Radiation Hydrodynamics of Dust-Driven Winds in Starburst and Star-Forming Galaxies

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The University of Virginia

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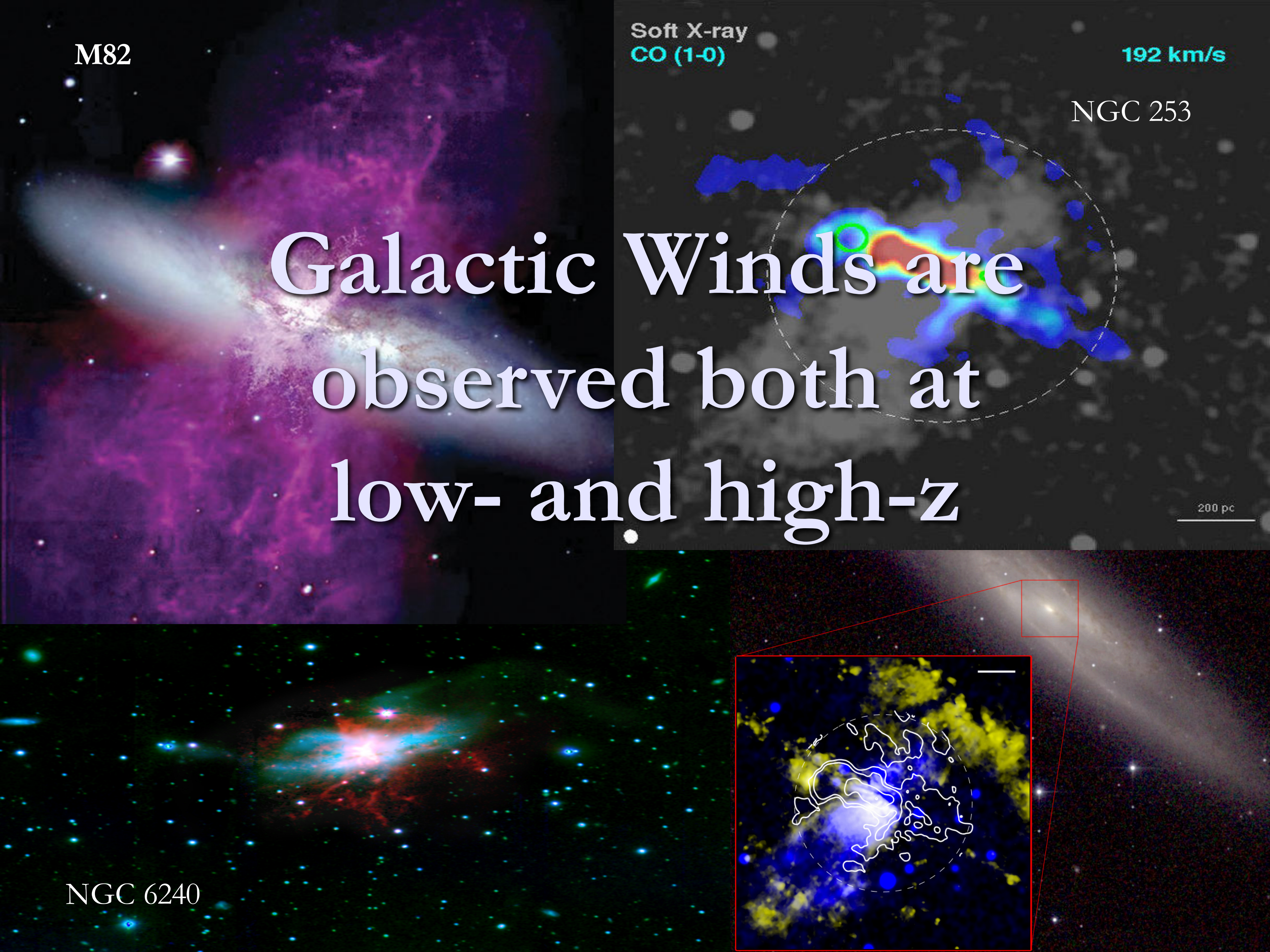
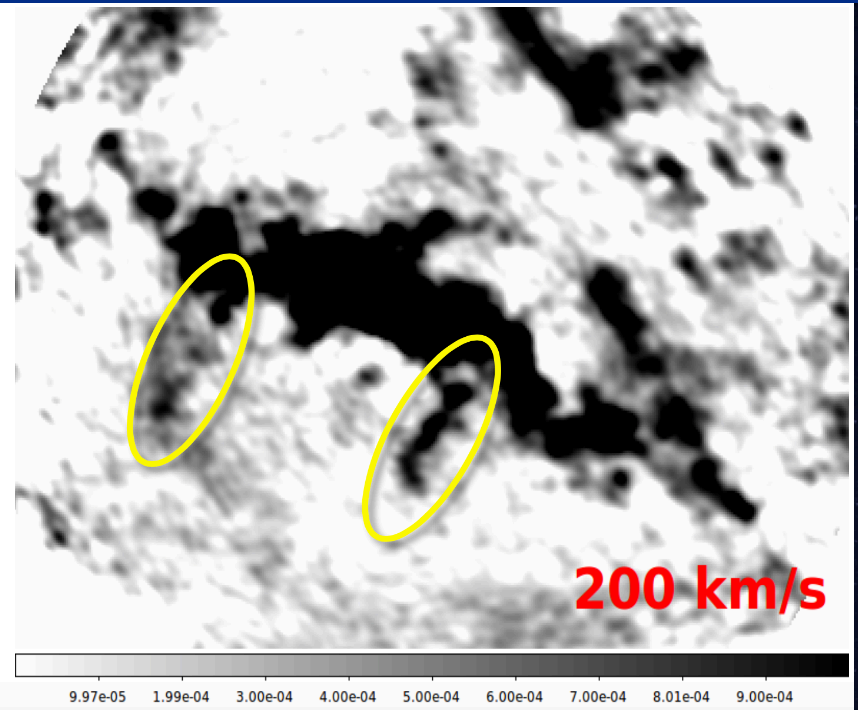
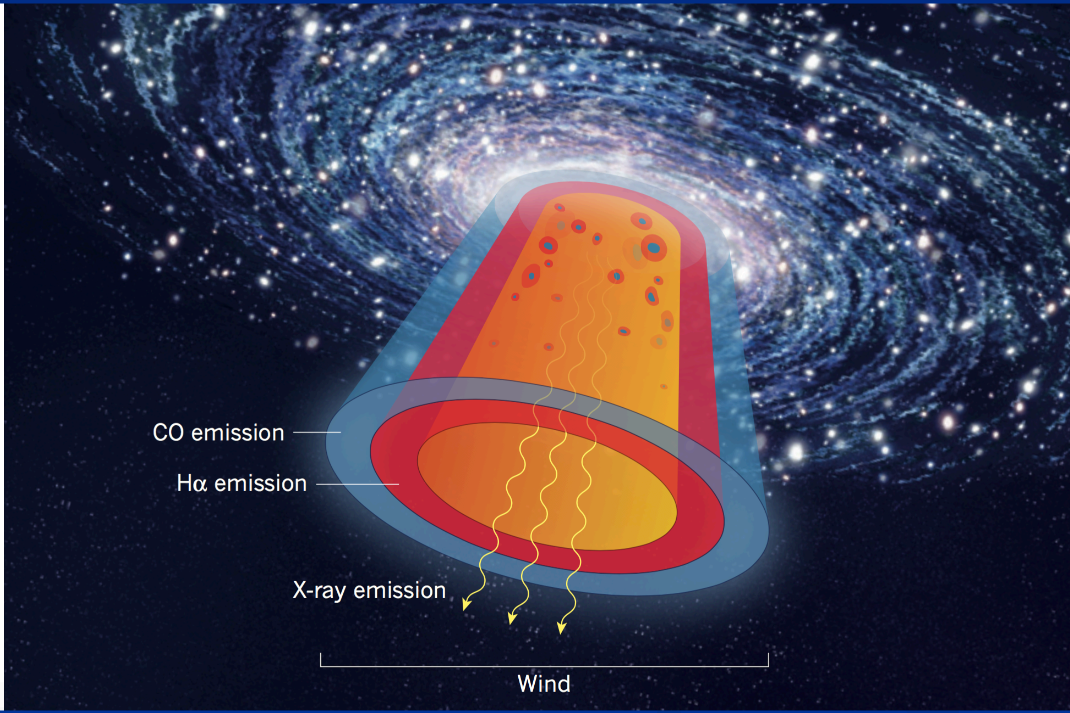
Jekyll Island, June 29, 2017

Galactic Winds are observed both at low- and high-z



Multi-Phase Structure of Galactic Winds





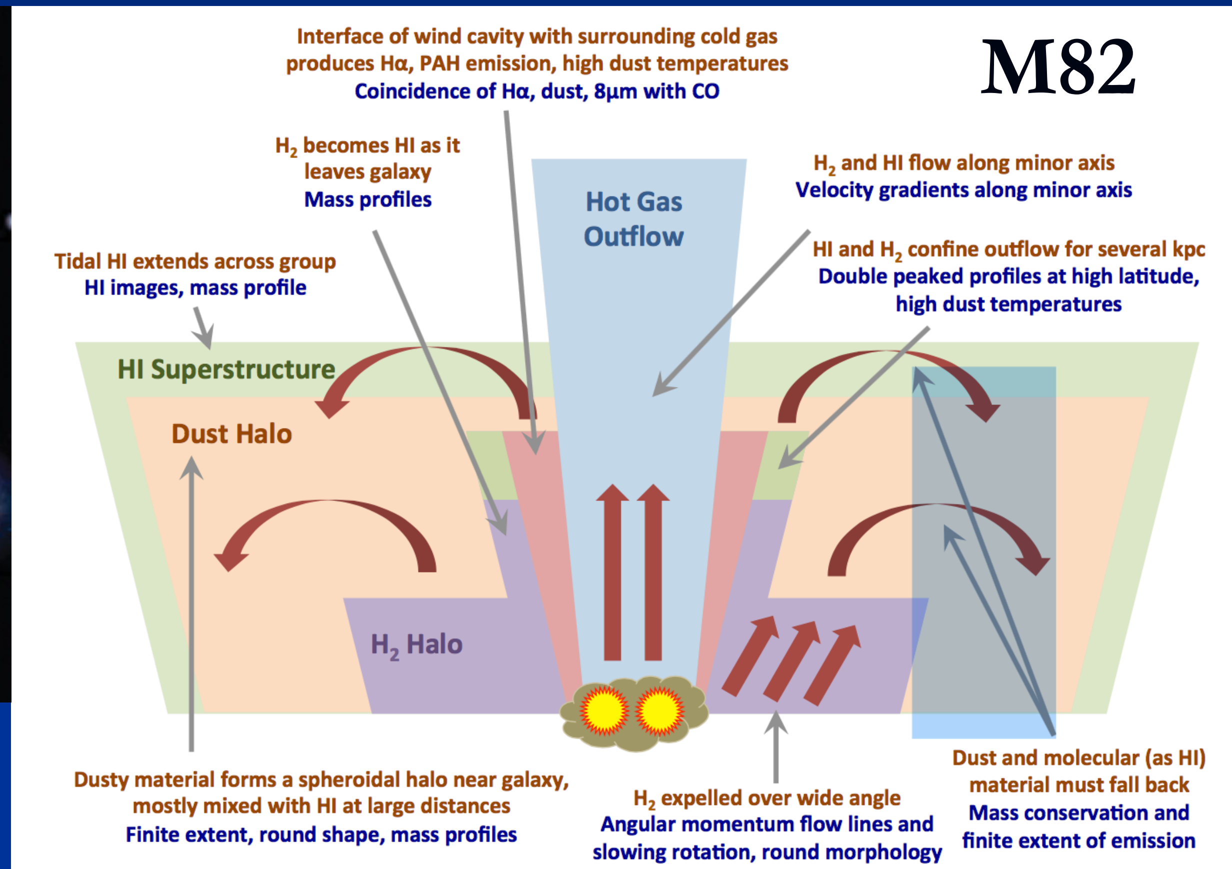
NGC 253

Jekyll Island, June 29, 2017

Westmoquette 2013

Multi-Phase Structure of Galactic Winds

Hubble & WIYN



Leroy et al. 2015

On the Theory of Galactic Winds

Hot Winds Driven by Supernovae	• ***CC85 model:*** Chevalier & Clegg (1985) • ***Constrain CC85 model parameters by observation*** (Strickland & Heckman 2009, Zhang+ 2015) • ***Local and Global Simulations*** (Creasey+ 2013; Martizzi+ 2016; Fielding+ 2017; Zhang+ 2017 in preparation) • ***Cloud Acceleration by Ram Pressure of Hot Winds*** (Scannapieco & Bruggen 2015; Bruggen & Scannapieco 2016; Schneider & Robertson 2017; Zhang et al. 2017) • ***Cloud Formation in Hot Winds*** (Thompson+2016)
Radiation Pressure on Dust	○ ***Analytic Models*** (Murray et al. 2005; Murry 2007; Thompson+ 2015) ○ ***Observational Evidence*** (Martin 05; Andrews & Thompson 2011; Zhang & Thompson 2012) ○ ***Radiation Simulations on Momentum Coupling*** (Krumholz & Thompson 2012, 2013, Davis+ 2014; Zhang & Davis 2017) ○ ***Cloud Acceleration Simulations*** (Zhang+ 2017 in preperation)
Cosmic-Ray Driven	• ***Analytic Models*** (Ipavich 1975; Socrates+ 2008; Everett+ 2008) • ***Numerical Simulations*** (*Booth*+ 2013; Wiener+ 2016; Ruszkowski+ 2016)

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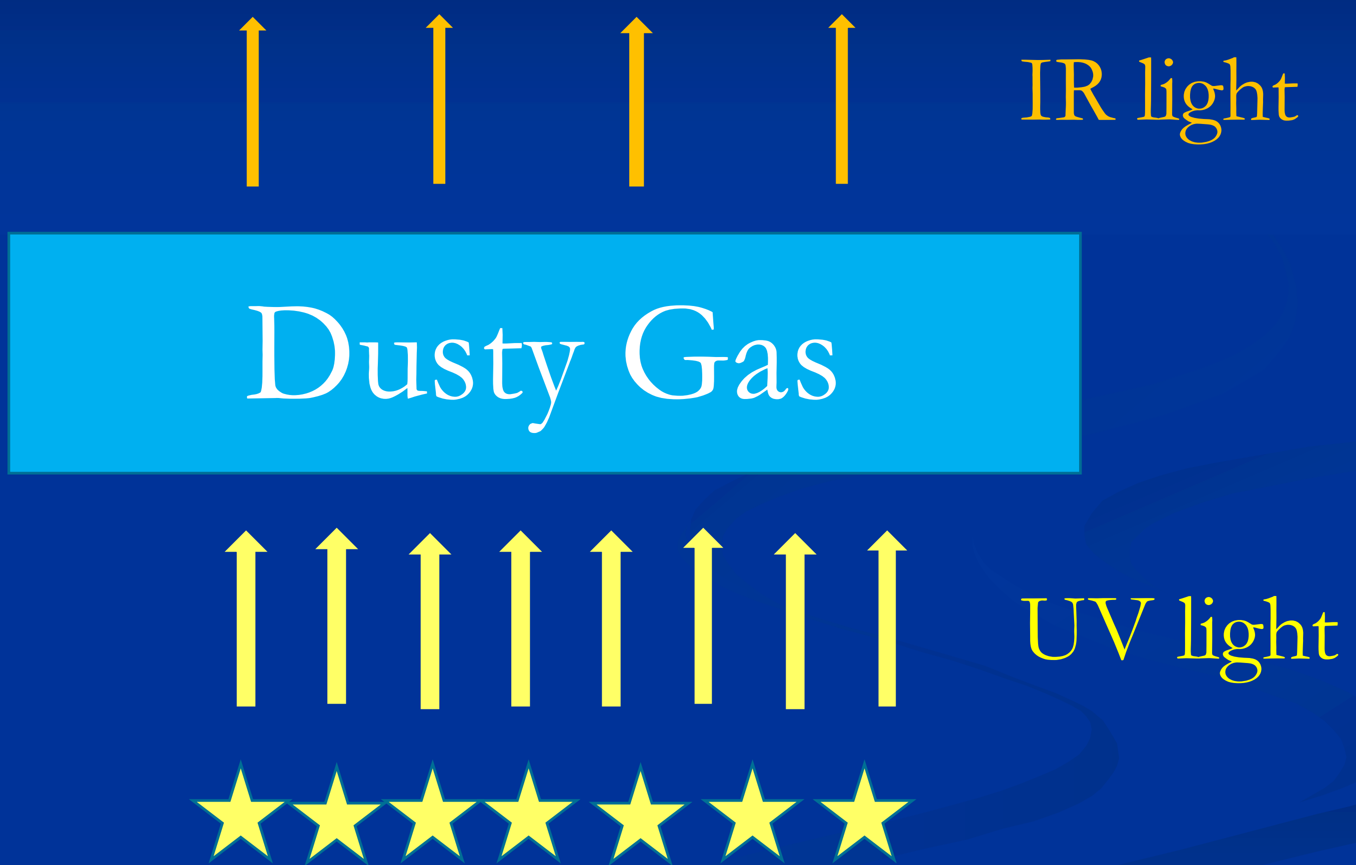
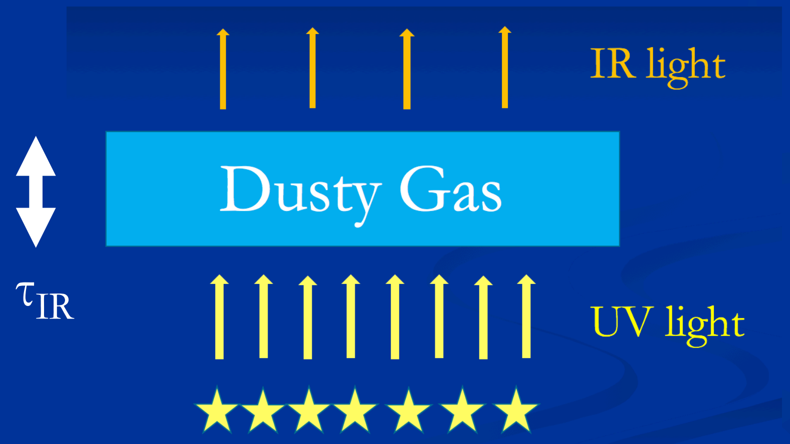
Radiation Pressure Driven Wind in Starbursts and Star-Forming Galaxies



Gas-Radiation Interaction
Radiation Hydrodynamic Simulations

- **Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?**

$$\frac{dp_{\rm wind}}{dt} \simeq (1 + \eta\tau_{\rm IR})\frac{L}{c}$$



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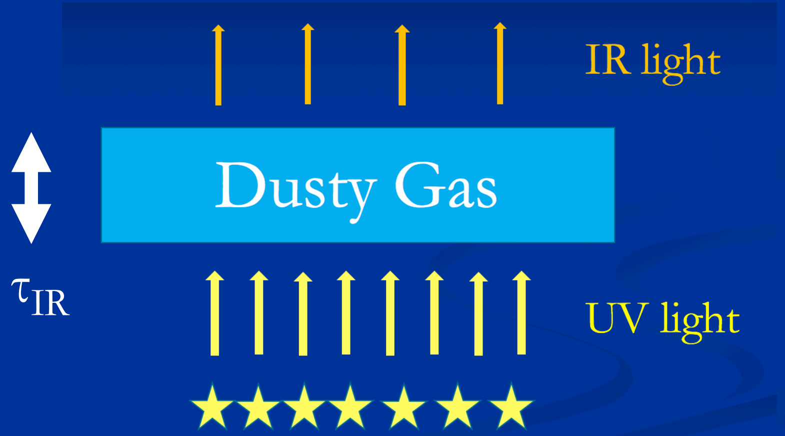


Gas-Radiation Interaction
Radiation Hydrodynamic Simulations

- Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?

$$\frac{dp_{\mathrm{wind}}}{dt} \simeq (1 + \eta\tau_{\mathrm{IR}})\frac{L}{c}$$

- η = 1, analytic model (Murray, Quataert & Thompson 2005; Thompson et al. 2015)
- η << 1 (Krumholz & Thompson 2012, 2013)

Gas-Radiation Interaction
Radiation Hydrodynamic Simulations

- Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?

$$\frac{dp_{\rm wind}}{dt} \simeq (1 + \eta\tau_{\rm IR})\frac{L}{c}$$

- We need a more sophisticated algorithm than previous numerical simulations.

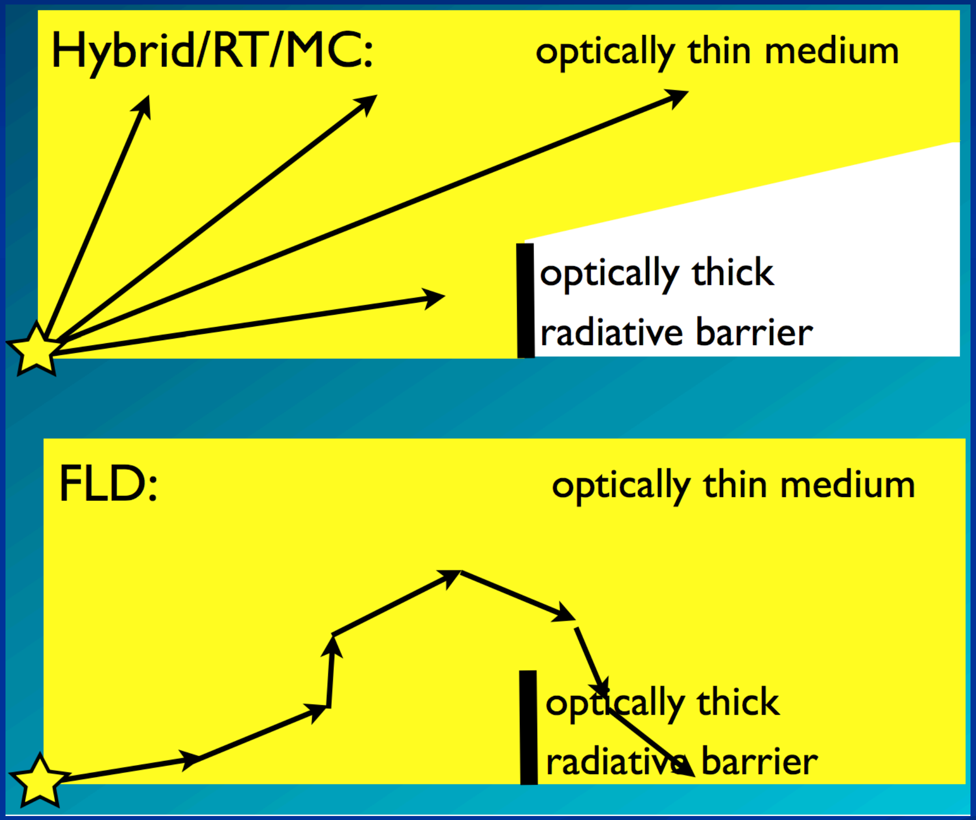
Radiation-Pressure on Dusts: RHD Simulation

Ray Tracing

$$\mathbf{F}_\nu(\mathbf{r}) = \frac{1}{4\pi} \int_{\mathbf{\Omega}} I_\nu(\mathbf{r}, \mathbf{\Omega})\, \mathbf{\Omega}\, d\mathbf{\Omega},$$

Flux Limited Diffusion

$$\mathbf{F}_r = -\frac{c\lambda}{\sigma_F} \nabla E_r$$



Kuiper 2014

Radiation-Pressure on Dusts: RHD Simulation

Ray Tracing

$$\mathbf{F}_\nu(\mathbf{r}) = \frac{1}{4\pi}\int_{\mathbf{\Omega}} I_\nu(\mathbf{r}, \mathbf{\Omega})\, \mathbf{\Omega}\, d\mathbf{\Omega},$$

Flux Limited Diffusion (FLD)

$$\mathbf{F}_r = -\frac{c\lambda}{\sigma_F}\nabla E_r$$

Variable Eddington Tensor (VET)

$$\hat{n}\cdot\nabla I = \sigma_F\left(\frac{a_r c}{4\pi}T^4 - I\right)$$

$$\mathsf{f} = \frac{\mathsf{P}_r}{E_r} = \frac{\int I(\hat{n})\mu_i\mu_j d\Omega}{\int I(\hat{n}) d\Omega}$$

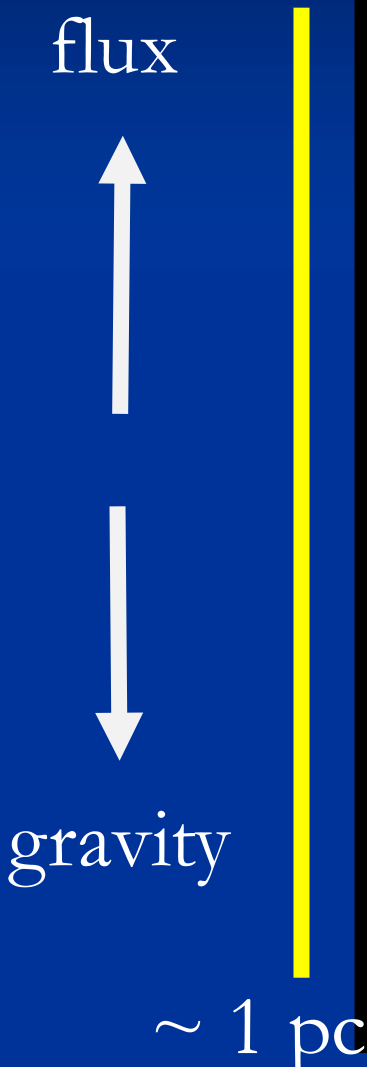
$$E_{\rm rad} = \frac{4\pi}{c}\int_0^\infty J_\nu d\nu,$$

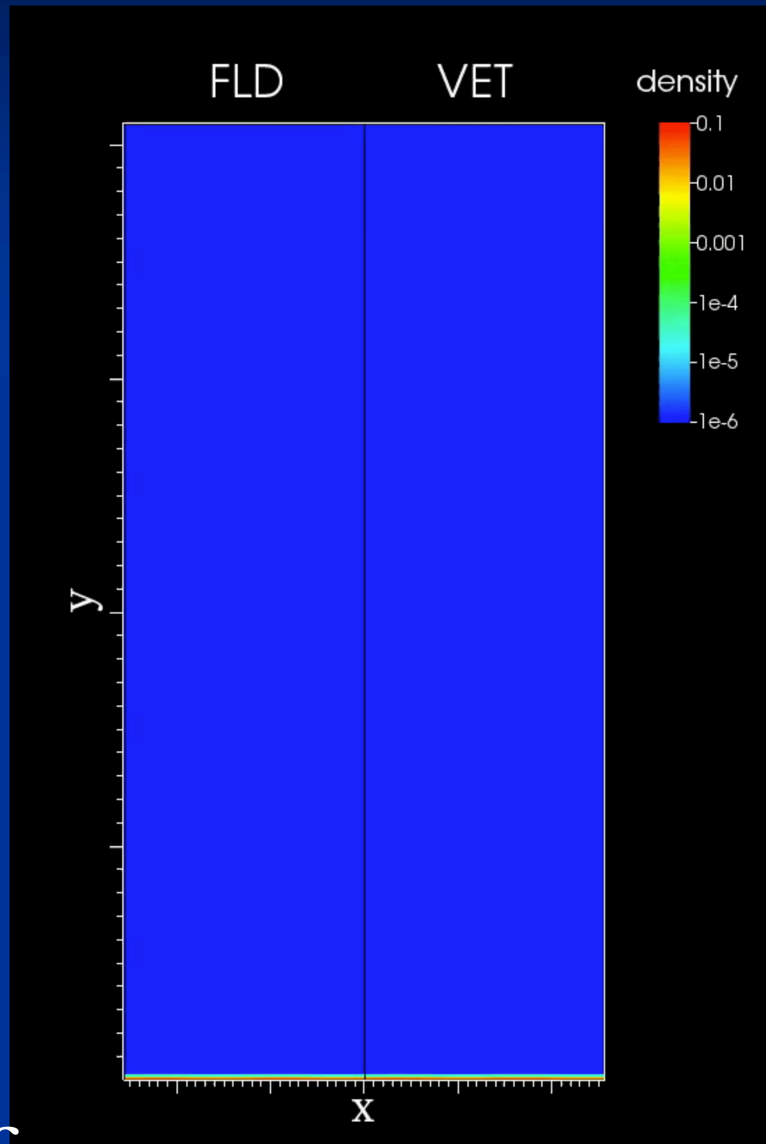
$$\mathbf{F}_{\rm rad} = 4\pi\int_0^\infty \mathbf{H}_\nu d\nu,$$

$$\mathsf{P}_{\rm rad} = \frac{4\pi}{c}\int_0^\infty \mathsf{K}_\nu d\nu.$$

Davis et al. 2014

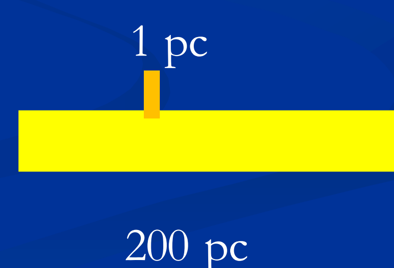
FLD vs VET





Sub-Eddington System

$$f_{\mathrm{E},*} = \frac{\kappa_{\mathrm{R},*} F_*}{gc}$$

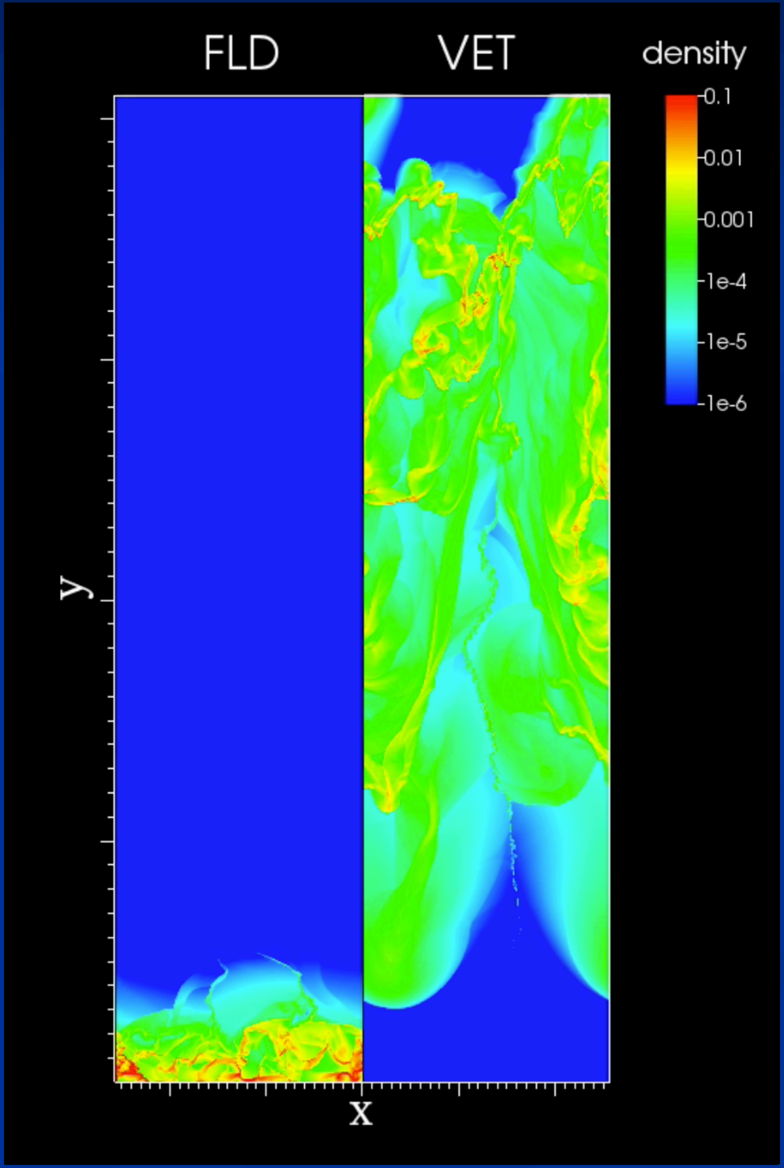


Davis et al. 2014

FLD vs VET

flux

gravity



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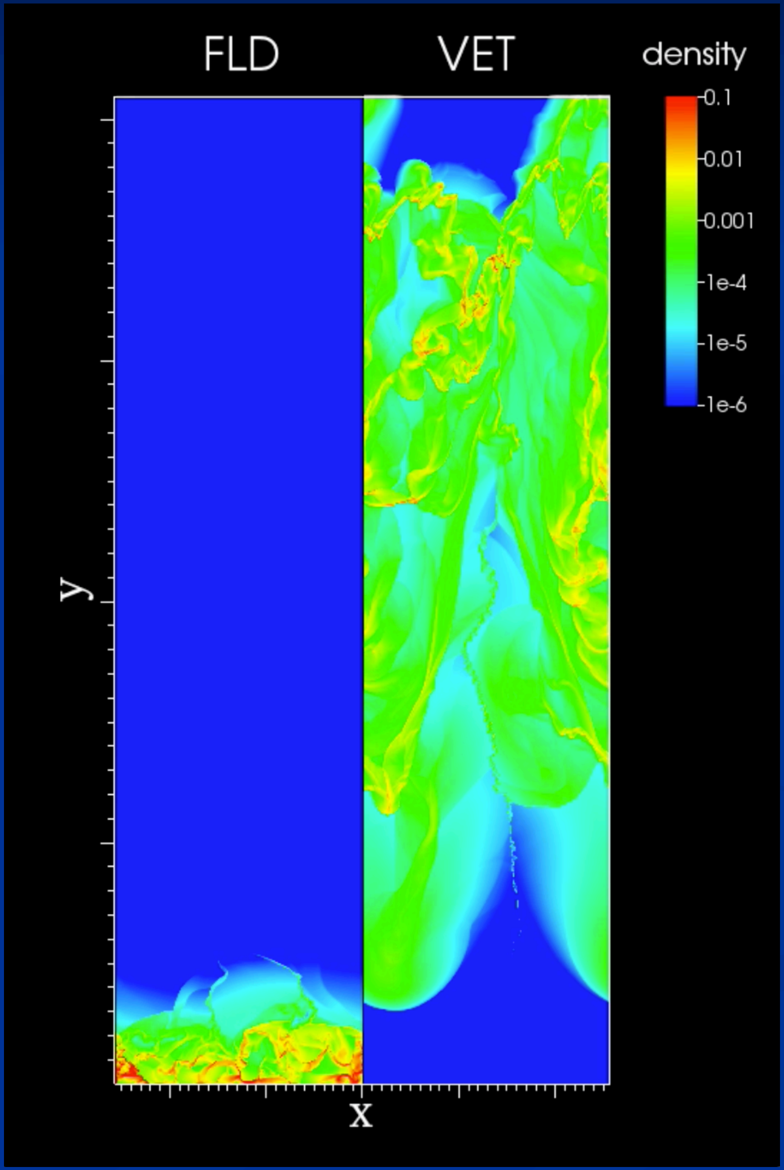
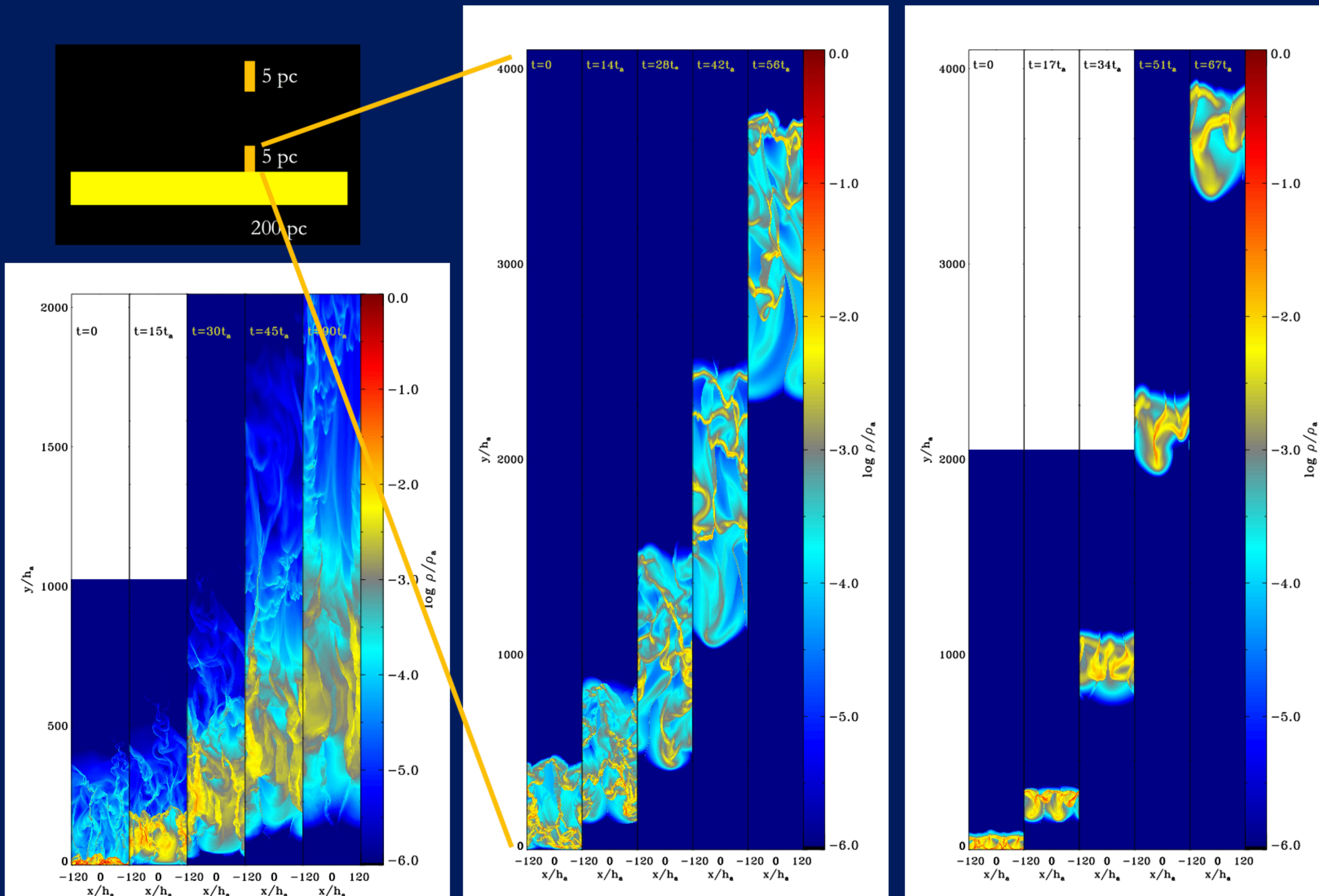


$$f_{\mathrm{E},*} \rightarrow \infty$$

Zhang & Davis 2017

FLD vs VET

Zhang & Davis 2017



τ_{IR}=3, gravity free, FLD method

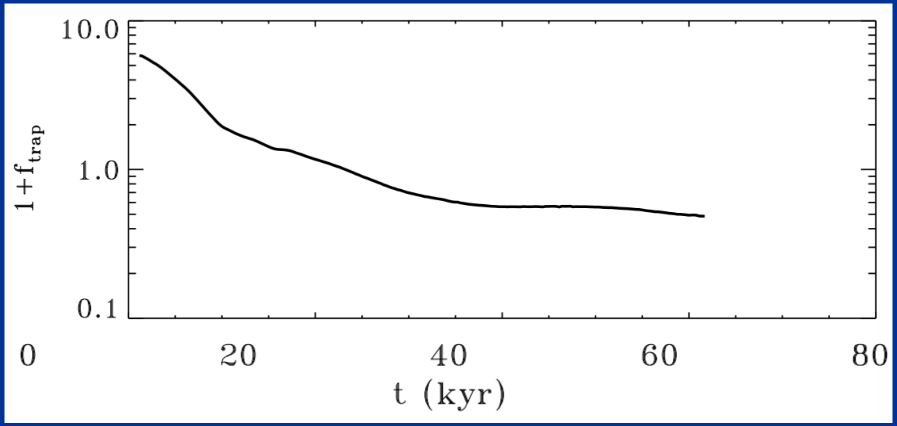
τ_{IR}=3, gravity free, VET method

τ_{IR}=1, gravity free, VET method

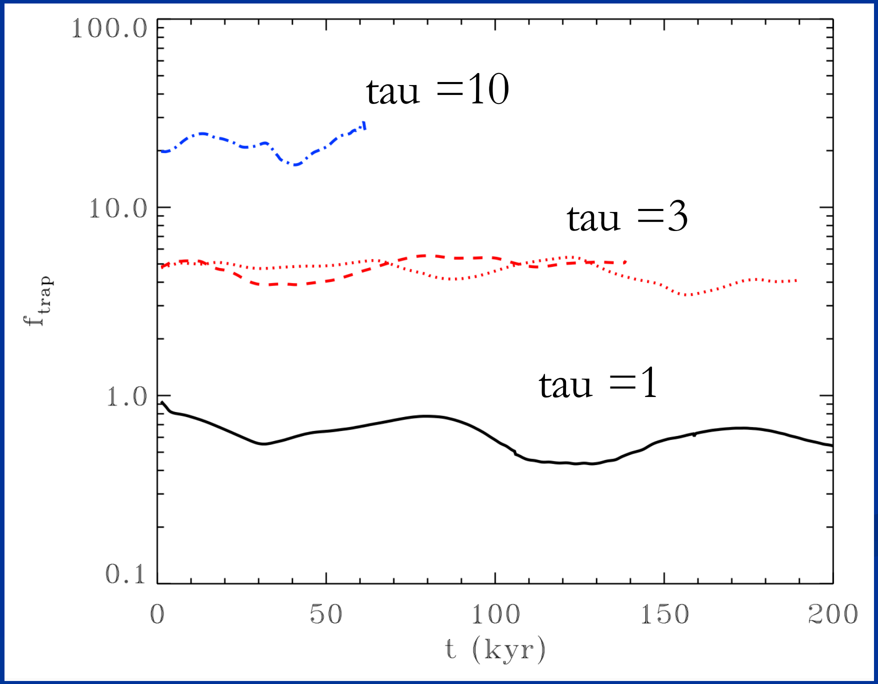
Trapping Factor
(Measure the Momentum Coupling)

$$\frac{dp_{\rm wind}}{dt} \simeq (1 + f_{\rm trap})\frac{L}{c}$$

FLD



VET



Zhang & Davis 2017

Brief Summary

- **Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?**

$$\frac{dp_{\rm wind}}{dt} \simeq (1 + \eta\tau_{\rm IR})\frac{L}{c}$$

$\tau_* = 1, 3, 10$

$\tau_{\rm IR} = 1.8, 7.9, 48.5$

$\eta = 0.90, 0.69, 0.47$

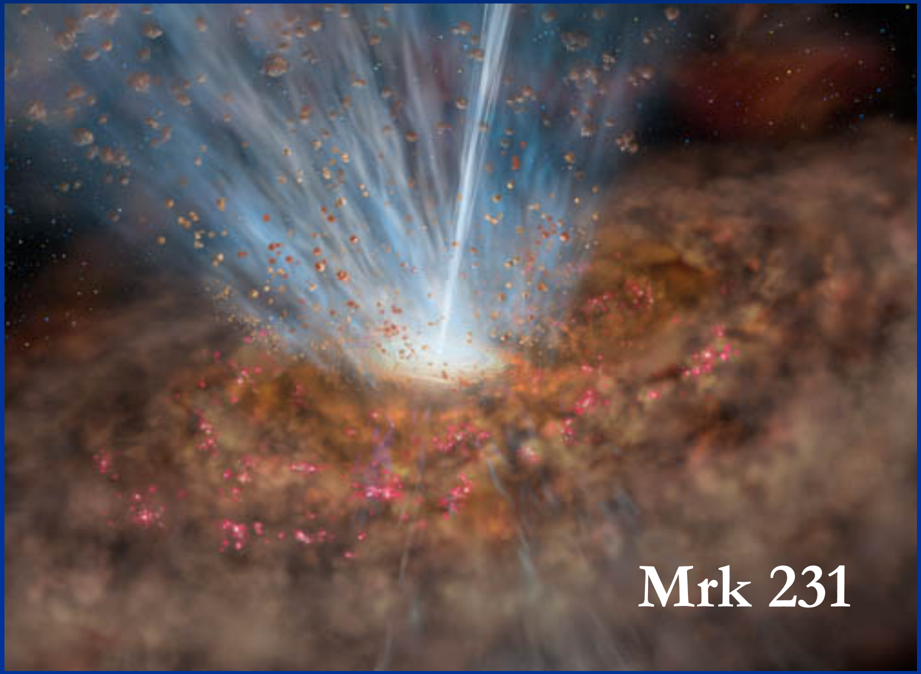
Brief Summary

- Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?

$$\frac{dp_{\rm wind}}{dt} \simeq (1 + \eta\tau_{\rm IR})\frac{L}{c}$$

- $\eta \sim 0.5$ -0.9

LIRGs and ULIRGs

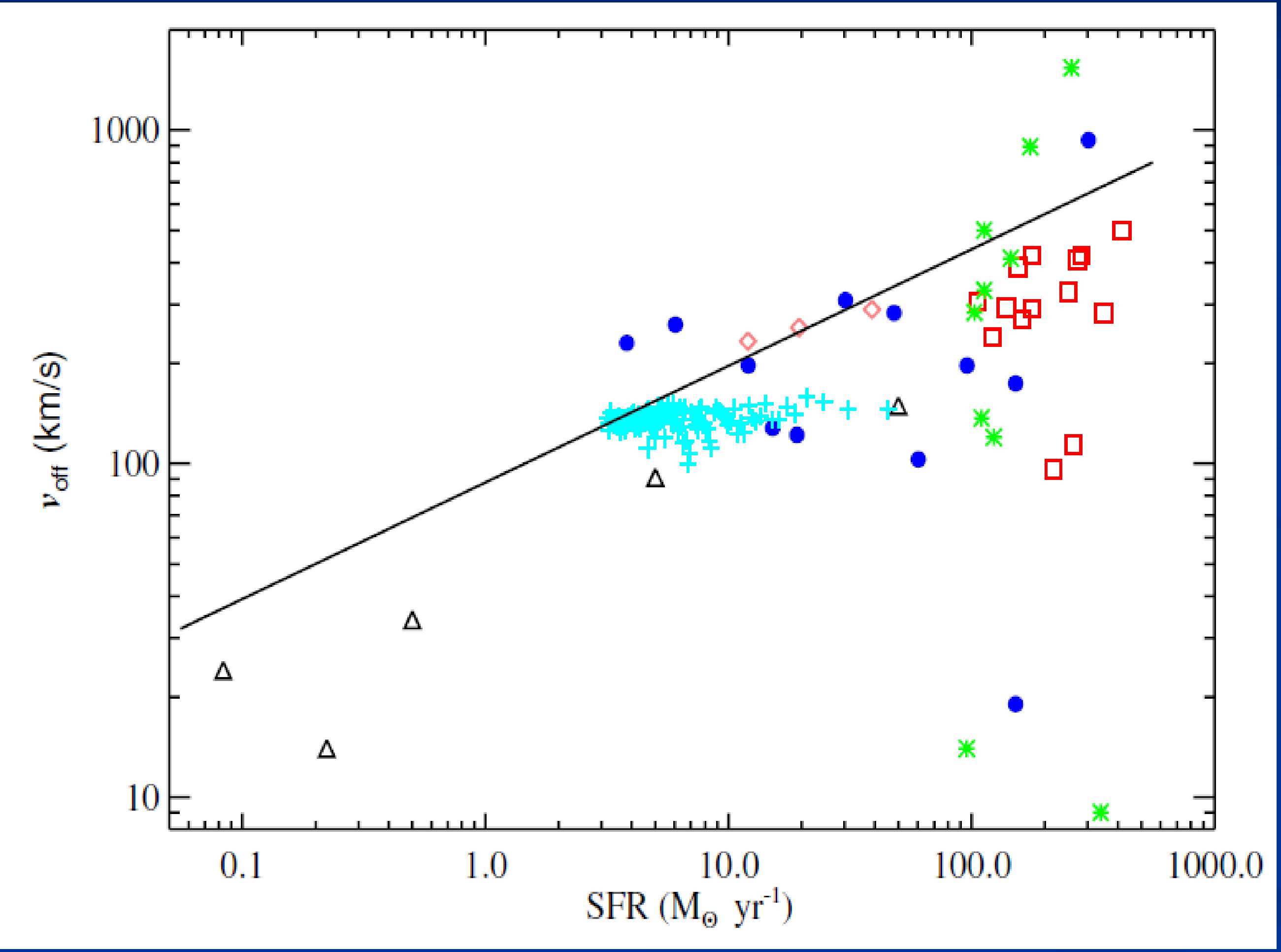


$f_{E,*} \sim 0.3$
$\tau_* \sim 30$

$f_{E,*} \sim 0.8$
$\tau_* \sim 230$

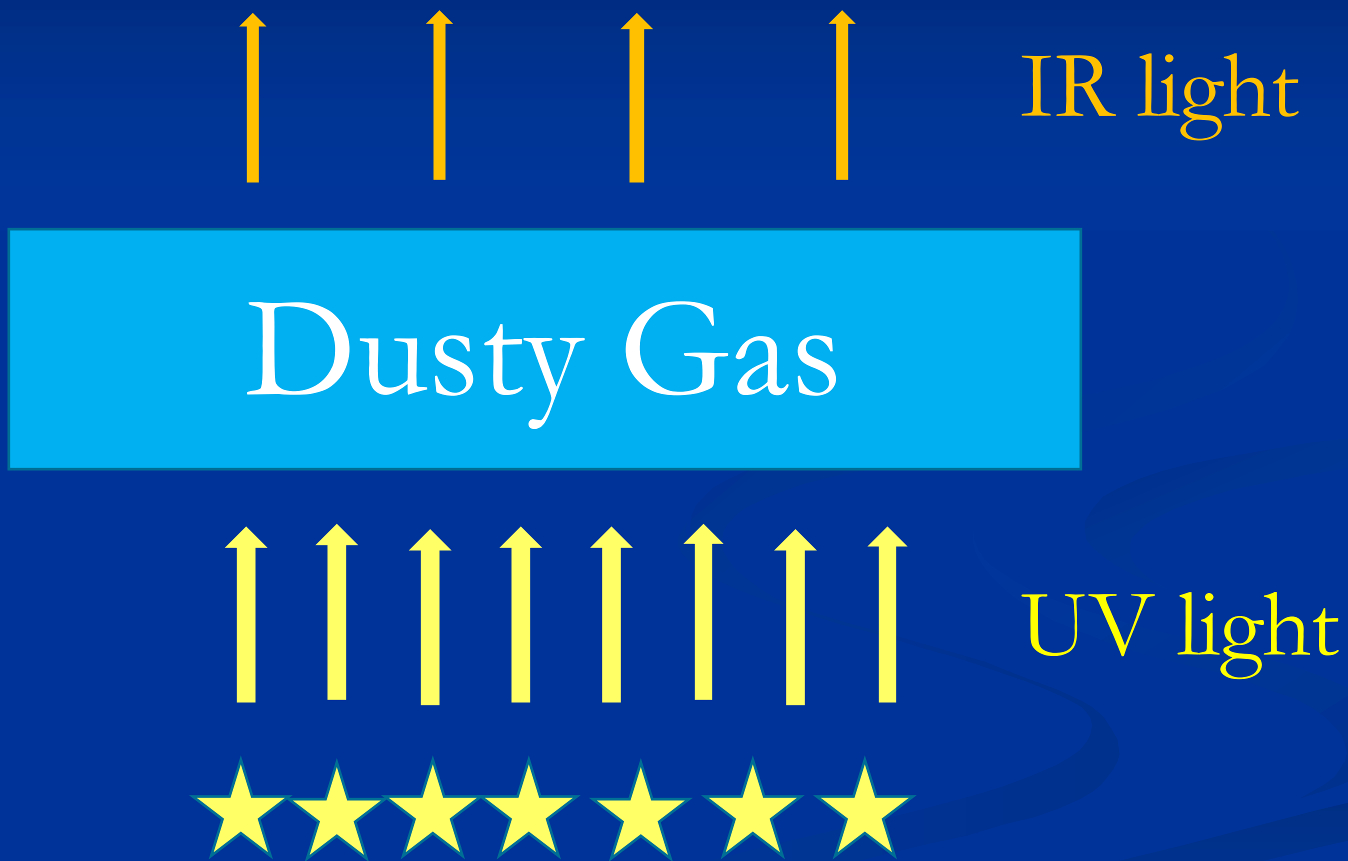
Cloud Acceleration in Radiation Field

Observation: Cloud Outflows in Star-Forming Galaxies (z<1)

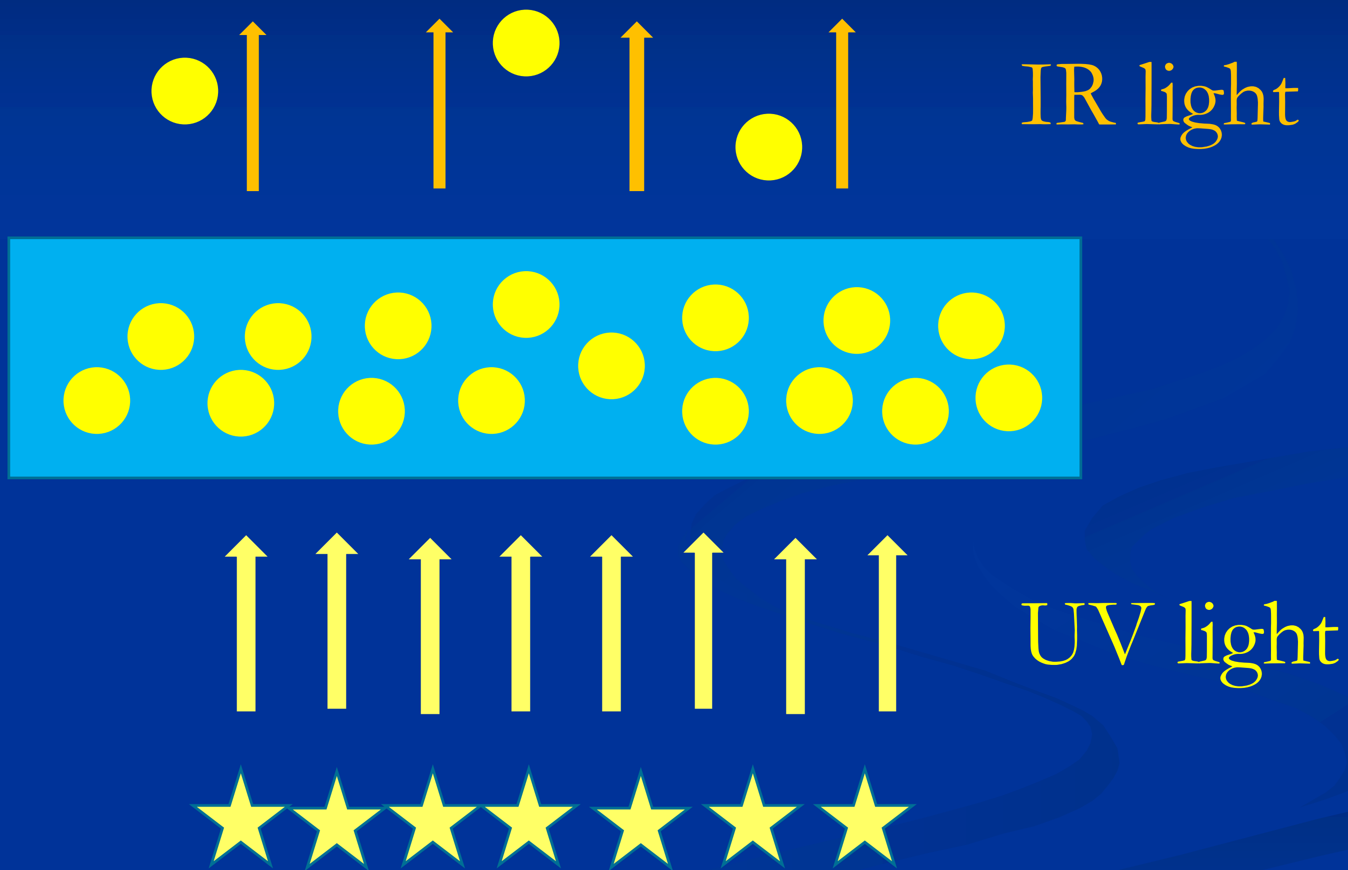


Chen et al. 2010

Radiation Pressure Driven Wind in Starbursts and Star-Forming Galaxies

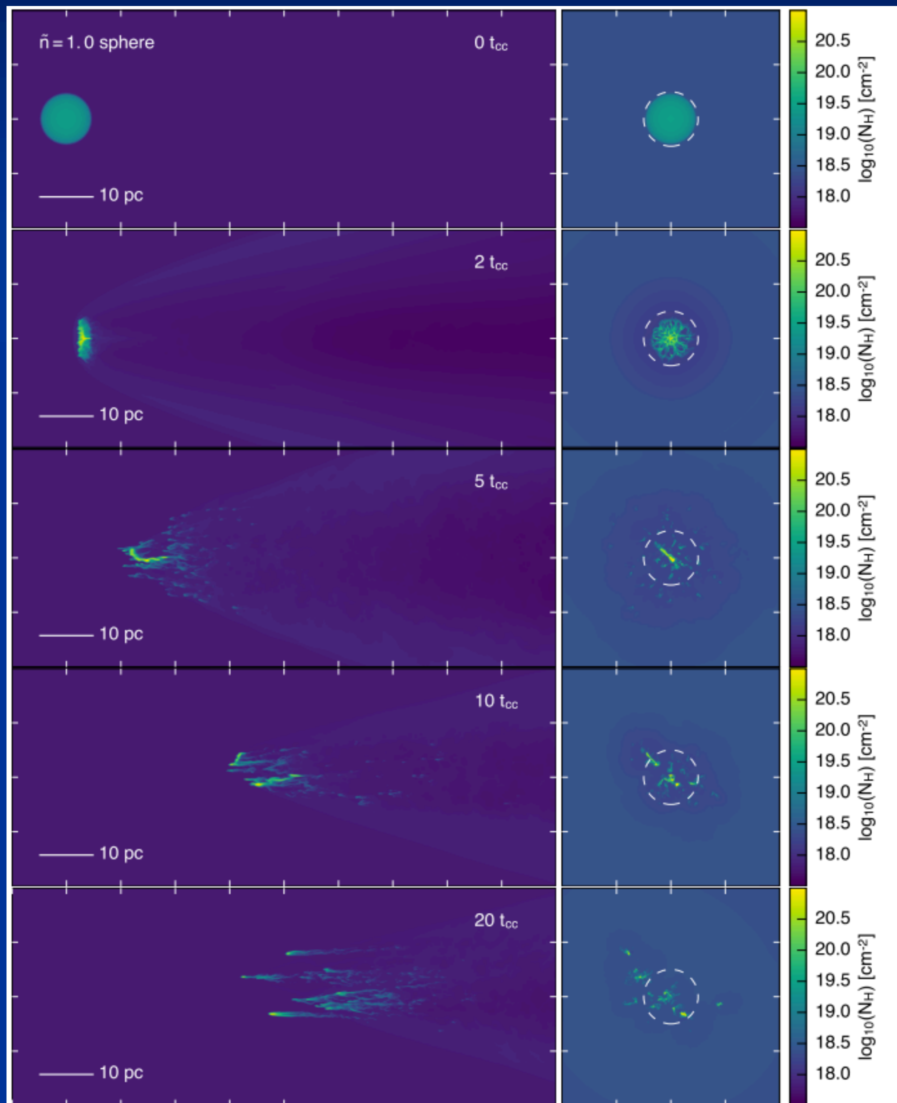


Radiation Pressure Driven Clouds ?

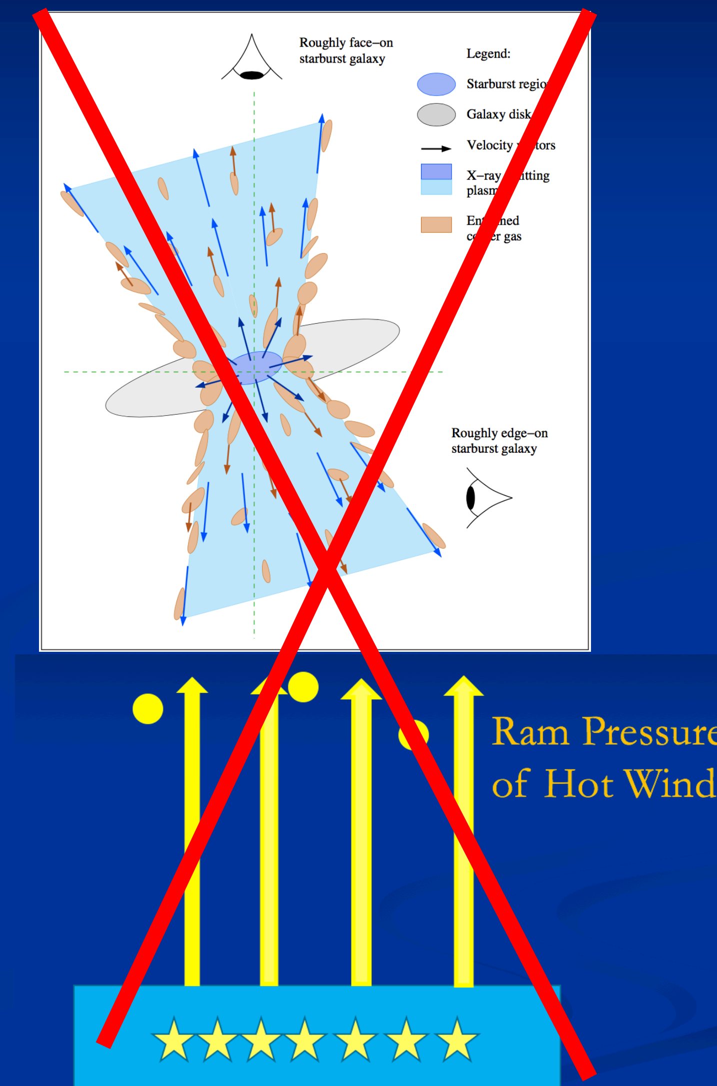


Ram Pressure Driven Clouds in Starbursts and Star-Forming Galaxies

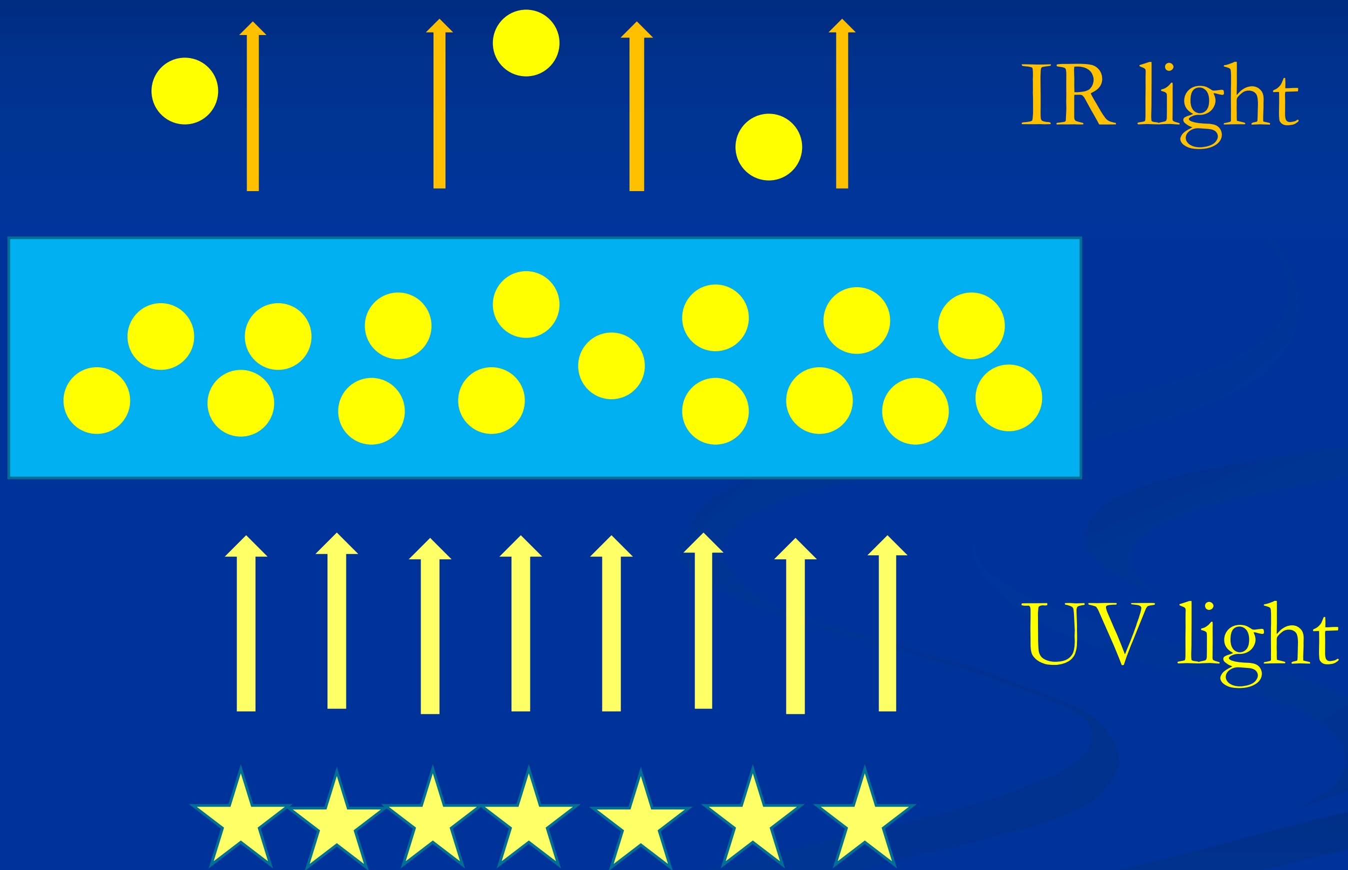
Cloud Acceleration by Hot Wind



Schneider & Robertson (2017)



Cloud Acceleration by Radiation



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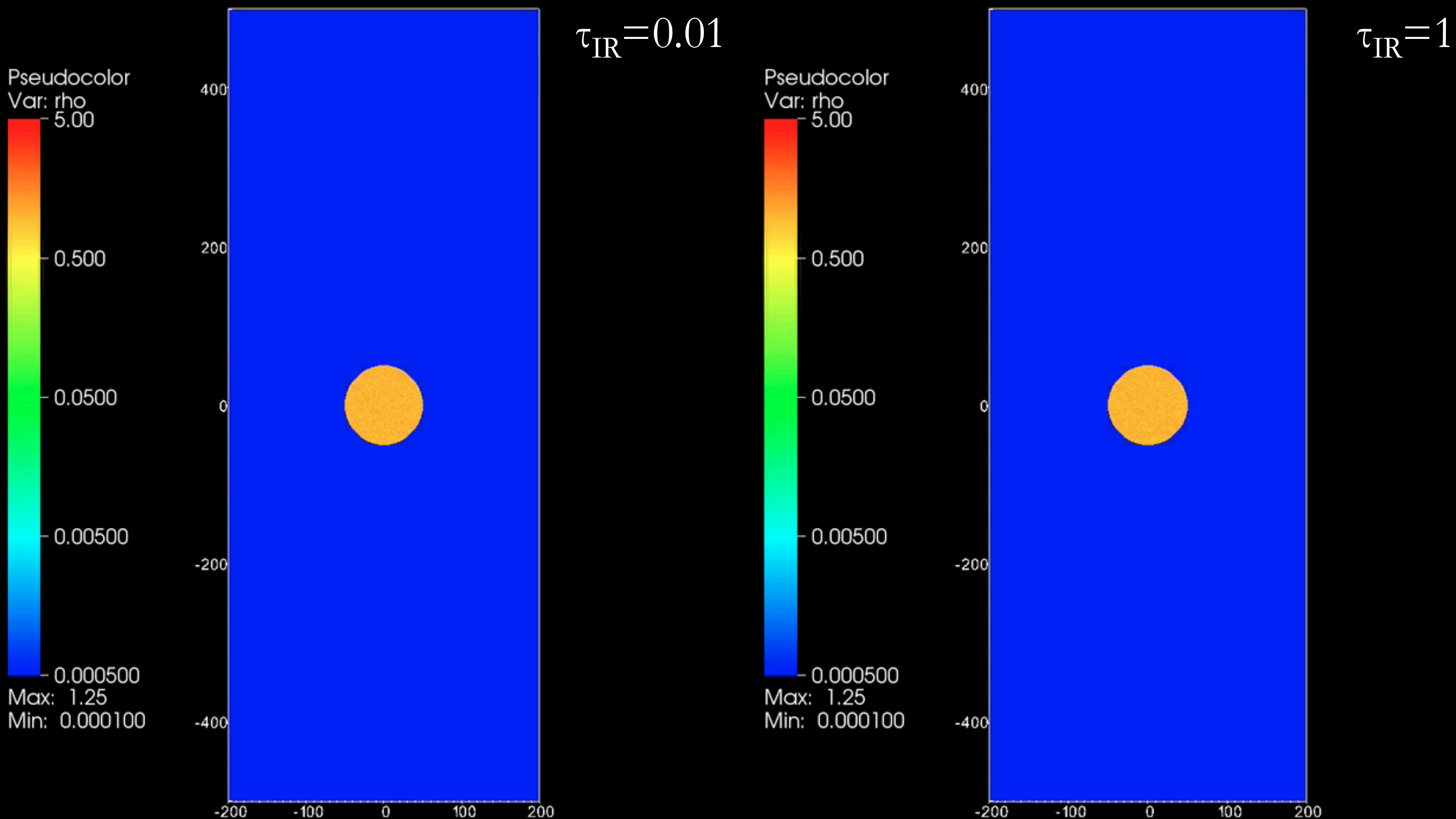
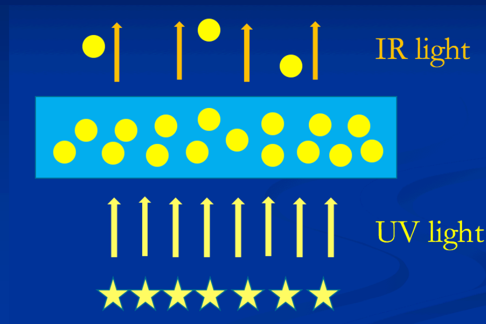
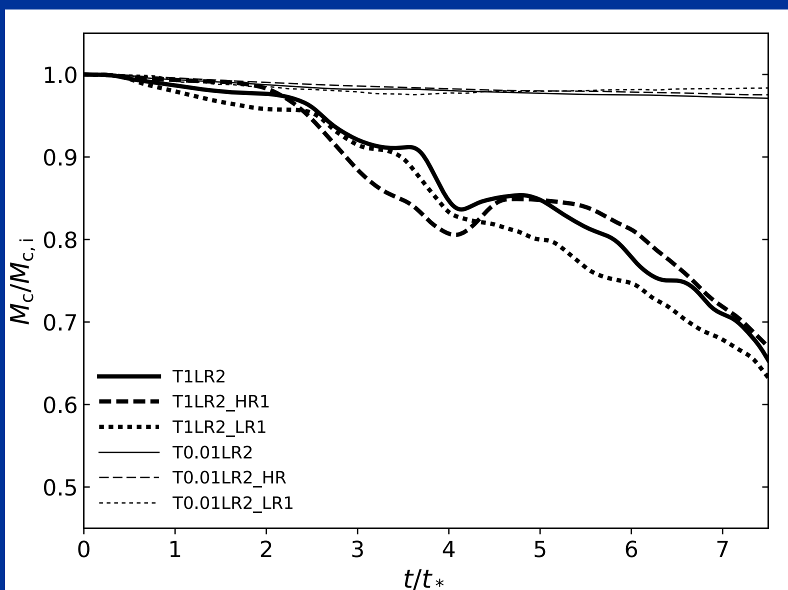
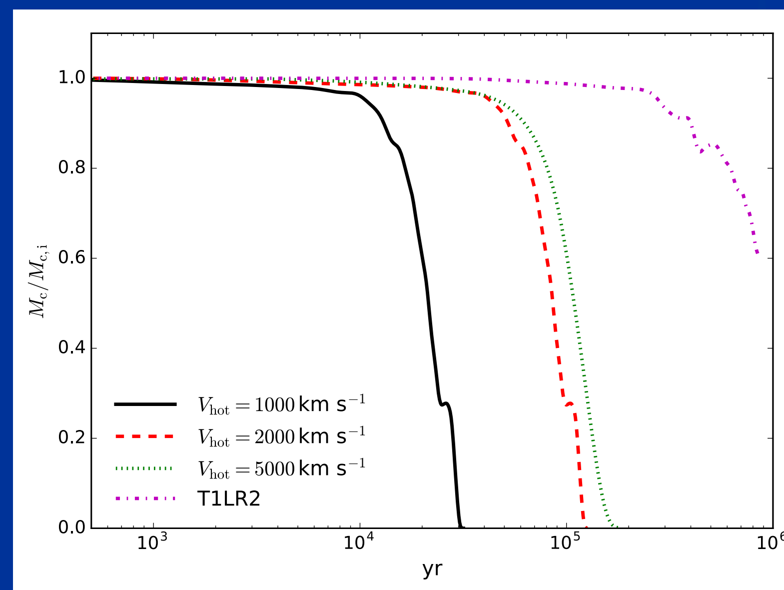


Zhang et al. 2017b, in preparation

Cloud Lifetime







Zhang et al. 2017b, in preparation

Summary

- Disks radiating at or even somewhat below the Eddington limit are unstable to driving large-scale winds by radiation pressure.

- Momentum Coupling between gas and radiation is more efficient using the VET method for simulations.

- We find a moderate amplification factor η, which measures the momentum couple between radiation and dusty gas.

- Clouds accelerated by radiation has longer lifetime than hot-wind-pushed clouds.