# Probing Halo Gas Dynamics Using Absorption Spectroscopy

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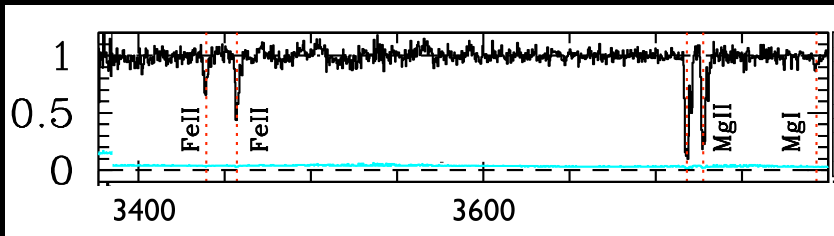
# Outline

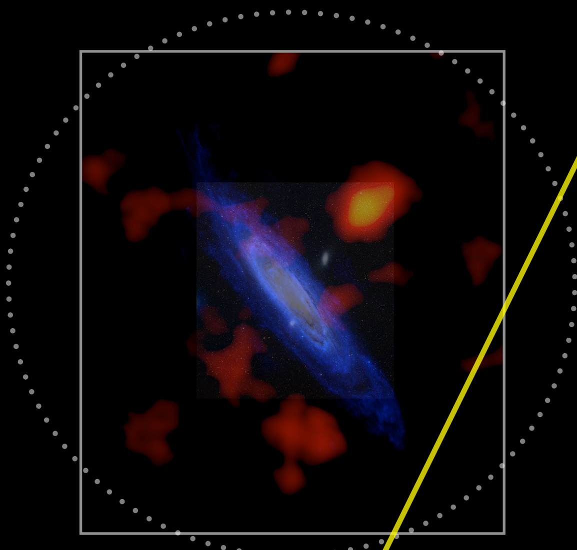
- Redshift evolution of the circumgalactic medium
- Empirical constraints on super-galactic winds at $z \gtrsim 0.5$

# Probing the CGM using Absorption Spectroscopy

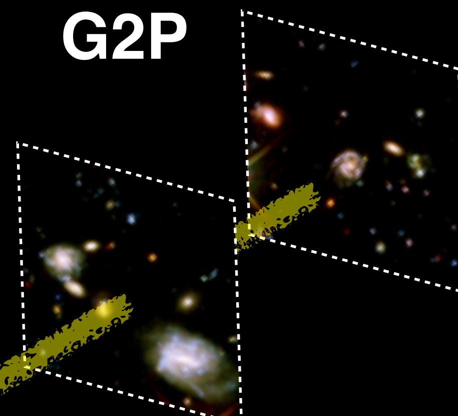


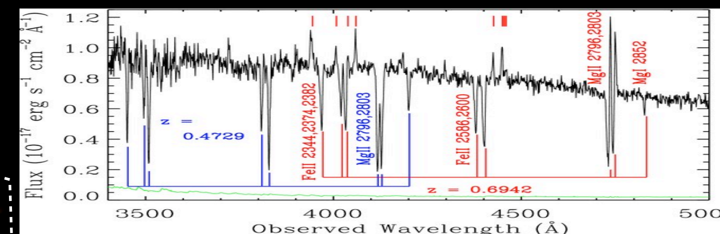

QGP

Bergeron ‘86; Guillemin & Bergeron ‘97; Le Brun+’97; Lanzetta & Bowen ’90,’92; Lanzetta+’95; Chen+‘98,01a; Chen +01b; Chen & Tinker ’98; Chen & Mulchaey ’09; Chen+‘10a,b; Gauthier+’09,’10; Gauthier & Chen ’11,’12; Steidel ’93; Steidel+’94; Steidel+’97; Steidel+’02; Adelberger +’03,’05; Churchill ’01; Churchill+’03; Kacprzak+’07,’10; Bowen+’95; Tripp+’98; Bowen+’02; Borthakur+’11; Tripp+’11; Rao+’03; Nestor+’07; Rao+’11; Nestor+’11; Barton & Cooke ’09; Prochaska+’11; Tumlinson+’11; Ménard+’11

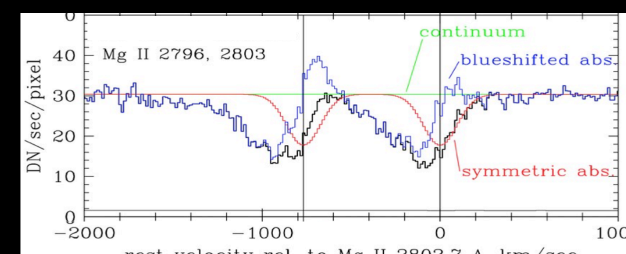


G2P






Rubin+’10; Steidel+’10; Bordoloi+’11



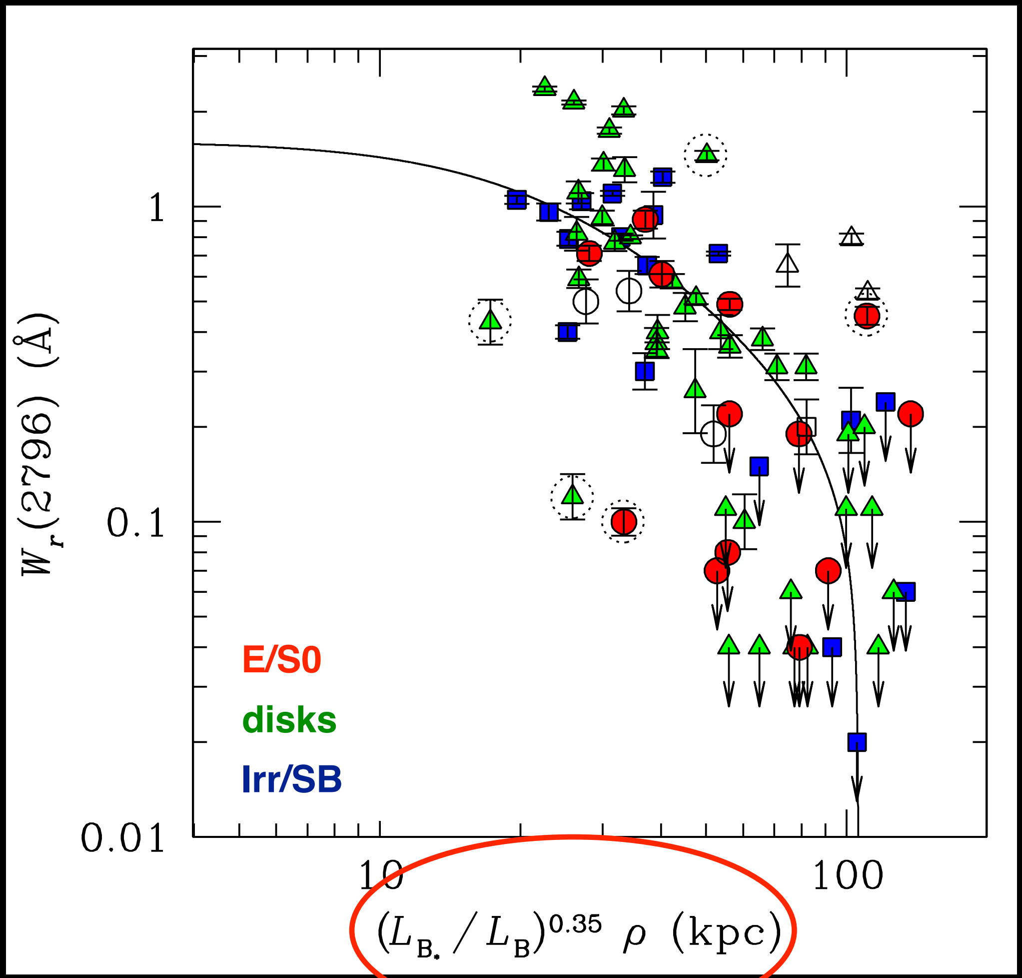

GSA

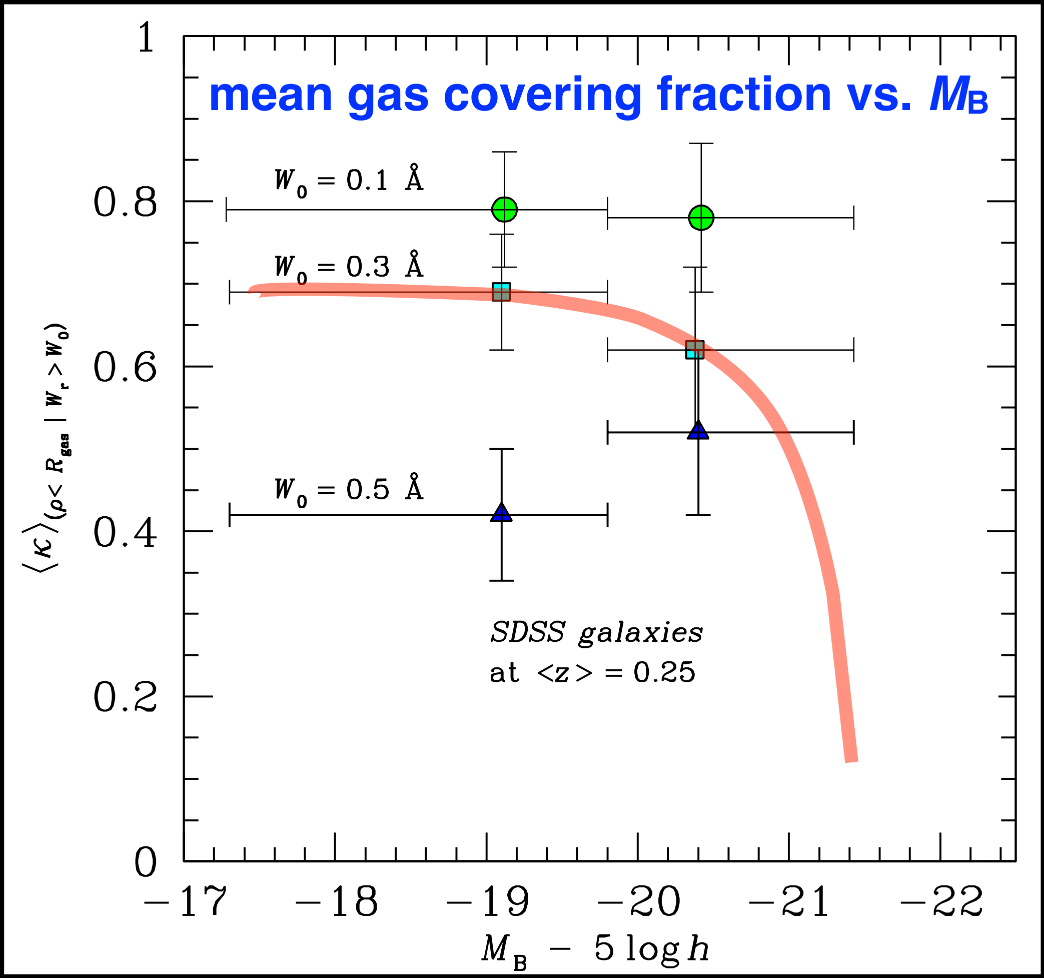
Martin & Bouché ‘09; Weiner+’09; Rubin+’10; Kornei+’12

# The Chemical Enriched Circumgalactic Medium at z < 1

## Probing cool, photo-ionized halo gas using MgII 2796, 2803

## *The QGP approach*

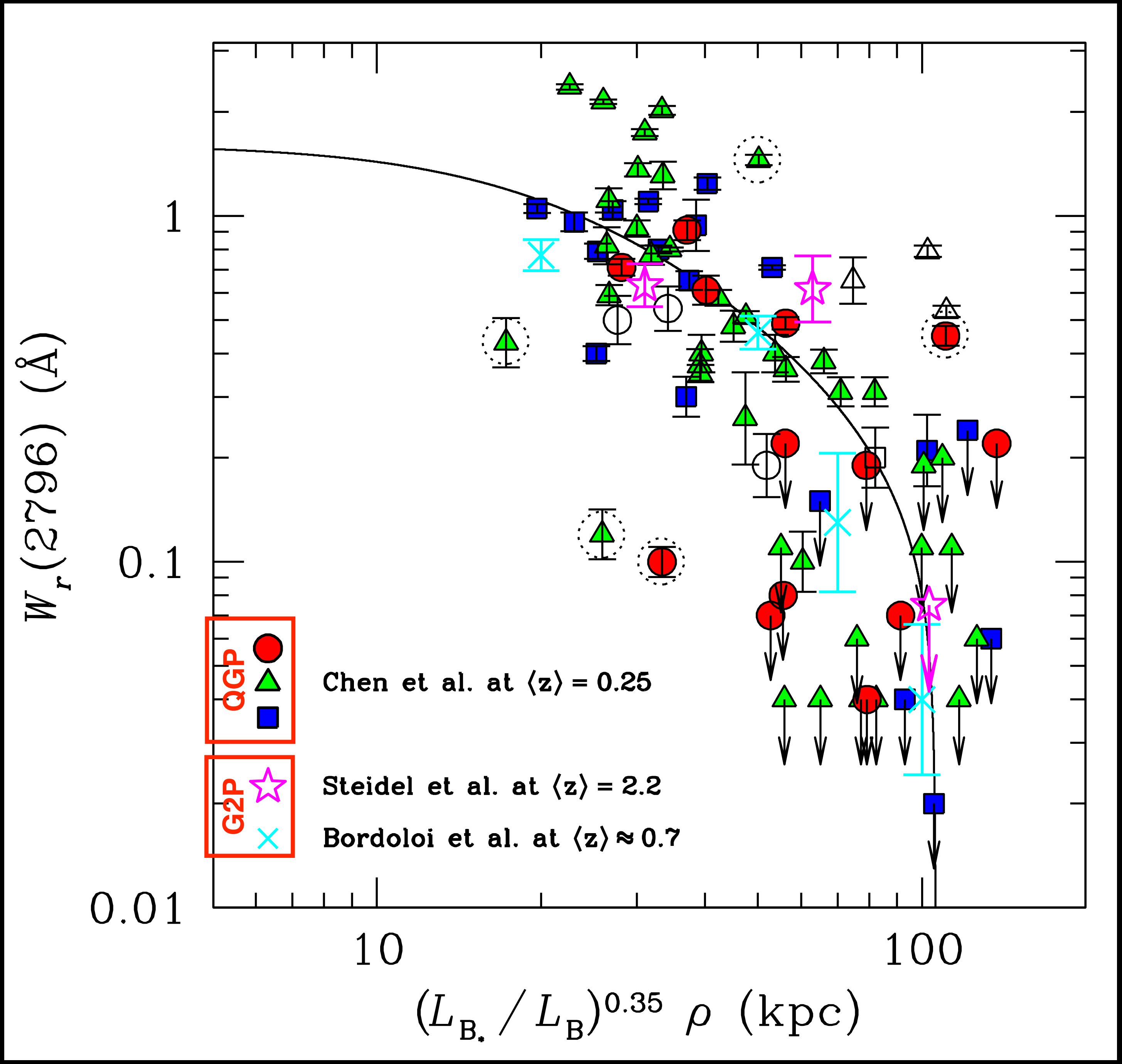



**Chen & Tinker (2008)**
**Chen, Helsby, Gauthier, Shectman, Thompson, & Tinker (2010)**
**Chen, Wild, Tinker, Gauthier, Helsby, Shectman, & Thompson (2010)**
**Gauthier, Chen, & Tinker (2009, 2010)**

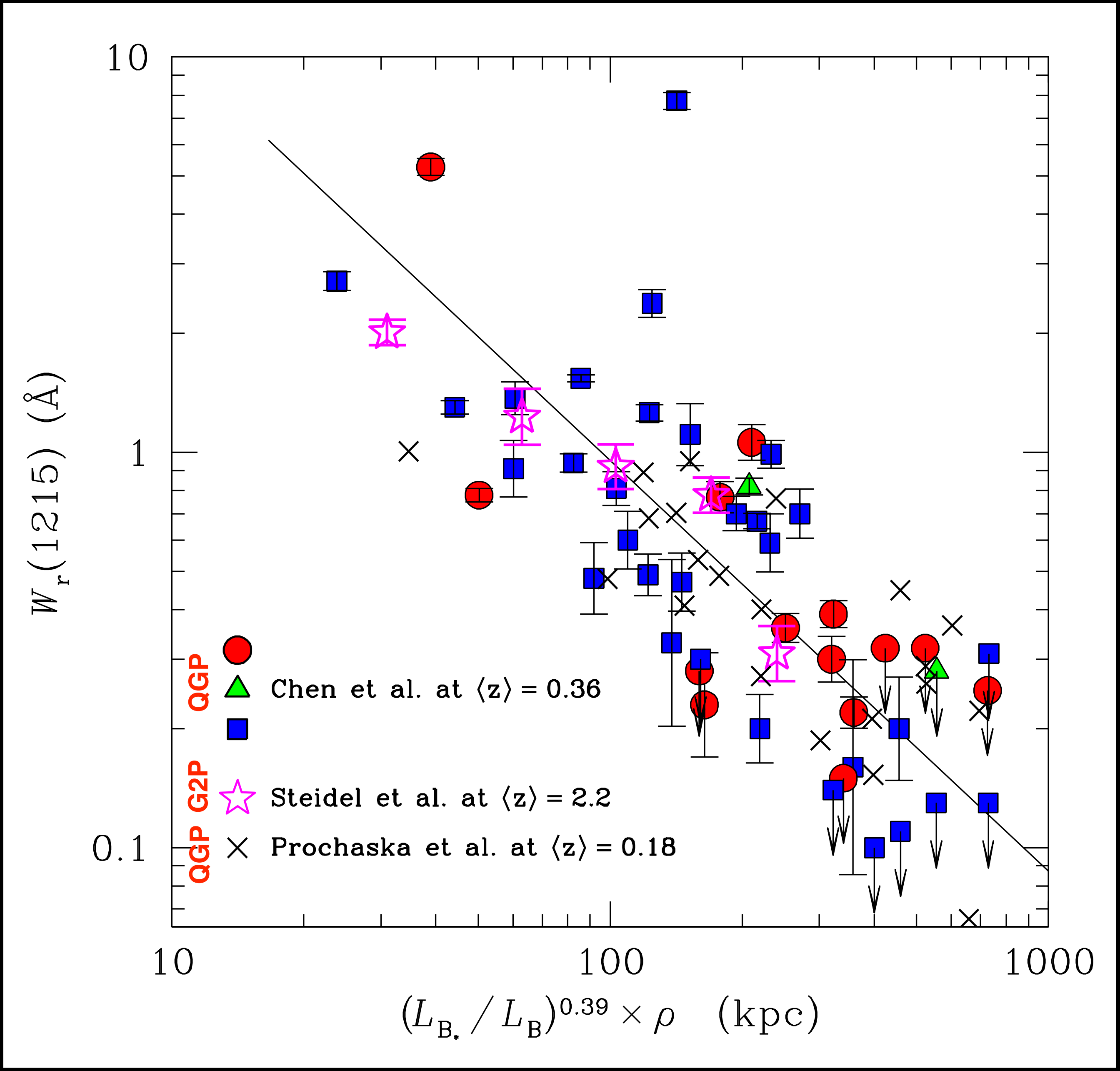
**A declining covering fraction of cool gas in high-mass halos**

# The Unchanging Circumgalactic Medium Since $z \sim 2.2$



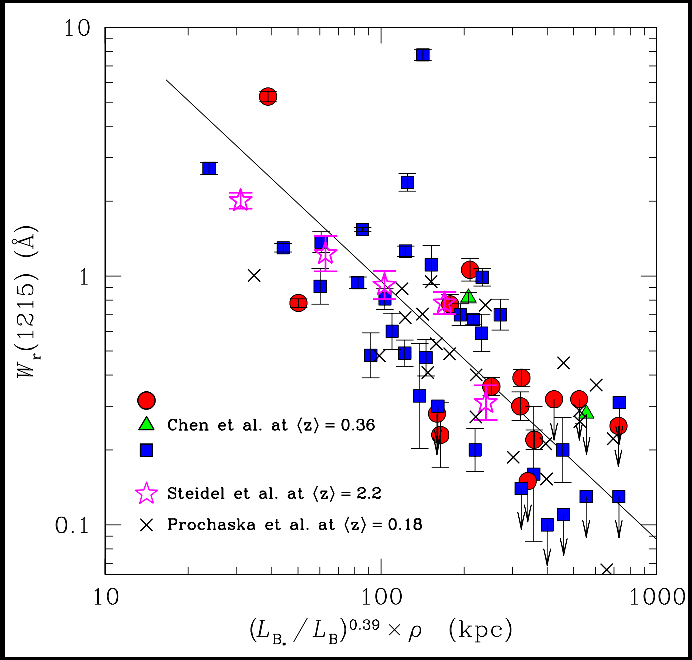
# The Unchanging Circumgalactic Medium Since $z \sim 2.2$

Tenuous gas traced by Lyα 1215

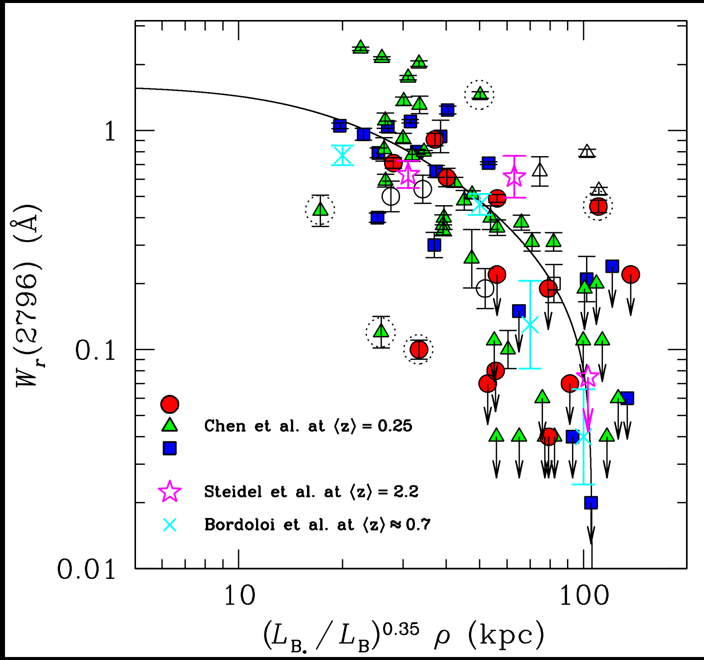


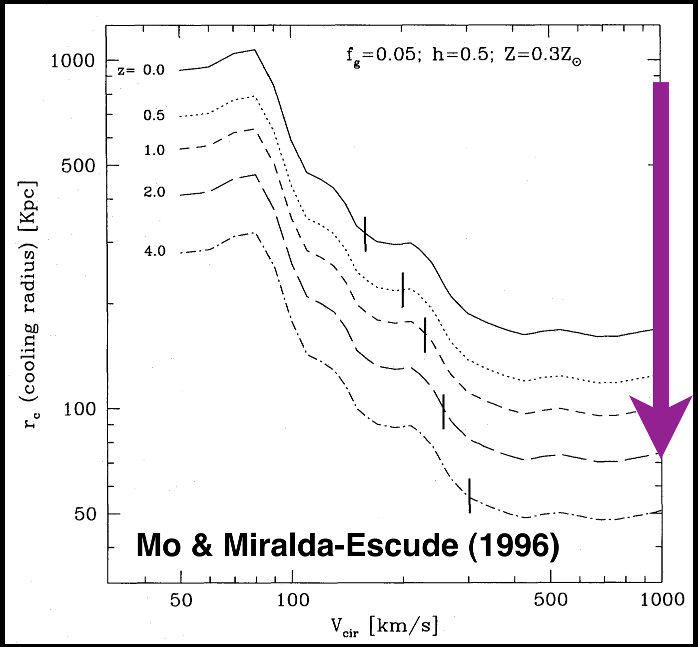
# The Unchanging Circumgalactic Medium Since $z \sim 2.2$

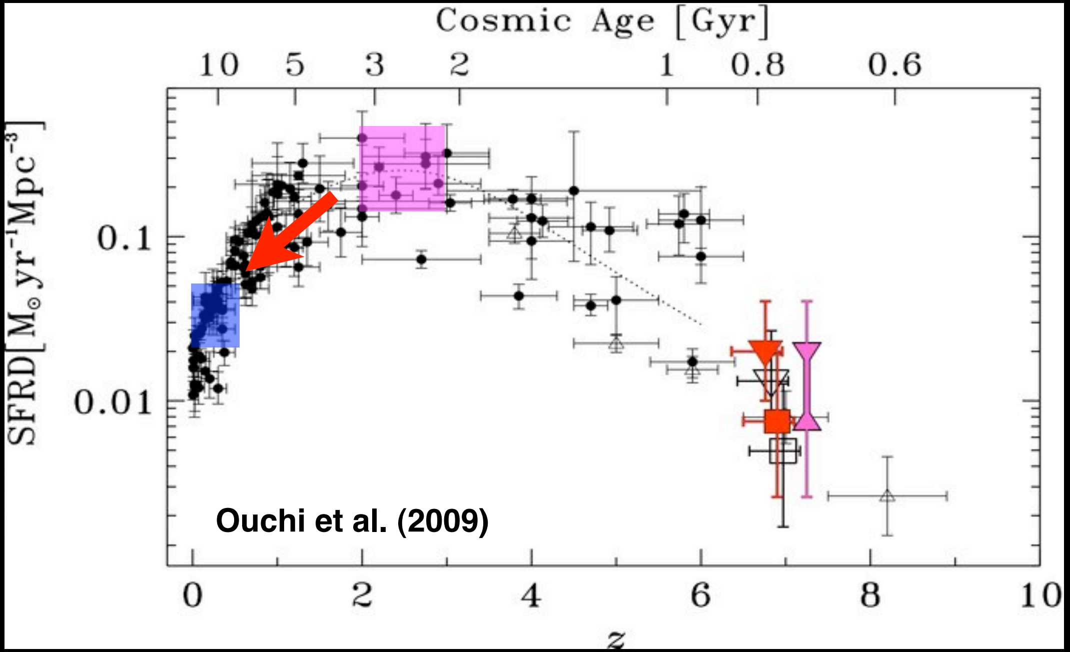
## Lyα Absorbers




## MgII Absorbers



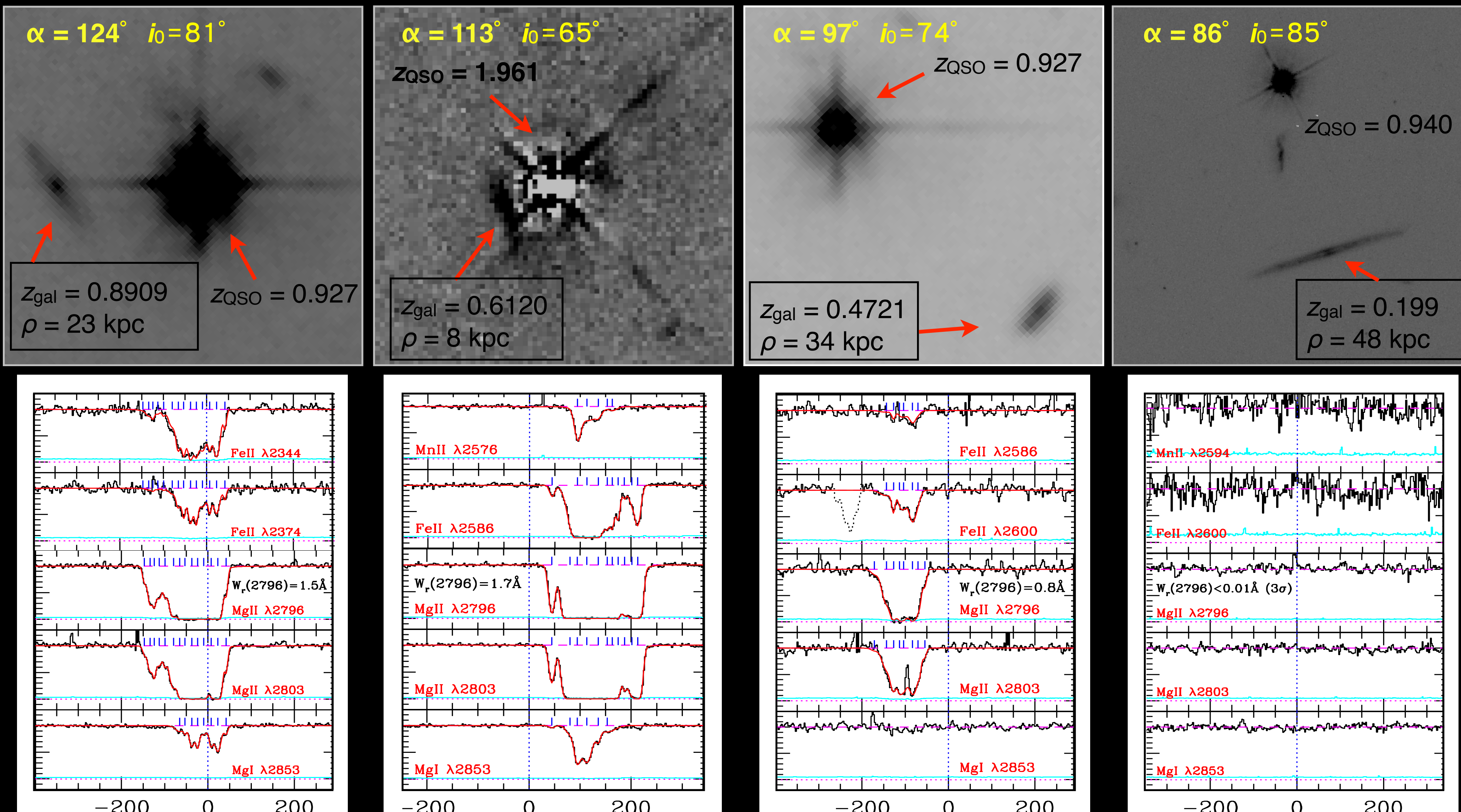



# Empirical Constraints of Supergalactic Winds at $z \gtrsim 0.5$

Jean-René Gauthier & H.-W. Chen 2012, MNRAS in press (arXiv:1205.4037)

## four highly inclined disk galaxies with a background QSO probing the CGM within 45 degrees of the rotation axis



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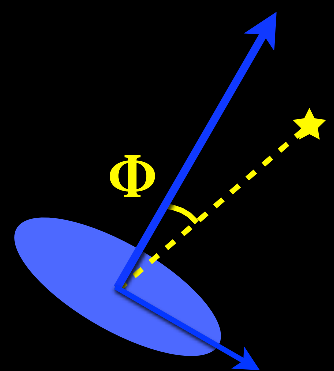
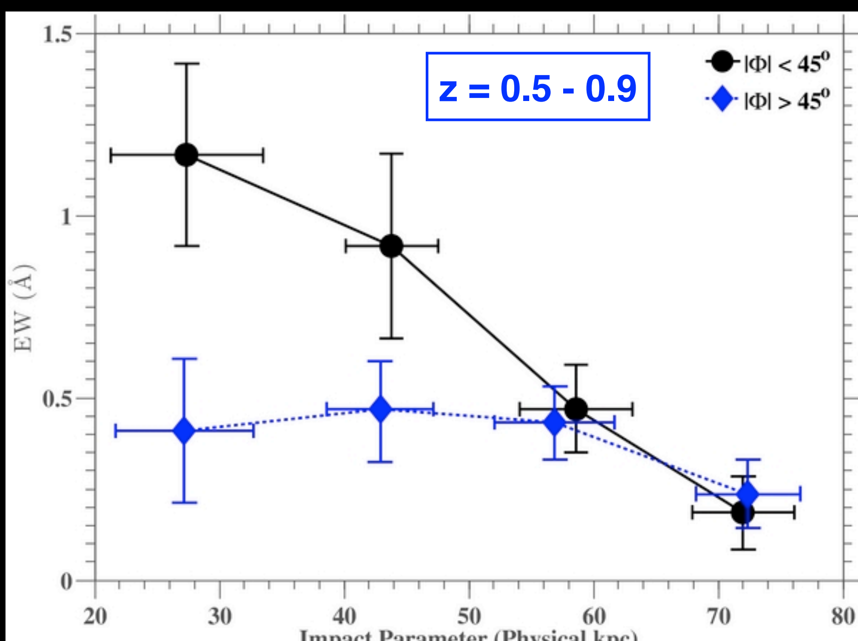
**Enhanced Absorber Strength Near the polar Axis**



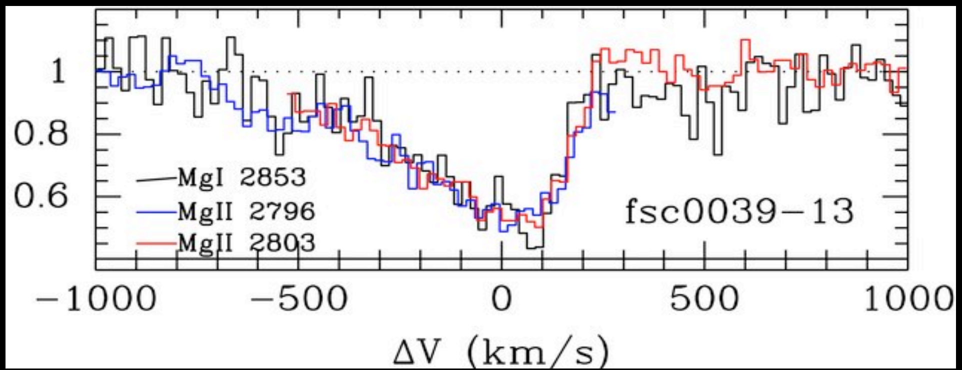

Bordoloi et al. (2011) **G2P**

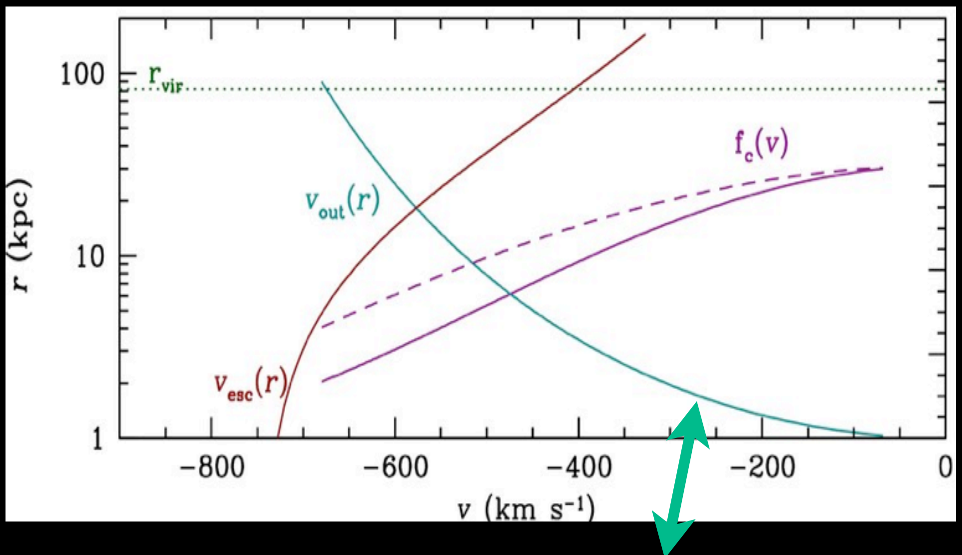



**Accelerated outflows**

Martin & Bouché (2009)
Steidel et al. (2010)

**GSA**




$$v_{\rm out}(r) = \left(\frac{2A}{\alpha - 1}\right)^{0.5} \sqrt{r_{\rm min}^{1-\alpha} - r^{1-\alpha}}$$

# A Simple Conical Outflow Model

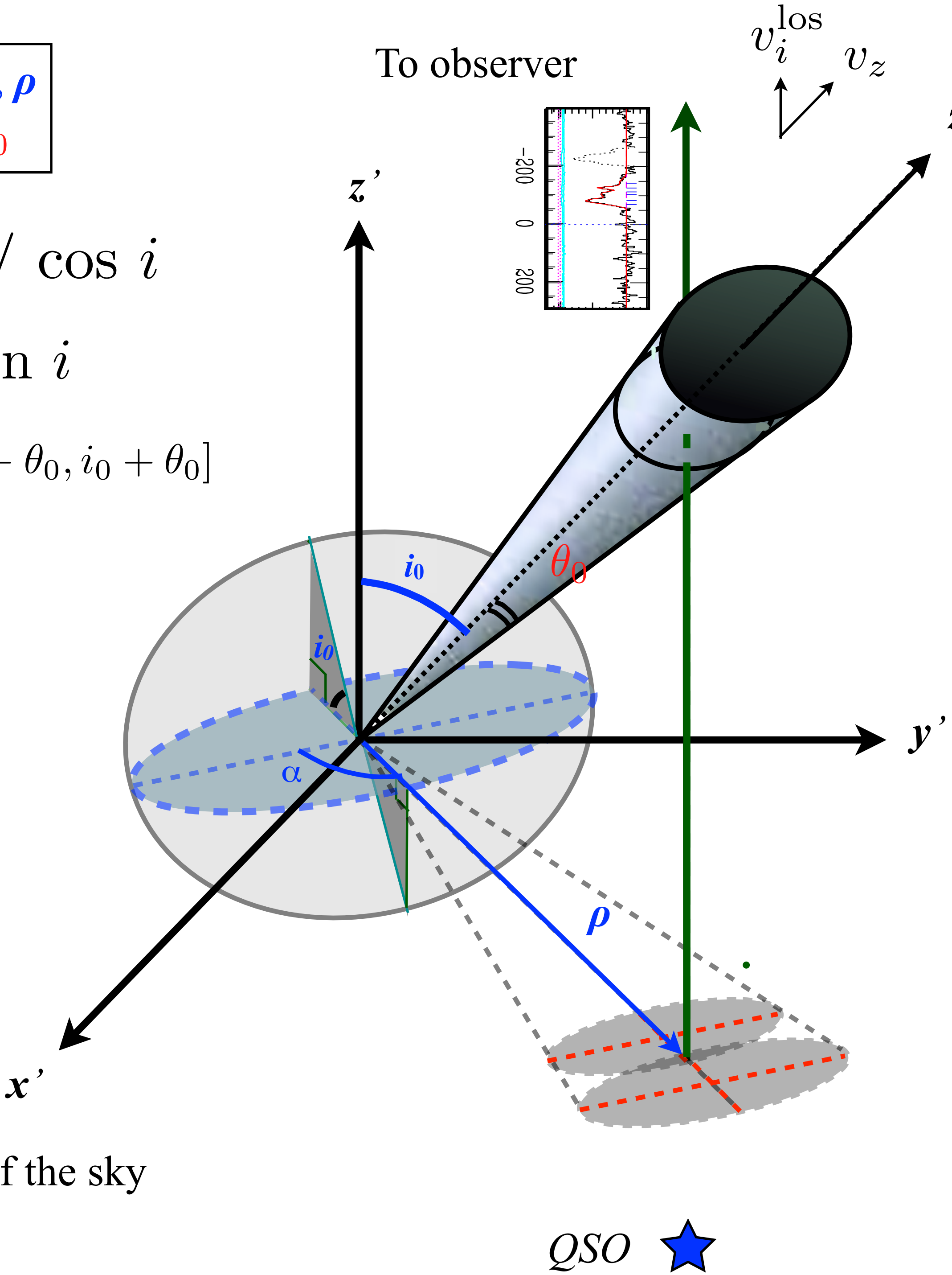
Jean-René Gauthier & H.-W. Chen 2012,
MNRAS in press (arXiv:1205.4037)

Knowns: $i_0$, $\alpha$, $\rho$
Unknowns: $\theta_0$

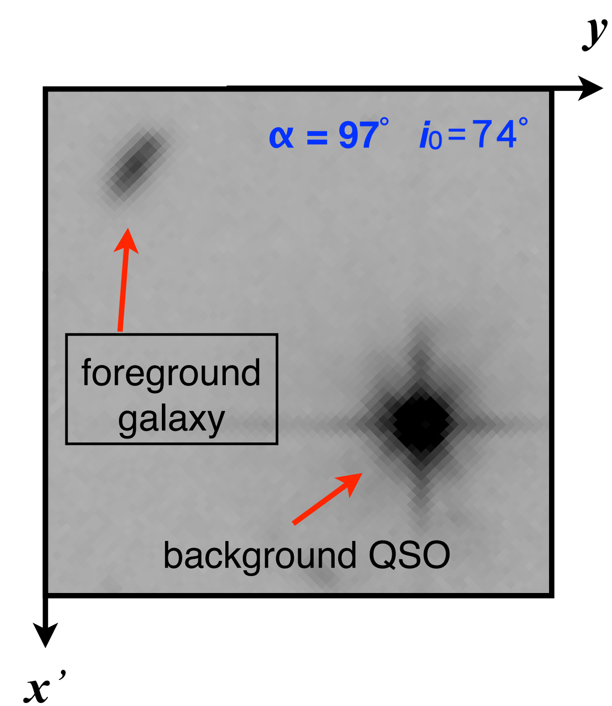
$$v_z = v_i^{\rm los} \, / \, \cos\, i$$

$$z \approx \rho \, / \, \sin\, i$$

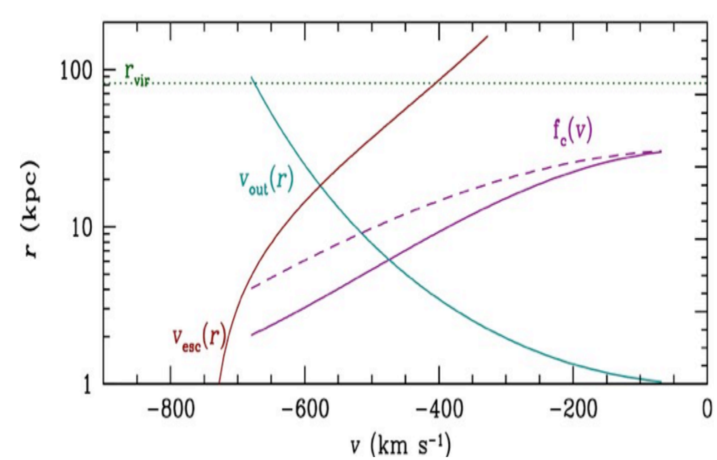
where $i \in [i_0 - \theta_0, i_0 + \theta_0]$




x'-y' : plane of the sky




**For each allowed $\theta_0$, we can work out $v_z(z)$**



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Jean-René Gauthier & H.-W. Chen 2012, MNRAS in press (arXiv:1205.4037)

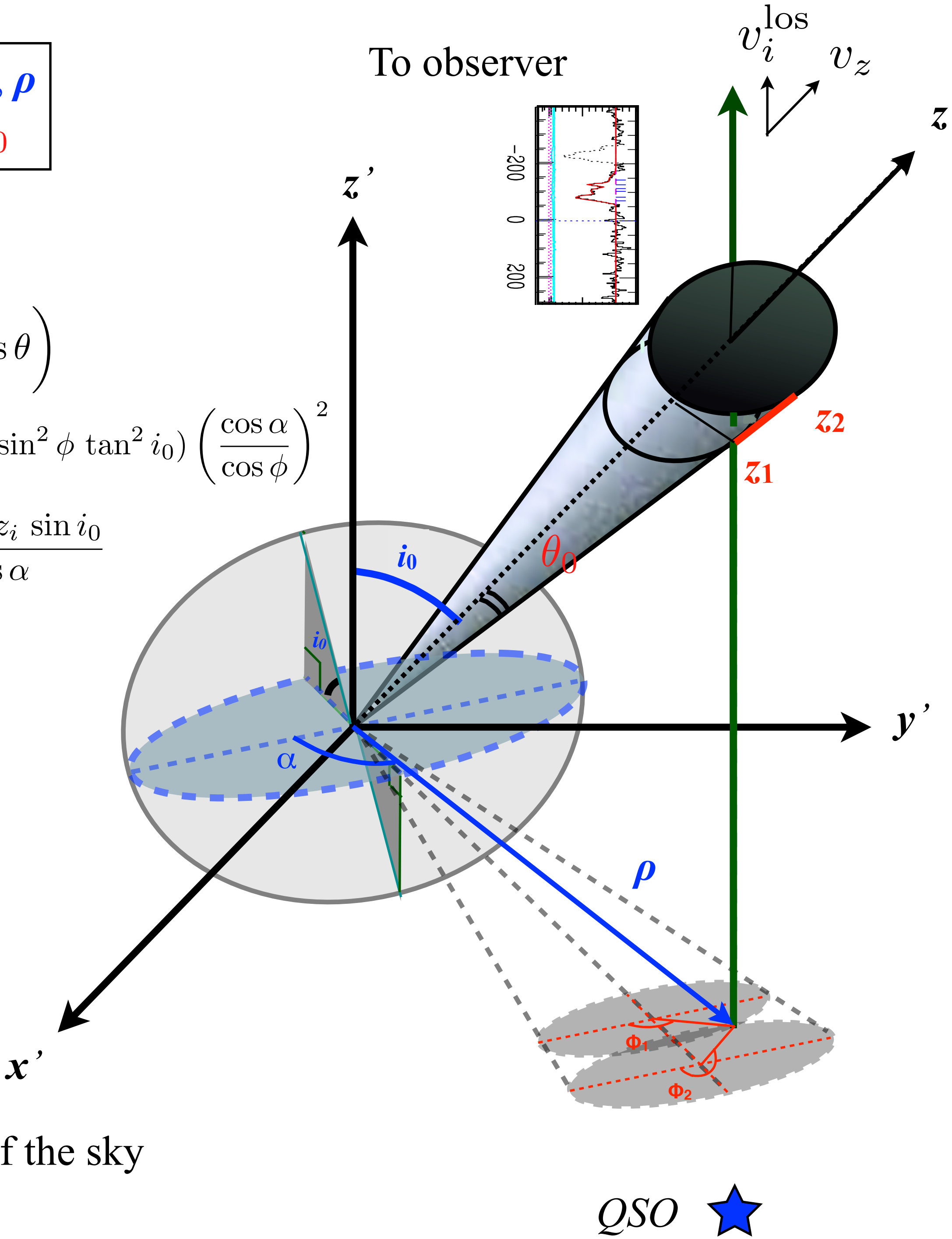
Knowns: $i_0$, $\alpha$, $\rho$
Unknowns: $\theta_0$

$$v_i^{\rm los} = v_{z_i} \cos i$$

$$i = \sin^{-1}\left(\frac{\rho}{z_i}\cos\theta\right)$$

$$z_i^2 \tan^2\theta = \rho^2\left(1+\sin^2\phi\,\tan^2 i_0\right)\left(\frac{\cos\alpha}{\cos\phi}\right)^2$$

$$\tan\phi = \frac{\rho\sin\alpha - z_i\sin i_0}{\rho\cos\alpha}$$

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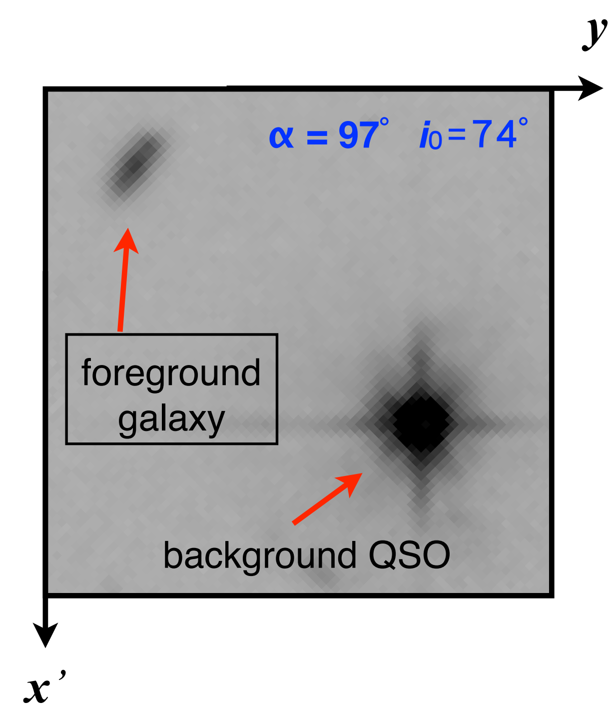
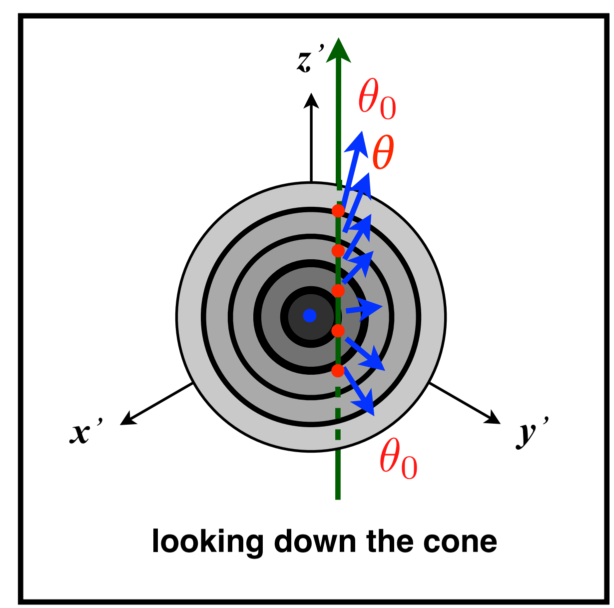
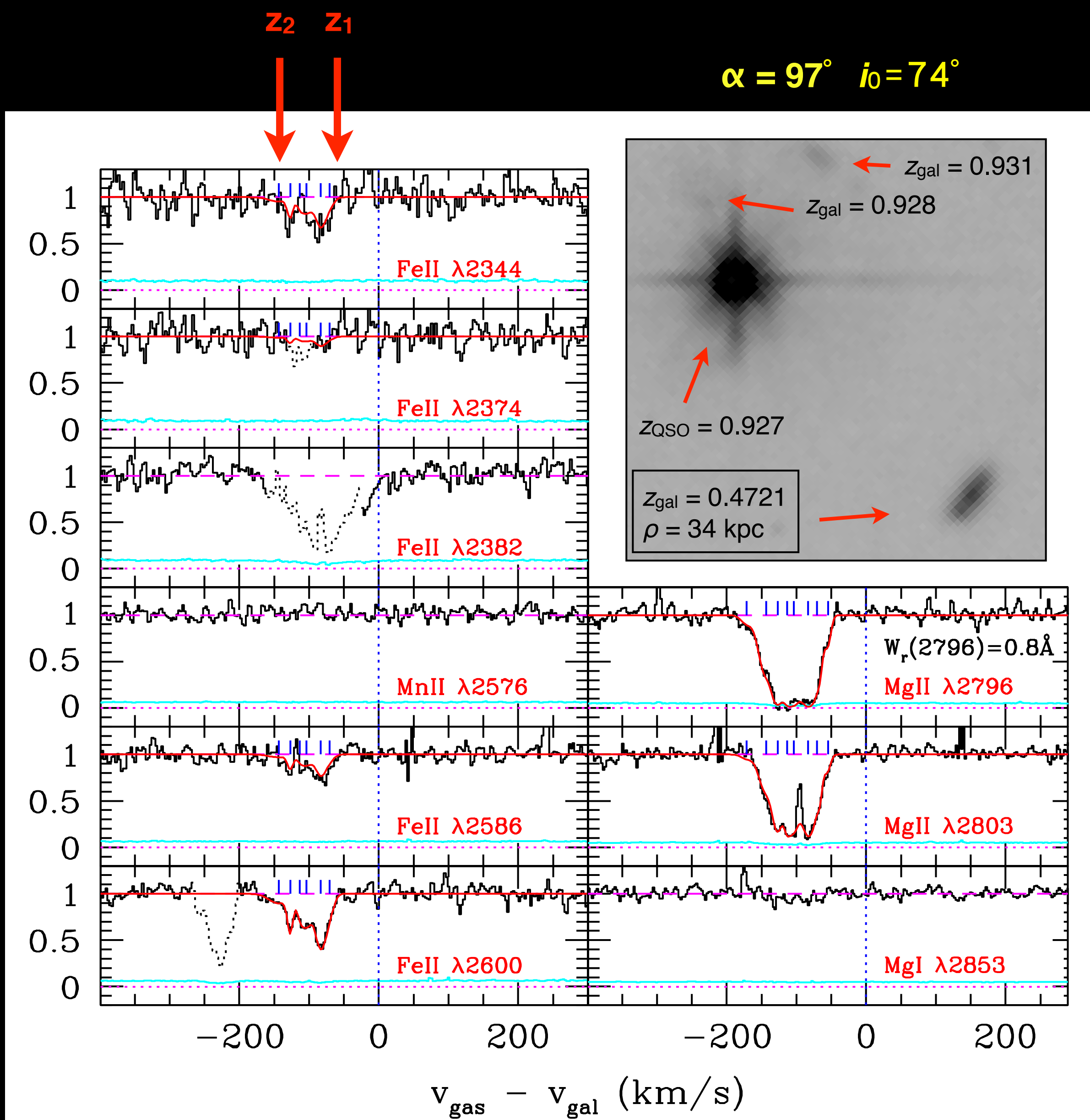


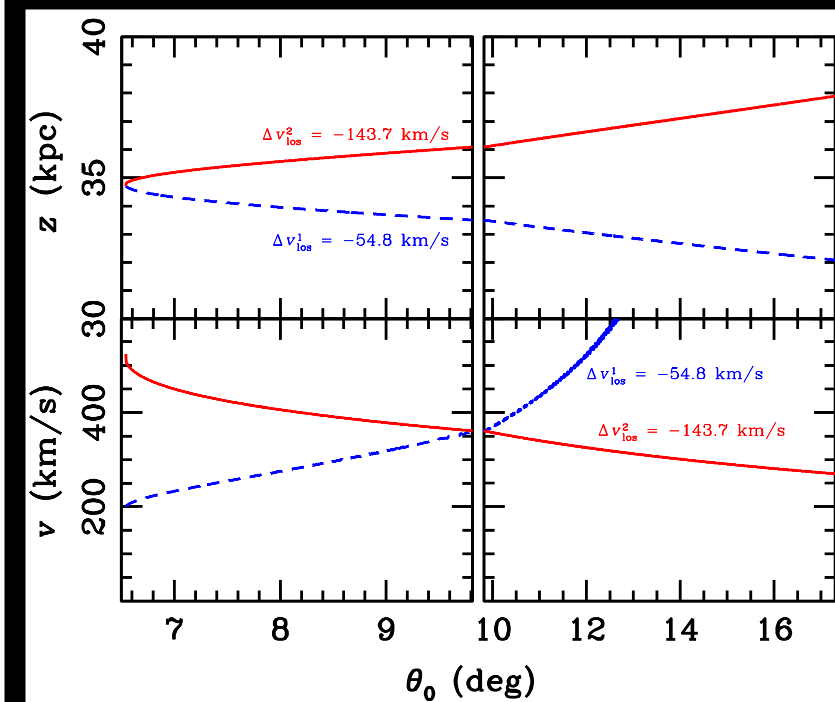



# Empirical Constraints of Supergalactic Winds at $z \gtrsim 0.5$

Jean-René Gauthier & H.-W. Chen 2012, MNRAS in press (arXiv:1205.4037)

$\alpha = 97^\circ$ $i_0 = 74^\circ$

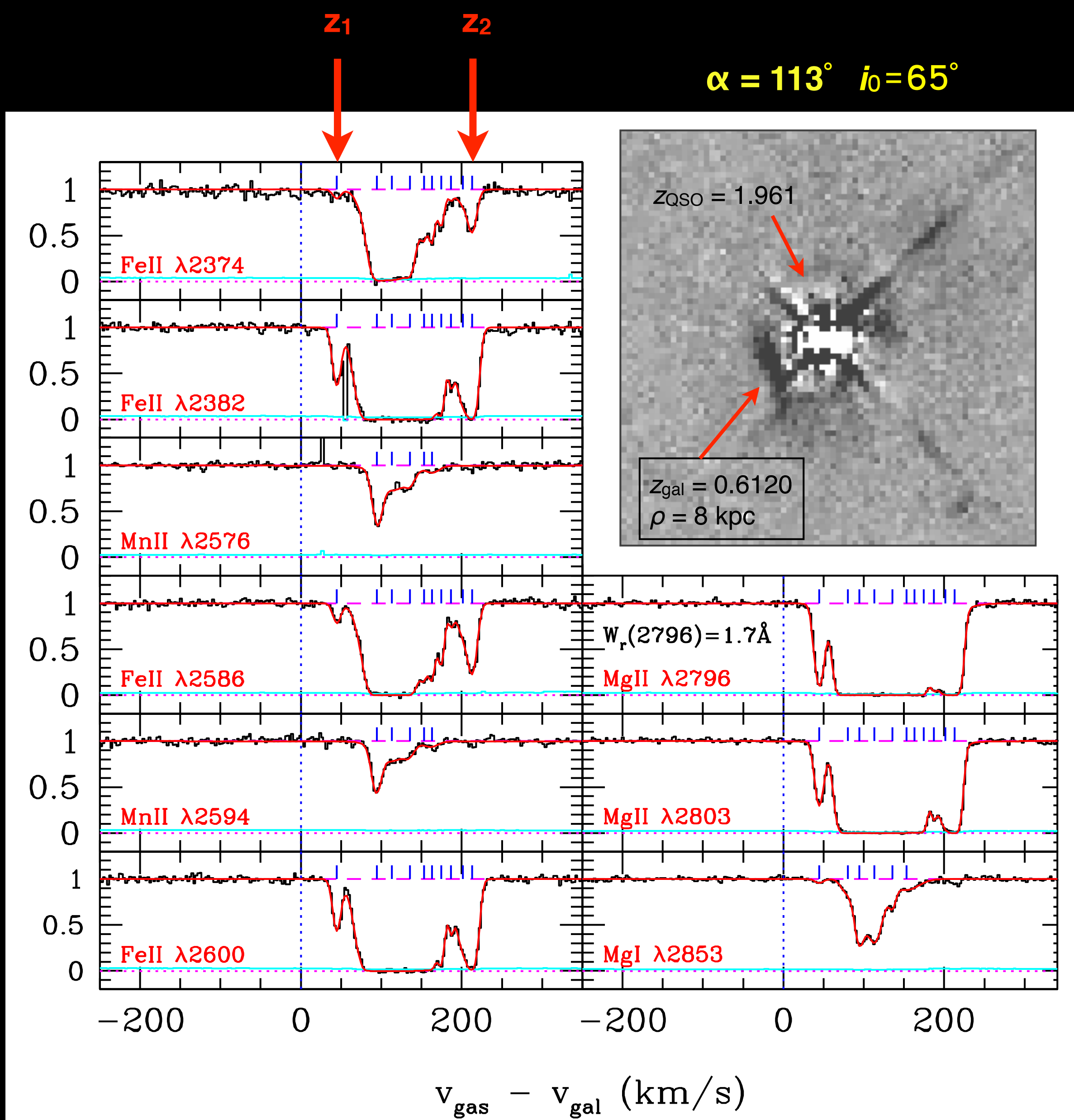


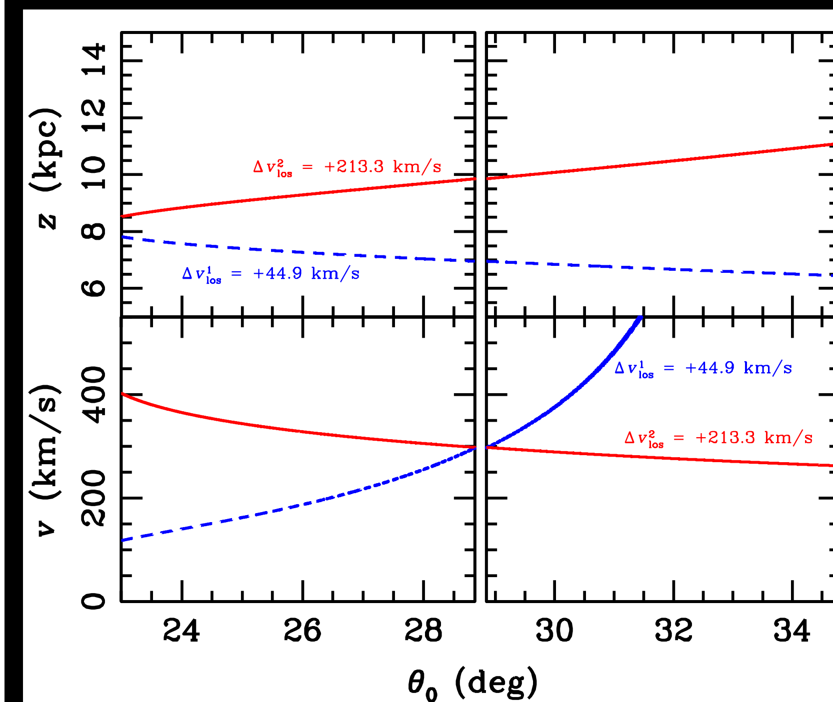



# Empirical Constraints of Supergalactic Winds at $z \gtrsim 0.5$

Jean-René Gauthier & H.-W. Chen 2012, MNRAS in press (arXiv:1205.4037)

$\alpha = 113^\circ \quad i_0 = 65^\circ$



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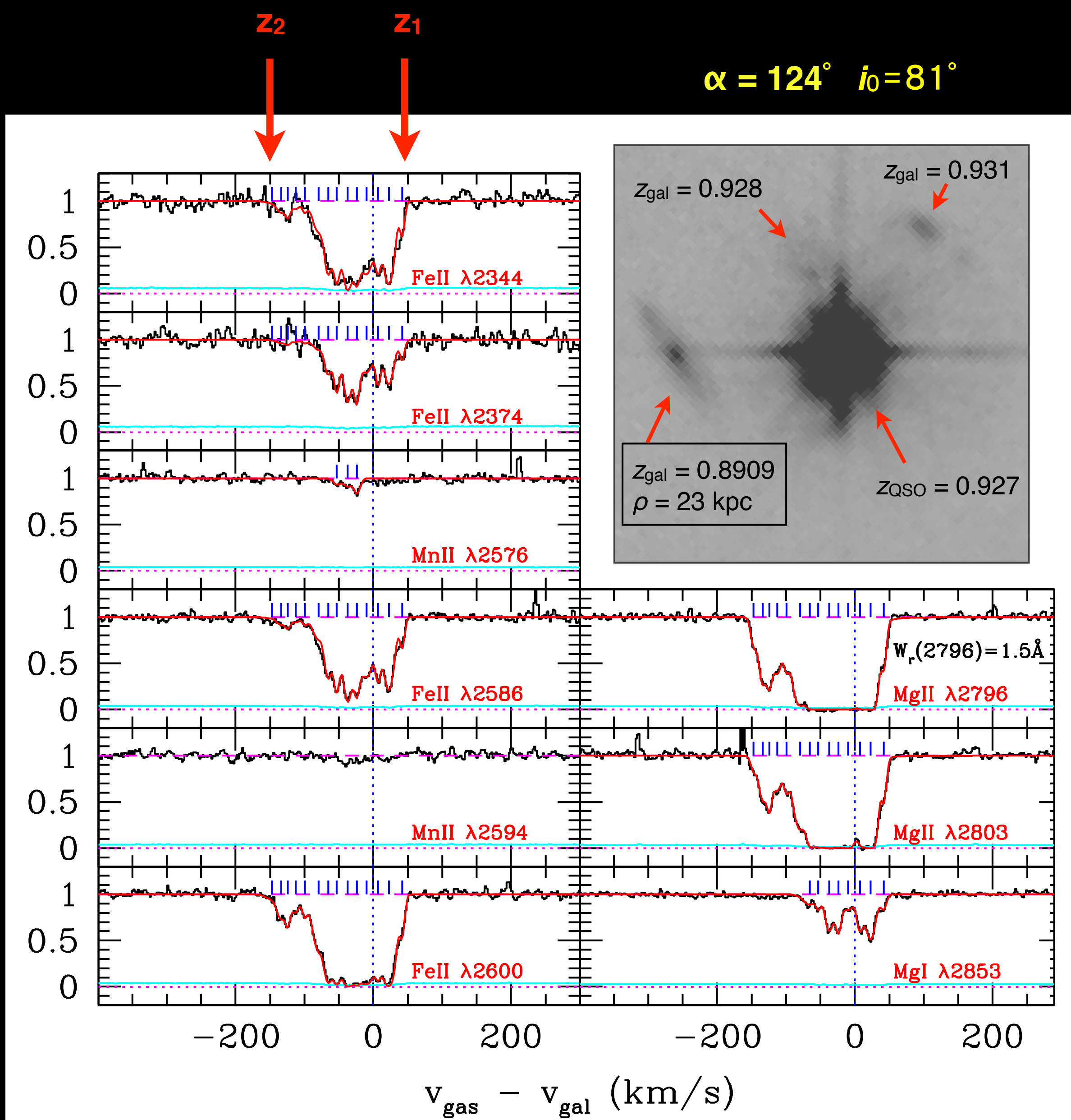
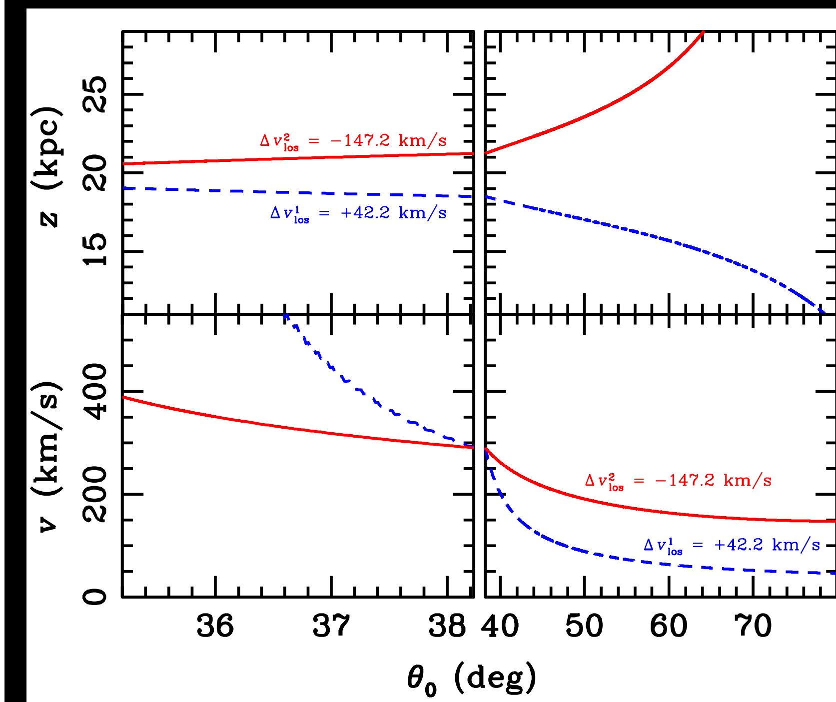
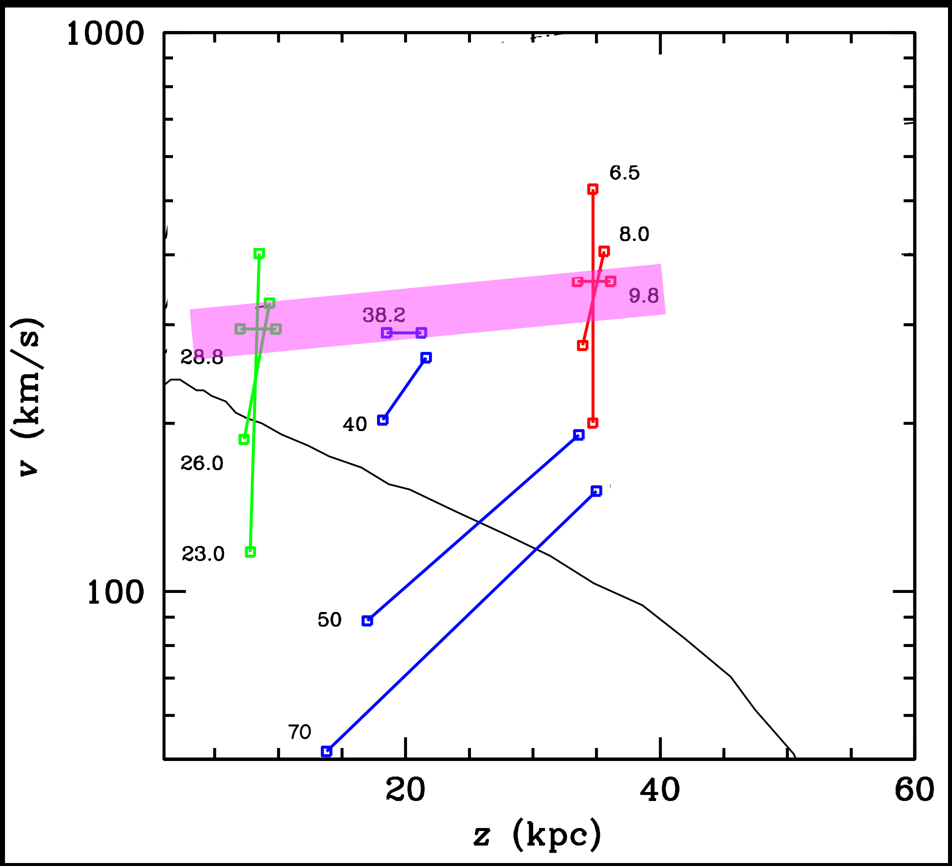


# Empirical Constraints of Supergalactic Winds at $z \gtrsim 0.5$

Jean-René Gauthier & H.-W. Chen 2012, MNRAS in press (arXiv:1205.4037)

**Derived velocity field for accelerated outflows**




**accelerated outflows due to radiation pressure can explain the observations for specific values of opening angle**

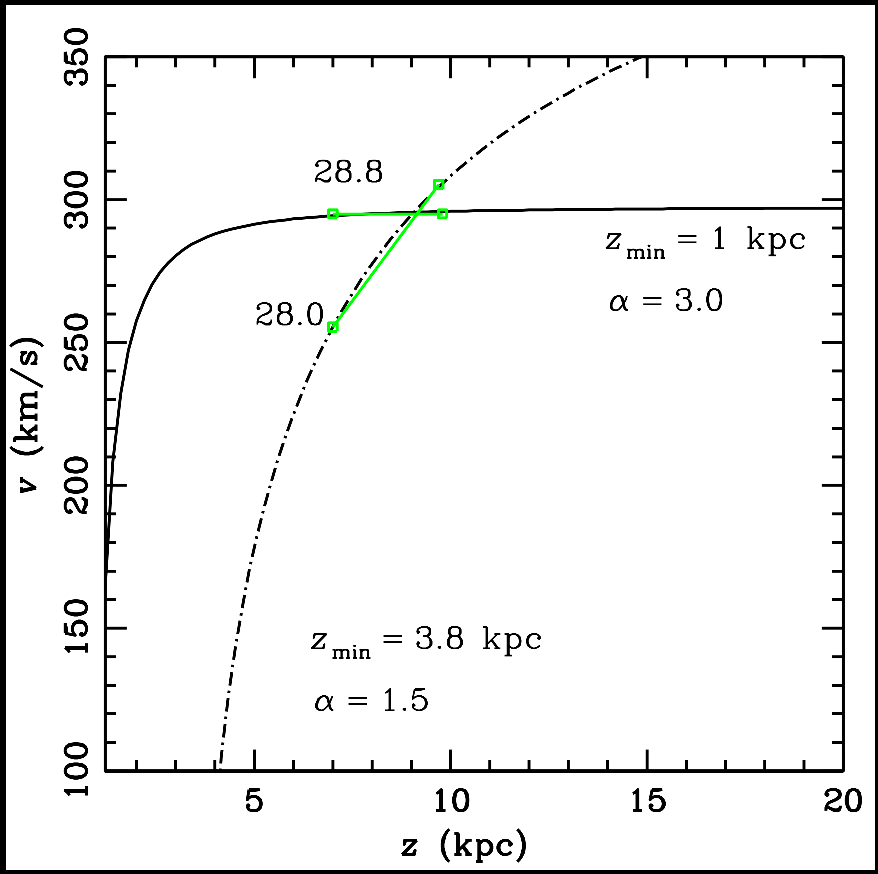
Given $\beta = 1 - 17,\ \epsilon \lesssim 0.01$

**Characterizing the acceleration using a power-law function** $a(z) = A\, z^{-\alpha}$

Steidel et al. (2010)

$$\boxed{v(z) = \left(\frac{2A}{\alpha - 1}\right)^{1/2} \sqrt{z_{\rm min}^{1-\alpha} - z^{1-\alpha}}}$$

**where $z_{\rm min}$ is the $z$-height where superwinds are launched**



# Summary

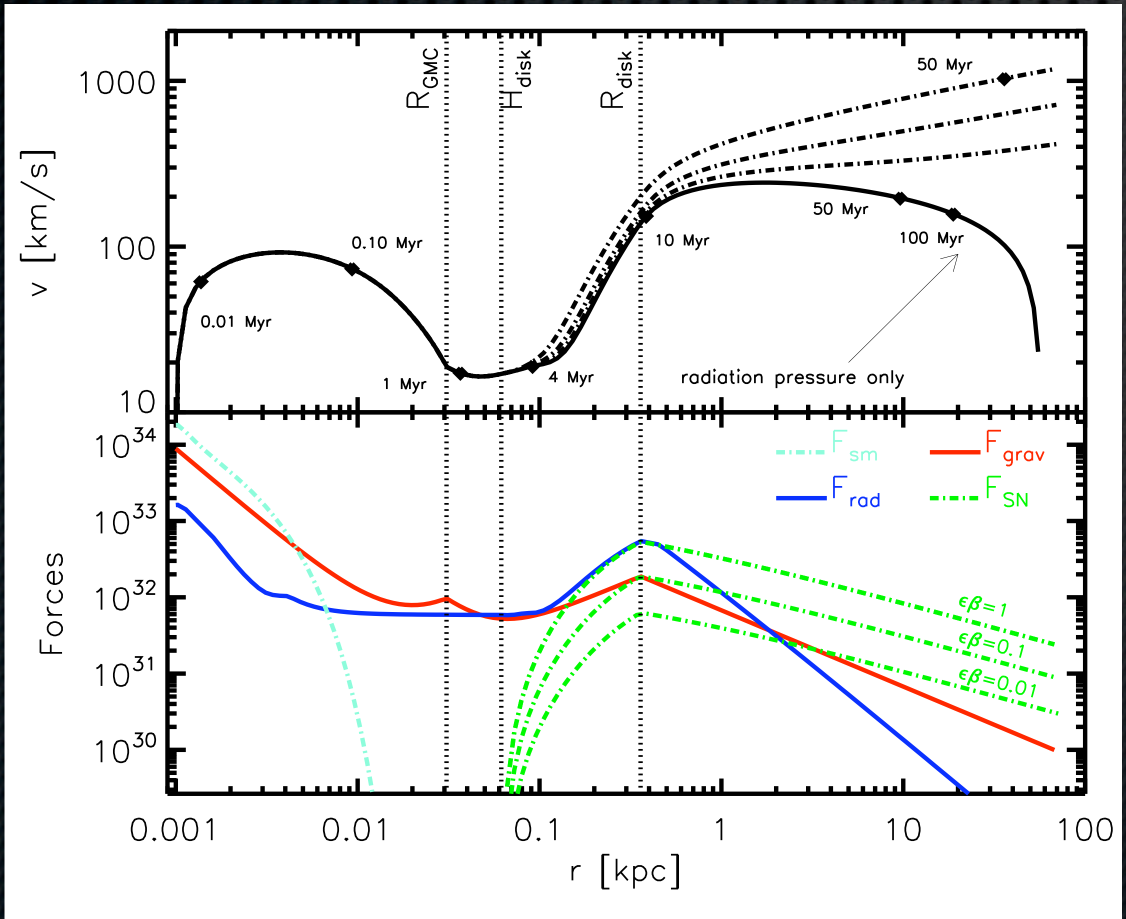
- The spatial extent and absorption strength of the *circumgalactic medium* has changed little *since z ~ 2.2*.
- Explaining the observed absorption profiles as due to accelerated outflows constrains *the opening angle* to a limited range and SNe *thermal input efficiency* to $\lesssim 0.01$.
- Characterizing the acceleration field as a power-law function, we find a *steep power-law index* of $\alpha = 3$ for a typical launch radius of 1 kpc. For $\alpha = 1.5$, compatible with GSA findings at z ~ 2, the outflows would be *launched at > 4 kpc*

# Launching mechanism for super-galactic winds

(Murray et al. 2010, Murray et al. 2011)

## How far does the gas travel?

M82 -- $10^6$ M$_\odot$ star cluster




distance from the cluster center (kpc)

**At r ≳ 1 kpc :**

- Radiation pressure

$$F_{\rm rad} = F_{\rm rad,cl} + \frac{L_{\rm gal}}{c}\frac{1}{r^2}$$

- Gravity

$$g_{grav} = \frac{v_c^2}{r}$$

- Ram pressure force from SNe hot outflow

$$F_{\rm ram} = C_D \pi l_\perp^2 \rho_h (v_h - v_c)^2$$

$$\frac{1}{2}\dot{M}_h v_h^2 = \epsilon L_{\rm SN} \qquad \dot{M}_{\rm h} = 0.2\beta\dot{M}_*$$