Radiation Pressure
and
Turbulence
in AGN Tori

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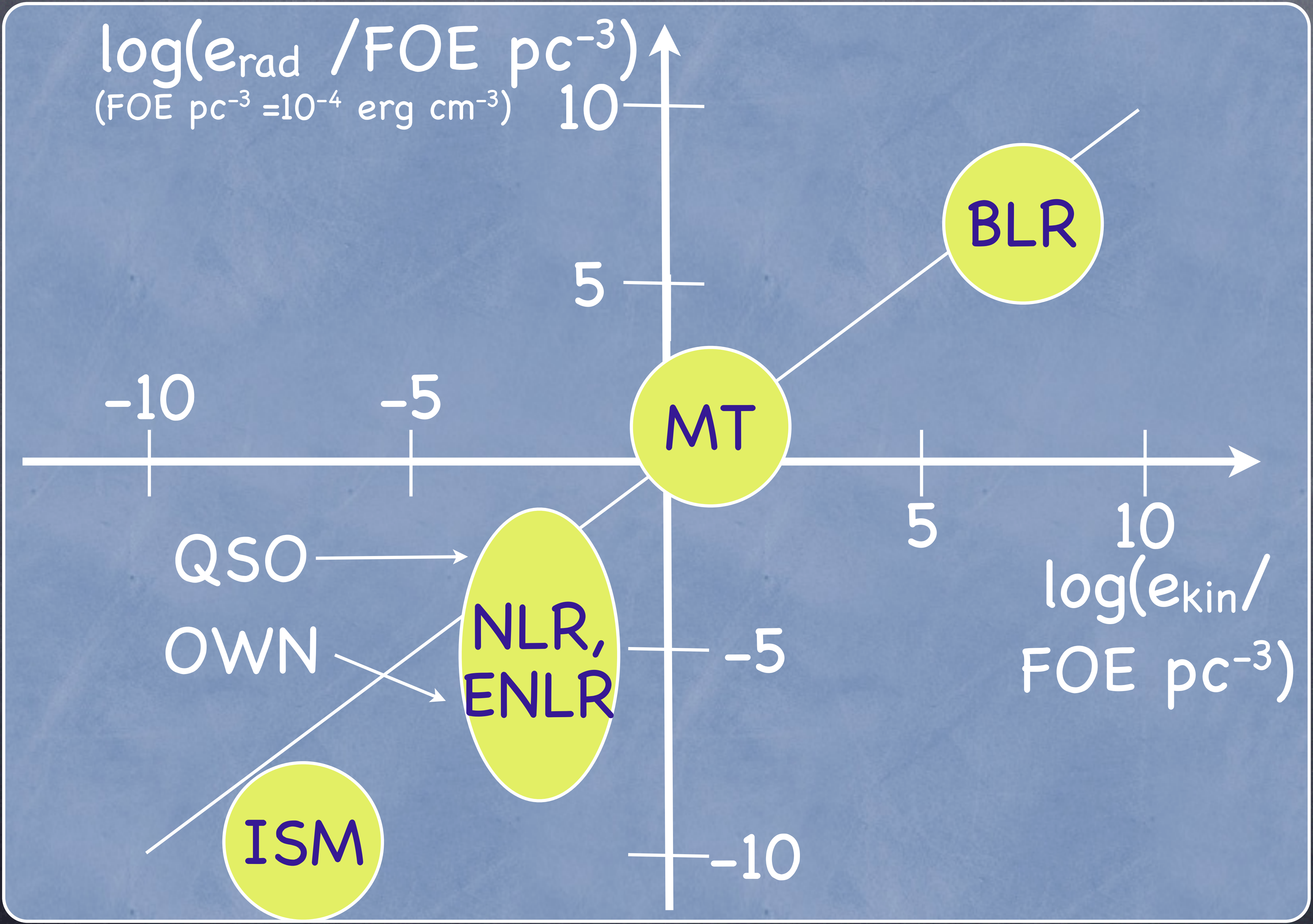
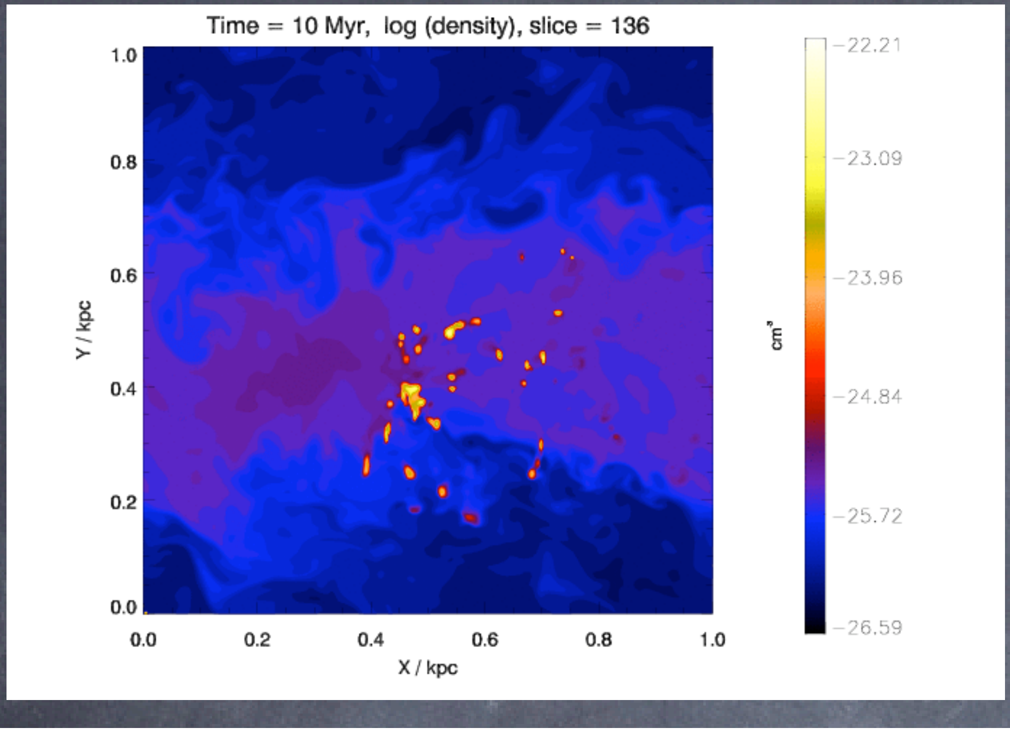
Overview

- Radiative and kinetic energy in the ISM
- The literature
  - the geometrical thickness problem
  - the importance of radiation pressure
- A toy model for radiative interactions
  - enhanced elasticity
  - radiatively driven turbulence

Multi-phase turbulence: radiative versus kinetic

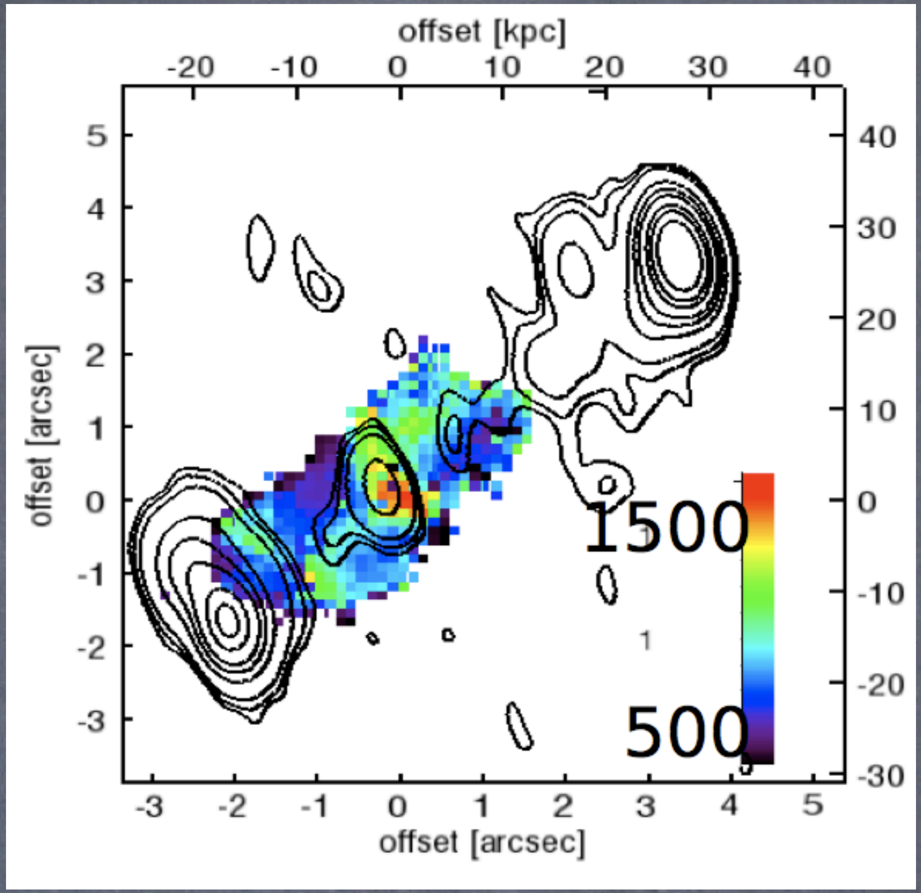


Extended Narrow Line Regions



Simulation:
- hydro (grid) + o.thin cooling
- contains all three phases (rel., hot, cold)
- e.g. Krause & Alexander 2007

Results:
- EL-gas survives stirring
- Phase equilibrium depends on energy in box
- Decay due to shocks/radiation

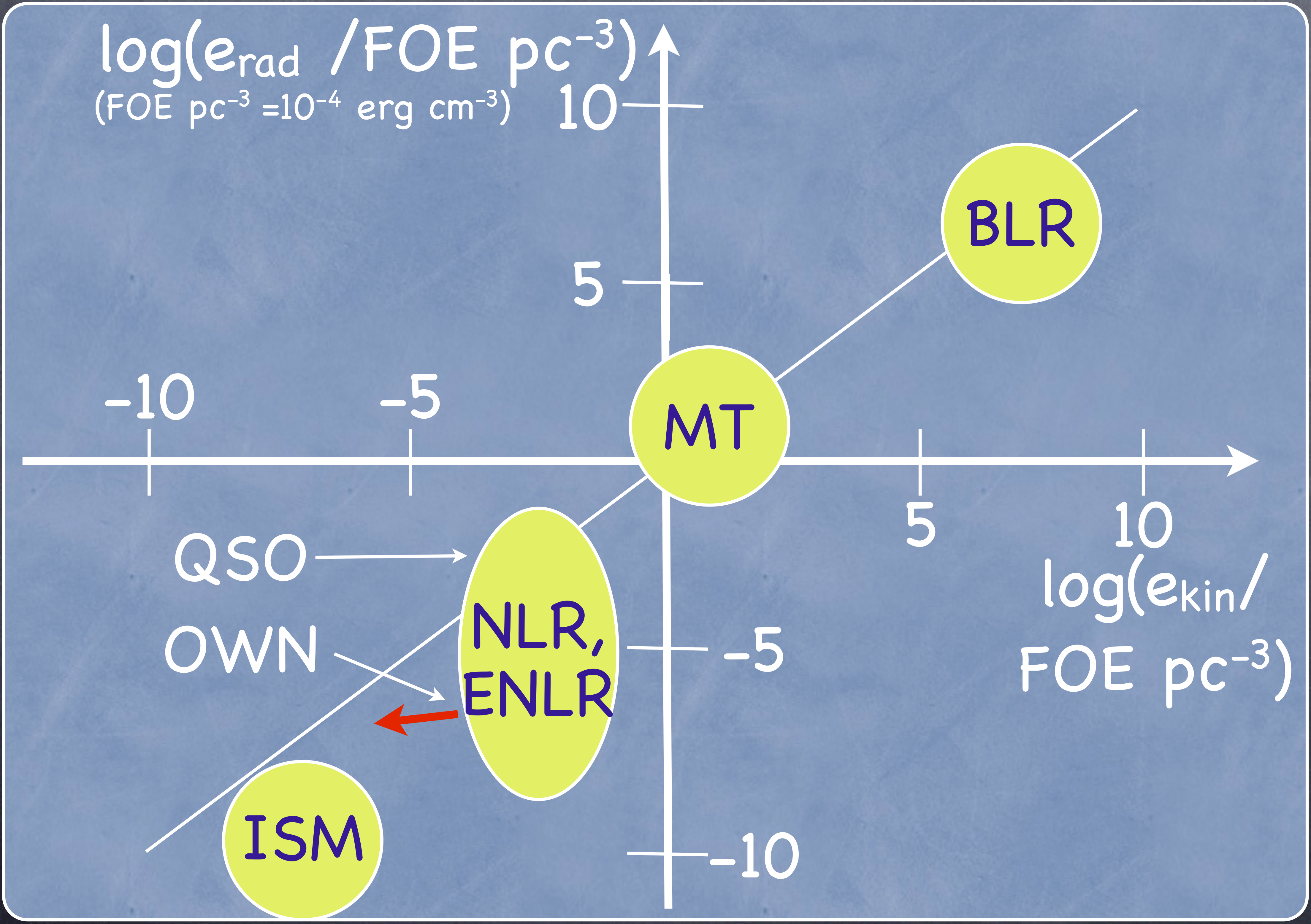


0406-242: z=2.4, [OIII], Hβ, >10^{10} M☉, v≈1000 km/s (Nesvadba et al. 2008)

- massive star forming galaxies at z = 2-5
- gas expelled permanently by jet feedback
- Radiative decay, 100 Myr

Evolves towards equilibrium, i.e. produces radiation by reducing turbulent energy

Multi-phase turbulence: radiative versus kinetic



Geometry known: example: NGC 1068

- IR interferometry
- size: 1pc
- shape: torus
- hot interior
- cooler outskirts

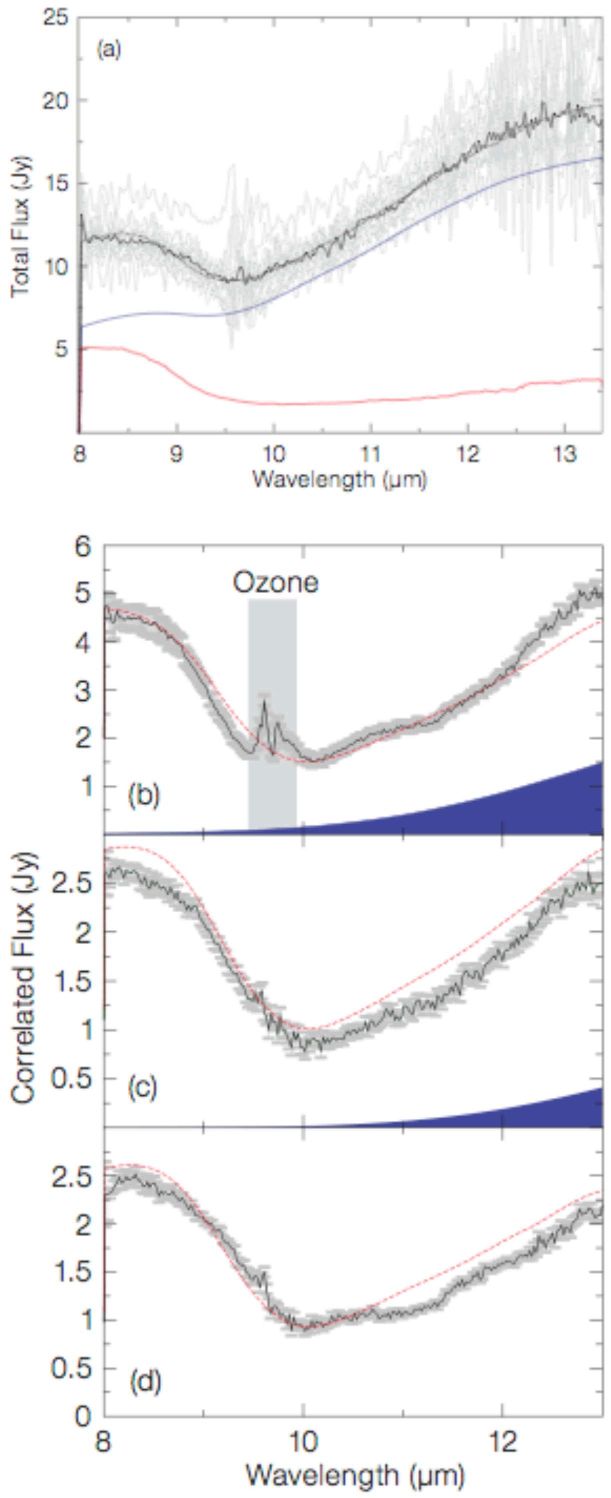


Figure 1. Results of MIDI observations of NGC 1068. (a) Total flux $F_{tot}(\lambda)$: the contribution of the hot component is shown in red, that of the extended component in blue. (b) Correlated flux $F_{corr}(\lambda)$ obtained with a 40-m baseline orientated along position angle P. A. = 36°. The red dotted line gives the model fit and the blue shaded area shows the contribution of the extended component. (c) $F_{corr}(\lambda)$ for 52 m baseline along P. A. = 112°. (d) $F_{corr}(\lambda)$ for 97 m baseline along P. A. = 36°. The comparison between (b) and (c) shows that the hot component is more extended (better resolved) in SE–NW direction.

← Meisenheimer et al. 2008 →

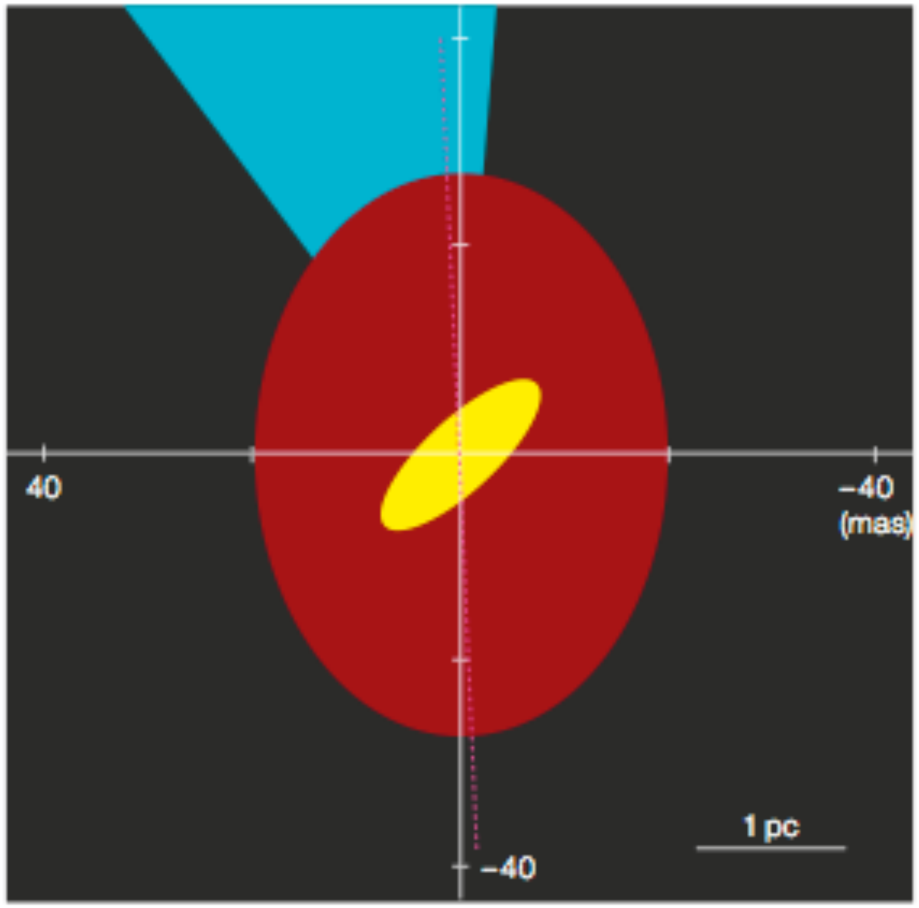


Figure 2. Observational model of the dust torus in NGC 1068. A hot component (yellow) is embedded in an extended cooler component (brown). The orientation of the radio axis is indicated by a purple dotted line and the blue wedge gives the opening angle of the ionisation cone, observed on 100-pc scales.

The literature

- Krolik & Begelman 1988
  - obs: h/r≈0.7 & dust, => v≈100km/s, if thermal => no dust, => clumpy
  - inner edge: sublimation radius
  - cloud merger & tidal shear => cov.fac.>≈1, size dist., N≈10^{24} cm^{-2} @ Jeans limit
  - accretion due to cloud-cloud collisions => reduces scale height => thin disc
  - stirring by stellar processes not enough
  - suggestion: ellastic clouds, i.e there are no hard collisions, due to magnetic fields

The literature

- Beckert & Duschl 2004
  - accretion torus model, viscosity due to cloud-cloud collisions
  - relies on magnetic field model to produce sufficient vertical turbulence
- Hönig & Beckert 2007
  - Expands BD04: direct UV radiation pressure on torus clouds
  - consistent with $\theta \propto 1/L$ (receeding torus model)
  - still imply magnetic clouds to isotropize motions

The literature

- Pier & Krolik 1992
  - radiation pressure dominates over central gravity in the hot dust region
  - fluctuating part of radiation force might drive turbulence
- Krolik 2007, Shi & Krolik 2008
  - magnetic cloud model: “required field strenghts are not terribly plausible”
  - self-consistent solutions, IR-radiation pressure supported torus
- Krolik et al 2007, Blaes et al 2007
  - MRI turbulent disk increase scale height by radiation pressure

May the radiation force drive turbulence or make the clouds elastic?

- toy model -

A nice new formalism: radiative potential

$$\mathbf{F}_{\mathrm{ij}} = \frac{L_{\mathrm{j}}}{4\pi r_{\mathrm{ij}}^2 c} \pi R_{\mathrm{i}}^2 \mathbf{e}_{\mathrm{ij}},$$

$$\tilde{m}_{\mathrm{i}} = \sqrt{\frac{\pi\sigma}{cG}} T^2 R_{\mathrm{i}}^2,$$

$$\mathbf{F}_{\mathrm{ij}} = G \frac{\tilde{m}_{\mathrm{i}} \tilde{m}_{\mathrm{j}}}{r_{\mathrm{ij}}^2} \mathbf{e}_{\mathrm{ij}},$$

$$E_{\mathrm{pot}} = G \frac{\tilde{m}_{\mathrm{i}} \tilde{m}_{\mathrm{j}}}{r_{\mathrm{ij}}^2}.$$

- two clouds i,j
- force $\propto 1/r^2$
- introduce radiative mass
- symmetric material properties
- here: optically thick
- analogy: gravity

Two cloud system (uniform clouds)

$$\frac{1}{2} m v_{\mathrm{c}}^2 = G\frac{\tilde{m}\tilde{m}}{R}$$

$$\begin{aligned}\frac{\tilde{m}}{m} &= \frac{3}{4}\sqrt{\frac{\sigma}{\pi c G}\frac{T^2}{\rho R}} \\ &= 2,300\left(\frac{T}{1000\,\mathrm{K}}\right)^2\left(\frac{\rho}{10^{-17}\,\mathrm{g\,cm^{-3}}}\right)^{-1}\left(\frac{R}{10^{-3}\,\mathrm{pc}}\right)^{-1}\end{aligned}$$

$$\begin{aligned}v_{\mathrm{c}} &= \sqrt{\frac{3\sigma}{2c}\frac{T^2}{\rho^{1/2}}} \\ &= 168\,\mathrm{km\,s^{-1}}\left(\frac{T}{1000\,\mathrm{K}}\right)^2\left(\frac{\rho}{10^{-17}\,\mathrm{g\,cm^{-3}}}\right)^{-1/2}\end{aligned}$$

- clouds need high T => radiative > gravitational mass
- approaching clouds bounce like protons
- **require $v > v_c$ for direkt hit**

Optically thick cloud ensemble

$$\lambda n_{\rm cl} \pi R^2 = 1,$$

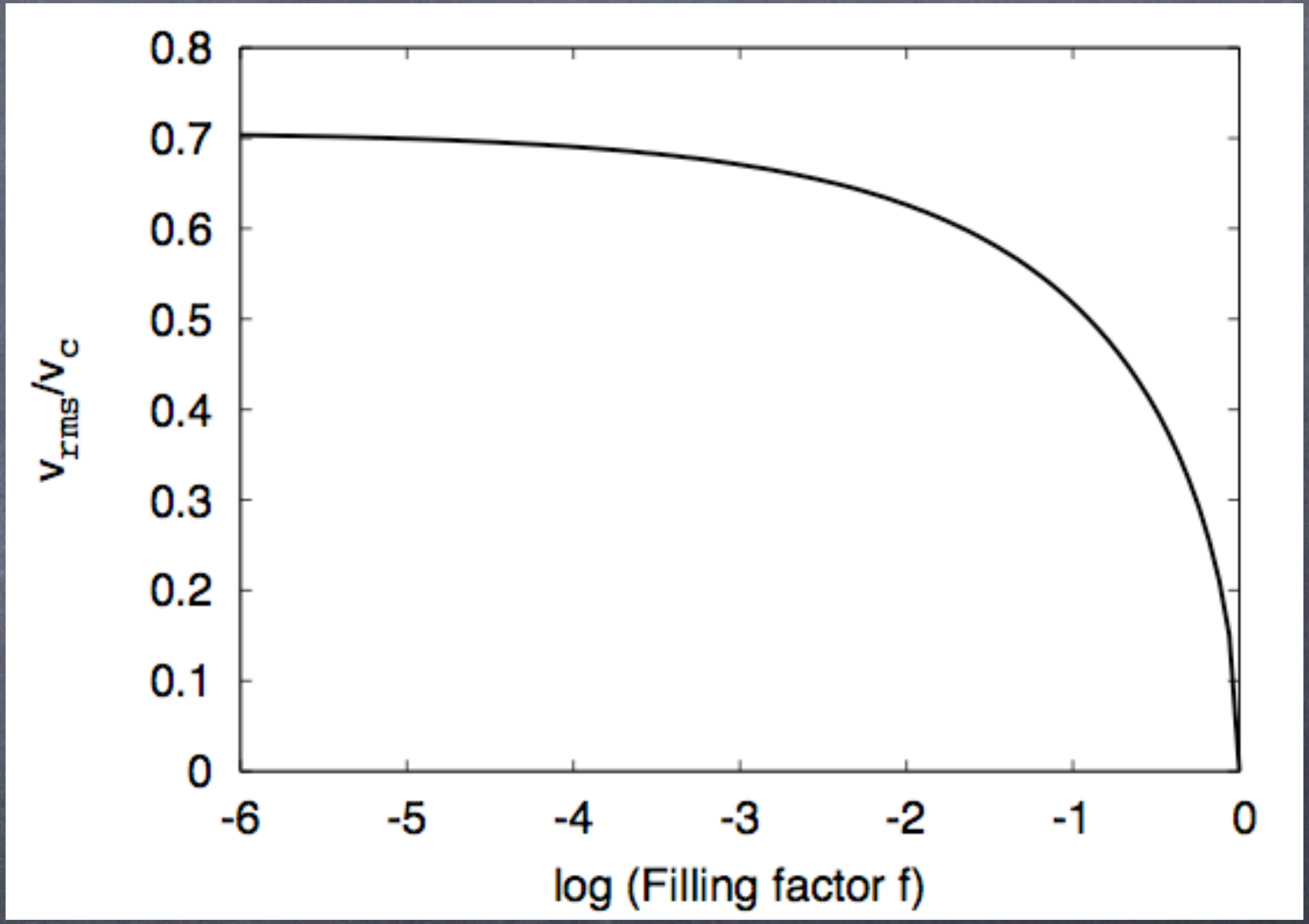
$$N = n_{\rm cl} (4/3) \pi \lambda^3 = (4/3)^3 f^{-2},$$

$$E_{\rm pot}(r) = \int_0^\infty G \frac{\tilde{\rho}(r') 4\pi r'^2 dr'}{(r - r')^2}$$

- Define horizon λ (=mean free path)
- filling factor f small (clumpy) => number of clouds within λ is large
- all clouds within sphere (λ) interact with origin
- may define radiative mass density
- From shell potential, force within smooth shells = 0

Optically thick cloud ensemble

- Two body interactions dominate
- Shadow effects negligible =>> Radiation force is conservative
- Virial theorem: 2T=ΔE
- =>> $v_{\mathrm{rms}} = \sqrt{\frac{1-f^{1/3}}{2}}\, v_{\mathrm{c}}$



$$\Delta E = G\tilde{m}^2\left(\frac{1}{R}-\frac{1}{\bar{d}}\right) = G\frac{\tilde{m}^2}{R}(1-f^{1/3})$$

Other cloud types

- Easily find cloud parameters where radiation dominates over cloud gravity
- All examined cloud models in principle permit rms-velocities > 100 km/s @ T(dust) = 1000K
- Opt. thin dusty clouds unstable against own radiation pressure @ T> 30K

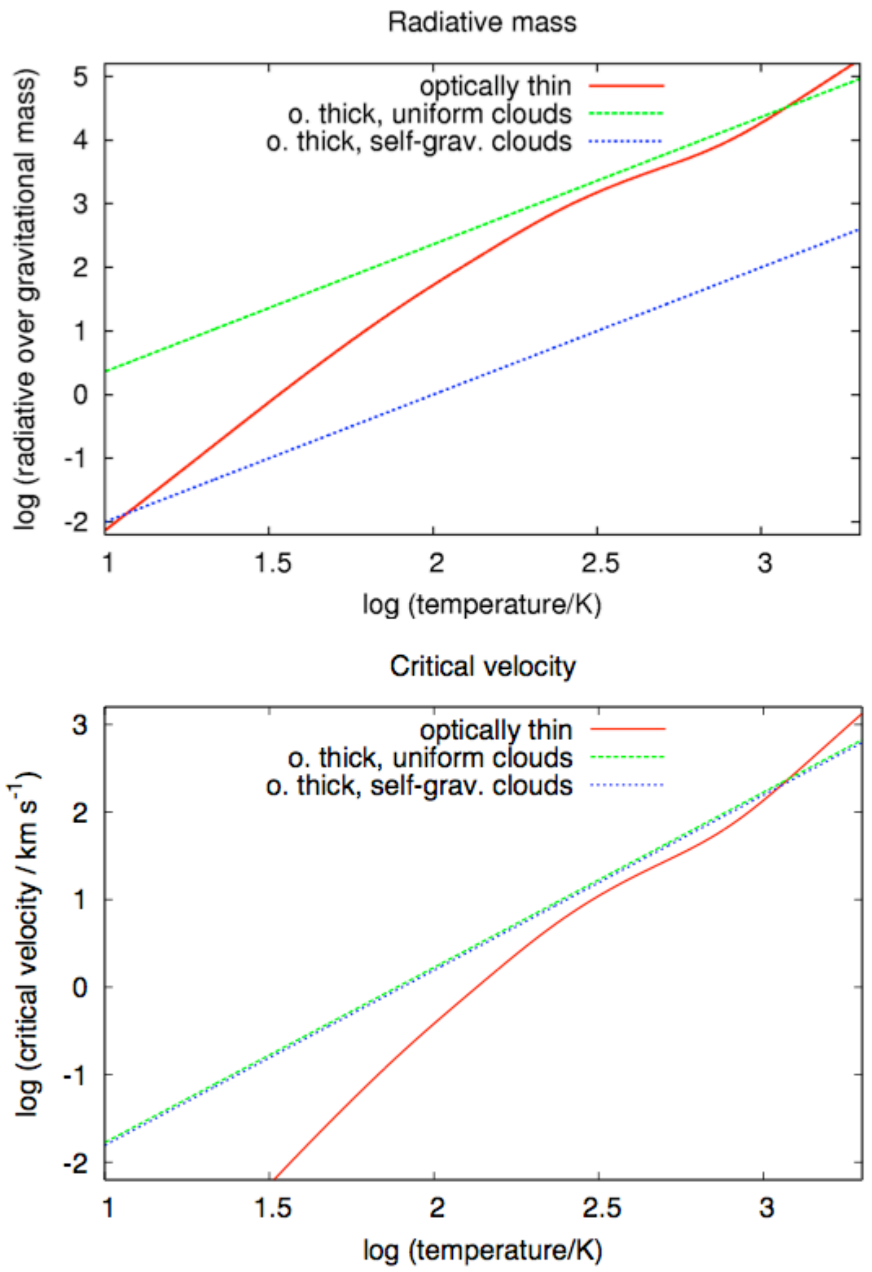


Figure 2. Radiative mass and critical velocity for reference clouds (uniform optically thick: $R = 10^{-3}$ pc, $\rho = 10^{-17}$ g cm^{-3}, self-gravitating optically thick: $R = 2 \times 10^{-2}$ pc, $c_s = 1$ km s^{-1}, optically thin: $R = 10^{-2}$ pc, $\rho = 10^{-21}$ g cm^{-3}).

Conclusions

- Rarely find $E_{rad} > E_{kin}$
- In torus & BLR: $E_{rad} \approx E_{kin}$
- In BLR radiation pressure thought to be important
- Presented toy model of fluctuating radiation force
- For reasonable cloud parameters, find
    - enhanced elasticity
    - turbulence > 100 km/s

acloud = 0.001pc
rho = 3.e-17 g/cm^3
Tsub = 1000K
Mbh = 7.9d6 Msun
eddratio = 0.005
n_clouds = 5000