The impact of black holes on the Universe

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Outline

- Quasars and the growth of galaxy-centre BHs
- The physics of accretion discs
  - Accretion-driven jets
- Black holes and star formation through cosmic history

Part I: BH growth

- In SNe black holes with M ~ 10 $M_\odot$ form suddenly
- But we don’t think the BHs with M>10^6 $M_\odot$ in galactic nuclei formed suddenly
  - they formed small and grew by feeding
- A massive BH can eat a star like the Sun whole
  - But galaxies cannot feed stars to their BH fast enough to account for growth to current masses
  - So galactic BHs must have grown by accreting gas

Soltan argument

- Suppose that when M grows by m energy E = κ mc^2 is released, where $\kappa \simeq$ 0.1 is the efficiency factor
- Now in (large) unit volume E released in Hubble time is (Soltan 1982)

$$E = \frac{4\pi}{c}\int \mathrm{d}\underset{\substack{\uparrow \\ \text{redshift}}}{z}\,(1+z)\int \mathrm{d}\underset{\substack{\uparrow \\ \text{Flux density}}}{S}\; S\,n(S,z)$$

- i.e., energy released per unit volume is easily inferred from n(S,z), the number of sources at redshift z per unit solid angle, flux density & redshift
- The resulting mass density in BHs is ρ = E/(κc^2)
- Soltan predicted typical galactic BH mass from this mass density and the number density of galaxies M $\simeq$ ρ/n$_g$

Soltan revisited by Yu & Tremaine (2003)

- From counts of quasars in optical bands
  - $\rho = 2.1 \times 10^5\ (0.11/\kappa)\ M_\odot\ \mathrm{Mpc}^{-3}$
- From correlation between M_{BH} and the galaxy's central velocity dispersion and Sloan Digital Sky Survey, mass density of BHs in galaxies is
  - $\rho = (2.5 \pm 0.4) \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$
- The mass density of BHs agrees (amazingly!) well with value predicted by assuming quasars powered by accreting gas with efficiency ~ 10%
- Caveat: role of obscured quasars (light absorbed but still contribute to ρ)

Part II: Accretion discs

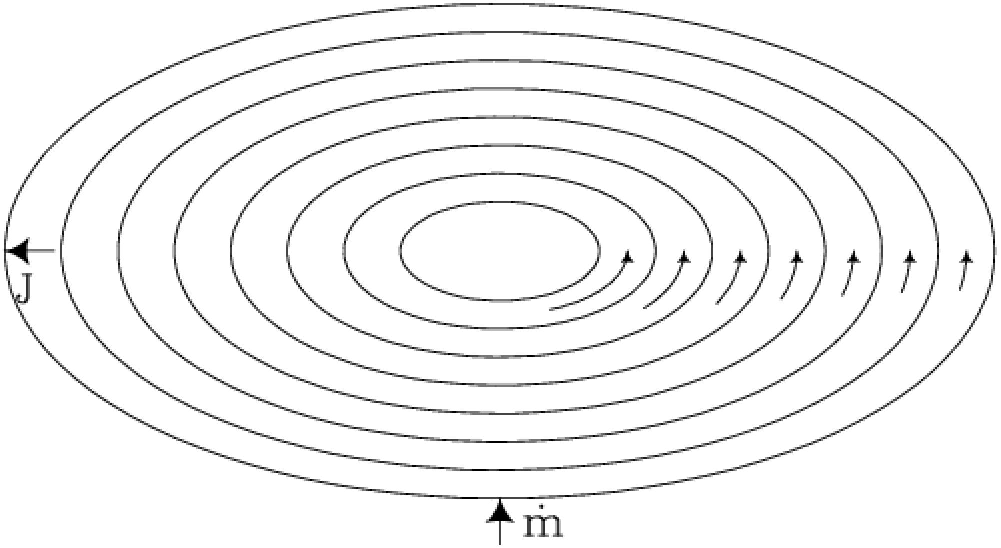
- BHs gigantic drains
- When washing-up water goes down the plughole, it swirls around in a vortex
- Similarly hurricanes, tornadoes
- Same happens when gas falls onto a star or BH

Kornmesser (ESO)

Disc dynamics

- Consider steady state: mass spirals in at rate dm/dt shedding energy E and angular momentum J as it goes
- Material is on essentially circular orbits at all times
- Energy shed as mass moves in is radiated from disc's upper & lower surfaces
- A viscous torque carries angular momentum to larger & larger radii

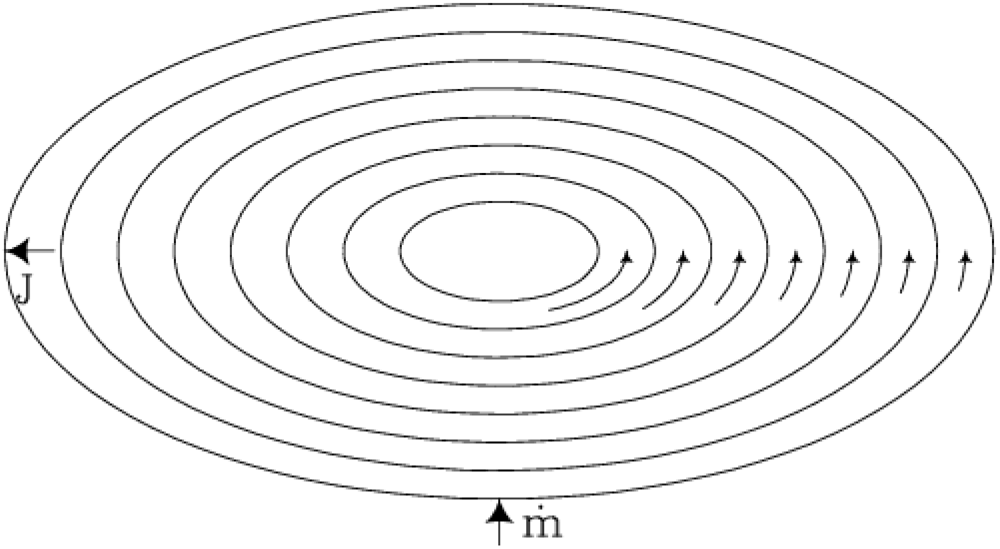
Disc dynamics



- Conceptually decompose disc into annuli
- Within an annulus deposition of energy by flowing matter gives power (rate of working)

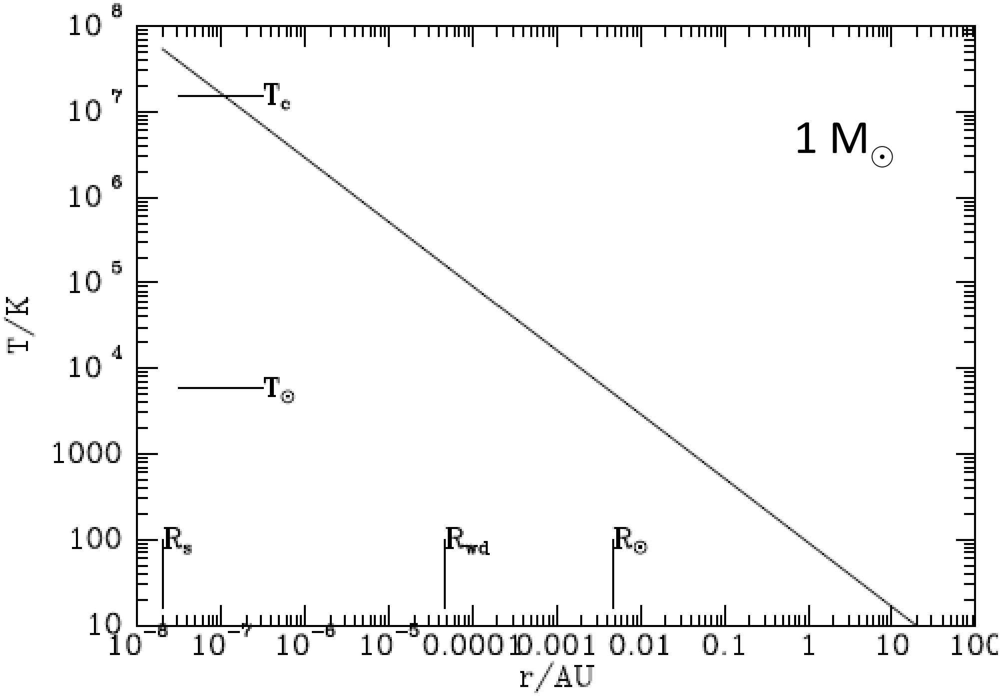
$$P_m = \tfrac{1}{2}\left(\frac{GM}{r} - \frac{GM}{r+\delta r}\right)\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{GM}{2r^2}\frac{\mathrm{d}m}{\mathrm{d}t}\delta r$$

Disc dynamics

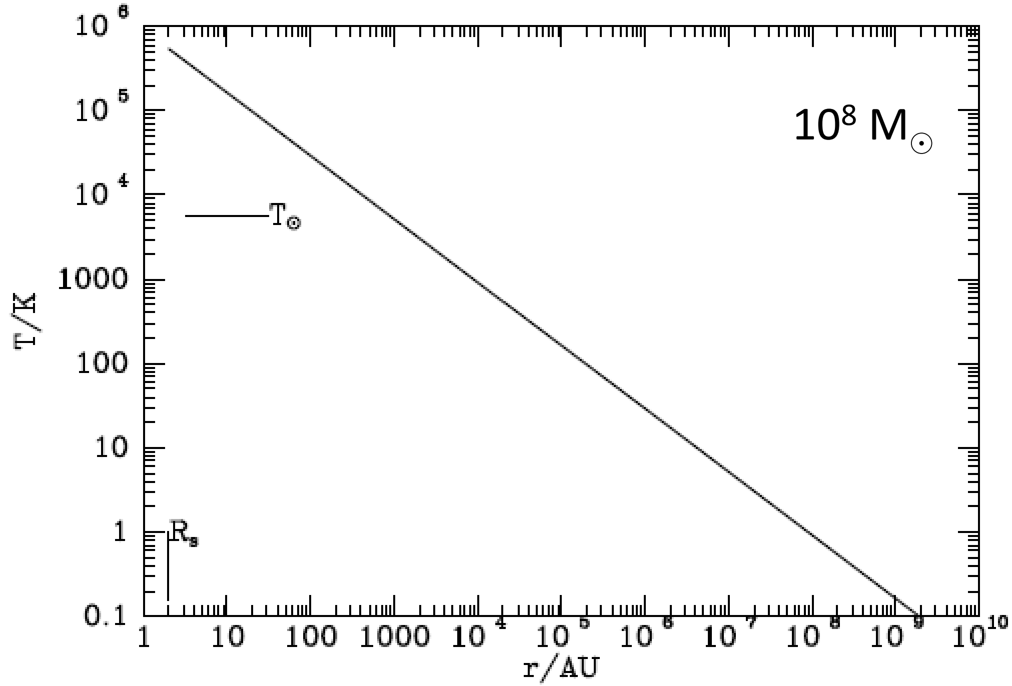


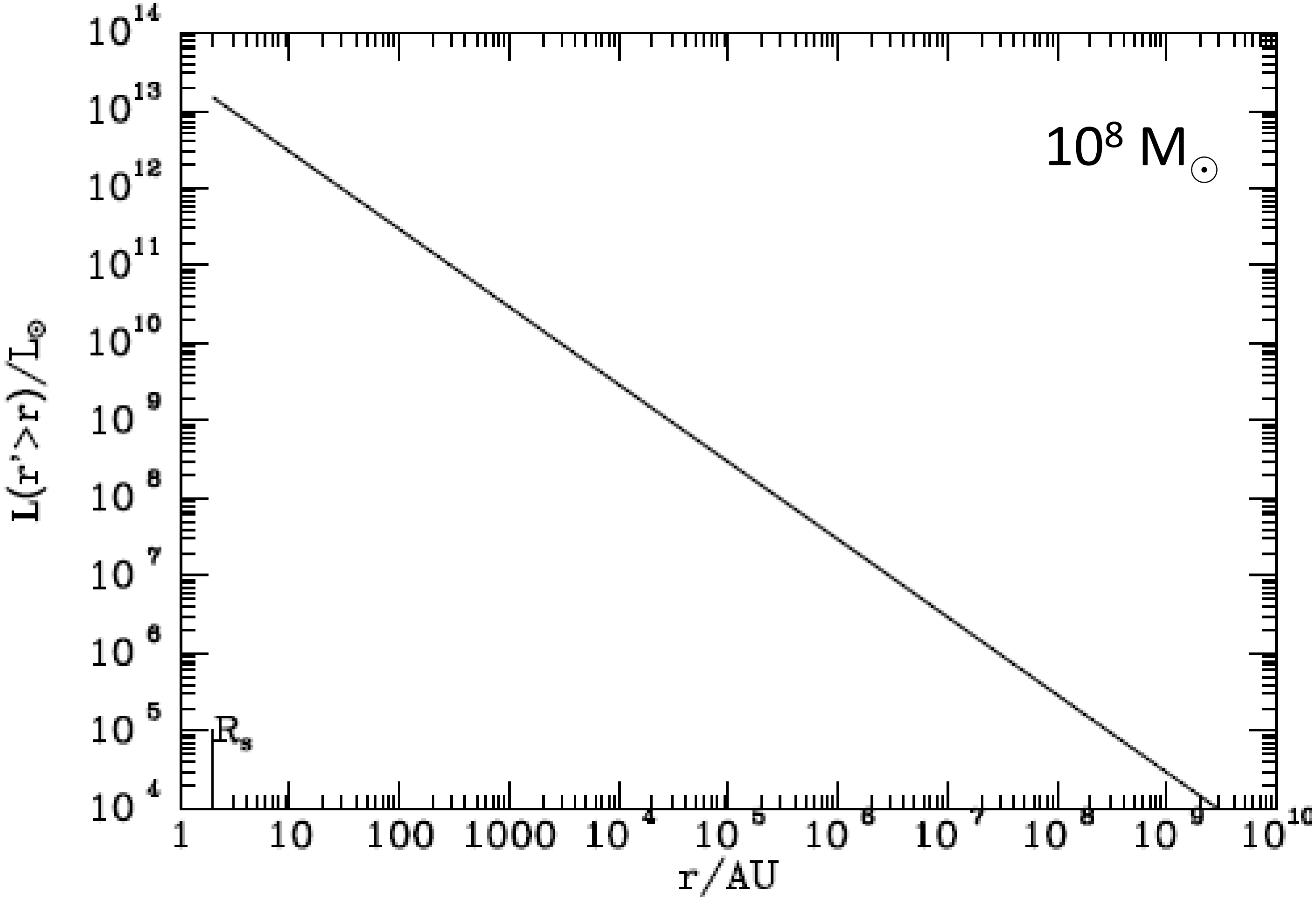
- Inner annuli rotate faster than outer annuli
- Each annulus has work done on it by annulus inside it, and does work on annulus outside it
- The difference between work done on an annulus and the work the annulus does turns out to give a power
  - $P_{visc} = 3P_m$
- Assume disc radiates as a black body (σT^4 per unit area & time) so luminous power is $P_L=\sigma T^4(4\pi r\delta r)$
- Now equate P_L to total power = $4P_m = (2GM/r^2)(dm/dt)\delta r$
- Choose dm/dt to give characteristic BH growth time 100 Myr and solve for T and L

Temperatures of disc for M = $M_\odot$ or M= 10^8 $M_\odot$ BH



- Take dm/dt = $M_\odot$/100 Myr or 1 $M_\odot$/yr
- At a given multiple of R_s =2GM/c^2 the solar-mass BH disc is hotter by factor 100
- For quasar most L in UV rather than X or gamma rays





- Plotted: Luminosity at r'>r
- Accreting at 1 $M_\odot$/yr a galactic BH by far outshines its galaxy of ~10^{11} stars
- 90% of L from inside Pluto's orbit
- Consistent with quasars

You may be impressed
But you shouldn’t be!

- The stupendous E output of a quasar is degraded into visual or IR photons close to the BH
- These photons criss-cross intergalactic space without significant impact
- Quasars are just histrionics

Getting something done

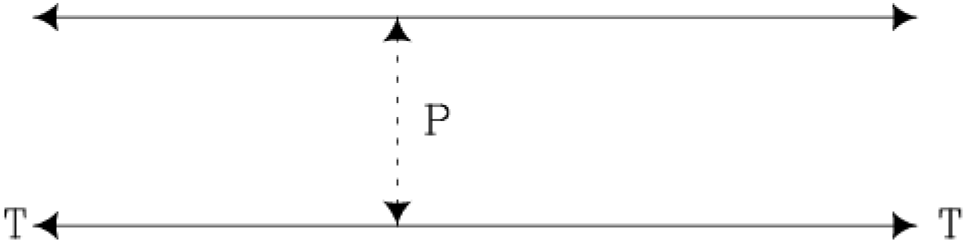
- What provides the all important viscosity?
- Magnetic field!
- Field lines carry tension
- When lines are stretched, work is done on the field, which is amplified
- The disc’s plasma is effectively a perfect conductor
- Field lines are trapped within the plasma of the accretion disc
- Within a differentially rotating disc, field lines are constantly stretched and the field is amplified

shear (shear.exe)

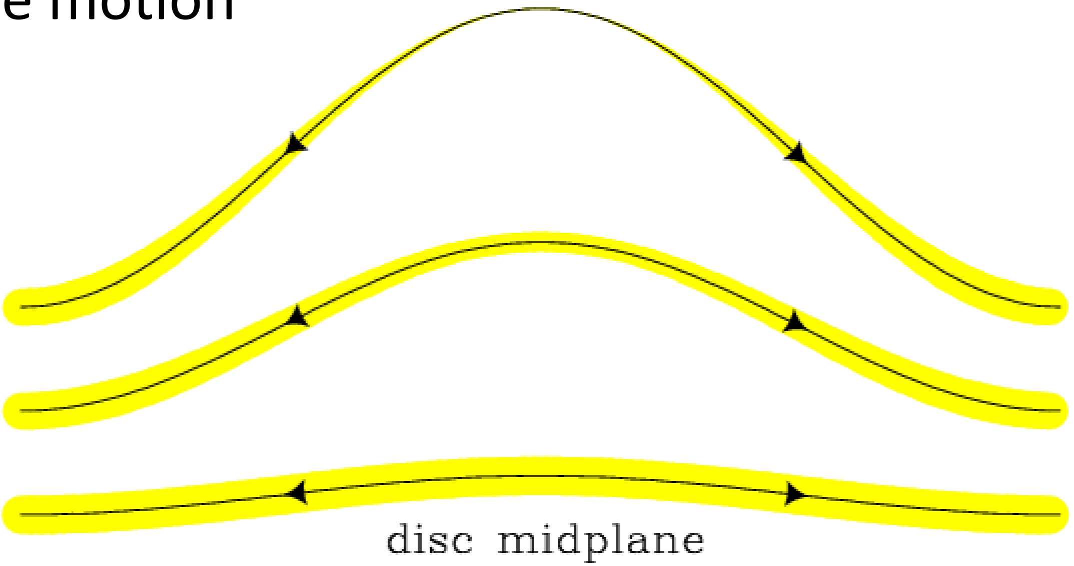
Magneto-Rotational Instability (MRI)

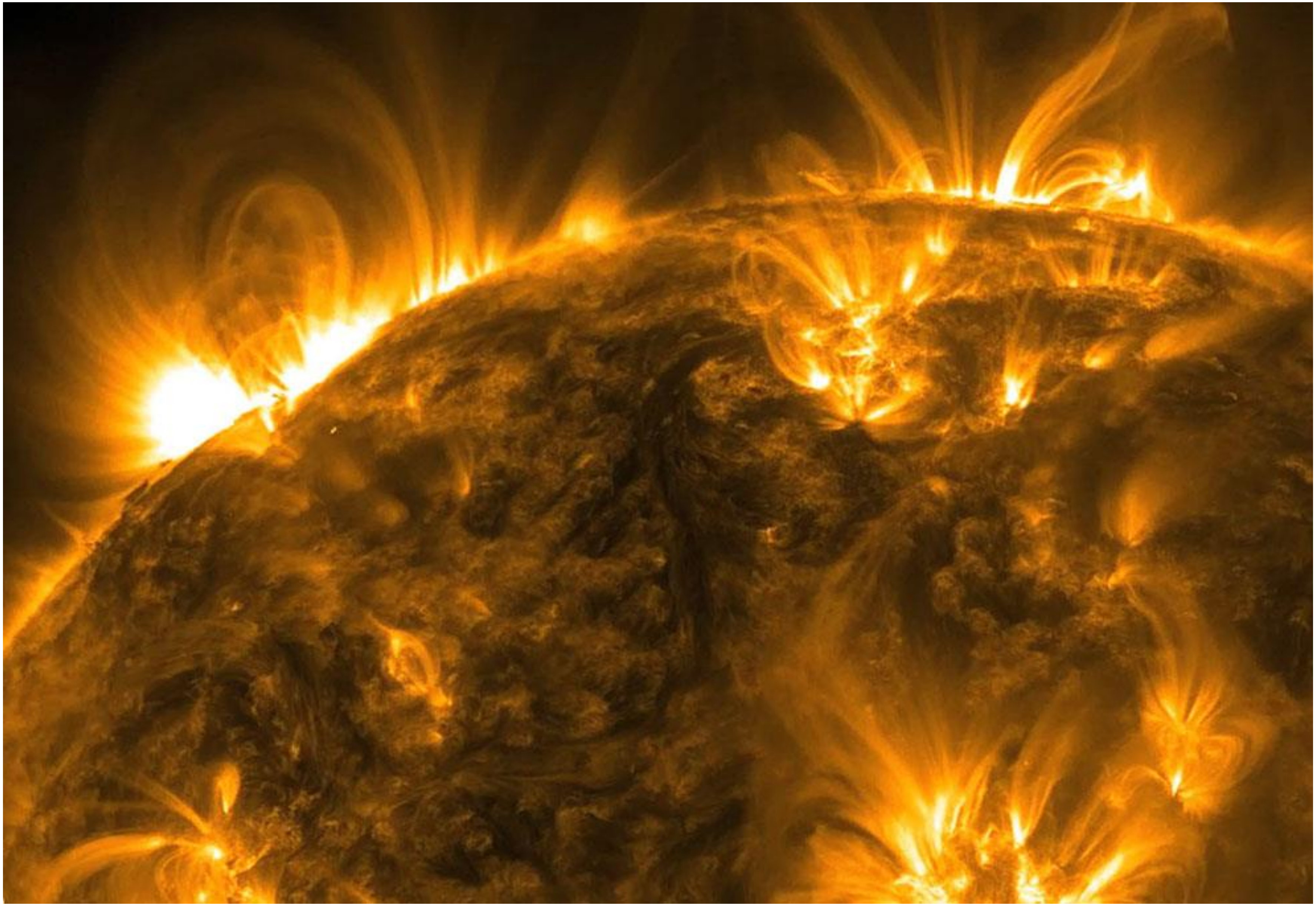
- No matter how weak the field was originally, it is soon strong enough to modify the flow that was amplifying it
- In other words, it becomes capable of carrying dynamically significant J outwards

Coronal heating



- The field doesn't stay in the disc plane because:
  - B provides pressure $\perp$ to field lines
  - Plasma can flow along but not across field lines.
  - A section of a line with less plasma is less weighed down, so B-pressure causes it to arch up, speeding flow of plasma from this section (Parker instability)
  - Soon there are loops of field connecting foot points in the disc that are in relative motion

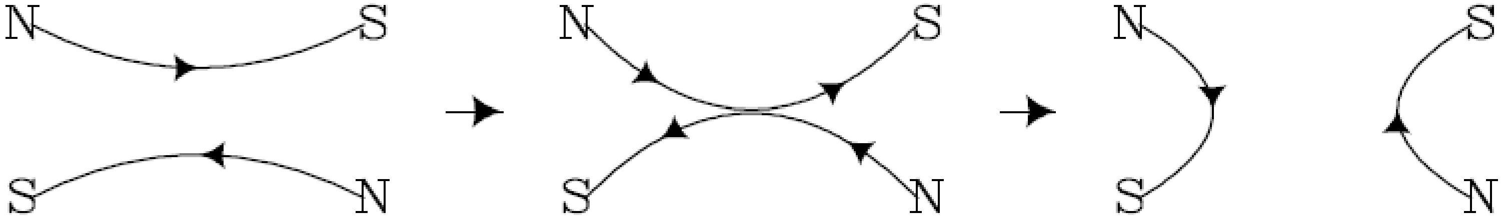




Sun in UV (NASA)

Reconnection

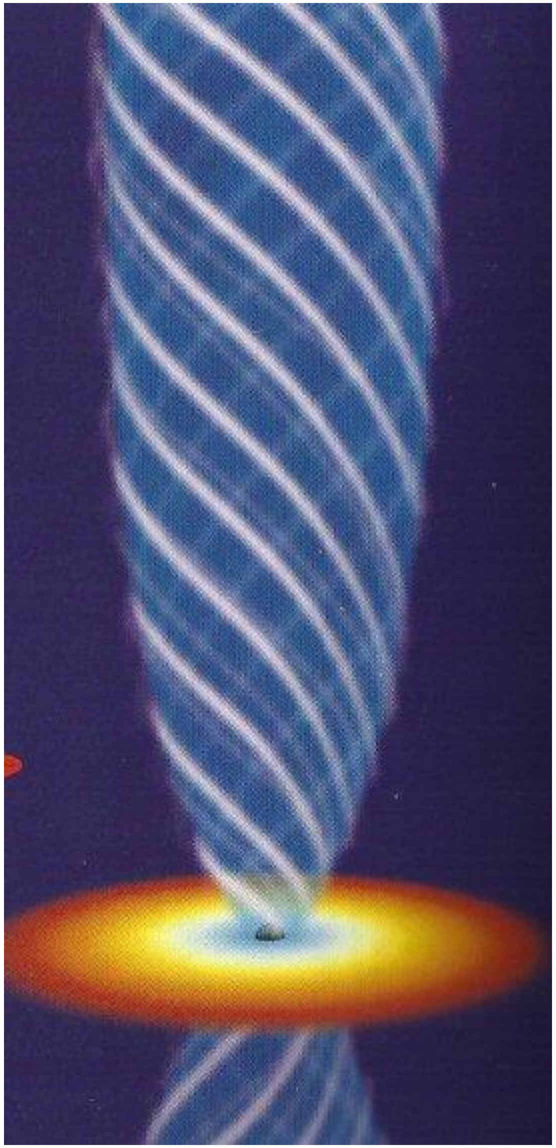
- Field lines moving in opposite directions can reconnect



- As field geometry changes, E previously stored in the field is released
- E used to accelerate particles and heat local plasma
- So region above/below the disc becomes too hot to be confined by the gravitational field: it flows away in a wind

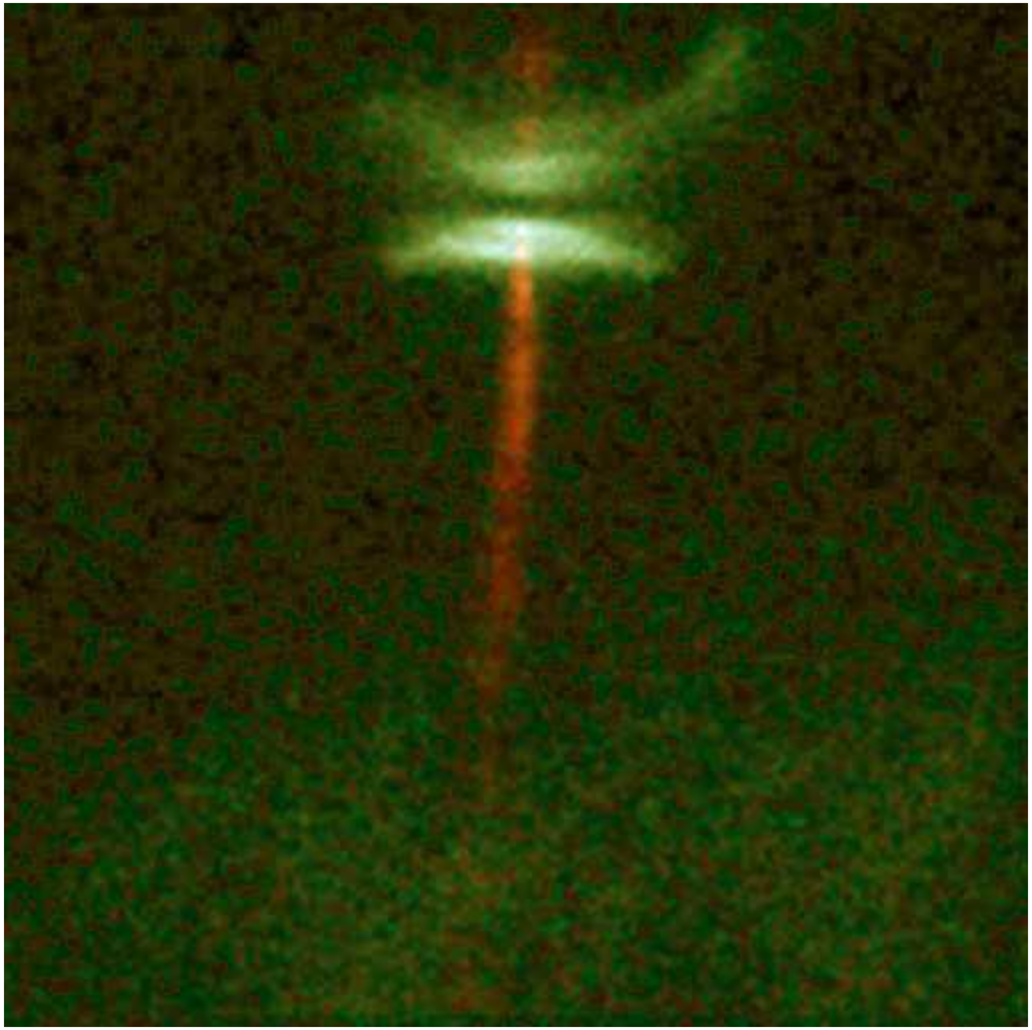
Magnetic collimation

- Magnetic field lines collimate the flow parallel to the disc’s spin axis
- This physics is not fully understood but observations show it is scale-free and generic:
  - Accreting objects most readily detected by their bi-polar outflows



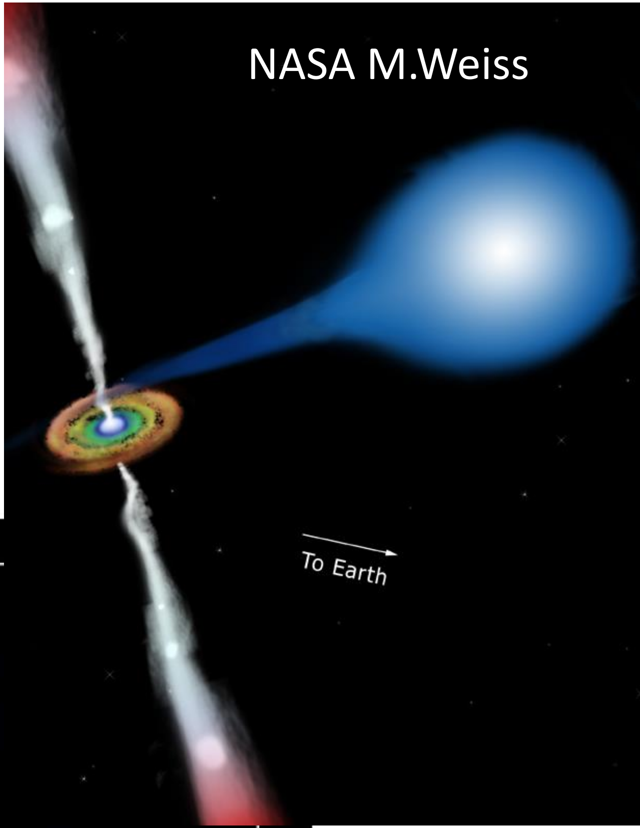
Accreting objects

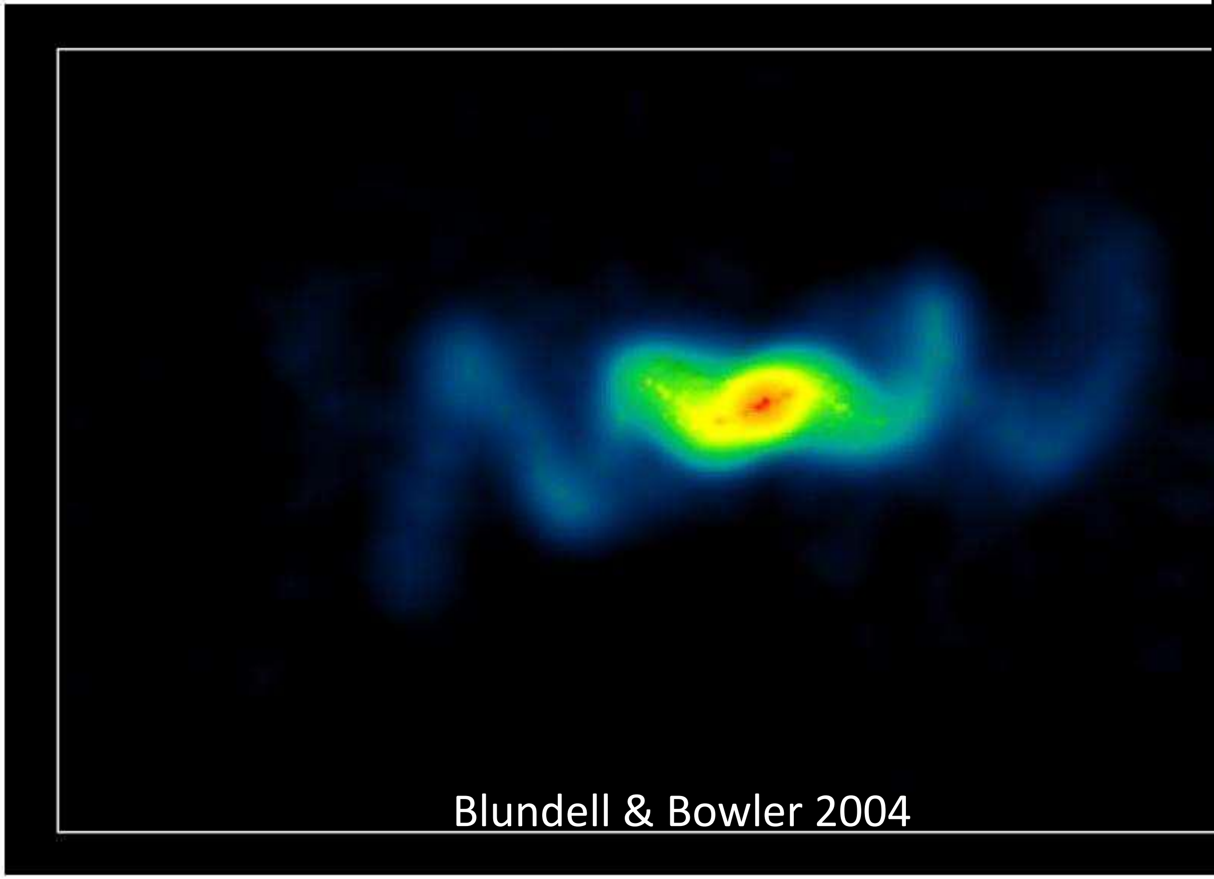
proto-star Herbig Haro 30



Accreting objects

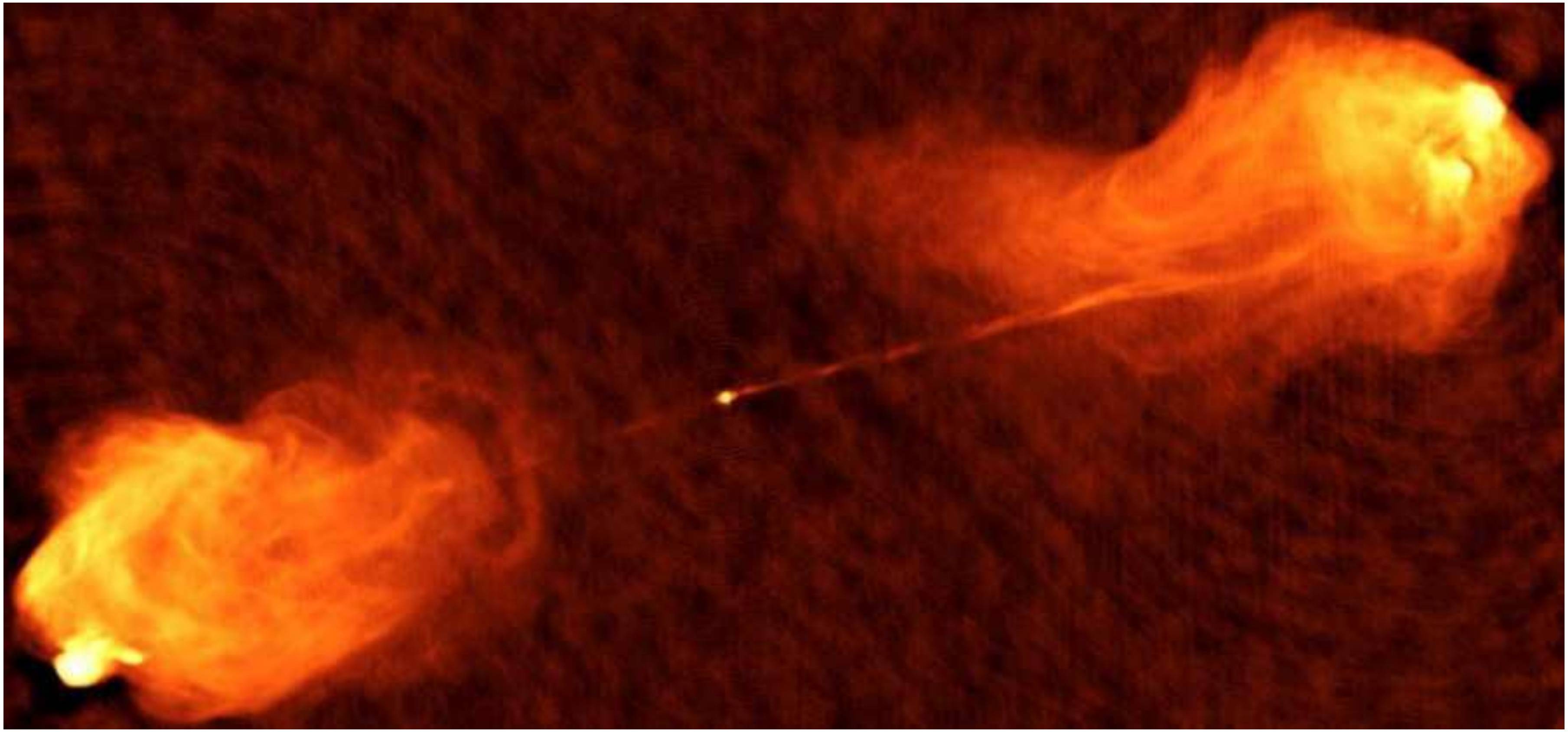
stellar-mass BH SS433


NASA M.Weiss


Blundell & Bowler 2004

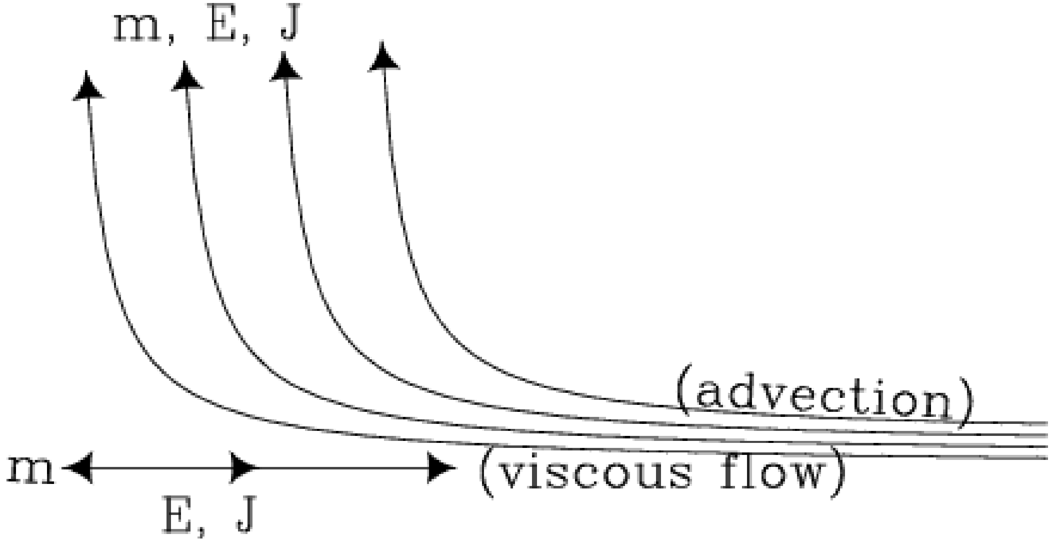
Accreting objects

$10^8\ M_\odot$ BH Cygnus A



Modified accretion disc picture

- The wind feeding the jet carries m, E, and J away from the disc with the consequence that
  - Only a fraction of what falls onto the disc reaches the BH
  - The disc now has a mechanical power output: the jet
  - The radiative luminosity is smaller than we estimated

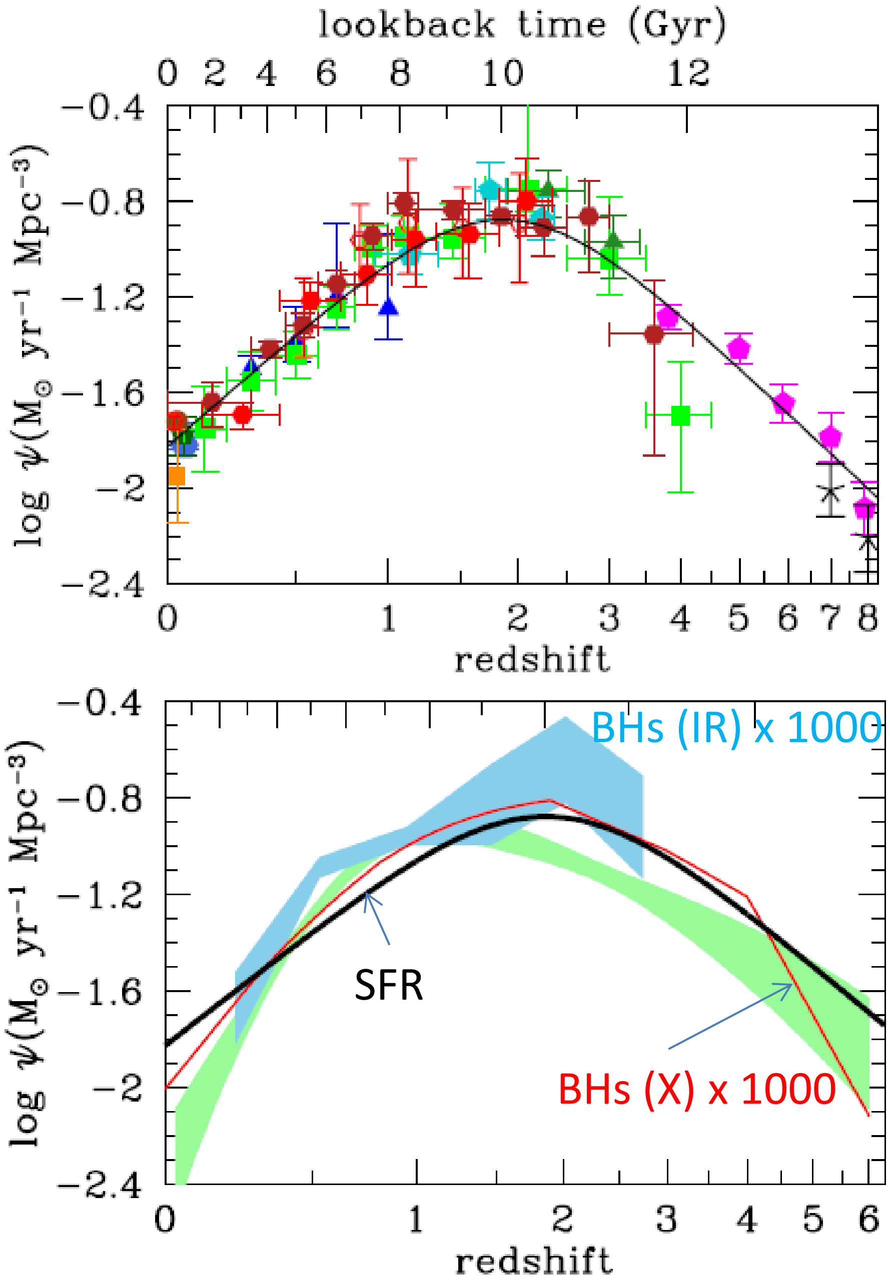


Mechanical vs radiative power

- Observations indicate that
  - Mechanical power can significantly exceed radiative power
  - Systems can switch rapidly between radiative and mechanical (quasar/radio) modes
- This best studied in solar-mass BHs because their timescales shorter by 10^8
  (yr for SS433 = 100 Myr for Cygnus A)

Part III: Black holes and star formation

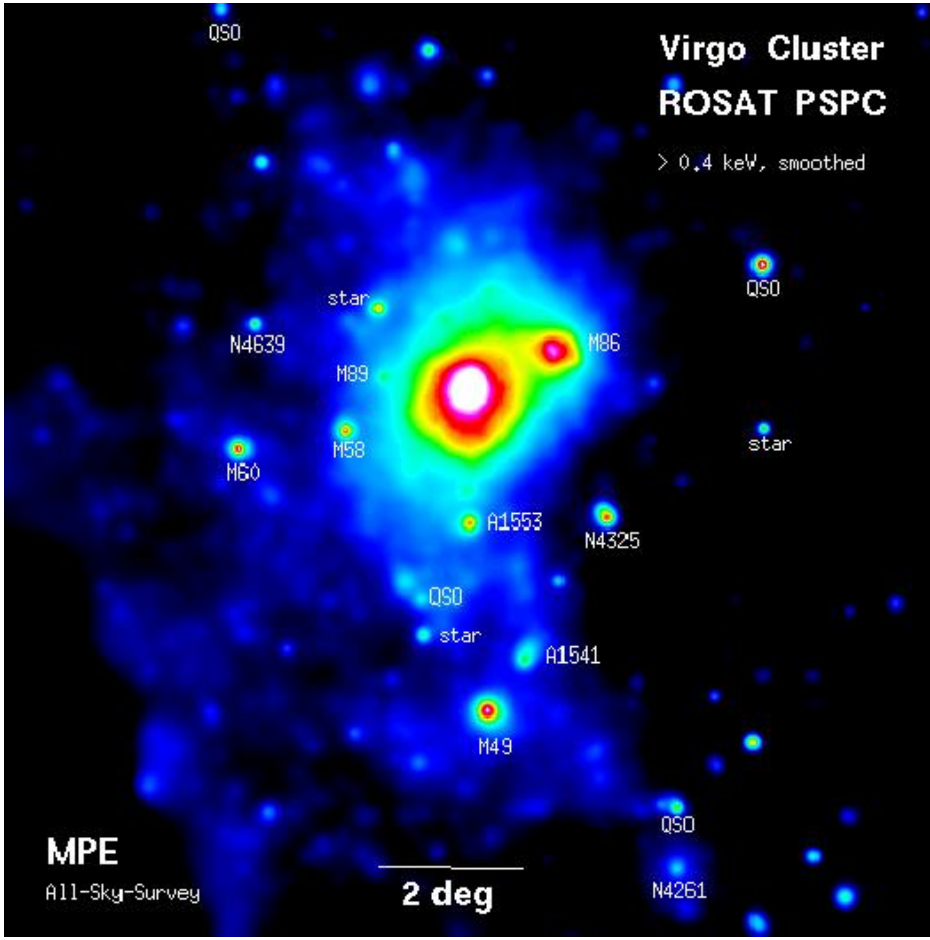
- The rate of star formation has fallen dramatically since redshift z=2
- The radiative luminosity of BHs in galaxies has tracked star-formation rate so $L_{QSO} \propto$ SFR
- BHs are now mostly in mechanical mode



Madau & Dickinson 2014

Cool-core clusters

- In clusters like Virgo, T of plasma falls by factor ~3 as the centre is approached
- The cooling time of the plasma becomes much shorter than age of system
- But there is much less gas at $T < 10^6$K than expected if the plasma were steadily cooling
- Conclude: plasma radiates but does not cool

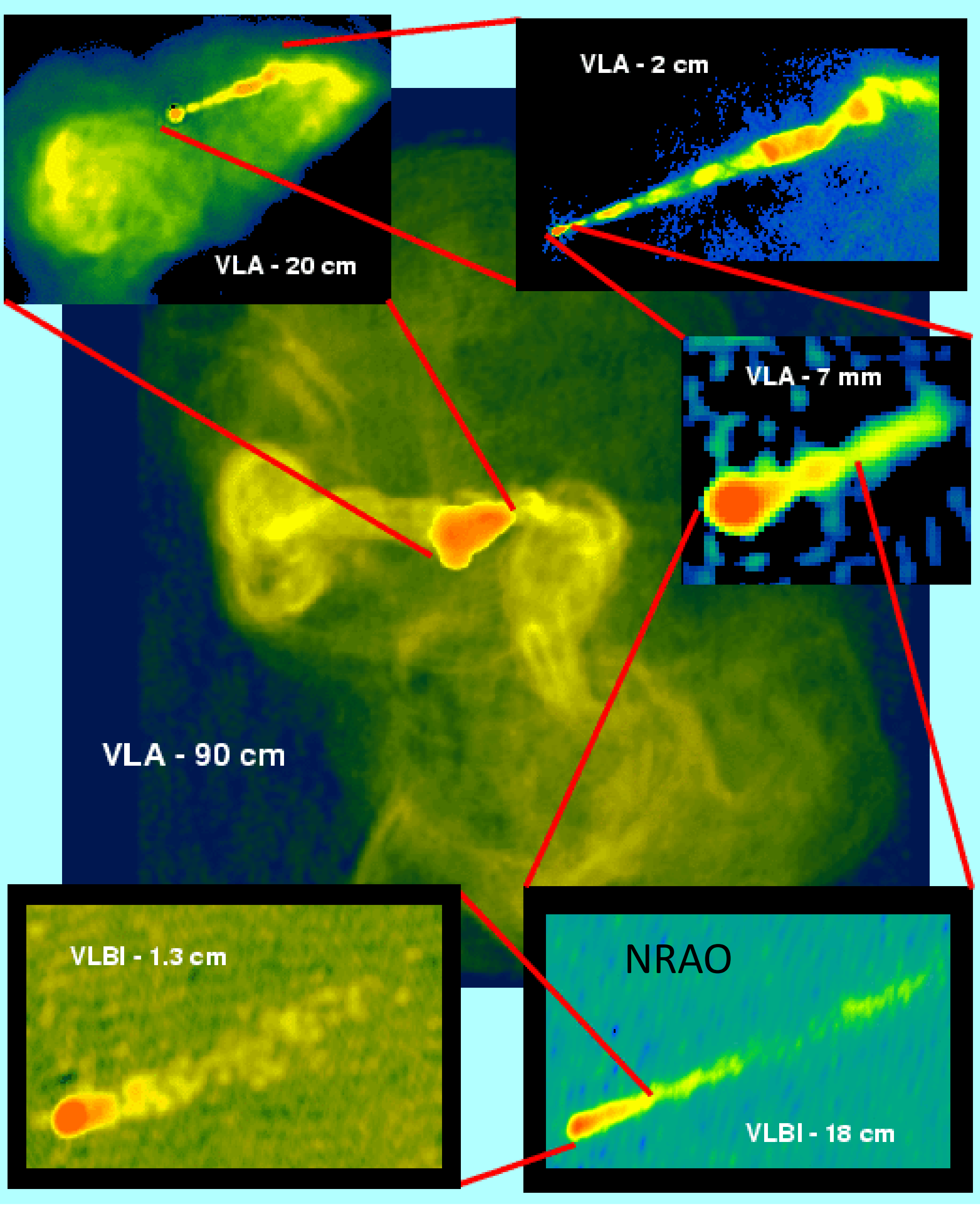


X-rays

Jets @ work in Virgo

- Jets driven by accretion onto a BH with M = 4 × 10^9 $M_\odot$ at centre of the galaxy M87 replaces energy radiated by dense plasma near the cluster centre
- 4/5 of the clusters baryons are invested in this plasma
- The BH keeps it too hot to form stars
- The rate of accretion onto central BH (M ~ 4×10^9 $M_\odot$) should vary as $T^{-5/2}$, so BH can act as a thermostat for intergalactic plasma much as nuclear fusion thermostats the Sun

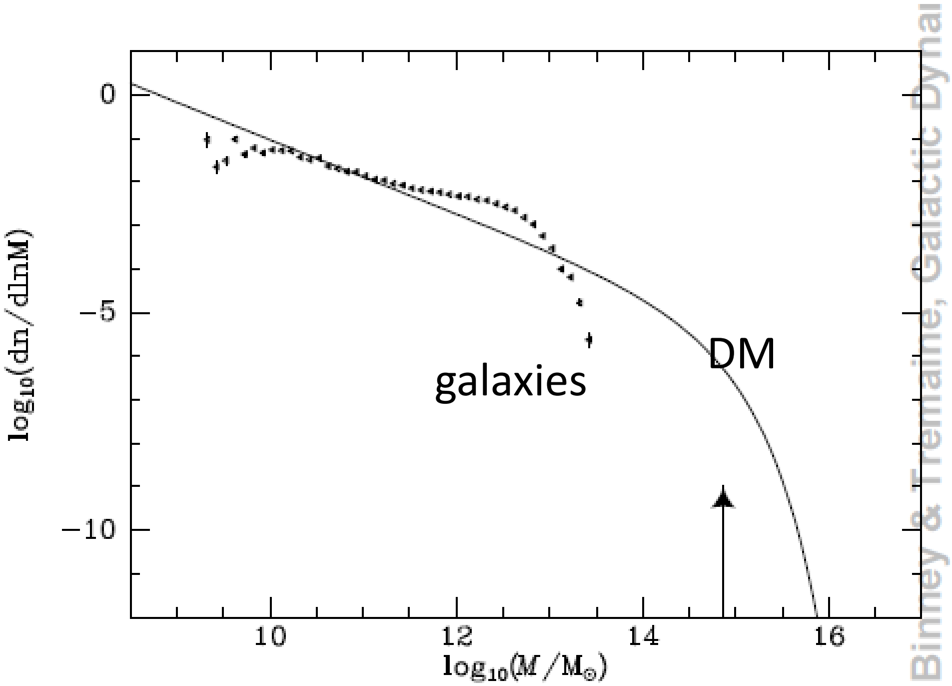
Radio



Virgo A (=M87) at the centre of the Virgo cluster

Inhibiting galaxy growth

- The scale of DM clustering has continually grown
- But BHs have prevented the formation of supermassive galaxies



Binney & Tremaine, Galactic Dyna

Conclusions

- BH growth mirrored growth of stellar populations
- Energy released during BH growth mostly radiated by quasars with little impact
- This a natural consequence of BHs and stars feeding off cold, dense gas
- BH growth and SFR have declined strongly since z=2
- Not because of a shortage of gas but a shortage of cold gas
- There are 2 modes of accretion: radiatively and mechanically efficient
- Magnetic field key in both modes but especially important in mechanical mode
- After z=2 more & more BHs shifted to mechanical mode
- They then truncated galaxy growth by thermostating intergalactic plasma
- Hence BHs have played a major role in shaping the visible Universe