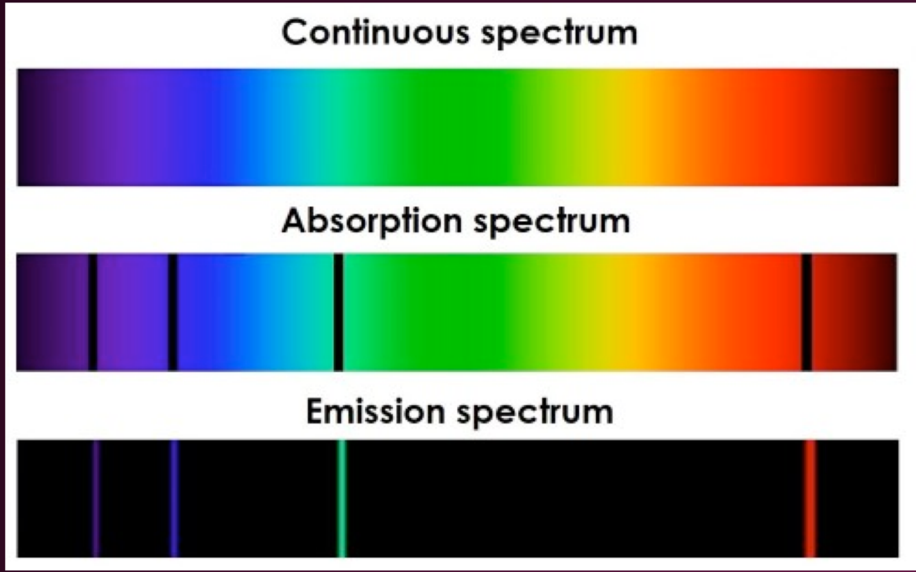
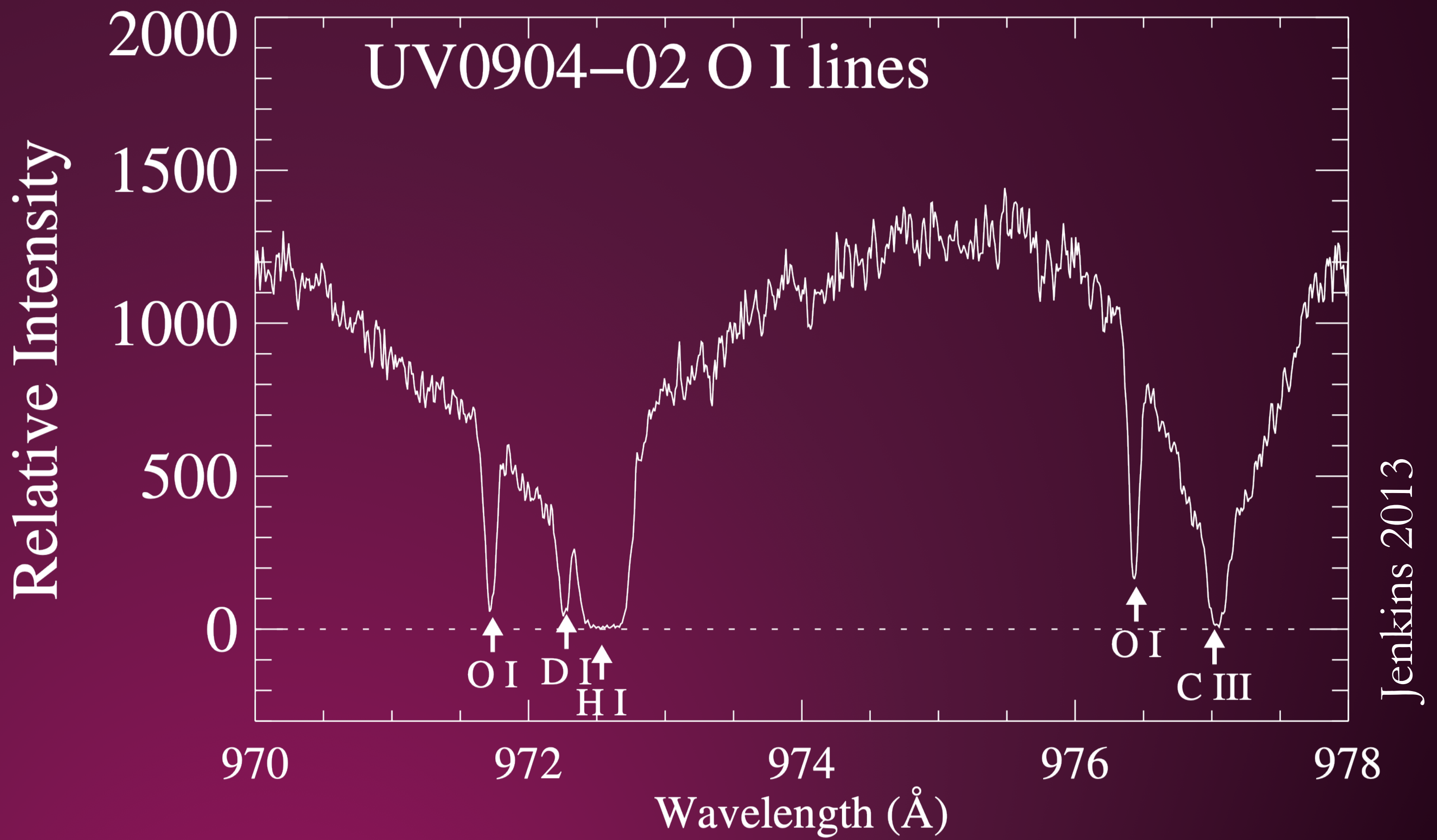
Absorption lines



Magnus Manske/Jhausauer



ASTR 605
Joe Burchett
9/29/2021

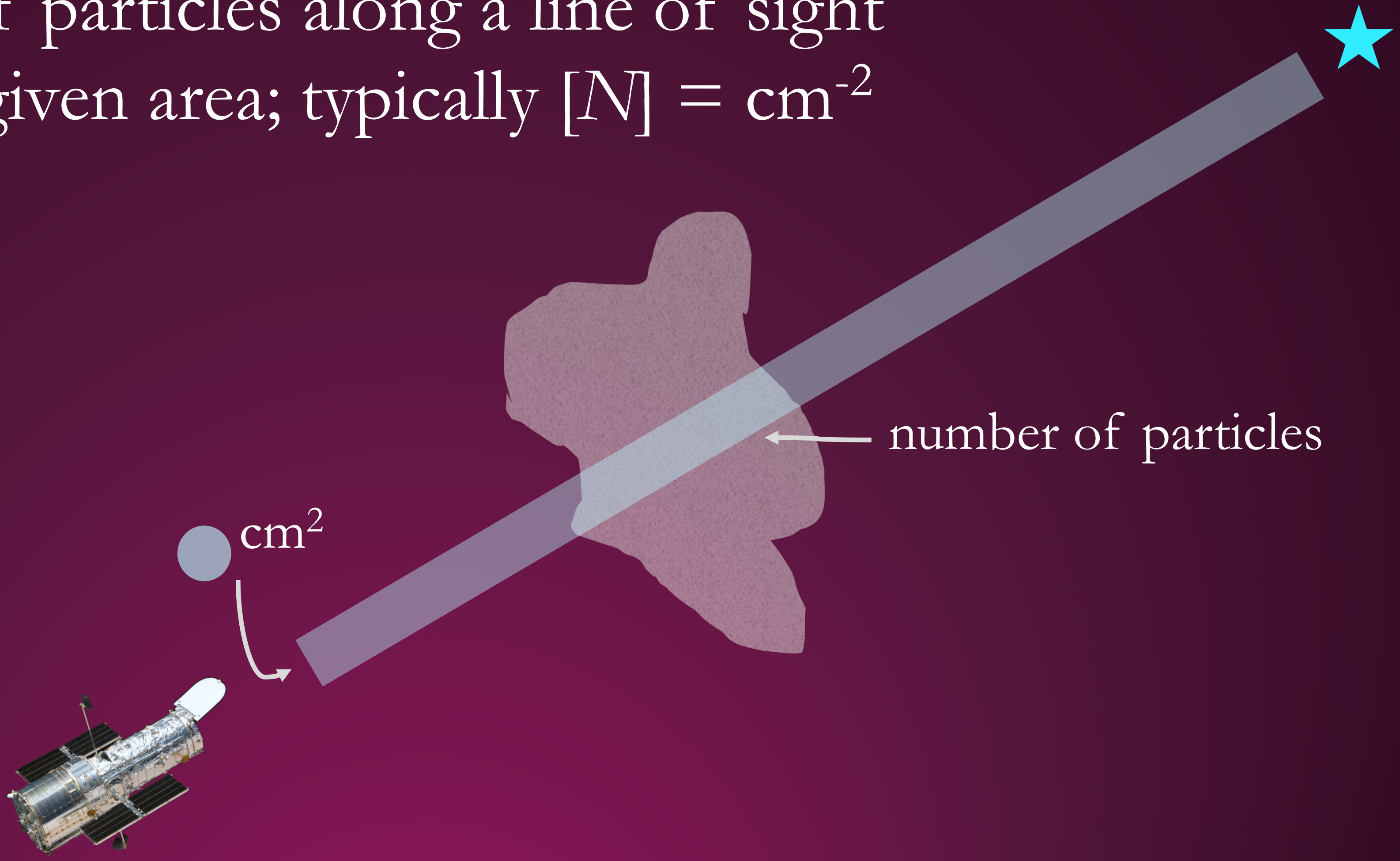
Quick points

- Absorption lines in the ISM/CGM/IGM almost always represent transitions from the *ground state*.
  - Unlike stellar atmospheres, where excited states might be sufficiently populated
  - Think Balmer lines in A stars
- Absorption lines are extremely sensitive probe of diffuse gas
  - Absorption strength proportional to density
  - Emission strength proportional to density squared (usually)
- Most key ISM/CGM/IGM lines have rest frame wavelengths in the ultraviolet
  - < 3200 Å

Some definitions

Column density N :

The average number of particles along a line of sight within an aperture of given area; typically $[N] = \mathrm{cm}^{-2}$



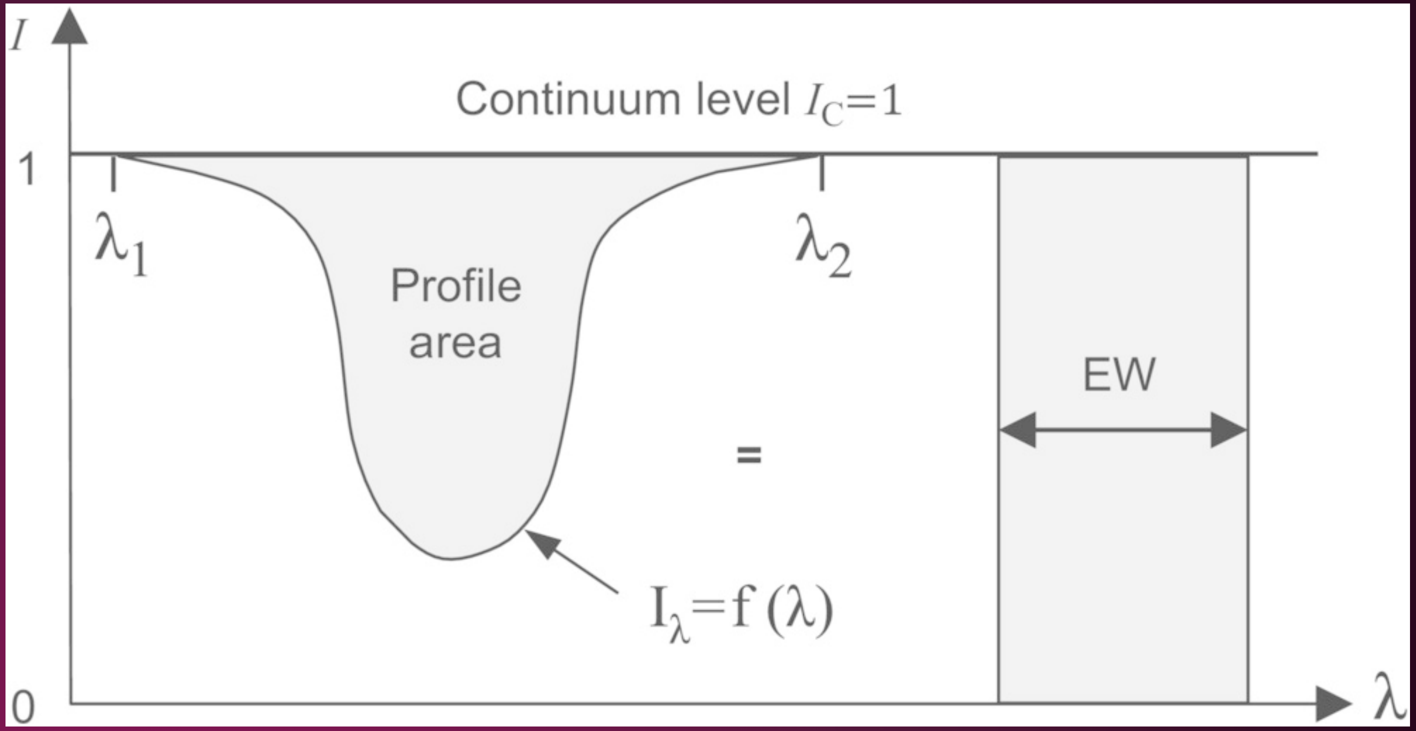
Some definitions

Equivalent width W:
If one took the area of an absorption line and constructed a rectangle between the continuum and zero flux limit (the rectangle's height), W is the width of that rectangle.

We'll mostly talk in wavelength space, so $[W]$ = Å or nm

$$W_\lambda \equiv \int d\lambda \left(1 - \mathrm{e}^{-\tau_\nu}\right) \approx \lambda_0 W$$

Draine eqn. 9.4



Marc F. M. Trypsteen, Richard Walker

Some definitions

Oscillator strength f :

The 'strength' of an absorption line, equivalent to the absorption cross section, but dimensionless. All species in the absorbing cloud technically have absorption transitions, but only those with substantial f values will be detectable.

$$f_{\ell u} \equiv \frac{m_e c}{\pi e^2} \int \sigma_{\ell u}(\nu) d\nu$$

$$\tau \propto N f \lambda_0$$

Verner 1994

Species	Transition	Multiplet	λ, Å	g_i	g_k	f_{ik}	f'_{ik}	P	Ref
OIV	$2s^2 2p - 2s2p^2$	$^2P^o - ^4P$	1399.780	2	2	-	0.610e−06	5.86	1
			1397.232	2	4	-	0.340e−07	4.61	1
OIV	$2s^2 2p - 2s2p^2$	$^2P^o - ^2D$	787.711	2	4	0.111e+00	0.110e+00	10.87	2
OIV	$2s^2 2p - 2s2p^2$	$^2P^o - ^2S$	608.398	2	2	0.670e−01	0.694e−01	10.54	2
OIV	$2s^2 2p - 2s2p^2$	$^2P^o - ^2P$	554.075	2	2	0.224e+00	0.218e+00	11.02	2
			553.330	2	4	0.112e+00	0.110e+00	10.72	2
OIV	$2s^2 2p - 2s^2 3s$	$^2P^o - ^2S$	279.631	2	2	0.314e−01	0.278e−01	9.87	2
OIV	$2s^2 2p - 2s^2 3d$	$^2P^o - ^2D$	238.360	2	4	0.504e+00	0.491e+00	11.01	2
MgII	$2p^6 3s - 2p^6 3p$	$^2S - ^2P^o$	2803.531	2	2	0.314e+00	0.305e+00	10.52	1
			2796.352	2	4	0.629e+00	0.612e+00	10.83	1
MgII	$2p^6 3s - 2p^6 4p$	$^2S - ^2P^o$	1240.3947	2	2	0.185e−03	0.134e−03	6.94	1
			1239.9253	2	4	0.372e−03	0.268e−03	7.24	1
MgII	$2p^6 3s - 2p^6 5p$	$^2S - ^2P^o$	1026.1134	2	2	0.468e−03	0.426e−03	7.26	1
			1025.9681	2	4	0.936e−03	0.852e−03	7.56	1

Line Profiles

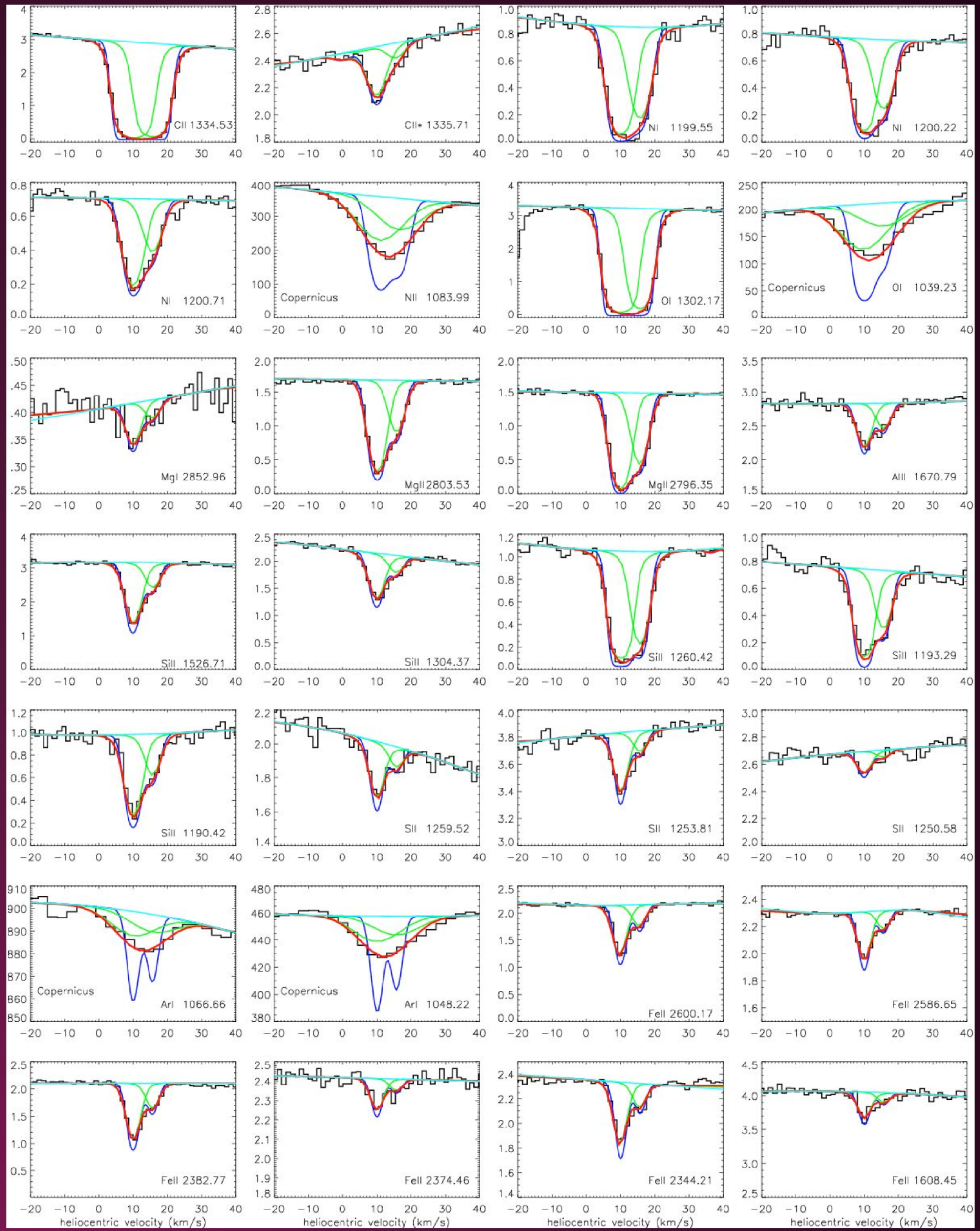
Spectral transitions, in general, occur at specific energies.

Q: Why do we not see infinitesimal blips in spectra at wavelengths and frequencies correspond to those energies?

A: First, spectrographs have finite resolution. But, lines have *intrinsic* profiles due to quantum effects and are further broadened by gas motions (think Doppler effect).

$$\sigma^{\text{intr.}}(\nu) = \frac{\pi e^2}{m_e c} f_{\ell u}\, \phi_\nu^{\text{intr.}} \qquad \left(\int \phi_\nu^{\text{intr.}} d\nu = 1 \right)$$

The Gaussian and Lorentzian functions are handy descriptors of line profiles in certain regimes



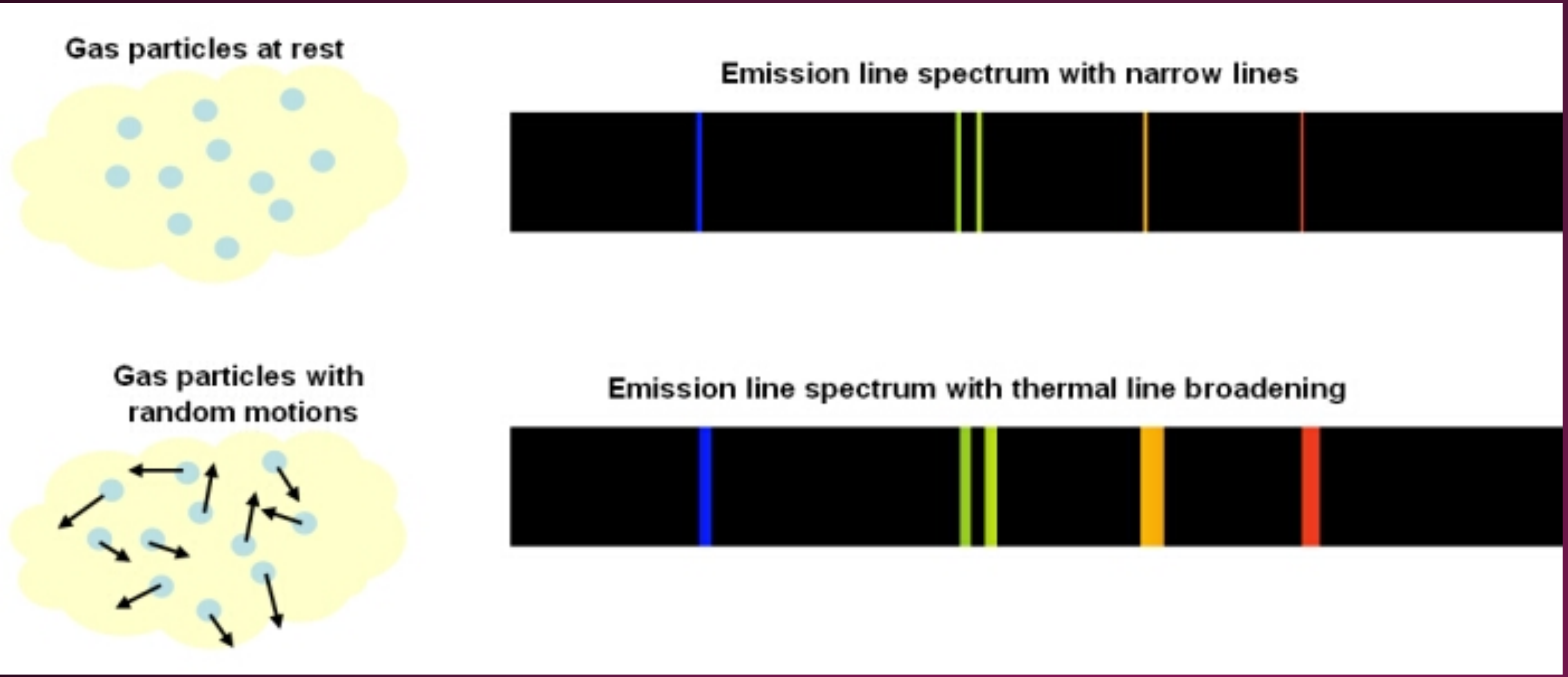
Gry & Jenkins 2017

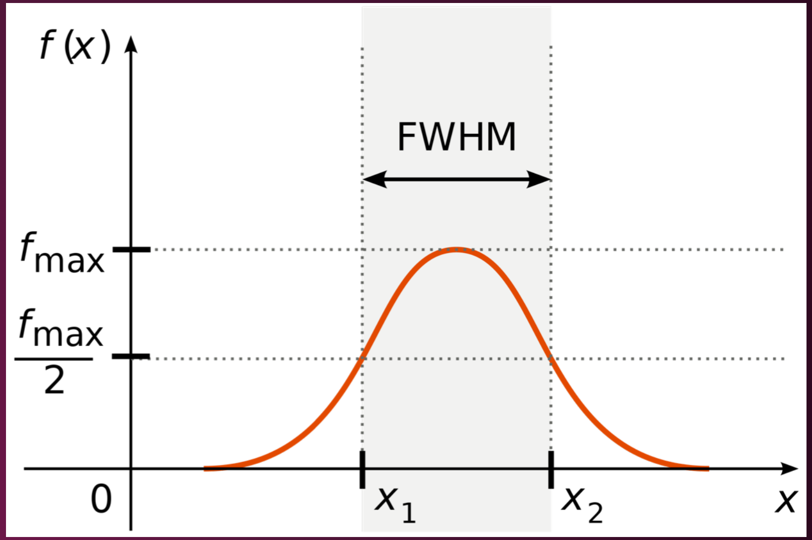
Doppler broadening of lines

Velocities purely thermal (Maxwell-Boltzmann) $$p_v = \frac{1}{\sqrt{2\pi}}\frac{1}{\sigma_v}\,\mathrm{e}^{-(v-v_0)^2/2\sigma_v^2} = \frac{1}{\sqrt{\pi}}\frac{1}{b}\,\mathrm{e}^{-(v-v_0)^2/b^2}$$

Full width at half maximum (FWHM) $$(\Delta v)_{\mathrm{FWHM}} = \sqrt{8\ln 2}\,\sigma_v = 2\sqrt{\ln 2}\,b$$

astronomy.swin.edu.au/cosmos/





Curve of growth

- The equivalent width is *always* measurable and uncertainties given directly from the data:

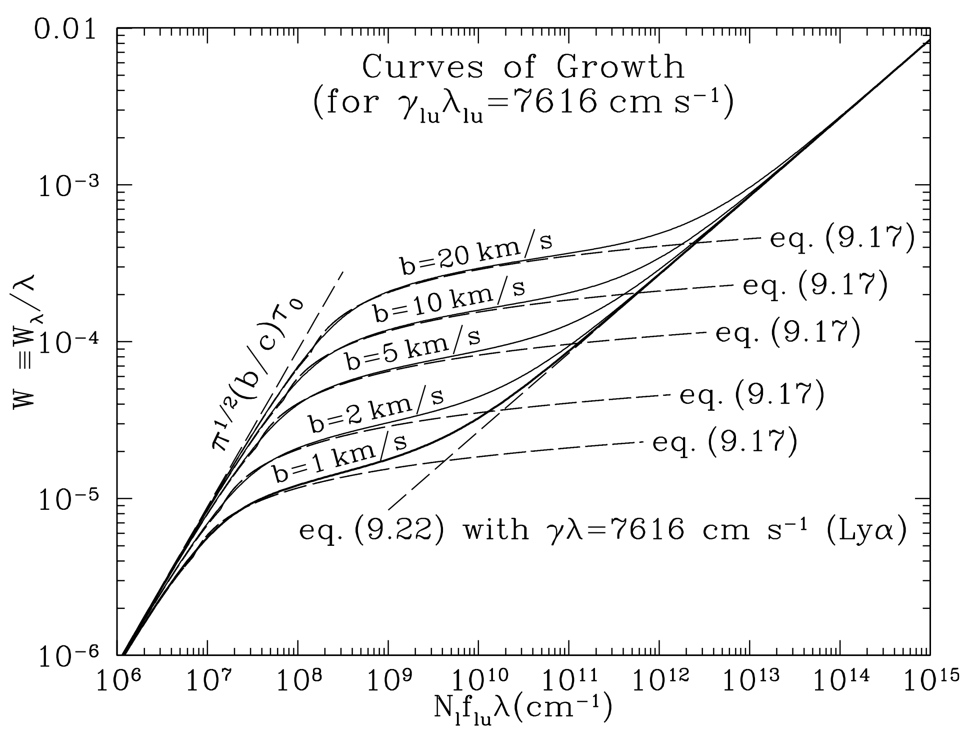
$$\sigma^2_{W(\lambda)} = \sum_i \left(\Delta\lambda(i)\left[\frac{\sigma_{I(\lambda_i)}}{I(\lambda_i)}\right]\right)^2$$

$\sigma_{I(\lambda)}$ = flux at wavelength λ
$I(\lambda)$ = continuum flux

Burchett+2015

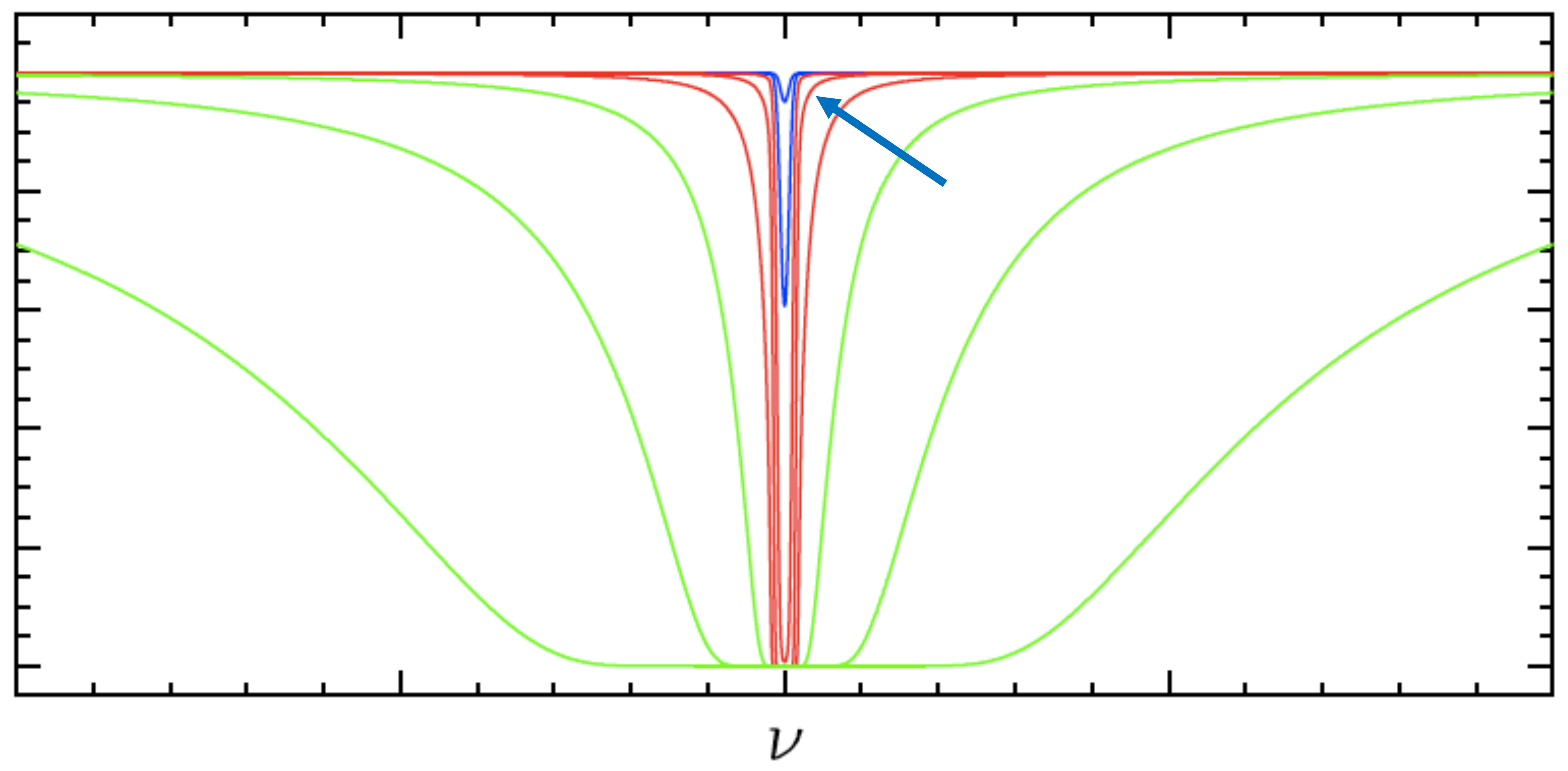
Column density, not so much

- Very uncertain, particularly with saturated lines
- Inferring column density from equivalent width measurements depends critically on where we are on the **curve of growth.**



Three regimes of optical depth

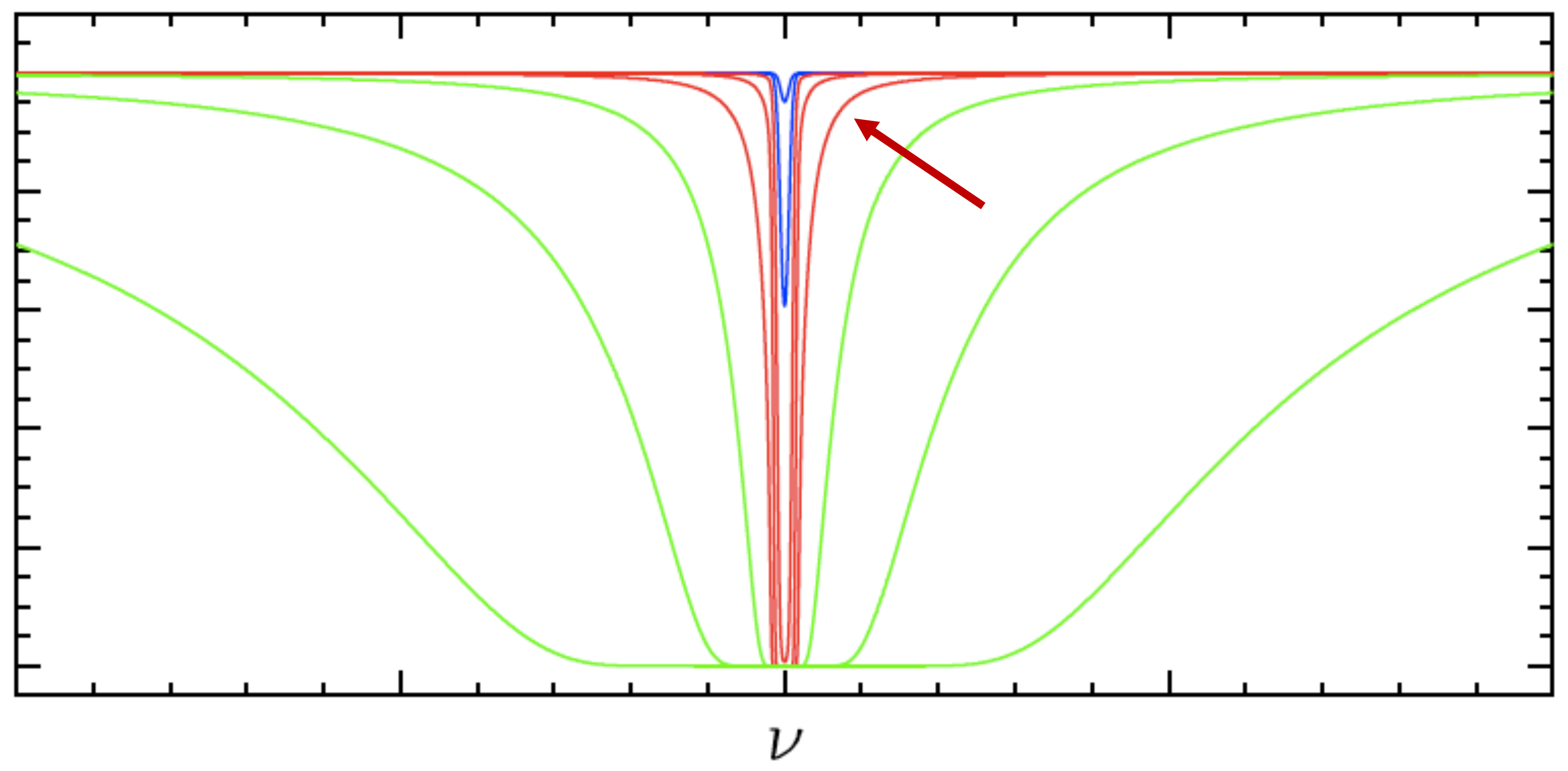
• Gaussian dominates • Area increases with τ.



Unsaturated: $\tau_0 < 1$

Three regimes of optical depth

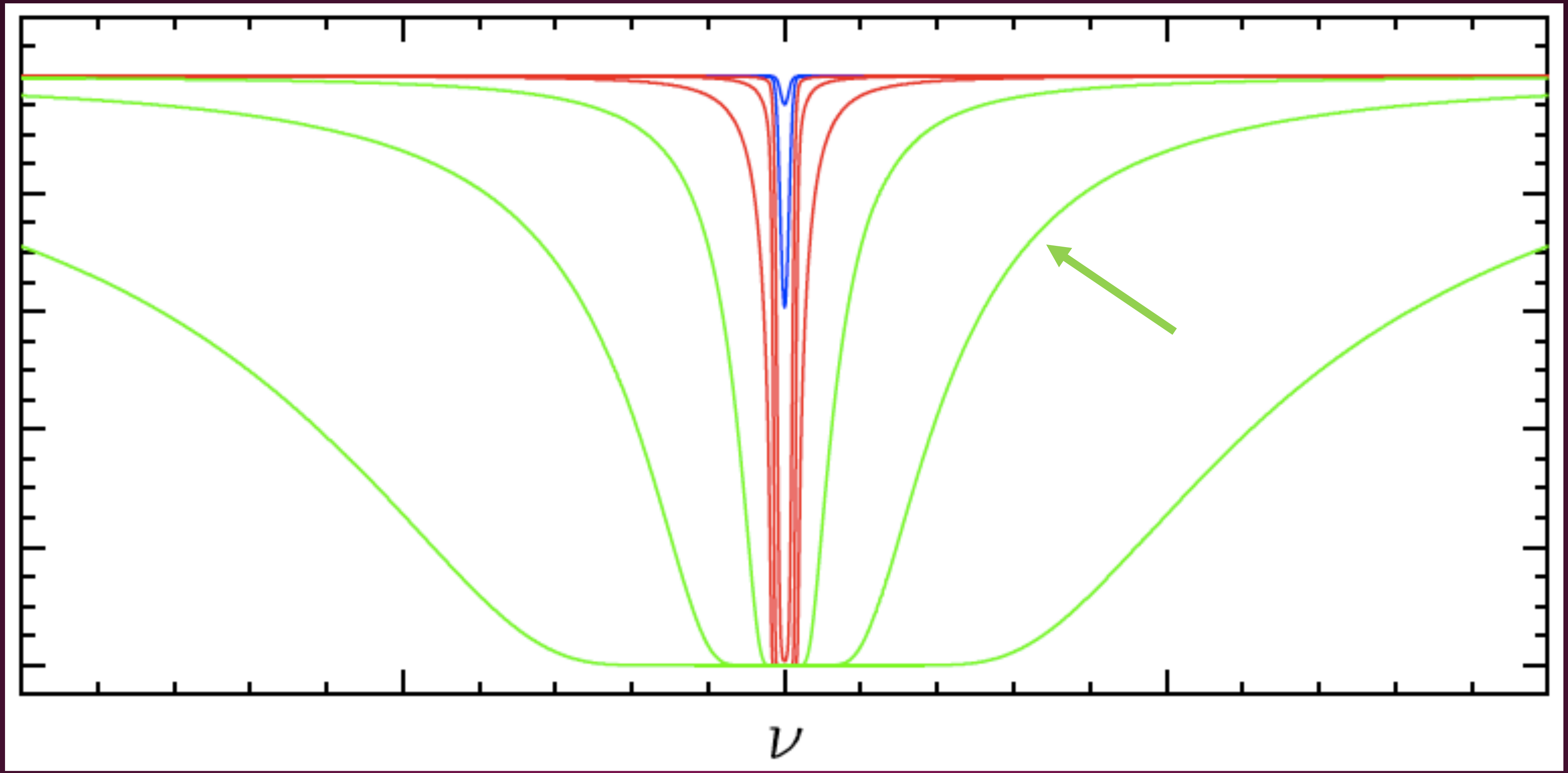
• Gaussian dominates • Little increase in area with τ.



Saturated: $1 < \tau_0 < 1000$

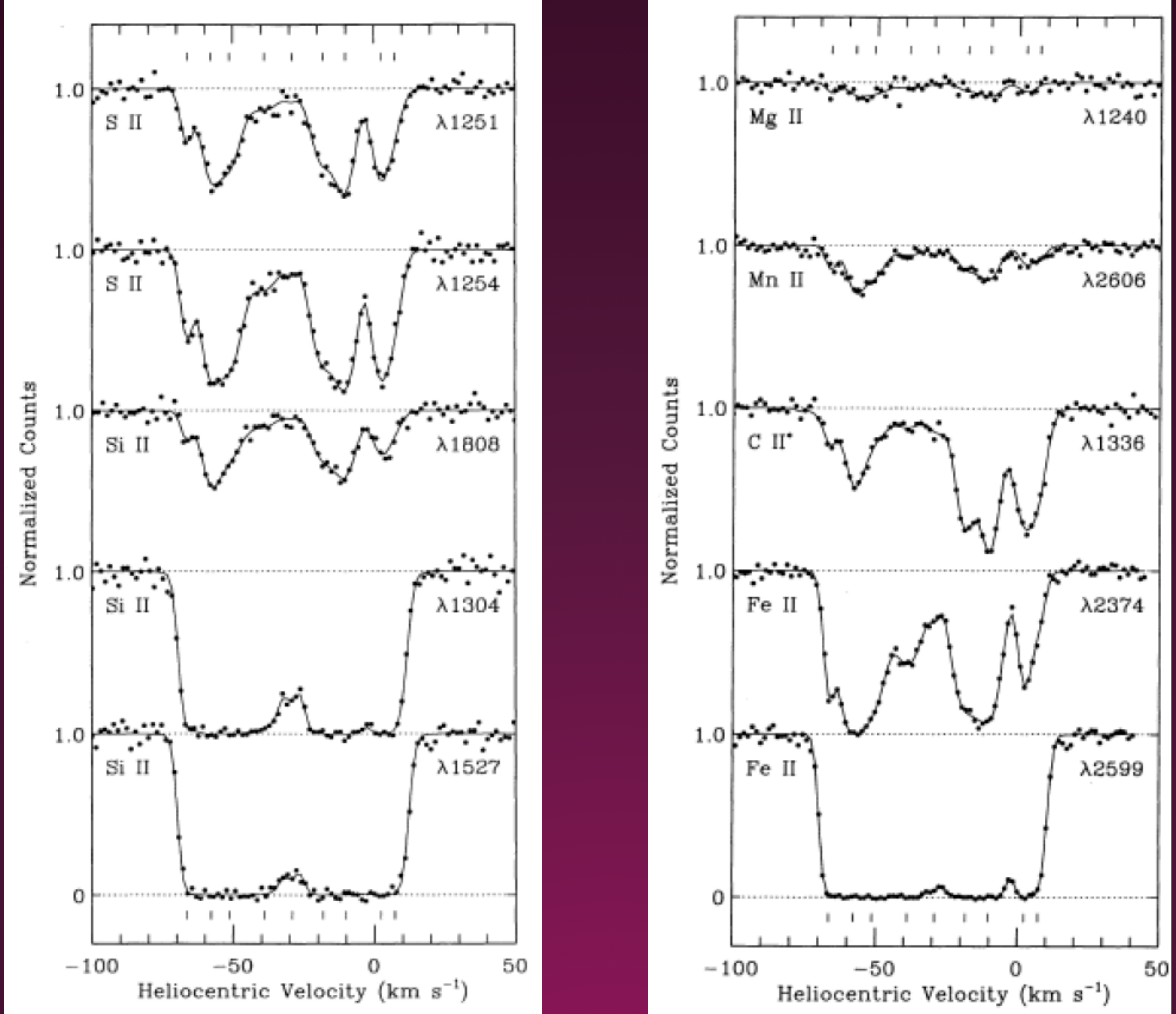
Three regimes of optical depth

• Lorentzian dominates • Area increases with τ

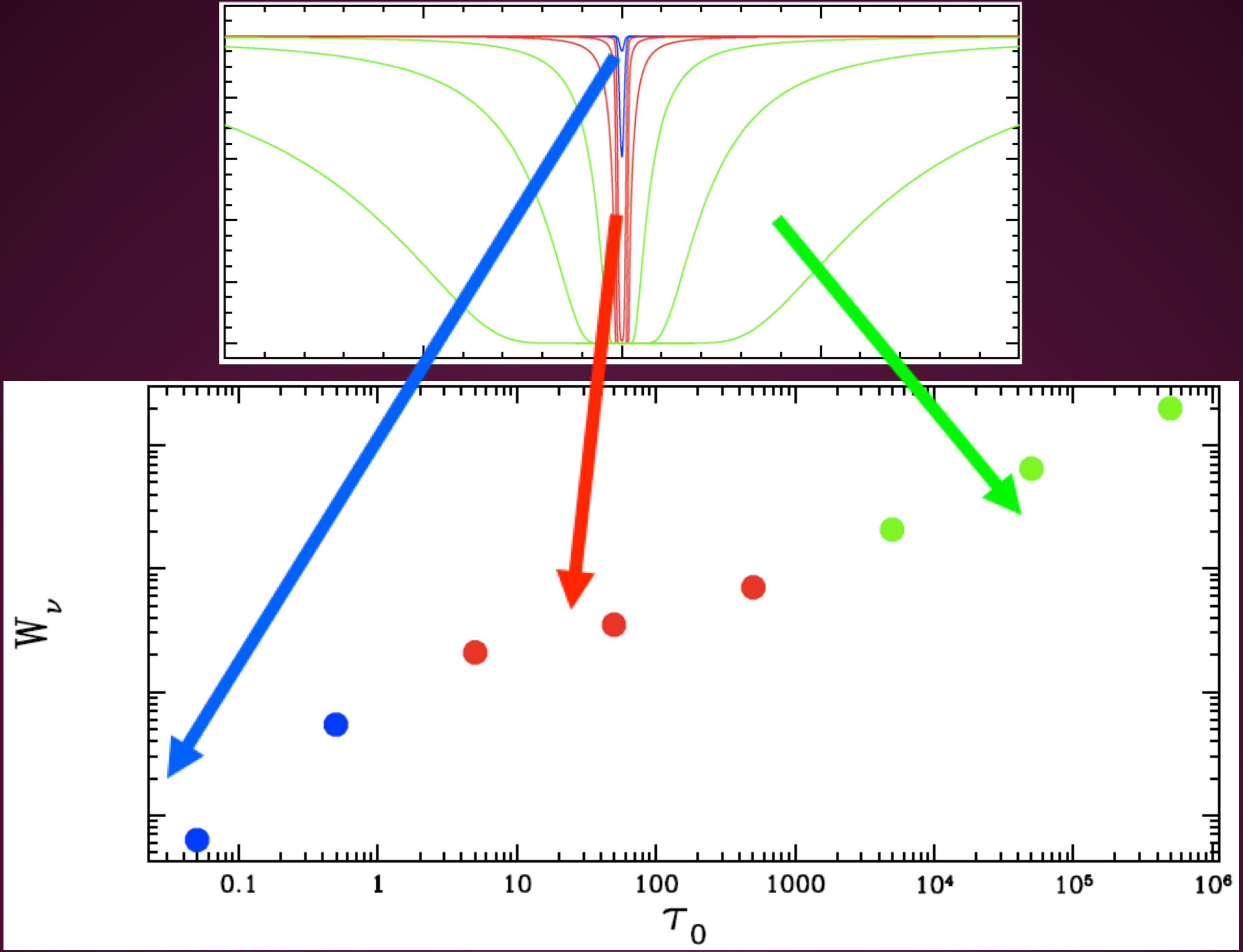


Highly Saturated (damped): $10^3 < \tau_0$

←Increasing Saturation

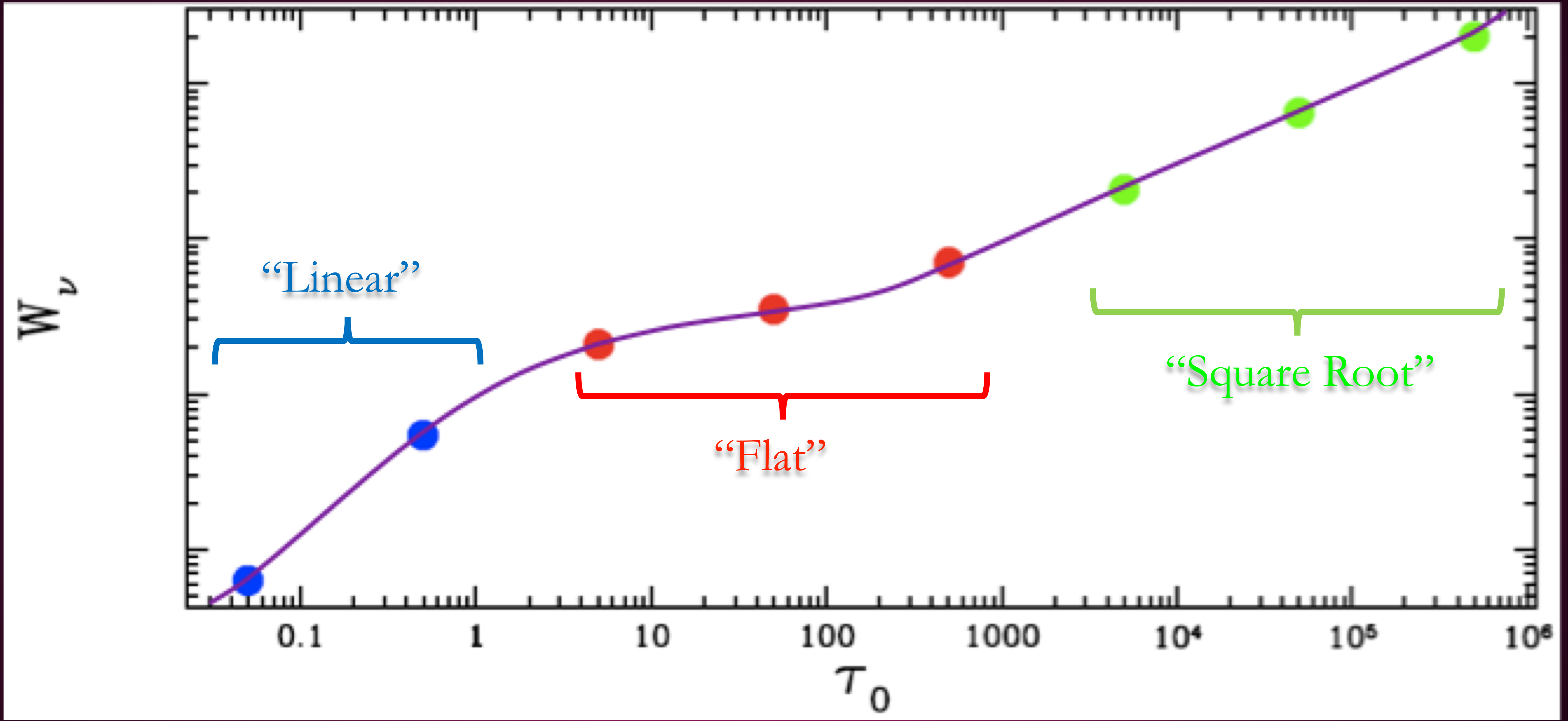


Spitzer & Jenkins 1993



0.1
1
10
100
1000
10^4
10^5
10^6
W_ν
τ_0

Curve of Growth!



A closer look at the three regimes

$$N_\ell = 1.130 \times 10^{12}\,\mathrm{cm}^{-1}\,\frac{W}{f_{\ell u}\lambda_{\ell u}}$$

if $\tau_0 \ll 1$.

$$N_\ell \approx \frac{\ln 2}{\sqrt{\pi}}\frac{m_e c}{e^2}\frac{b}{f_{\ell u}\lambda_{\ell u}}\exp\left[\left(\frac{cW}{2b}\right)^2\right]$$

$$N_\ell = \frac{m_e c^3}{e^2}\frac{W^2}{f_{\ell u}\gamma_{\ell u}\lambda_{\ell u}^2}$$