Radiation Hydrodynamics of Dust-Driven Winds

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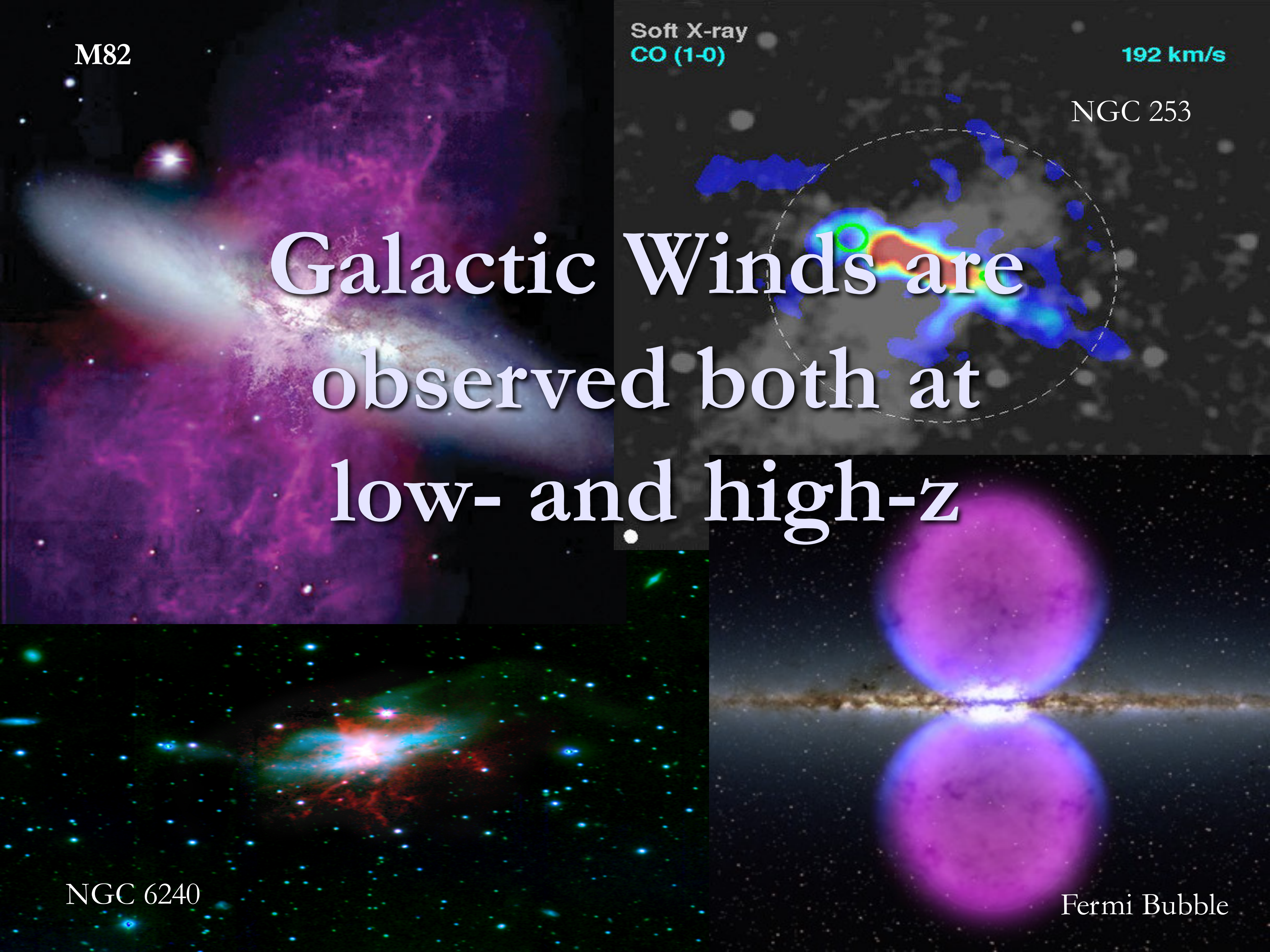
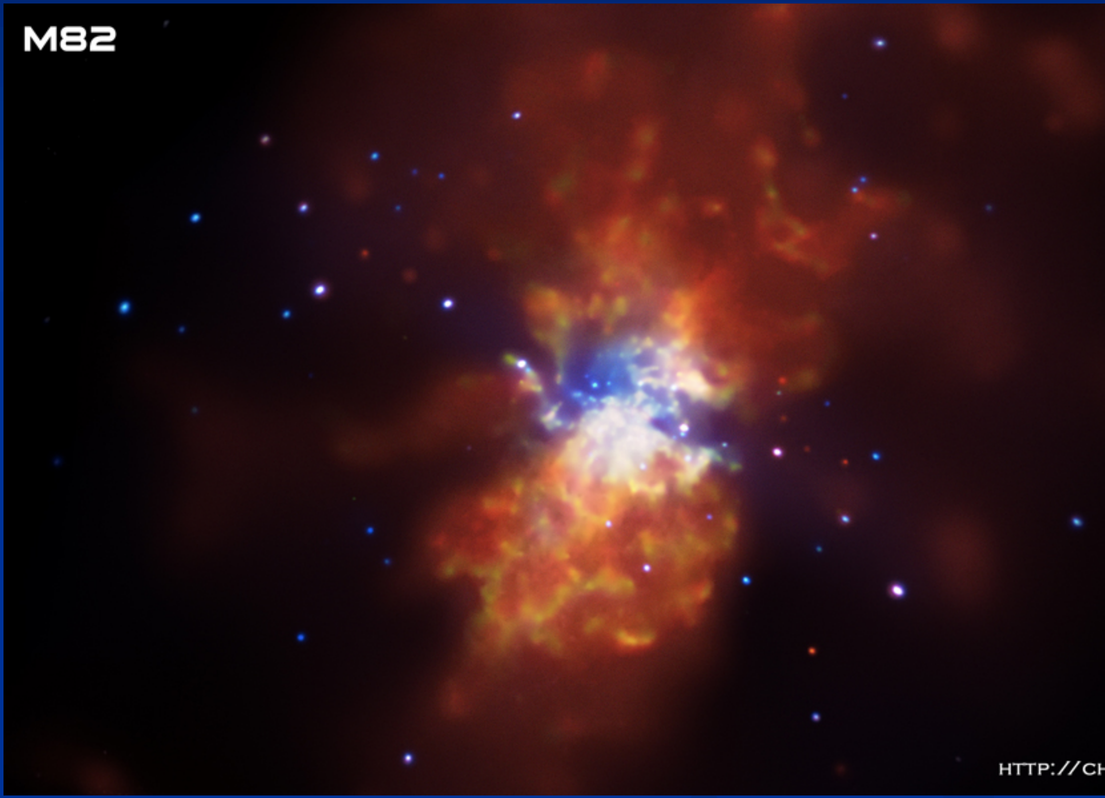
NRAO, March 28, 2017



M82
Soft X-ray
CO (1-0)
192 km/s
NGC 253
Galactic Winds are observed both at low- and high-z
NGC 6240
Fermi Bubble

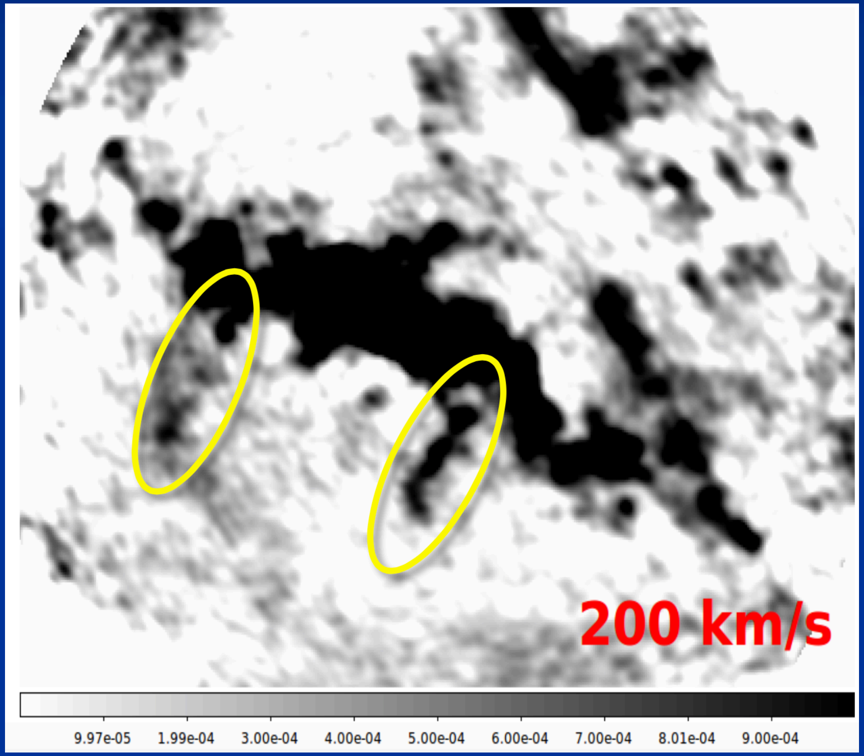
M82

Hubble & WIYN

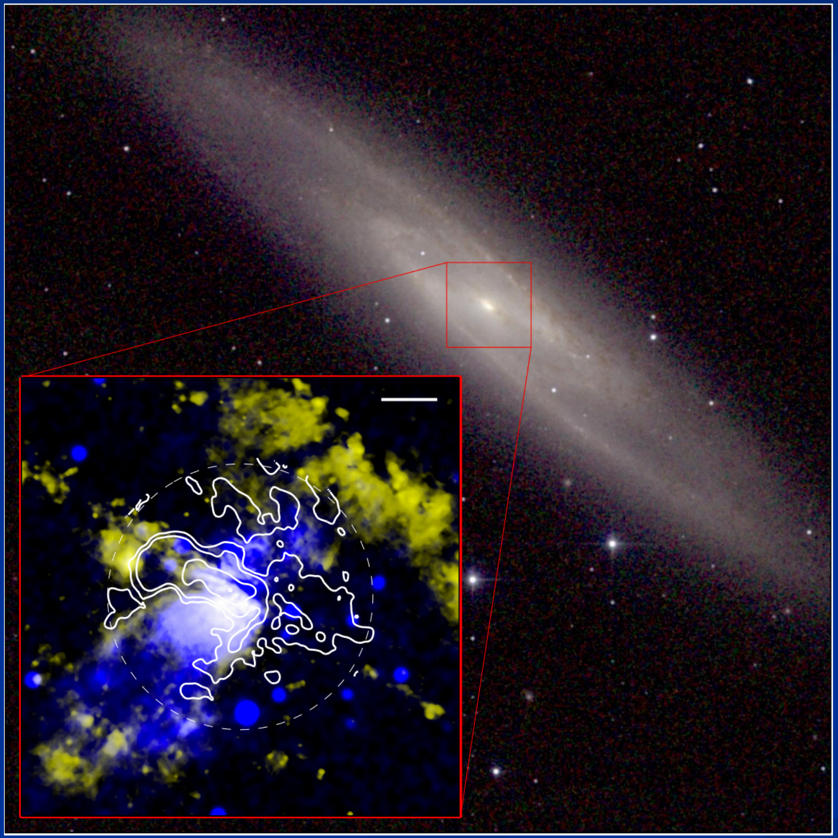


Chandra

NGC 253

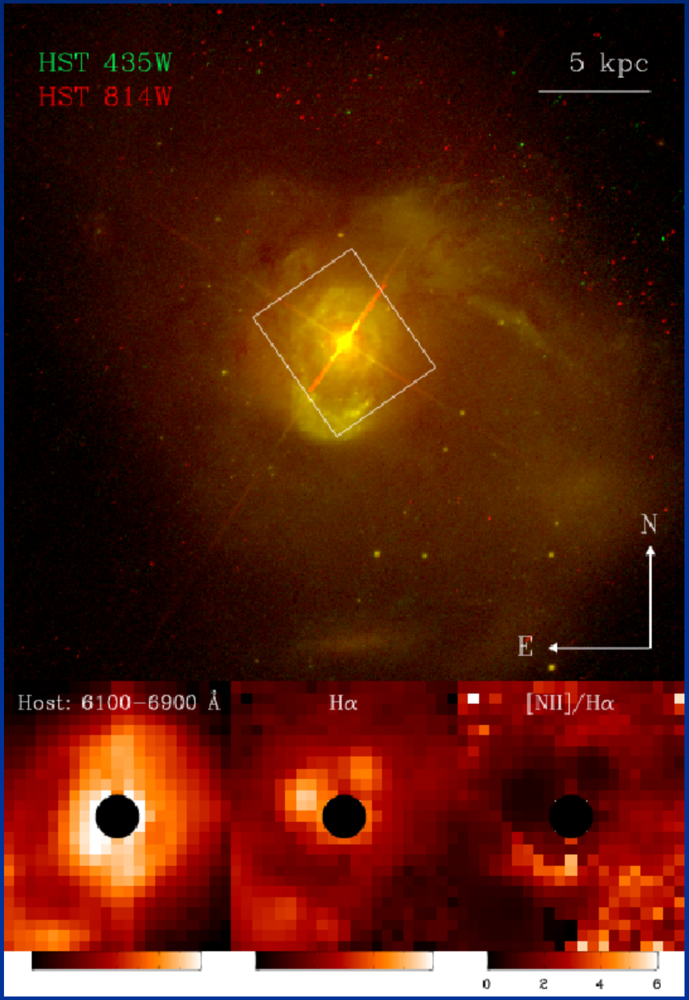


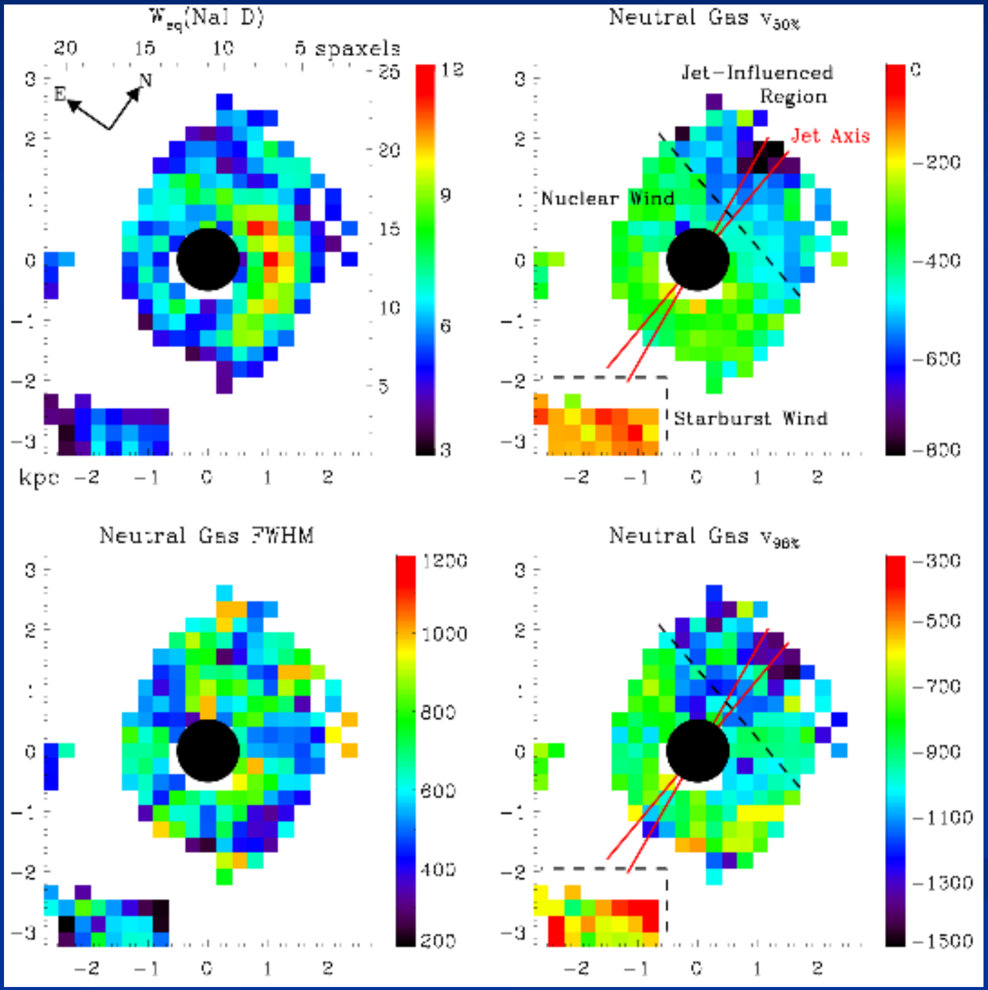
ALMA



X-ray and **Hα**

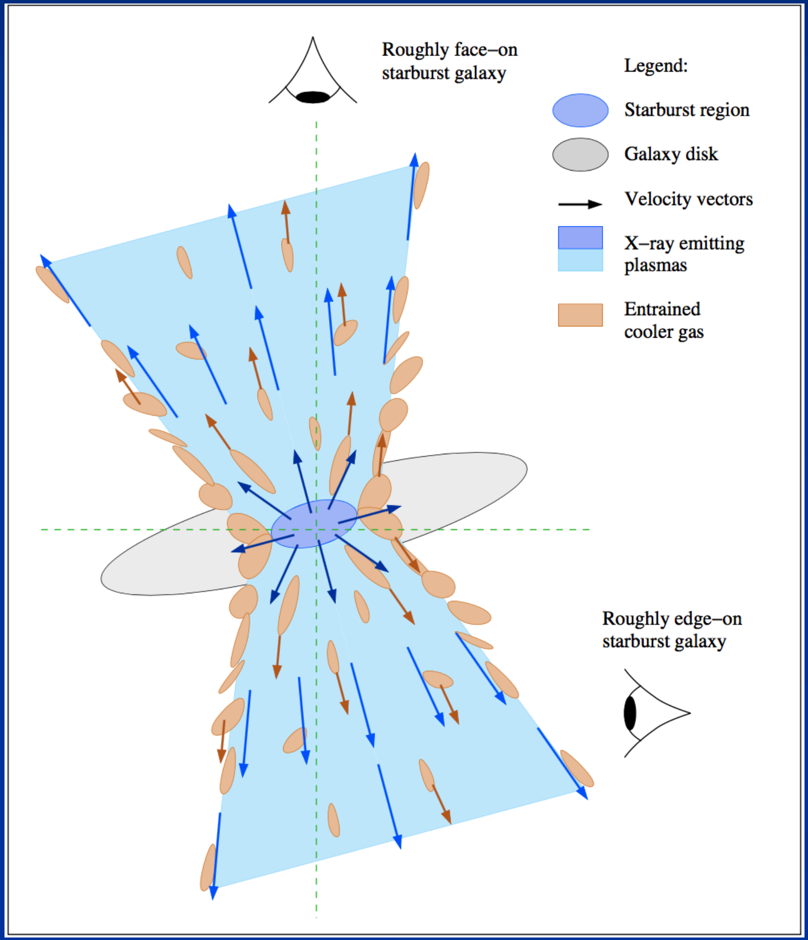
Mrk 231





Rupke & Veilleux 2011

Neutral Outflow in Star-Forming Galaxies (z<1)



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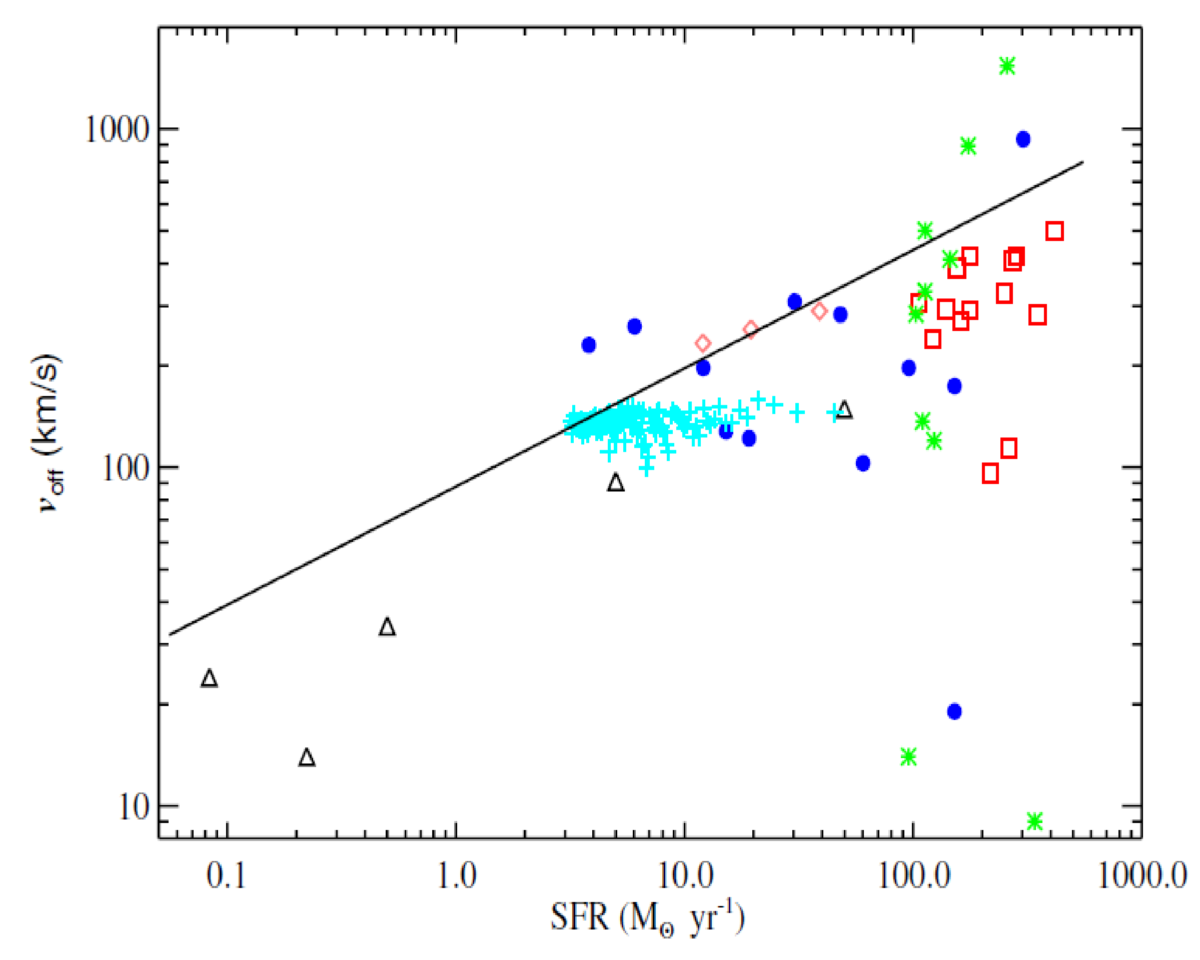
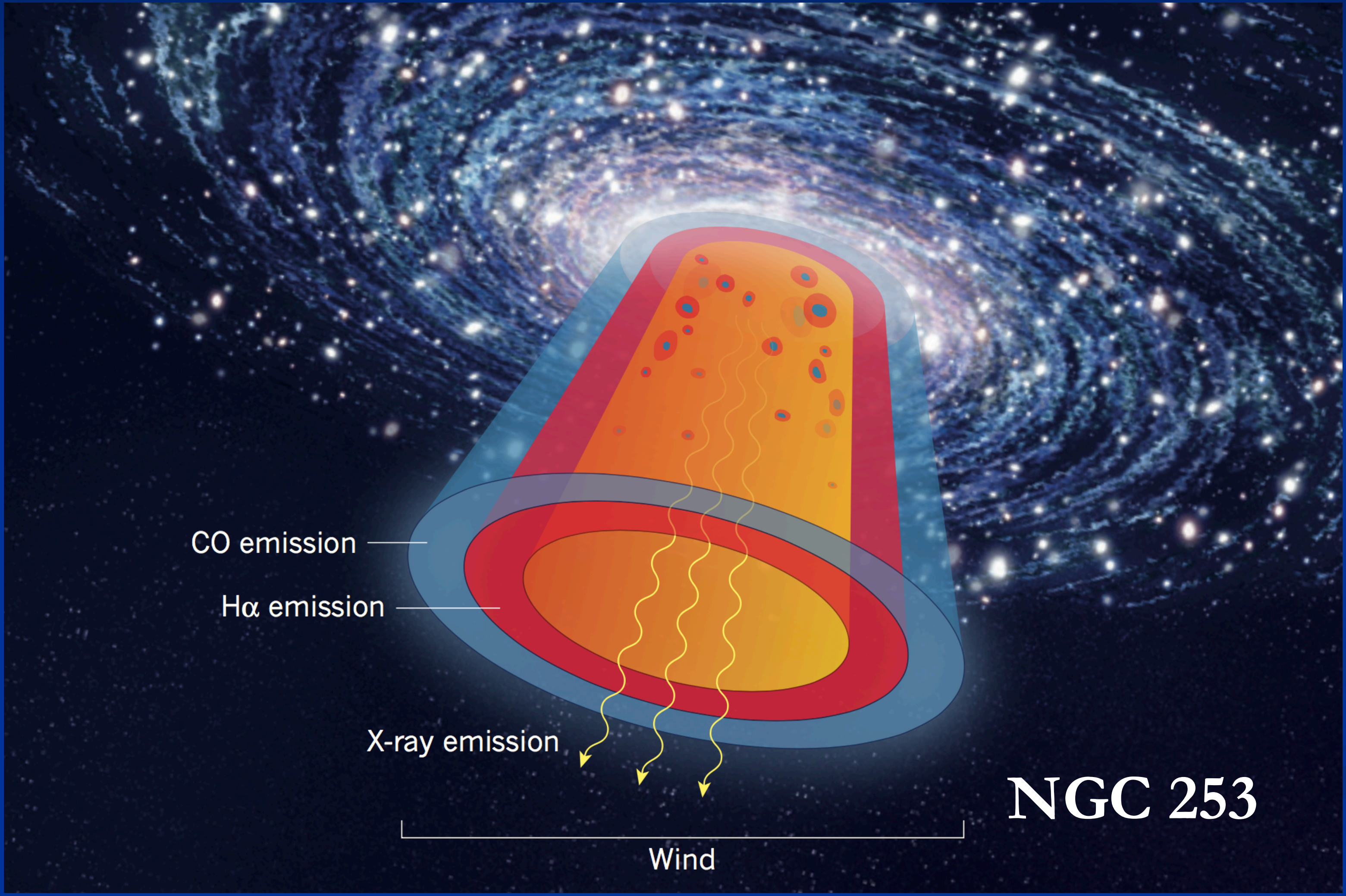


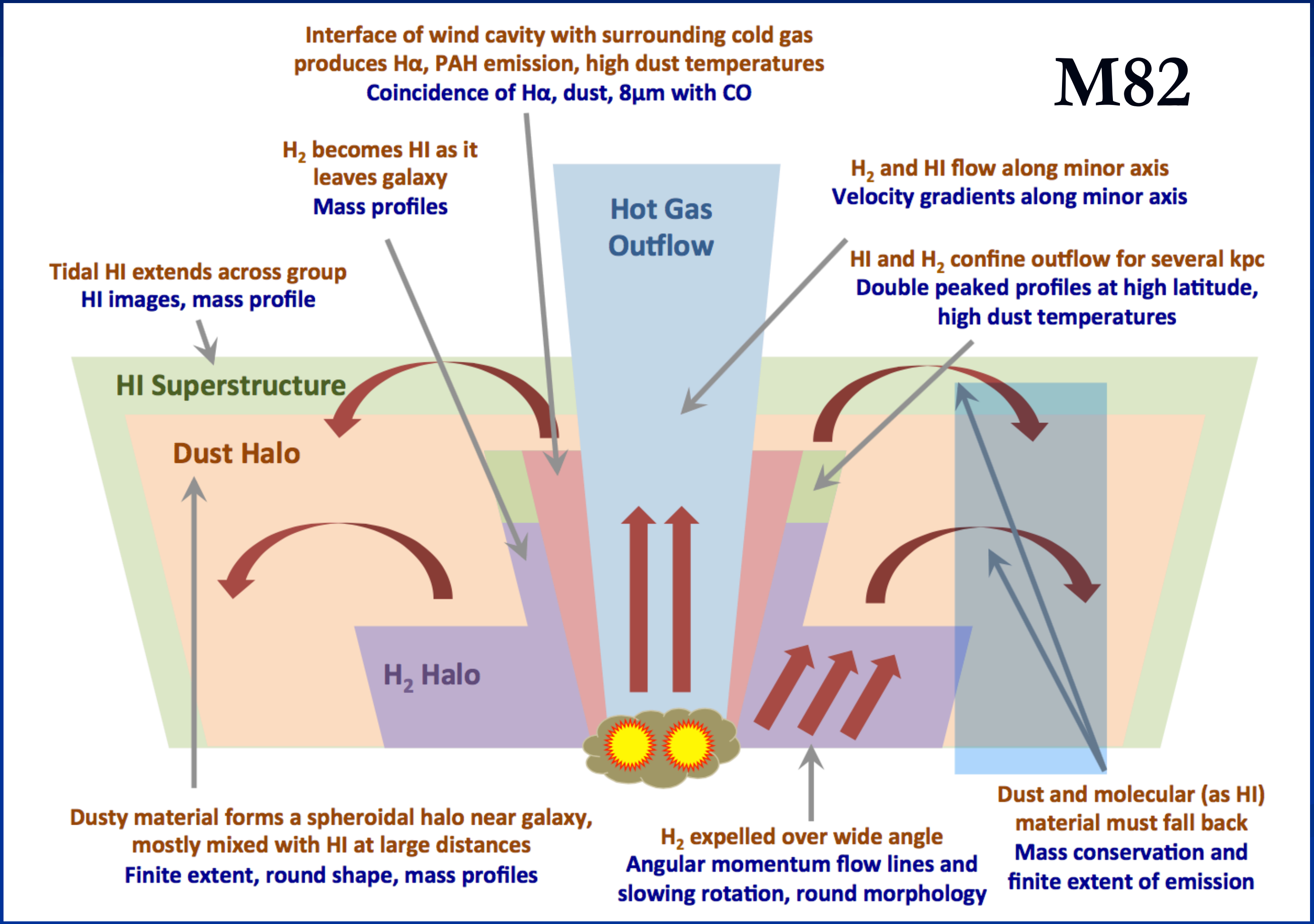
Chen et al. 2010

Multi-Phase Structure of Galactic Winds



Westmoquette 2013

Multi-Phase Structure of Galactic Winds



Leroy et al. 2015

What Drives Galactic Winds

- **Supernova-Driven Winds** (Larson et al. 1974, Chevalier & Clegg 1985, Dekel & Silk 1986)
- **Radiation Pressure** (Murray et al. 2005, Zhang & Thompson, 2012)
- **Cosmic Ray** (Ipavich 1975, Socrates et al. 2008)

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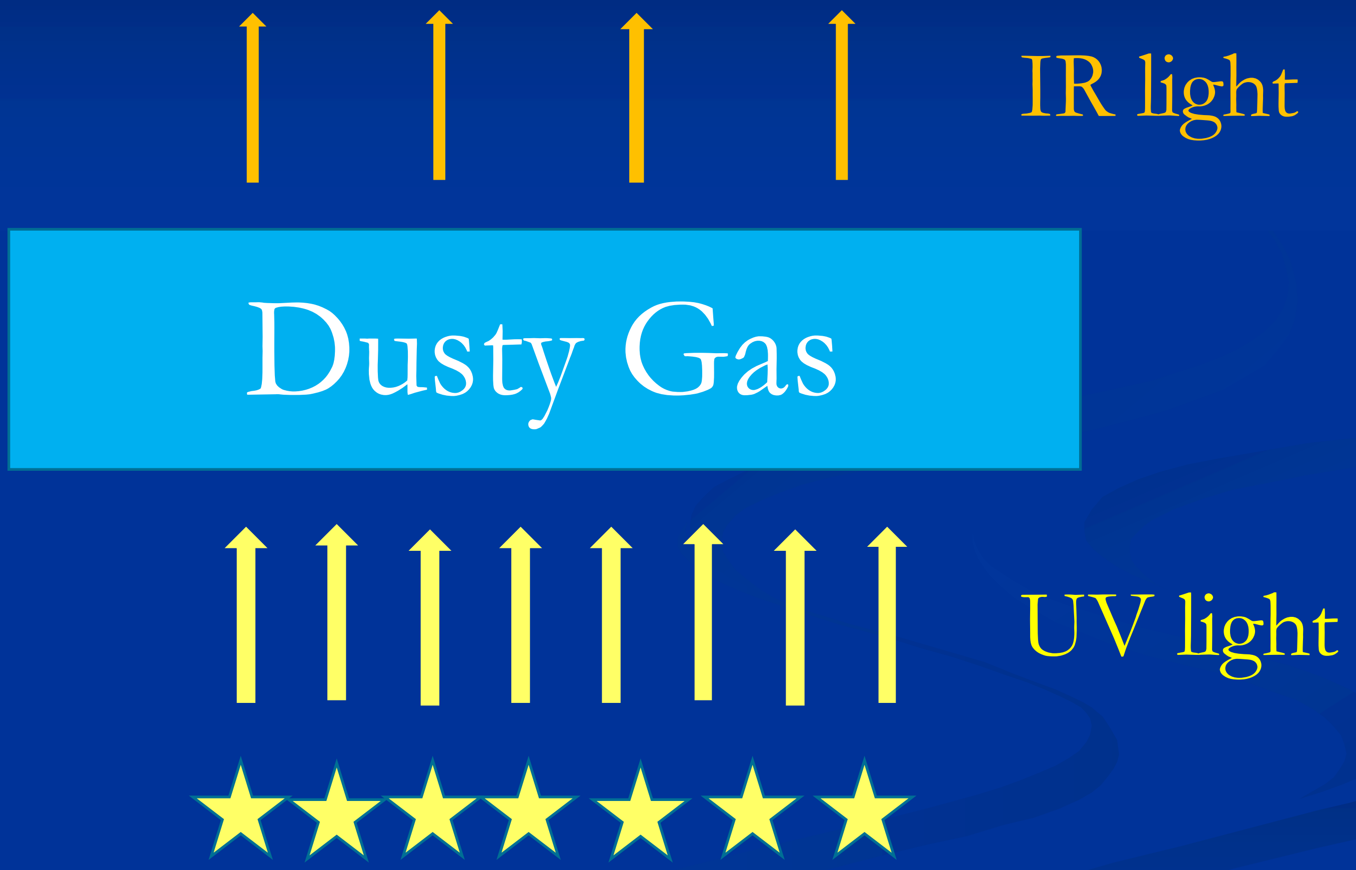
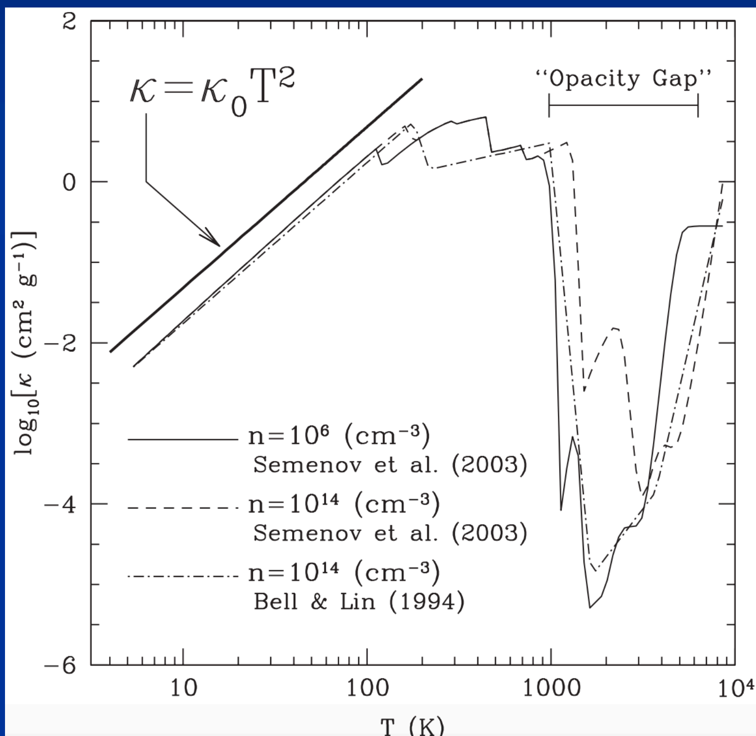
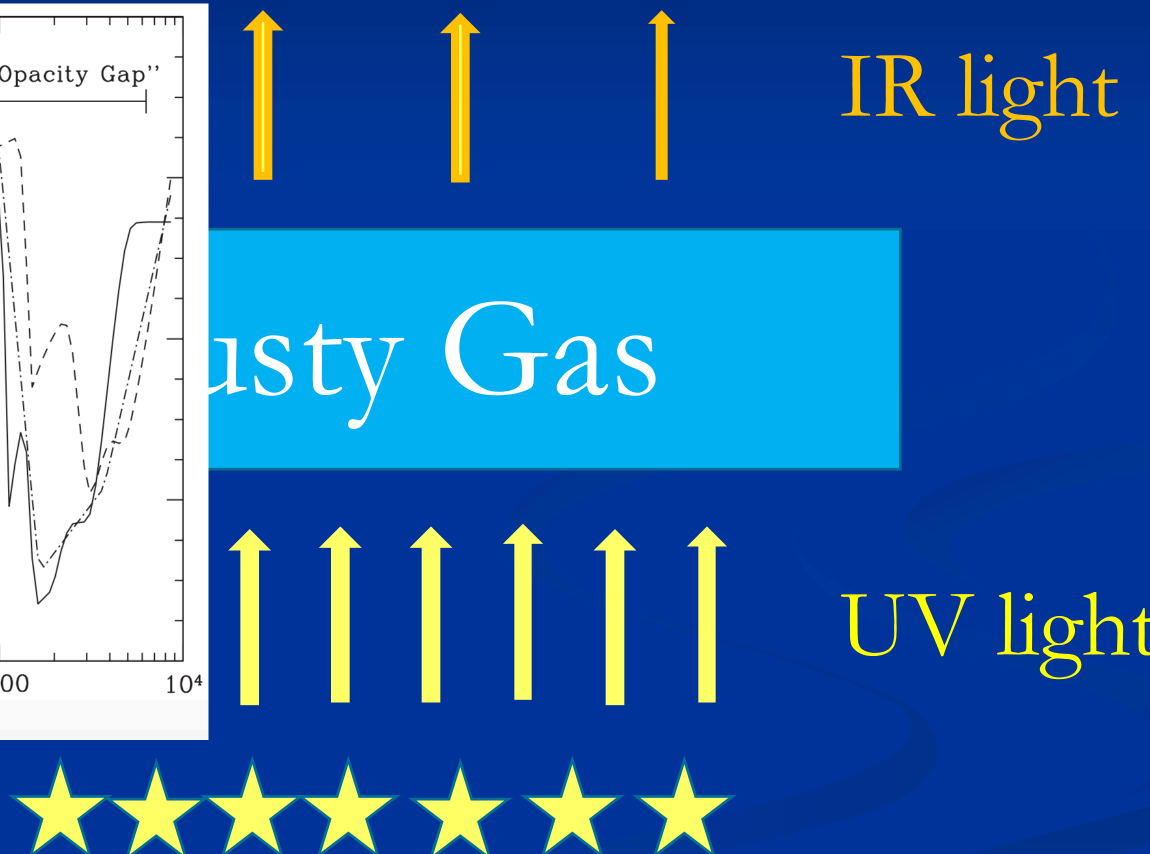
Radiation Pressure Driven Wind in Starbursts and Star-Forming Galaxies



Radiation Pressure Driven Wind in Starbursts and SFG



Thompson et al. 2005



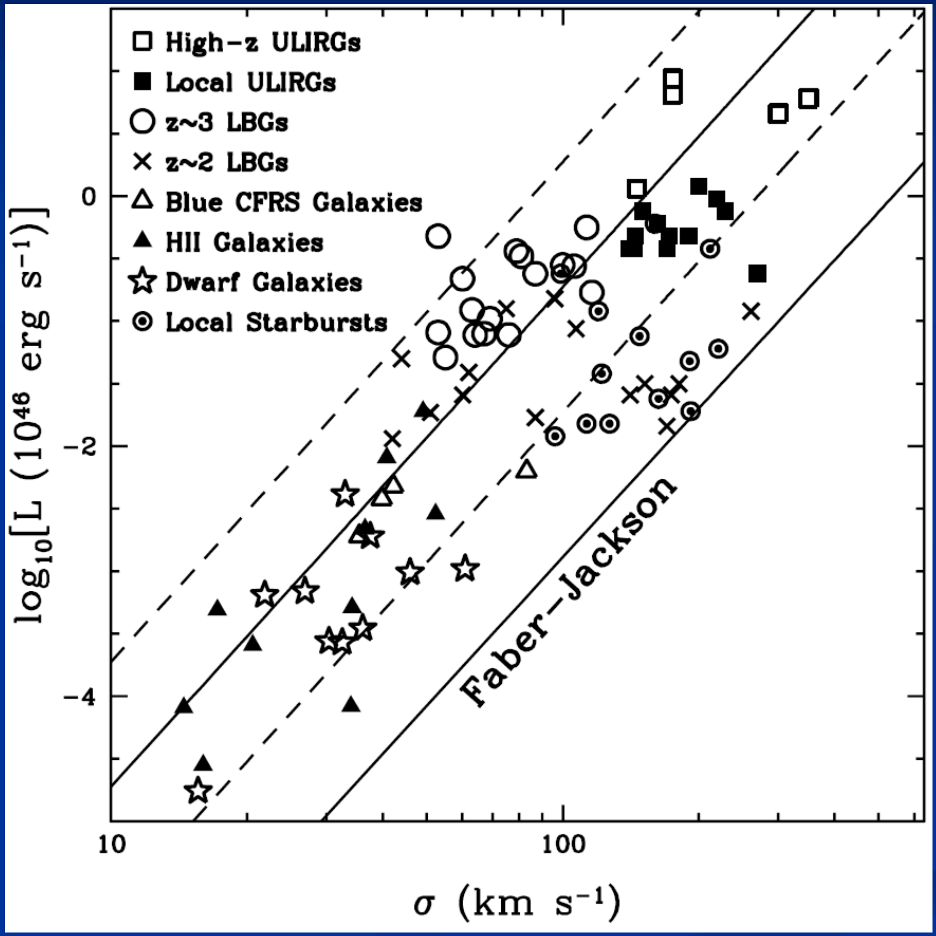
Radiation-Pressure on Dust: analytic

Optically Thick Limit
(at the base of the wind)

$$M_g(r)\frac{dV}{dt} = -\frac{GM(r)M_g(r)}{r^2} + \frac{L(t)}{c}$$

$$M_g(r) = \frac{2f_g\sigma^2 r}{G}$$

$$L_M = \frac{4f_g c}{G}\sigma^4$$



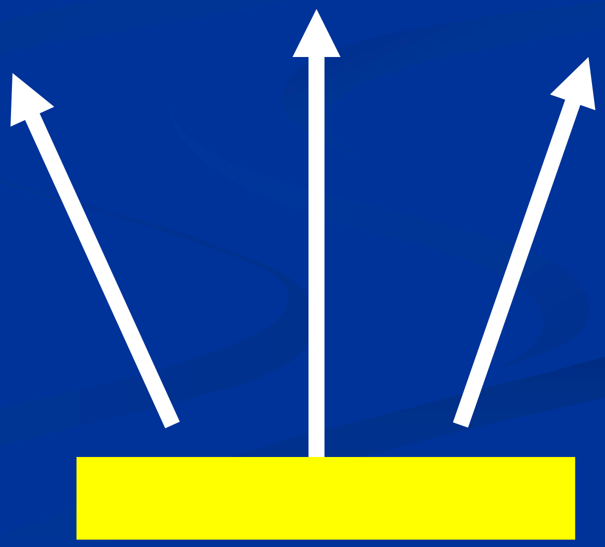
Murray, Quataert, Thompson 2005

Uniform Self-Gravitating Disk

-- Uniformly Bright Disk

-- Optically Thick (to IR)

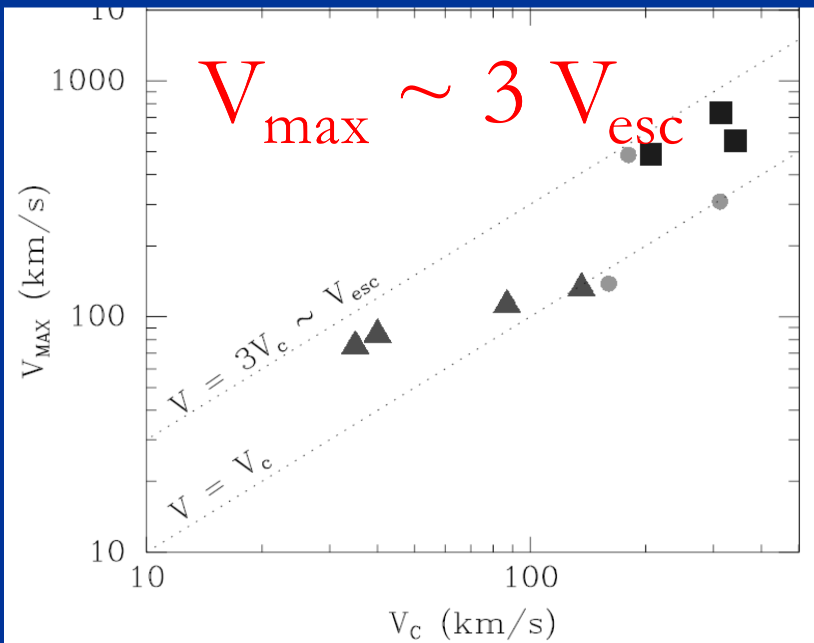
-- Radiating at Eddington Limit

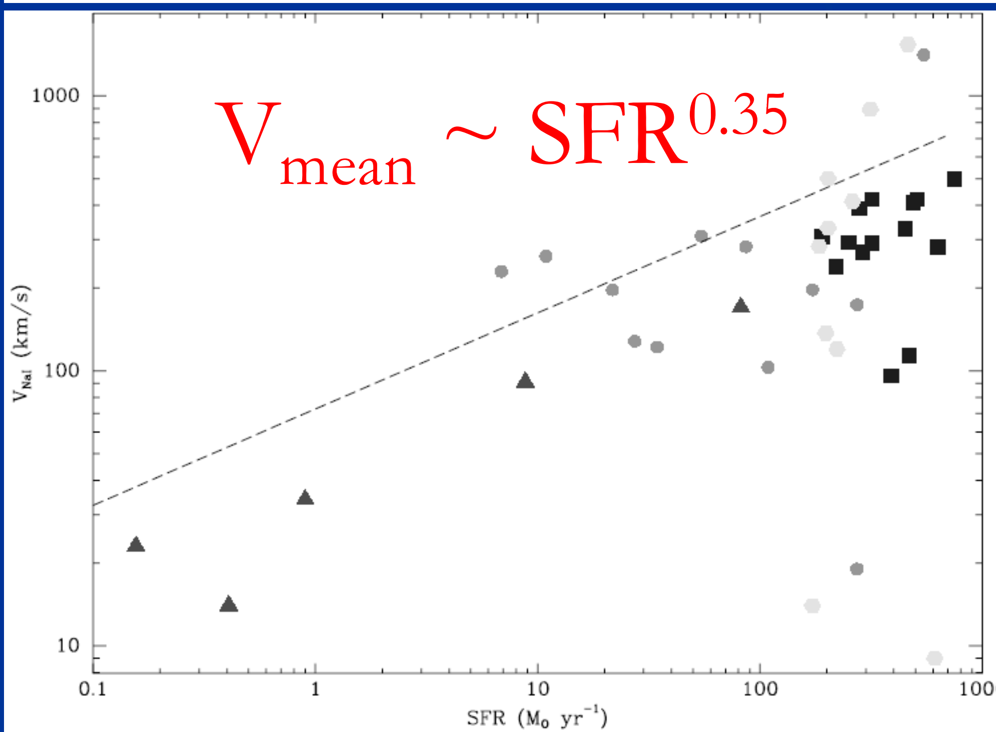


V_{wind} and V_{rot} May be match the observation

$$v_\infty \simeq 2\sqrt{\pi/2 - 1}\, v_{\rm rot} \simeq 1.5\, v_{\rm rot}$$

$$\begin{aligned} v_\infty &\sim 150\,{\rm km\,s^{-1}}\, f_{g,0.5}^{-0.5} \left(\frac{\Sigma_{\rm SFR}}{M_\odot\,{\rm yr^{-1}\,kpc^{-2}}}\right)^{0.36} r_{D,1kpc}^{0.5} \\ &\sim 400\,{\rm km\,s^{-1}}\, f_{g,0.5}^{-0.5} \left(\frac{\rm SFR}{50 M_\odot {\rm yr}^{-1}}\right)^{0.36} r_{D,1kpc}^{-0.21}, \end{aligned}$$





Zhang & Thompson 2012

Dusty Winds
Radiation Hydrodynamic Simulations

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Radiation Hydrodynamic Simulations

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

Gas-Radiation Interaction
Radiation Hydrodynamic Simulations

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

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- $\eta << 1$, (Krumholz & Thompson 2012, 2013)
- $\eta = 1$, analytic model (Murray, Quataert & Thompson 2015)

Gas-Radiation Interaction
Radiation Hydrodynamic Simulations

- Is Gas Turbulence important?
- Momentum Coupling between Radiation and Gas?
- We need a more sophisticated algorithm than previous numerical simulations.

Radiation-Pressure on Dusts: RHD Simulation

Flux Limited Diffusion

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

Levermore & Pomraning 1981

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Levermore & Pomraning 1981

Variable Eddington Tensor

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

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

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

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

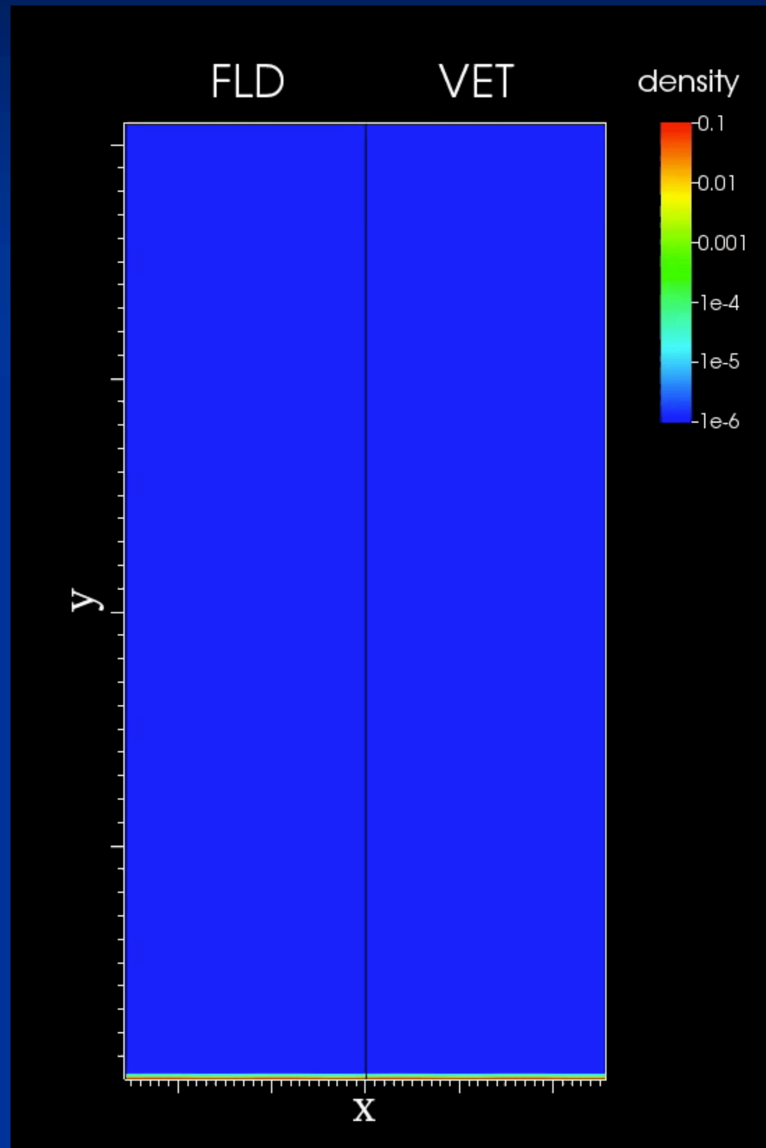
$$\mathsf{P}_{\rm rad} = \frac{4\pi}{c} \int_0^\infty \mathsf{K}_\nu d\nu.$$

Davis et al. 2014

FLD vs VET

flux

gravity



Sub-Eddington System

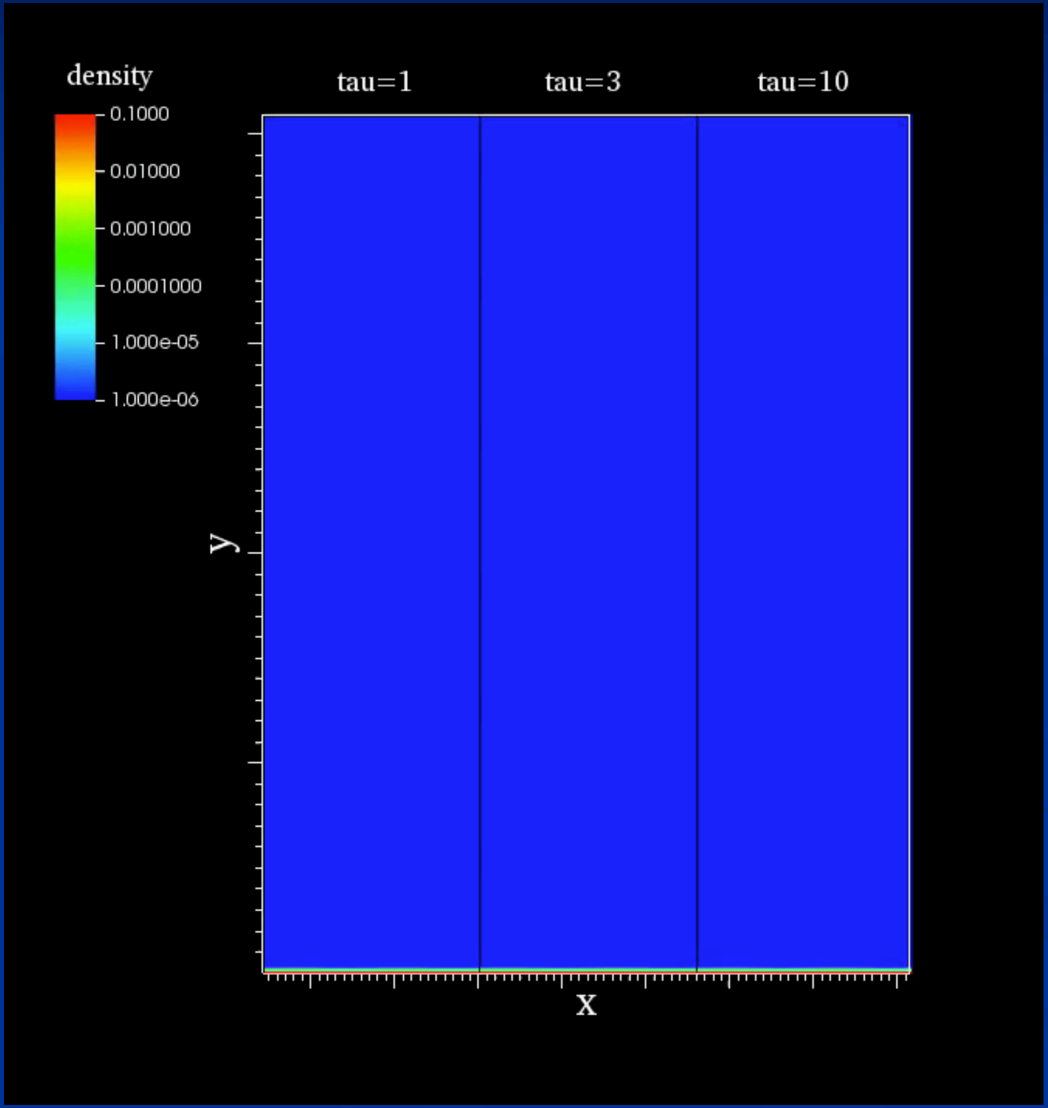
$$f_{\mathrm{E},*} = \frac{\kappa_{\mathrm{R},*} F_*}{gc}$$

Davis et al. 2014

Various Optical Depth

flux

gravity



Sub-Eddington System

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

$$\tau_* = \kappa_{\mathrm{R},*} \Sigma_*$$

Davis et al. 2014

FLD vs VET

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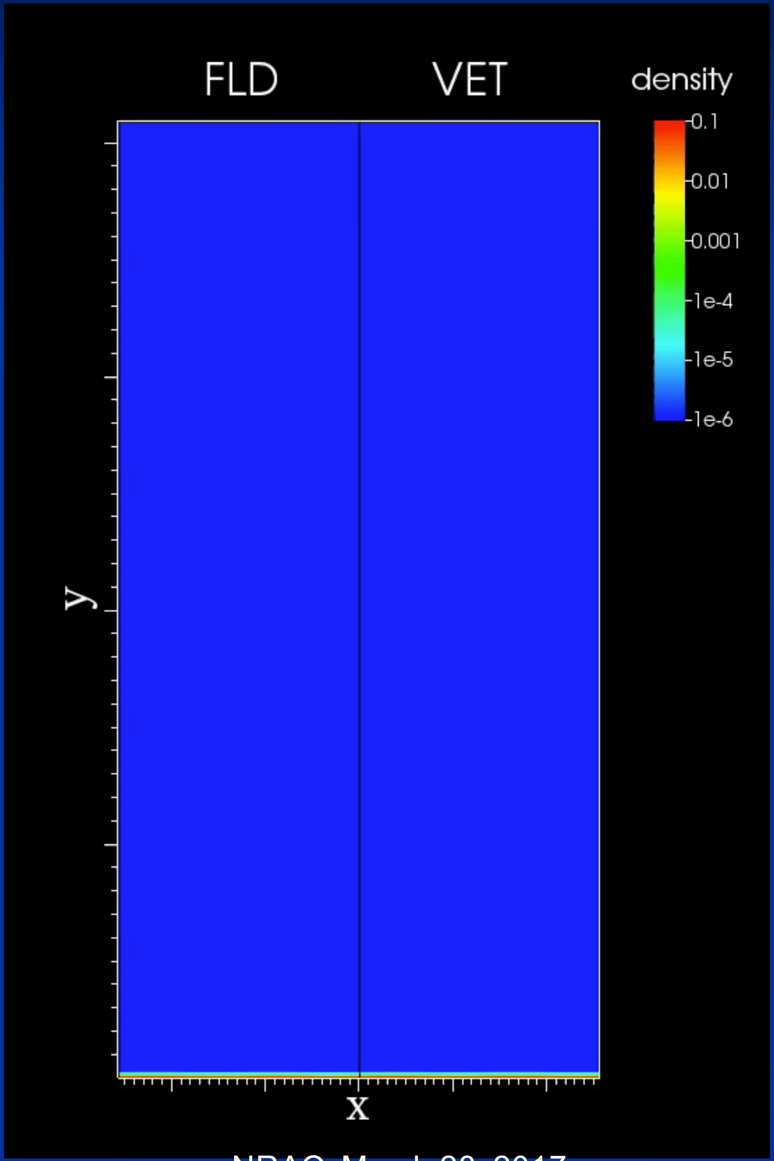

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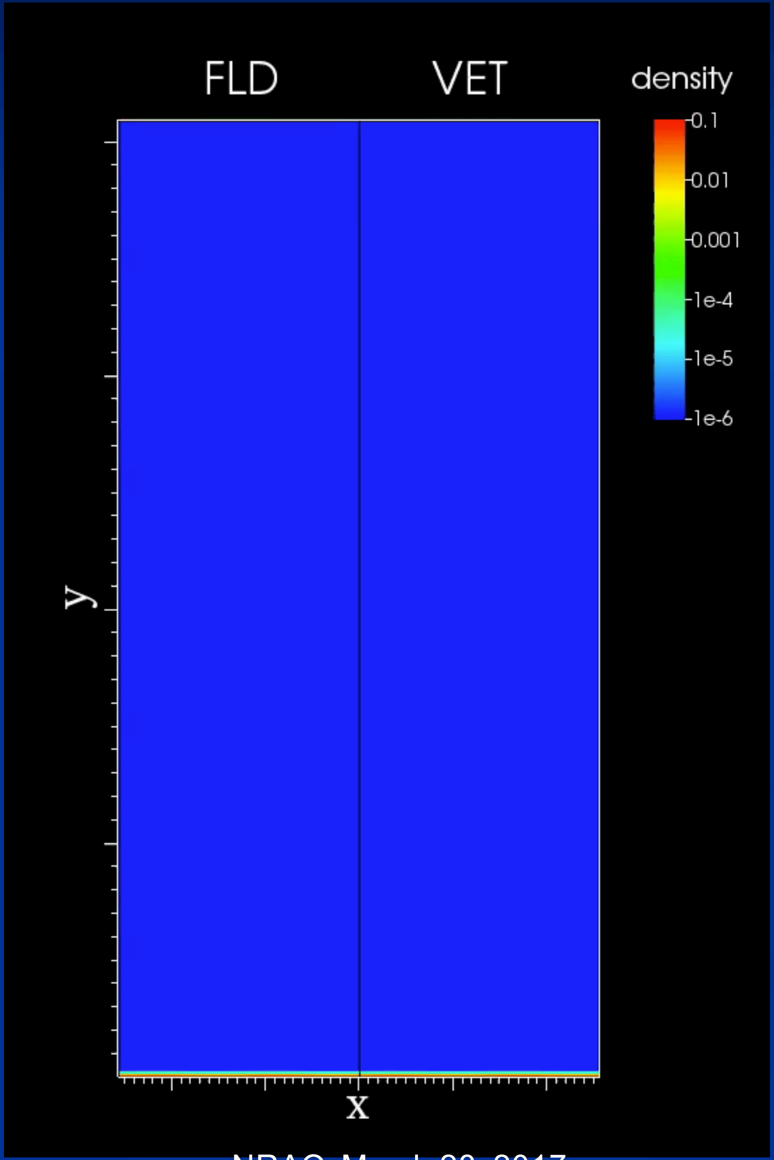
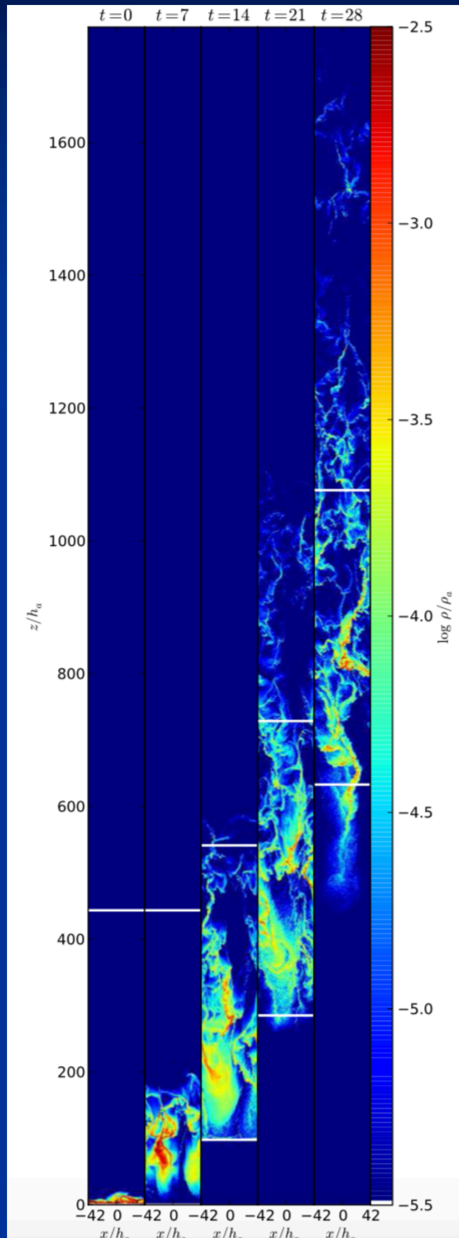


$$f_{\mathrm{E},*} \to \infty$$

Wind-Radiation Interaction (FLD)

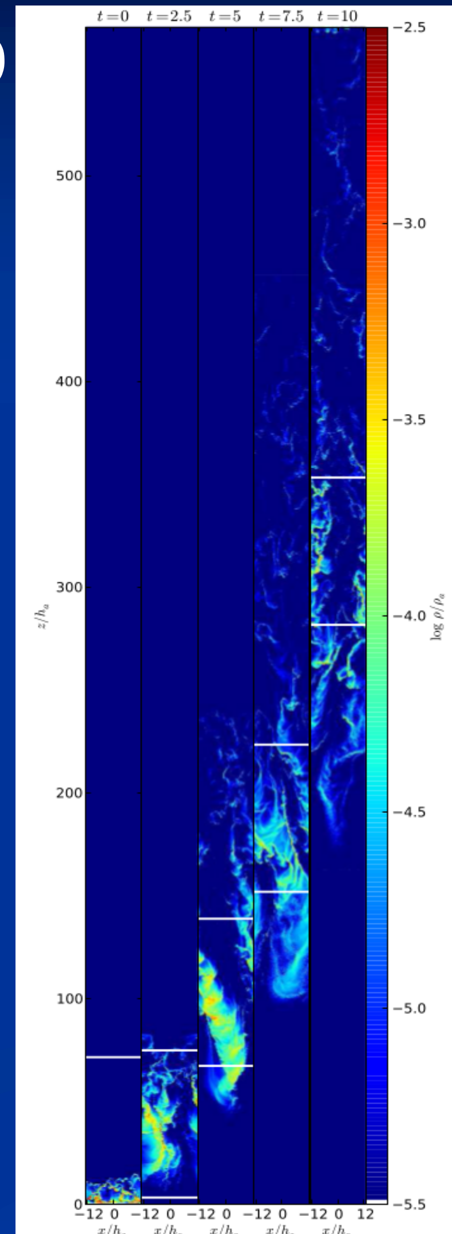
$\tau_* = 3$



flux

no gravity

$\tau_* = 10$



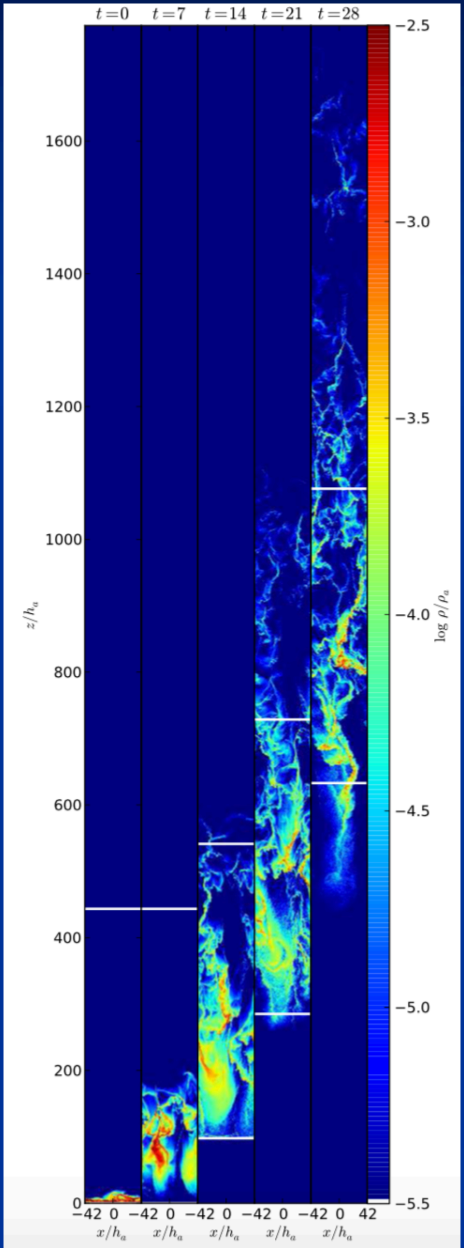
Krumholz & Thompson 2013

Wind-Radiation Interaction (FLD)

$\tau_* = 3$

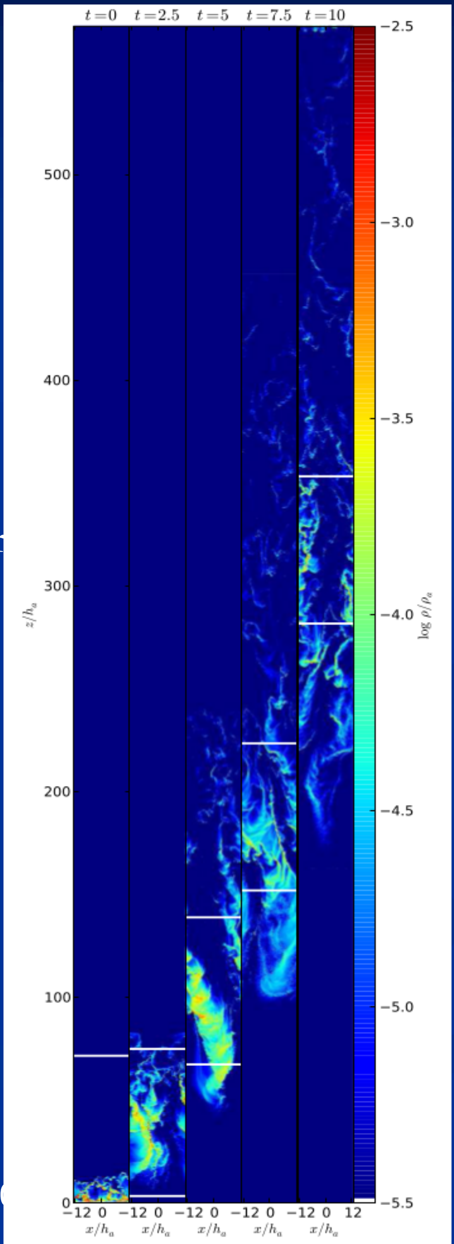
flux

no gravity



Radiative
Rayleigh-Taylor
Instability
(RRTI)

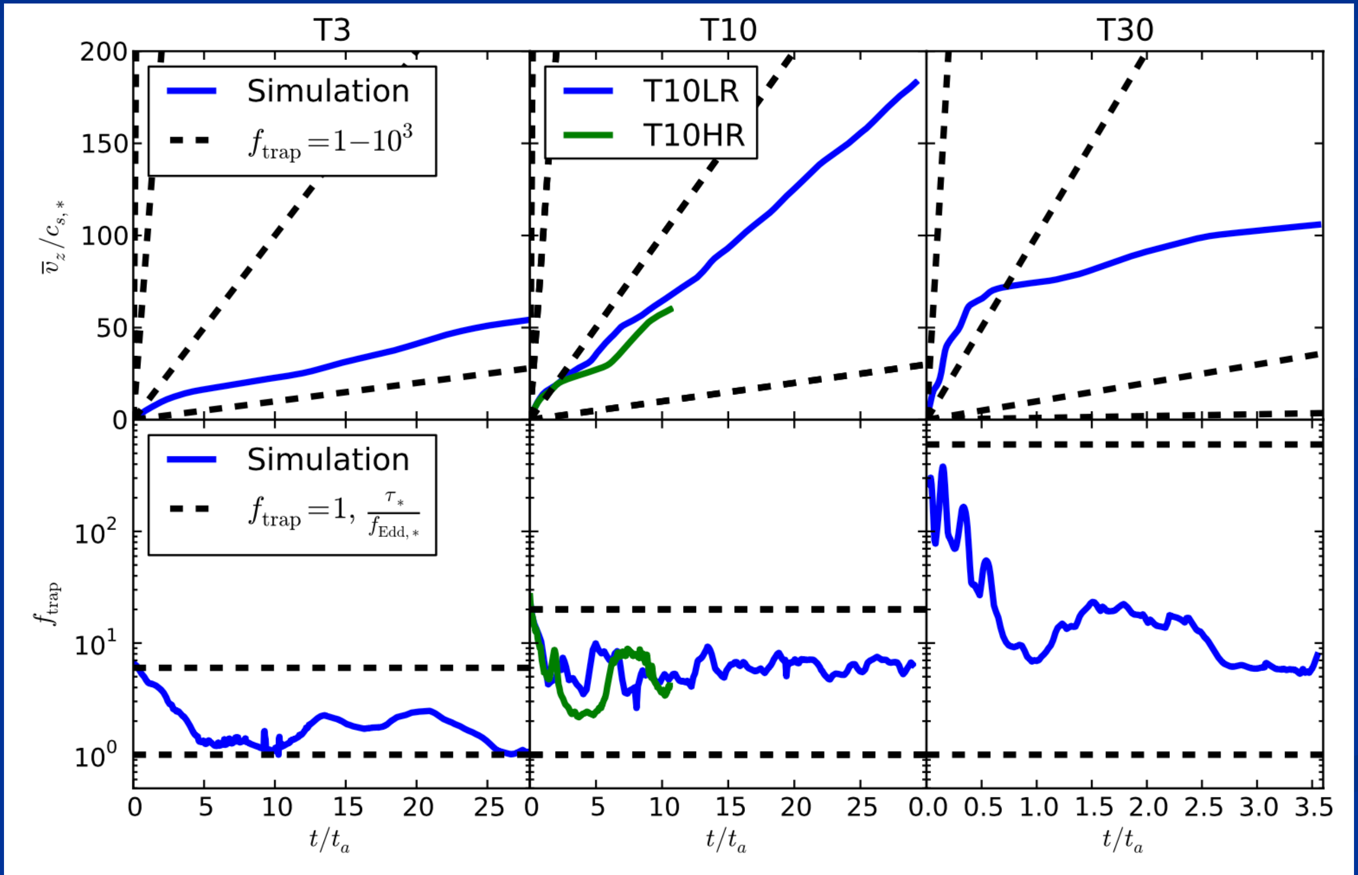
$\tau_* = 10$



Krumholz & Thompson 2013

Trapping Factor

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



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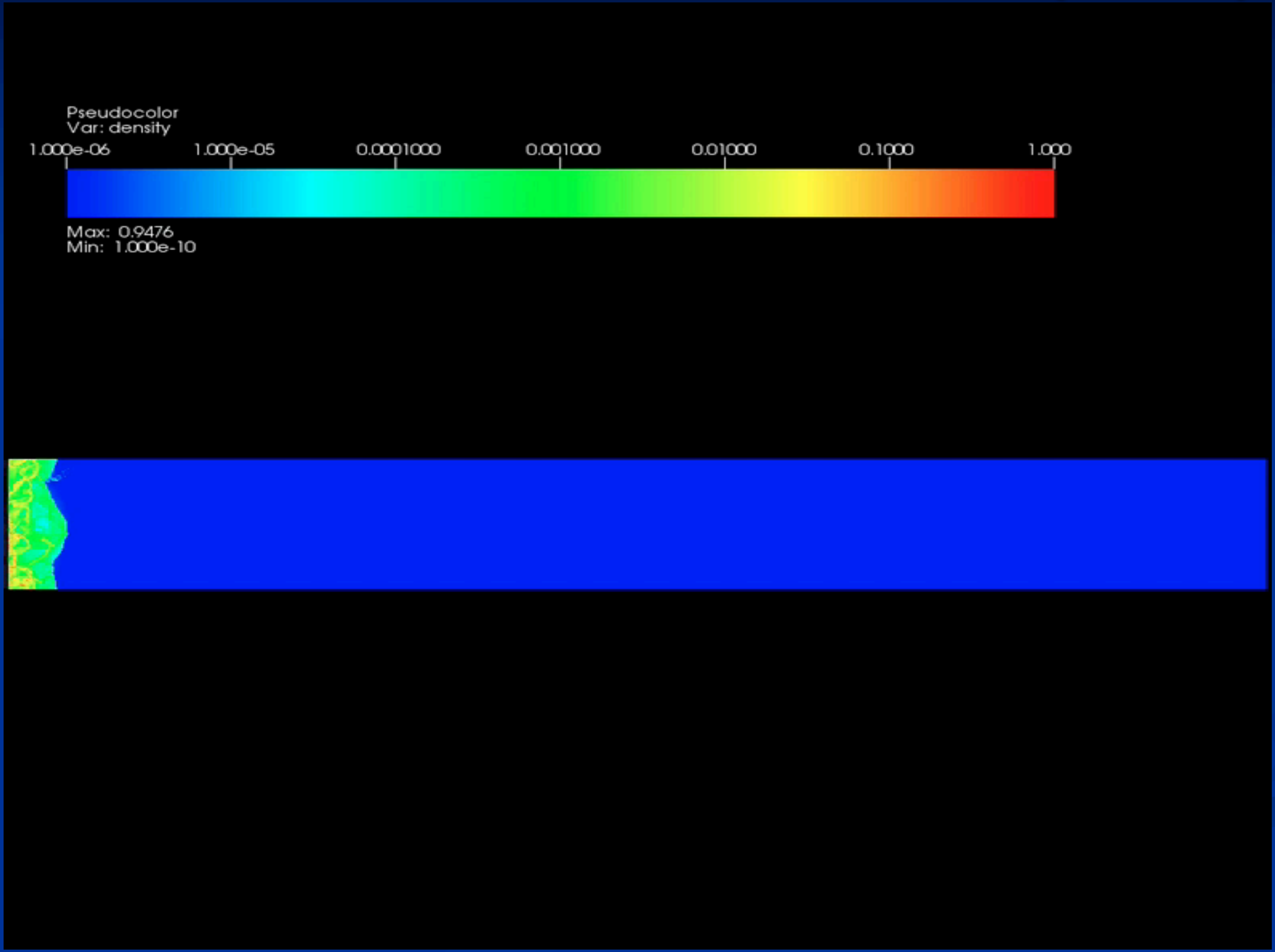
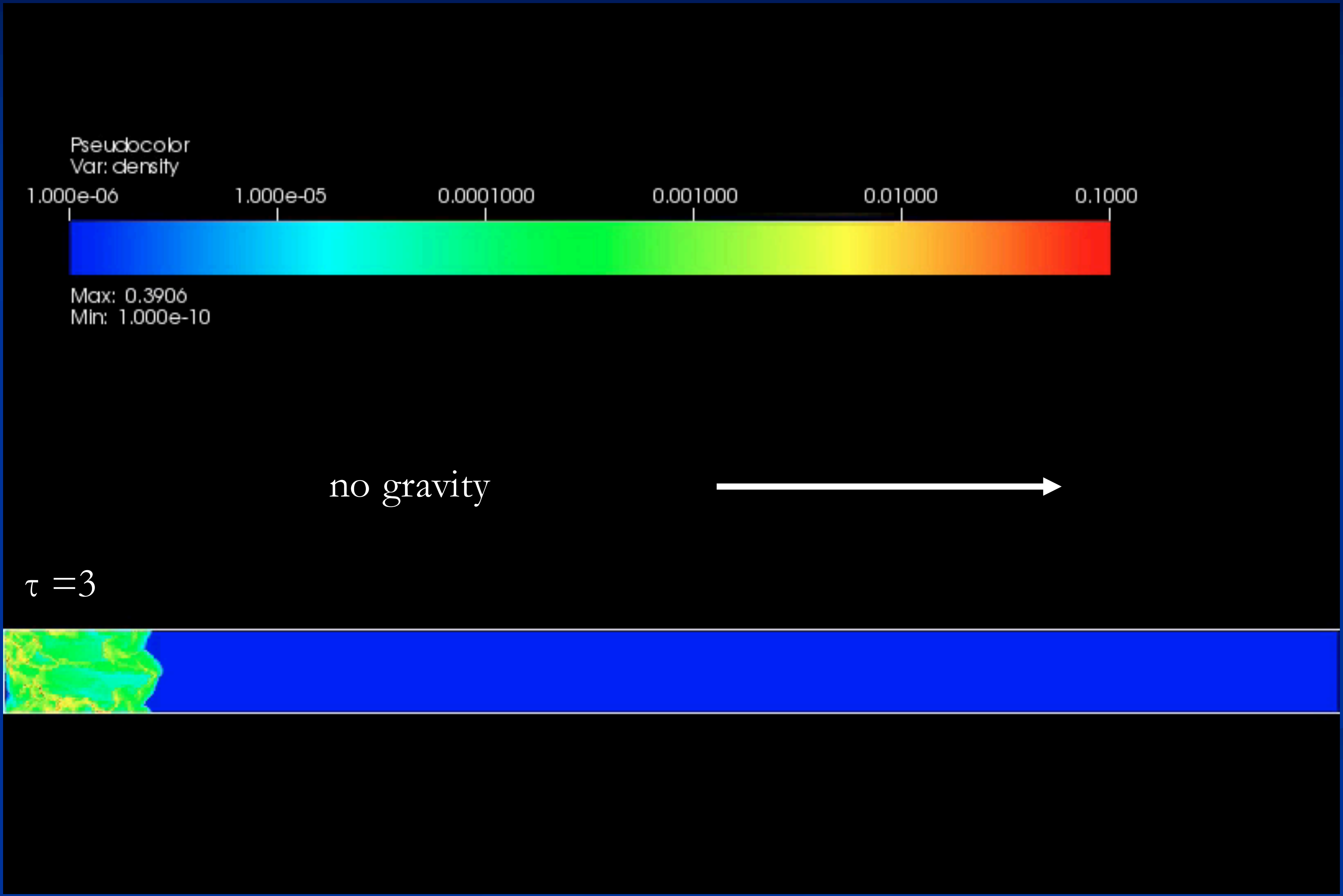
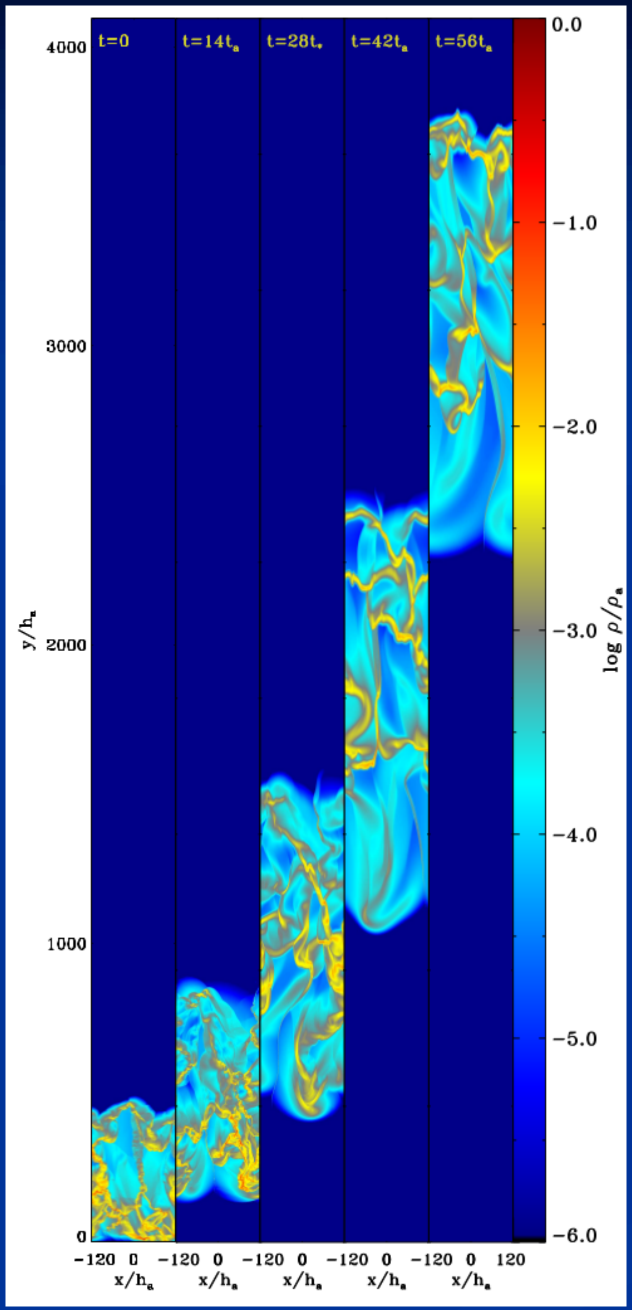


Wind-Radiation Interaction (VET)

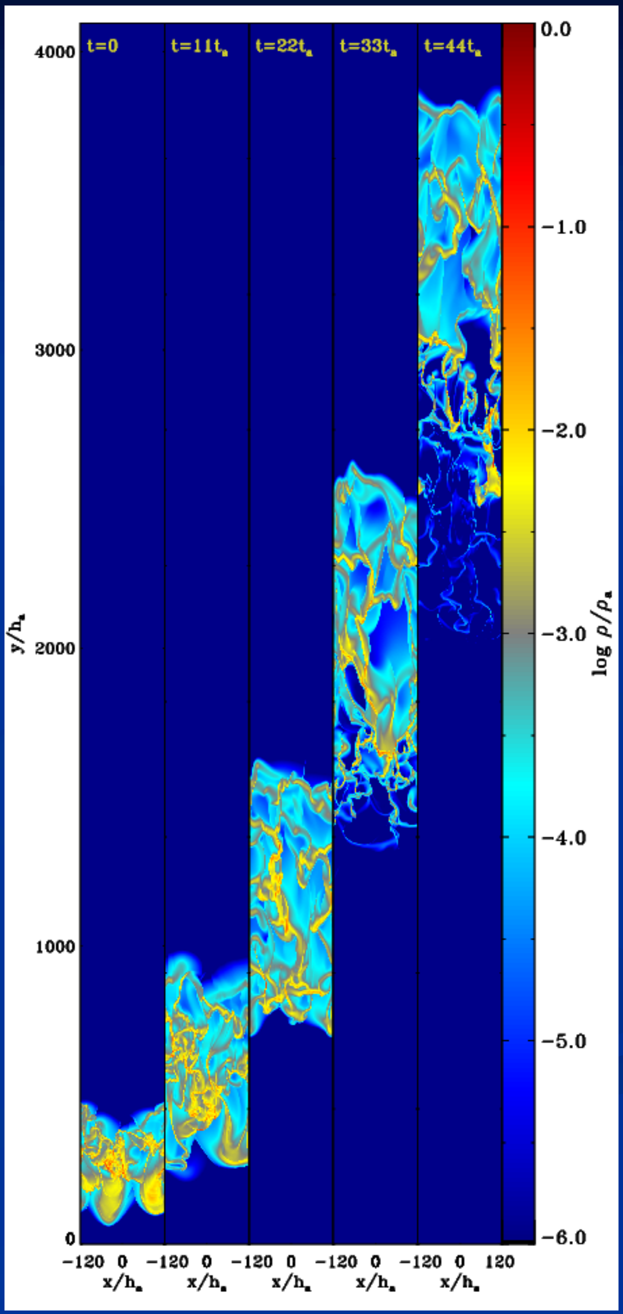


VET

τ =3



τ =10

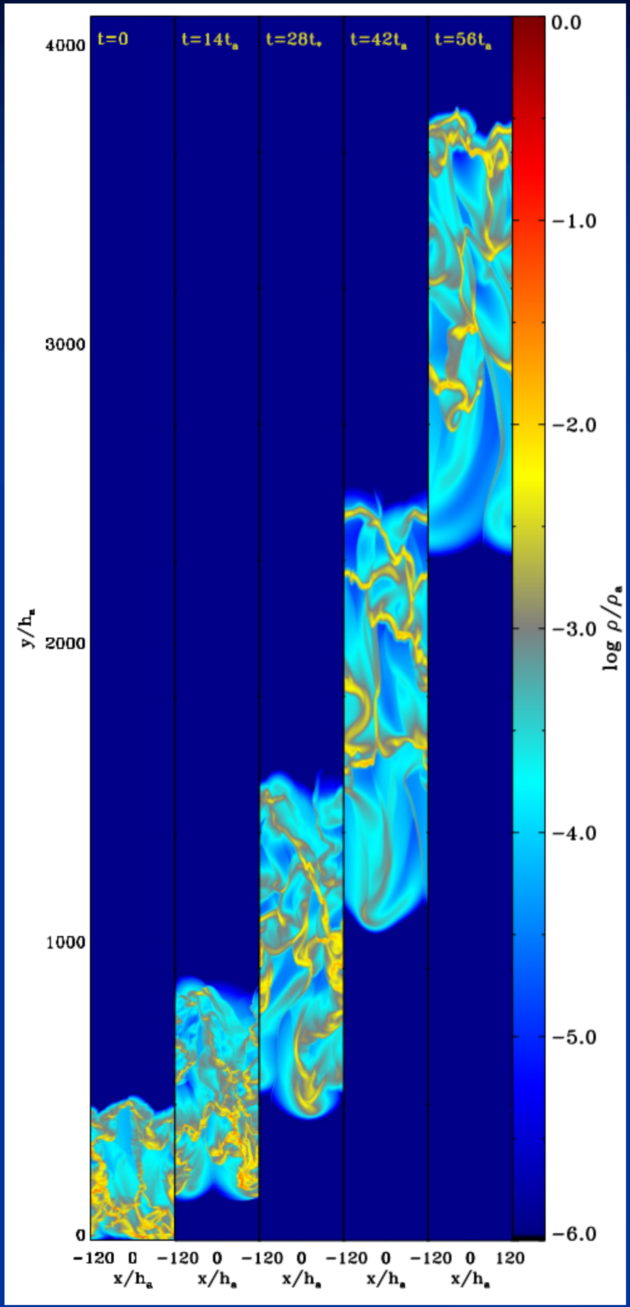


flux

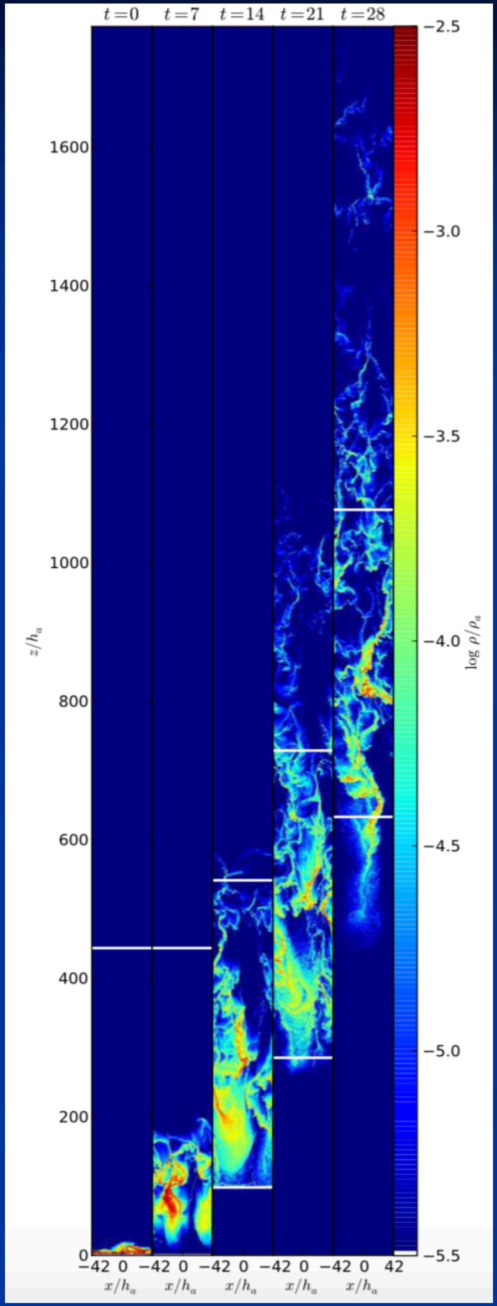
no gravity

Zhang & Davis 2016

τ =3, VET



τ =3, FLD



flux

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Zhang & Davis 2016

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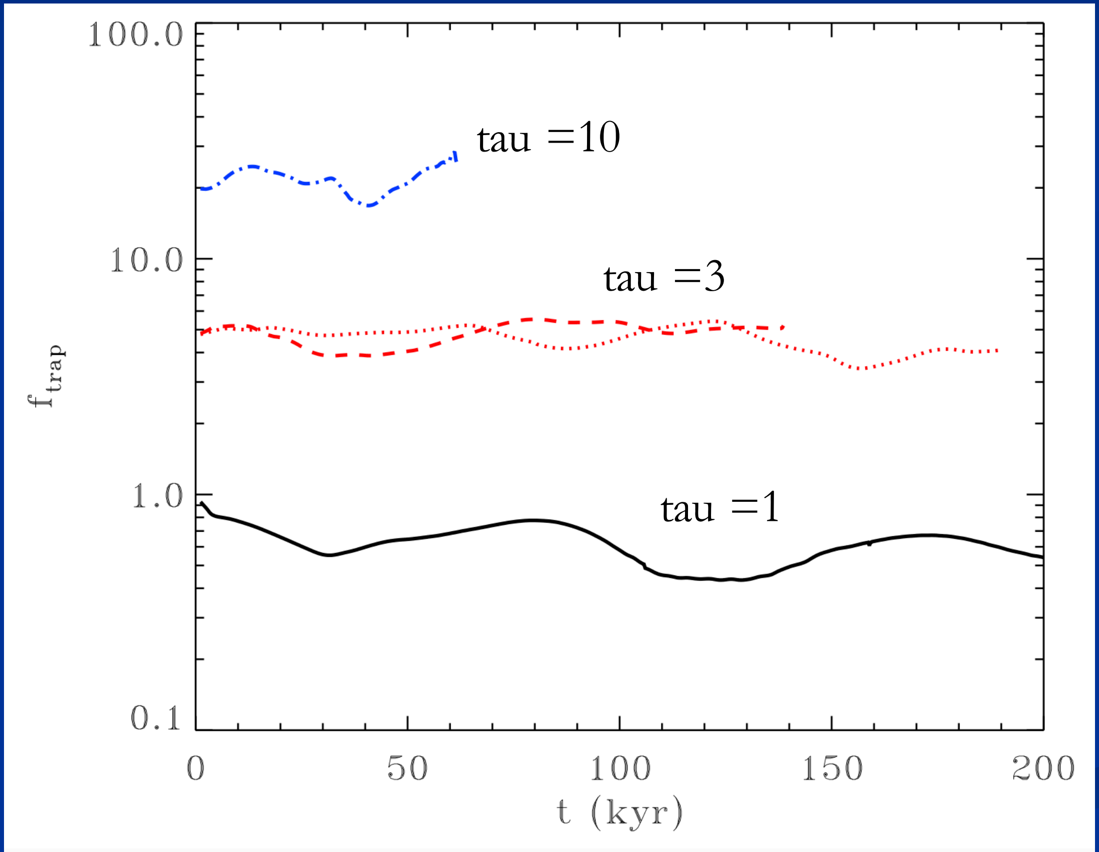

Radiation-Pressure-Driven Wind

$$\frac{dp_{\rm wind}}{dt} \simeq \left\{1 + \eta\tau_{\rm IR}\left[1 - \frac{(f_{E,*})_0}{f_{E,*}}\right]\right\}\frac{L}{c}$$

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

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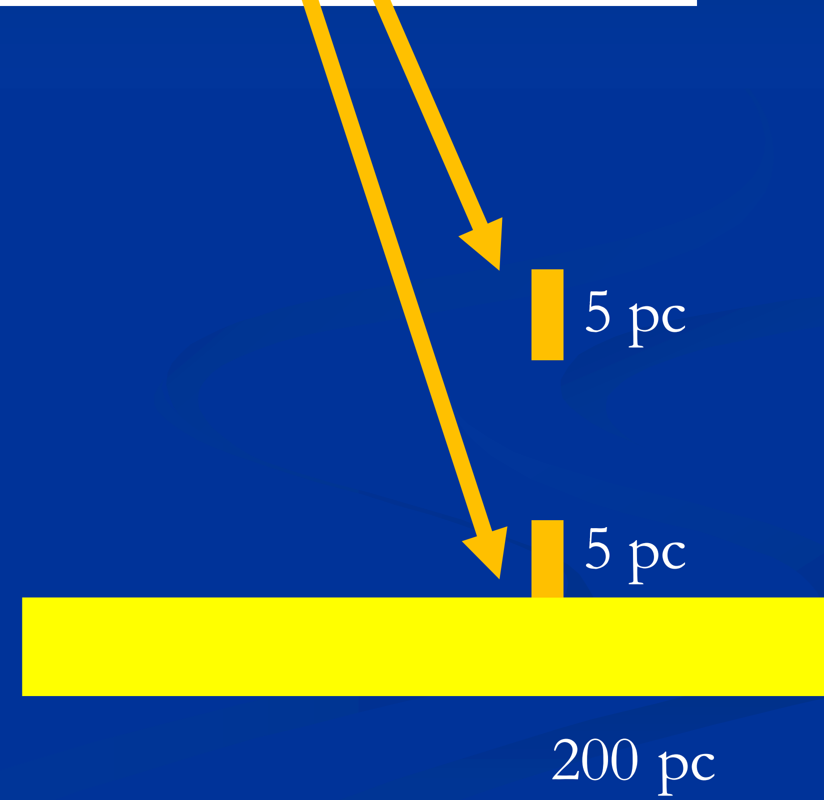

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$\tau_* = 1, 3, 10$

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

$\eta = 0.90, 0.69, 0.47$

Gas-Radiation Interaction
Radiation Hydrodynamic Simulations

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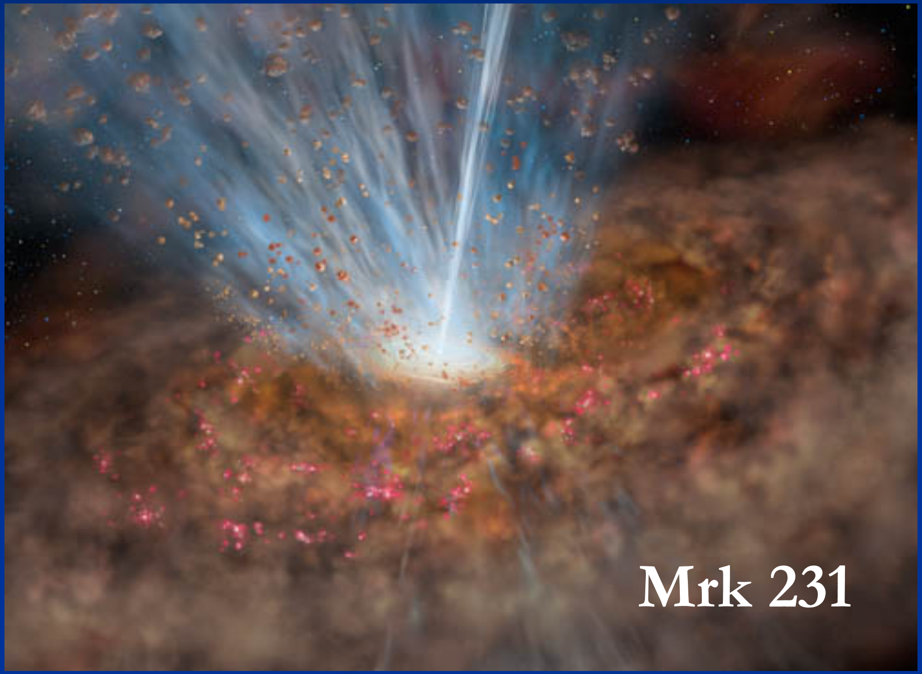
- $\eta \sim 0.5 - 0.9$

LIRGs and ULIRGs



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

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

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 simulation.
- We find a moderate amplification factor η.

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