AGN Feedback and the Lifecycles of Radio Galaxies

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Radio galaxies and AGN feedback

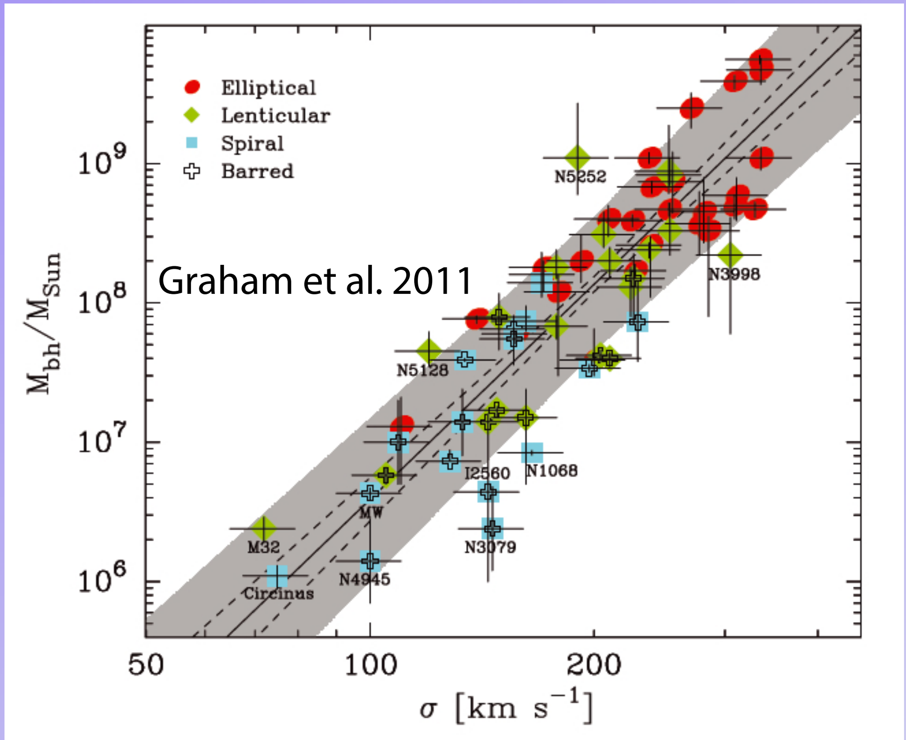
- Radio-active phase part of the life-cycle of all galaxies
- Significant amount of energy and momentum injected into the ISM during this phase
- Radio galaxies heat cooling flows - prevent further accretion
- Used in modelling the galaxy luminosity function (Croton+'06)

Feedback at earlier epochs

Contrasting physics:

- ISM in evolving galaxies is inhomogeneous
- AGN feedback is not just a matter of heating the ISM
- Dispersal of gas (-ve feedback) and/or compression leading to star formation (+ve feedback)
- Proposition: AGN feedback connected to the physics of Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum (CSS) radio sources

M-sigma relation



$$M \propto \sigma^{5-6}$$

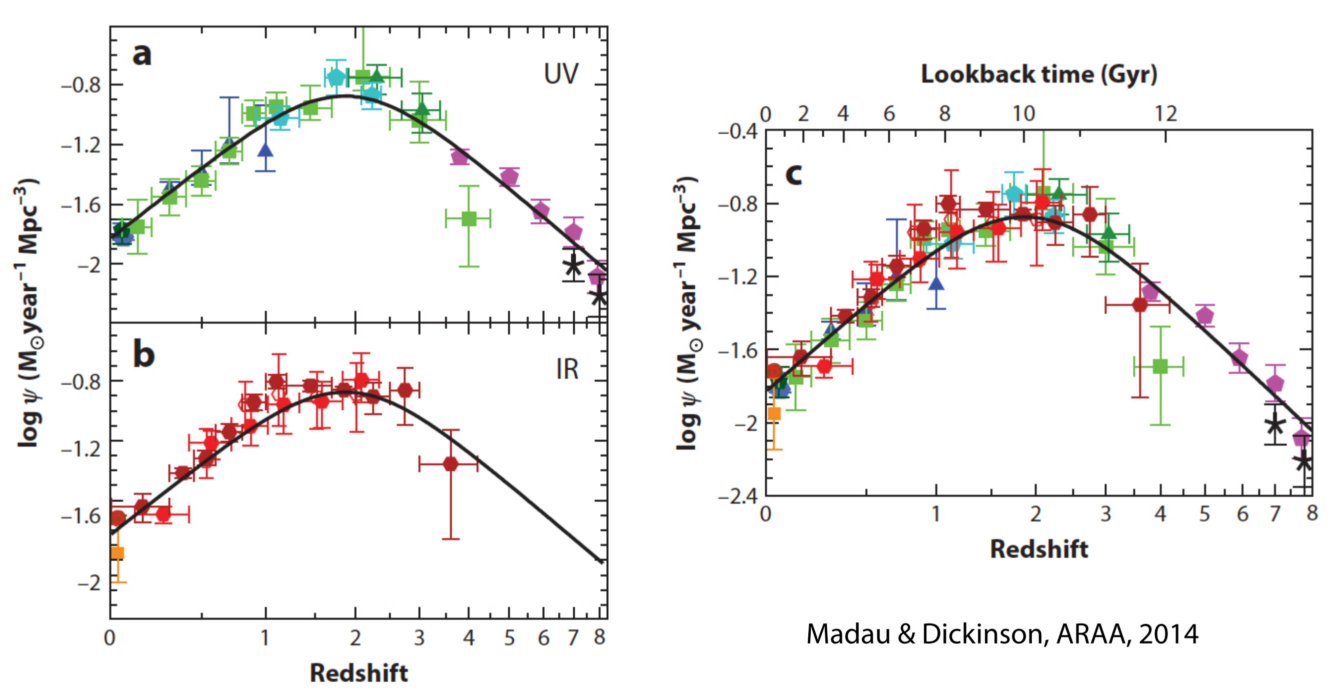
- Magorrian+ 1998 - Relationship between black hole mass and mass of bulge
- Gebhardt+ 2000 - relationship between mass and velocity dispersion

$$M \propto \sigma^4$$

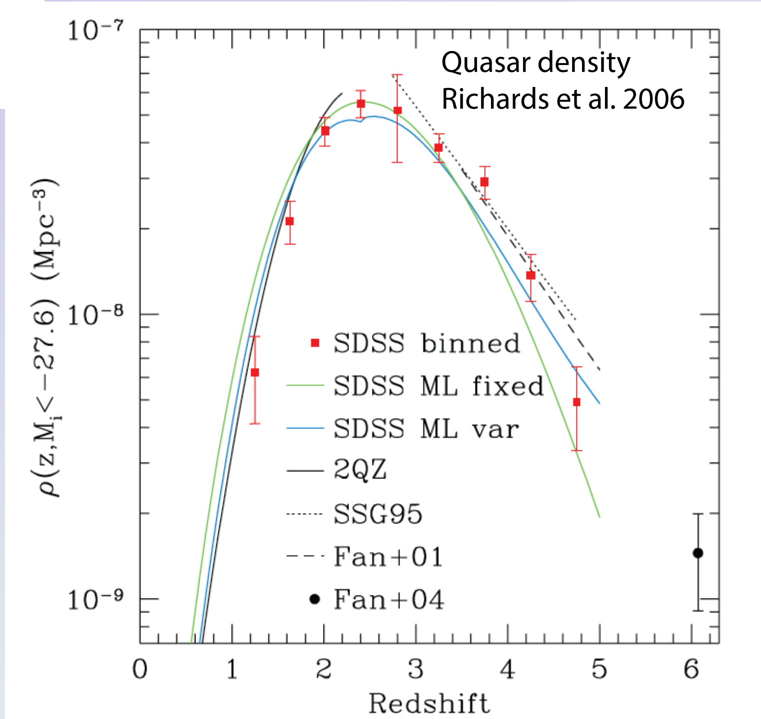
- Silk & Rees 1998 - relationship the result of feedback

$$M \propto \sigma^5$$

Star formation rate as a function of redshift



Madau & Dickinson, ARAA, 2014



Peak in star formation rate coincides with peak in quasar density – indicates star formation (and quenching of star formation?) linked with AGN activity

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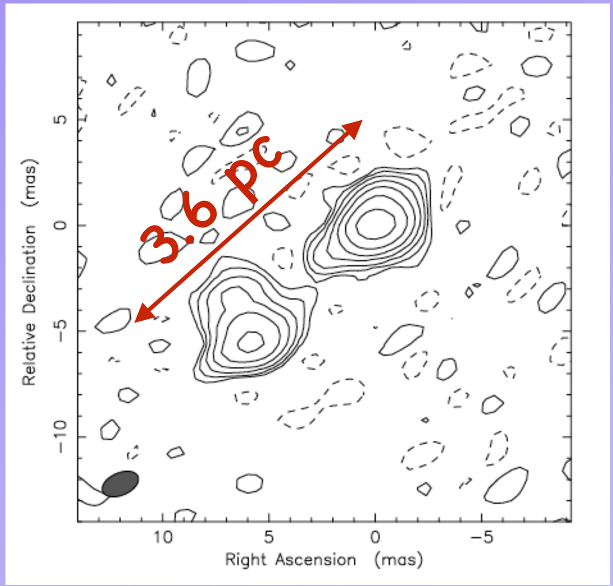
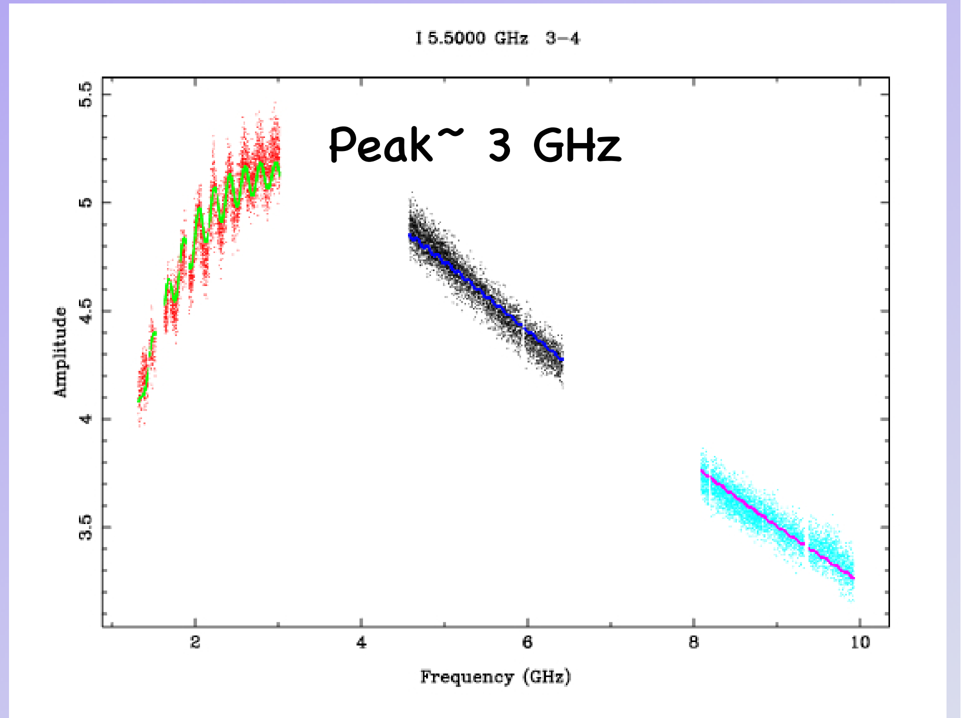
GPS & CSS sources

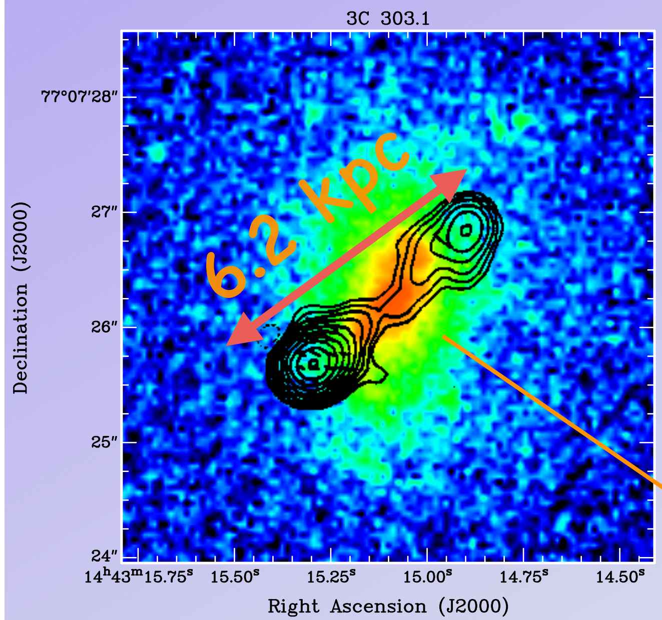


GPS source

PKS1718-649

Tingay+ '15



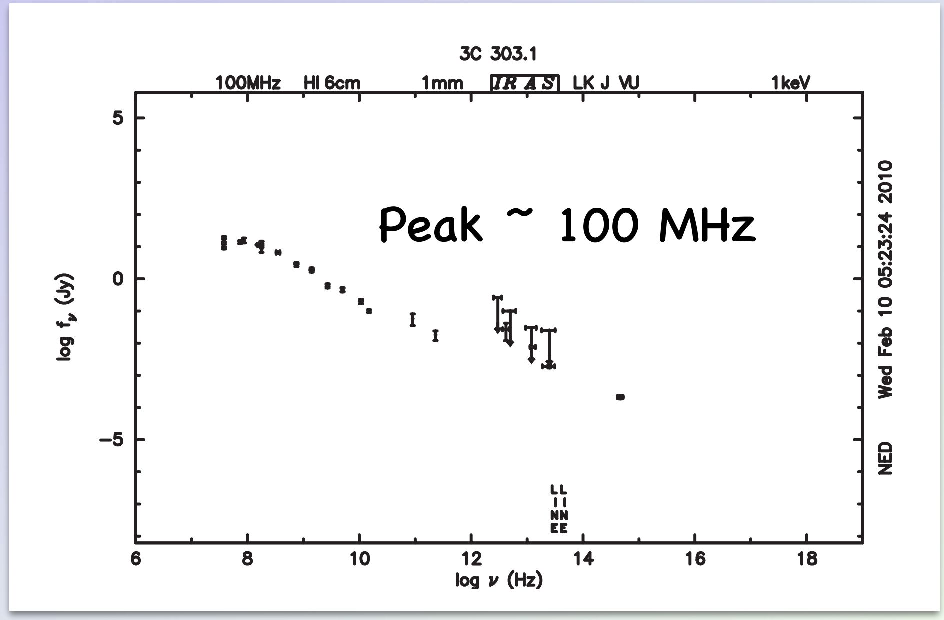


CSS source

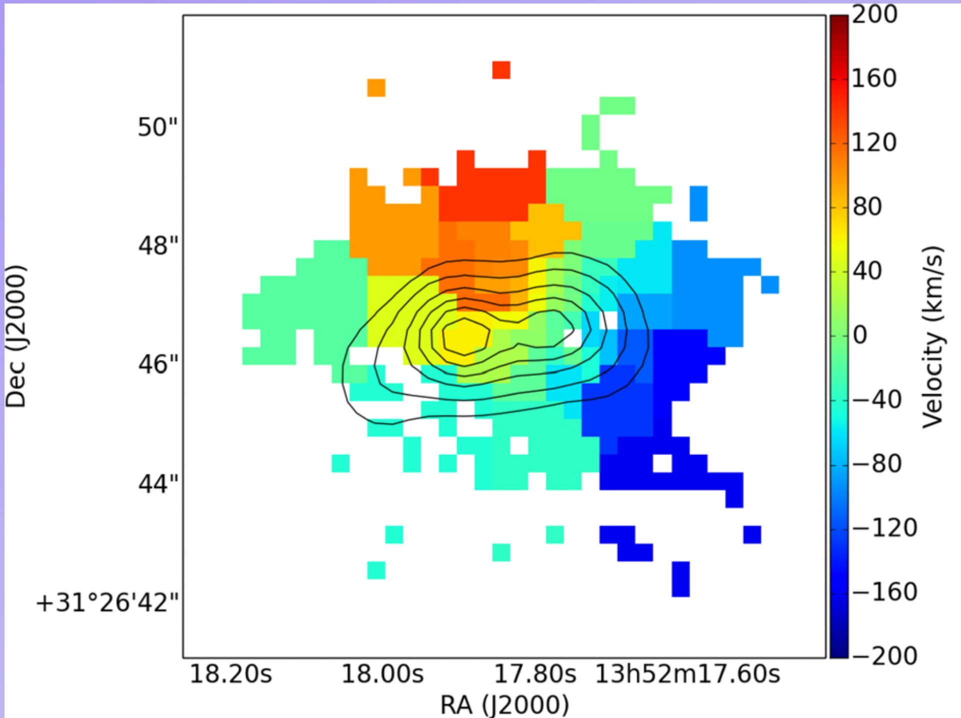
3C303.1

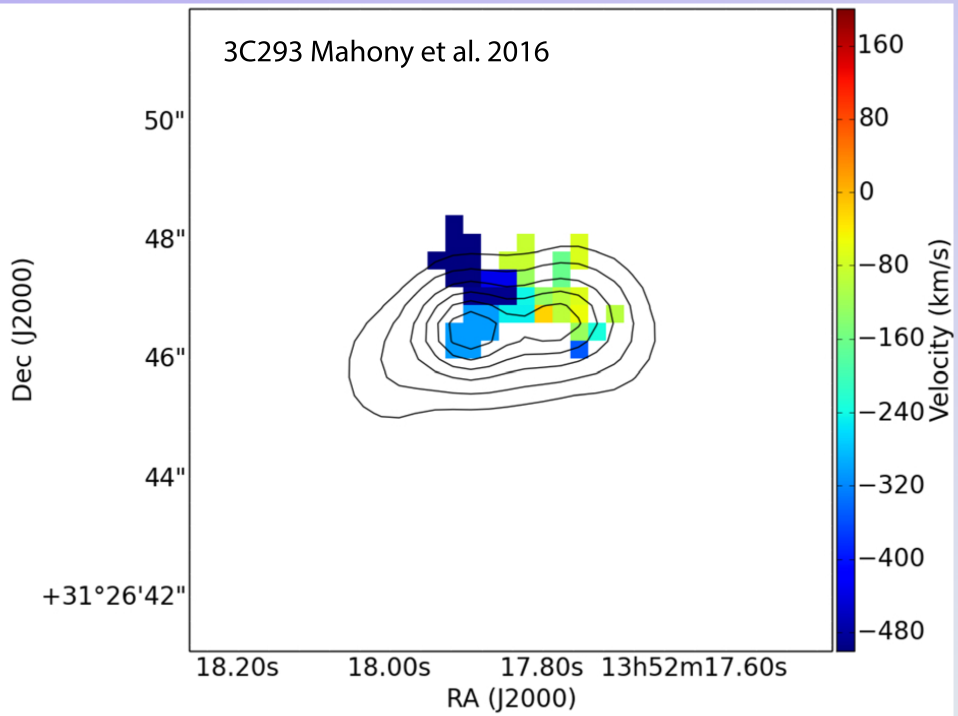
Leahy & Perley '91

OIII emission



3C293: Mahony+ 2016





Narrow [OIII] component shows rotation

Broad [OIII] component shows outflow on one side

To follow:

- Parameters of simulations from optical spectroscopic data
- Clumpy atmospheres
- Low frequency spectral slope
- Implications of steep slopes
- Comparison with peak frequency – size anticorrelation

Environment:

Galaxy & atmosphere parameters @ z~2-3

- Ryan Sanders+ 2016: Electron densities in star-forming galaxies @z~2.3 ~ 200-300 cm^{-3}
- Shirazi+ 2016: Electron densities in z~2.6-3.4 star-forming galaxies range from 120 - 2800 cm^{-3}
- Förster-Schreiber+ 2009 (Clumpy) Hα Velocity dispersions ~ 35-280 km s^{-1}

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Simulations:

Baryonic and dark matter parameters

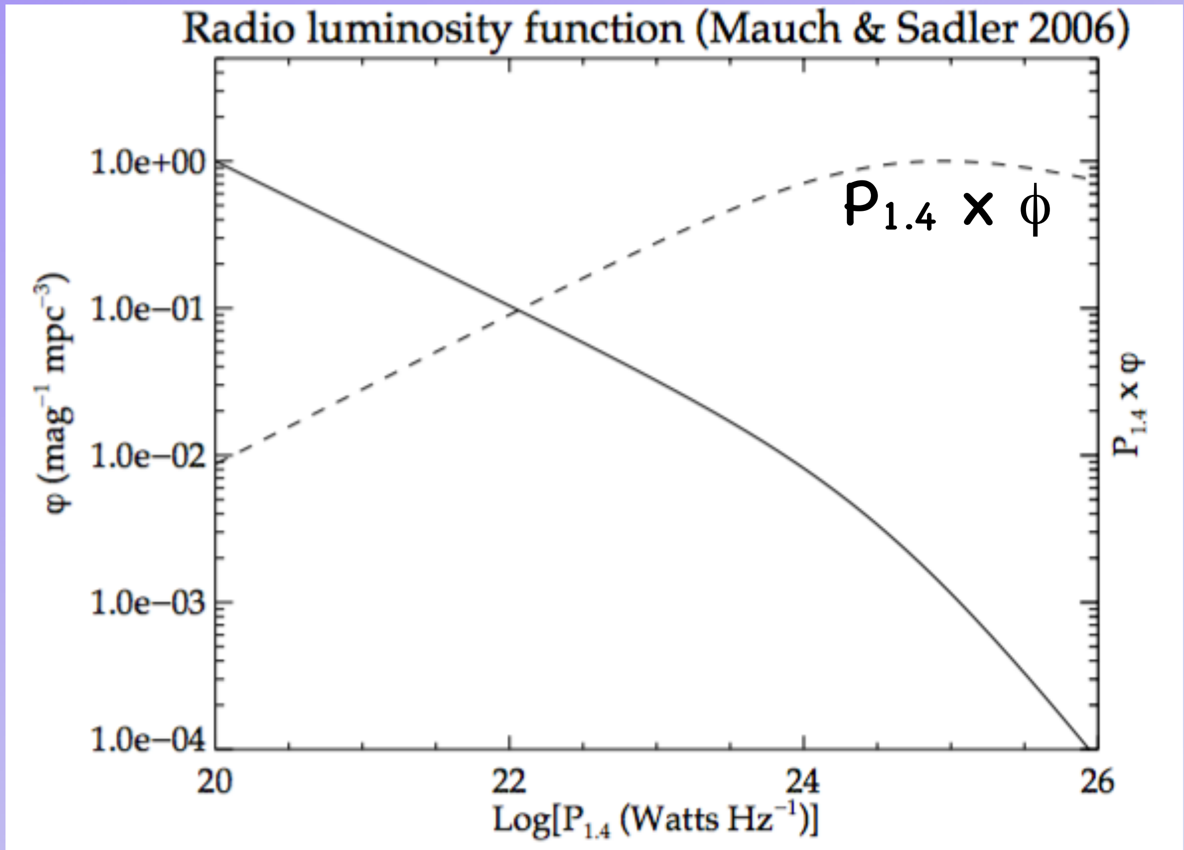
Parameters		Value
Baryonic velocity dispersion	σ_B	250 km s^{-1}
Baryonic core radius	$r_{\rm B}$	0.4, 1.0 kpc
Ratio of dark matter to baryonic core radii	$r_{\rm D}/r_{\rm B}$	5
Dark matter velocity dispersion	$\sigma_{\rm D}$	500 km s^{-1}
Halo Temperature	$T_{\rm h}$	10^7 K
Central hot halo density	$n_{\rm h,0}$	0.5 cm^{-3}

Jet and ISM parameters

Model	$\log P_{\rm jet}$ ergs s^{-1}	Warm clouds σ_c km s^{-1}	n_0 cm^{-3}	Mass $M_\odot$	$T_{\rm floor}$ K	r_B kpc
A	44	50	400	6.46×10^9	10^2	1.0
B	44	100	150	2.89×10^9	10^4	1.0
C	45	50	400	6.46×10^9	10^2	1.0
D	45	100	150	2.89×10^9	10^4	1.0
E	45	100	200	2.44×10^9	10^2	1.0
F	45	100	300	9.24×10^9	10^4	1.0
G	45	250	400	6.61×10^9	10^2	1.0
H	45	250	1000	3.47×10^9	10^2	0.4
I	46	250	1000	3.47×10^9	10^2	0.4
J	46	250	2000	4.76×10^{10}	10^2	1.0
K	46	300	1000	1.20×10^{10}	10^2	0.4

Gas masses at higher end of range inferred for high z radio galaxies by Nesvadba+ 2011, Cano-Diaz+ 2012, Carnian+ 2015

Jet power



Most important range of 1.4 GHz radio power around

10^{25} W Hz^{-1}

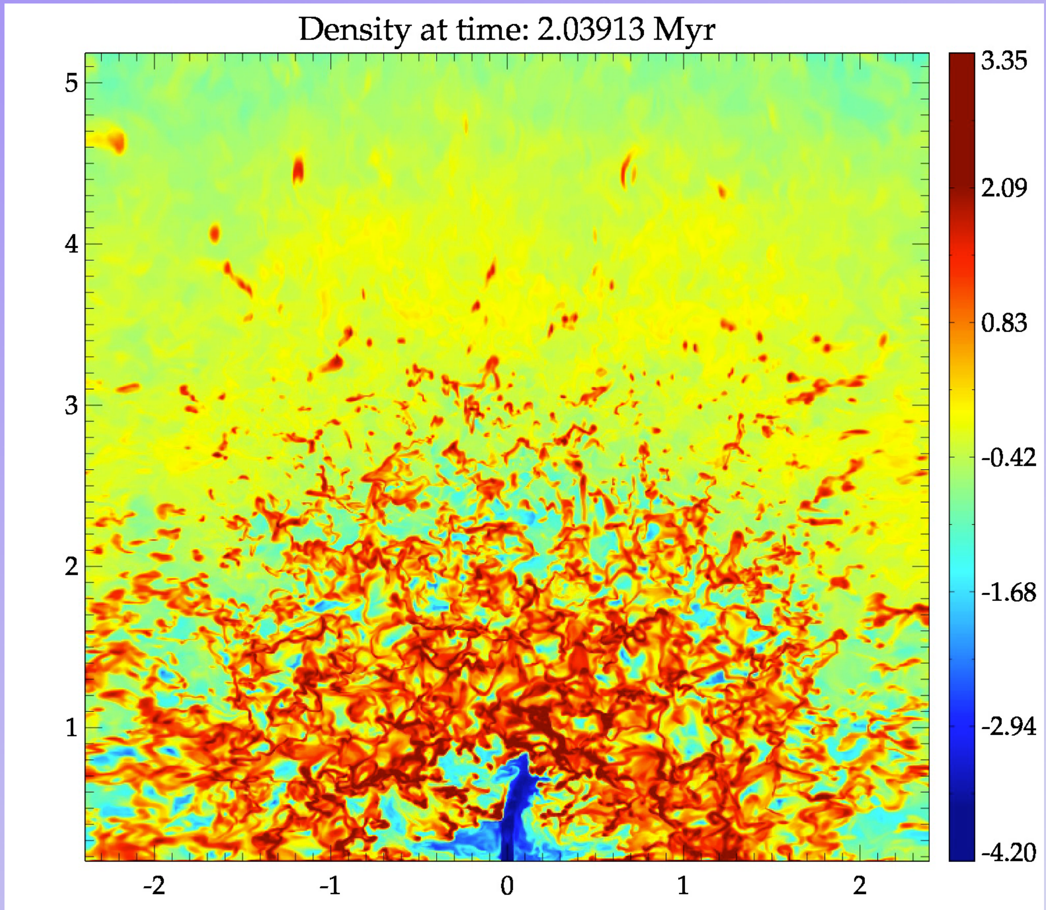
Corresponds to jet power ~ 10^{43-45} ergs s^{-1}

Establishing a clumpy medium

Clouds embedded in hot atmosphere:

- Log normal density distribution
- Power-law in Fourier space
- Pressure equilibrium with hot ISM - defines temperature
- Supported by turbulent velocity dispersion in gravitational field
- Low density cutoff when $T > 3.4 \times 10^4$ K - produces clumpy distribution

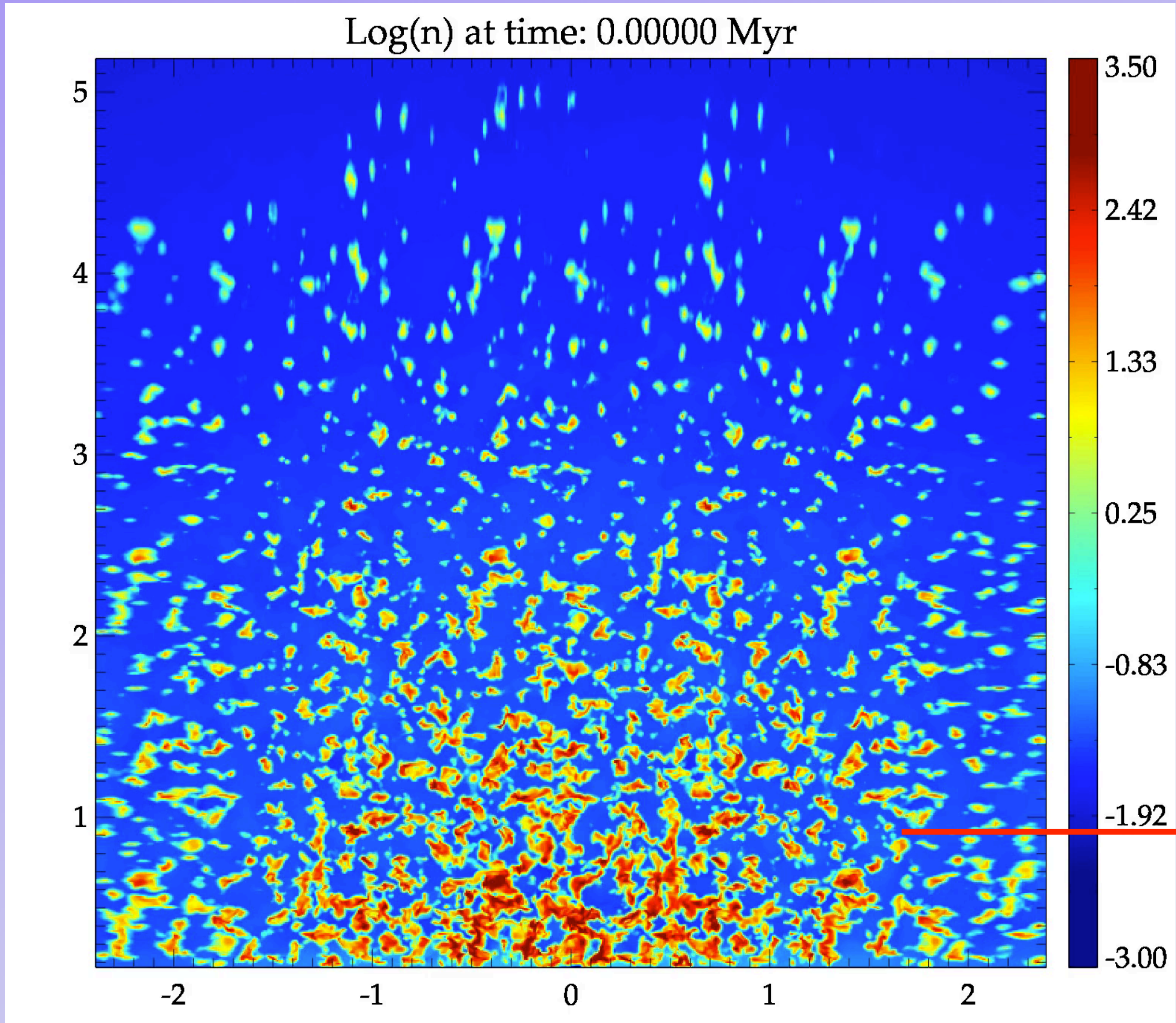
Gas distribution



- Holes in distribution of dense gas result of low density cutoff
- Radial distribution of dense gas result of turbulent pressure support in gravitational field - turbulent hydrostatic equilibrium

Simulation of jet - ISM interaction

Mid-plane slice of log(density)



10^{45} erg/s relativistic jet propagating through dense clouds embedded in a hot atmosphere

Radio source disperses gas inhibiting star formation - AGN feedback

Clouds free-free absorb radio emission producing low frequency peak in spectrum

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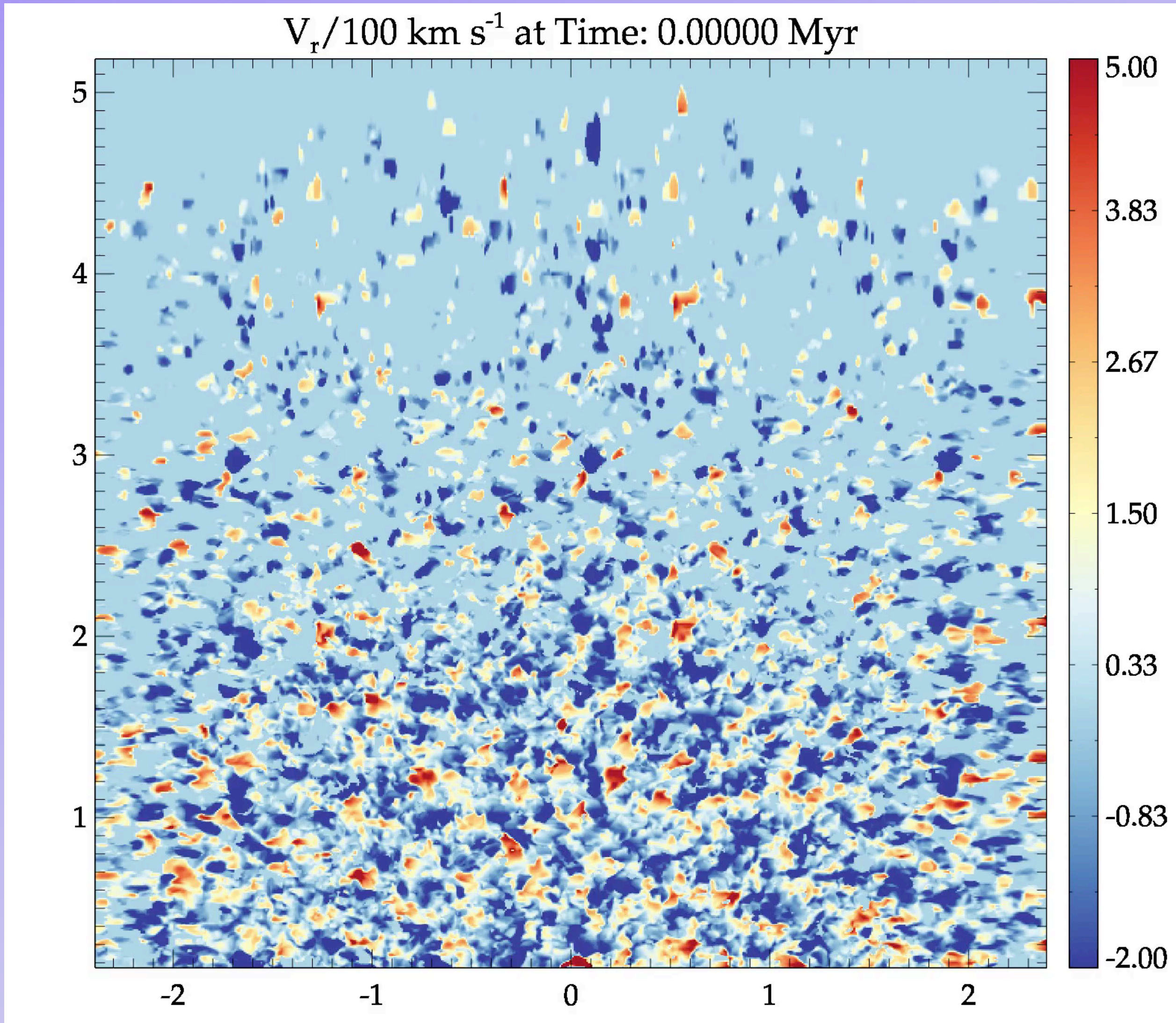
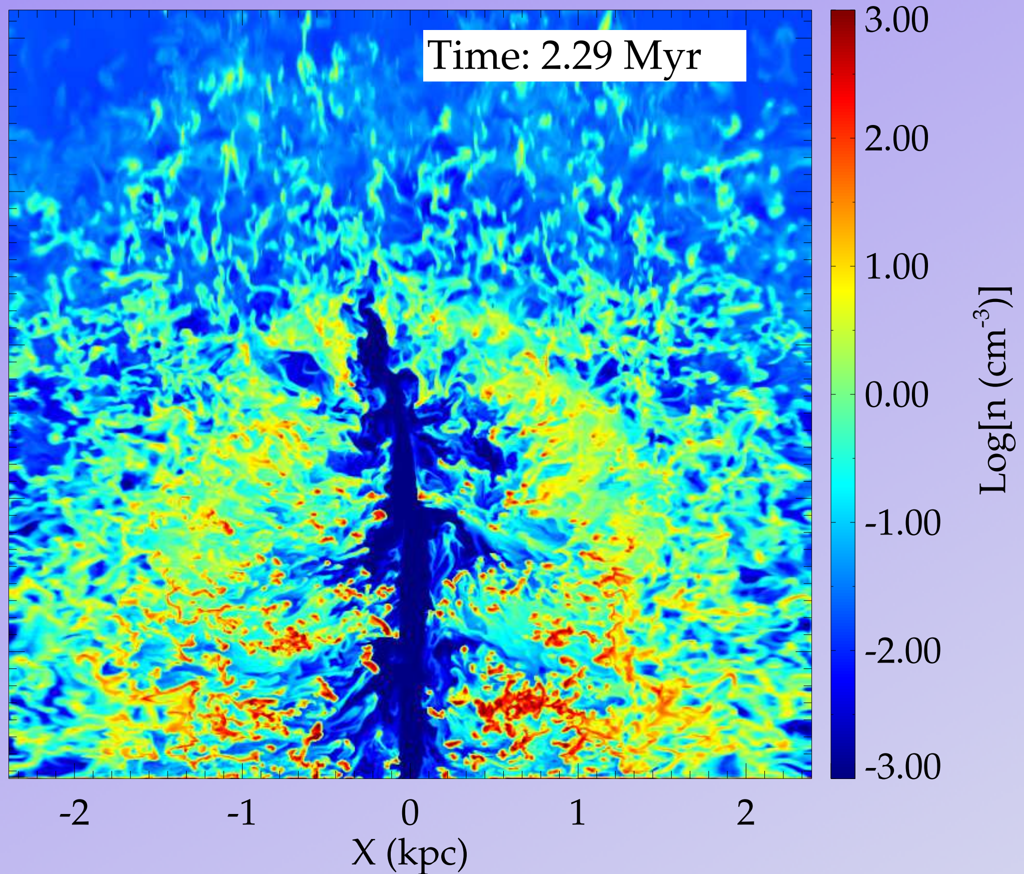
Radial component of gas velocity

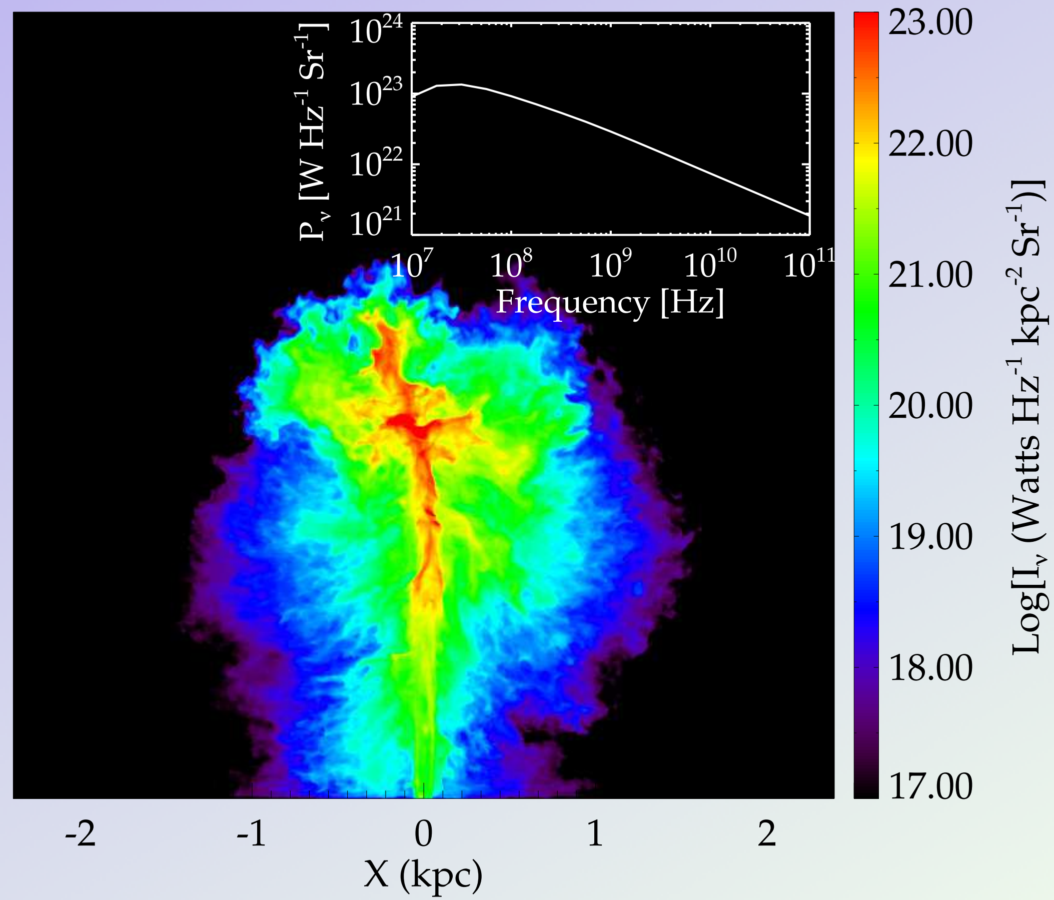


ISM becomes turbulent but gas not driven to escape velocity

Duty cycle of activity important

Density, radio surface brightness, spectrum





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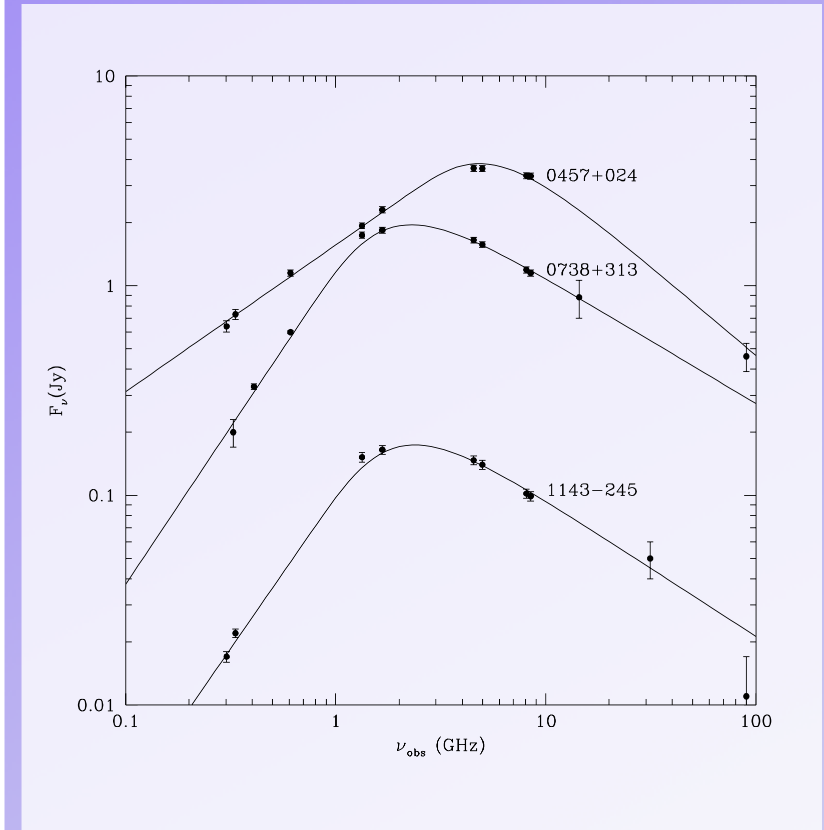
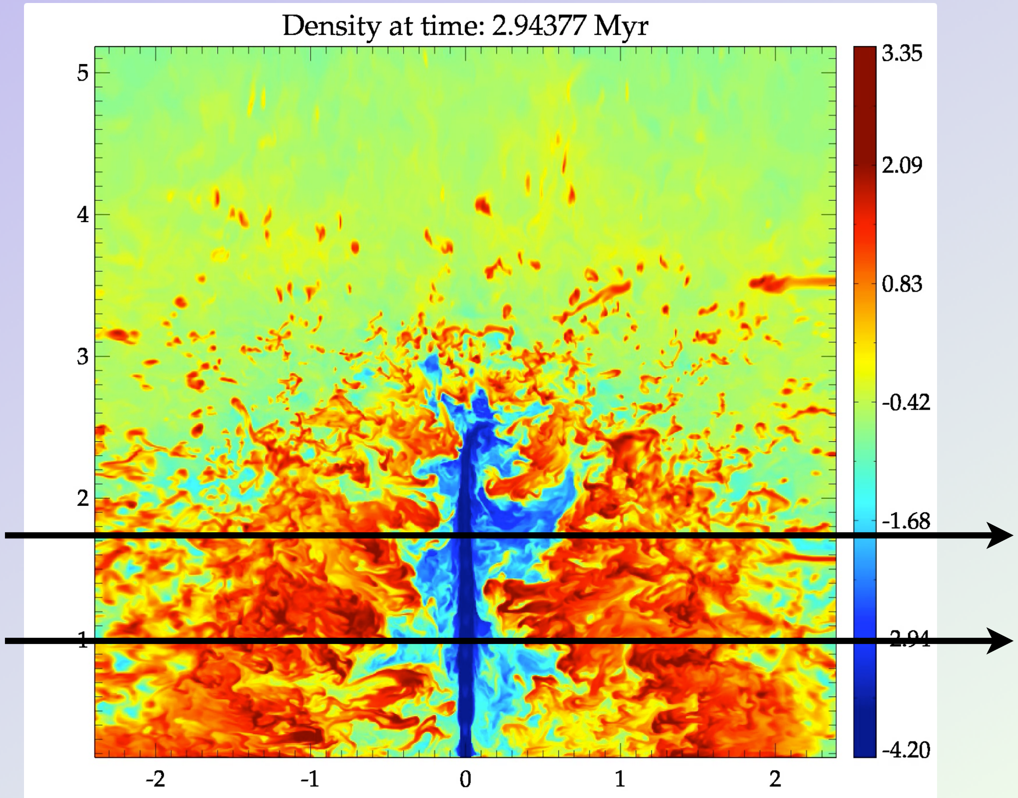
GPS and CSS sources



- Low frequency power-law attributed to distribution of free-free optical depths (GB, Dopita, O'Dea 1997)

Integrate through simulation to determine surface brightness and spectrum



Synchrotron emissivity

Assume electron energy density and magnetic energy density proportional to total energy density

Electron energy distribution: $N(\gamma) = K\gamma^{-a} \quad a = 2\alpha + 1$

Doppler factor

Jet tracer

$$\langle j_\nu \rangle = \text{Constants} \times \; \delta^{2+\alpha} \phi_{\text{jet}} \, f_{\text{e}} \, f_{\text{B}}^{(a+1)/4} \left(\frac{\epsilon_{\text{tot}}}{\epsilon_0} \right)^{(a+5)/4} \left(\frac{\nu}{\nu_0} \right)^{-\alpha}$$

$$\epsilon_e = f_e \times \epsilon_{\text{tot}}$$
$$f_e = 0.1$$

$$\epsilon_B = f_B \times \epsilon_{\text{tot}}$$
$$f_B = 0.1$$

Free-free absorption

Density^2 dependence

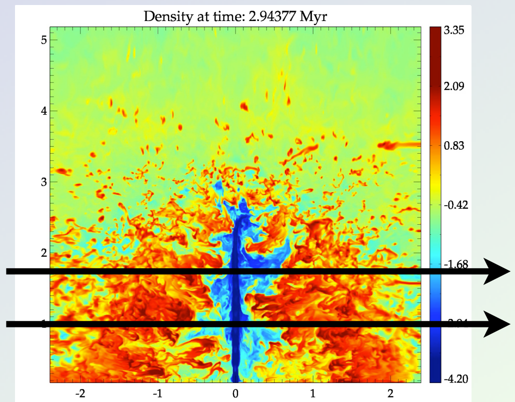
$$\alpha_\nu(Z) = \text{Constants} \times \left(\frac{kT}{m_{\rm e}c^2}\right)^{-3/2} n_{\rm e}\, n_{\rm i}(Z)\, Z^2\, g_\nu(T,Z)\, \nu^{-2}$$

Frequency dependence

Integrate

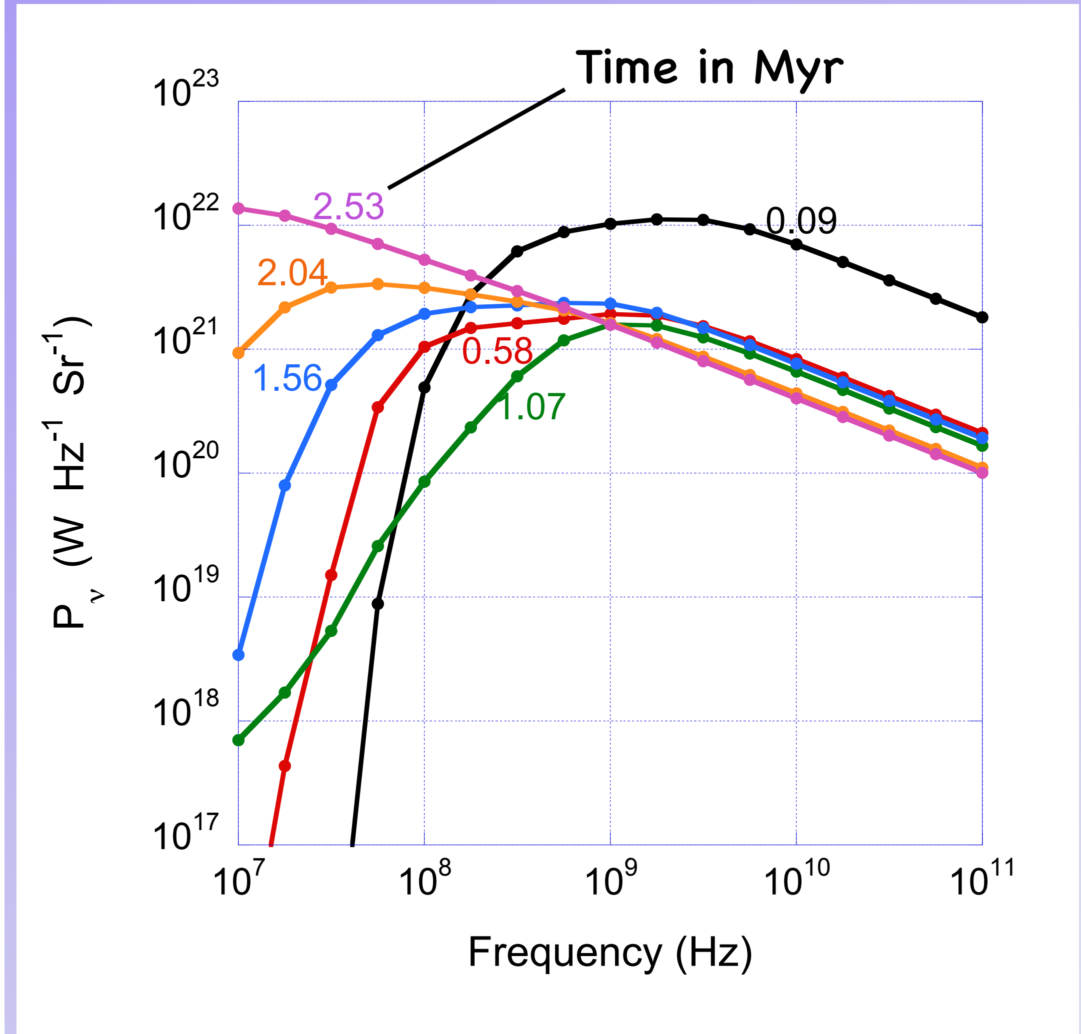
$$\frac{dI_\nu}{ds} = \langle j_\nu \rangle - \alpha_\nu I_\nu$$

along rays through volume



Spectral evolution:

$P_{jet}=10^{45}$ ergs/s $\sigma_{cloud}=250$ km s^{-1} $n_{cloud,0}$ = 400 cm^{-3}



- Peak moves to lower frequencies as source evolves – Effect of decreasing density and path length
- Spectral slope flattens – Effect of increasing dispersion in optical depth

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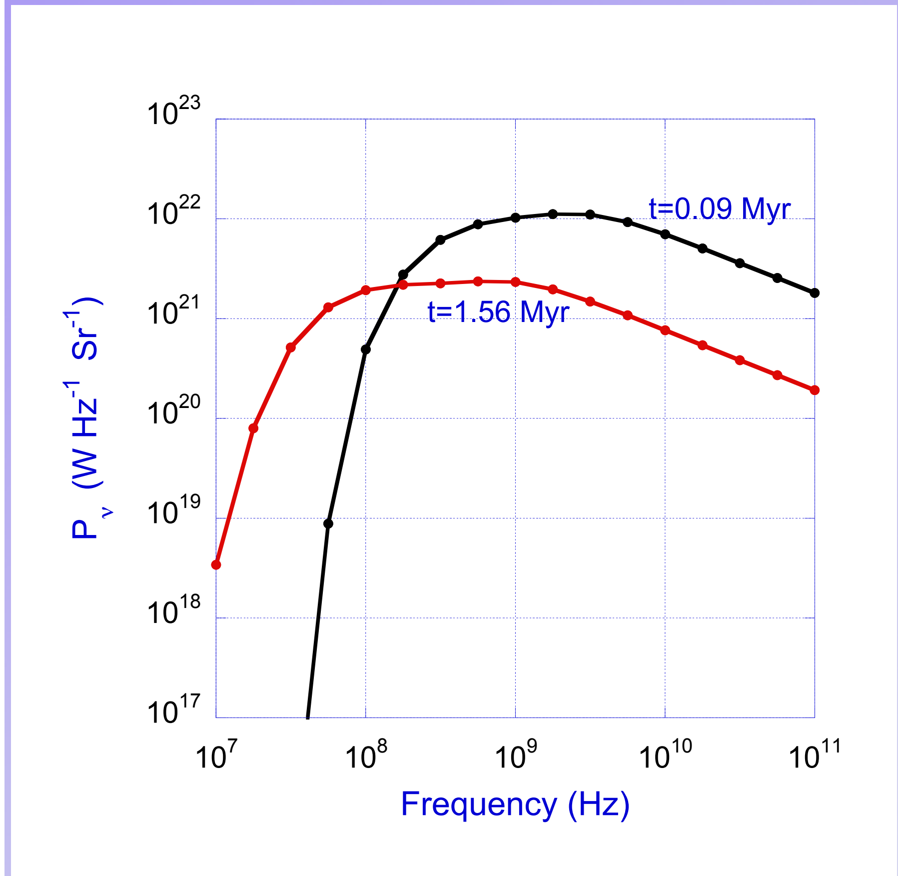
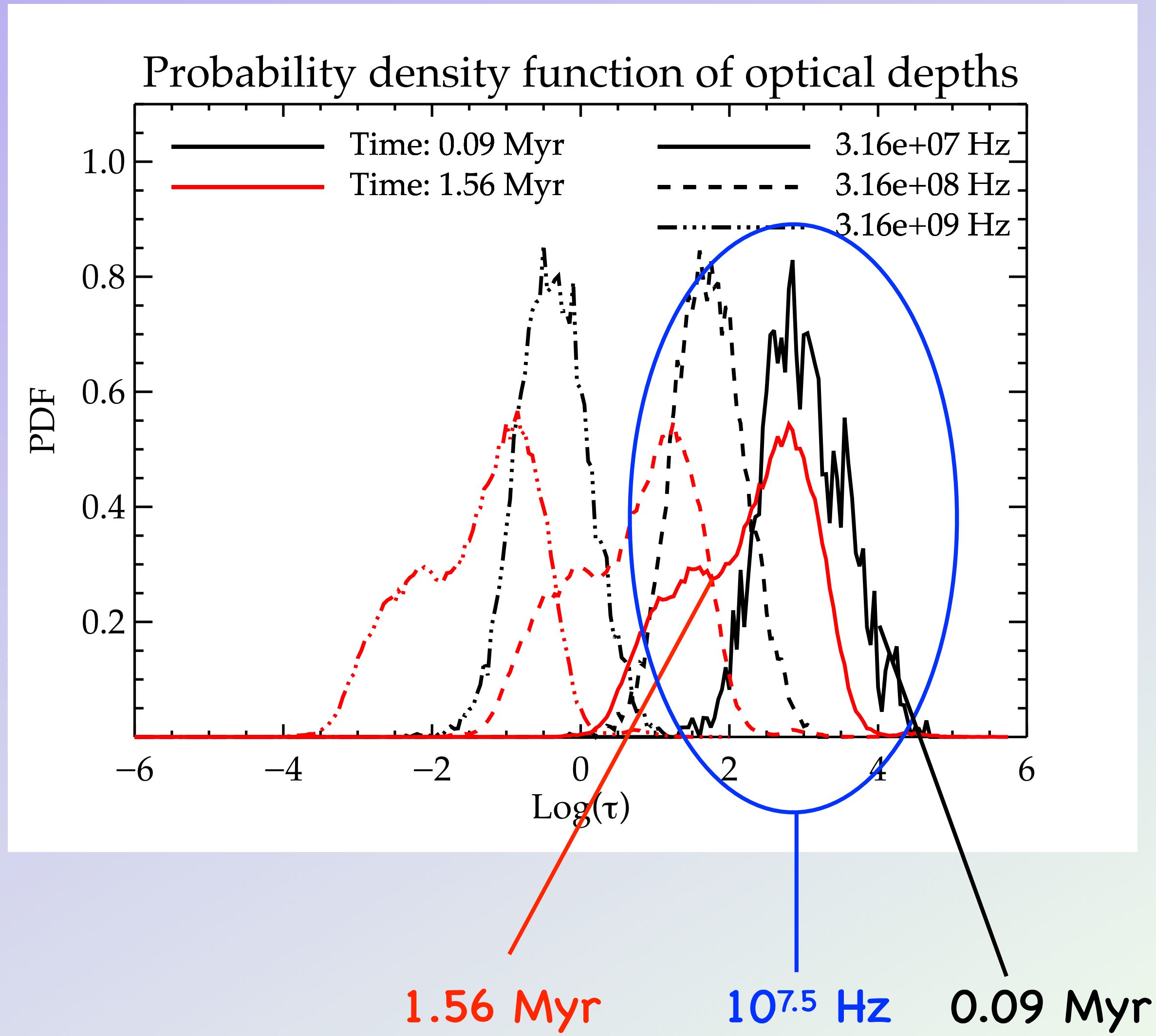
Spectrum and optical depth

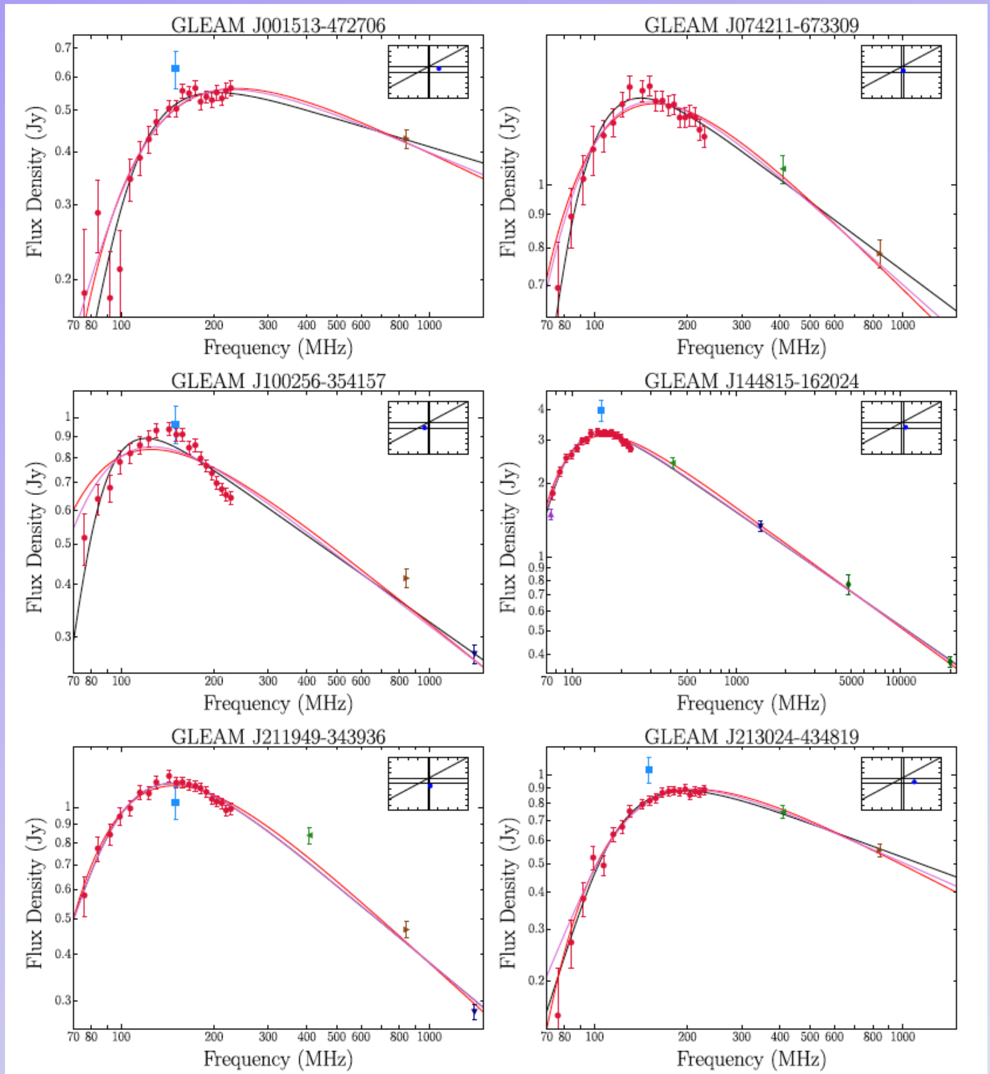
Comparison of 0.09 Myr and 1.56 Myr spectrum





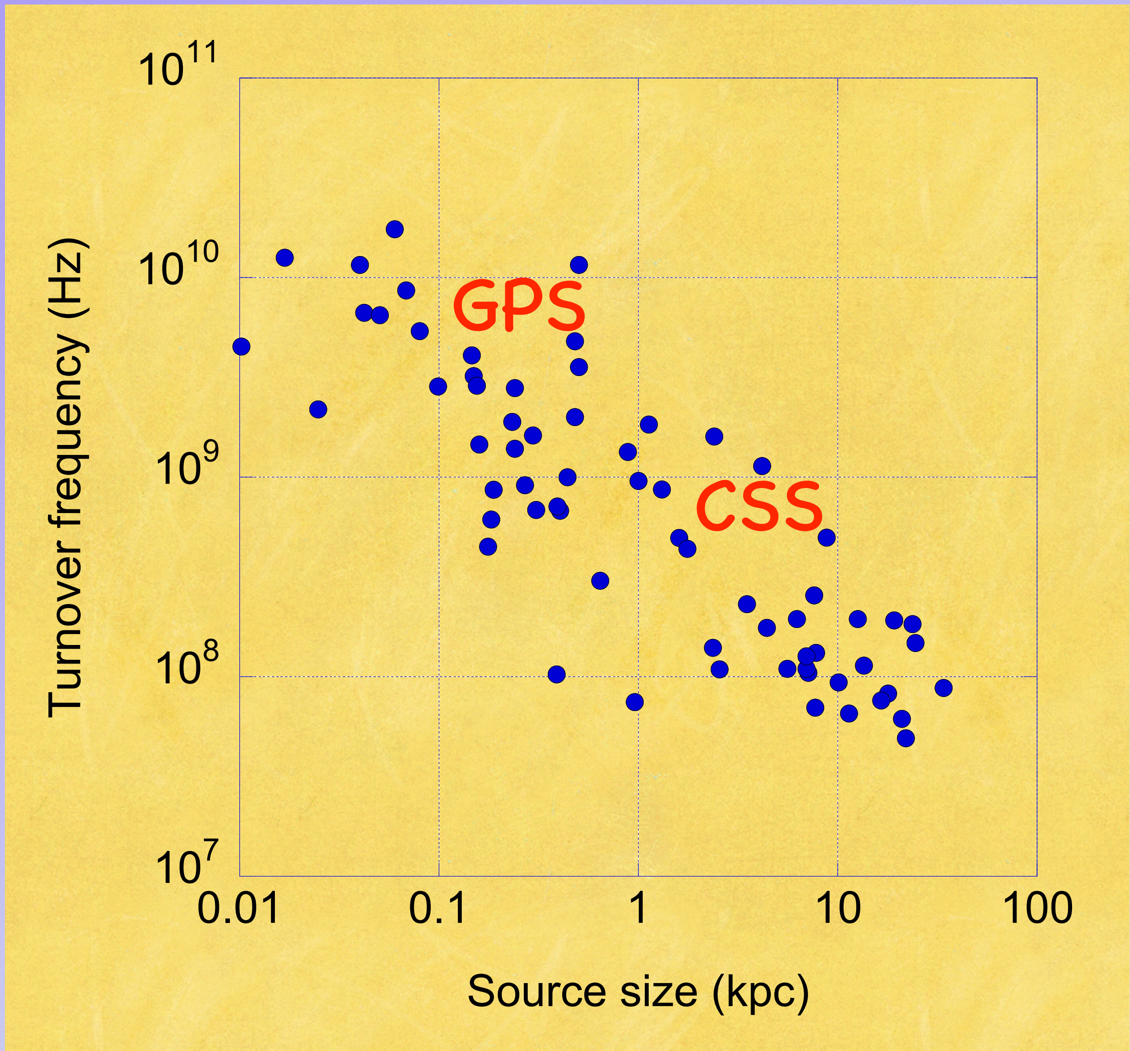
GLEAM survey (Hurley-Walker+ 2017)

Peak spectrum sources: Callingham+ 2017



- 6 sources from Callingham+ 2017 with low frequency spectral index > 2.5
- Rules out synchrotron self absorption as the cause of low frequency peak
- Models suggest that these are young sources

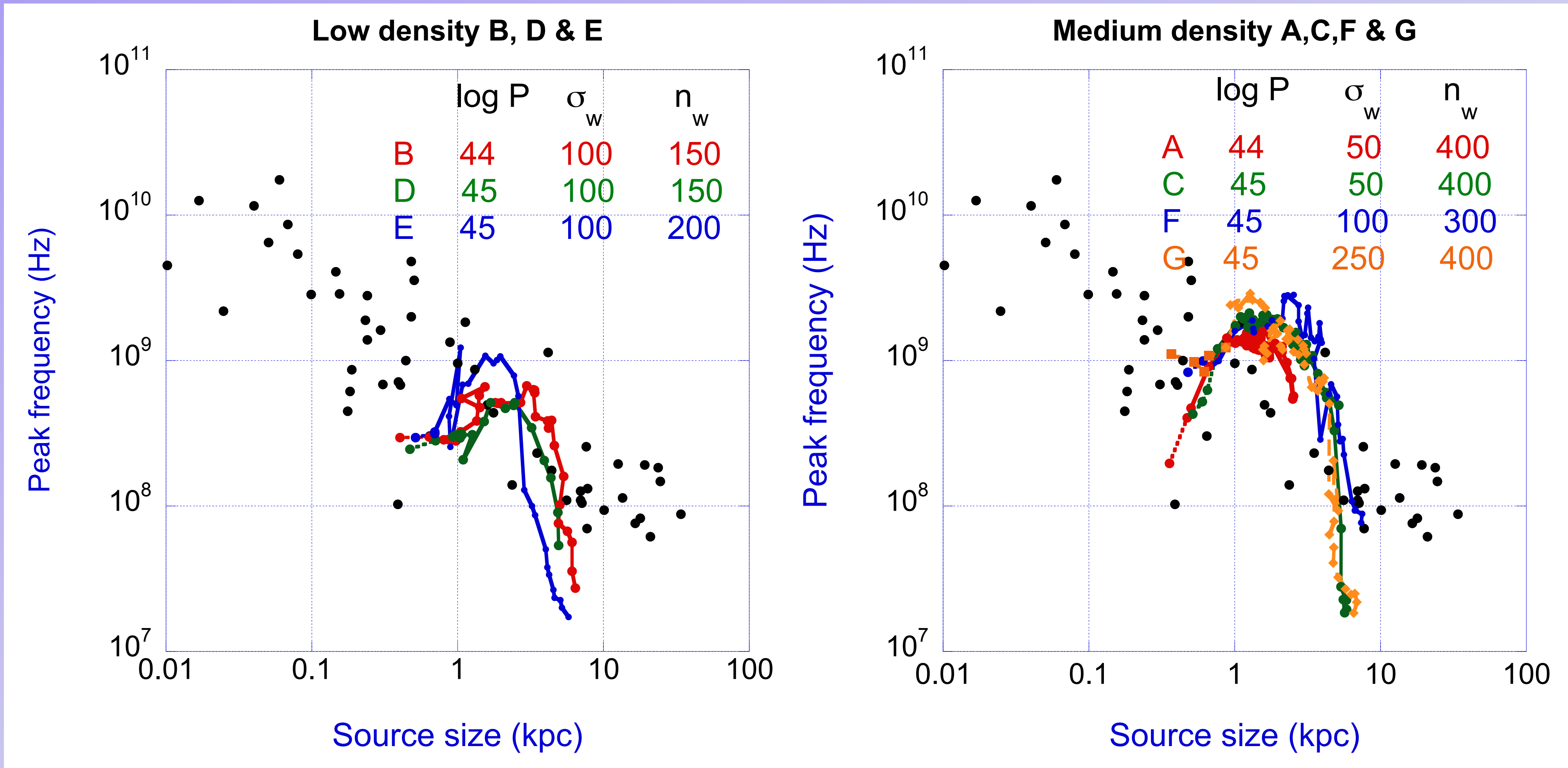
Turnover frequency and size (O'Dea & Baum '91)



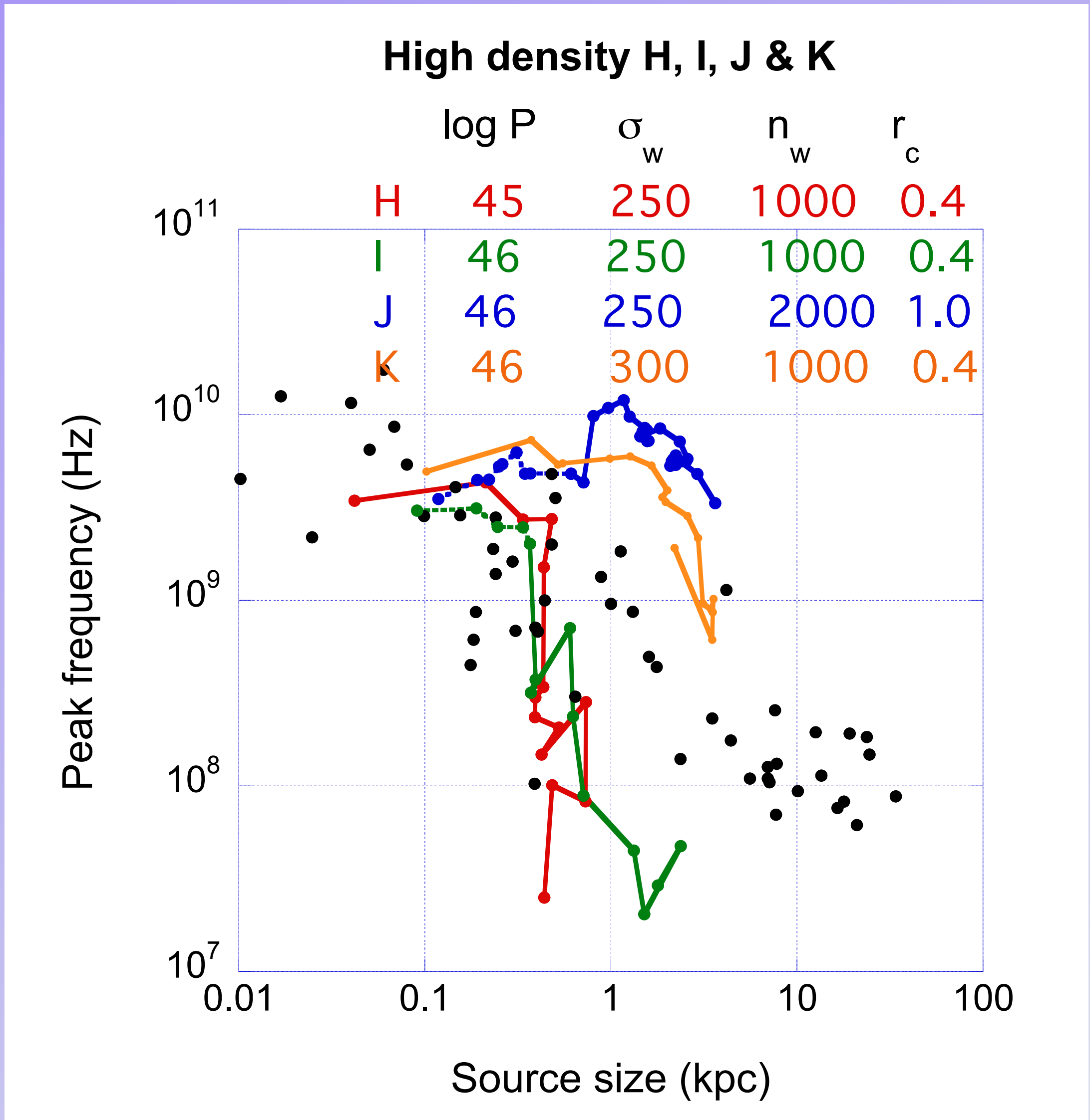
Inverse correlation

GPS and CSS sources represent different evolutionary stages of radio galaxies

Low density (150-200 cm^{-3}) & medium density (300-400 cm^{-3})



Higher densities (n ~ 1000 cm^{-3})



- High density starts to populate upper part of correlation
- Very high density (n=2000 cm^{-3}) pushes source well off correlation
- Still have a decrease in peak frequency resulting from decrease in gas density beyond core radius

Dark matter, stars and gas

Parameters of dark matter and stars (baryons):

$$\kappa = \text{Ratio of velocity dispersions} = \frac{\sigma_D}{\sigma_B}$$

$$\lambda = \text{Ratio of core radii} = \frac{r_D}{r_B}$$

Asymptotically:

$$\frac{\rho_B}{\rho_{B,0}} \sim r^{-2\kappa^2}$$

For $\kappa^2 = 3/2 \quad \rho_B \sim r^{-3} \approx$ Reynolds-Hubble law

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Gas distribution

Gas distribution defined by dispersion relative to baryons:

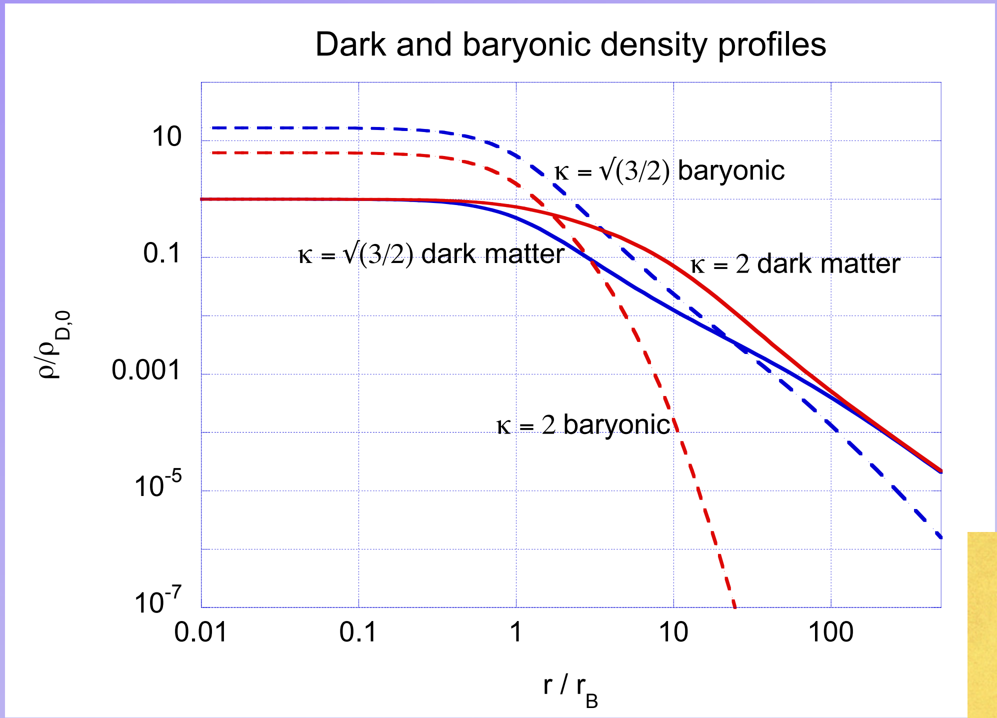
$$\frac{\sigma_W}{\sigma_B}$$

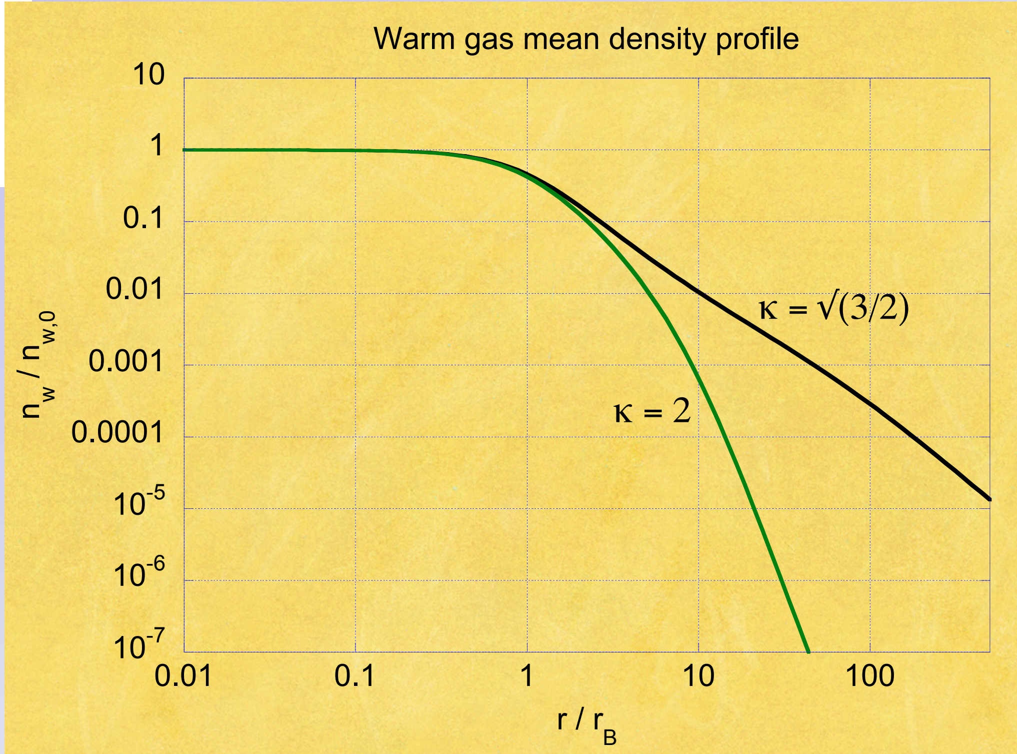
$$\frac{n_W}{n_{W,0}} \sim r^{-2\kappa^2(\sigma_W/\sigma_B)^{-2}}$$

New simulation:

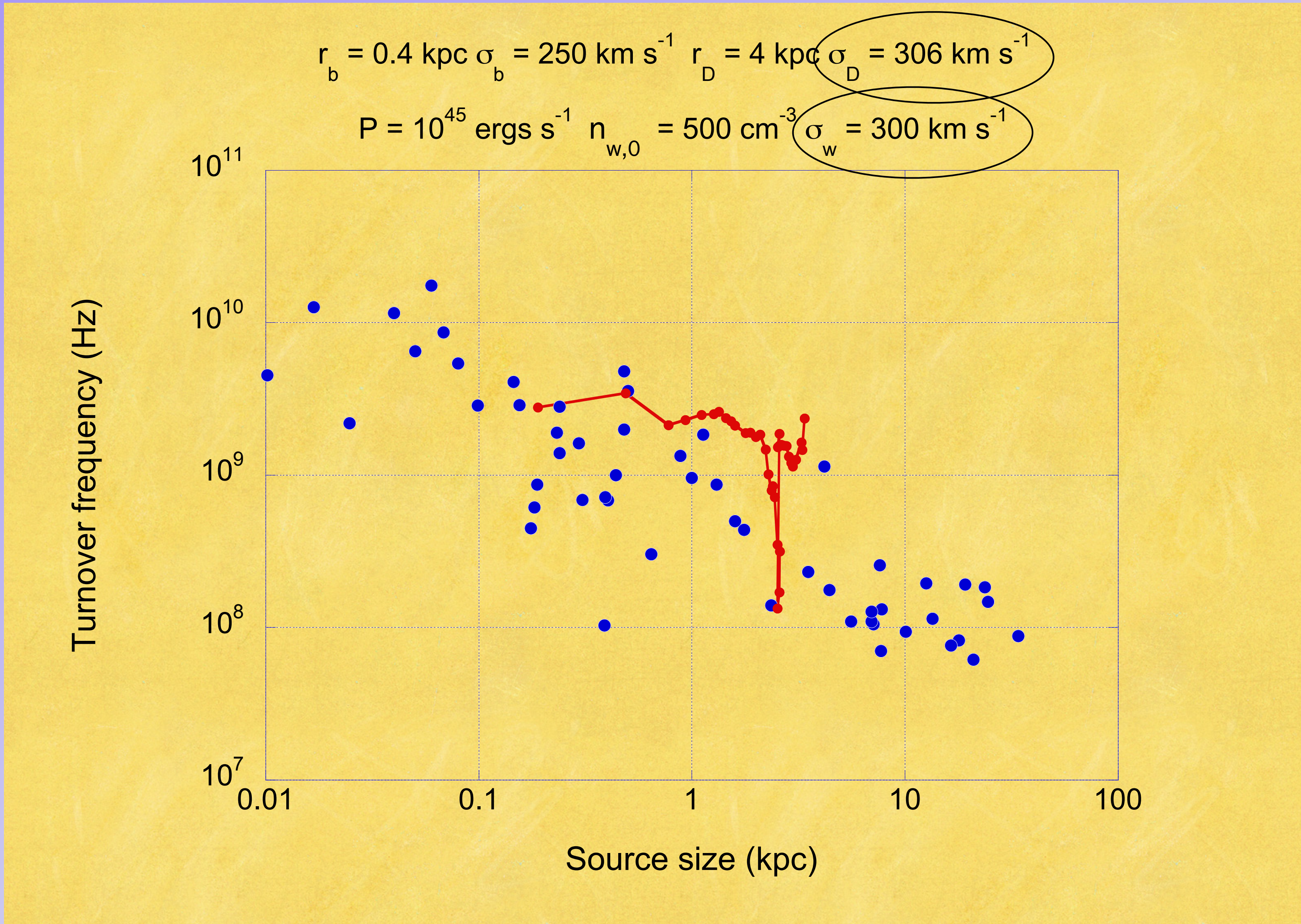
$$\kappa = \sqrt{3/2} \quad \frac{\sigma_W}{\sigma_B} = 1.2 \Rightarrow n_W \sim r^{-2.08}$$

Distribution of dark and baryonic matter

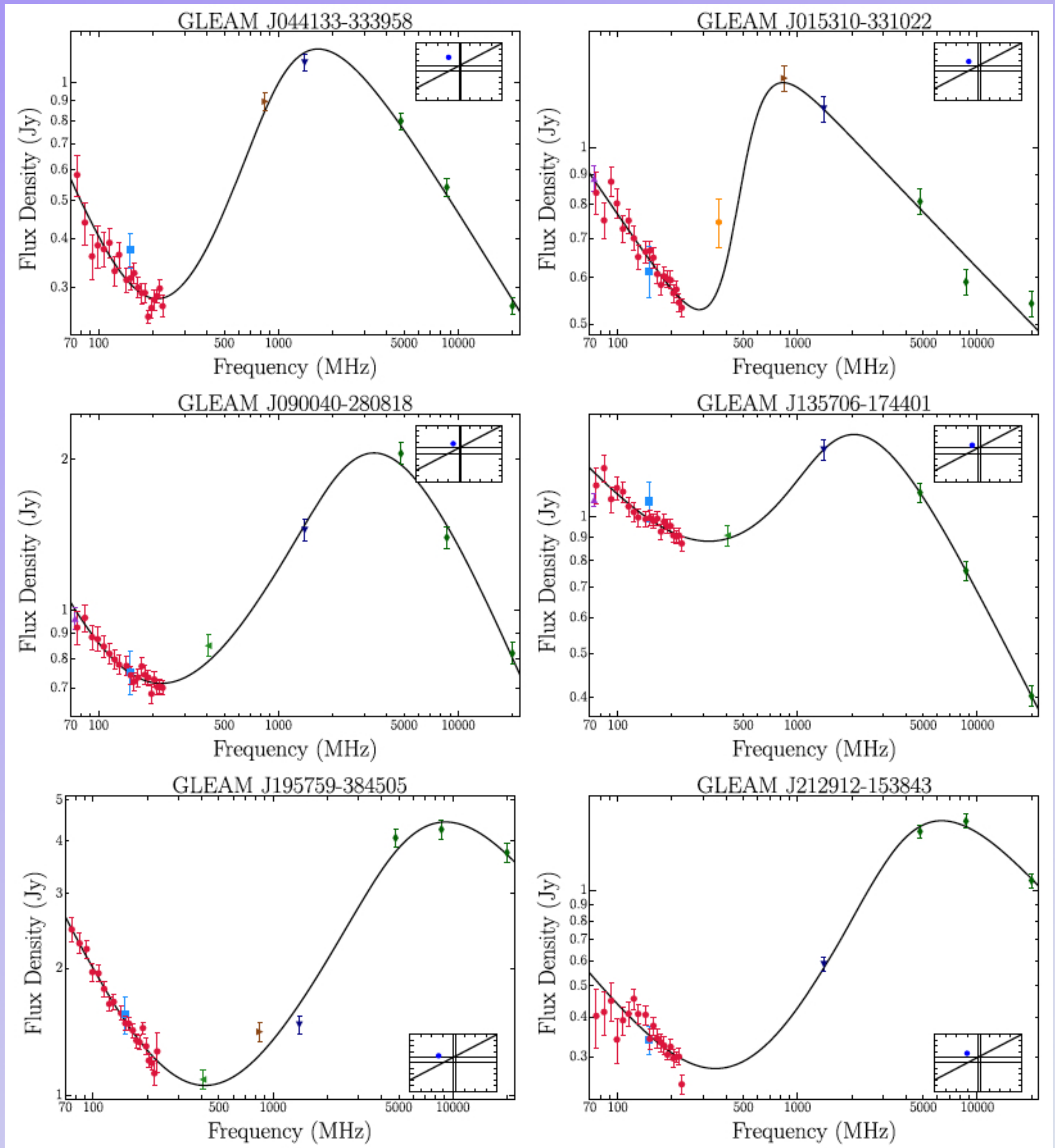




More extended warm gas

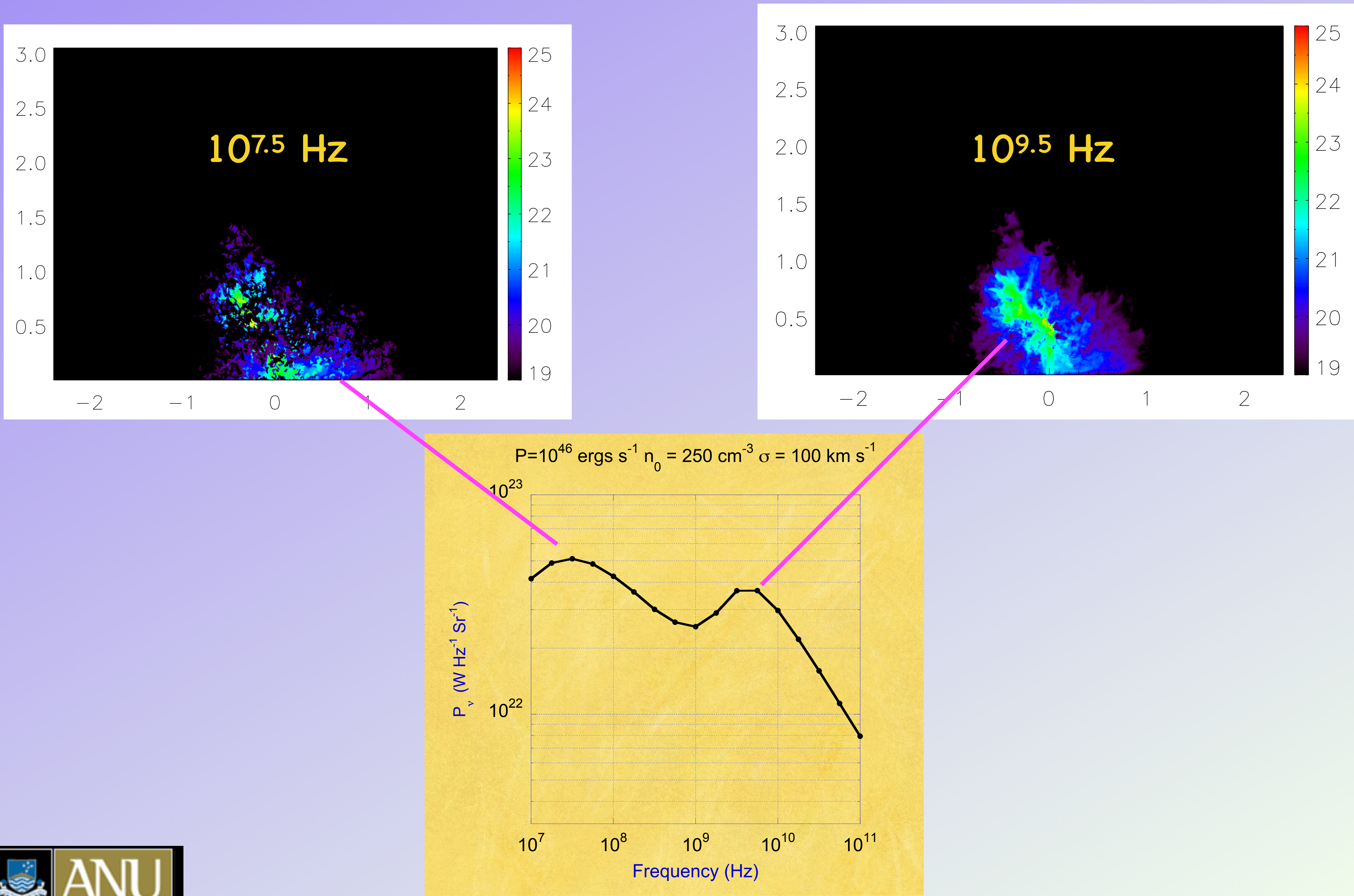


Low frequency upturns



Spectra from Callingham+ 17, which turn up at low frequency

Patchy absorption



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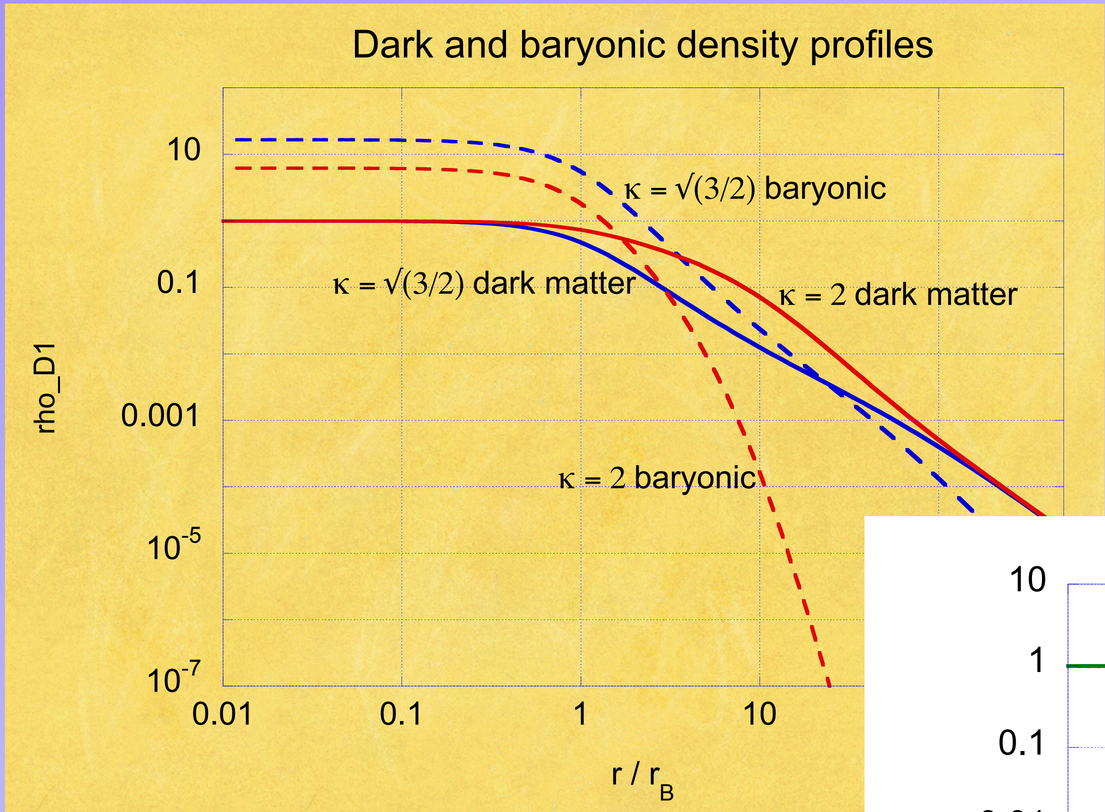
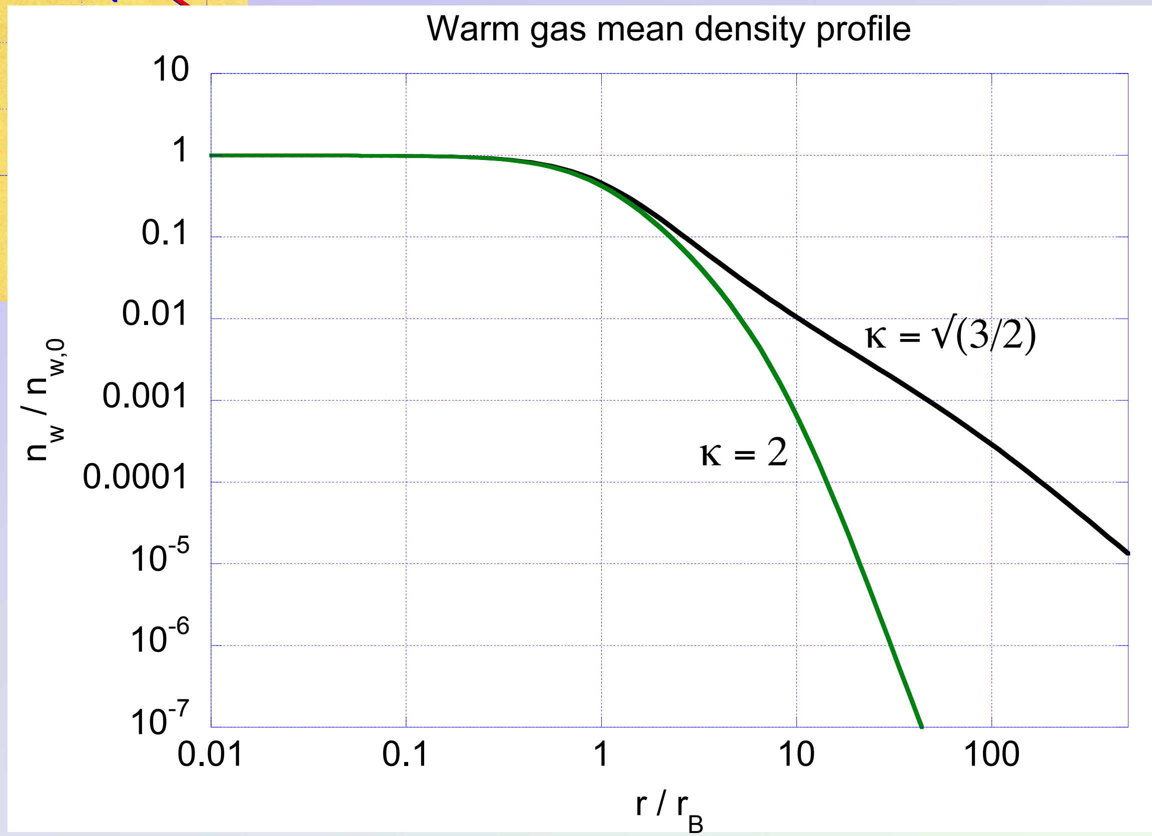
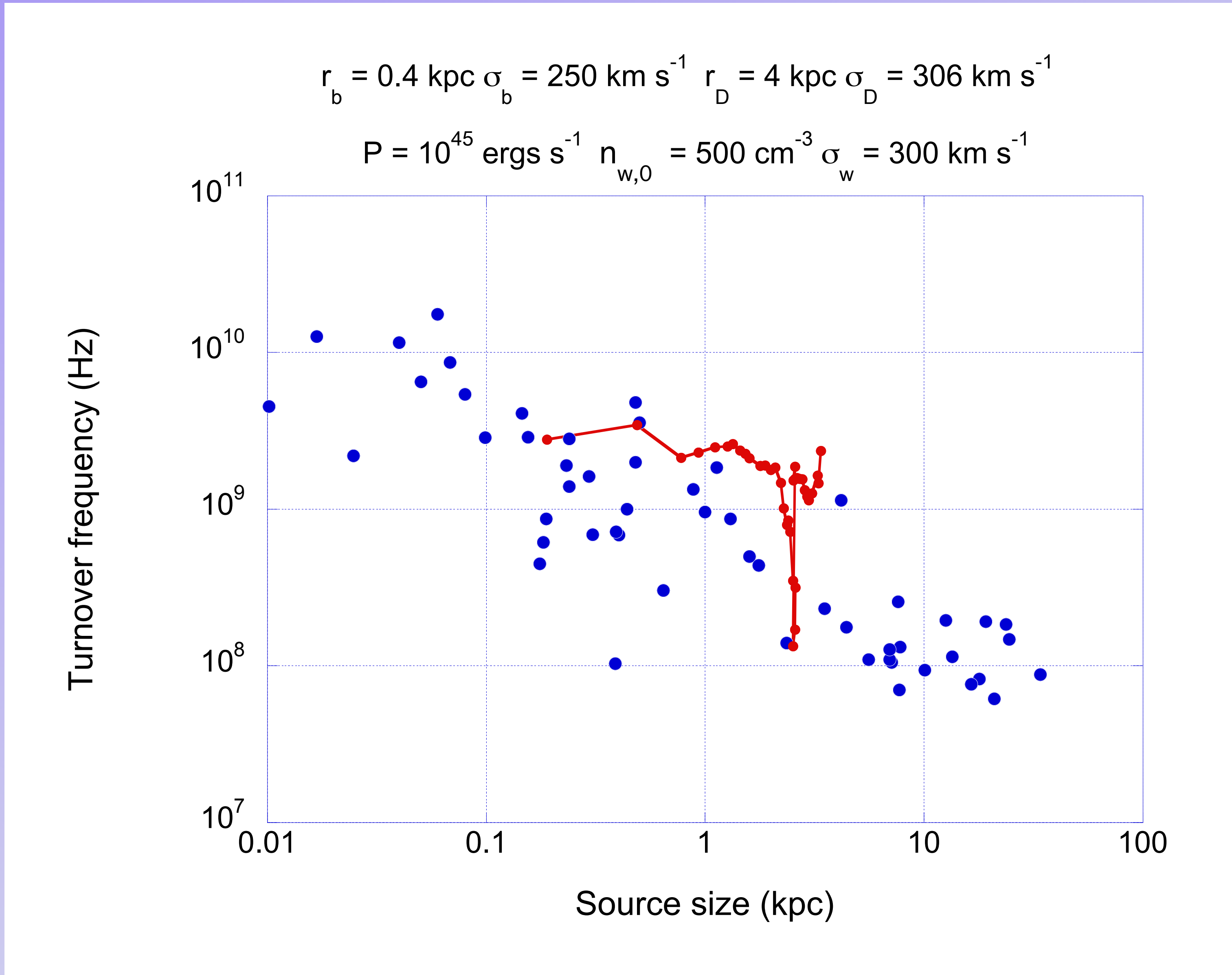
Effect of dark matter parameters

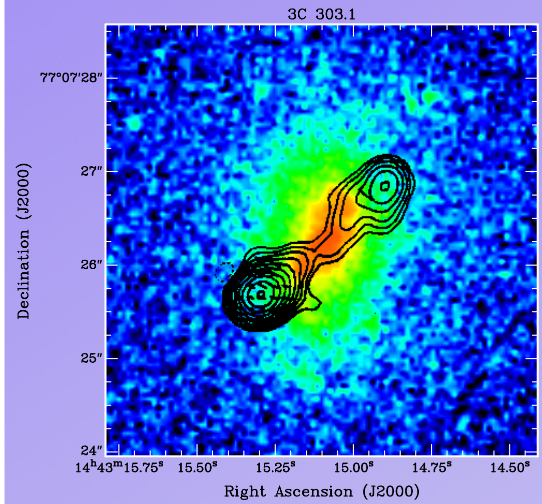


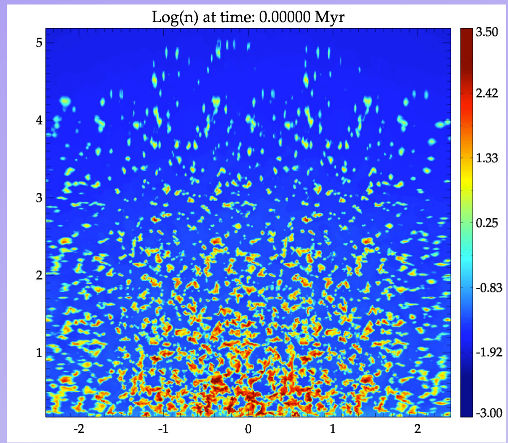


New simulation

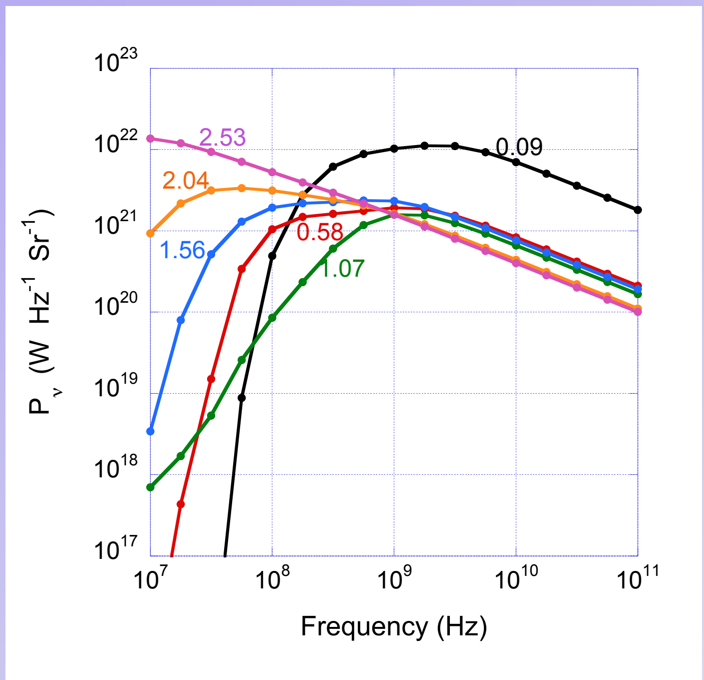


Summary

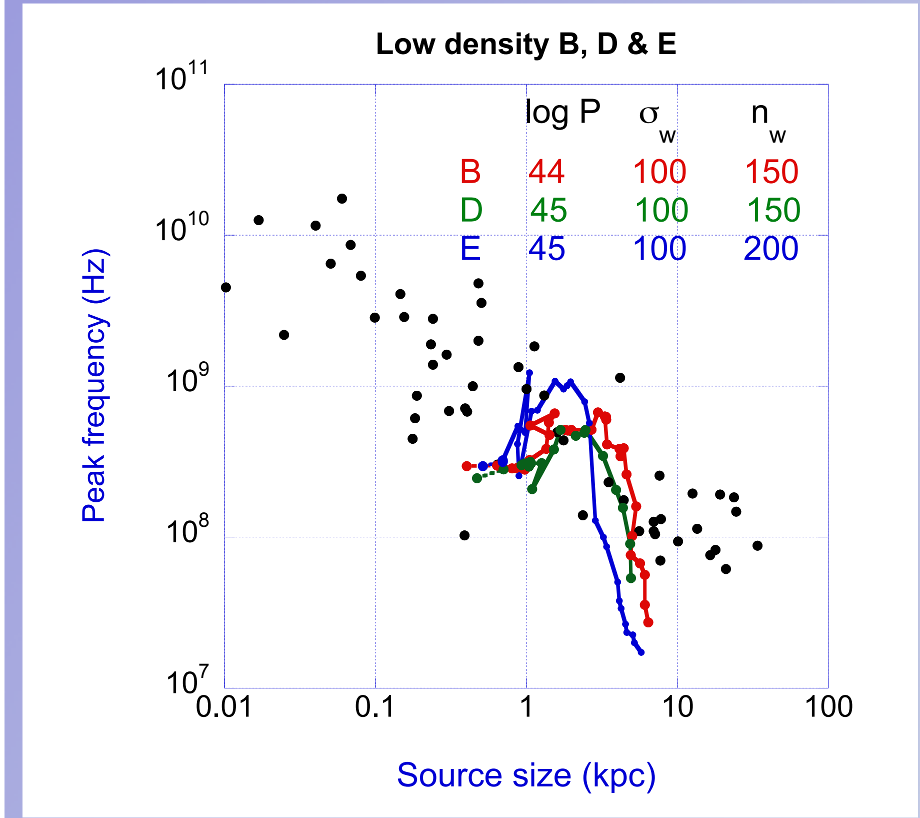




- GPS and CSS sources are strongly related to AGN feedback in early stages of galaxy evolution

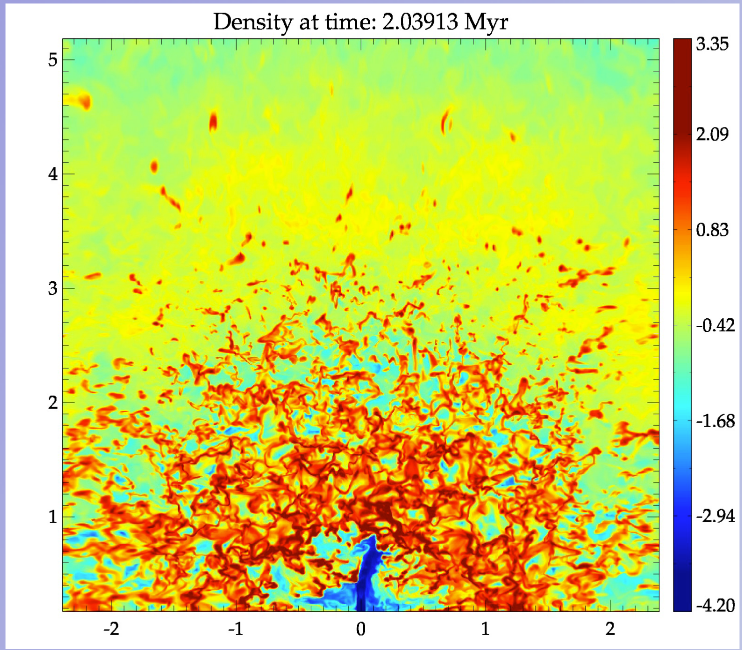


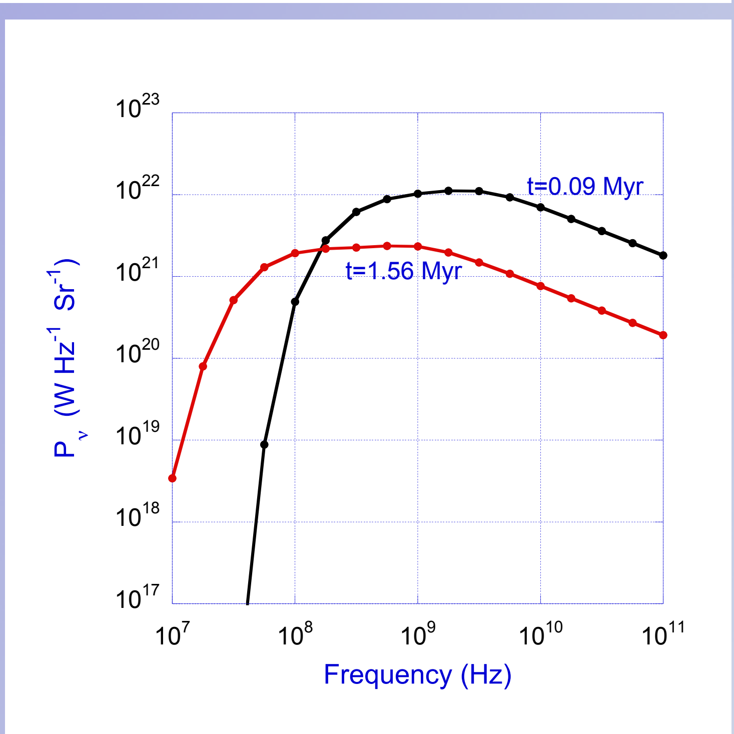
- Low frequency turnover plausibly related to free-free absorption by inhomogeneous ISM with variable opacity
- Sources with steep low frequency spectra are young and rule out Synchrotron Self Absorption



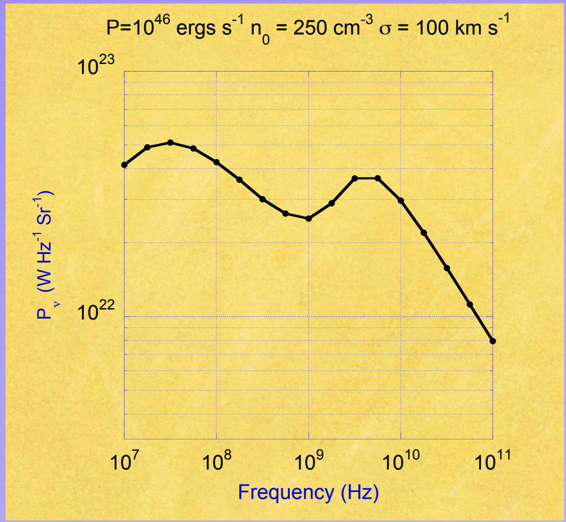
- Required central densities compatible with optical studies of star-forming galaxies at z~2-3

- To better replicate the anticorrelation between peak frequency, we need to consider initial distributions of gas, that are more extended





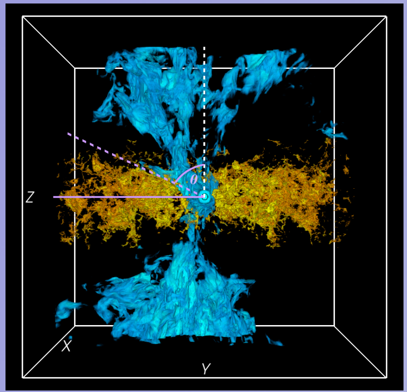
- Radio spectrum (both turnover and low frequency slope) provides independent information on ISM density, turbulence, spectrum of density fluctuations and extent – important for understanding feedback – in particular at redshifts ~2-3
- Necessity for more extended distribution of gas emphasises this point

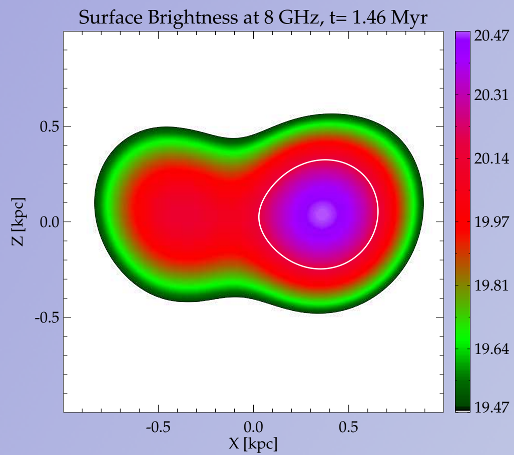


- Patchy absorption leads to multiple peaks in spectrum

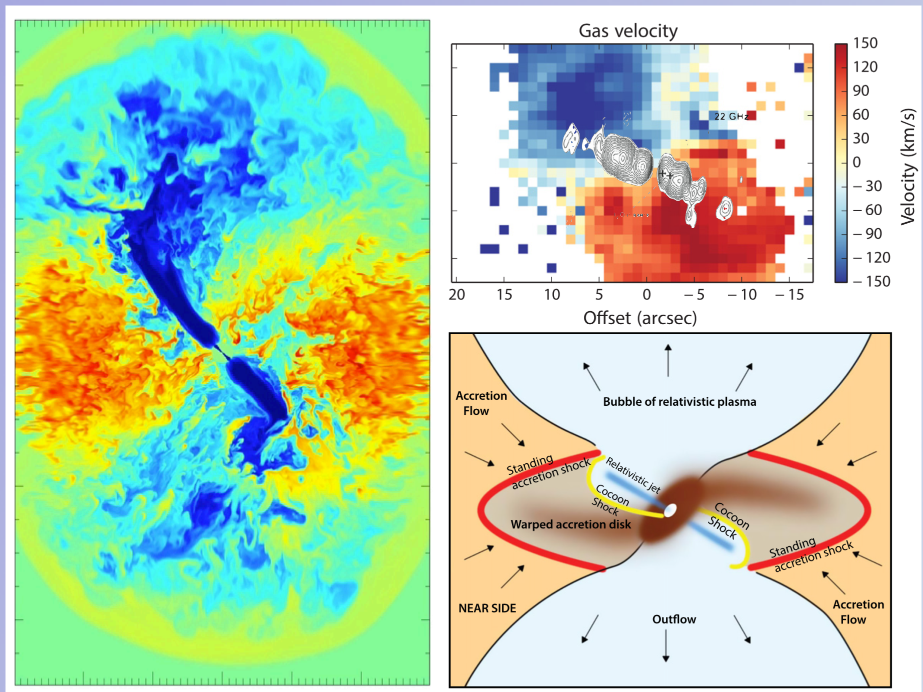
- Note: Mean z of O'Dea-Baum GPS/CSS sample ~ 0.97. Need to explore densities of ionised gas in sample and find more GPS sources at high z

Dank je!





Interaction of jet with disk of IC5063 reveals powerful jets and significant disruption of star-forming region – consistent with radio morphology and rotation curve



45° Jet-ISM interaction consistent with morphology of NGC1052

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