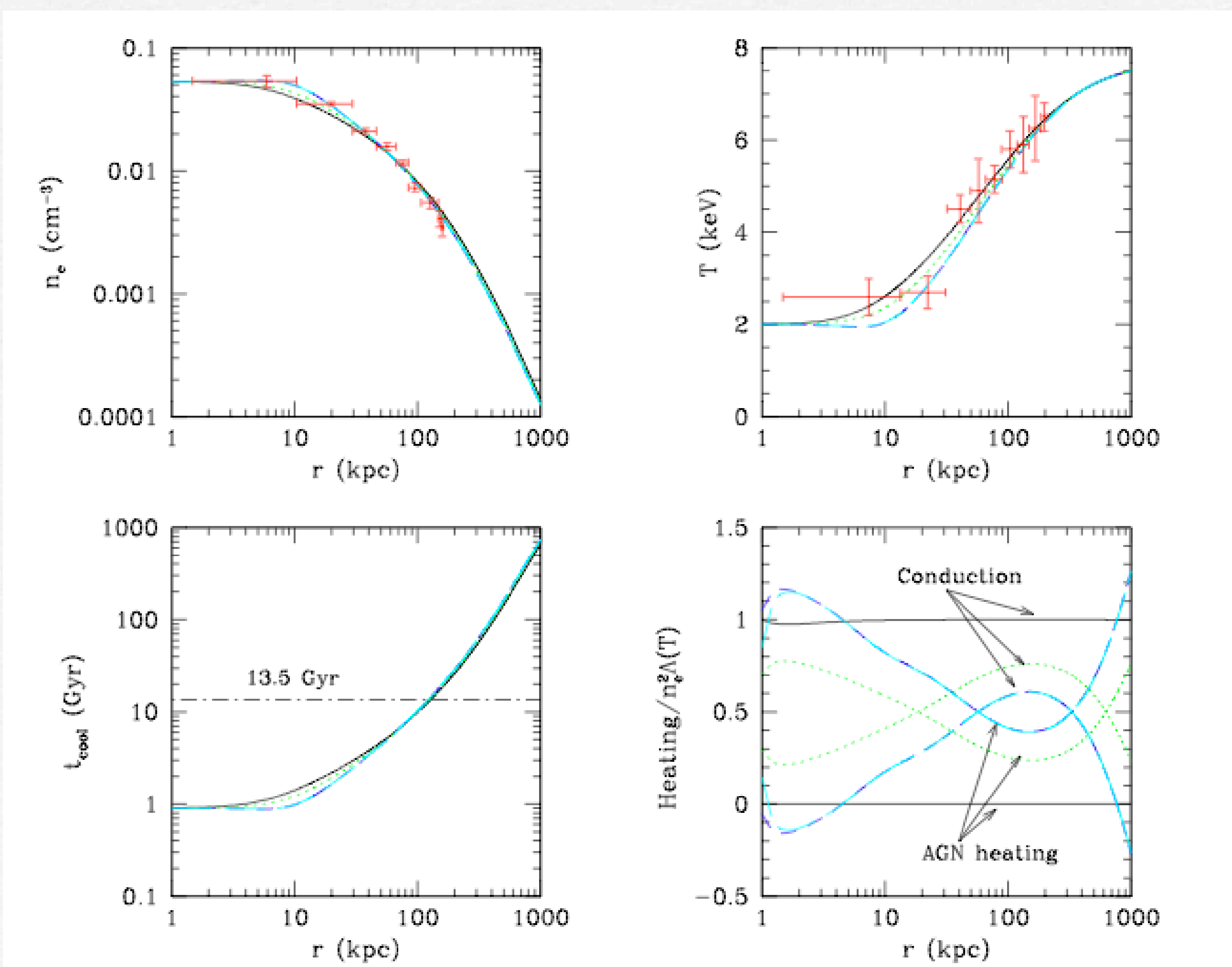
Guo & Oh 2007

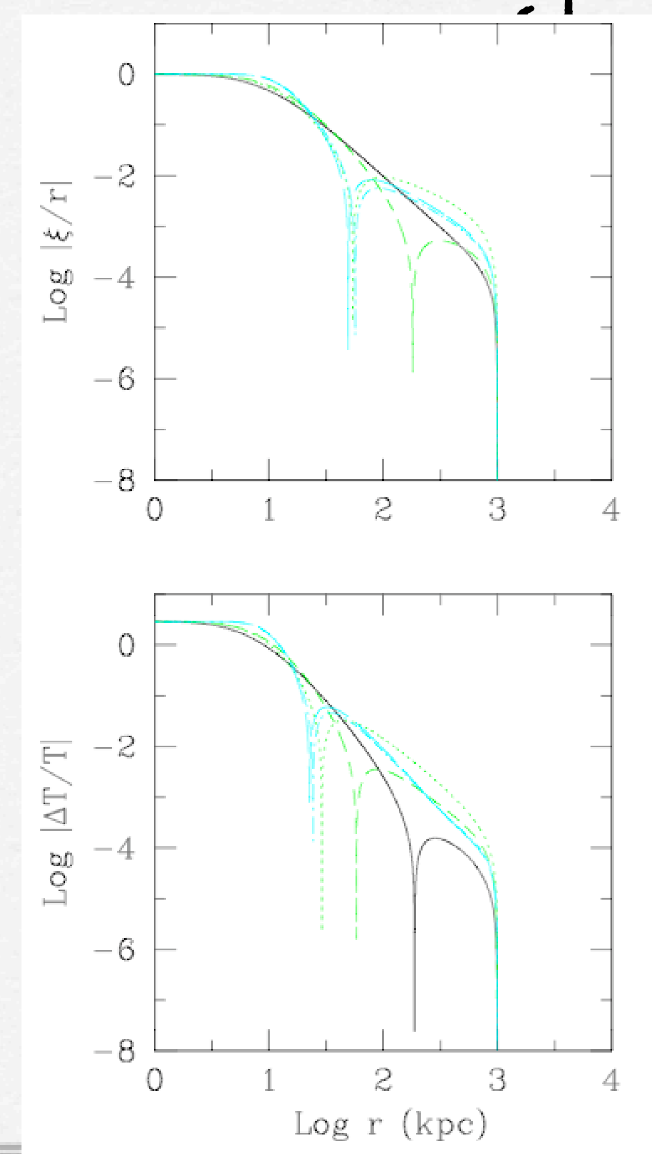
But it won't evolve toward this state in general...

Global Stability Analysis

Guo, Oh & Ruszkowski 2007, in prep

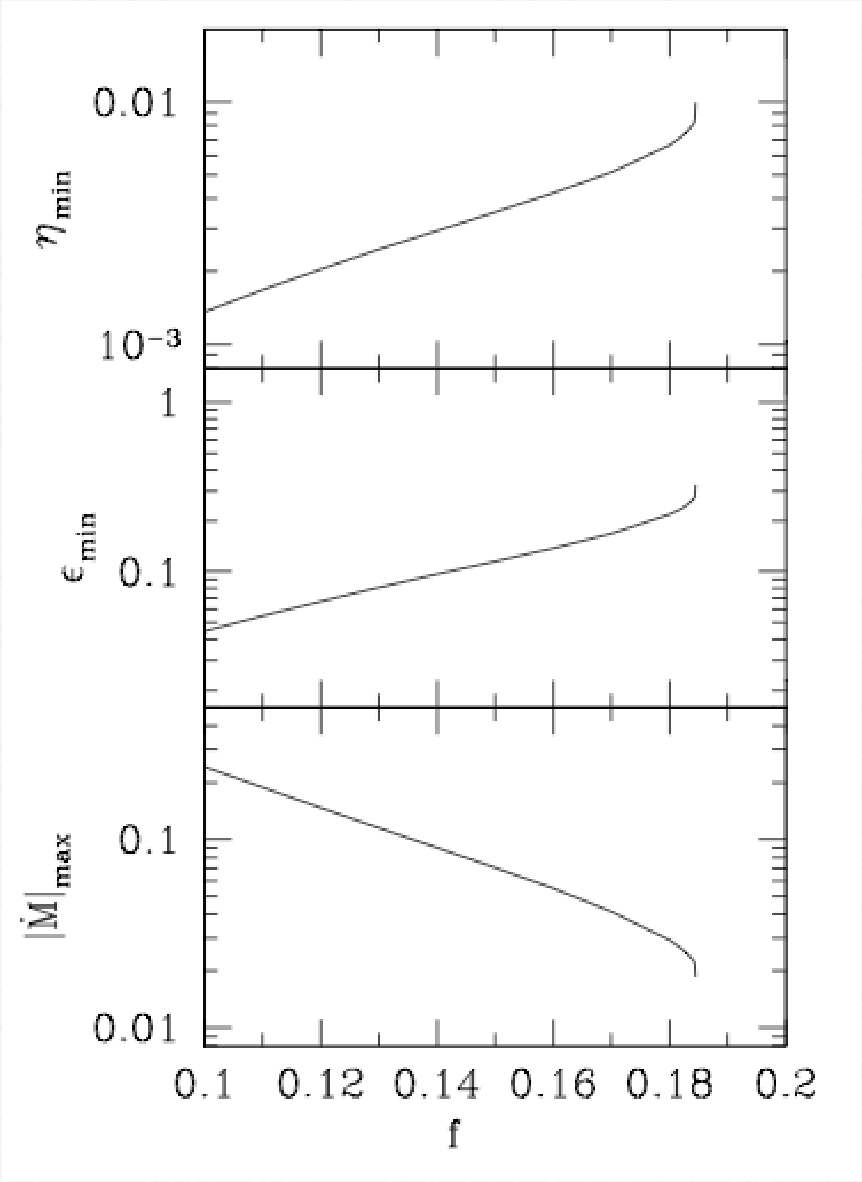
Perform Lagrangian global stability analysis





Find unstable eigenmodes

Global Unstable modes are suppressed with AGN!



(note: this never happens for conduction only model)

Useful tool for analysing models w/out sims