LA-UR-18-26583
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Title: Thermal Instability in the presence of turbulence

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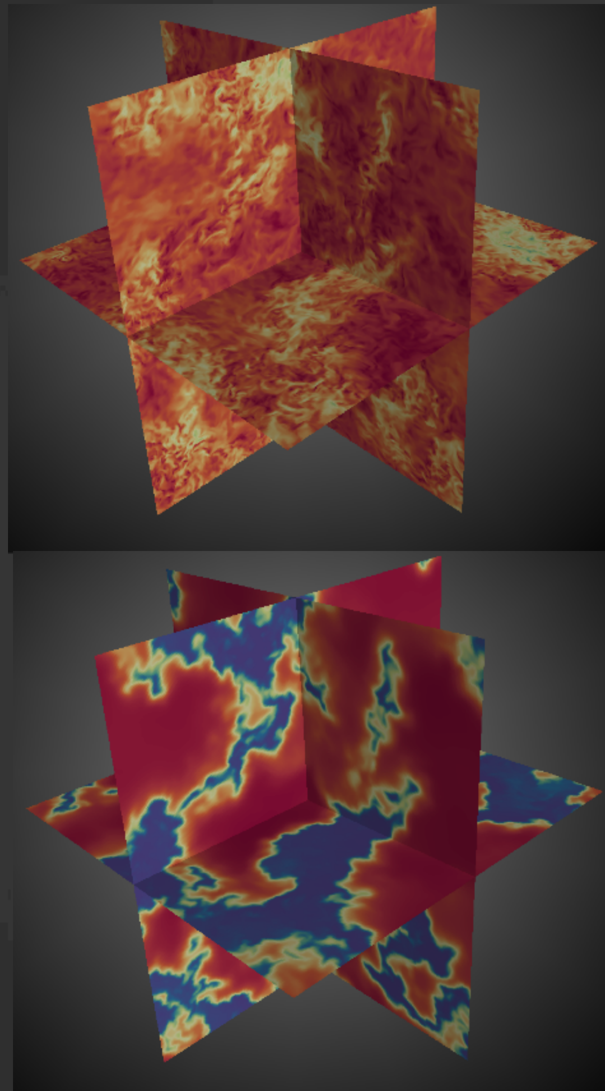
Intended for: Multiphase AGN feeding and feedback, 2018-07-09/2018-07-13 (Sesto, Italy)
Invited talk

Issued: 2018-07-24 (rev.1)



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Thermal Instability in the presence of turbulence

Multiphase AGN feeding & feedback @ Sesto

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UNLV - D. Proga, R. Dannen

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Outline

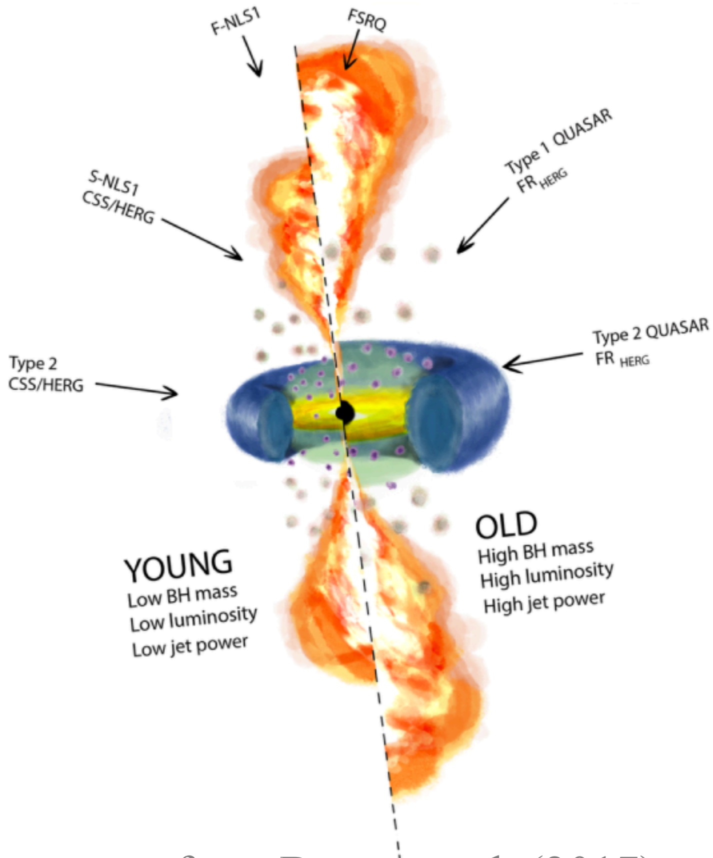
- BLRs: Discrete clouds vs. the clumpy wind paradigm
- Review of thermal instability
- Turbulent TI simulations: inside a patch of a clumpy outflow

Bachall (1966):

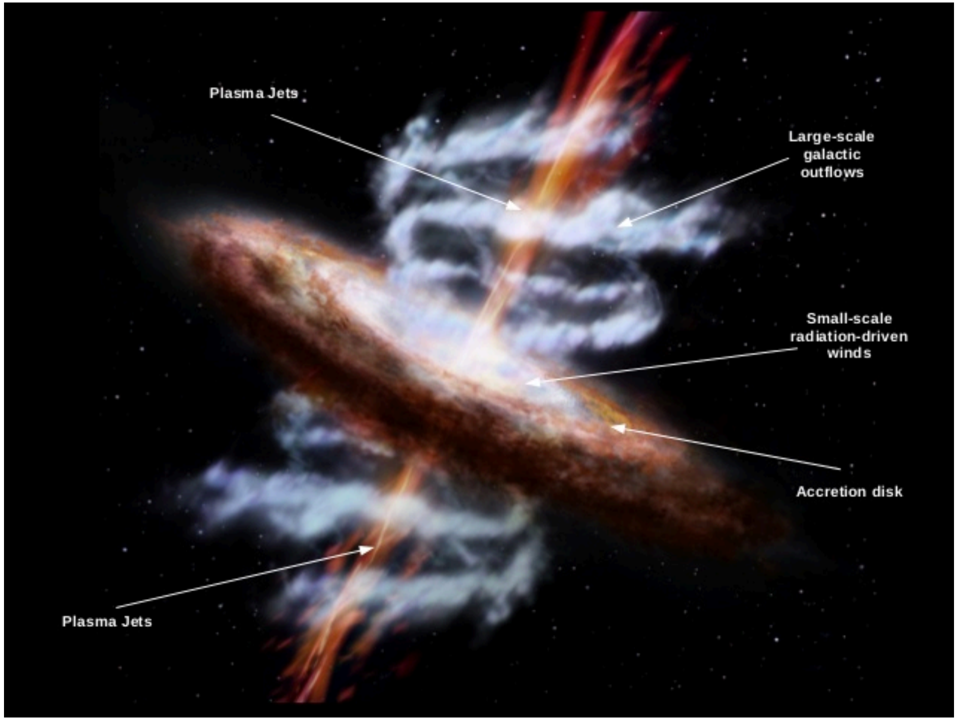
"If one assumes that the emission lines of a QSS originate in a collection of turbulently moving elements (gas clumps or filaments), then the predicted widths are in agreement with observation if the average turbulent speeds are of the order of a few thousand kilometers per second."

This idea underlies the 'microturbulence' parameter in photoionization codes but highly supersonic turbulence in the BLR is considered unrealistic (see Kraemer et al. 2012)

The broad line region: discrete clouds, continuous winds, or something in between?



from Berton et al. (2017)



from Tombesi et al. (2017)

Discrediting discrete AGN cloud models

Two strategies have been taken:

1. Show line-driven wind models can obtain similar success fitting observations
   - Schurch et al. (2009)
   - Sim et al. (2010)
2. Study discrete clouds in detail and demonstrate infeasibility of this scenario

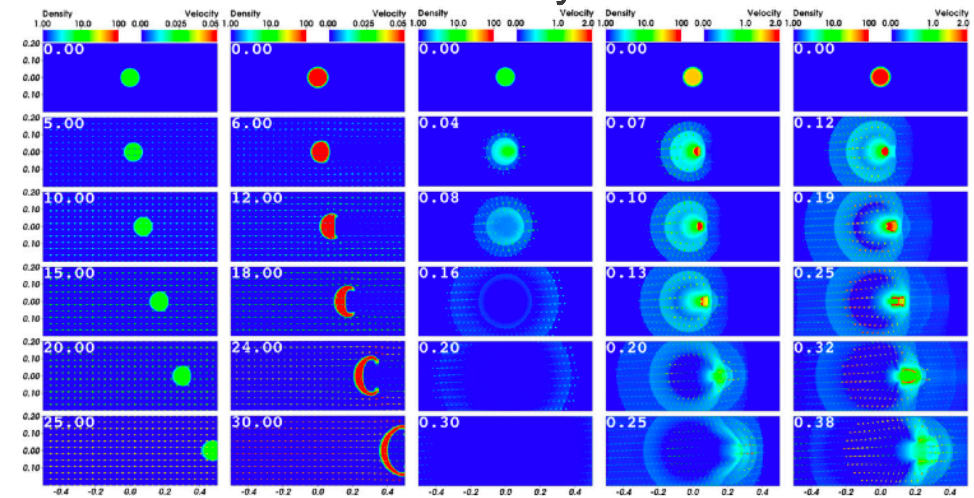


Figure 1. Sequences of density maps overplotted with the velocity fields for runs S10, S200, A10, A40, and A80 (left to right) at five different times, shown at upper left in each panel.

from Proga et al. (2014)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + P + B^2/2 - \mathbf{B}\mathbf{B}) = -\mathbb{P}\mathbf{S}_{\mathbf{M}}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{v} + (B^2/2)\mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] = -\mathbb{P}\mathbb{C}S_E$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

$$\frac{\partial E_r}{\partial t} + \mathbb{C}\nabla \cdot \mathbf{F}_r = \mathbb{C}S_E$$

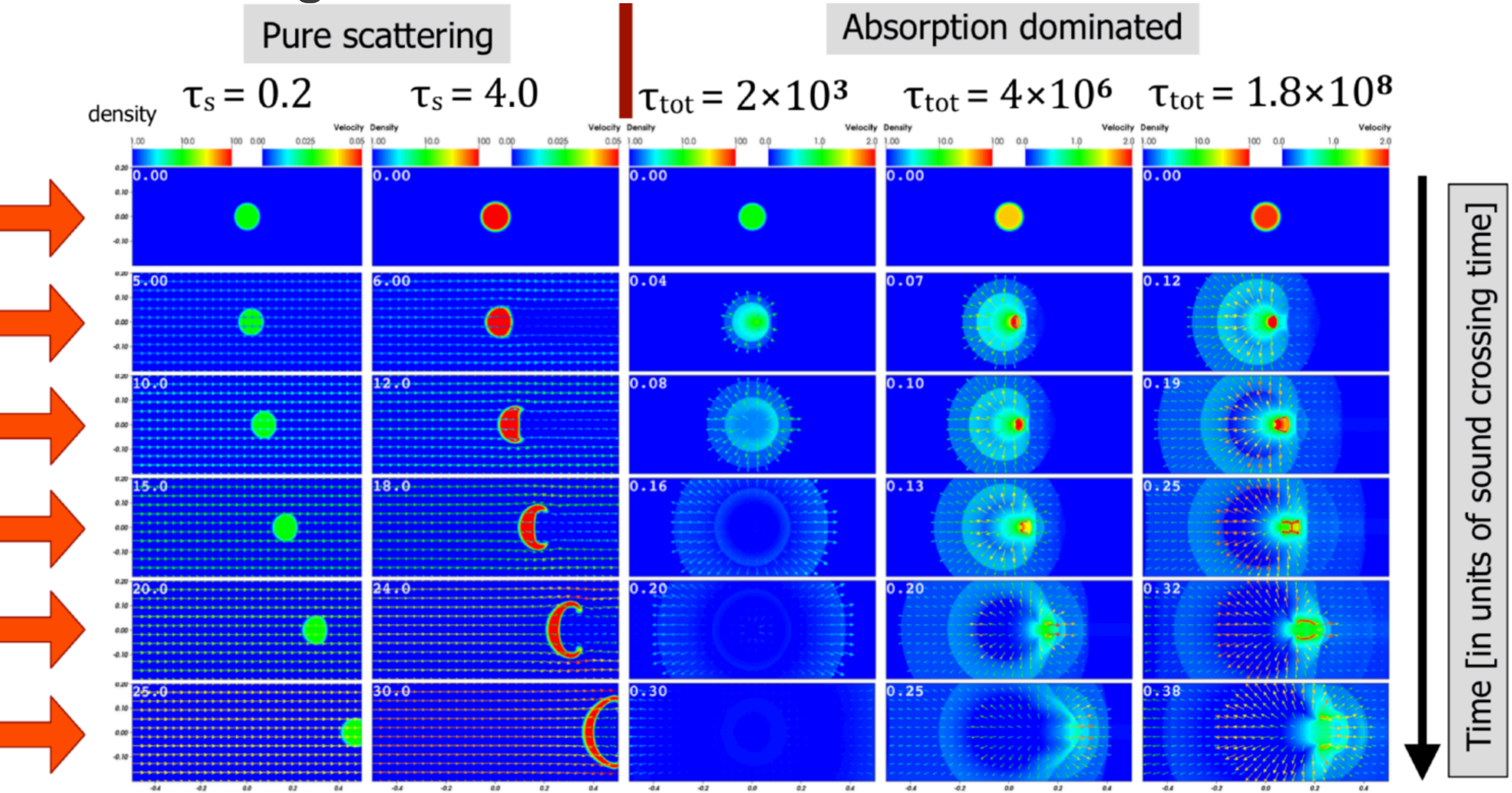
$$\frac{\partial \mathbf{F}_r}{\partial t} + \mathbb{C}\nabla \cdot \mathsf{P}_r = \mathbb{C}\mathbf{S}_{\mathbf{M}}$$

$$\mathbf{S}_{\mathbf{M}} \approx -(\sigma_a + \sigma_s)\boldsymbol{F}_r$$

$$S_E \approx \sigma_a (T^4 - E_r)$$

Proga+14 solved the eqns of RHD (w/o B-fields)

Discrediting discrete AGN cloud models



$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + P + B^2/2 - \mathbf{B}\mathbf{B}) = -\mathbb{P}\mathbf{S}_{\mathrm{M}}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{v} + (B^2/2)\mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] = -\mathbb{P}\mathbb{C}S_E$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

Equations of radiation hydrodynamics (LTE version)

$$\frac{\partial E_r}{\partial t} + \mathbb{C}\nabla \cdot \mathbf{F}_r = \mathbb{C}S_E$$

$$\frac{\partial \mathbf{F}_r}{\partial t} + \mathbb{C}\nabla \cdot \mathsf{P}_r = \mathbb{C}\mathbf{S}_{\mathrm{M}}$$

$$\mathbf{S}_{\mathrm{M}} \approx -(\sigma_a + \sigma_s)\boldsymbol{F}_r$$

$$S_E \approx \sigma_a(T^4 - E_r)$$

The H/C source term that triggers thermal instability follows by taking the optically thin limit of full RHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\,\mathbb{I}) = \mathbf{f}_{rad},$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathrm{v}] = -\rho\mathcal{L} + \kappa_{eq}\nabla^2 T + \mathbf{f}_{rad}$$

Discrediting discrete AGN cloud models

Dynamics of the nonlinear regime of thermal instability (TI)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

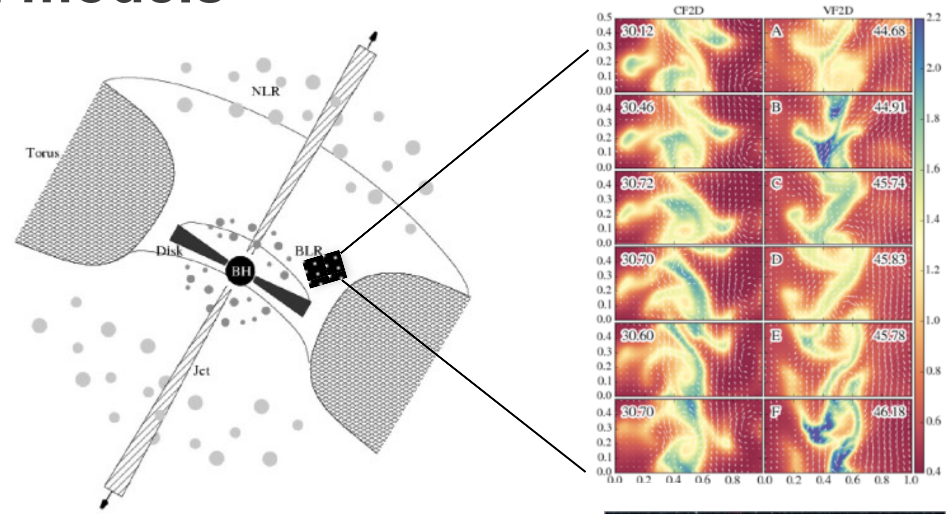
$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\,\mathbb{I}) = \mathbf{f}_{rad},$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathrm{v}] = -\rho\mathcal{L} + \kappa_{eq}\nabla^2 T + \mathbf{f}_{rad} \cdot \mathbf{v}. \qquad (3)$$

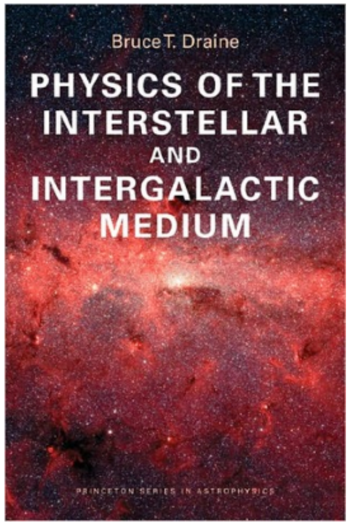
$$\mathbf{f}_{rad} = \frac{\rho\sigma_{tot}\mathcal{F}_{tot}}{c}\hat{x} = \frac{\rho\sigma_e\mathcal{F}_X}{c}\left[(1 + f_{\rm UV}) + \sigma_X + f_{\rm UV}M_{\rm max}\right]$$

The radiation force is negligible for the ISM/IGM applications considered by Field (1965), but it becomes very important in the BLR where the radiation field is completely anisotropic.

See Proga & Waters (2015), Waters & Proga (2016)



vs.



The clumpy outflow paradigm

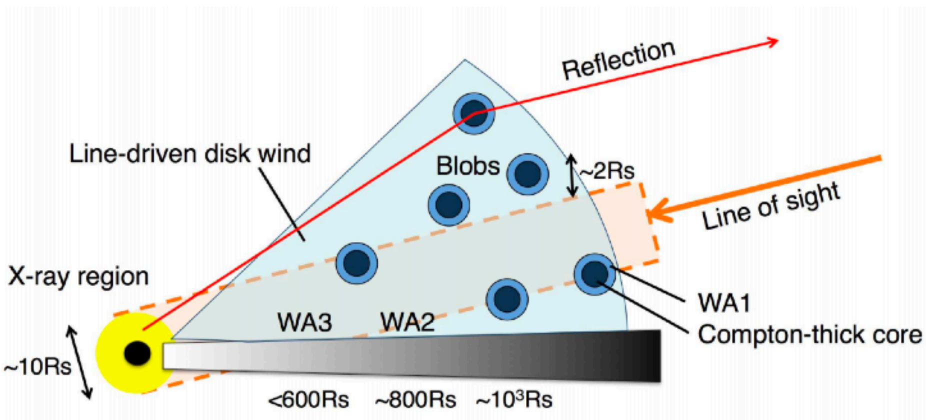
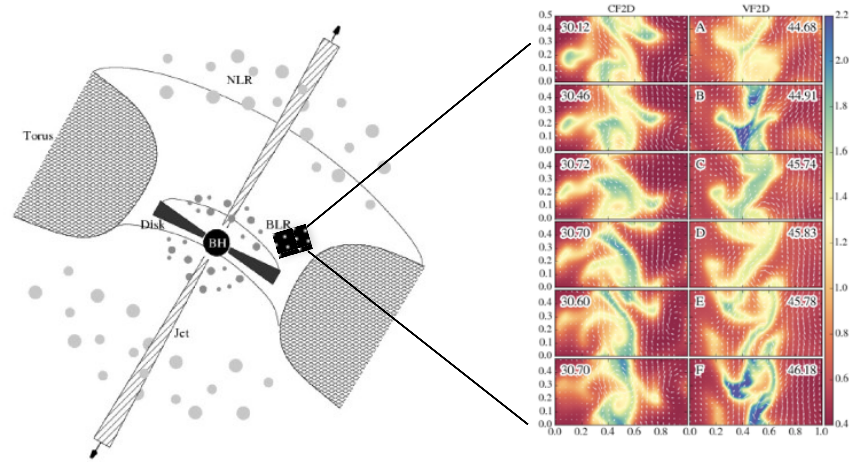


Figure 15. Schematic picture of geometry of warm absorber outflows in NGC 4051

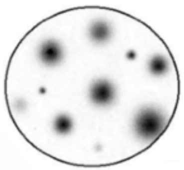
From Mizumoto et al. 2017



see Waters et al. (2017)

Instead of occultation, clumps can simply be evolving (continuously reforming and evaporating) along the line of sight

A spectral signature for cloud acceleration



<u>PPC model</u>

$$I_r = (1 - C_\nu) + C_\nu \, e^{-\tau_{\nu,r}};$$
$$I_b = (1 - C_\nu) + C_\nu \, e^{-2\,\tau_{\nu,r}}.$$

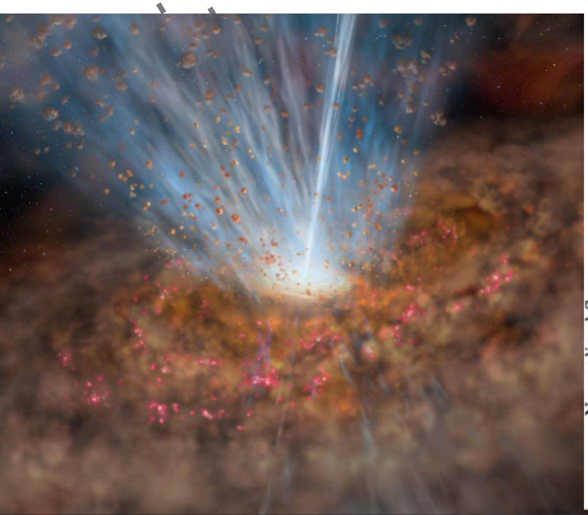
==>

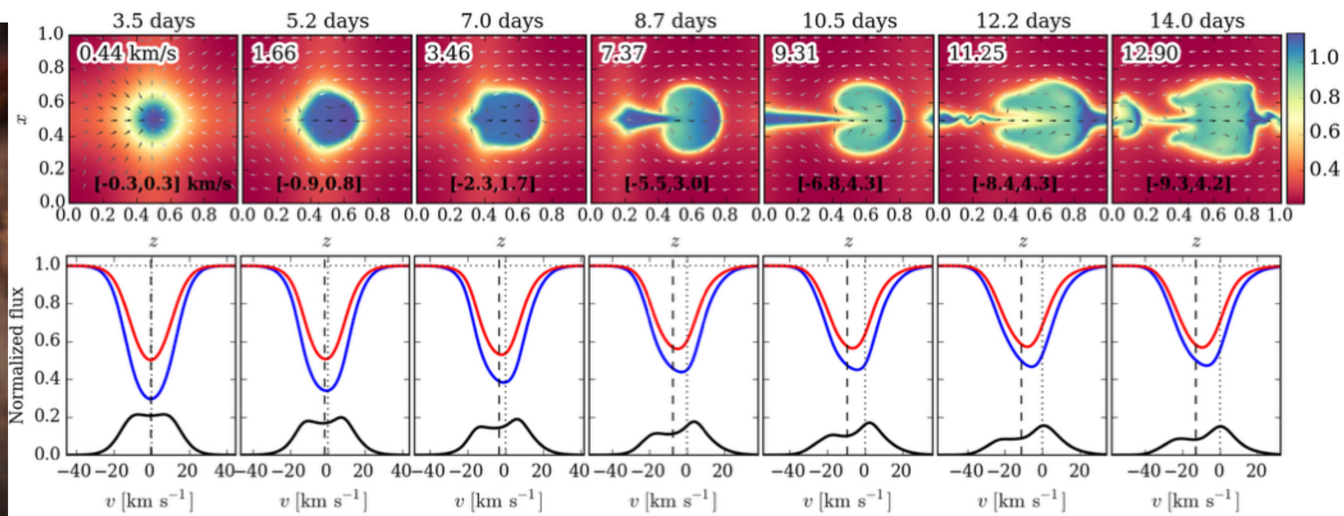
$$\tau_{\nu,r} = -\ln I_r - \ln\left[\frac{I_r - I_b}{I_r - I_r^2}\right],$$
$$C_\nu = \frac{1}{1 + (I_b - I_r^2)/(1 - I_r)^2}.$$

$$I_r - I_b = C_\nu e^{-\tau_{\nu,r}}(1 - e^{-\tau_{\nu,r}}),$$
$$\approx \begin{cases} C_\nu e^{-\tau_{\nu,r}} & \text{(near line center);} \\ \tau_\nu C_\nu e^{-\tau_{\nu,r}} & \text{(in the line wings).} \end{cases}$$

Crenshaw, Kraemer, & George ARA&A 2003

From Waters et al. 2017:





The clumpy outflow paradigm implies turbulent flow

Outflows are already prone to being turbulent since the Reynolds number is very large

$$\lambda_{\rm mfp} \approx 7.1 \times 10^4\,{\rm cm} \left(\frac{\rm T}{10^5\,{\rm K}}\right) \left(\frac{\rm n}{10^9\,{\rm cm}^{-3}}\right)$$

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

Vorticity generation always accompanies clumps

- flow is not barotropic, there's velocity shear (KH instability), disruption from radiation forces, etc

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

- Possible scenarios that further stirs up the flow. Clumpy [wind type]:
  - ✳thermal winds - self-shadowing can cause a shielded clump to not suffer strong heating, causing relative velocity shear
  - ✳line driven winds - perturbations at the wind base propagate downstream (Dyda & Proga 2017, 2018)
  - ✳magnetically driven winds - the higher inertia of clumps can cause field line draping, thereby twisting the fields

Turbulent flow in turn implies a narrow range of cloud sizes

What is the characteristic size of a newly condensed clump?

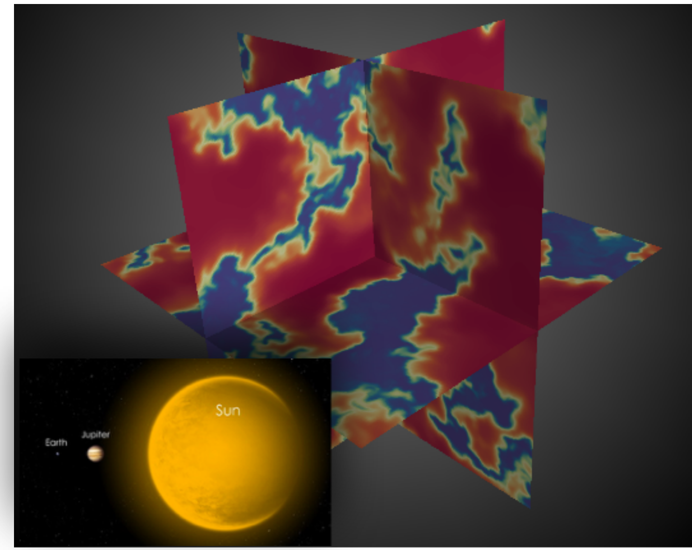
By mass conservation:

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

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

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

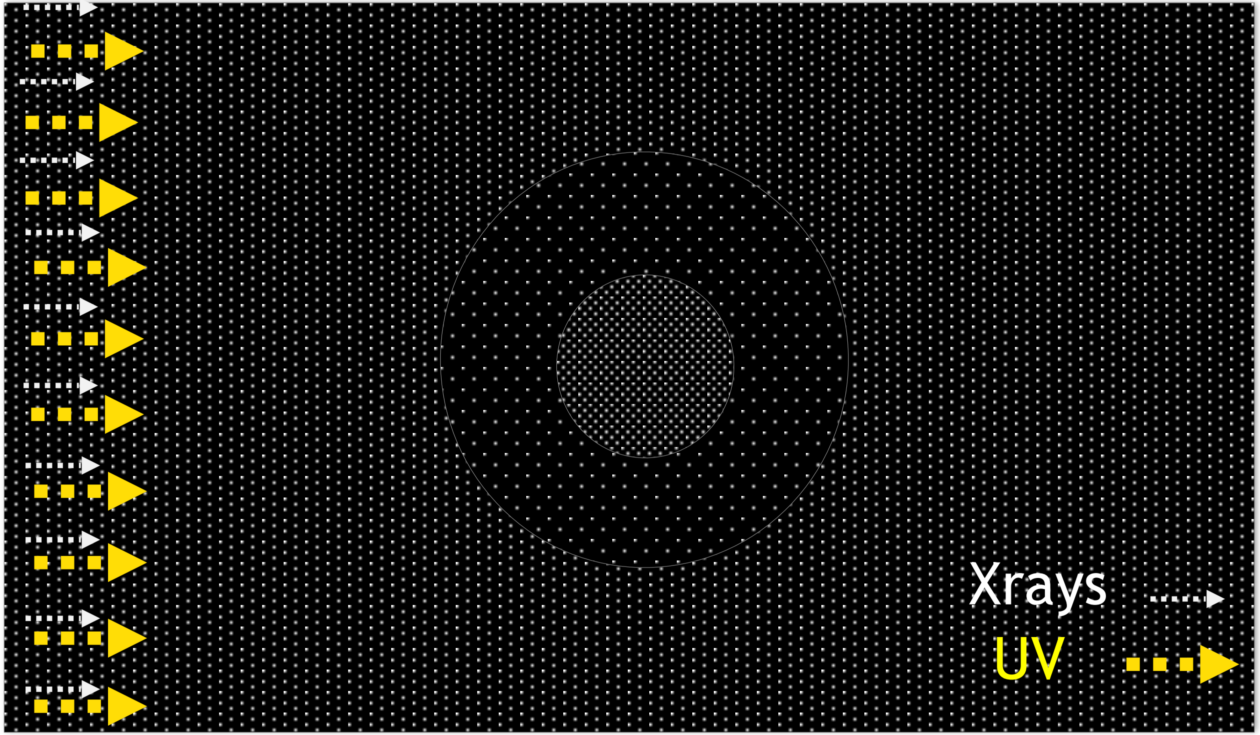
$$R_c \sim \frac{\lambda_{\rm max}}{(\rho_c/\rho_{eq})^{1/3}}$$



Approximate scales for the parameters used in PW15 simulations. Condensing clumps are about the size of the sun, the Field length is roughly Jupiter-sized, and our grid scale is Earth-sized. (The last slide shows how much this parameter space can vary.)

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).



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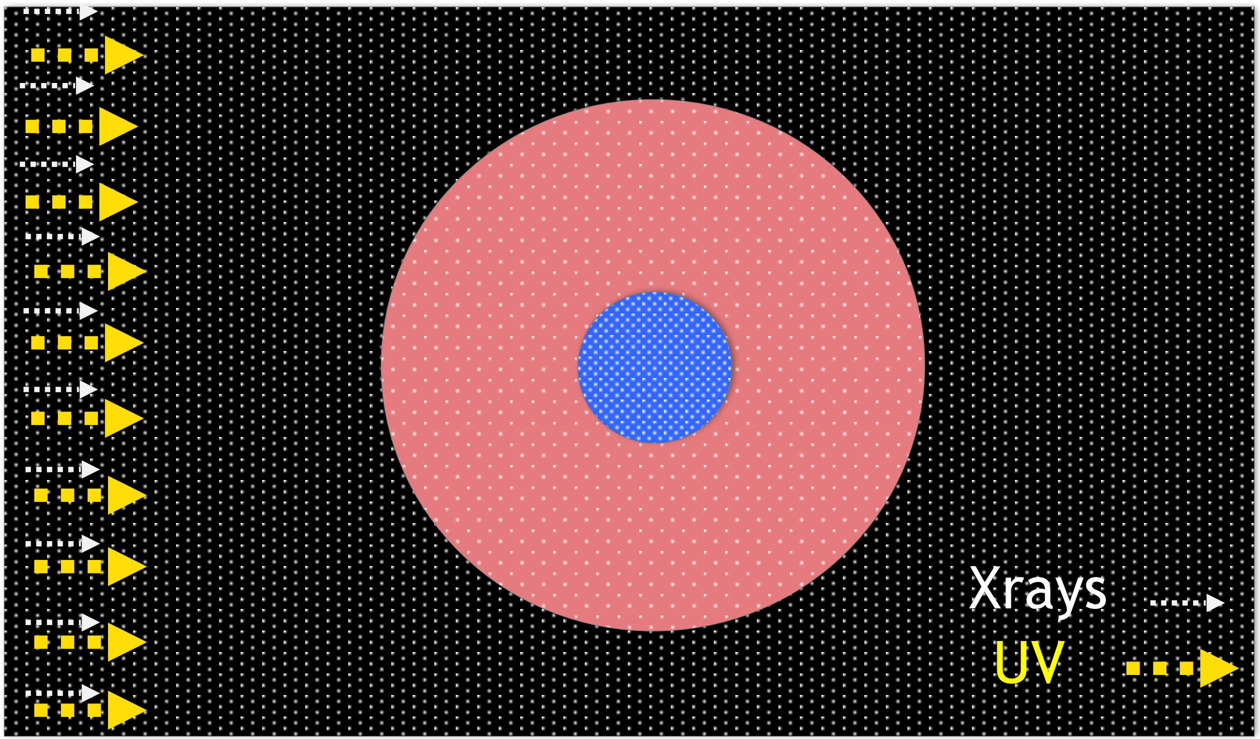

Review of TI: the nonlinear isobaric regime

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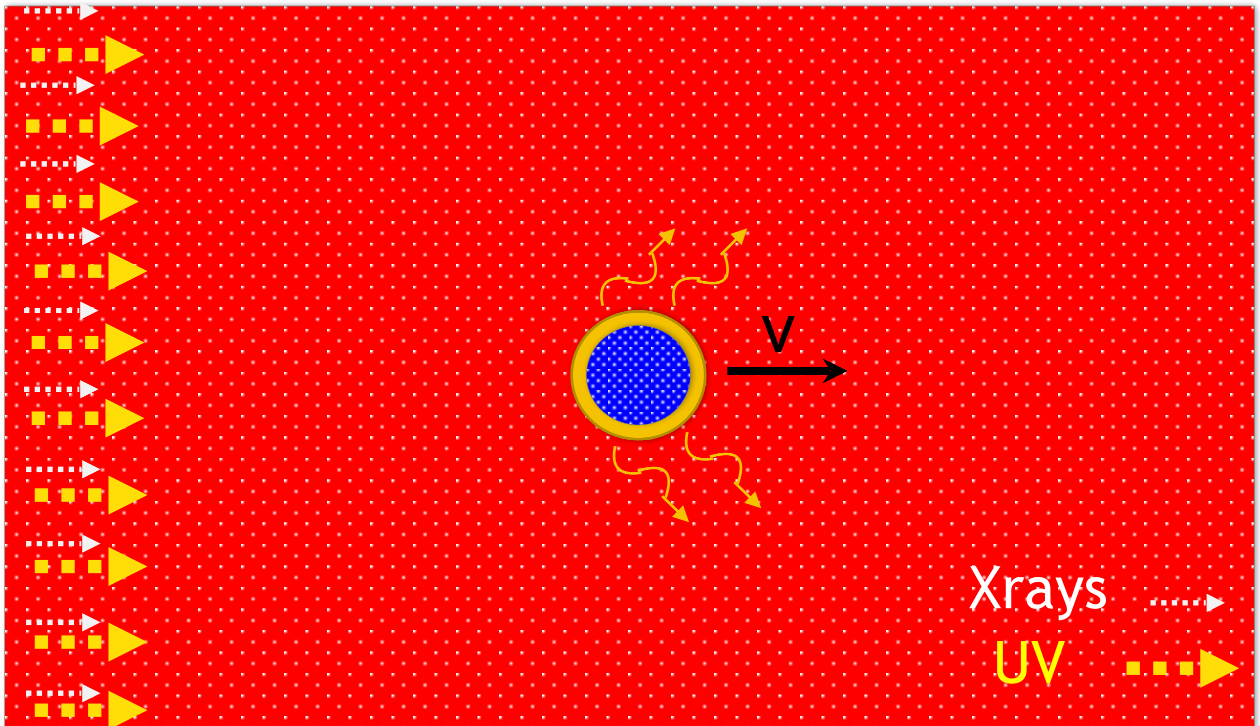
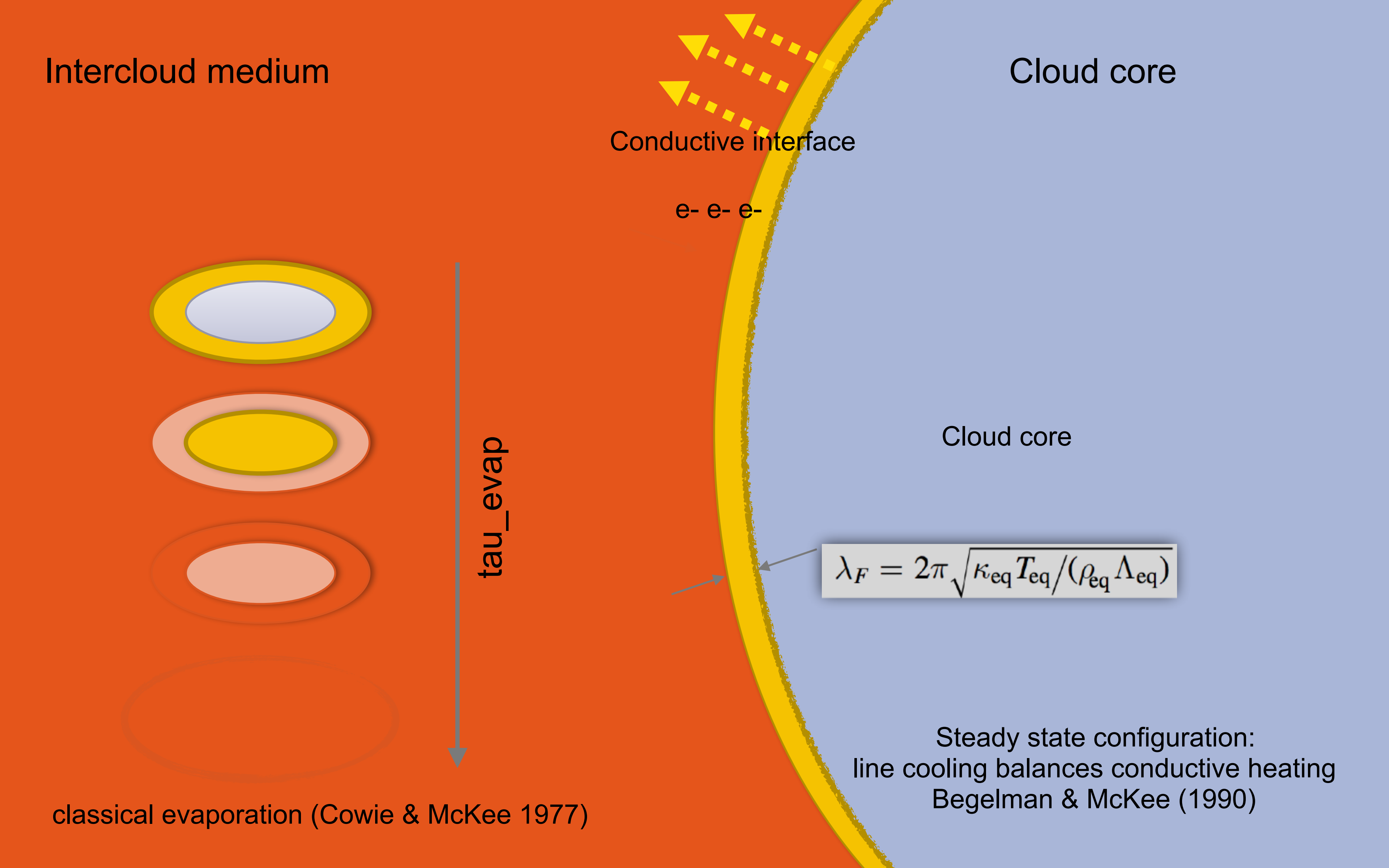
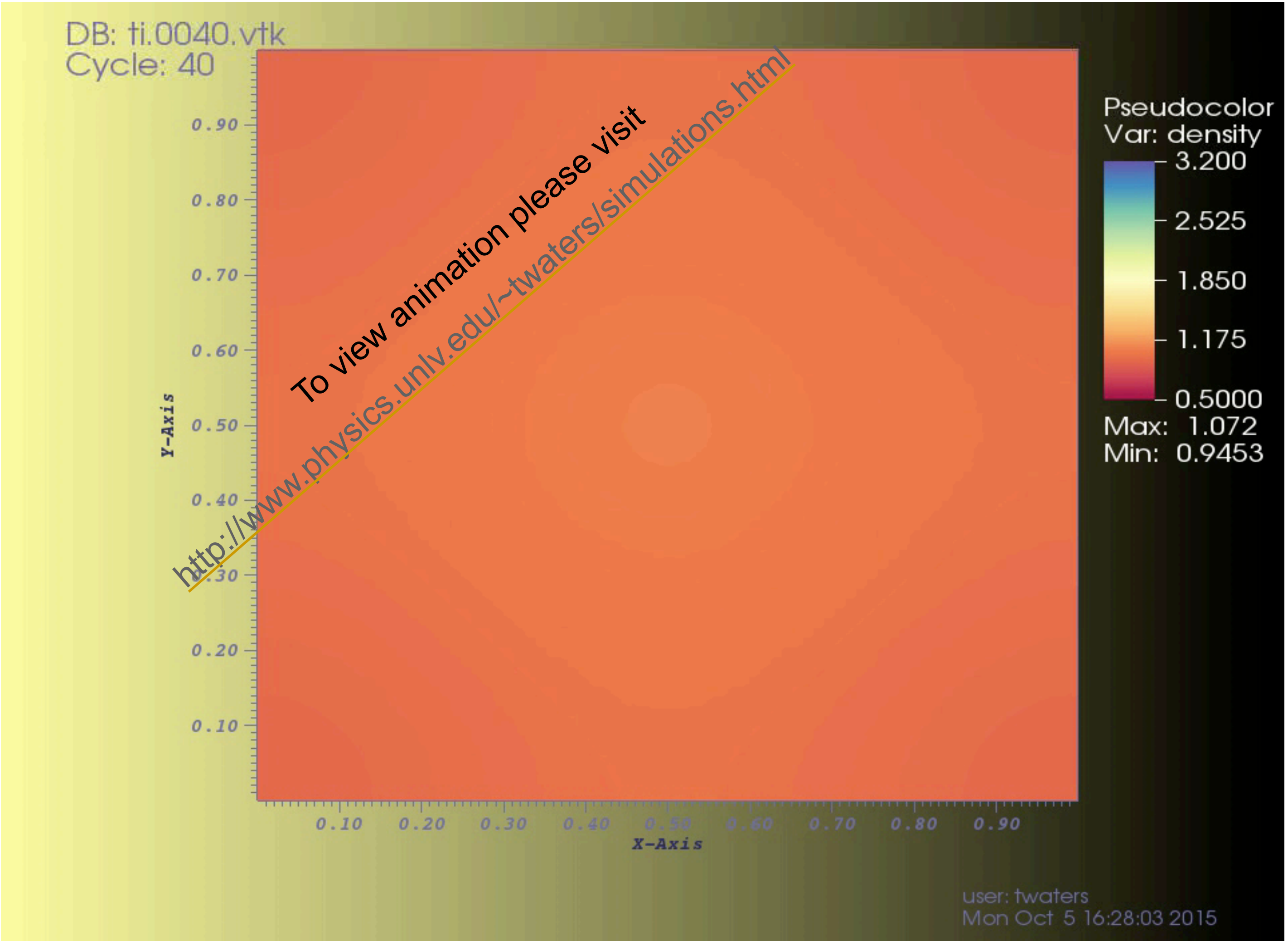



Intercloud medium
Cloud core
Conductive interface
e- e- e-
tau_evap
Cloud core
$\lambda_F = 2\pi\sqrt{\kappa_{eq} T_{eq}/(\rho_{eq}\Lambda_{eq})}$
Steady state configuration:
line cooling balances conductive heating
Begelman & McKee (1990)
classical evaporation (Cowie & McKee 1977)

CLOUD DYNAMICS:
ACCELERATION, EVAPORATION, AND REGENERATION
(SPITZER CONDUCTIVITY T^5/2)



Review of TI: instability criteria

$$\mathcal{L} = \Lambda - \Gamma \; [\mathrm{erg\,g^{-1}\,s^{-1}}]$$

Instability criterion:

$$\left(\frac{\partial \mathcal{L}}{\partial T}\right)_p < 0 \;(\text{isobaric})$$

$$\left(\frac{\partial \mathcal{L}}{\partial T}\right)_\rho < 0 \;(\text{isochoric})$$

$$\left(\frac{\partial \mathcal{L}}{\partial T}\right)_s < 0 \;(\text{isentropic})$$

<u>ICM Example:</u>

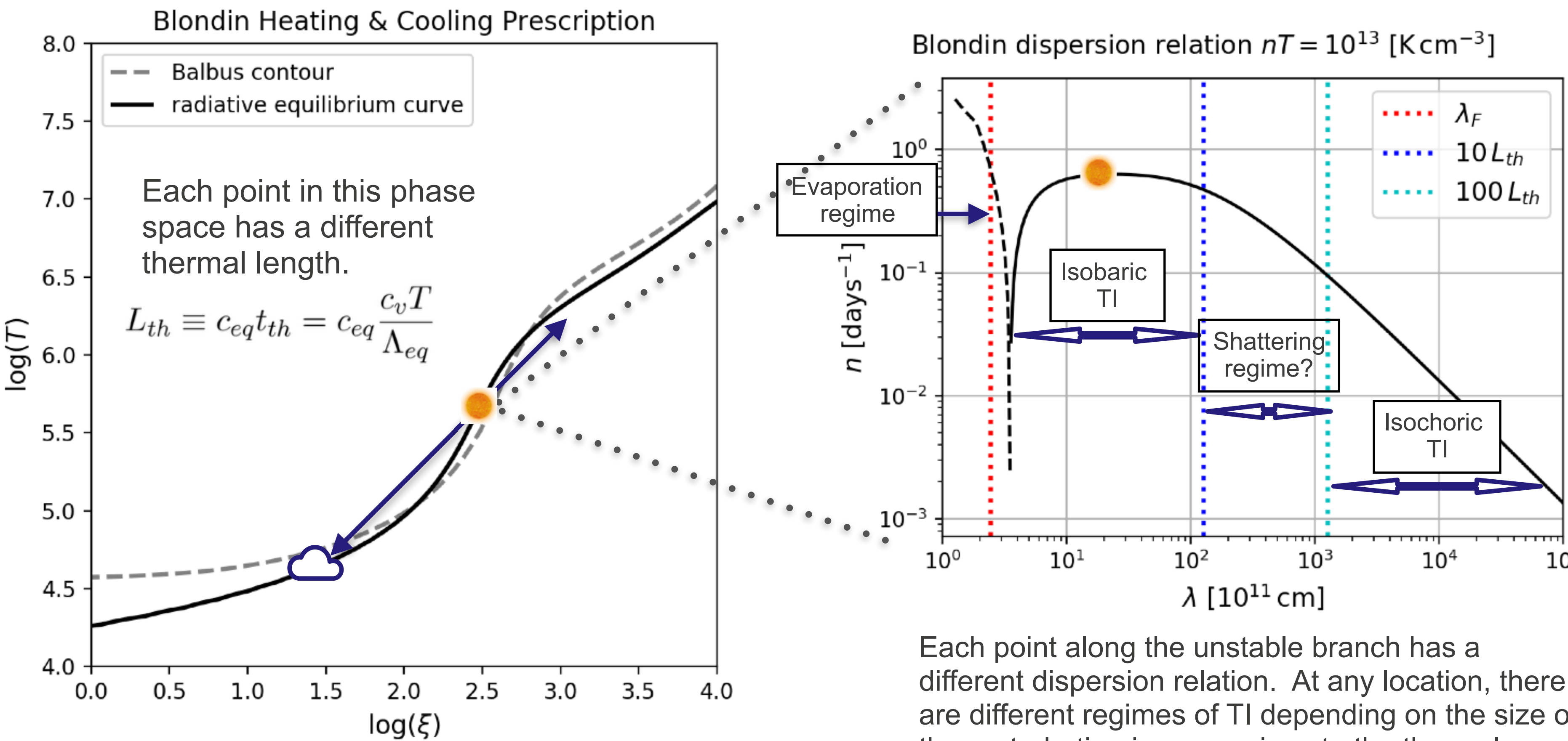
A uniform medium with a constant heating rate that cools by free-free emission has

$$\begin{aligned}\mathcal{L} &= C\rho T^{\frac{1}{2}} - H \\ &= C' p T^{-\frac{1}{2}} - H\end{aligned}$$

(Actual cooling prescription used by McCourt et al. 2012)

➔Stable to isochoric perturbations but unstable to isobaric ones

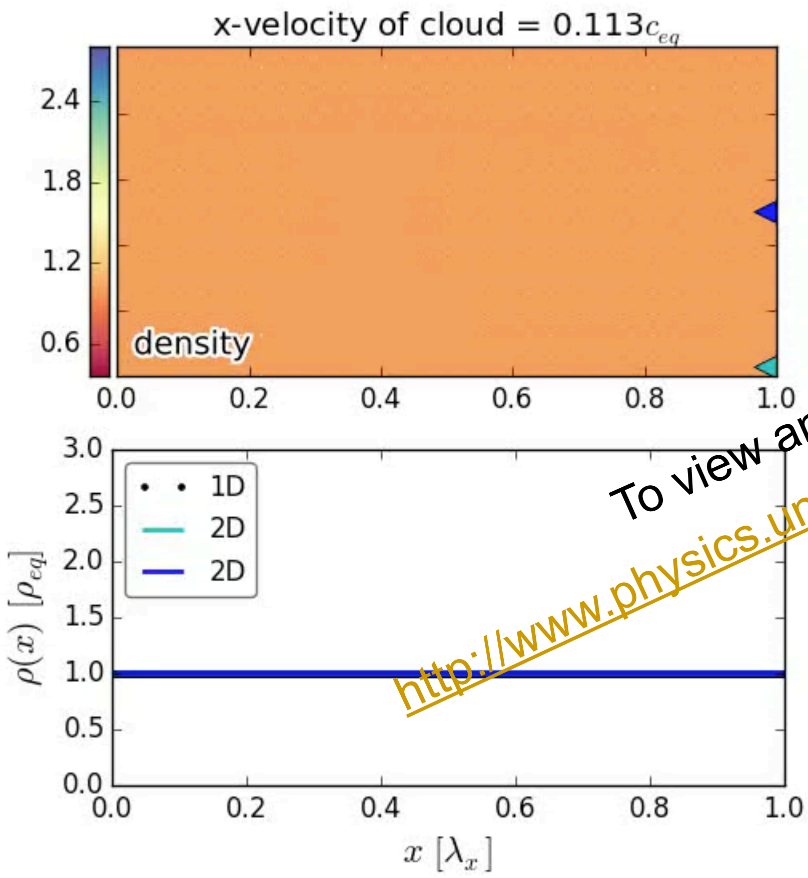
Review of TI: S-curves and instability regimes

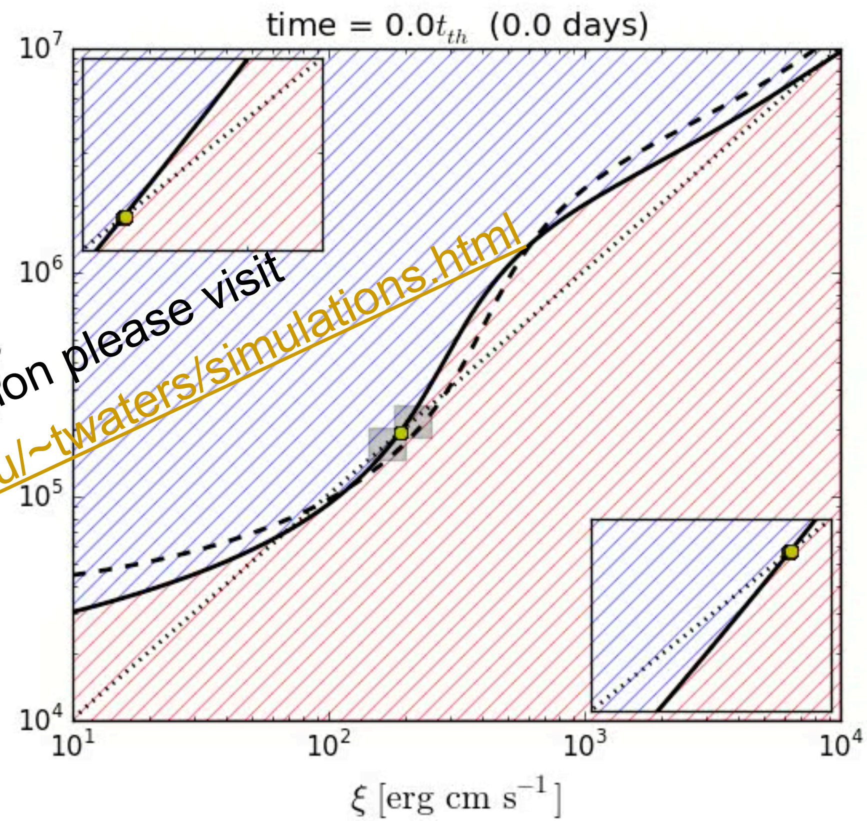


$$\xi \equiv \frac{4\pi F_X}{n} = \frac{L_X}{nr^2}$$

Each point along the unstable branch has a different dispersion relation. At any location, there are different regimes of TI depending on the size of the perturbation in comparison to the thermal length. The shattering/isochoric regimes are currently being explored (Waters & Proga, in prep.)

Review of TI: nonlinear outcome in AGN





To view animation please visit http://www.physics.unlv.edu/~twaters/simulations.html

Simulation by Tim Waters and Daniel Proga, UNLV

Local simulations of multiphase turbulence

Forced driving is appropriate

- Locally optically thick or globally high column density regions lead to self-shadowing effects that tend to randomize the radiation forces

The turbulent Mach number is the only new parameter

- This parameter can be constrained by absorption line widths

These turbulence simulations are predictive!

- They have the necessary resolution to accurately capture mixing
- They include thermal conduction, which is necessary to form interfaces and permit evaporation
- One can compute self-consistently turbulently broadened line profiles
- The computational domains can be ‘stacked’ in order to compute synthetic absorption/emission line profiles

Driven turbulence simulations use local periodic boxes. What are the important questions to ask?

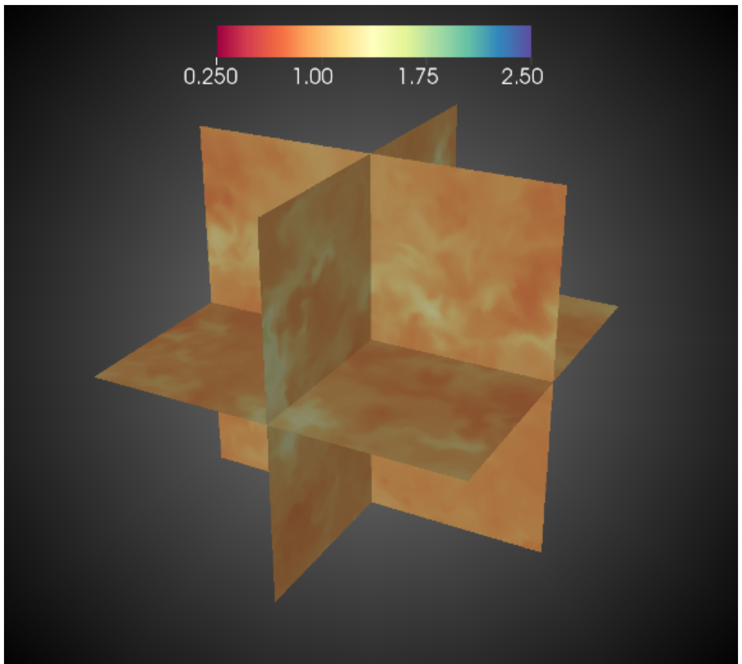
- Statistical properties?
  - Differs for supersonic vs. subsonic turbulence
  - Sensitivity to compressive vs. solenoidal driving?
- Size and slope of the inertial range?

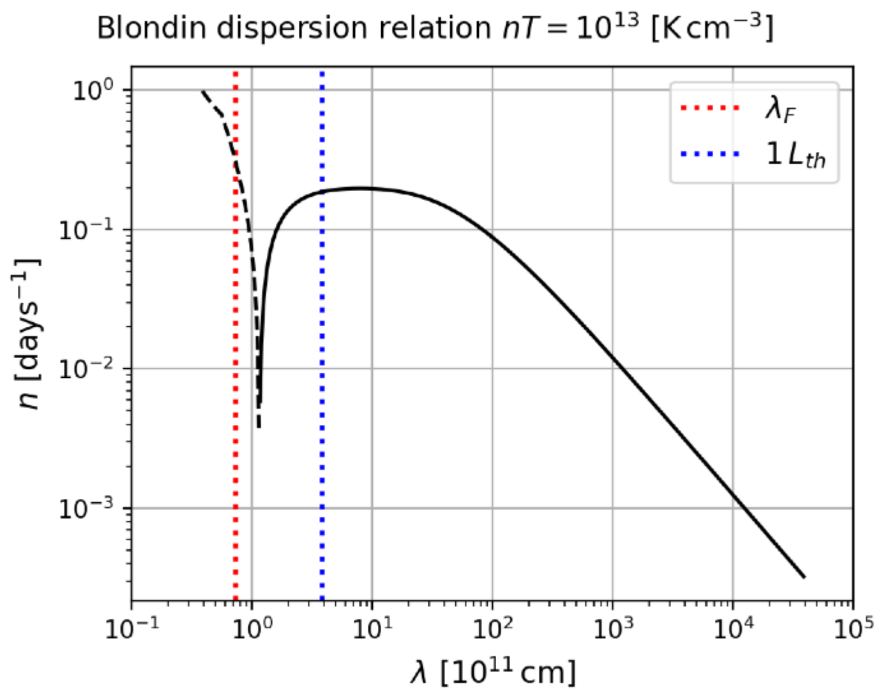
Turbulence + TI simulations also use local periodic boxes. What additional questions are there?

- What should the box size be?
- Filling factor of cold gas?
- Distribution of clump sizes and lifetimes?
- Sensitivity of properties to the unstable parameter space?

Main result: clump sizes corresponding to maximum growth rate perturbations are indeed favored

In particular, condensations don’t arise in runs with with box sizes too small to capture the fastest growing mode when the turbulent Mach number exceeds ~0.3





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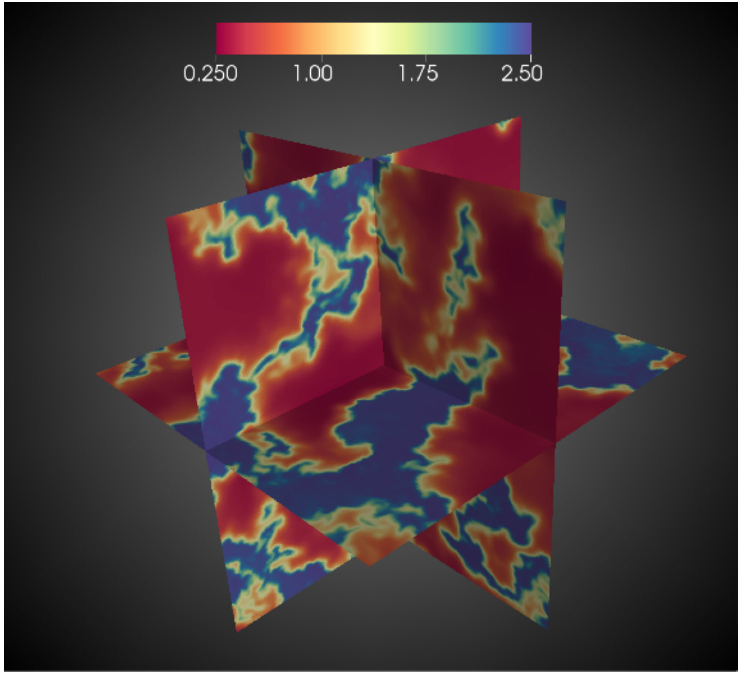
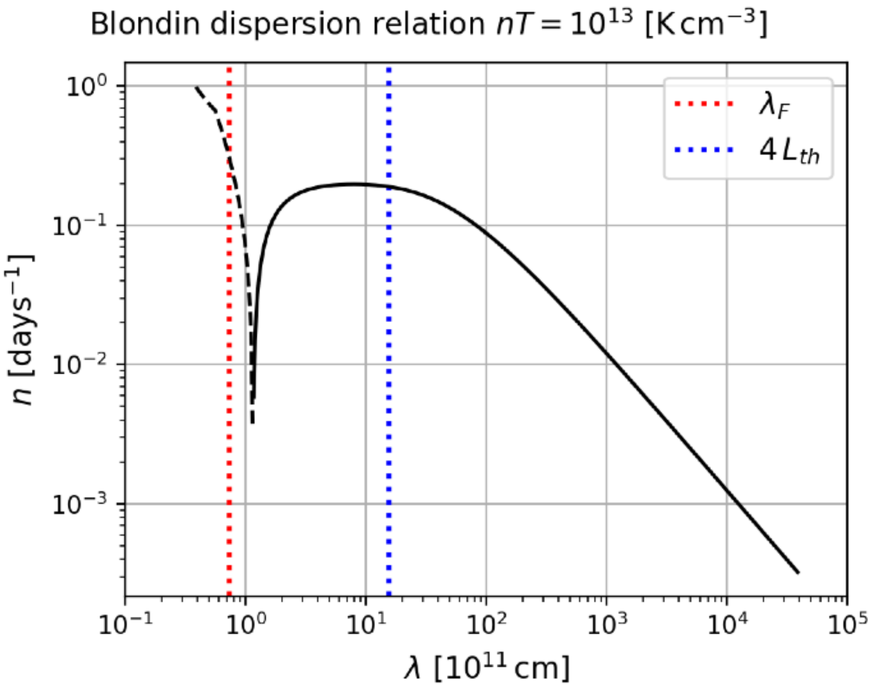
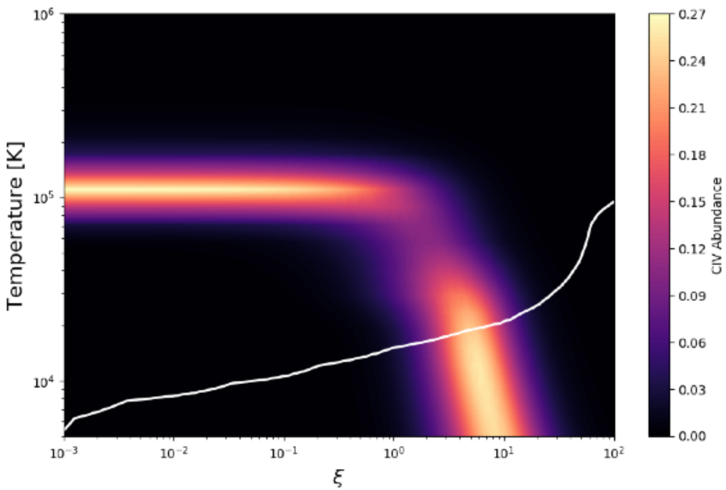




Application: turbulent TI simulations provide a physical interpretation of LOC-type models

- A ‘background’ global wind model can be used to inform parameter space, and local turbulent TI simulations apply at different distances to sample a possibly large range of cloud properties

Example of LOC model selection effects — CIV abundance map:



From Baldwin et al. (1995):

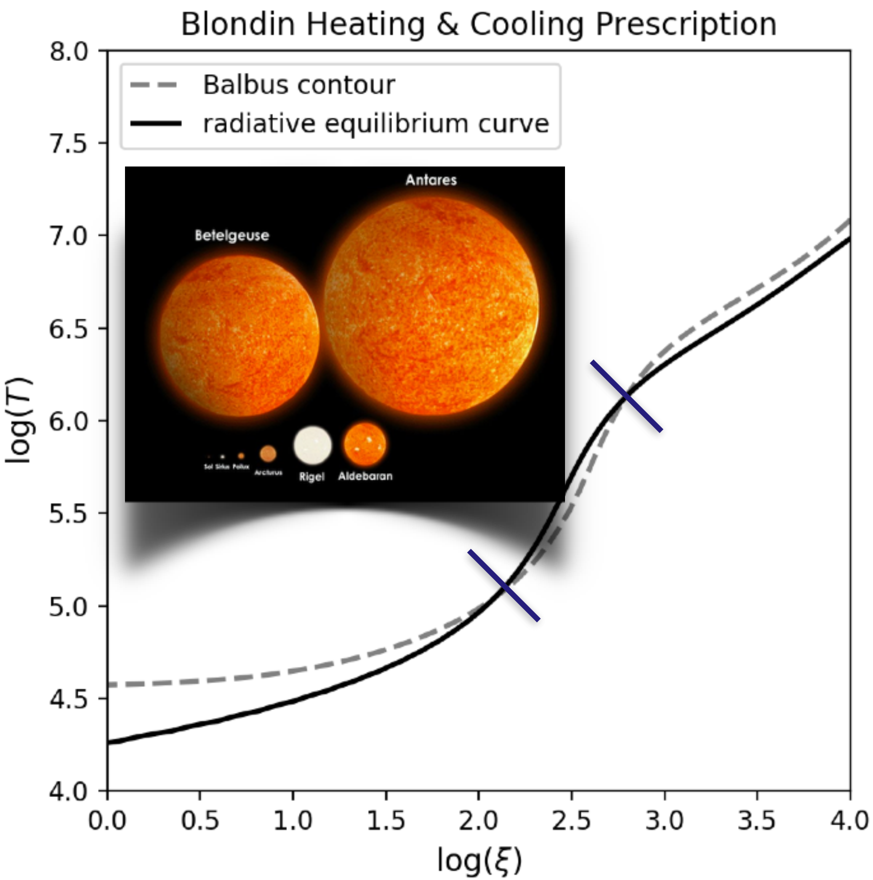
TABLE 1

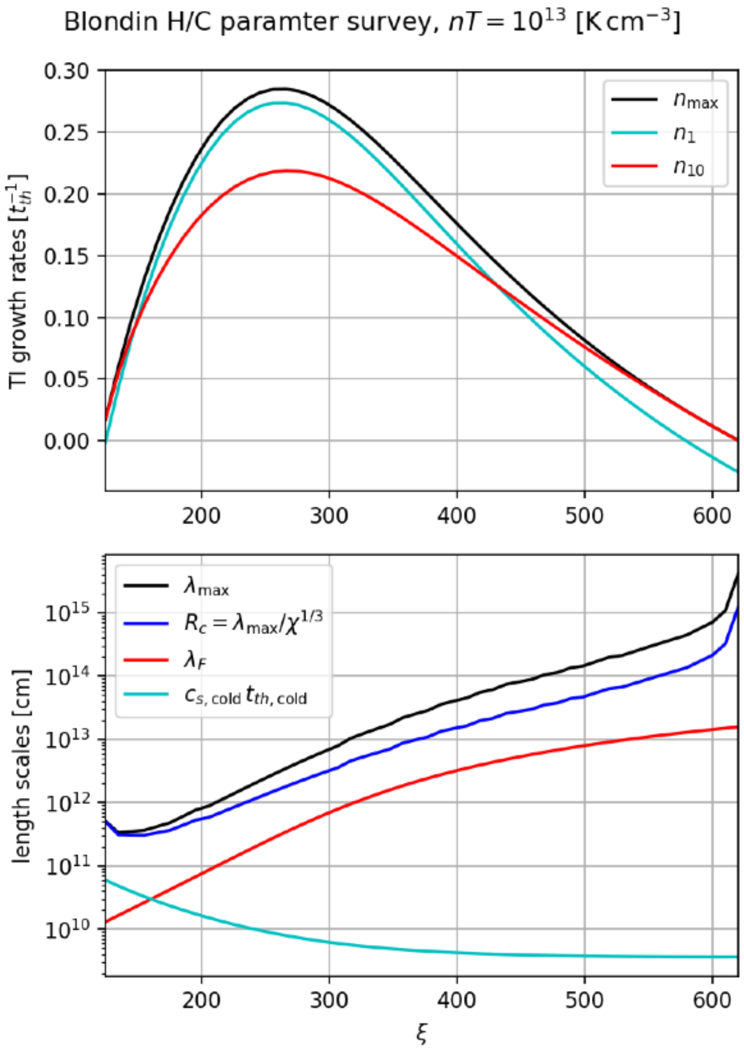
OBSERVED AND PREDICTED LINE INTENSITIES

Emission Line (1)	Observed Intensity[a] (2)	Maximum Reprocessing (3)	LOC Integration[b] (4)
O VI λ1034 + Lyβ λ1026........	0.1–0.3	0.28	0.16
Lyα λ1216	1.00	1.00	1.00
N V λ1240	0.1–0.3	0.06	0.04
Si IV λ1397 + O IV] λ1402......	0.08–0.24	0.08	0.06
C IV λ1549.......................	0.4–0.6	0.54	0.57
He II λ1640 + O III] λ1666......	0.09–0.2	0.11	0.14
C III] + Si III] + Al III λ1900....	0.15–0.3	0.28	0.12
Mg II λ2798......................	0.15–0.3	0.38	0.34
Hβ λ4861........................	0.07–0.2	0.08	0.09

[a] Intensity relative to Lyα λ1216, combining data from Baldwin et al. 1989, Boyle 1990, Cristiani & Vio 1990, Francis et al. 1991, Laor et al. 1995, Netzer et al. 1995, and Weymann et al. 1991.
[b] Co-addition of emission from clouds as described in the text.

Parameter space of TI





Conclusions

- Driven (3D periodic box) turbulence simulations of TI…

1. allow simulating a local patch of a clumpy outflow

3. properly capture mixing and evaporation

5. pick out cloud sizes corresponding to the maximum TI growth rate

7. are a realization of LOC-type models

See Waters & Li (in preparation)

Can spectral fitting (using say XSPEC) that incorporates this theory of turbulent condensations be performed?