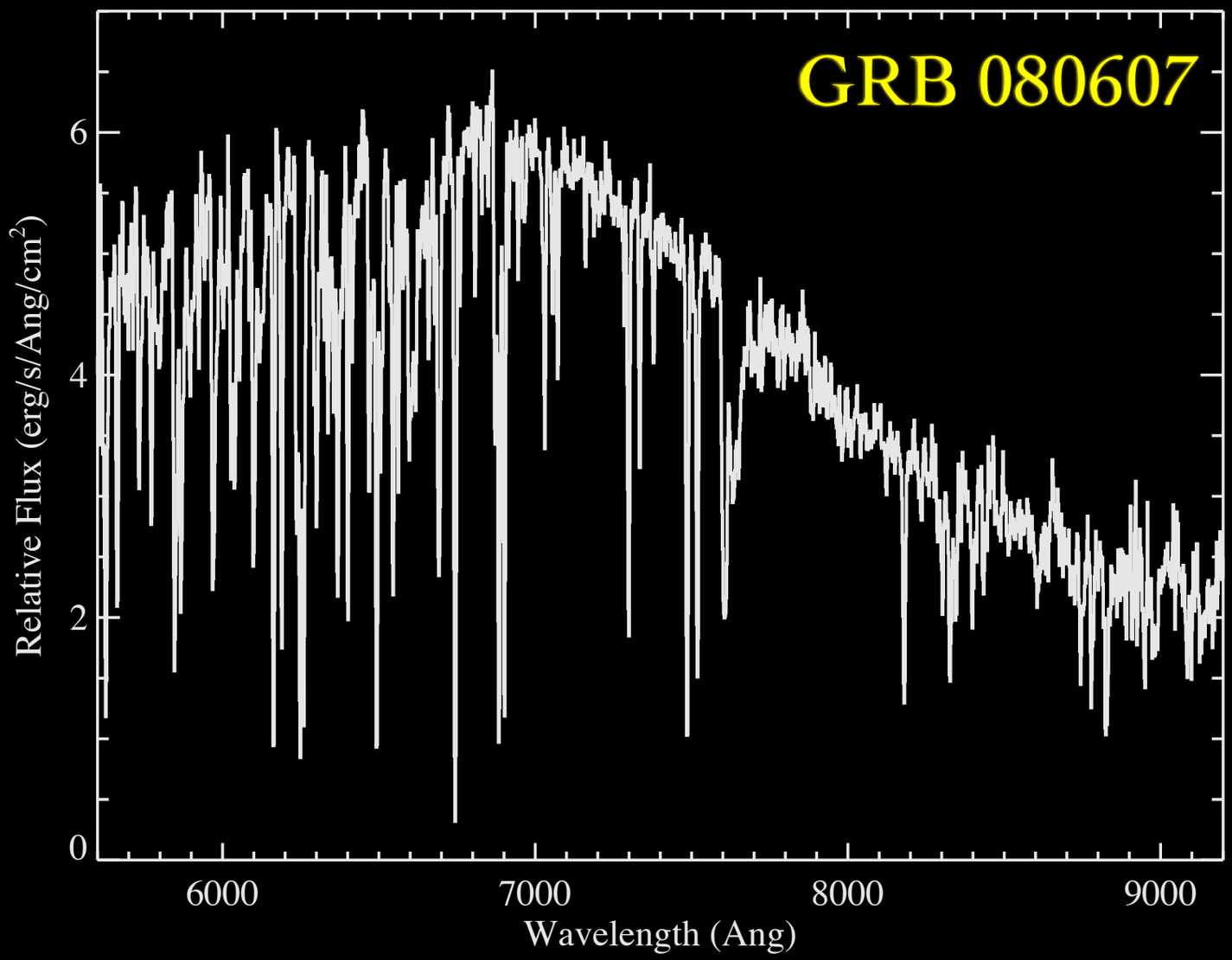
GRB Absorption Line Spectroscopy



J. Xavier Prochaska
Inter(stellar+galactic) Medium Program of Studies (IMPS)
UC Santa Cruz

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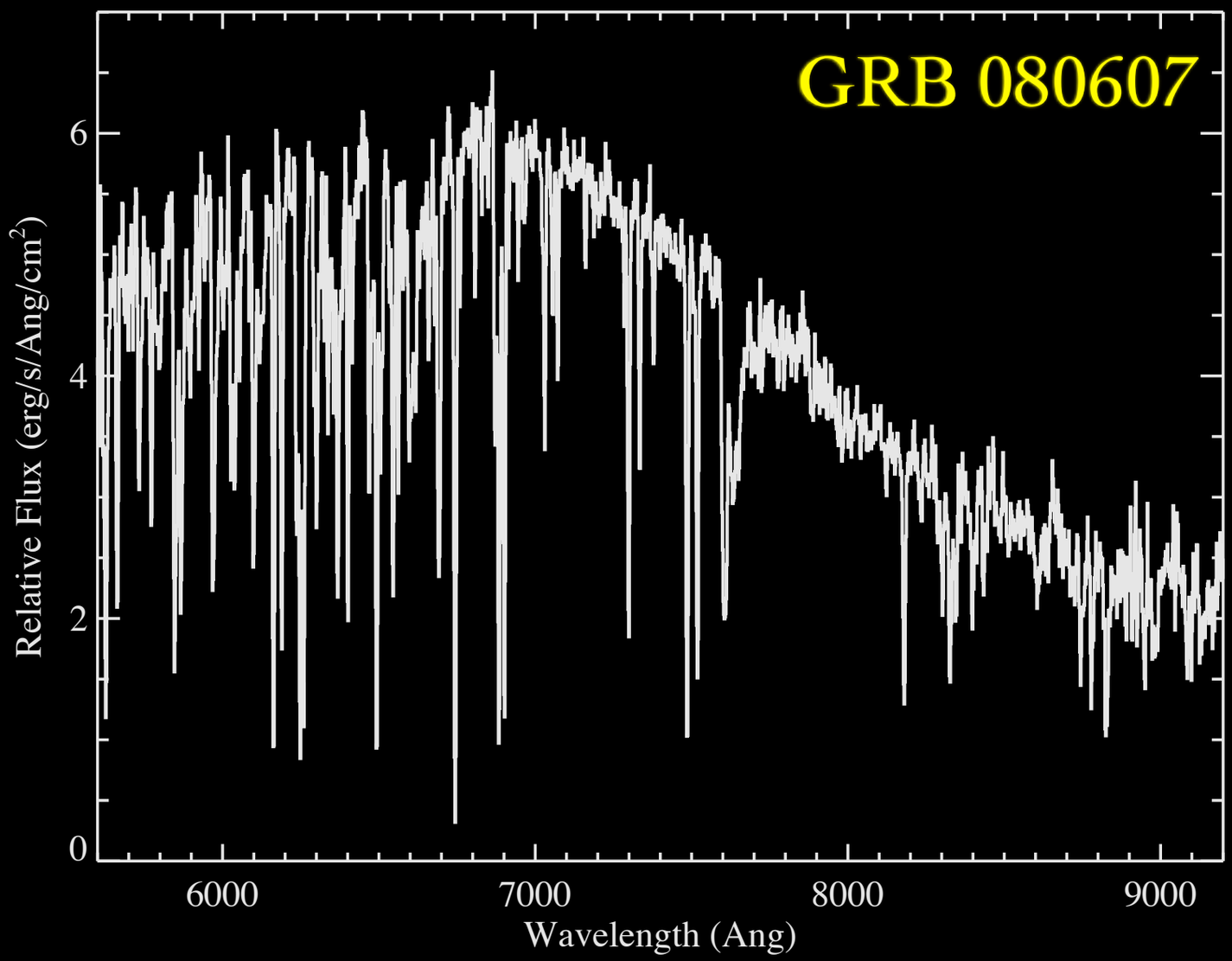

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Note: There will be no discussion of SGRBs here

Part I: Formalism and Methodology

More than you ever wanted to know about absorption lines. (Don't worry, it's good for you)

Absorption Line Spectroscopy

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a.k.a., “a**-backwards astronomy”

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Traditional Astronomy

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How many objects are there?

Absorption Line Spectroscopy

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How many objects are there?

Are they bright or faint?

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How many objects are there?

Are they bright or faint?

What are their color?

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How many objects are there?

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How big are they?

Absorption Line Spectroscopy

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Traditional Astronomy

How many objects are there?

Are they bright or faint?

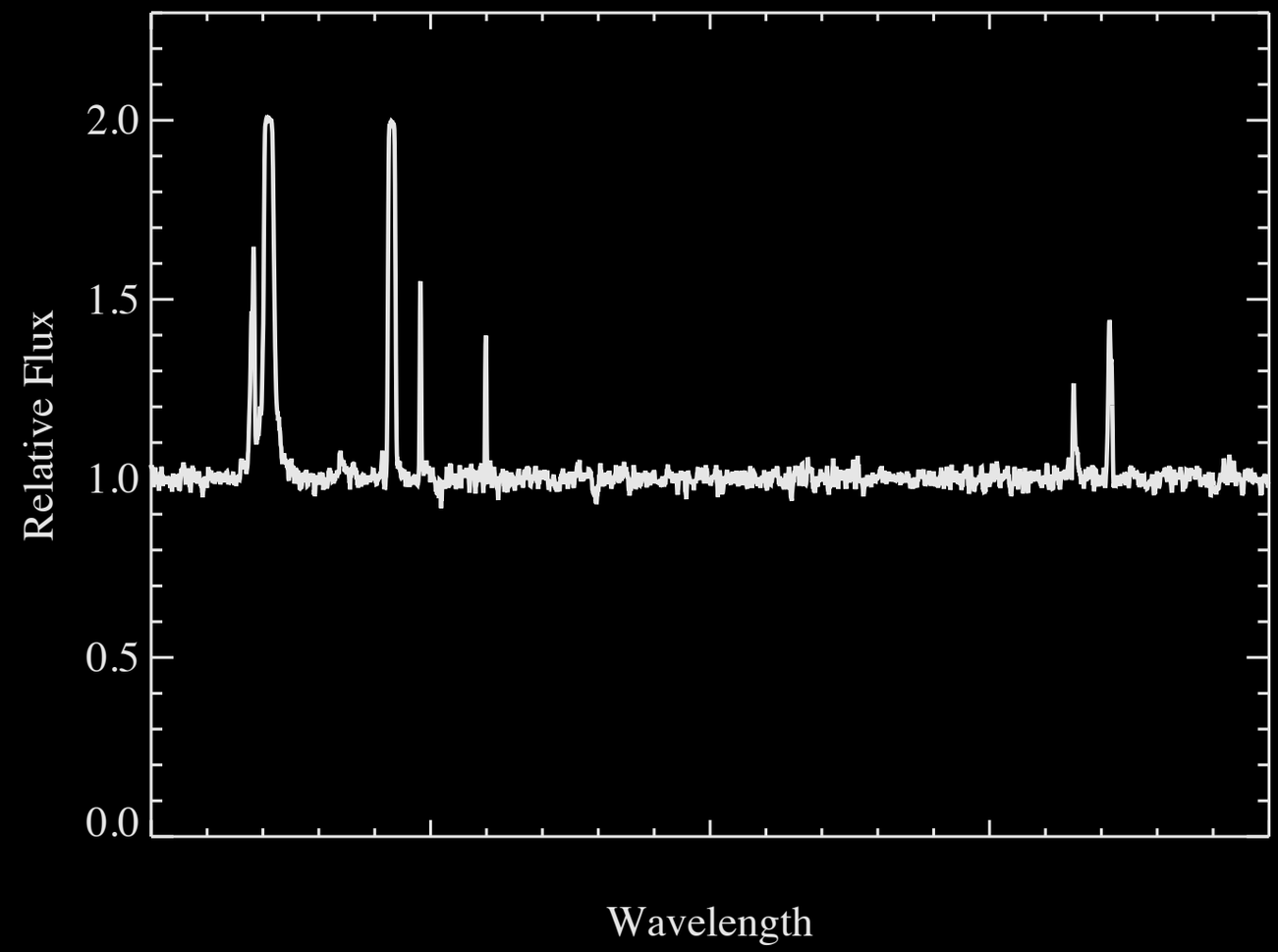
What are their color?

How big are they?

What is the shape (ellipse or an ellipse with arms)?

Absorption Line Spectroscopy

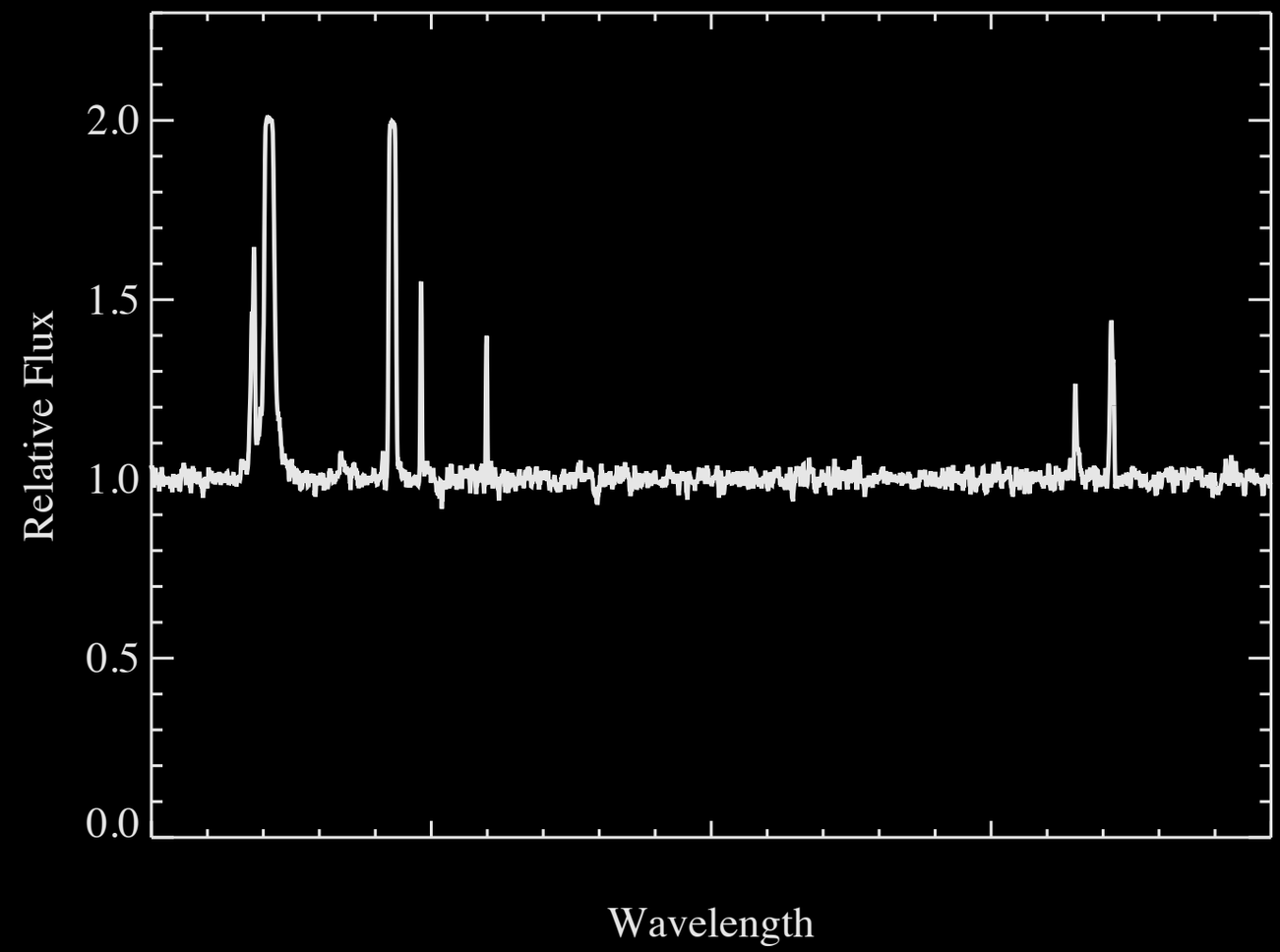
a.k.a. Astronomy in Silhouette



Absorption Line Spectroscopy

a.k.a. Astronomy in Silhouette

- **Most astronomers count photons to do their science**
  - Flux in a pass-band
  - Flux in emission lines

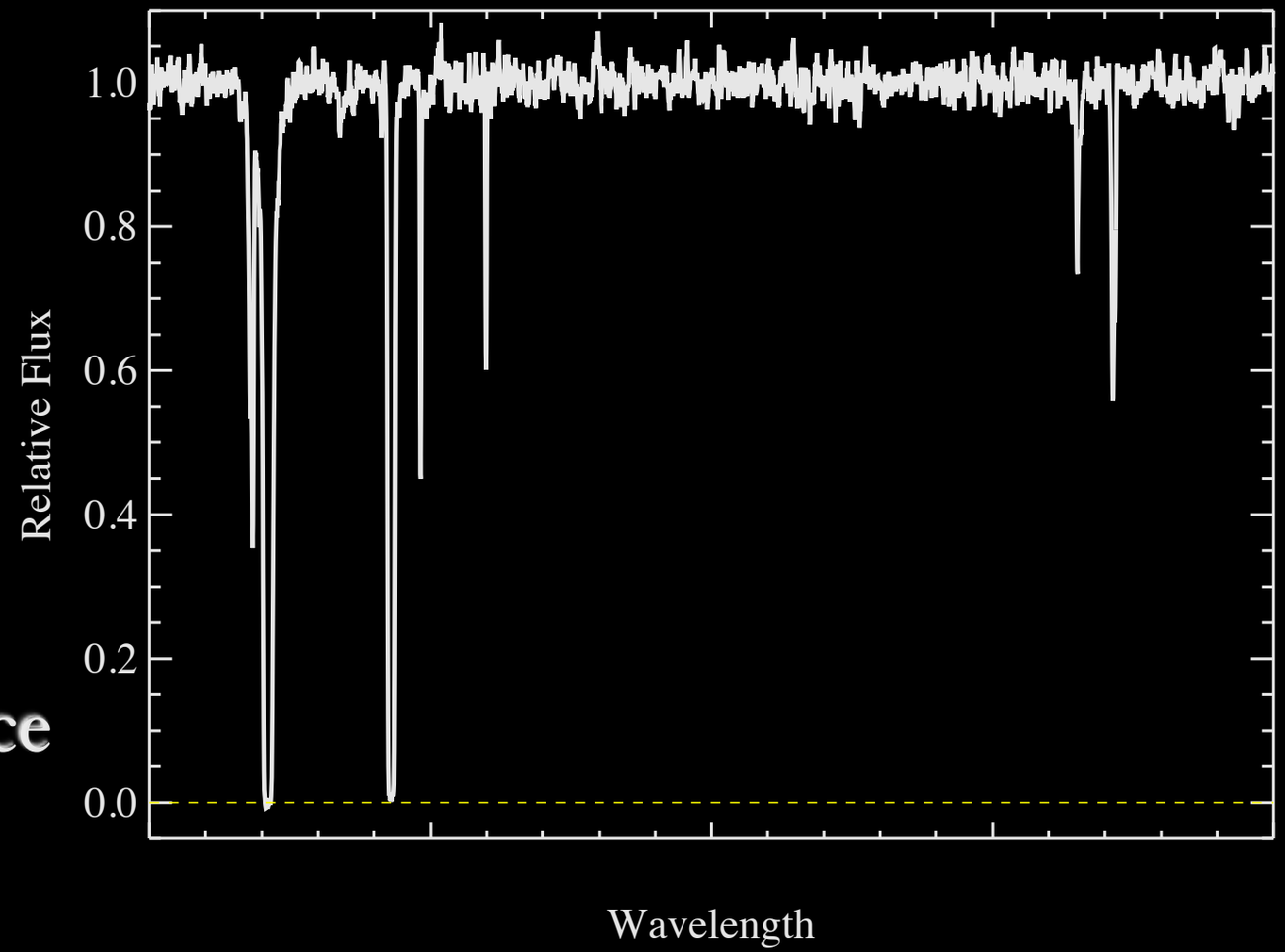


Absorption Line Spectroscopy

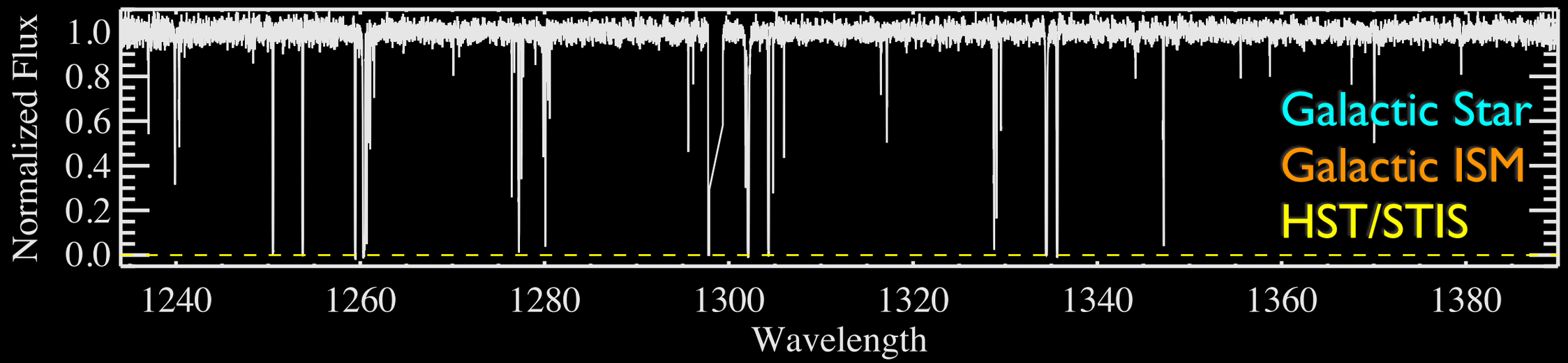
a.k.a. Astronomy in Silhouette

- **Most astronomers count photons to do their science**
  - Flux in a pass-band
  - Flux in emission lines

- **Absorption line astronomers count the photons that are missing**
  - They observe the universe in silhouette
  - This requires a background source



Examples of Absorption Line Spectra



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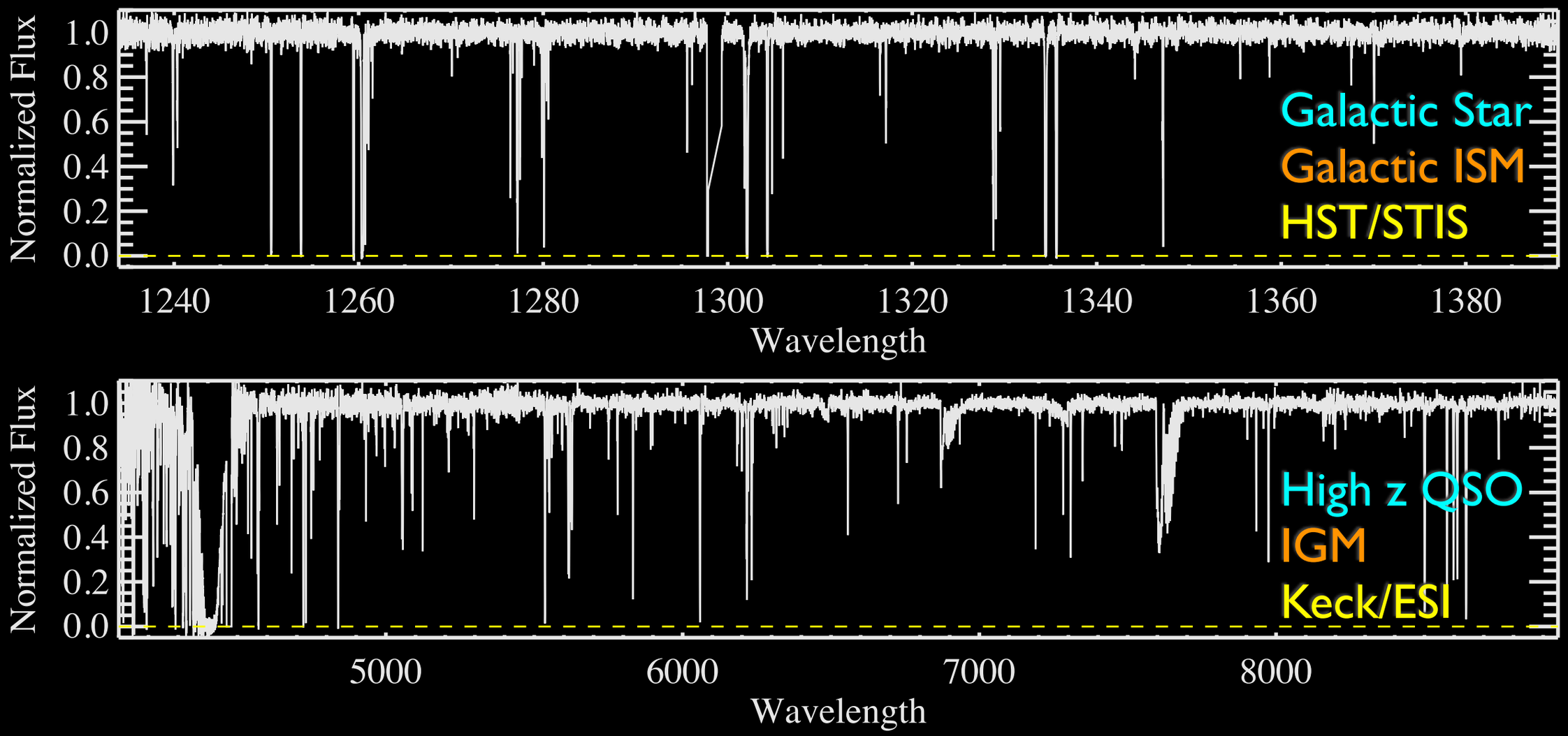

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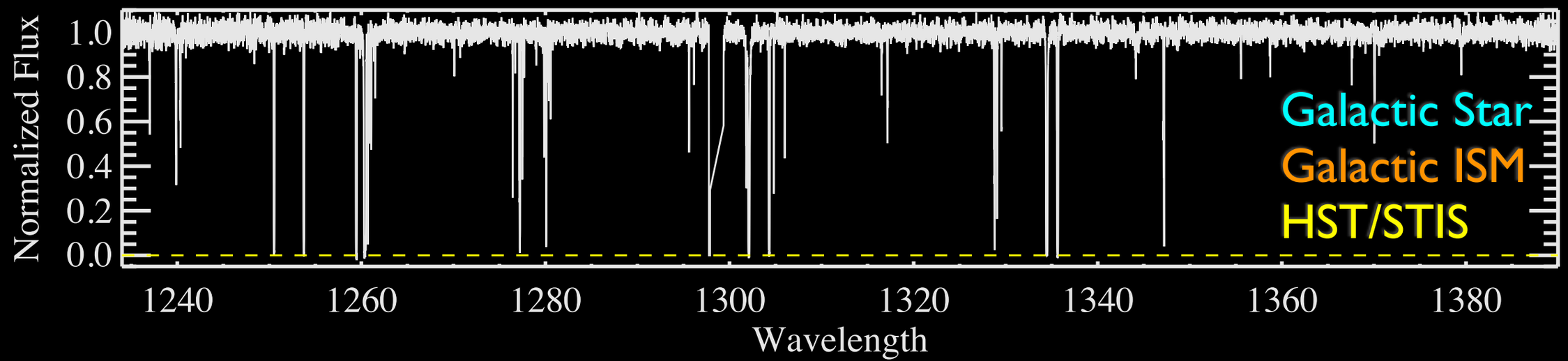

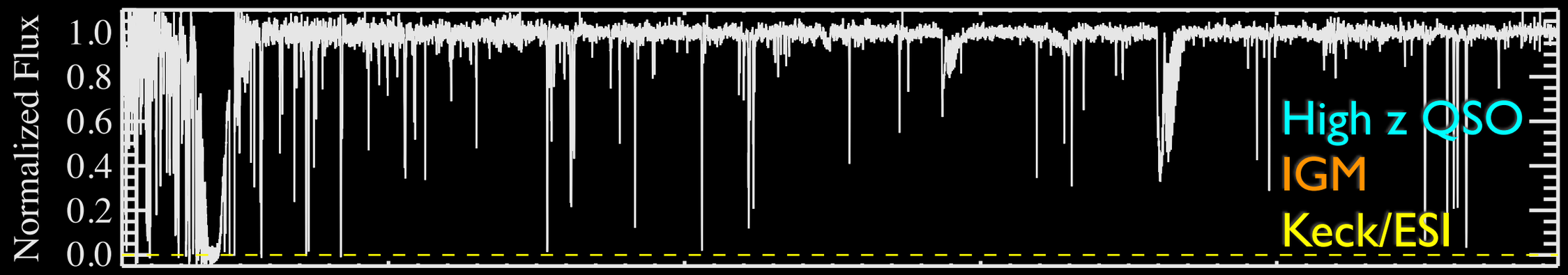

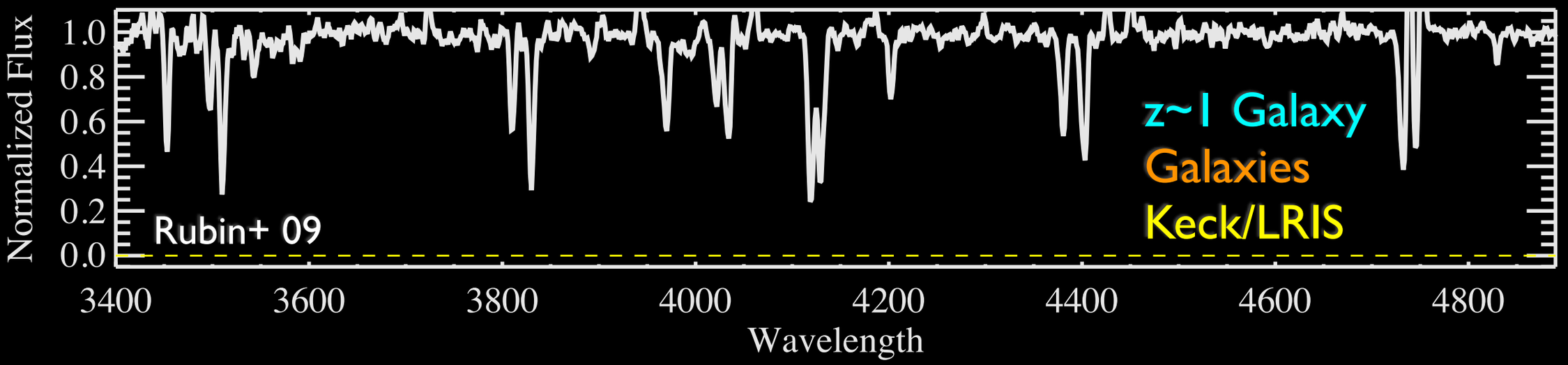

Absorption Line Spectroscopy: Cartoon

Gas

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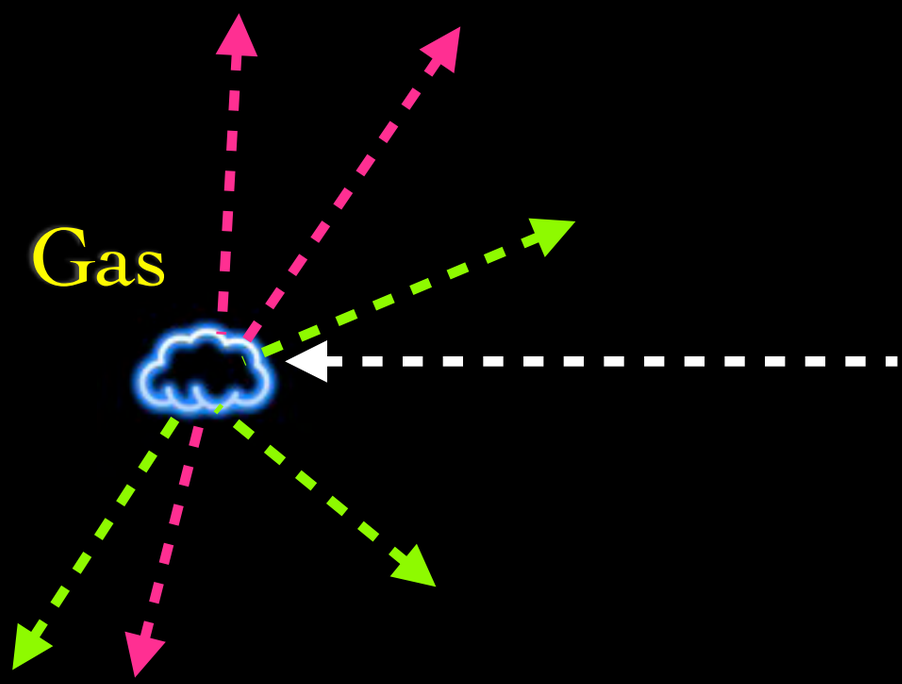
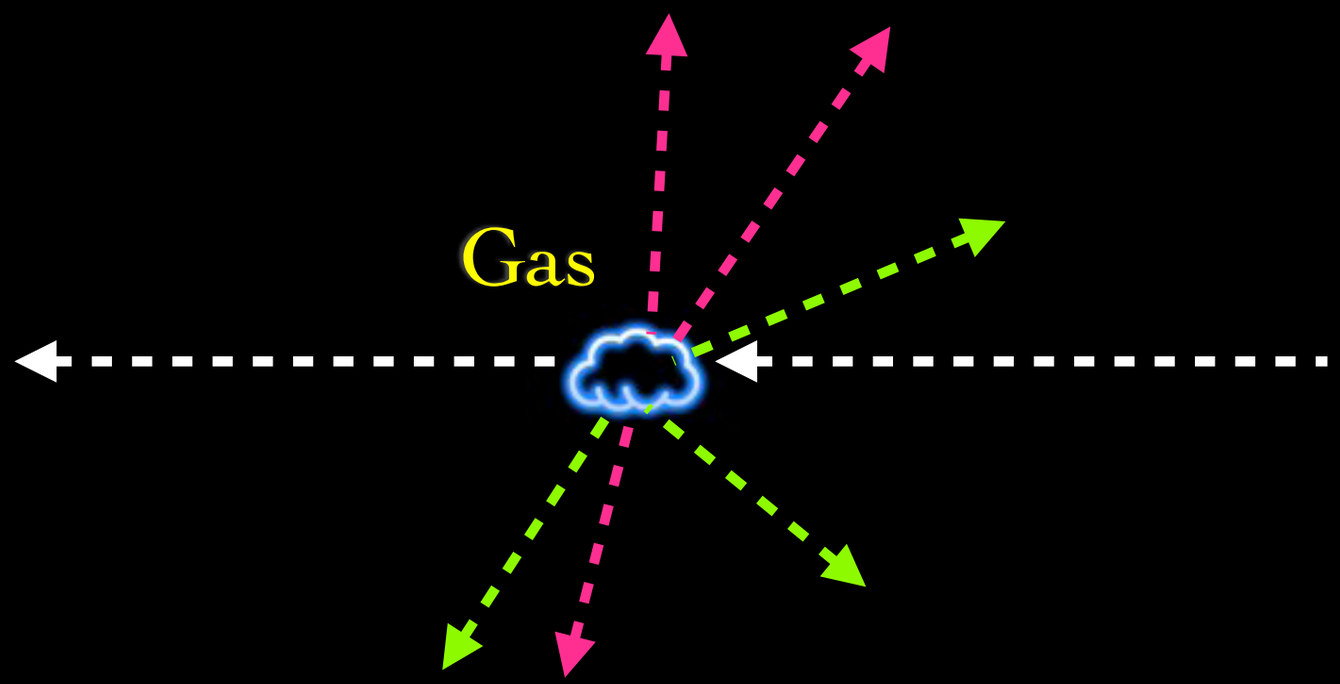


Light scatters in random
directions at a few frequencies

Absorption Line Spectroscopy: Cartoon



Light scatters in random
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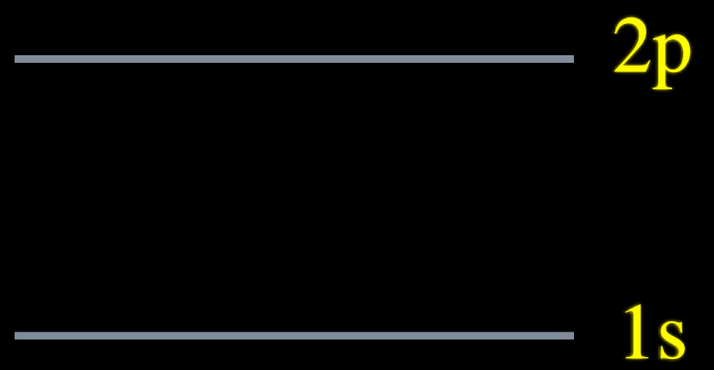
Absorption Line: Defined

e.g. Lyα for HI atoms*



$\Delta E = 10.2$ eV

$\nu = \Delta E/h = 2.5 \times 10^{15}$ Hz

$\lambda = hc/\Delta E = 1215.6701$ Å

- Well defined (unique) energy
- Resonance Line
  - Electric dipole transition
  - Electron begins in the ground-state
- Fine-structure transition
  - Electron begins in an excited state just above the ground state

*The 2p level is actually split and Lyα is a doublet. They are usually treated together.

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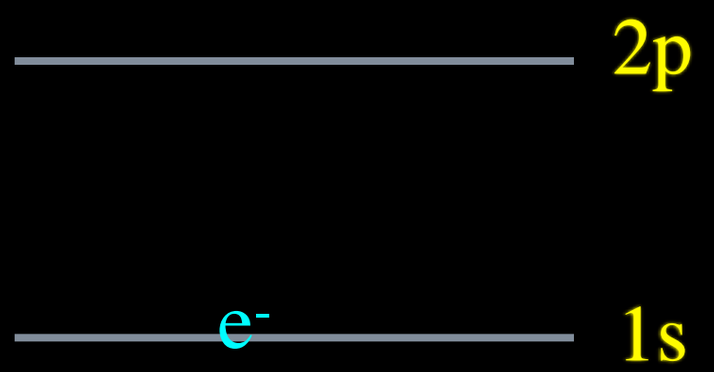

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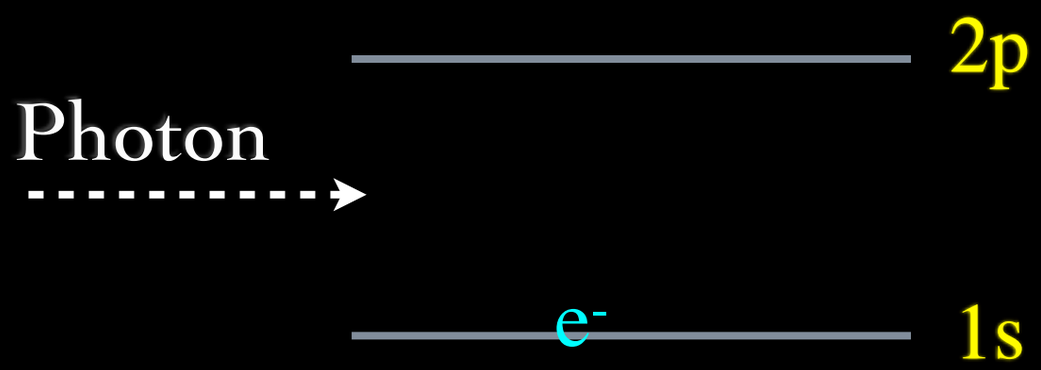

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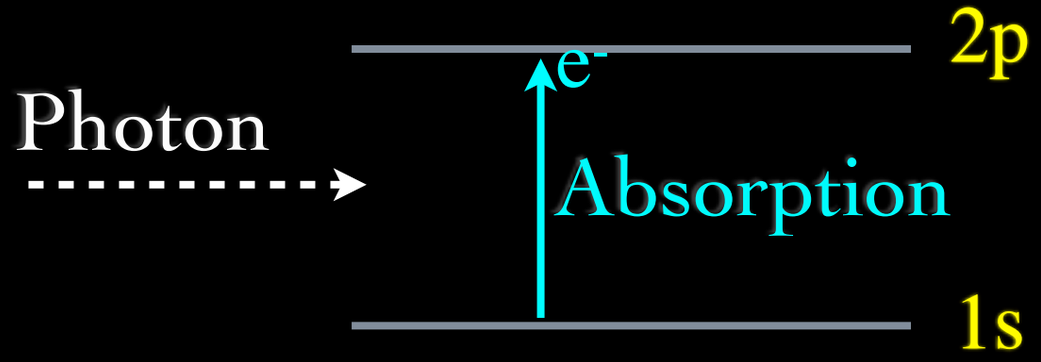

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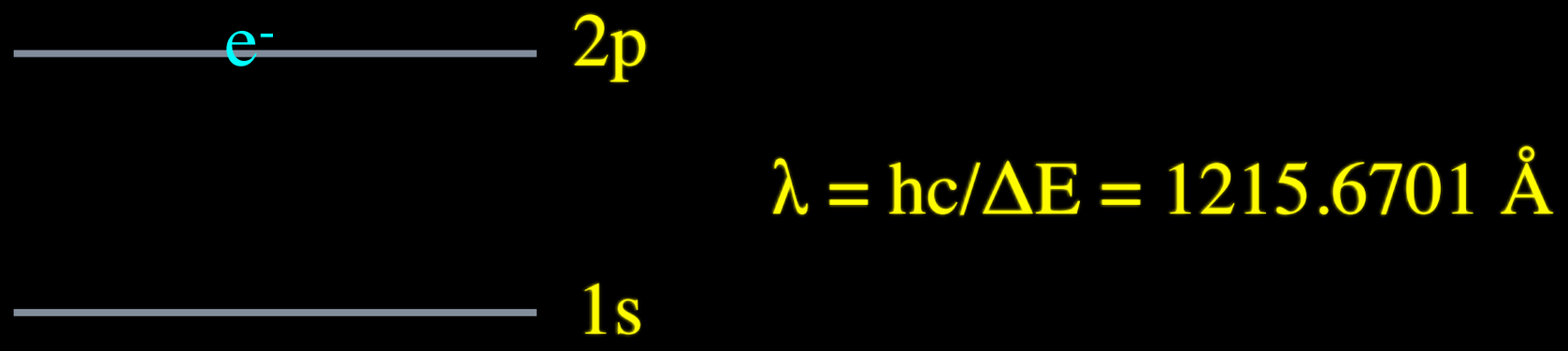
Spontaneous Emission



- Spontaneous emission
  - Occurs with a half-life of $t_{1/2}$
  - Emits a photon with energy ΔE
- Spontaneous emission coefficient
  - Describes the probability of emission
  - (Einstein's constants)
  - Define: $A_{kj} = 1 / t_{1/2}$
    - Generally determined from experiment
    - $A_{kj} = 6.3 \times 10^8\ s^{-1}$ for HI Lyα

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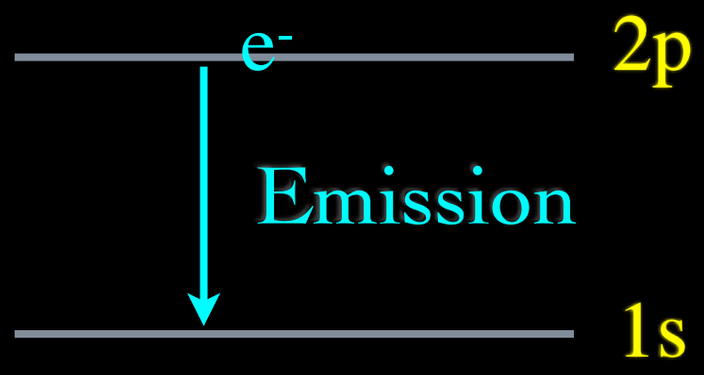

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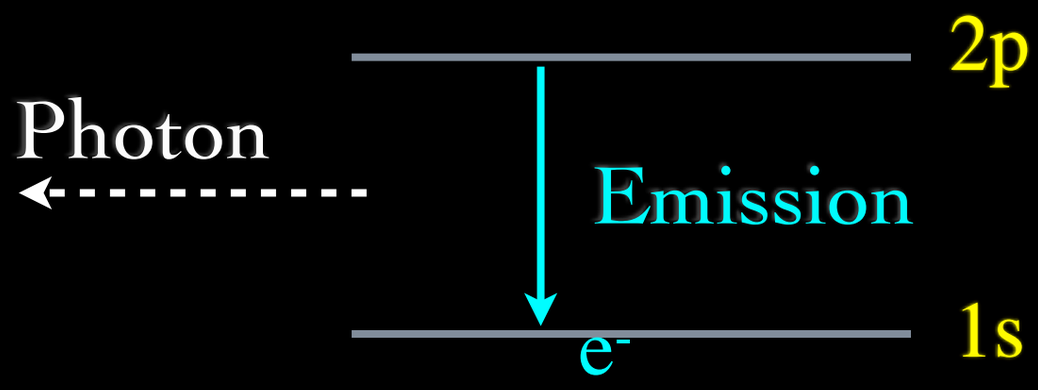

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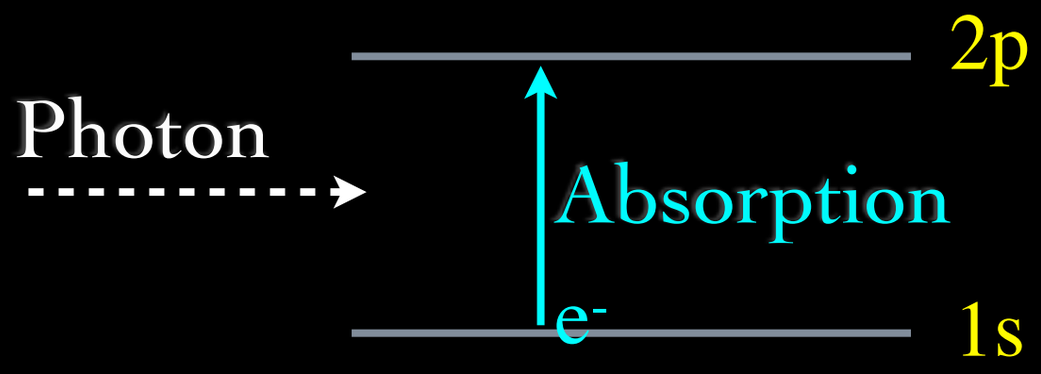
Oscillator Strength (f-value)



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$\lambda = hc/\Delta E = 1215.6701$ Å

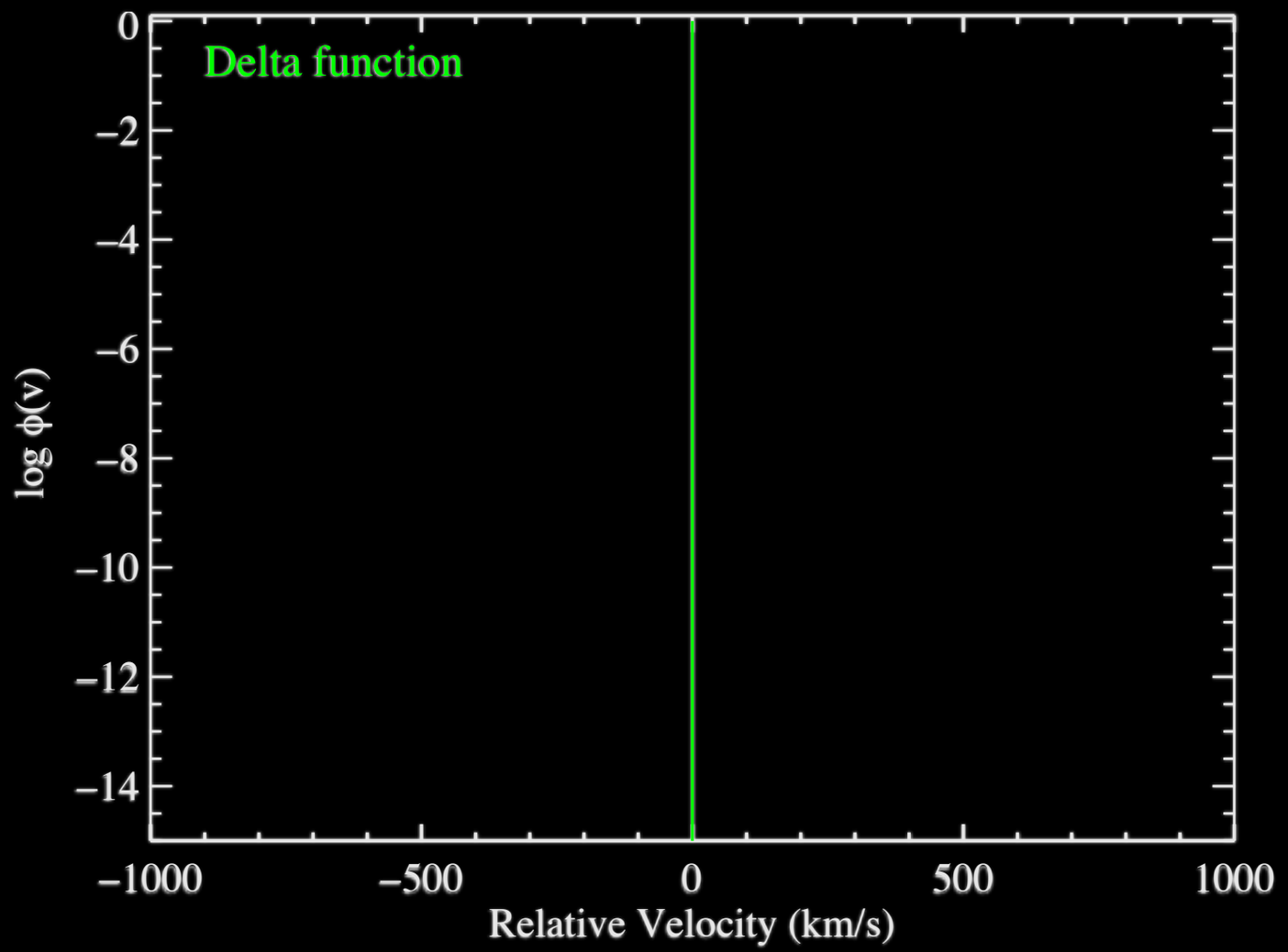
- Defines, in part, the probability for a given transition
  - i.e., the 'strength' of the line
  - Relates to the A_{kj} coefficient
- f-value:

$$f_{jk} = \frac{mc}{8\pi^2 e^2} \frac{g_k}{g_j} \lambda^2 A_{kj}$$

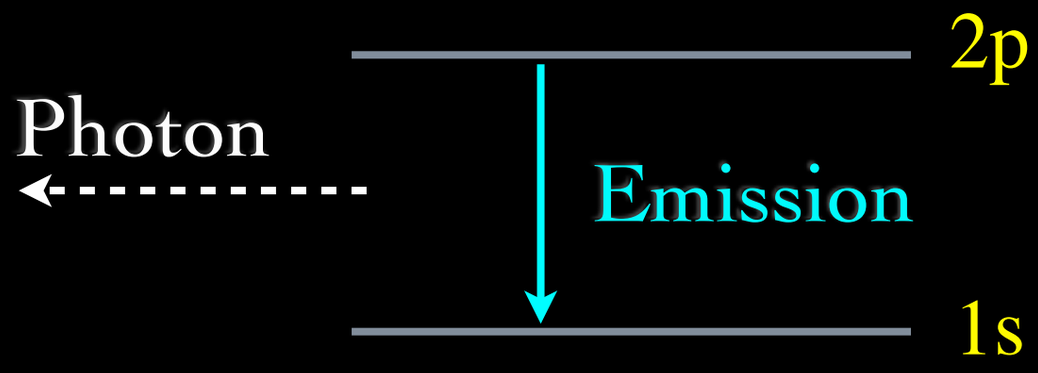
  - g_j, g_k are the degeneracies of each level
- For electric dipole transitions
  - f ~ 0.1 to 1

Line Profile: φ(ν)

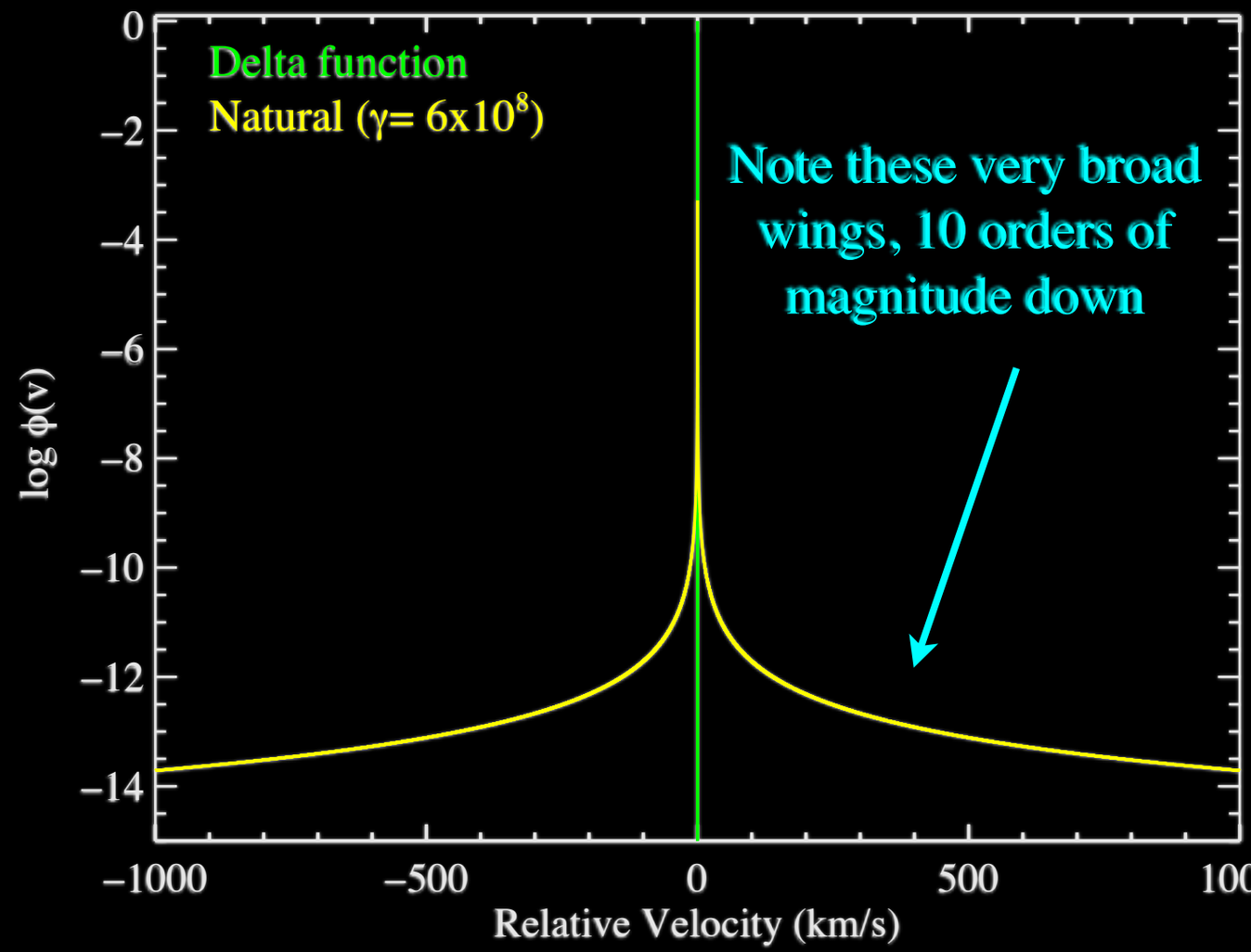
- **Definition**
  - The line-profile defines the probability of absorption (and emission) off of line-center
  - $\phi(\nu)d\nu = \phi(v)dv = \phi(\lambda)d\lambda$
- **One option: A delta function!**
  - $\phi(\nu) = \delta(\nu-\nu_{jk})$
  - i.e. zero probability off of the line-center (as shown)
- **Adopt velocity units (easier)**
  - $v = c\,(\nu-\nu_{jk})/\nu_{jk}$
  - This is what is plotted



Natural Broadening (a.k.a. Damping)



This process occurs with a $t_{1/2}$ half-life



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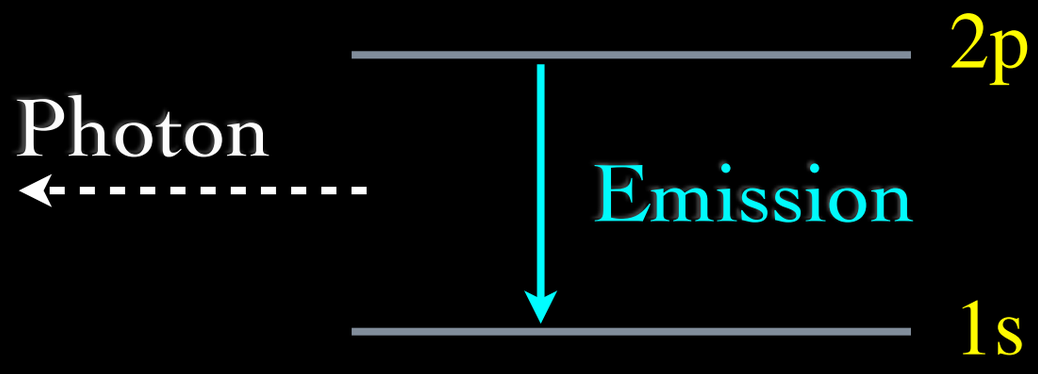
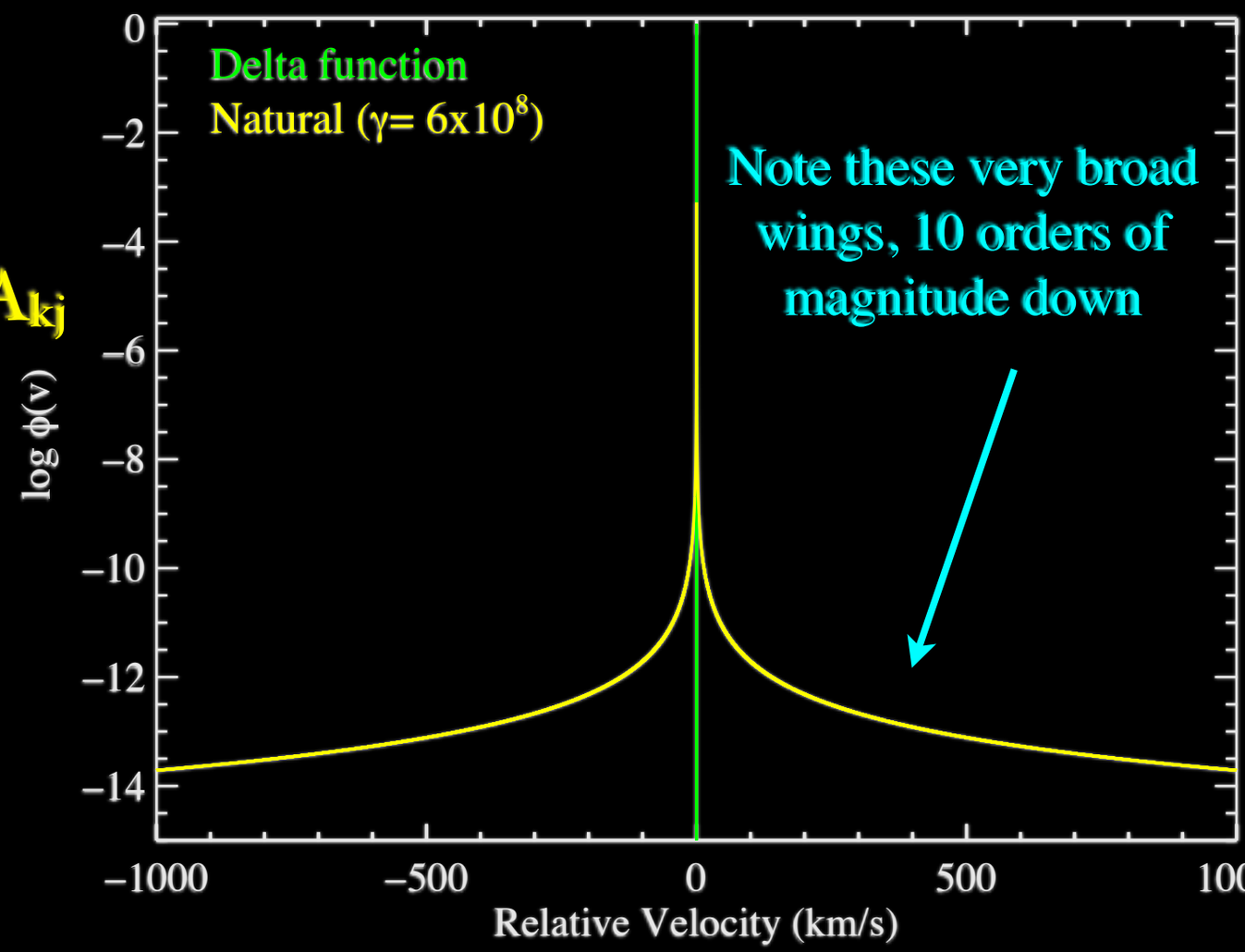


This process occurs with a $t_{1/2}$ half-life

- **Uncertainty in lifetime**
  - => Uncertainty in the Energy
  - i.e., Heisenberg
  - $\Delta t\, \Delta E \sim h \Rightarrow \Delta E \sim h/\Delta t \sim hA_{kj}$



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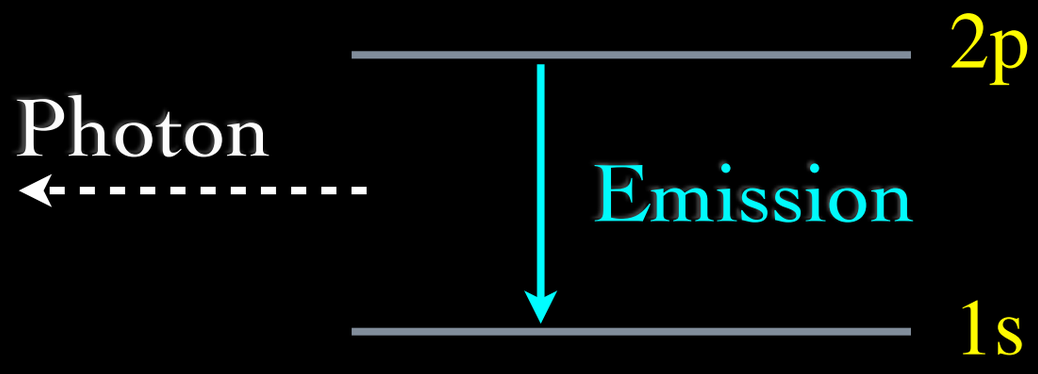

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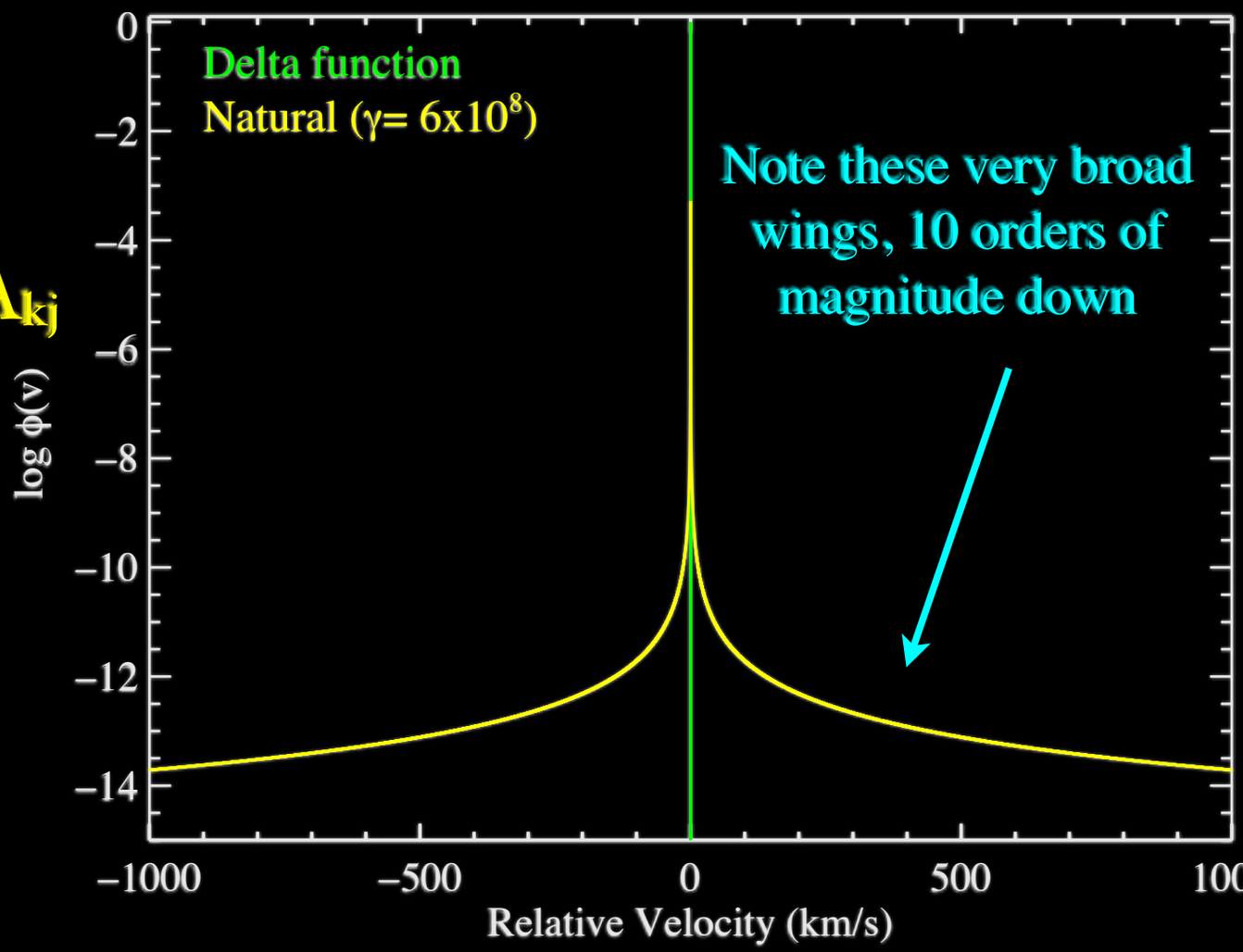
  - $\Delta t\, \Delta E \sim h \Rightarrow \Delta E \sim h/\Delta t \sim hA_{kj}$
- **Natural line profile: $\phi_N(\nu)$**
  - Lorentzian

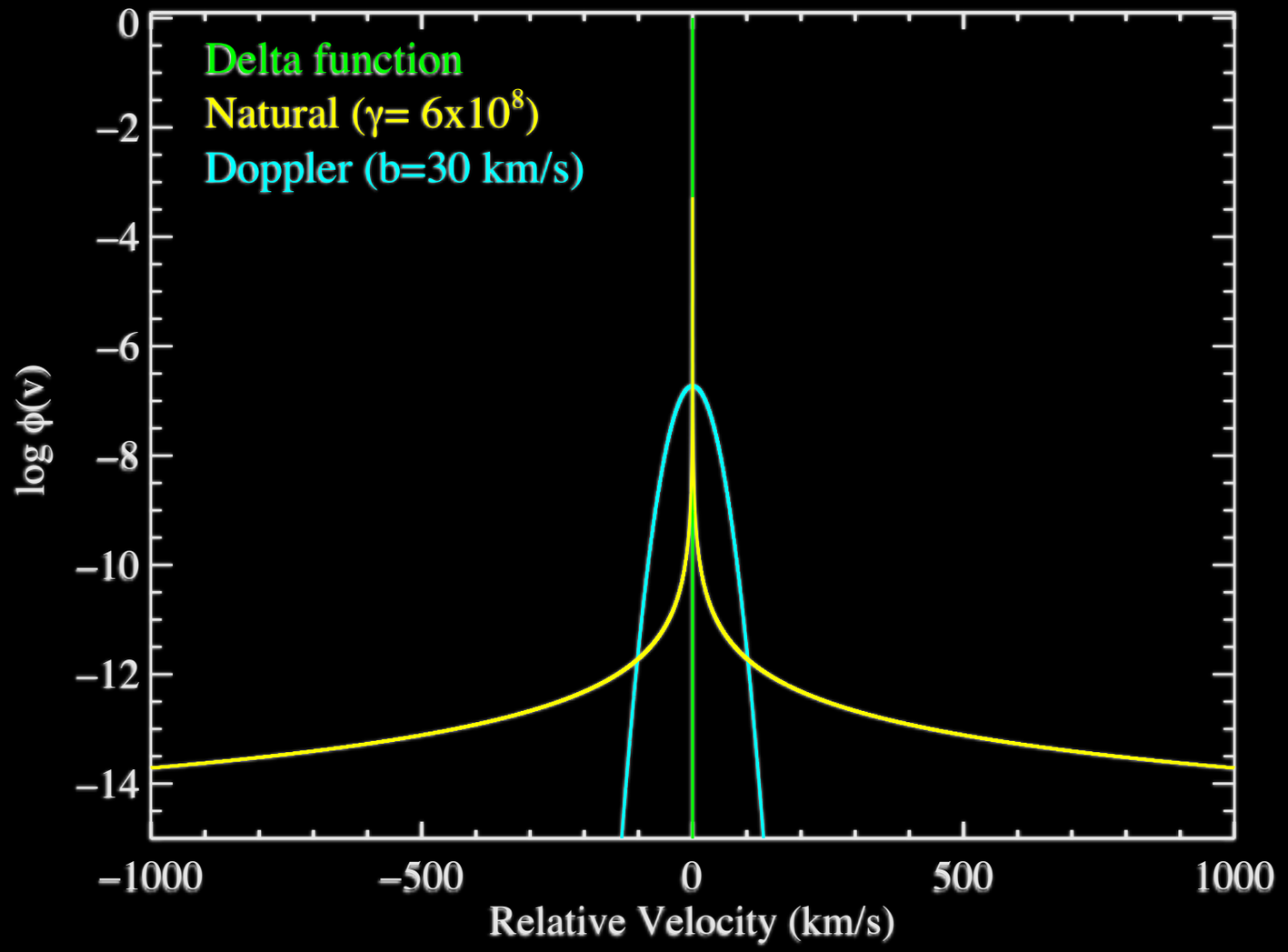
$$\phi_N(\nu) = \frac{2}{\pi}\left[\frac{(\gamma_j + \gamma_k)/4\pi^2}{(\nu - \nu_{jk})^2 + (\gamma_j + \gamma_k)^2/(4\pi)^2}\right]$$

$$\gamma_j \equiv \sum_{i<j} A_{ij}$$

  - Minimum line width $(\gamma_j+\gamma_k/4\pi)$

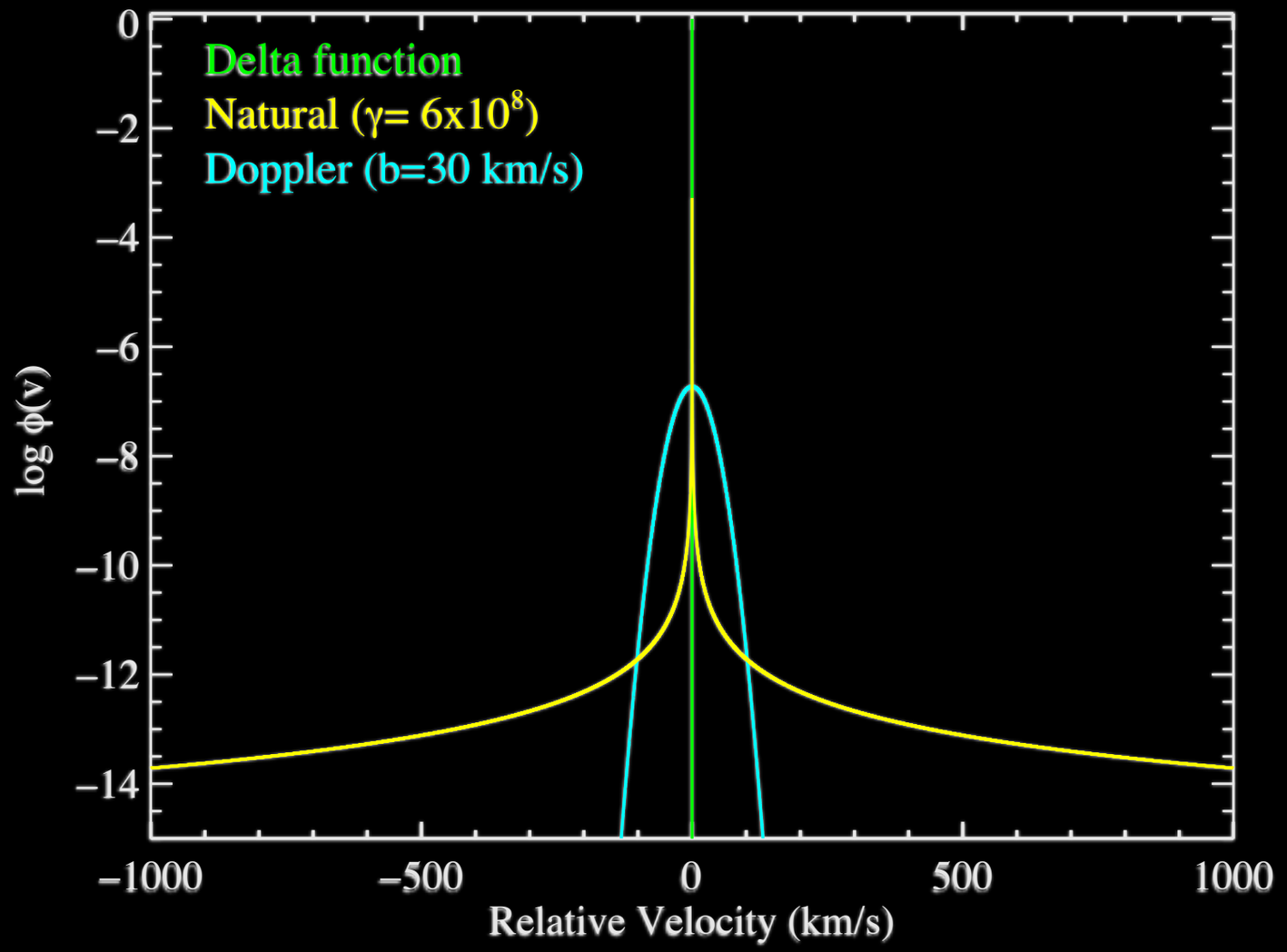


Doppler Broadening



Doppler Broadening

- Particles are rarely at rest
  - Their motions shift the effective energy of absorption
  - Simple Doppler effect



Doppler Broadening

- **Particles are rarely at rest**
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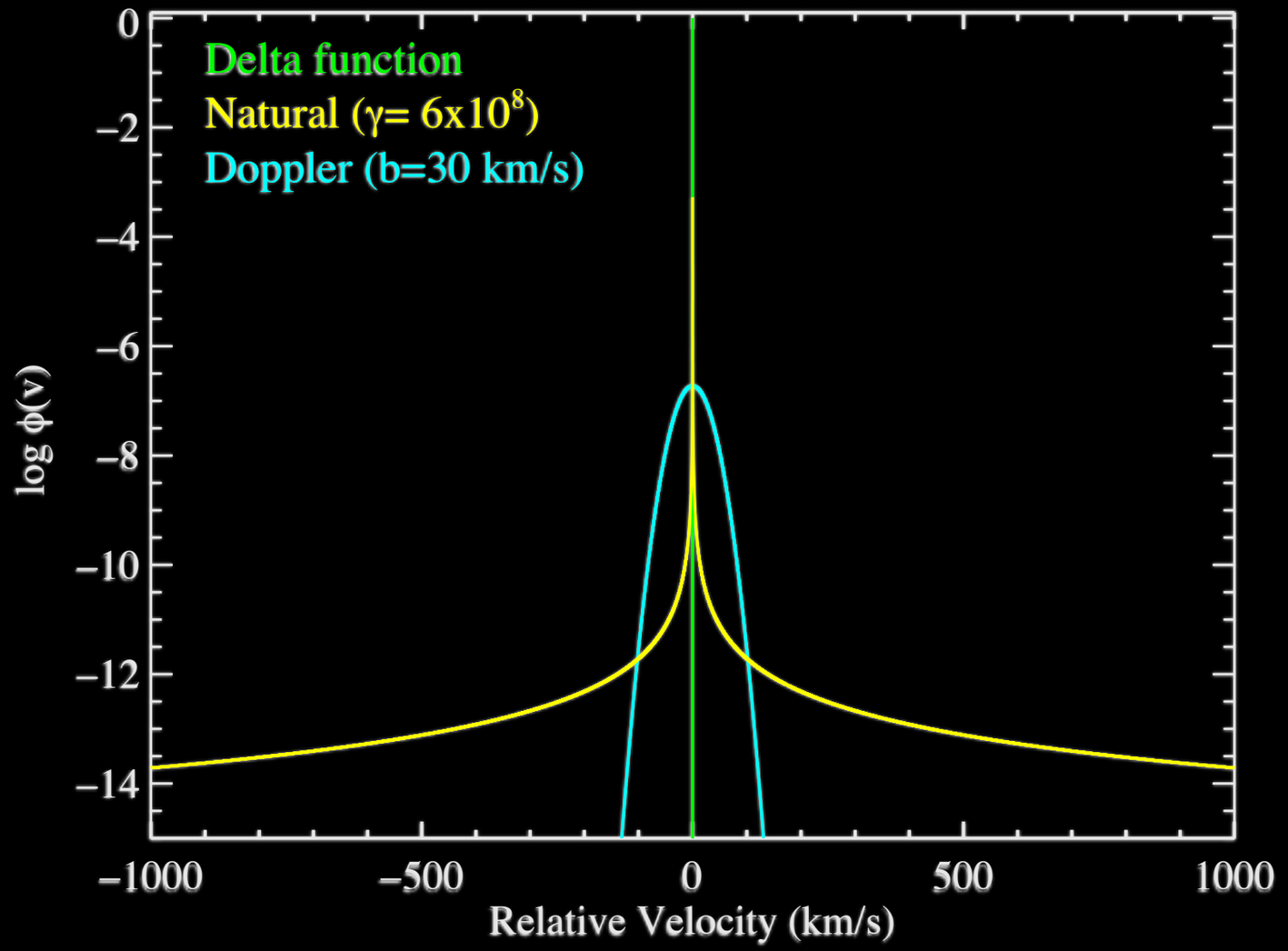
- **Doppler parameter**
  - a.k.a., the "b value"
  - Characterizes the thermal and turbulent motions of a gas

$$b = \sqrt{b_{\rm Therm}^2 + b_{\rm turb}^2} \qquad b_{\rm Therm}^2 = \frac{2kT}{m_A}$$



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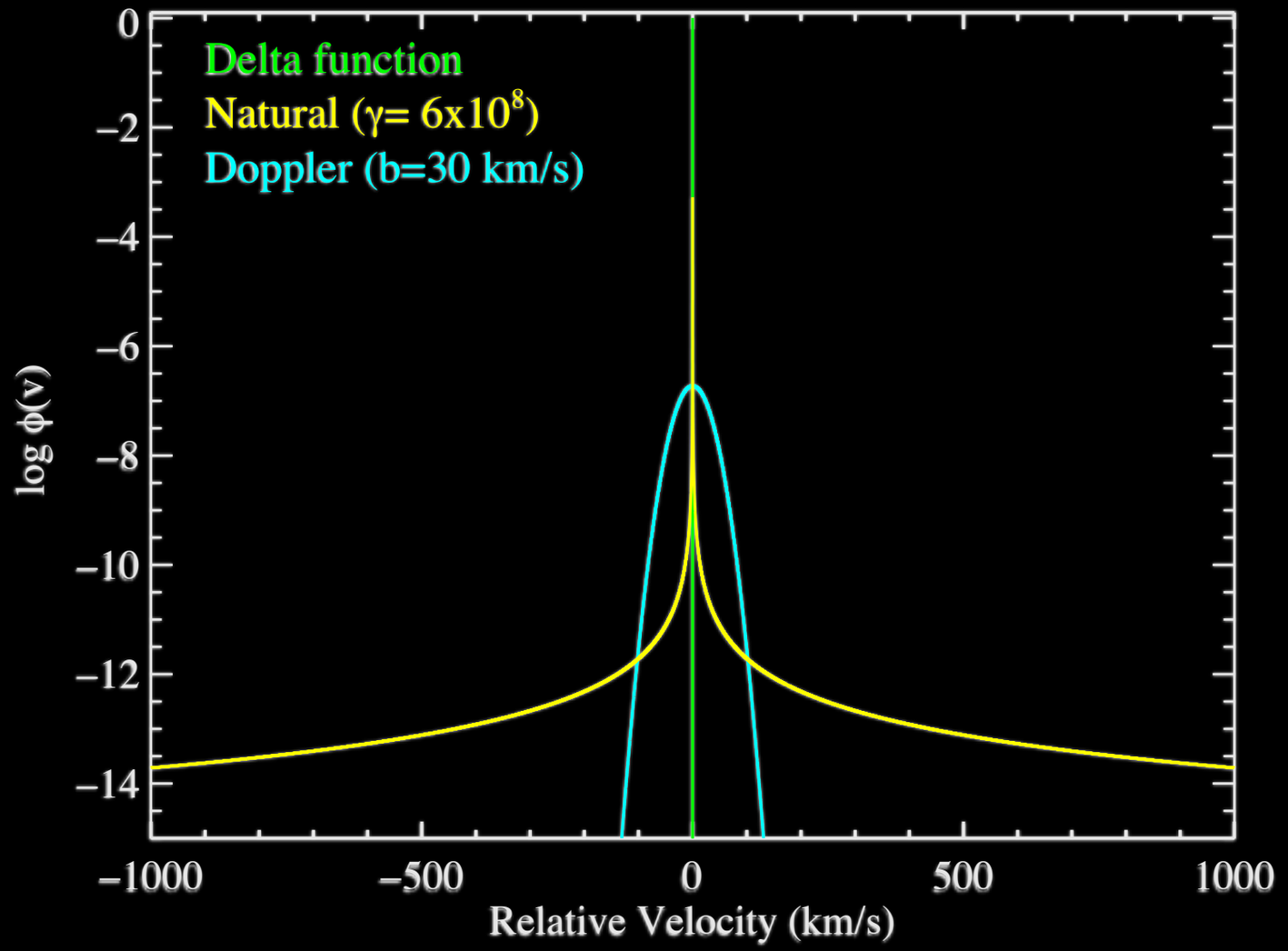
- **Line profile (Gaussian)**

$$\phi_D(v) = \frac{1}{b\sqrt{\pi}} \exp\left[-\frac{v^2}{b^2}\right]$$

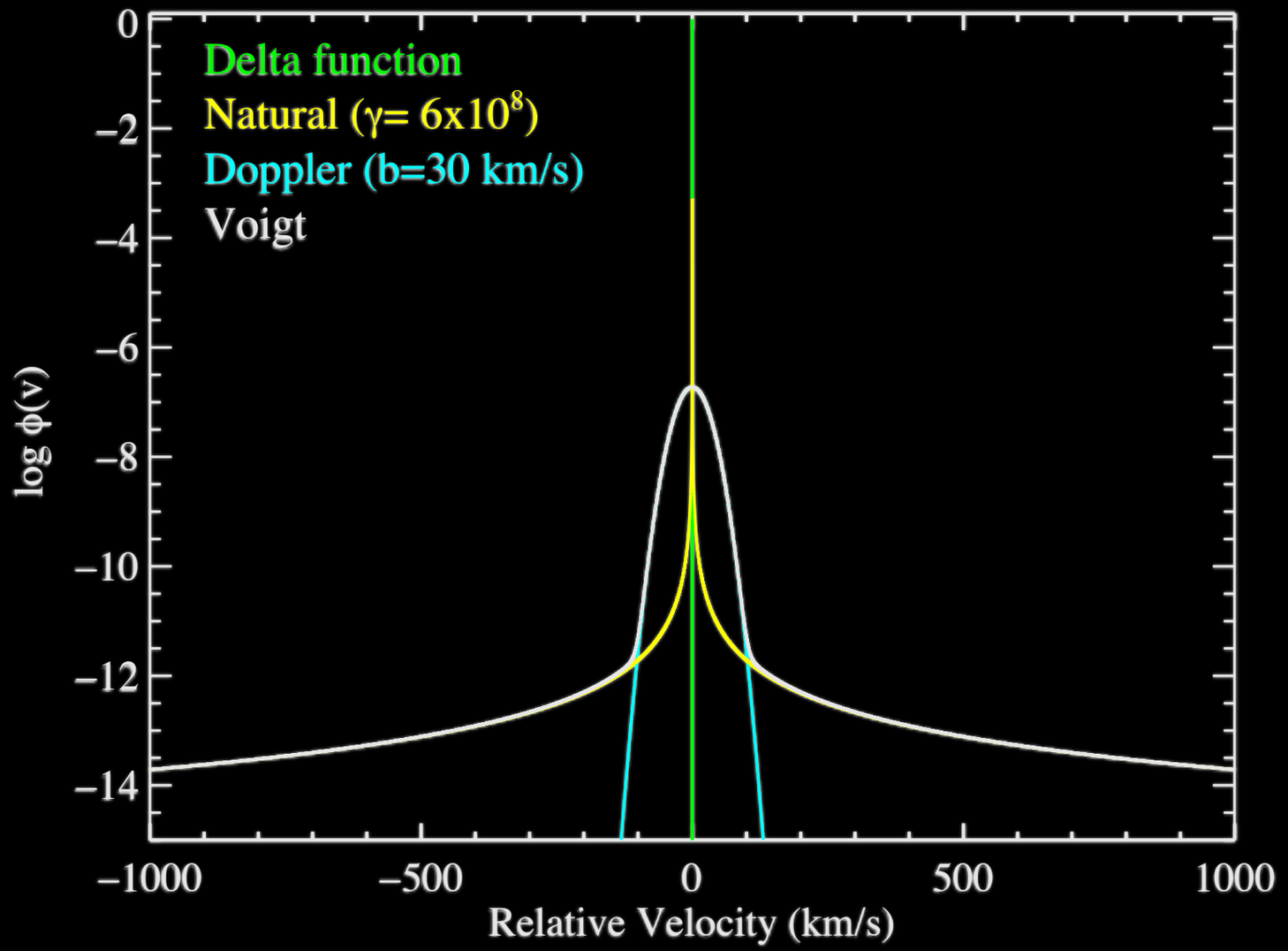


Voigt Profile

- **Voigt**
  - Convolution of Natural and Doppler broadening
  - No physics, just math
- **Formalism**

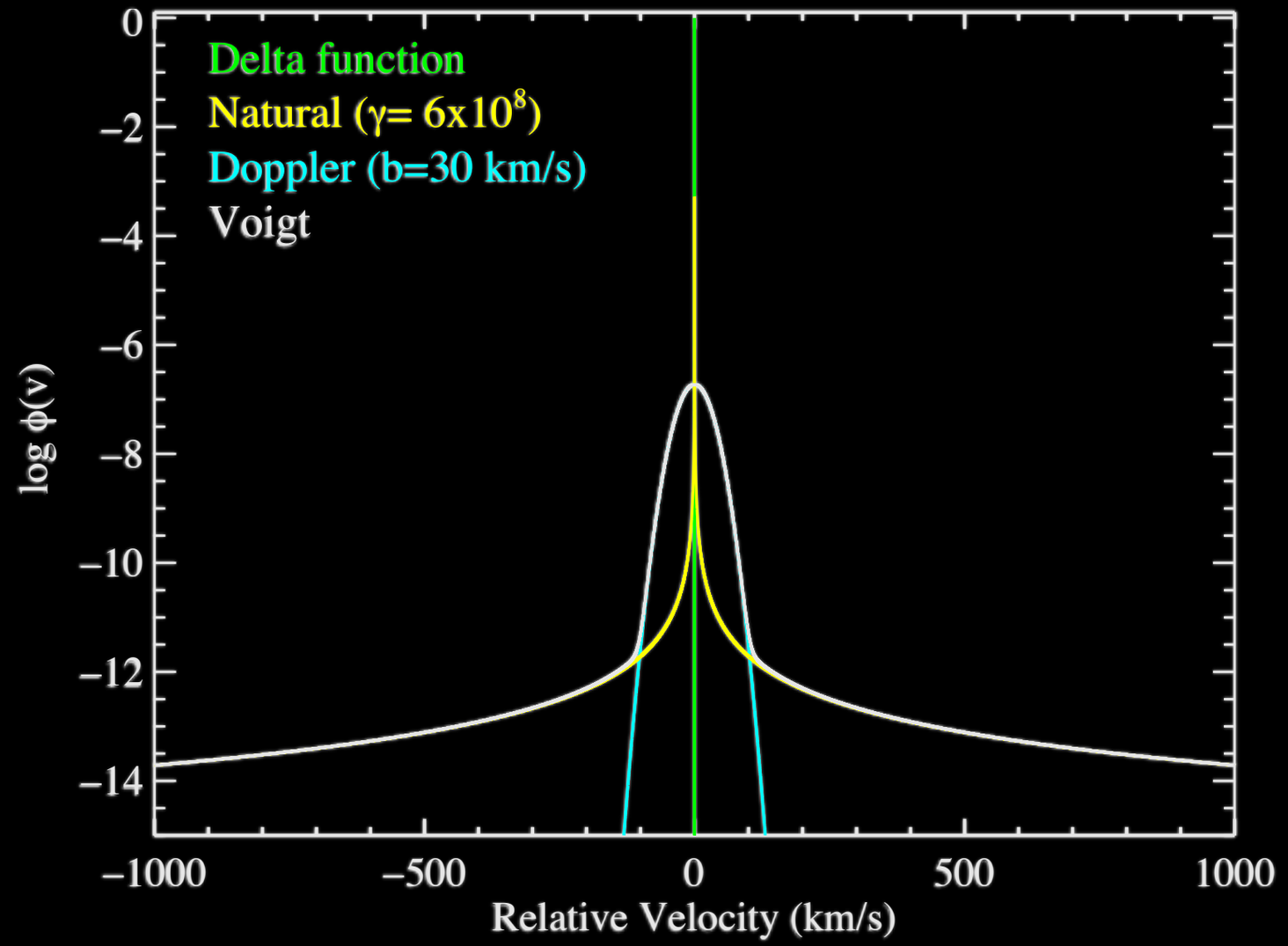
$$\phi_V(\nu) = \frac{\gamma}{4\pi} \int_{-\infty}^{\infty} \frac{\frac{1}{b\sqrt{\pi}} \exp\left(-\frac{v^2}{b^2}\right)}{(\nu - \nu_{jk} - \nu_{jk} v/c)^2 + (\gamma/4\pi)^2} dv$$

  - A messy expression, and one that is slow to evaluate
  - But it is the way things work..
- **Examining the profile**
  - Doppler dominates inner profile
  - Natural dominates outer profile



Summary so Far

- **Line parameters**
  - ν_{jk} (λ_{jk})
  - Akj
  - f
  - γ
  - b
- **Line profiles**



Natural broadening (QM)
+ Doppler broadening (CM)
= Voigt Profile

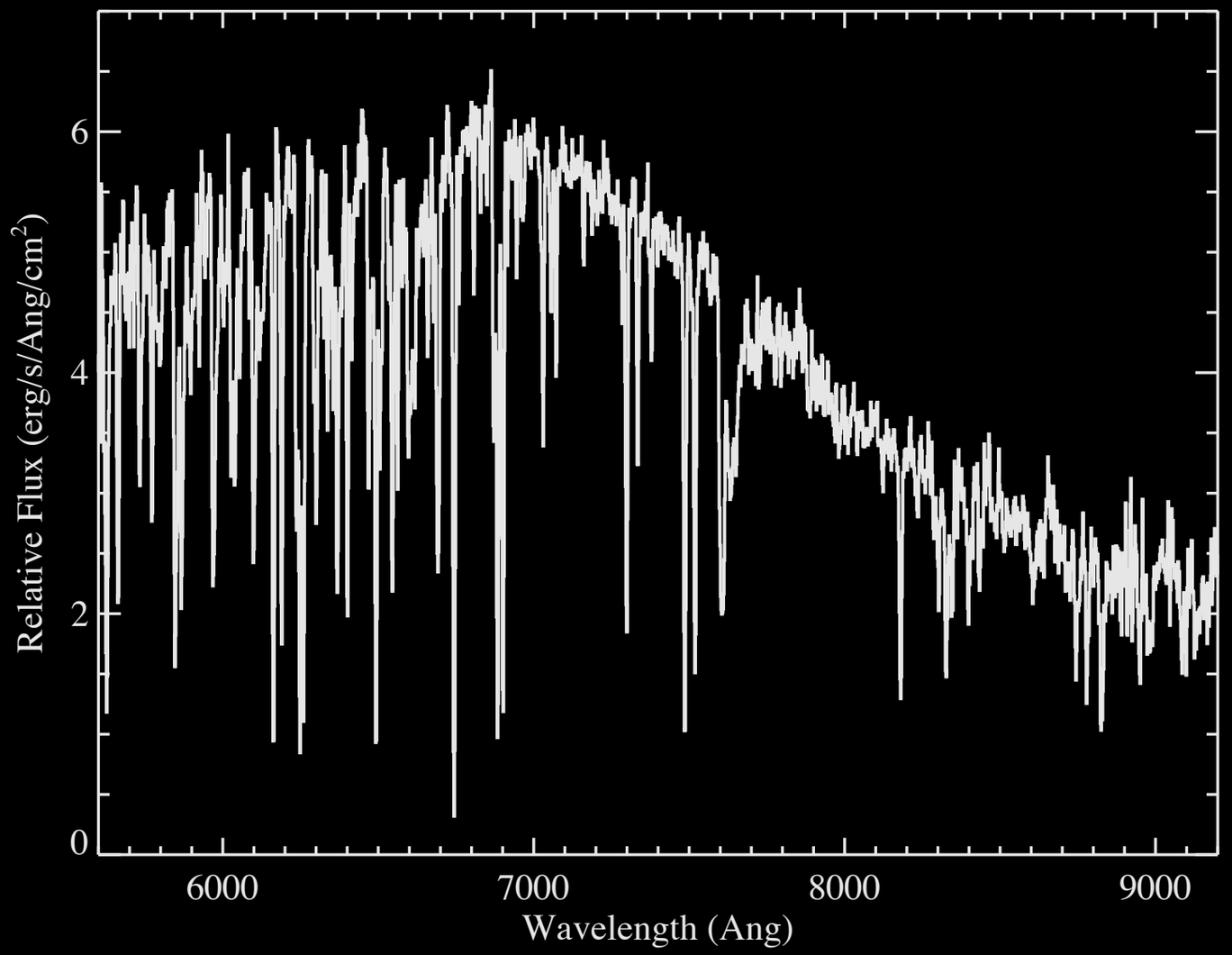
What are Absorption Lines good for?

(1) Assessing motions of gas

- Redshift: $\lambda_{obs} = \lambda_{jk}\,(1+z)$ [Centroid]
- Doppler motions [Width]
  - Thermal
  - Macroscopic turbulence
  - Dynamics (e.g. rotation, flows)

(2) Counting atoms

- Ions and molecules, too
- Mass (surface density)
- Metallicity
- Ionization/excitation state
- Dust, chemical evolution
- Distance from the GRB



Counting Atoms

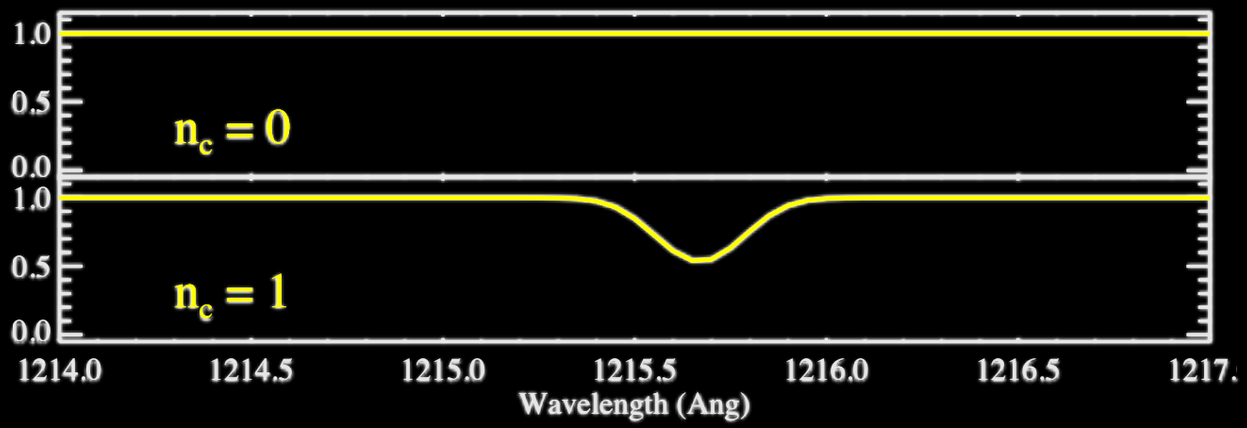
(with missing photons)

0 ‘clouds’

Counting Atoms

(with missing photons)

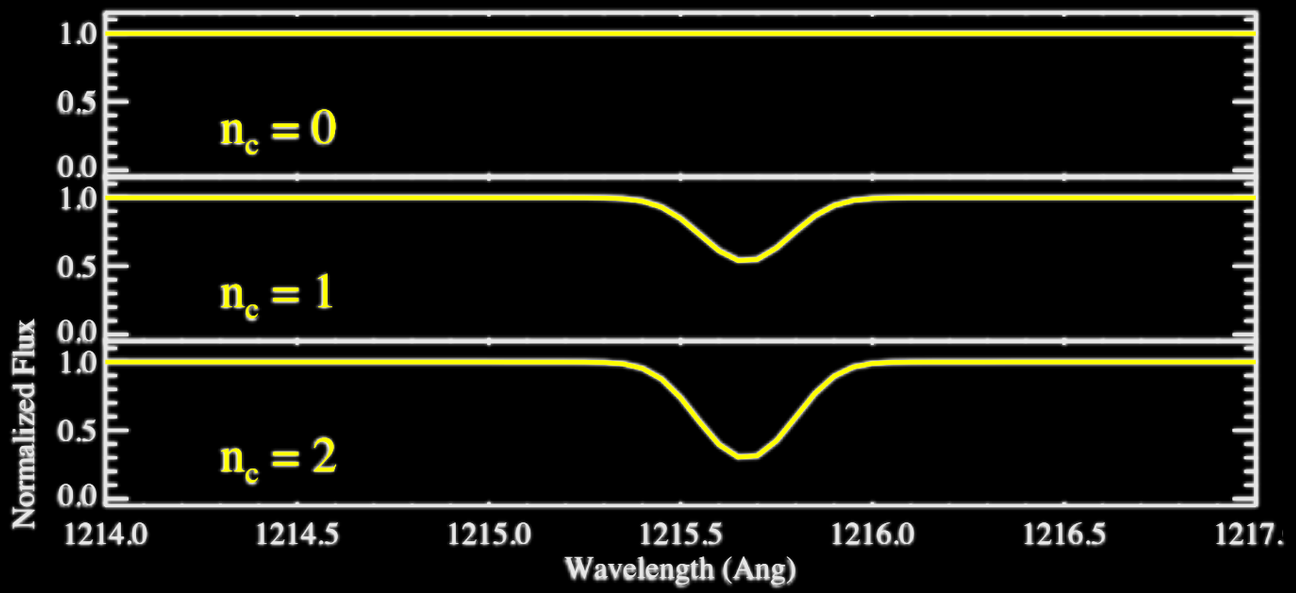
1 'clouds'



Counting Atoms

(with missing photons)

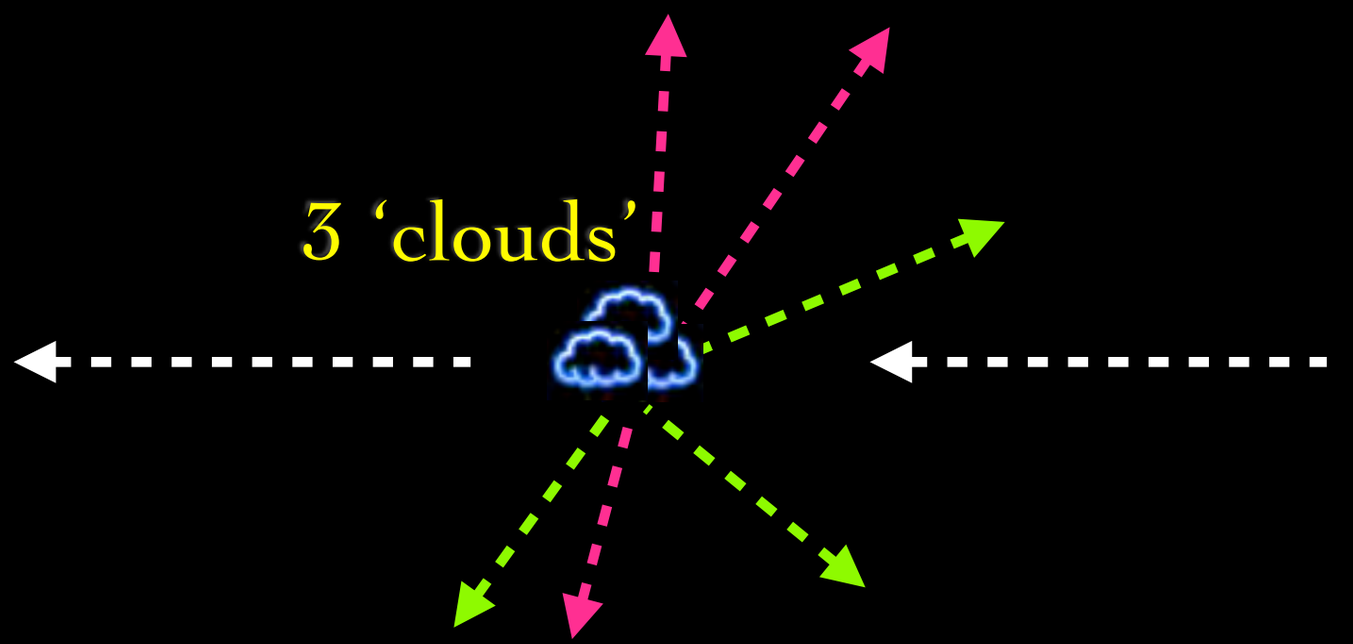
2 ‘clouds’

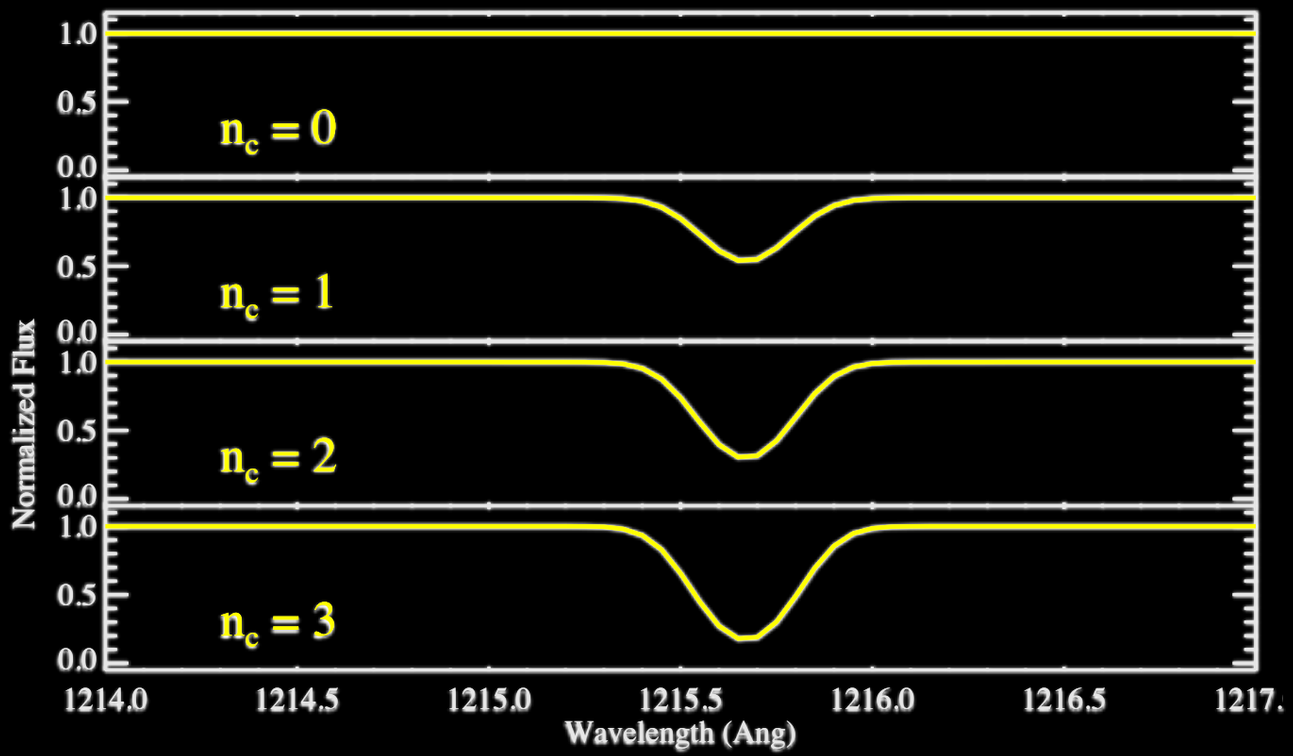


Counting Atoms

(with missing photons)

3 ‘clouds’

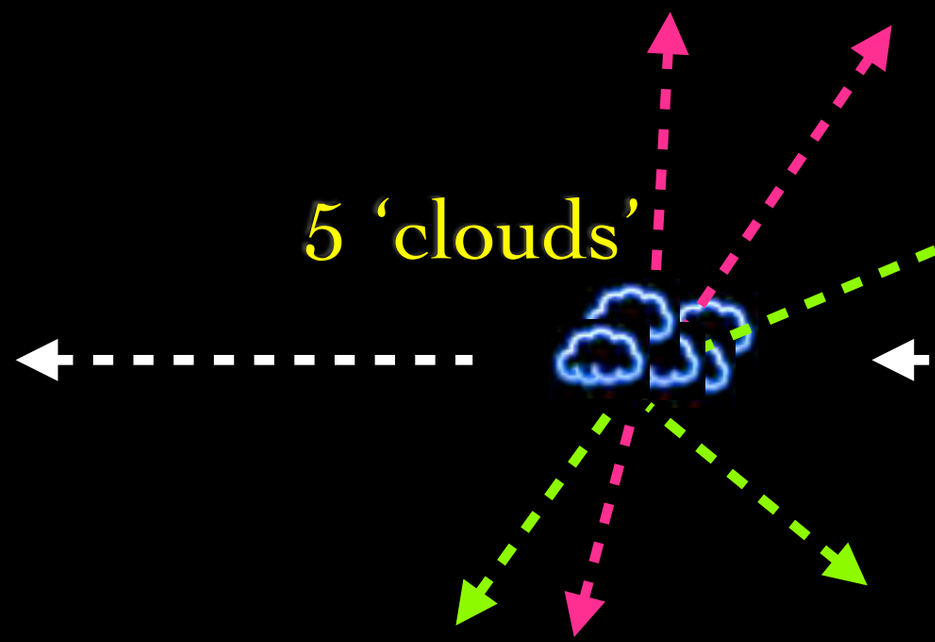


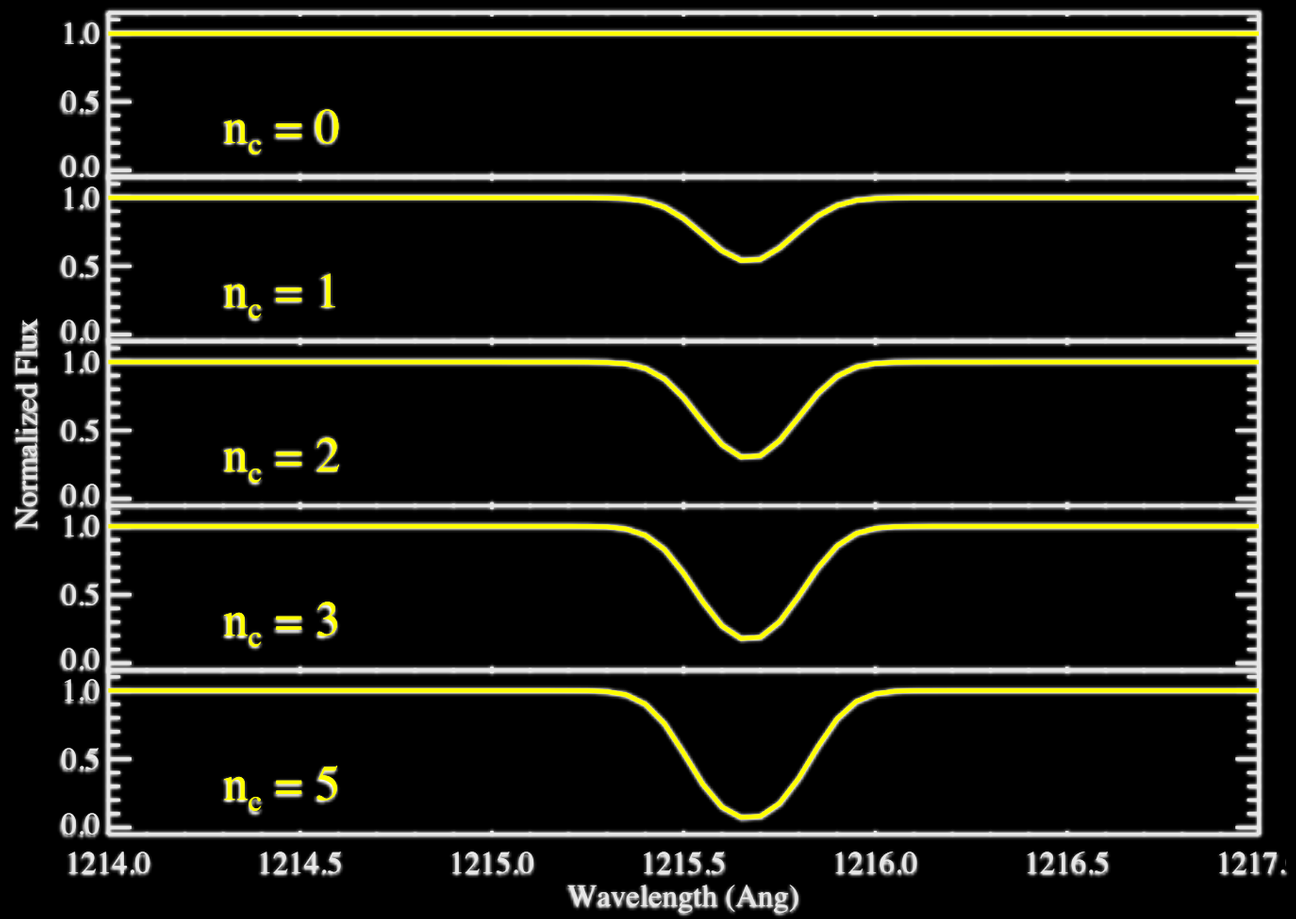


Counting Atoms

(with missing photons)

5 ‘clouds’





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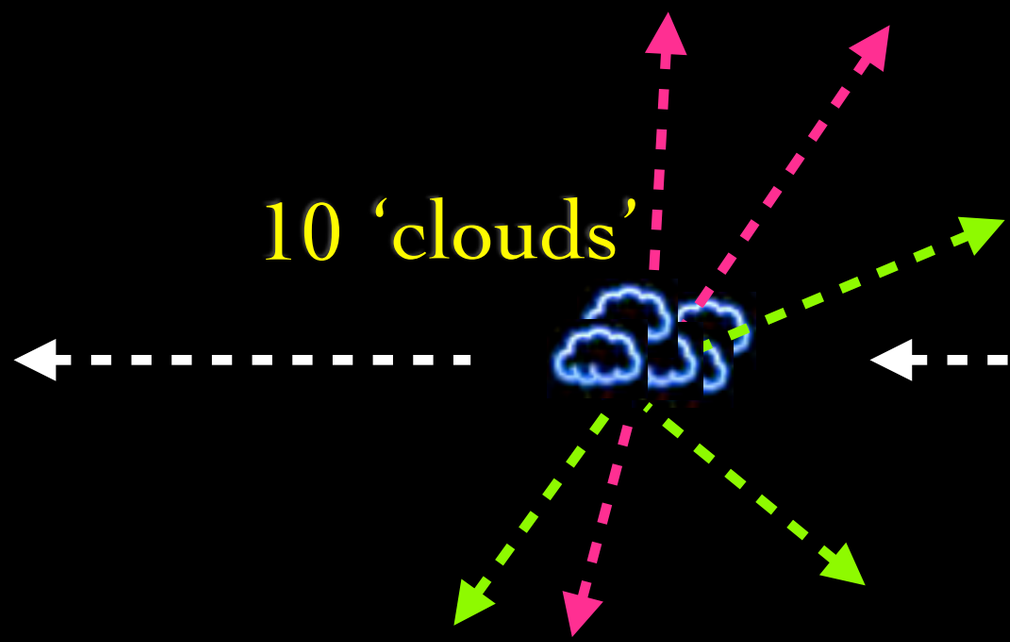

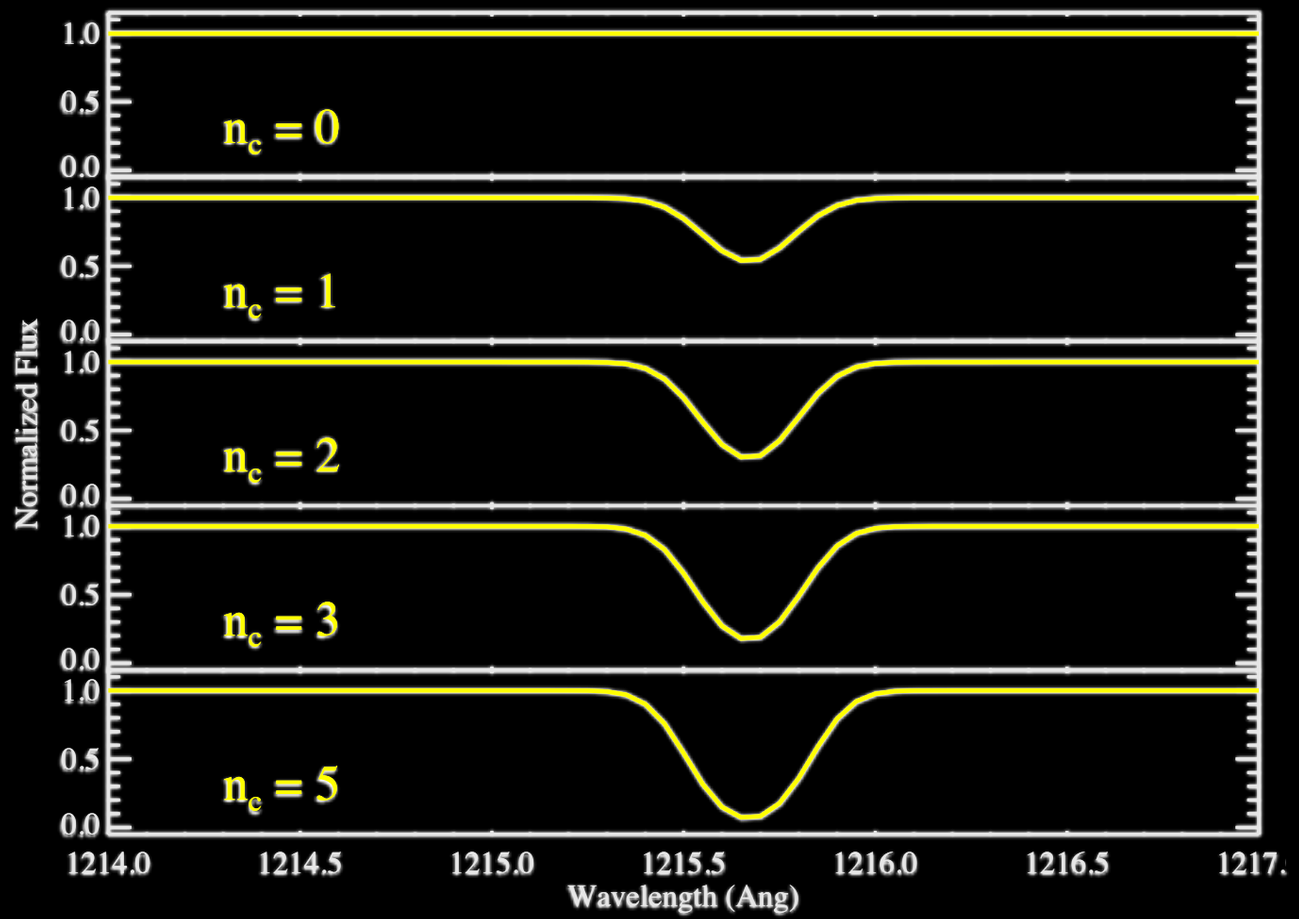

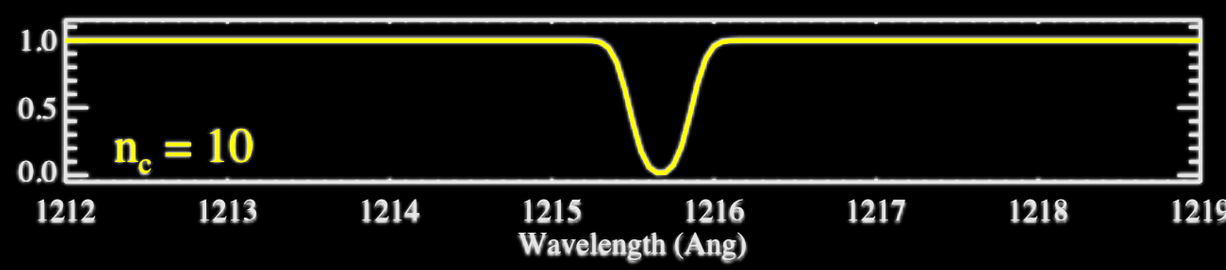

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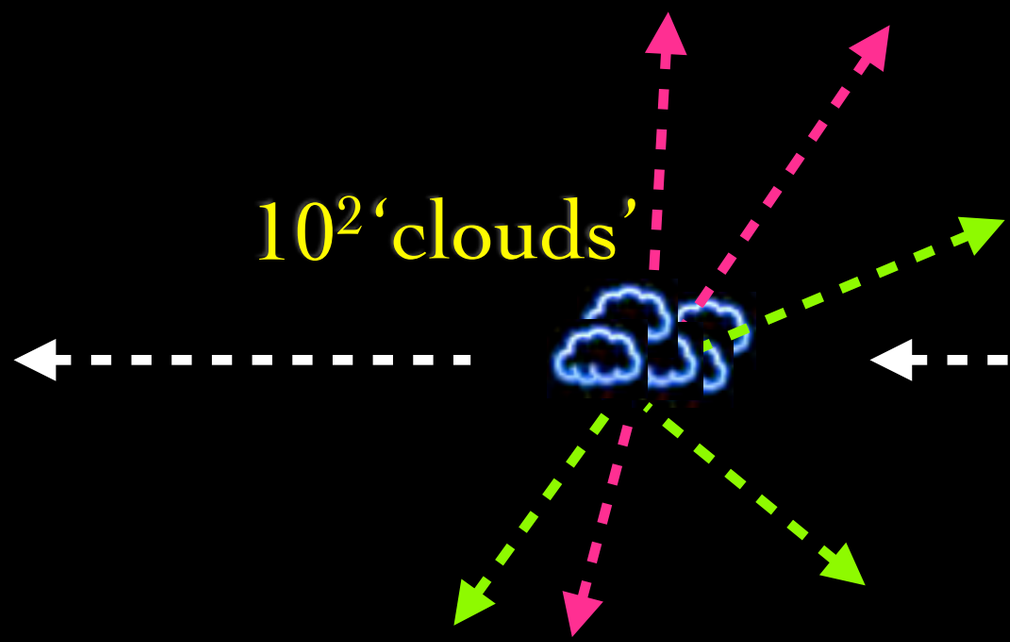

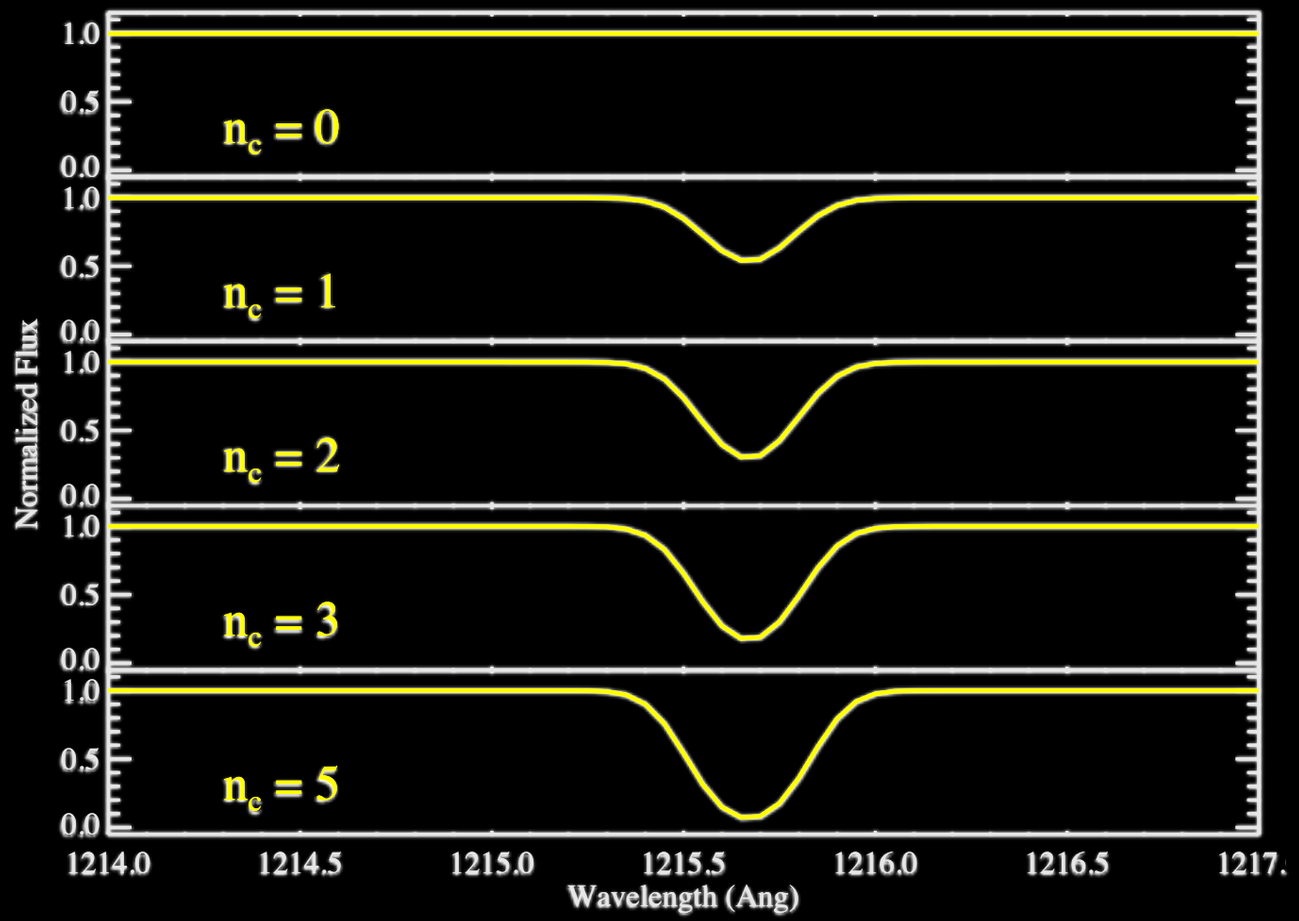

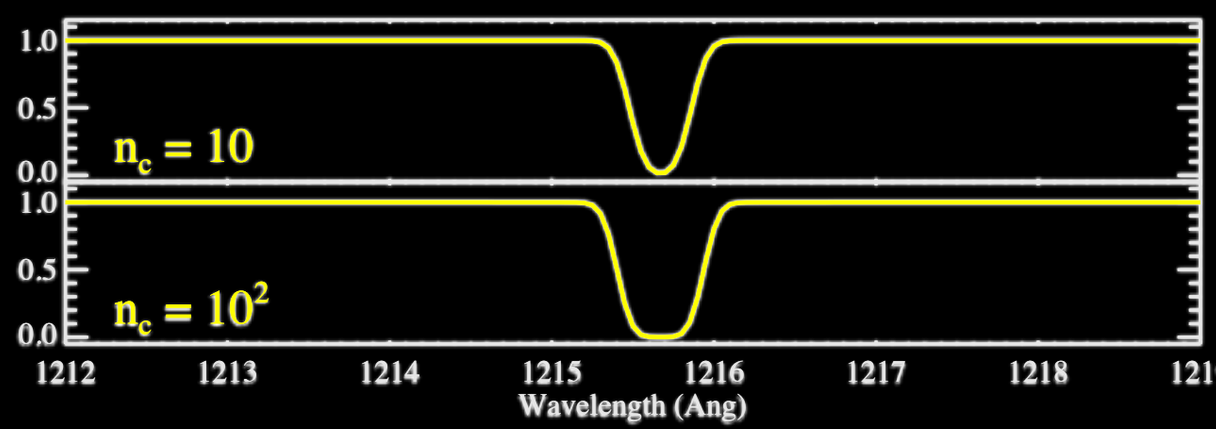

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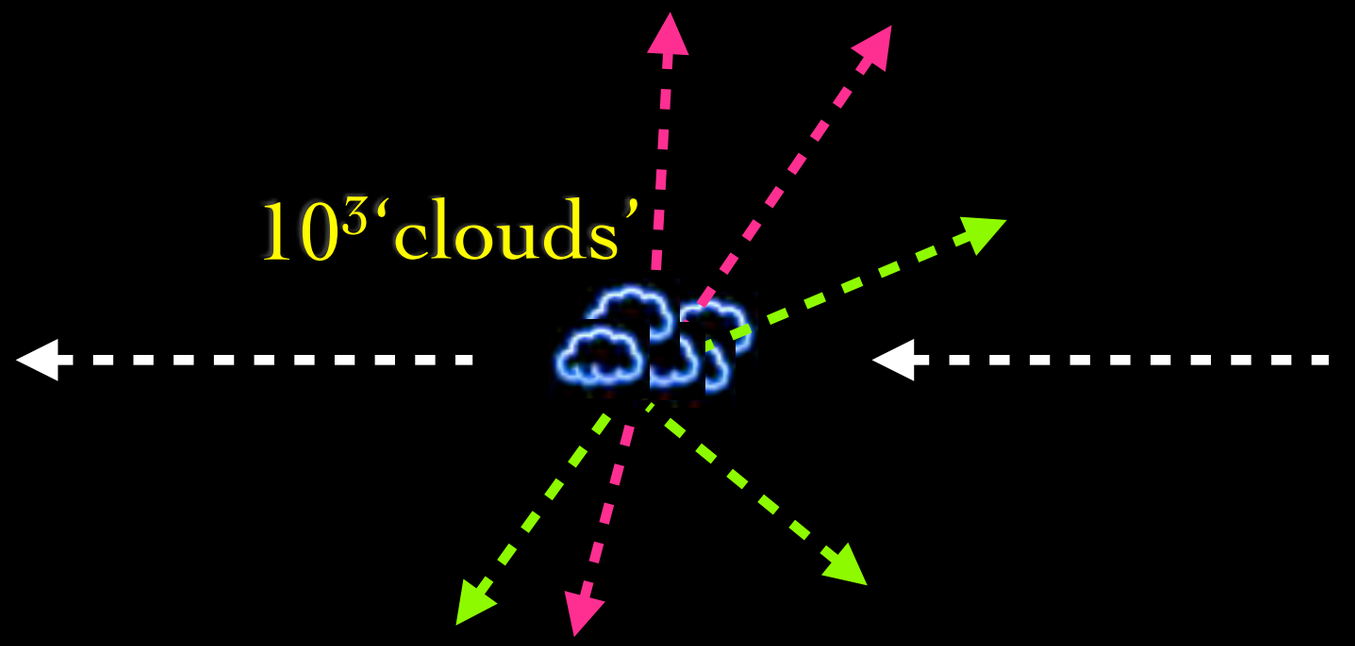

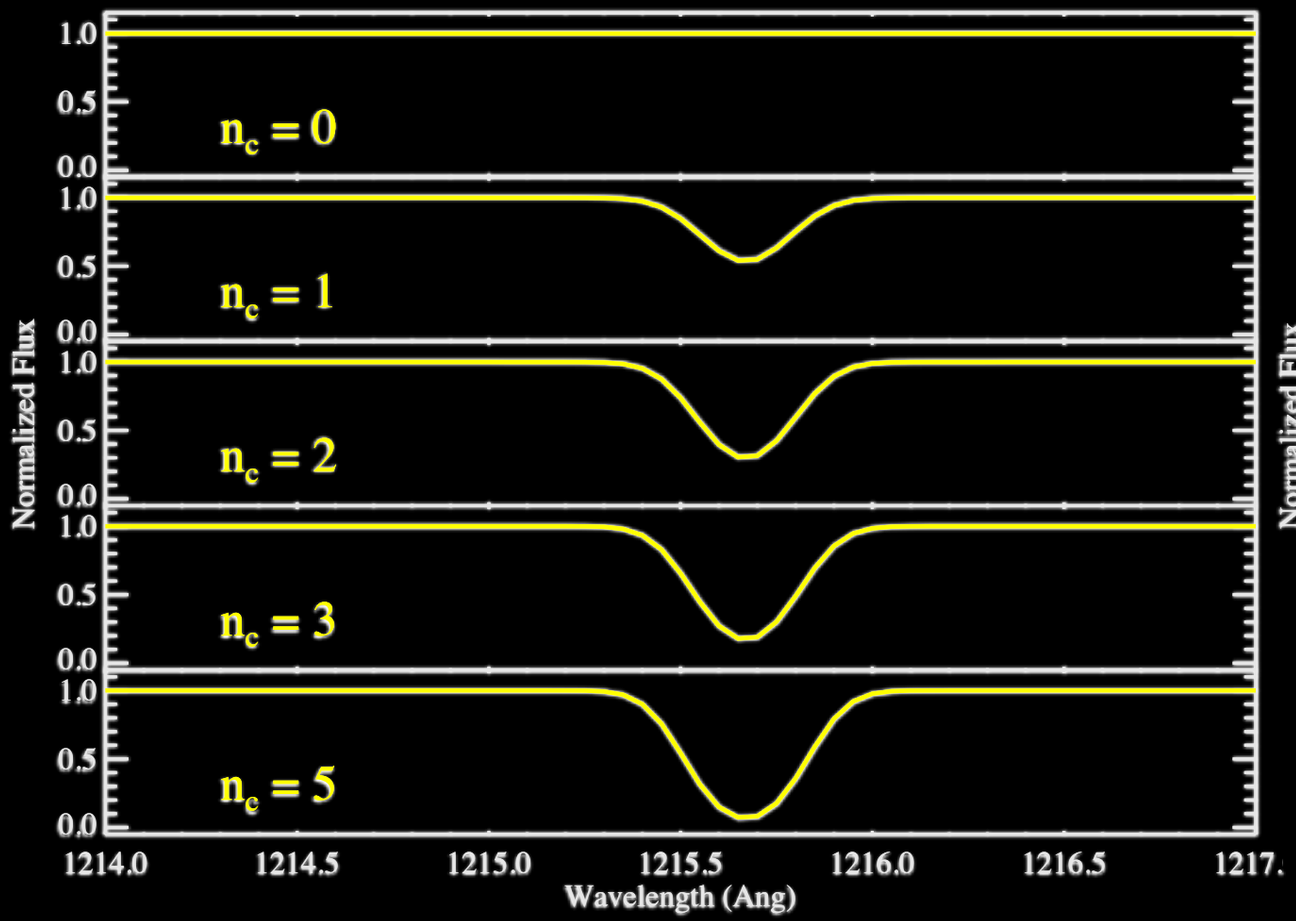

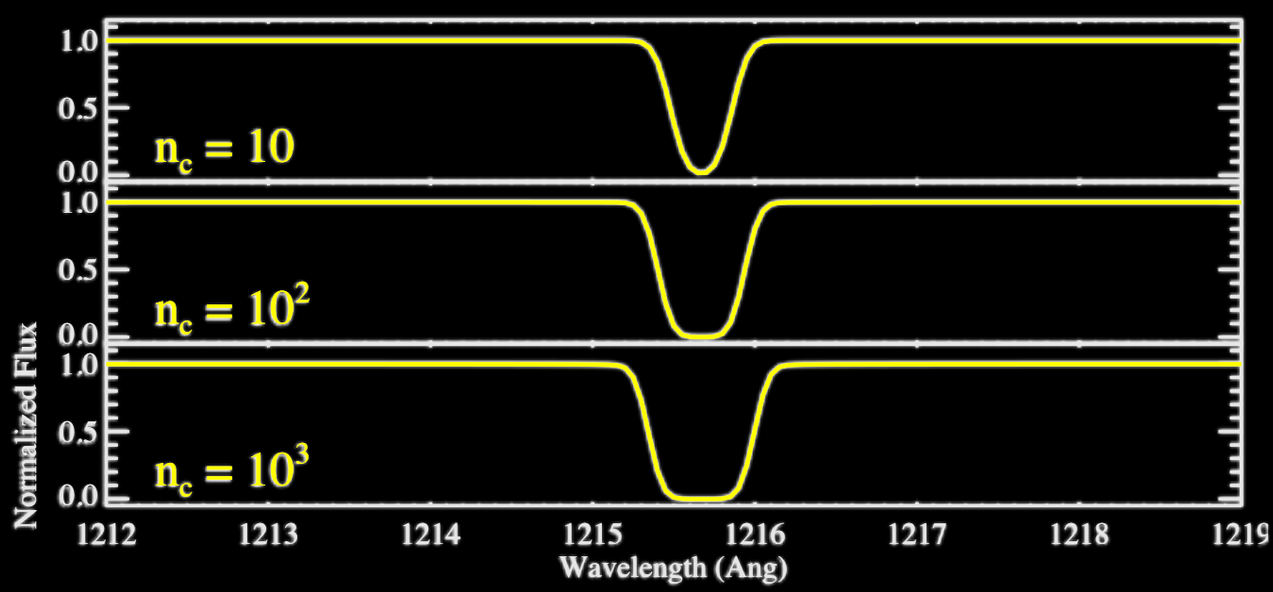

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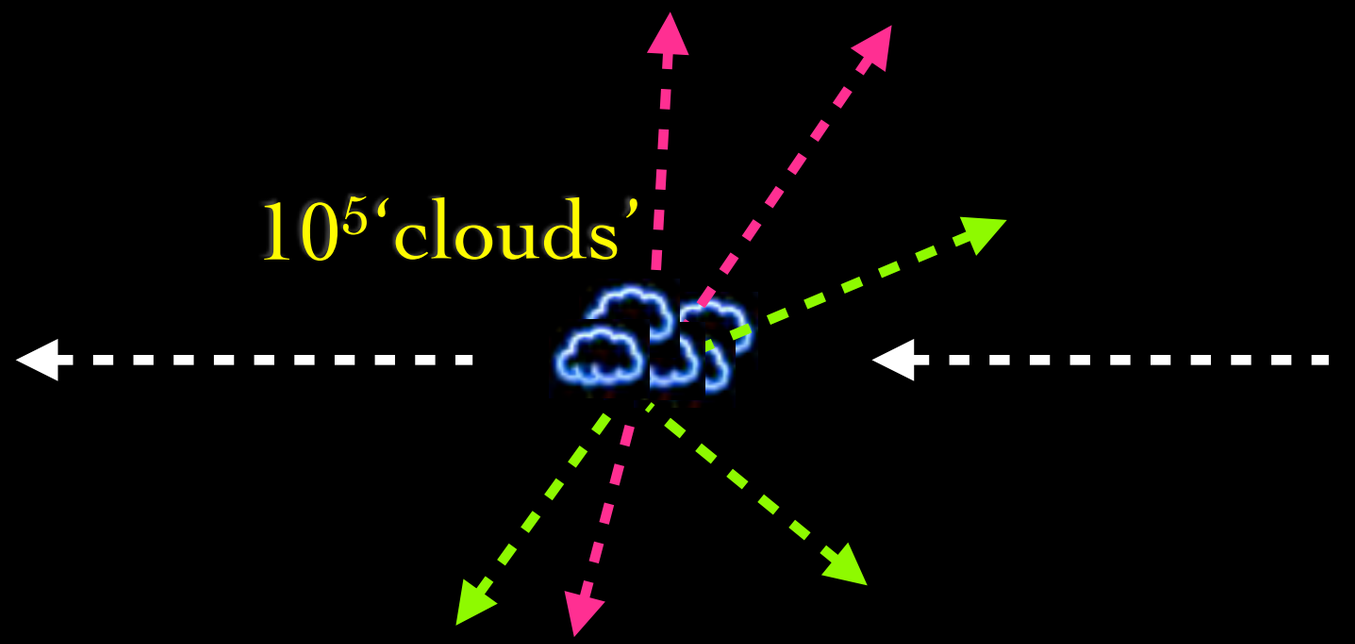

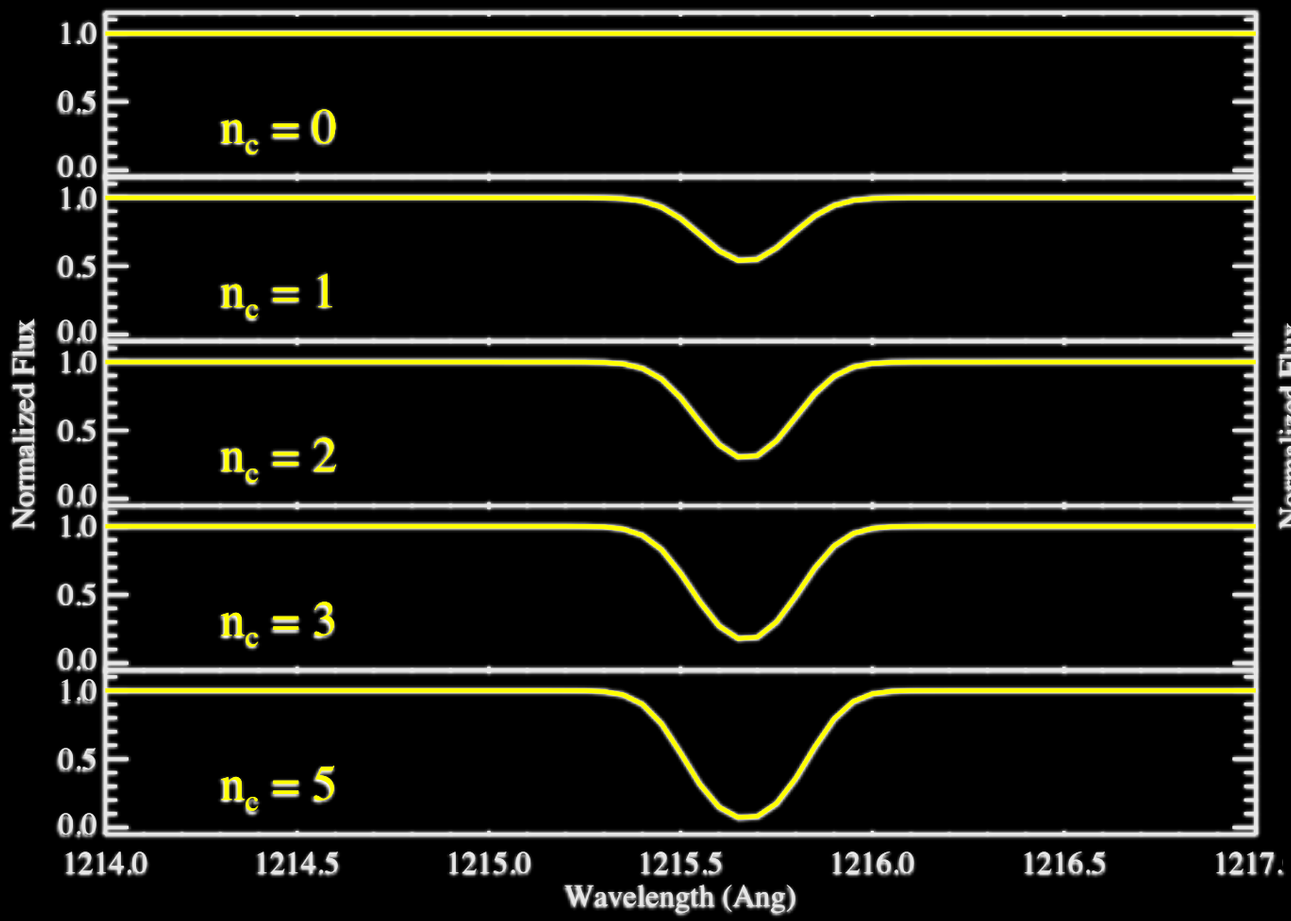

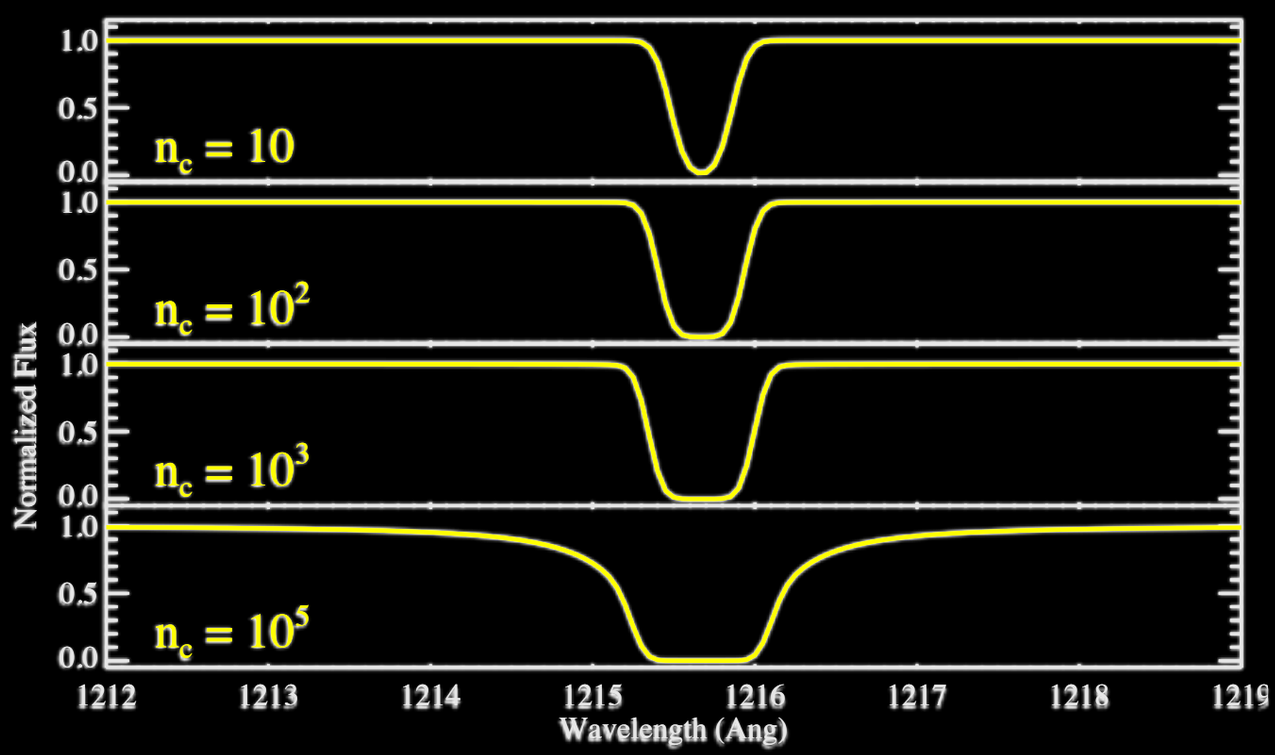

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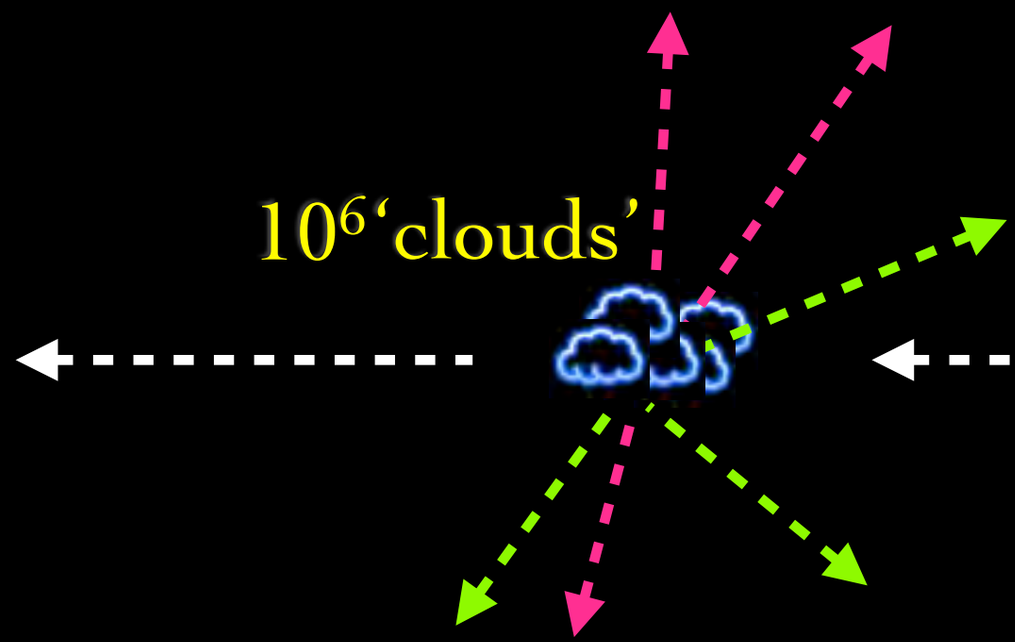
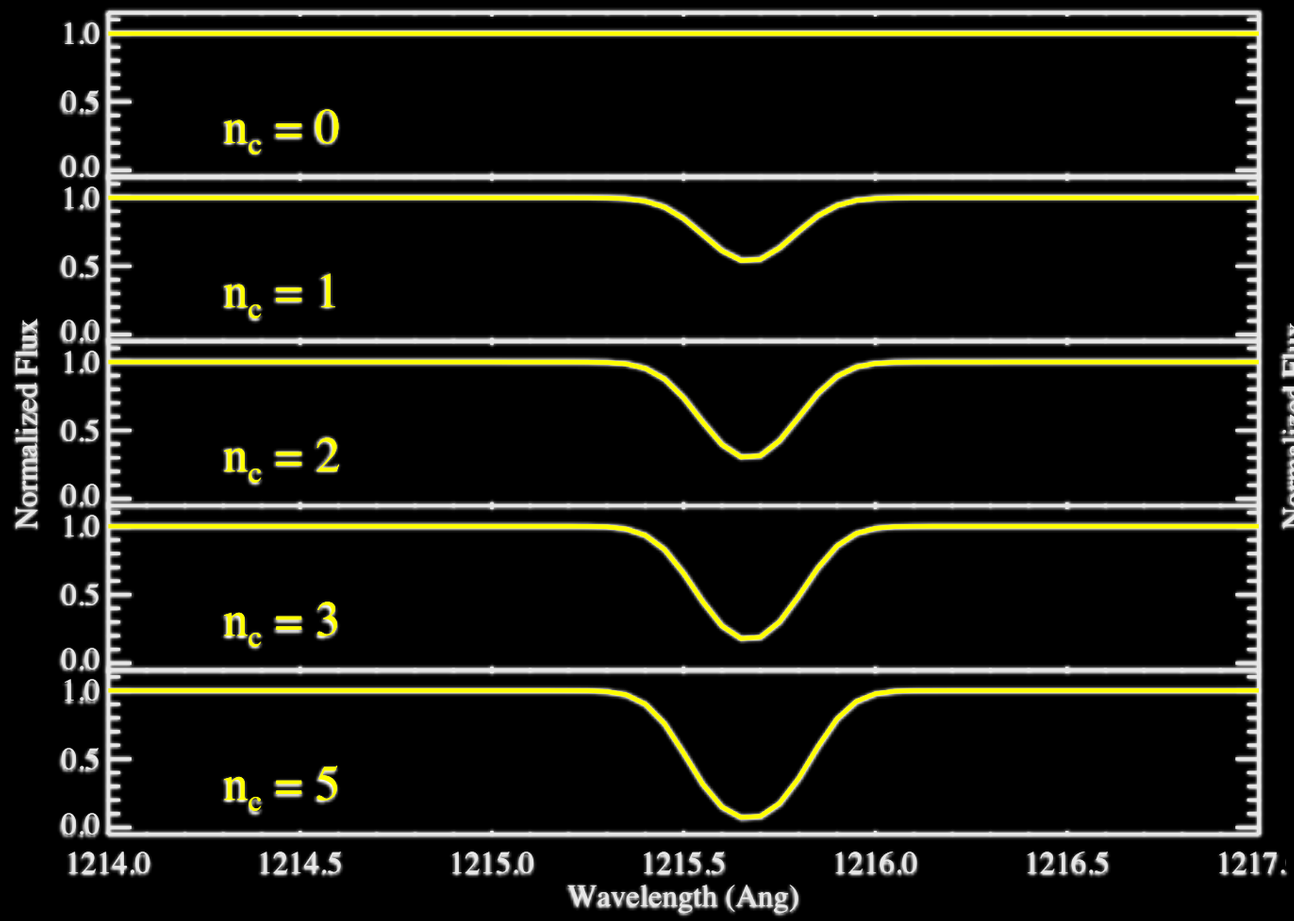
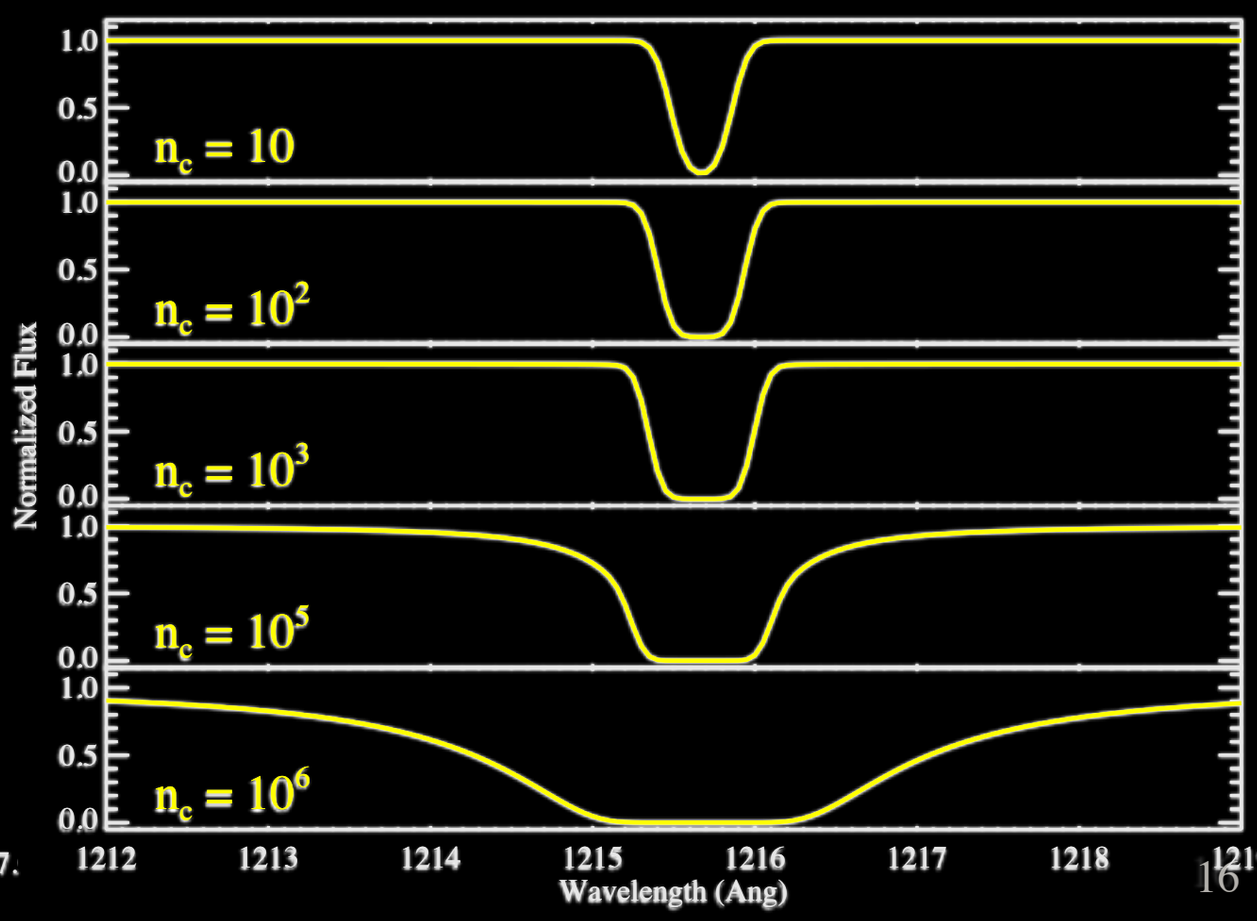


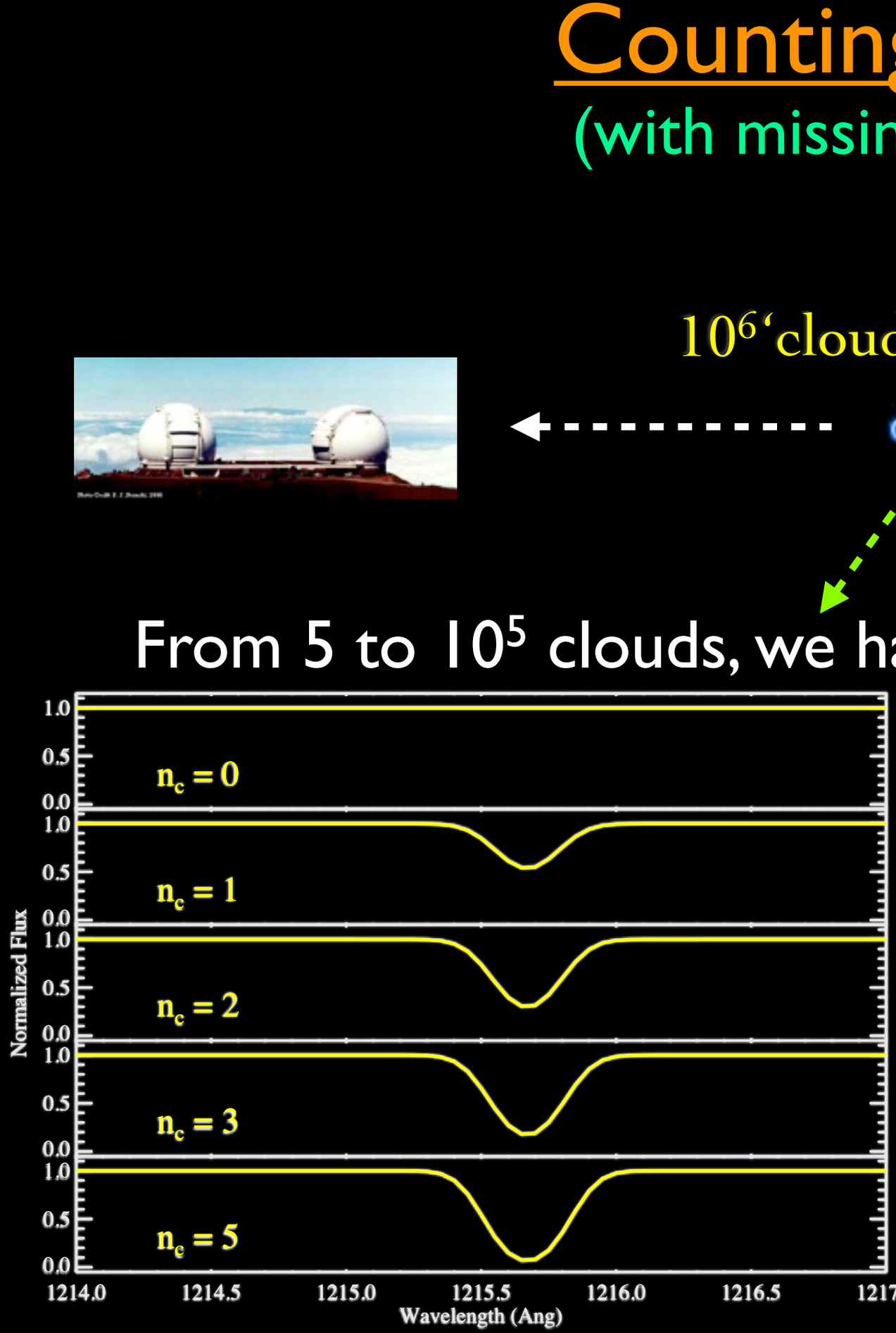


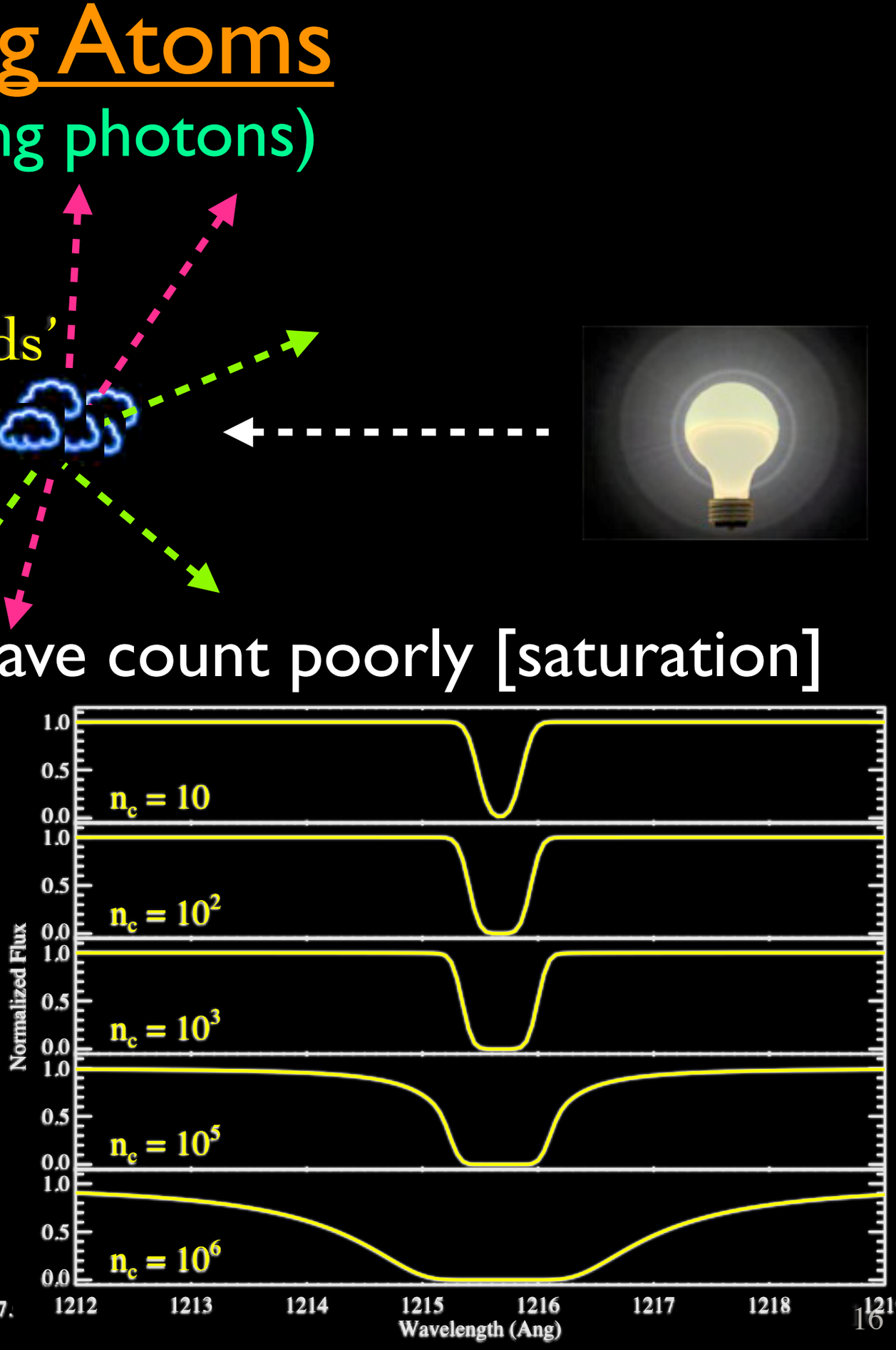


Counting Atoms

(with missing photons)

From 5 to 10^5 clouds, we have count poorly [saturation]





Simple Radiative Transfer

I_ν

Opacity, Emissivity

κ_ν, j_ν

I^0_ν

Equation of Transfer

$$\frac{dI_\nu}{dl} = -\kappa_\nu I_\nu + j_\nu$$

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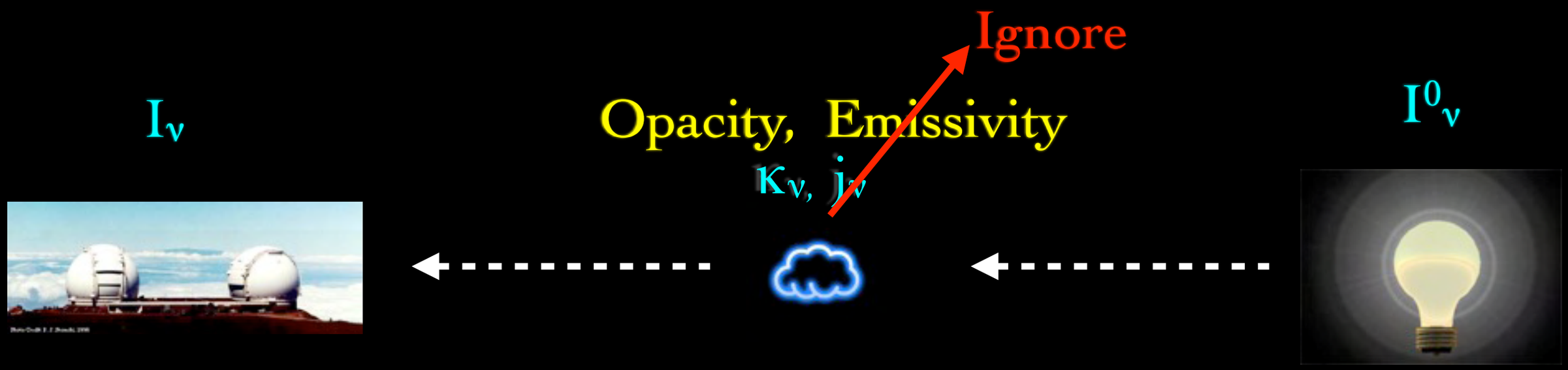

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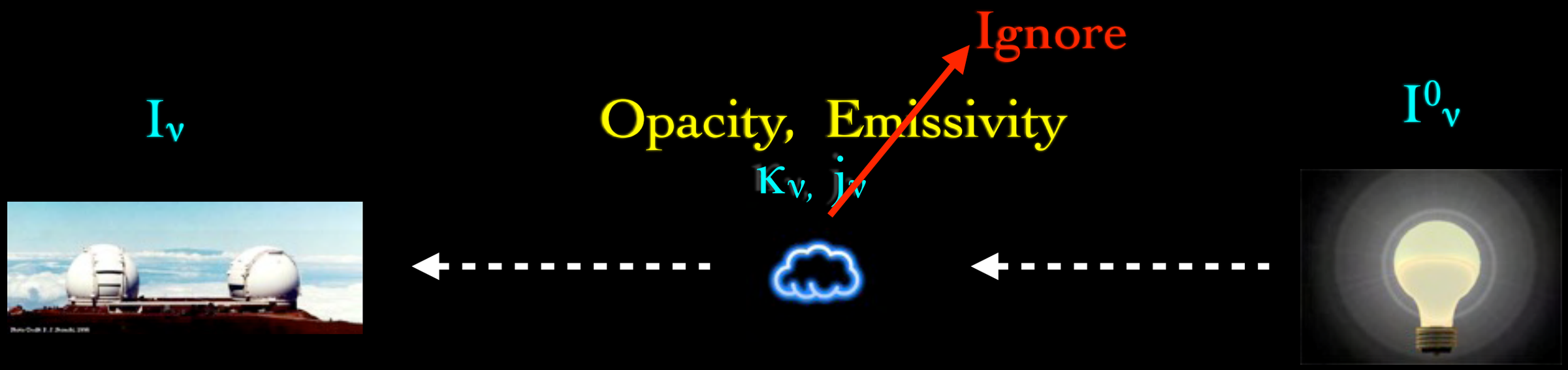

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Ignore

Opacity and Optical Depth

$$\kappa_\nu = s_\nu n$$

$$s_\nu = \frac{\pi e^2}{m_e c} f\ \phi(\nu)$$

Opacity and Optical Depth

- Opacity: κ_ν
  - Defines the energy absorbed from the path
    - ✦ per unit time, volume and dν
  - Inversely proportional to the mean free path

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Integrating: $I_\nu = I_\nu^0 \exp(-\tau_\nu)$

Column Density

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- N
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    - particles cm^{-2}
  - Consider a cylinder
    - Integrate particles within
    - Divide by area

Column Density

- N
  - # of particles per unit area
    - particles cm^{-2}
  - Consider a cylinder
    - Integrate particles within
    - Divide by area
- This is the key physical quantity
  - Derived from the observations
  - Trivial relation with the volume density:

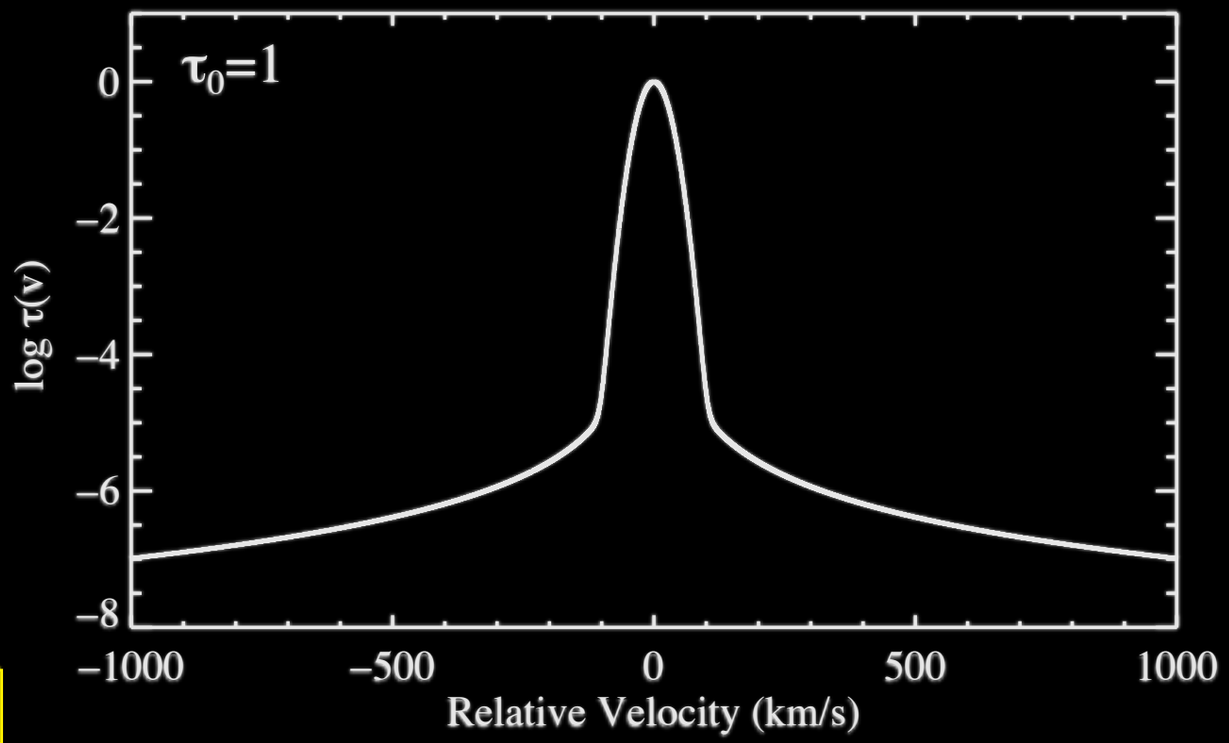
$$N = \int n \, dl$$

Putting it all together...

$$\tau_\nu = s_\nu N$$

$$\tau_0 = \frac{\pi e^2}{m_e c} N f \phi(\nu = \nu_{jk})$$

$$= \frac{\sqrt{\pi} e^2}{m_e c} \frac{N f \lambda_{jk}}{b} \quad \text{[Doppler]}$$



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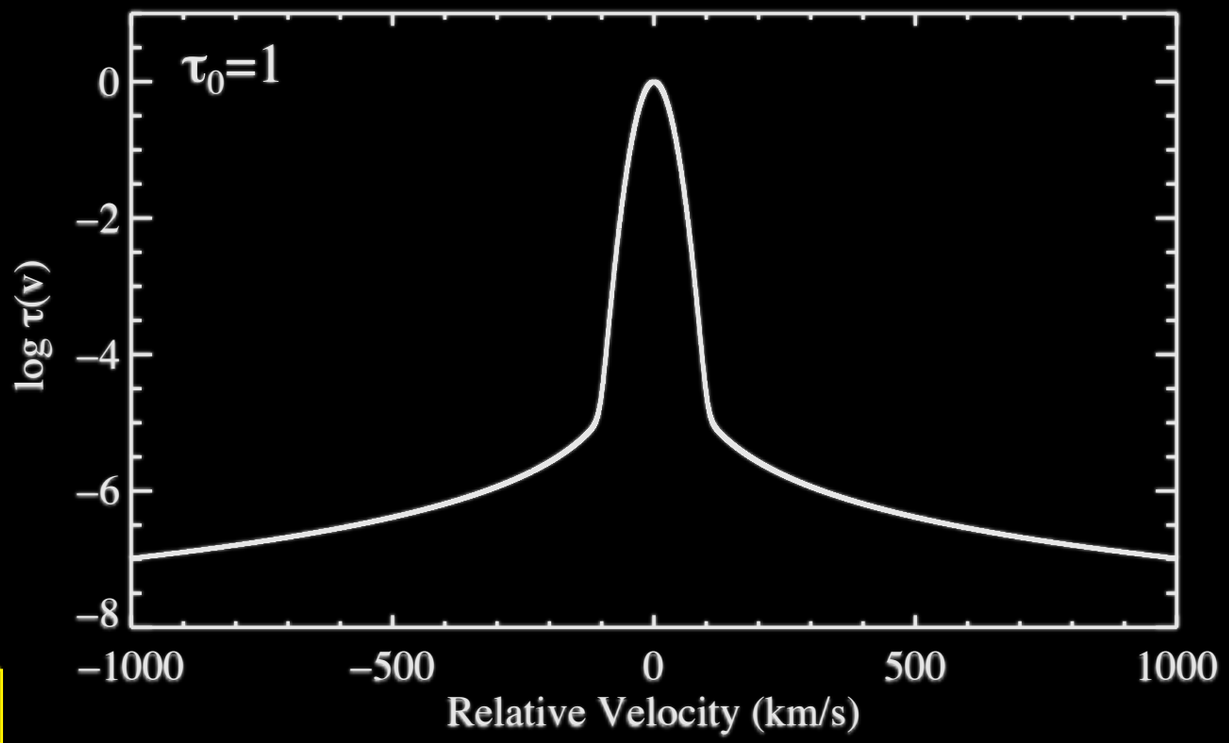

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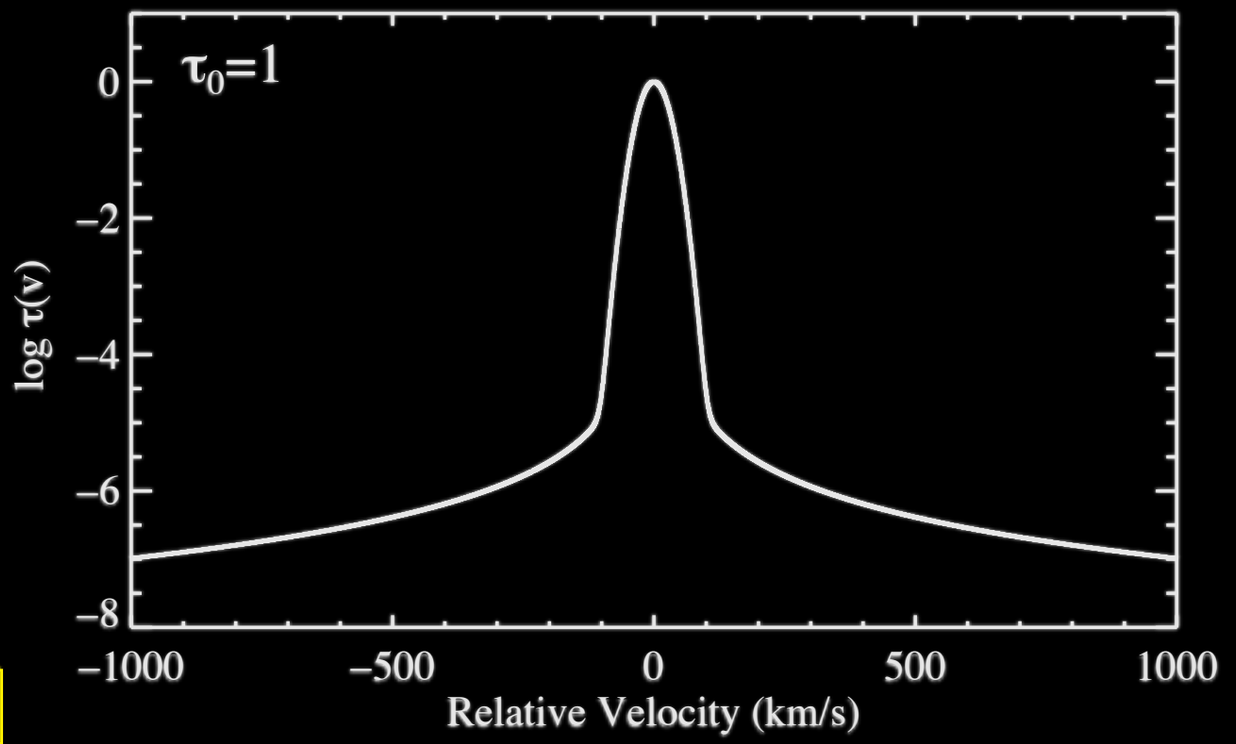

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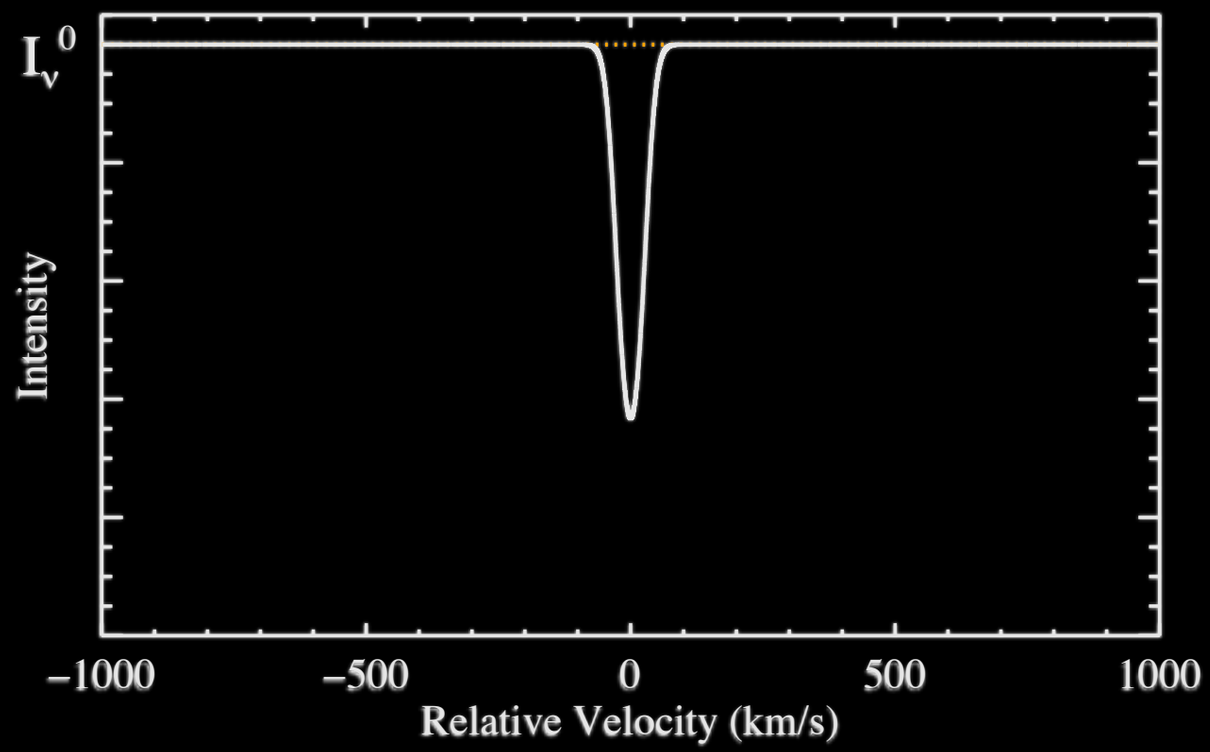

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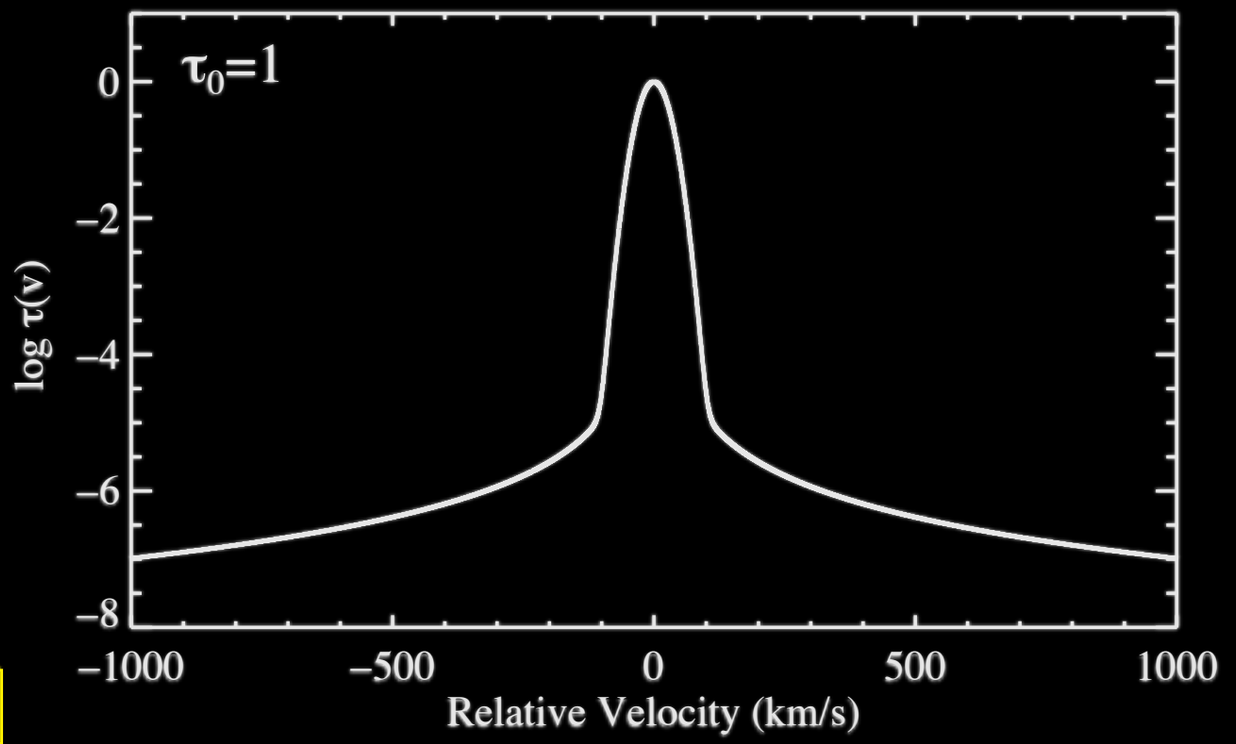

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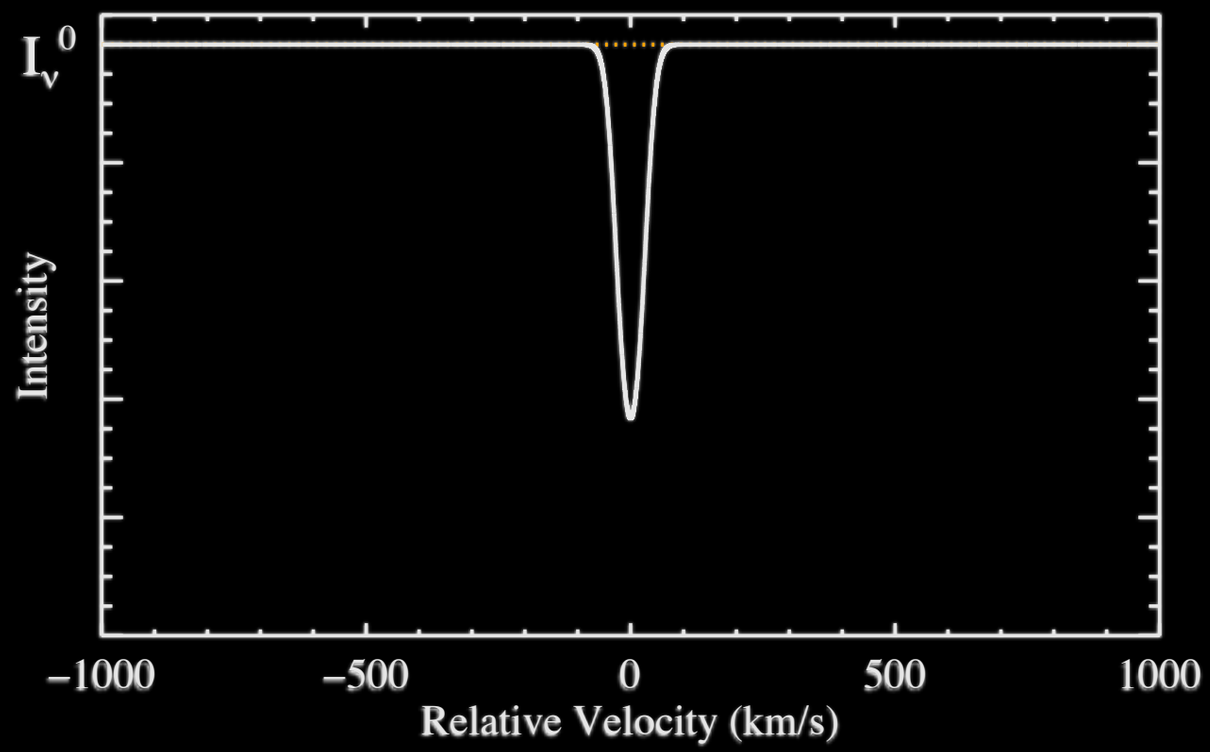
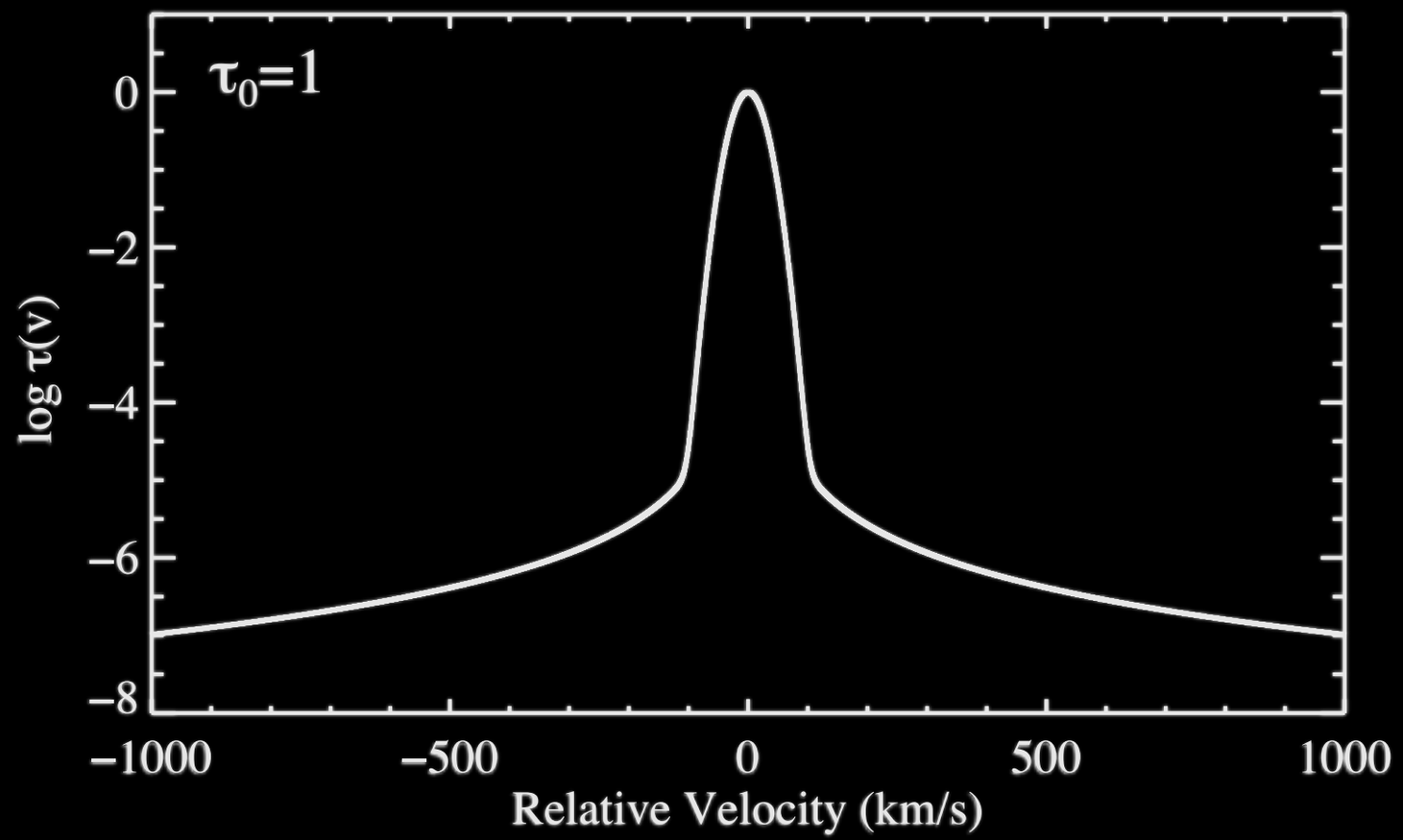
Note: Optical depths add, not Intensities



Lyα: An Example

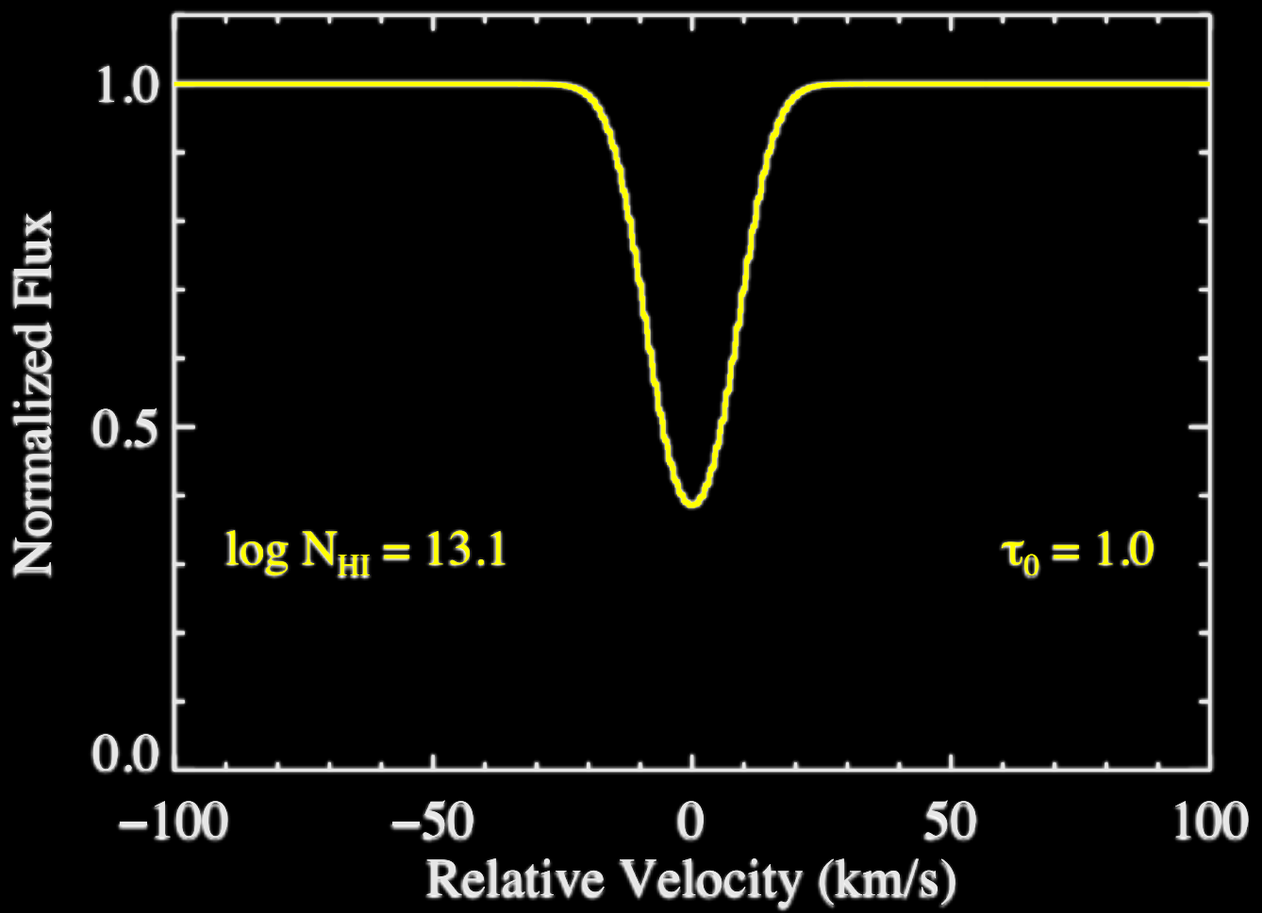
- 1s to 2p transition
  - f = 0.4164
  - λ = 1215.6701 Angstroms
- 'Cloud' of HI atoms
  - N_{HI} = 10^{12} to 10^{21} cm^{-2}
  - T = 1000 K
  - b_{Therm} = 4 km/s
  - b_{Turb} = 5 to 30 km/s

$$\tau_0^{\mathrm{Ly}\alpha} = \frac{N_{\mathrm{HI}}}{10^{13.1}\,\mathrm{cm}^{-2}} \left[\frac{b}{10\ \mathrm{km\,s}^{-1}} \right]^{-1}$$



Lyα: Varying N_{HI} and b

Vary N_{HI}; b=10 km/s



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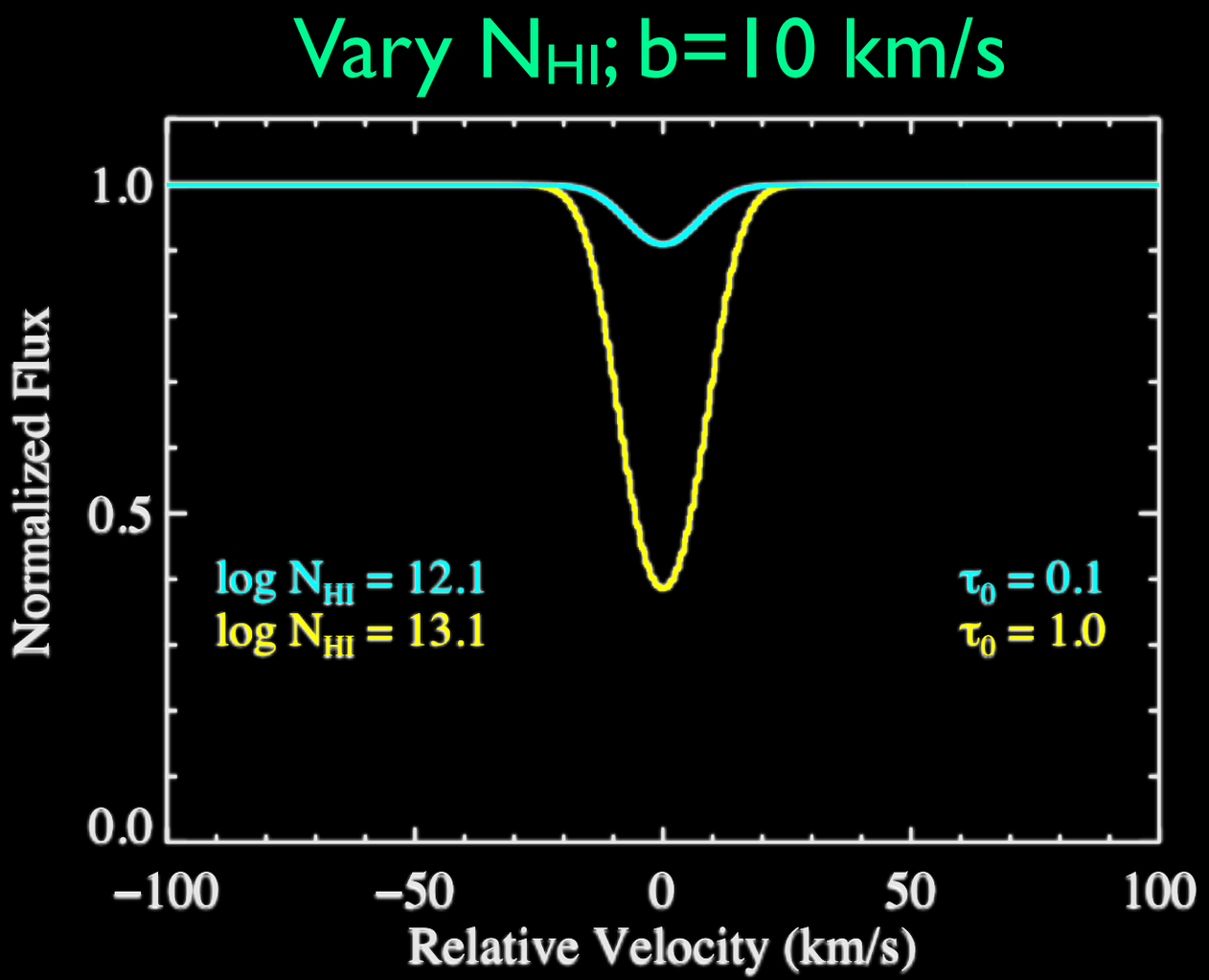

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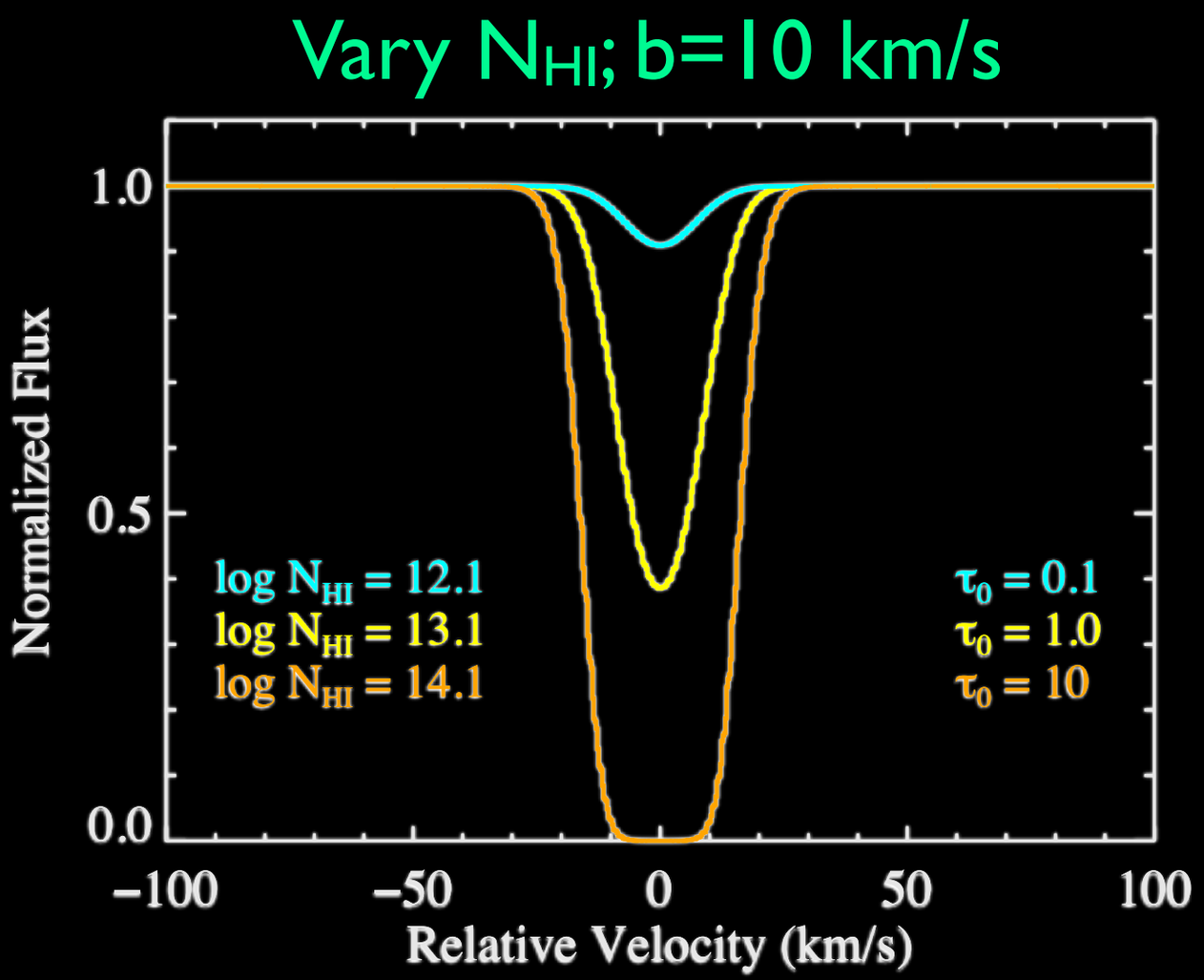

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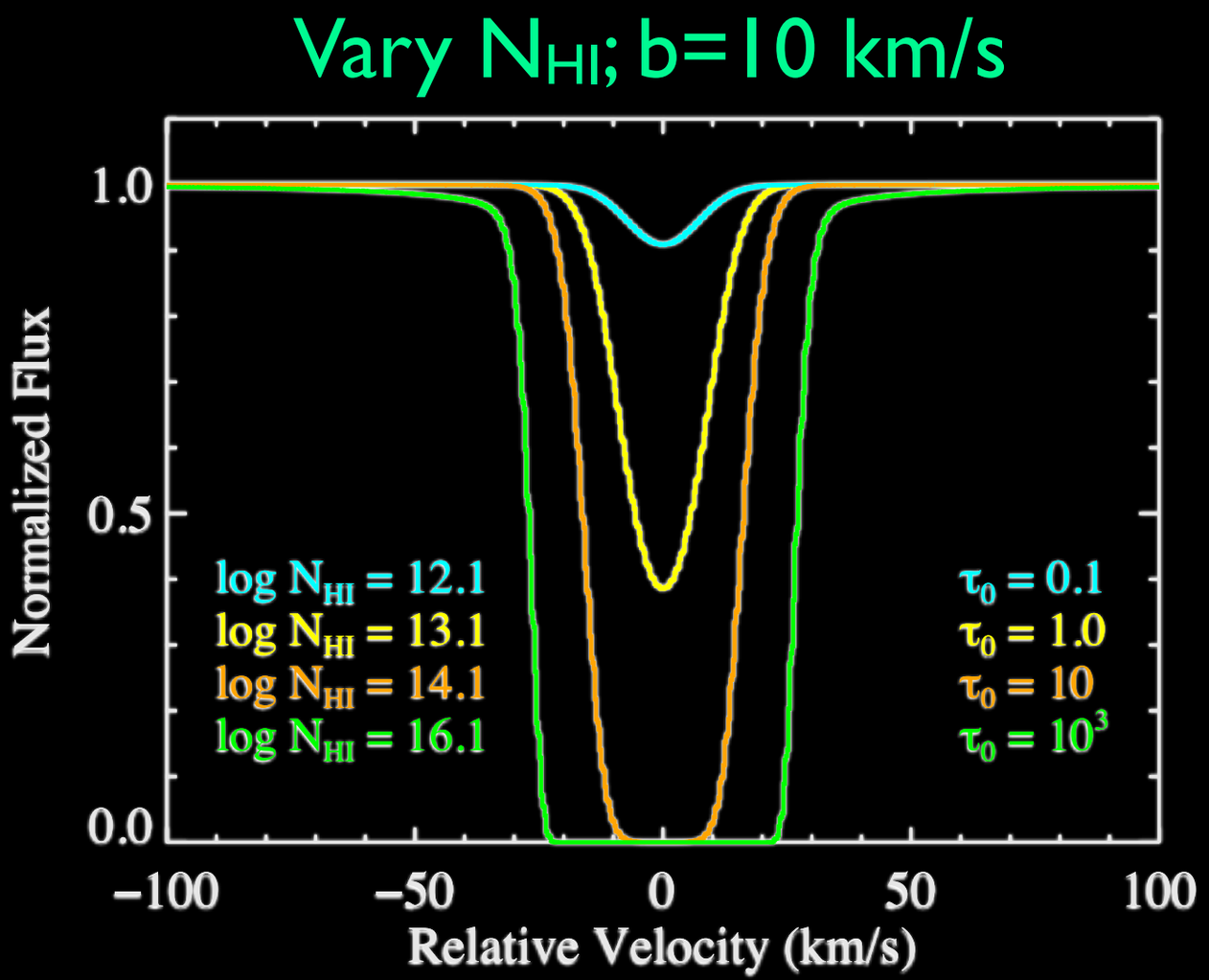

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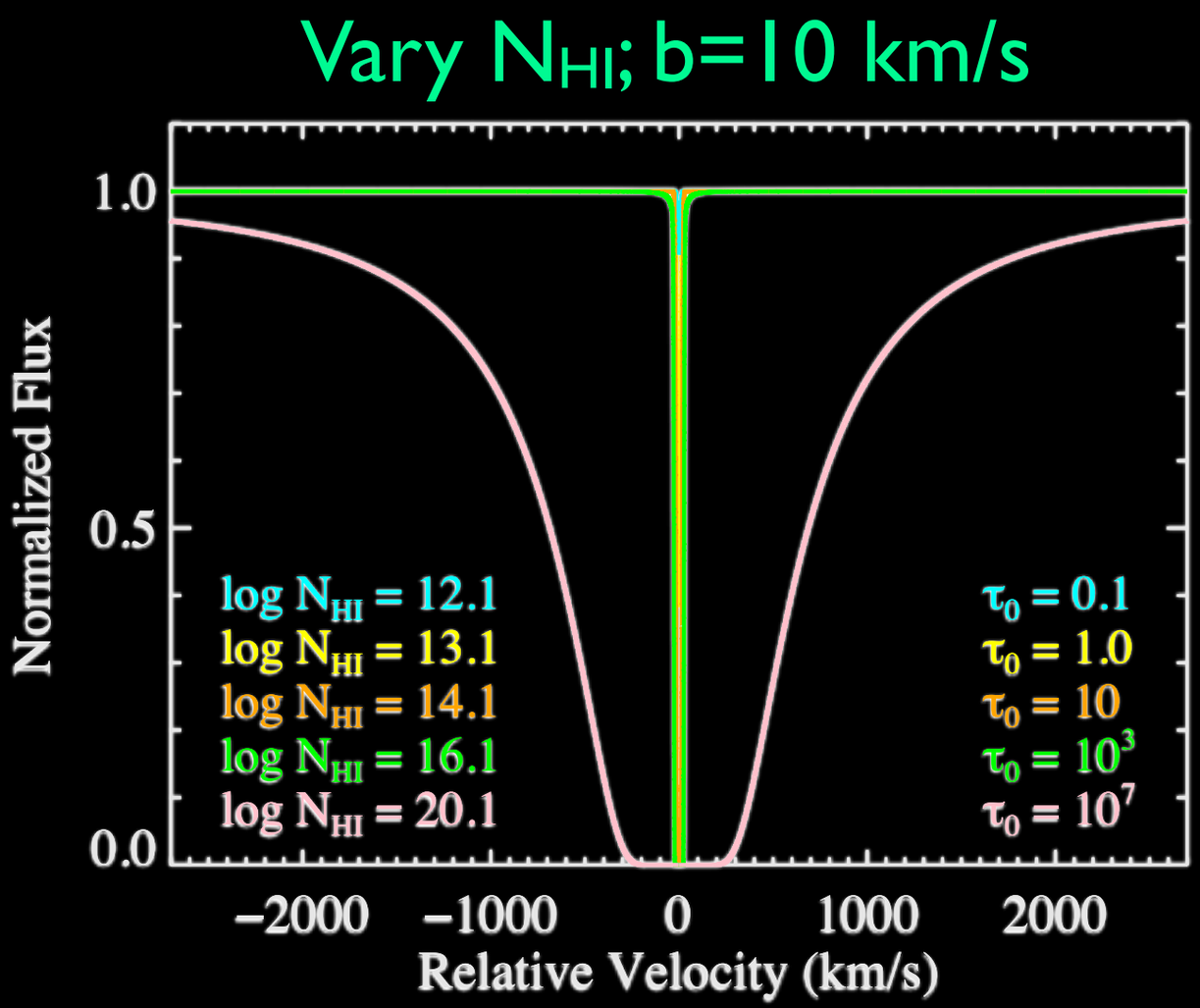

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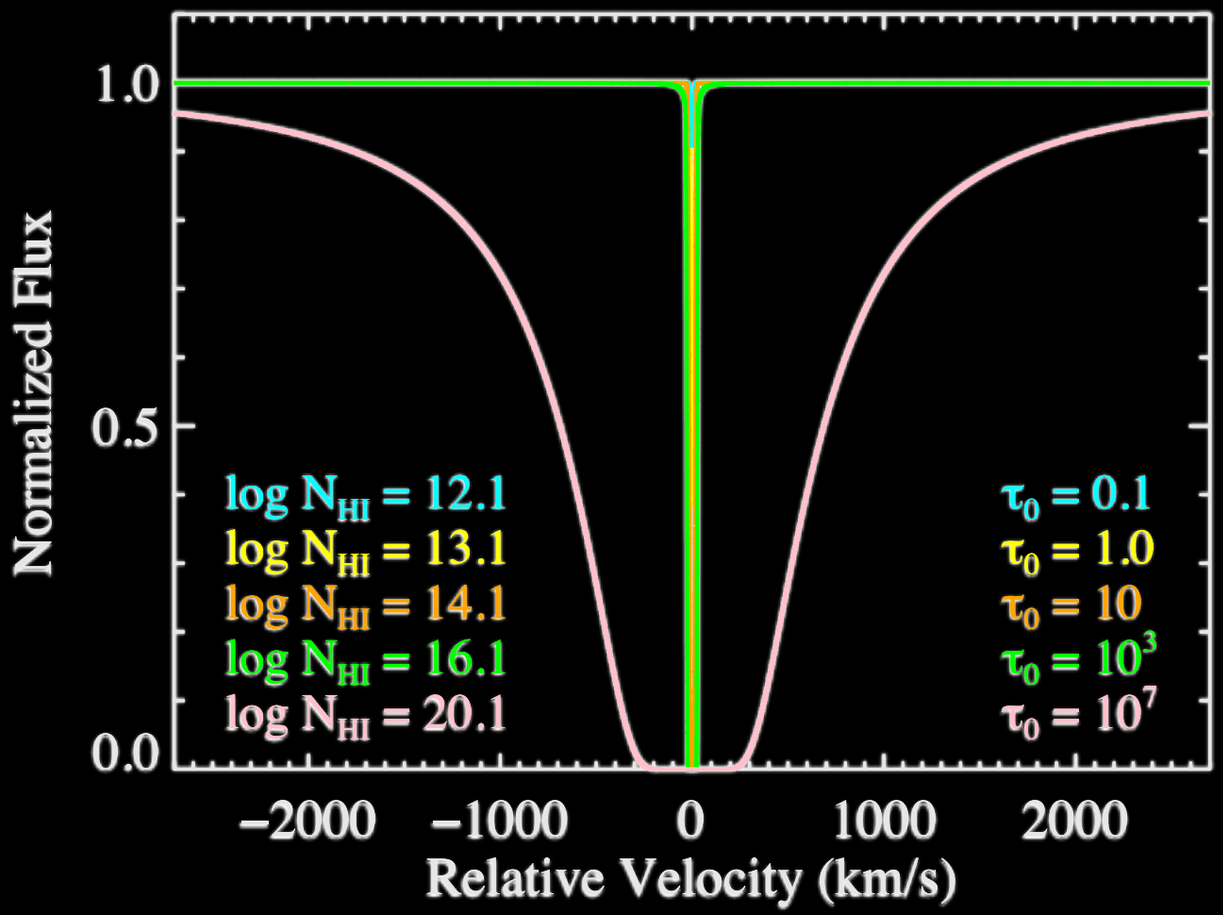

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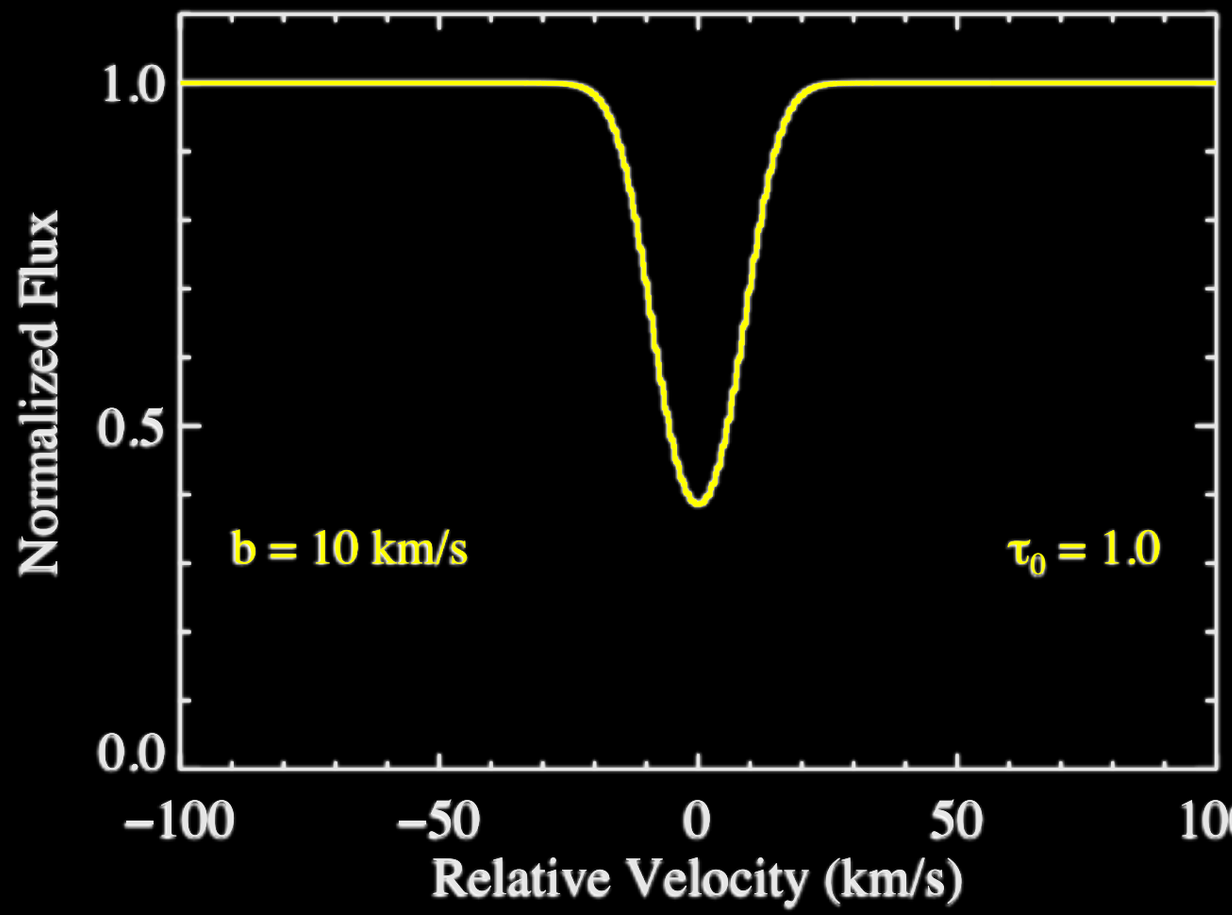

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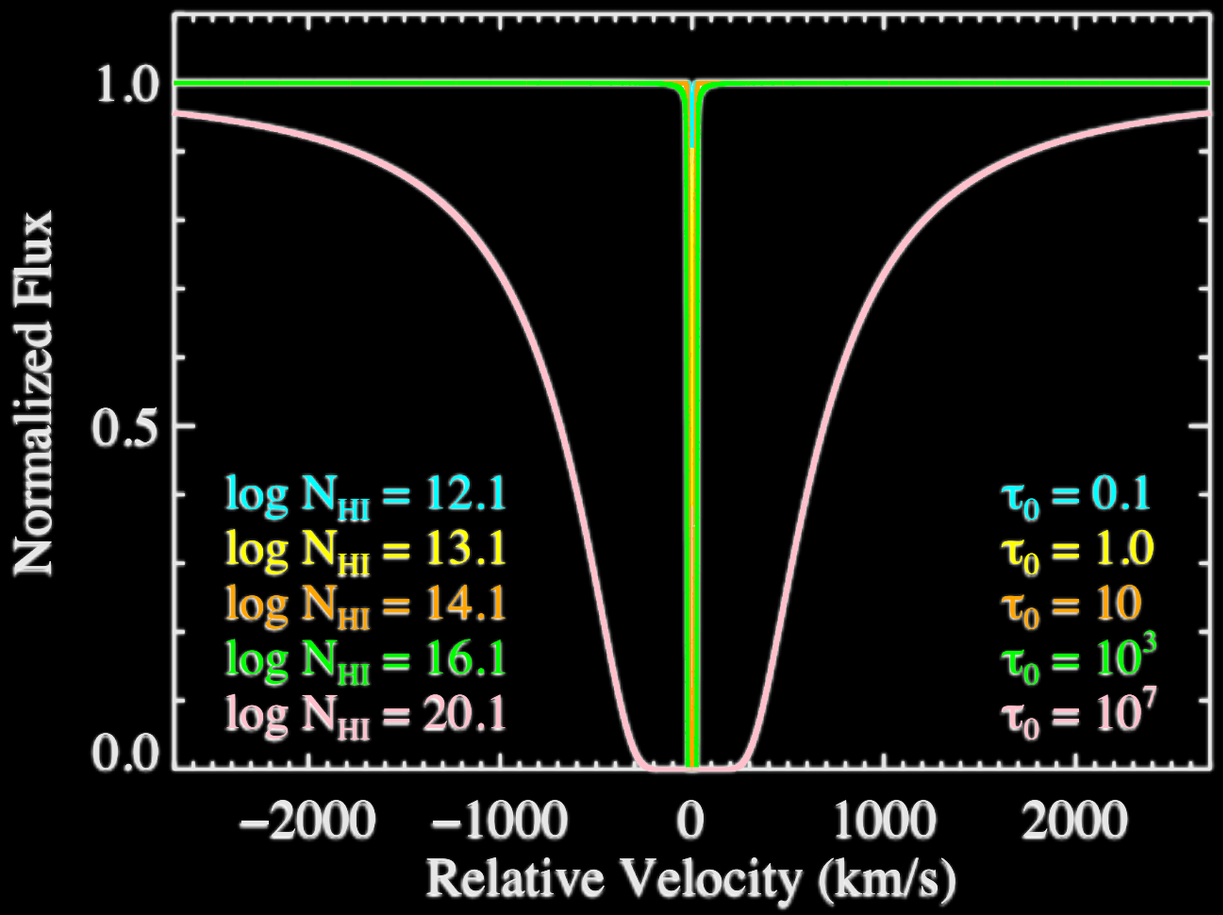

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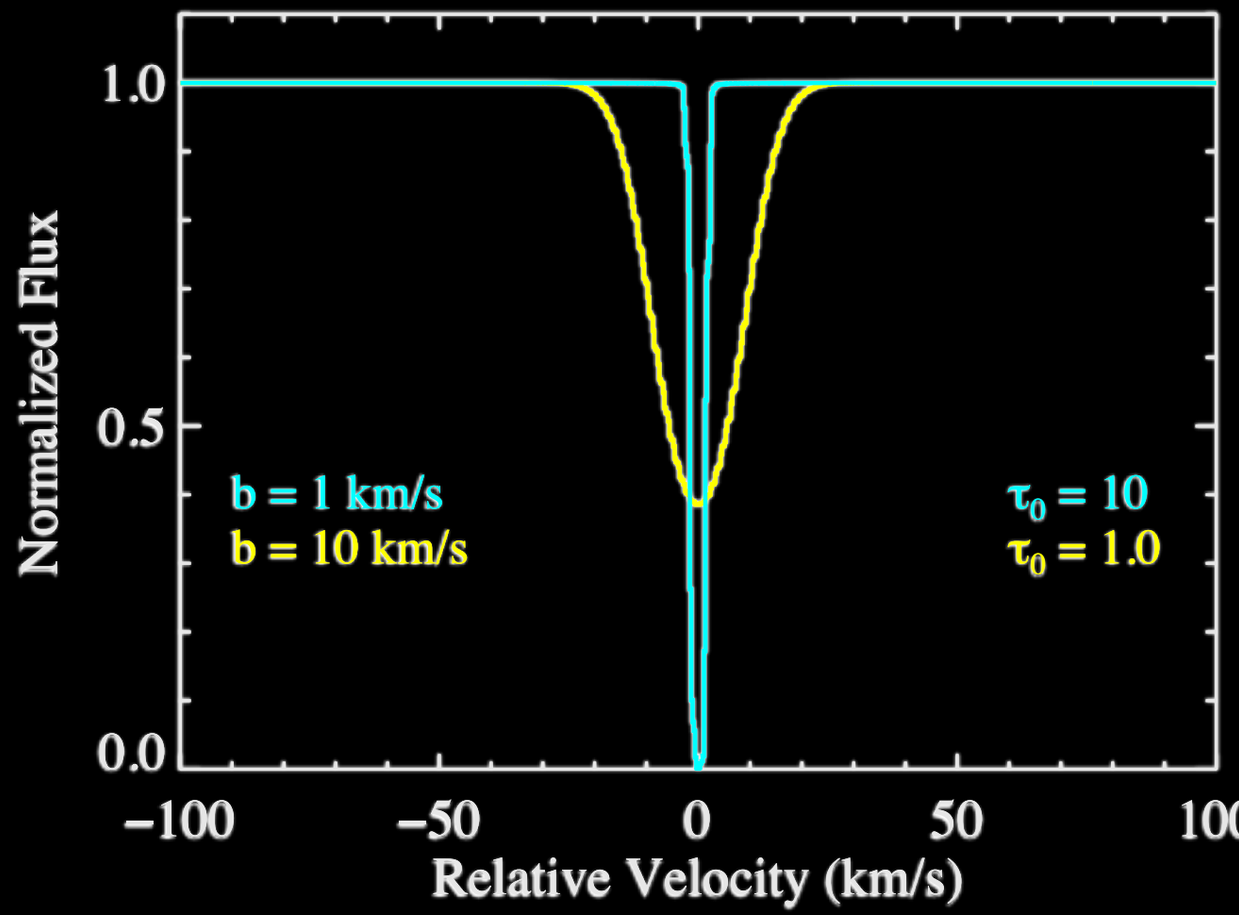

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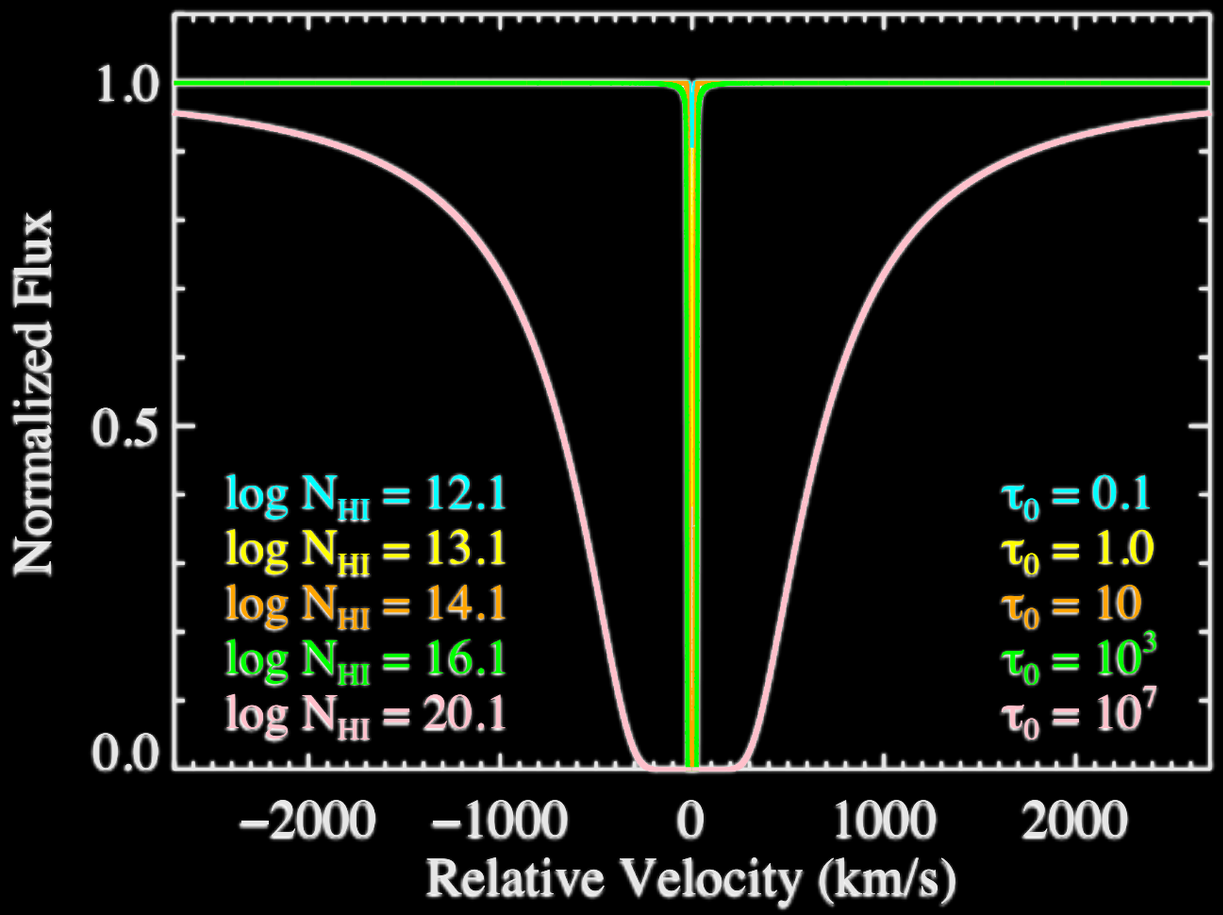

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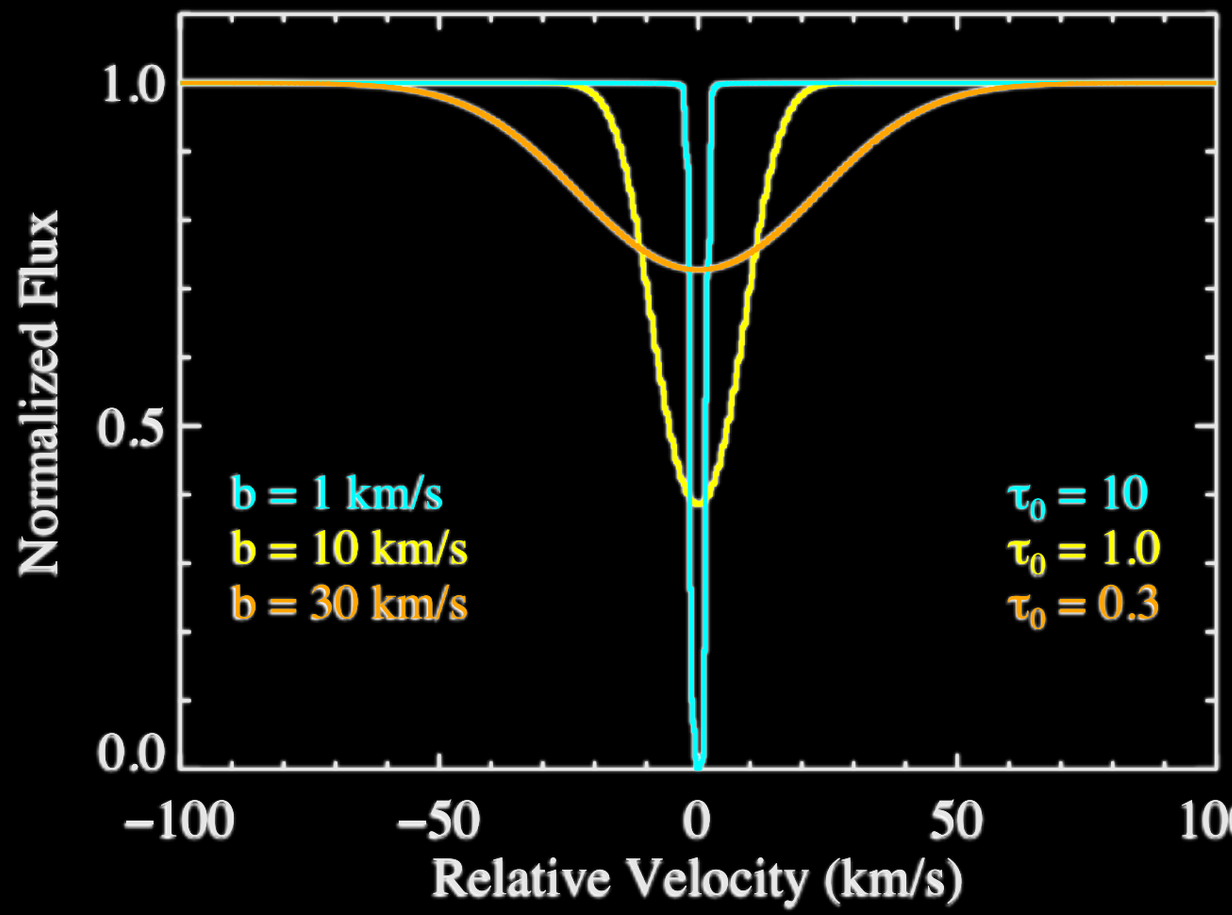

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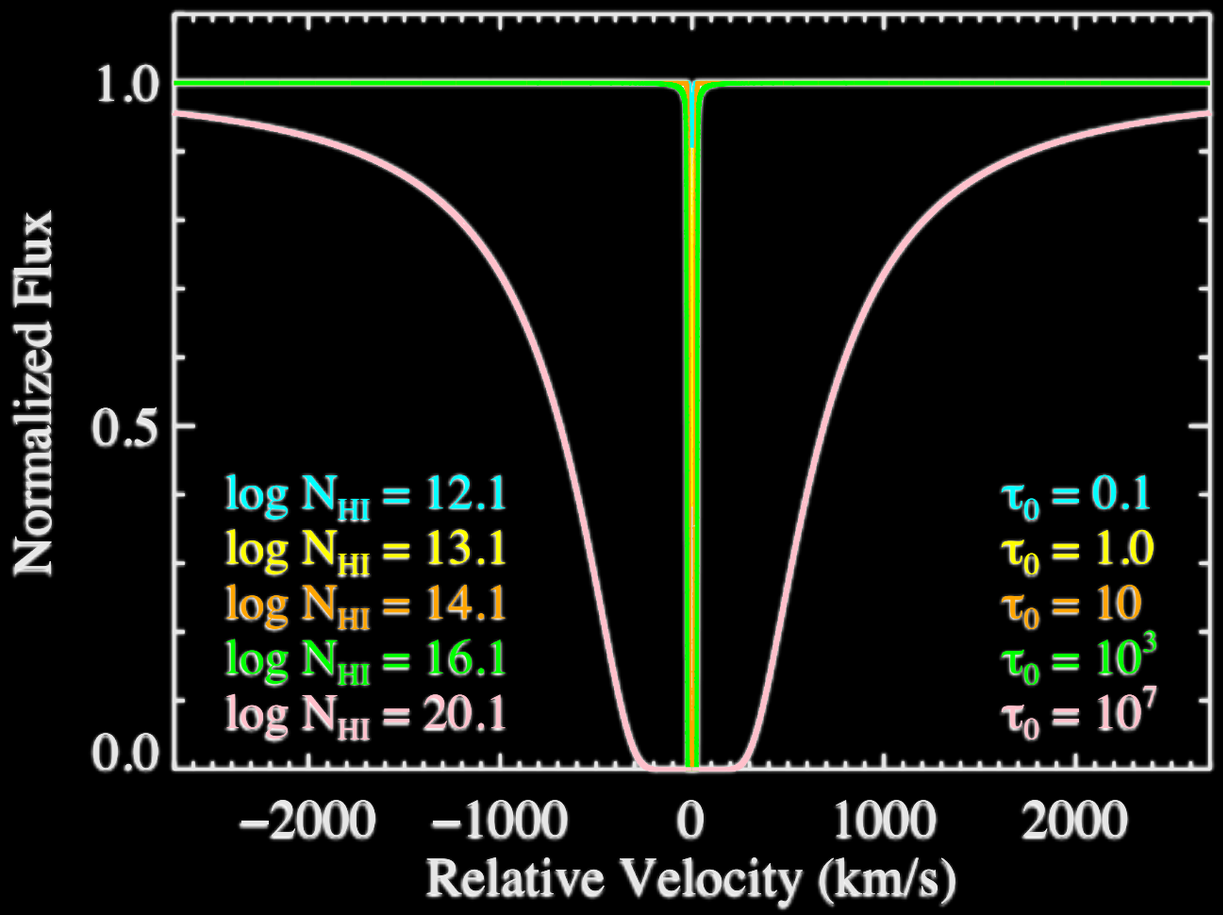

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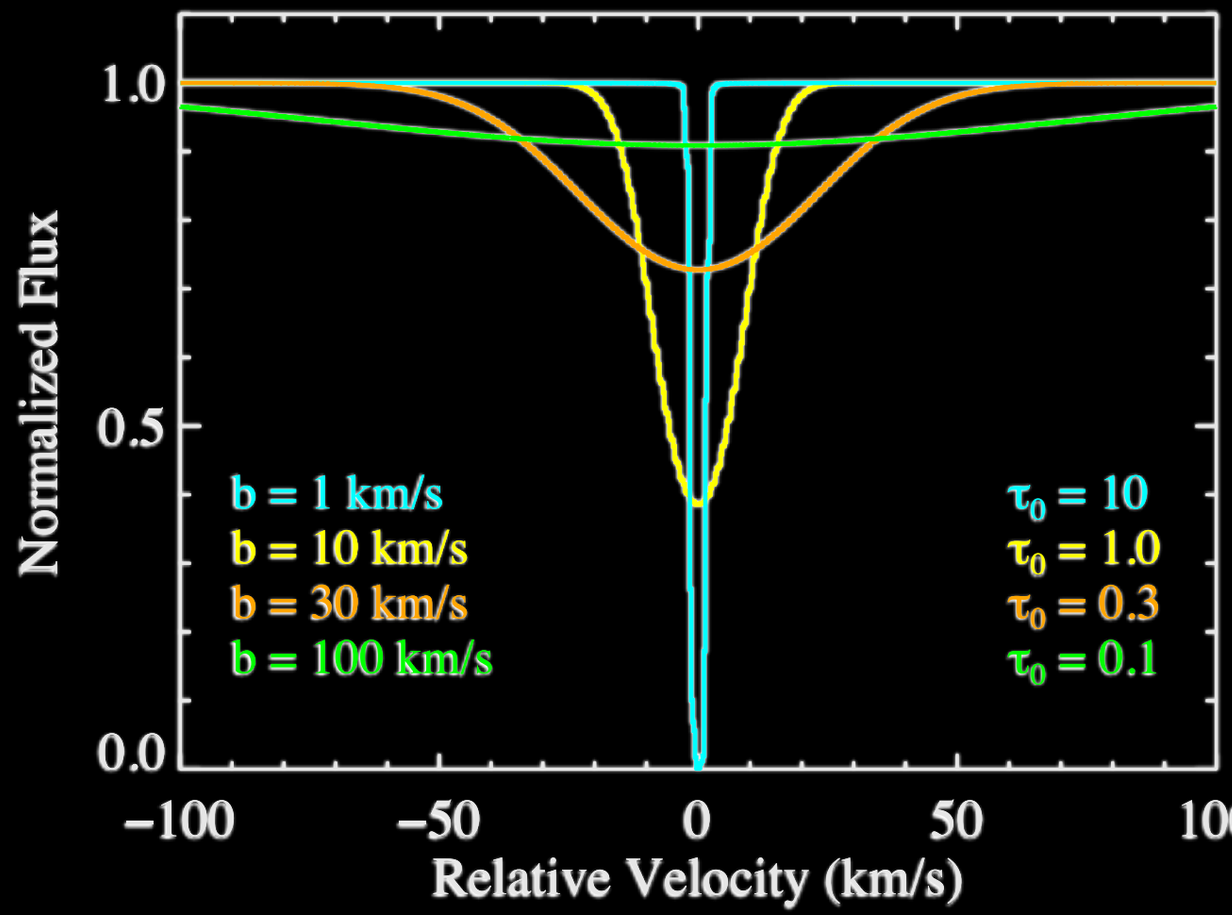
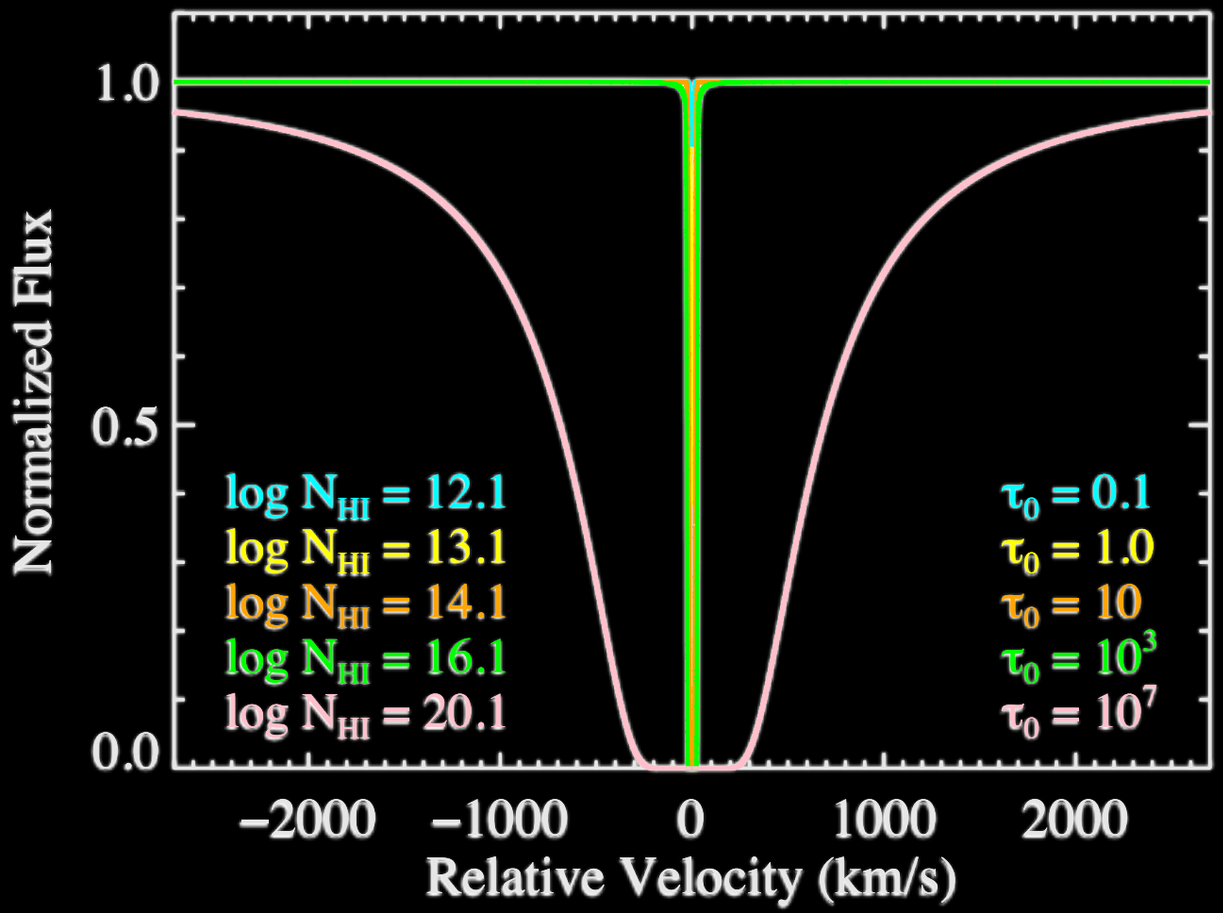


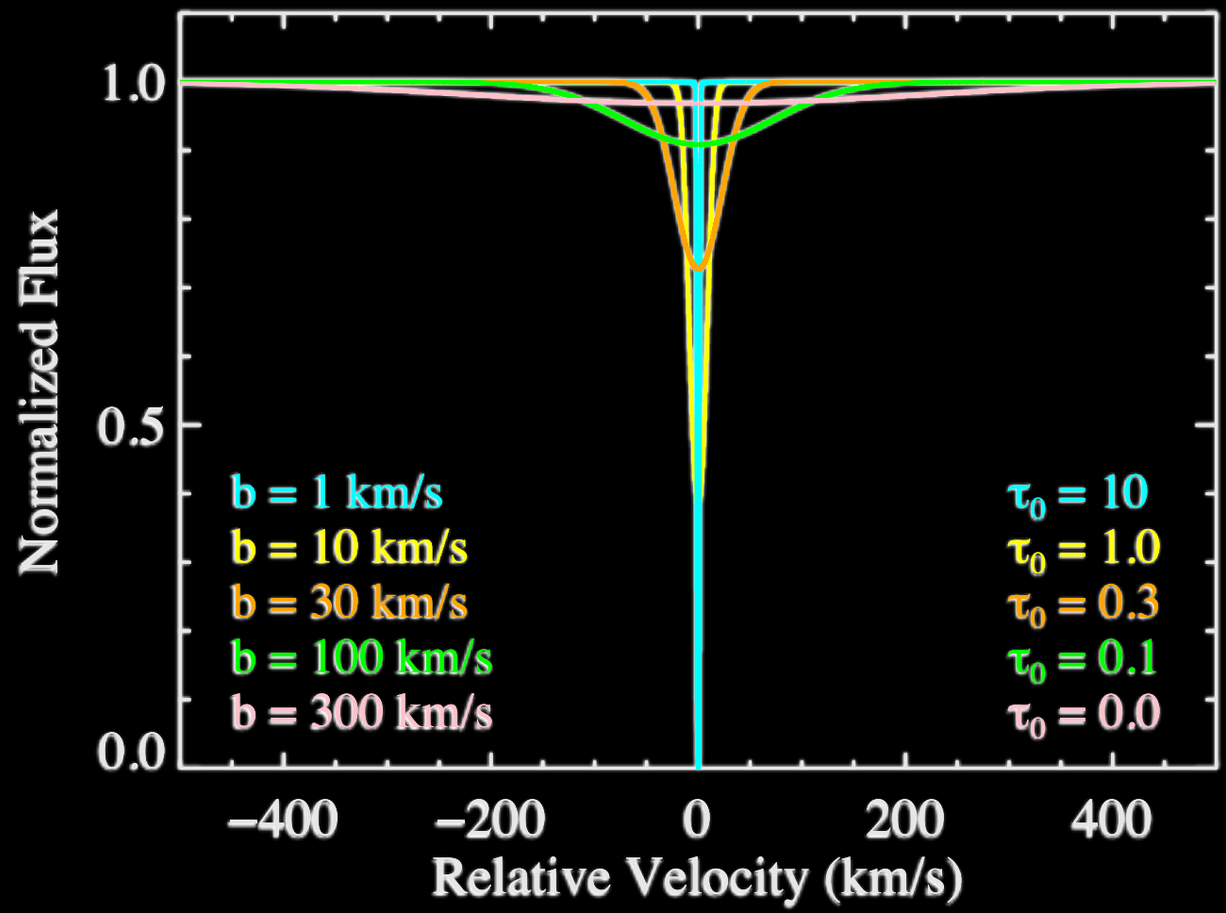
$$\tau_0^{\mathrm{Ly}\alpha} = \frac{N_{\mathrm{HI}}}{10^{13.1}\,\mathrm{cm}^{-2}} \left[\frac{b}{10\ \mathrm{km\,s}^{-1}} \right]^{-1}$$

Lyα: Varying N_{HI} and b

Vary N_{HI}; b=10 km/s



Vary b; $N_{HI}=10^{13.1}$ cm^{-2}



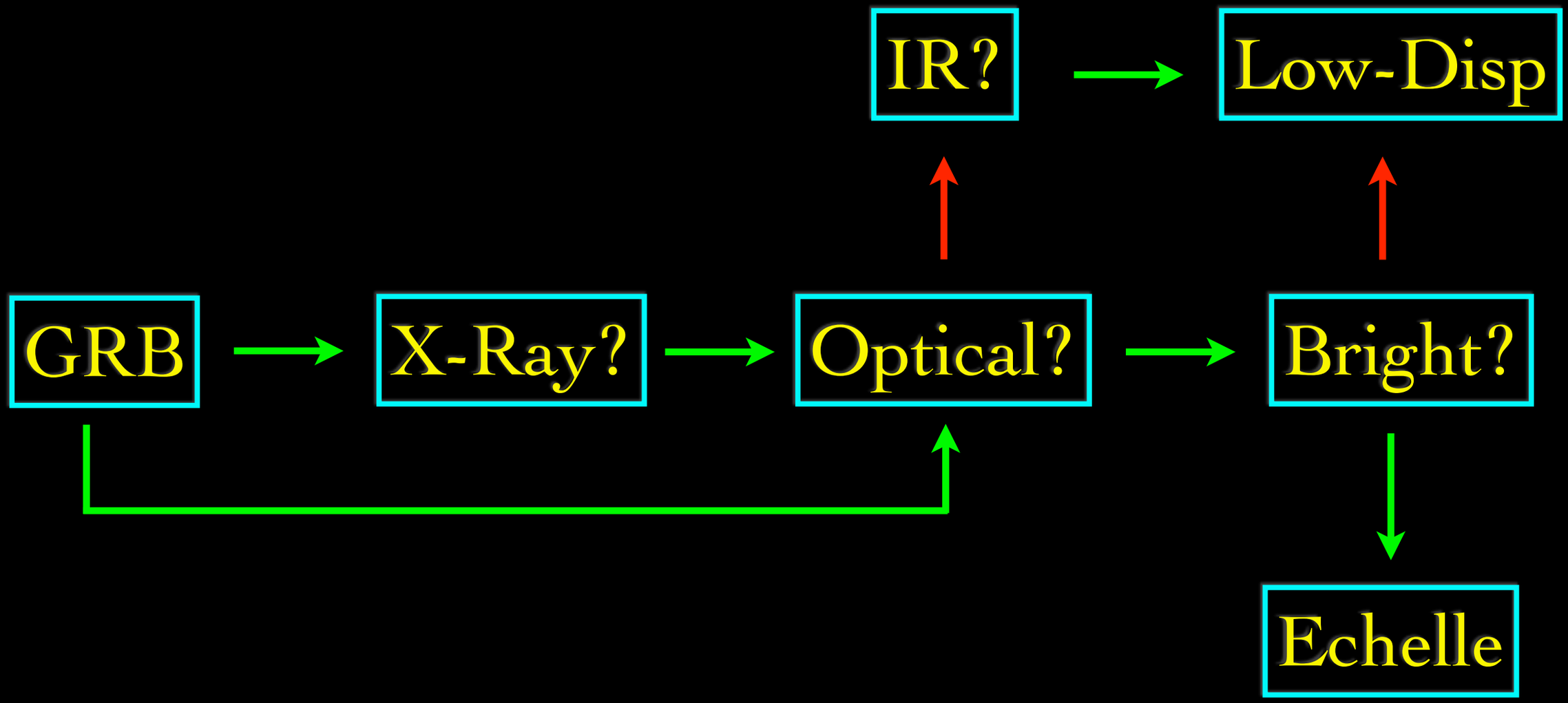
$$\tau_0^{\mathrm{Ly}\alpha} = \frac{N_{\mathrm{HI}}}{10^{13.1}\,\mathrm{cm}^{-2}} \left[\frac{b}{10\ \mathrm{km\,s}^{-1}} \right]^{-1}$$

Connecting Observables to Science

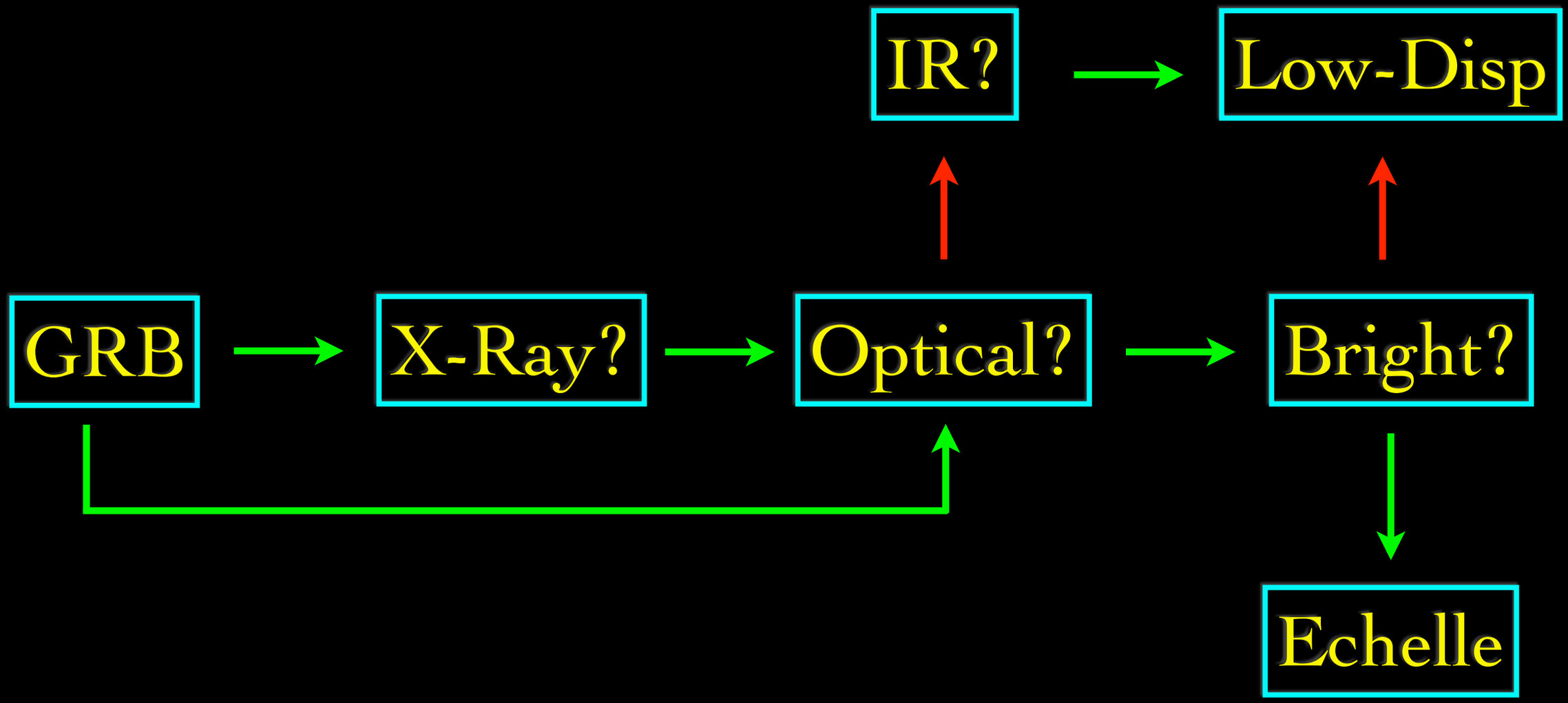
Connecting Observables to Science

All of this theory (formalism) is all well and good, but does it have any use?

Obtaining the Data

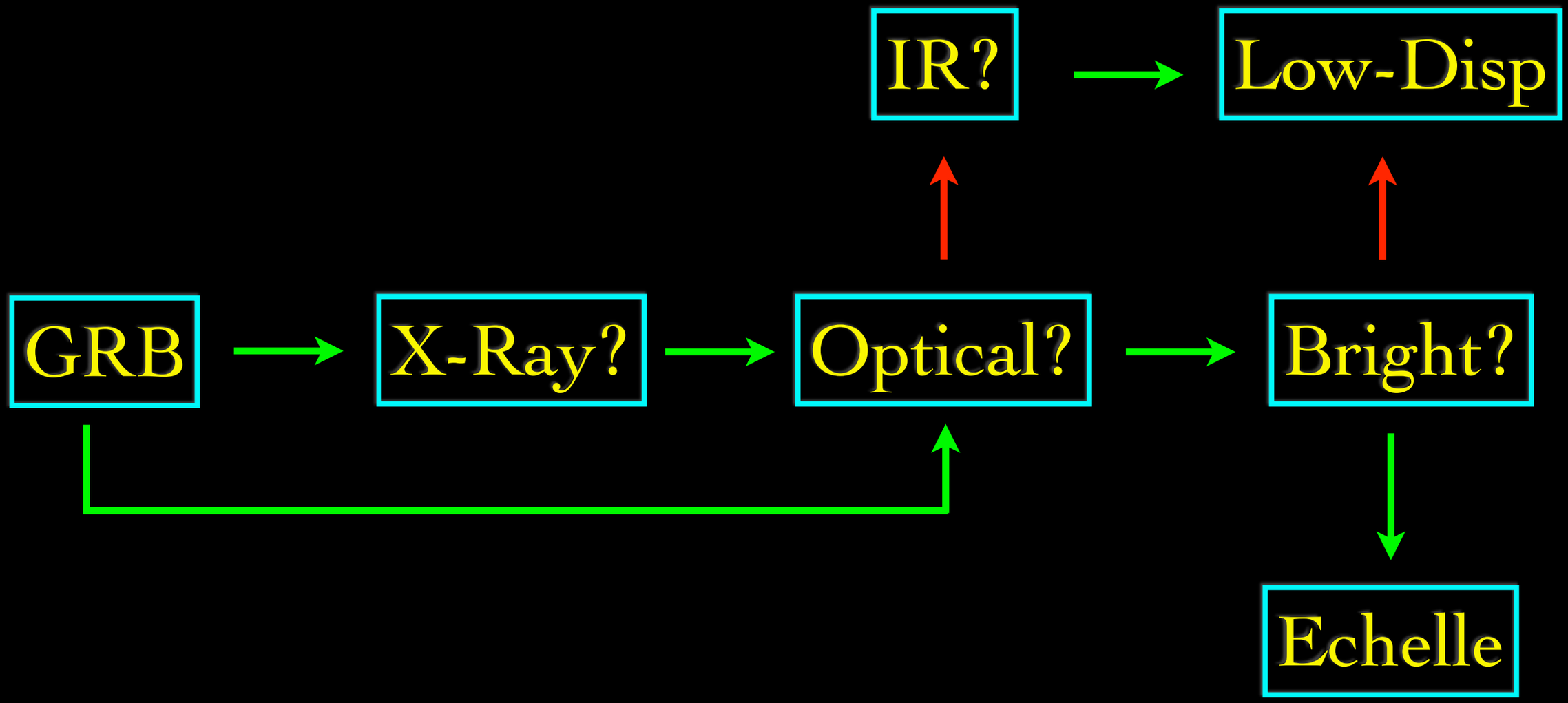


Obtaining the Data



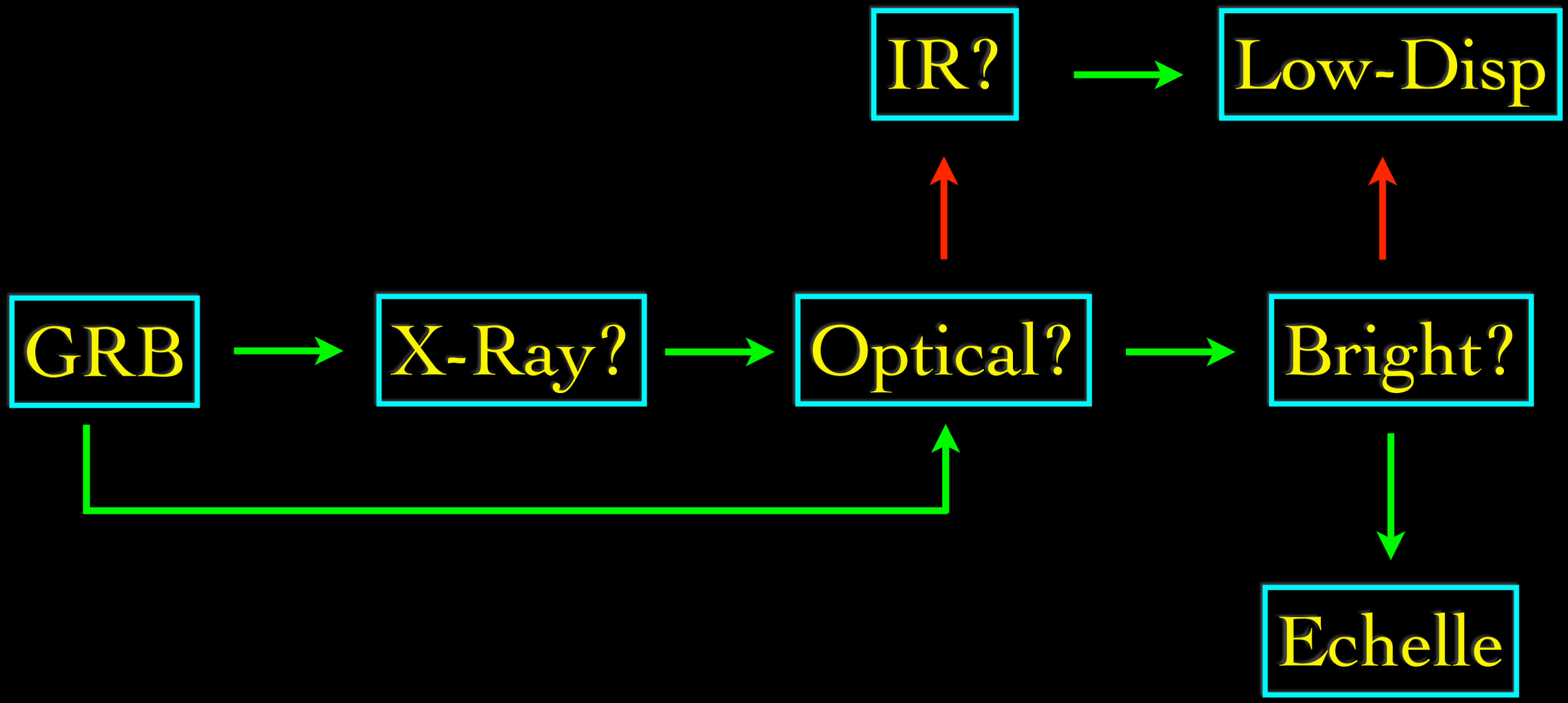
- Time from GRB to spectra can take minutes, hours or even days.

Obtaining the Data



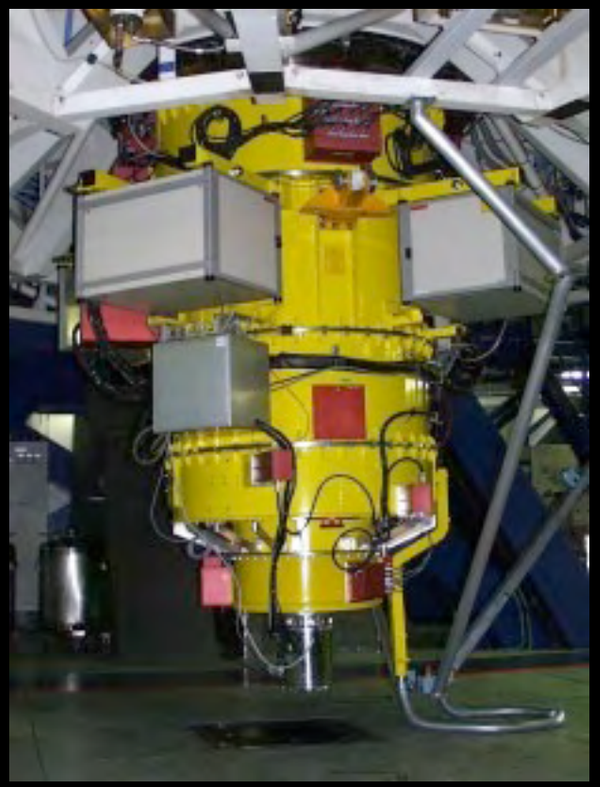
- Time from GRB to spectra can take minutes, hours or even days.
- This generally involves multiple telescopes and groups.

Obtaining the Data

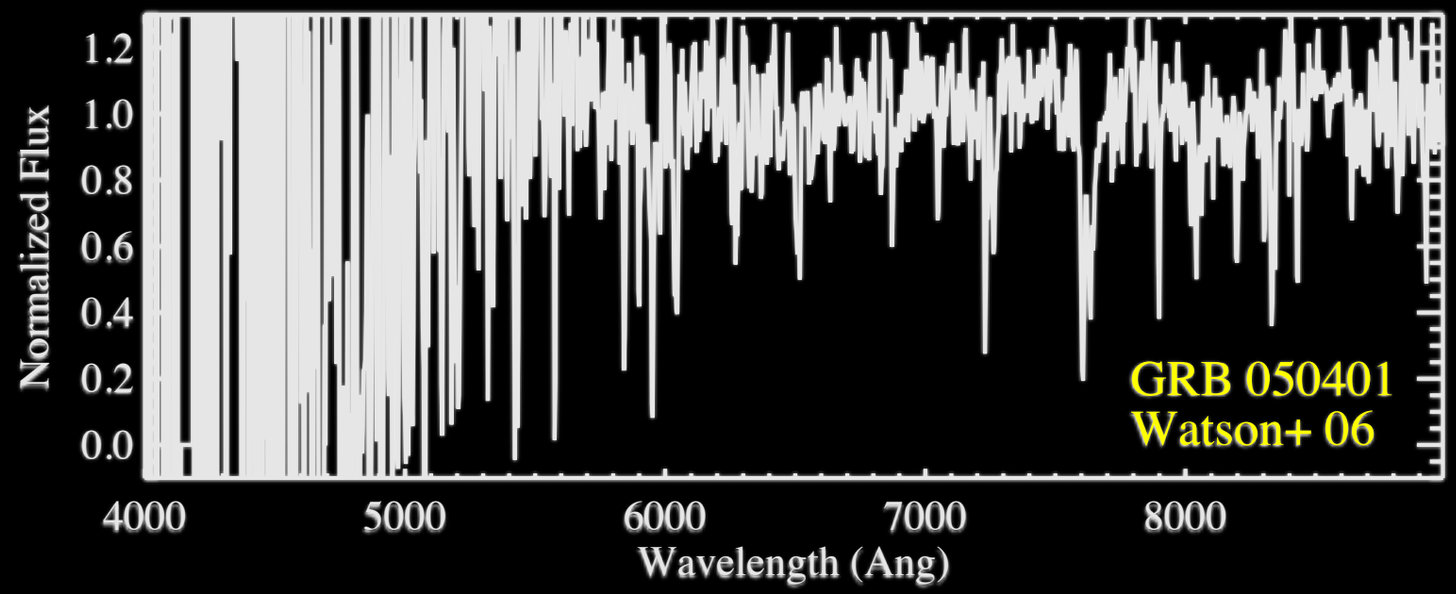


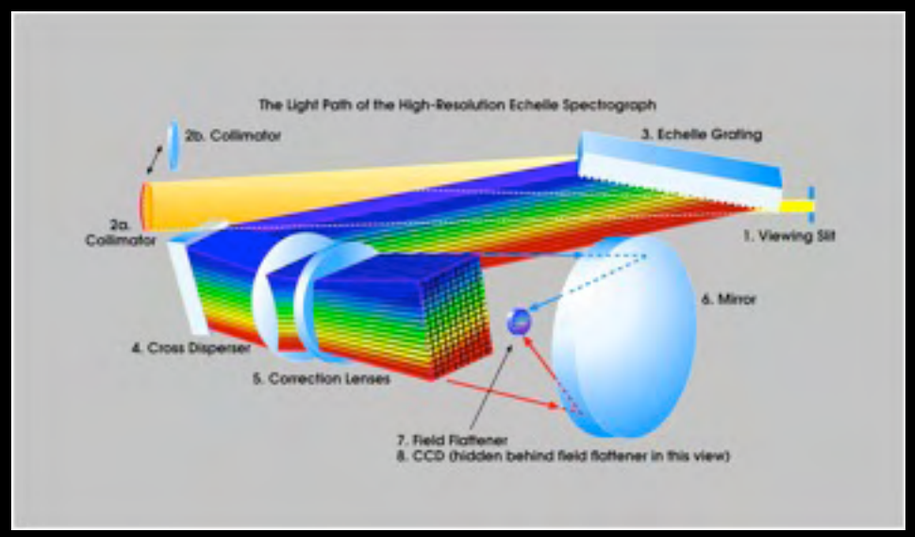
- Time from GRB to spectra can take minutes, hours or even days.
- This generally involves multiple telescopes and groups.
- Spectra are rarely obtained at the optimal resolution, S/N, or wavelength range.

The Data

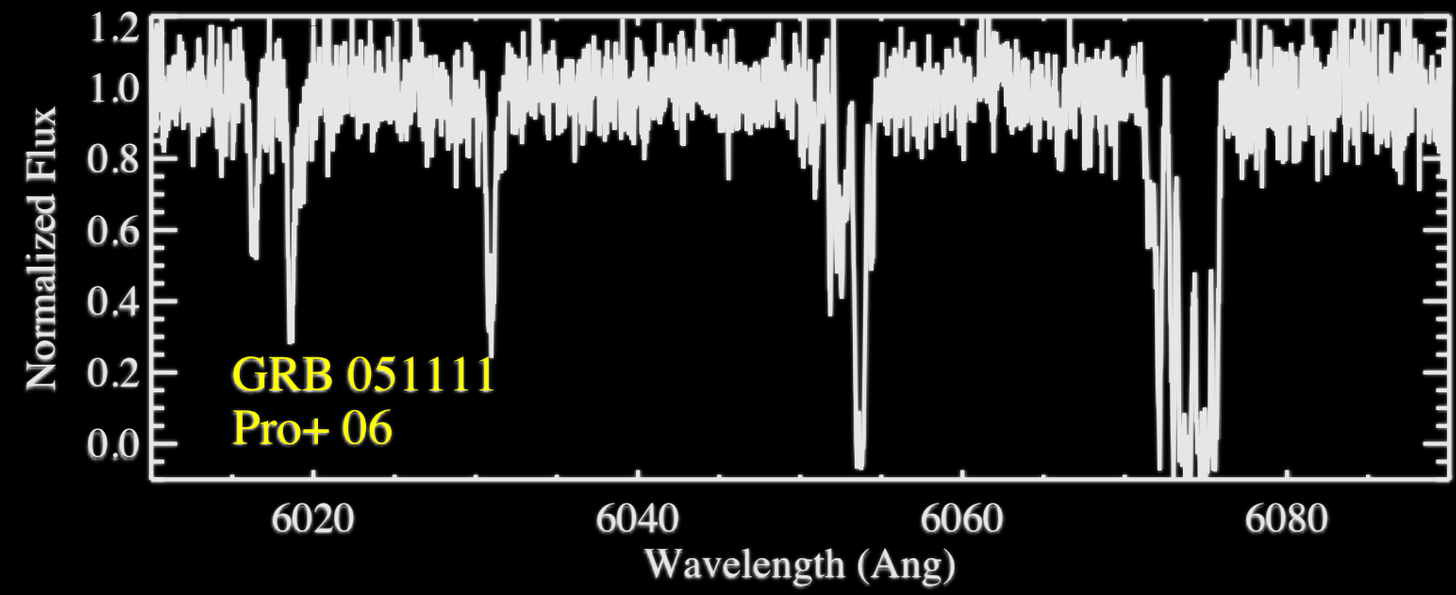


VLT/FORS

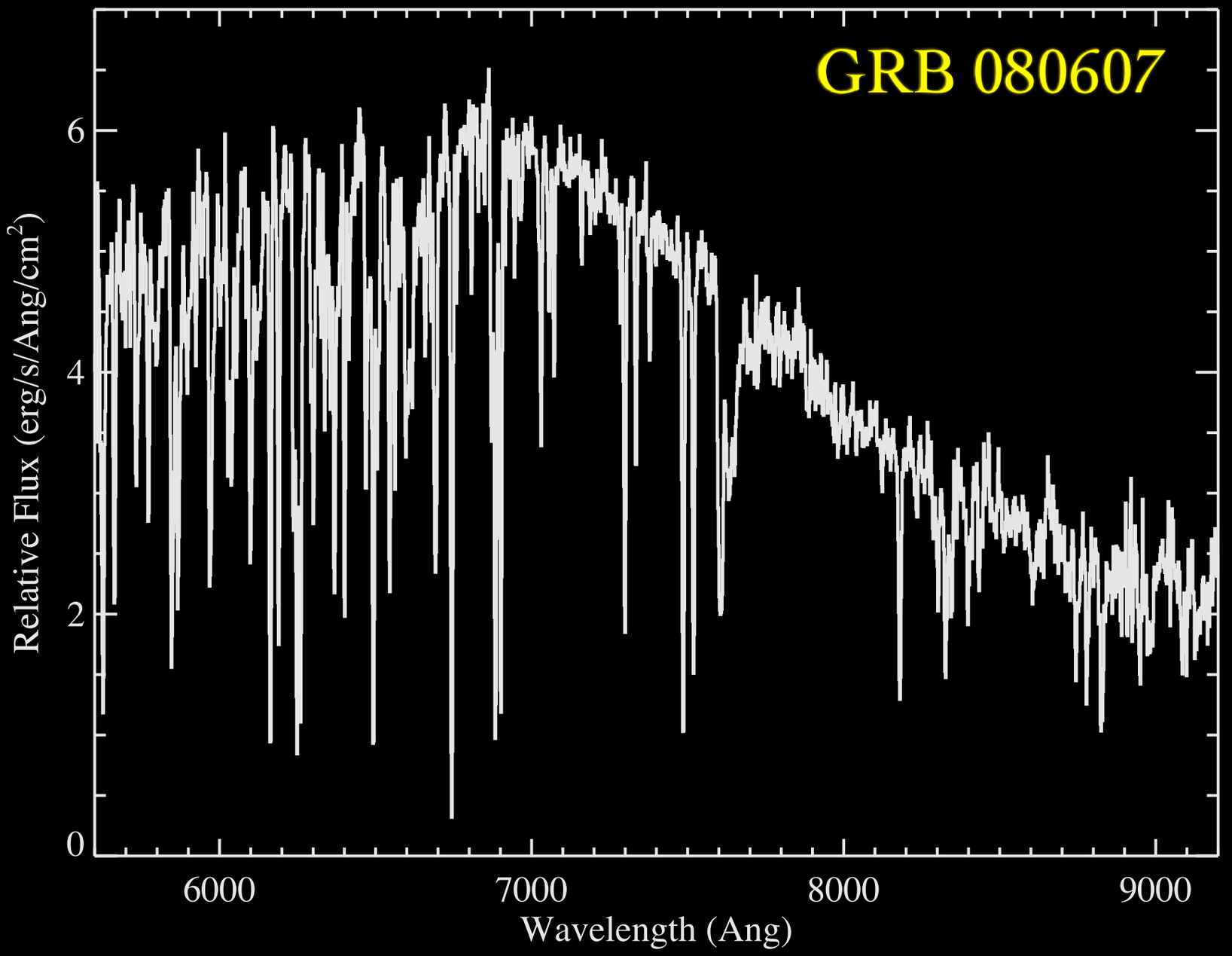




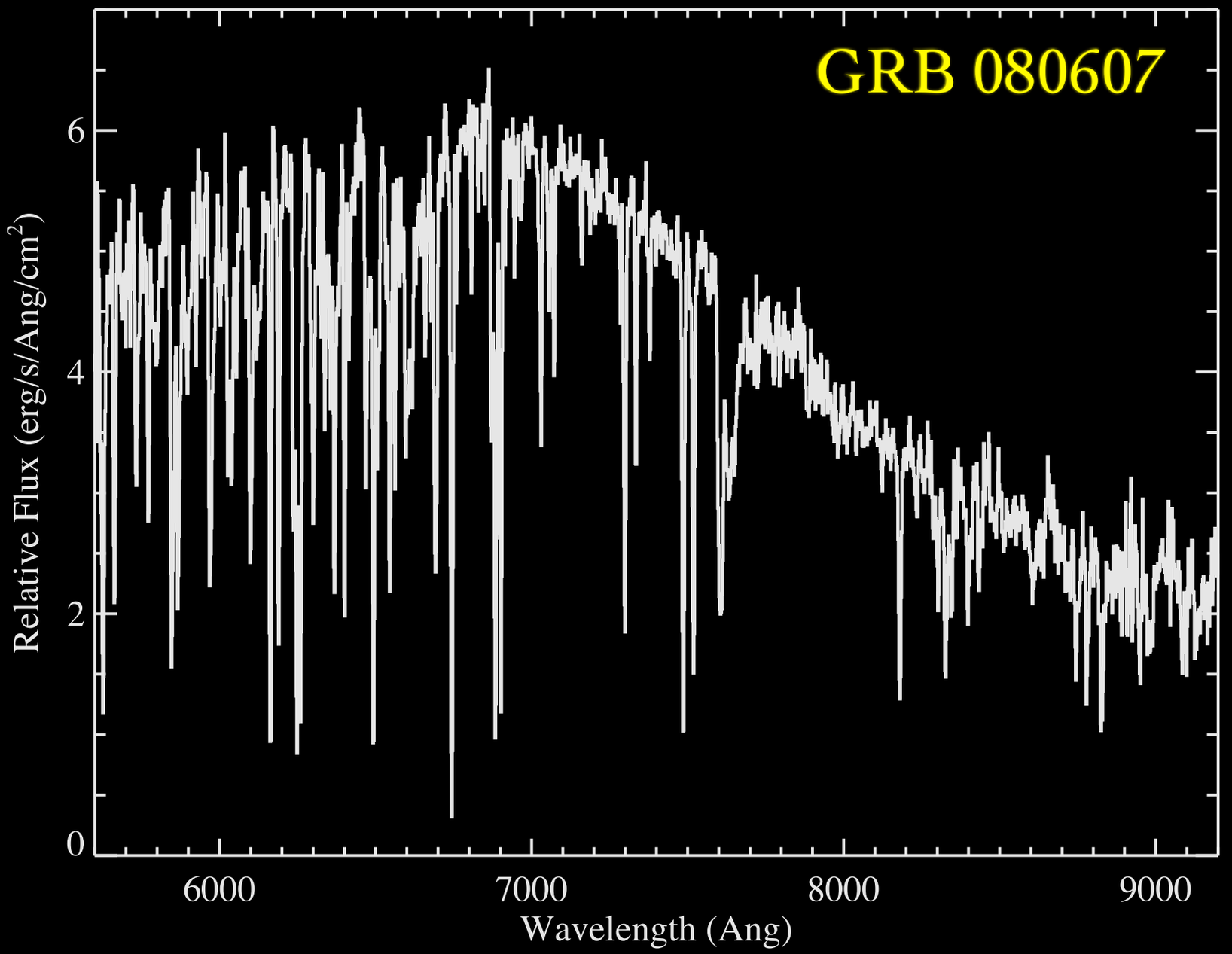
Keck/HIRES



Mining the GRB Spectrum

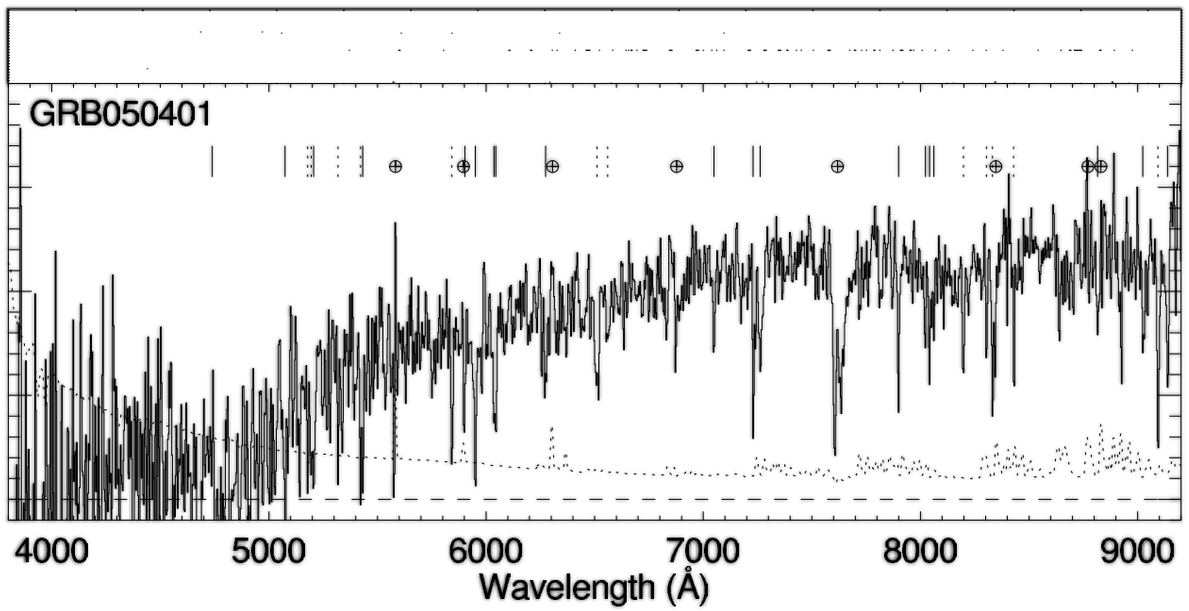


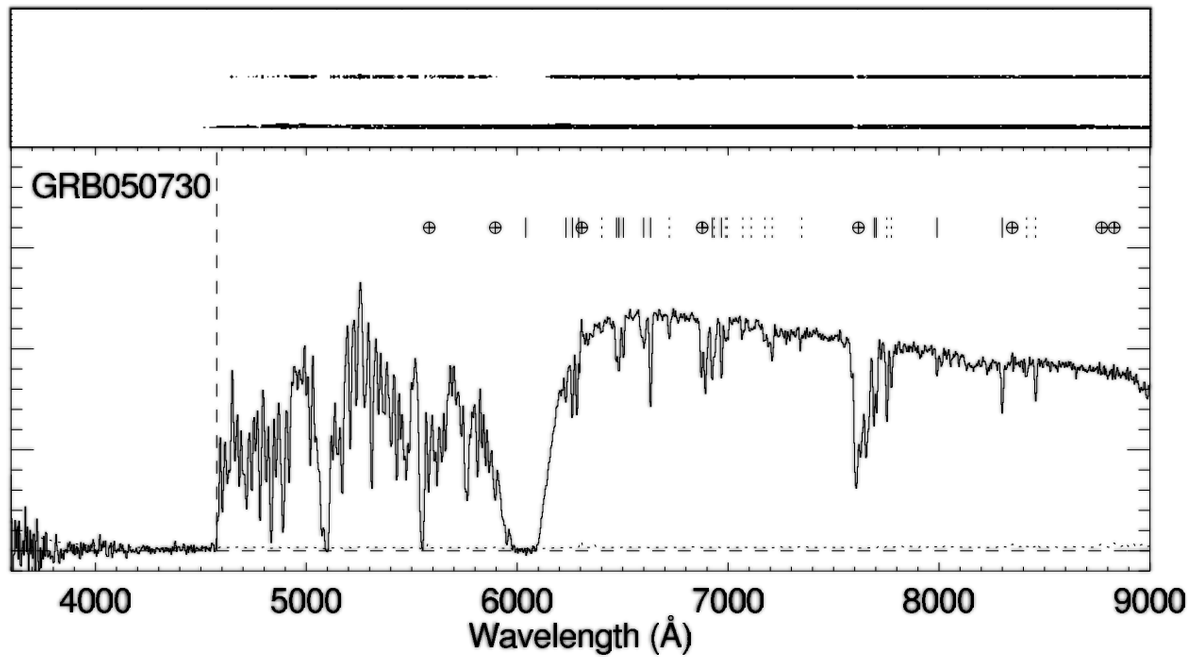
Mining the GRB Spectrum

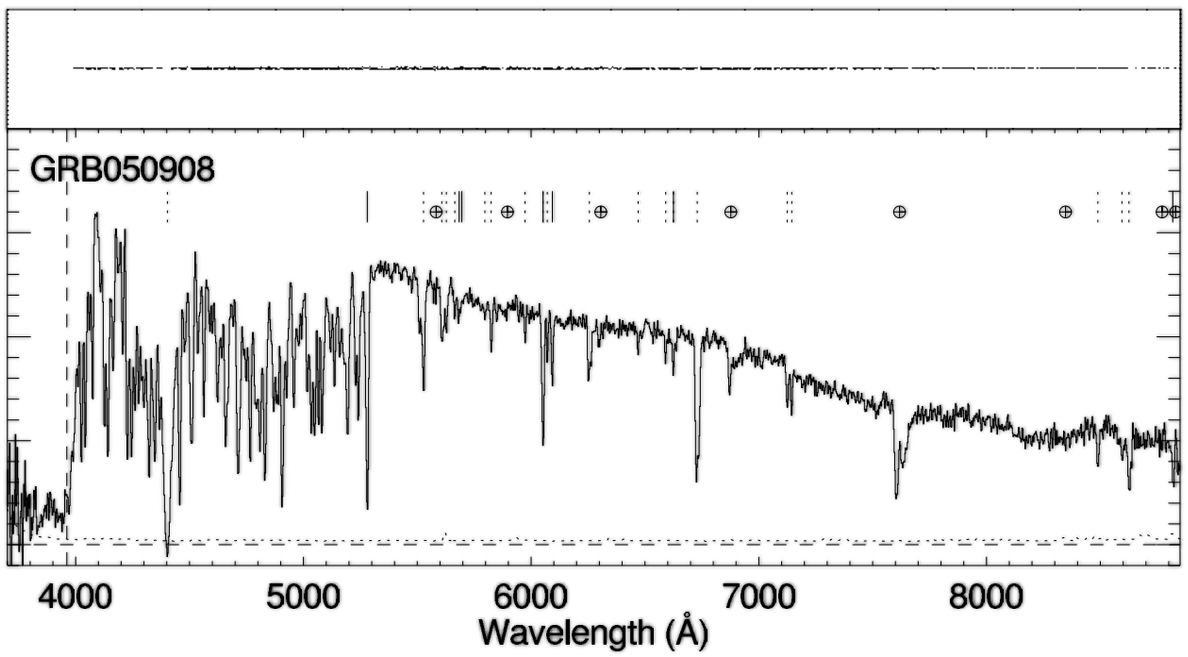


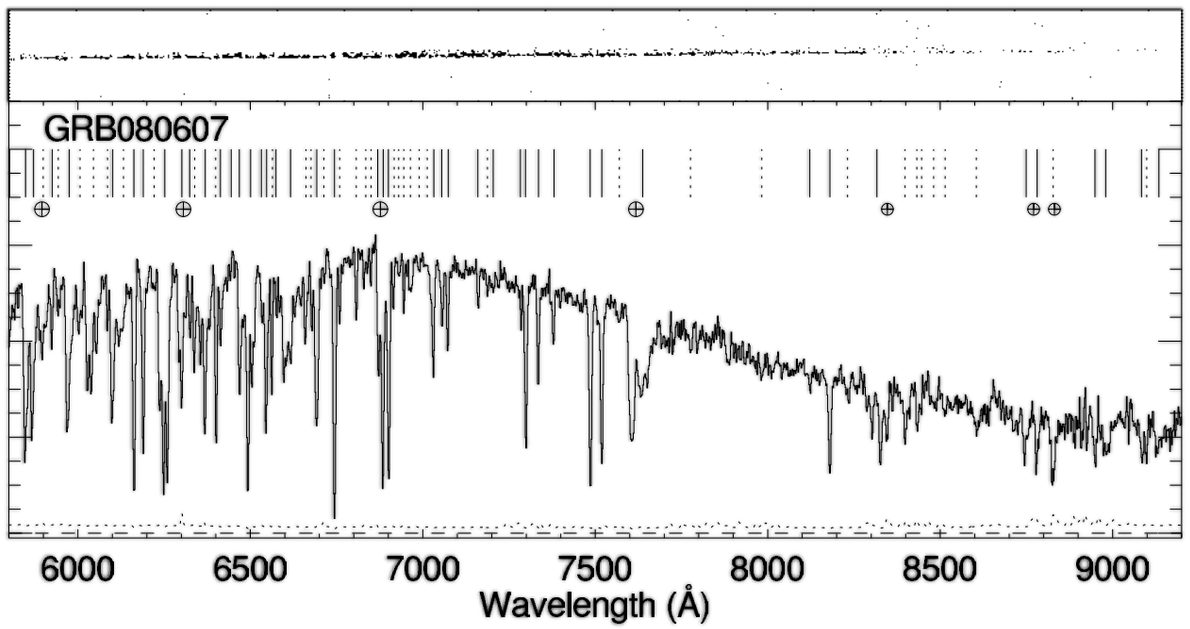
- GRB afterglow provide a plethora of absorption lines
- **How do know which is which?**
- And, how do we produce the science?

GRB: Afterglow Spectra



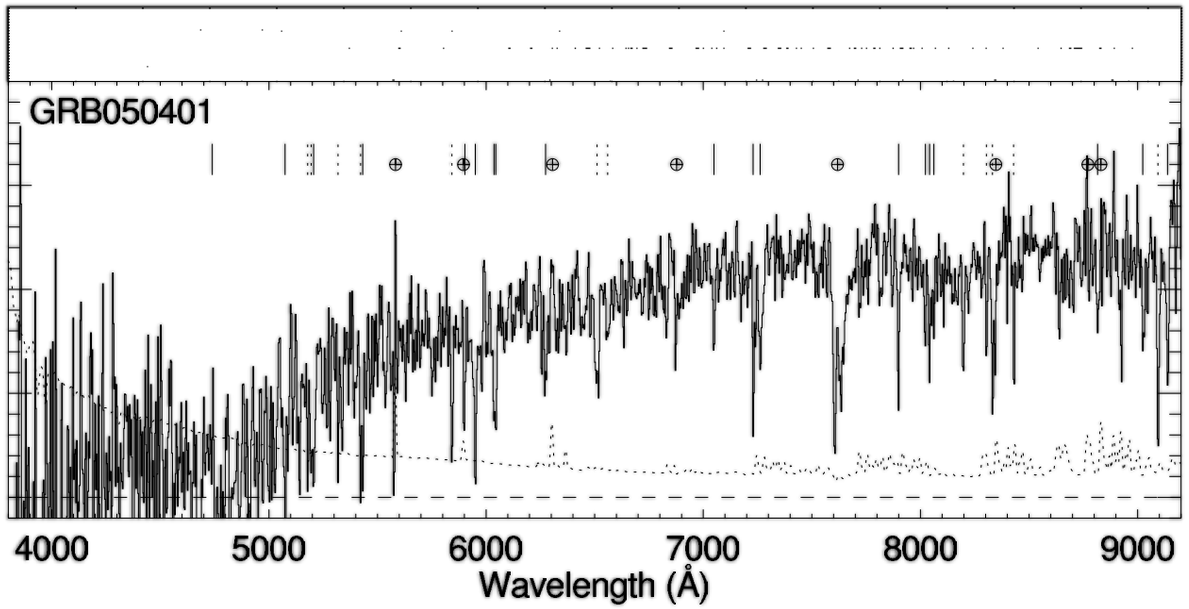


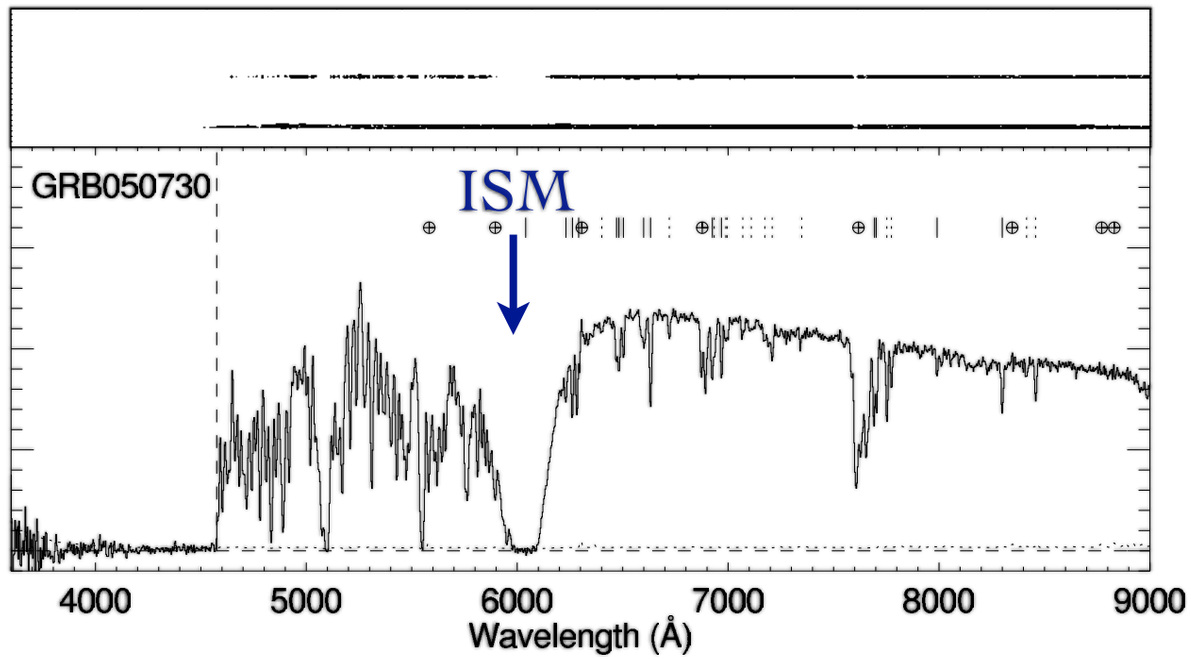


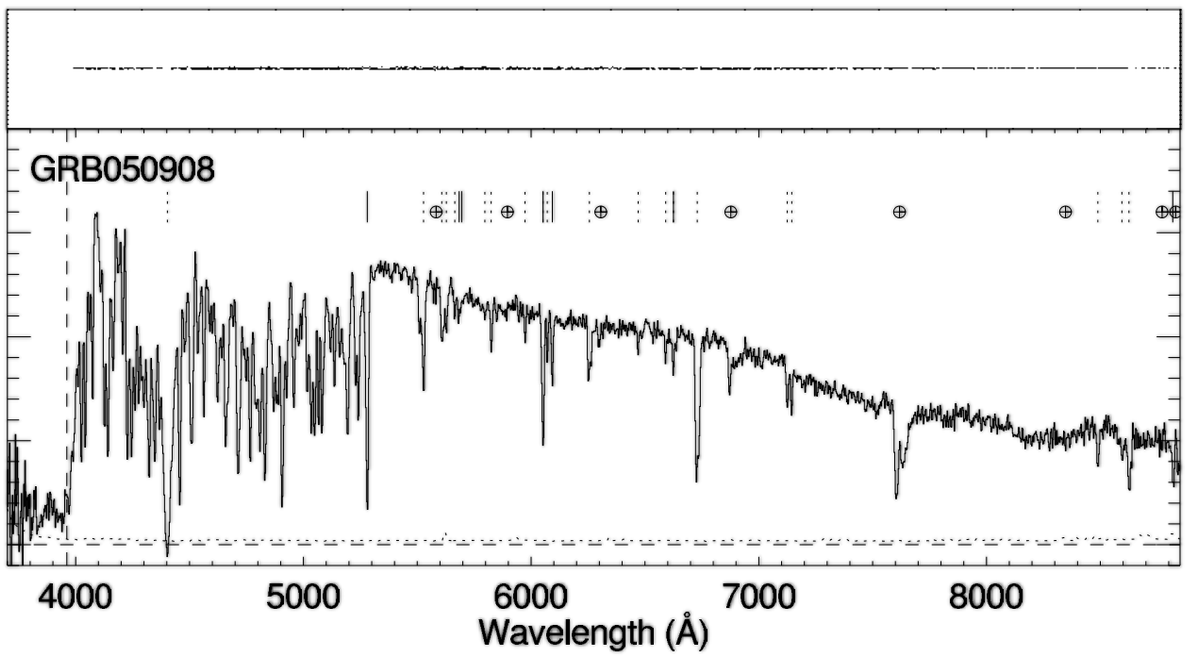


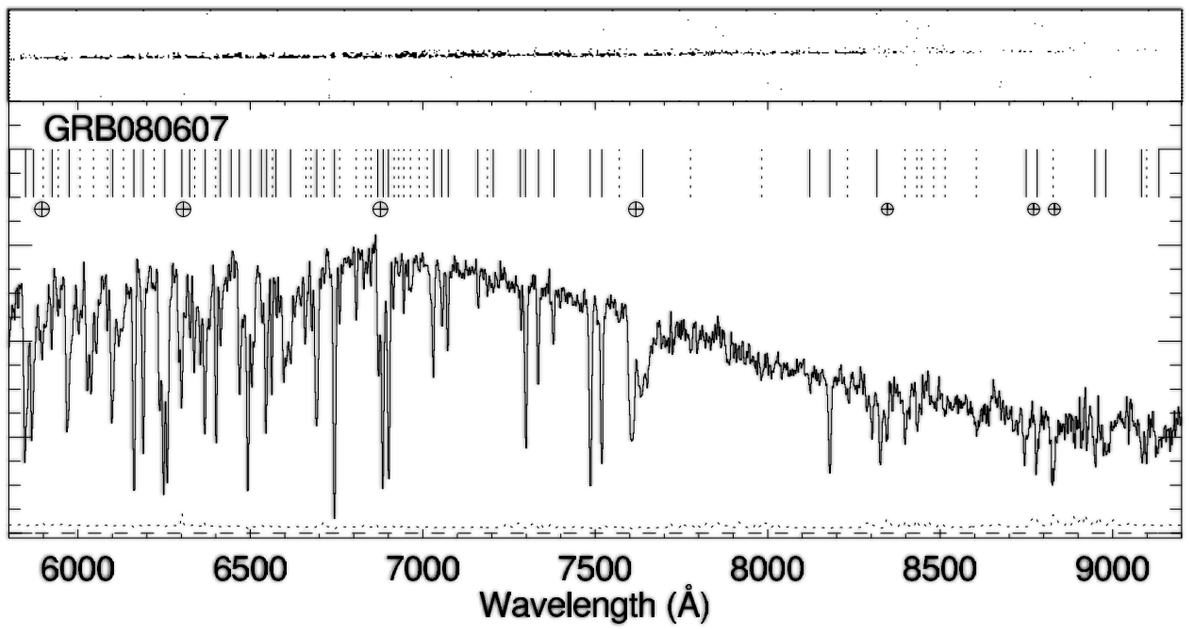
Fynbo+ 09

GRB: Afterglow Spectra









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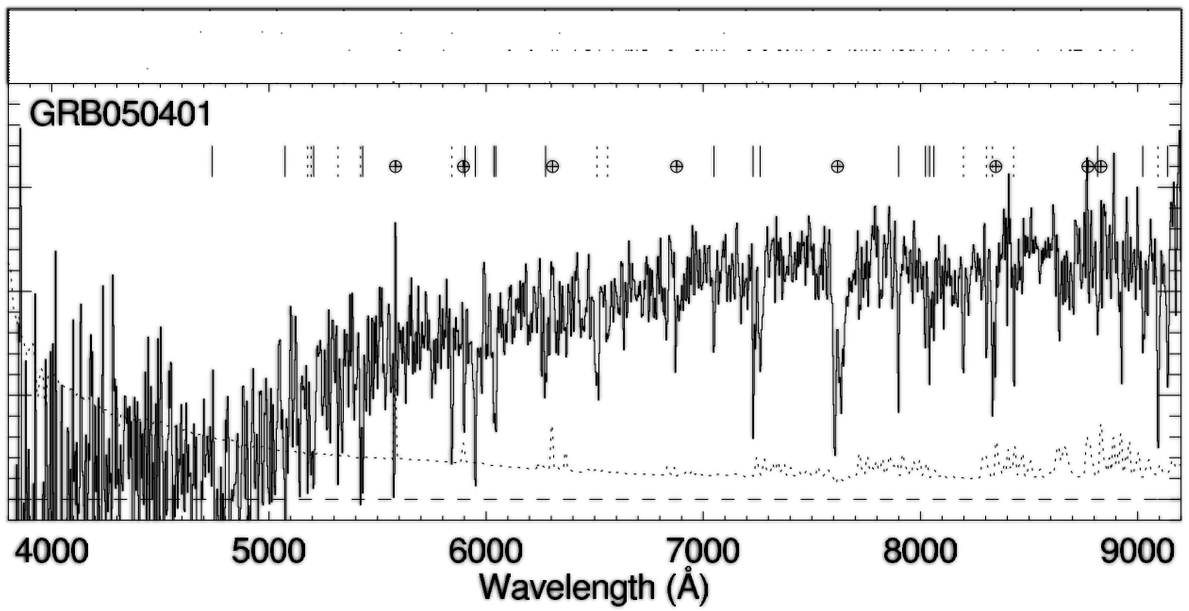

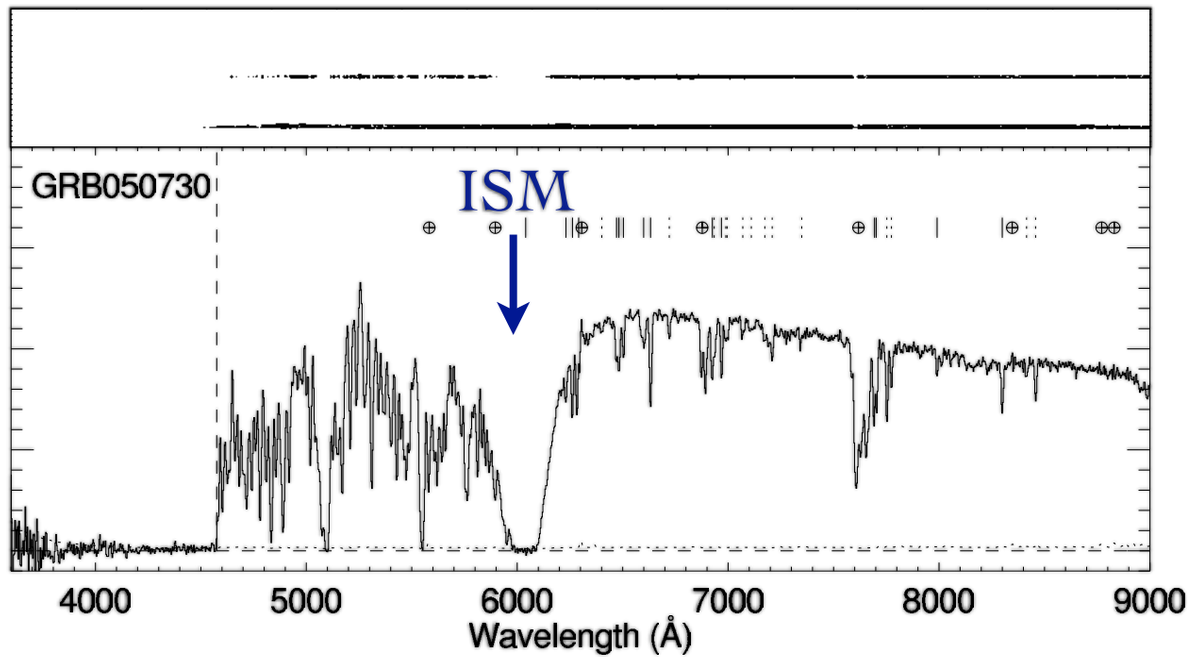

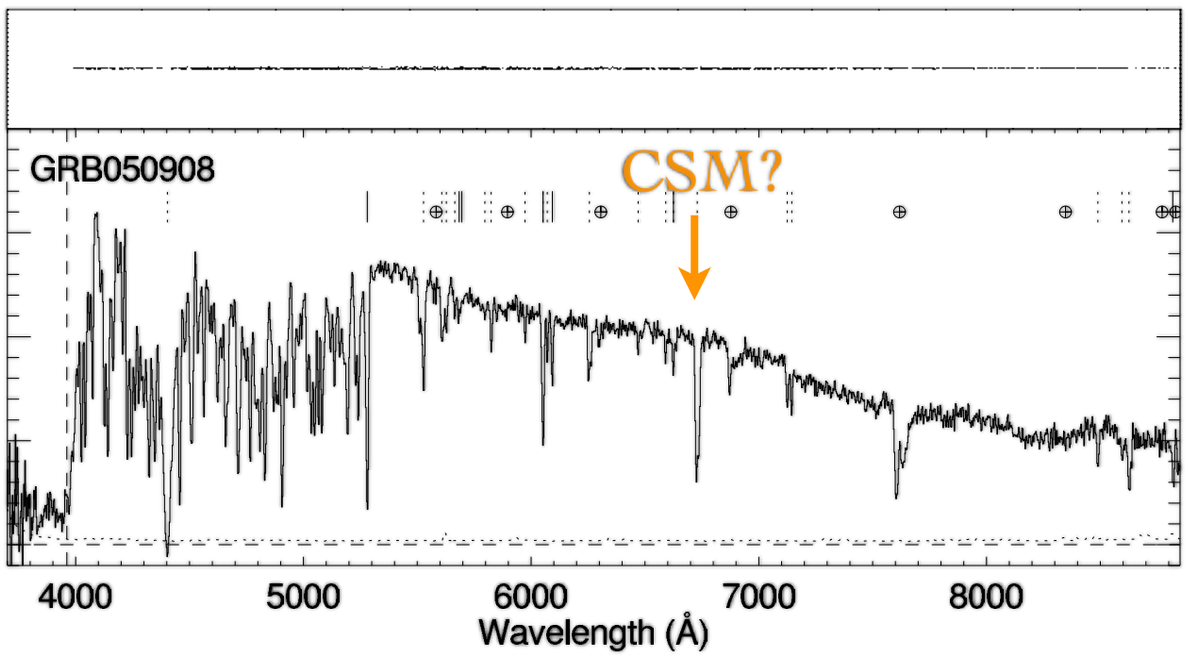

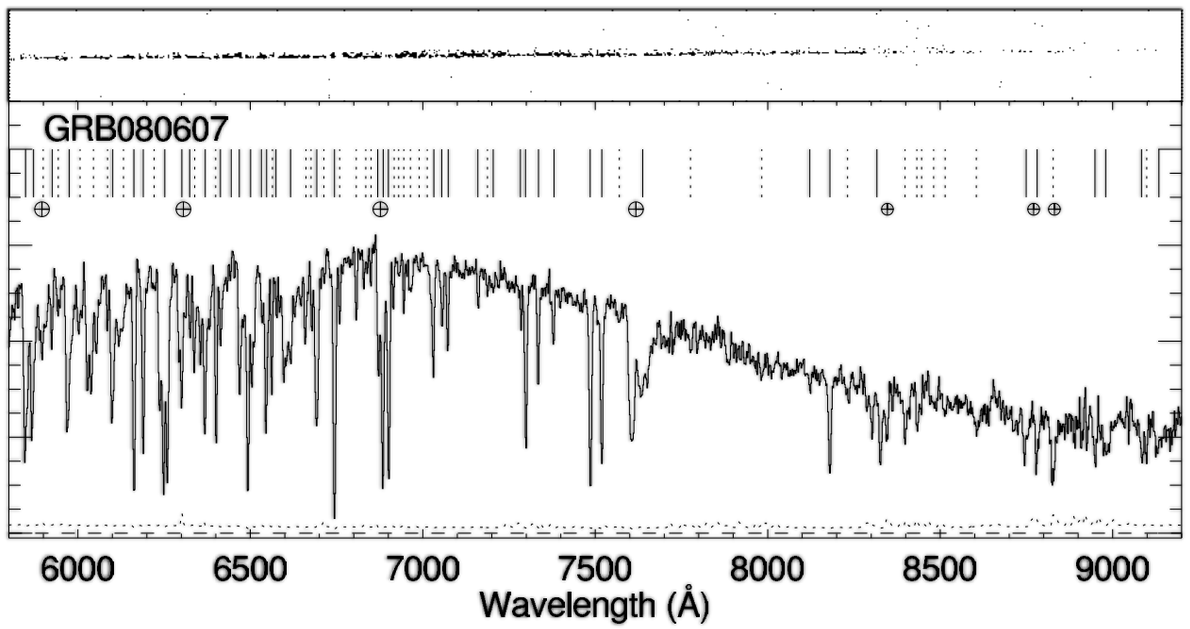

Fynbo+ 09

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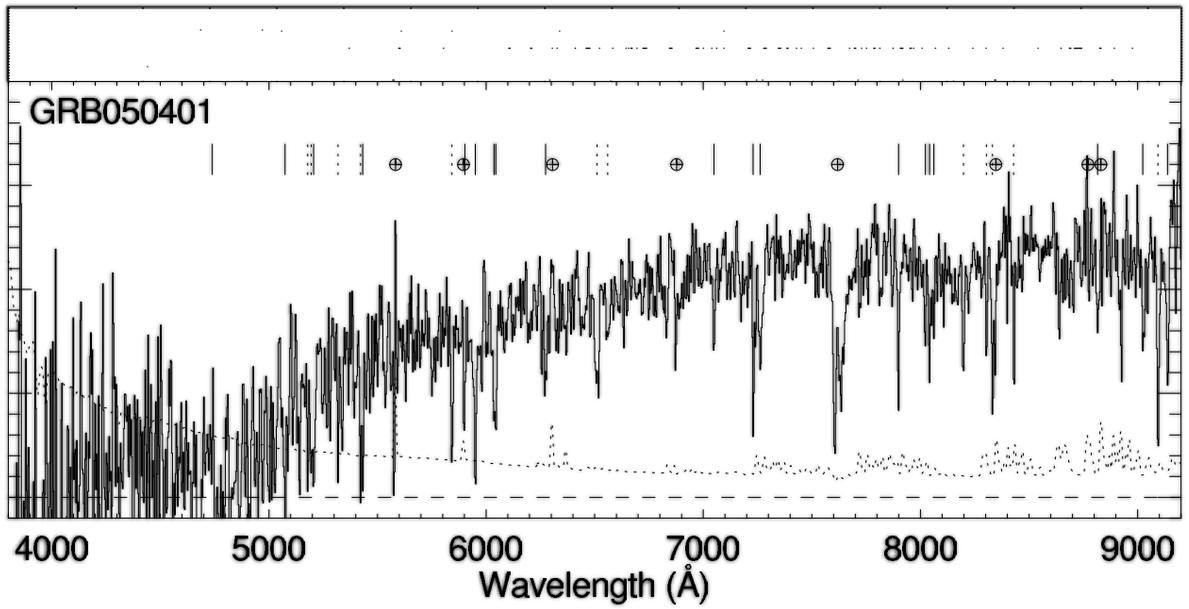

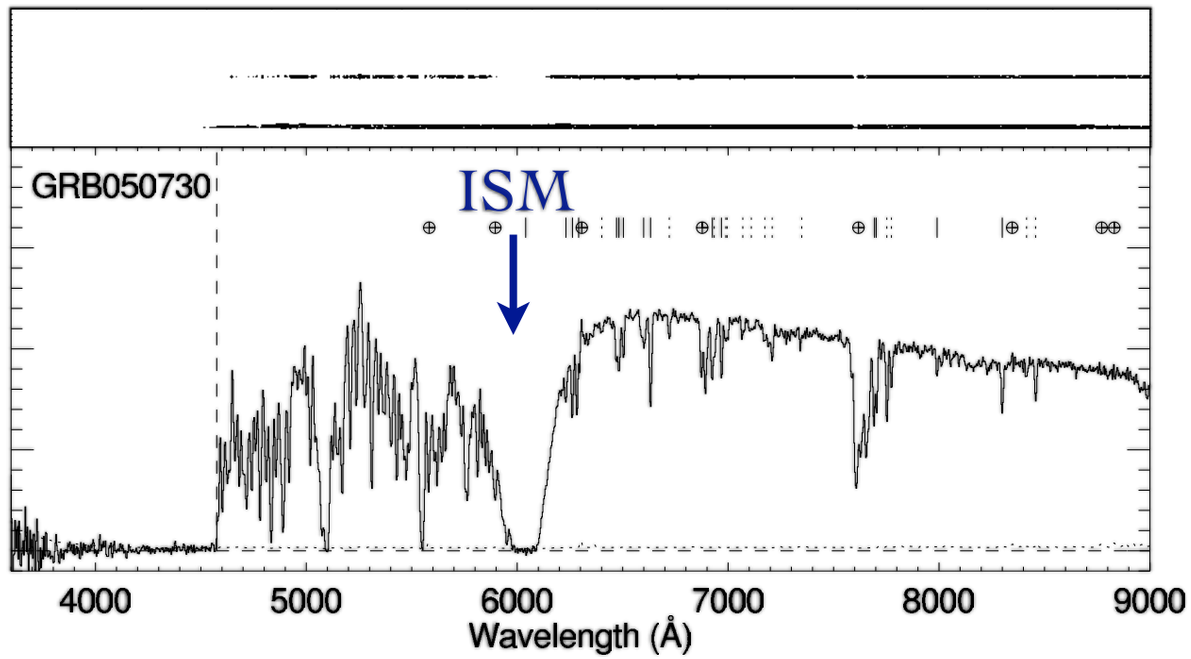

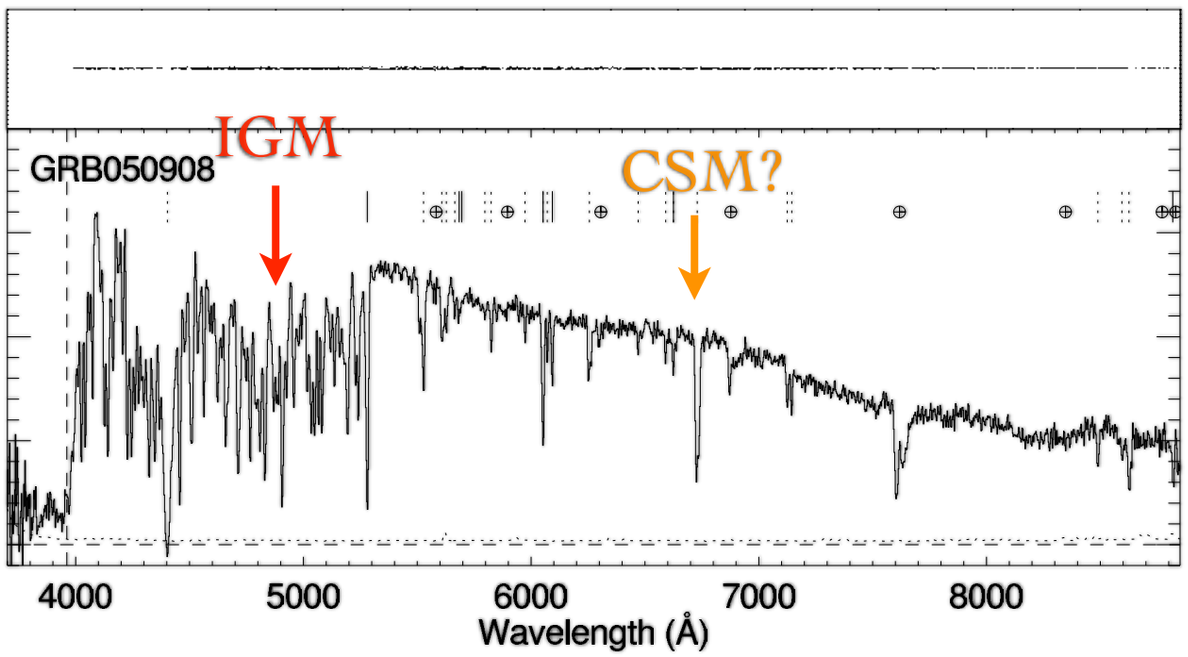

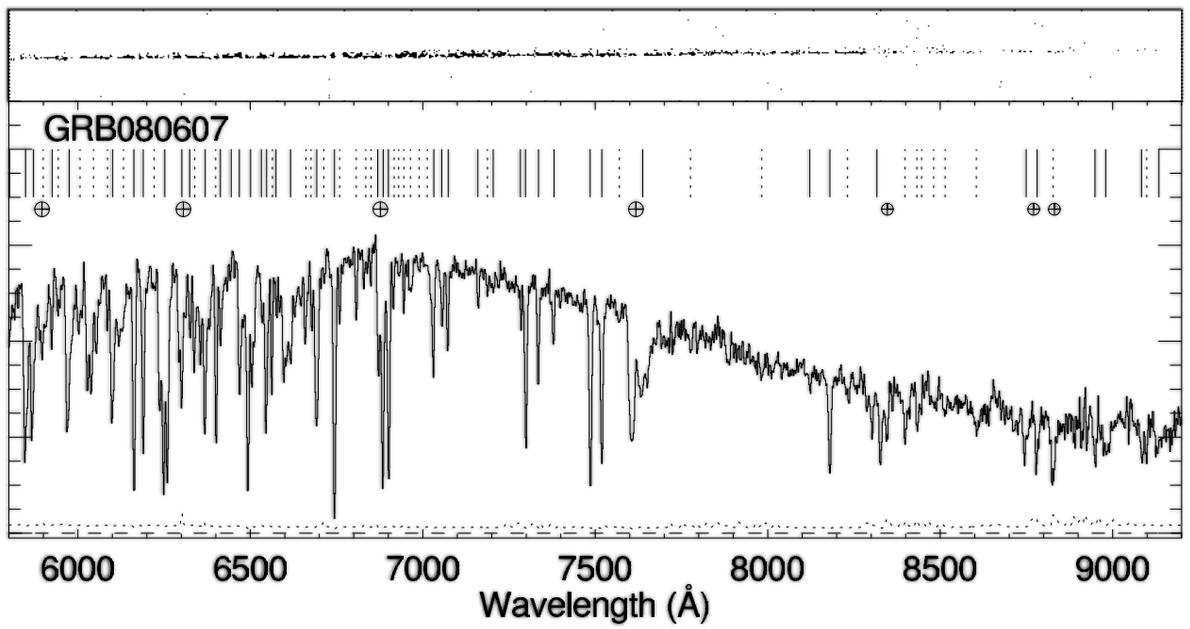

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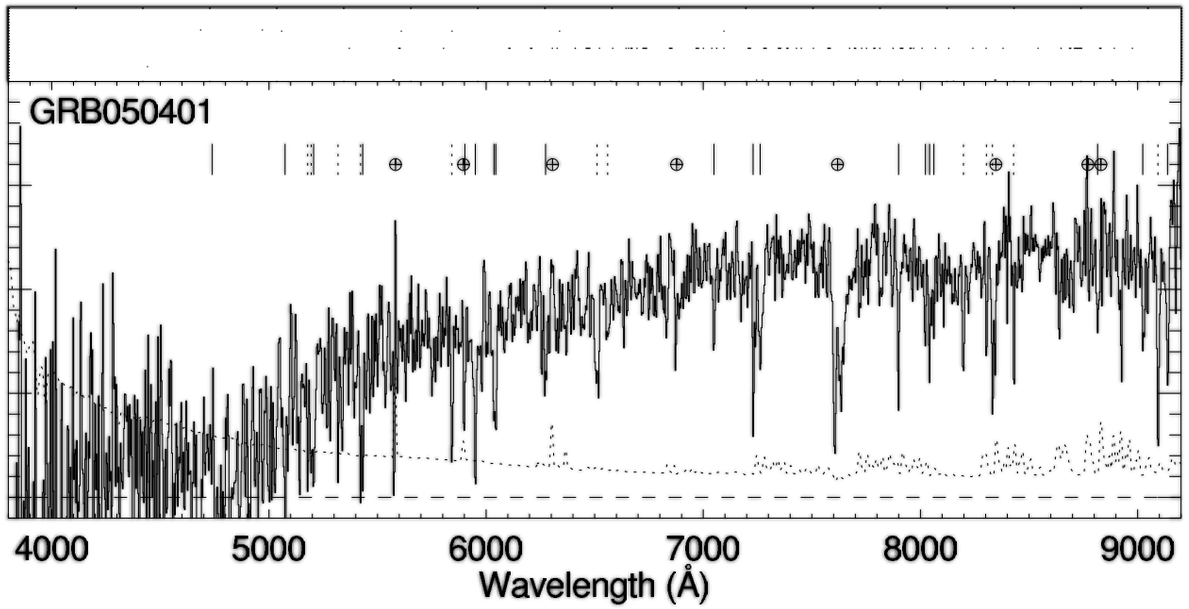

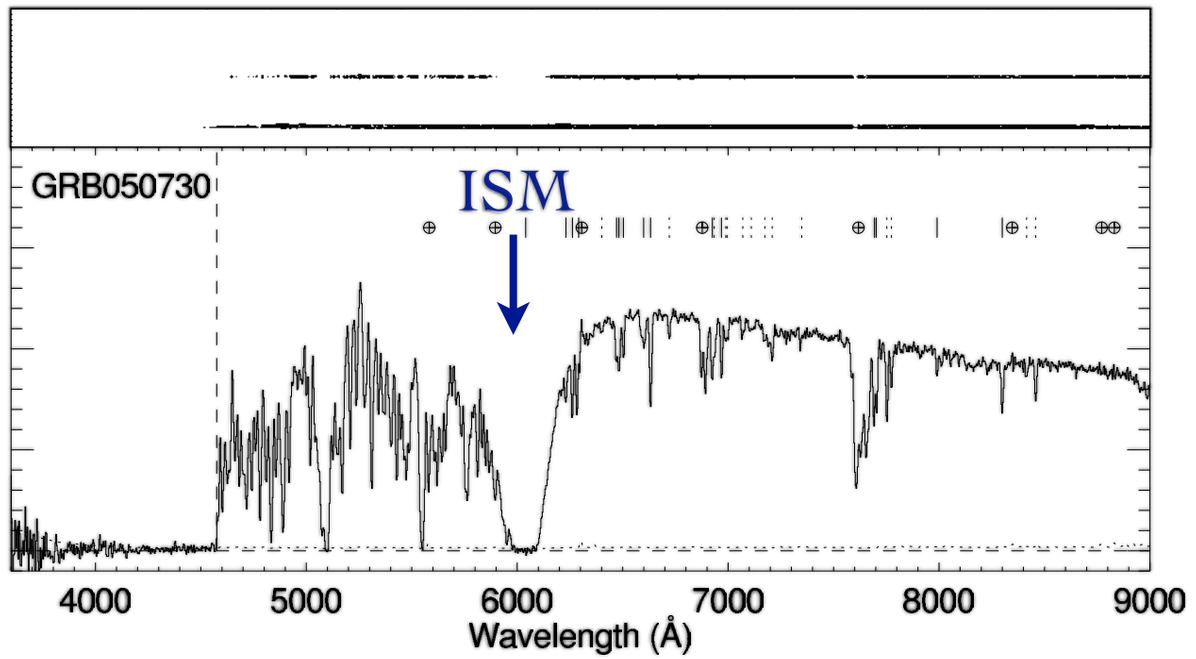

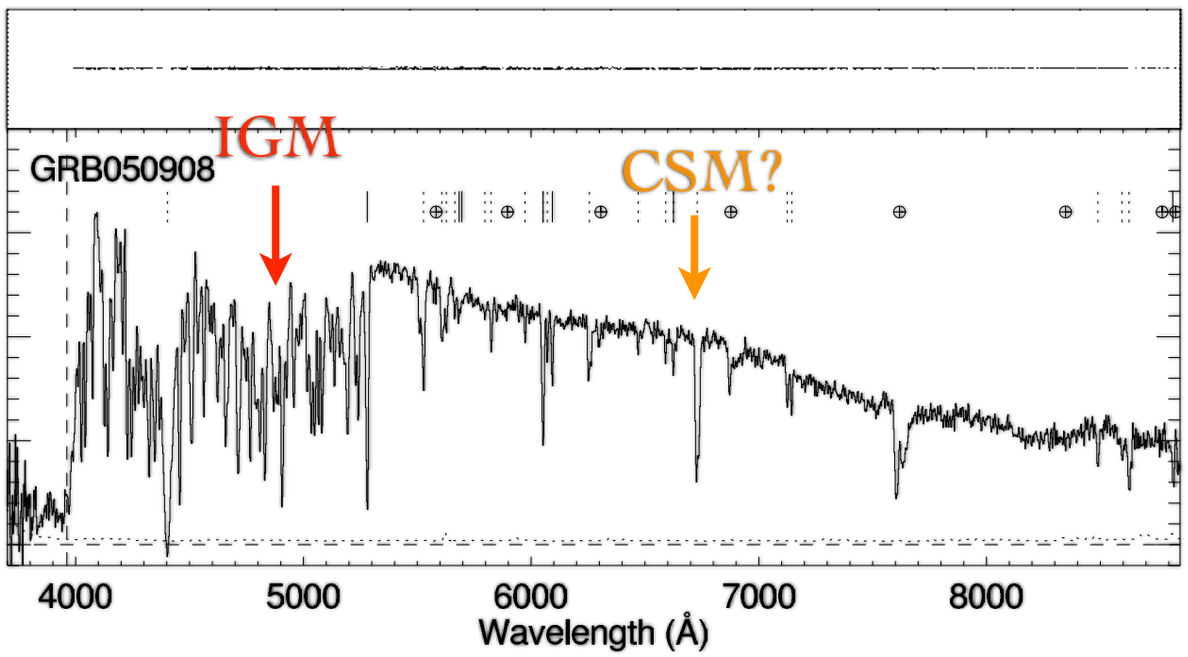

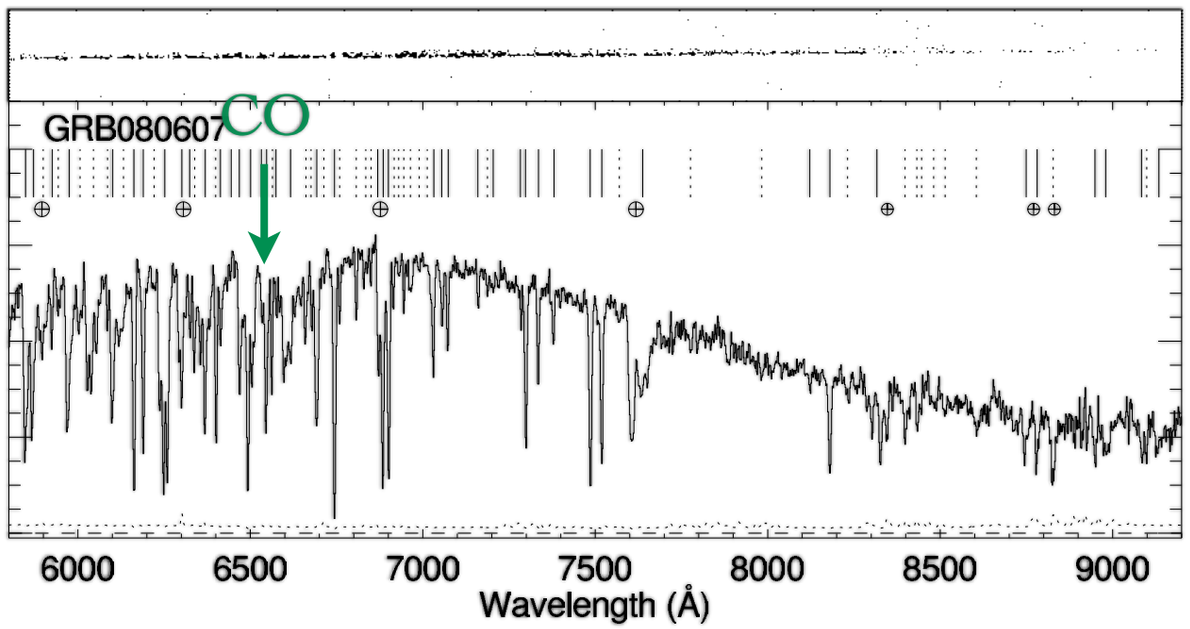

Fynbo+ 09

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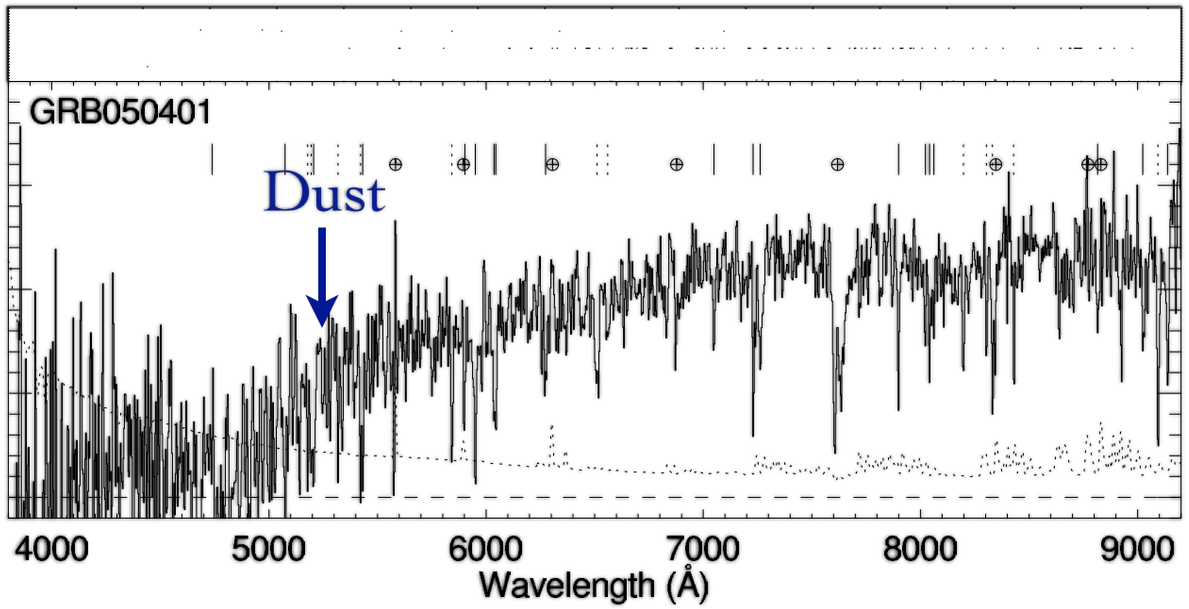

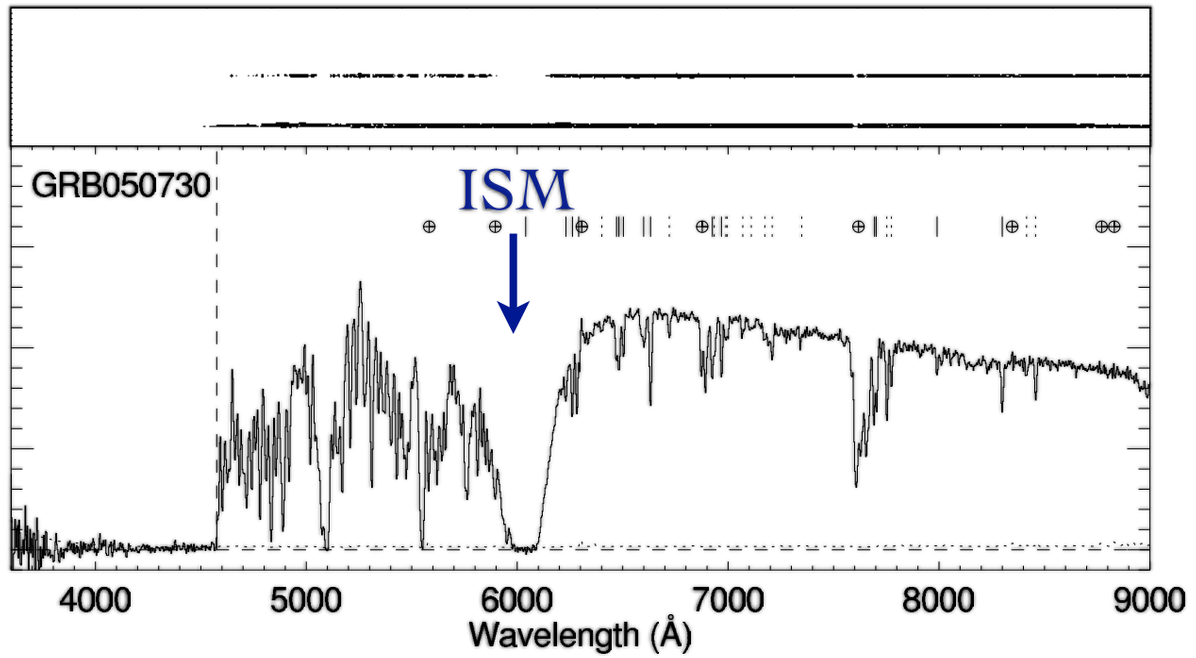

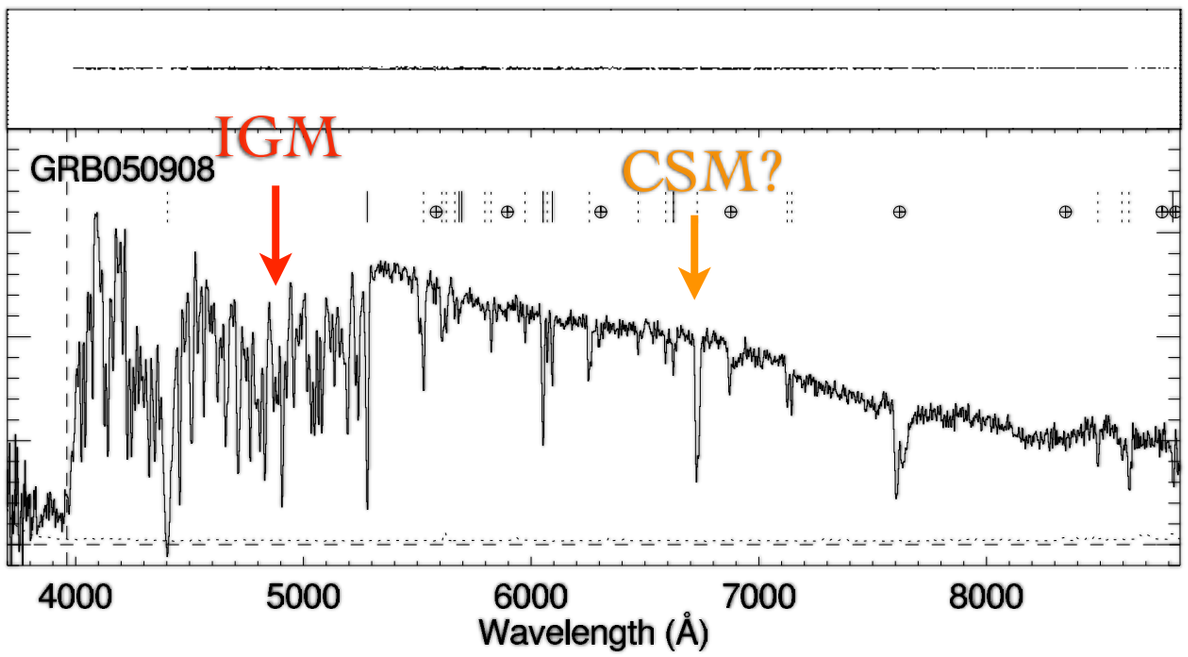

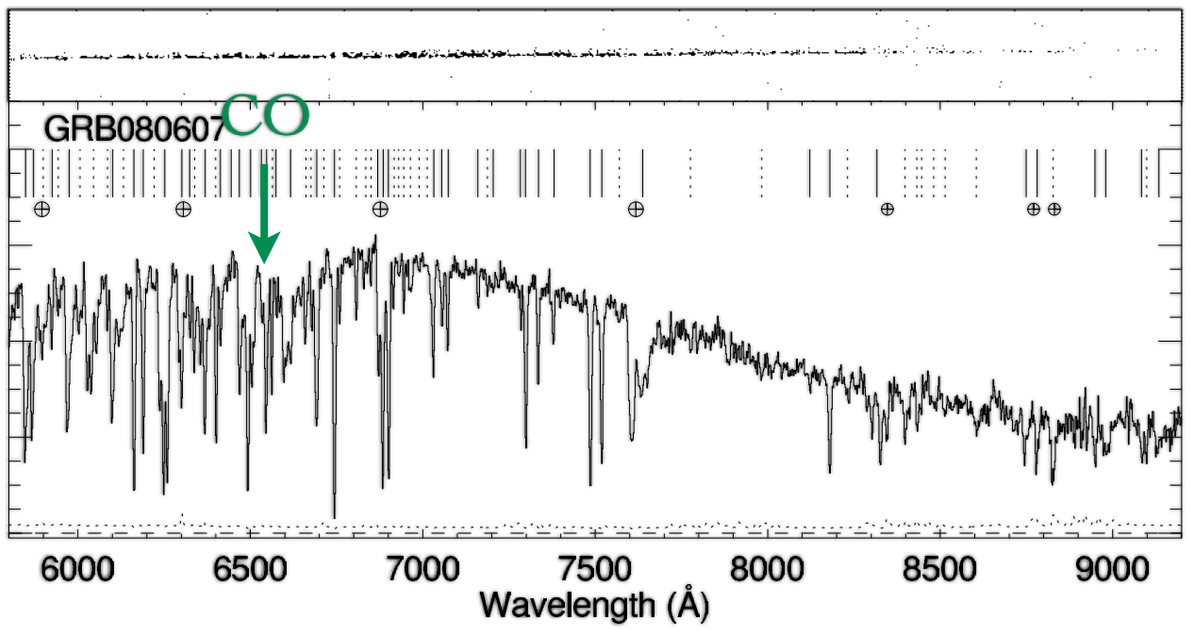

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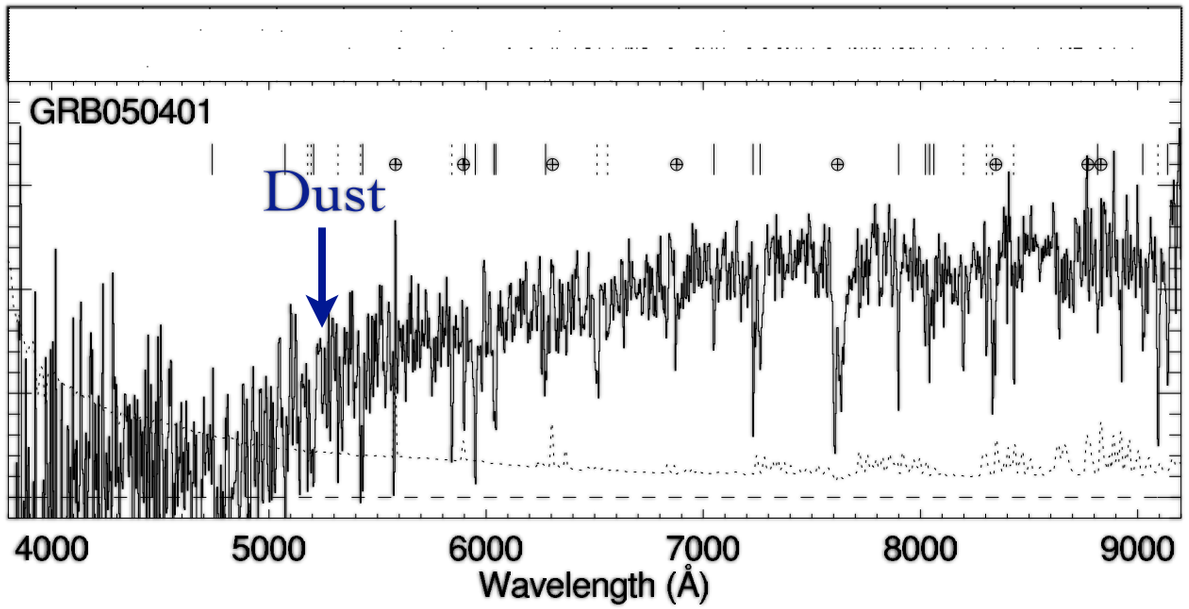

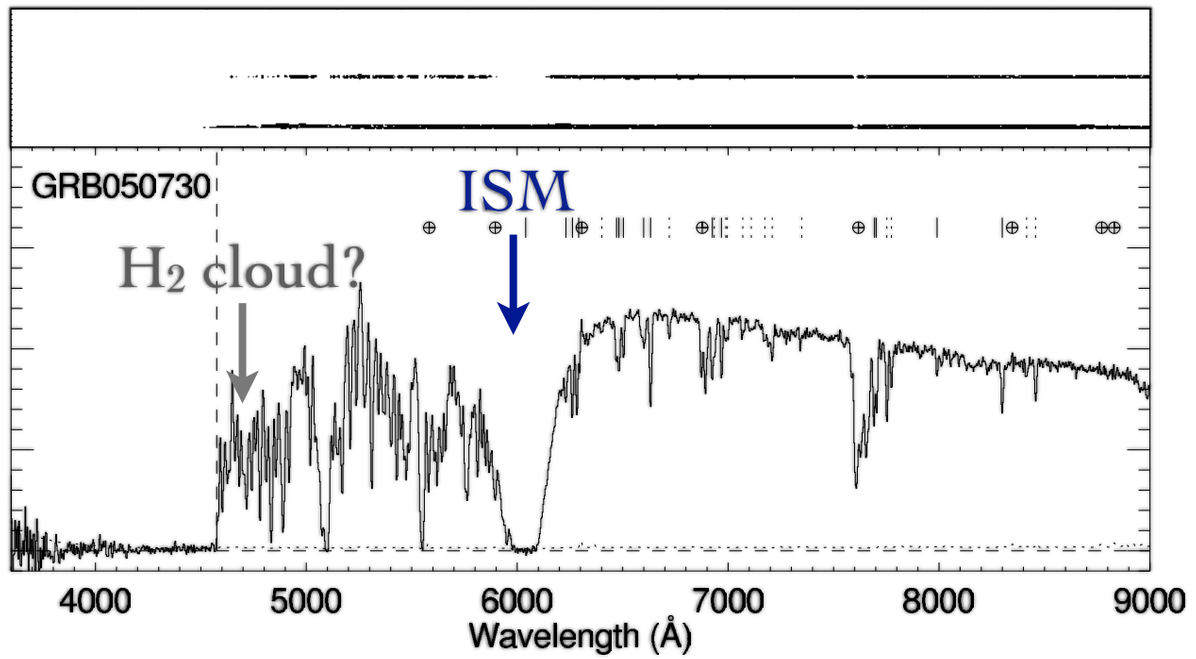

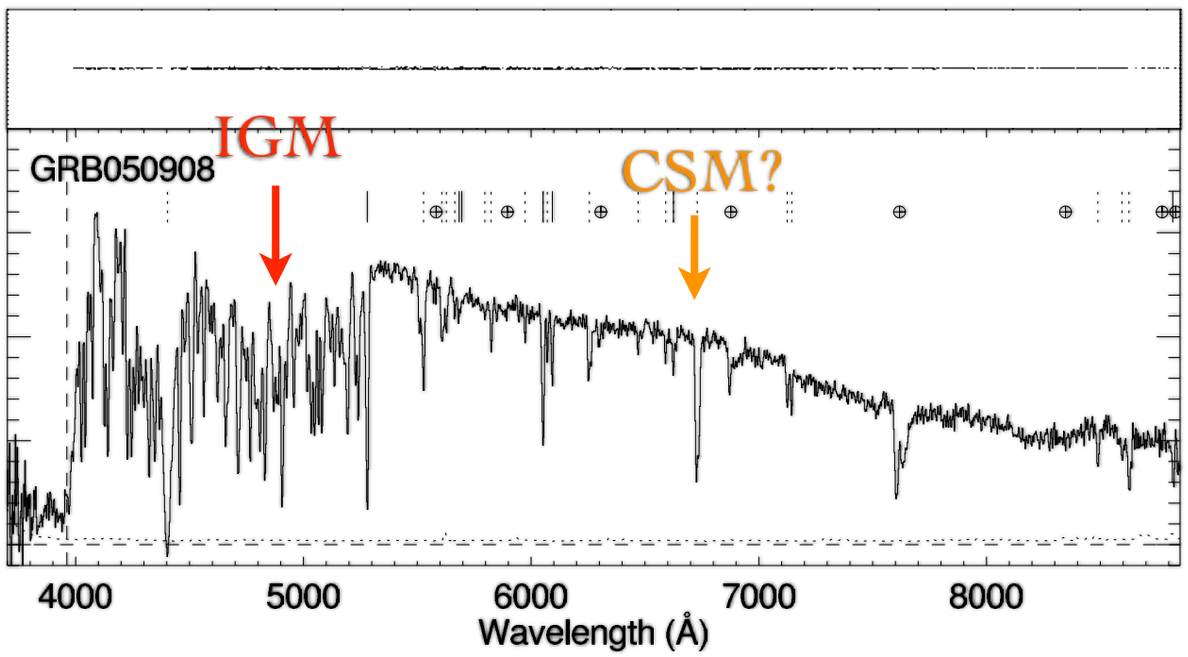

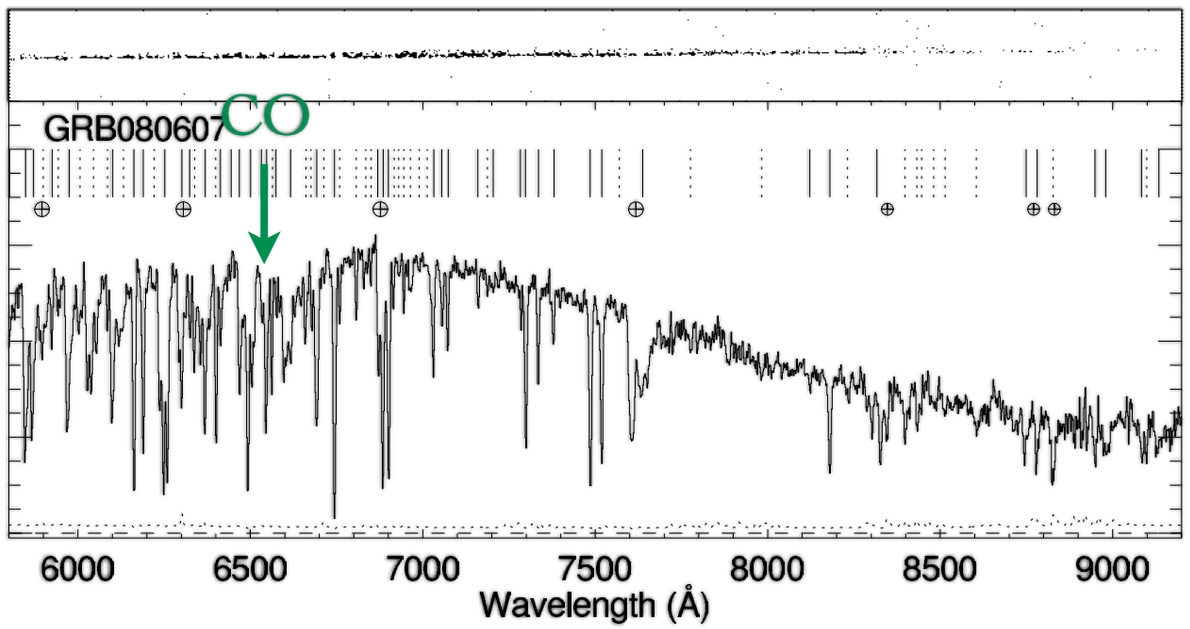

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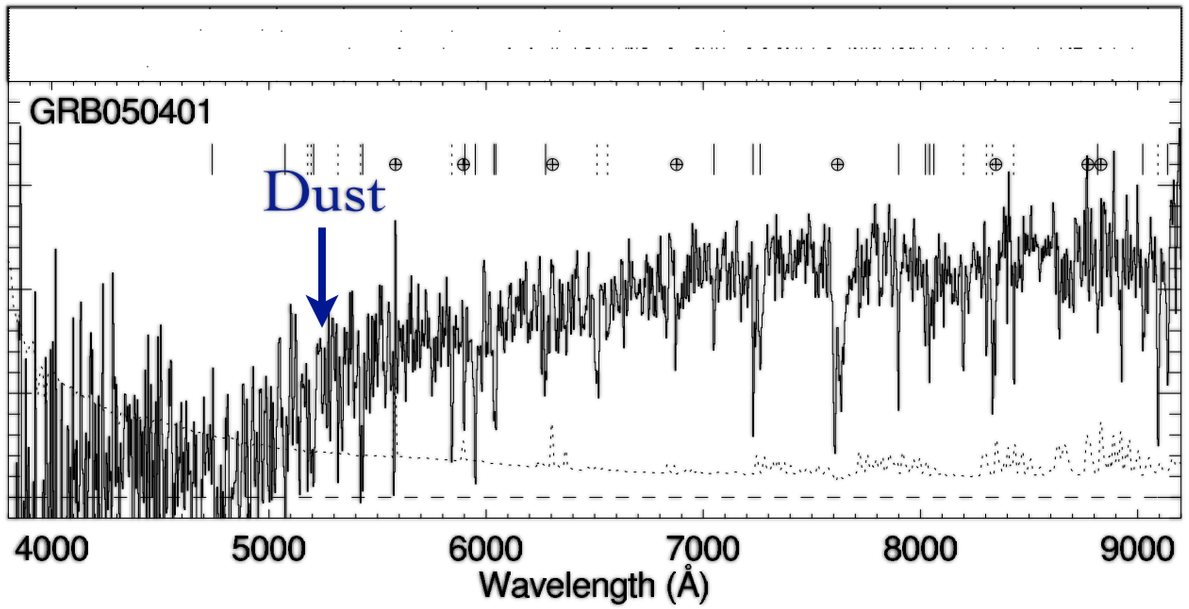
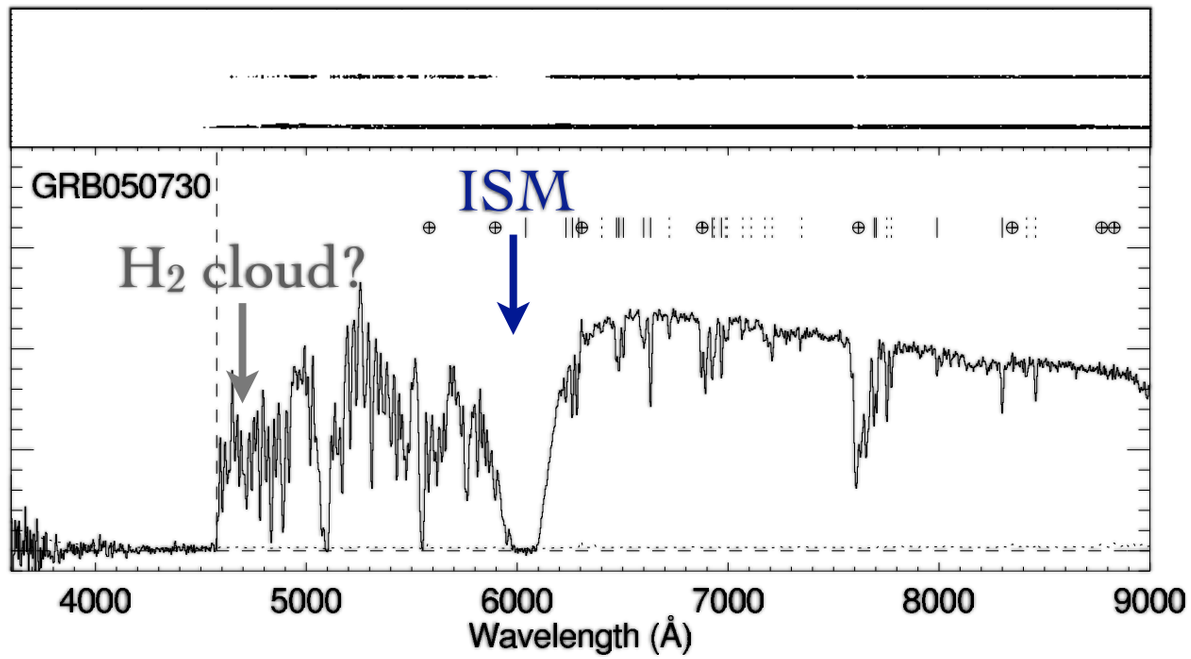
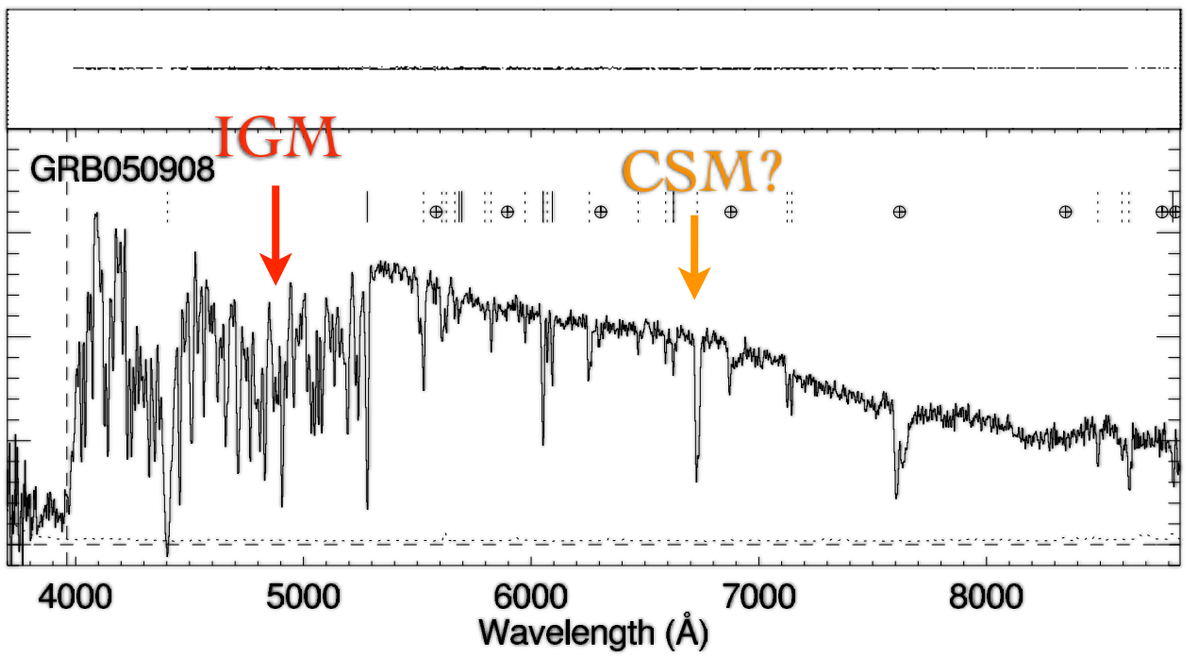
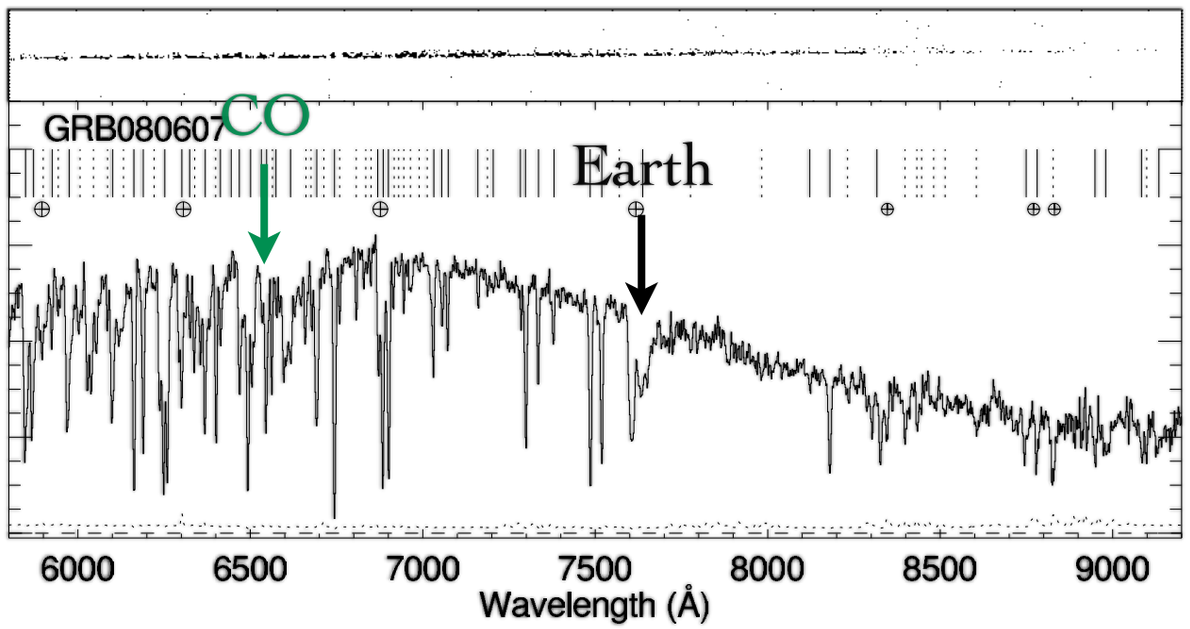








Fynbo+ 09

GRB Afterglows as Probes

Keck

Massive Star

The progenitor of a Gamma-Ray Burst (GRB) is a massive star embedded in a star-forming region of a galaxy.

GRB Afterglows as Probes

Keck

GRB

After approximately 30 million yrs, this star collapses to a Black Hole and explodes as a GRB.

GRB Afterglows as Probes

Keck

GRB

Afterglow

The GRB produces an “afterglow”, a pulse of radiation, that is briefly brighter than all other astrophysical events.

GRB Afterglows as Probes

Keck

GRB

Afterglow

This light travels to Earth, encoding information on the "layers" of gas and dust it intersects along the way.

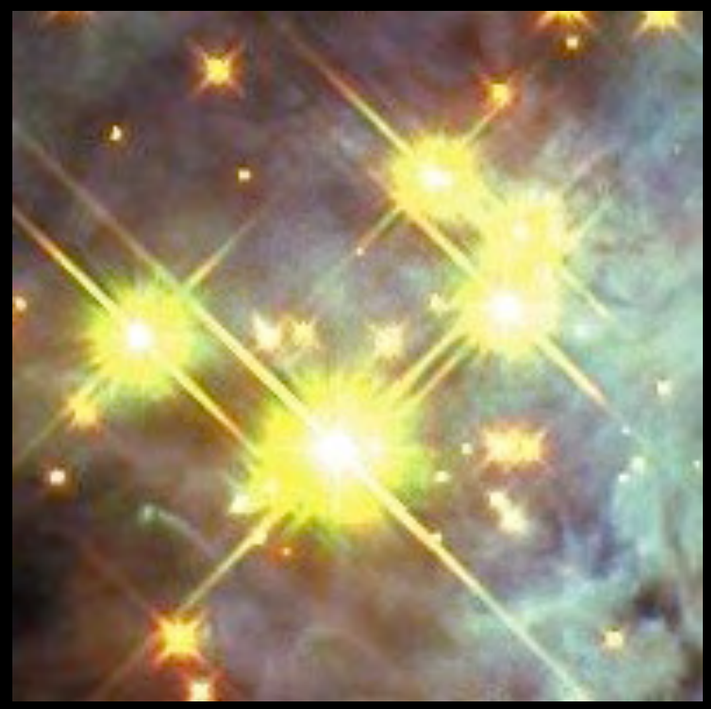
GRB Afterglows as Probes

CSM: Late-time evolution of massive stars.

HII: Density, abundance, composition of stellar regions in the early universe.

Keck

HII Region



d ~ 10 pc

GRB

The GRB is surrounded by a 10 to 100 pc region of highly ionized gas (HII region) produced by the now dead star.

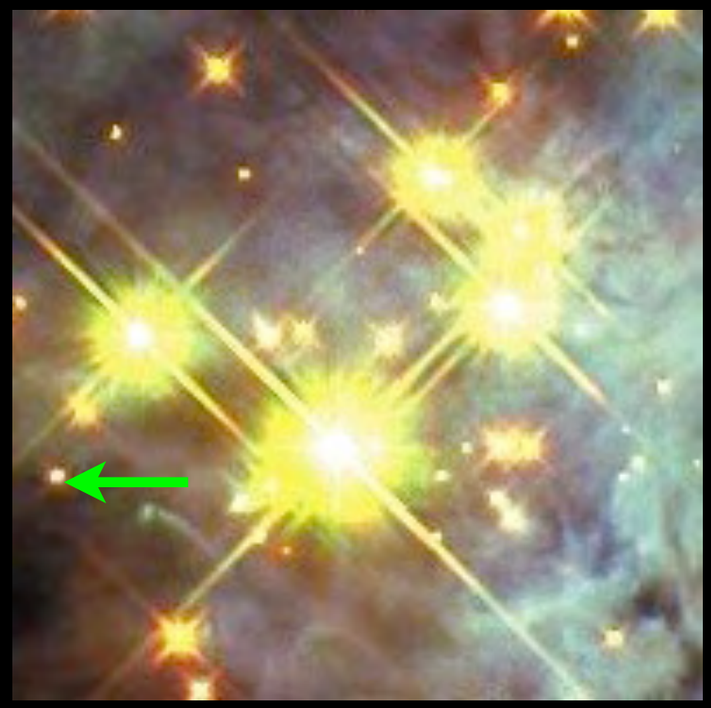
GRB Afterglows as Probes

CSM: Late-time evolution of massive stars.

HII: Density, abundance, composition of stellar regions in the early universe.

Keck

HII Region



d ~ 10 pc

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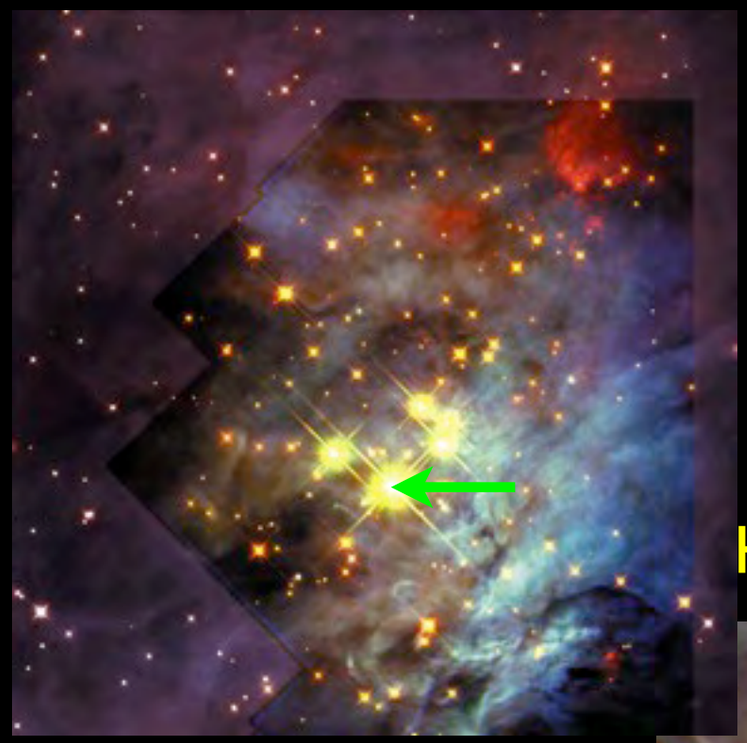
The GRB is surrounded by a 10 to 100 pc region of highly ionized gas (HII region) produced by the now dead star.

GRB Afterglows as Probes

Keck

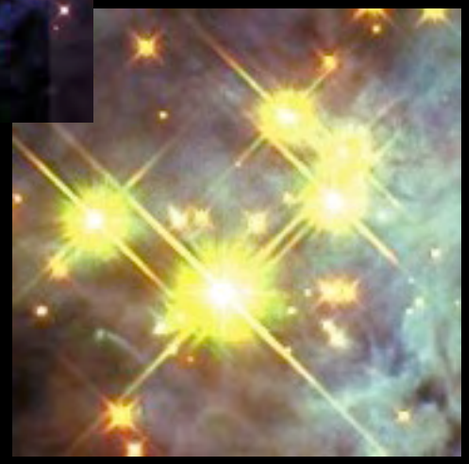
SF Region: Molecular content, dust composition, structure of SF complex.

SF Region



d ~ 100 pc

HII Region



d ~ 10 pc

GRB

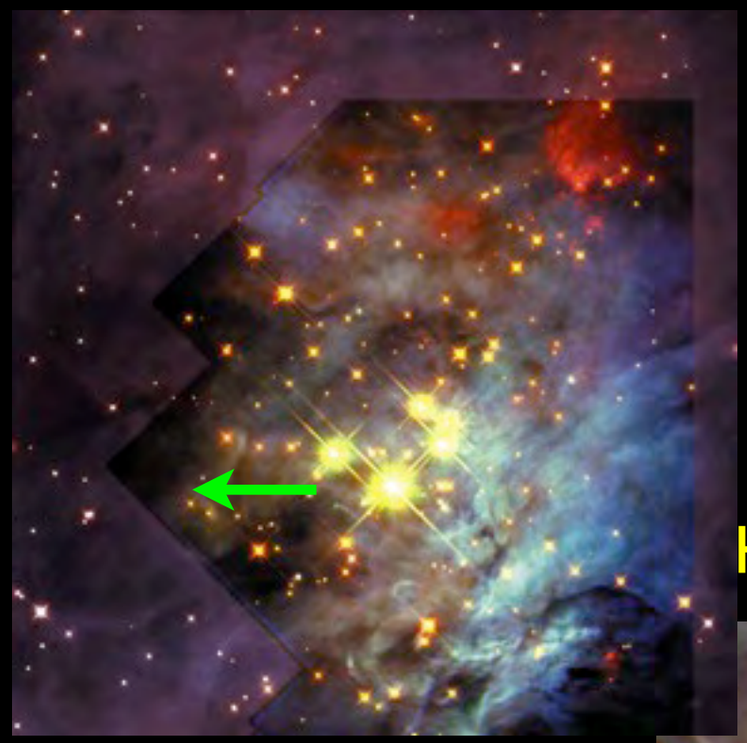
The dust, molecules and gas of the nearby star-forming (SF) region strongly absorb, redden, and scatter the light.

GRB Afterglows as Probes

Keck

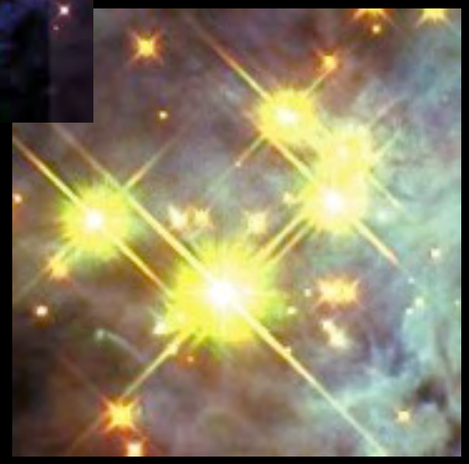
SF Region: Molecular content, dust composition, structure of SF complex.

SF Region



d ~ 100 pc

HII Region



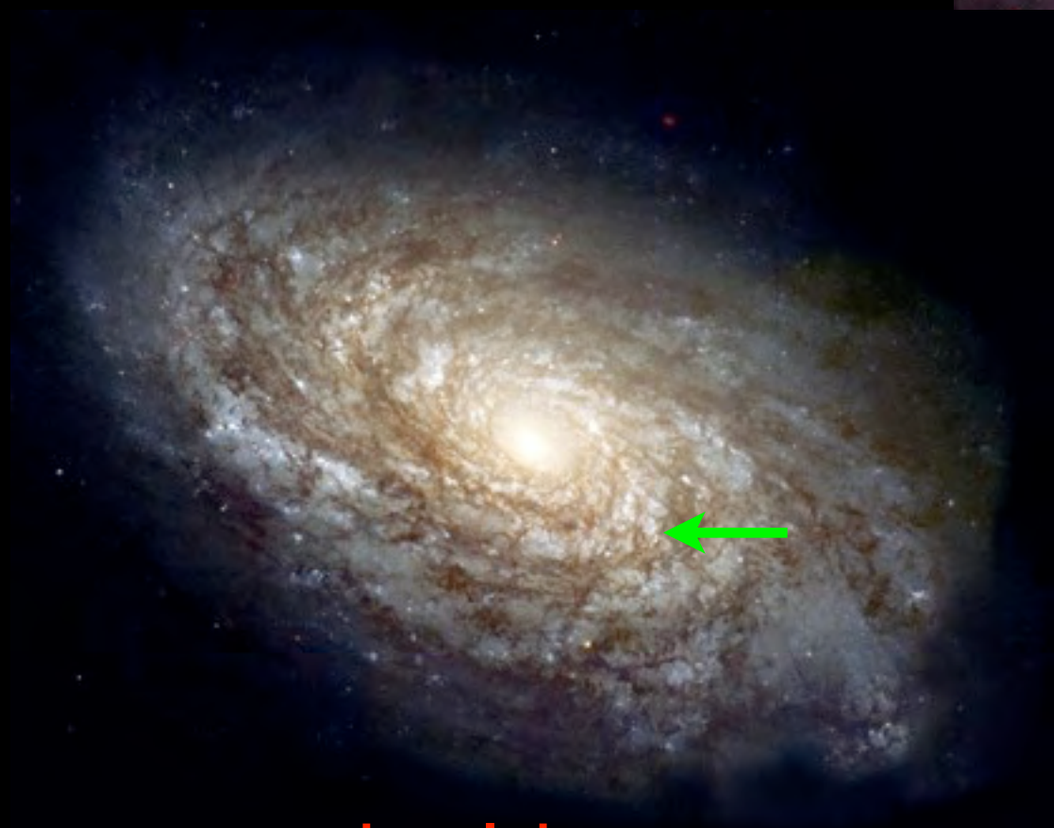
d ~ 10 pc

GRB

The dust, molecules and gas of the nearby star-forming (SF) region strongly absorb, redden, and scatter the light.

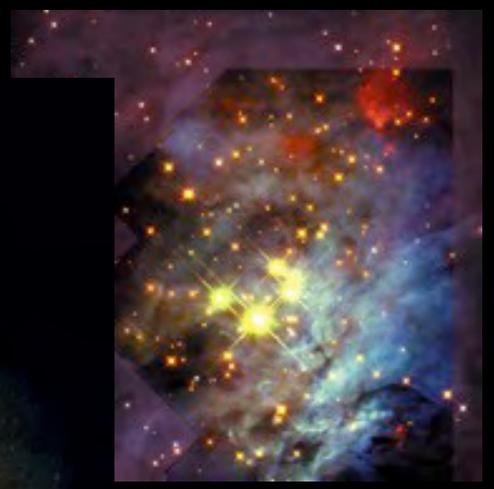
GRB Afterglows as Probes

ISM



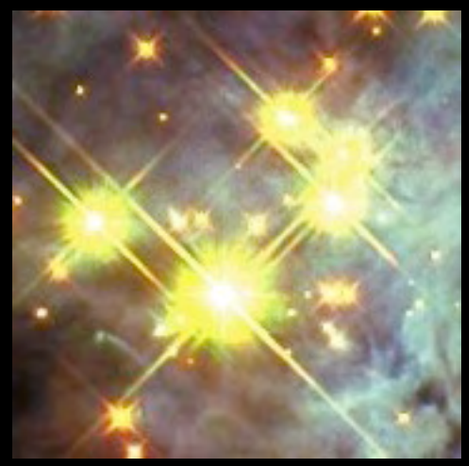
d ~ 1 kpc

SF Region



d ~ 100 pc

HII Region



d ~ 10 pc

Keck

GRB

ISM: Kinematics, composition, surface density of gaseous 'disk' in SF galaxies. Establish the redshift.

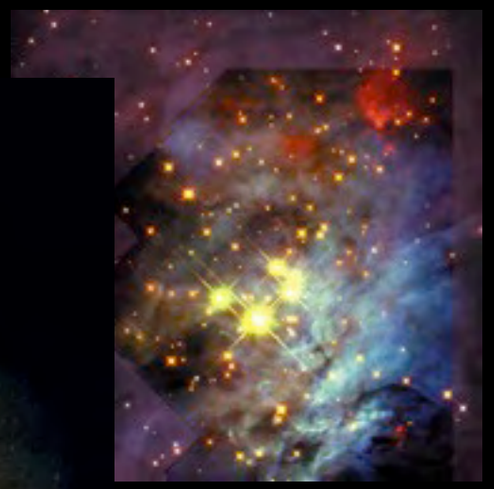
The Interstellar Medium (ISM) is full of gas, metals, and dust. It further absorbs and scatters light from the GRB.

GRB Afterglows as Probes

ISM

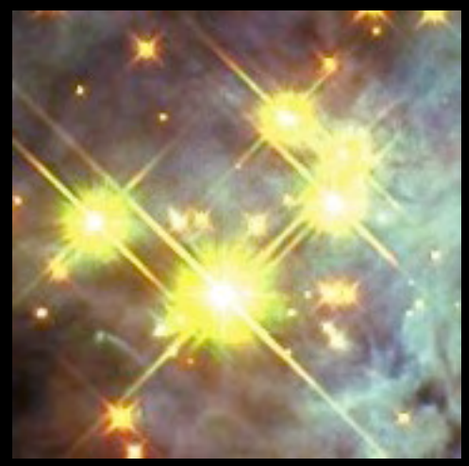
d ~ 1 kpc

SF Region



d ~ 100 pc

HII Region



d ~ 10 pc

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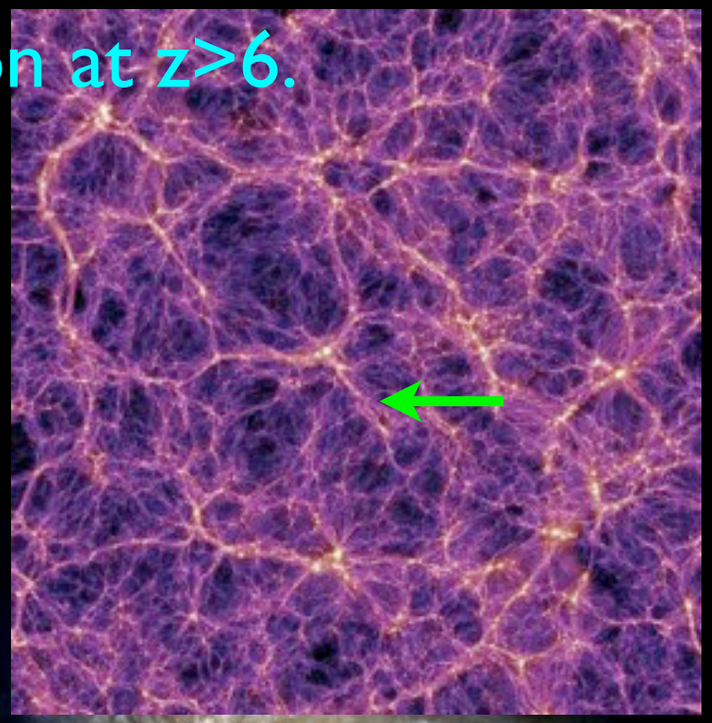
GRB Afterglows as Probes

IGM: Structure and abundance of the universe. Study reionization at z>6.

Keck

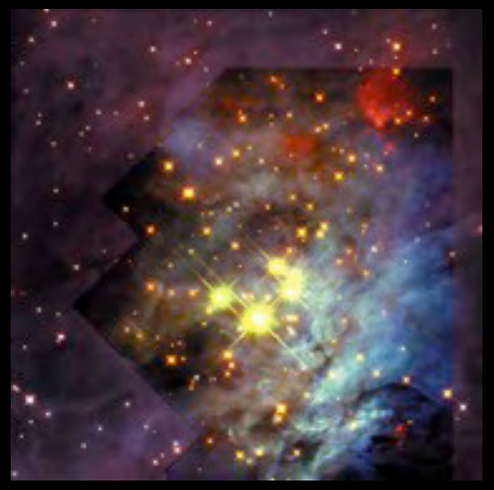
IGM



d ~ 10 Gpc

d ~ 1 kpc

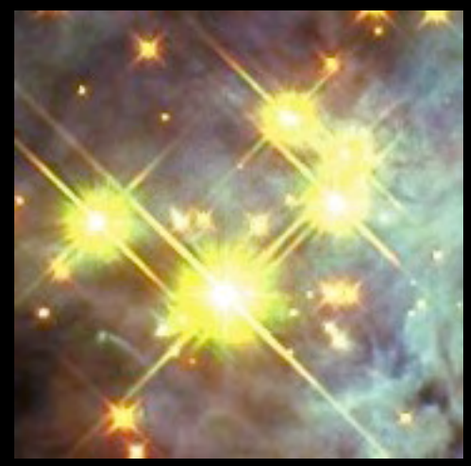
SF Region



d ~ 100 pc

GRB

HII Region



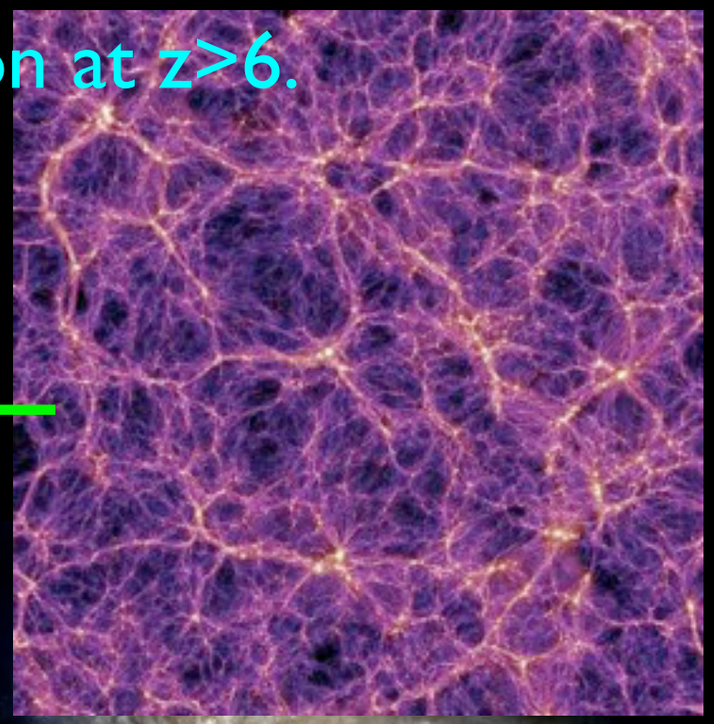
d ~ 10 pc

As the light travels to Earth it passes through gas that lies between galaxies, a.k.a. the Intergalactic Medium (IGM).

GRB Afterglows as Probes

IGM: Structure and abundance of the universe. Study reionization at z>6.

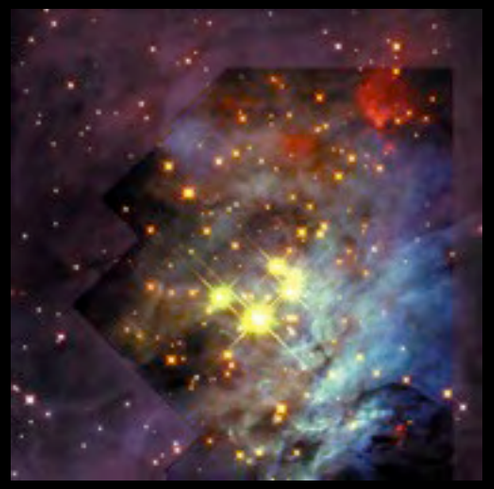
IGM



d ~ 10 Gpc

Keck

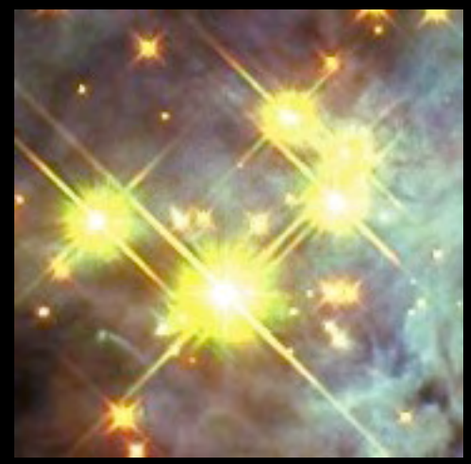
SF Region



d ~ 100 pc

GRB

HII Region



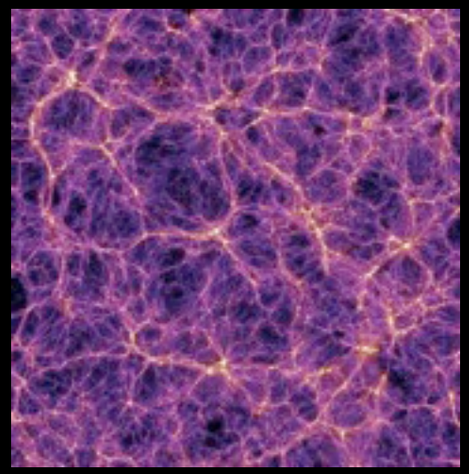
d ~ 10 pc

d ~ 1 kpc

As the light travels to Earth it passes through gas that lies between galaxies, a.k.a. the Intergalactic Medium (IGM).

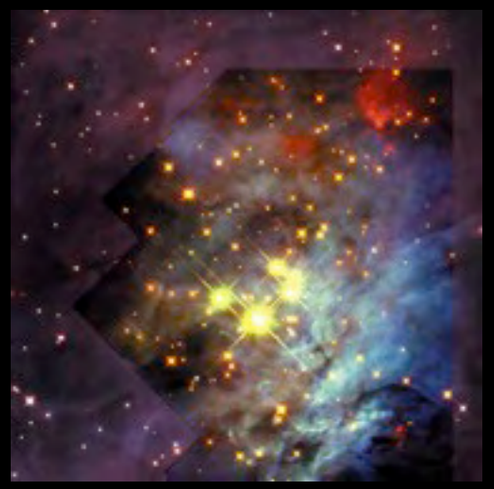
GRB Afterglows as Probes

IGM



d ~ 10 Gpc

SF Region



d ~ 100 pc

Keck

GRB

ISM

d ~ 1 kpc

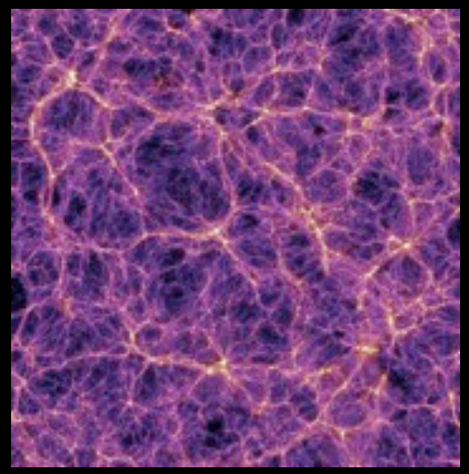
HII Region

d ~ 10 pc

The light is recorded as a spectrum at Keck, starting about 15min after the GRB alert from the *Swift* satellite.

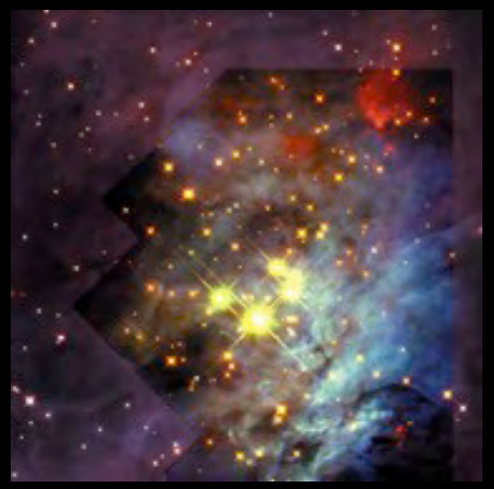
GRB Afterglows as Probes

IGM



d ~ 10 Gpc

SF Region



d ~ 100 pc

Keck

GRB

ISM

d ~ 1 kpc

HII Region

d ~ 10 pc

The spectrum is akin to a core sample of the Earth, allowing us to study "layers" of the Universe.