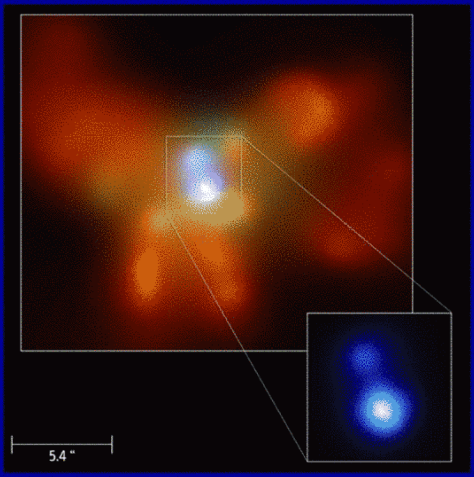
Radiation Pressure Supported Disks Writ Large

Eliot Quataert (UC Berkeley)

w/ Todd Thompson & Norm Murray

Arp 220 w/ HST



NGC 6240 w/ Chandra

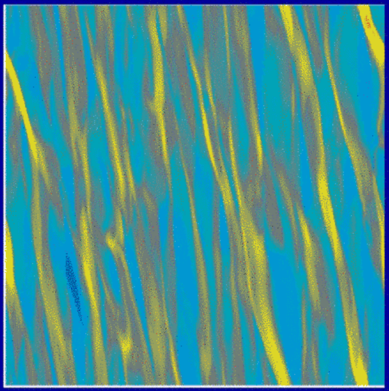
Outline

- Gravitational Instability in Galactic Disks
- Observational Context: Ultraluminous Infrared Galaxies
- Eddington-Limited Starbursts
- Inward Bound: Self-Gravity in AGN Disks
- Conclusions

Local Gravitational Instability in Disks

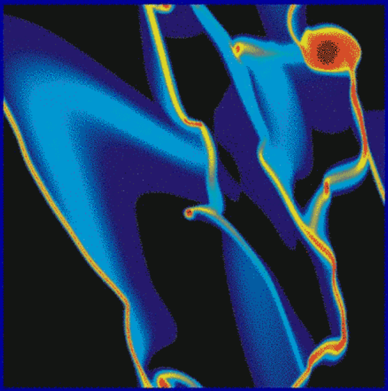
- Instability for Toomre's Q < 1: $Q \equiv \dfrac{\delta v\ \kappa}{\pi G \Sigma}$
- Nonlinear evolution depends on ability of gas to cool and contract (Shlosman et al. 1990; Gammie 2001)

$\Omega t_{cool} >> 1$: “gravitoturbulence”

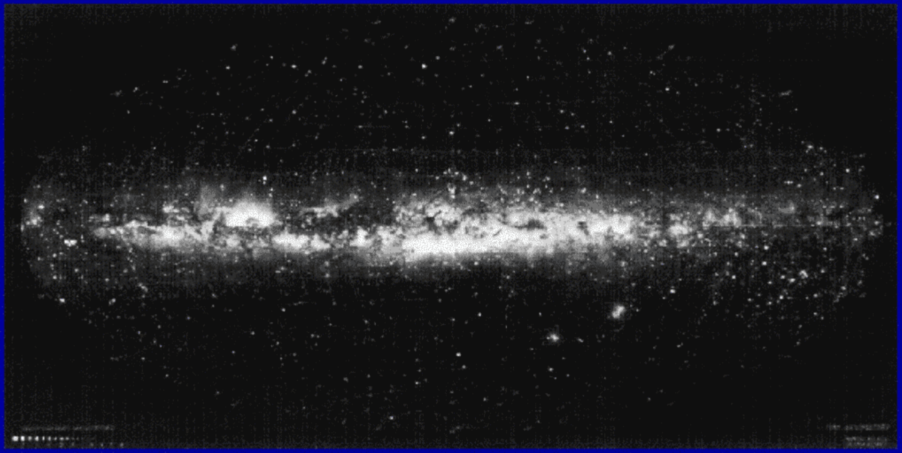


Johnson & Gammie 2003

$\Omega t_{cool} << 1$: disk fragments



Nonlinear Outcome: Galactic Disks!



Self-Regulated Disks

- Grav. Instability ⇒ Collapse on ~ Dynamical Time?

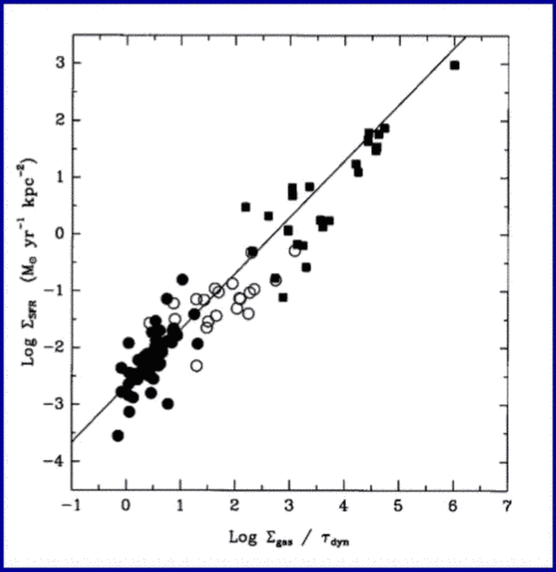
- **SFR ~ 0.02 Σ/t_{dyn}**
- **Q ~ 1 observed**

(e.g., Martin & Kennicutt 2001)

- Energy/Momentum supplied by star formation (e.g., SN, winds) may help stave off self gravity of disk and maintain Q ~ 1

- MRI may be important as well

(Sellwood & Balbus 1999; Piontek & Ostriker 2004)

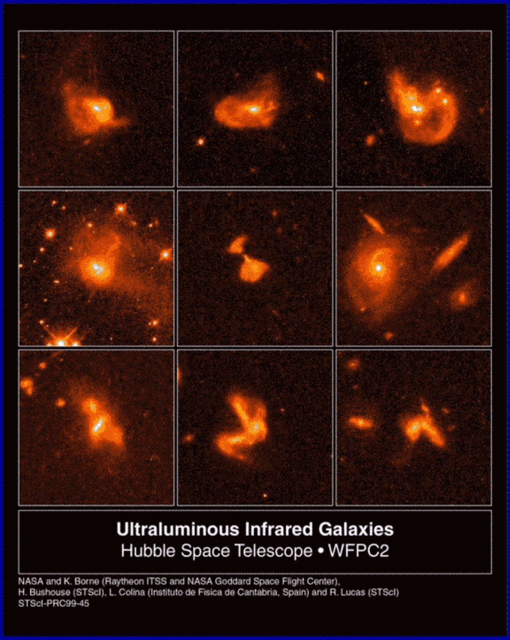


Kennicutt 1998

Ultraluminous Infrared Galaxies (ULIRGs)

- Discovered by IRAS in mid 80's
- $L_{FIR} > 10^{12} L_{\odot} >> L_{optical}$ (dusty)
- Disturbed Morphologies: Mergers
- Powered by nuclear starbursts &/or obscured AGN (much debated)
- Key Phase in Growth of Elliptical Galaxies and Massive BHs?

(e.g., Sanders et al. 1988; Kormendy & Sanders 1992)


Ultraluminous Infrared Galaxies
Hubble Space Telescope • WFPC2

NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center), H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)
STScI-PRC99-45

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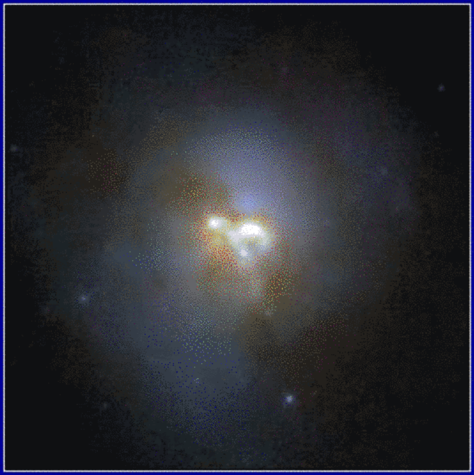
Josh Barnes

also Mihos & Hernquist 1996

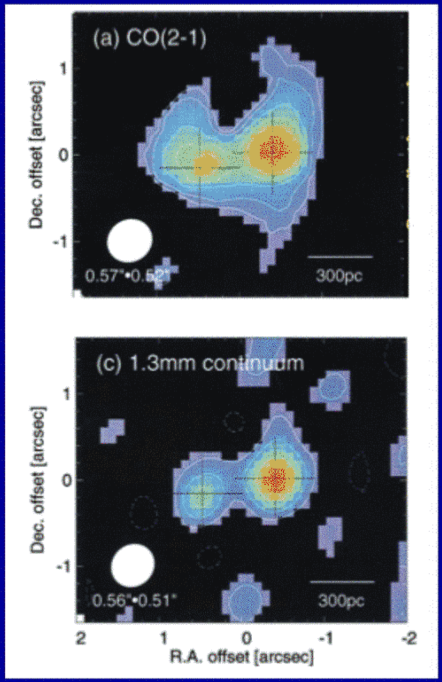
Mergers ⇒ Angular Momentum Transport ⇒ Nuclear Activity

Physical Conditions: Arp 220

HST Nicmos Image

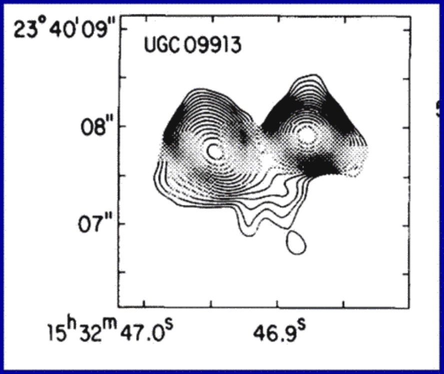


$L_{FIR} \sim 10^{12} L_\odot \sim 10^{46}$ ergs/s
Double Nuclei ~ 350 pc apart
2 ~ 100 pc scale disks with ~ $10^9 M_\odot$ gas
$\Sigma_{gas} \sim 10$ g/cm^2 ~ $4000\ \Sigma_{MW}$ ($N_H \sim 10^{25}$)
(optically thick to FIR)
$<n> \sim 10^4$ cm^{-3} vs. $<n>_{MW} \sim 1$ cm^{-3}



Sakamoto et al. 1999

Physical Conditions: Arp 220

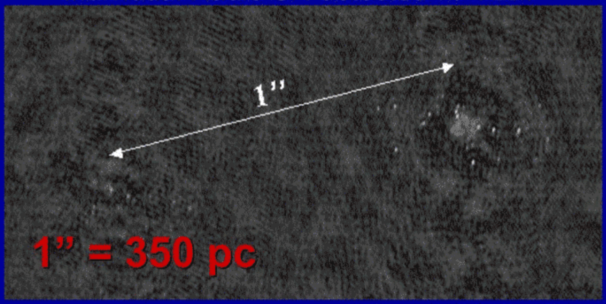


Condon et al. 1991

Radio Emission ~ on FIR-Radio Correlation + Radio SN ⇒

~ 100 pc scale starbursts with ~ 100 $M_\odot$/yr

Individual Radio SN detected w/ VLBI



Smith, Lonsdale, Diamond

The Case For Radiation Pressure

Σ, T_{eff}

$P,\ T_c,\ \dot{\Sigma}_*$

Hydro Equil: $P = \pi G \Sigma^2$

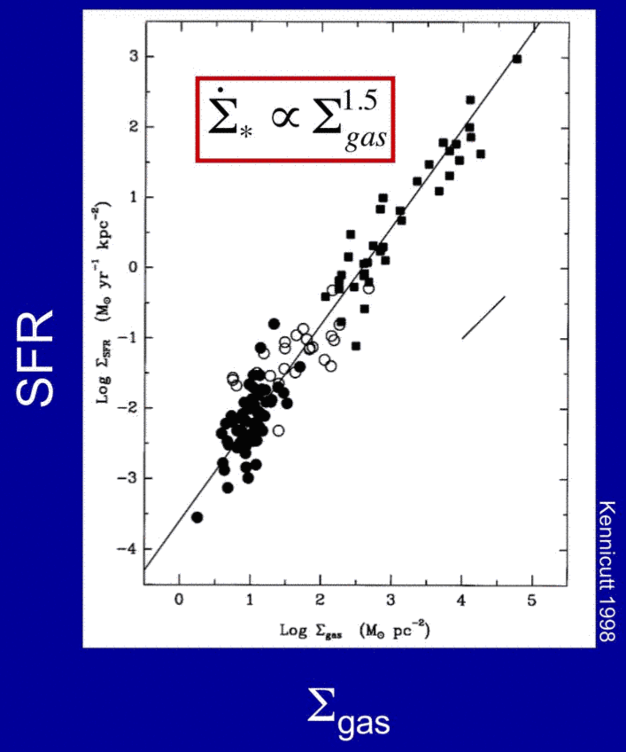
Turbulence/Pressure supplied by star formation (probably)
(e.g., in normal galaxies, SN, stellar winds, HII regions, …)

$$\tau_{IR} \sim 1 \text{ at} \sim 300 \text{ pc}$$

$$P_{rad} \approx \tau F / c \approx \tau \varepsilon \dot{\Sigma}_* c$$

$$(\text{Flux}:\ F = \varepsilon \dot{\Sigma}_* c^2)$$

The Schmidt Law



Kennicutt 1998

$$P_{hydro} = \pi G \Sigma^2$$

$$P_{rad} \propto \tau \dot{\Sigma}_* \propto \kappa \Sigma \dot{\Sigma}_*$$

$$\rightarrow P_{rad} \propto \kappa \Sigma^{2.5}$$

For sufficiently large Σ, $P_{rad} \rightarrow P_{hydro}$ & the disk reaches the Eddington limit (and the Schmidt Law breaks down)

$\Sigma \sim$ 3-5 g/cm^2

(the inner ~ few 100 pc of gas-rich starbursts)

Radiation Pressure vs. Supernovae

Radiation Pressure : $P_{rad} \approx \tau \varepsilon \dot{\Sigma}_* c$

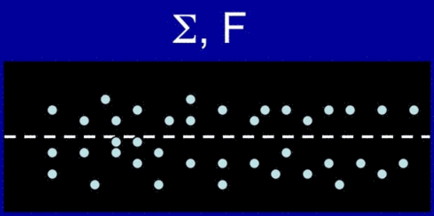
SN stirring: radiative losses are strong, but each SN supplies a momentum ~ $\xi M_{sh} v_{sh}$ to the ISM

Salpeter IMF + assuming all SN add constructively (optimistic) ⇒

$$P_{SN} \approx \xi \varepsilon \dot{\Sigma}_* c$$

Radiation Pressure Dominates SN for Optically Thick Starbursts (the inner few 100 pc of gas-rich starbursts)

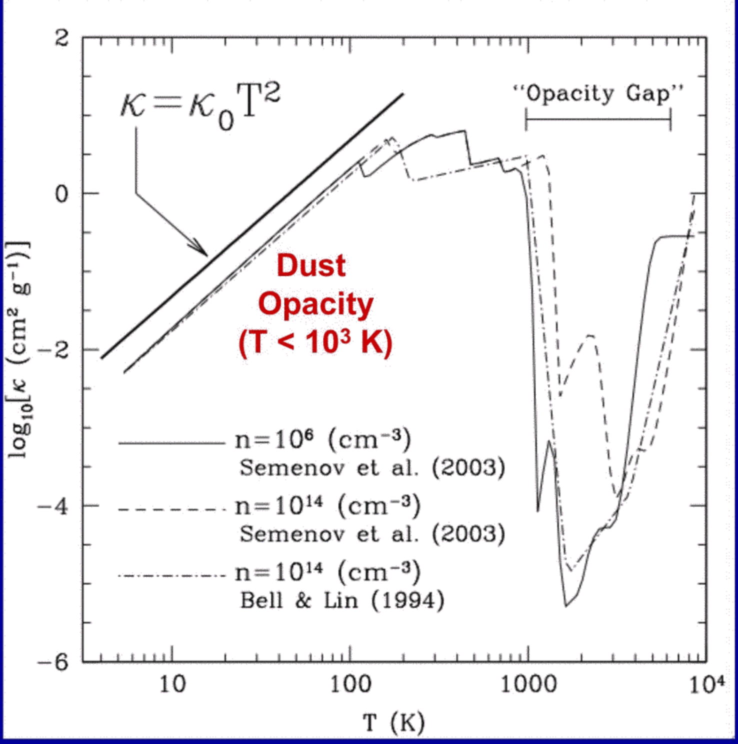
Eddington-Limited Starbursts



$$F = F_{EDD} = \frac{2\pi G \Sigma c}{\kappa}$$

$$\Rightarrow \dot{\Sigma}_* \propto \Sigma/\kappa$$

Opacity



Eddington-Limited Starbursts

$$F = F_{EDD} = \frac{2\pi G \Sigma c}{\kappa}$$

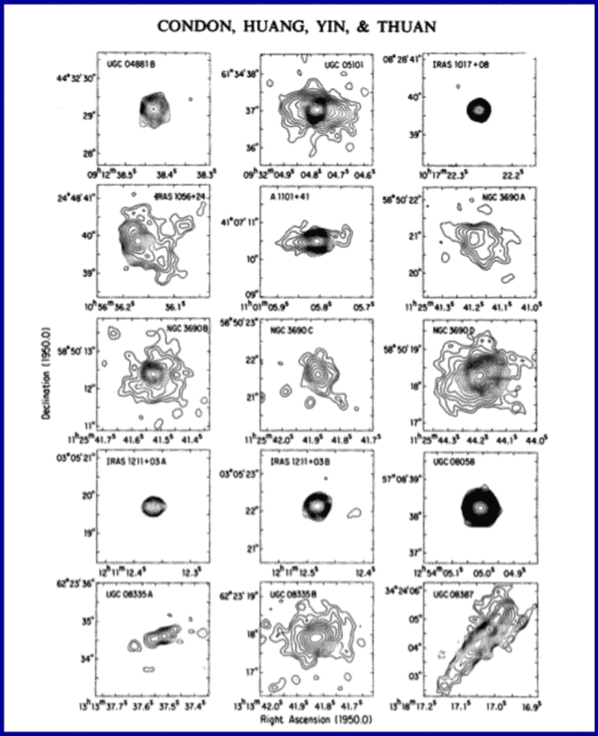
$$p_{rad} \propto T^4 \propto \Sigma^2 \;\&\; \kappa \propto T^2 \Rightarrow \kappa \propto \Sigma$$

$$\boxed{F \sim 10^{13} L_\odot \ \mathrm{kpc}^{-2}}$$

$$\boxed{\dot{\Sigma}_* \sim 10^3 M_\odot \ \mathrm{yr}^{-1} \ \mathrm{kpc}^{-2}}$$

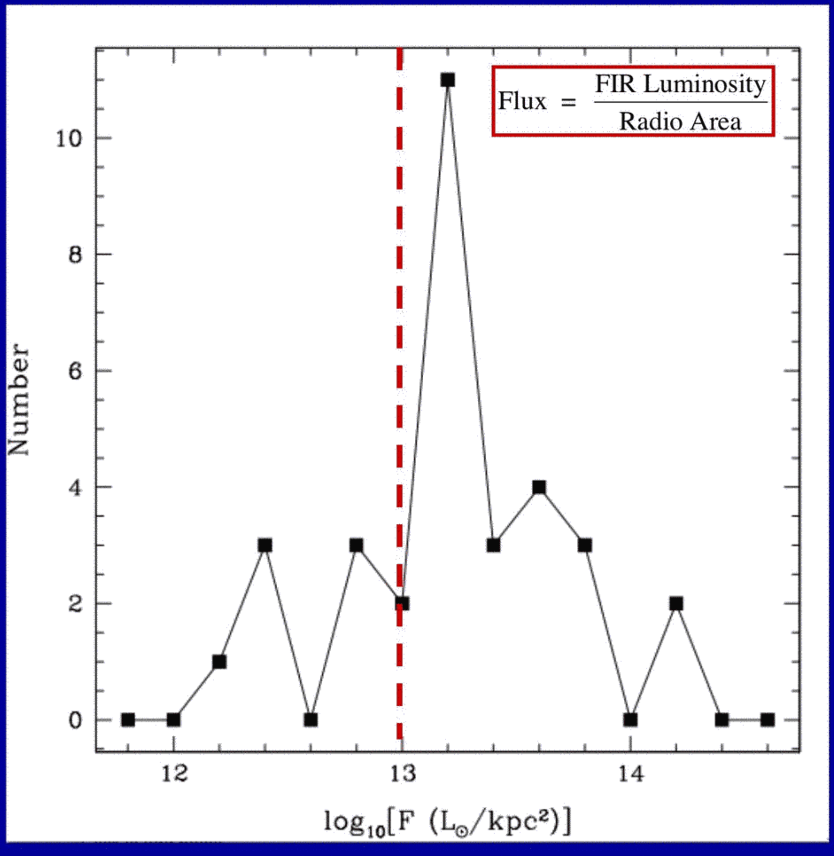
$$\boxed{T_{eff} \sim 90 \ \mathrm{K}}$$

Radio Sizes of ULIRGs ~ 100s pc



Condon et al. 1991

Number of ULIRGs vs. Inferred Flux



Radiation-Pressure Supported Starburst Disks

- $\Omega t_{diff} << 1$
  - convection unlikely to grow; photon bubbles may be important
  - MRI present but unclear if $B^2/8\pi \sim U_{rad}$
- $Q \sim 1 \;\Rightarrow\; \delta v \sim 40\ \Sigma^{1/2} M_9^{1/2} Q \text{ km s}^{-1}$
  - Consistent w/ observed random velocities ~ 50-100 km/s ~ c_{rad}
  - Significant inflow plausible …

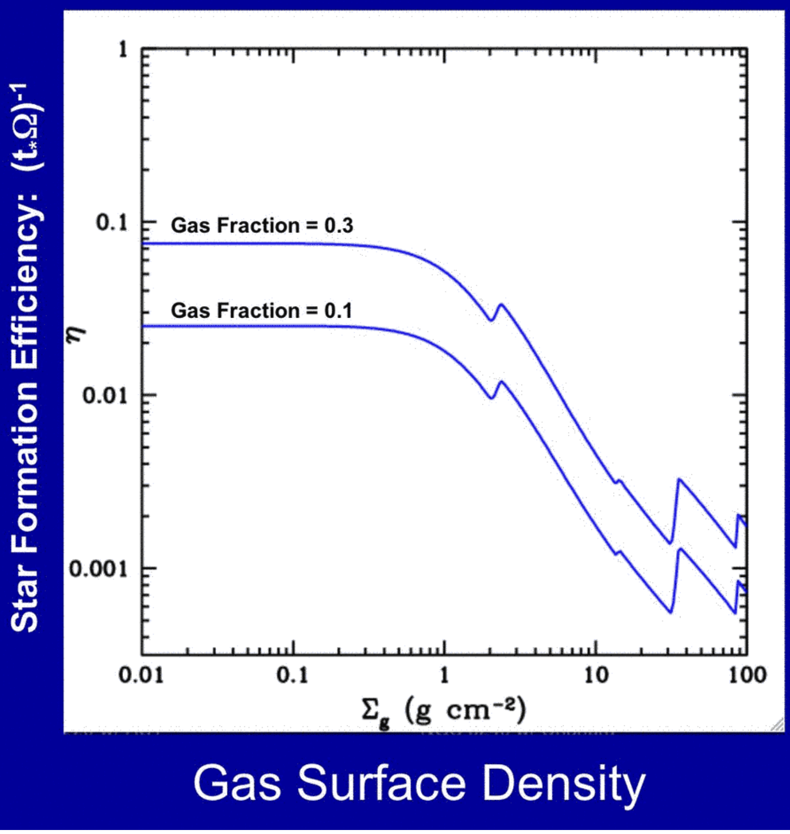
$$\dot{M}_{acc} \sim \frac{3\alpha(\delta v)^3}{G} \sim 100\alpha\left(\frac{\delta v}{50 \text{ km/s}}\right)^3 M_\odot yr^{-1} \sim \dot{M}_*$$

Inward Bound: Self Gravity in AGN Disks

- Canonical AGN Disks (e.g., Shakura & Sunyaev) are Gravitationally Unstable, with Toomre's Q << 1 outside ~ 0.01-0.1 pc
  (e.g., Shlosman & Begelman 1989; Goodman 2003)
- Fragmentation & Star Formation Plausible (Inevitable?) & Problematic
- Irradiation by the Central AGN does not appear to stabilize the disk
  (e.g., Goodman 2003)

$$Q \sim 1 \;\; \alpha\text{-Disk}: \quad t_{\rm inflow} \sim 3000 \frac{M_8}{\alpha^{1/3}\dot{M}_1^{2/3} R_{pc}} \; \Omega^{-1}$$

- $t_{\rm inflow} < t_*$ requires
  - Low Star Formation Efficiency (< 0.1% on ~ pc scales)
  - Efficient Angular Momentum Transport (spiral waves, bars, winds, etc.)
  - Really Efficient Transport: Spherical Inflow (But Dust Free)

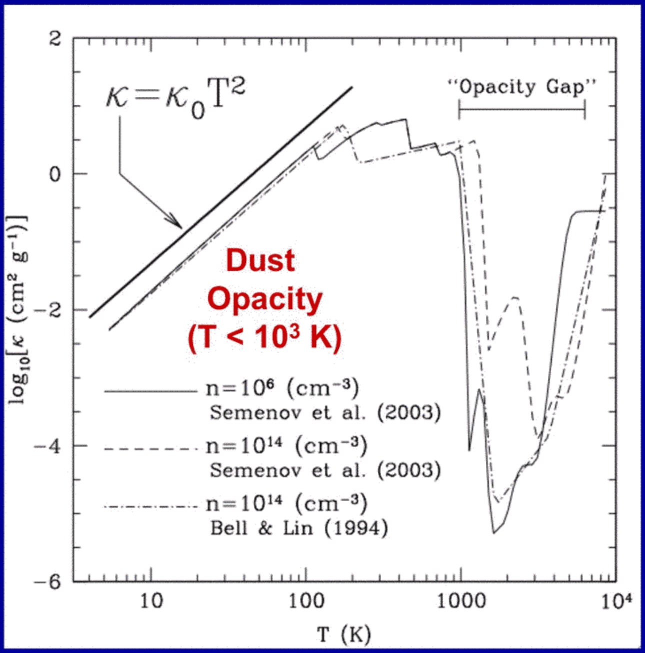


Local Disk Model

1. $Q \sim 1$
2. $P = P_{\rm rad} + P_{\rm SN}$
   (Schmidt + Eddington)

$\Rightarrow \;\; \dot{\Sigma}_*$

Opacity



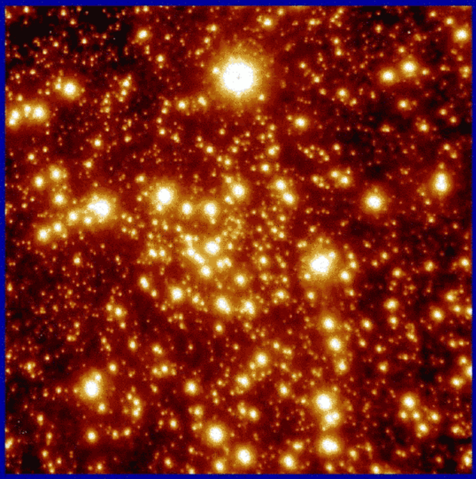
Self Gravity Particularly Problematic at T ~ 10^3 K

Radiation Pressure Support Decreases & Gas Cools Rapidly

$$R_{sub} \sim 1 \left(\frac{\dot{M}_1}{\alpha}\right)^{2/9} M_8^{1/3} \text{ pc}$$

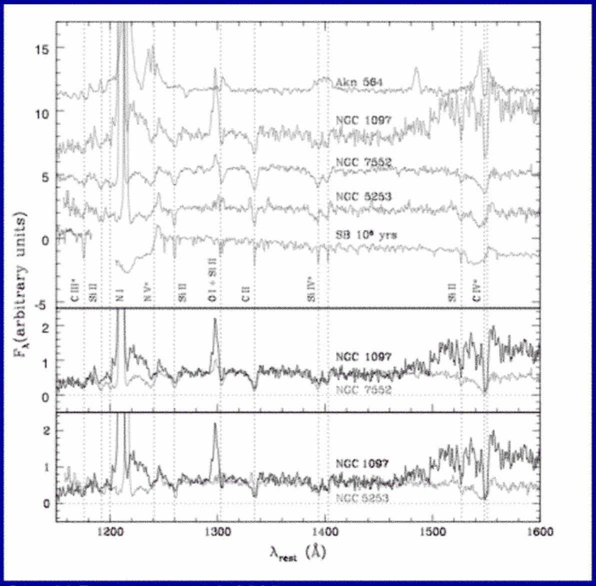
Stars Do Form Close to Massive BHs

Galactic Center



∃ Disk of Young Stars w/in ~ 0.2 pc of BH

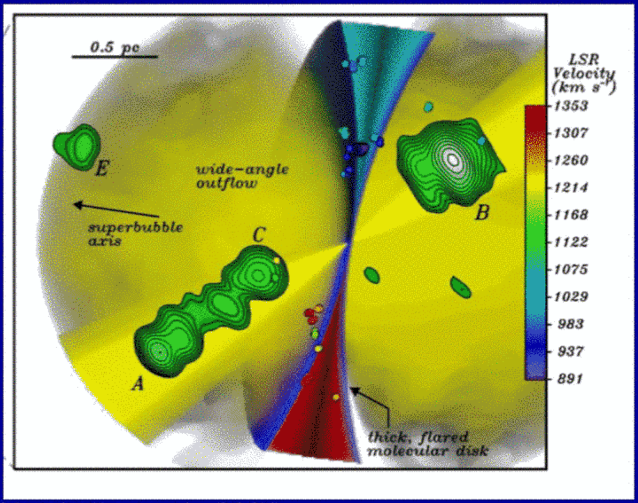
~ 10^6 $M_\odot$ starburst < 9 pc from NGC 1097



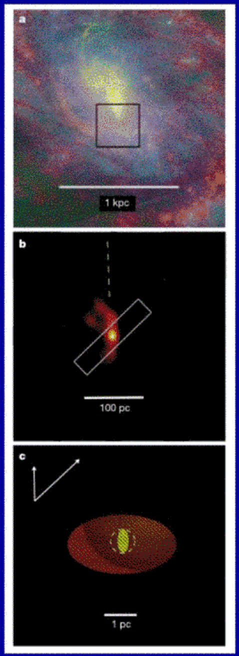
Storchi-Bergmann et al. 2005

Conjecture: Star Formation Dynamically Important in Parsec Scale AGN "Disks"?

Clumpy Self-Gravitating Masing Disk in NGC 3079



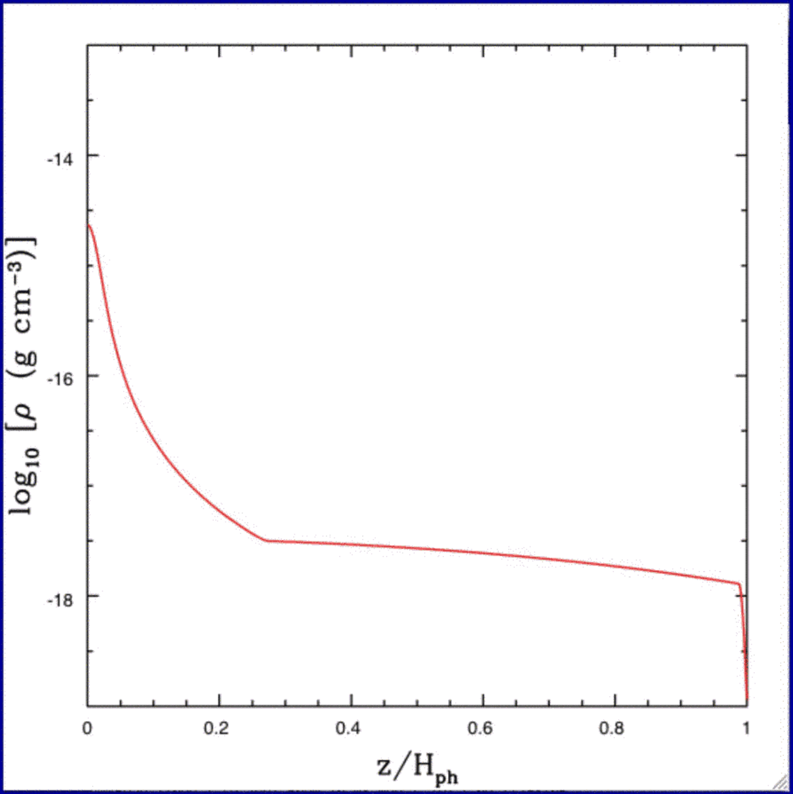
Kondratko et al. 2004



Jaffe et al. 2004

Parsec Scale "Torus"
In NGC 1068

Vertical Structure of Q ~ 1 pc scale Disk



Photosphere is extended well off the midplane

$$F = F_{EDD} = \Omega^2 cz/\kappa$$

$$\kappa_{ph} > \kappa_{mid}$$

Nuclear Obscuration (for luminous AGN)?

Conclusions

- Radiation Pressure Regulated Starbursts in the Inner ~ 100 pc of Galactic Nuclei
  - Radiation Pressure from Massive Stars Dominates Other Sources of Stellar “Feedback”
  - Good Agreement w/ ULIRGS: **$F \sim 10^{13}\, L_\odot\, \mathrm{kpc}^{-2}$**
  - Interesting analogies to Shakura & Sunyaev Radiation Dominated Disks (e.g., photon bubble?)
  - Outer Boundary Condition for BH Fueling/Growth?

- Self Gravity Problematic Down to ~ 0.1 pc in AGN Disks
  - Fueling a central AGN requires low star formation efficiency and rapid inflow ⇠◆
  - Particularly problematic at $T \sim 10^3$ K, $R \sim$ pc
  - Star Formation may play a role in ~ pc scale phenomonology of AGN (masers, torus, …)