

Quasar Feedback

Martin Elvis

Harvard-Smithsonian Center for Astrophysics

Lecture 3

R. Somerville: OIR lunch talk, 3/29/05

AGN as a panacea?

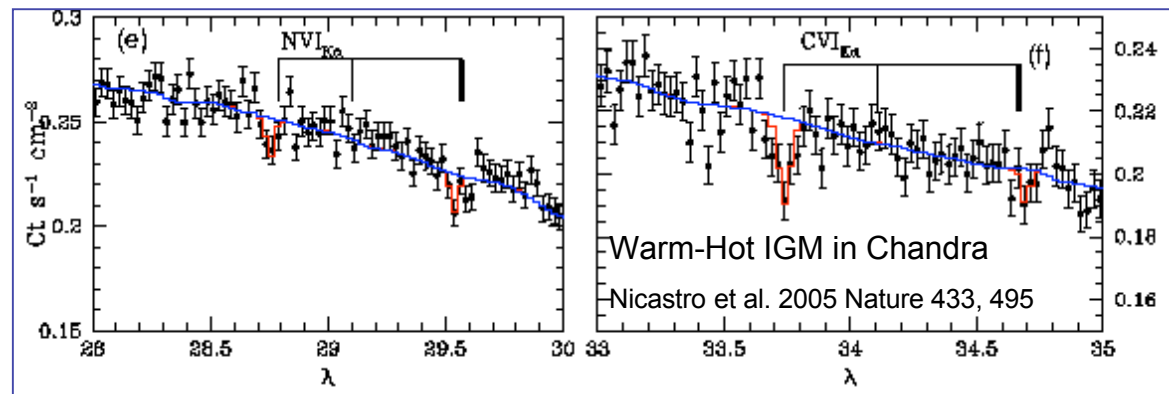
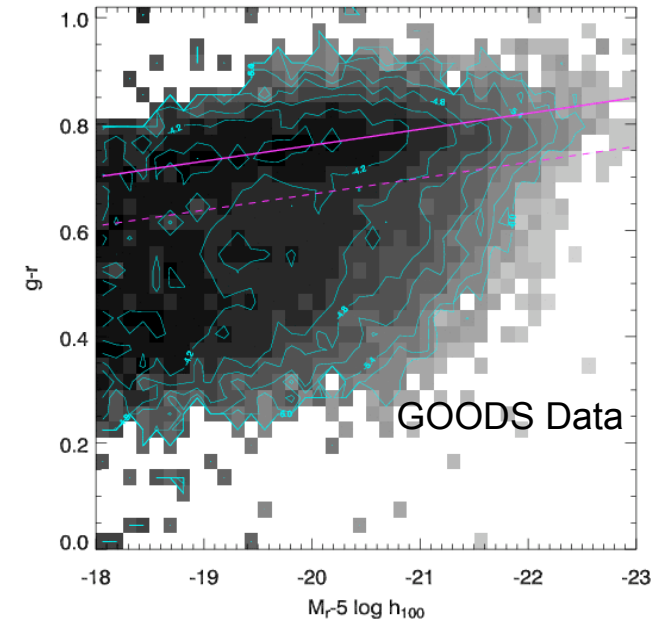
- o overcooling problem/LF shape
- o galaxy red sequence & bimodality
- o decline of bright QSO's
- o $M_{\text{BH}}-\sigma$ relation
- o QSO and galaxy 'downsizing'
- o cluster cooling flow problem/entropy floor

Quasars now repeatedly invoked in Cosmology

AGN as a ‘panacea’[©]:

1. BH-galaxy mass (M - σ) relation
2. Prevention of Star formation in massive mergers ‘Dry Mergers’
3. Limiting the upper mass of galaxies
4. Inhibition of cooling flows
5. Enrichment of the Intergalactic Medium
6. Creation of dust at $z \sim 6$

AGB stars only form at $t \sim 1$ Gyr



Pathways for AGN feedback

1. **Radiation:** *the quasar continuum*

- Universal in AGNs
- Heat, ionize, accelerate host ISM
- Easily absorbed esp. by 'torus'

2. **Relativistic Jets**

- Powerful
- Rare (10%) duty cycle? Massive galaxies only?

3. **Slow Outflows:** *quasar winds*

- Common (>50%)
- 1000 - 10,000 km/s - escape to IGM

4. **Impulsive events**

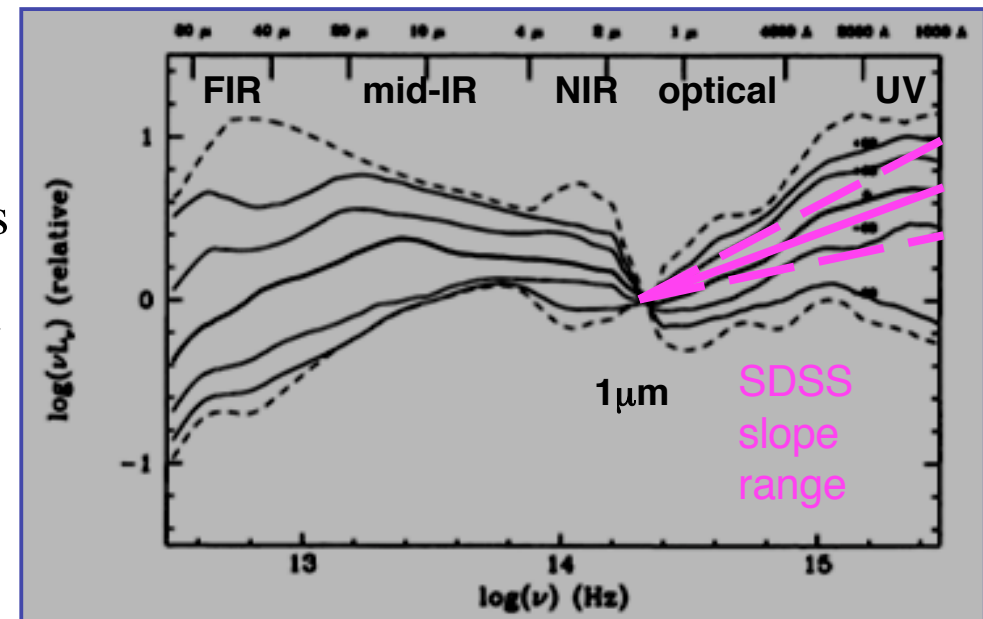
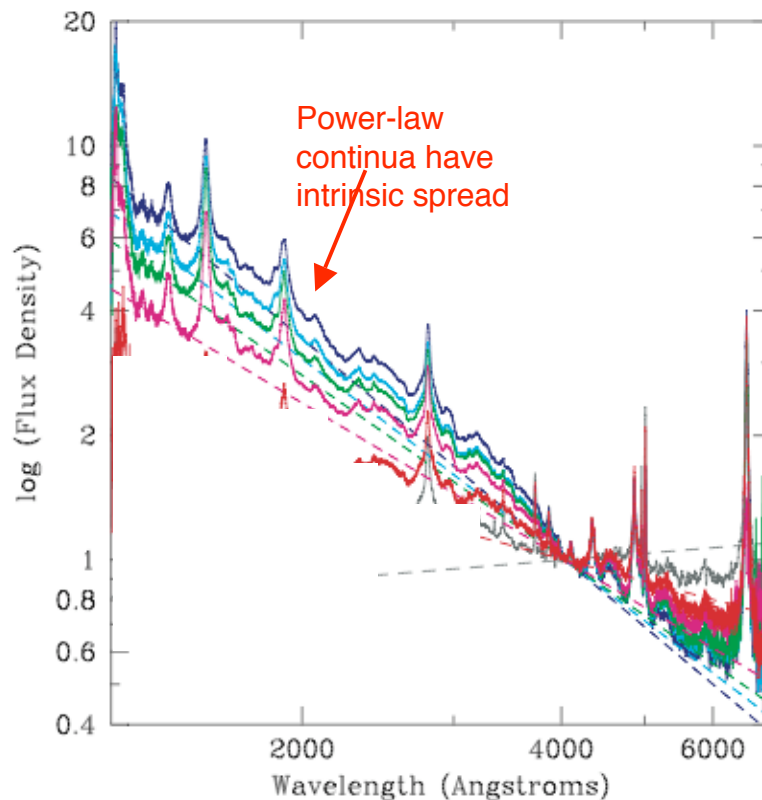
- E.g. during mergers

Radiation

- Effect on host ISM
 - Ionization
 - Heating
 - acceleration
- Ostriker & Ciotti
 - Compton heating only
- Opt/UV/soft-X-ray
 - Much higher efficiency
 - blocked by obscuring torus
 - Location, geometry of torus a big effect

Bolometric Radiative output of Quasars

- Estimate total (bolometric) luminosity from limited data
- Hard X-ray/UV ratio (α_{OX}) particularly important to gauge effects of heavily obscured AGNs
- Requires good knowledge of range of continuum shapes with (L, z)



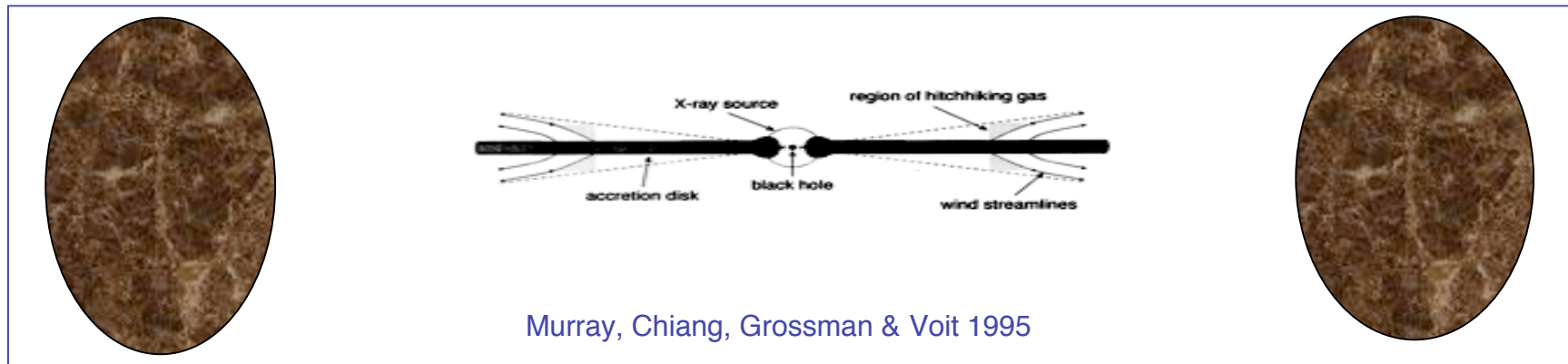
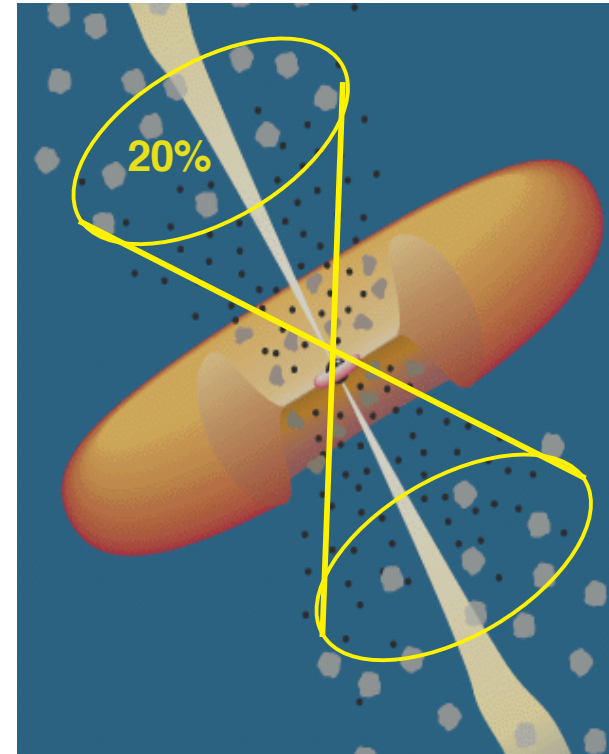
Elvis et al., 1994, ApJ, 95, 1

- Cannot determine L_{bol} for population
- Need correlation of SED shape to M_{BH} , m_{dot} to predict L_{bol} for whole quasar population at all L, z
- Need a theoretical understanding to make precision predictions

Richards et al. 2002, ApJ, 126, 1131. SDSS

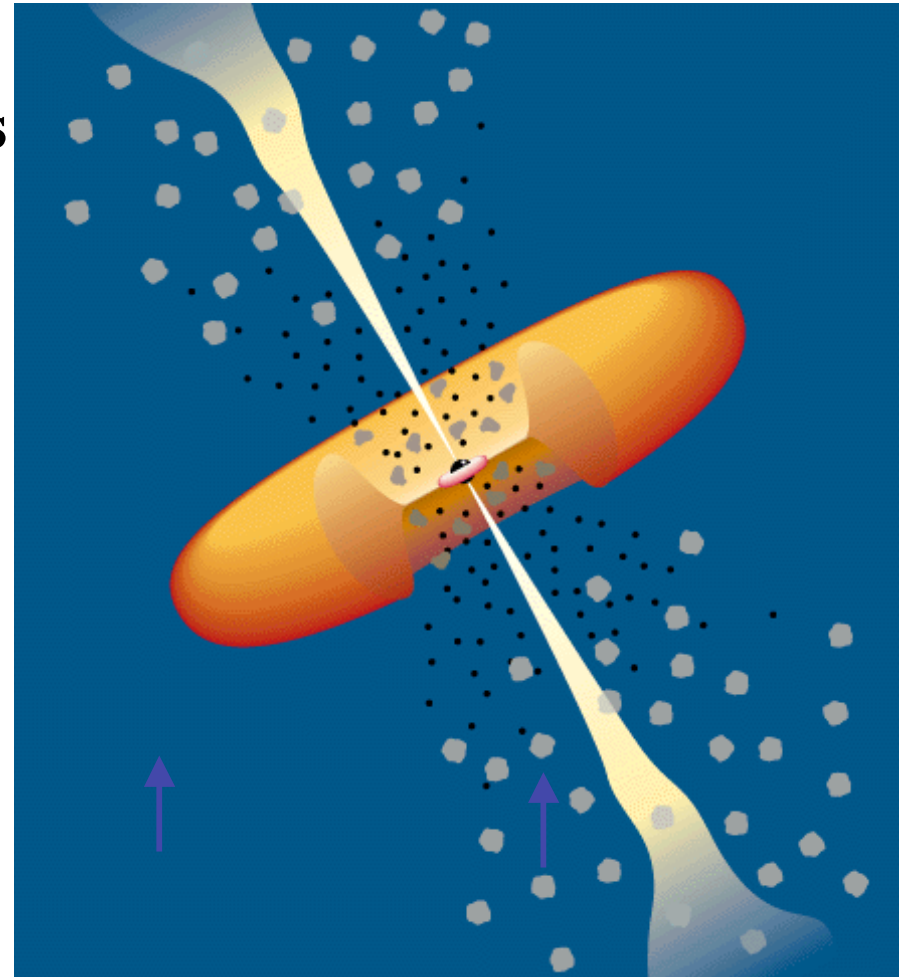
Obscuring Tori affect Feedback

- Standard torus blocks 80% of radiation feedback to ISM
 - X-ray to near-IR absorbed
 - thermalized
 - re-radiated in Far-IR
- Torus aligned with accretion disk blocks equatorial winds
 - no mass, KE escape, no effect on host, IGM
 - some fireworks: few 1000 km/s impacting mol. cloud: large, ongoing SNR shocks



Tori in AGNs

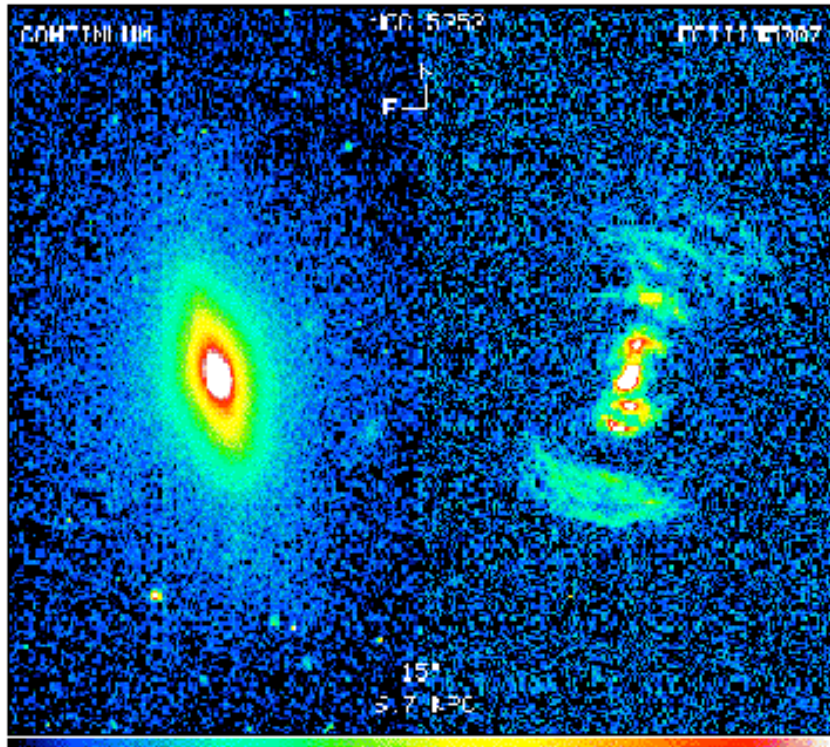
- **Clearly there is a flattened obscuring region in most AGNs**
 - >20 year old result
 - Keel 1980, Lawrence & Elvis 1982, deZotti & Gaskell 1985, Antonucci & Miller 1985....
 - Axisymmetry requires a torus
- ***But is this toroid the `donut' shaped parsec-scale object usually invoked?***



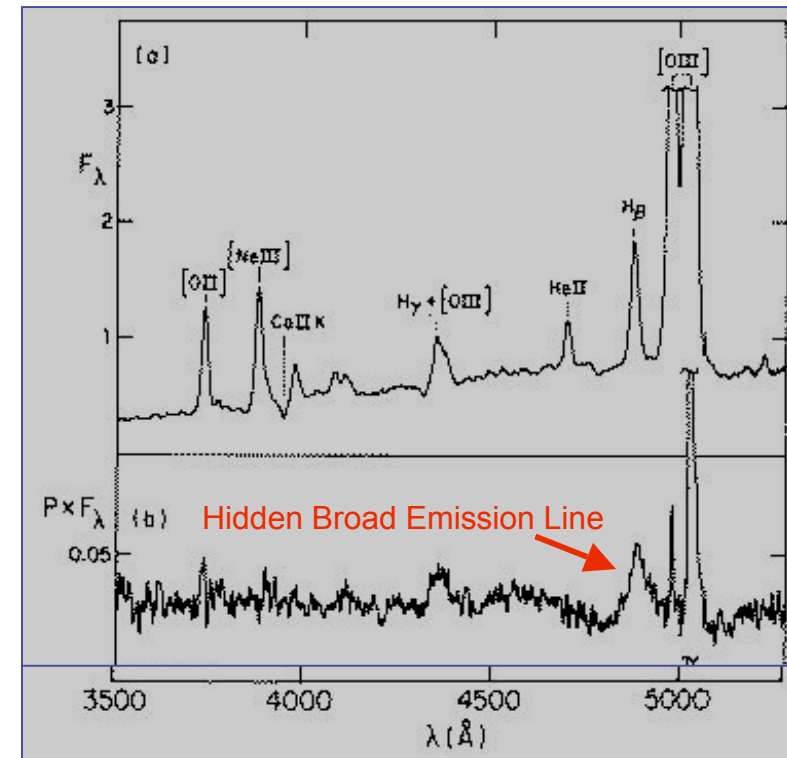
Urry C.M. & Padovani P. 1985 PASP, 107, 803. [706 ADS citations]

AGN Obscuring Torus Explains:

1. Hidden Broad Line Regions
2. Ionization cones
3. 4:1 ratio of type2/type1 AGNs



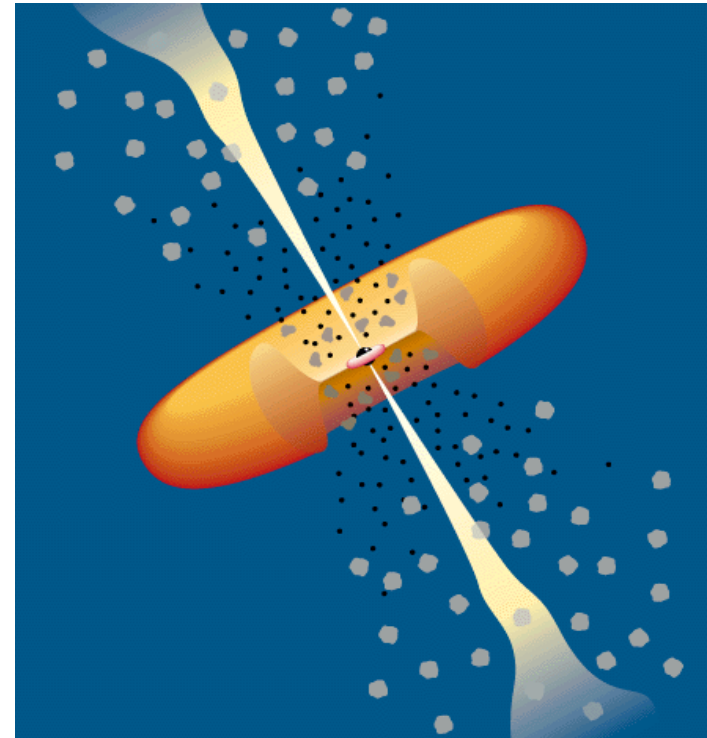
Tadhunter & Tsvetanov 1989 Nature 341, 422



Antonucci & Miller 1985 ApJ 297, 621

The Standard Torus

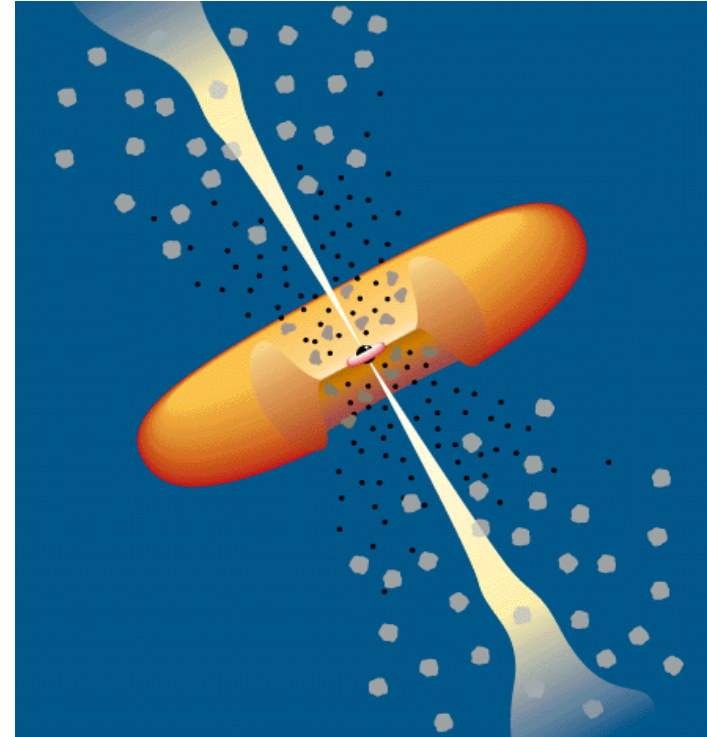
- *Molecular Torus* posited by Krolik & Begelman (1988 ApJ 392, 702):
 - Large scale height: $h/r \sim 0.7$
 - $r \sim 1 \text{ pc}$ [set by dust sublimation radius]
 - $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2} \sim \text{Compton thick}$



Standard Torus: Standard Issues

- *How is donut supported?*
 - Covering fraction $>50\%$,
yet cold (dusty)
 - Cloud-cloud collisions should
flatten structure
 - Thick clumpy accretion needs
 $M_{\text{torus}} > M_{\text{Edd}}$ *see SgrA**

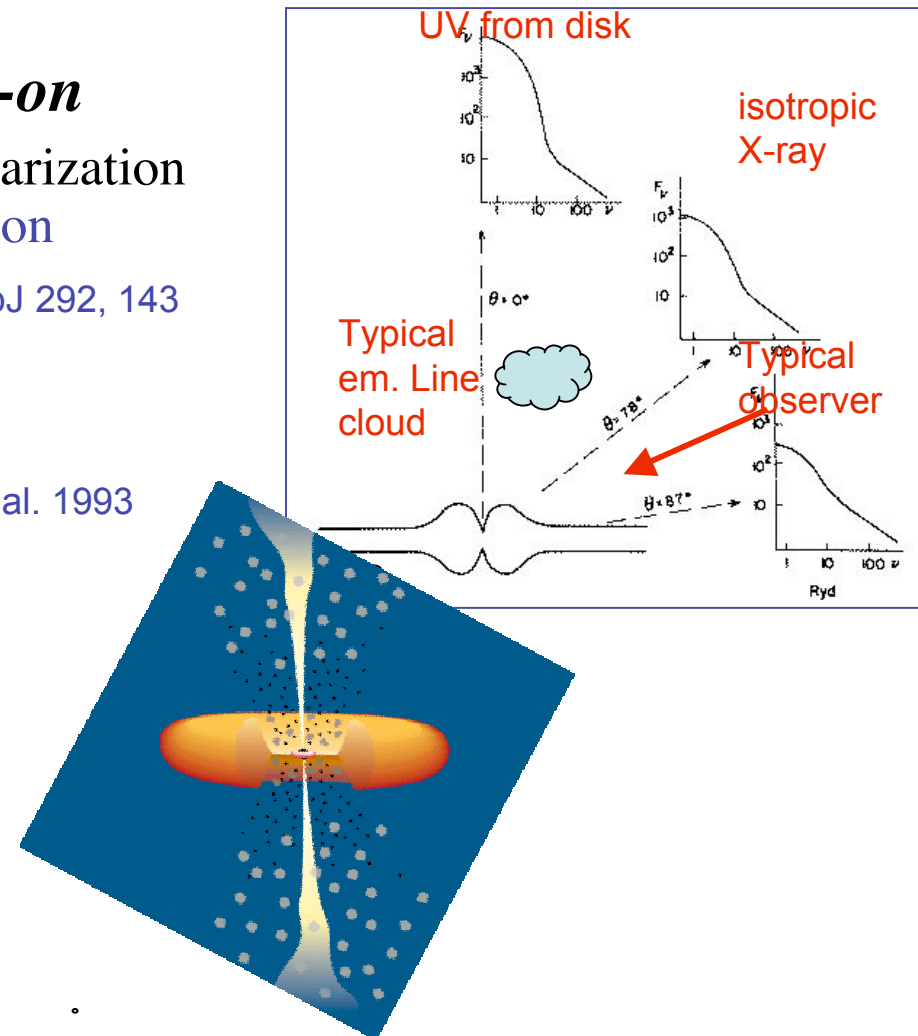
Vollmer, Beckert & Duschl 2004 A&A 413, 949



Standard Torus: two more Issues

- ***Disk - torus co-aligned***
Equatorial wind can't escape
- ***Can't see accretion disk edge-on***
 - Difficult for rotation of BEL polarization PA - all type 1 AGNs are \sim pole-on
 - Viewing angle **Netzer et al. 1985, ApJ 292, 143** can't be used to explain 'continuum energy deficit' and 'ionizing photon deficit' **Binette et al. 1993 PASP 105, 1150**

Netzer 1987 MNRAS 225, 55



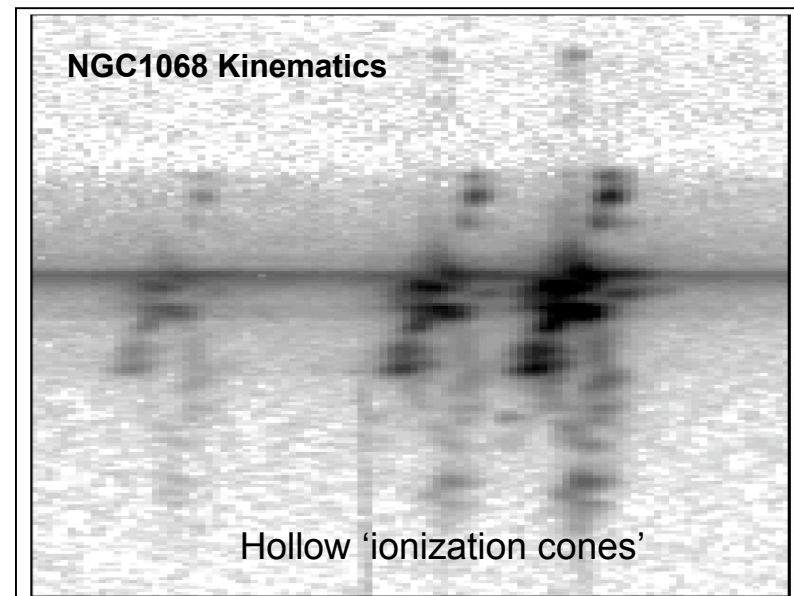
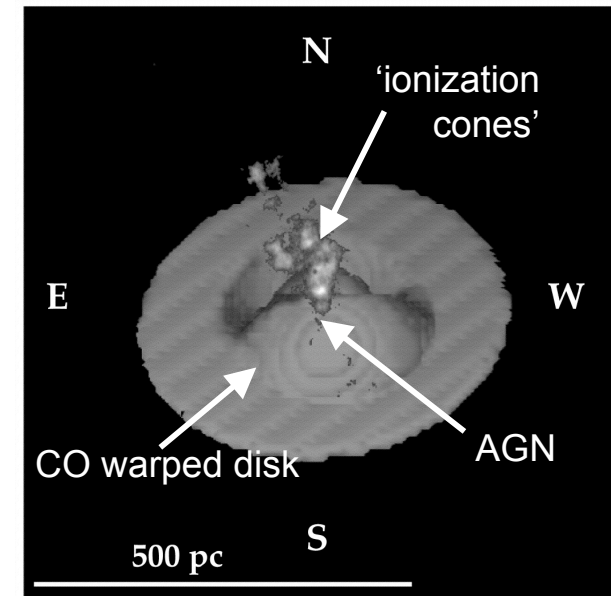
Torus Invented for NGC1068

... Yet not needed in NGC 1068 itself:

- Warped CO disk on ~ 100 pc scale
Schinnerer et al. 2000 ApJ 533, 850
- NGC 1068 has *hollow* 'ionization' cones
Crenshaw & Kraemer 2000 ApJ 532, L101

I.e. **Matter bounded - a true outflow cone**

- *Not* ISM illuminated by collimated continuum
- Still leaves type1:type2 ratio

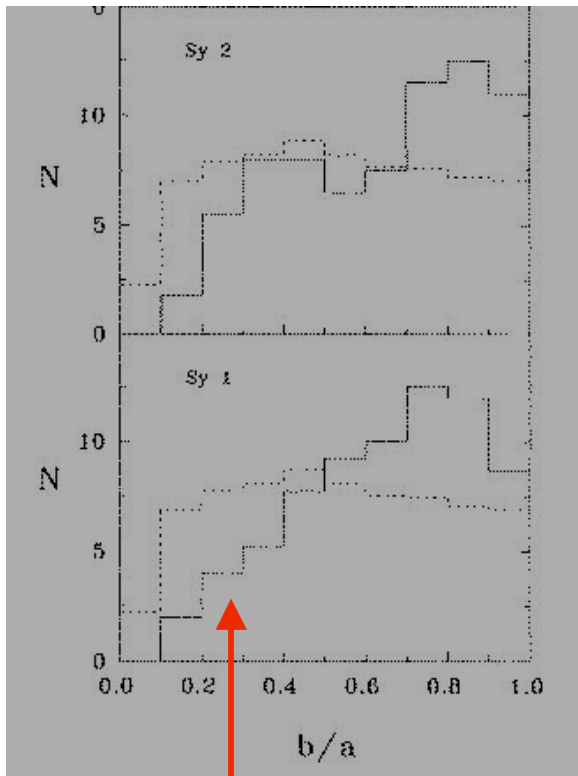


Obscurer is Aligned with Host Disk

Lawrence & Elvis 1982 ApJ,

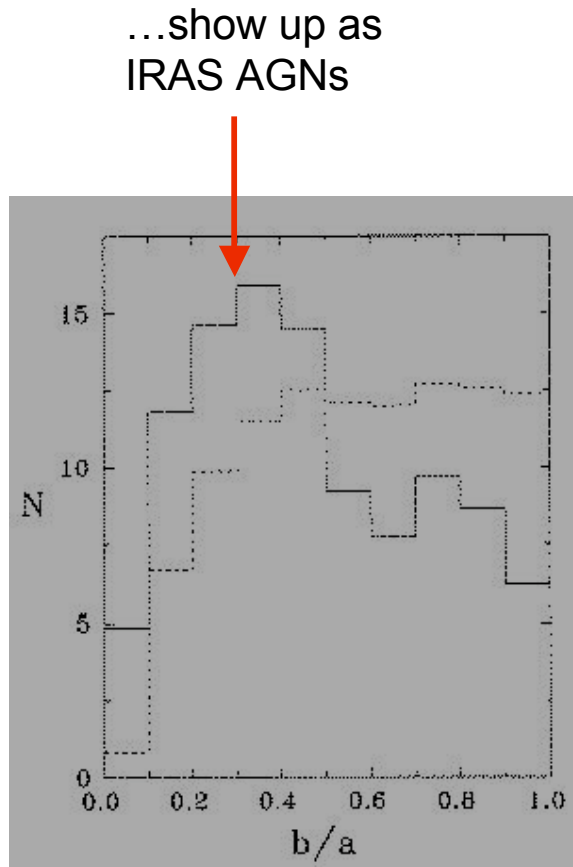
Kirhakos & Steiner 1990, AJ 99 1722

Thompson & Martin 1988 ApJ 330, 121

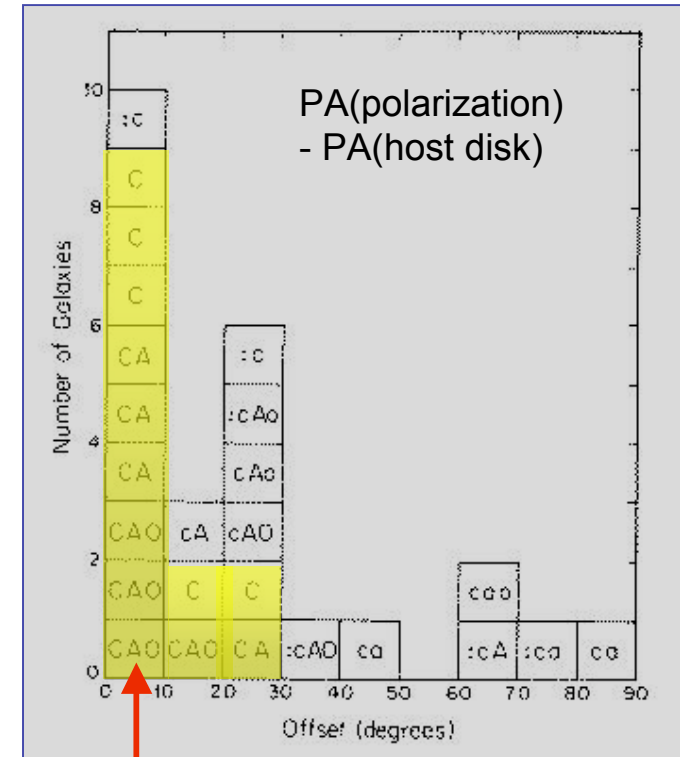


The missing edge-on type 1 AGNs...

Host galaxy Axial ratio

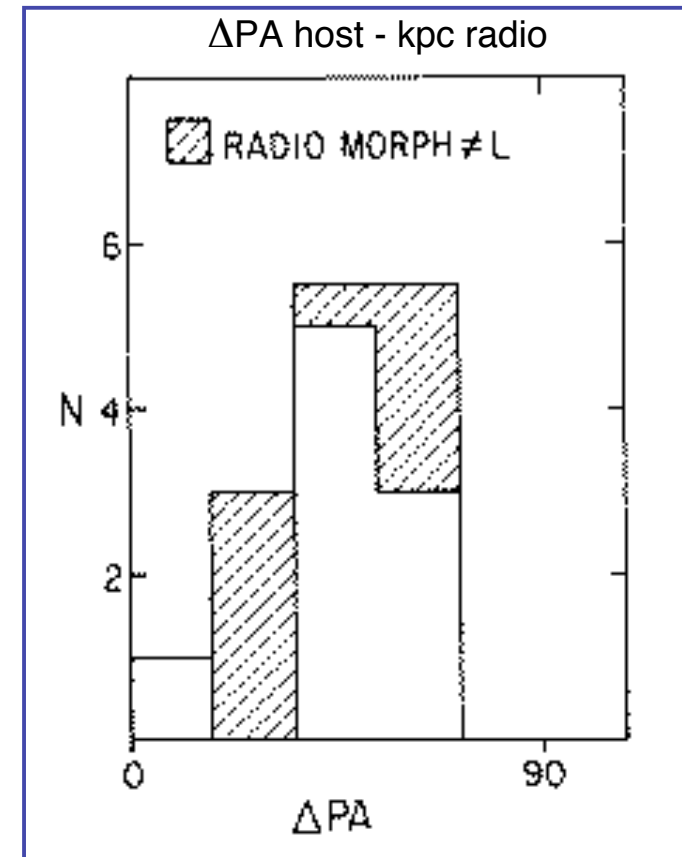
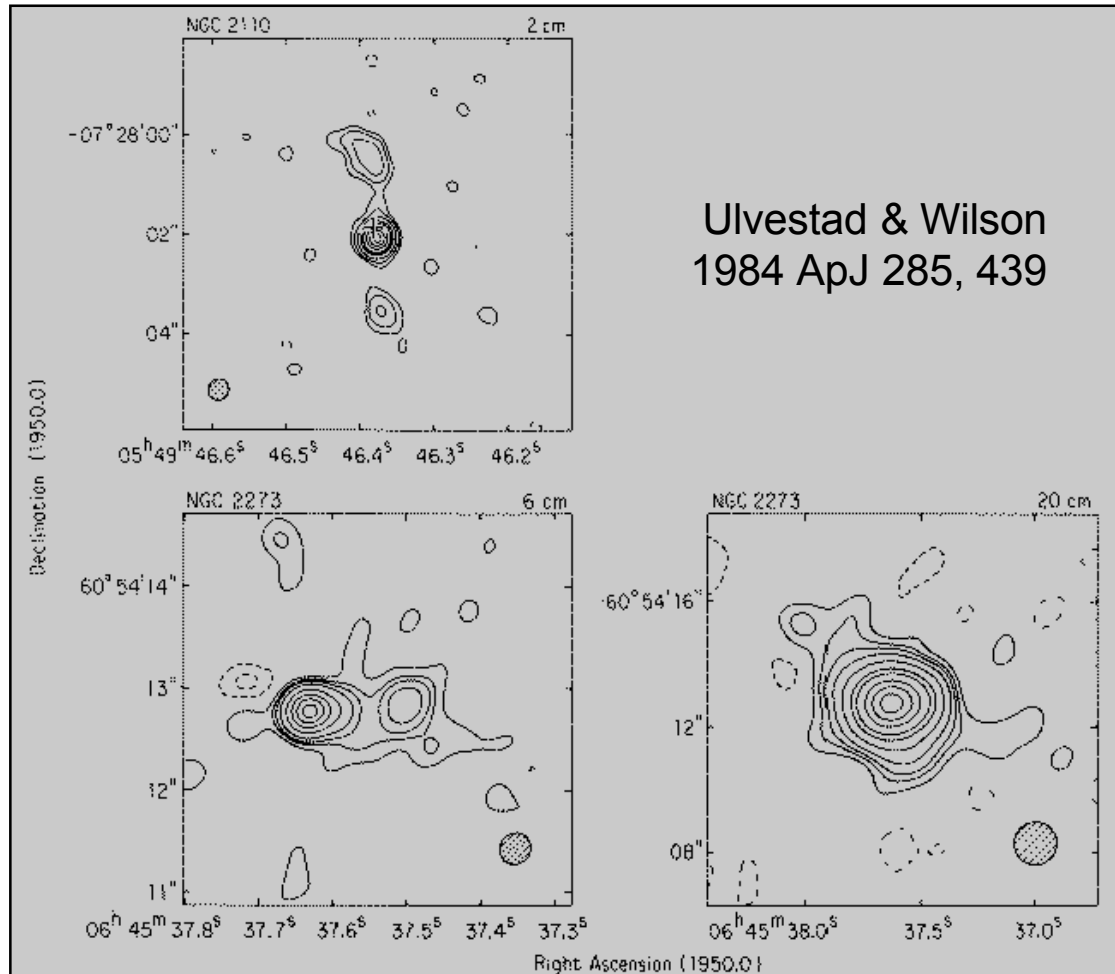


Host galaxy Axial ratio



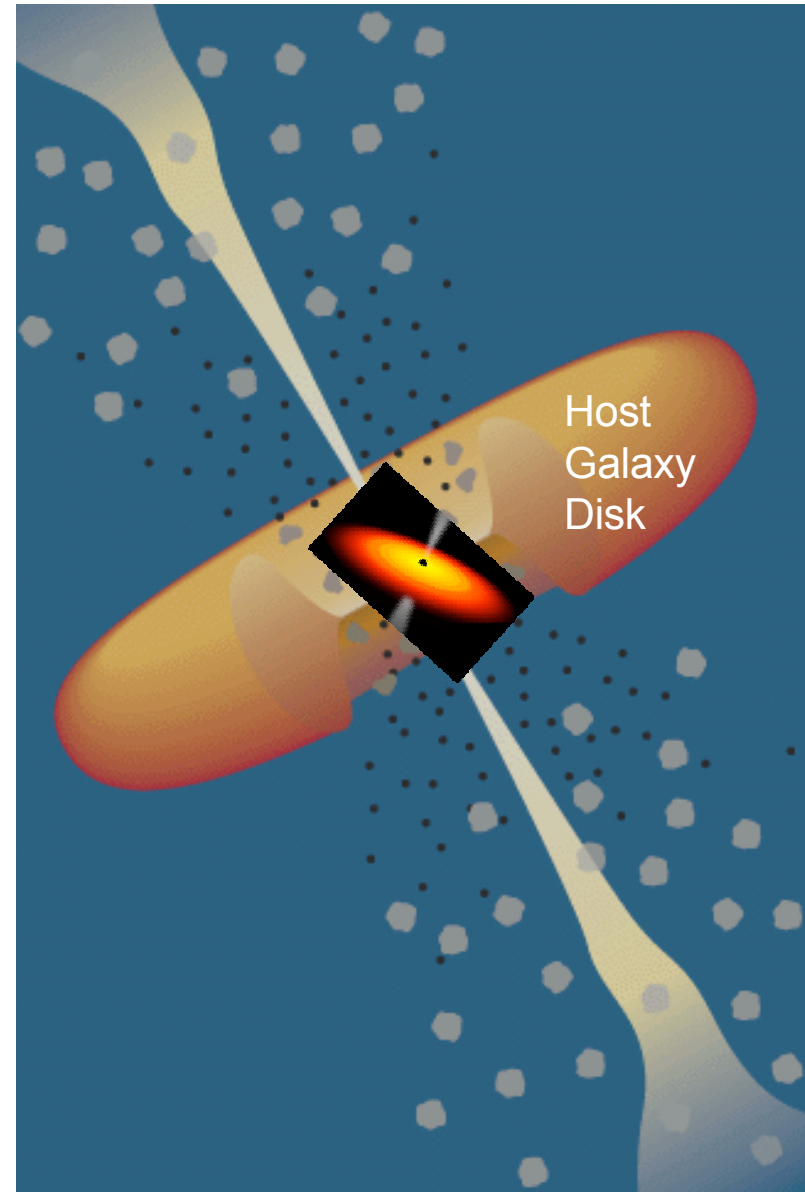
Strong continuum polarization

But radio structures/Accretion Disk are *misaligned* with Host disk



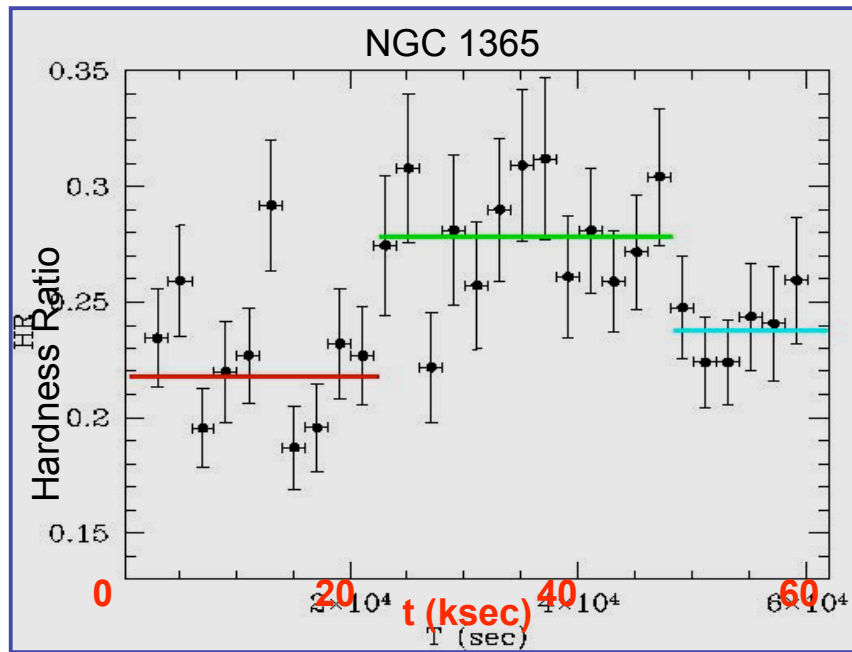
⇒ Obscurer & Accretion Disk are Misaligned

- Unobscured lines of sight sample all disk inclinations
- Netzer deficit can be solved
- AGN continuum reaches host ISM
= torus
- Host ISM may be blown away,
but not instantly, else no obscuration will be seen

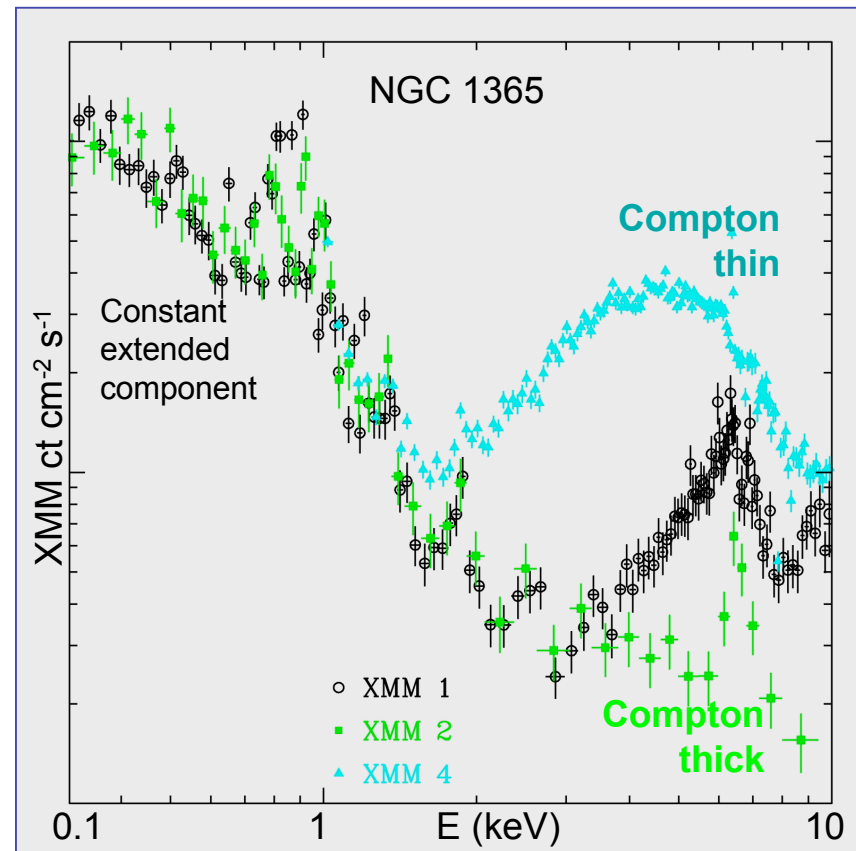


Rapid Compton-thick/-thin transitions

- $\Delta N_H \sim 10^{24} \text{cm}^{-2}$ in 3 weeks
- $\Delta N_H \sim 10^{23} \text{cm}^{-2}$ in 6 hours



Risaliti et al. 2005 ApJ 623, L93



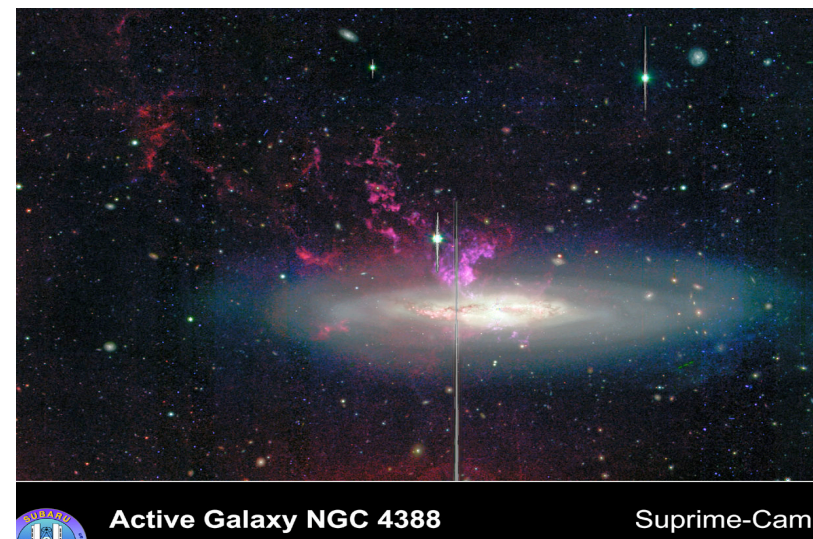
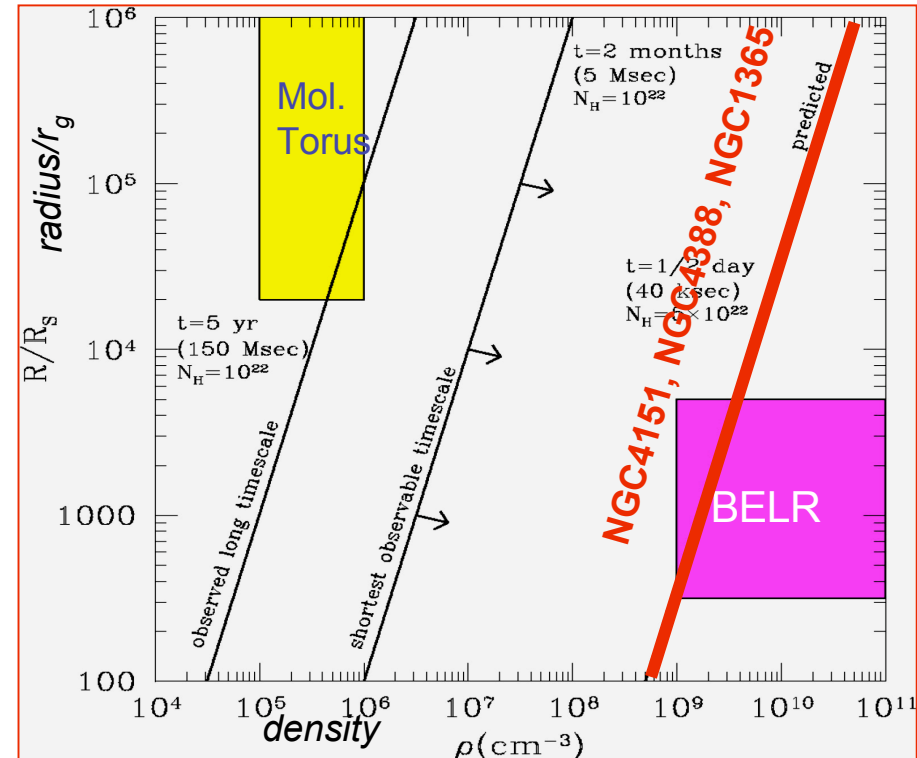
Rapid N_H Variability \rightarrow Small Obscurer Size

- 3 cases:
 - NGC4388, Elvis et al. 2004
 - NGC1365, Risaliti et al. 2005
 - NGC4151, Puccetti et al. 2006
- Hard for dusty absorber on parsec-scale
- Assume Keplerian motion of obscuring matter

$$R < 10^4 \rho_{10}^{-2} t_4^2 R_s$$

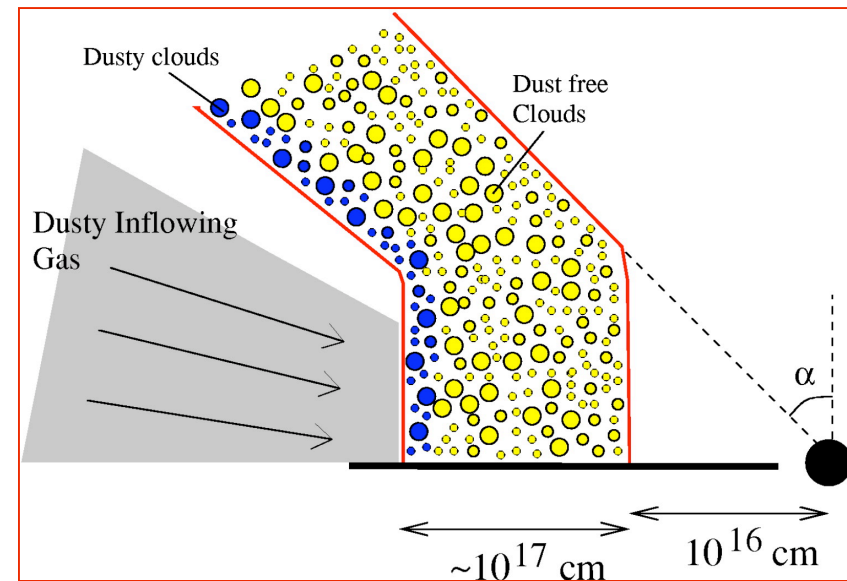
(t_4 in 4-hours, ρ in cm^{-3})

- On scale of broad emission line region (BELR)



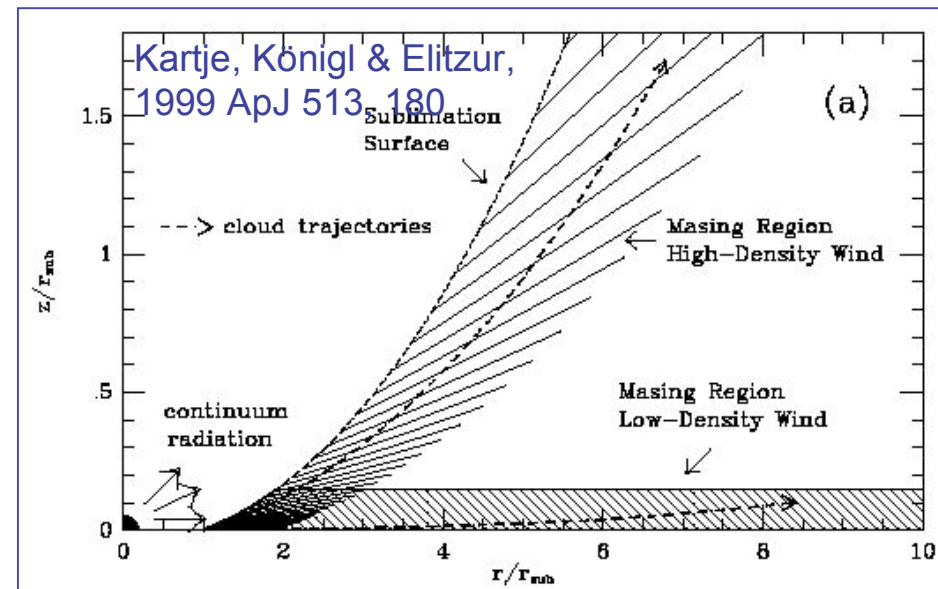
Is the Inner Torus the Disk Wind?

- **Eases torus physics:**
 - Wind is steady state, but not static
 - No problem supporting obscuring structure
 - Large covering factor easy to create
 - oversupply of BEL clouds?
 - **Low dust-to-gas ratio natural**
If disk from ISM, not disrupted stars
 - Hydromagnetic wind?



- **Aids Feedback:**
 - **Radiation still blocked**
 - **Matter escapes**
Host ISM can be affected

Paradigm - Theory convergence



Relativistic Jets:

Heating of Clusters by Cavities and Shocks

- The cluster ‘cooling flow’ problem
 - hot intracluster medium (ICM) in clusters
 - Dense at centers:
 - short cooling time
 - Huge \dot{m} - 100's $M_{\odot}/y = 10^{11} M_{\odot}/Gyr$
 - But no cool gas (<1keV) seen. [XMM](#)
 - What stops cooling? 20 year old problem
- Radio jets
 - Common in brightest cluster elliptical galaxies - at centers of cooling flows
 - Can radio plasma heat ICM?
 - *Chandra results: YES*

Many thanks to

Paul Nulsen

Harvard-Smithsonian Center for Astrophysics

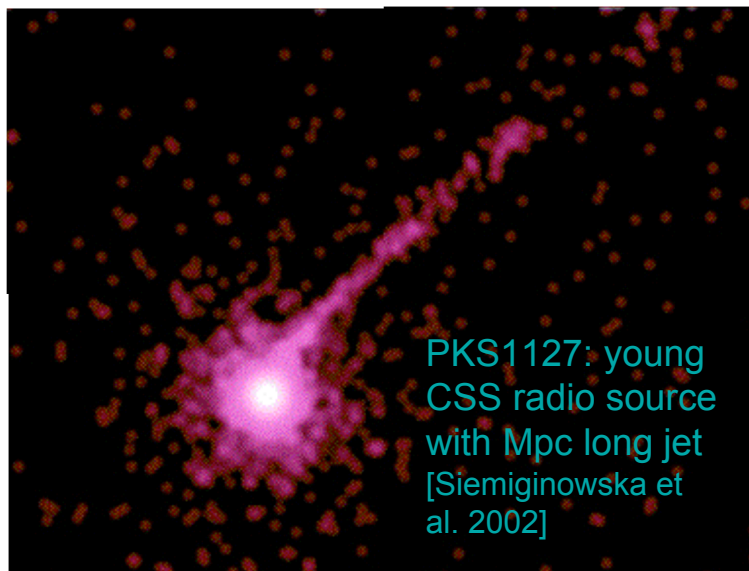
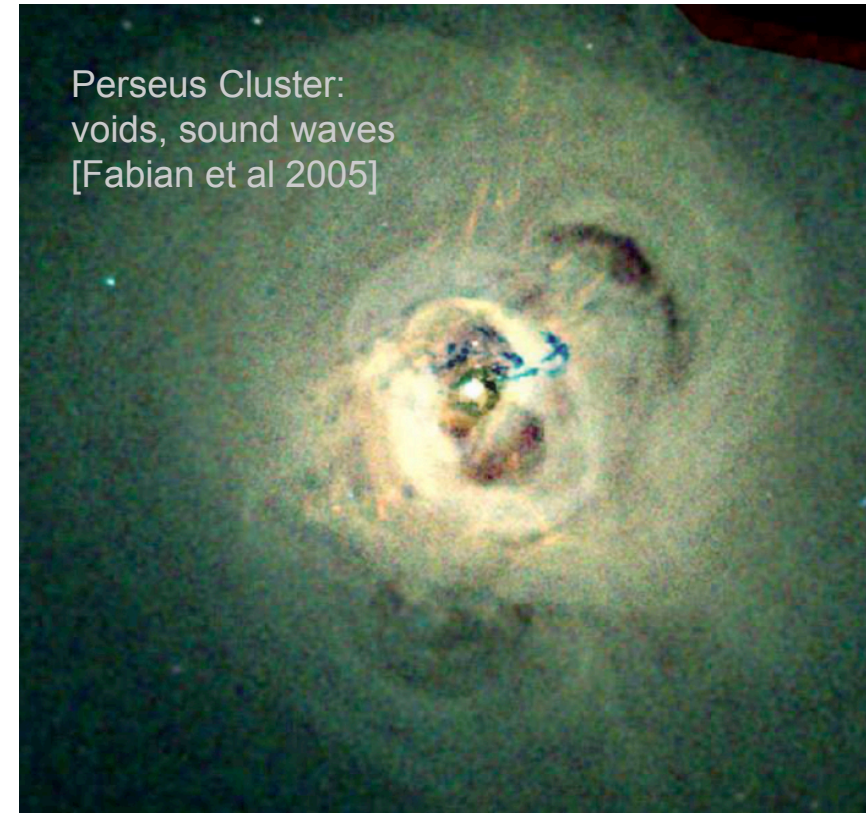
And to his collaborators

Larry David, Bill Forman, Christine Jones (CfA),

Laura Birzan, Brian McNamara, David Rafferty
(Ohio U), Mike Wise (Amsterdam)

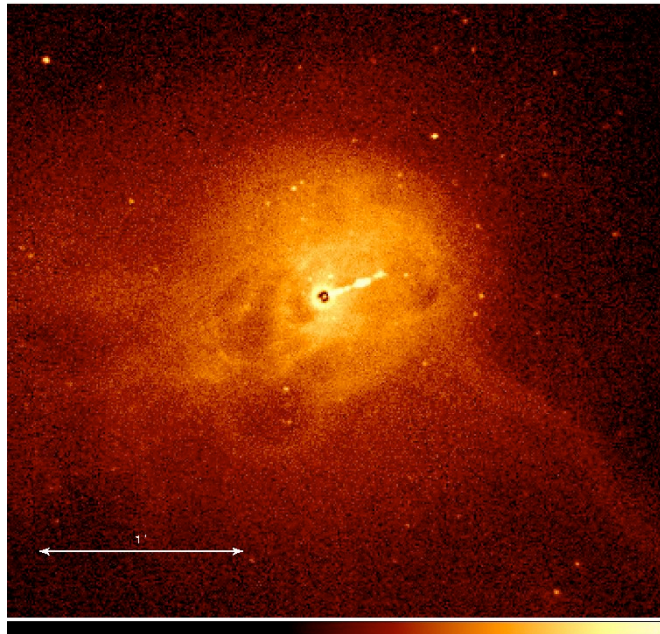
AGN radio jets stop cooling flows

- Chandra shows voids in X-ray hot intracluster medium
- radio structures fill voids
- relativistic plasma from radio jets expands into radio lobes,
- creating cavities and shocks in the hot intracluster (interstellar) gas
- Heats cooling flows via repeated AGN outbursts



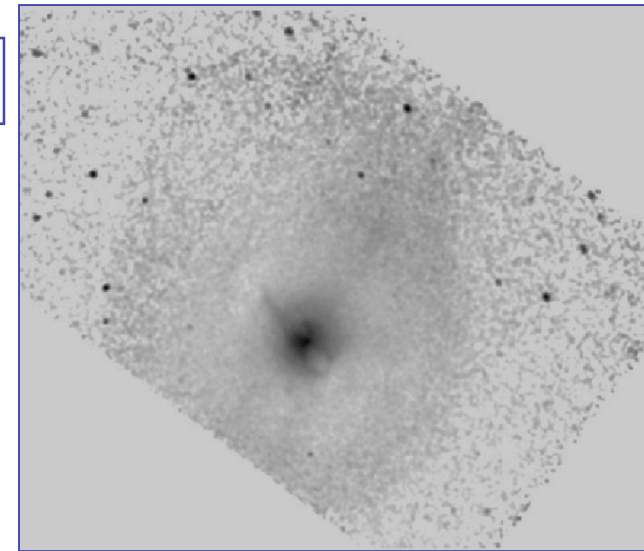
AGN created cavities are common

thanks to Paul Nulsen

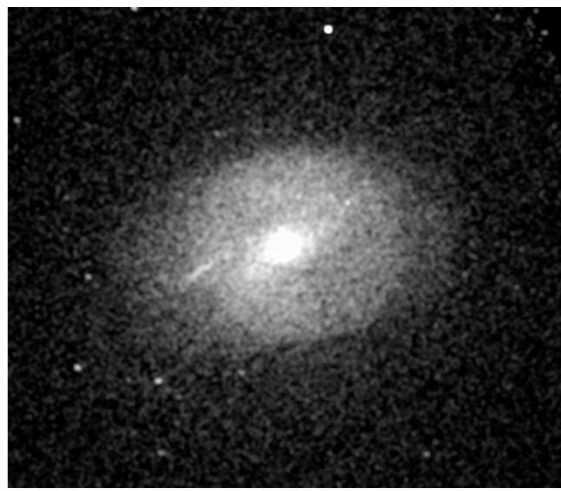


M87 Forman et al. 2006

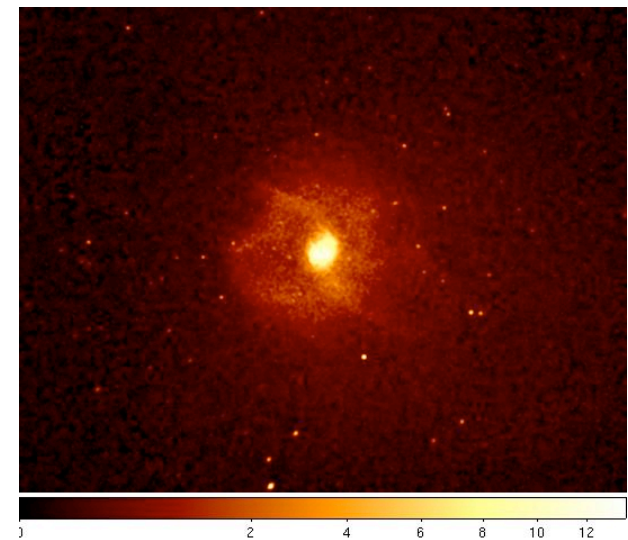
~30 systems known



Hydra A Nulsen et al. 2005



Hercules A Nulsen et al. 2005



NGC 4636 Jones et al. 2002

Energy to Create Cavity

$$pV + E = H = (\gamma/(\gamma-1)) pV$$

(Mechanical work to inflate) + (thermal energy of contents) = enthalpy, H

$H \sim \text{few } \times pV$ for an ideal gas, with constant ratio of specific heats, γ

γ (i.e. equation of state) not known

- “monatomic” classical gas, $\gamma = 5/3$, $H = 2.5 pV$
- relativistic gas, $\gamma = 4/3$, $H = 4 pV$

V , volume uncertain due to:

- unknown geometry
- filling factor

Cavity Heating

- Buoyant cavities rise and intracluster gas falls inward.
- Gravitational potential energy is converted to gas kinetic energy in the wake of a rising cavity.
- Kinetic energy is dissipated (locally) in the wake.
- When cavity rises a distance dR , the gravitational PE liberated is:

$$M g dR = V\rho g dR = -V dp/dR \cdot dR = -V dp$$

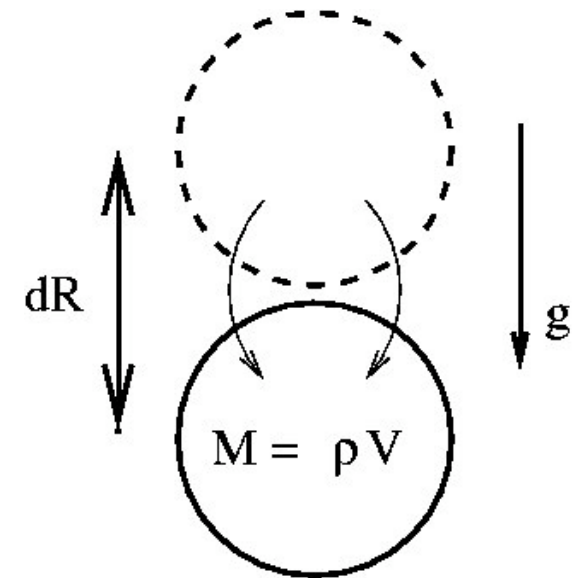
- First law of thermodynamics: $dE = T dS - p dV$,
and $H = E + pV$ give

$$dH = T dS + V dp = V dp,$$

for an adiabatic cavity.

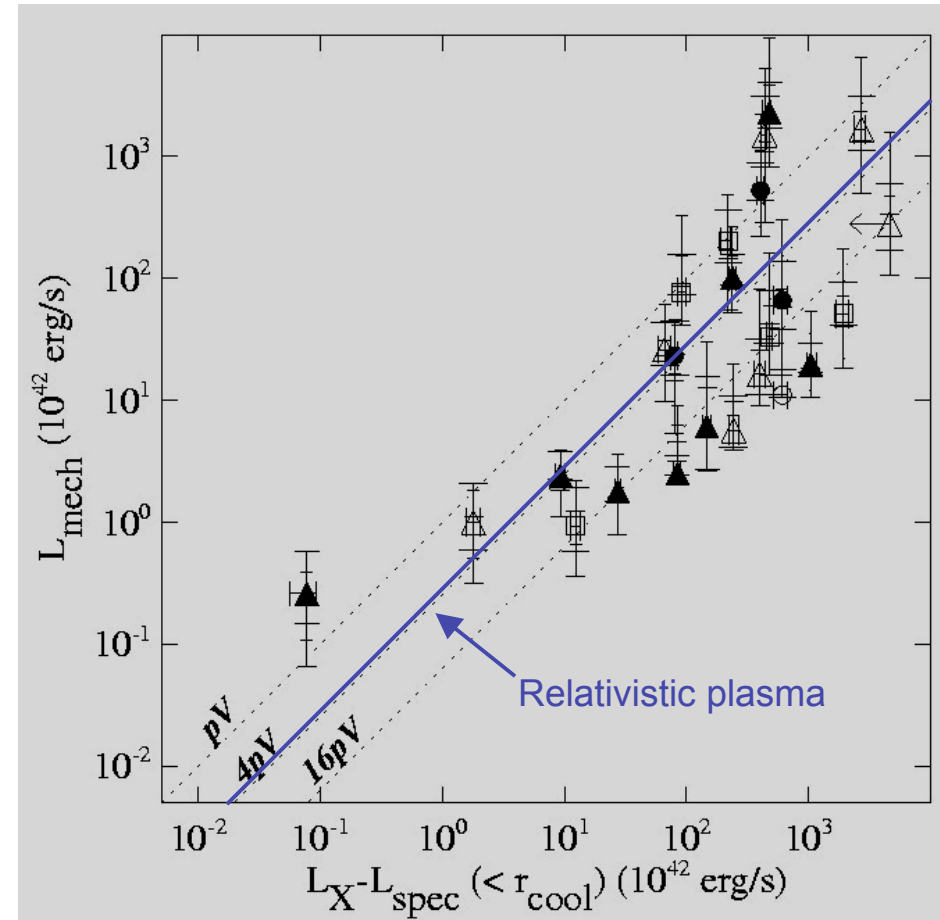
Kinetic energy = decrease of cavity enthalpy

NB: Approximation: cavity displaces same mass of gas as it rises
 $[\rho(dp/dR)/(d_\rho/dR)]_{\text{gas}} = V(dp/dV)_{\text{cav}}$ – if not, there is also some
 adjustment of the atmosphere (second order in cavity size/R).



Observed Cavity Heating Rate

- Measured cavity heating rates and ICM cooling rates. [Birzan et al. \(2004\)](#)
 - for systems with cavities in Chandra archive
 - For $H = 4pV$ - relativistic plasma case - cavity heating rate prevents ICM cooling for $\sim 1/2$ of the sample
- Selection effects:
 - no allowance for cooling flows without cavities.
 - bright rims
 - projection effects
 - shape and filling factor
 - stability [Brüggen & Kaiser 2002](#); [Ruszkowski, Brüggen & Begelman 2004](#); [Jones & de Young 2005](#)

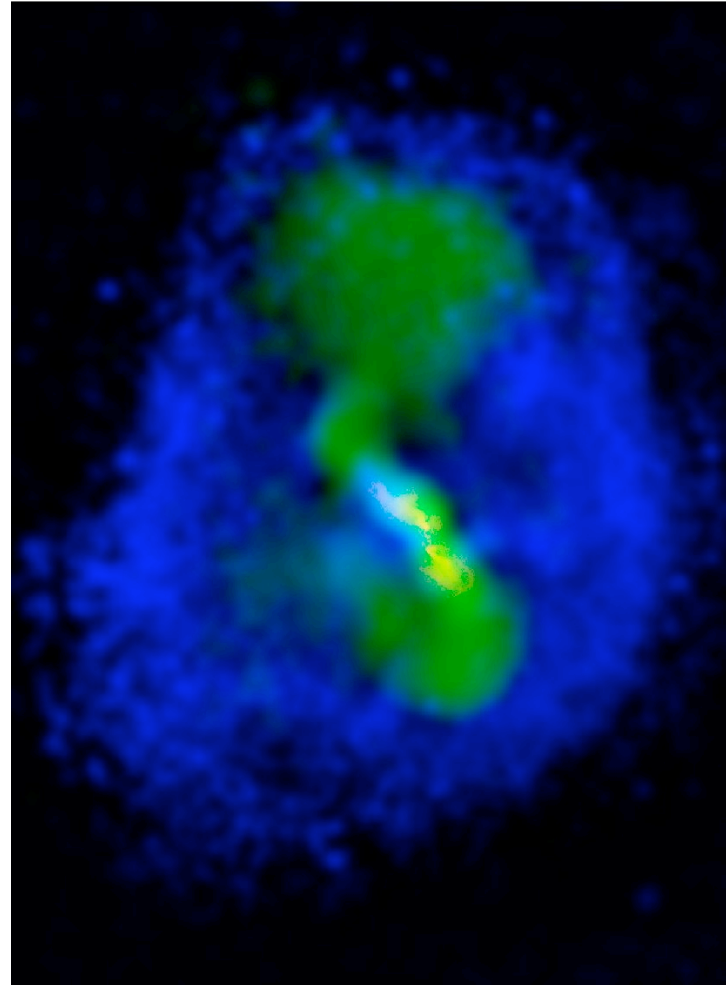


Rafferty et al. (2006)

Cavity Powers Underestimated

thanks to Paul Nulsen

- Outer cavities in Hydra A (Nulsen et al. 2005; Wise et al., in prep.) boost estimated jet power by $\sim 6x$.
- Close examination of “underachievers”
- systems with lowest $L_{\text{mech}}/L_{\text{cool}}$ - finds additional cavities in $\sim 50\%$ Rafferty et al., in prep

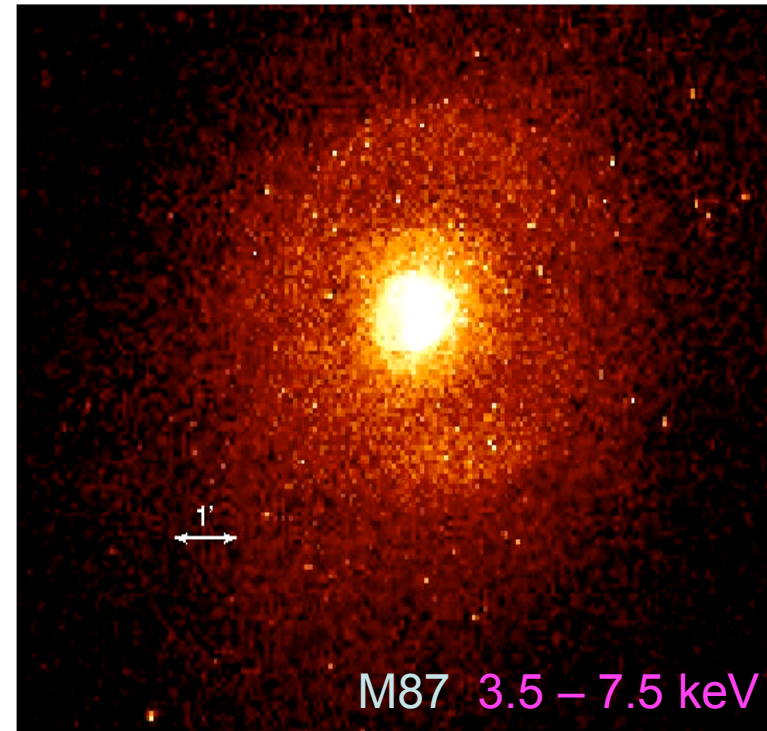


Quantifying Weak Shocks

- Cavity enthalpy cannot heat inside radius where cavities form.
- Weak shocks common [*Chandra*]
- Shock heating supplements dissipation of cavity enthalpy: heat change,

$$\Delta Q = T \Delta S = [1/(\gamma-1)] p/\rho \Delta \ln(p/\rho^\gamma) = E \Delta \ln(p/\rho^\gamma)$$

- 0.8' shock in M87:
 - Mach ~ 1.4
 - age 2.4×10^6 y
 - energy 2×10^{57} erg
 - $T \Delta S / E \approx 0.022$
- Another shock at twice the distance –
 - one shock every 2.5×10^6 y?
- Cooling time at shock radius $\sim 2.5 \times 10^8$ y
- *Repeated shocks are sufficient to prevent cooling*
 - $100 \text{ shocks} \times 0.022 = 2.2$
- Implies history of AGN outbursts over 10^8 y



Forman et al. 2006

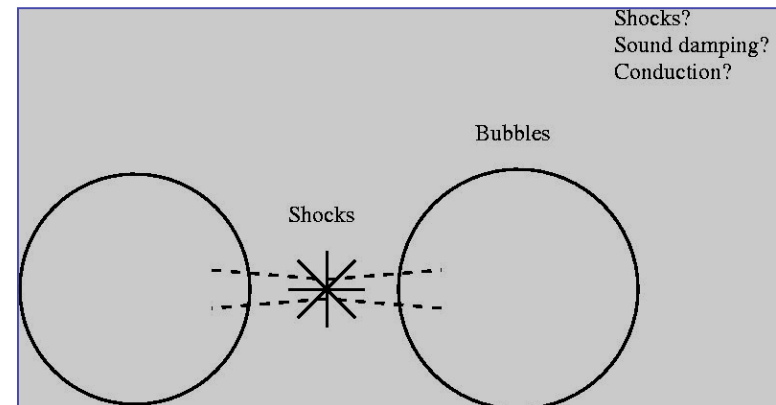
Distribution of Heat

Energy conservation for sound waves gives:

$$(\delta p/p) \sim \rho^{-1/2} T^{-3/4} R^{-1}$$

- Bubble heating is most centrally concentrated – outside R_0
Ruzskowski, Brueggen & Begelman 2004
- Weak shock heating is intermediate – but dominates inside R_0 Nulsen et al.
- Heating by sound damping is most extended (Spitzer scaling of viscosity and thermal conductivity) Fabian et al., 2003

Scaling for shock heating close to AGN depends on outburst history.

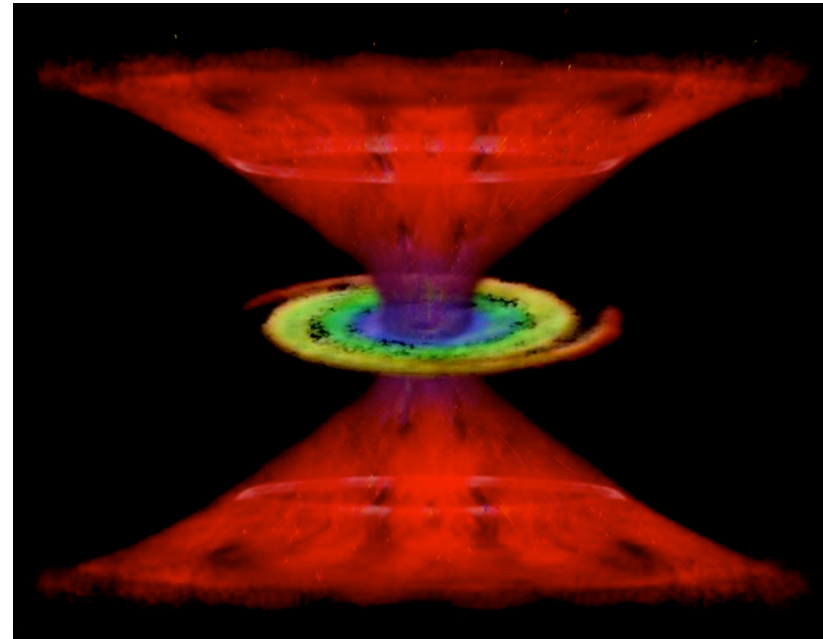


AGN Heating of clusters: Summary

- Cavity heating rates sufficient to stop ICM cooling in ~50% clusters
 - Cavity heating rates are almost certainly underestimated
 - Shock heating supplements dissipation of cavity enthalpy for converting AGN outbursts to thermal energy in the ISM and ICM
 - Heating by shocks dominates close to the AGN, cavity heating where the radio lobes form, sound damping, etc. on large scales.
 - Some circulation is also required to prevent gas from cooling
- BUT: radio jets are rare: ~10% of AGNs are radio-loud
 - Need other mechanisms for most AGN effects on galaxies

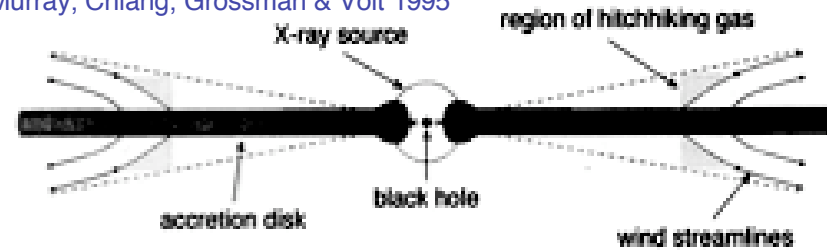
‘Slow’ Winds

- Common: $>50\%$ of all AGN, quasars
 - Available for all size galaxies, not just brightest cluster ellipticals
- Mass, energy loss rates?
 - Assume 10%
 - What is true value?
 - Are AGN winds important compared with starbursts in ULIRGs, and dwarf galaxies?
 - Need a physical theory to know



Slow Winds affect Feedback

Murray, Chiang, Grossman & Voit 1995



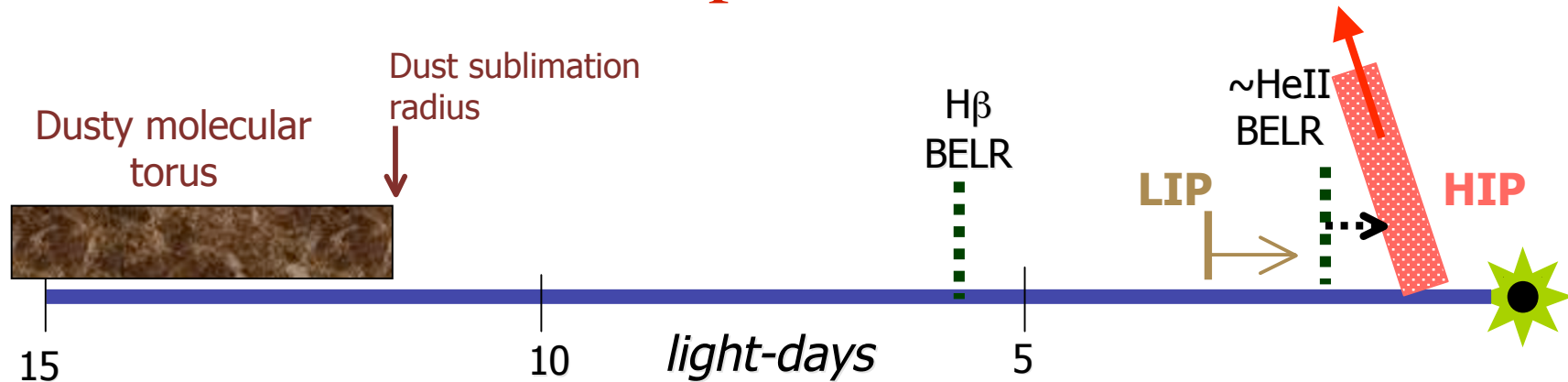
- Slow Winds:

1. Location: mass, KE, mv , Z rates

2. Geometry: f_c , v_{escape} , escape route

Unknown to factor 10^6 because on
unknown starting radius

Scale Map of an AGN



- Warm absorber $\sim 0.5\text{-}1.0$ light-day = $(1.3\text{-}2.6) \times 10^{15}$ cm
 $\sim 0.5\text{-}1$ light-day $\sim 2200 - 4400 R_g$
 - $M_{\text{bh}} = 1.9 \pm 0.78 \times 10^6 M_{\text{sol}}$
 - Disk winds arise from accretion disk
- Small size leads to low mass loss rate

AGN Cosmological Feedback

- 10% normally assumed
- WA location determines mass loss rate to factor 2

$$\begin{aligned} \dot{M}_{\text{dot out}} &= 0.8 \pi m_p N_H v_r R f(\theta, \varphi) \\ &= 2\text{-}5\% \dot{m}_{\text{dot}}(\text{acc}) \end{aligned}$$

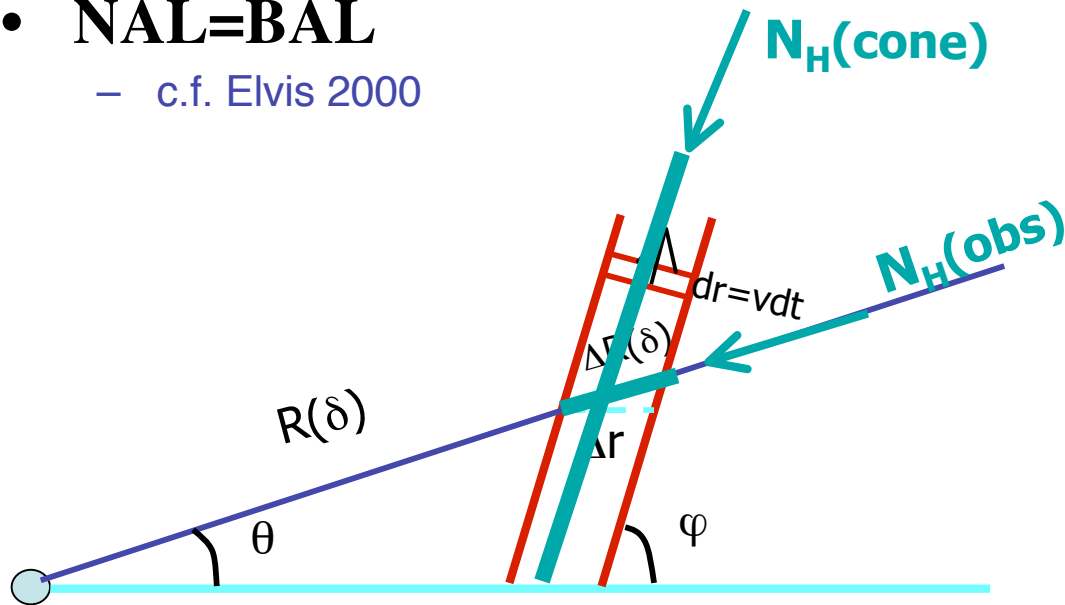
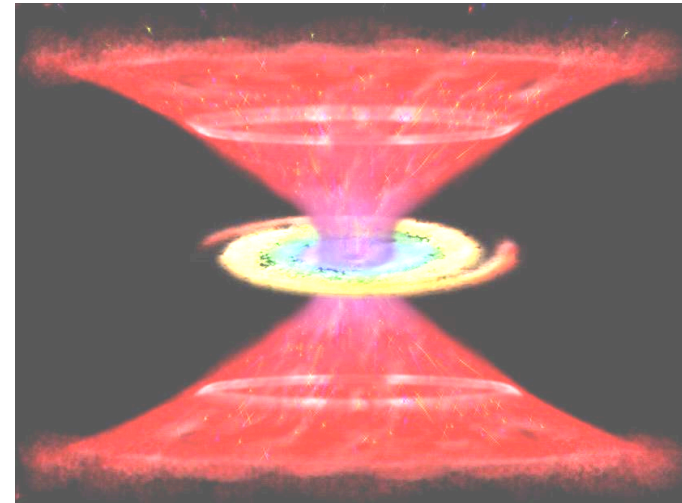
- Total WA mass deposited in Intergalactic Medium:
 - If: **lifetime = 10^8 yr** $\rightarrow M_{\text{tot}}(\text{out}) = (0.4\text{-}2) \times 10^4 M_{\text{sol}}$ in NGC4051
 - $\dot{M}_{\text{dot}}(\text{out}) \propto M(\text{BH})$ for constant R_g
 - Quasar $M_{\text{BH}} = 10^8\text{-}10^9 M_{\text{sol}}$

$$\Rightarrow M_{\text{tot}}(\text{quasar}) = 10^6\text{-}10^7 M_{\text{sol}}$$

- comparable with ULIRGs

Large N_H , velocity along flow: BALs

- N_H along flow direction $N_H(\text{cone}) \sim R \cdot n_e$
- $R \cdot n_e(\text{HIP}) \sim 5 \times 10^{22} \text{ cm}^{-2}$
 - $N_H(\text{cone}) > 10 \times N_H(\text{obs})$
- Approaches BAL column densities
- Larger velocity & velocity spread
 - $V(\text{cone}) \sim 4 v_r \sim 4000 - 8000 \text{ km/s}$
- **NAL=BAL**
 - c.f. Elvis 2000

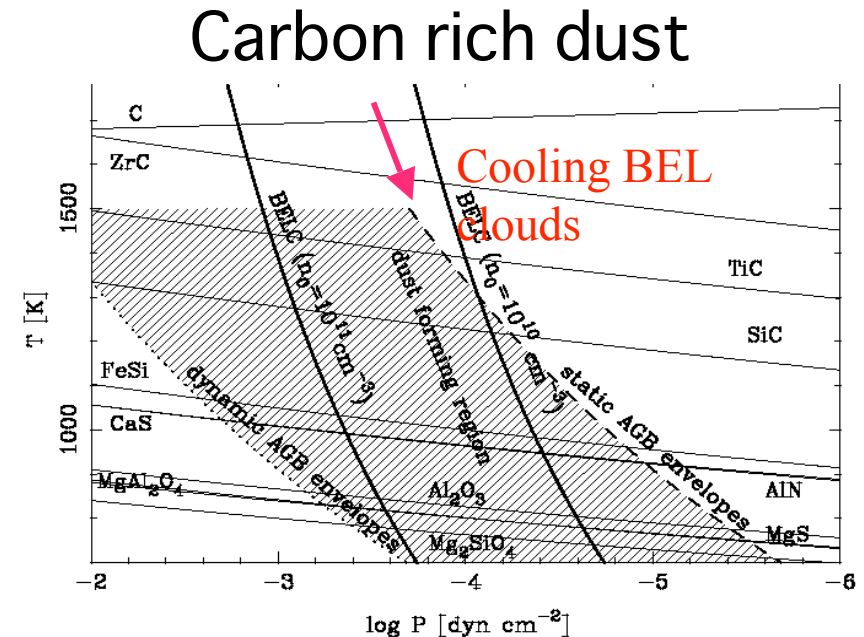


Feedback:
 Power in wind
 underestimated by
 $(v_{\text{rad}}/v_{\text{los}})^2 \sim 100$

High Redshift Dust Creation : Use the BELR?

Elvis, Marengo & Karovska, 2002 ApJ, 567, L107

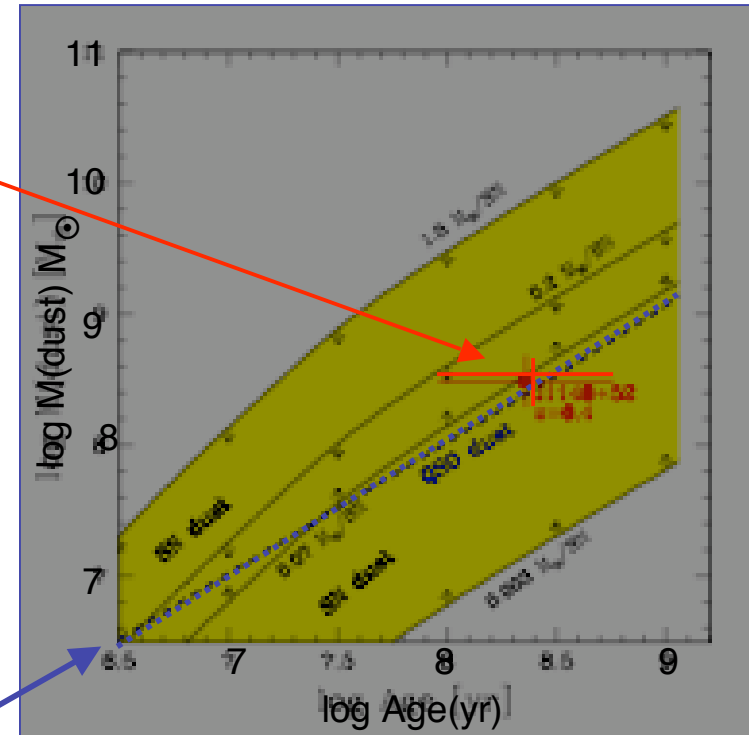
- Large amounts of dust in $z > 4$ quasars:
how is this dust made?
 - AGB stars dominate in Milky Way, but need ~ 1 Gyr to be formed
- SNIIE proposed. Production rate highly uncertain; not calibrated in Milky Way
- New mechanism: Expanding BEL gas in a wind?
 - BEL adiabats track through dust formation zone of **AGB stars**
 - Works for both Carbon-rich and Oxygen-rich grains
 - High abundances - all C/O in dust?
- Quasar BEL gas will make copious dust at high z



Quasar Dust: an example

Maiolino et al. 2006, astro-ph/0603261

- SDSSJ1148+52 at $z=6.4$
 - $M_{\text{dust}} = 10^{8.5} M_{\odot}$ Bertoldi et al. 2003
 - Assume:
 - $M_{\text{dot}} = m_{\text{dot}}(\text{Edd})$, always
 - $M_{\text{dot}}(\text{wind}) = 0.5 \times 10^{-8} M_{\text{BH}}/M_{\odot}$
 - $Z = 10Z_{\odot}$
 - Depletion into dust as in Milky Way
 - Then m_{dust} (quasar) formation rate is sufficient
 - Assumptions extreme, but this quasar is extreme too
- dust creation in quasar winds may be important at high z



4. Impulsive Events at Mergers

Smoke Ring: $R \sim 8$ kpc; $kT \sim 0.6$ keV

$L_X \sim 4 \times 10^{38}$ erg/s

$E_{th} \sim 1.2 \times 10^{55}$ ergs

$\sim 100 E_{tot}(\text{wind})$ in NGC4051

$M_{gas} \sim 10^6 M_{sol}$ Includes swept up ISM

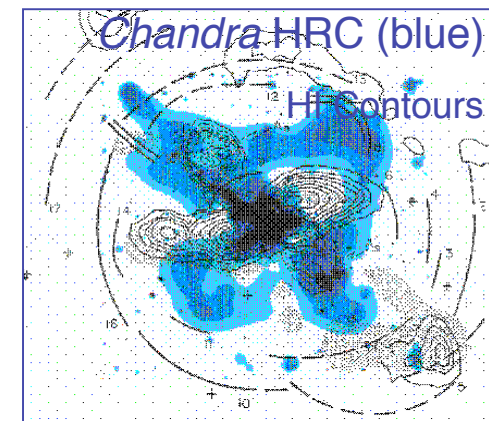
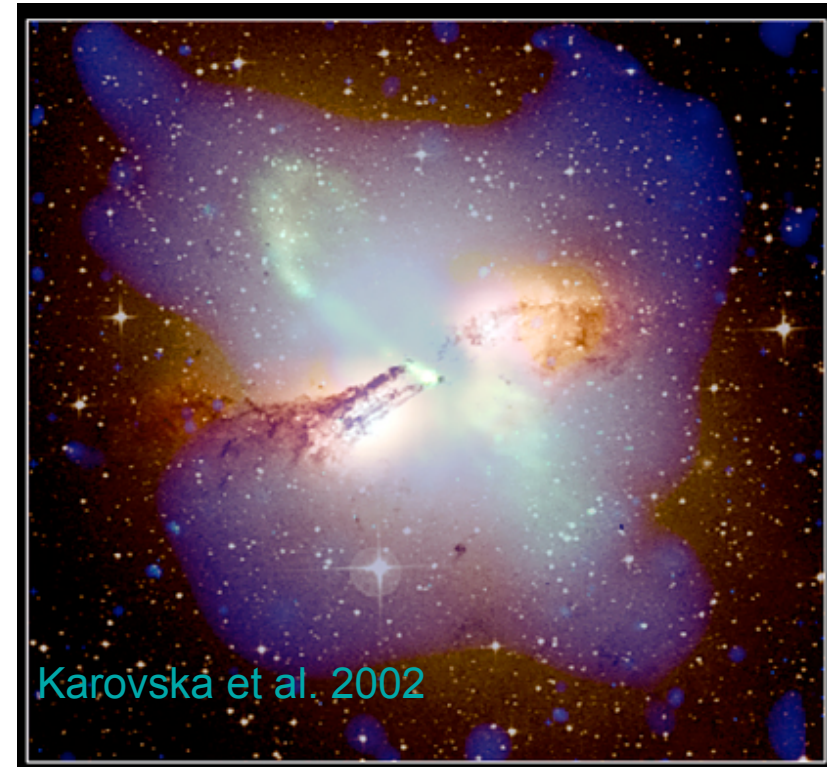
→ $v \sim 600$ km/s;

→ $t(\text{outburst}) 10^7$ yrs \sim Merger age

→ Impulsive injection?

Only visible in Cen A ($D=3$ Mpc)

Could be common



Quasars effects on Cosmology

New subject - impressive progress quickly:

1. BH-galaxy mass (M - σ) relation

Must be true - but too many mechanisms

2. Prevention of Star formation in massive mergers 'Dry Mergers'

Possibly - need better understanding of radiation/obscuration; winds

3. Limiting the upper mass of galaxies

Probably - same as cooling flows

4. Inhibition of cooling flows YES - numbers look good. Better samples needed

5. Enrichment of the Intergalactic Medium

YES - but is it dominant?

6. Creation of dust at $z \sim 6$

YES - but is it dominant?

I hope this is not your conclusion

There is too much confusion

I can find no way out

Bob Dylan,

All Along the Watchtower,

John Wesley Harding