Quantifying the feedback from radio Active Galactic Nuclei

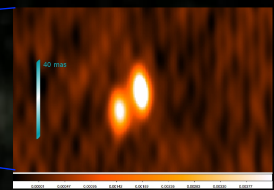


Image: A. Deller

Stas Shabala

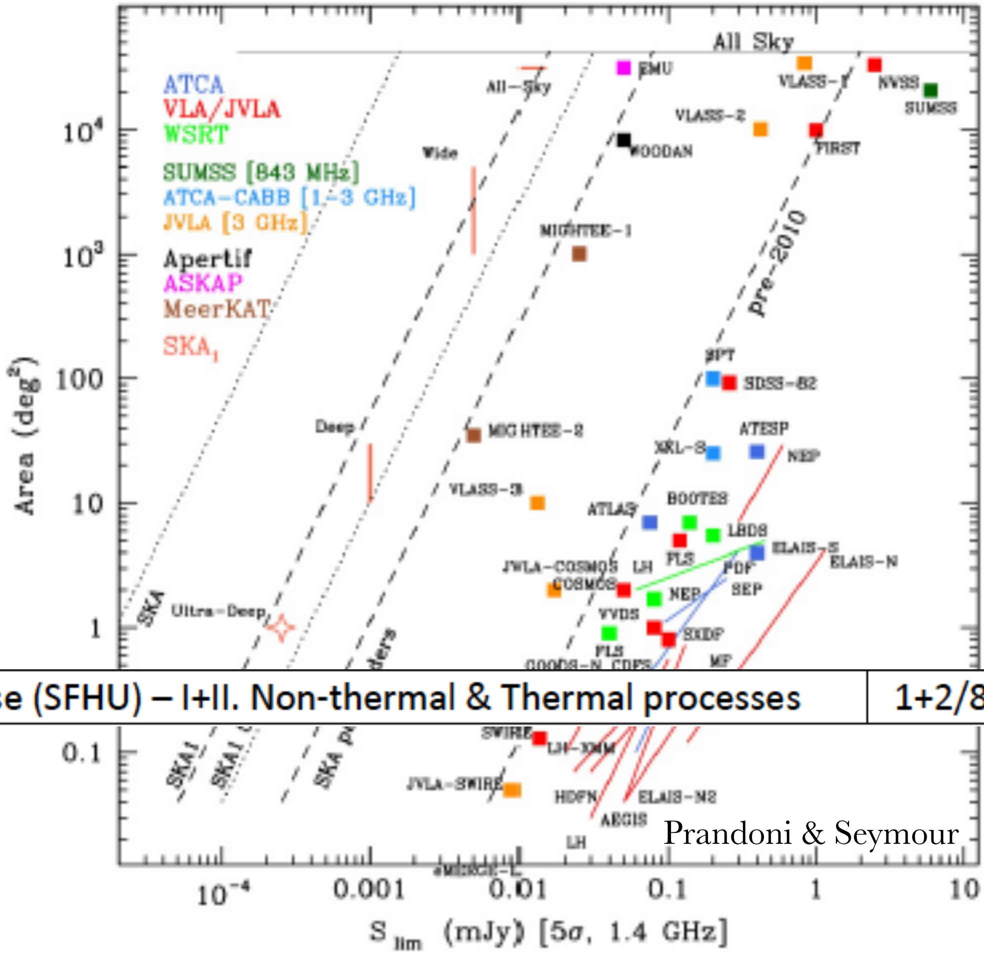
University of Tasmania

SKA + pathfinders

- Detect radio AGN to $z > 6$

How do we interpret them?

- AGN physics
- AGN feedback



Continuum	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8

Surveys + models will…

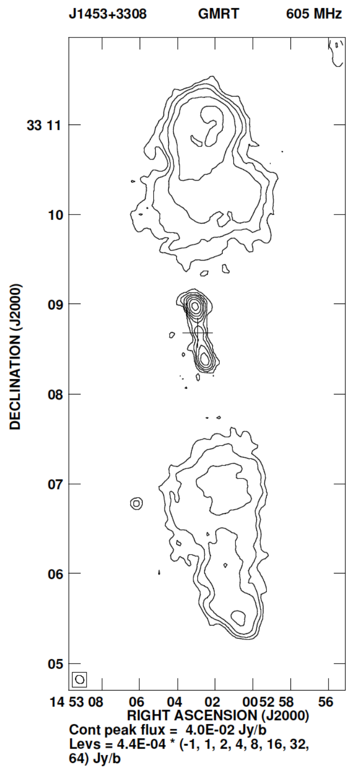
① Identify triggers of AGN activity

② Test jet production mechanisms

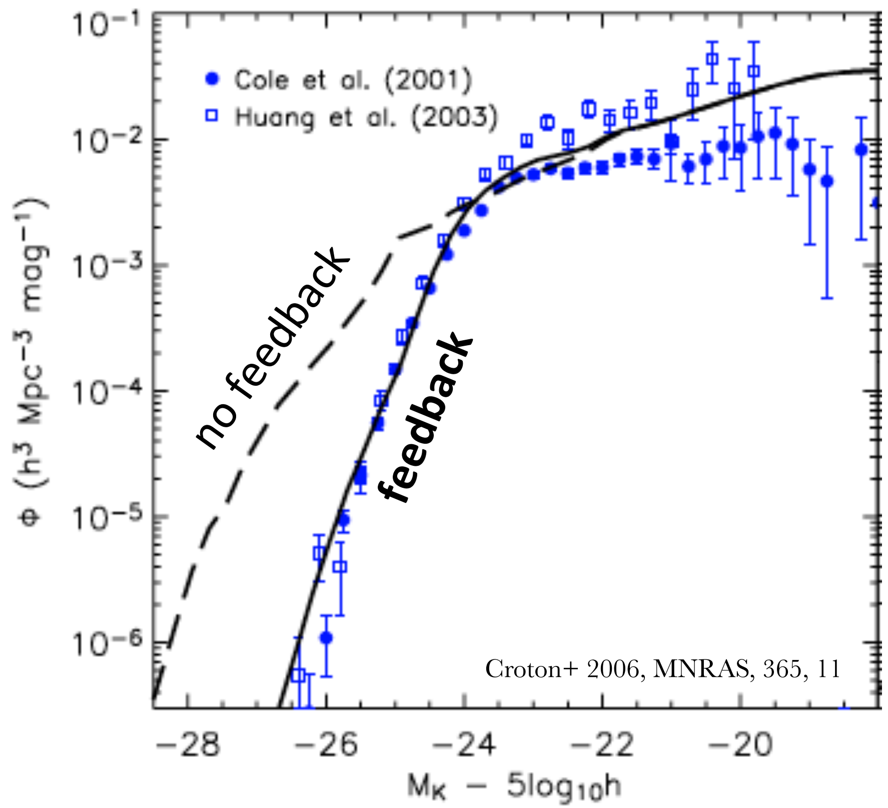
③ Quantify the efficiency of AGN feedback

AGN feedback from radio jets

- Stops runaway cooling and SF in massive galaxies
- Intermittent
  - Double – double radio sources
  - Heating – cooling interplay



Saikia+ 2007, ASPC, 373, 217



Croton+ 2006, MNRAS, 365, 11

Quantifying feedback

For negative feedback from a single AGN,

$$E_{\text{feedback}} = \varepsilon_{\text{coupling}} E_{\text{AGN}}$$

Time-averaged rate is

$$\dot{E}_{\text{feedback}} = \underbrace{\left(\frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}}\right)}_{\text{AGN fraction}} \underbrace{\varepsilon_{\text{coupling}}}_{\text{Coupling efficiency}} \dot{E}_{\text{AGN}}$$

AGN power

Quantifying feedback

$$\dot{E}_{\text{feedback}} = \underbrace{\left(\frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}}\right)}_{\text{AGN fraction}} \underbrace{\varepsilon_{\text{coupling}}}_{\text{Coupling efficiency}} \dot{E}_{\text{AGN}}$$

AGN power

Observational constraints:

- AGN fraction
- Radio luminosity
- Size
- Spectral index

[function of : mass, environment, AGN type…]

Quantifying feedback

$$\dot{E}_{\rm feedback} = \underbrace{\left(\frac{t_{\rm on}}{t_{\rm on}+t_{\rm off}}\right)}_{\text{AGN fraction}} \underbrace{\varepsilon_{\rm coupling}}_{\text{Coupling efficiency}} \dot{E}_{\rm AGN}$$

AGN power

Observational constraints:

- AGN fraction
- Radio luminosity
- Size
- Spectral index

[function of : mass, environment, AGN type…]

Physics:

- Mechanisms of AGN triggering
  - How often
  - For how long
- Jet production mechanisms
  - How powerful
- Interaction with environment
  - Observed AGN properties
  - Feedback

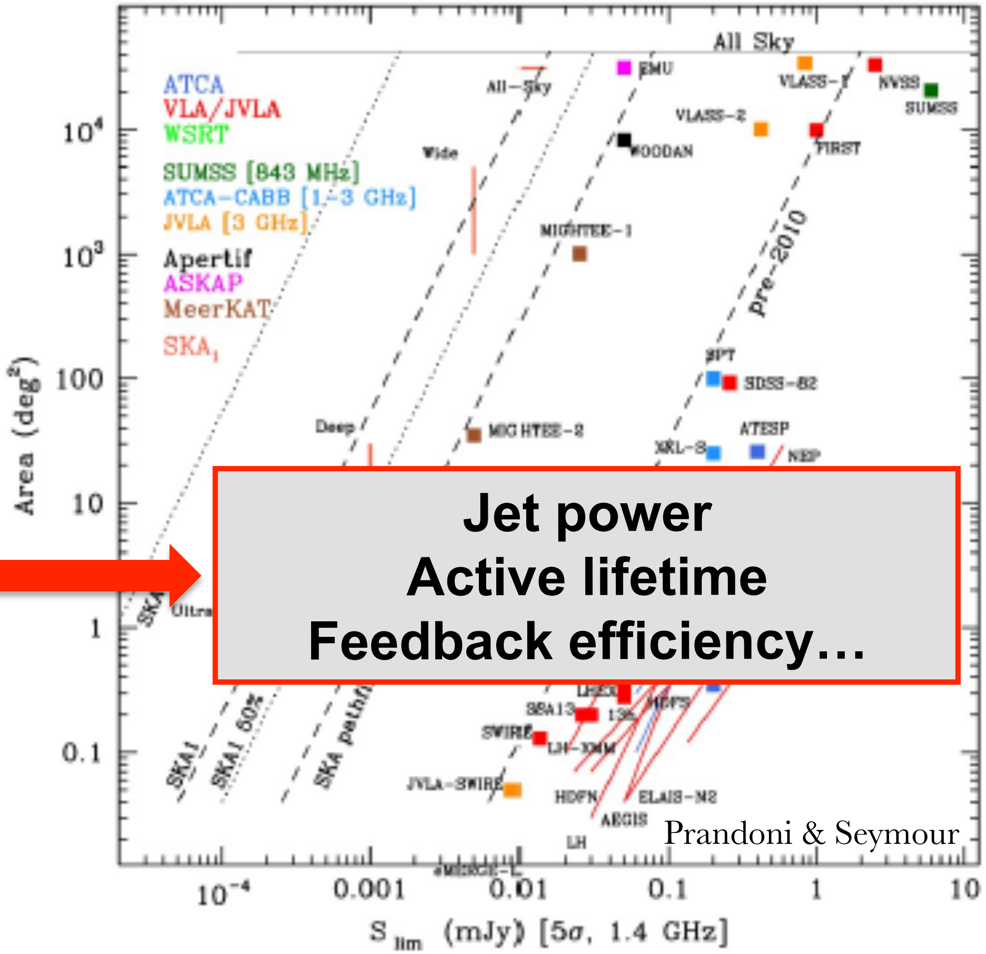
SKA + pathfinders

- Detect radio AGN to $z > 6$

How do we interpret them?

- AGN physics
- AGN feedback

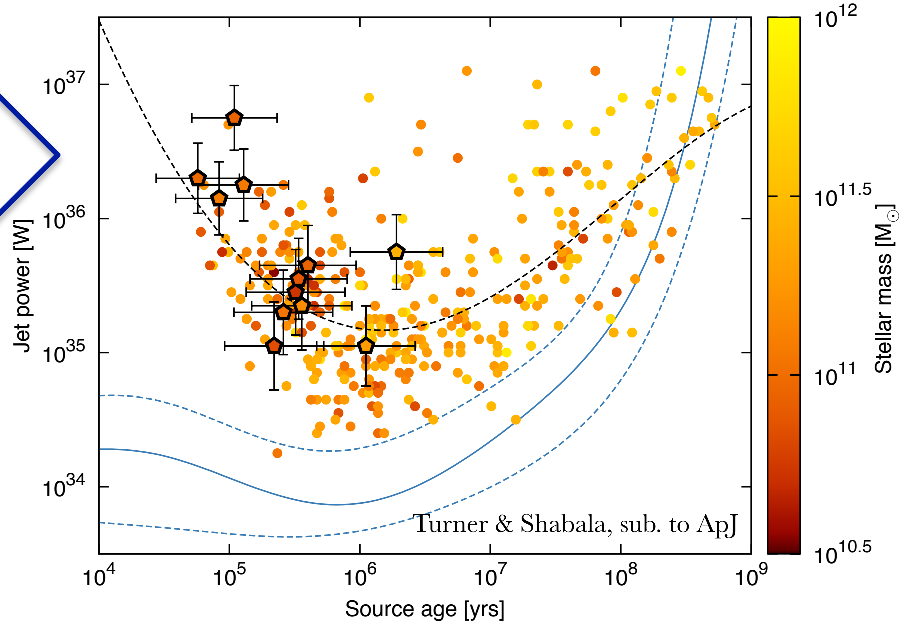
Radio luminosity
(+ other observables?)



Jet power
Active lifetime
Feedback efficiency…

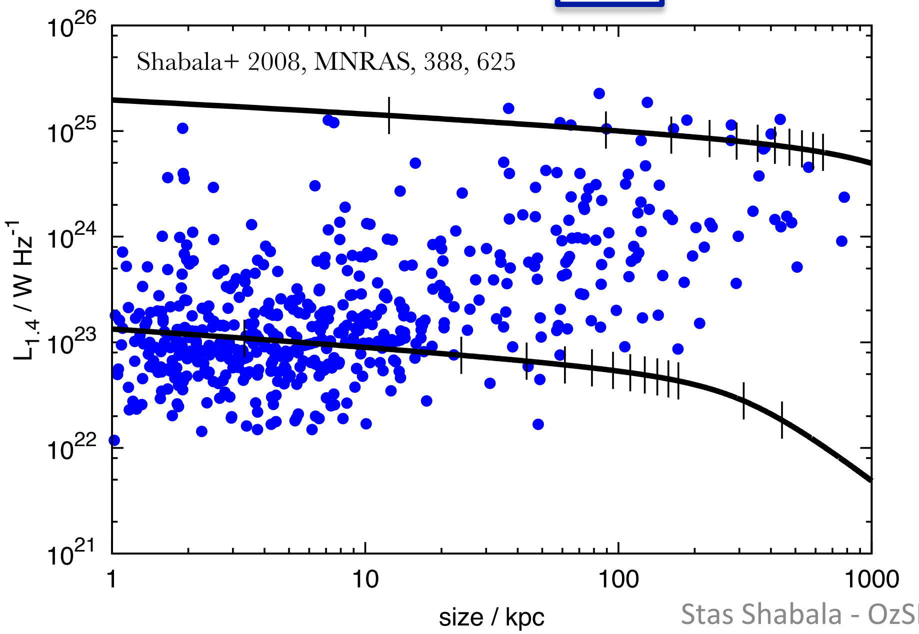
Dynamical models of radio AGN

Know
1. AGN luminosities
2. AGN sizes

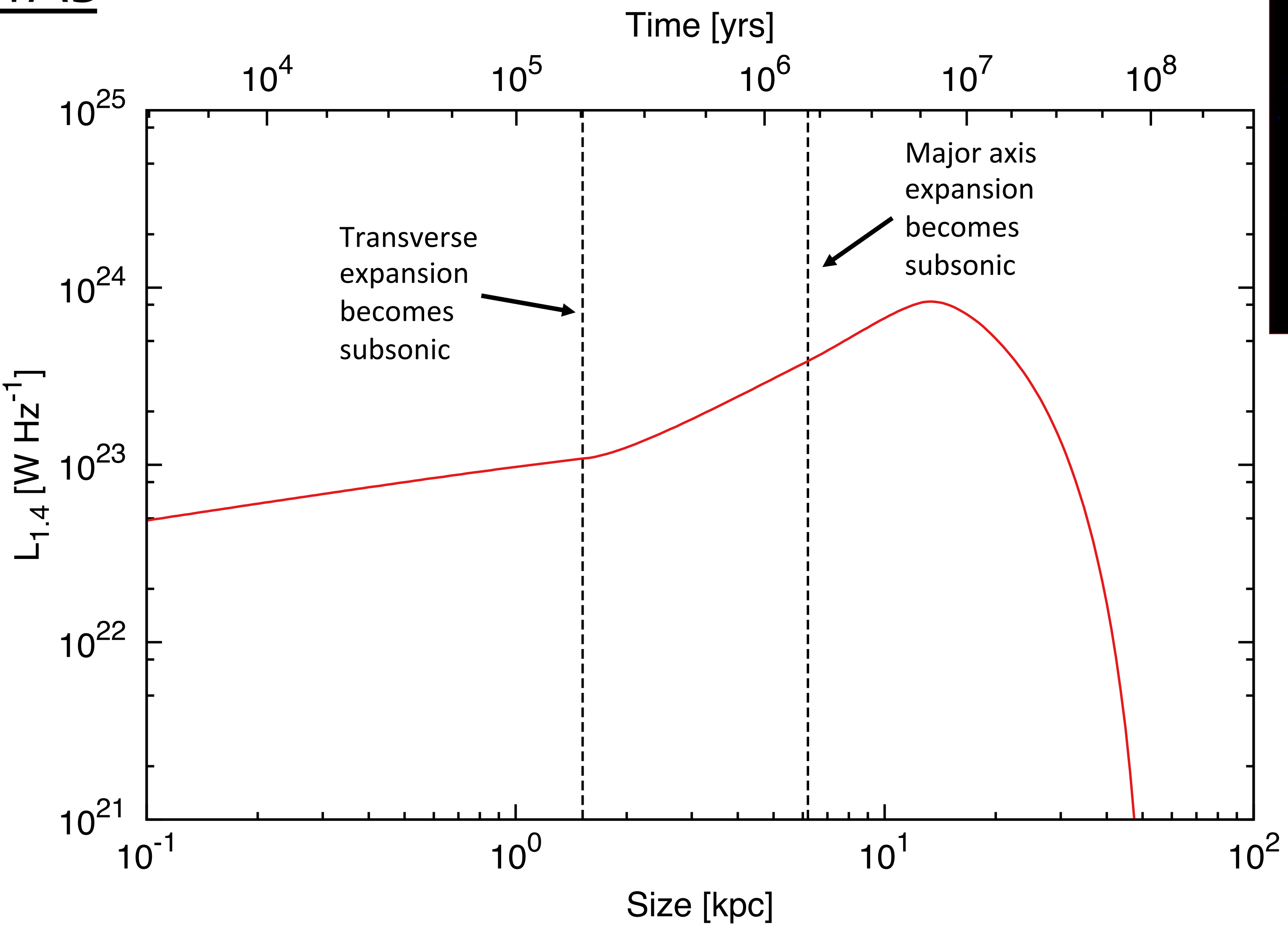


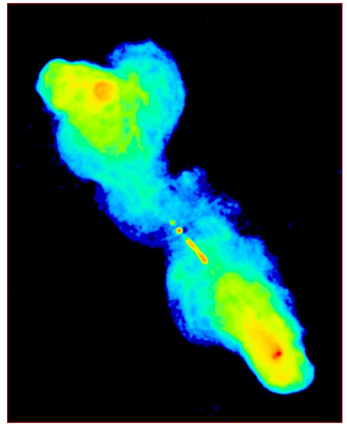
Want to know
1. How powerful the AGN are
2. How long lived

AGN triggering
AGN feedback



Size – luminosity evolution





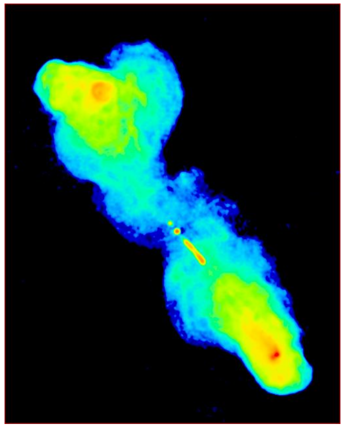
Environments

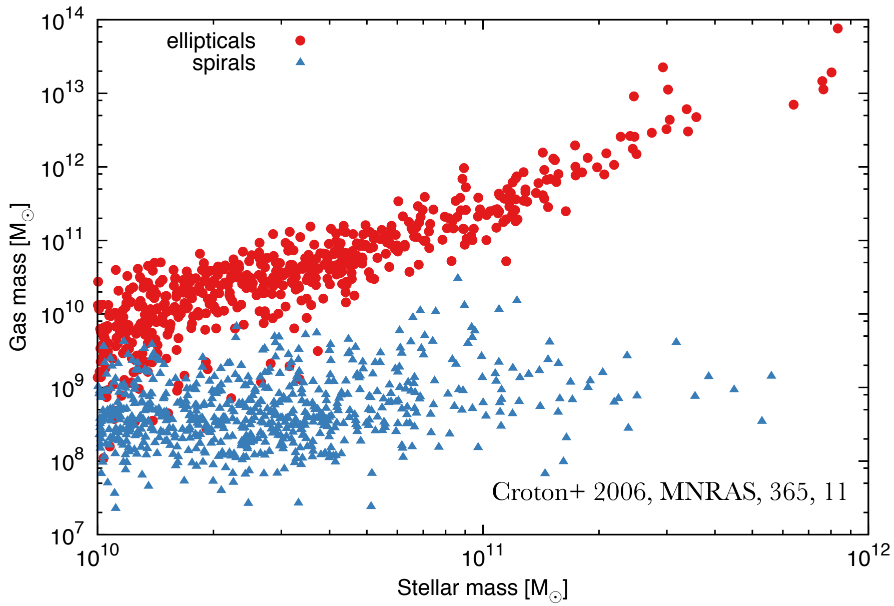
Dynamical models
AGN size and luminosity evolution

Are **very** sensitive to environment

$$L_{\text{radio}} \propto \rho^{7/6}$$

NEW
Gas masses from semi-analytic models





Physical properties of local AGN

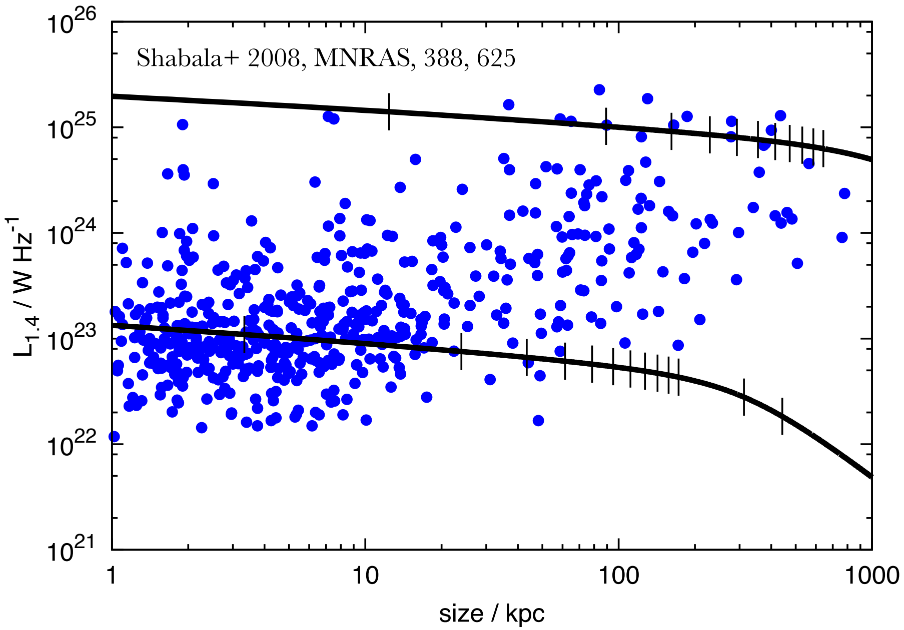
615 AGN (Shabala+ 2008)

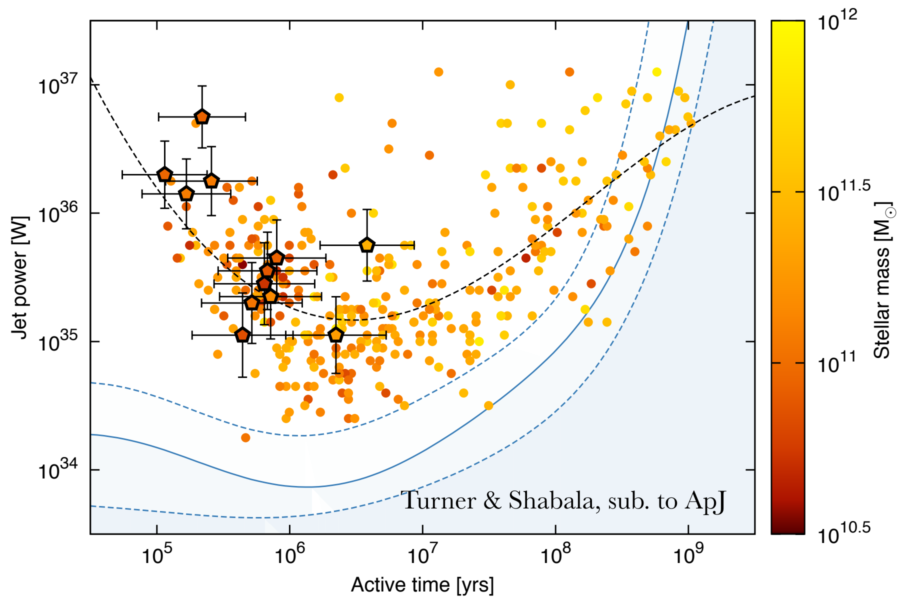
- $0.03 < z < 0.1$ (volume-limited)
- Stellar masses
- Cocoon sizes
- Radio luminosities

Size + Luminosity + Stellar mass

use semi-analytic models for gas density

Jet power + age





Selection effects

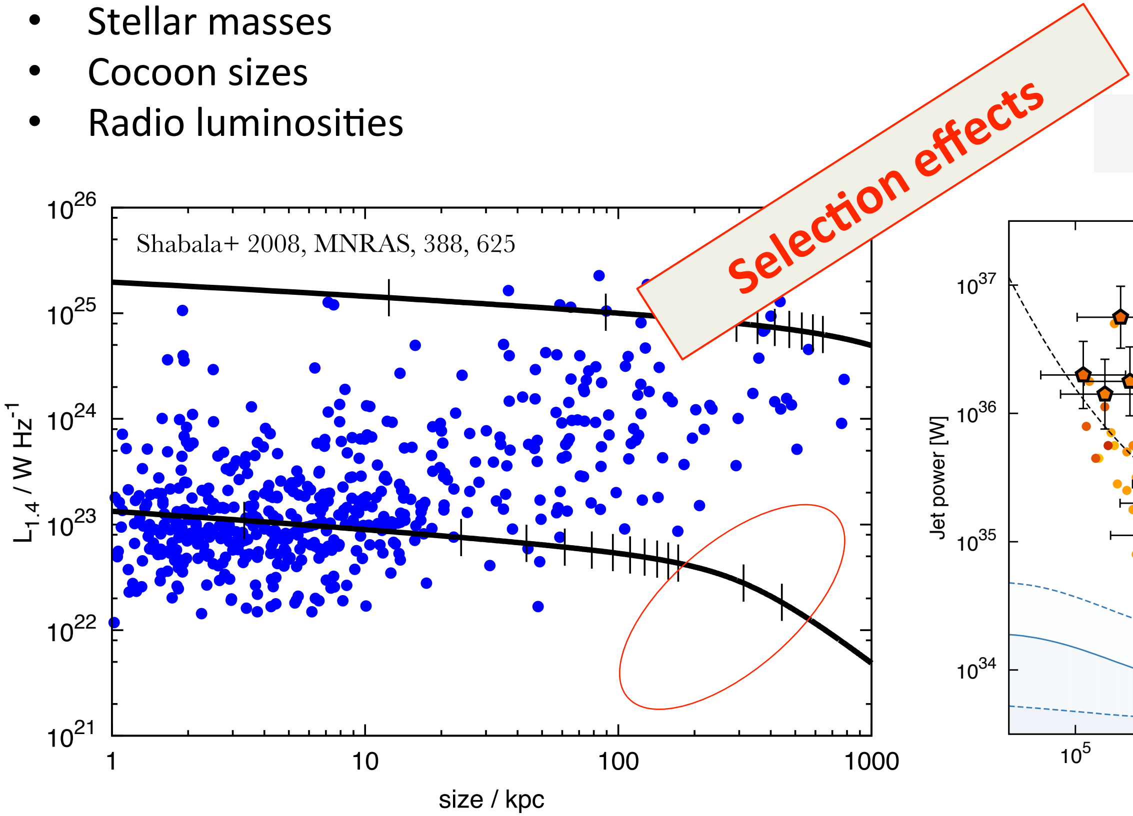
615 AGN (Shabala+ 2008)

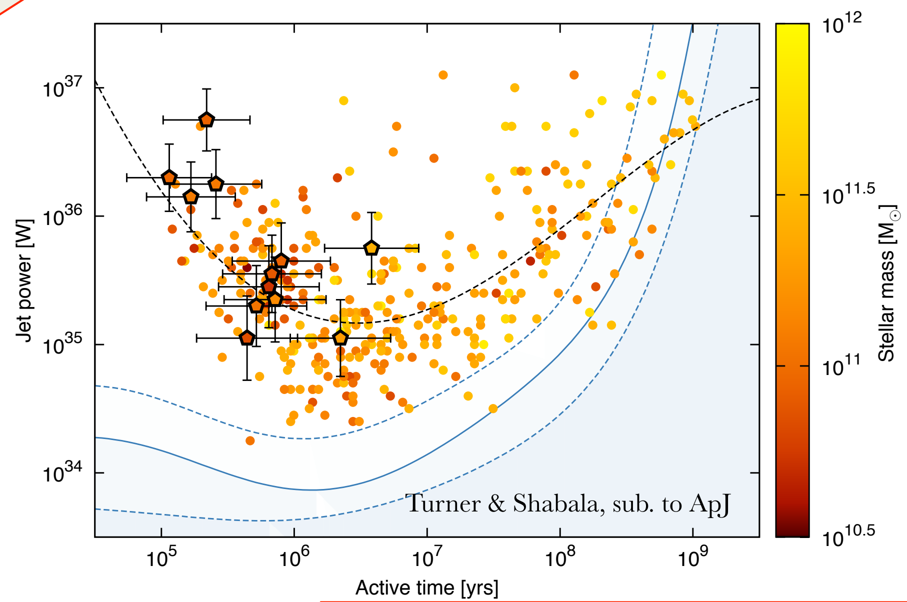
- 0.03 < *z* < 0.1 (volume-limited)
- Stellar masses
- Cocoon sizes
- Radio luminosities

Size + Luminosity + Stellar mass

use semi-analytic models for gas density

Jet power + age





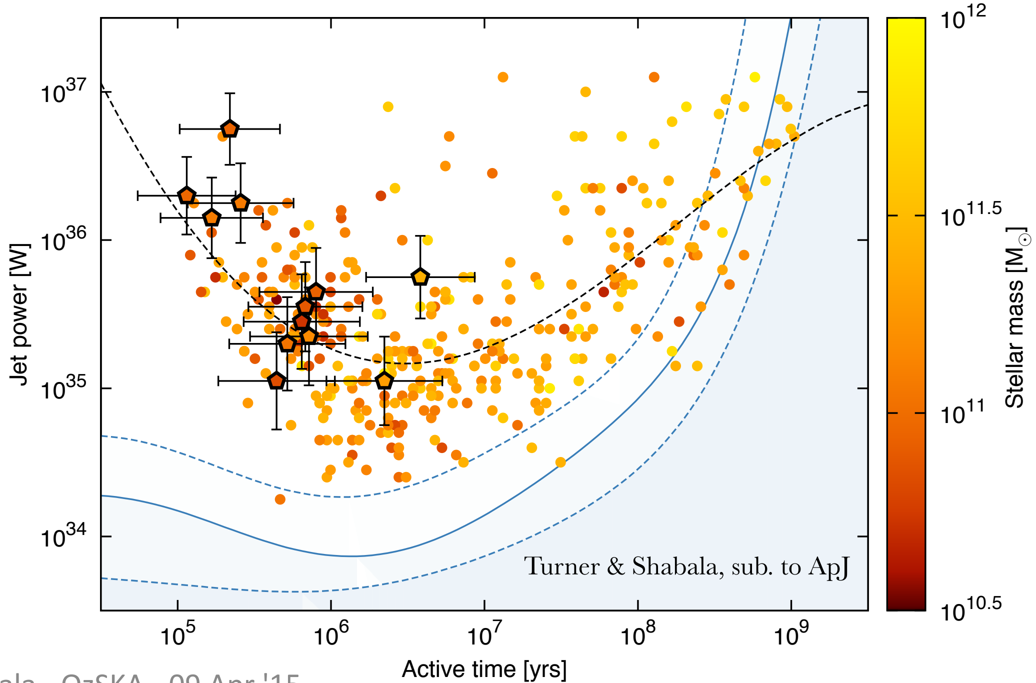
Low power, old sources have low surface brightness

Questions…

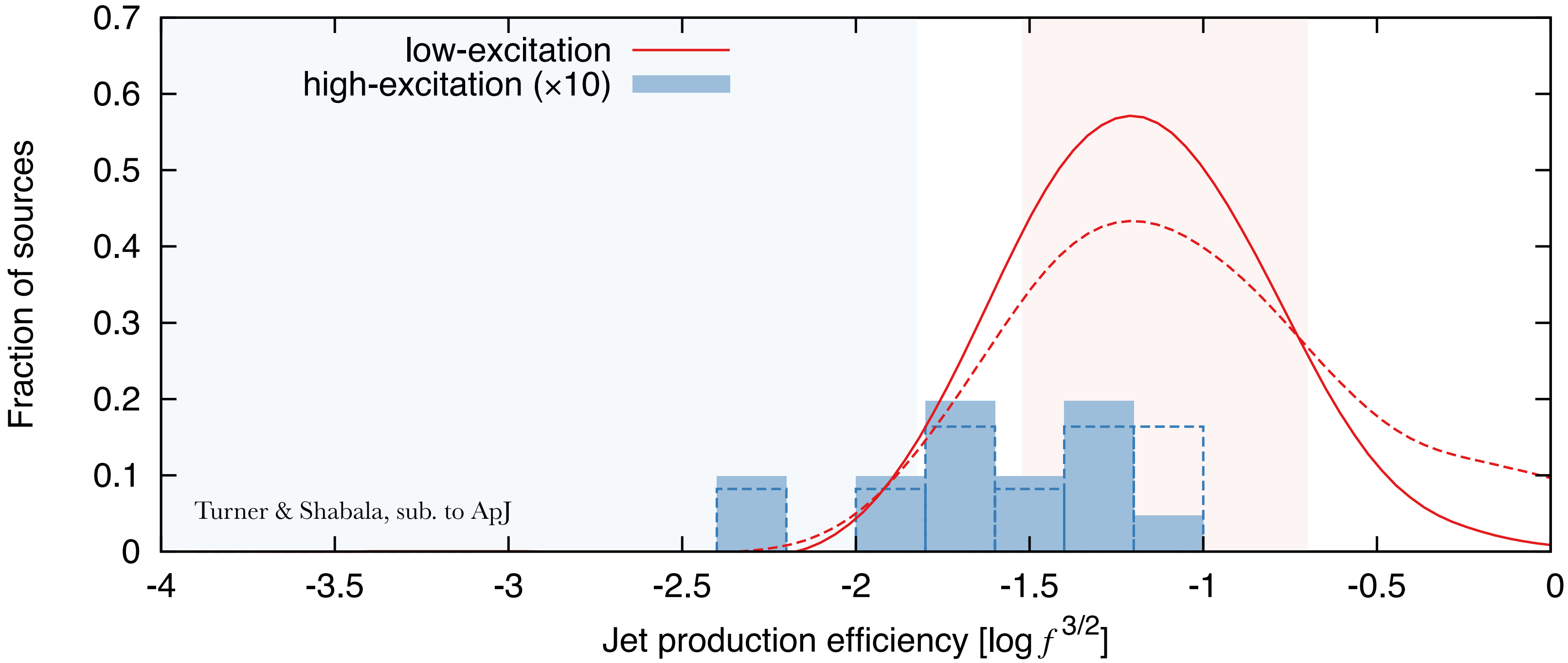
1. **How are the radio jets produced ?**
   - test theoretical models of thin disks, ADAFs etc.

2. **Do AGN properties depend on galaxy properties ?**

3. **Can AGN feedback produce observed galaxies ?**



1. How are the radio jets produced ?



Jet generation efficiency

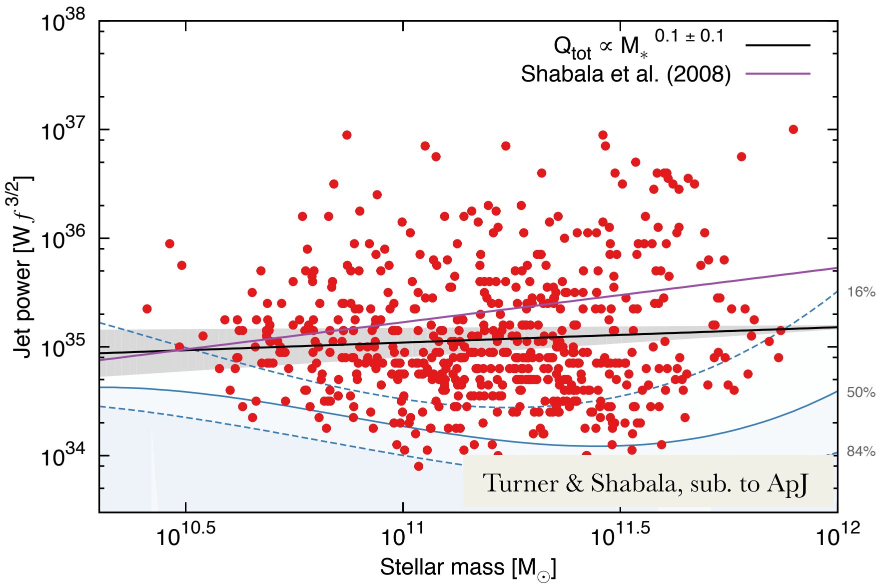
- Q_{jet} / L_{bol}

Jet powers are **consistent with predictions** of ADAF / thin disk models

2. Do AGN properties depend on galaxy properties ?

UTAS

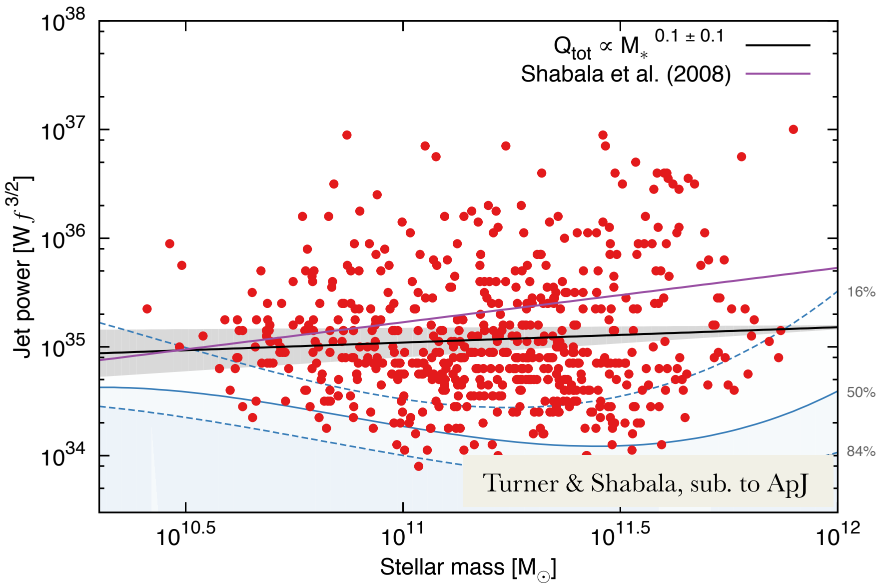
Jet powers



- Large scatter
- **Independent** of host galaxy mass

2. Do AGN properties depend on galaxy properties ?

Jet powers



Theory

In heating – cooling balance ("maintenance mode" feedback), expect

$Q_{\rm jet} \sim \dot{M}_{\rm cool} / f_{\rm AGN}$

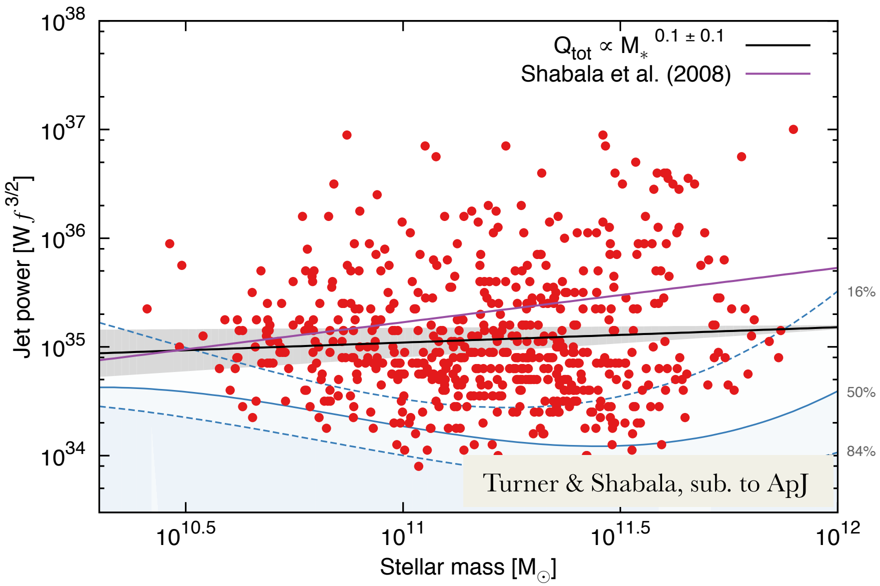
$\dot{M}_{\rm cool} \sim M_{\rm stars}^{1.5}$ from $L_X - L_{opt}$, $L_X - T$ and $M - \sigma$ relations

$f_{\rm AGN} \sim M_{\rm stars}^{1.5}$ consistent with fuelling via hot-mode (Pope+ 2012, MNRAS, 419, 50)

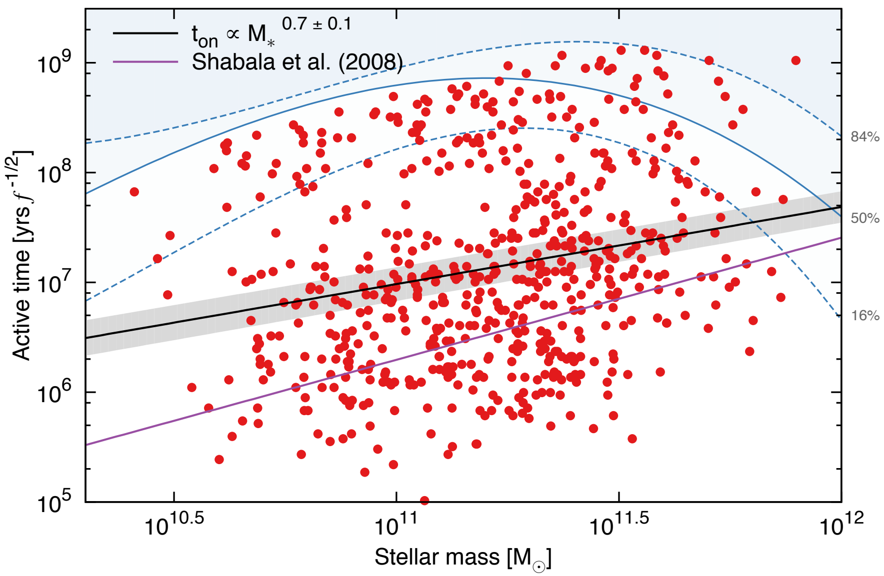
Hence expect $Q_{\rm jet} \sim M_{\rm stars}^{0}$ ✔

2. Do AGN properties depend on galaxy properties ?

Jet powers

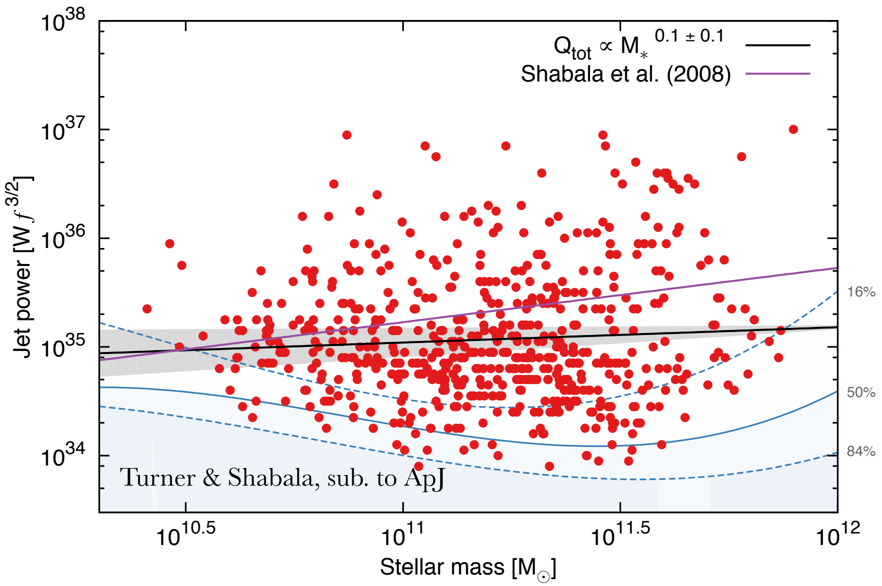


Active lifetimes

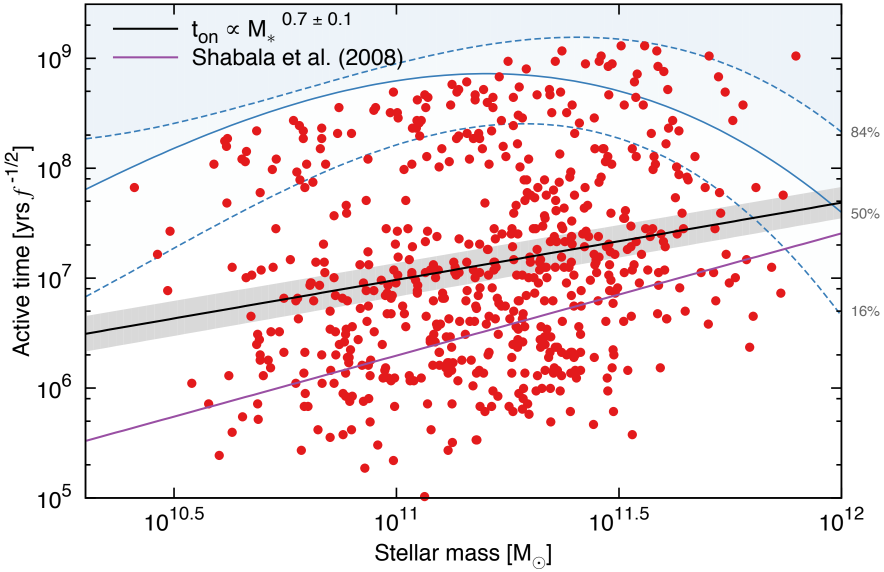


2. Do AGN properties depend on galaxy properties ?

Jet powers



Active lifetimes



Massive galaxies have

- jets similar in kinetic power to low-mass galaxies
- stay on for **longer**

They also have hot haloes that cool rapidly without AGN feedback…

Answers…

1. **How are the radio jets produced ?**
   - Accretion in radiatively inefficient flows (ADAFs)

2. **Do AGN properties depend on galaxy properties ?**
   - Massive galaxies preferentially host longer lived jets

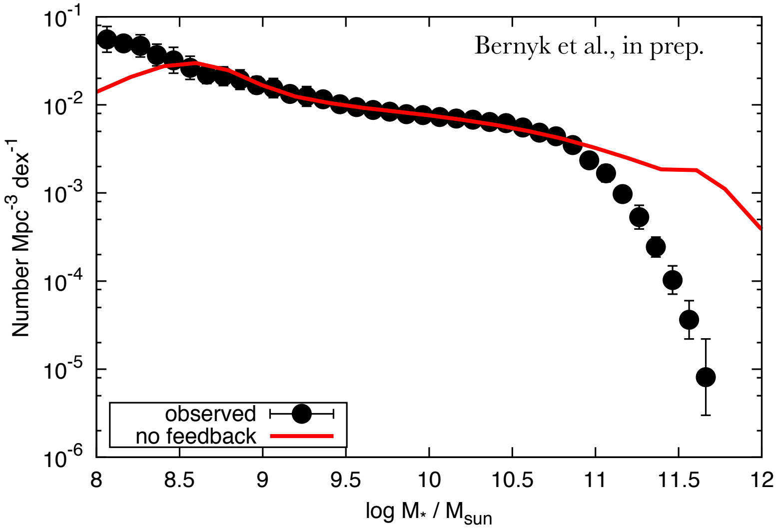
3. **Can AGN feedback produce the right galaxies ?**

Observational constraints on the amount of AGN feedback available to galaxies

Do we get the right galaxies ?

Semi-analytic AGN feedback

Stellar mass function (*z* = 0)



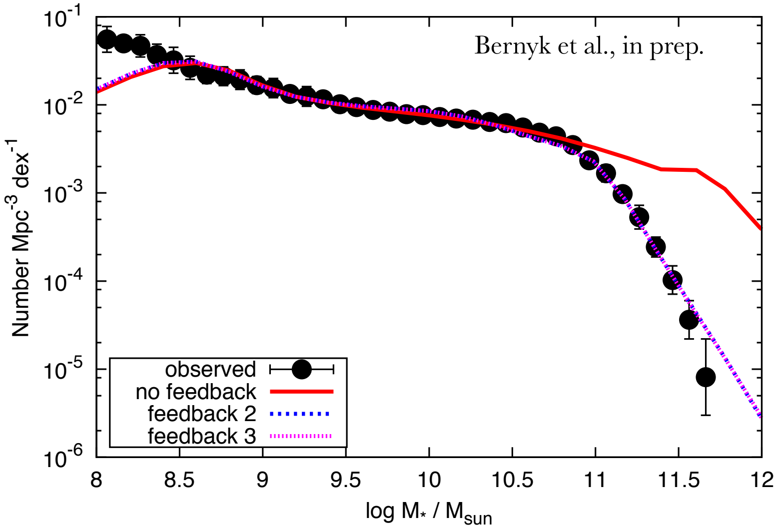
Feedback implementation

- Occasionally switch on AGN
  - how often
  - how powerful
  - for how long

  are **constrained by observations**

Semi-analytic AGN feedback

Stellar mass function (*z* = 0)



Feedback implementation

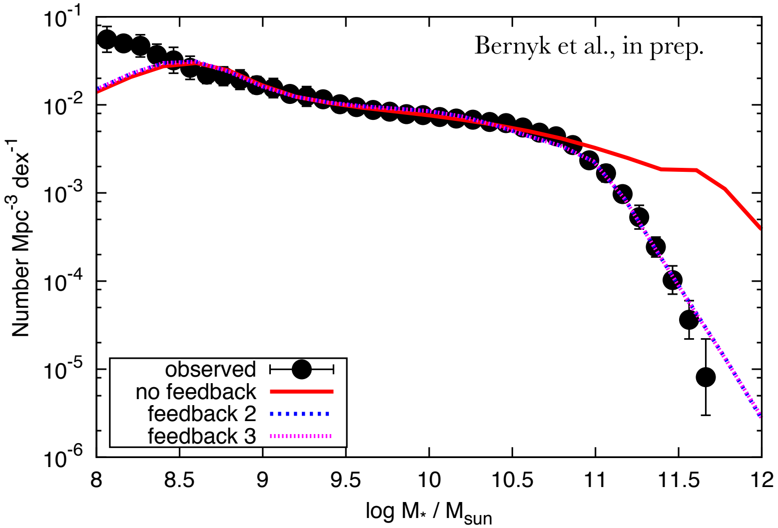
- Occasionally switch on AGN
  - how often
  - how powerful
  - for how long

  are **constrained by observations**

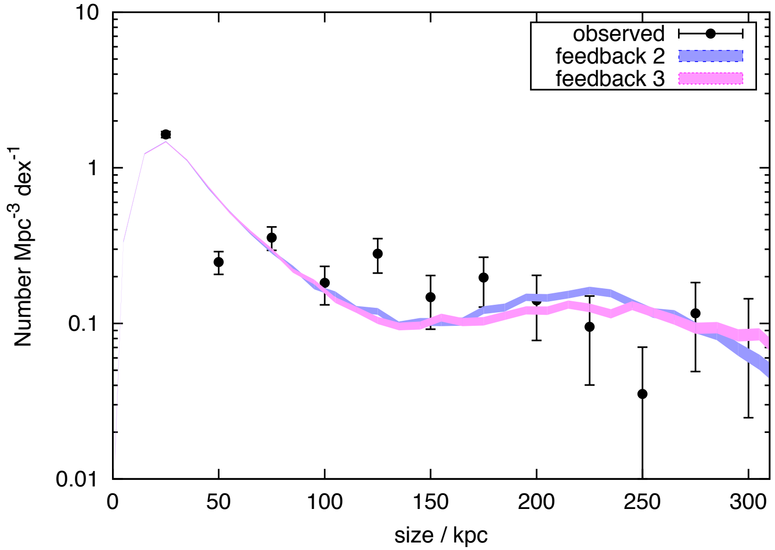
UTAS

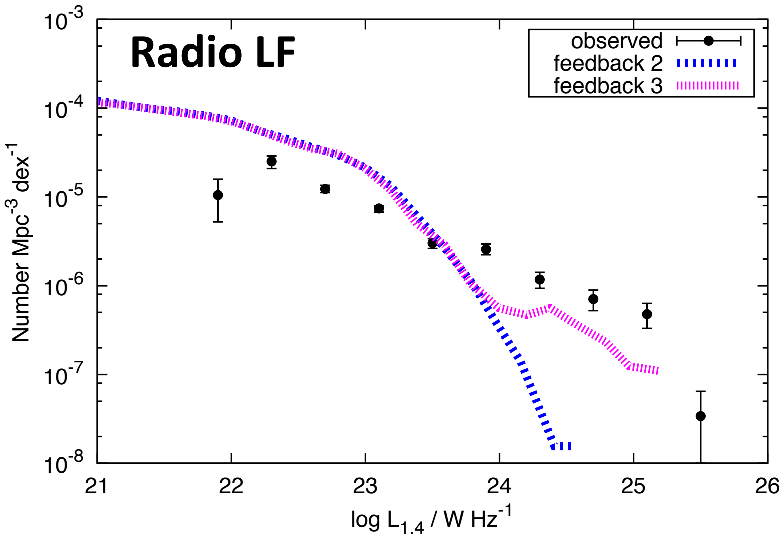
Semi-analytic AGN feedback

Stellar mass function (z = 0)



Sizes of radio AGN





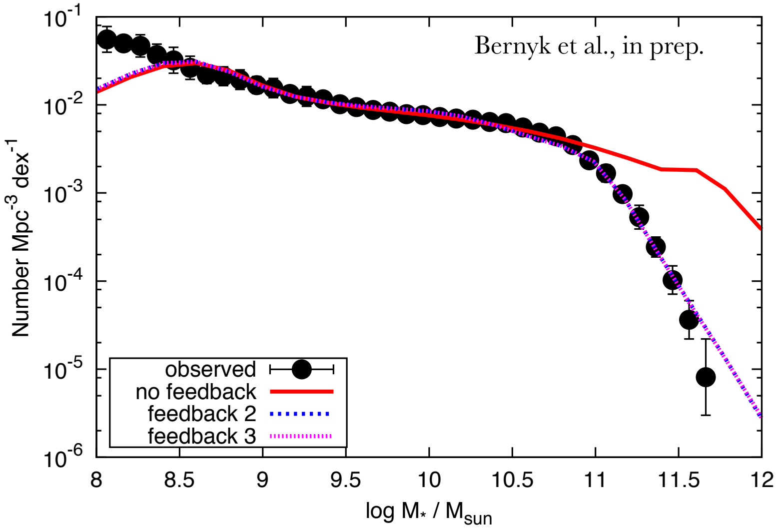
Feedback implementation

- Occasionally switch on AGN
  - how often
  - how powerful
  - for how long

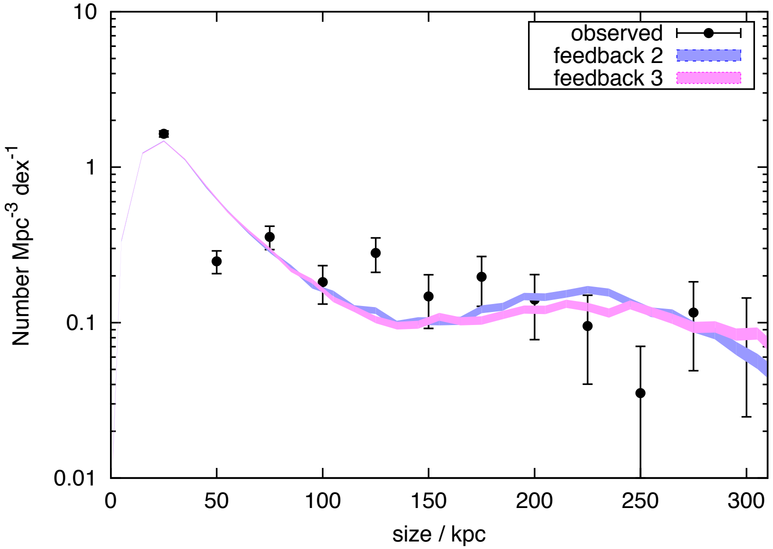
  are **constrained by observations**

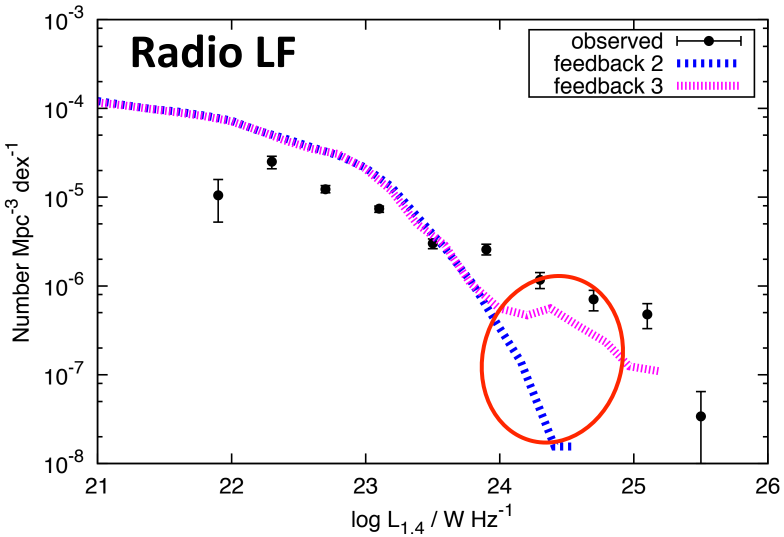
Semi-analytic AGN feedback

Stellar mass function (z = 0)



Sizes of radio AGN





Model must explain observations of both **AGN *and* galaxies** at z = 0

…and higher…

➔ constraints on feedback physics

Self-consistent AGN feedback

Feedback models must explain observations of both **AGN *and* galaxies**

across all redshifts

Strategy

- **AGN observations + models:** identify triggers, quantify AGN energetics
- **Galaxy formation models**: test whether AGN feedback can produce the right galaxies

Self-consistent AGN feedback

Feedback models must explain
observations of both **AGN *and* galaxies**

across all redshifts

Strategy

- **AGN observations + models:** identify triggers, quantify AGN energetics
- **Galaxy formation models**: test whether AGN feedback can produce the right galaxies

ASKAP EMU : will probe same AGN populations at z ~ 0.8

Follow-up observations: ASKAP has 10 arcsec resolution
(~70 kpc at z=0.8)
-> need higher res for source sizes and energetics… **SKA1-mid**

Summary

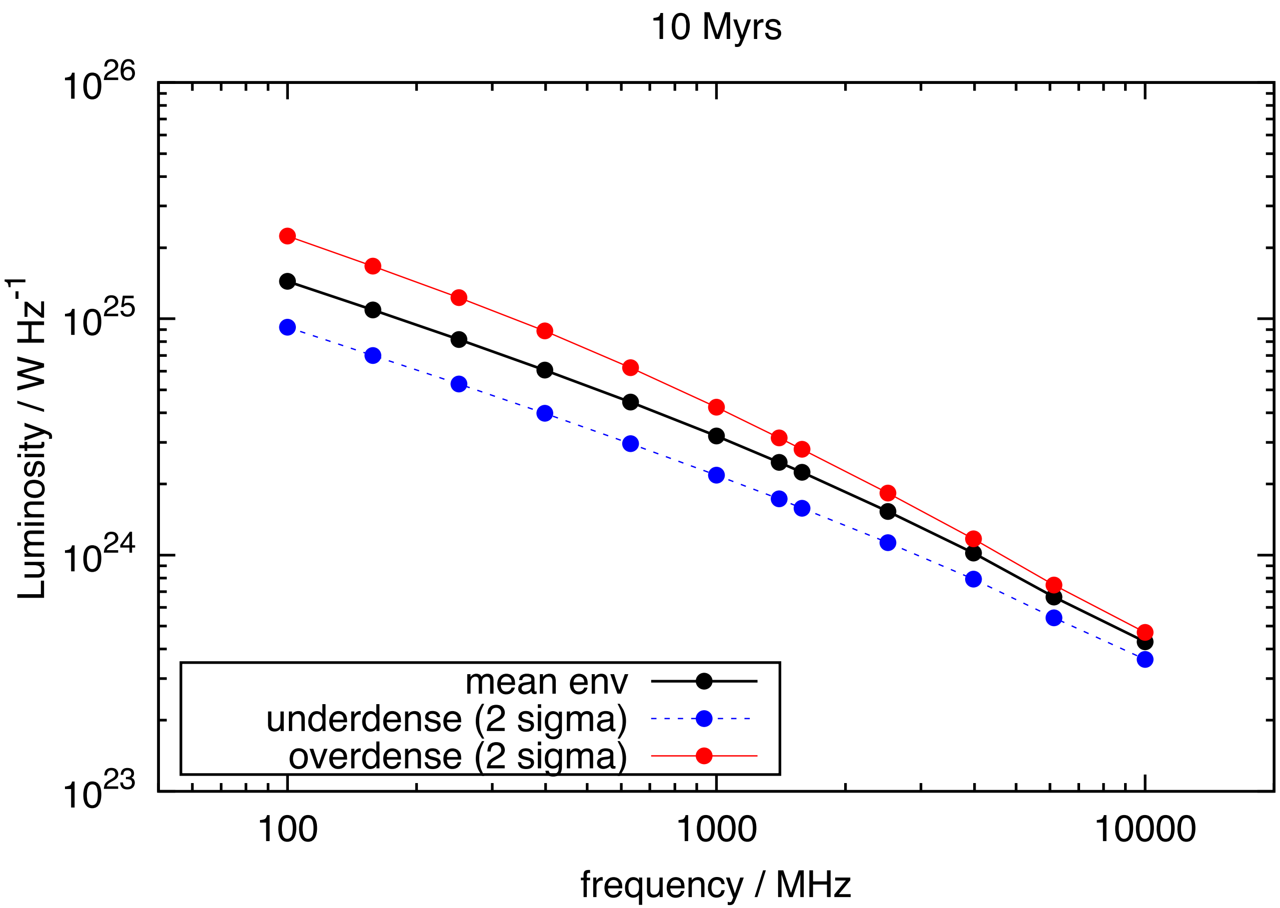
① **Studying AGN populations**

- Dynamical modeling of size and luminosity evolution of radio AGN
- Quantify: energetics, lifetimes, triggering rates
- Test: jet production, AGN feedback mechanisms
- At $z\sim0$. SKA and pathfinders will take this beyond z=1.

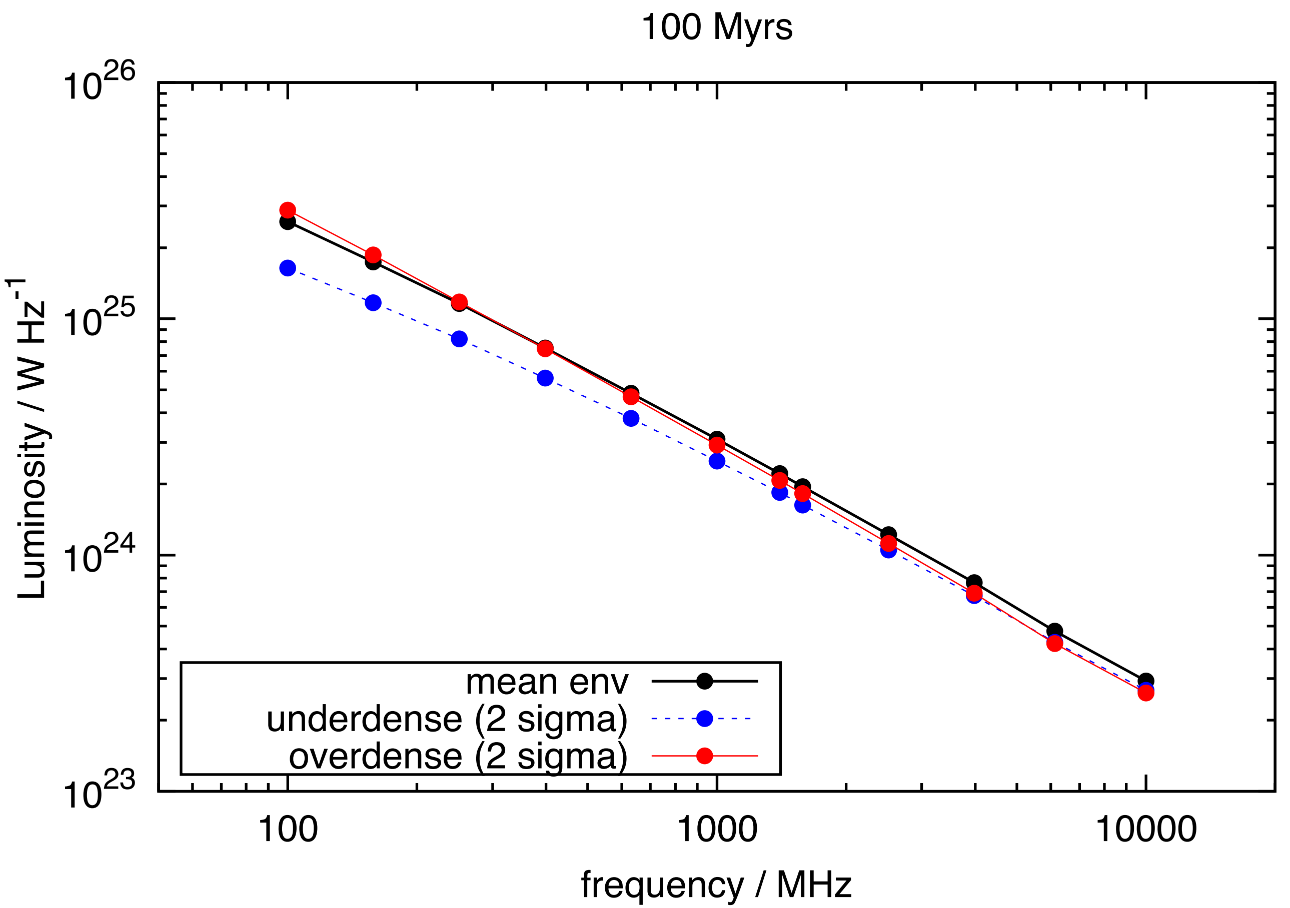
② **AGN feedback**

- Semi-analytic models + intermittent radio AGN
- Using both AGN and galaxy observational constraints

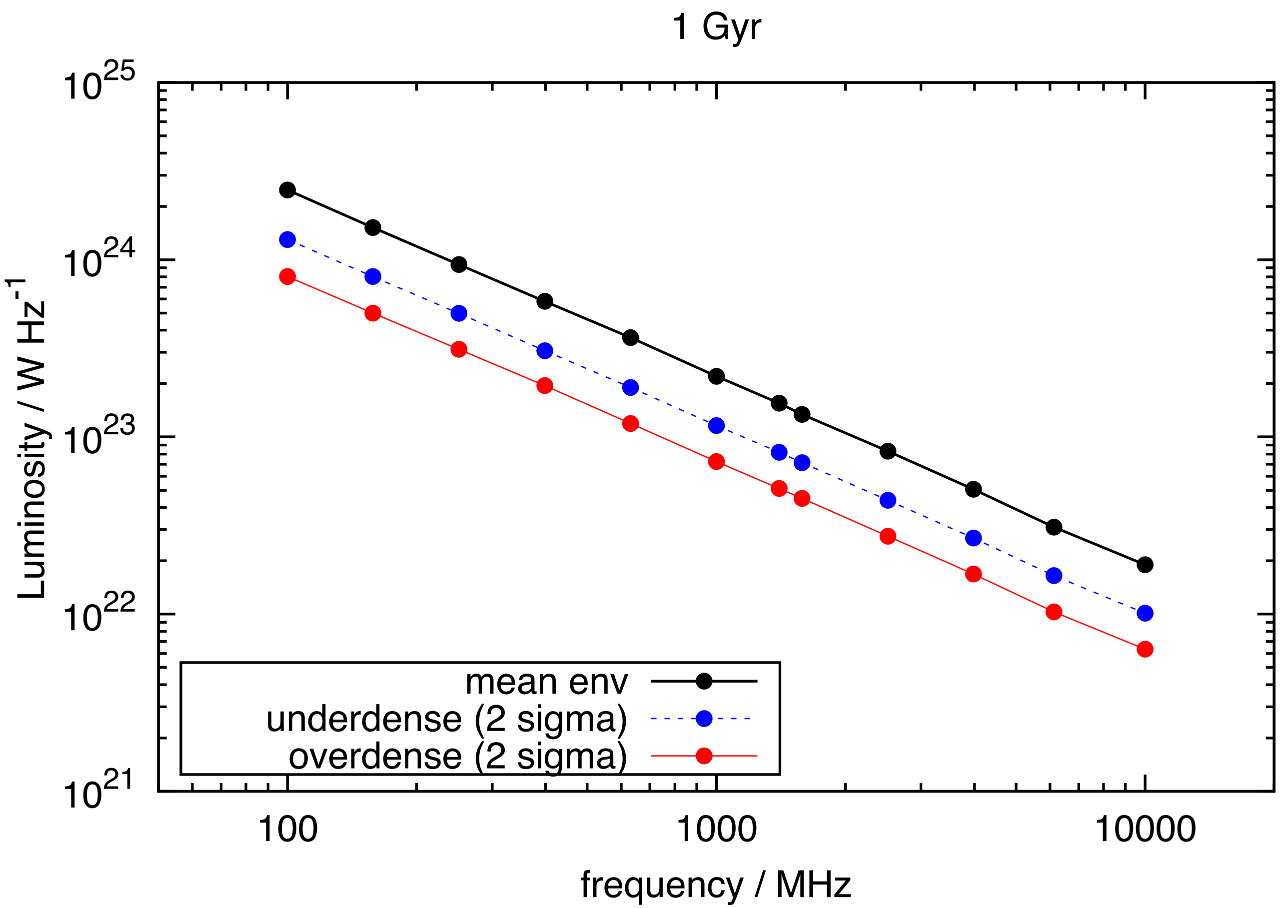
Environment-dependent SEDs



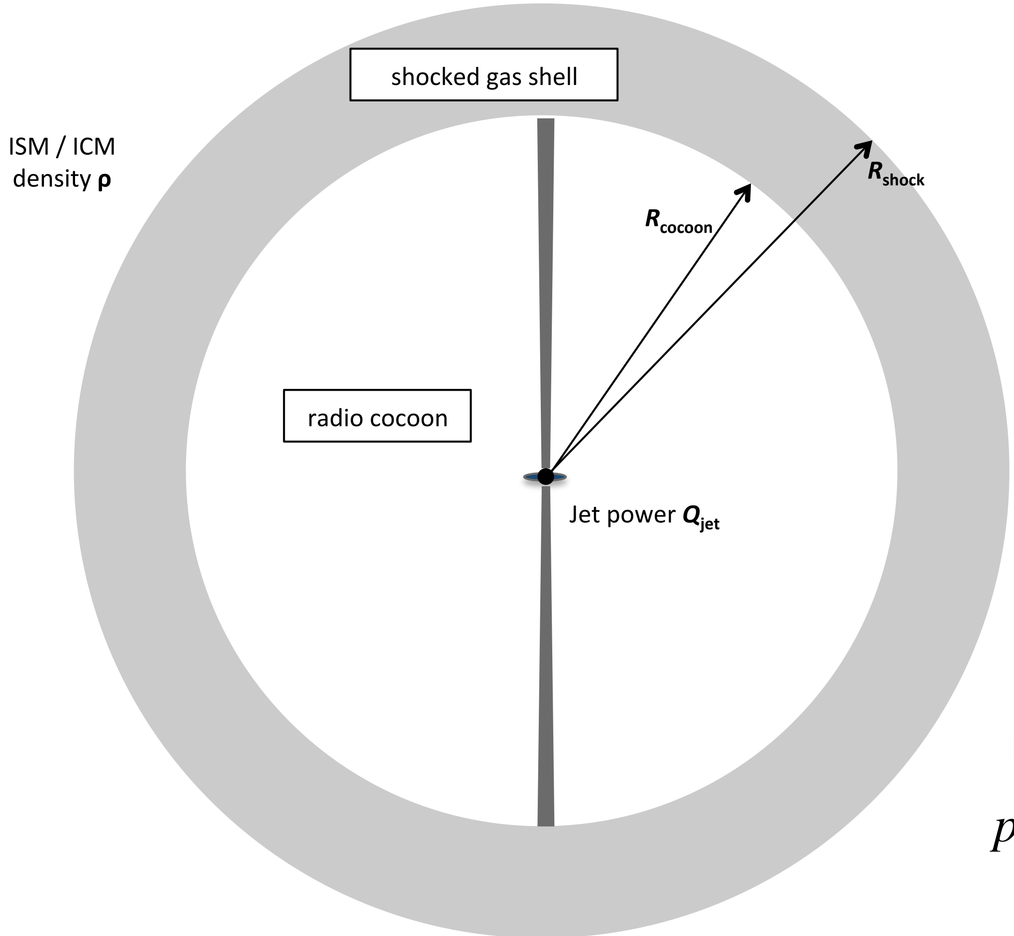
Environment-dependent SEDs



Environment-dependent SEDs



Size evolution



Conservation of energy in cocoon

$$\left(\frac{1}{\gamma_c - 1}\right)\left(V_c \dot{p}_c + \gamma_c \dot{V}_c p_c\right) = Q_{\rm jet}$$

Conservation of momentum in shell

$$\left(\frac{1}{\gamma_s - 1}\right)\left(V_s \dot{p}_s + \gamma_s \dot{V}_s p_s\right) = \frac{1}{2}\left(4\pi R_s\right)^2 \dot{R}_s^3$$

rate of KE flux into shell

Continuity of pressure

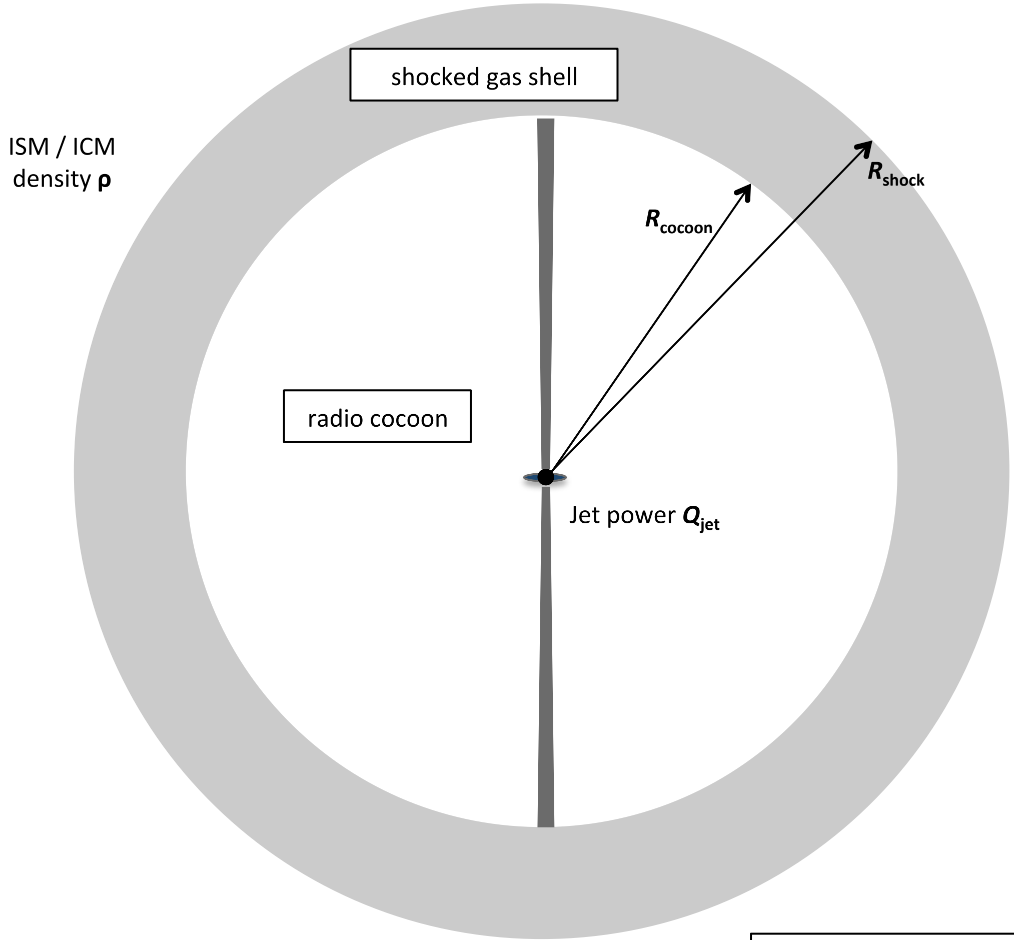
$$p_c = p_s$$

Ram pressure balances cocoon pressure

$$p_c = p_s = \rho \dot{R}_s^2$$

Assumptions:
- Strong shock
- Adiabatic expansion
- Energy driven (i.e. shock heated gas not radiative)

Size evolution

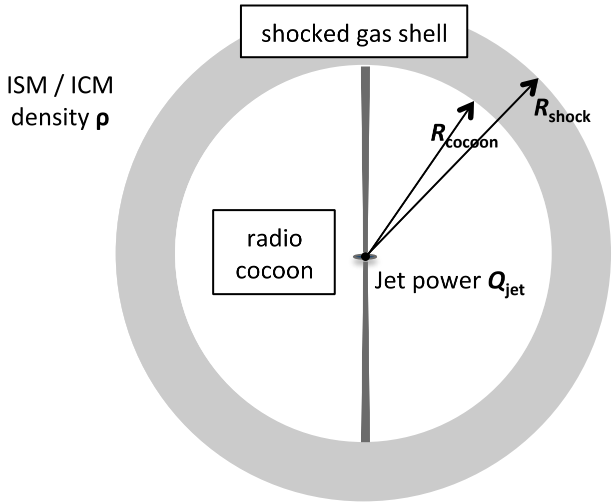


- Use geometry for volume of cocoon and shell
- Have 3 variables (p, R_c, R_s) and their derivatives (1st and 2nd)
- Assume power-law form for evolution of these with time
  $R_s = At^{\alpha}, p = Bt^{\beta}$ etc.
- Solve equations to get time dependence of R_s

$$R_s = \left(\frac{125}{154\pi} \frac{Q_{jet}}{\rho} \right)^{1/5} t^{3/5}$$

Size evolution depends on jet power and density

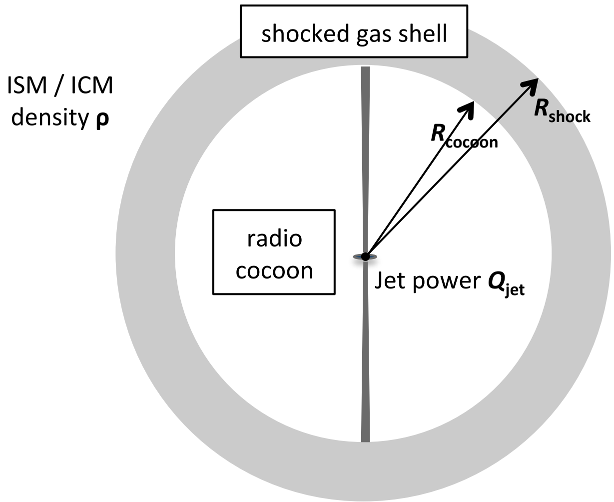
Luminosity evolution



- Radio emission comes from synchrotron-emitting cocoon electrons gyrating about magnetic field lines
- Luminosity is related to emissivity integrated over cocoon volume
- Depends on *B*-field, electron energy distribution, and volume

$$L_\nu = \left(\frac{2}{3}\right)\sigma_{\mathrm{T}} c u_B \frac{\gamma^3}{\nu} n(\gamma) V_{\mathrm{cocoon}}$$

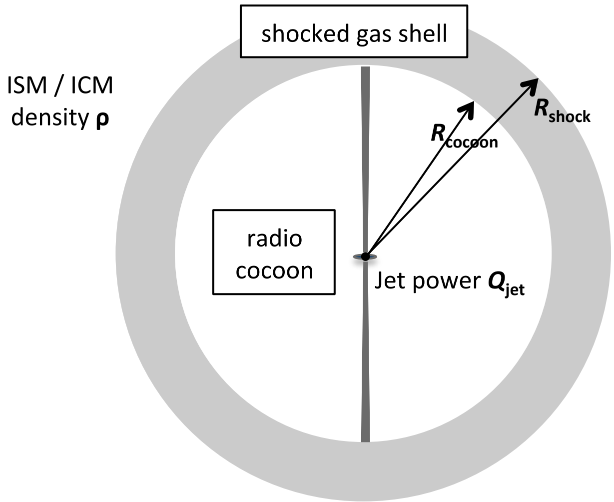
Luminosity evolution



- Radio emission comes from synchrotron-emitting cocoon electrons gyrating about magnetic field lines
- Luminosity is related to emissivity integrated over cocoon volume
- Depends on *B*-field, electron energy distribution, and volume

$$L_\nu = \left(\frac{2}{3}\right)\sigma_T c \boxed{u_B} \frac{\gamma^3}{\nu} \boxed{n(\gamma)} \boxed{V_{cocoon}}$$

Luminosity evolution



- Radio emission comes from synchrotron-emitting cocoon electrons gyrating about magnetic field lines
- Luminosity is related to emissivity integrated over cocoon volume
- Depends on *B*-field, electron energy distribution, and volume

$$L_\nu = \left(\frac{2}{3}\right)\sigma_{\mathrm{T}} c u_B \frac{\gamma^3}{\nu} n(\gamma) V_{\mathrm{cocoon}}$$

Time evolution

1. Electrons lose energy
2. B-field changes
3. Cocoon expands

Assumptions

Adiabatic, synchrotron, IC (CMB) losses

Equipartition between cocoon pressure and *B*-field energy density

Use dynamical model

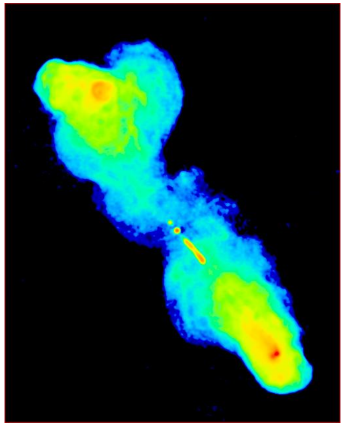
$$\frac{d\gamma}{dt} = \boxed{-\alpha\frac{\gamma}{t}} - \frac{4}{3}\frac{\sigma_{\mathrm{T}}}{m_e c}\gamma^2\left(\boxed{u_B} + \boxed{u_C}\right)$$

$$u_B \approx p_C$$

$$V_{\mathrm{cocoon}} \propto t^{-3\alpha}$$

Radio source models

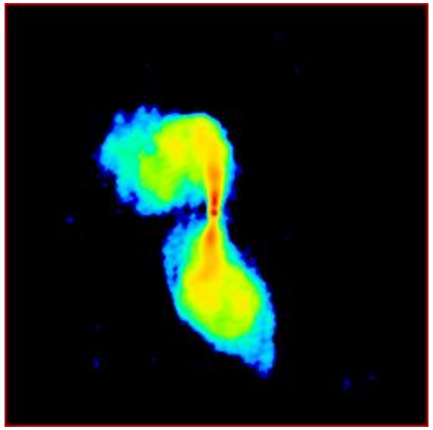
FR - II



Strong shock **supersonic** limit
(e.g. Falle 1991, Kaiser & Alexander 1997)

- Ram-pressure driven expansion
  $p_{\mathrm{lobe}} \propto \dot{r}^2$
- Ignores external pressure

FR - I

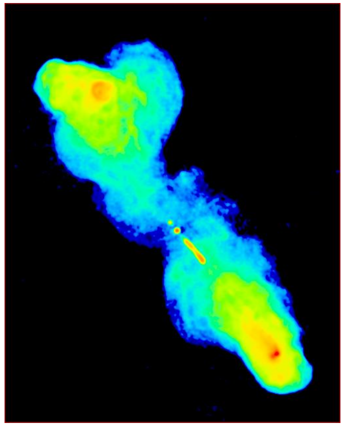


Pressure-limited expansion
(e.g. Luo & Sadler 2010)

- "Coasting" down ext. pressure gradient
  $p_{\mathrm{lobe}} \approx p_{ext}$
- Ignores ram pressure

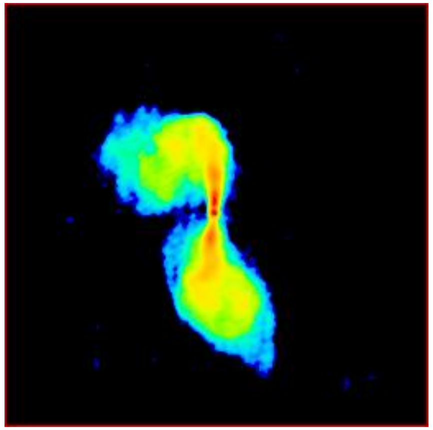
Radio source models

FR - II



All sources initially supersonic FR-IIs
Evolve into FR-Is as expansion slows

FR - I



Strong shock **supersonic** limit
(e.g. Falle 1991, Kaiser & Alexander 1997)

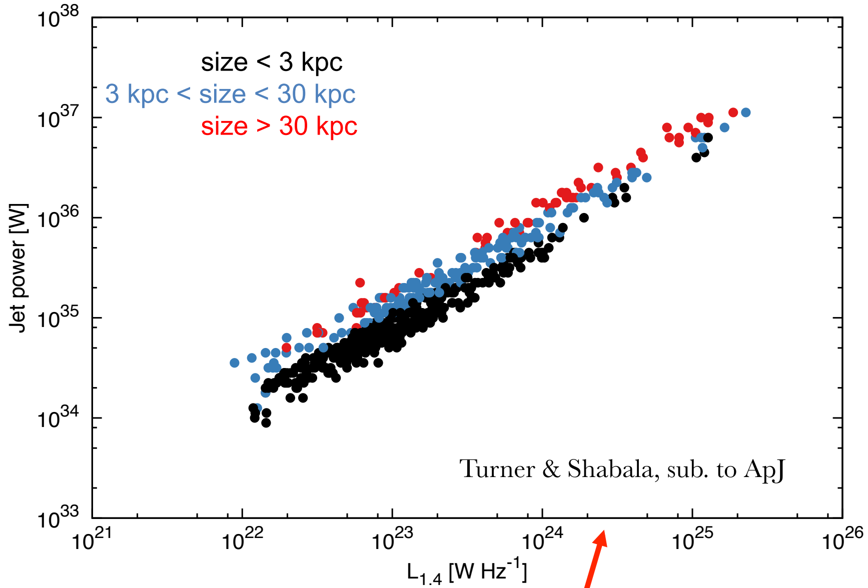
- Ram-pressure driven expansion
  $p_{\text{lobe}} \propto \dot{r}^2$
- Ignores external pressure

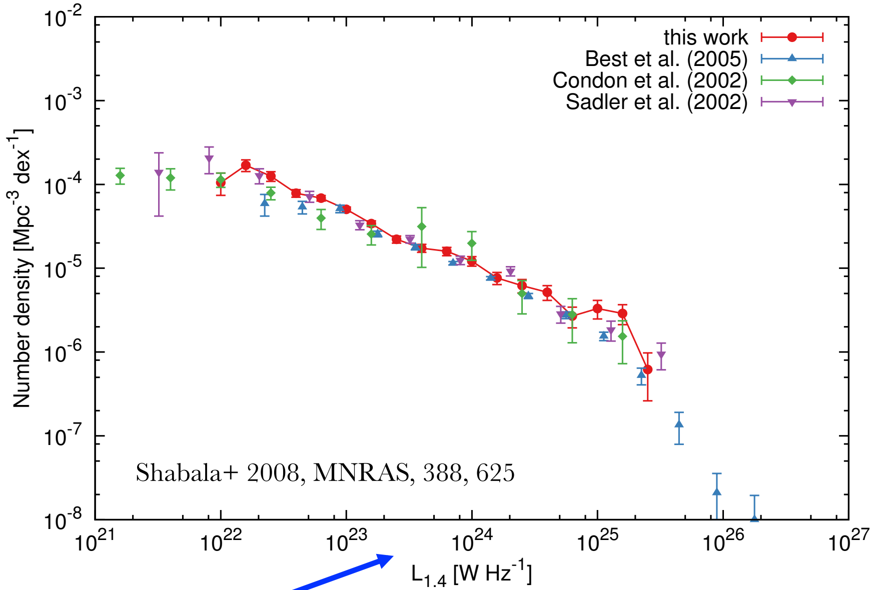
Pressure-limited expansion
(e.g. Luo & Sadler 2010)

- "Coasting" down ext. pressure gradient
  $p_{\text{lobe}} \approx p_{ext}$
- Ignores ram pressure

NEW: Combined model, with FR-I / II as limiting cases

3. Which AGN dominate energetics ?





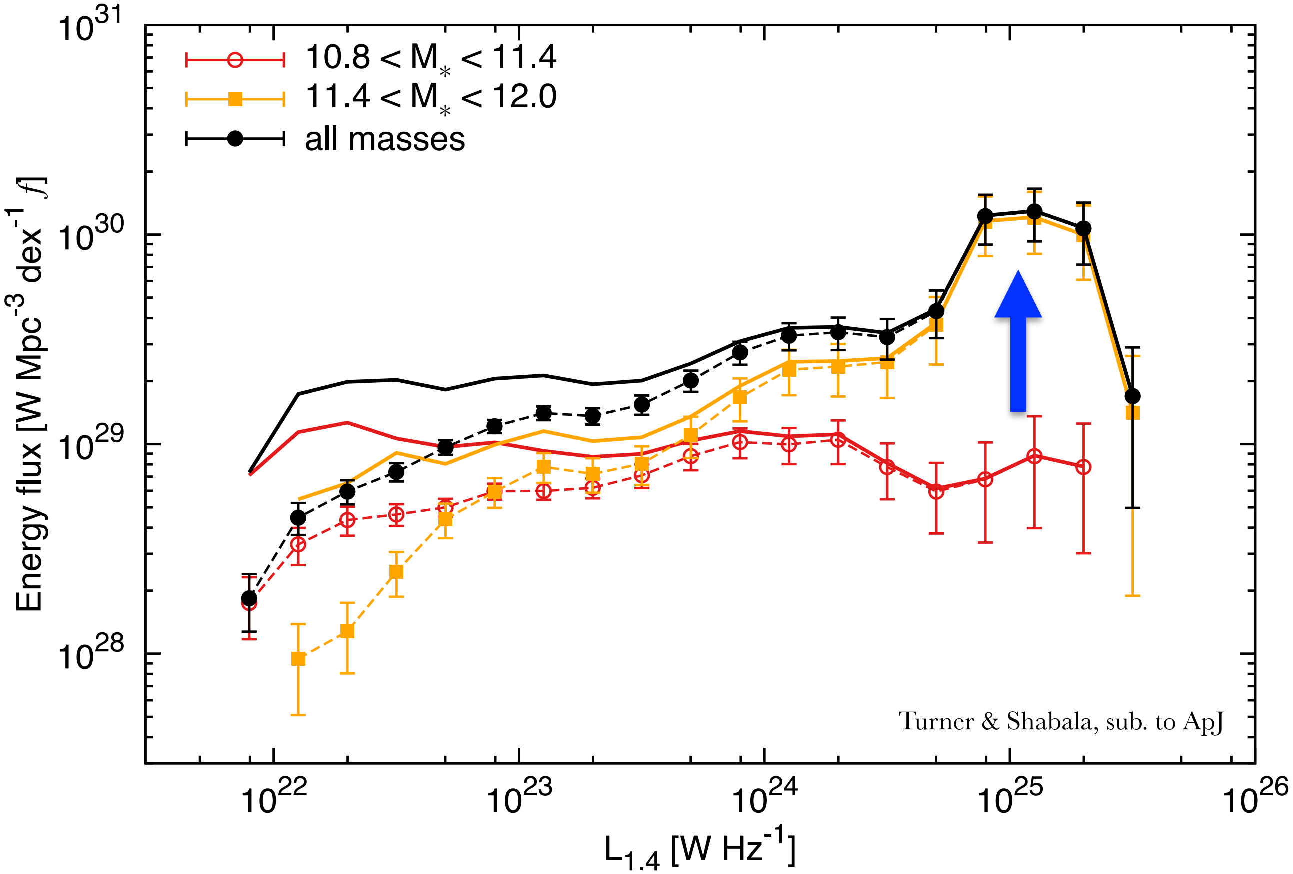
Bright sources have **higher** jet powers…

… but are more **rare**

➔ which radio sources dominate feedback energetics?

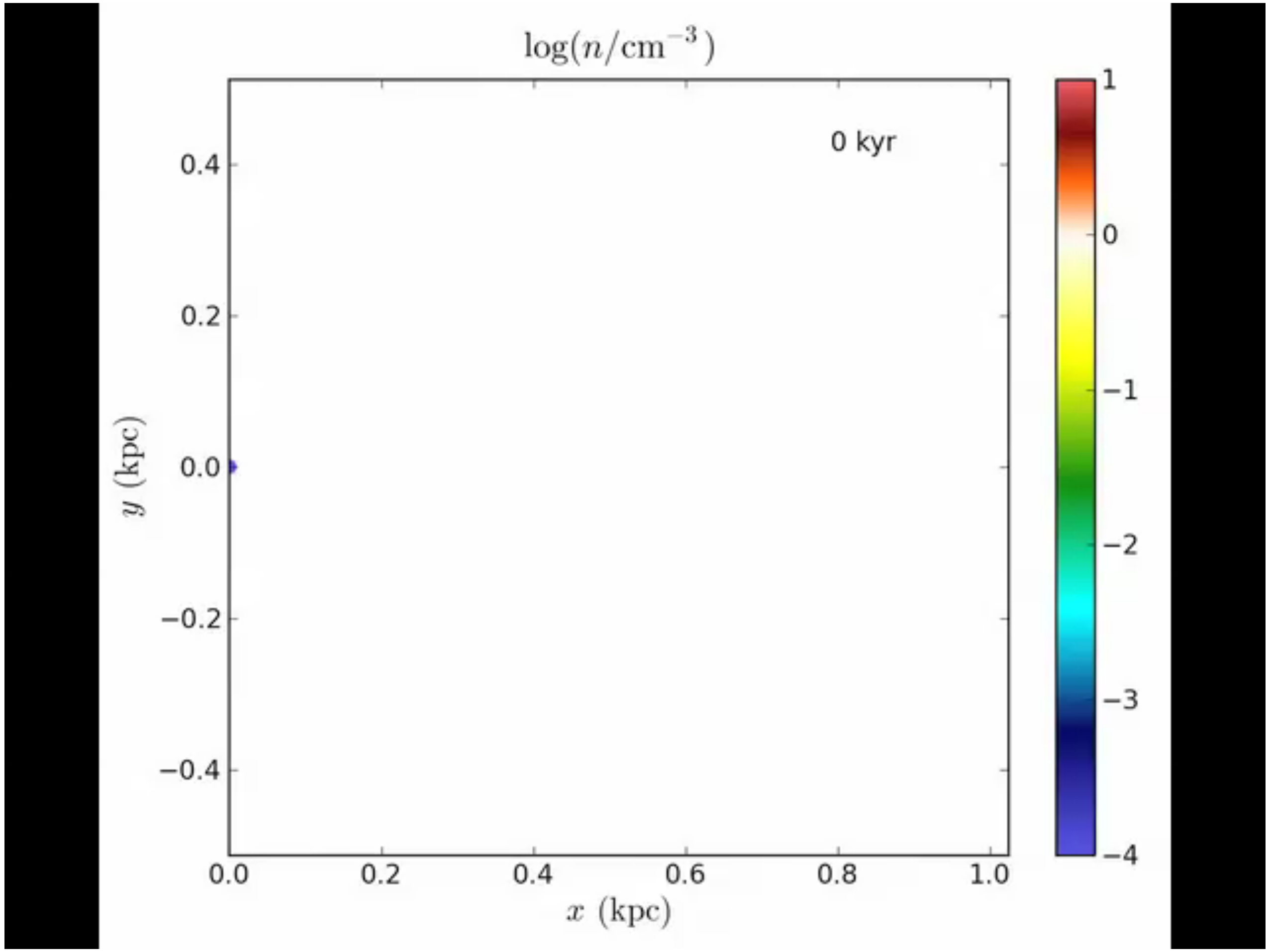
Convolve $Q_{jet} - L_{radio}$ relation with RLF

3. Which AGN dominate energetics ?



Powerful sources in **massive** galaxies do **more feedback**, despite being rare

Jet-driven radio bubbles



Wagner & Bicknell 2011, ApJ, 728, 29