Title: The Eddington Limit in Cosmic Rays

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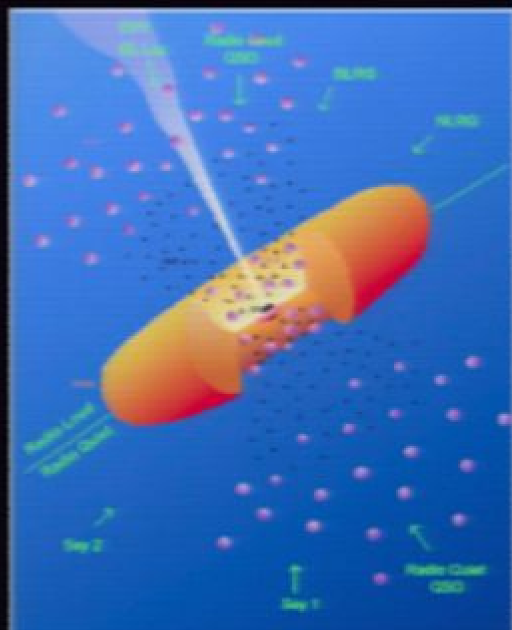
Abstract: In terms of their energetics, cosmic ray protons are an insignificant by-product of star formation and super-massive black hole growth. However, due to their small mean free path, their coupling with the interstellar medium is absolute. In fact, they are most likely, the dominant source of momentum, and therefore kinetic force on galactic scales. By defining an Eddington Limit in Cosmic Rays, we show that the maximum photon luminosity of bright galaxies and quasars are capped by the production and subsequent expulsion of cosmic ray protons. Such simple arguments may explain why bright galaxies are faint in comparison to quasars and why super-massive black holes are relatively mass-less in comparison to galaxies.

outline

- some basic motivation
- the central idea: Eddington Limit in Cosmic Rays
- Cosmic Ray "feedback"
- summary

two classes of persistent cosmological sources: Quasars and Galaxies



Their known properties pose some simple and intriguing questions

Questions

- Origin of $L_\star - \sigma_\star$ relation
- Origin of $M_\bullet - M_\star$ relation
- Why are galaxies faint compared to quasars
- Why are radio loud quasars relatively rare

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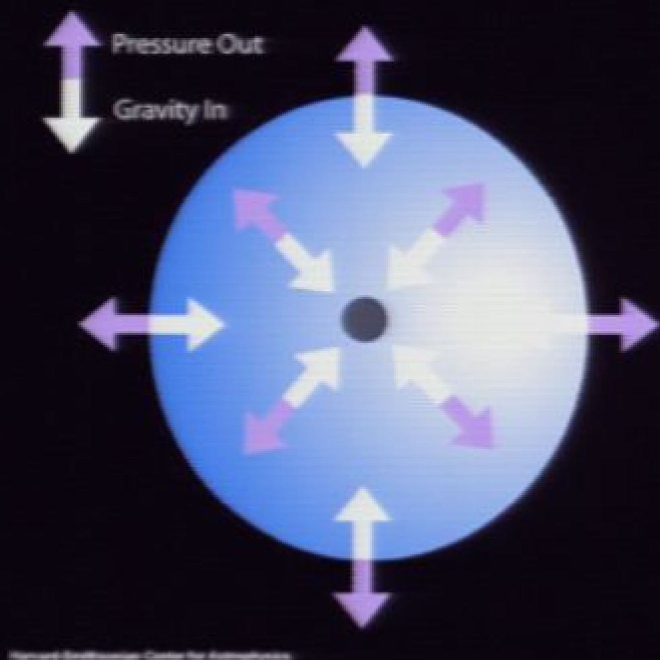
...galaxies, faint?

maximum luminosity of quasars: Eddington Limit



Radiation force = Gravity

$$\int d\mathbf{A}\cdot\frac{\kappa}{c}\mathbf{F} = \int d\mathbf{A}\cdot\mathbf{g}$$

$$\frac{\kappa}{c}L = \int d\mathbf{A}\cdot\mathbf{g} = -\int d\mathbf{A}\cdot\nabla\phi$$

$$\frac{\kappa}{c}L = -\int dV\,\nabla^2\phi = 4\pi G\int dV\,\rho$$

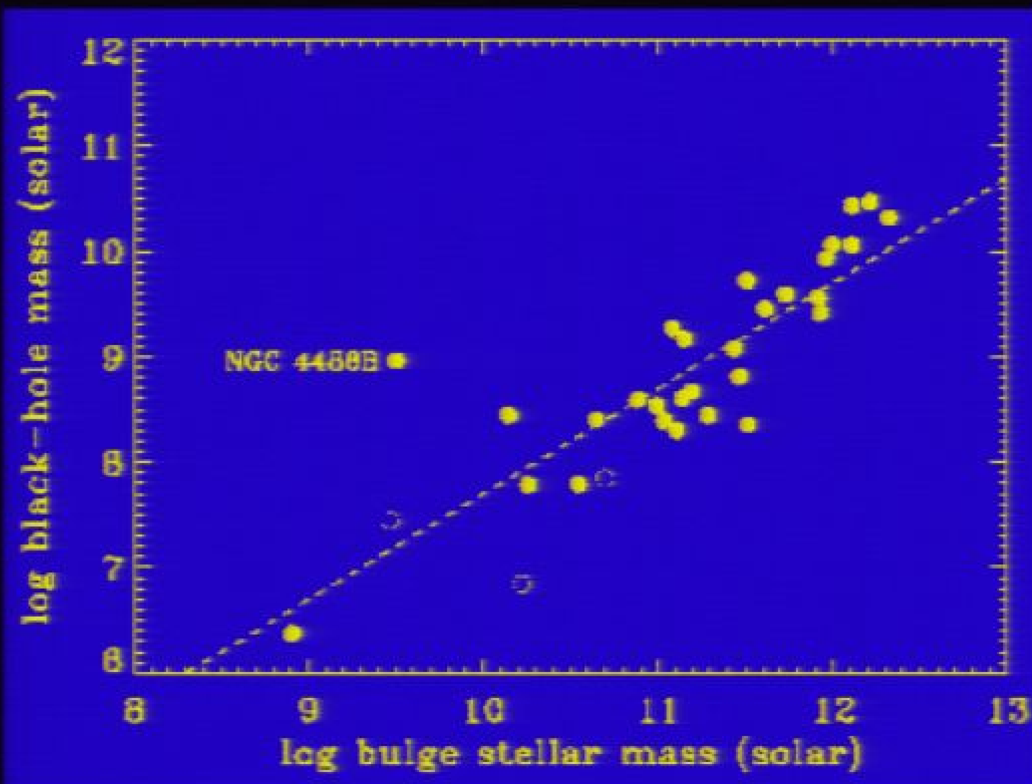
$$L_{\rm Q,max} \simeq 10^{47}\,\frac{M_{\rm BH}}{10^9\,M_\odot}\,\frac{\kappa_{es}}{\kappa}\,{\rm erg\,s^{-1}} \quad\longleftarrow\quad L_{\rm edd} = \frac{4\pi\,G\,cM_{\rm enc}}{\kappa}$$

independent of geometry for uniform opacity

Magorrian et 1998

...galaxies, faint?

So, the Eddington Limit $\propto M_{\rm enc}, \kappa^{-1}$



Galaxies are much more massive than quasars.

$$M_{\rm bulge} \simeq 300 M_{\rm BH}$$

the photon (Thomson) Eddington limit does not set a galaxy's luminosity

self-regulating winds

?

How do stellar winds work?

radiation/momentum vs. energy/thermal

cold vs. hot

e.g.,

planetary nebulae

winds from massive stars

stellar coronae

$(L > L_{edd}) \quad \frac{\kappa}{c} F > g$

result of momentum exchange between radiation and gas

$v_w \geq v_{esc}$

$\frac{1}{\rho} \nabla P > g \quad (T > T_{esc})$

results from catastrophic heating of the gas

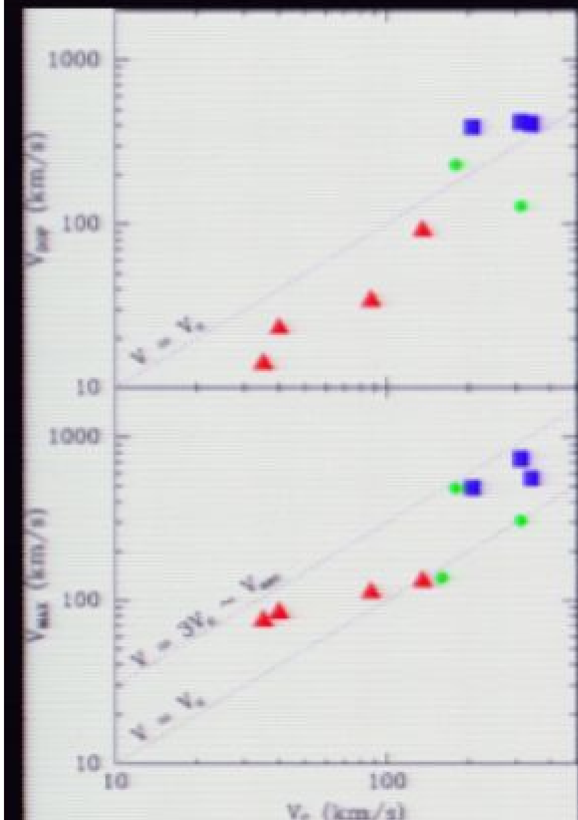
$v_w \sim c_s \sim v_{esc}$

C. Martin 2005

Abbott 1982

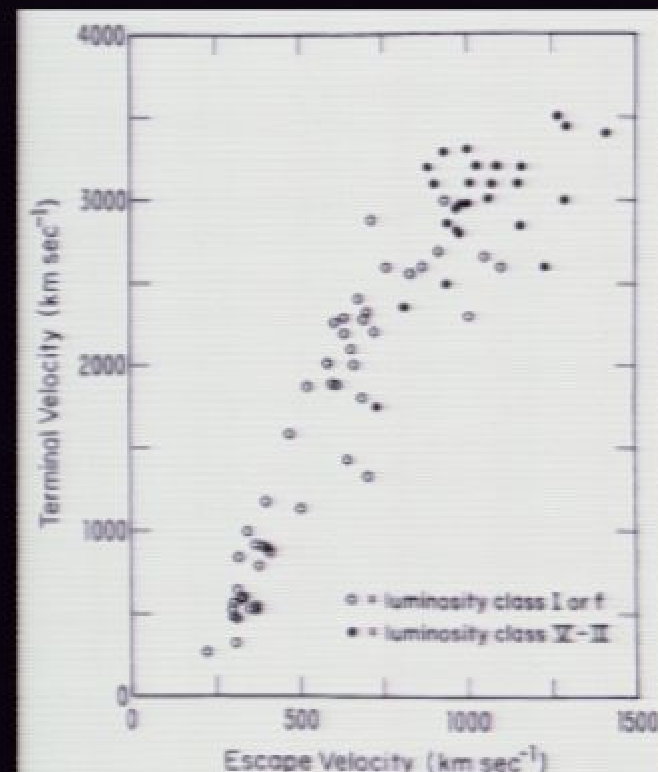
analogy w/ winds of massive stars

$v_w \geq v_{esc}$ ("fast")



"cold" Galactic winds ~ 2000 A.D.

"cold" (line) radiation-driven stellar winds ~ 1980 A.D.



$\longrightarrow \langle v_w v_{esc} \rangle \neq 0$

Perhaps some type of Eddington-Breaking *momentum injection* is at work, that leads to "cold" and "fast" winds.

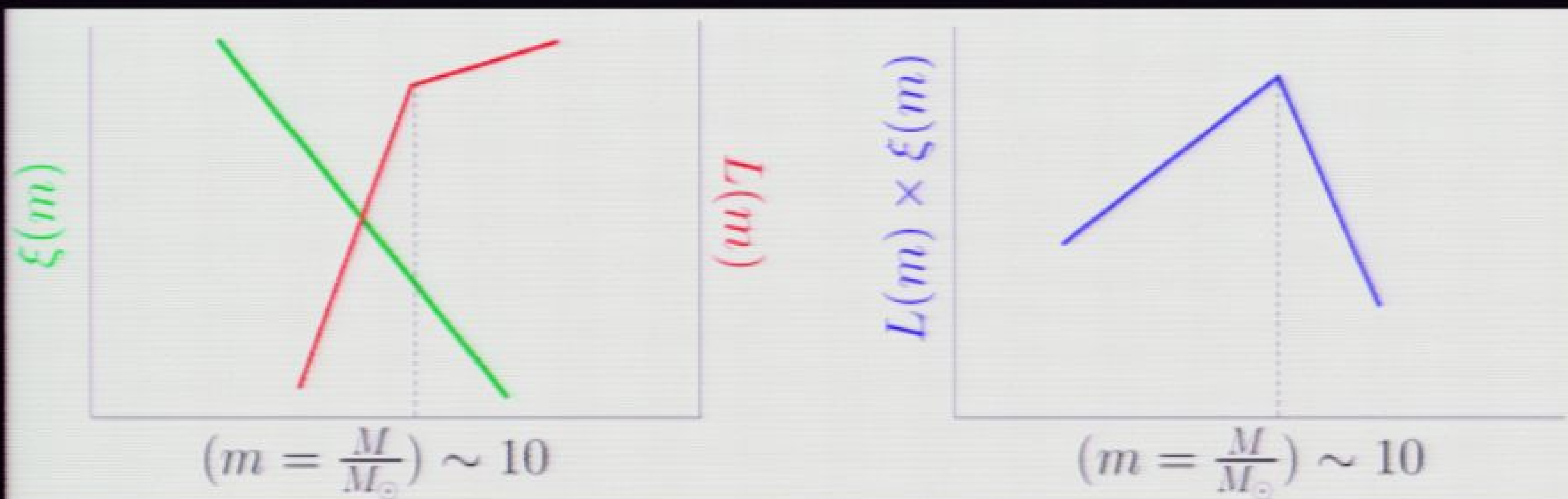
Socrates et al. 2008

Eddington Limit in Cosmic Rays

photons are not the only form of radiation produced

by the act of star formation:

star formation energetics



$$\epsilon_\star \sim 1\mathrm{MeV/baryon} \sim 10^{-3}$$
$$\epsilon_{\mathrm{SN}} \sim 10\,\mathrm{keV/baryon} \sim 10^{-5}$$
$$\epsilon_{\mathrm{CR}} \sim 1\,\mathrm{keV/baryon} \sim 10^{-6}$$

Massive stars are responsible for starlight, SNe, and cosmic ray power in starbursters.

Eddington Limit in Cosmic Rays

though photons dominate energy release, cosmic ray protons may dominate momentum injection.

$$\lambda_{\rm CR} \sim 1\,{\rm pc} \qquad \lambda_{es} \sim 1\,{\rm Mpc}$$

in the Milky Way

$$\therefore \kappa_{\rm CR}/\kappa_{es} \sim 10^{6}$$

now,

$$L_{\rm edd} = \frac{4\pi\, G c M_{\rm enc}}{\kappa} \rightarrow L_{\rm edd,CR} = 10^{-6} L_{\rm edd,ph}$$

Modest production of cosmic rays can disrupt

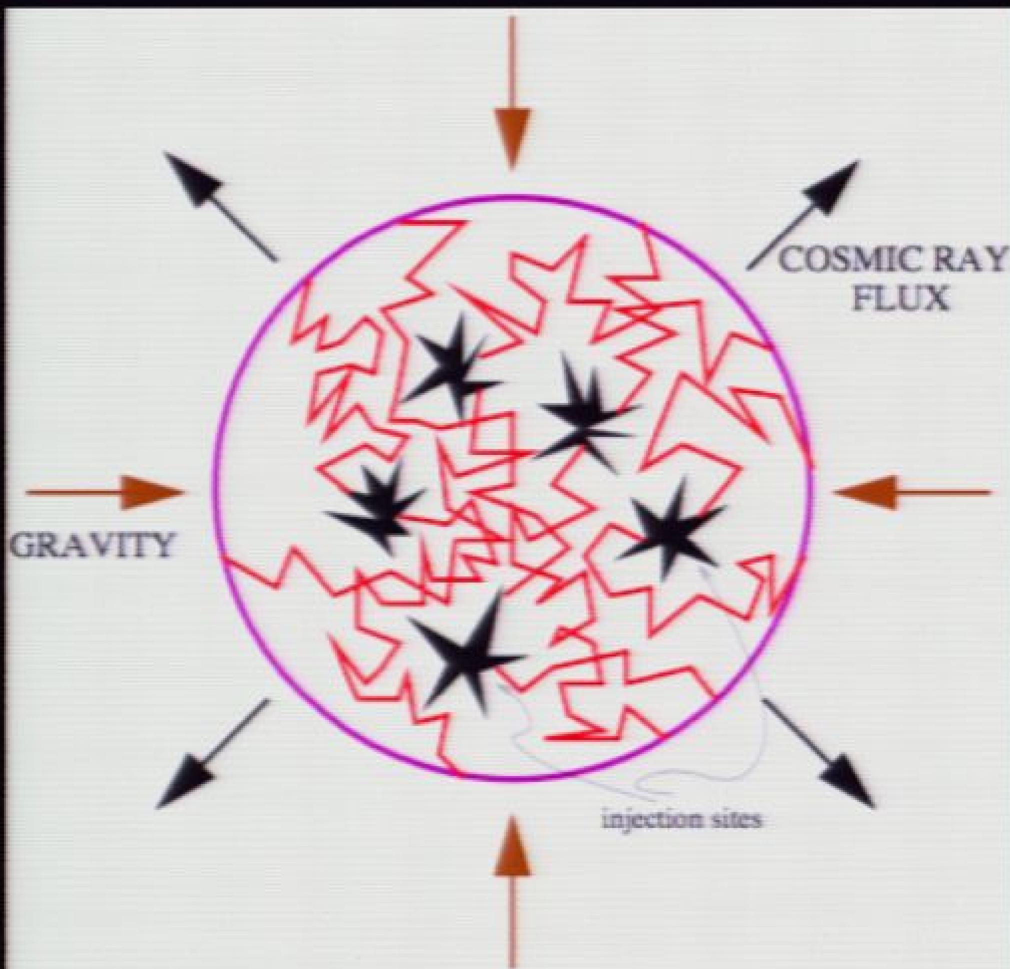
interstellar medium and eject gas.

$$L_{\rm gal} \leq \frac{\epsilon_\star}{\epsilon_{\rm CR}} \frac{L_{\rm edd,CR}}{L_{\rm edd,ph}} L_{\rm edd,ph} = \frac{\epsilon_\star}{\epsilon_{\rm CR}} \frac{L_{\rm edd,CR}}{L_{\rm edd,ph}} \frac{M_{\rm gal}}{M_{\rm BH}} L_{\rm Q,max}$$

$$L_{\rm gal} \leq \frac{1}{3} L_{\rm Q,max}$$

AS, Davis & Ramirez-Ruiz 2008

a galaxy as a "star"



Again, in the Milky Way

$$\tau_{\rm CR} \sim 10^3 - 10^4$$

for ~1-10 GeV CR protons

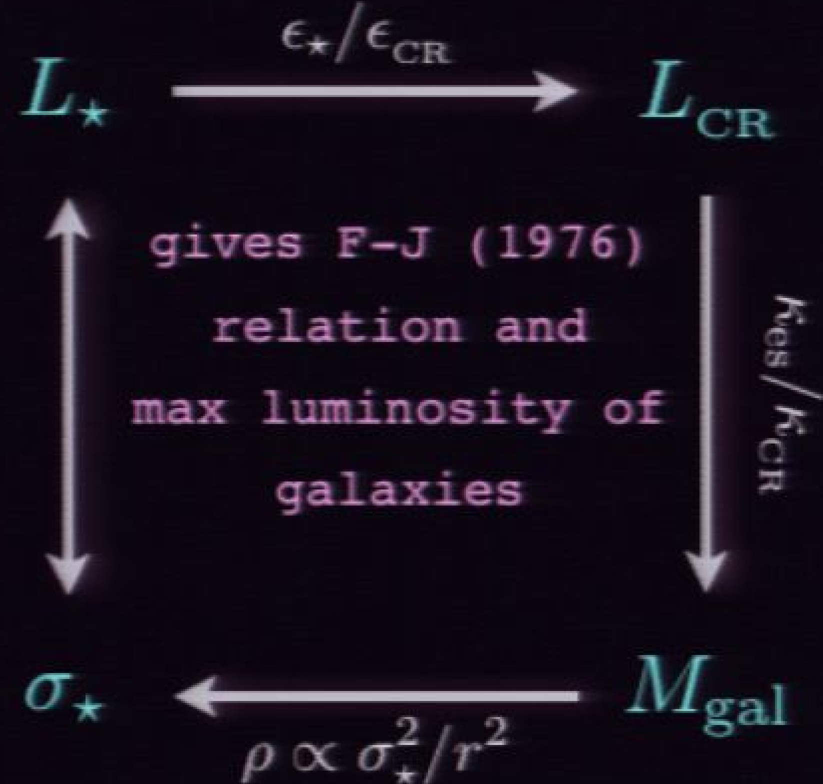
Useful to think of a Cosmic Ray Pressure

$$P_{\rm CR} \simeq \frac{\tau_{\rm CR}}{c} F_{\rm CR}$$

momentum response of the *magnetized* ISM is insensitive to the spatial distribution of injection sites.

1-zone model is justified, gives ability to connect stellar output to large scale properties of galaxy

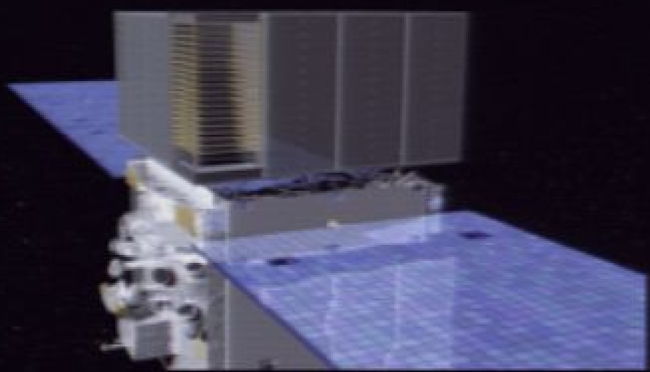
Galactic feedback

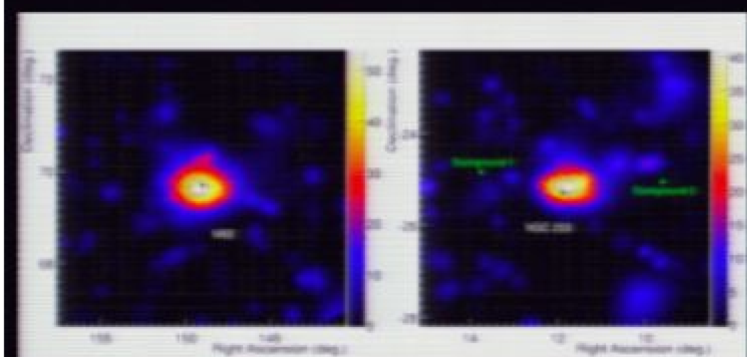


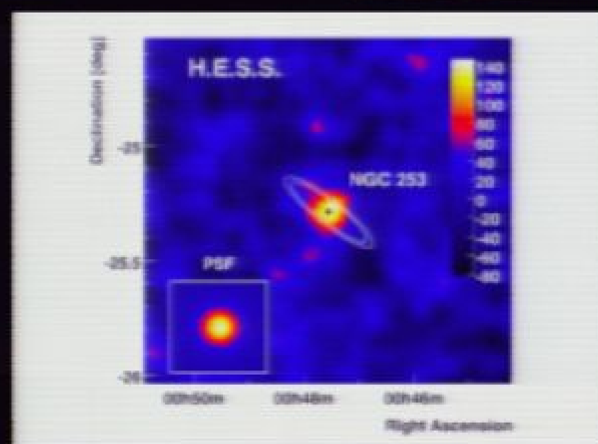
reproduces slope & normalization of F-J relation

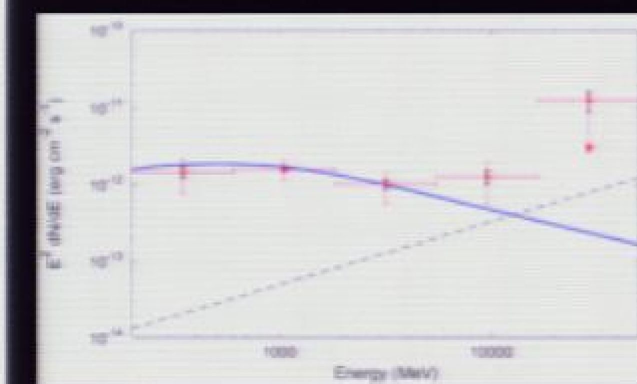
explains why galaxies are faint relative to quasars

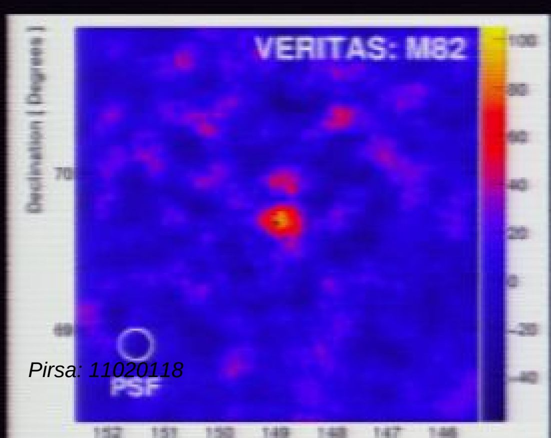
next steps & modern gamma-ray astronomy

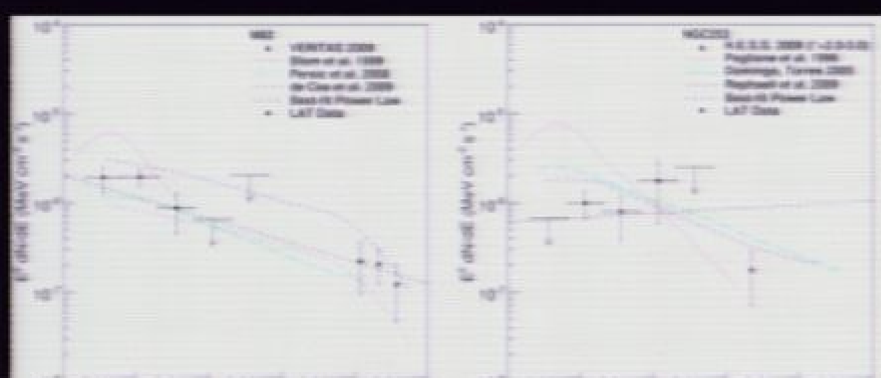


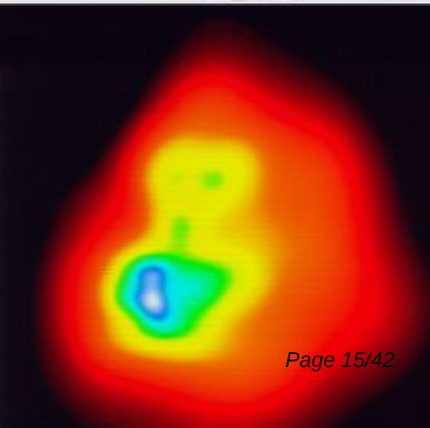












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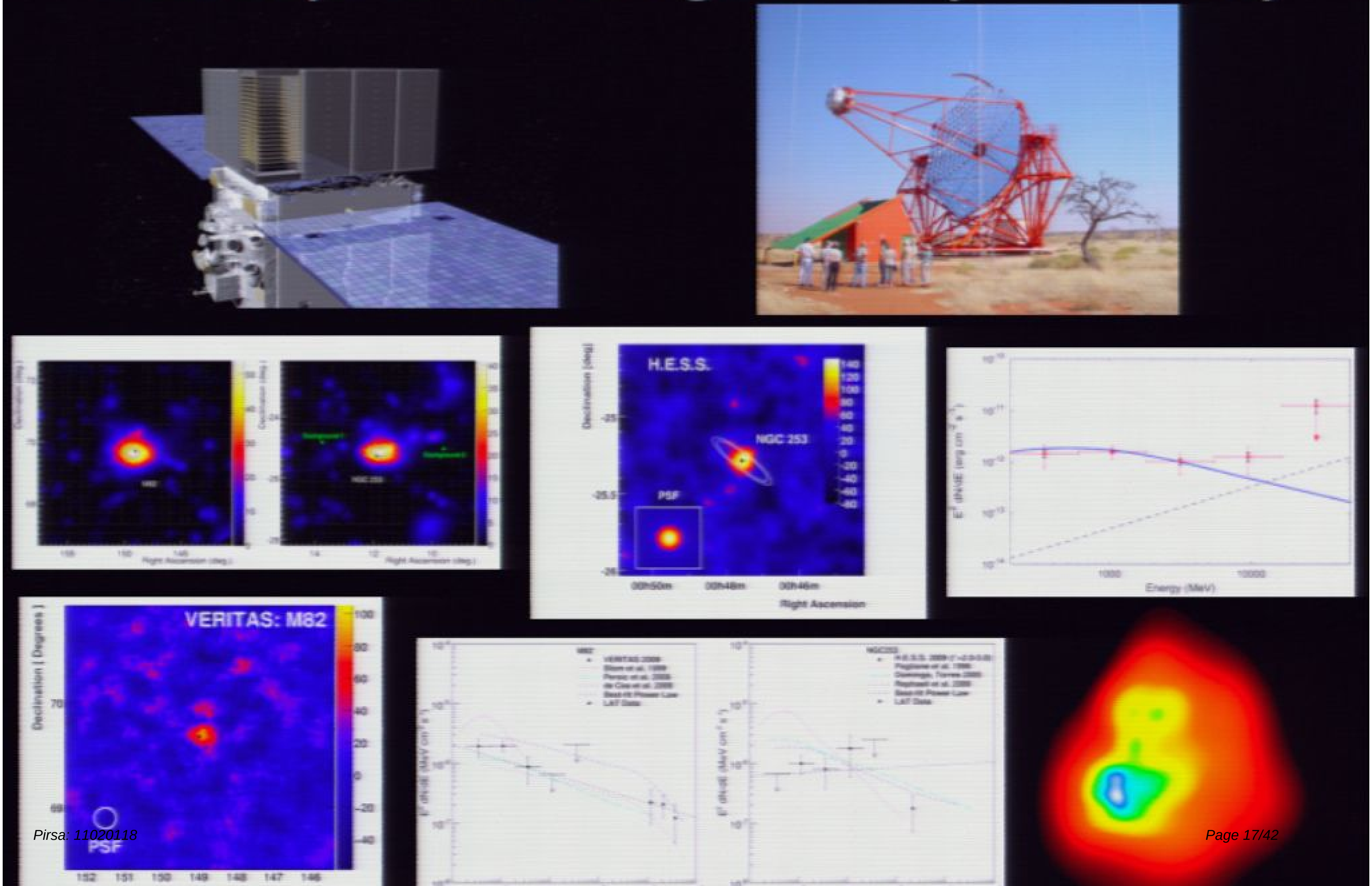

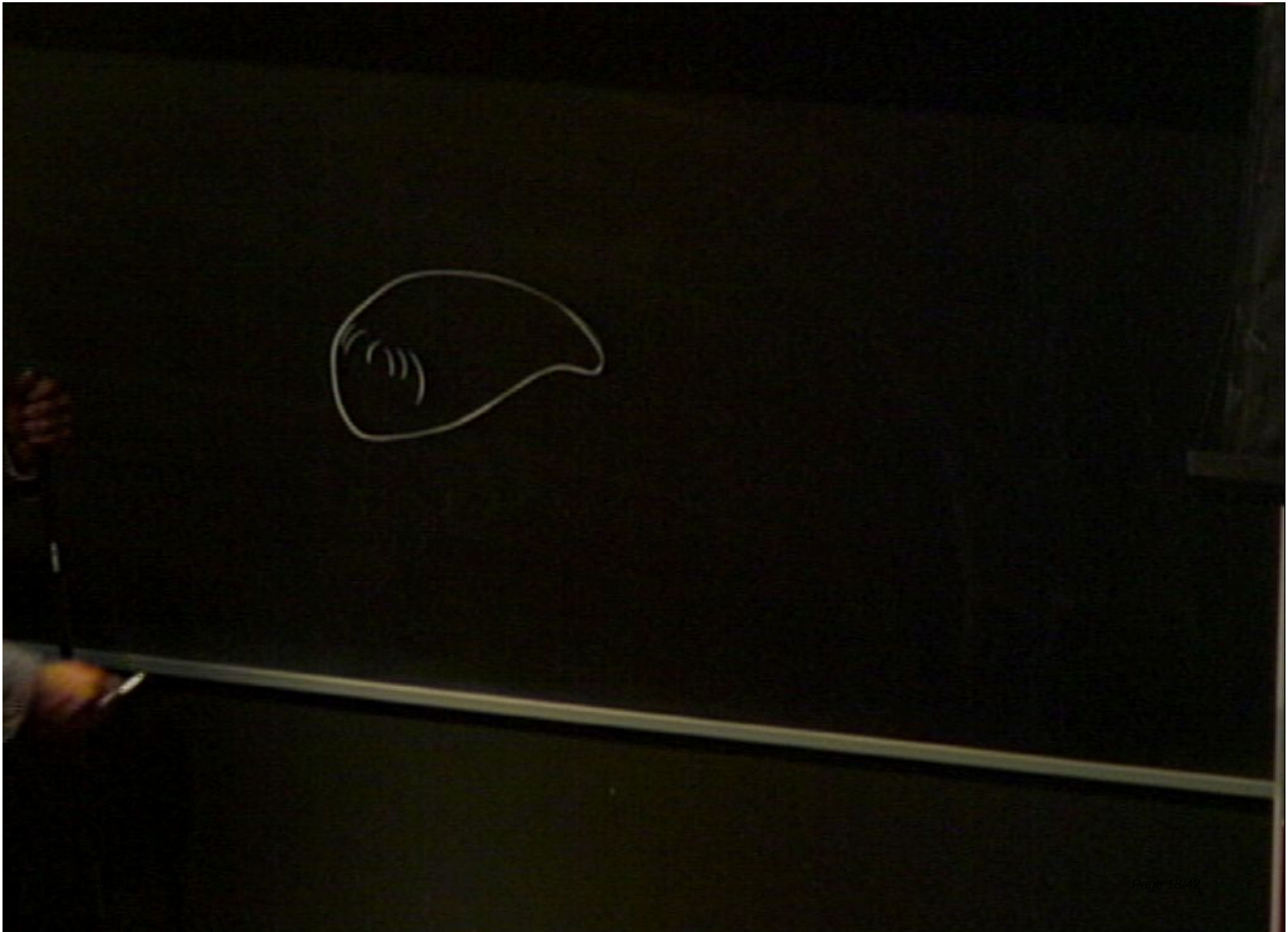

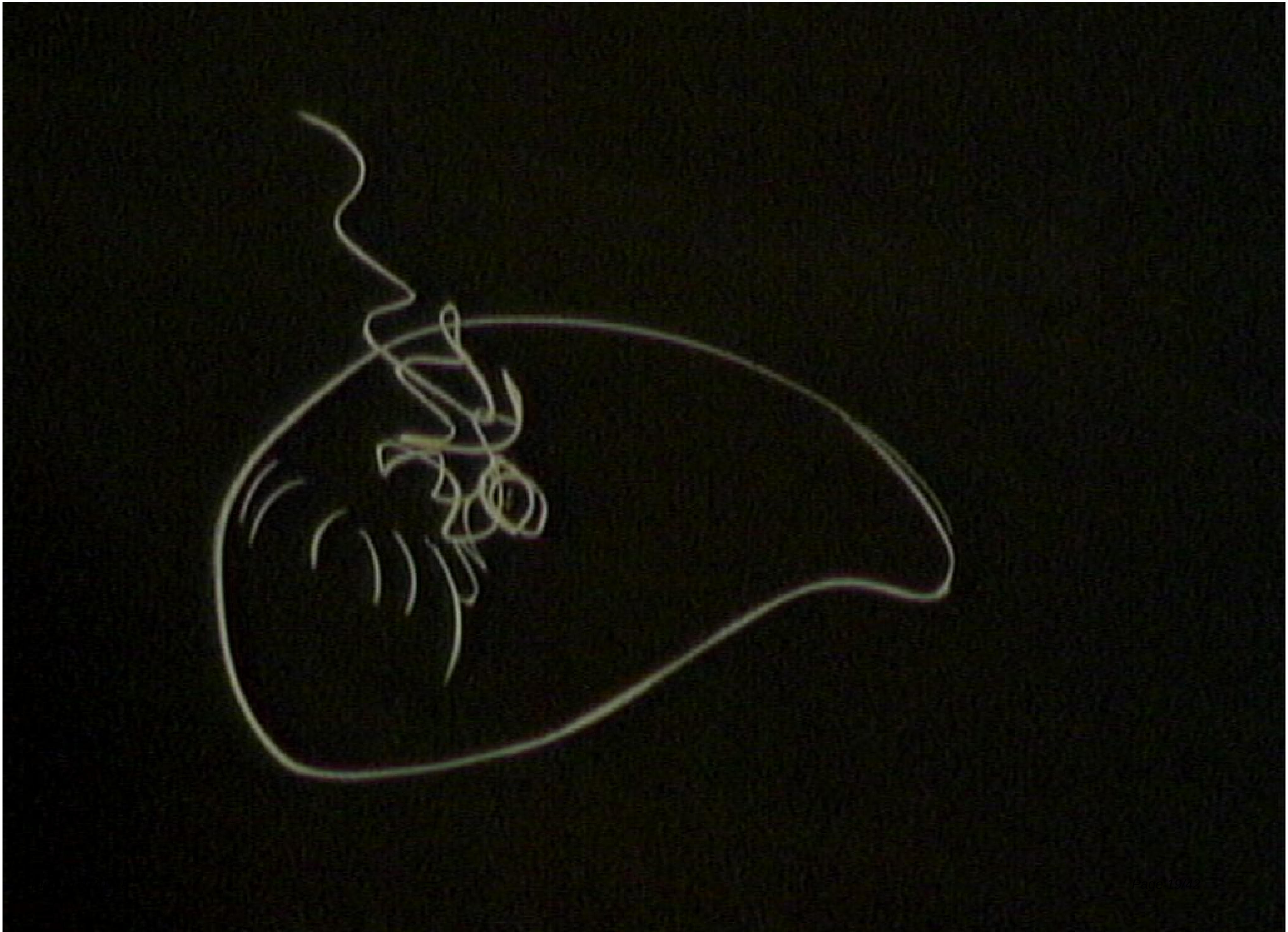

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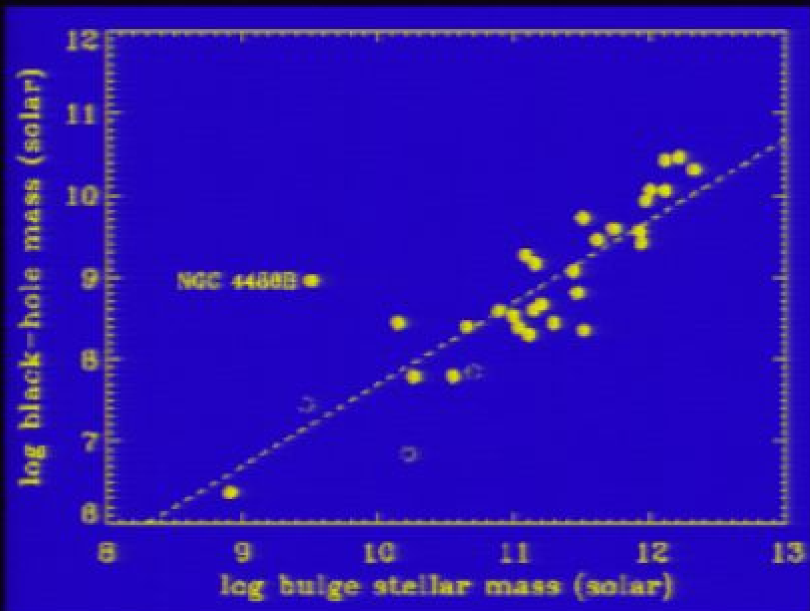
Quasars: a basic argument



but, $M_\bullet/M_\star \sim 10^{-3}$

$$\therefore \epsilon_\bullet \propto \sigma_\star^2$$

If BH growth in optically luminous phase is scale free (e.g. Yu & Tremaine 2002; Soltan 1982)

Party Line: BH Growth and feedback is scale-free with BH mass

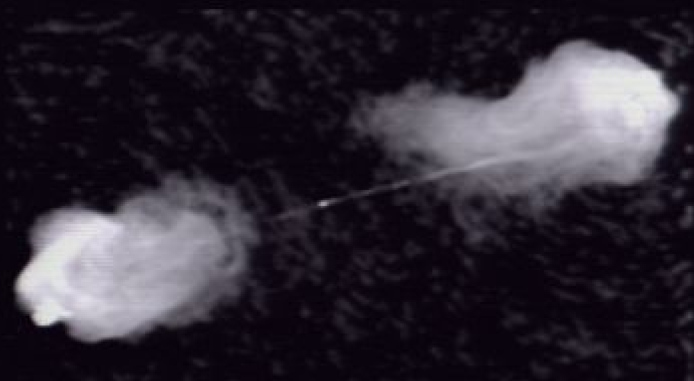
$$\epsilon_\bullet = \frac{f_g M_\star \sigma_\star^2}{\Delta E_\bullet} \propto \frac{M_\star \sigma_\star^2}{M_\bullet}$$

so, $\epsilon_\bullet \neq \text{const.}$

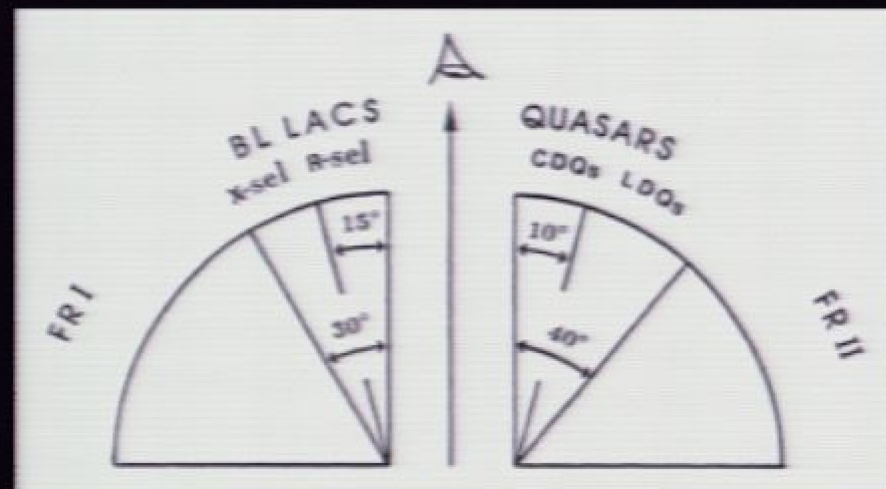
for feedback in the optically luminous mode of BH growth

Radio Loud Quasars/AGN

Adopt quasar unification (e.g. Antonucci)



Ghisellini et al. 1993

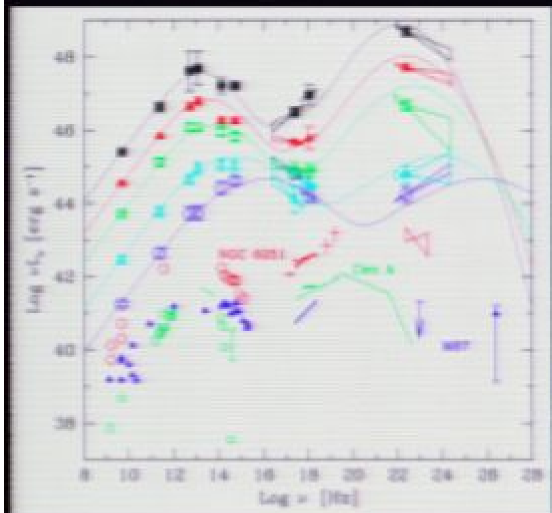


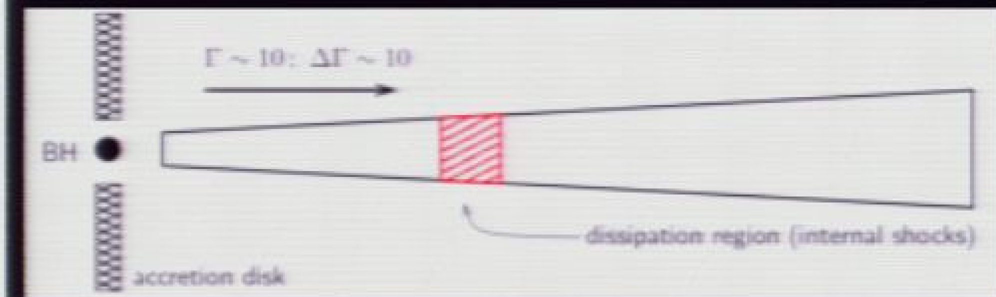
connect
RL activity
w/ accretion

⟹ FSRQs/FRIIs

Blandford, Begelman, Maraschi, Ghissellini, Rees, Levinson... (1967-1997)

CR protons from Radio Cores





sub-pc scale radio cores(e.g. blazars) are powered (synchrotron + Compton) by relativistic internal shocks

relativistic shocks = relativistic thermal ions

= cosmic ray protons

WHAT DO THESE COSMIC RAYS DO TO THE HOST GALAXY?

CRs leak out and unbind the galaxy

we estimate that

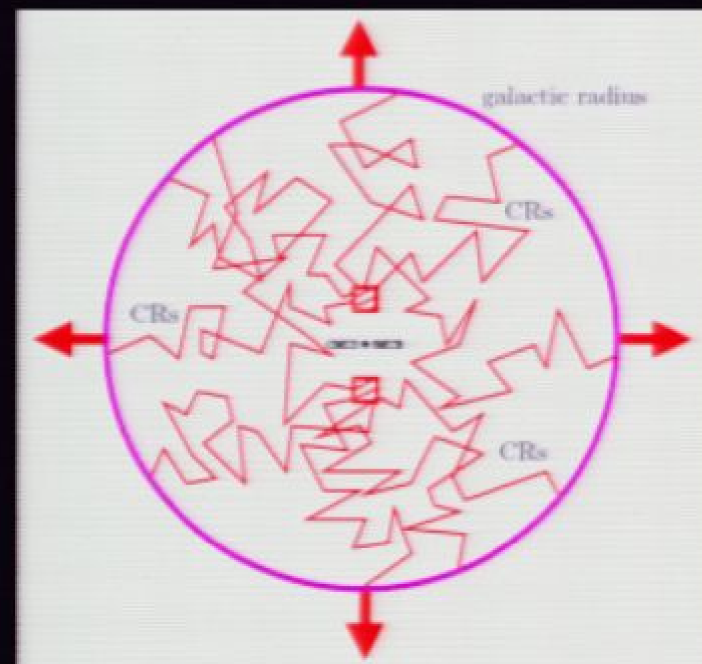
~ 10% of jet power L_J converted to thermal power $L_{\rm th}$.

$$\longrightarrow \Delta\Gamma \sim \Gamma$$

~ 10% of $L_{\rm th}$ escapes into ISM as CRs $L_{\rm CR}$.

$$B_{\rm core} \longrightarrow f_{esc}$$

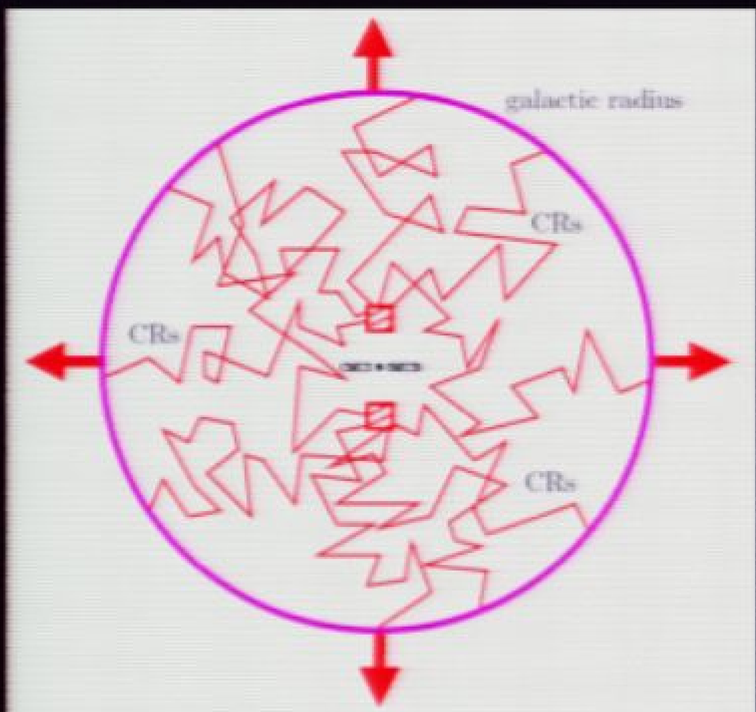
Calibrate L_J to measurements of FRII parent population



The escape fraction and $L_J/M_\bullet$ are independent of BH mass & the interstellar CR luminosity $L_{\rm CR}$ is super-Eddington for the host galaxy.

ignore our theory

and consider the following



in the Milky Way

$$L_{\rm CR} \sim 10^{41}\,{\rm erg/s}$$

for radiation pressure

$$P_{\rm CR} \sim F_{\rm CR}\frac{\tau_{\rm CR}}{c} \sim \frac{L_{\rm CR}}{A}\frac{\tau_{\rm CR}}{c}$$

for a big radio loud quasar

$$L_J \sim 10^{47}{\rm erg/s}$$

interstellar CR pressure due to RL quasar can be up to SIX ORDERS OF MAGNITUDE LARGER than the ISM pressure of the MW

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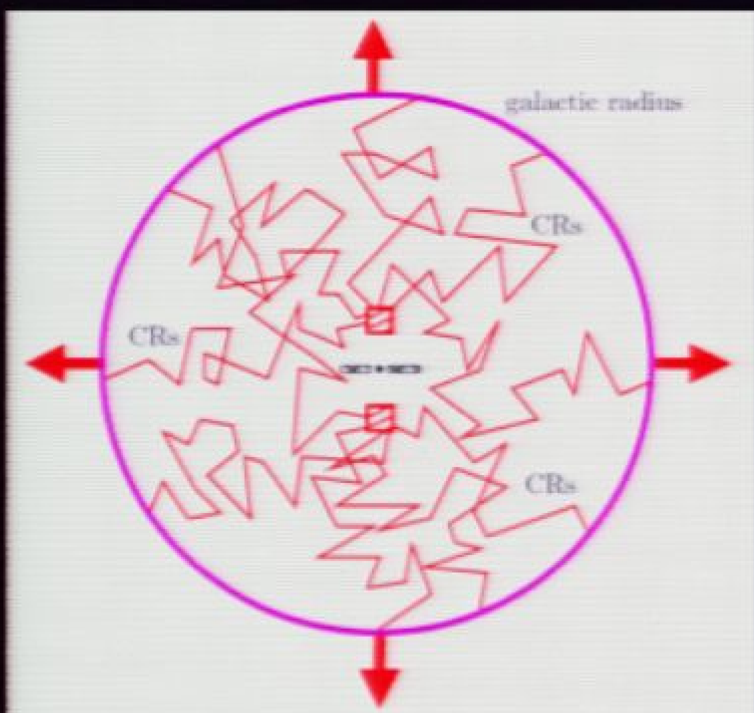

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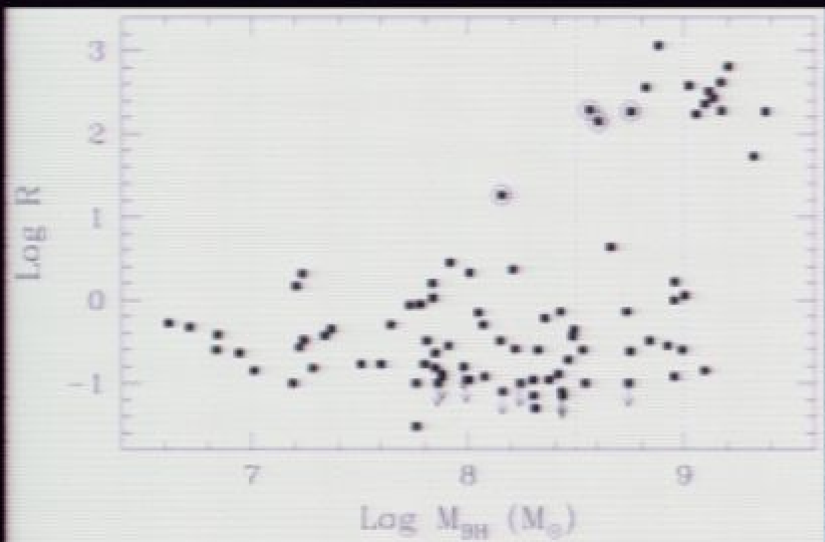
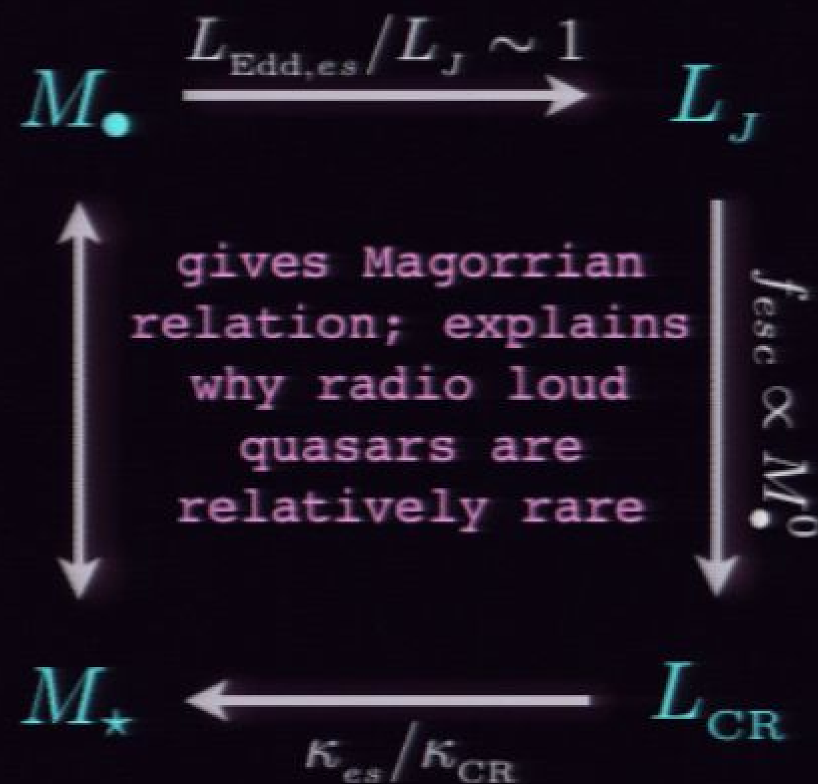
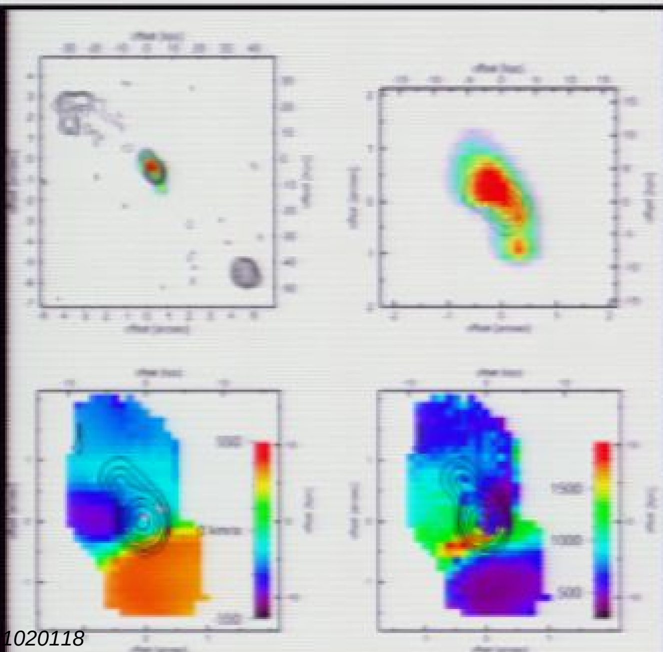
RL Quasars & Feedback

Laor 2000







Nesvadba et al 2008

how does this work?

TWO REQUIREMENTS:

energy

$$\Delta E_{\rm inj} \sim E_g \sim f_g M_\star \sigma_\star^2$$

momentum

$$L_{\rm CR} > L_{\rm Edd,CR}$$

for Radio Loud feedback

$$\Delta E_{\rm RP} \sim \epsilon_{\rm RP} \Delta t_{\rm RP} \Lambda_{\rm Edd} L_{\rm Edd,\bullet} \sim E_g$$ where $$\Lambda_{\rm Edd} = L_J / L_{\rm Edd,\bullet}$$

re-write as

$$\frac{M_\bullet}{M_\star} \sim \left(\frac{\sigma_T}{4\pi G m_p c}\right) \frac{f_g \sigma_\star^2}{\epsilon_{\rm RP} \Delta t_{\rm RP} \Lambda_{\rm Edd}}$$

and so $$\epsilon_{\rm RP} \Delta t_{\rm RP} \Lambda_{\rm Edd} \propto \sigma_\star^2$$

if your on Magorrian

$$\longrightarrow \quad \Delta t_{\rm RP} \propto \sigma_\star^2$$

explains why radio loud AGN are rare, if accretion is episodic

RL Quasars & Feedback

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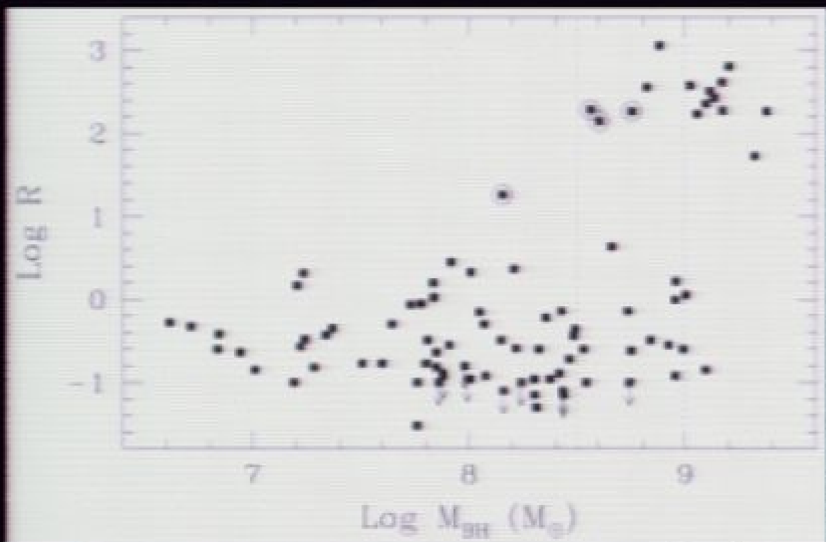


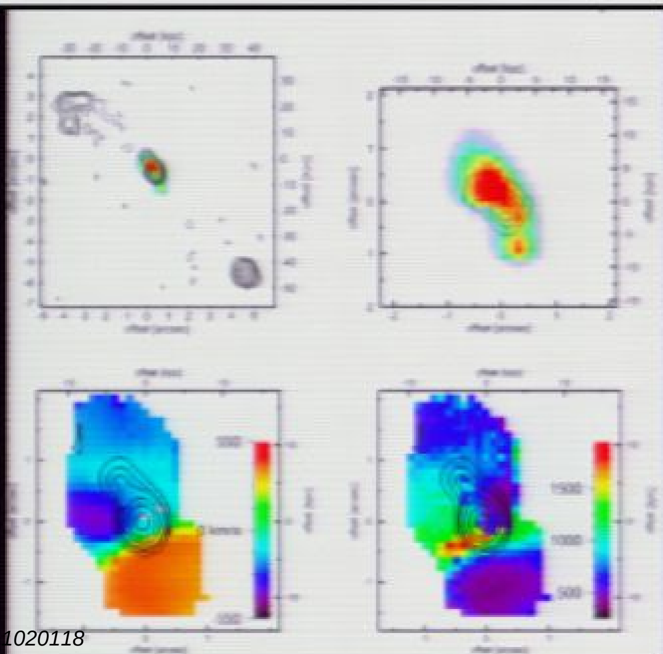
$$M_\bullet \xrightarrow{L_{\mathrm{Edd},es}/L_J \sim 1} L_J$$

$$L_J \xrightarrow{f_{esc} \propto M_\bullet^0} L_{\mathrm{CR}}$$

$$L_{\mathrm{CR}} \xrightarrow{\kappa_{es}/\kappa_{\mathrm{CR}}} M_\star$$

$$M_\star \leftrightarrow M_\bullet$$

gives Magorrian relation; explains why radio loud quasars are relatively rare



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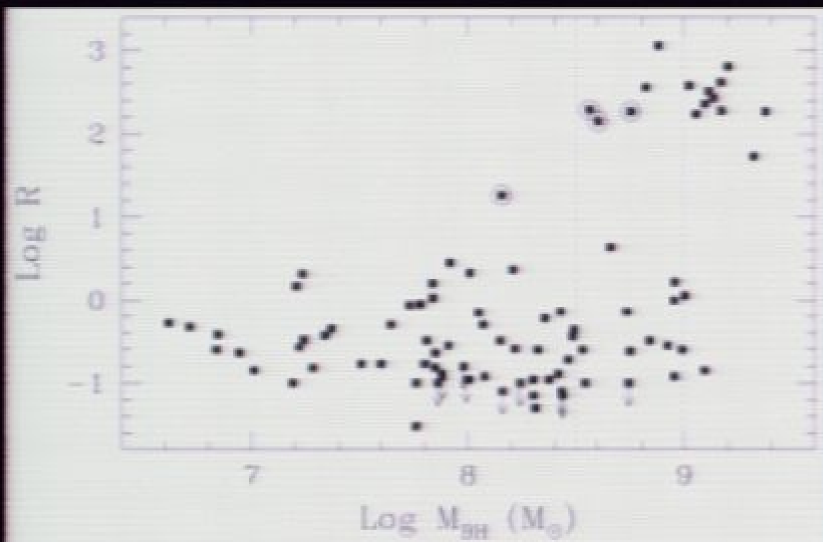

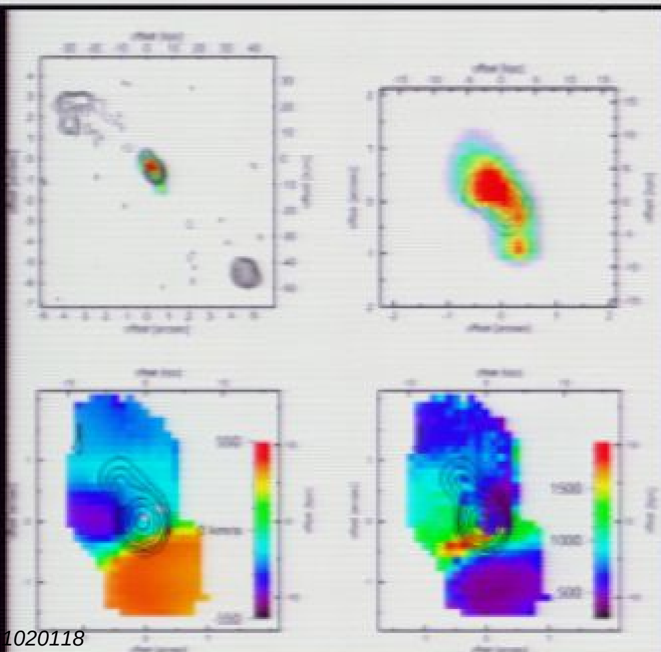

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$M_\bullet \leftrightarrow M_\star$

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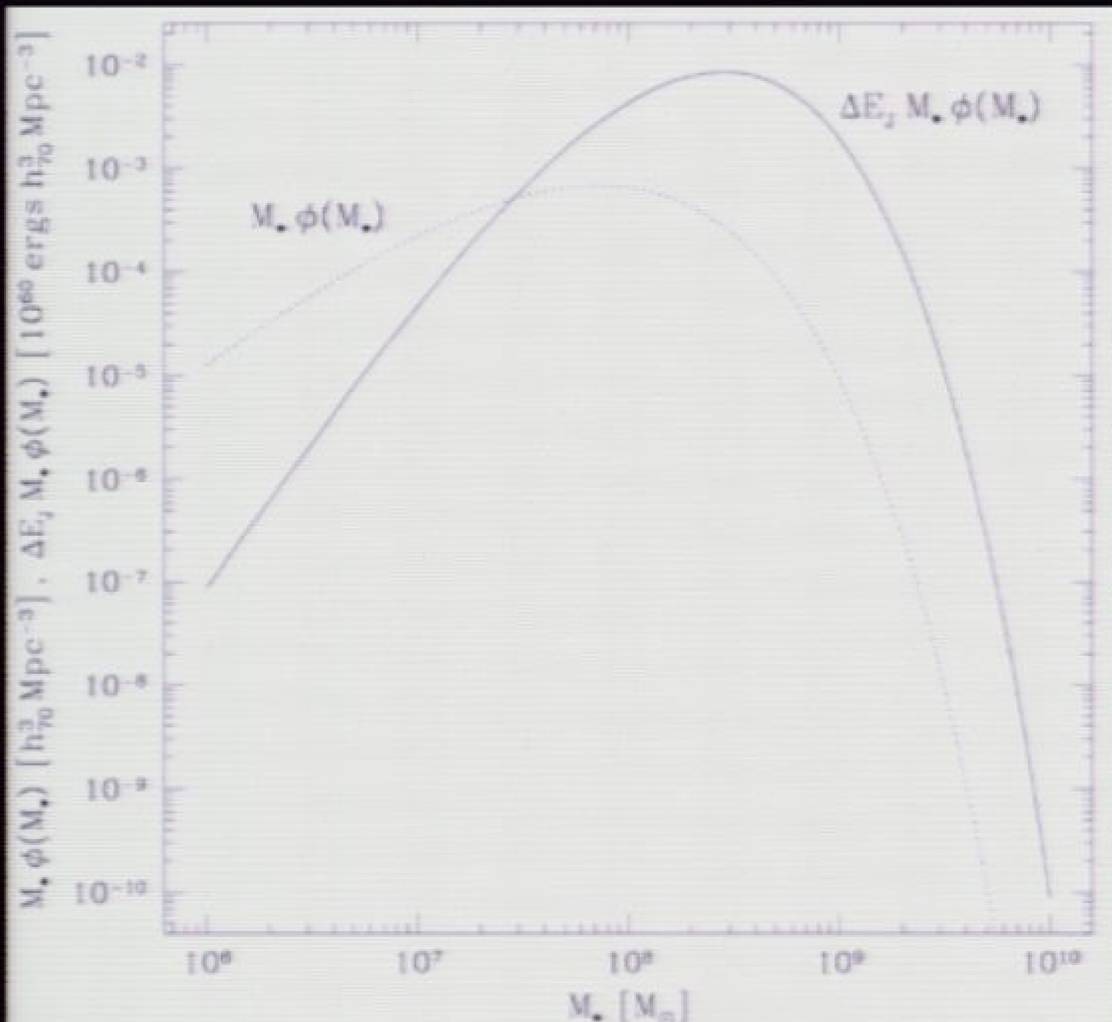
Nesvadba et al 2008

kinetic energy function



for fixed feedback efficiency, any model should produce an energy release function highly peaked at the high mass end if

$$M_\bullet / M_\star \sim 10^{-3}$$

which is what's observed for RL quasar/AGN activity

Summary

- Eddington Limit in cosmic rays: gives simple feedback model for limiting brightness of galaxies and masses of BHs
- provides explanation for why galaxies are faint and why radio loud quasars are rare
- basic idea stems from small CR mean free path

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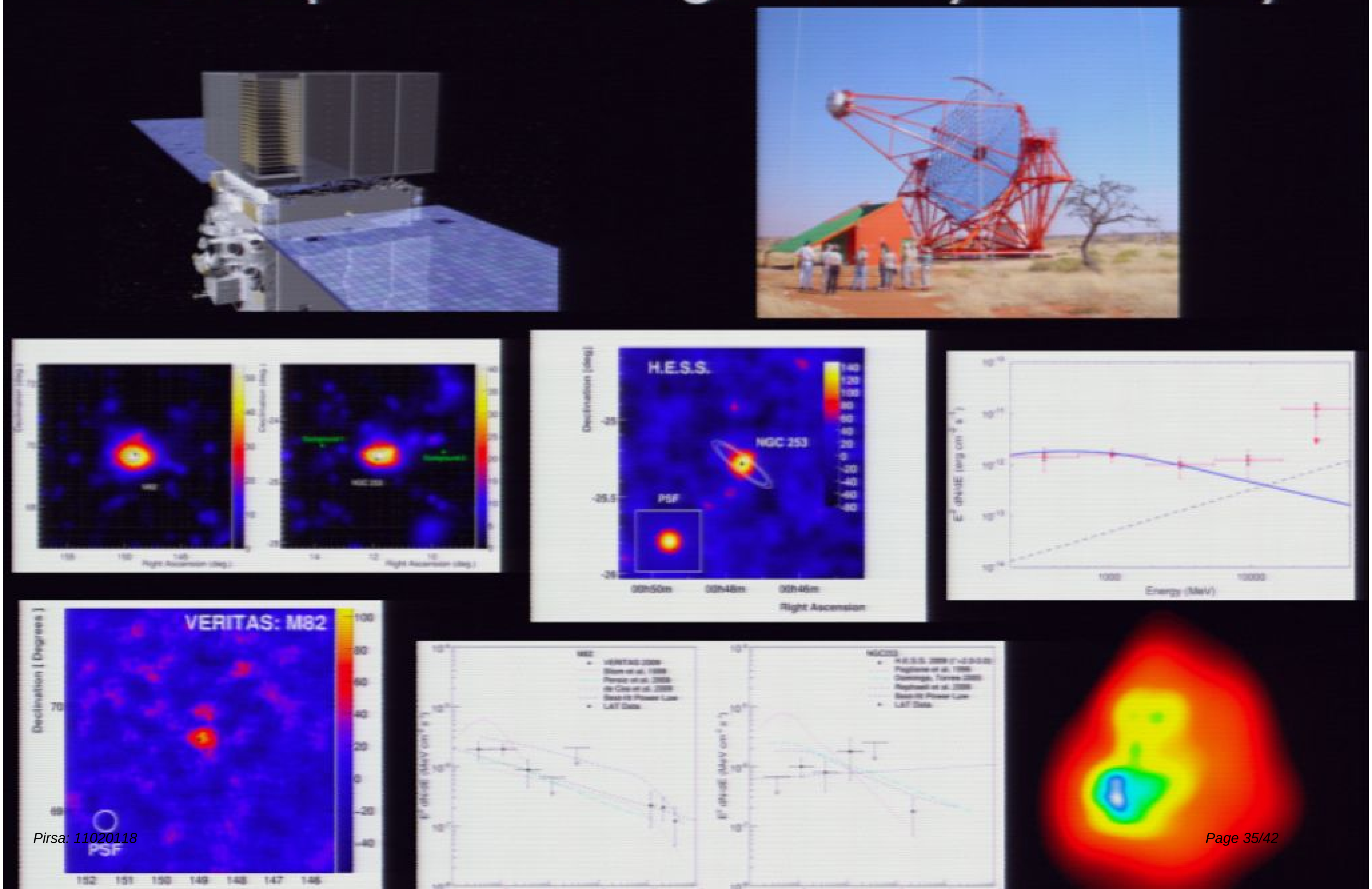
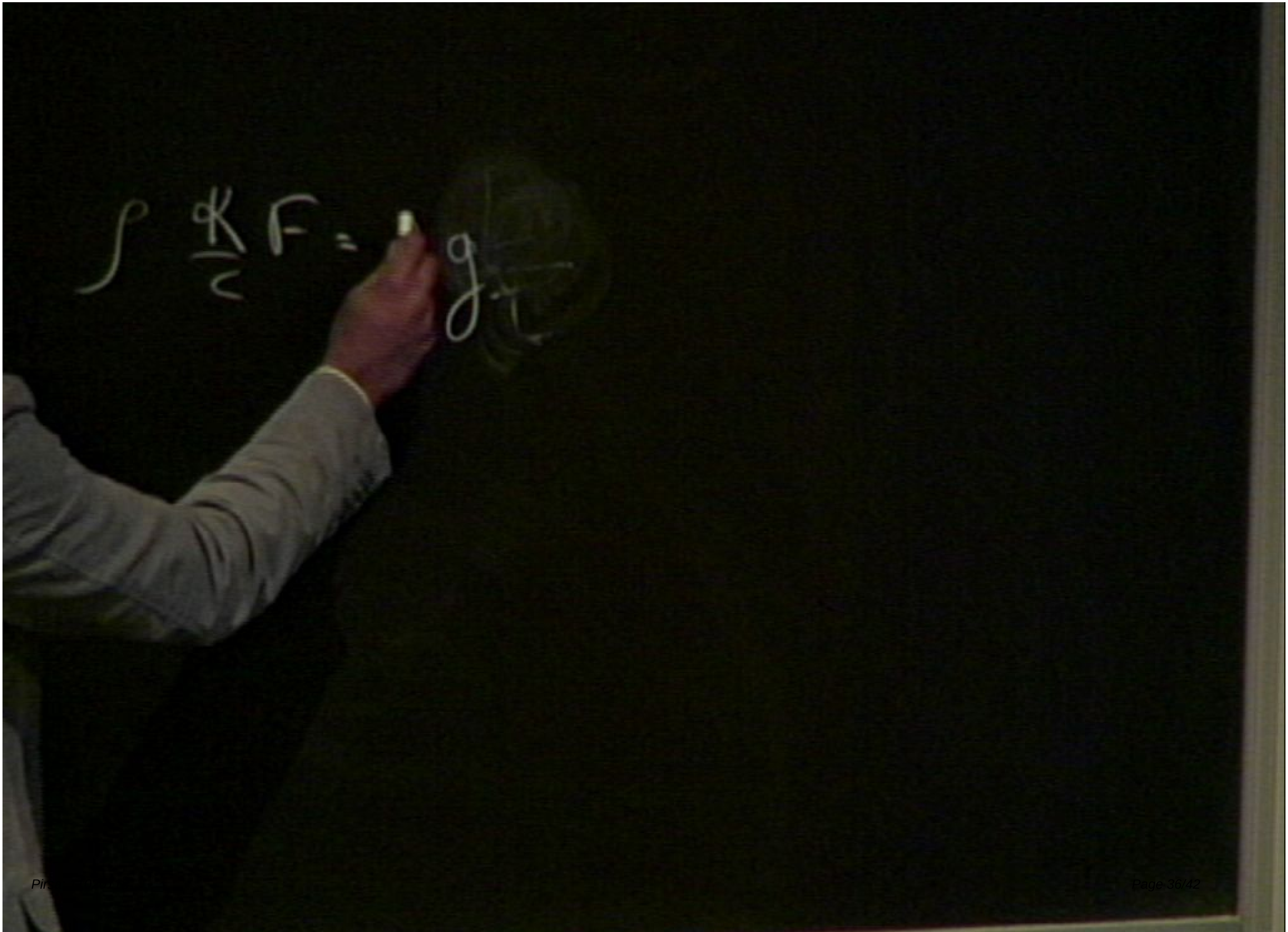
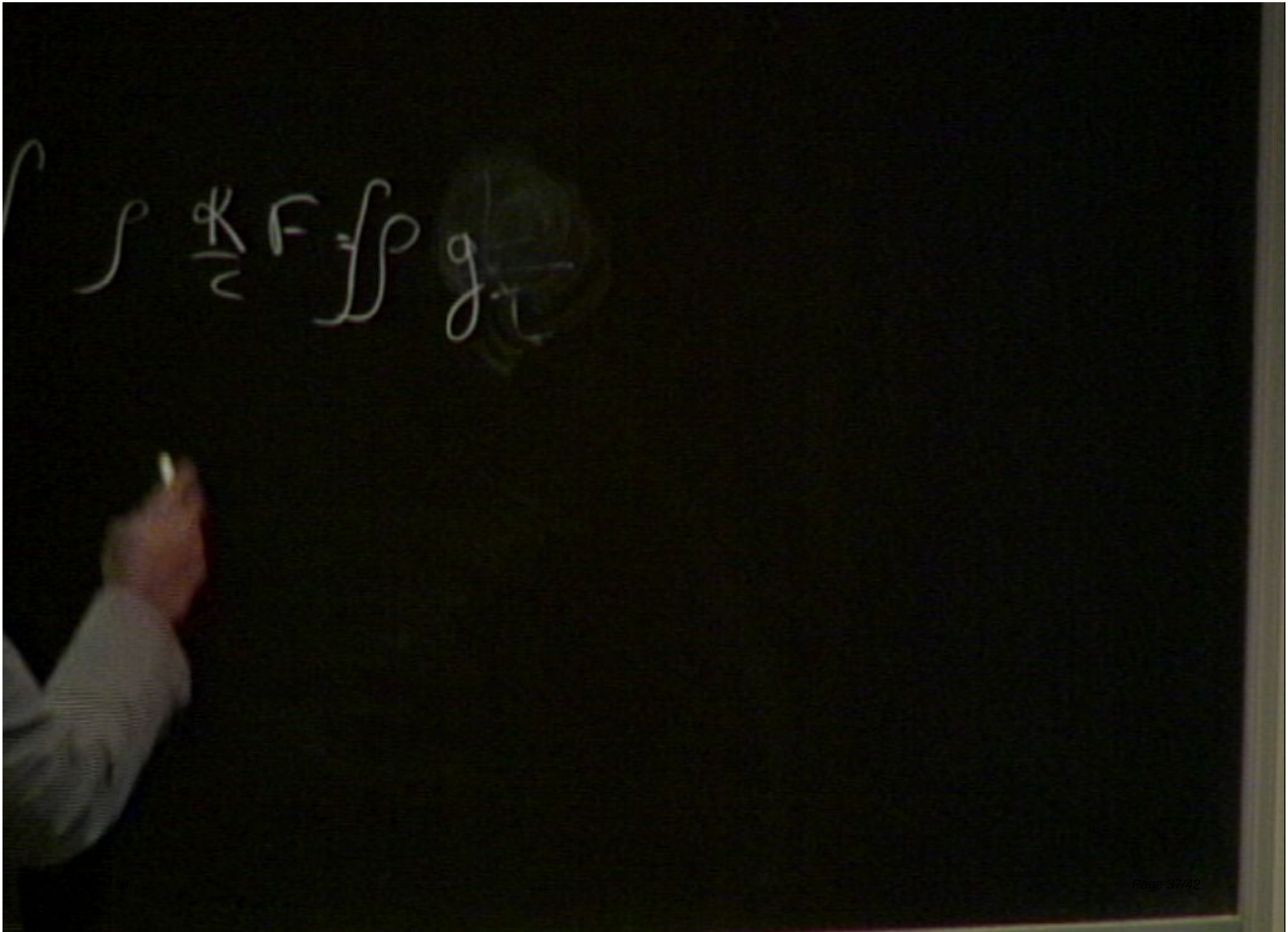
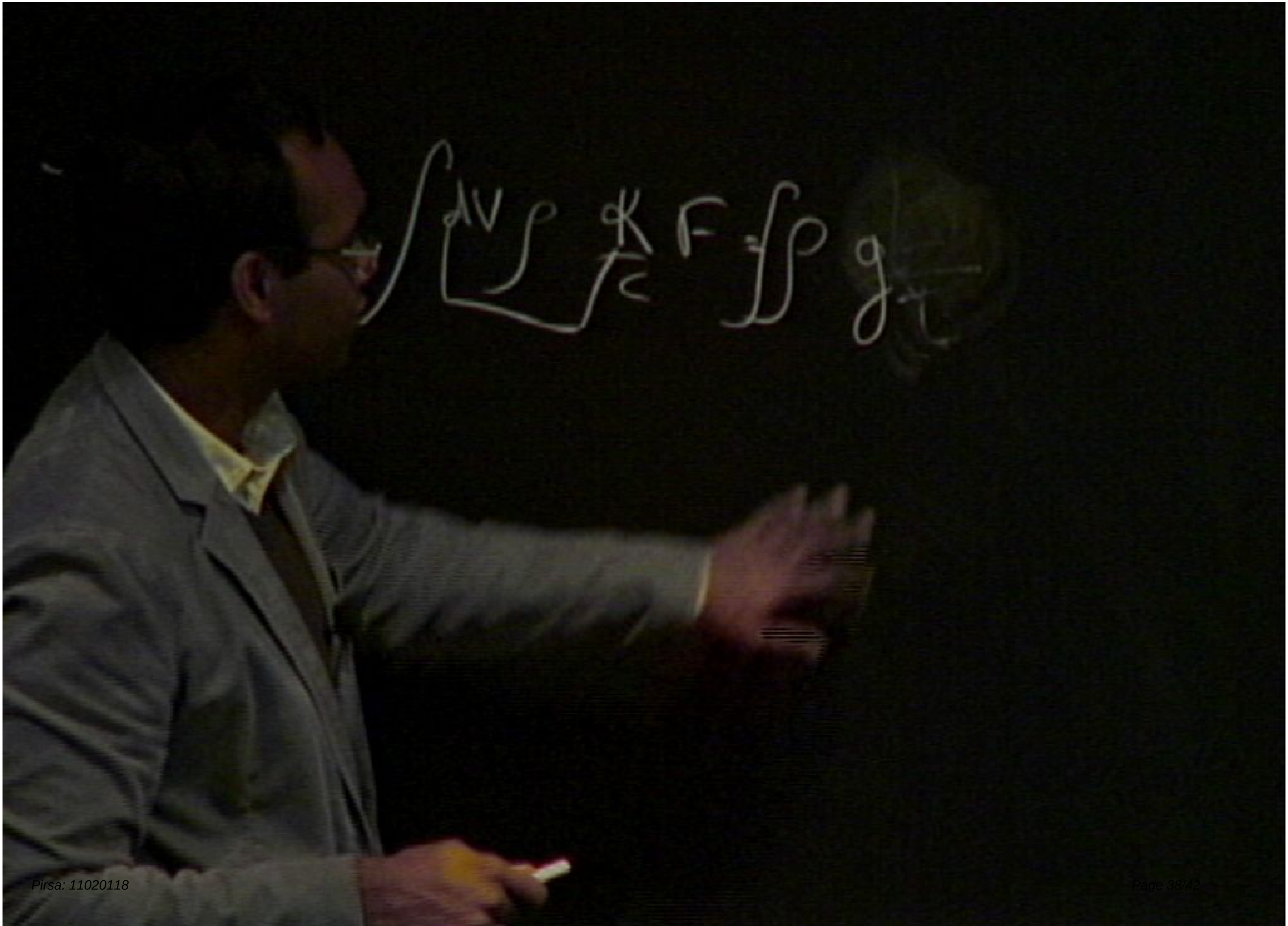
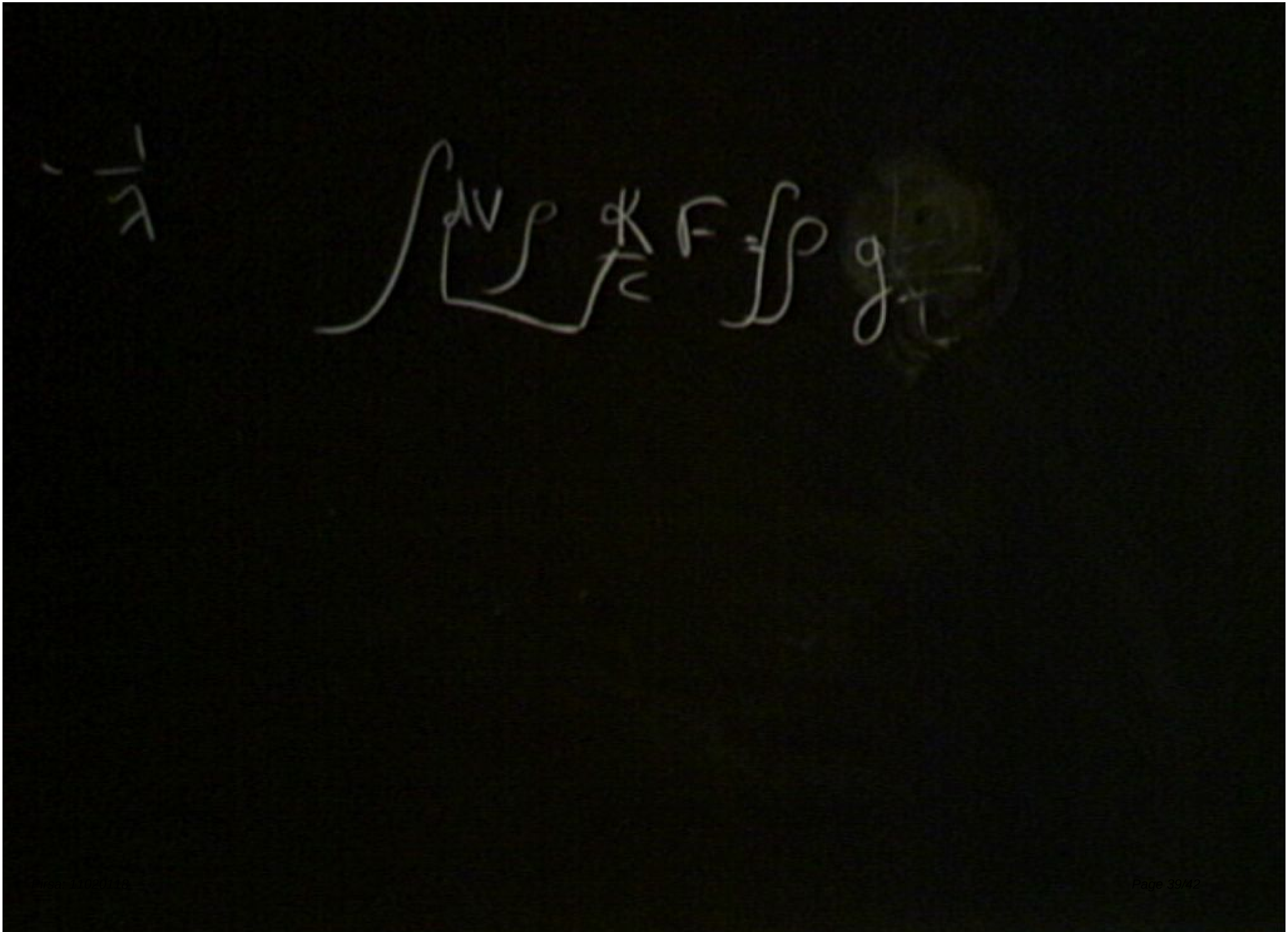
next steps & modern gamma-ray astronomy











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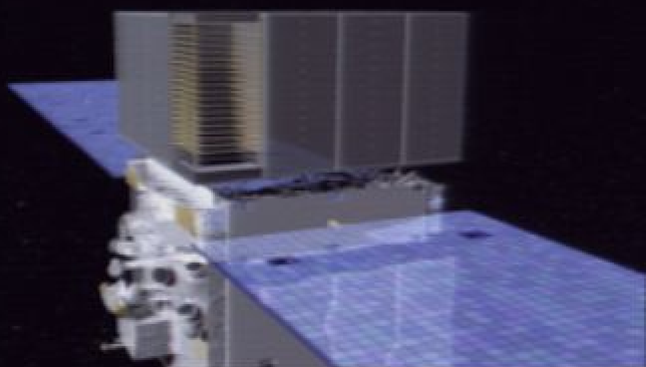
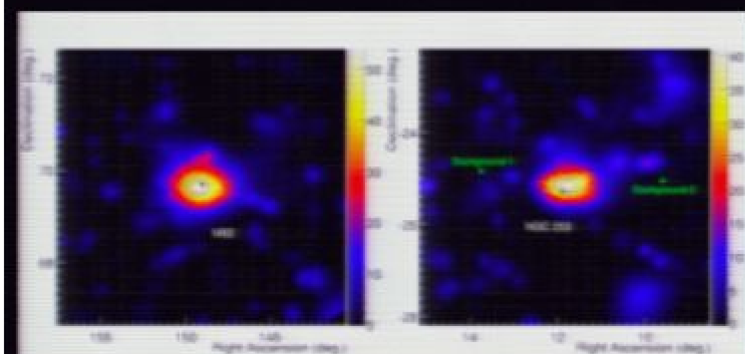
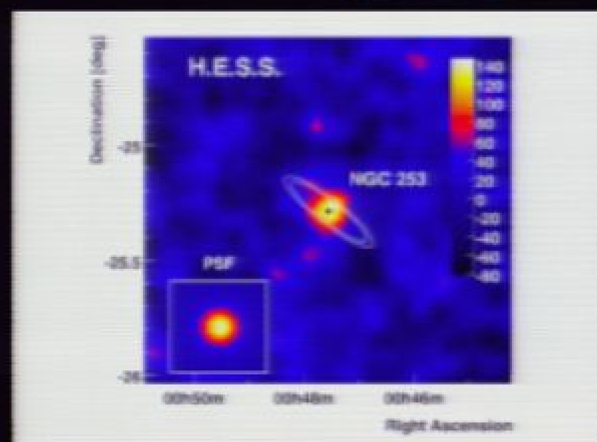
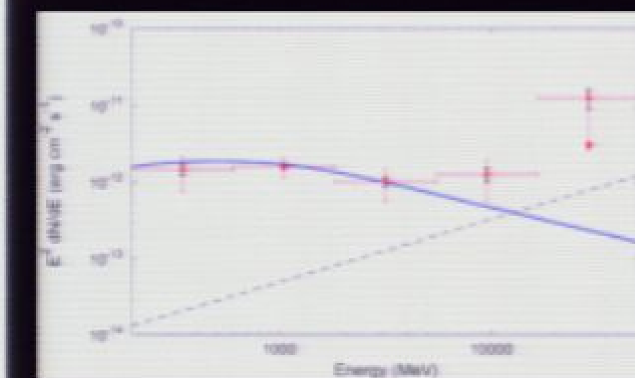
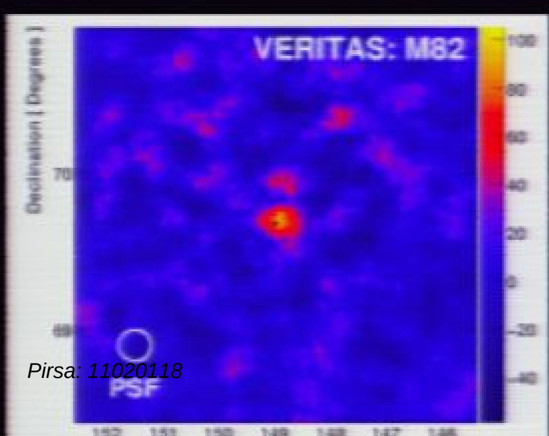
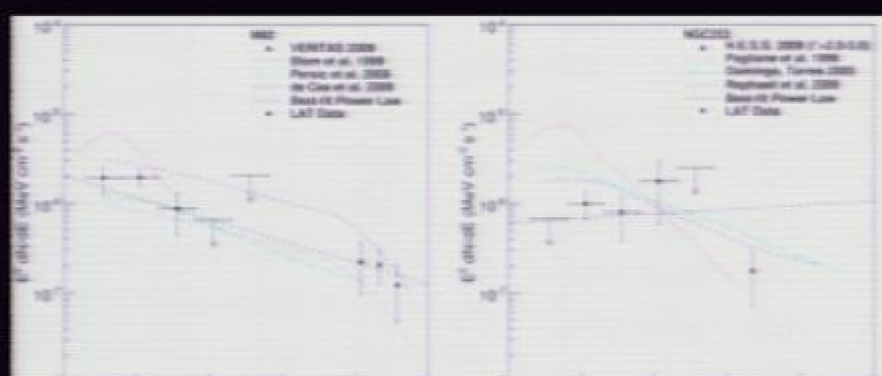


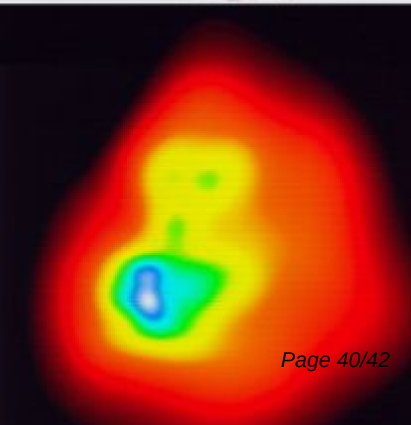






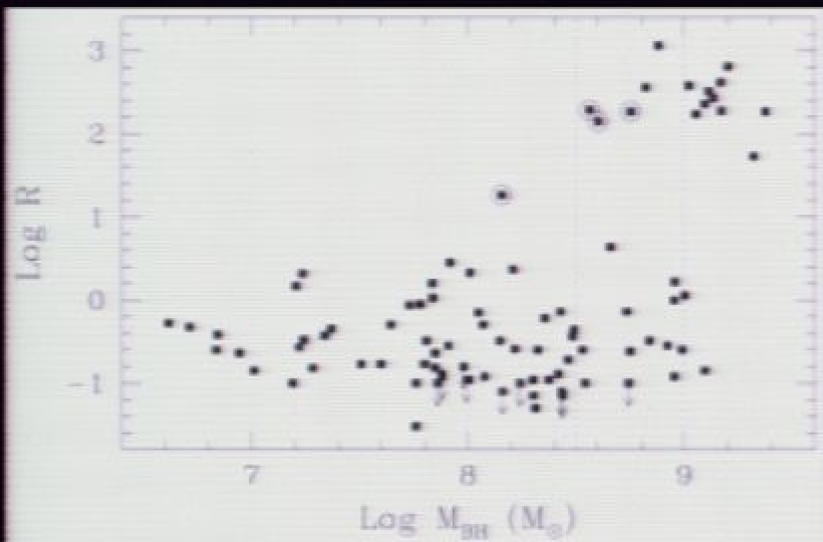


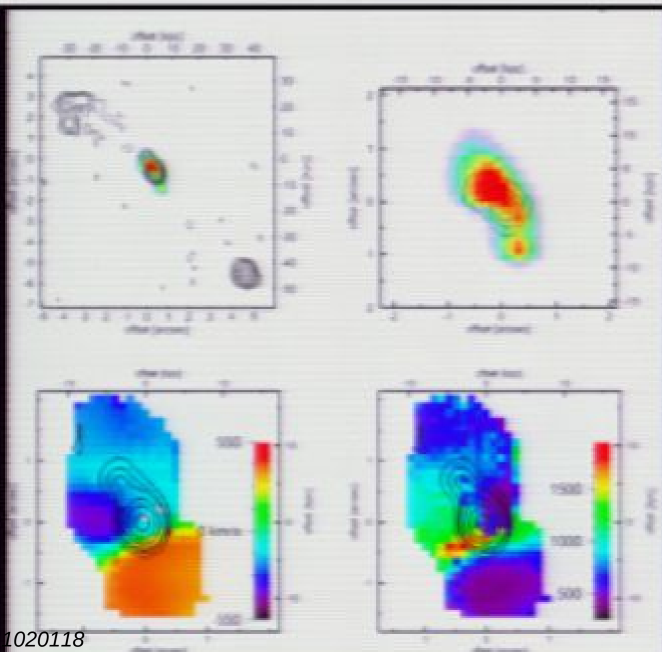




RL Quasars & Feedback

Laor 2000





Nesvadba et al 2008

$M_\bullet \xrightarrow{L_{\mathrm{Edd},es}/L_J \sim 1} L_J$

$L_J \xrightarrow{f_{esc} \propto M_\bullet^0} L_{\mathrm{CR}}$

$L_{\mathrm{CR}} \xrightarrow{\kappa_{es}/\kappa_{\mathrm{CR}}} M_\star$

$M_\star \leftrightarrow M_\bullet$

gives Magorrian relation; explains why radio loud quasars are relatively rare

Summary

- Eddington Limit in cosmic rays: gives simple feedback model for limiting brightness of galaxies and masses of BHs
- provides explanation for why galaxies are faint and why radio loud quasars are rare
- basic idea stems from small CR mean free path