The characteristic sizes of individual broad and narrow line region clouds

Torus 2018 @ Puerto Varas, Chile

Tim Waters

Postdoc, Theoretical Division

waters@lanl.gov

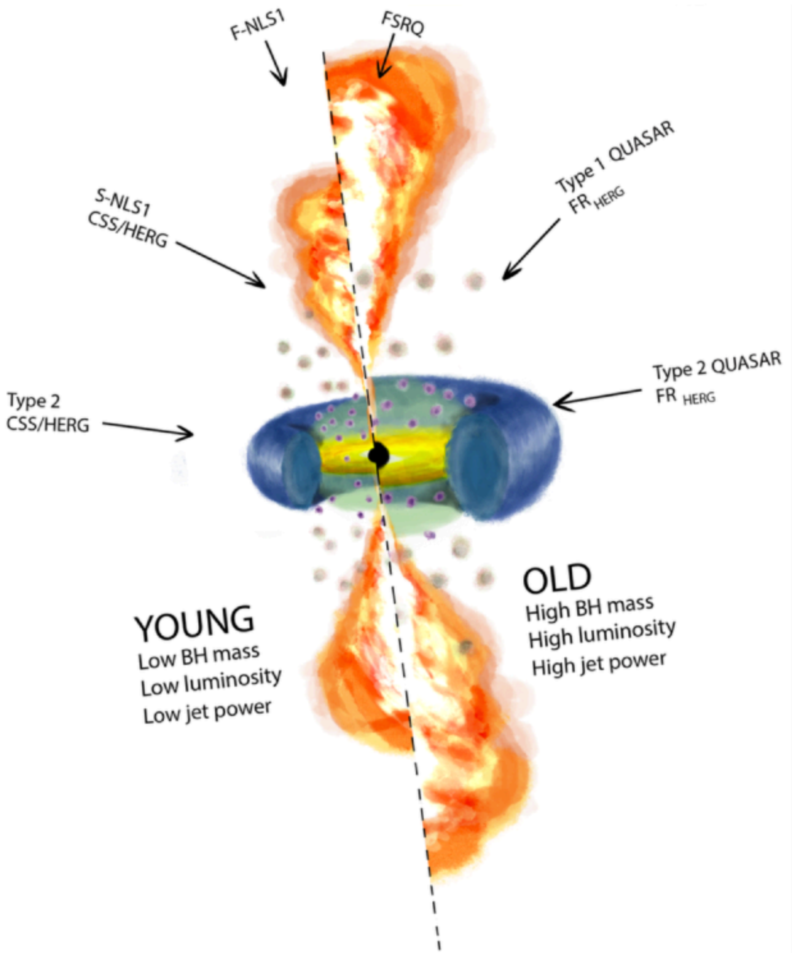
Los Alamos NATIONAL LABORATORY EST. 1943

Ongoing TI project collaborators:

D. Proga (UNLV)
R. Dannen (UNLV)
H. Li (LANL)
J. Johnson (LANL)
S. Dyda (Cambridge)
Y. Jiang (UCSB)
S. Davis (Virginia)
J. Stone (Princeton)

Outline

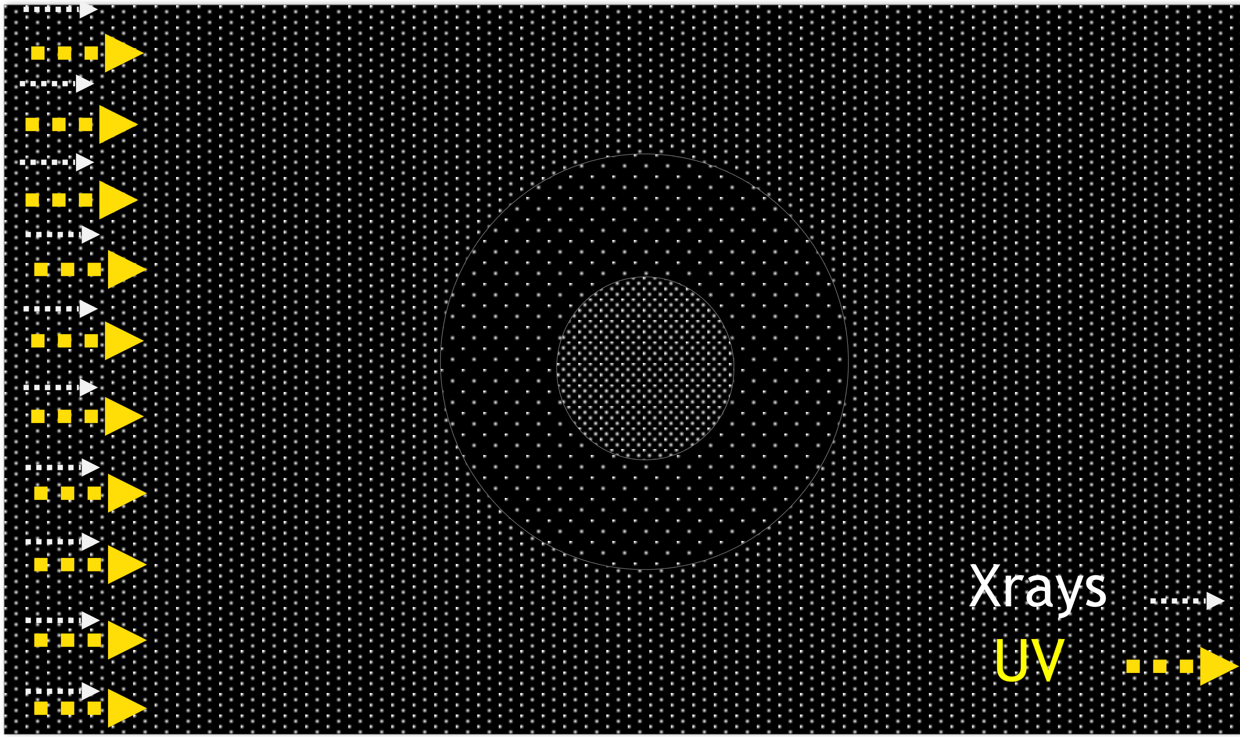
- Review of thermal instability (TI) as the basic mechanism to form AGN clouds
- Distinguishing the isobaric and non-isobaric regimes of TI
  - $\lambda_F < d_c < \lambda_{th}$ vs. $\lambda_{th} < d_c < \lambda_J$
- The crucial role played by turbulence in determining the final characteristic cloud sizes



from Berton et al. (2017)

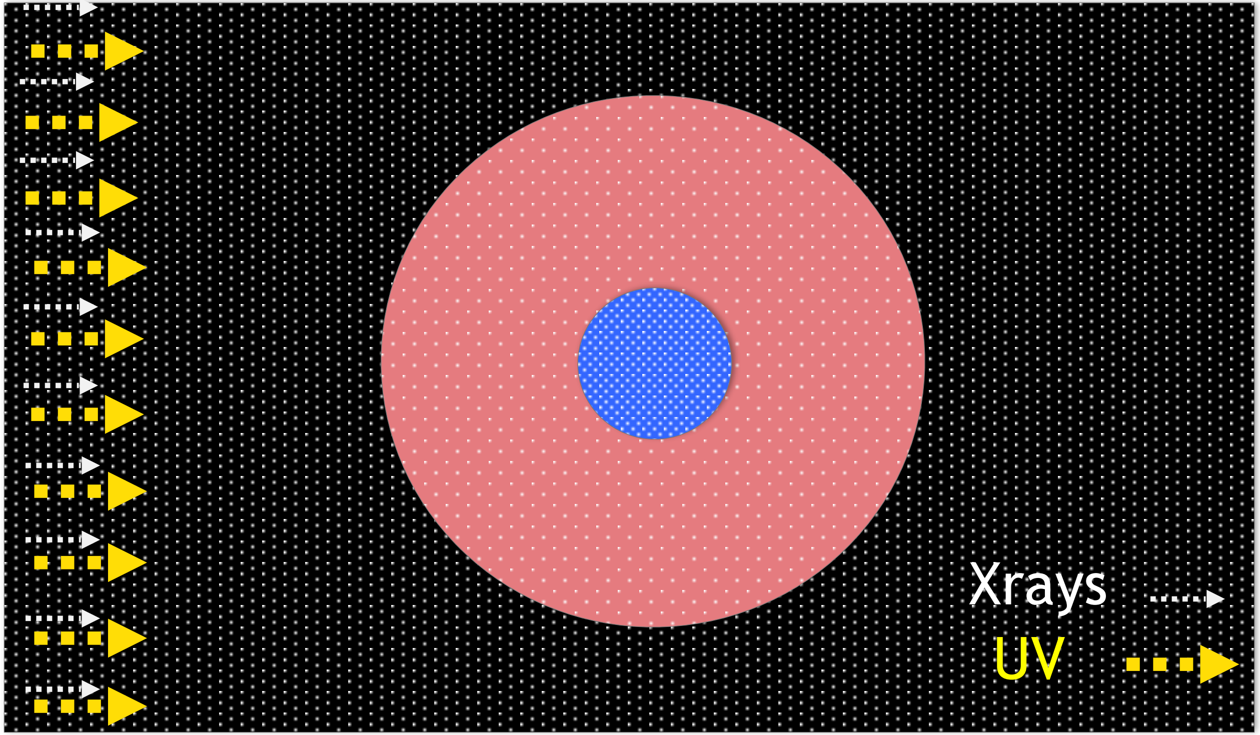
Review of TI: the linear isobaric regime

Saturation of TI is a cloud formation process,
but it also naturally leads to <u>cloud acceleration</u> (PW15).



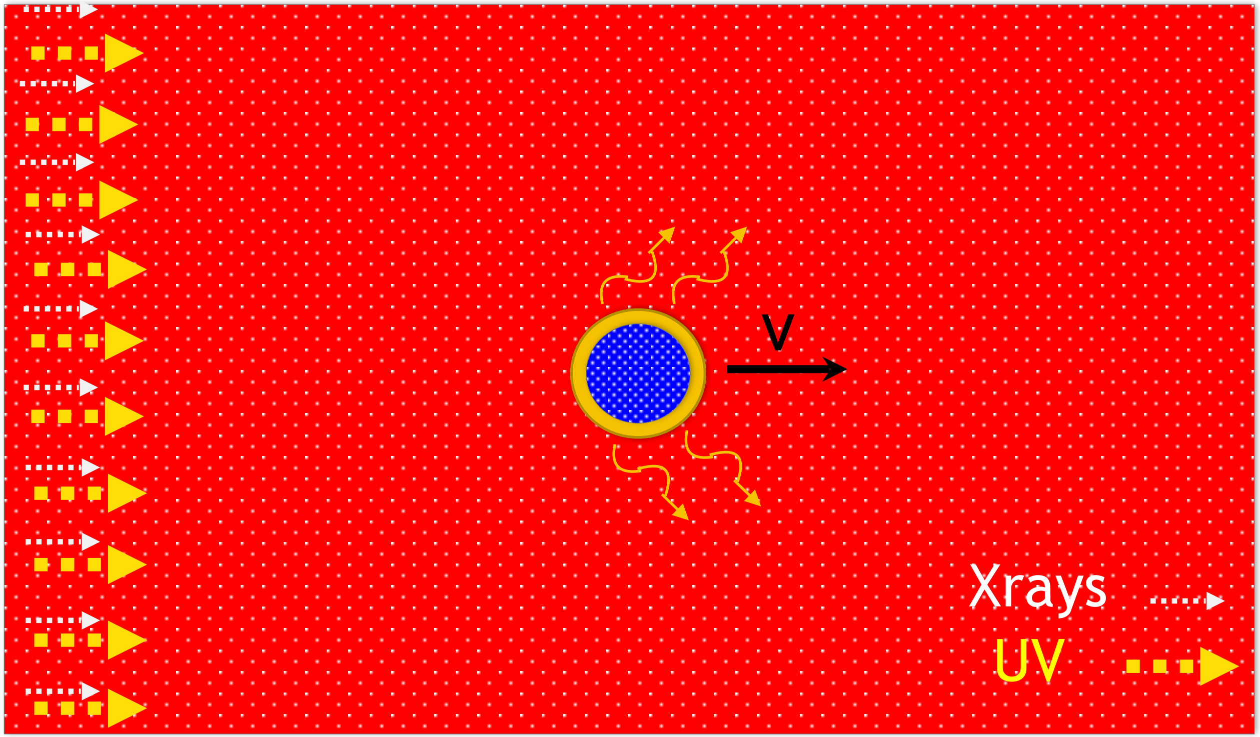
Review of TI: the linear isobaric regime

Saturation of TI is a cloud formation process,
but it also naturally leads to cloud acceleration (PW15).



Review of TI: the nonlinear isobaric regime

Saturation of TI is a cloud formation process,
but it also naturally leads to cloud acceleration (PW15).



AGN H/C rates and radiation forces

Start with the best-fit SED. Here is NGC 5548's (Mehdipour et al. 2015):

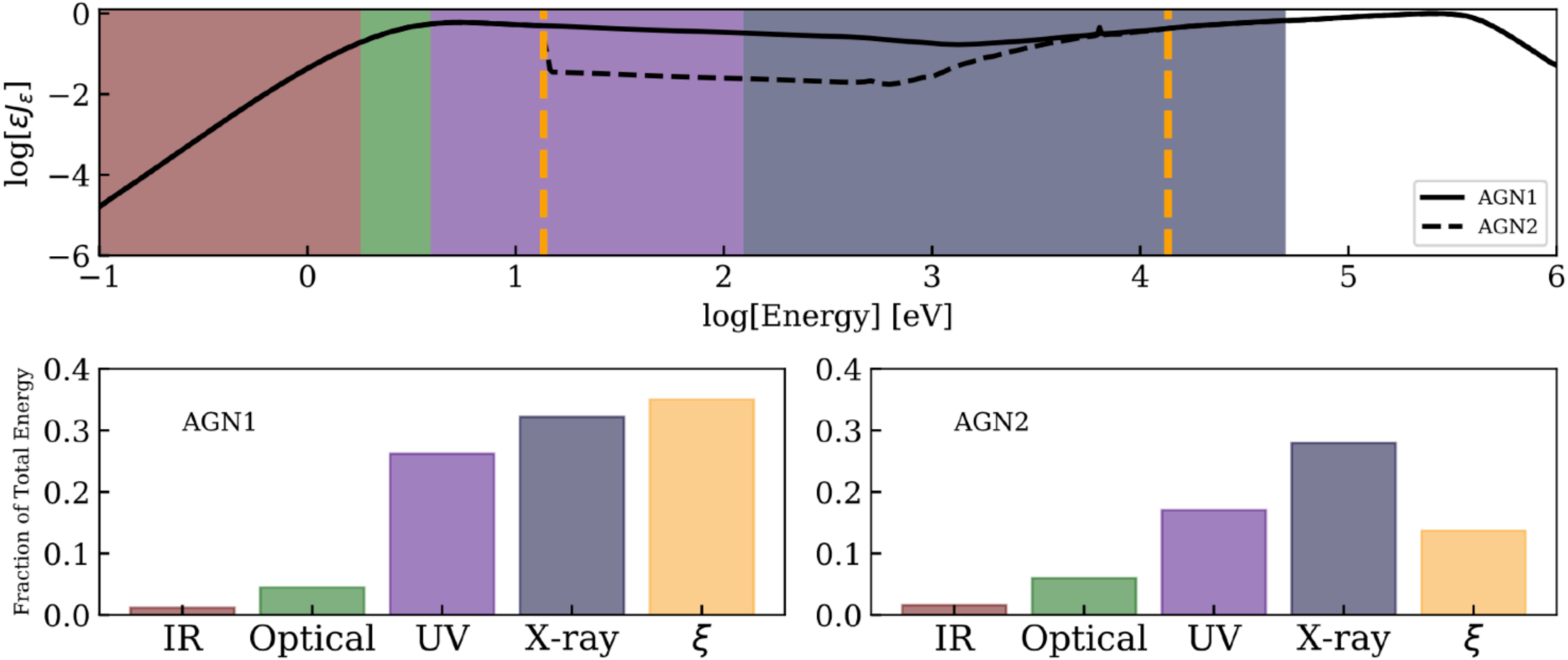
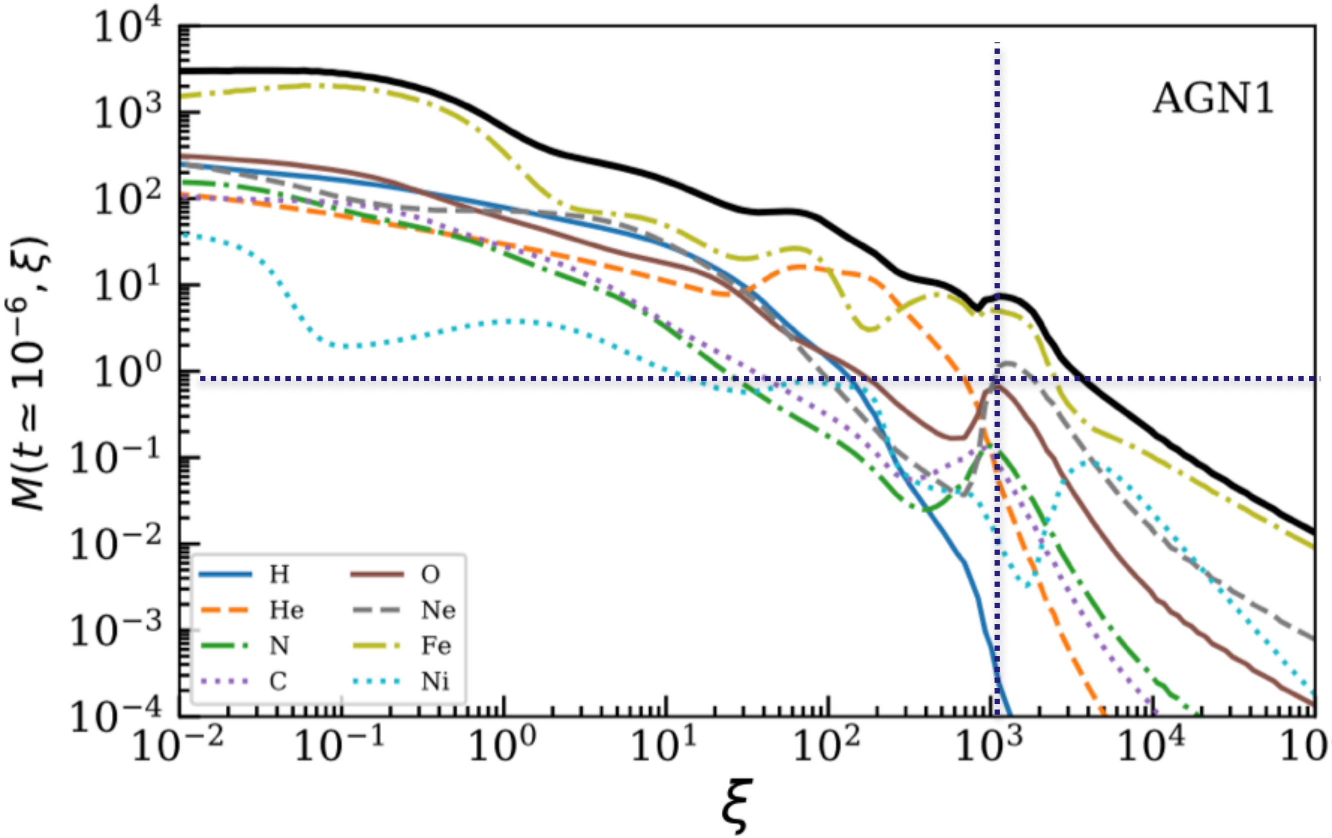


Fig.1 of Dannen et al. (submitted)

AGN H/C rates and radiation forces

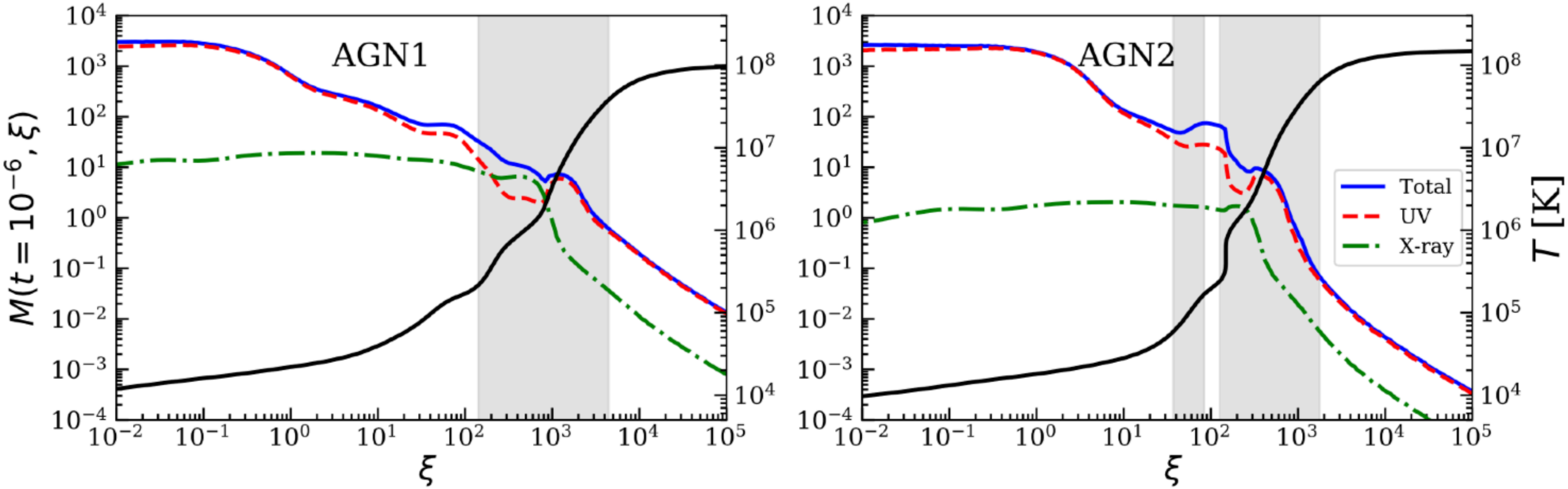
Use XSTAR/CLOUDY/etc. to calculate the photoionization balance and evaluate **force multipliers** (the biggest contributor to M are lines of iron and helium).



al. (submitted)

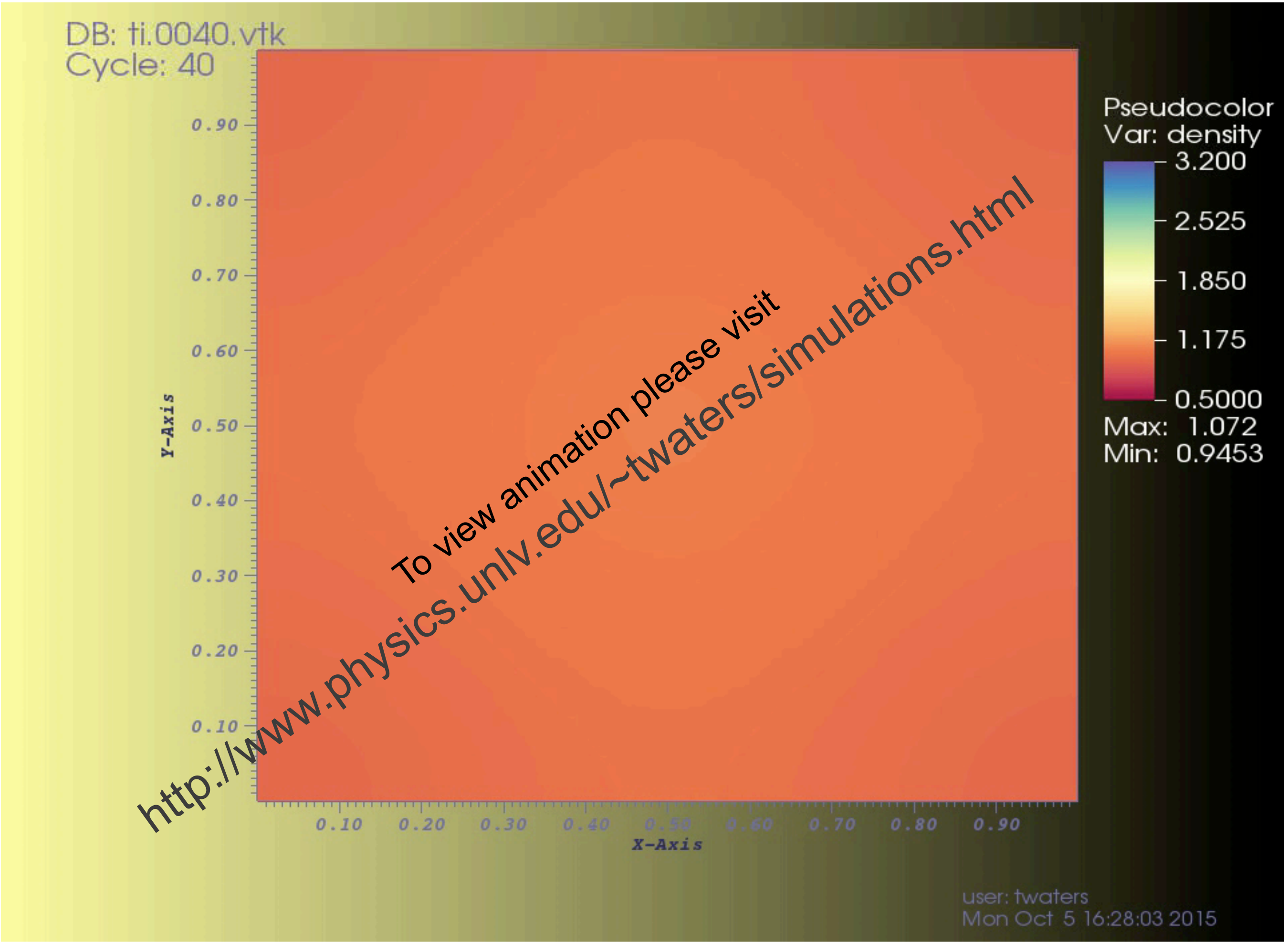
AGN H/C rates and radiation forces

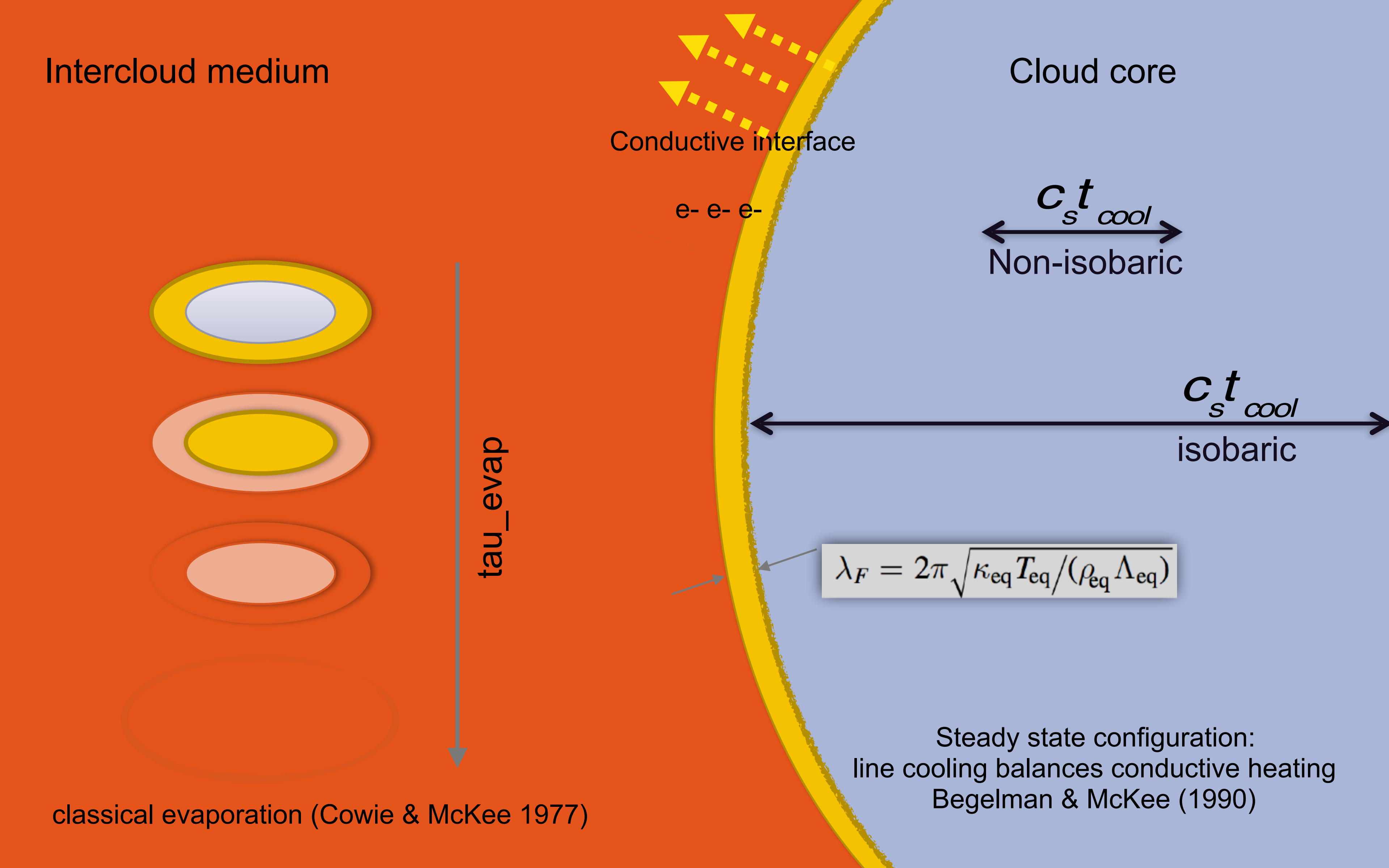
Use XSTAR/CLOUDY/etc. to calculate the photoionization balance and evaluate optically thin **heating and cooling rates** and thermal instability.



From Dannen et al. (submitted)

Local cloud formation and acceleration simulations



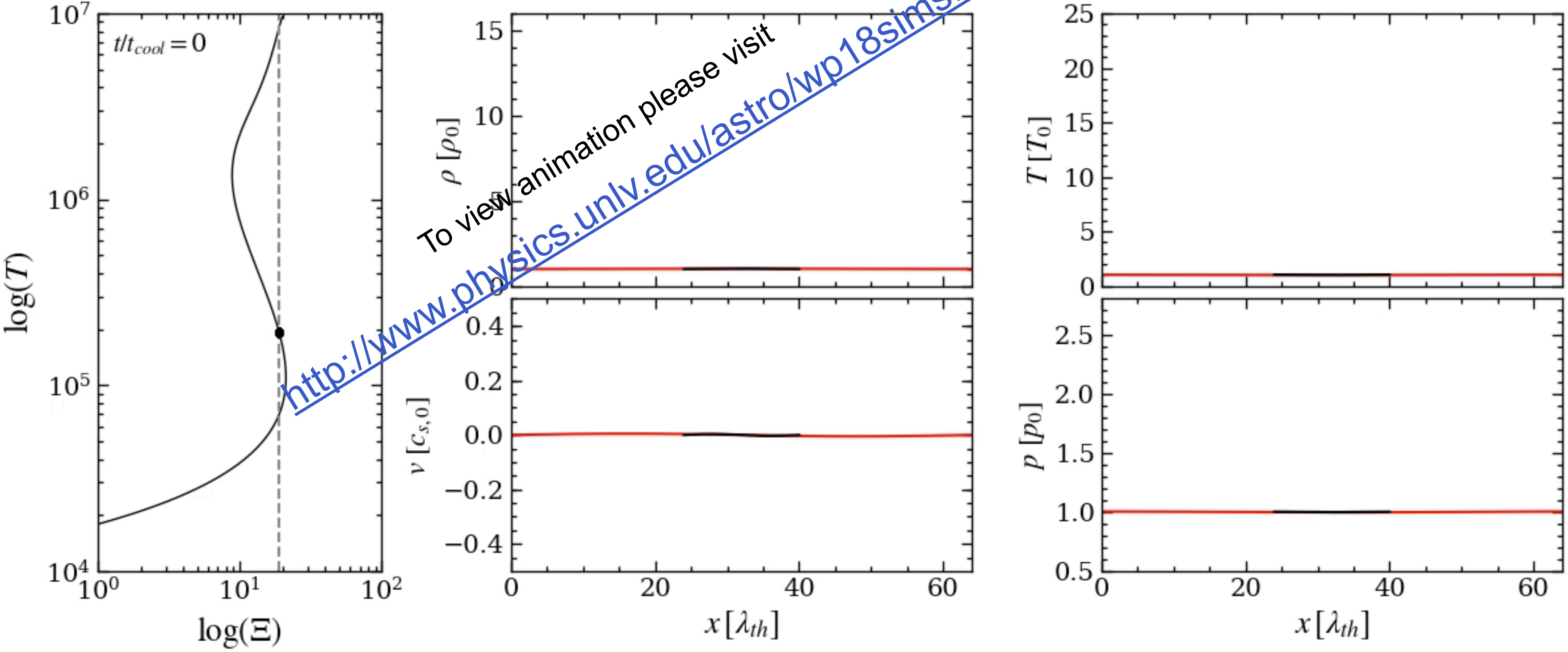


Intercloud medium
Cloud core
Conductive interface
e- e- e-
$c_s t_{cool}$
Non-isobaric
$c_s t_{cool}$
isobaric
tau_evap
$\lambda_F = 2\pi\sqrt{\kappa_{\rm eq} T_{\rm eq}/(\rho_{\rm eq}\Lambda_{\rm eq})}$
Steady state configuration:
line cooling balances conductive heating
Begelman & McKee (1990)
classical evaporation (Cowie & McKee 1977)

Non-isobaric TI simulations

- Larger clouds undergo increasingly larger damped oscillations

To view animation please visit
http://www.physics.unlv.edu/astro/wp18sims.html



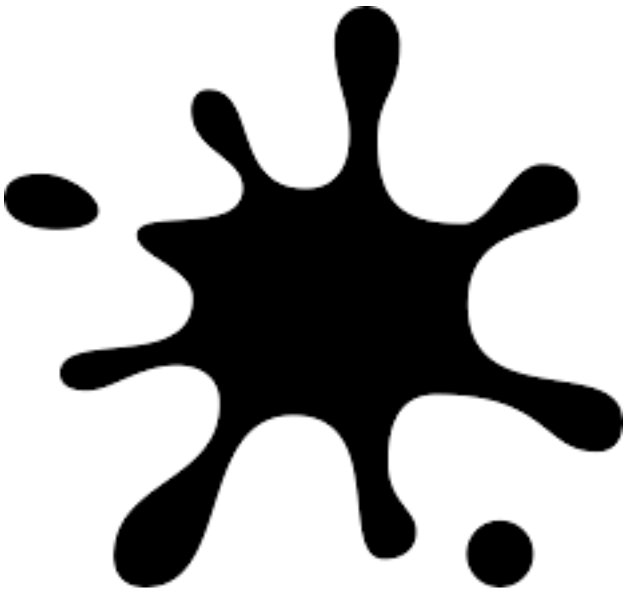
There are other regimes of TI (7 total)!

Table 1 in Waters & Proga (2018; submitted)

Rate dependence	Wavelength dependence			Mode Type & Stability			Mode	$n_R\, t_{cool}$ $(\lambda \to \infty)$
$R < 0$ $(N_p < 0)$ $(N_\rho > 0)$	$\lambda < \lambda_c$	$\lambda > \lambda_c$		condensation	condensation		E	$k'\sqrt{-R}$
				acoustic	condensation		S	$-k'\sqrt{-R}$
				acoustic	condensation		F	$-N_\rho$
$R < 0$ $(N_\rho < 0)$ $(N_p > 0)$	$\lambda < \lambda_c$	$\lambda > \lambda_c$		condensation	condensation		E	$-k'\sqrt{-R}$
				acoustic	condensation		S	$k'\sqrt{-R}$
				acoustic	condensation		F	$-N_p$
$0 < R < \frac{1}{9}$ $(N_p, N_\rho < 0)$	$\lambda < \lambda_-$	$\lambda_- < \lambda < \lambda_+$	$\lambda > \lambda_+$	condensation	condensation	acoustic	E	$k'^2(R-1)/(2N_\rho)$
				acoustic	condensation	acoustic	S	$k'^2(R-1)/(2N_\rho)$
				acoustic	condensation	condensation	F	$-N_\rho$
$\frac{1}{9} \le R < \frac{1}{3}$ $(N_p, N_\rho < 0)$	$\lambda < \lambda_o$	$\lambda > \lambda_o$		condensation	acoustic		E	$k'^2(R-1)/(2N_\rho)$
				acoustic	acoustic		S	$k'^2(R-1)/(2N_\rho)$
				acoustic	condensation		F	$-N_\rho$
$\frac{1}{3} \le R < 1$ $(N_p, N_\rho < 0)$	None			acoustic			E	$k'^2(R-1)/(2N_\rho)$
				acoustic			S	$k'^2(R-1)/(2N_\rho)$
				condensation			F	$-N_\rho$
$R \ge 1$ $(N_p, N_\rho < 0)$	None			acoustic			E	$k'^2(R-1)/(2N_\rho)$
				acoustic			S	$k'^2(R-1)/(2N_\rho)$
				condensation			F	$-N_\rho$
$R > 1$ $(N_p, N_\rho > 0)$	None			acoustic			E	$k'^2(R-1)/(2N_\rho)$
				acoustic			S	$k'^2(R-1)/(2N_\rho)$
				condensation			F	$-N_\rho$

Splattering can occur during cloud formation in isochorically unstable plasmas

<u>Cloud splattering:</u>
A new phenomenon that can turn stationary gas into high velocity blobs!



<u>Linearized solutions to non-adiabatic gas dynamics:</u>

$$\rho(\boldsymbol{x},t) = \rho_0 + A\rho_0 e^{n_R t}\cos(\boldsymbol{k}\cdot\boldsymbol{x})$$

$$v(\boldsymbol{x},t) = -A\left(\frac{n_R}{k}\right)e^{n_R t}\sin(\boldsymbol{k}\cdot\boldsymbol{x})$$

$$p(\boldsymbol{x},t) = p_0 - A\rho_0\left(\frac{n_R}{k}\right)^2 e^{n_R t}\cos(\boldsymbol{k}\cdot\boldsymbol{x})$$

Notice that for large enough wavelengths (small k), linear theory predicts supersonic motions during cloud formation!

The snag encountered when deriving characteristic cloud sizes…

What is the characteristic size of a newly condensed clump?

By mass conservation:

$$\rho_{eq}\,\lambda^3 \approx \rho_c\,\frac{4}{3}\pi R_c^3$$

$$R_c \sim \frac{\lambda}{(\rho_c/\rho_{eq})^{1/3}}$$

But we don't know the characteristic size of a perturbation in AGN.

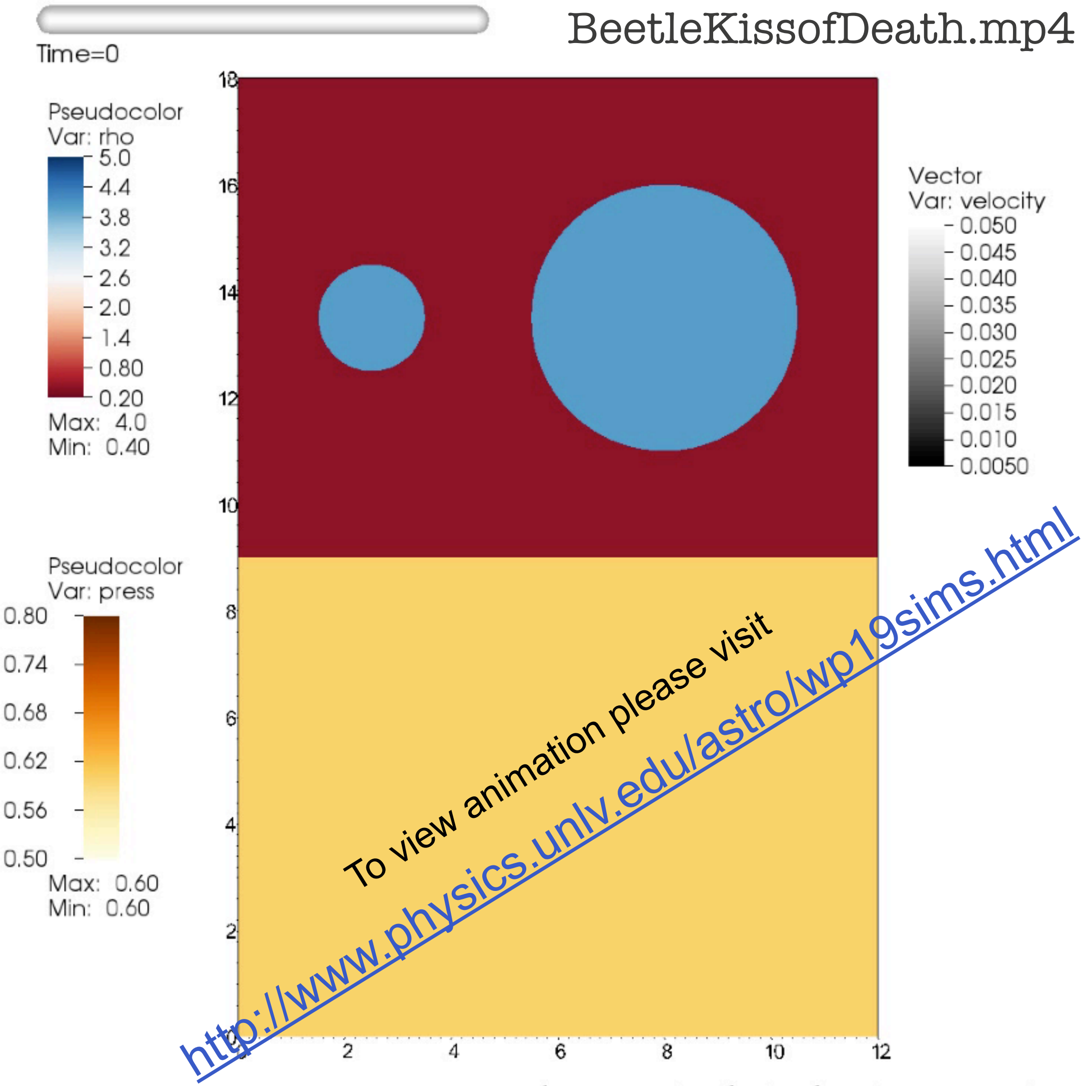
And even if we did, there as a bigger problem…

Cloud complexes are dynamically unstable.

Clouds tend to coalesce!

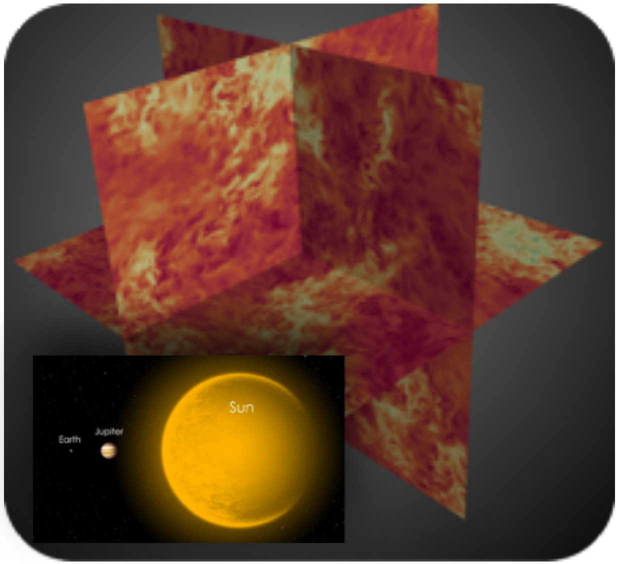
Safe to try at home: start with perfect spherical clouds in pressure equilibrium, add the necessary physics described above (i.e. optically thin cooling and thermal conduction, needed to form interfaces) and then evolve.

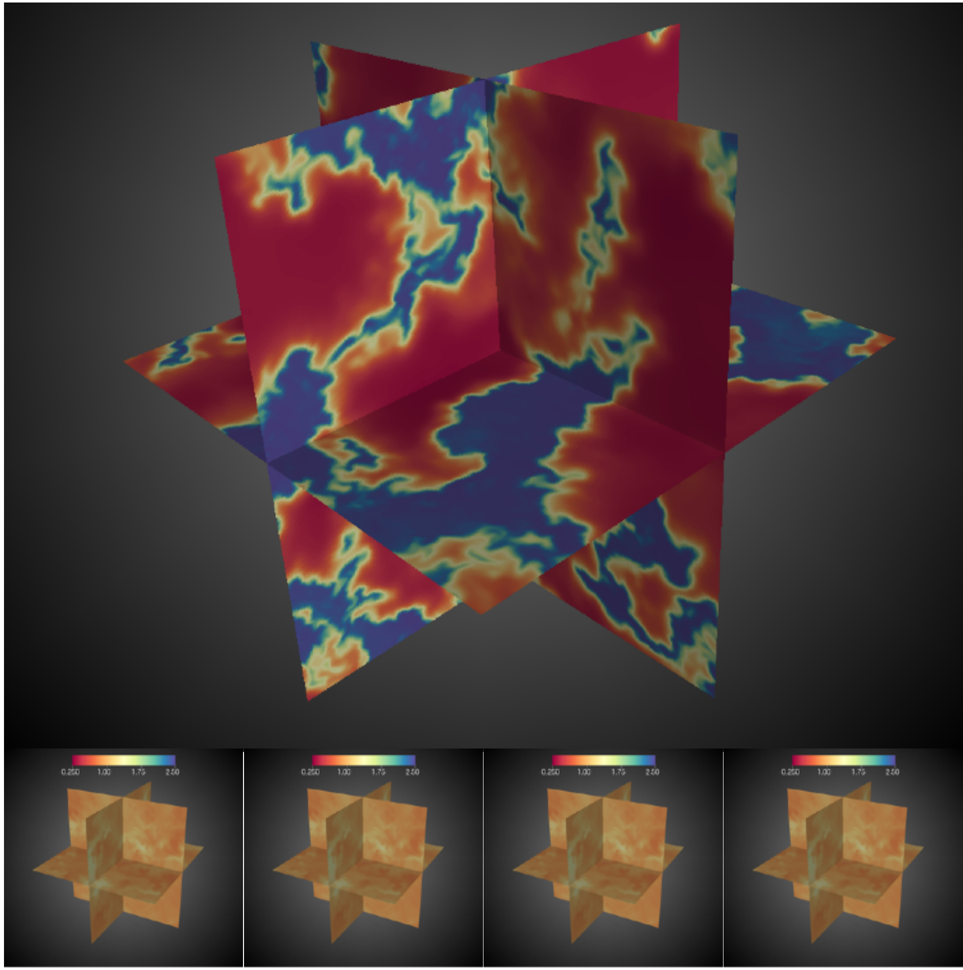
BeetleKissofDeath.mp4



Athena++ simulation by Tim Waters (LANL)

Turbulence to the rescue





Hypothesis: turbulence should favor clump sizes corresponding to wavelengths with maximum *linear* growth rates of TI:

$$R_c \sim \frac{\lambda_{\max}}{(\rho_c/\rho_{eq})^{1/3}}$$

Turbulent flow can suppress coalescence

The essence of turbulence…

"Big whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity." -Richardson

Why invoke turbulence? Otherwise…

"Small clumps merge with big clumps,
enhancing their advective velocity;
And big clumps join even bigger clumps,
And so on to self-gravity."

The clumpy outflow paradigm implies turbulent flow

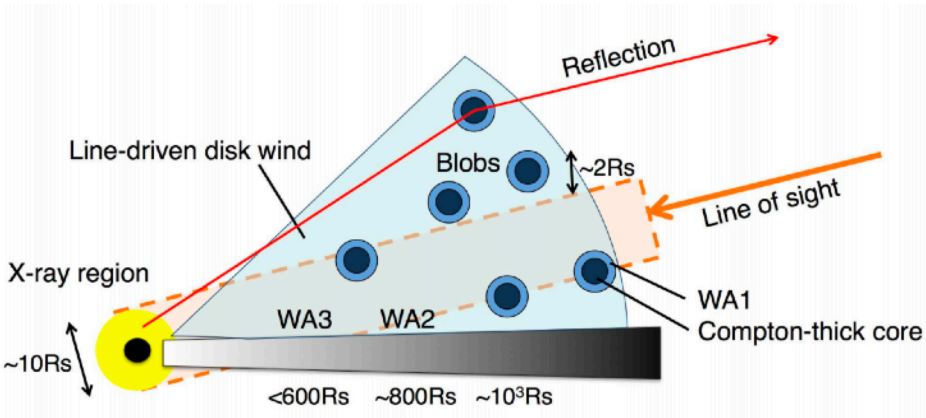
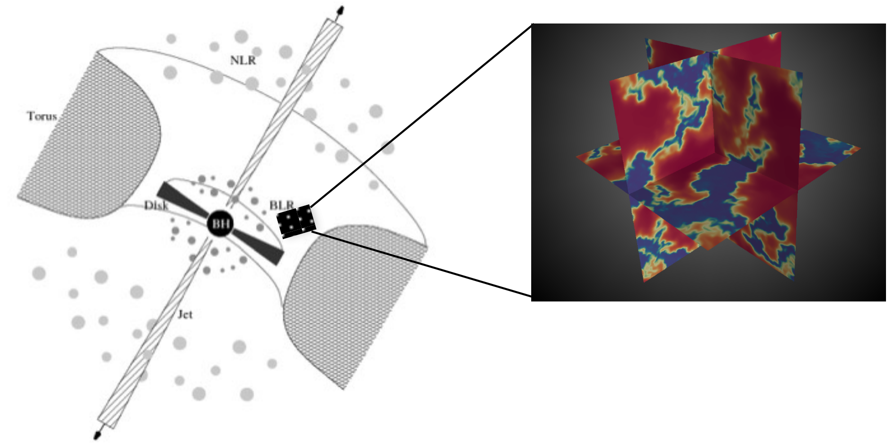


Figure 15. Schematic picture of geometry of warm absorber outflows in NGC 4051

From Mizumoto et al. 2017



see Waters et al. (in prep.)

-standard (triply periodic) driven turbulence simulations is likely an appropriate framework for studying the local multiphase gas dynamics

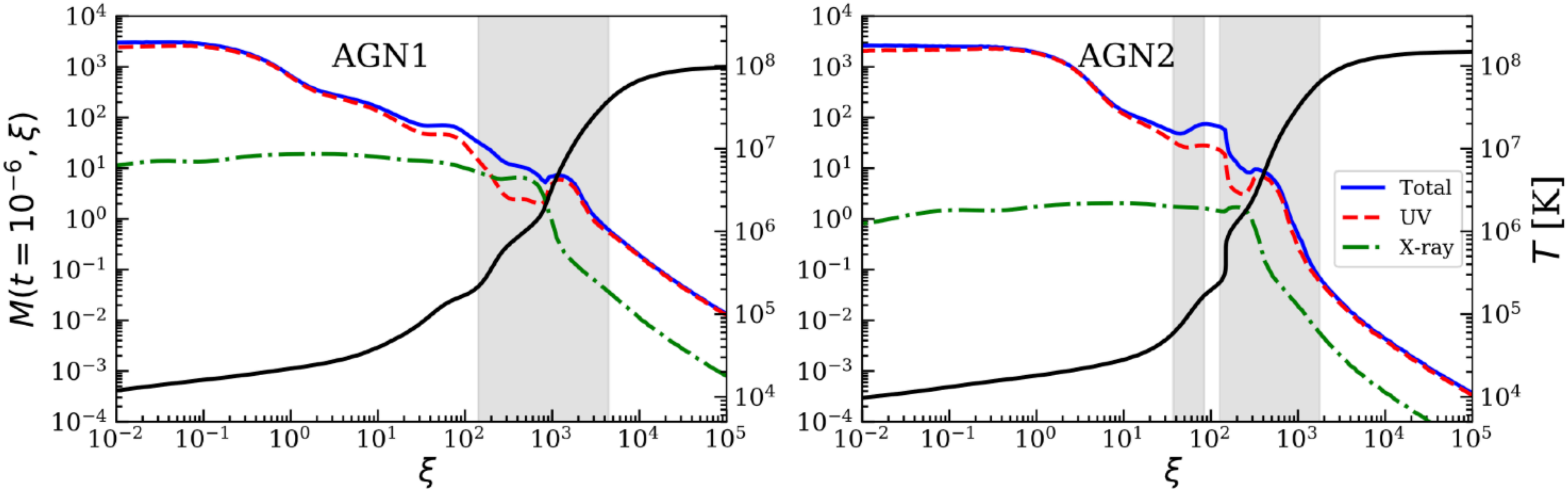
$$\mathrm{Re} \equiv \frac{\mathrm{v\,L}}{\nu} \approx \frac{10^2\,\mathrm{km\,s^{-1}L_{th}}}{\mathrm{c_s}\lambda_{\mathrm{mfp}}} \sim 10\left(\frac{\mathrm{L_{th}}}{\lambda_{\mathrm{mfp}}}\right) \sim 10^7$$

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \nabla \times (\boldsymbol{\omega} \times \boldsymbol{v}) = \frac{\nabla \rho \times \nabla p}{\rho^2} + \sum_i \nabla \times \mathbf{f}_i$$

BLR/NLR cloud sizes at last

$$\frac{\lambda_{th}}{\lambda_F} = 7.2 \left(\frac{T}{10^5\,\mathrm{K}}\right)^{-1/4} \left(\frac{L}{10^{-23}\,\mathrm{erg\,cm^3\,s^{-1}}}\right)^{-1/2}$$

This ratio does not depend on density!
- Begelman & McKee (1990); see also Waters & Proga (2018)

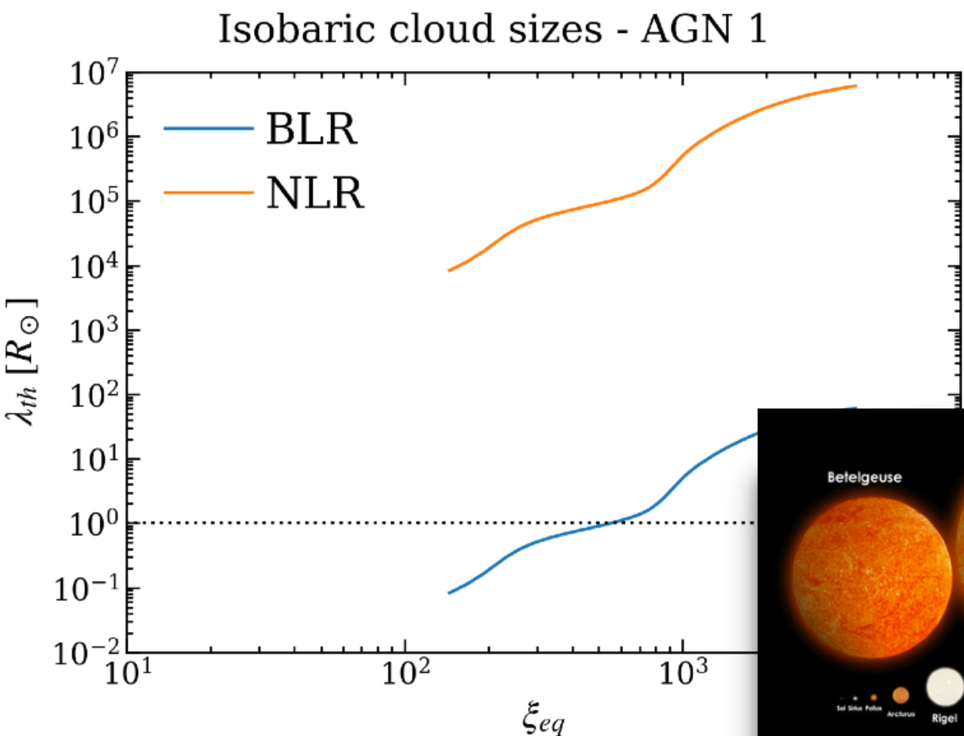


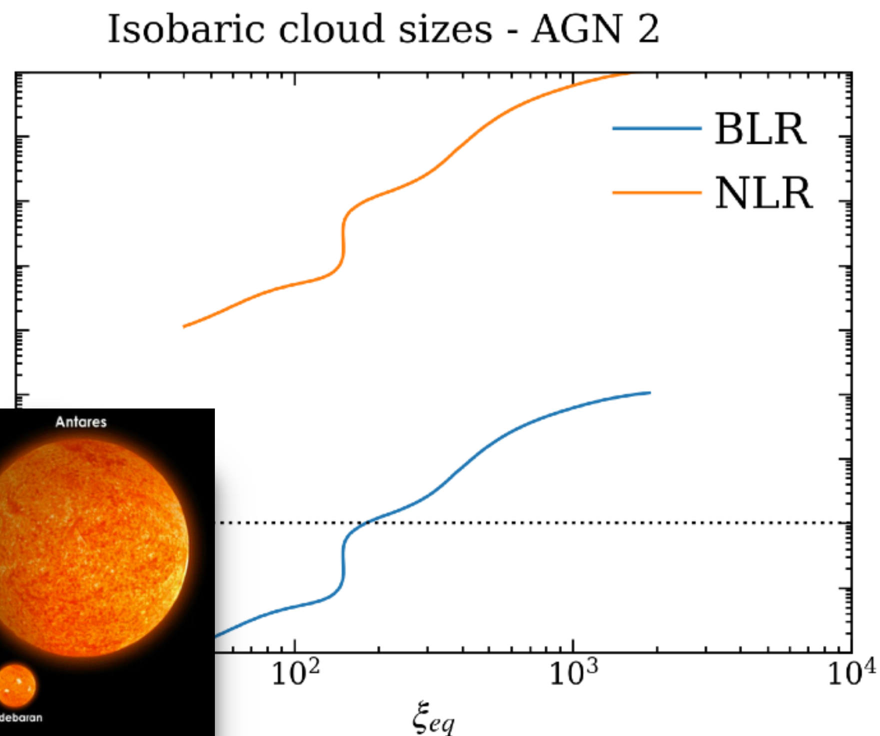
From Dannen et al. (submitted)

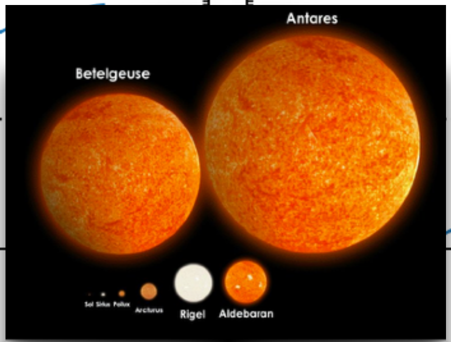
BLR/NLR cloud sizes at last

$$\frac{\lambda_{th}}{\lambda_F} = 7.2 \left(\frac{T}{10^5\,\mathrm{K}}\right)^{-1/4} \left(\frac{L}{10^{-23}\,\mathrm{erg\,cm^3\,s^{-1}}}\right)^{-1/2}$$

This ratio does not depend on density!
- Begelman & McKee (1990); see also Waters & Proga (2018)







Summary

(bolded: suitable for 3-year olds)

- **AGN clouds get happier as they grow bigger - they bounce up and down more** (i.e. larger non-isobaric clouds undergo stronger thermal response oscillations)
- **AGN clouds are a loving family - they like to kiss and hug** (i.e. they are dynamically unstable to coalescence)
- **Most AGN clouds die whenever they are pushed around. Only the fastest growing clouds can avoid death.** That is, turbulence picks out a preferred size corresponding to the fastest growing TI modes.
- **Sometimes AGN clouds go splat!** ('splattering' should occur in isochorically unstable plasmas according to linear theory)