Connections between LAE Properties and CGM/IGM Anisotropy

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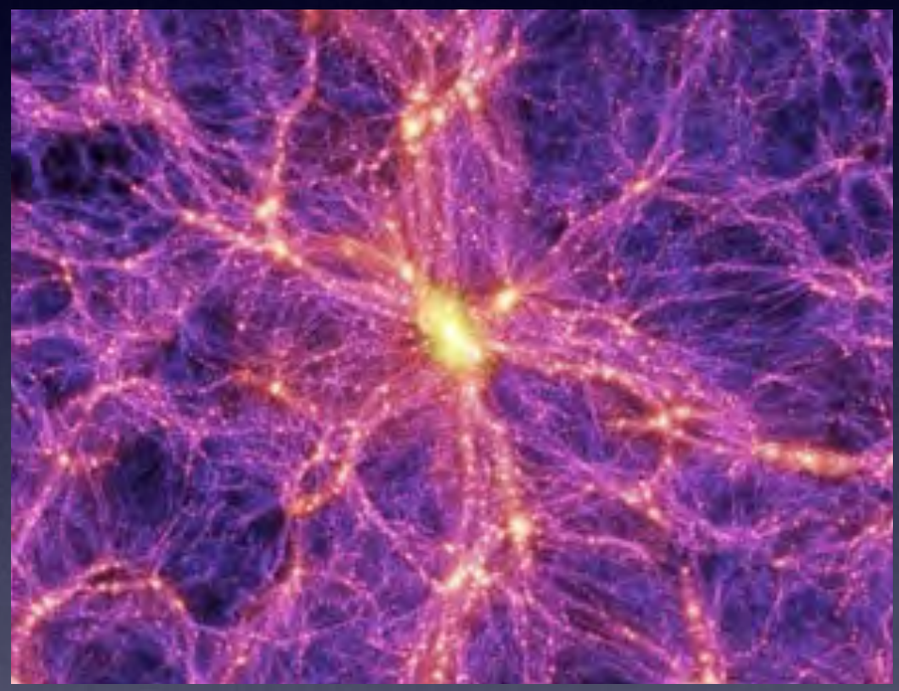
Shiyu Nie (Utah)
Raphael Sadoun (Utah)
Renyue Cen (Princeton)
Hy Trac (Carnegie Mellon)
Jordi Miralda-Escude (Barcelona)

Gas Environment of Star-Forming Galaxies

unlikely to be isotropic

disk, galactic wind / outflow

galaxy mergers



gas accretion from filaments, IGM

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Lyman-alpha photons from starforming galaxies (e.g., Lyman-alpha Emitters) experience resonant scatterings in the neutral gas of the circumgalactic and intergalactic media.

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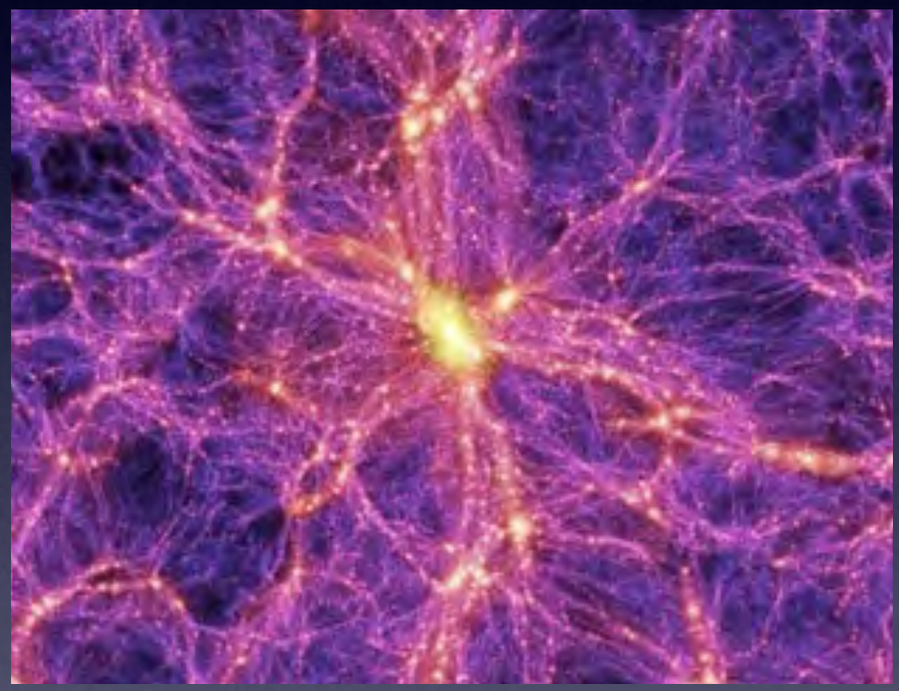

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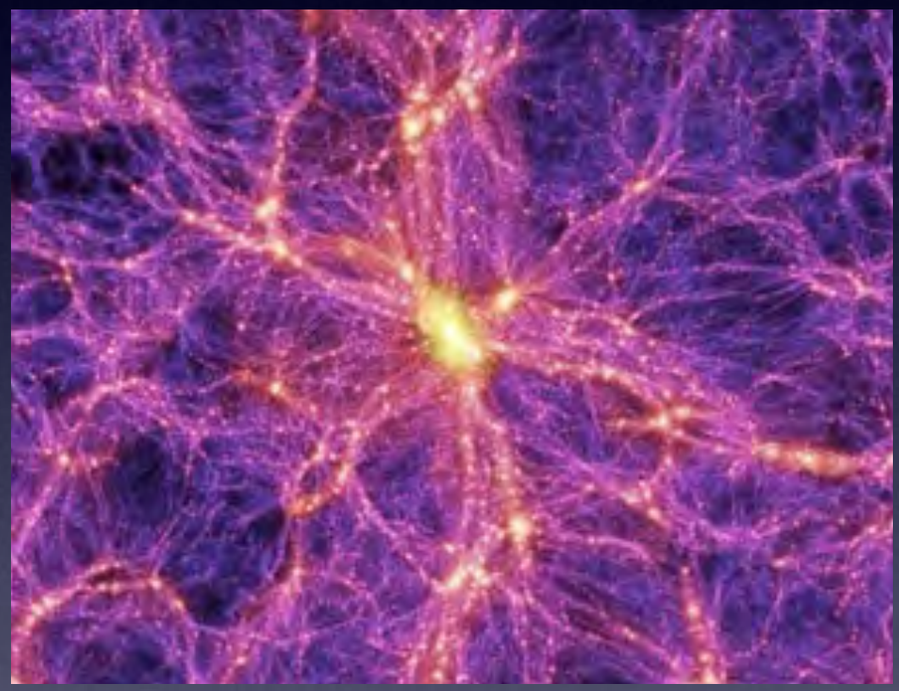
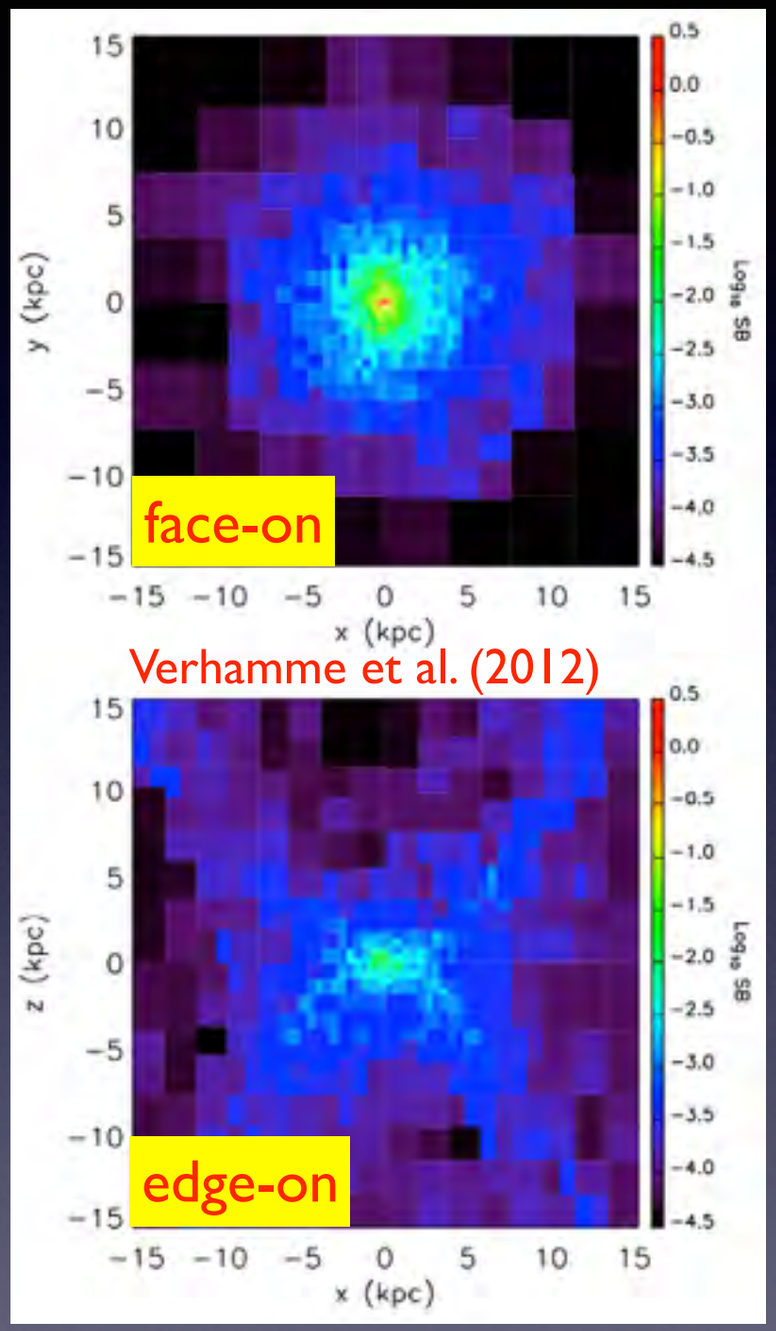


gas accretion from filaments, IGM

How would the anisotropic distribution of neutral gas affect the observational properties of Lyman-alpha emission?

How would we use the observed Lyman-alpha emission to probe the neutral gas?

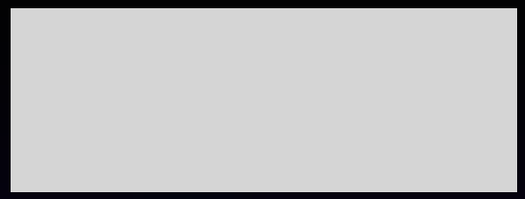
RT with simulated galaxies



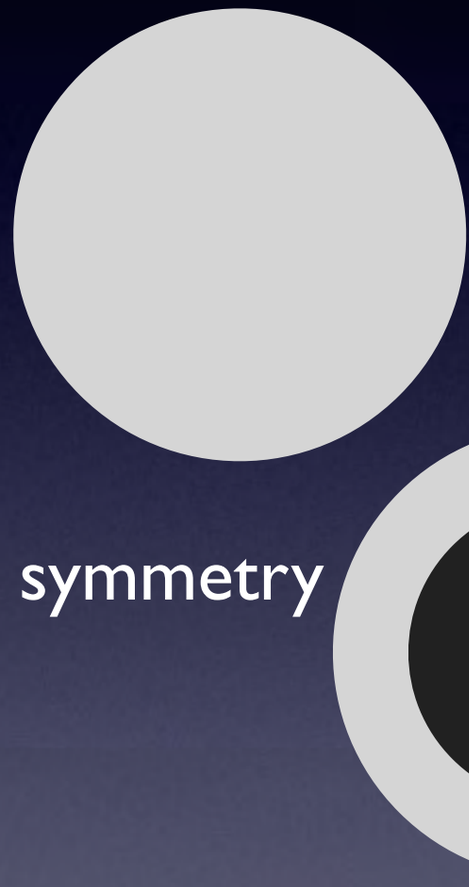
Verhamme et al. (2012)

(Laursen et al. 2009; Zheng et al. 2010; Barnes et al. 2011; Noterdaeme et al. 2012; Verhamme et al. 2012; Yajima et al. 2012, ...)

RT: analytic solution or analytic setup



plane-parallel



spherical symmetry

(Harrrington 1973; Neufeld 1990; Dijkstra et al. 2006; Loeb & Rybicki 1999; Auer 1968; Avery & House 1968; Adams 1972; Ahn et al. 2000, 2001, 2002; Ahn & Lee 2002; Zheng & Miralda-Escude 2002; Verhamme et al. 2006; Roy et al. 2009, 2010; ...)

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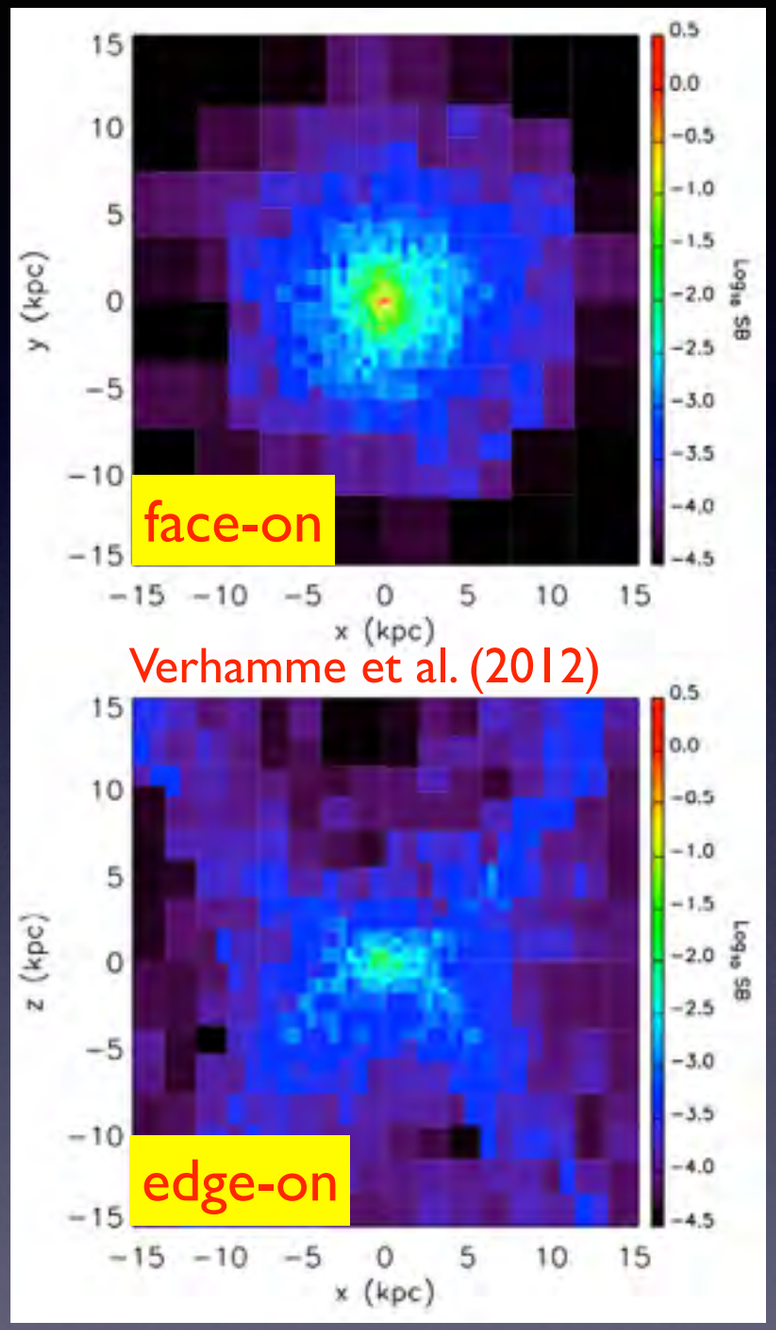

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Anisotropic Lyman-alpha Emission

Zheng & Wallace (2014)

Lyman-alpha emission from (analytic) anisotropic gas distribution

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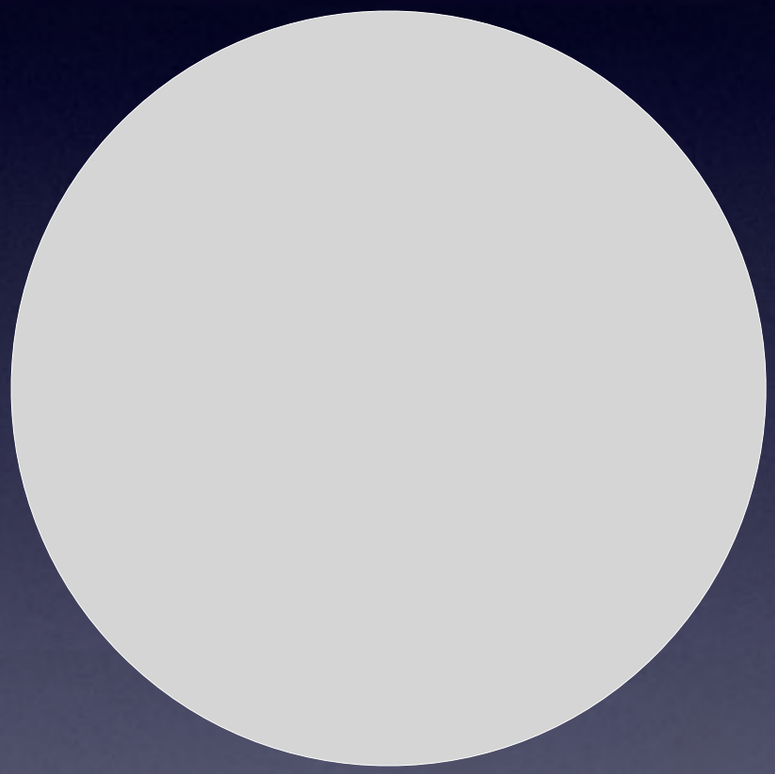

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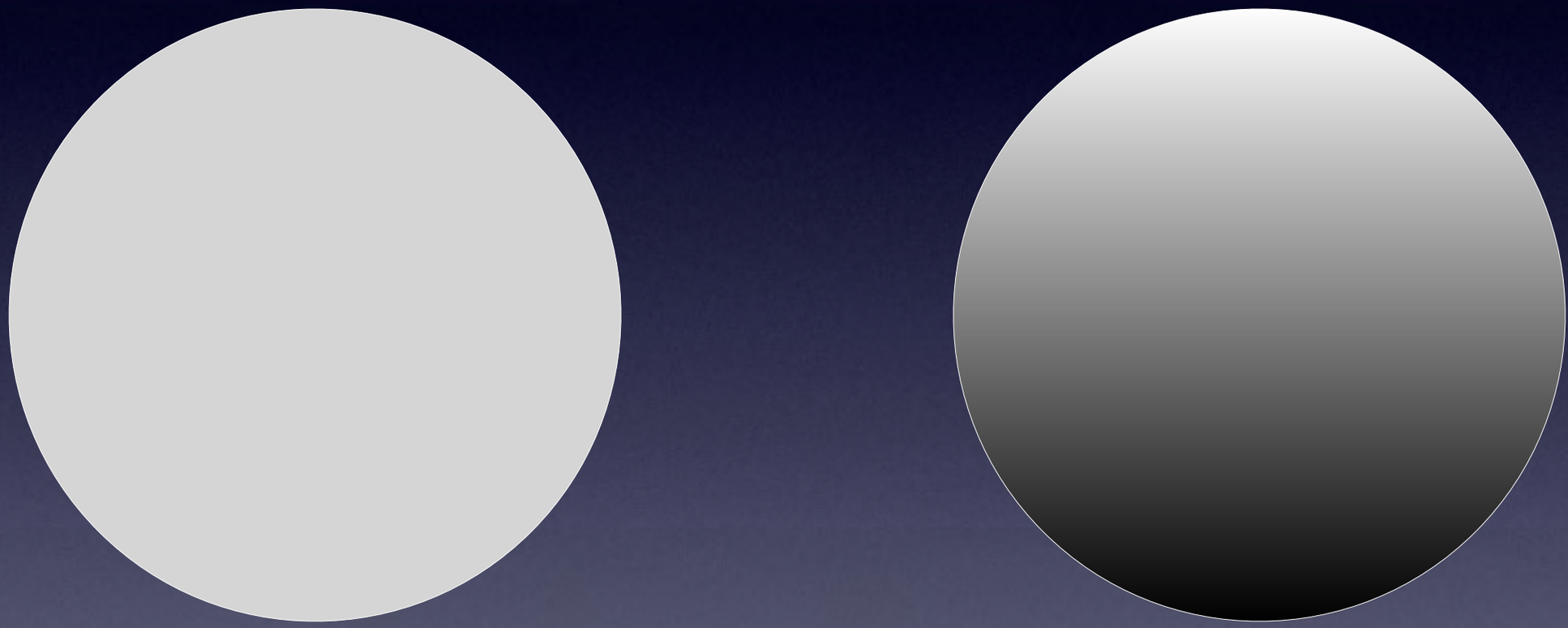

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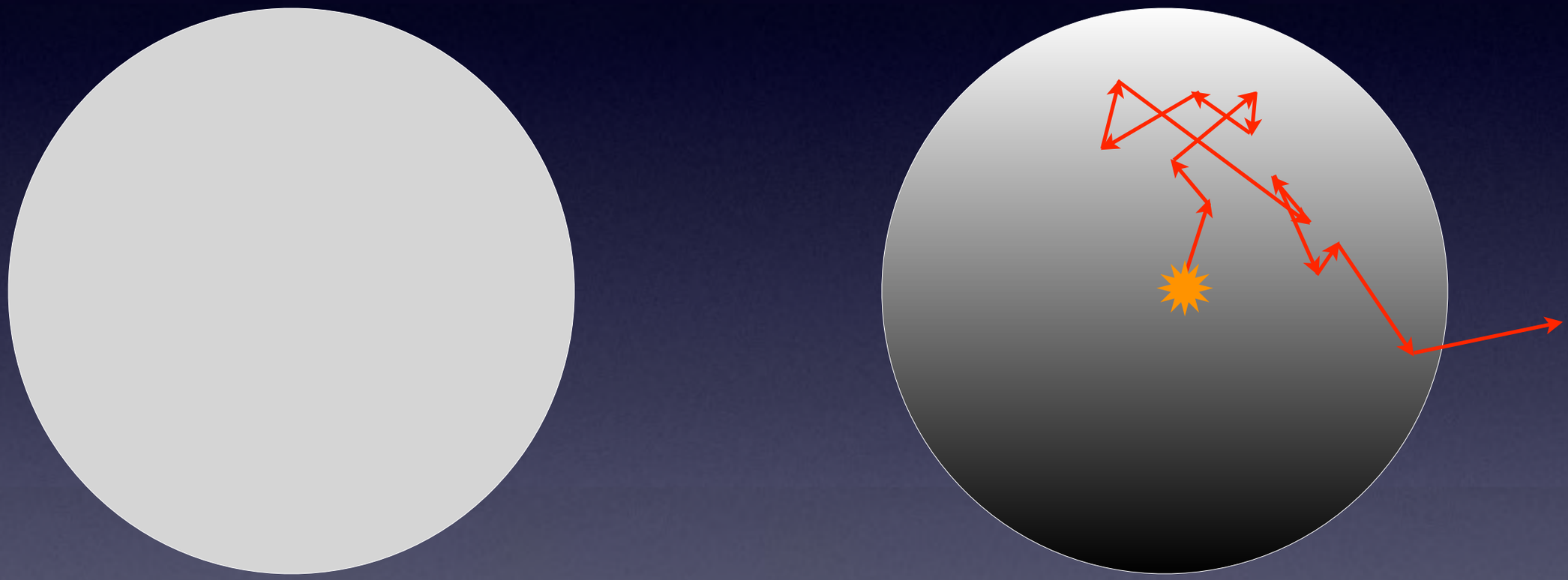

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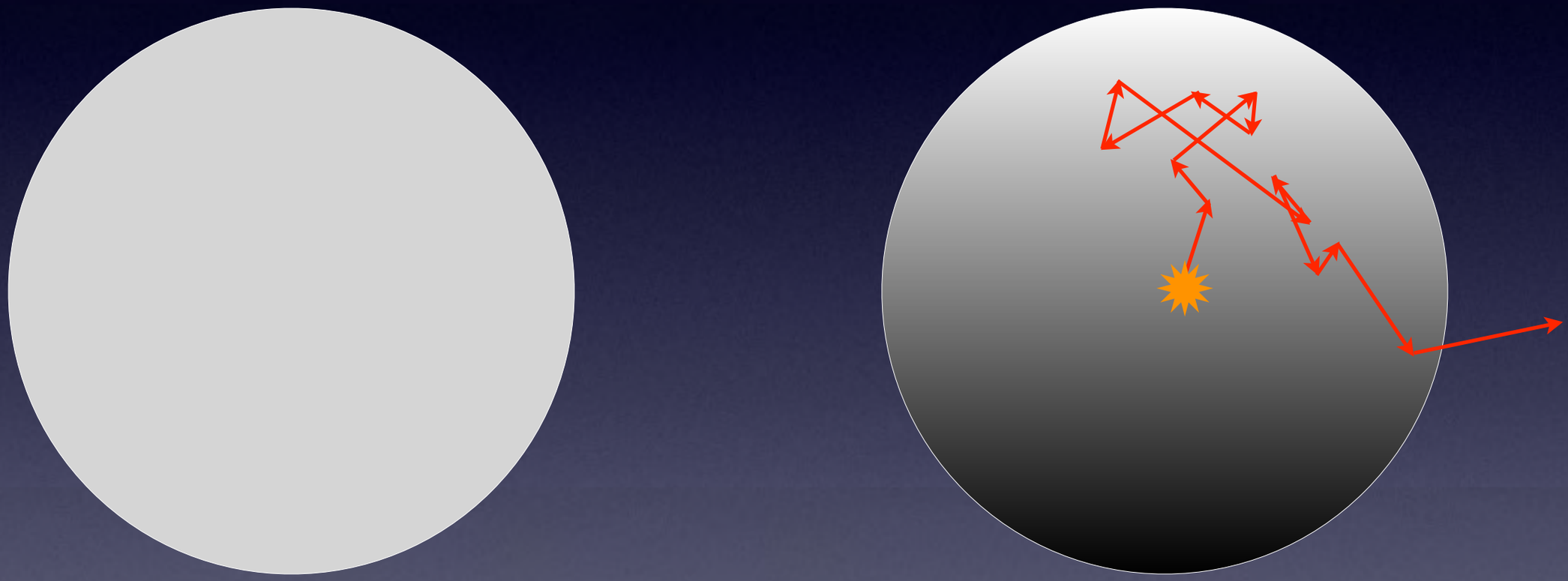
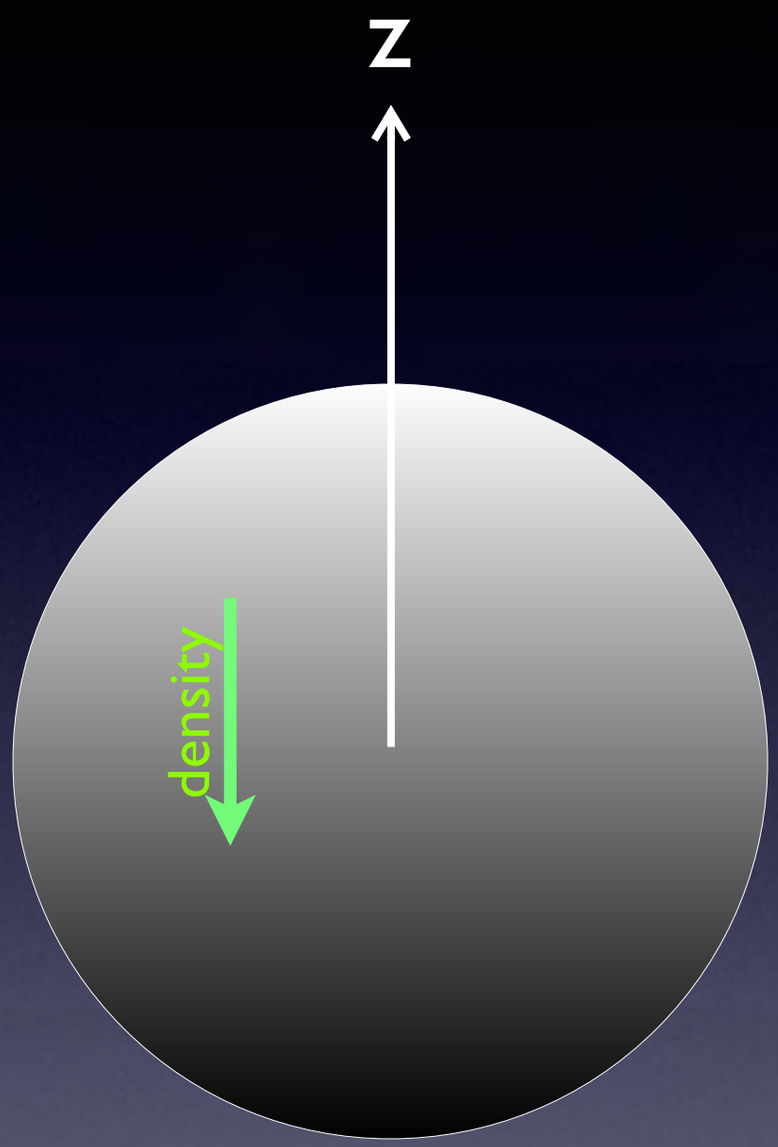


anisotropy in gas distribution: **density** and **velocity**

Density Gradient Case



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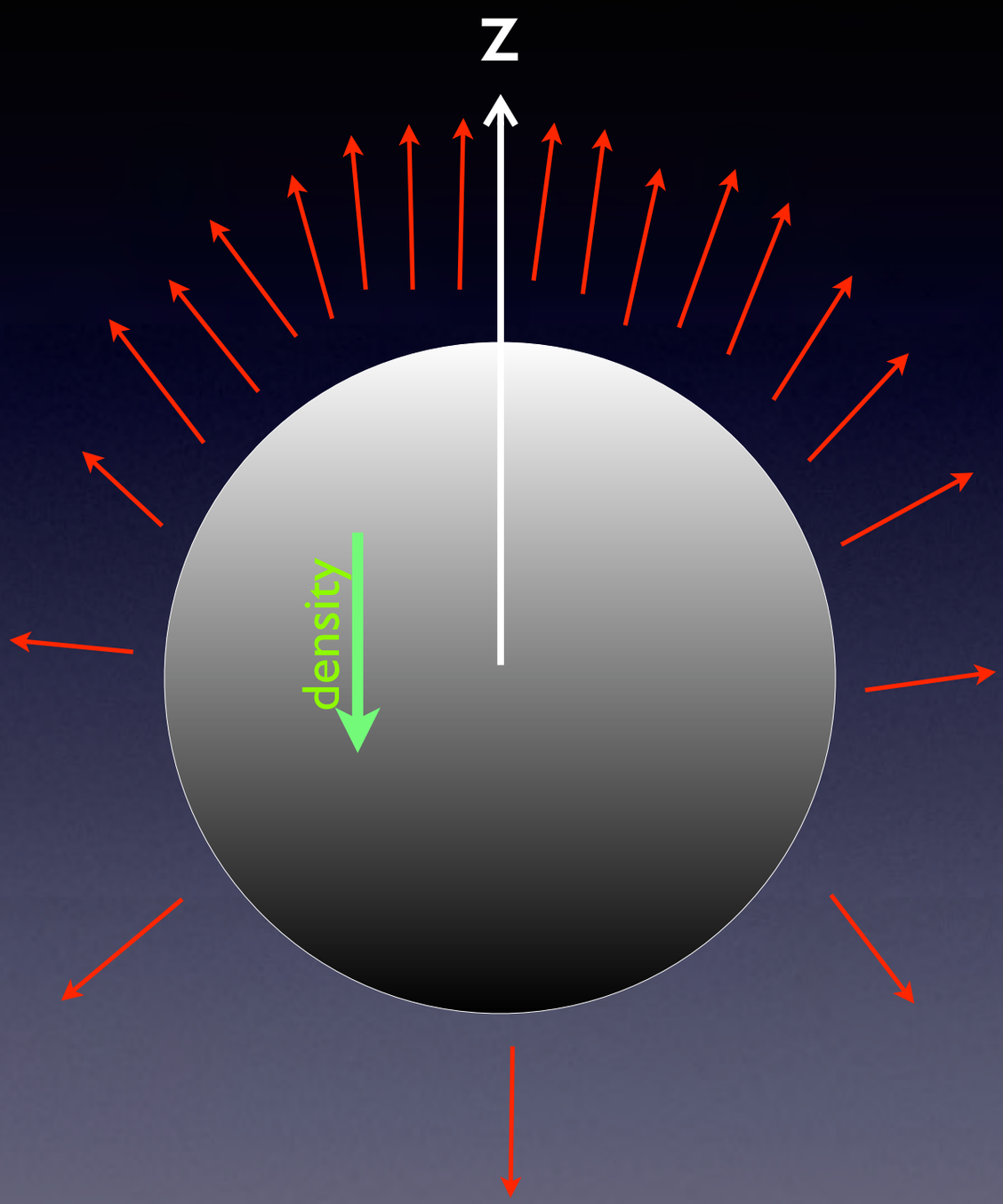

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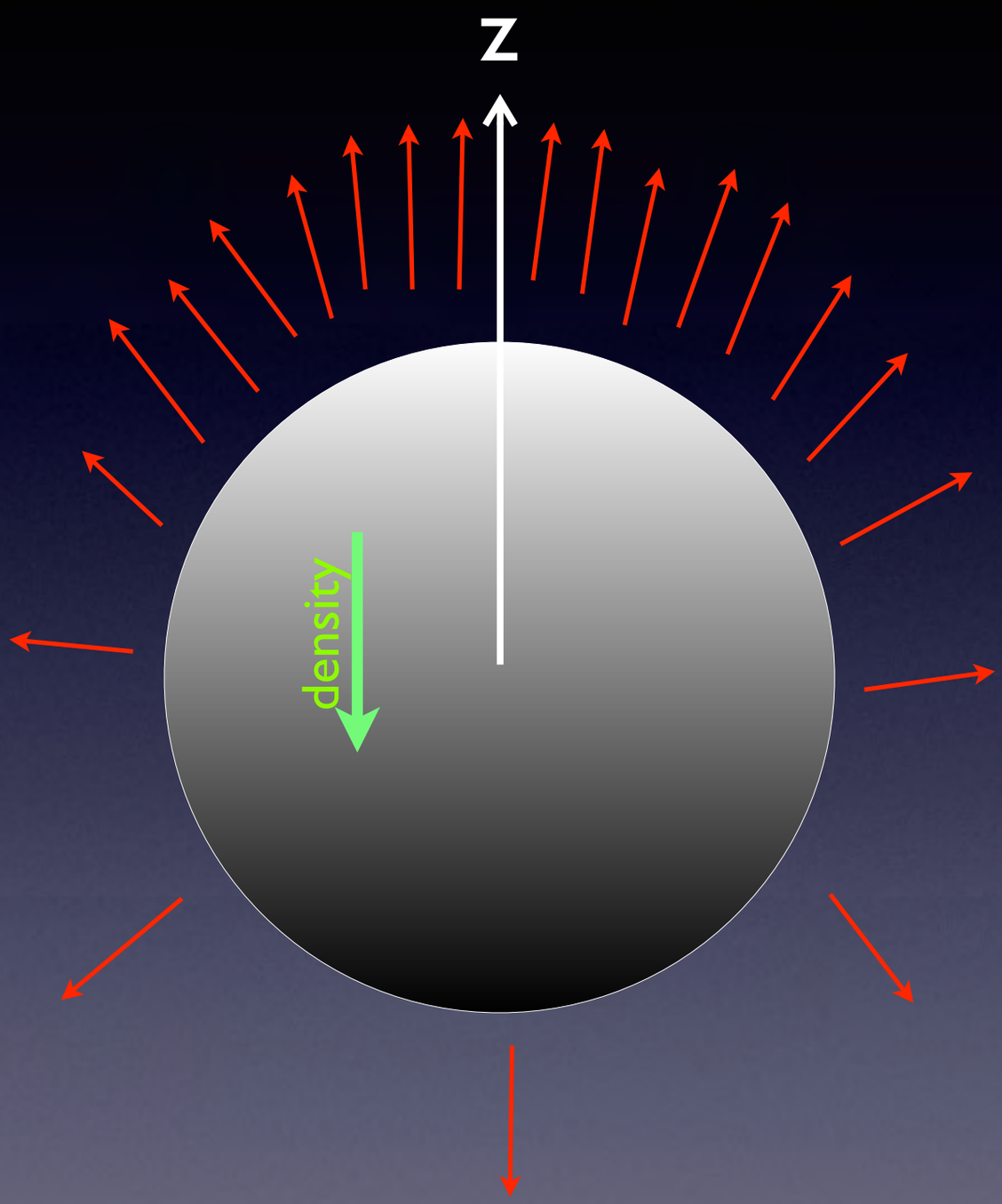
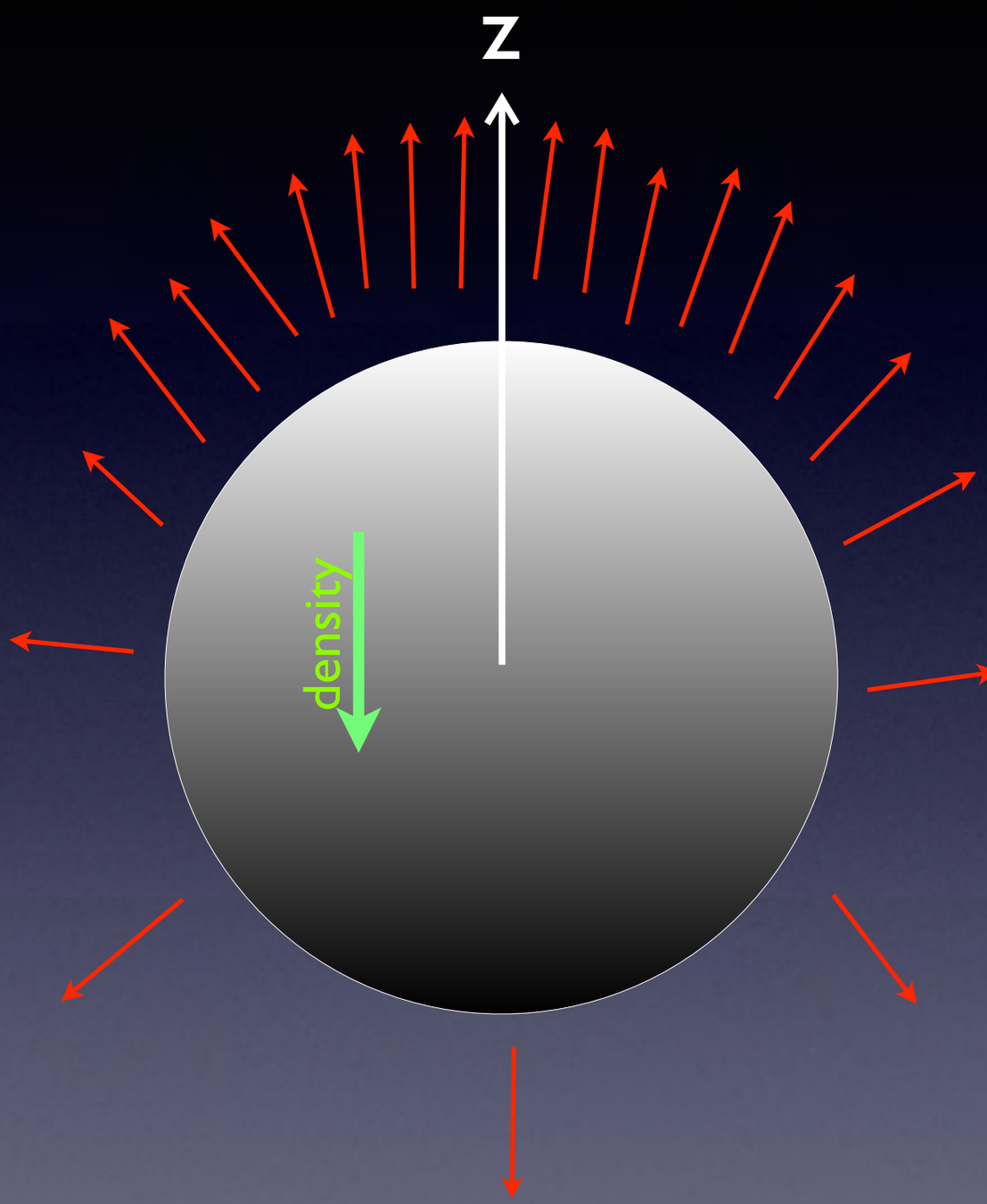
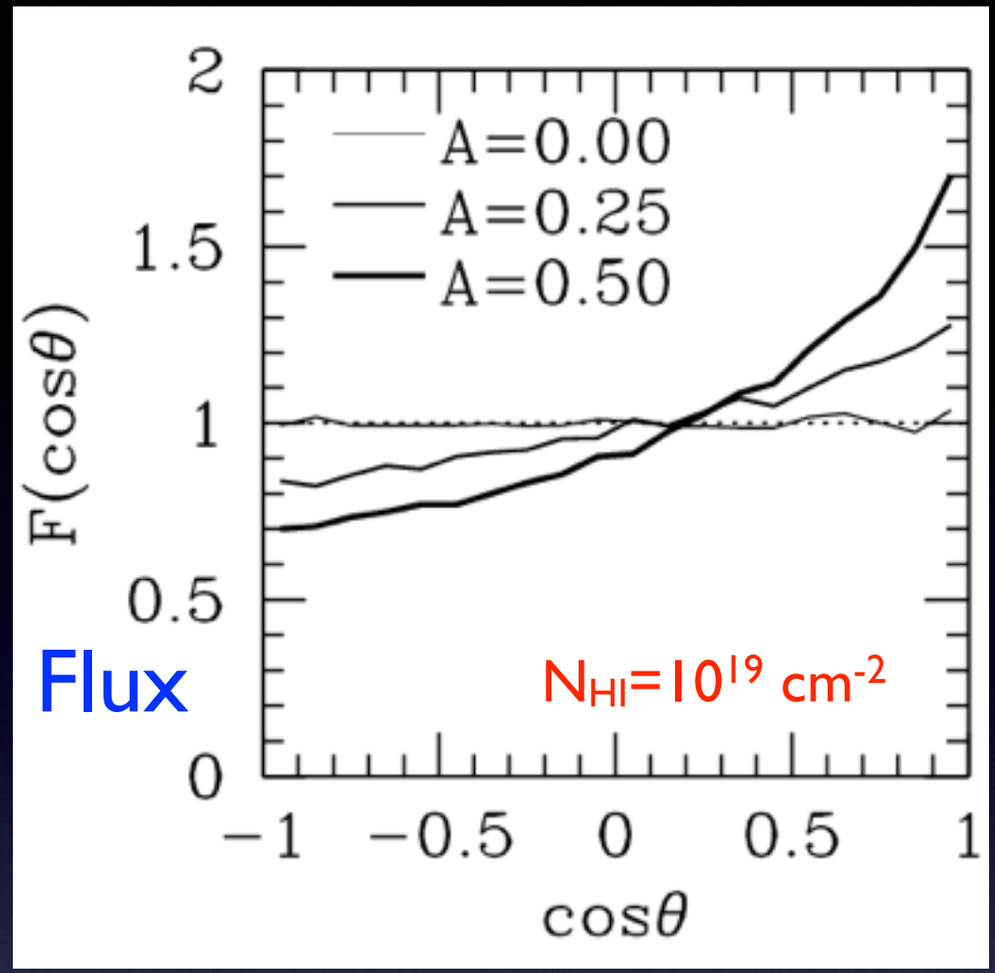


Density Anisotropy

$\Longrightarrow$ Lyman Alpha Emission Anisotropy

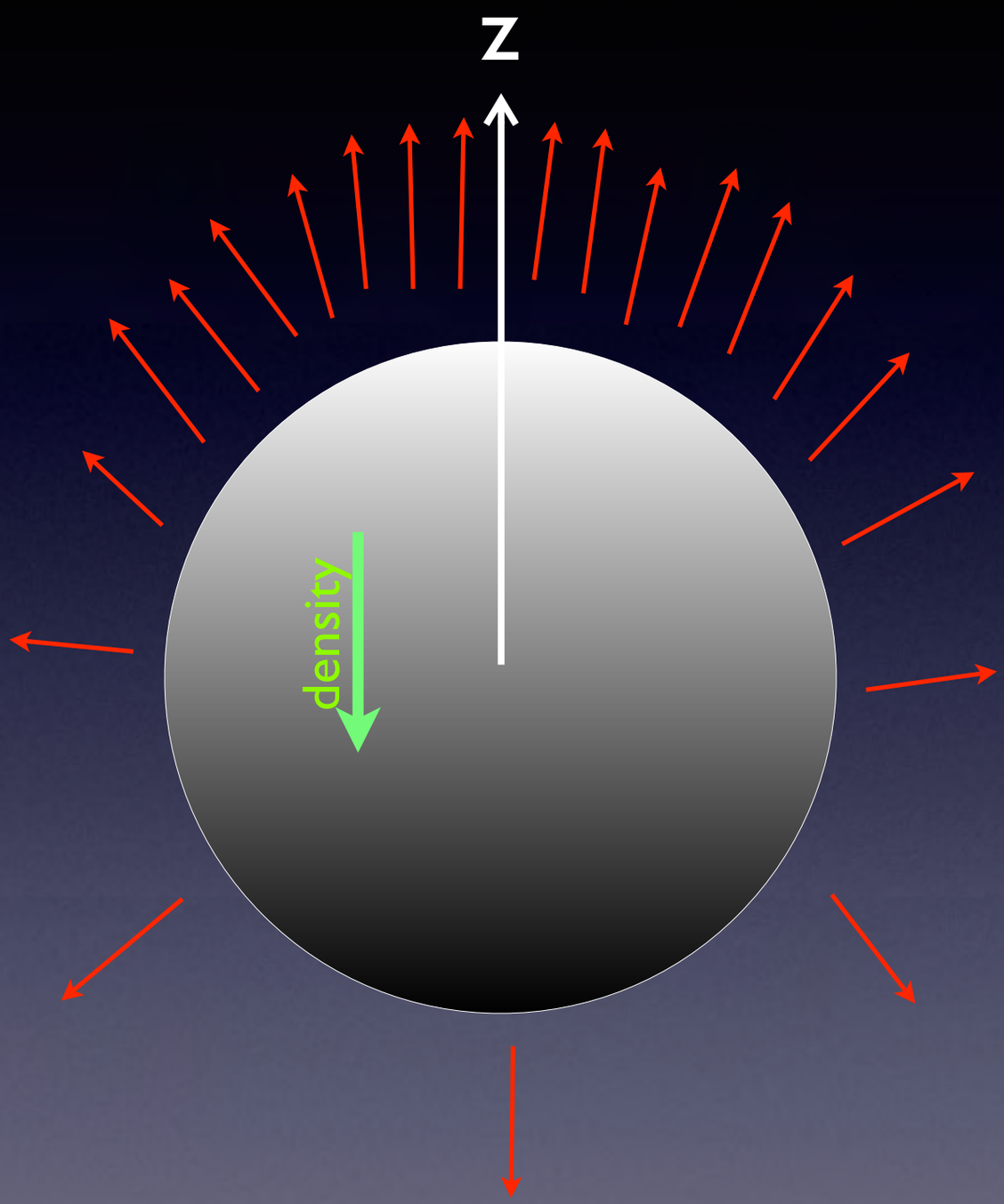
Density Gradient Case





Density Anisotropy
⟹ Lyman Alpha Emission Anisotropy

Density Gradient Case



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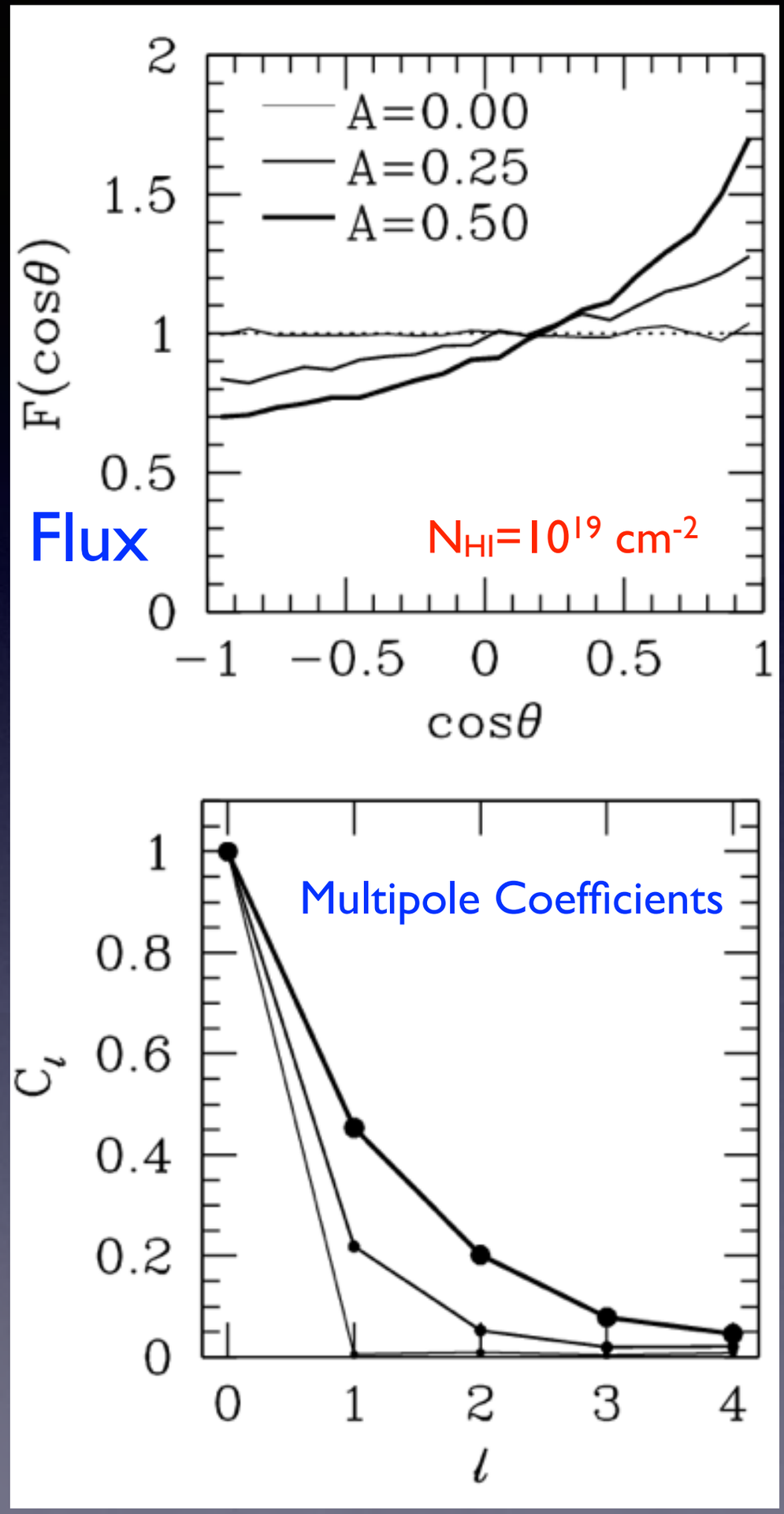

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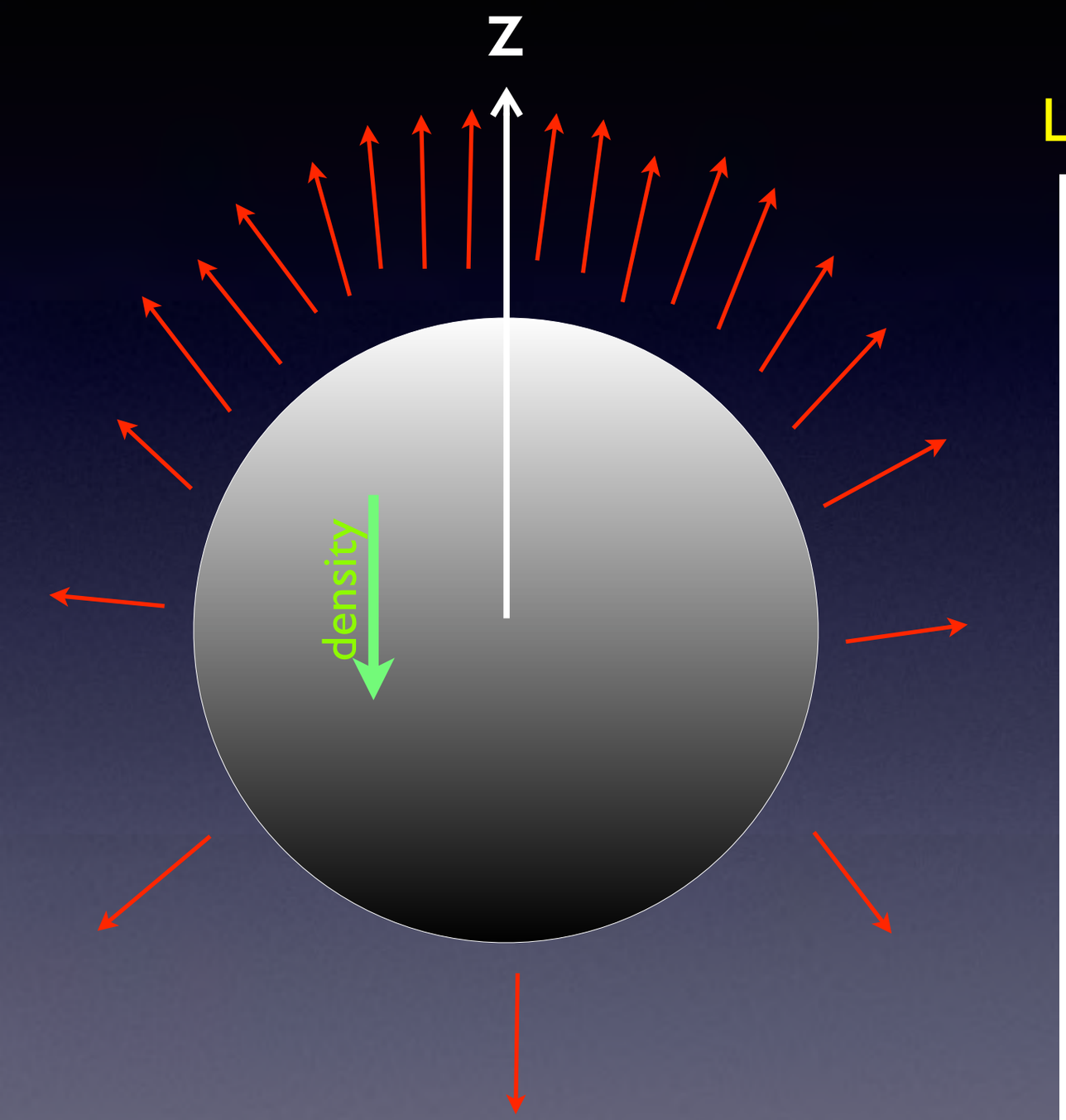
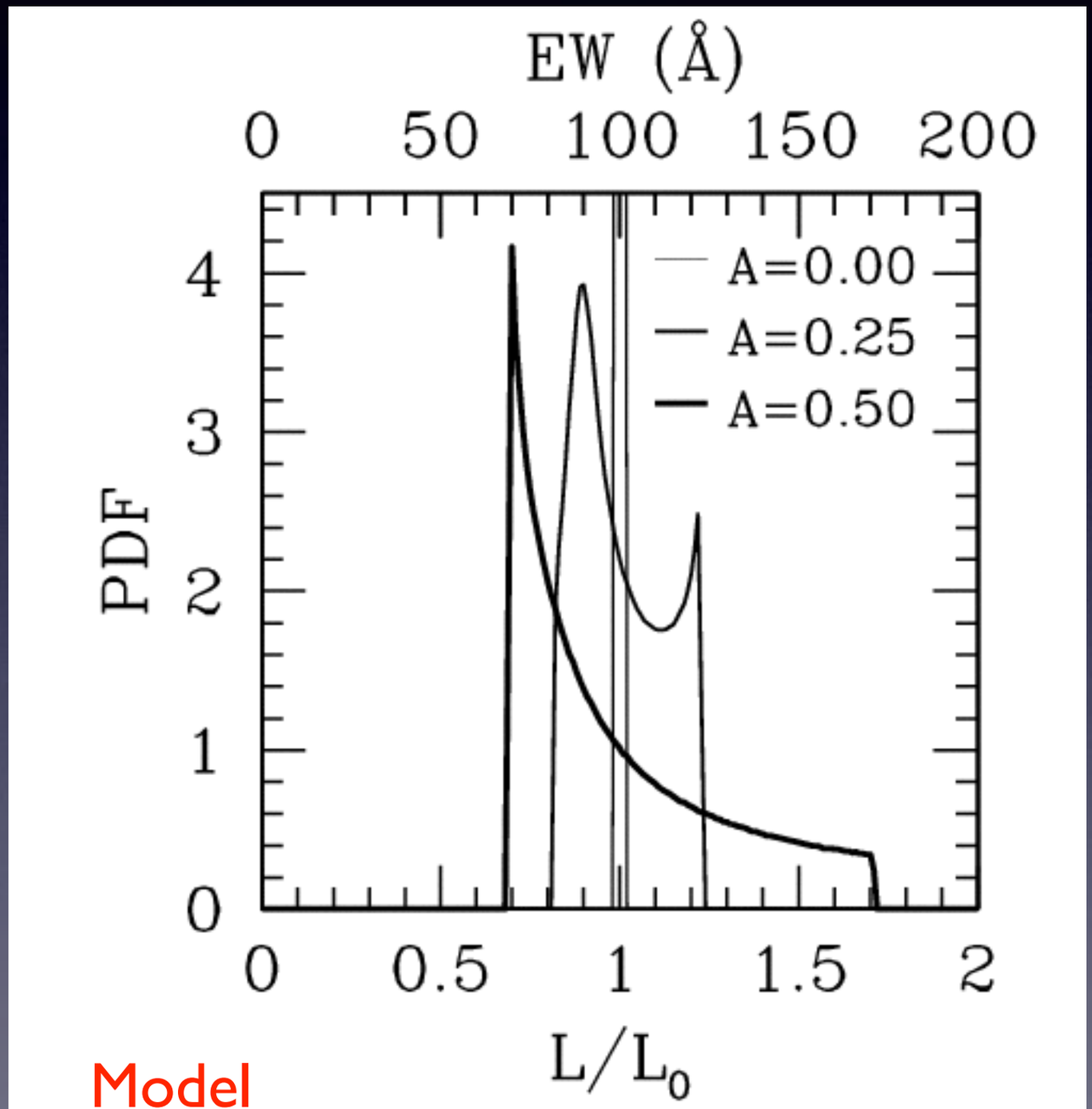
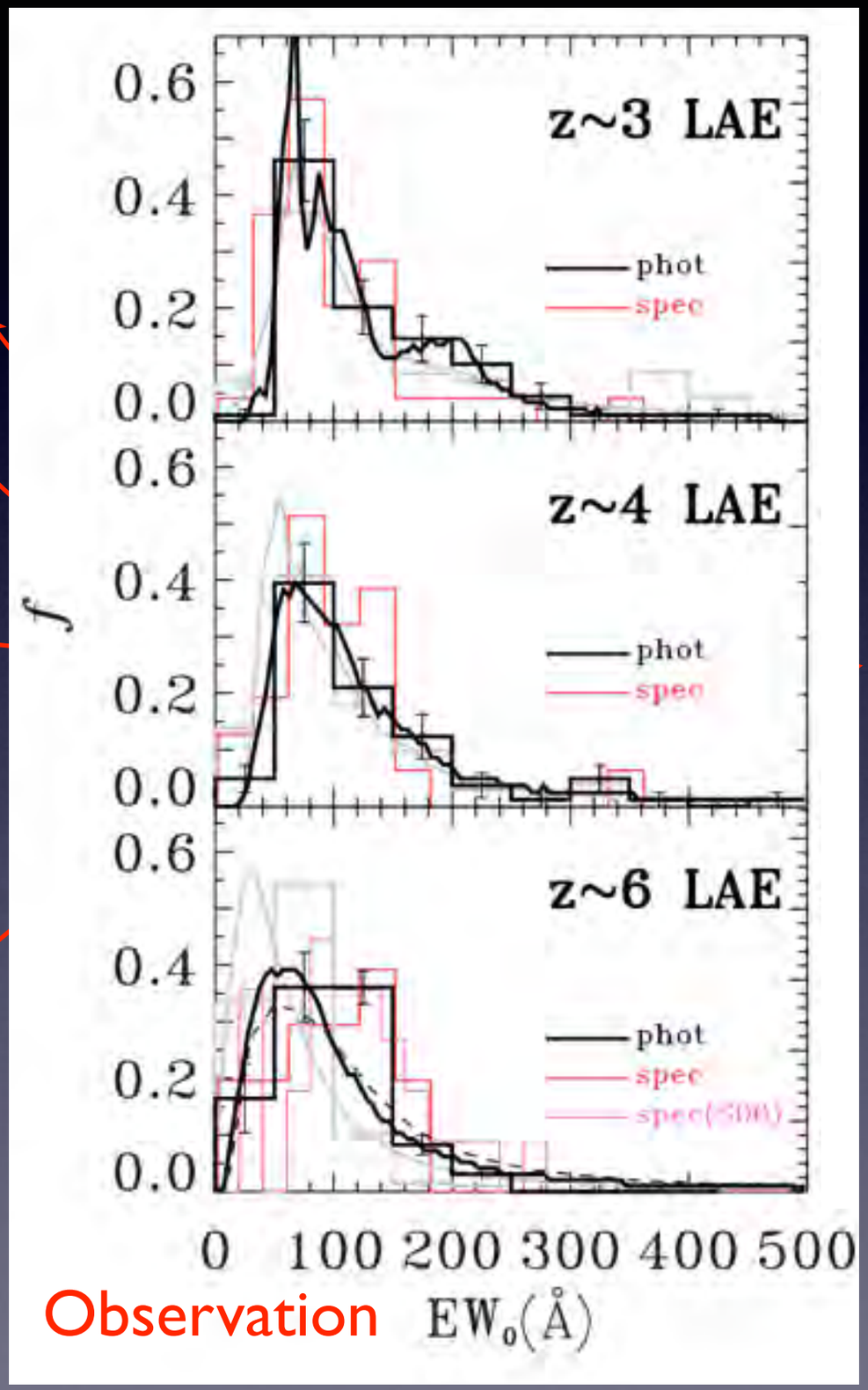


Lyman-alpha Equivalent Width Distribution



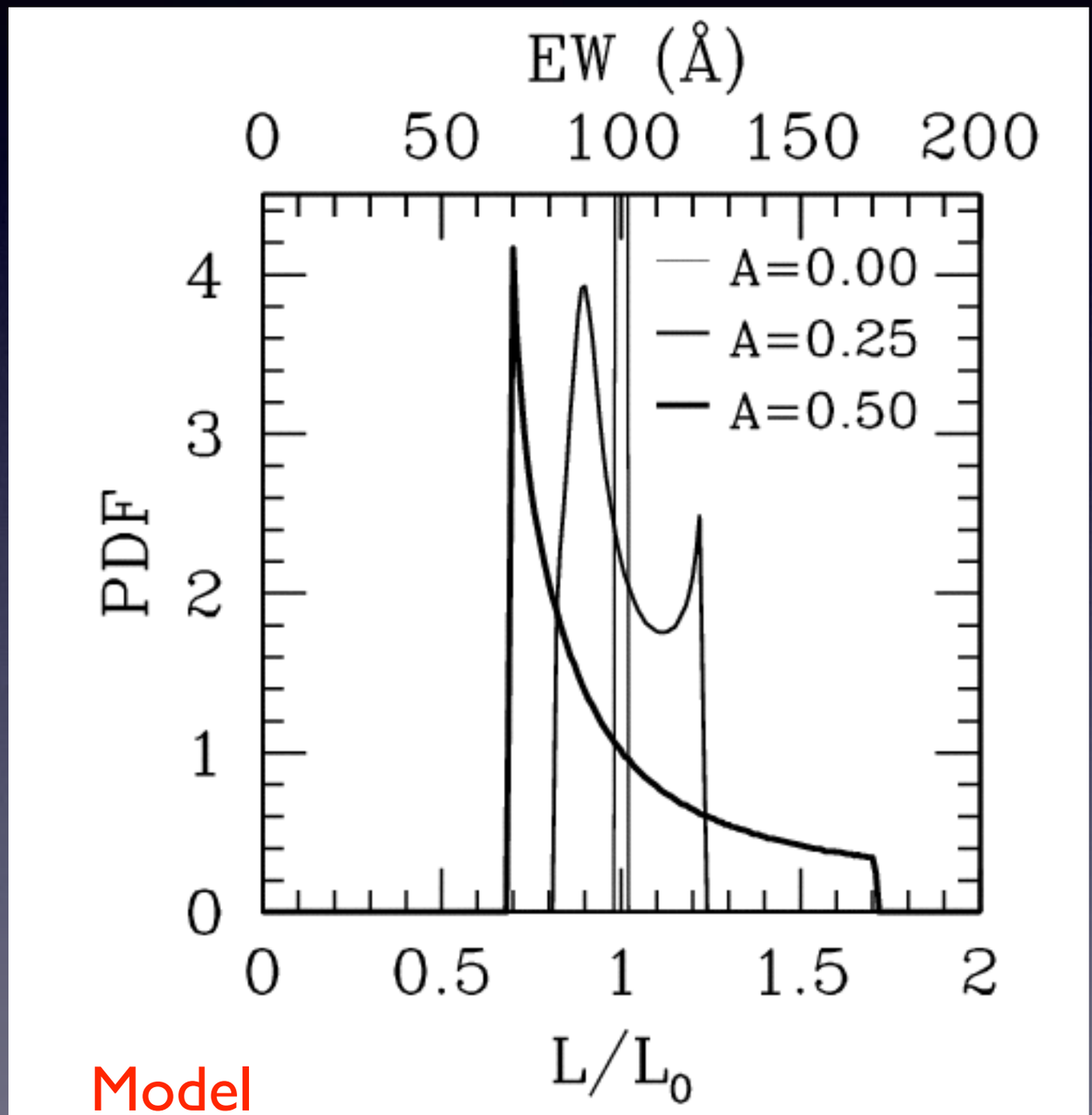
Model

Density Gradient Case



Observation

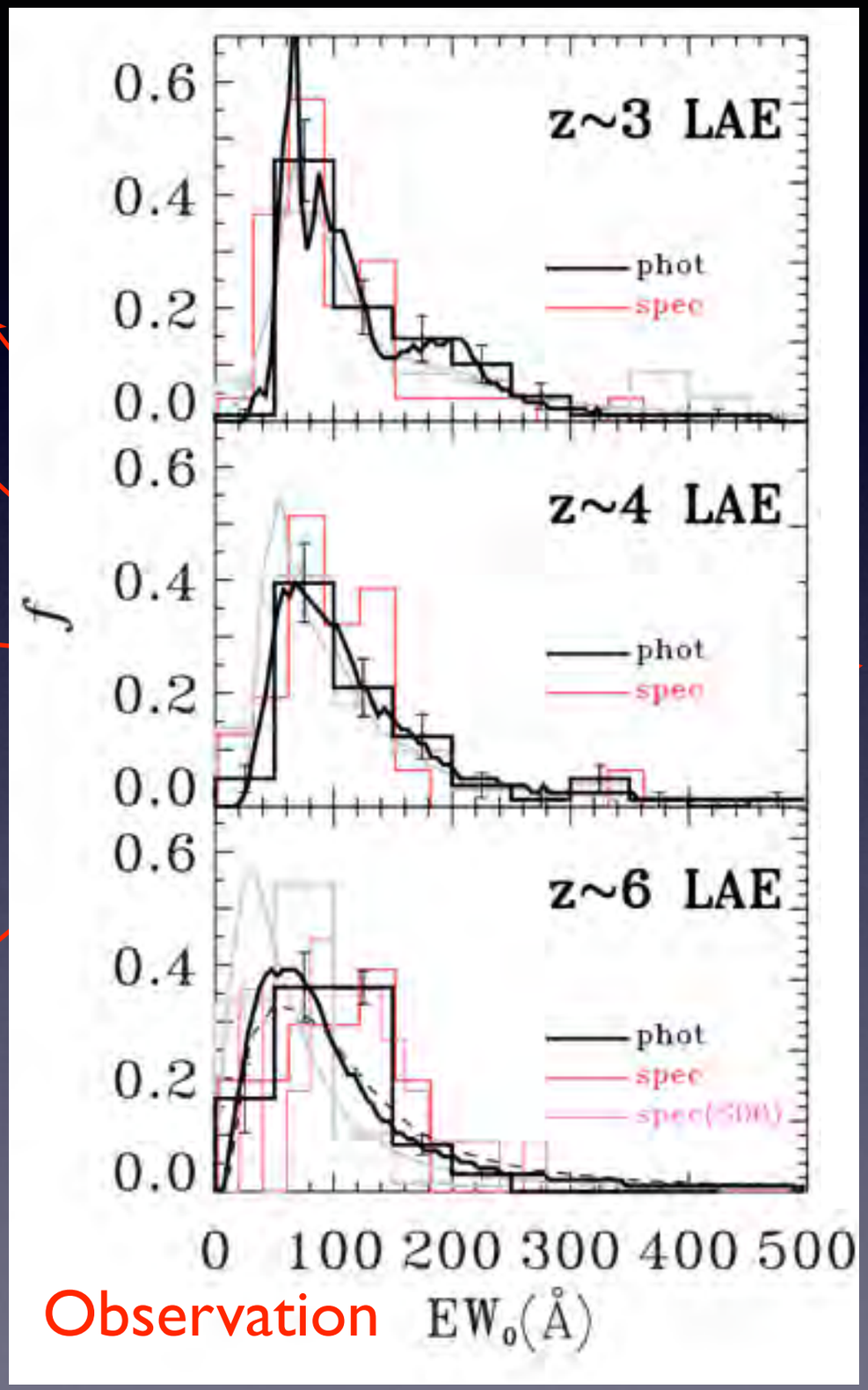
Lyman-alpha Equivalent Width Distribution



Model

Ouchi et al. (2008)

Density Gradient Case



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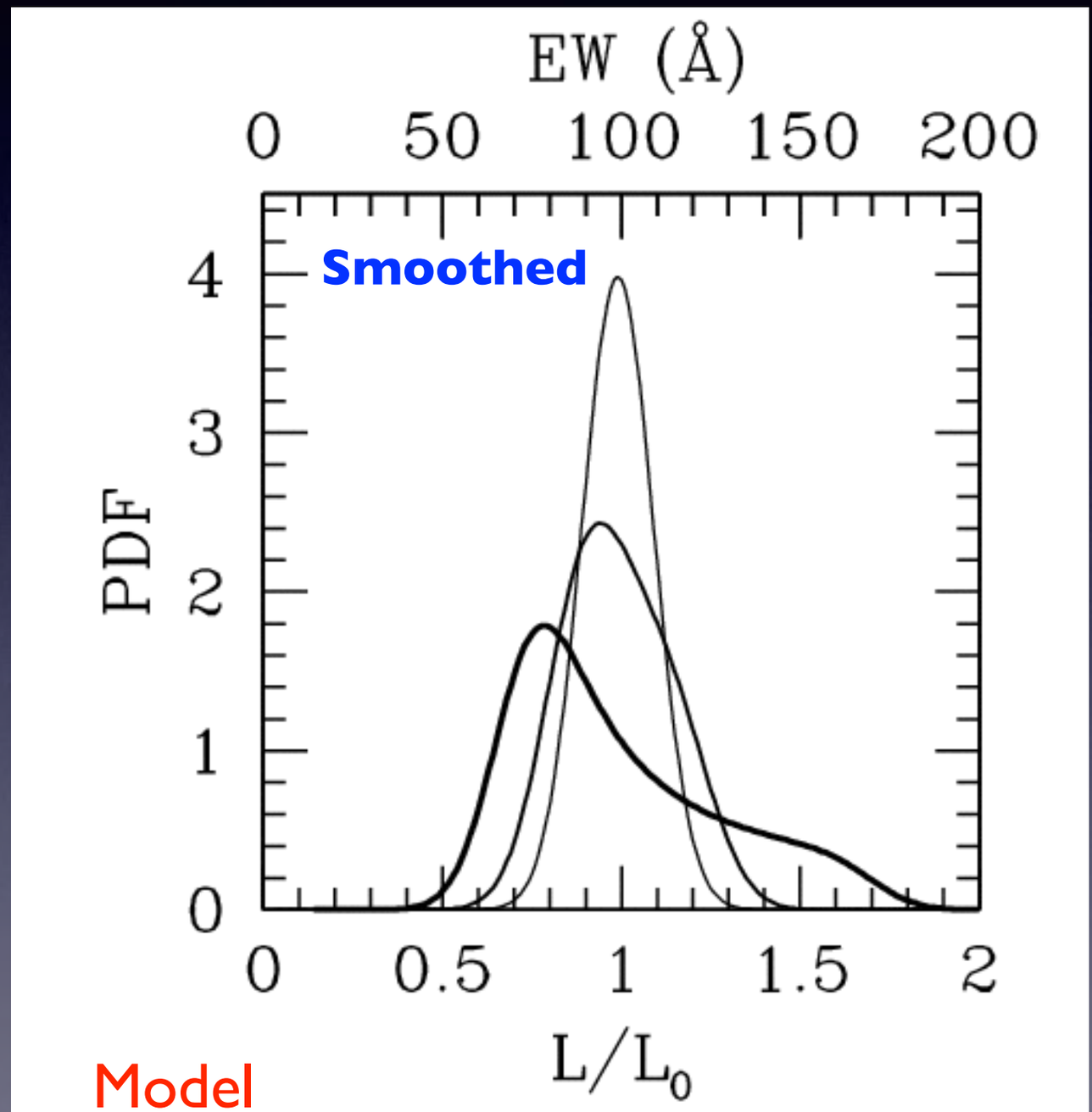

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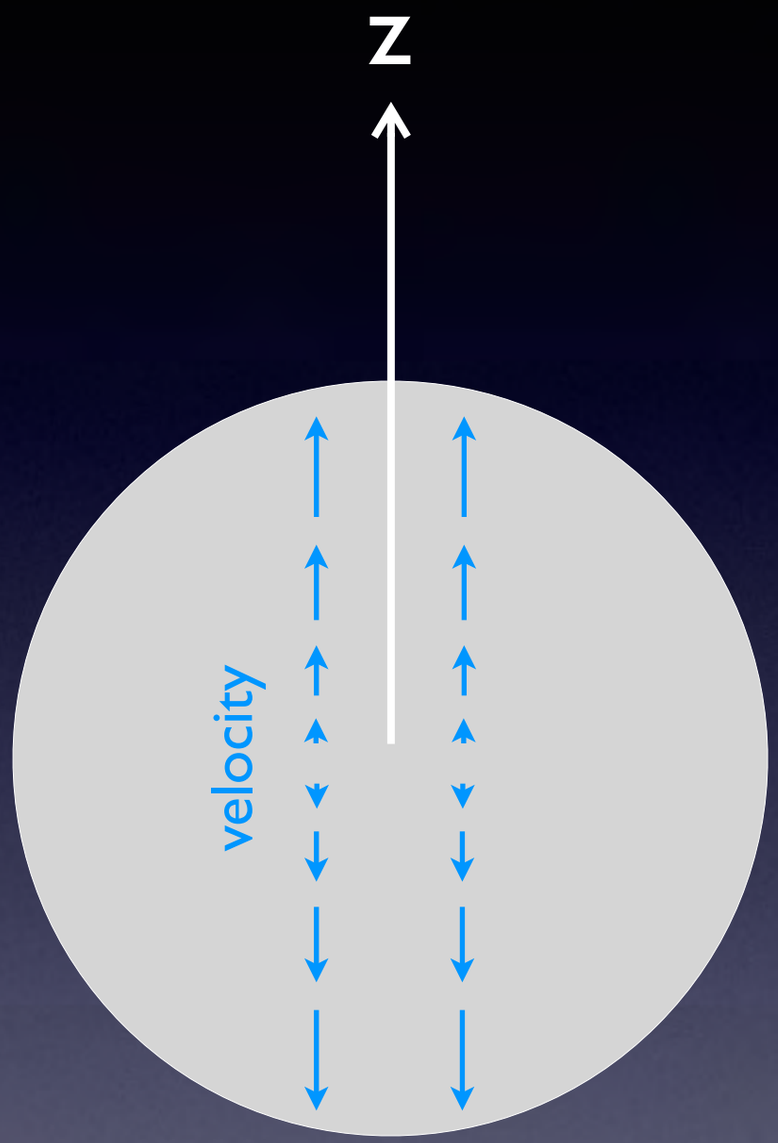

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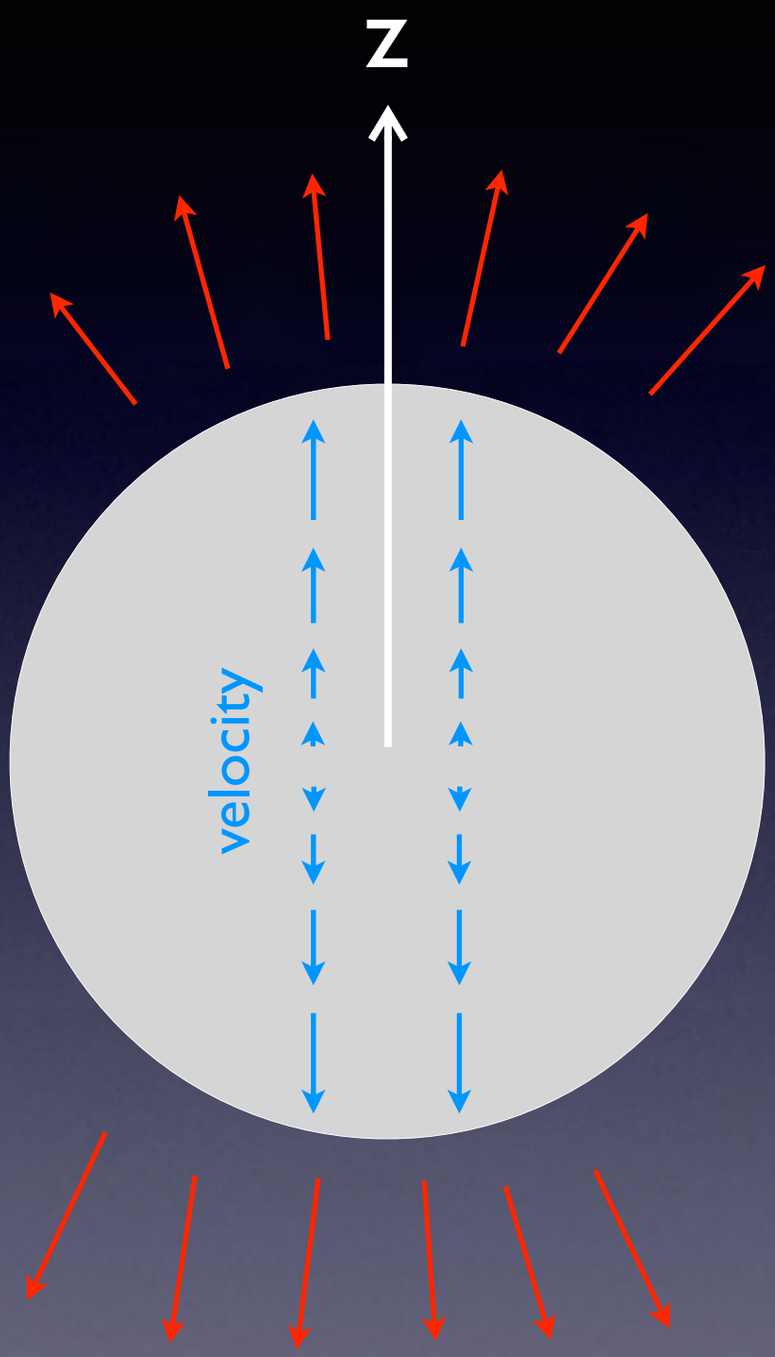
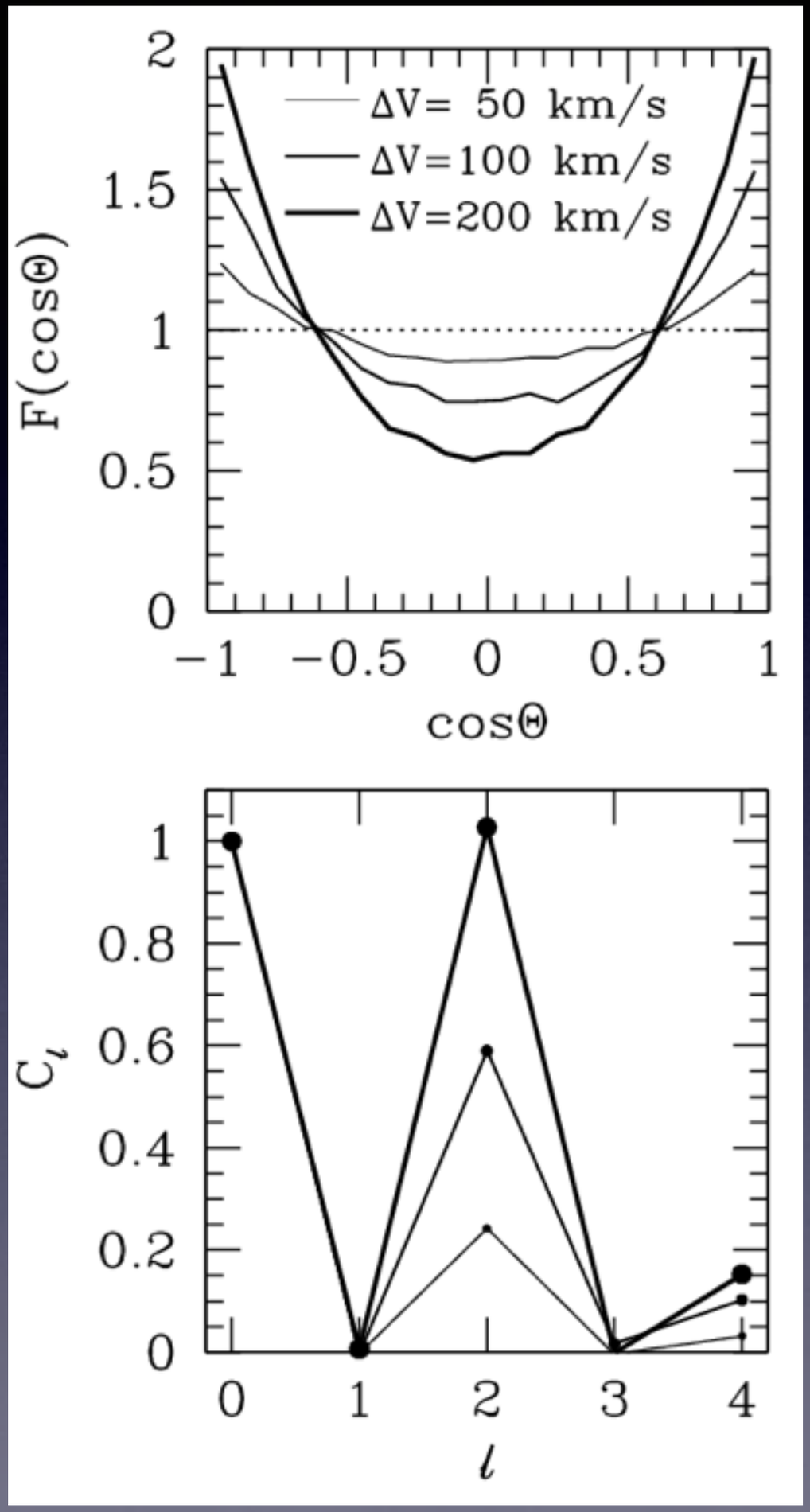


Velocity Anisotropy
$\Longrightarrow$ Lyman Alpha Emission Anisotropy



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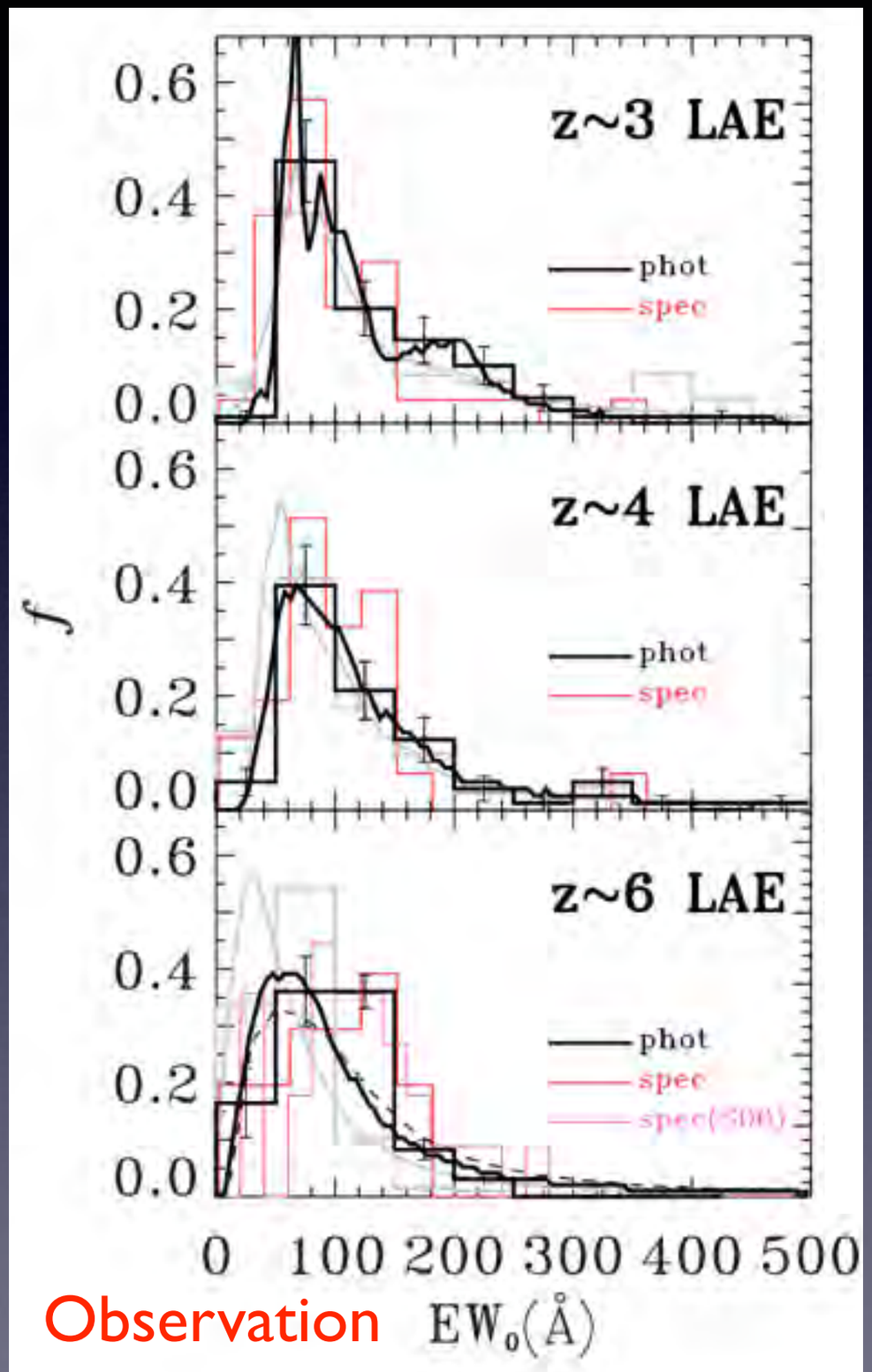

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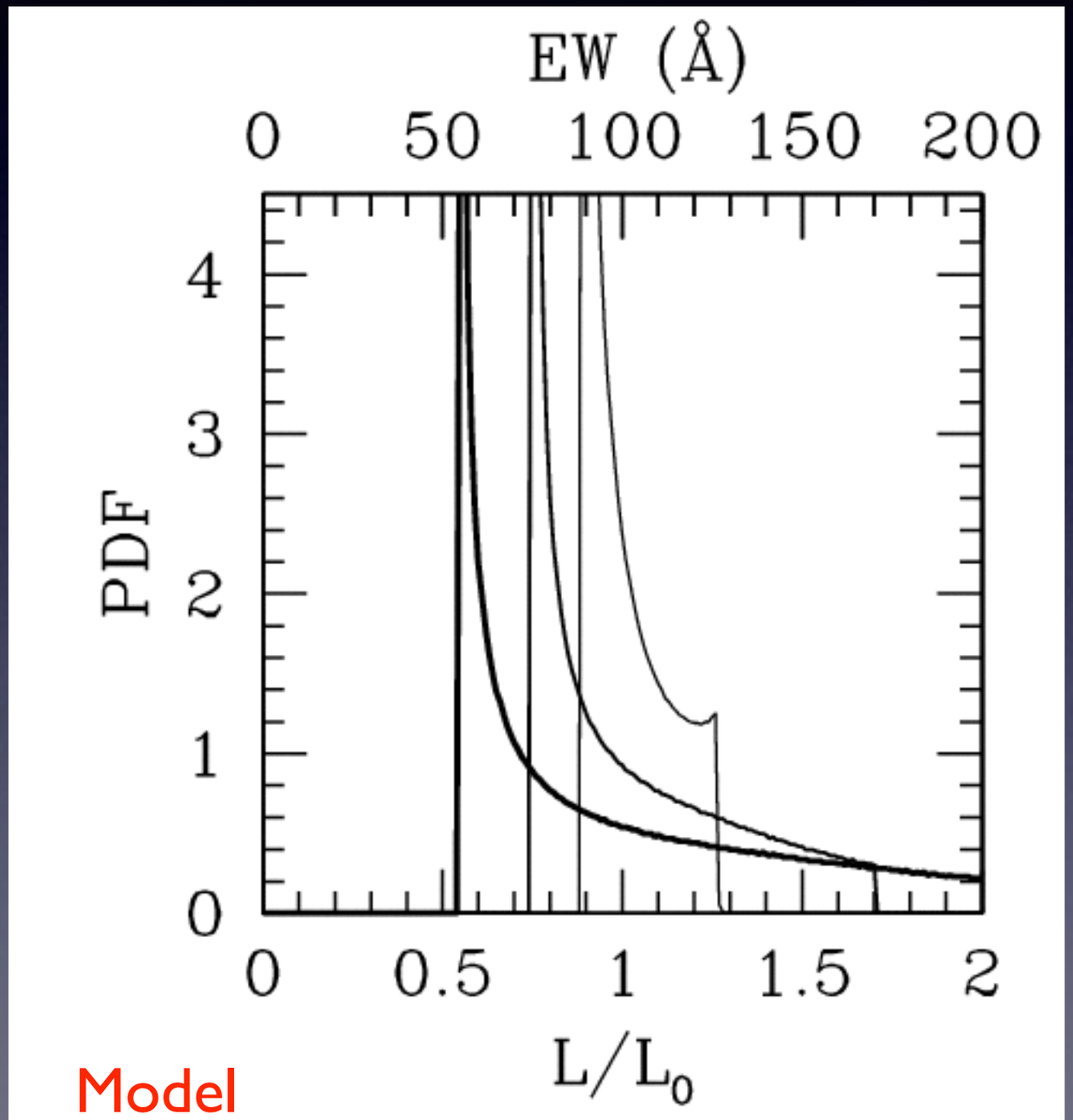

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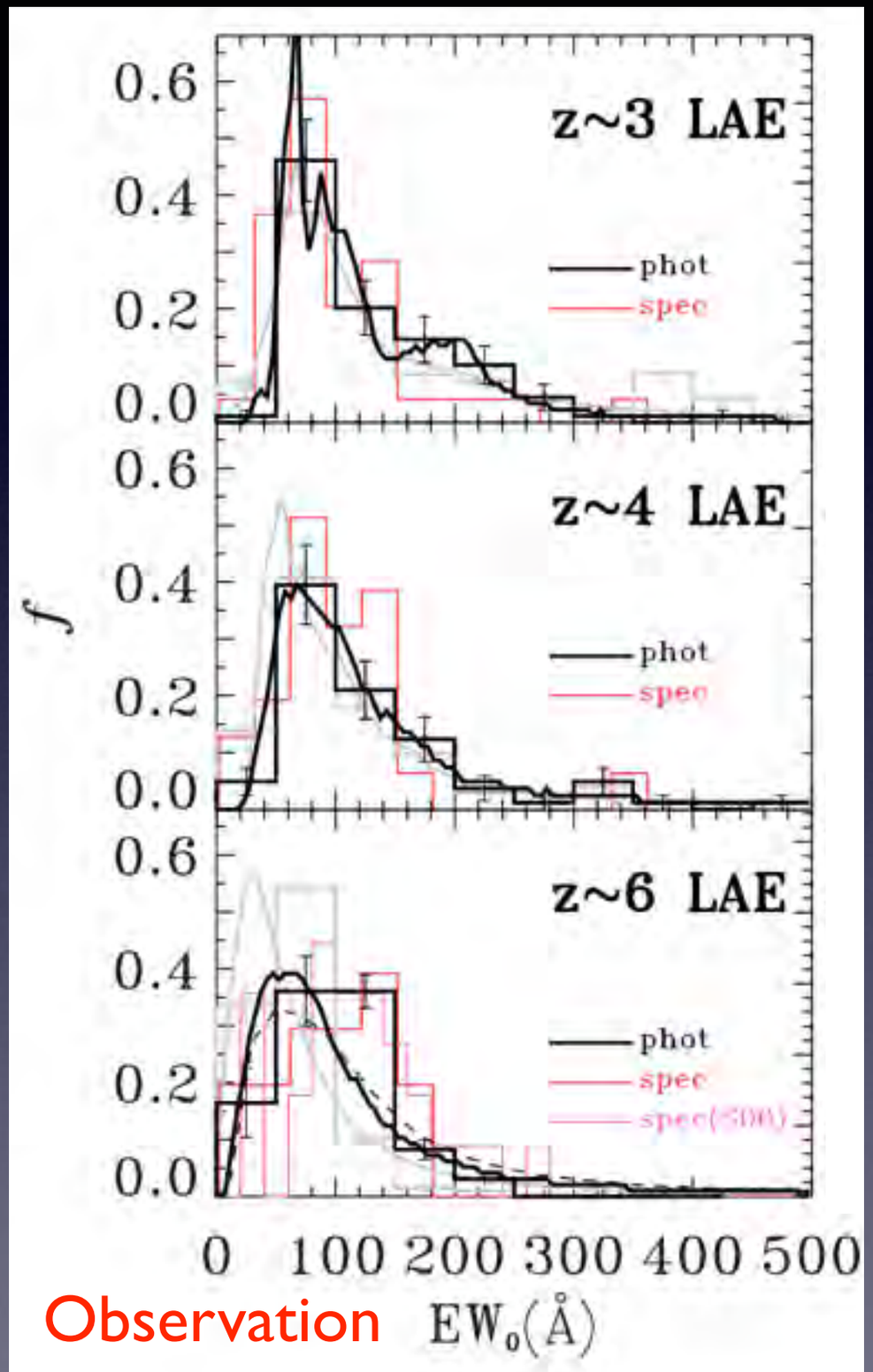

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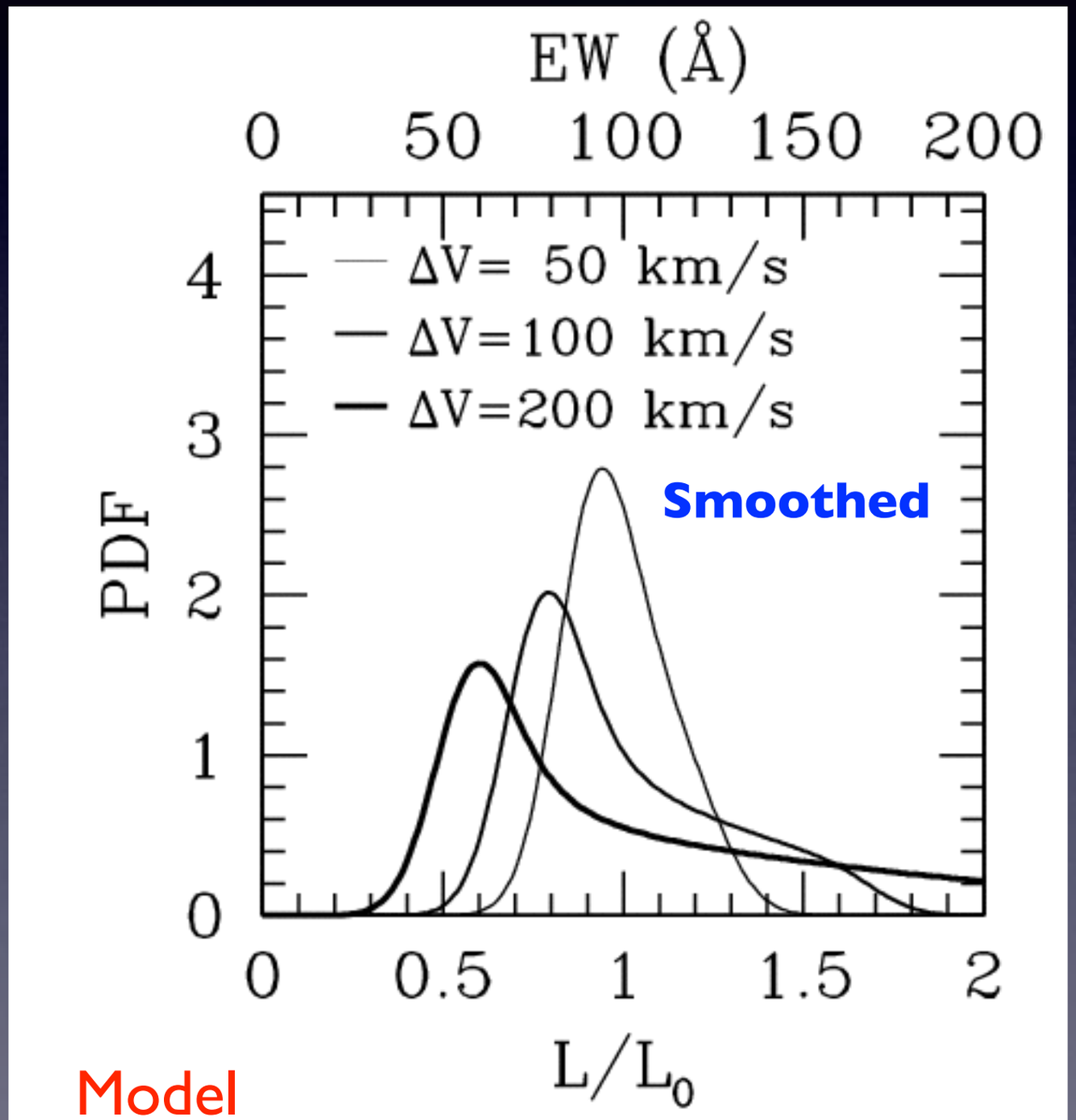
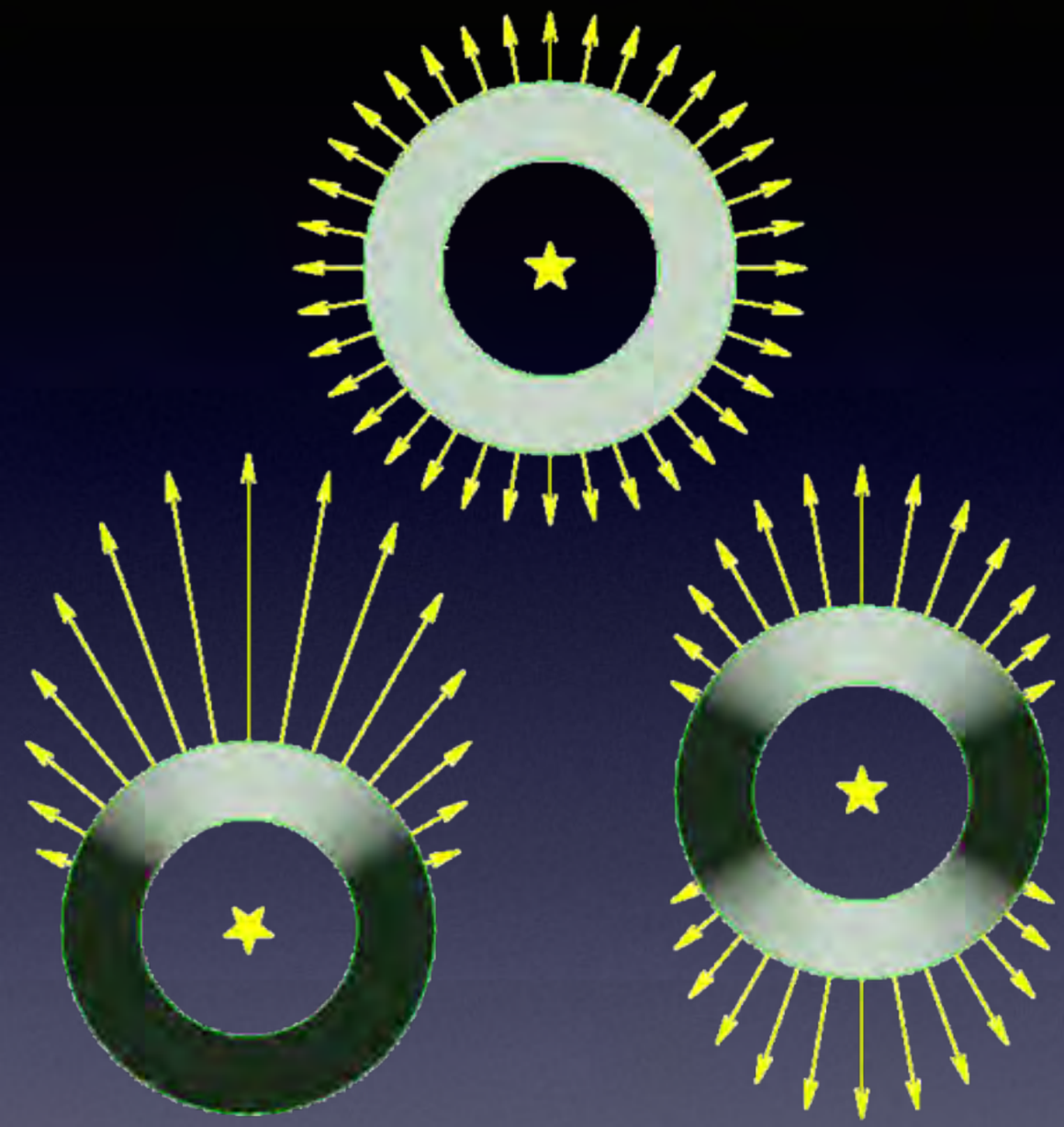


Model

Ouchi et al. (2008)

Anisotropic Lyman-alpha Emission



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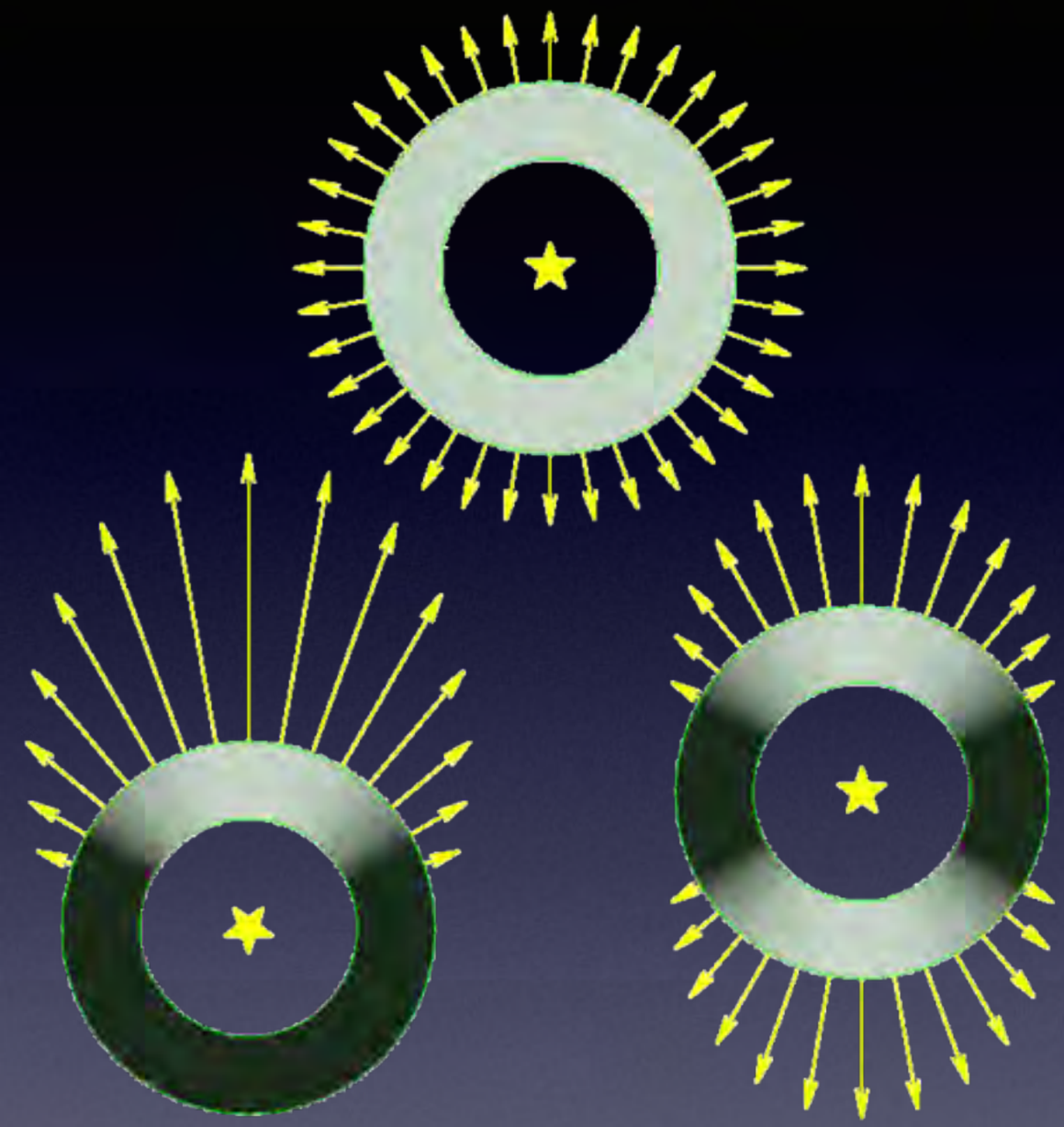

Relative rather than **absolute** optical depth determines the flux in a given direction.

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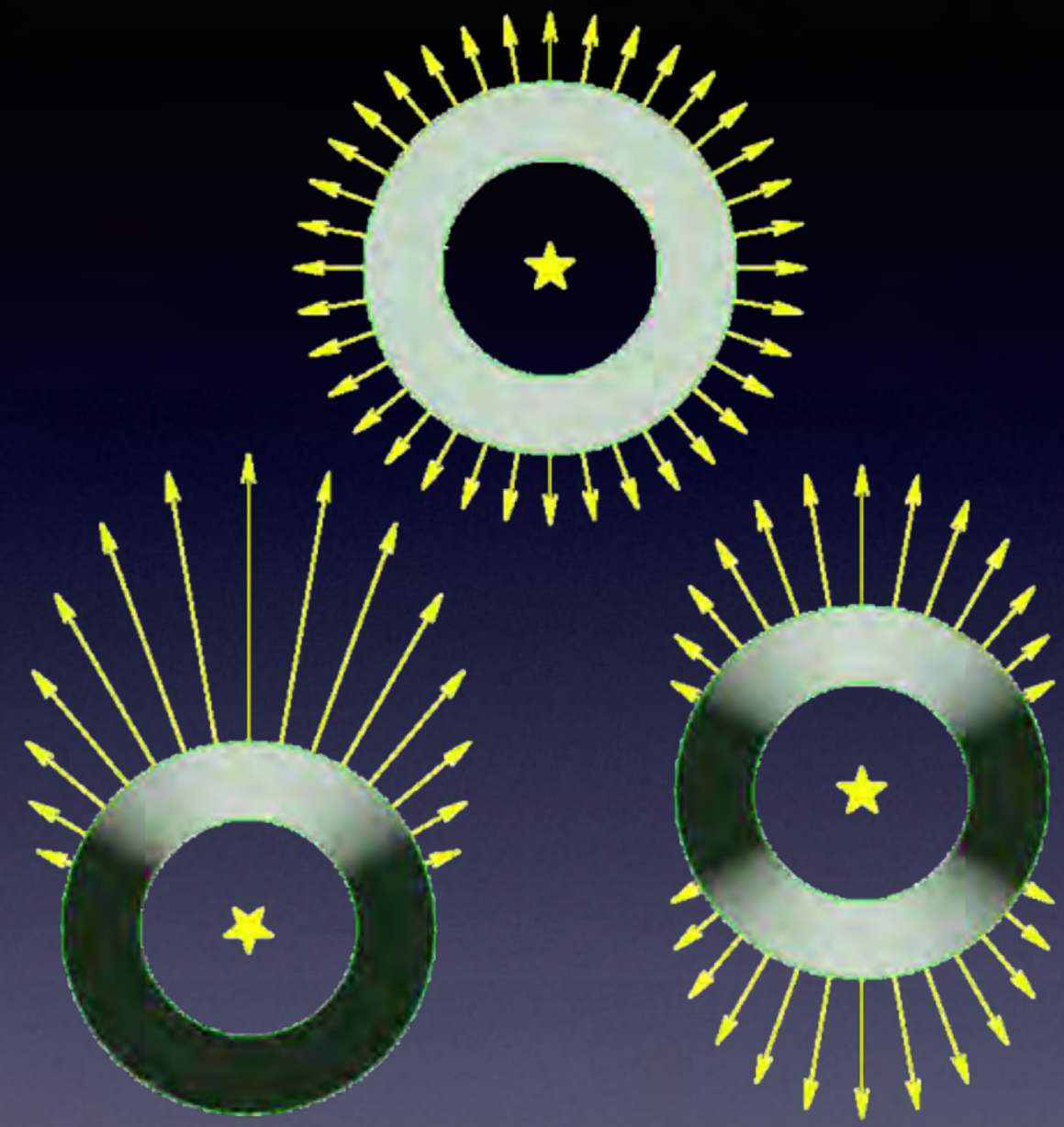
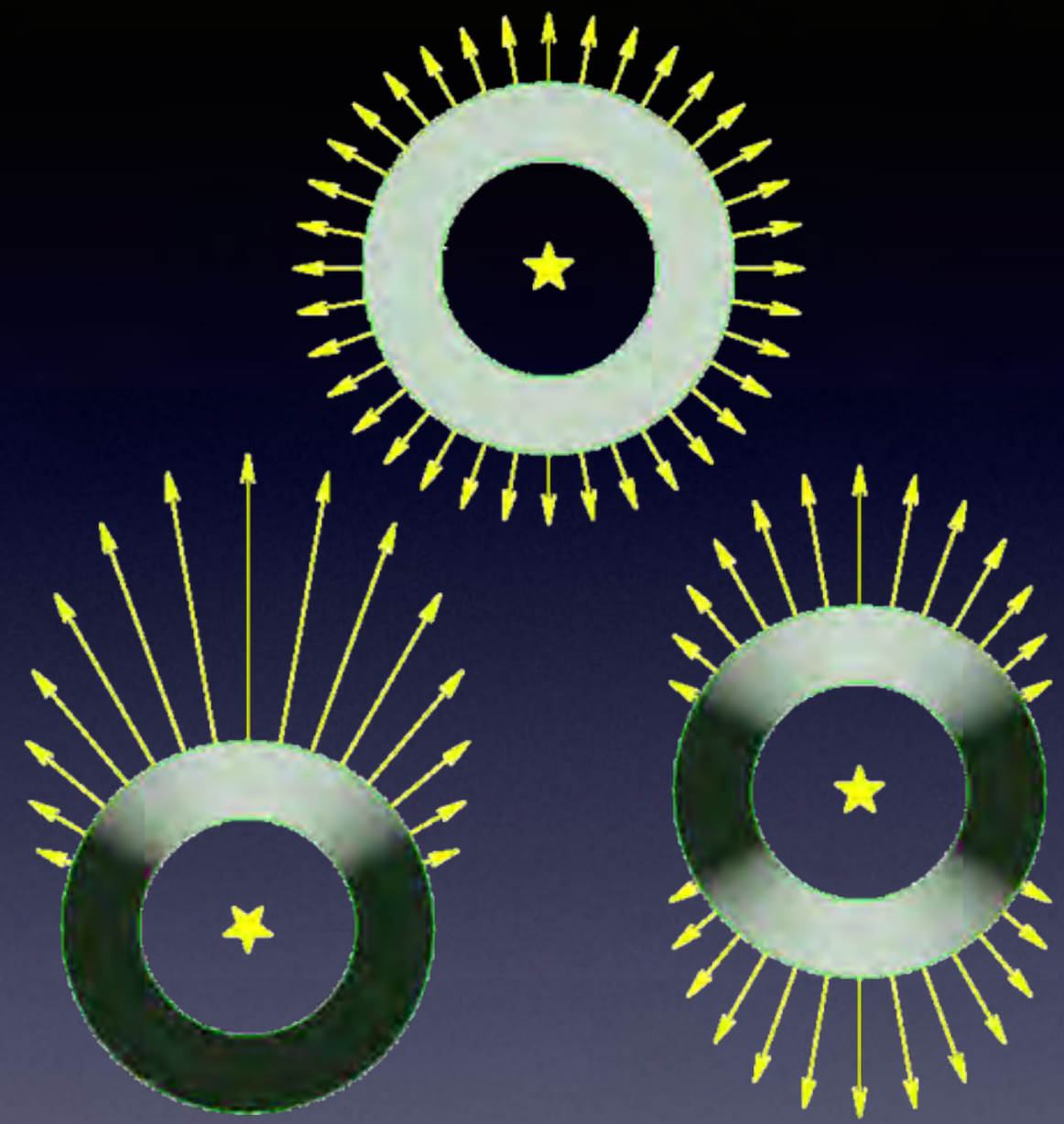
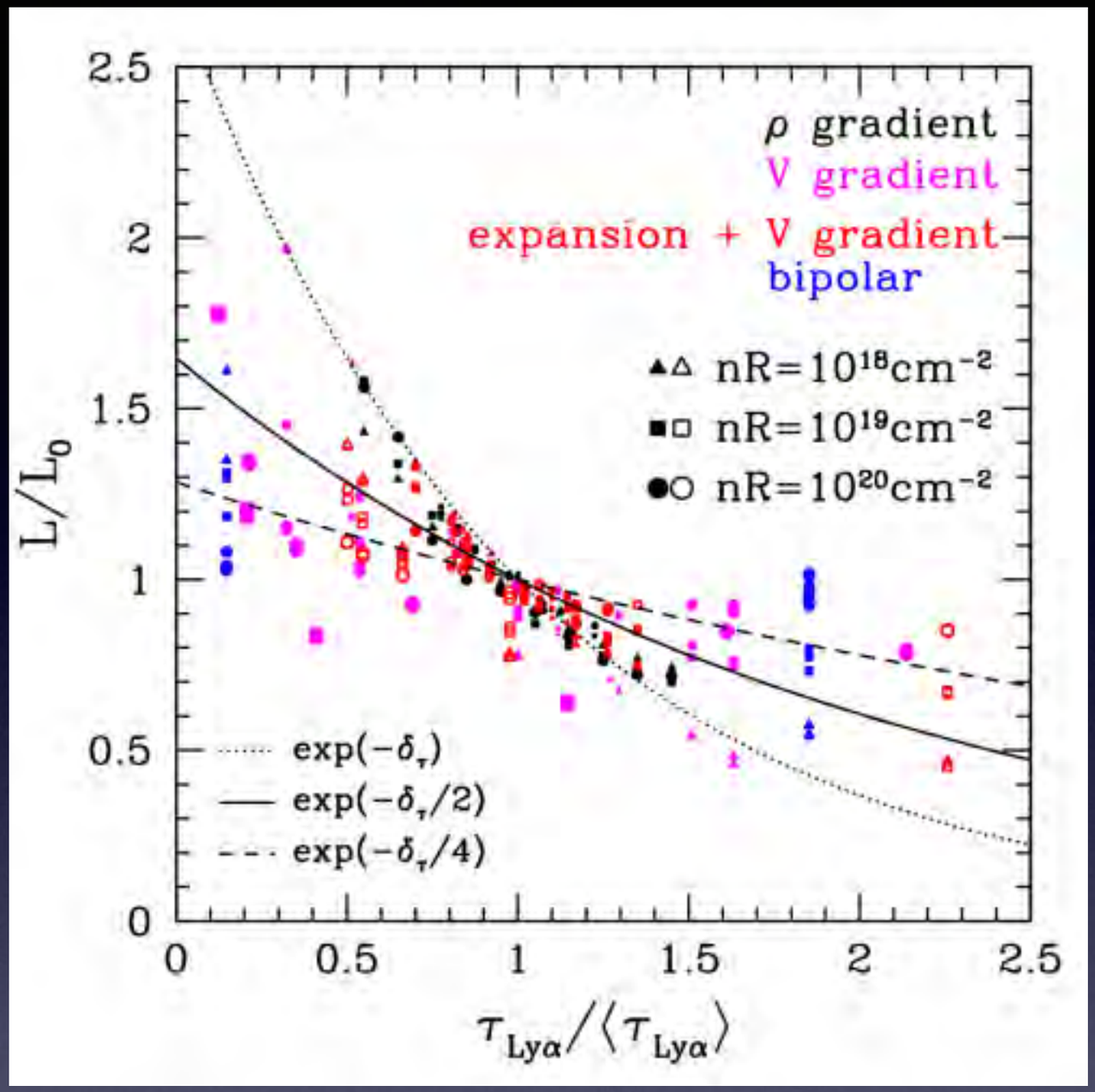


Relative rather than **absolute** optical depth determines the flux in a given direction.

$$\cancel{e^{-\tau}}$$

Anisotropic Lyman-alpha Emission





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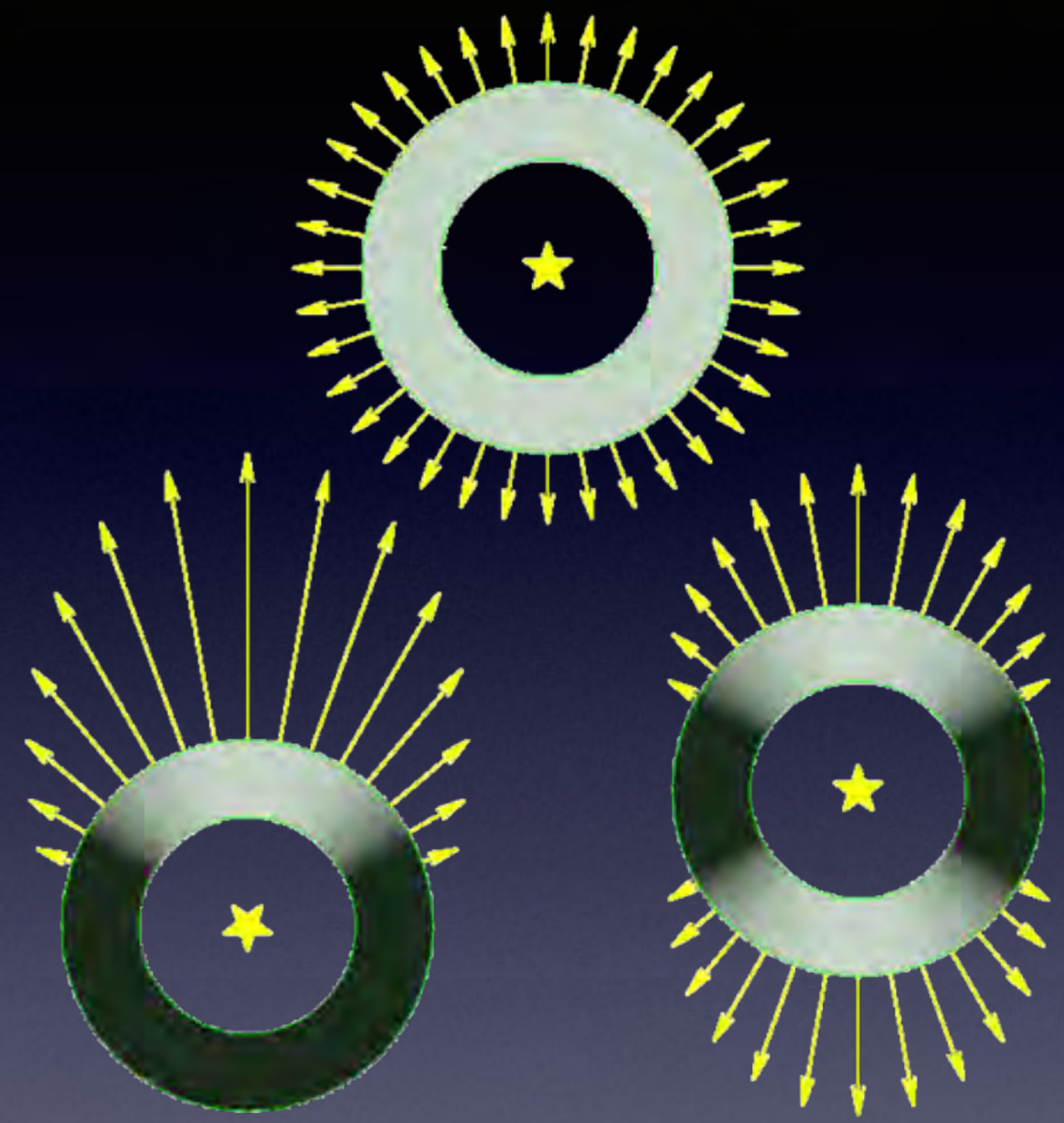
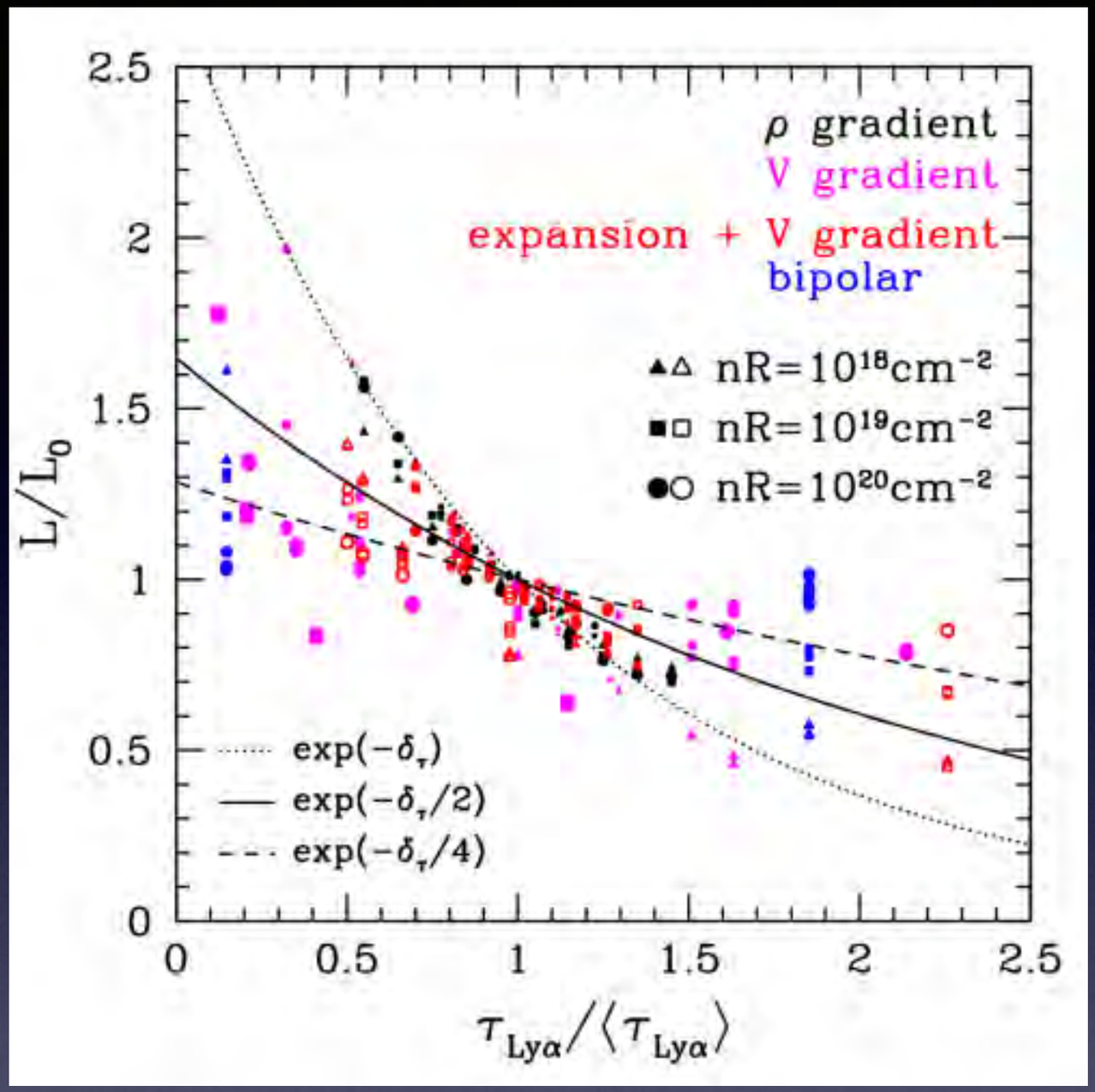




Relative rather than **absolute** optical depth determines the flux in a given direction.

$$e^{-\tau}$$

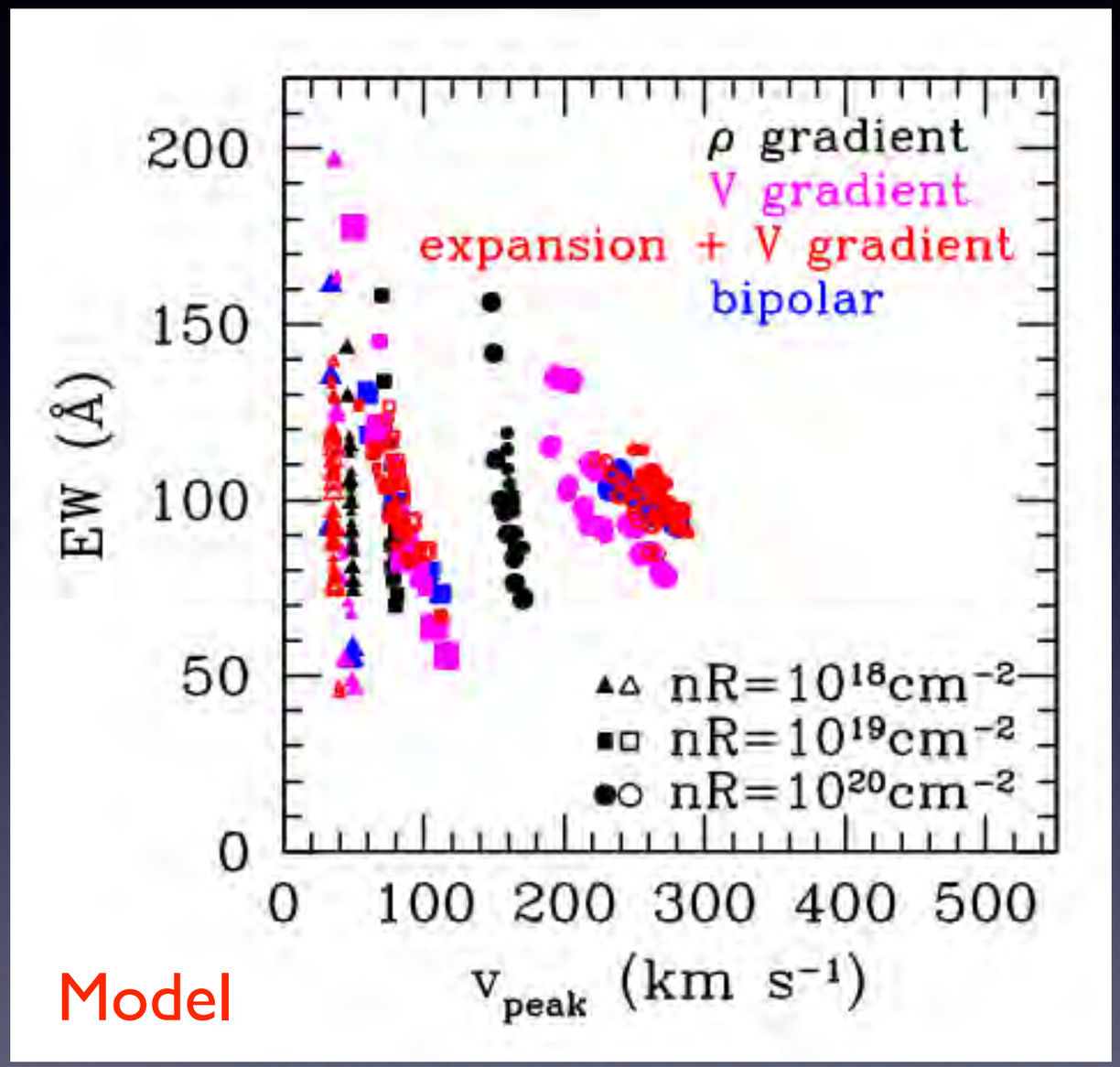
$$\sim e^{-\delta_\tau}$$

angular average

$$\delta_\tau = \frac{\tau - \langle\tau\rangle}{\langle\tau\rangle}$$

excess optical depth

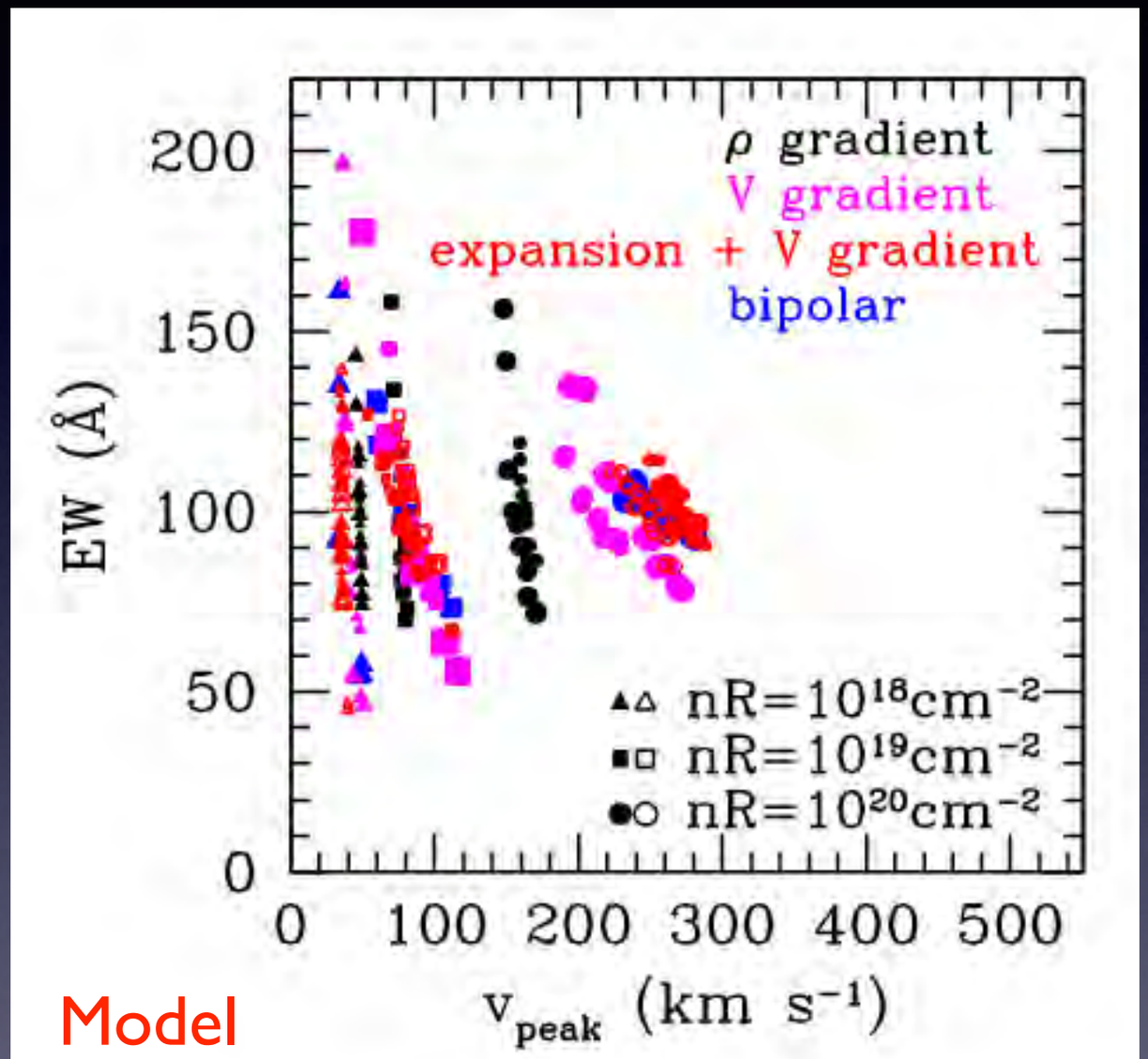
Anisotropic Lyman-alpha Emission



Model

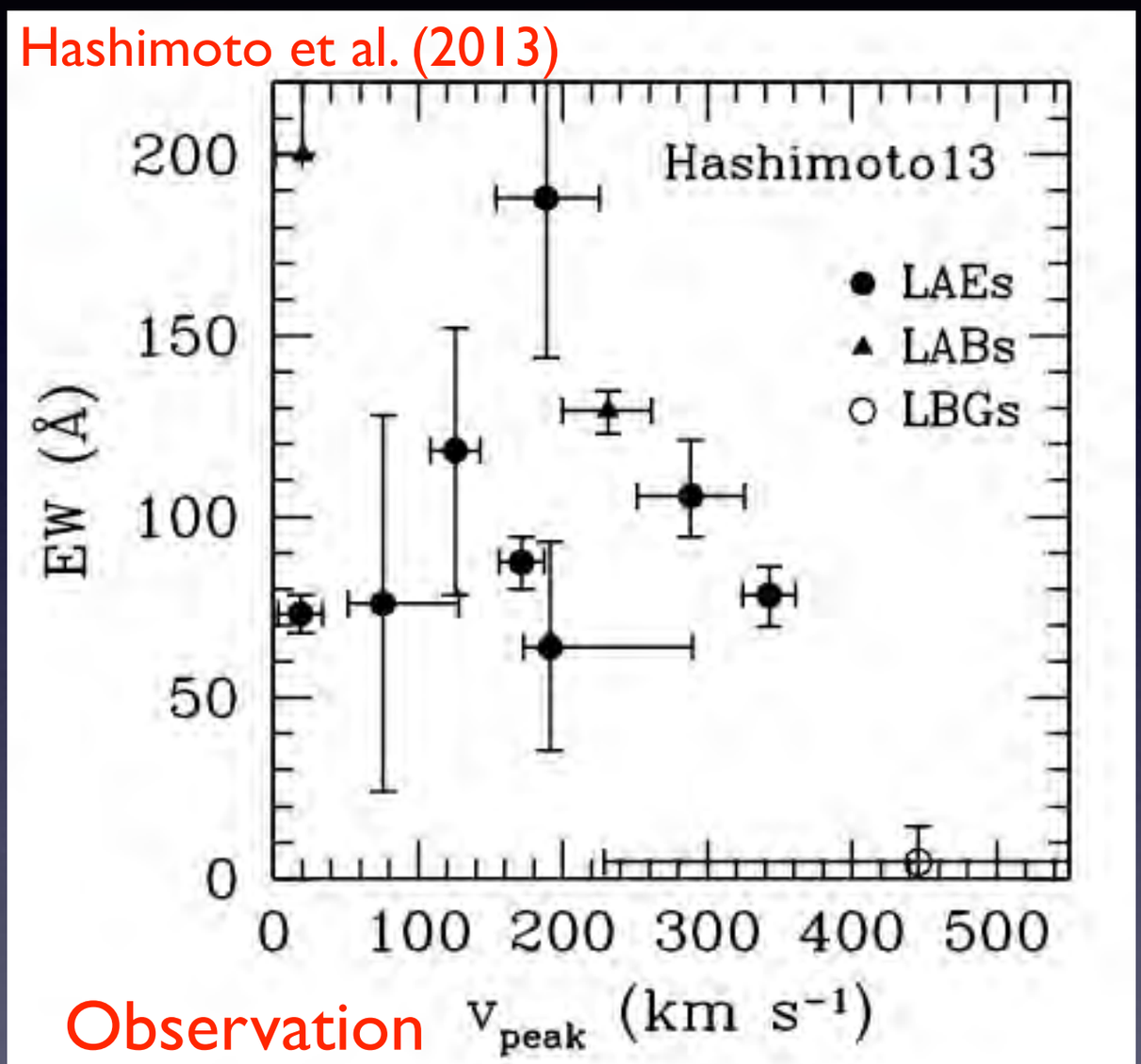
Relation between EW and Peak Offset

Anisotropic Lyman-alpha Emission



Model

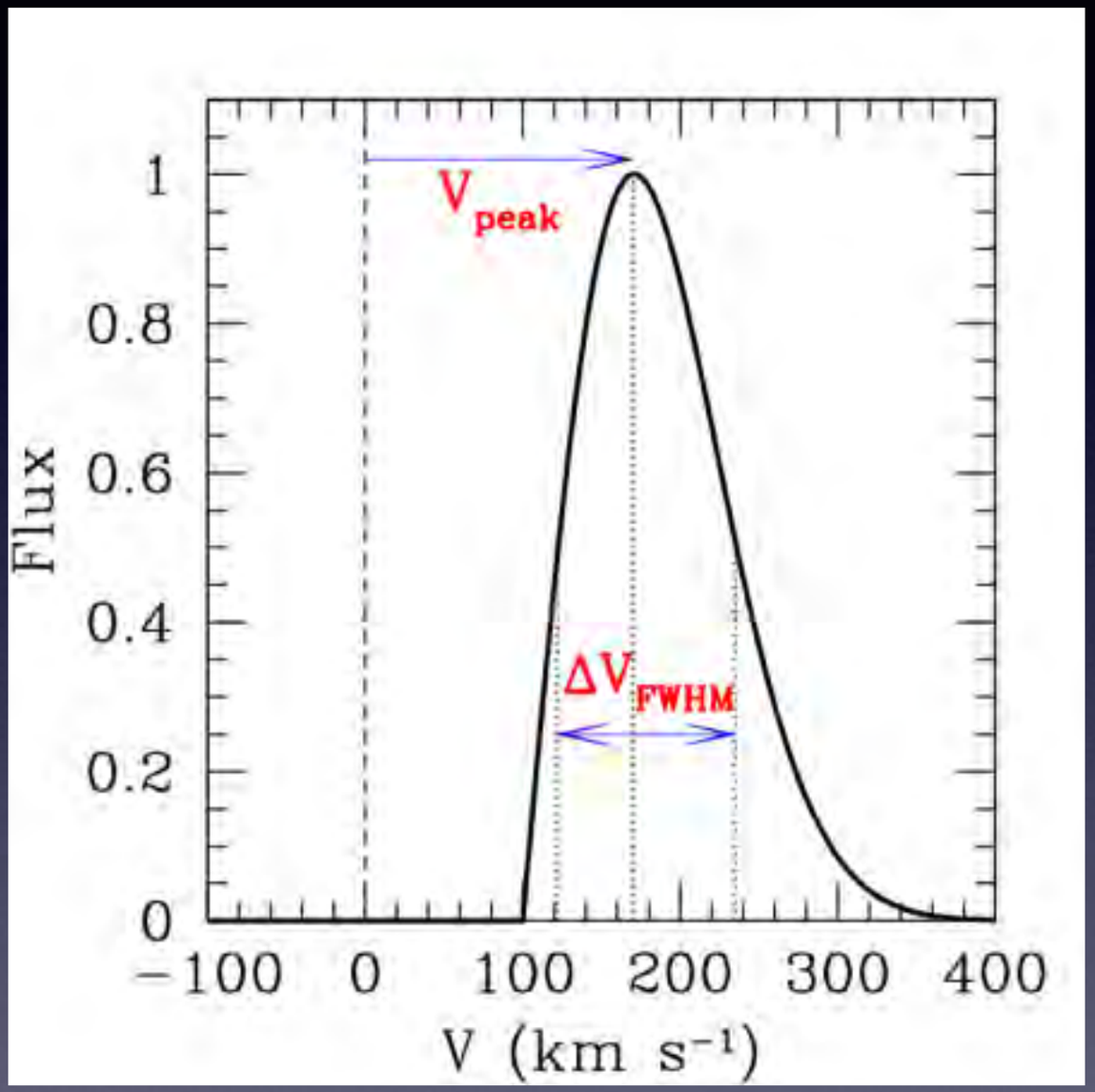
Hashimoto et al. (2013)

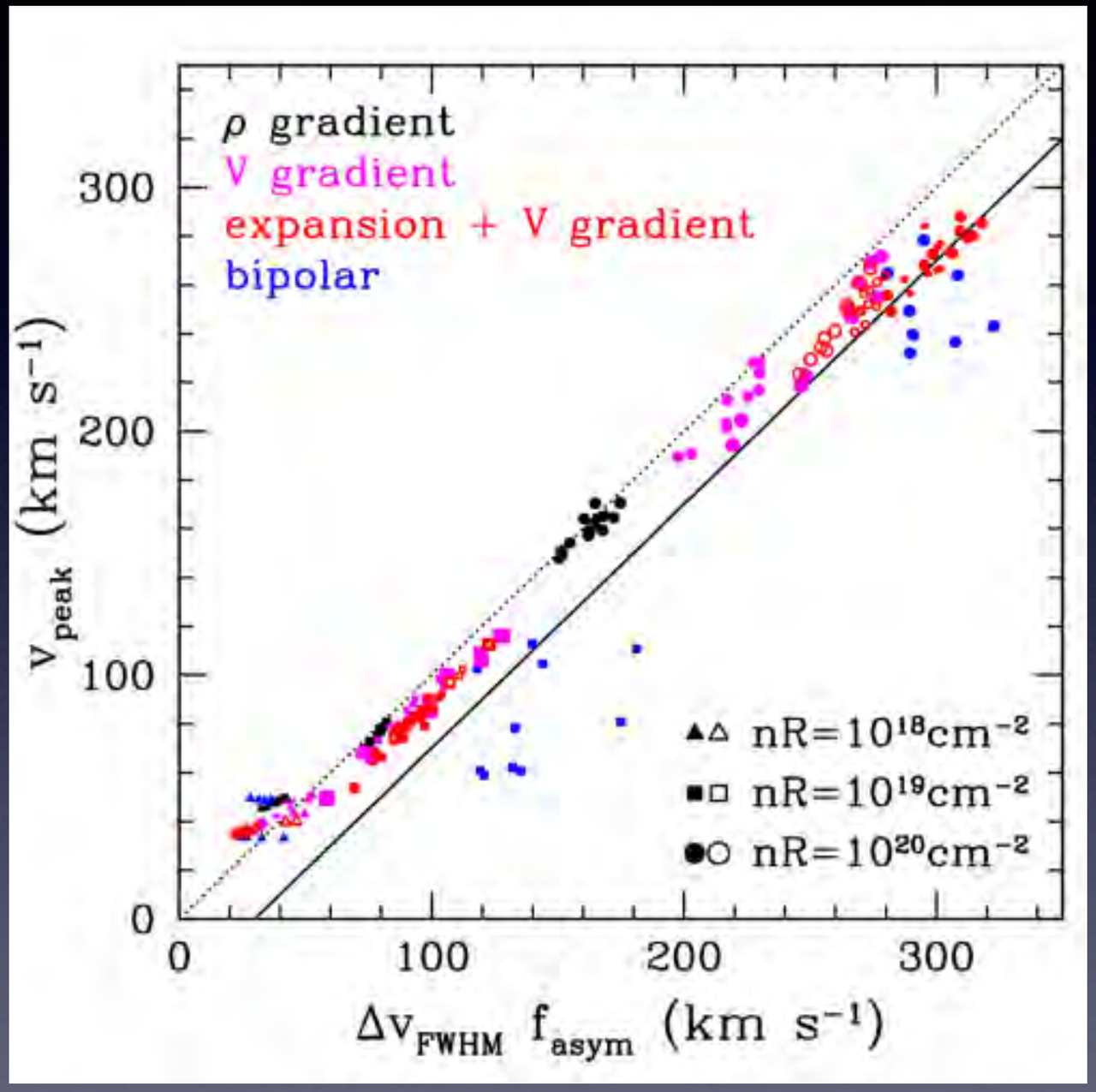


Observation

Relation between EW and Peak Offset

Anisotropic Lyman-alpha Emission

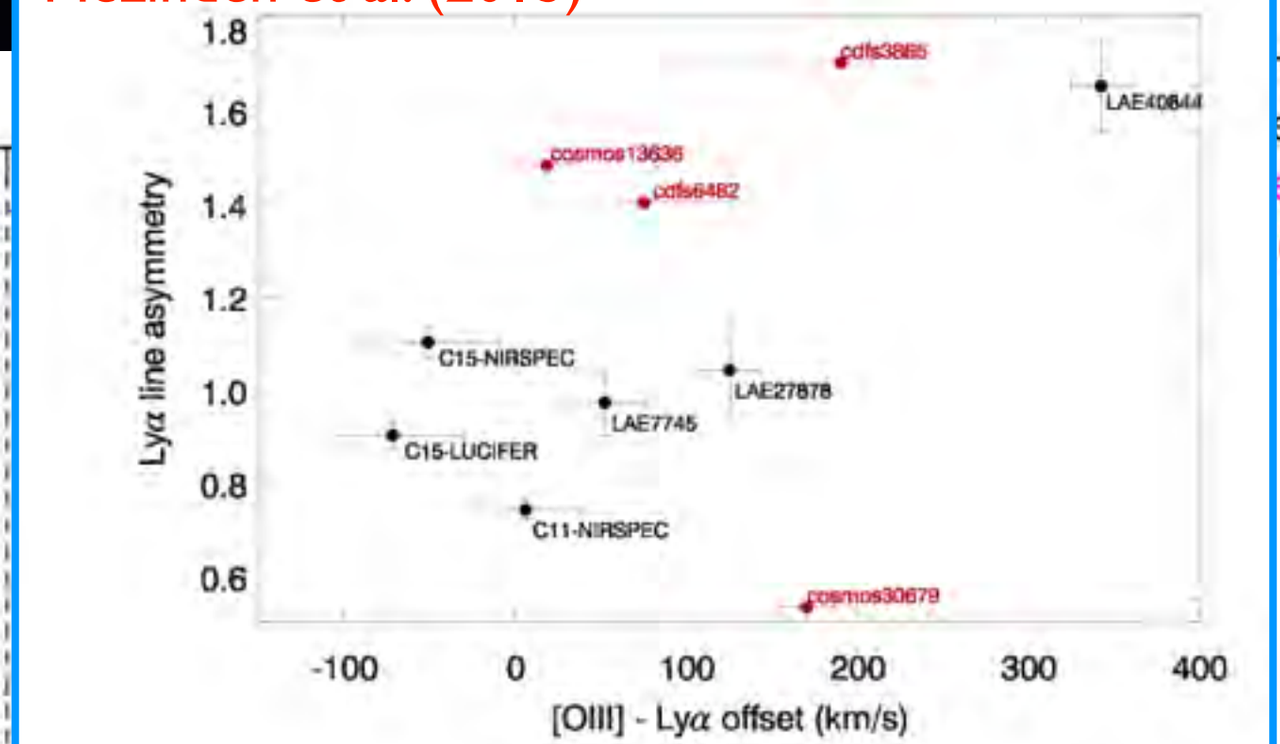


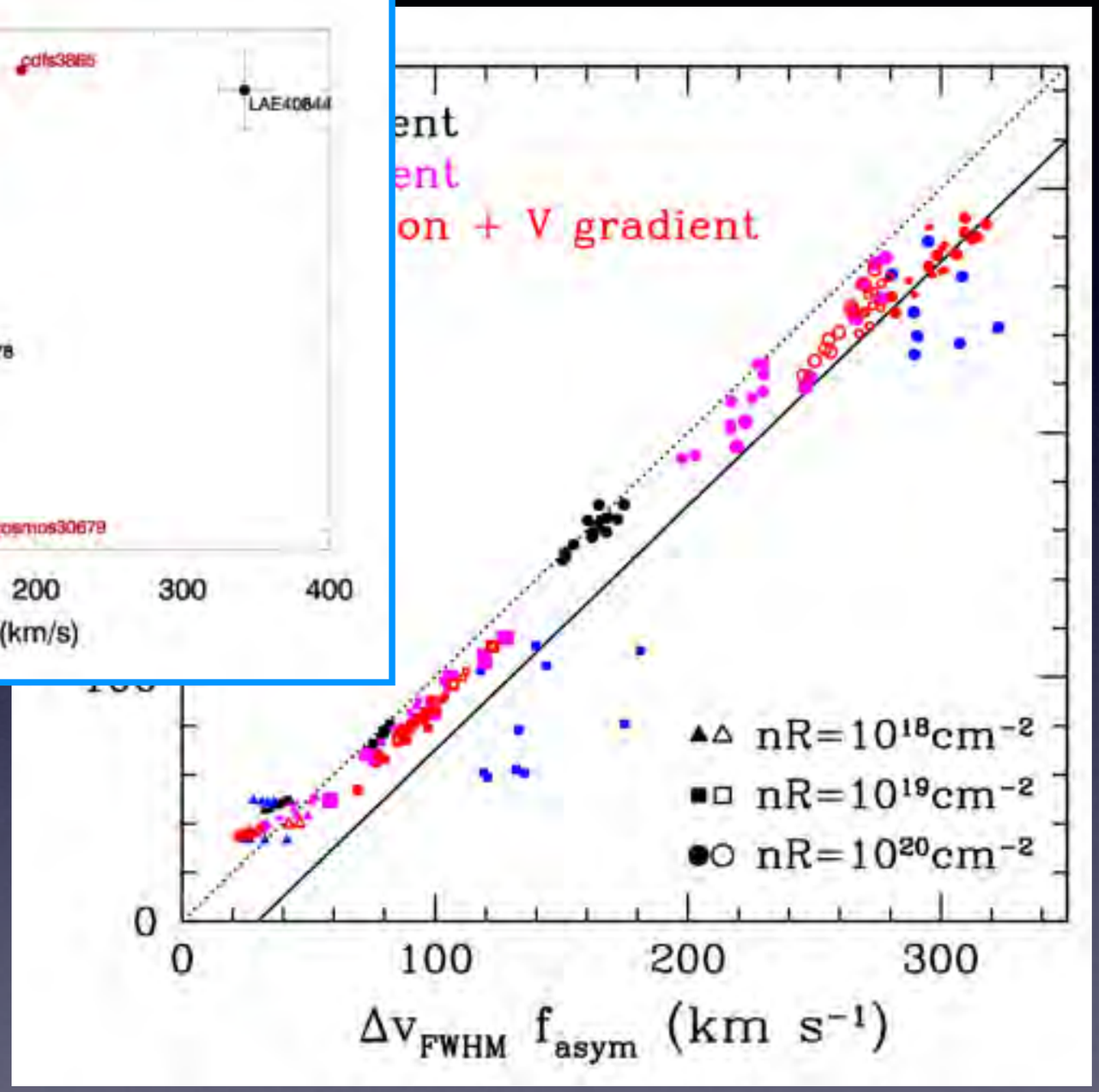


Relation between Peak Offset (hard to observe) and Line Profile (easy to observe)

Anisotropic Lyman-alpha Emission

McLinden et al. (2013)

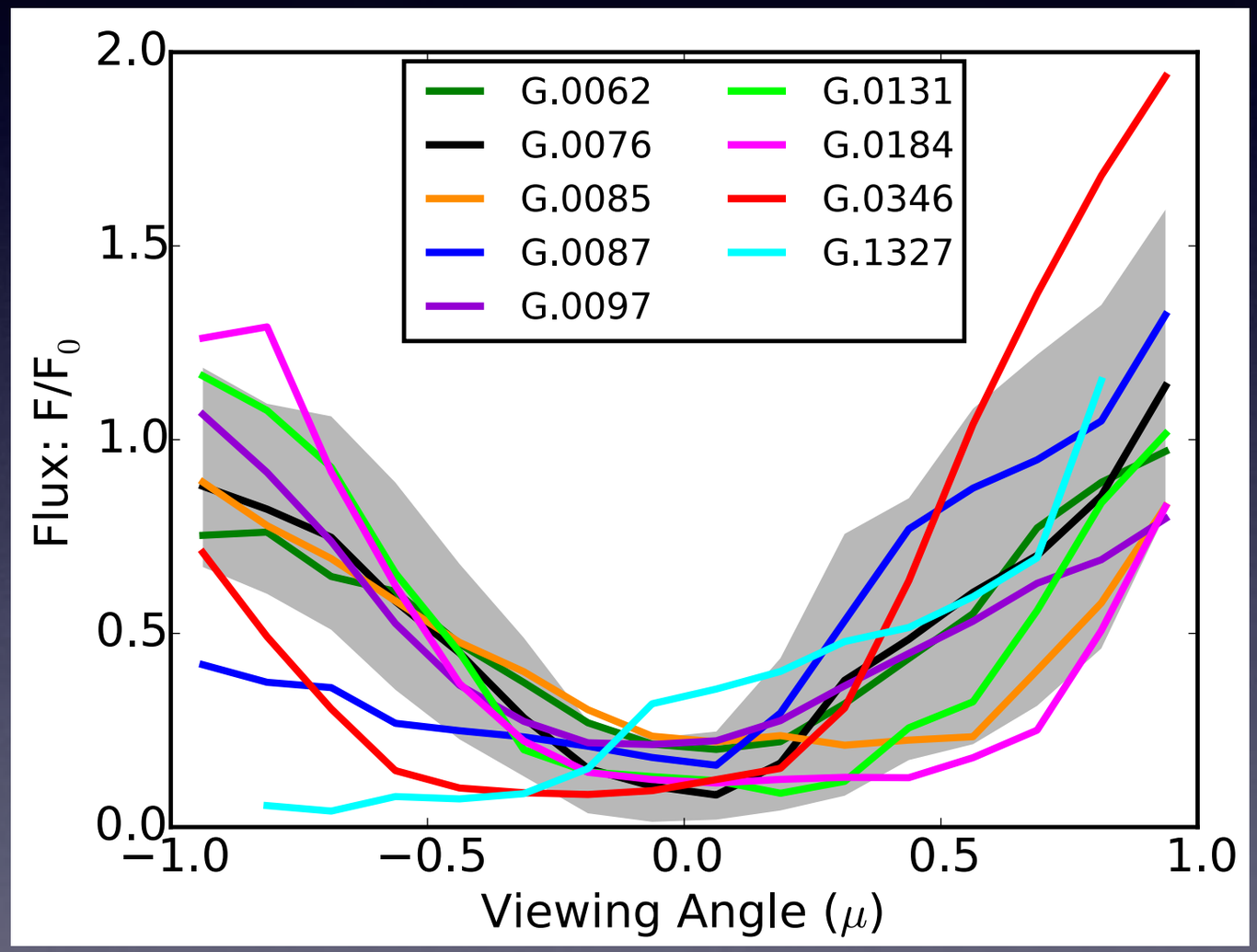




Relation between Peak Offset (hard to observe) and Line Profile (easy to observe)

Anisotropic Lyman-alpha Emission from Galaxies in High-resolution Hydrodynamic Galaxy Formation Simulations

viewing angle dependent Lyman-alpha flux

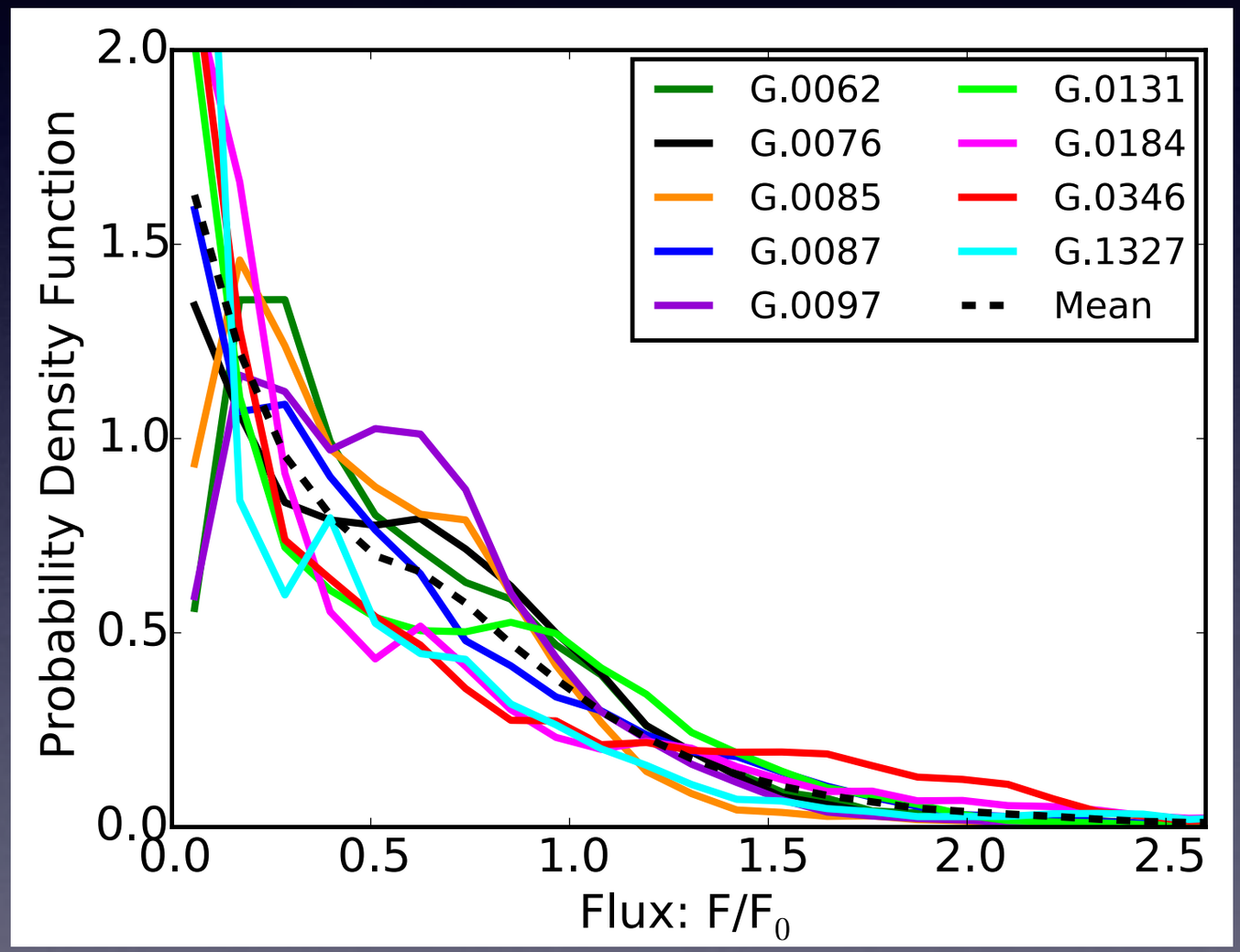


pole equator pole

Wallace, ZZ, Sadoun, & Cen (in prep)

Anisotropic Lyman-alpha Emission from Galaxies in High-resolution Hydrodynamic Galaxy Formation Simulations

flux distribution from randomly oriented galaxies



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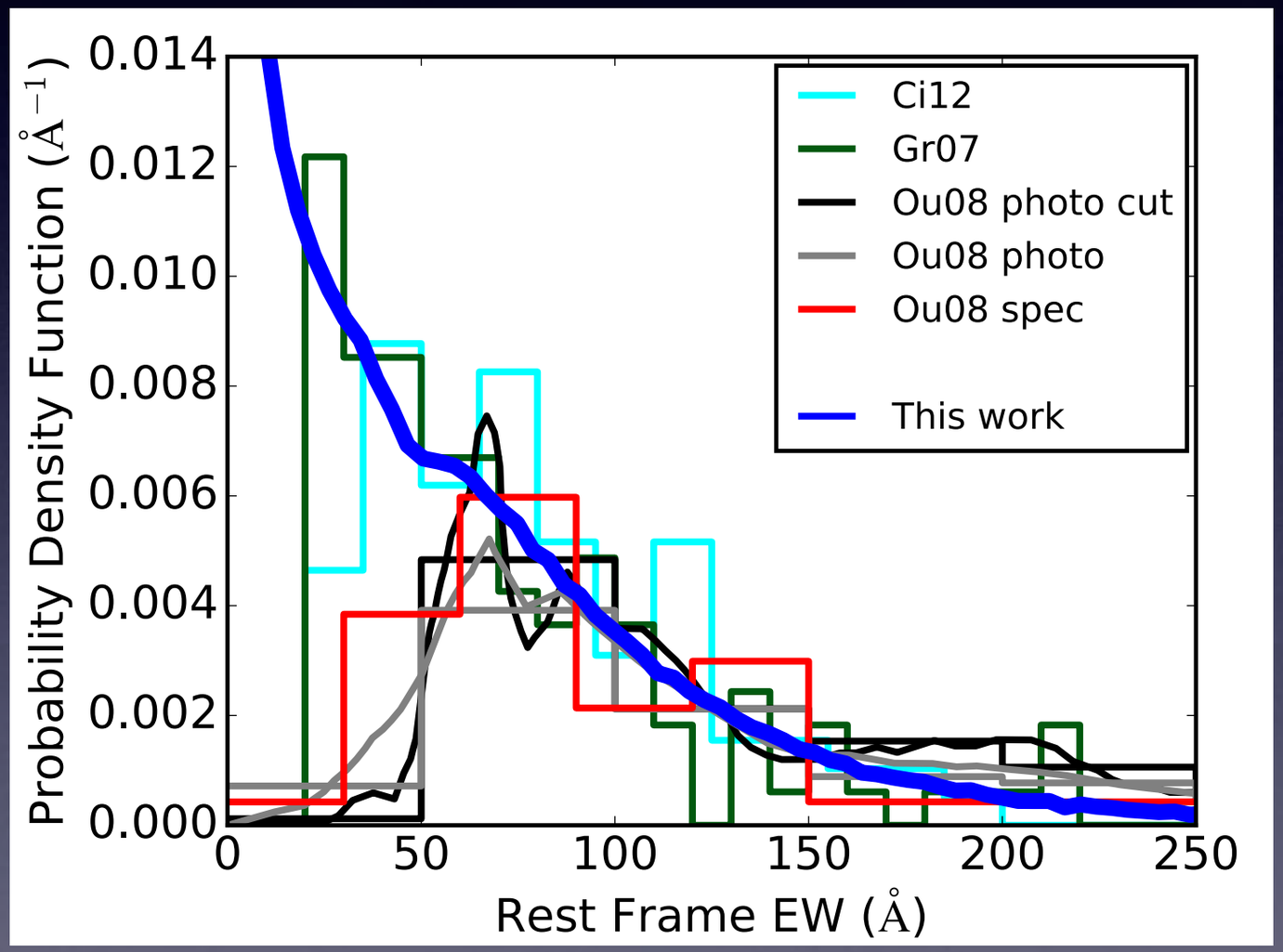
Anisotropic Lyman-alpha Emission from Galaxies in High-resolution Hydrodynamic Galaxy Formation Simulations

Lyman-alpha EW distribution: Model vs Observation



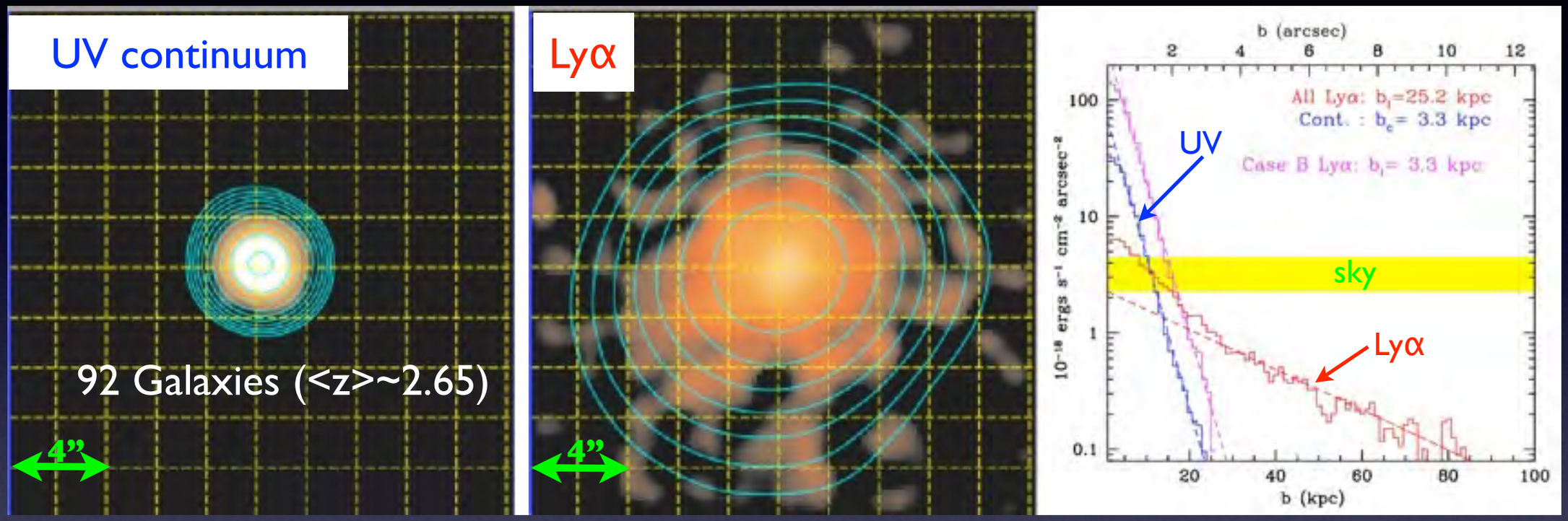
constraining Z and Age?

Wallace, ZZ, Sadoun, & Cen (in prep)

Extended Lyman-alpha Emission around Star-forming Galaxies

Observation

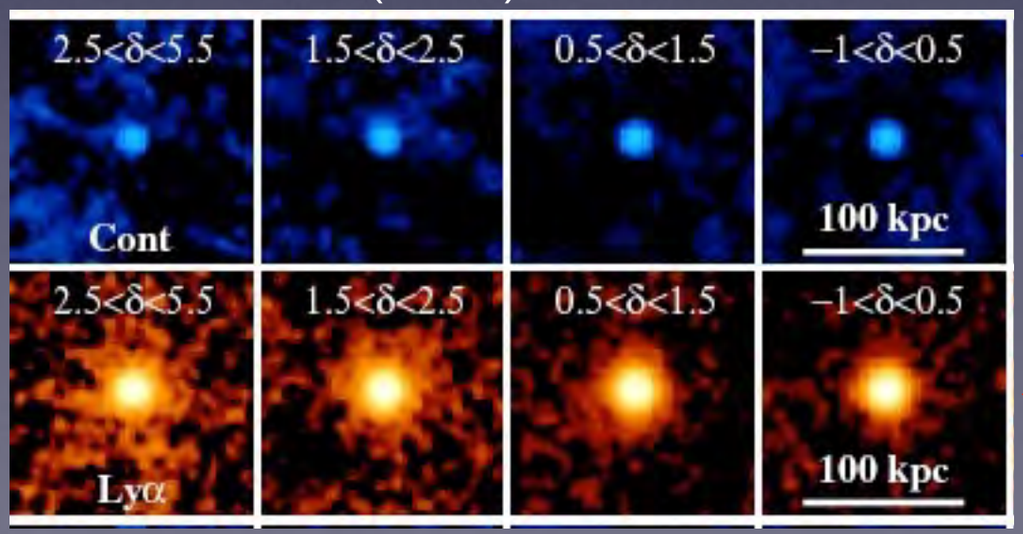
Steidel et al. (2011)

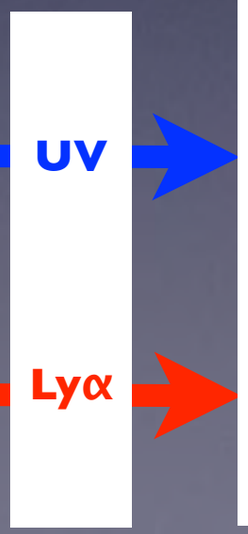


stacked images

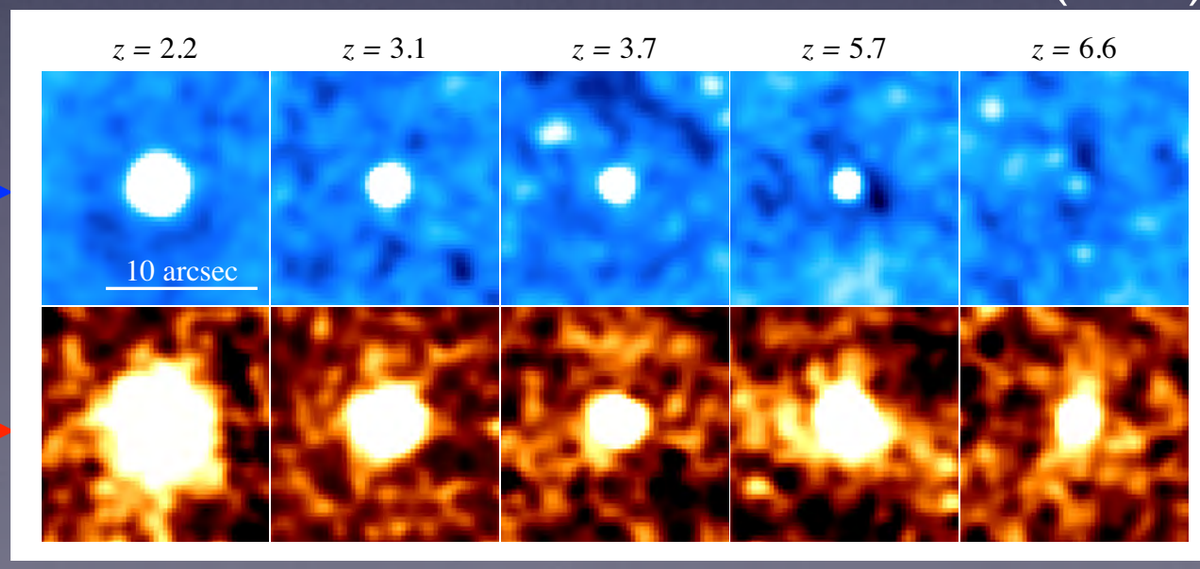
surface brightness profile

Matsuda et al. (2012)

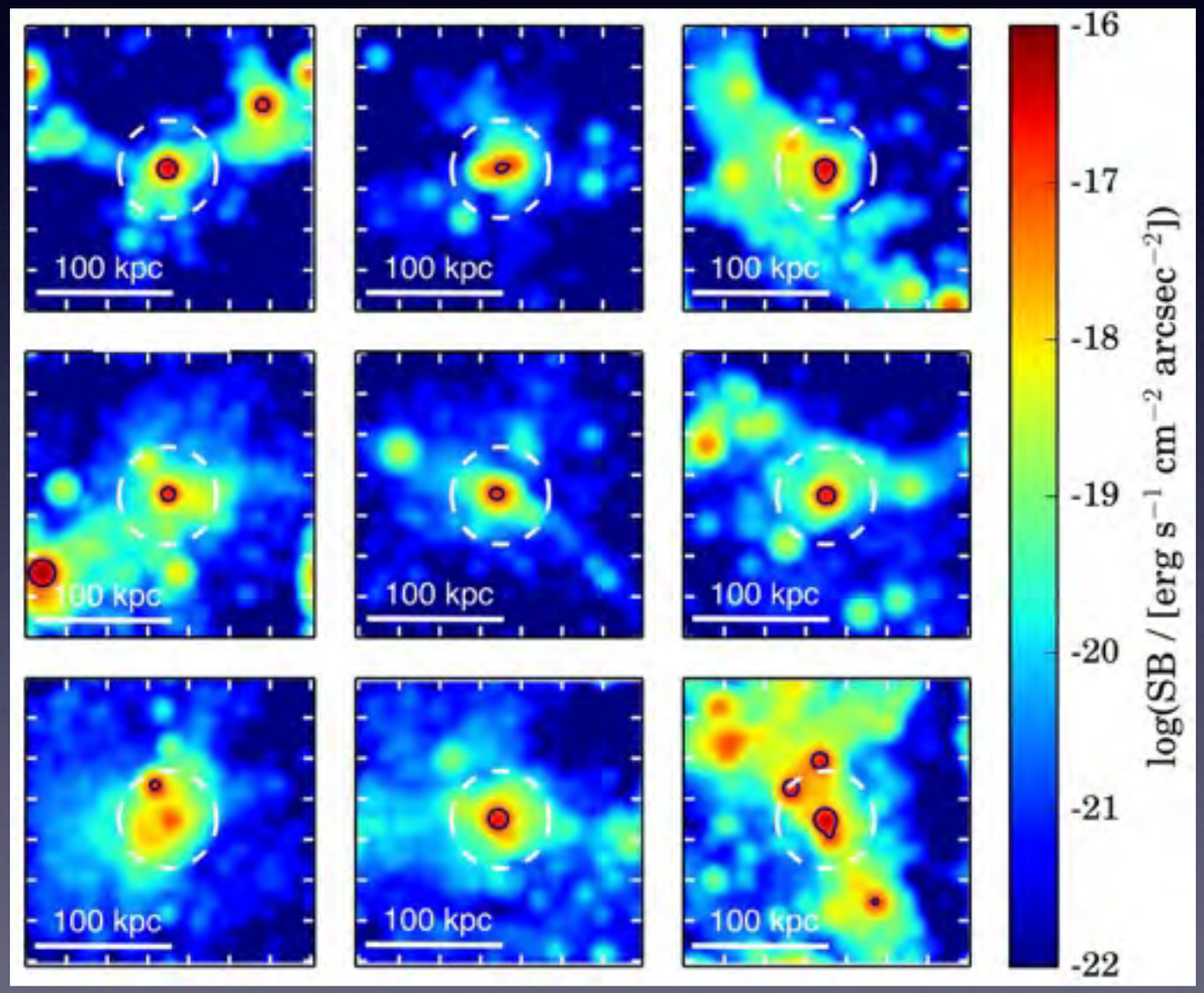


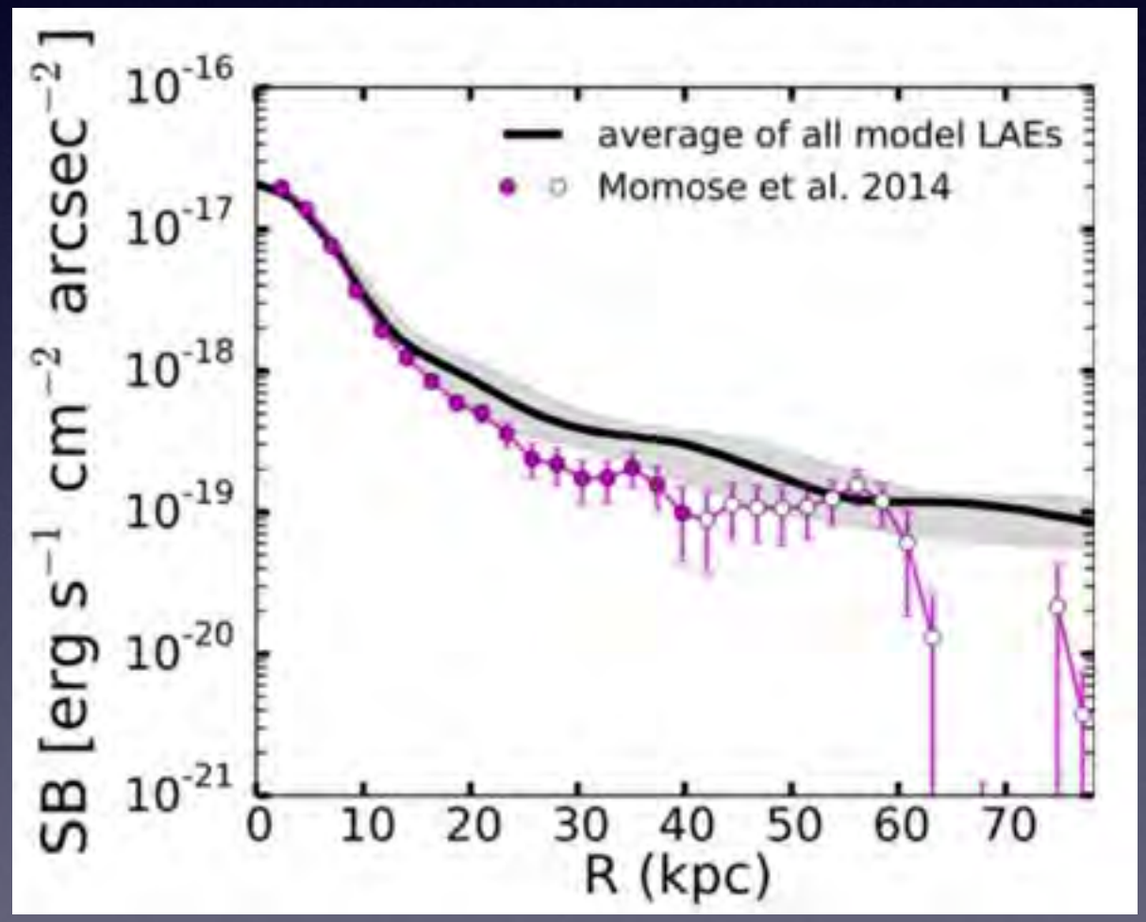


Momose et al. (2014)



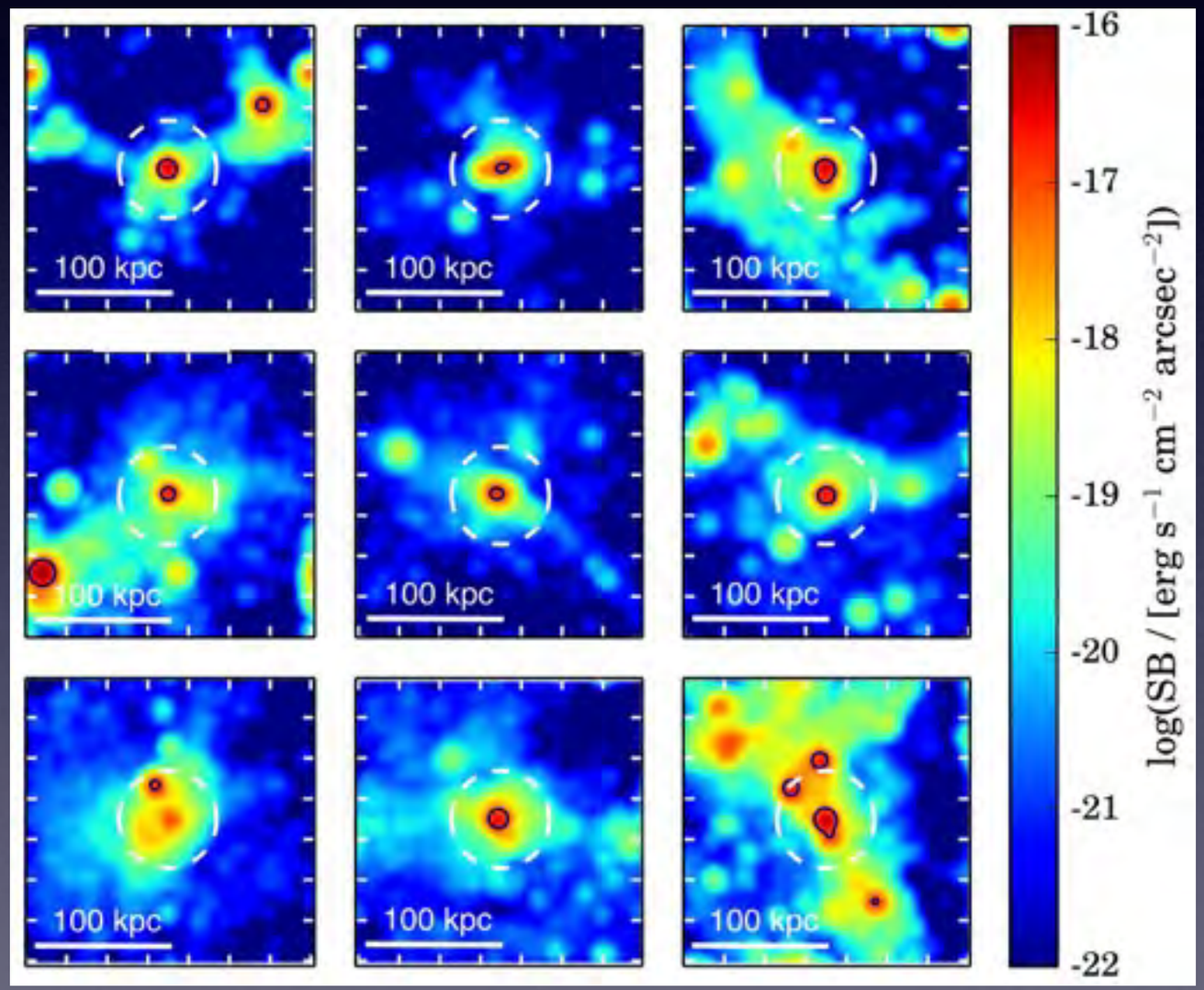
Extended (Diffuse) Lyman-alpha Emission from High-resolution Galaxy Formation Simulations

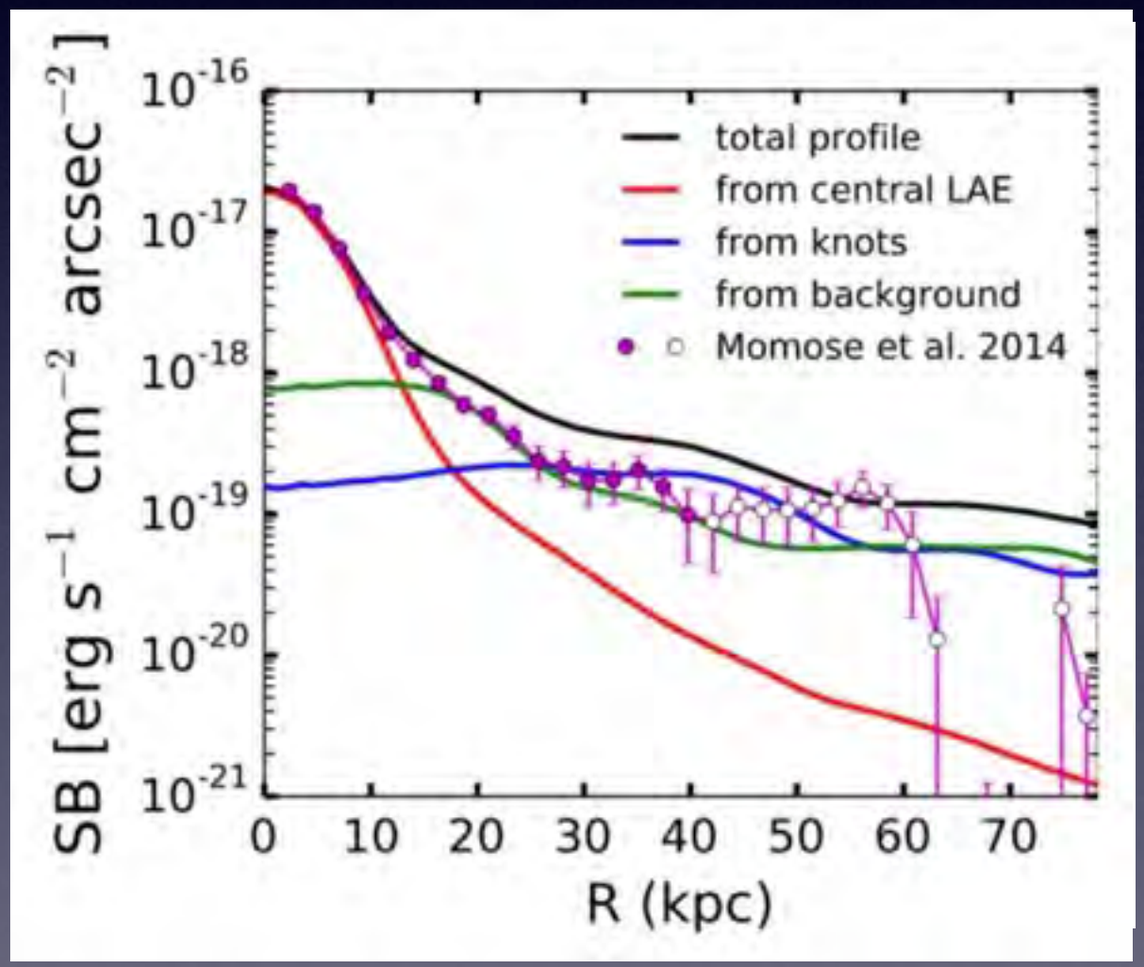




Lake, ZZ, Cen, et al. (2015)

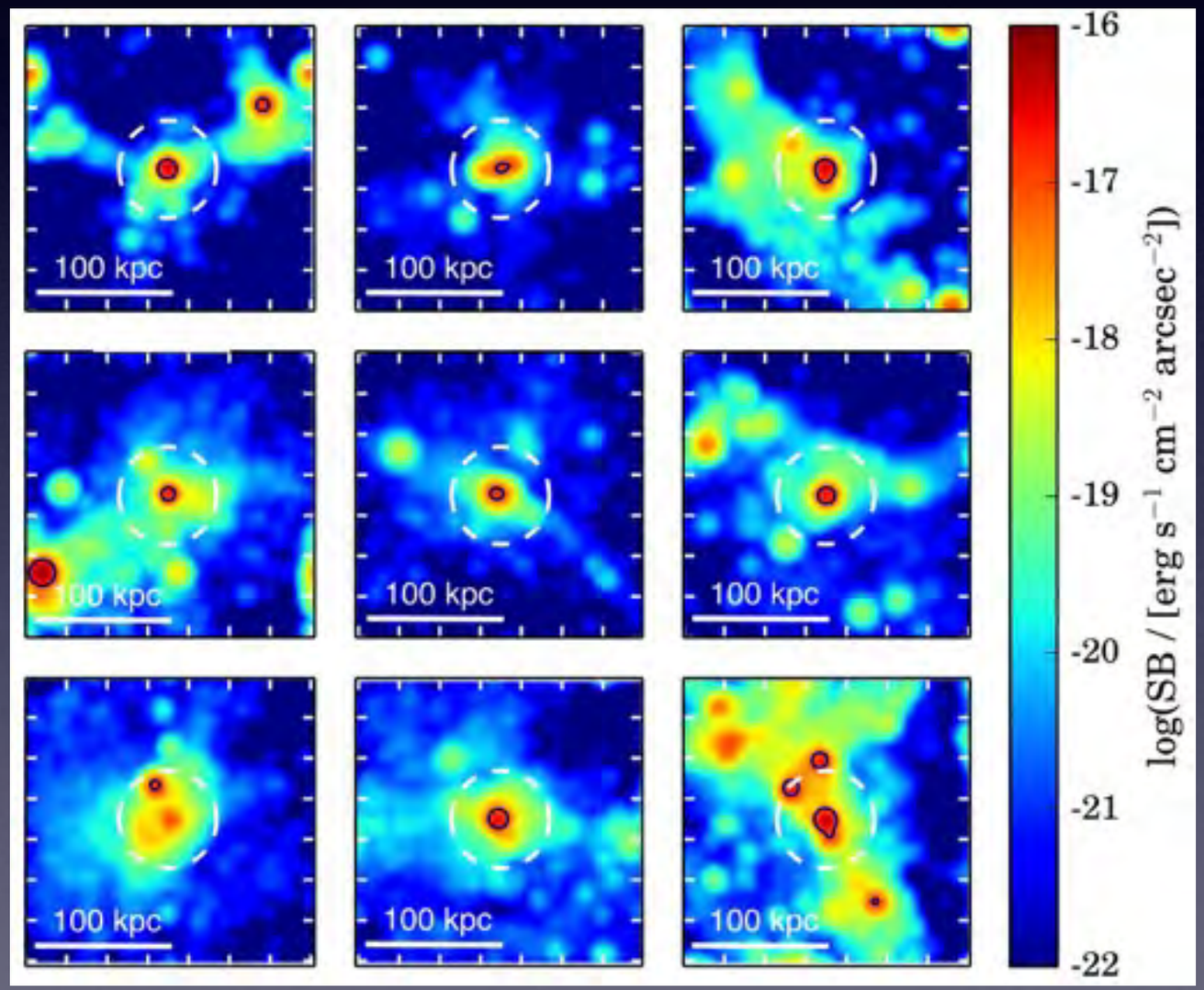
Extended (Diffuse) Lyman-alpha Emission from High-resolution Galaxy Formation Simulations

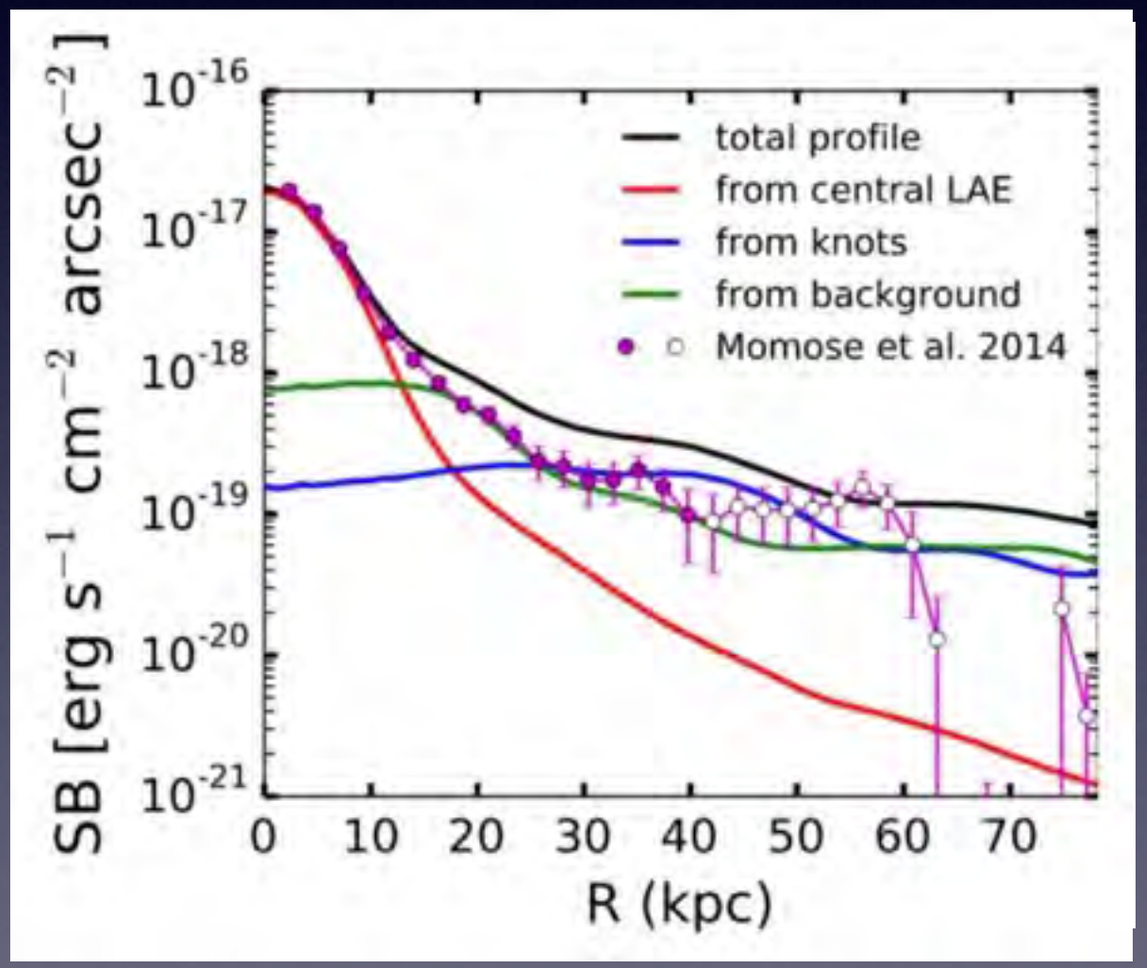




Lake, ZZ, Cen, et al. (2015)

Extended (Diffuse) Lyman-alpha Emission from High-resolution Galaxy Formation Simulations

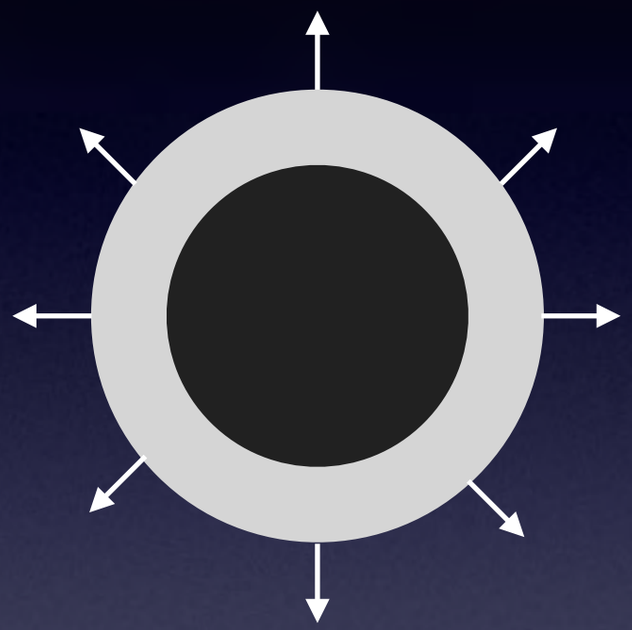




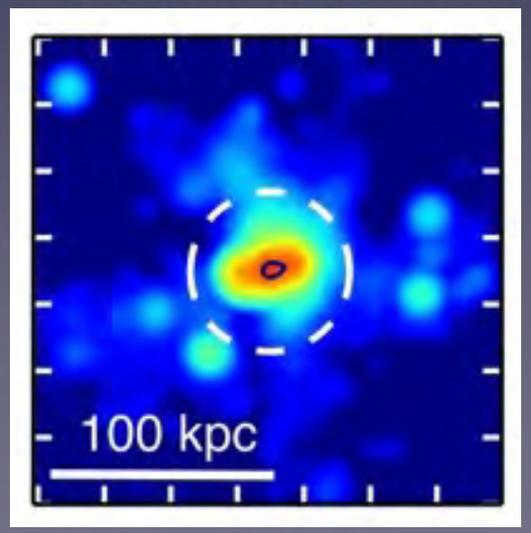
dependence on viewing angle?

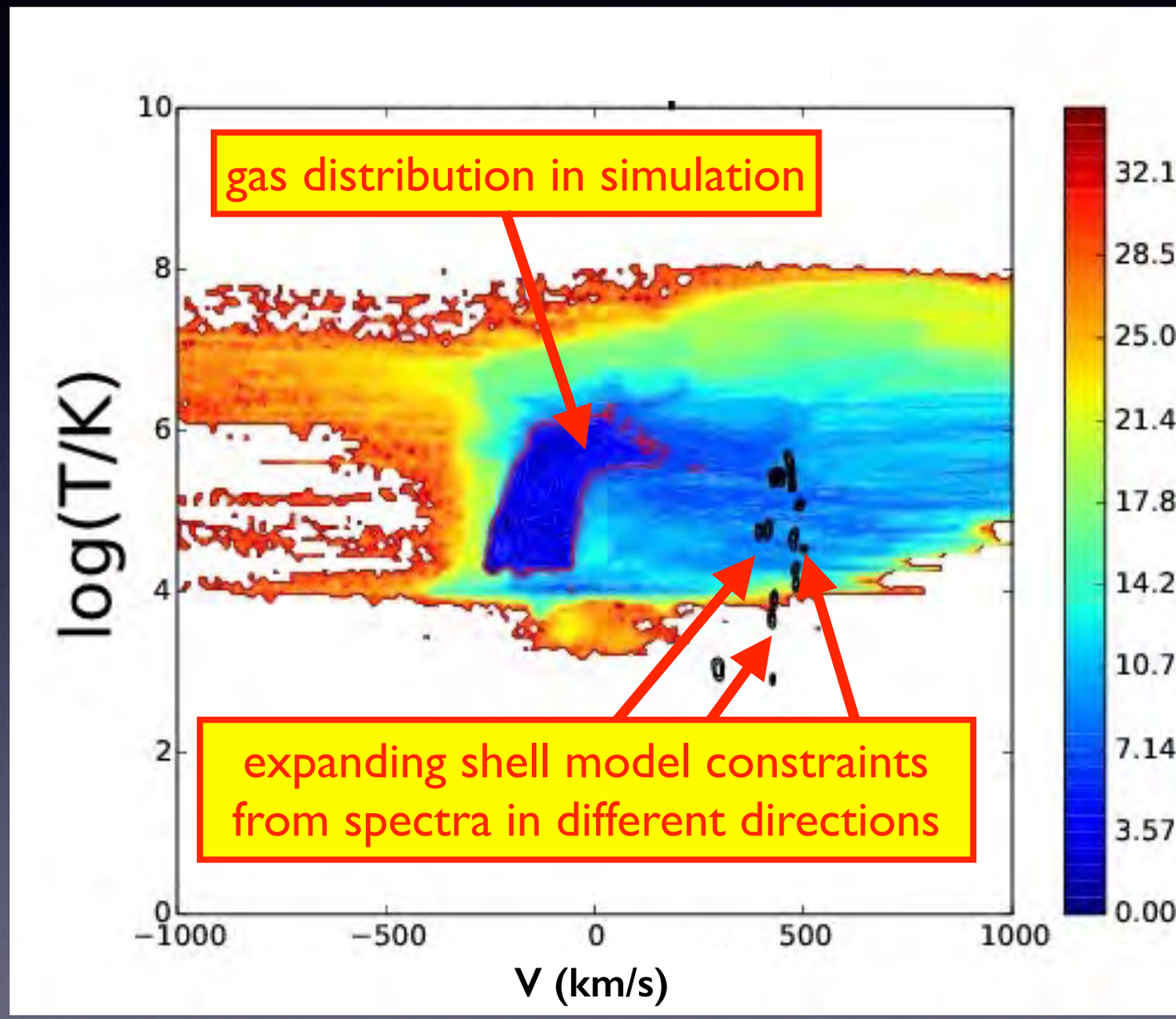
Lake, ZZ, Cen, et al. (2015)

Anisotropic Lyman-alpha Emission and Expanding Spherical Shell Model



VS



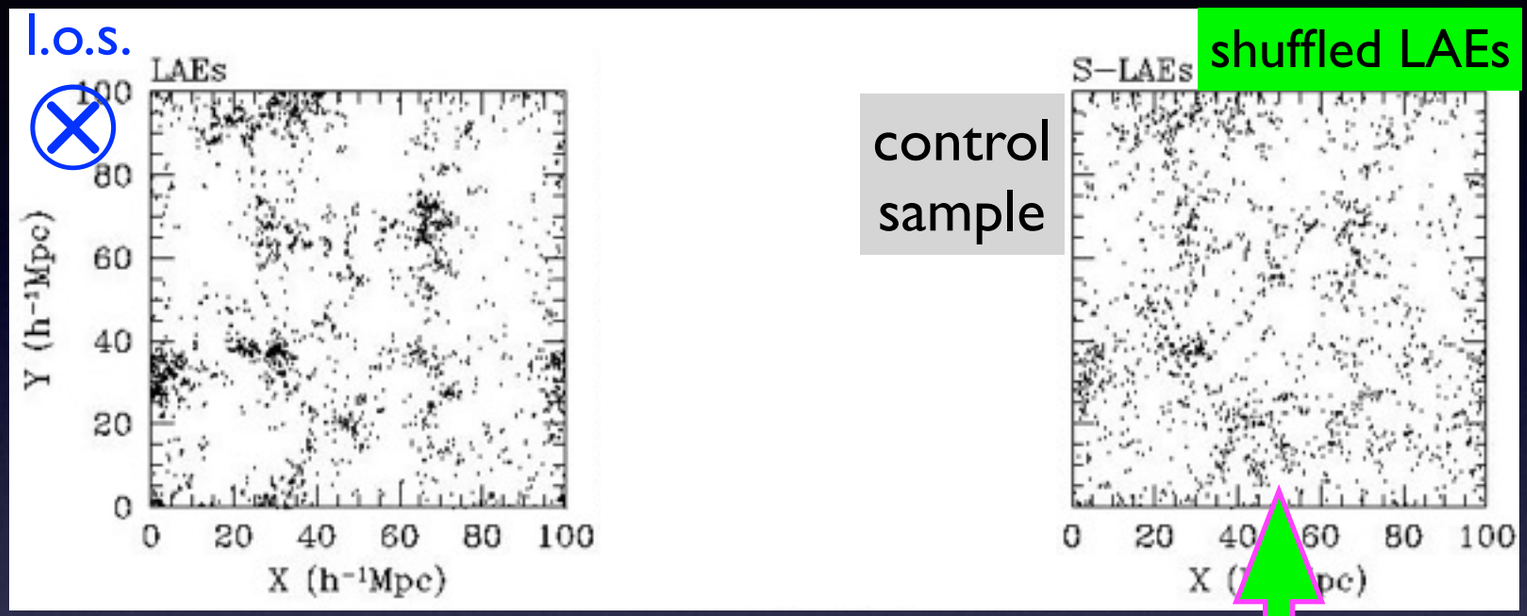


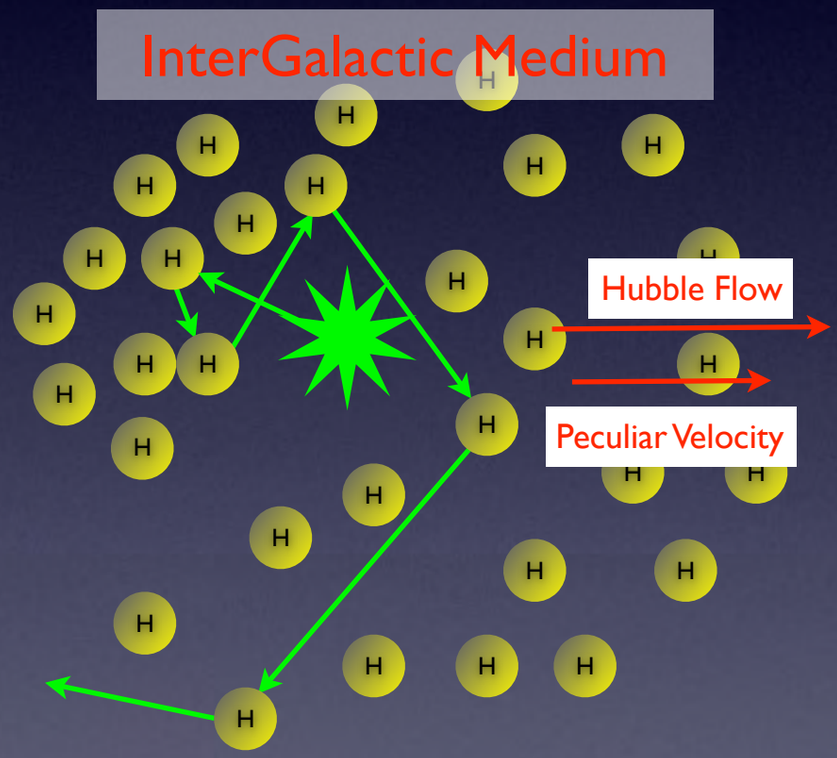
Nie, ZZ, et al. (in prep)

Clustering of LAEs: Model Prediction

enhancement in the transverse fluctuation

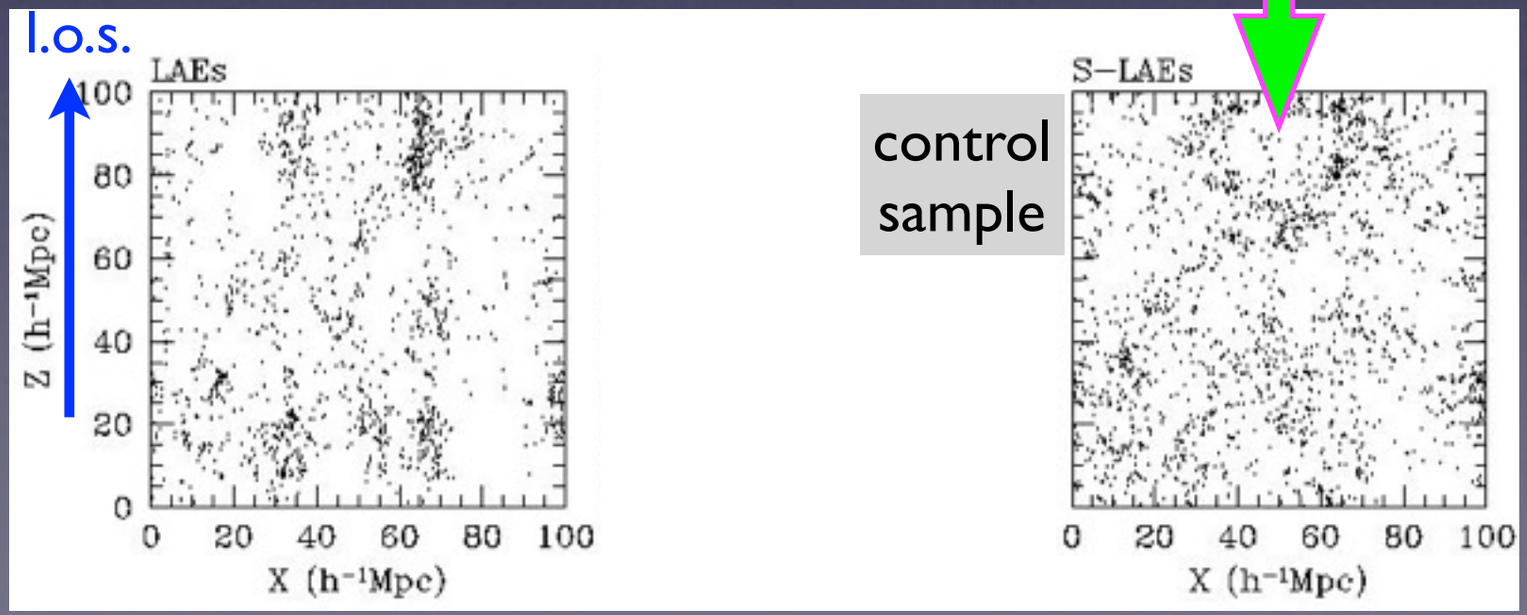
selection effect caused by environment dependent Lya RT





if the environment dependence of radiative transfer were eliminated

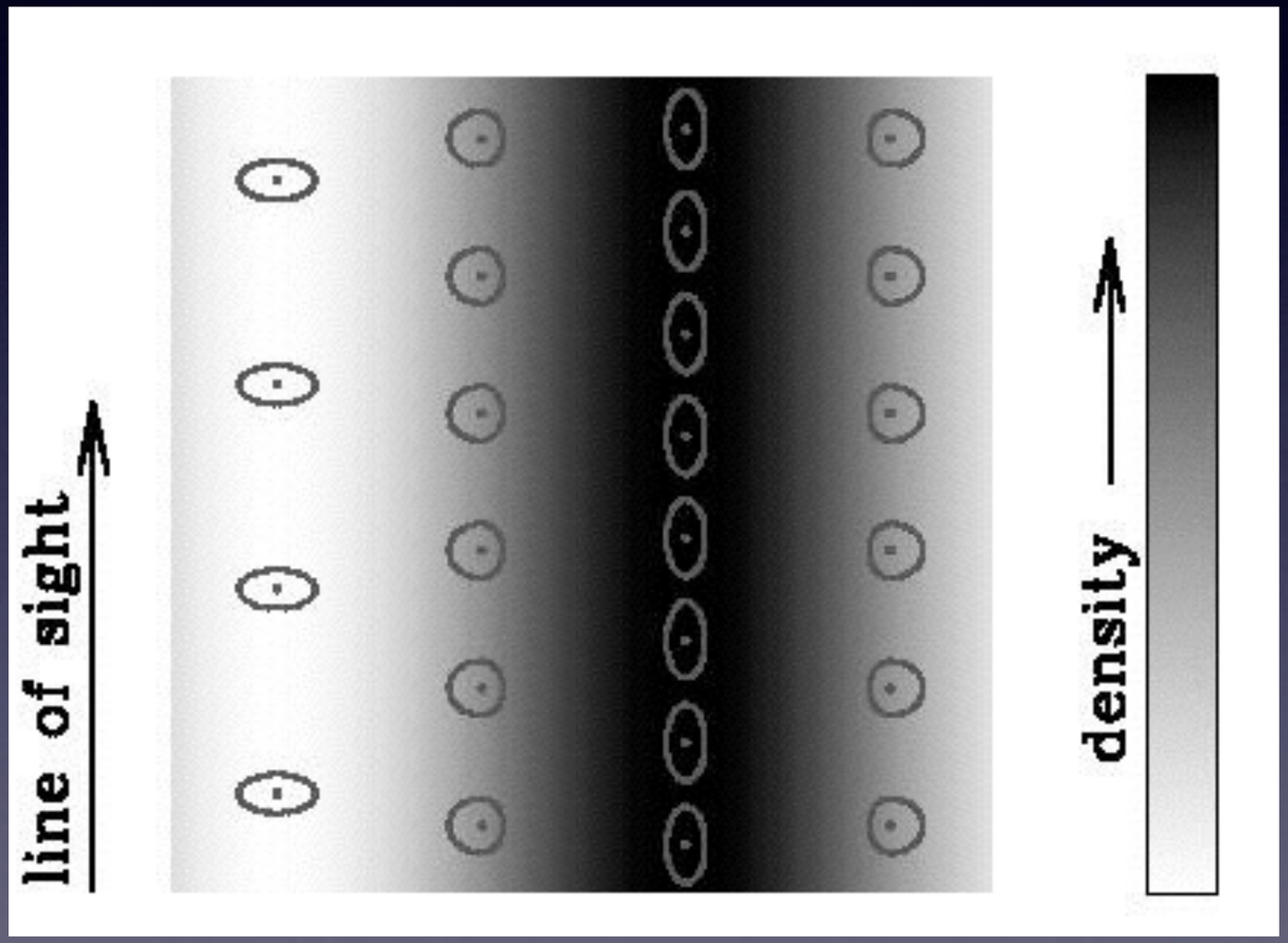
suppression in the line-of-sight fluctuation



Zheng, et al. (2011a)

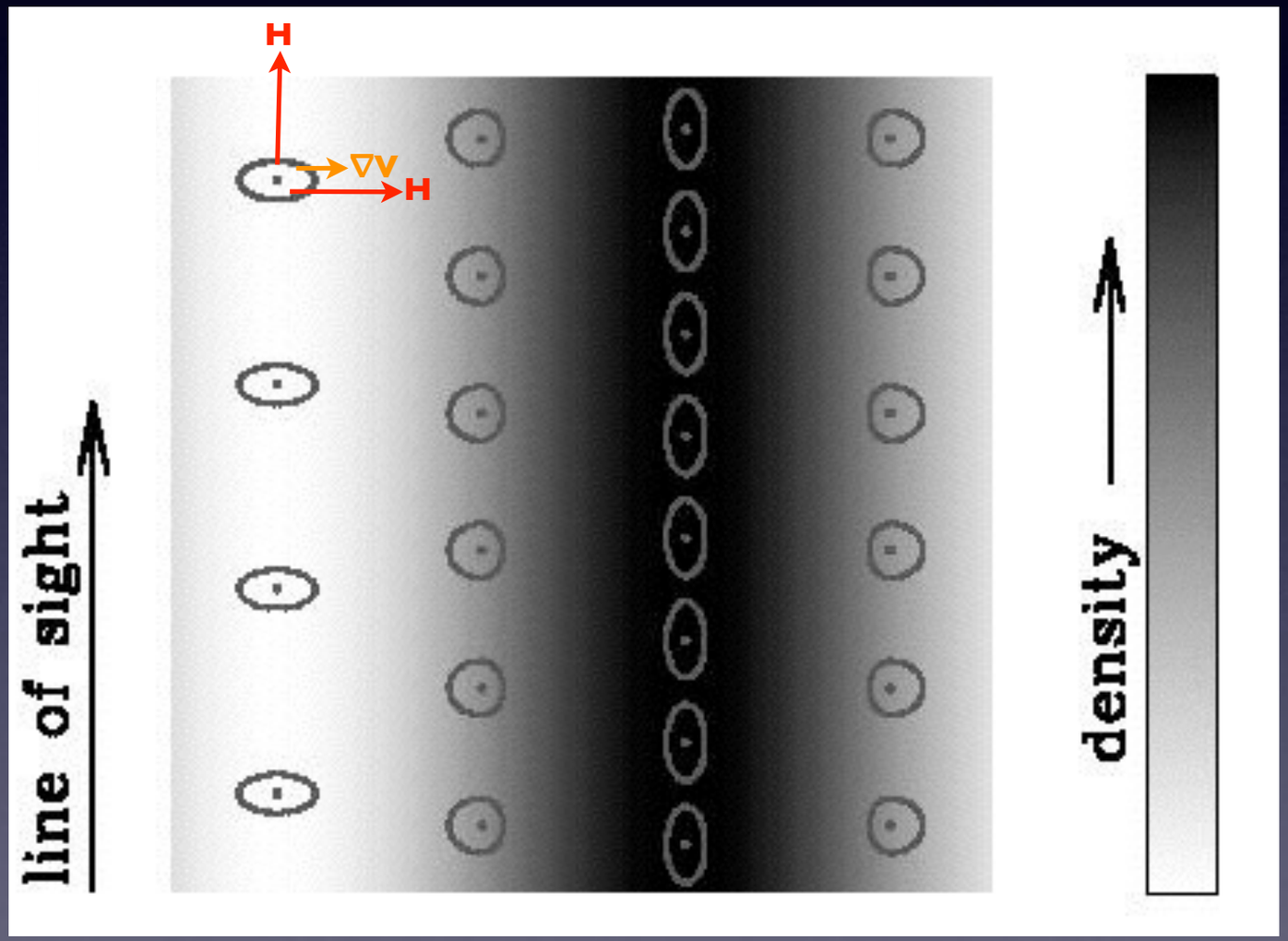
Clustering of LAEs: Model Prediction

An intuitive picture



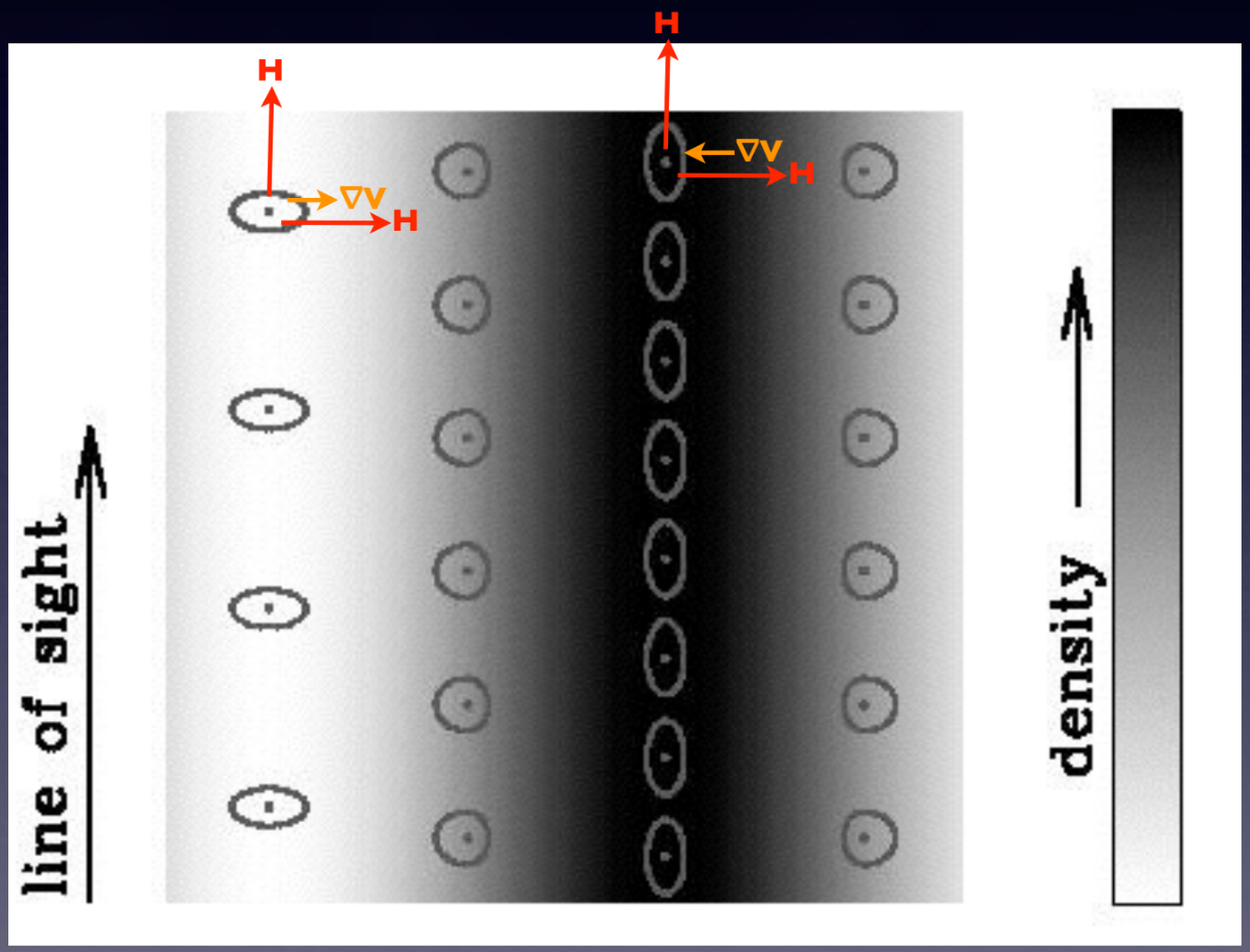
Clustering of LAEs: Model Prediction

An intuitive picture



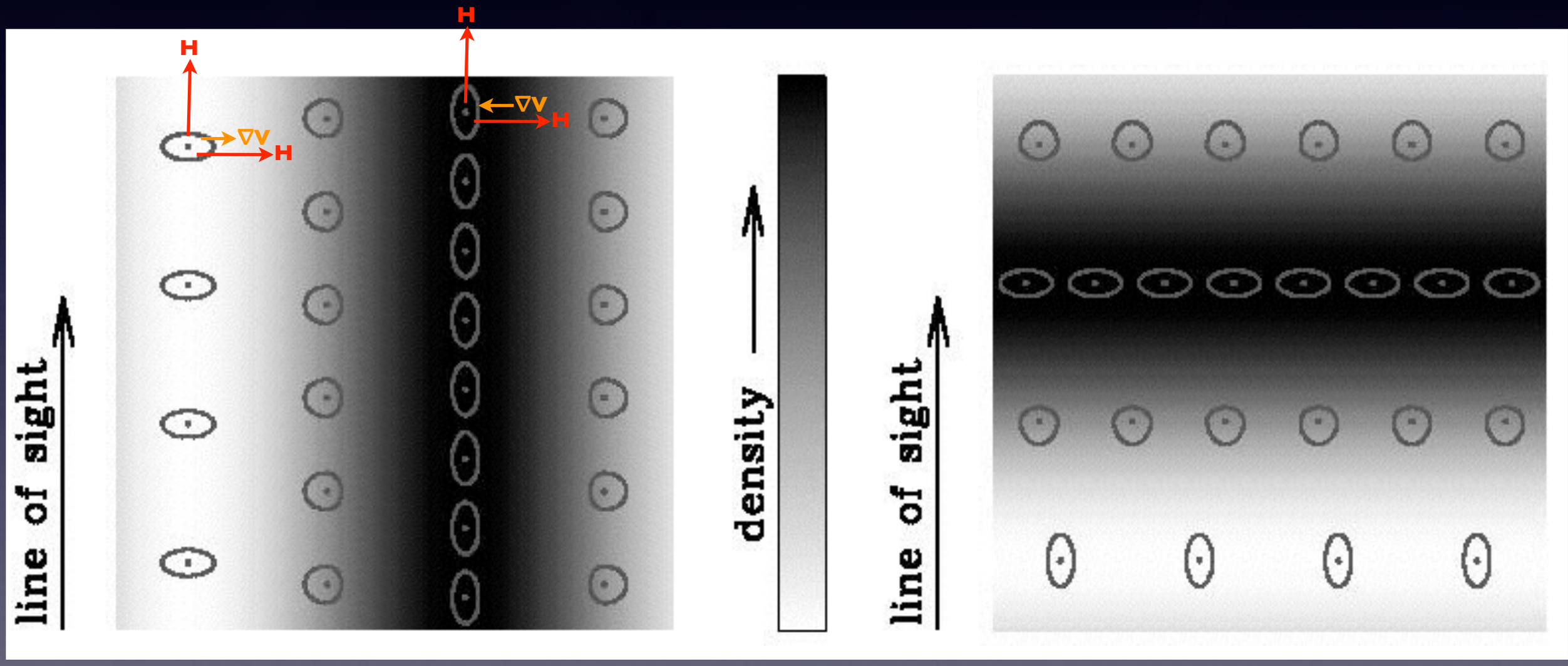
Clustering of LAEs: Model Prediction

An intuitive picture



Clustering of LAEs: Model Prediction

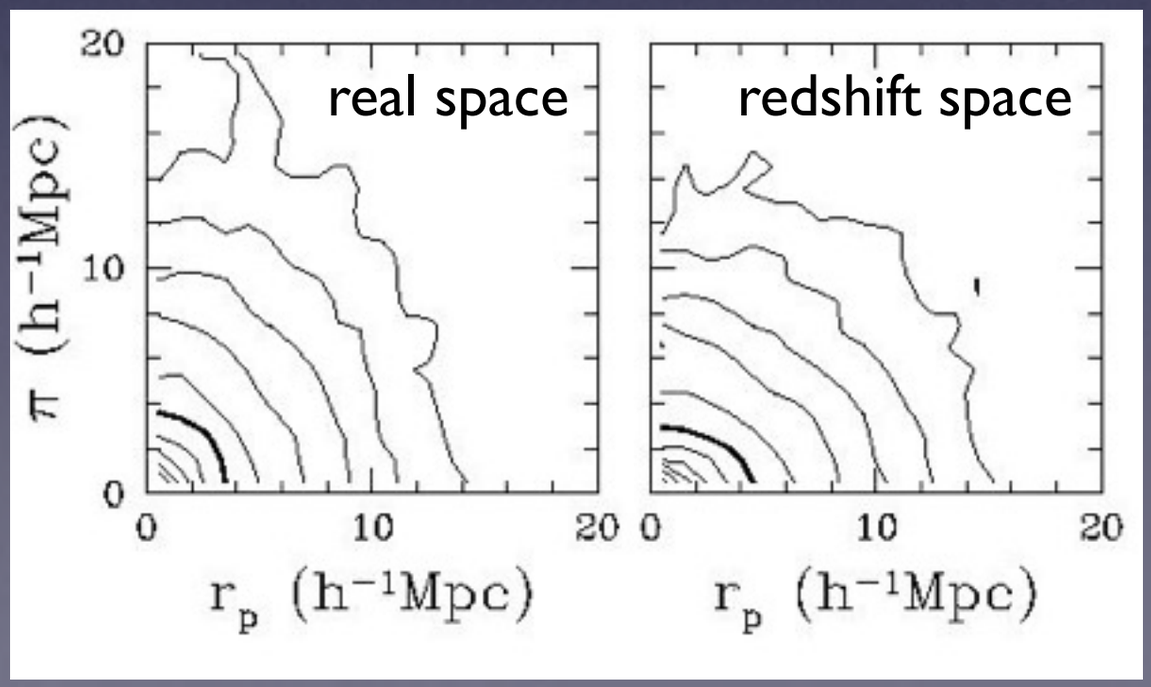
An intuitive picture



Clustering of LAEs: 3D Clustering

Anisotropic 3D two-point correlation function of LAEs

Zheng, et al. (2011a)

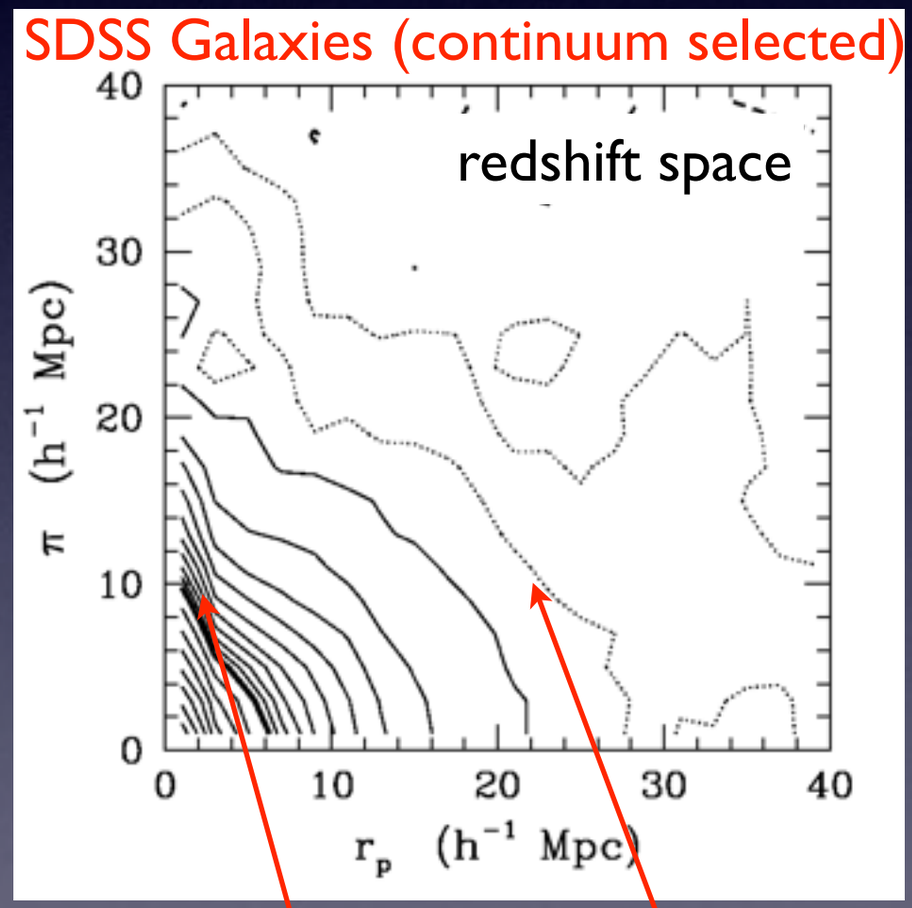


Shuffled LAEs

environment dependence of radiative transfer

Eliminated

Zehavi, Zheng, et al. (2011)



Finger-of-God Effect
nonlinear redshift distortion

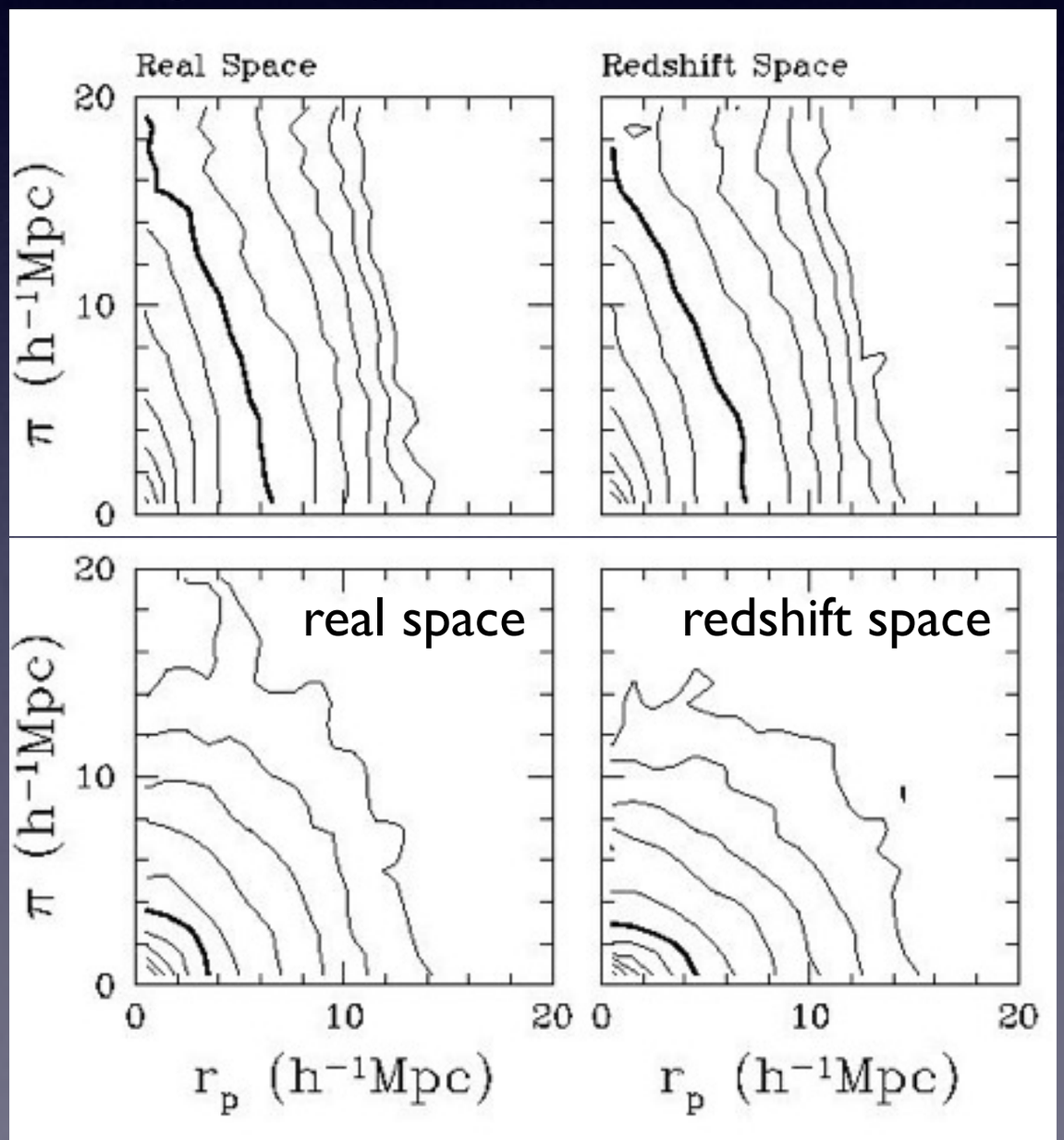
Kaiser Effect
linear redshift distortion

Clustering of LAEs: 3D Clustering

Anisotropic 3D two-point correlation function of LAEs

Zheng, et al. (2011a)

Radiative Transfer Effect



LAEs

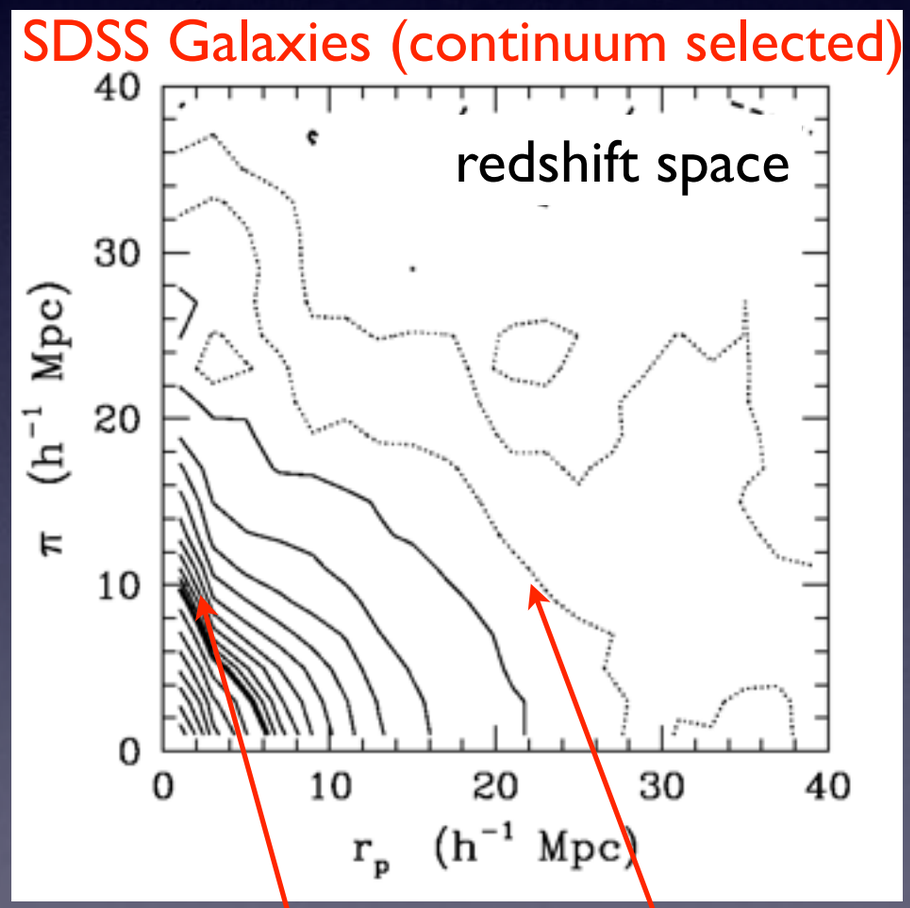
Shuffled LAEs

environment dependence of radiative transfer

Eliminated

Zehavi, Zheng, et al. (2011)

SDSS Galaxies (continuum selected)



Finger-of-God Effect
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linear redshift distortion

New, Strong Effects in Clustering of Lyman-alpha Emitters

Key Points:

- Enhancement in the transverse fluctuation
- Suppression in the line-of-sight fluctuation

- New anisotropy in the 3D two-point correlation function
- Scale-dependent bias (slope change in power spectrum)

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$$P_g^s(\mathbf{k}) = \left\{ \left[\left(1 + \frac{\alpha_1 - \alpha_3 f}{b} \right) + (1 - \alpha_2 + \alpha_3)\beta\mu^2 \right]^2 + \left(\alpha_4 \beta \frac{1}{kr_H} + \frac{\alpha_5}{b} kr_H \right)^2 \mu^2 \right\} b^2 P_m(\mathbf{k})$$

density

transverse velocity gradient

redshift distortion

l.o.s. velocity gradient

transverse velocity gradient

velocity

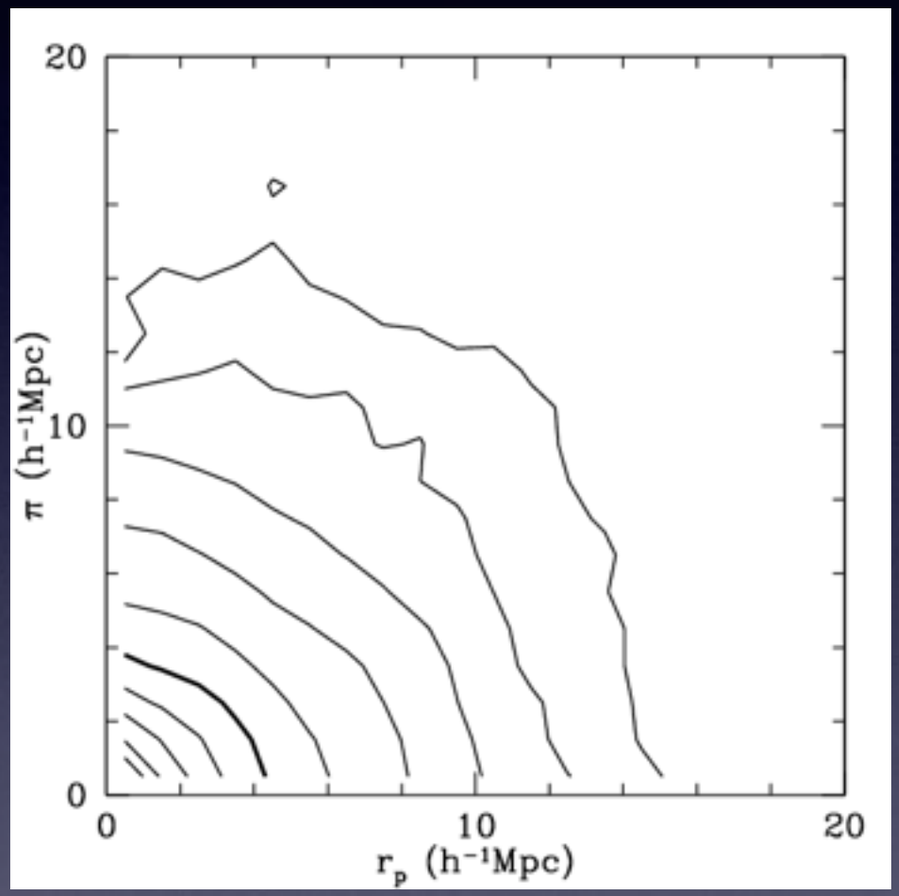
density gradient

Challenges and Opportunities

Initial Line Profile & Galactic Winds

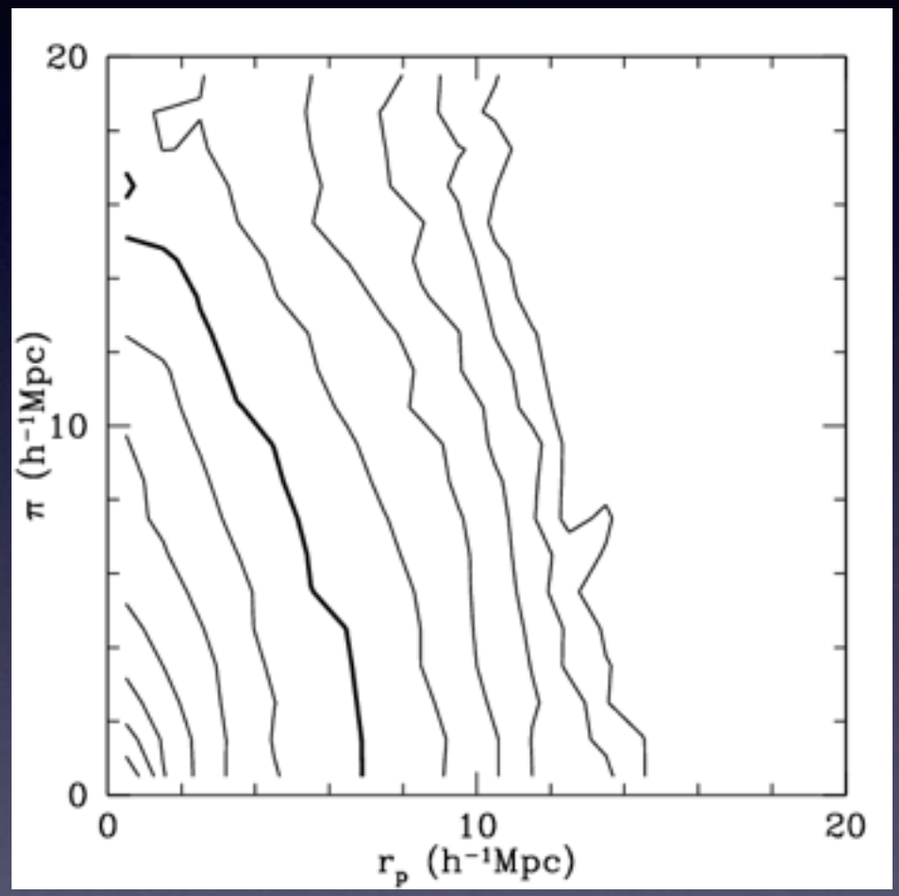
No Coupling

Kaiser effect dominated



Strong Coupling

RT effect dominated

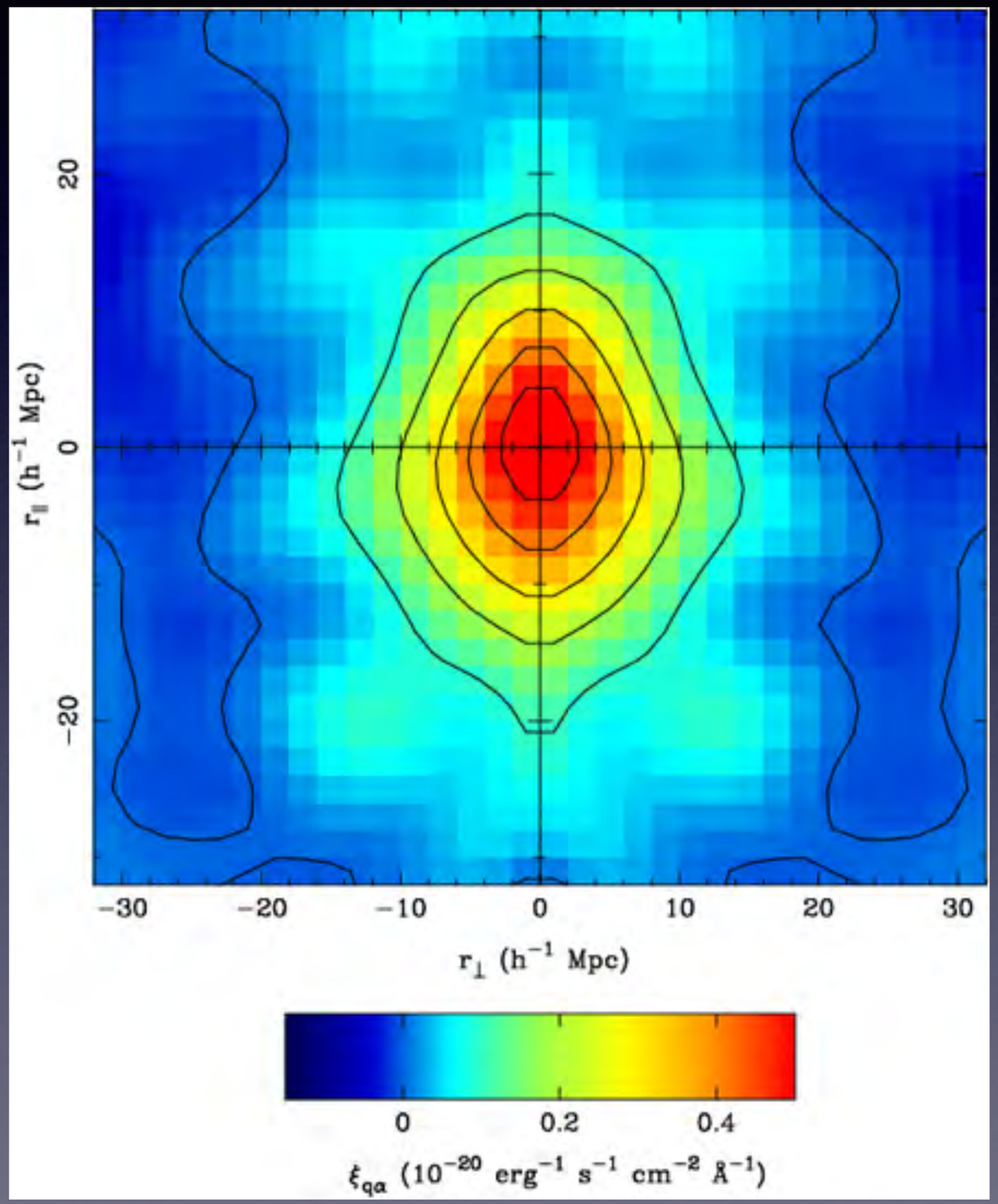


New role of galaxy clustering

putting constraints on galactic winds (e.g., wind strength and anisotropy)

(also see Wyithe & Dijkstra 2011)

A Tentative Observational Case from SDSS-III BOSS Quasar-LAE Cross-Correlation



Croft, Miralda-Escude, ZZ, et al. (2016)

Summary

- Anisotropic gas distribution leads to anisotropic Lyman-alpha emission.
  - ✳ Radiative transfer calculations are performed for simple models of anisotropic Lyman-alpha emission.
  - ✳ The simple models are able to qualitatively reproduce some statistical trends seen in Lyman-alpha emission from star-forming galaxies (e.g., EW distribution and EW-V_{peak} relation) and make interesting predictions (e.g., between V_{peak} and line profile).
  - ✳ The anisotropic Lyman-alpha emission could be one of the key factors in determining and in interpreting the observational properties of Lyman-alpha emission from star-forming galaxies.
  - ✳ Lya RT modeling with simulated galaxies shows that Lya EW distribution can be largely explained by the anisotropic Lya emission.
  - ✳ Implications for Lya Halos, expanding shell models, and clustering.