Rayleigh Taylor Instabilities in Magnetized Supernovae

50th Anniversary of GFDI
2017-05-15
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with
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Basic Outline

- Measuring Distances
  - This size of the whole dang universe.
- Details of Supernova
- MHD Impact

How far is this?
It changes every few years.
(about 740 light years, most recently)

Velocity vs. Distance

- Each joint in this Scissors lift is expanding a the same rate,
- So two joints away from you is moving away twice as fast as the next one over
- V = H0 D
- H0 = 70 km/s/Mpc (ish)

Expanding Universe

- The equation of motion for the universe is pretty simple.
  a = how large it is. a(now) = 1
  H0 = current expansion rate
  Omega = energy density

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t)$$

$$= H_0^2 \left[a^{-4}(t)\Omega_{\mathrm{r}} + a^{-3}(t)\Omega_{\mathrm{m}} + a^{-2}(t)(1 - \Omega_{\mathrm{m}} - \Omega_{\Lambda}) + \Omega_{\Lambda}\right]$$

Expanding Universe

- The equation of motion for the universe is pretty simple.
  a = how large it is. a(now) = 1
  H0 = current expansion rate
  Omega = energy density

$$\left(\frac{\dot{a}}{a}\right)^2 = \qquad = H_0^2 \left[\qquad + a^{-3}(t)\,\overset{\text{Matter}}{\Omega_{\mathrm{m}}} \qquad + \overset{\text{Integration Constant}}{\Omega_{\Lambda}} \right]$$

Accurate Brightness
begets
Accurate Distances.

$$F = \frac{L}{4\pi D^2}$$

Accurate Brightness
begets
Accurate Distances.

From the physics of the object

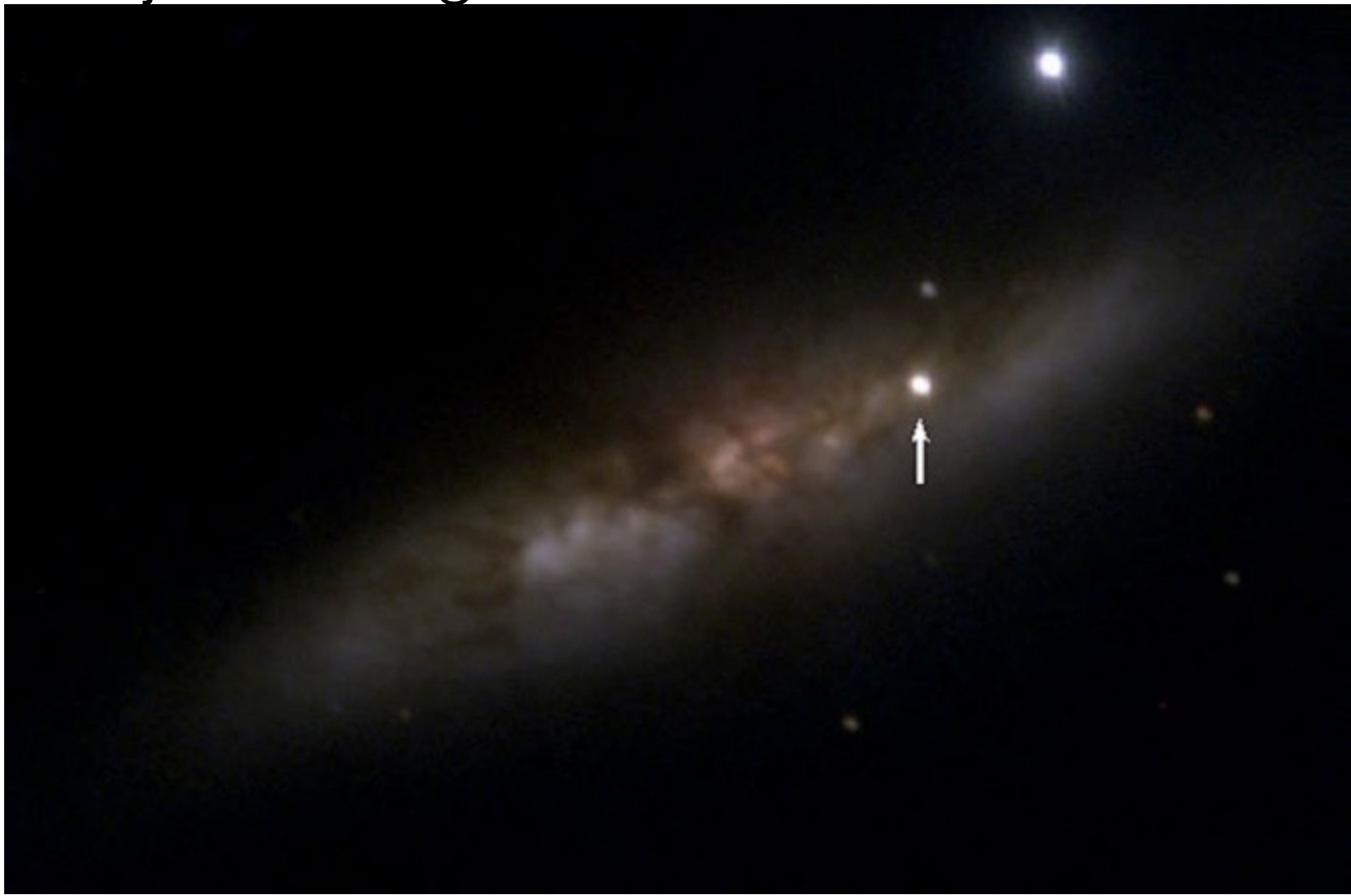
$$F = \frac{L}{4\pi D^2}$$

from
the
telescope

The thing I want

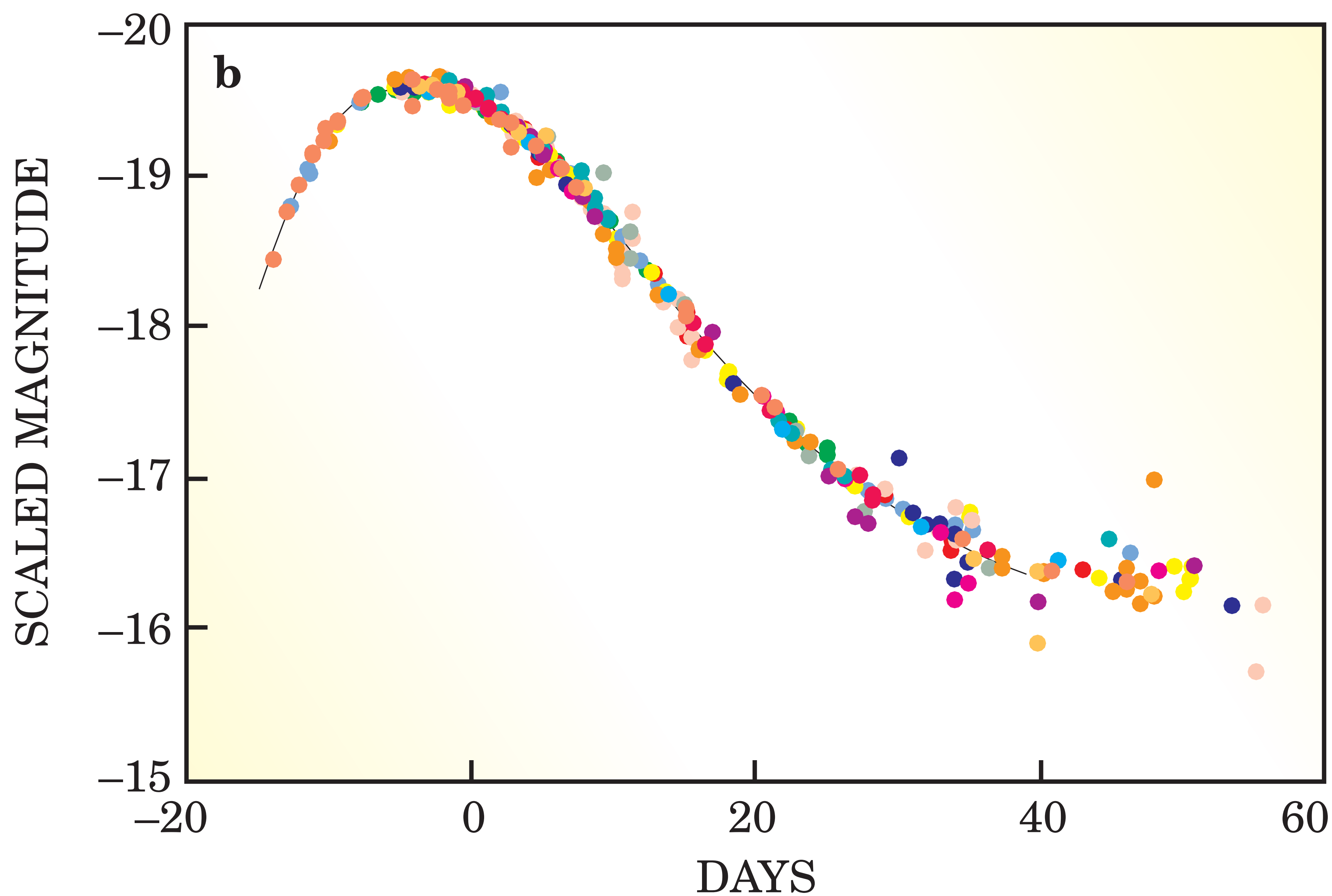
Supernovae are incredibly bright.

- This galaxy has ~10^9 stars (Greco+2012)
- This one solar mass object is bright.
- 2014j, in M82



Light Curve

- Light curves and spectra are extremely consistent
  (almost, more in a second)



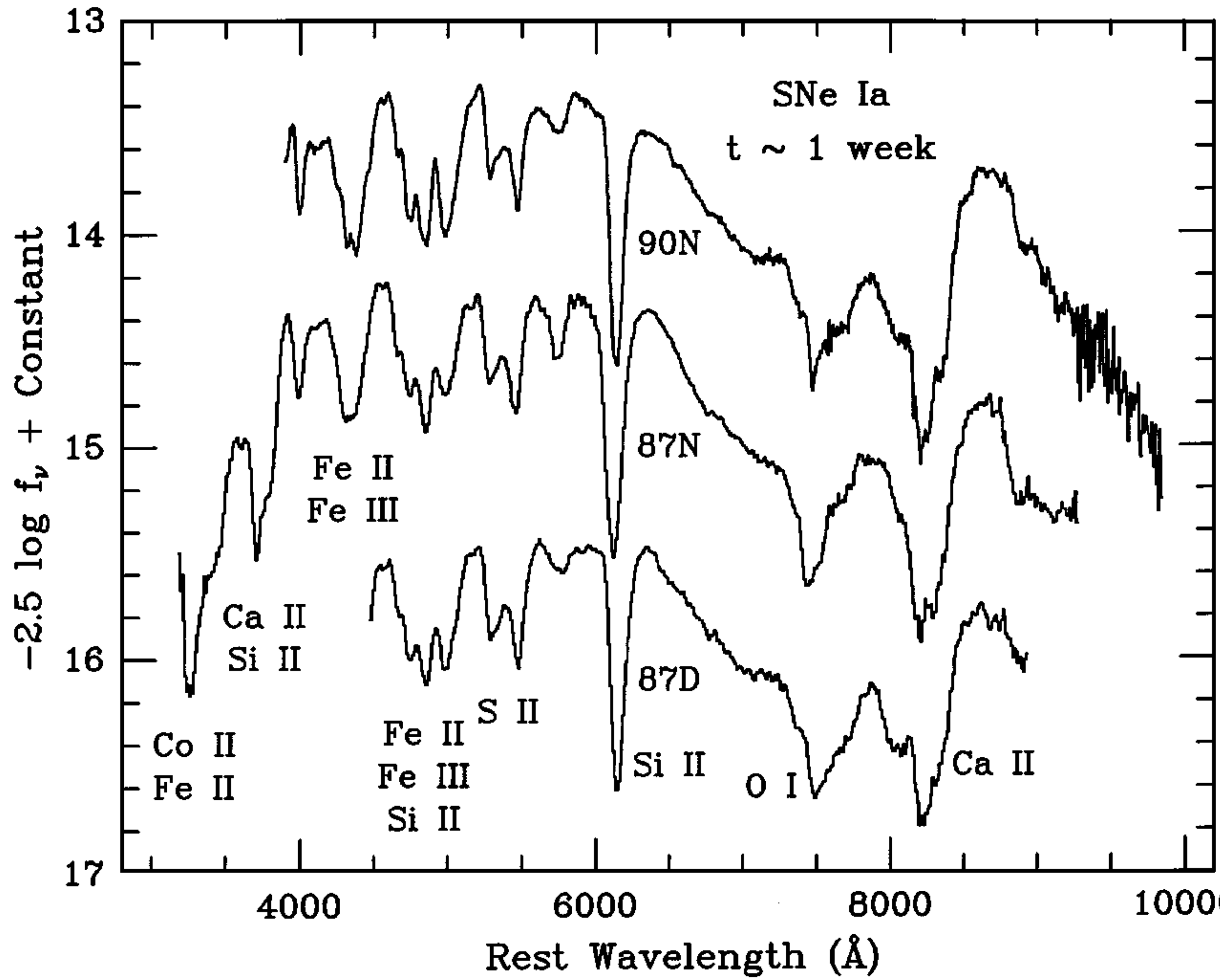
(Perlmutter 1997)

Spectra

- SNIa have very consistent spectra

- Spectra from 3 SNe in different galaxies (offset for clarity)

(Wait, what's a spectrum?)

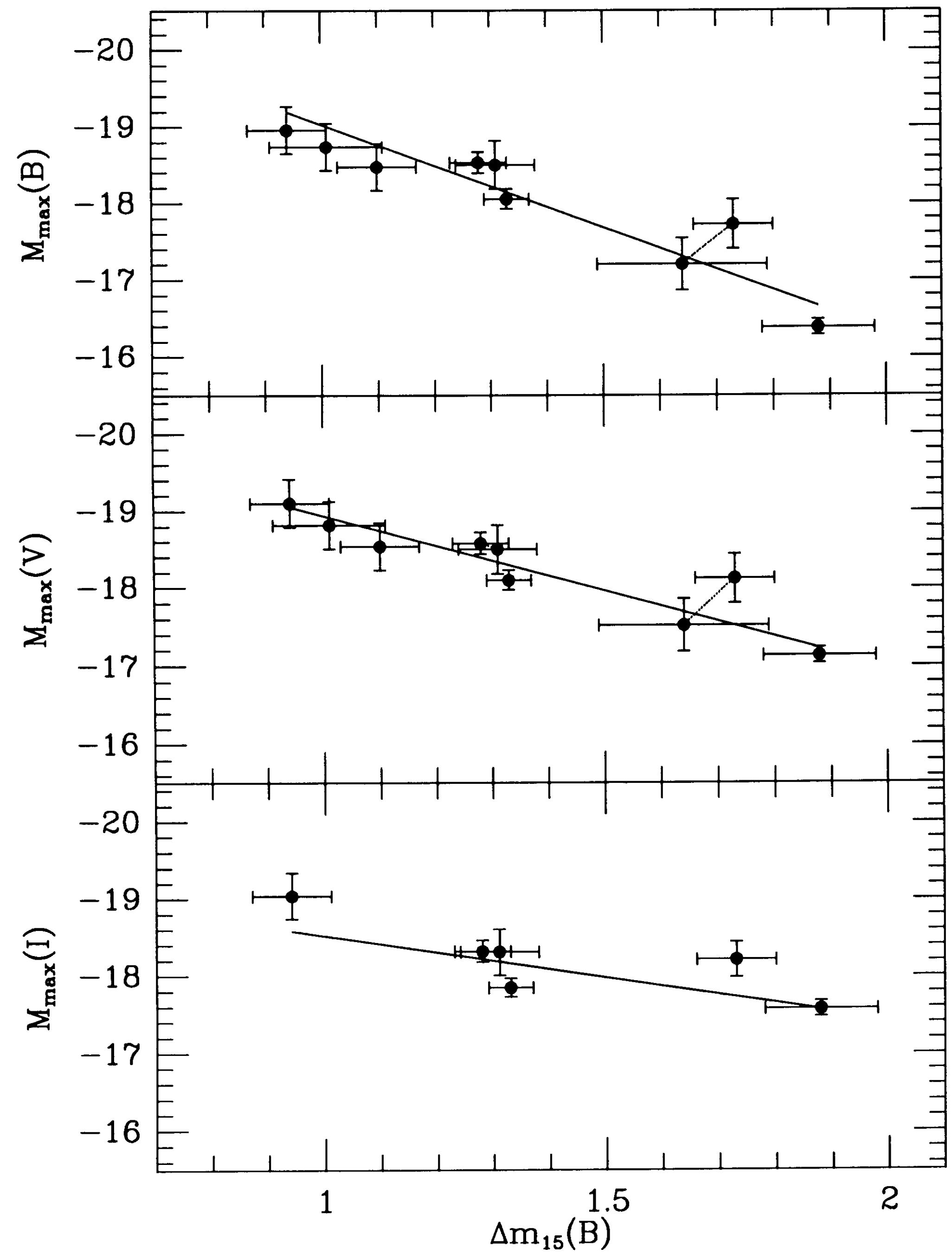


(Filippenko 1997)

Well, almost.

- They actually make a one parameter *family* of objects.

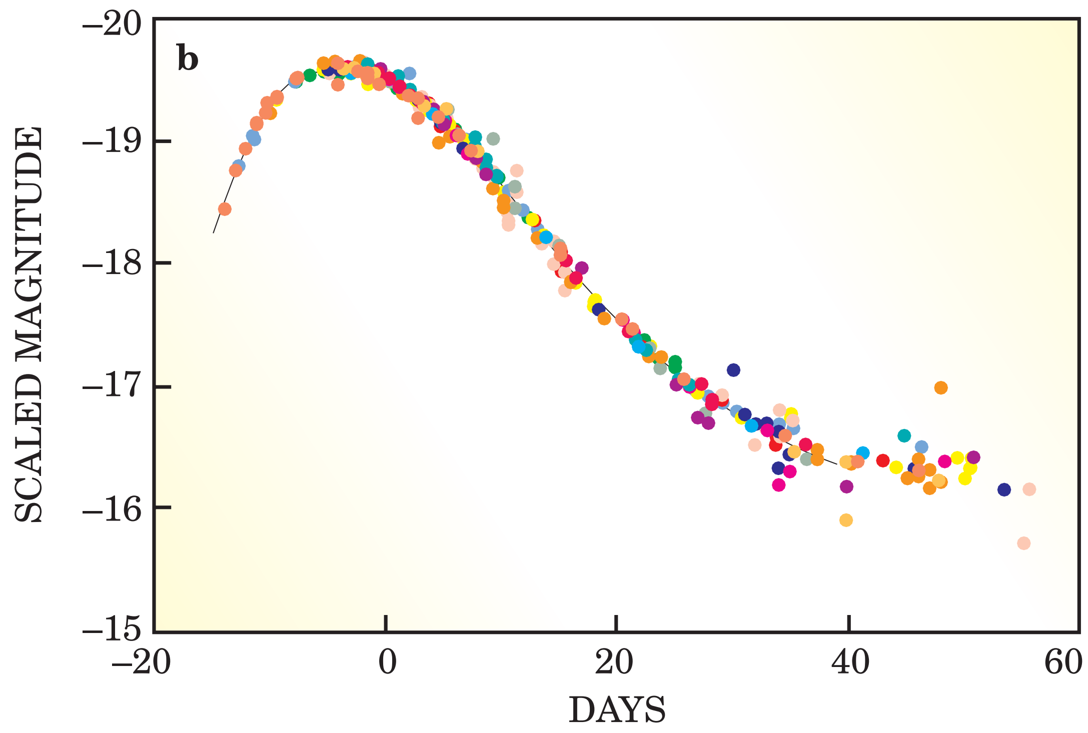
Peak Brightness in Various Colors

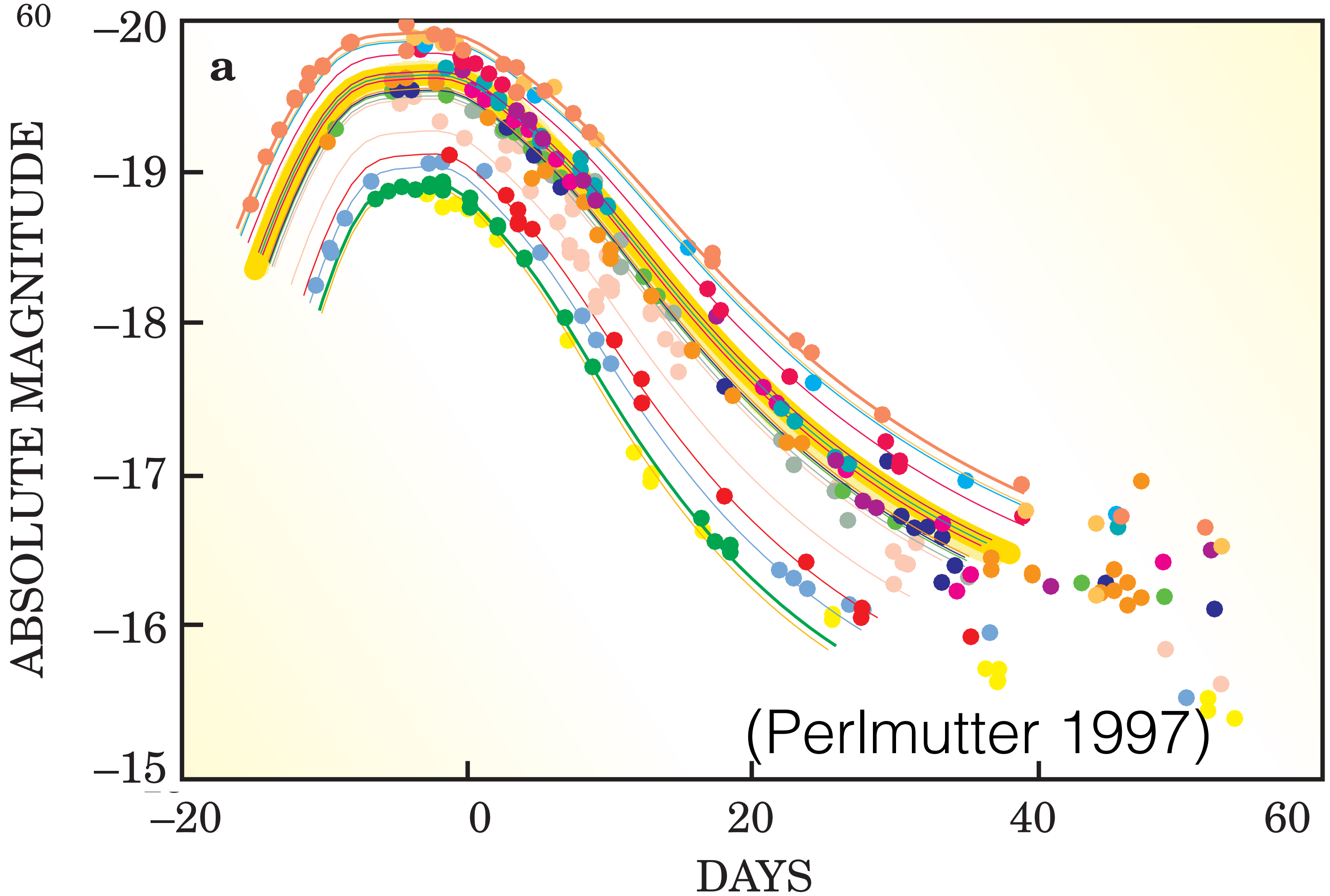


Change after 15 days

(Phillips 1993)

Well, almost.


b
–20
–19
–18
–17
–16
–15
SCALED MAGNITUDE
–20
0
20
40
60
DAYS

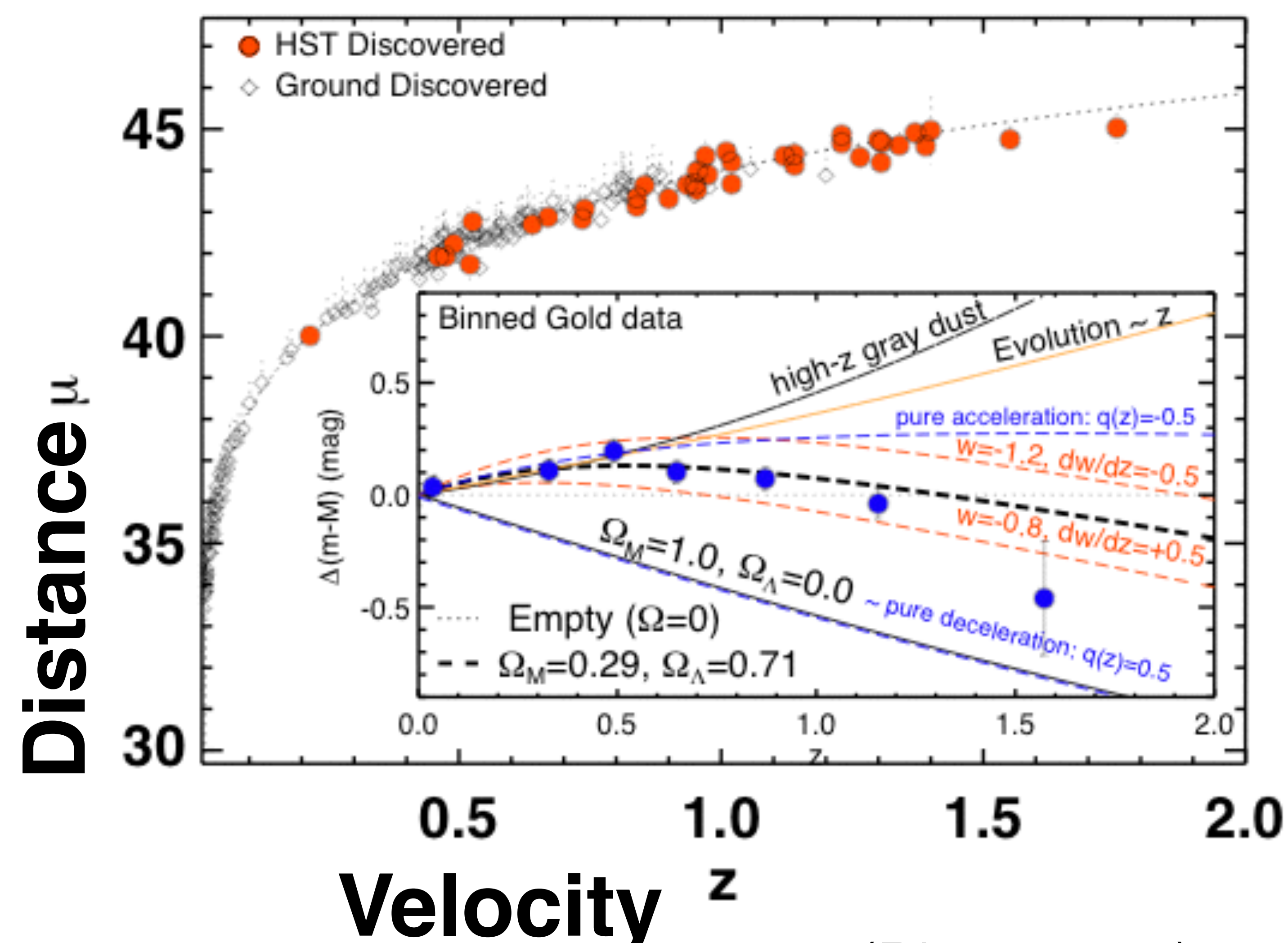

a
–20
–19
–18
–17
–16
–15
ABSOLUTE MAGNITUDE
(Perlmutter 1997)
–20
0
20
40
60
DAYS

Accurate Brightness begets Accurate Distances.

$$F = \frac{L}{4\pi D^2}$$

- Now we can measure the expansion rate of the universe.

- the take away, things are further than they should be if there weren't an insane amount of stuff we super don't understand.



(Riess 2007)

Expanding Universe

- The equation of motion for the universe is pretty simple.
  a = how large it is. a(now) = 1
  H0 = current expansion rate
  Omega = energy density

Matter

Integration Constant

$$\left(\frac{\dot{a}}{a}\right)^2 = \qquad = H_0^2 \left[\qquad + a^{-3}(t)\,\Omega_{\mathrm{m}} \qquad + \Omega_\Lambda \right]$$

Accurate Brightness begets Accurate Distances.

$$F = \frac{L}{4\pi D^2}$$

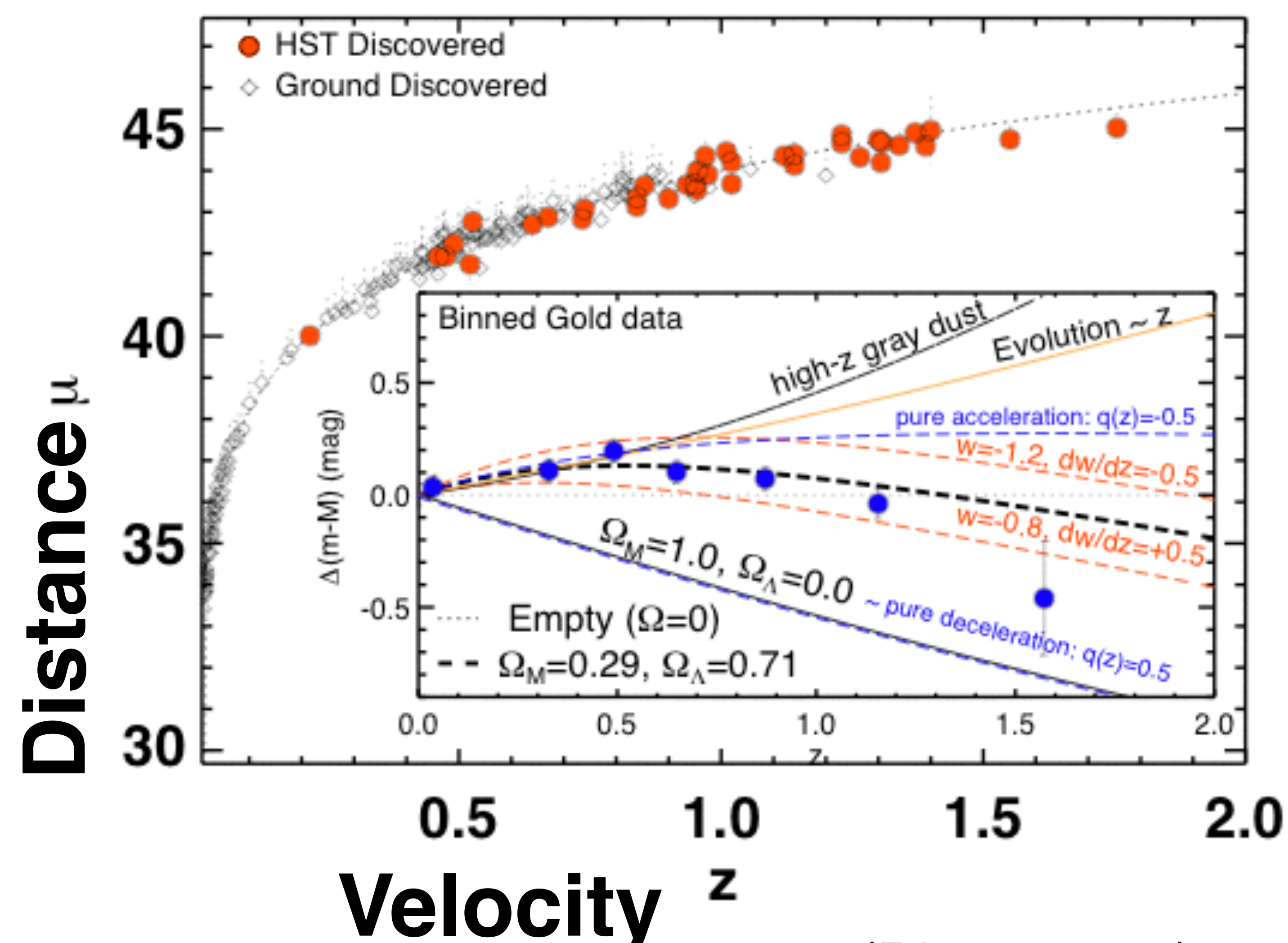
- Now we can measure the expansion rate of the universe.

- The inset:

  - flat is just expanding, nothing in it.

  - Blue line is only matter, and flat

  - Dots are flat, plus Dark Energy.

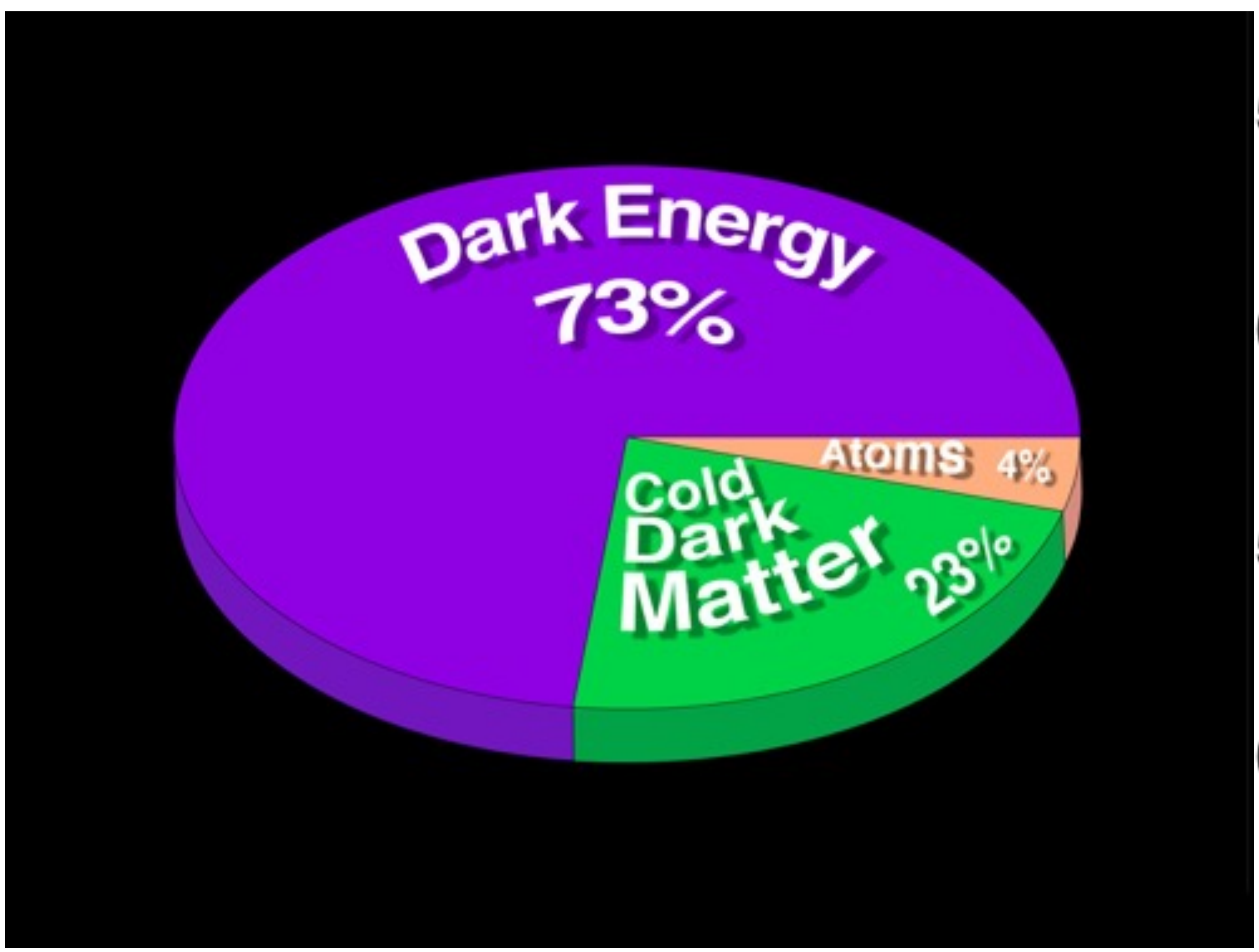


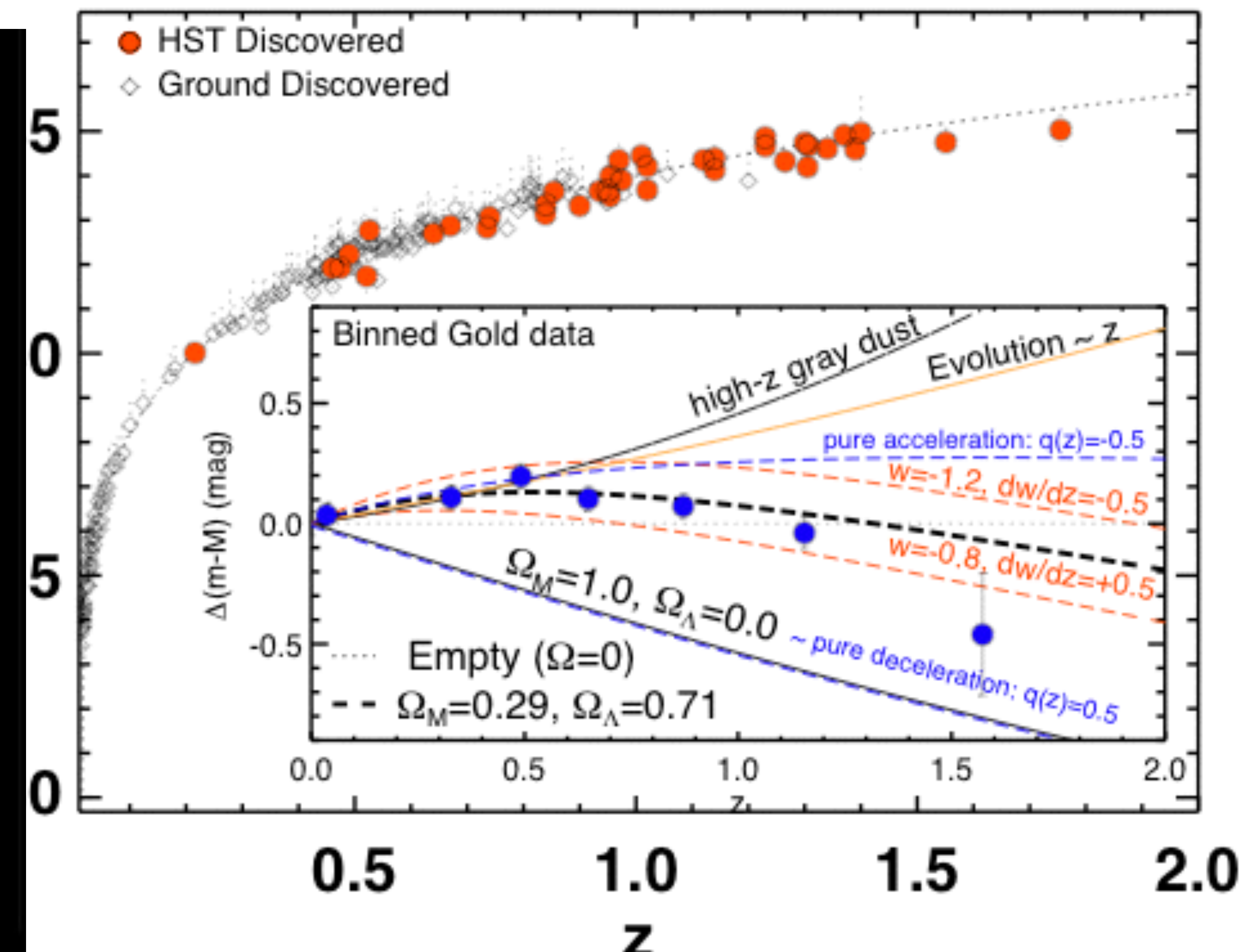
(Riess 2007)

(Flat? Ask me later. But the universe is definitely flat.)

We've learned that there *exists* dark energy

- To learn what it *is* we need to understand the systematics of supernovae much better. (error bars)



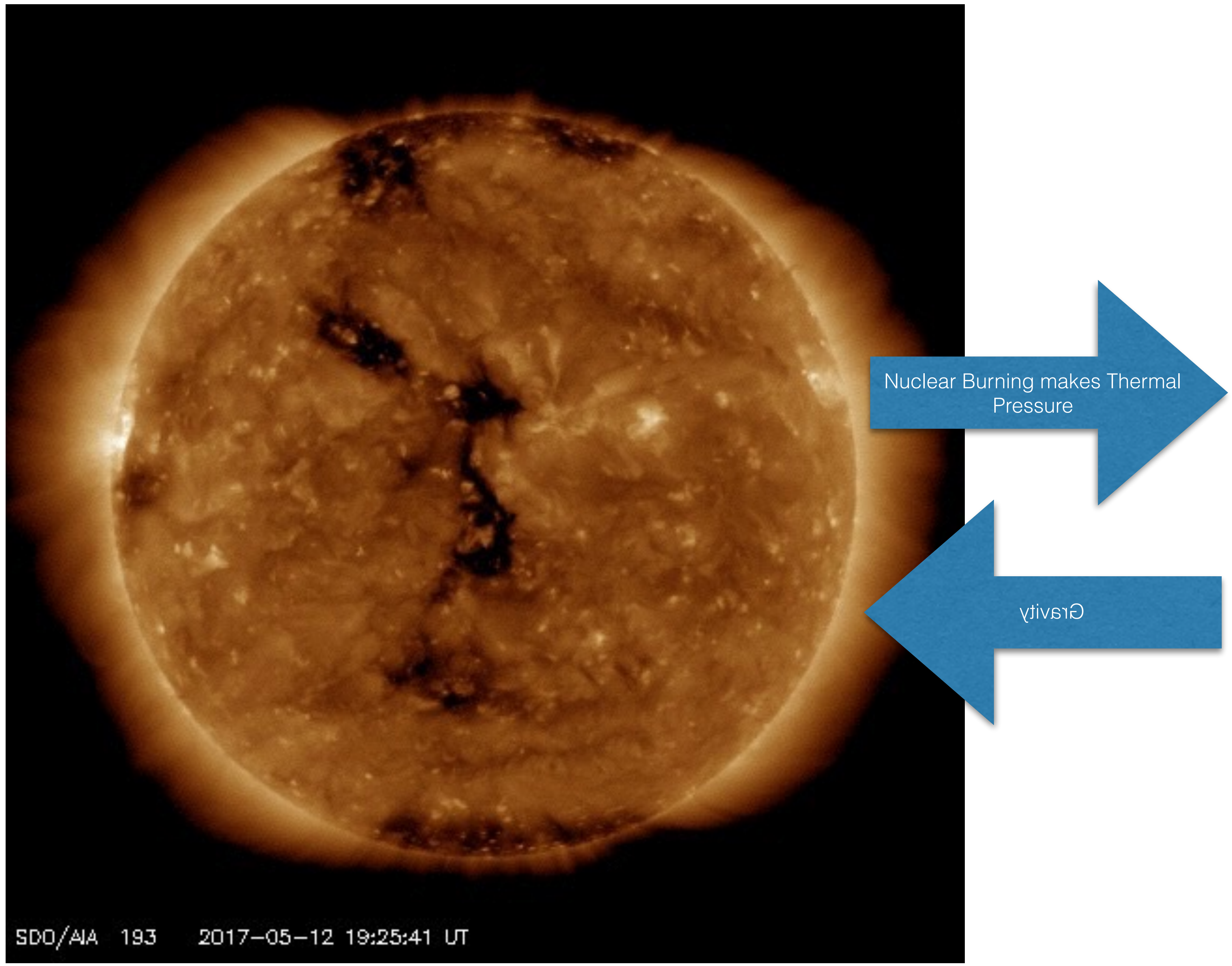


(and neutral atoms are less than 1% of the atoms.)

What we know so far

- Type Ia are explosions of White Dwarfs.
- What's a White Dwarf?
- Normal stars fuse Hydrogen at the core, that keeps them from collapsing.
- When that's done, the outer layers get blown off (that's another talk), and you're left with Carbon and Oxygen.
- What's left is <1.4 solar masses, held up by *electron degeneracy pressure*
  - ***Left alone, this is very stable.***
- If the mass gets bigger than 1.4 solar masses (by accreting from a nearby star?)
  - Too much gravity! Degeneracy pressure can't support the star
  - burning the Carbon and Oxygen to Nickel, plus a whole bunch of other stuff

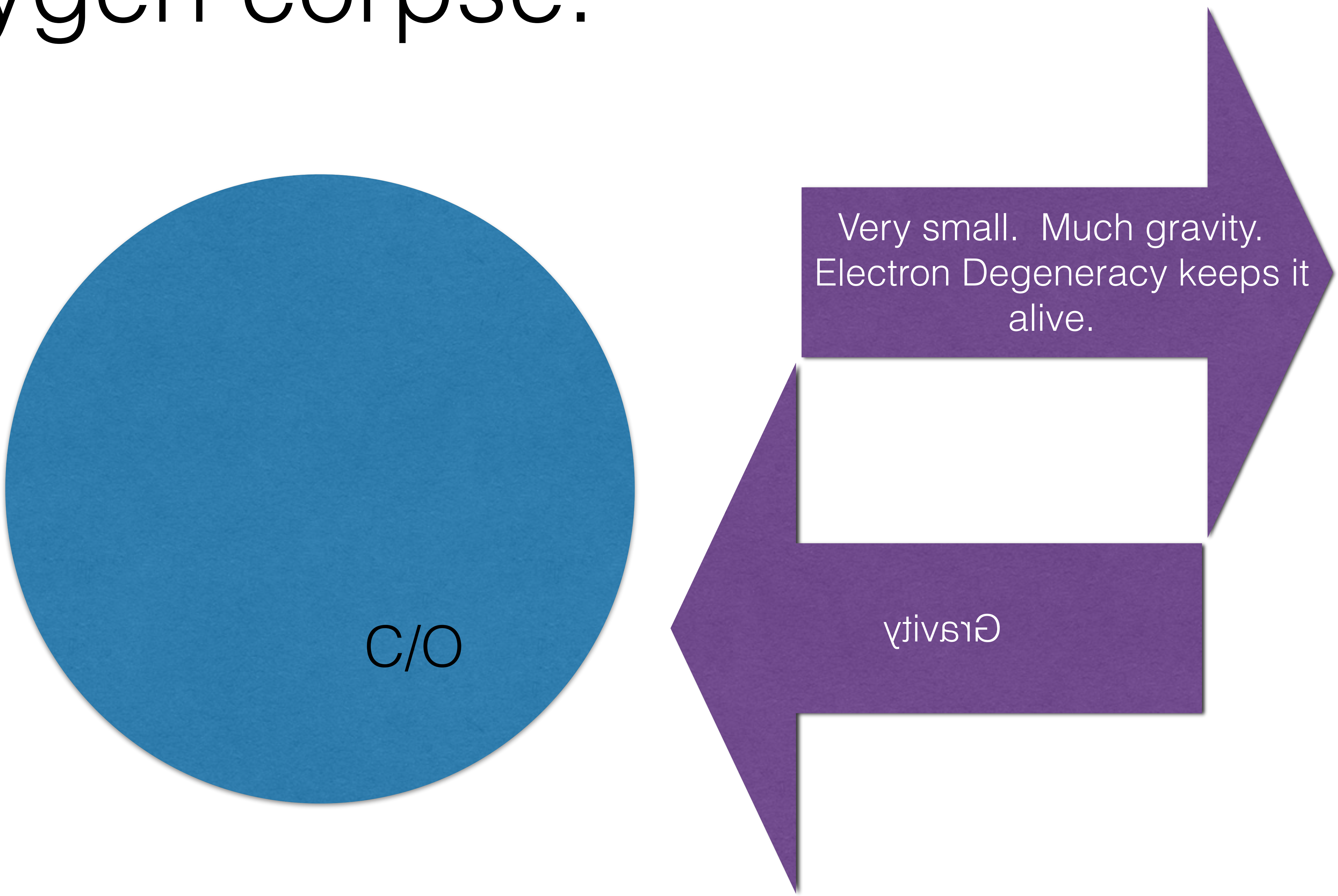
$$C + O \rightarrow \mathrm{stuff} \rightarrow^{56} \mathrm{Ni}$$


SDO/AIA 193 2017-05-12 19:25:41 UT
Nuclear Burning makes Thermal Pressure
Gravity

It will die, and give most of it’s material to it’s next of kin.

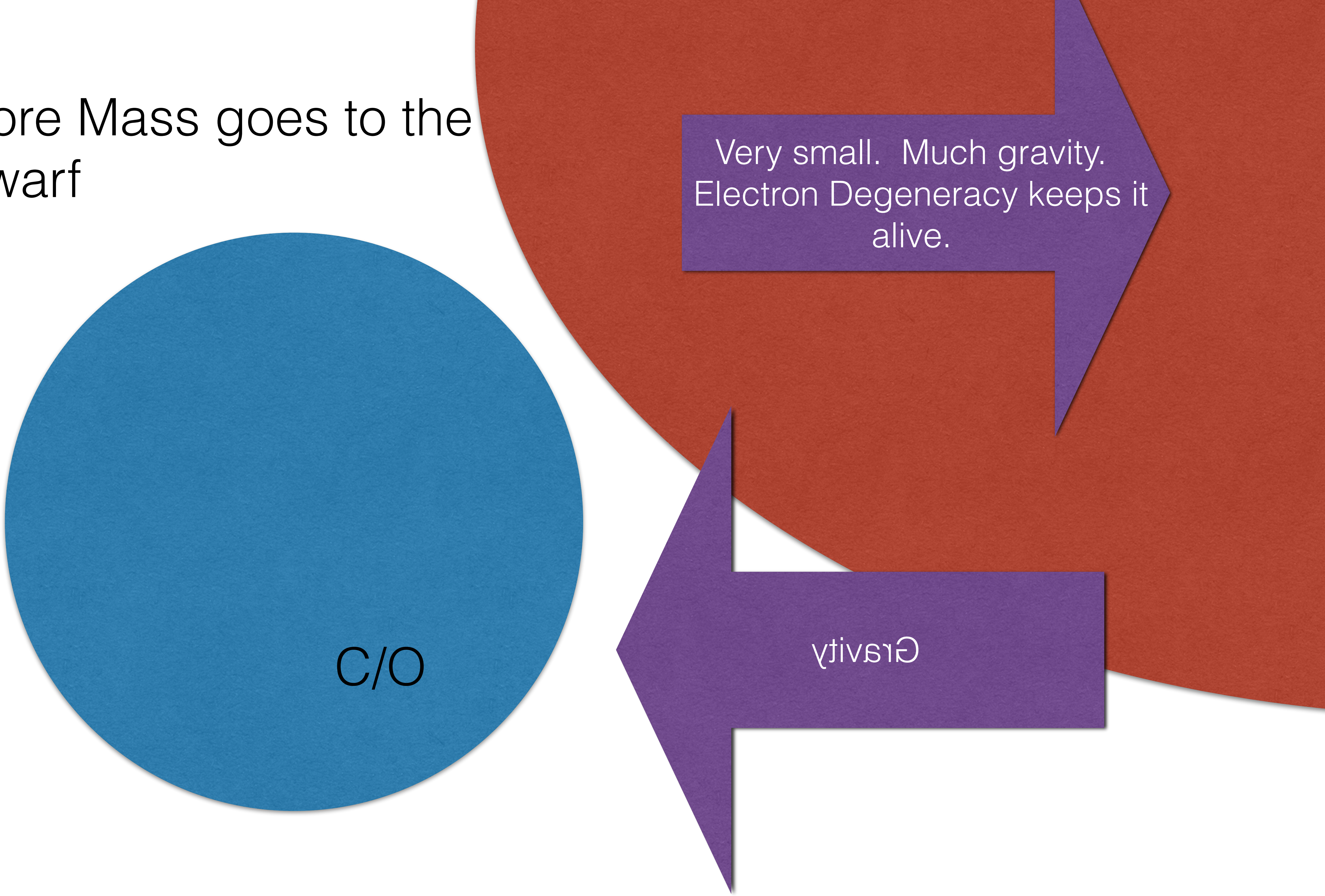
- sun is tiny here

All that's left it a carbon & oxygen corpse.



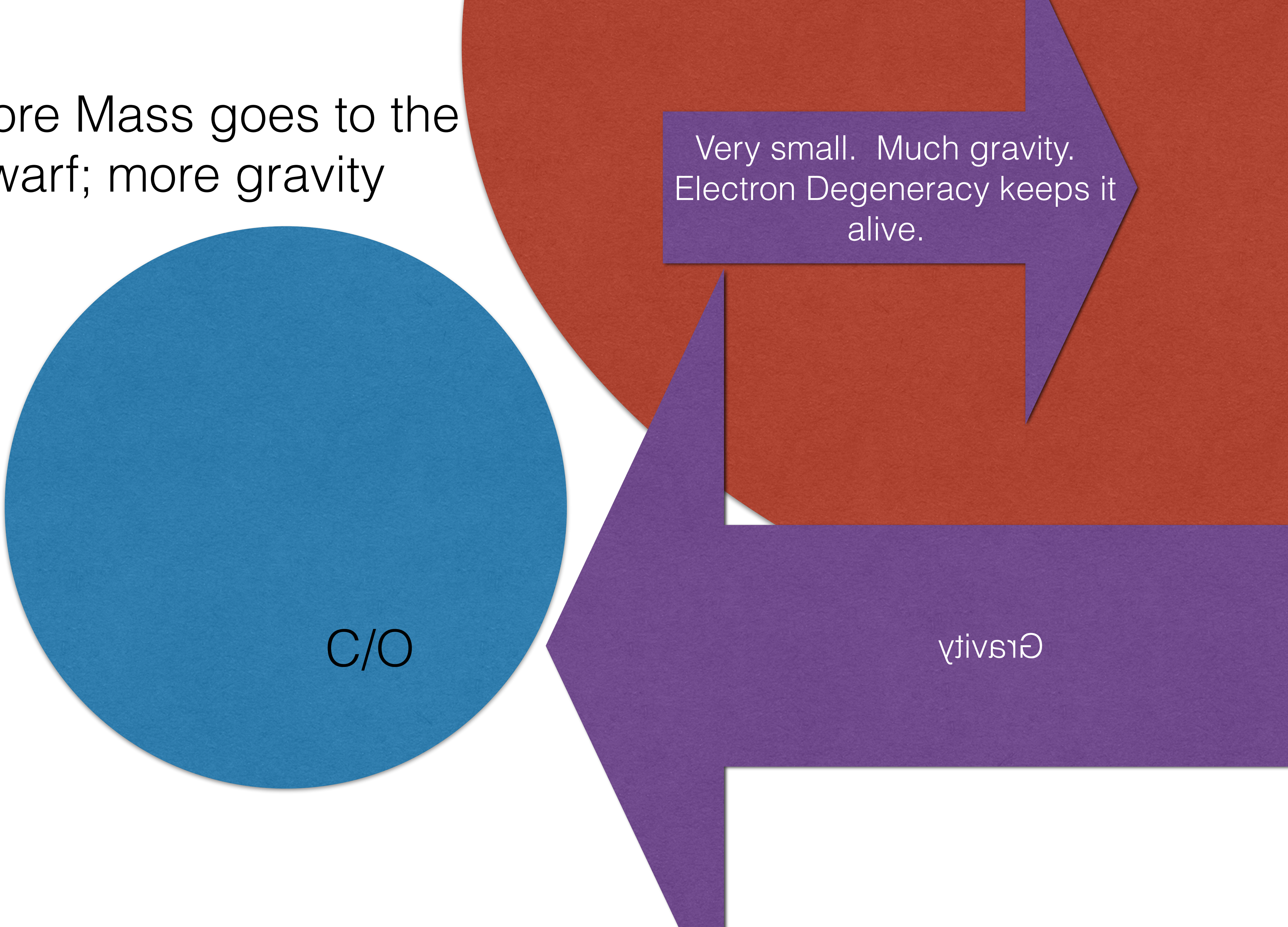
Most stars are in Binaries

- More Mass goes to the Dwarf



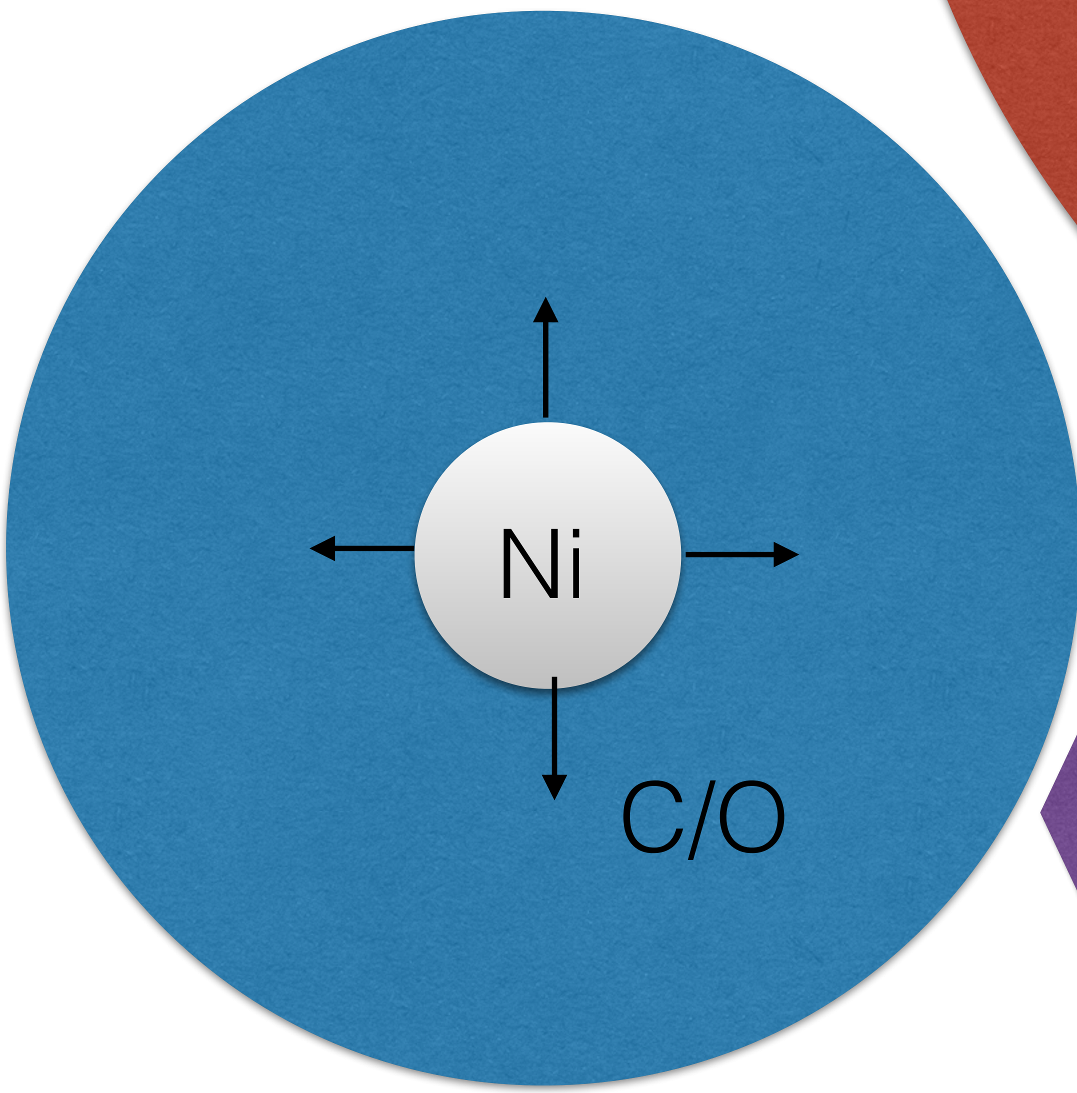
Most stars are in Binaries

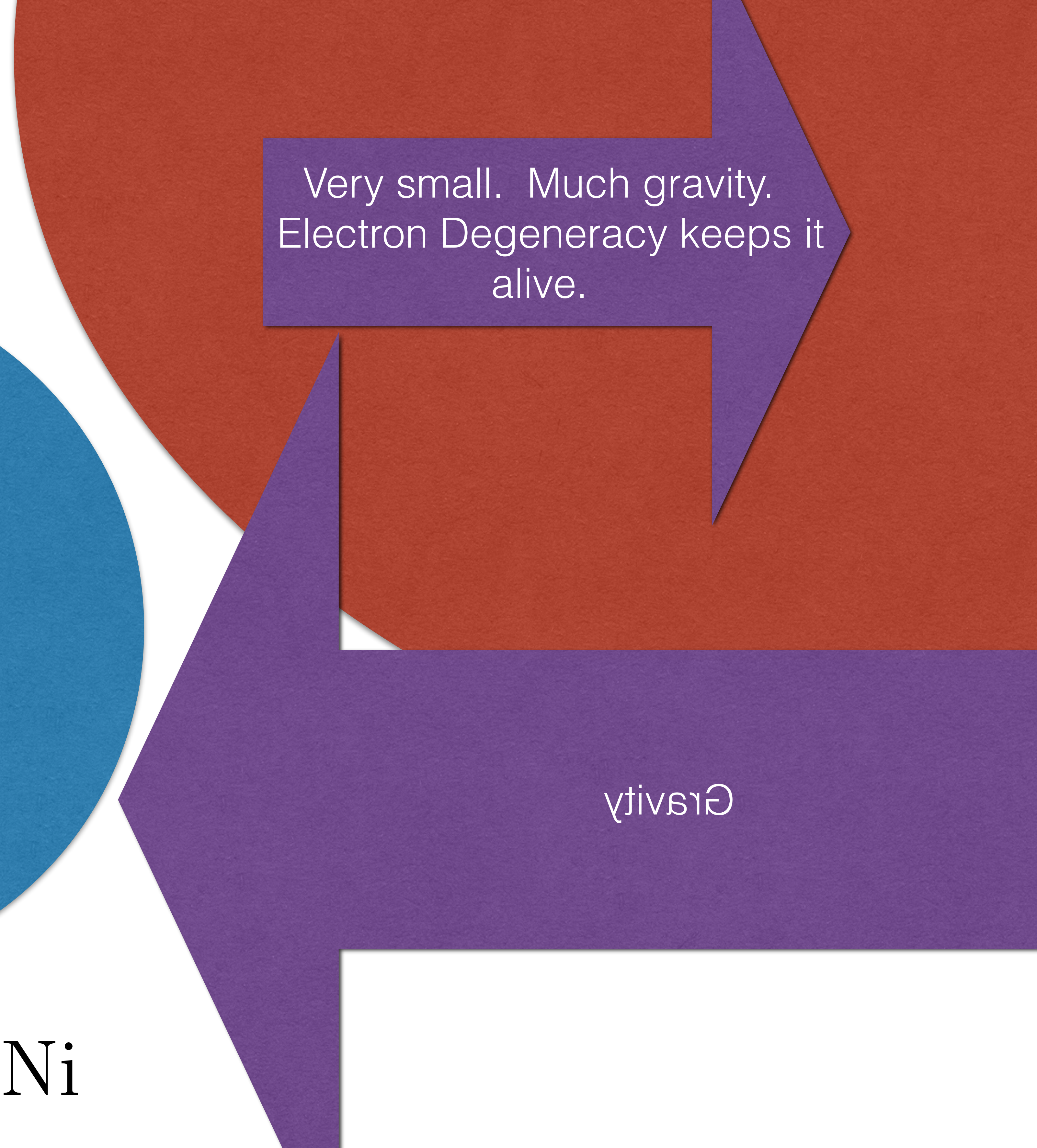
- More Mass goes to the Dwarf; more gravity



Most stars are in Binaries

- Degeneracy Pressure Loses. Stars to Burn.

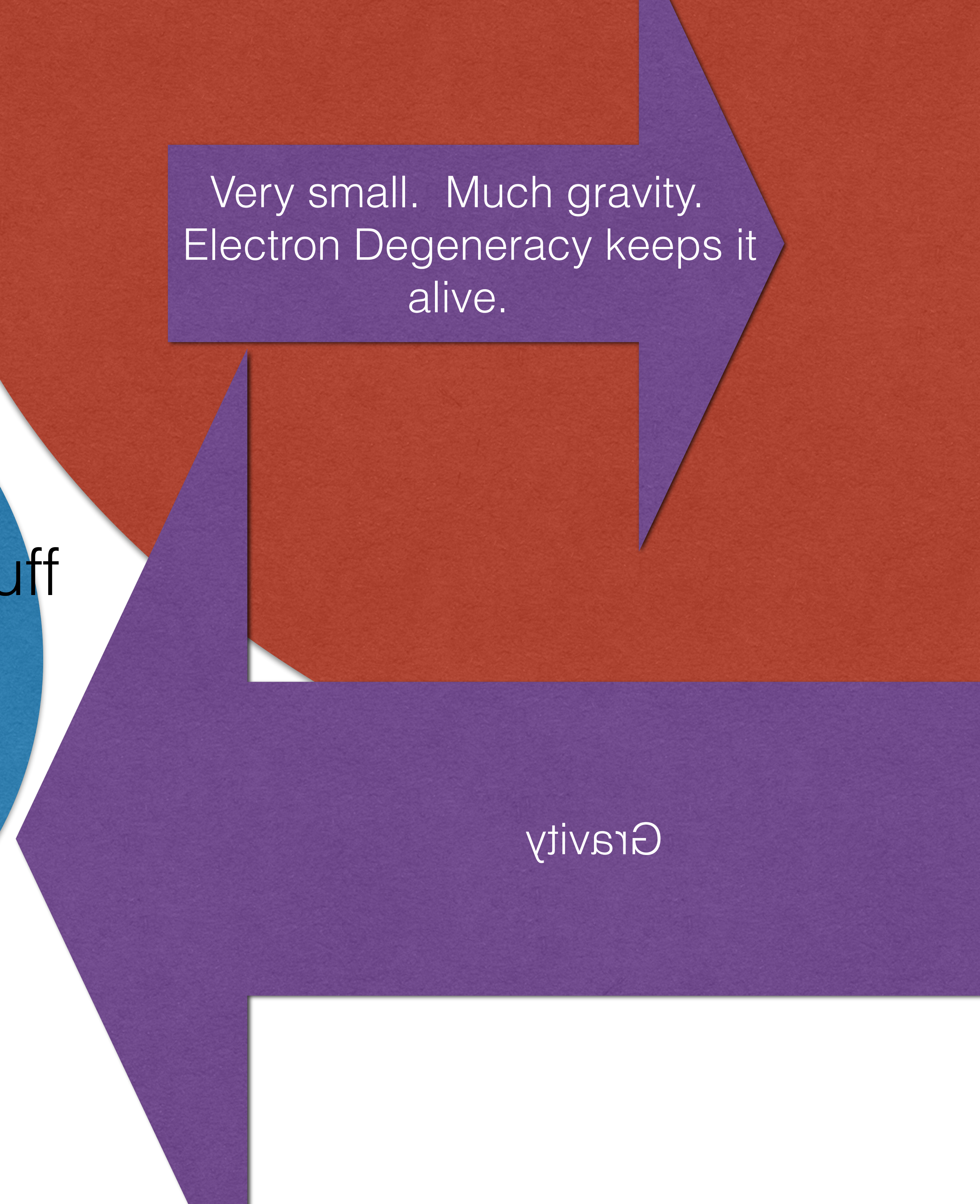


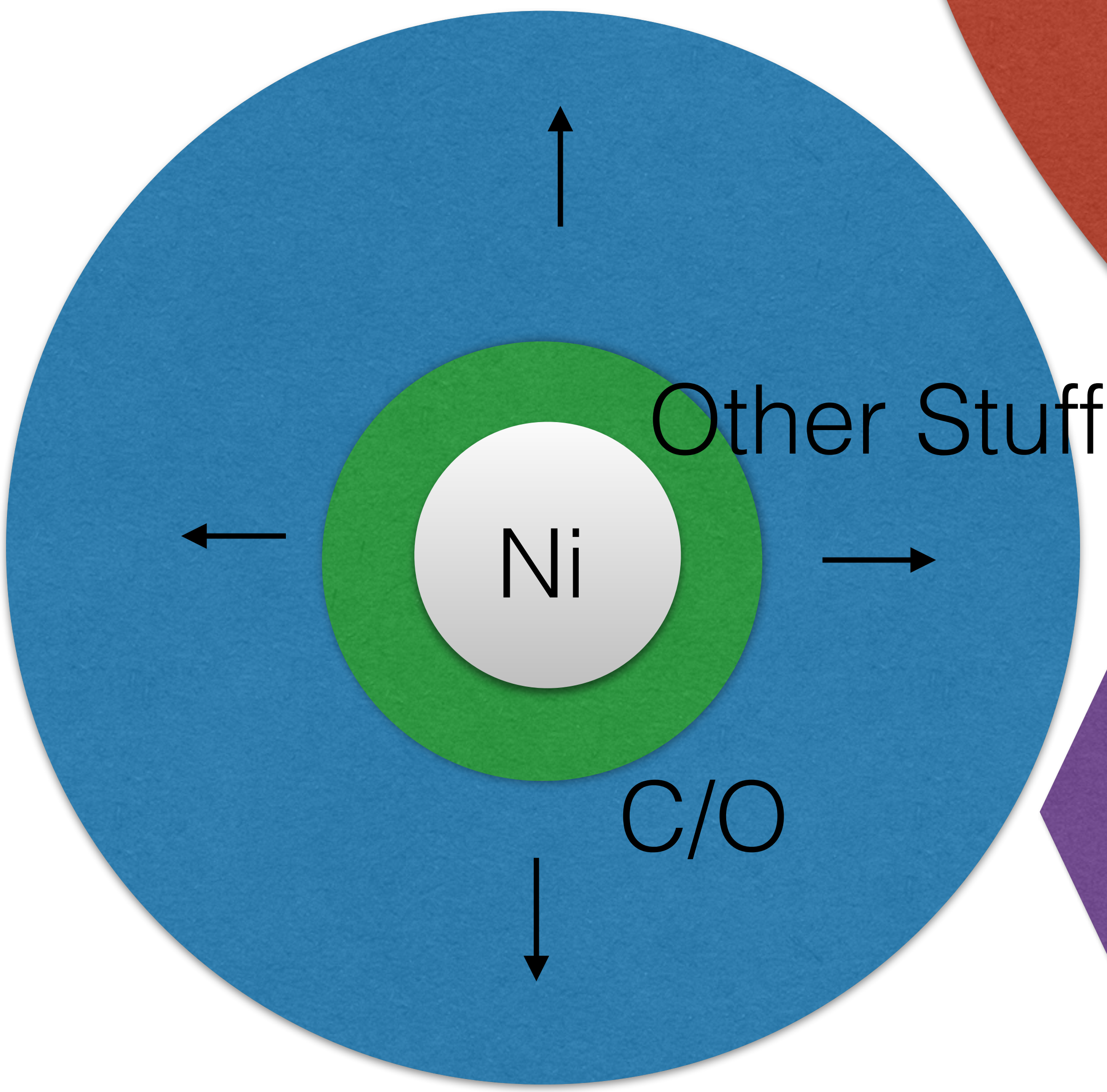


$$C + O \rightarrow \mathrm{stuff} \rightarrow^{56}\mathrm{Ni}$$

Most stars are in Binaries

- Composition depends on density and temp.





$$C + O \rightarrow \text{stuff} \rightarrow {}^{56}\,\text{Ni}$$

- Expands.
- Cools.
- **Nickel decays**, gives off an insane amount of light.

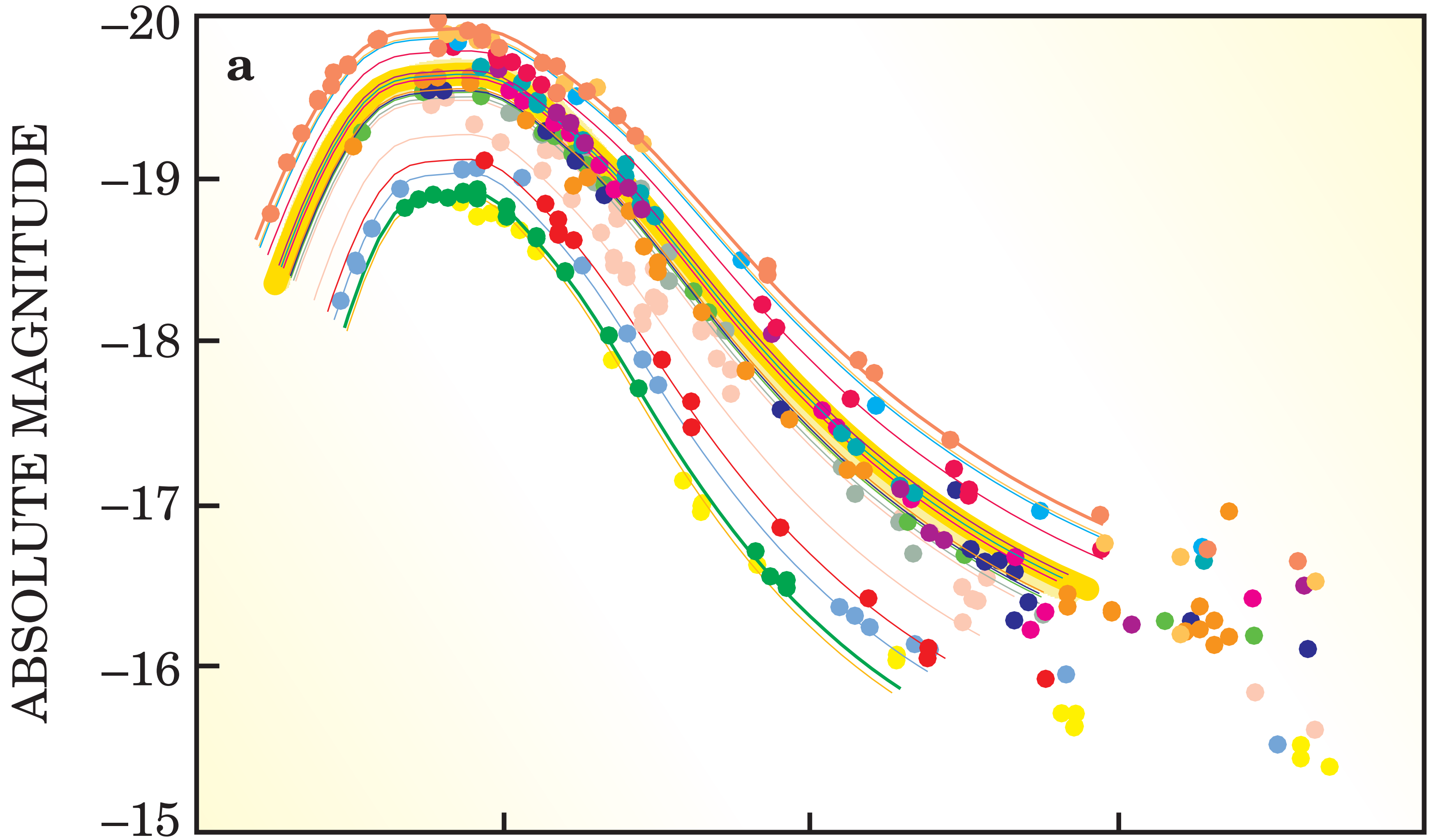
NICKLE DECYAY MAKES THE LIGHT.

The explosion happens before we see anything.

This is an image of the nickel decay.

Less Ni = less brightness,

also lower temperature, lower opacity, and faster decay.



(Perlmutter 1997)
(Hoeflich+ 2003)

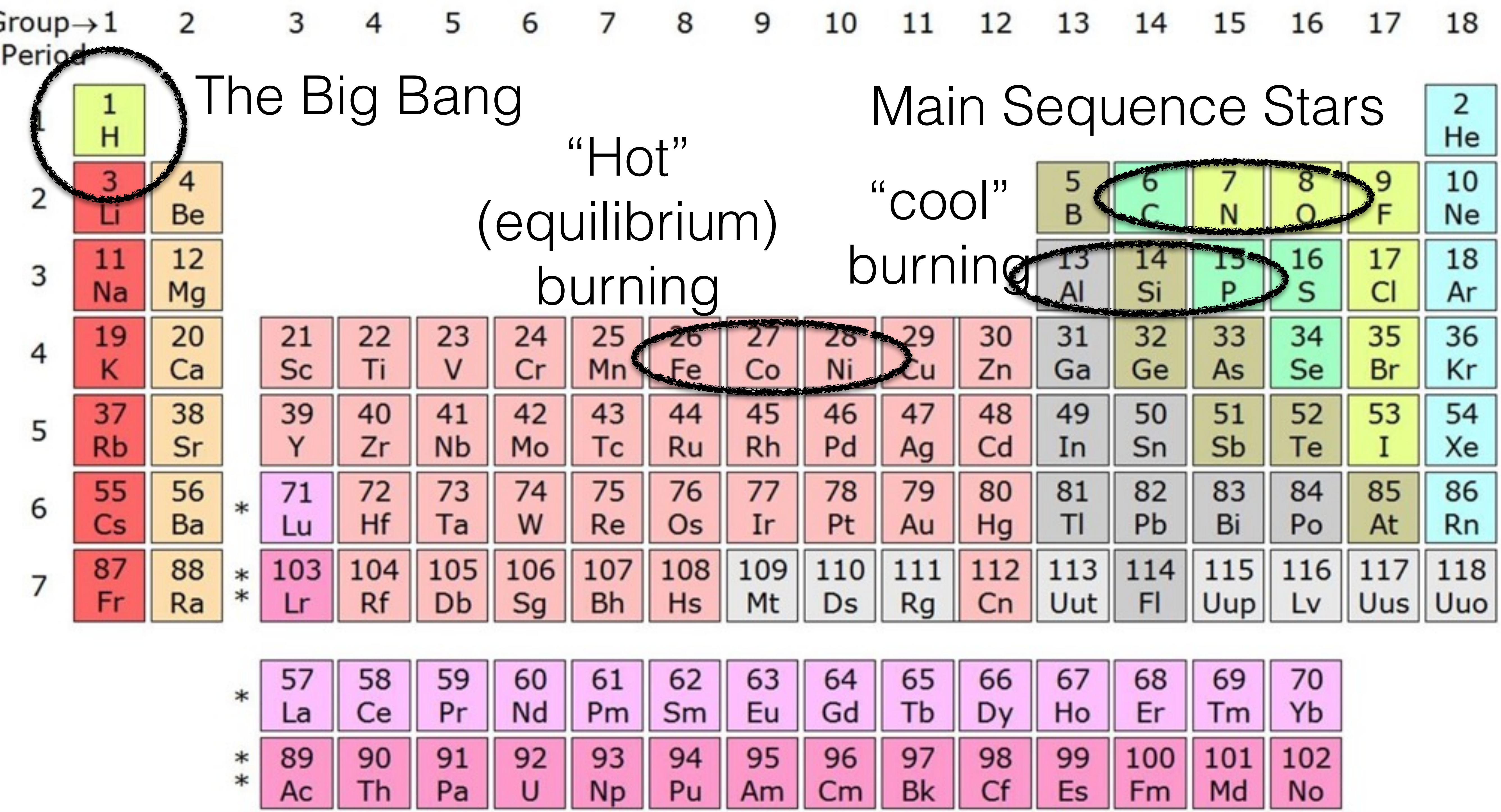
DDT

- Stars off with the front carried by ***thermal conduction*** and is ***subsonic****.* This is DEFLAGRATION

- The density is a monotonically decreasing function of radius. At some threshold density, the flow becomes *supersonic,* and the burning is triggered by *compression.* This is DETONATION.

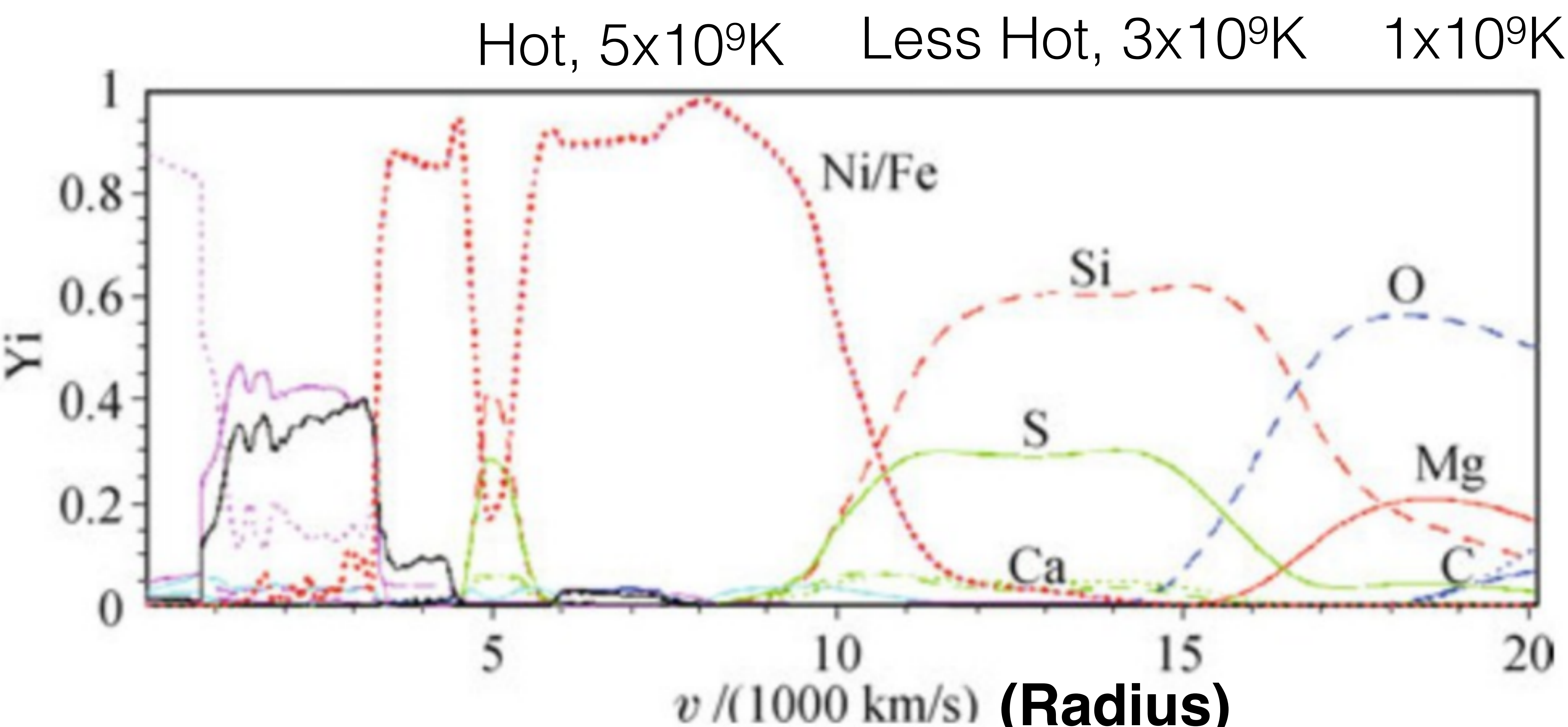
How are you for time? Consider skipping this.

The details of the burning are important for higher precision cosmology.

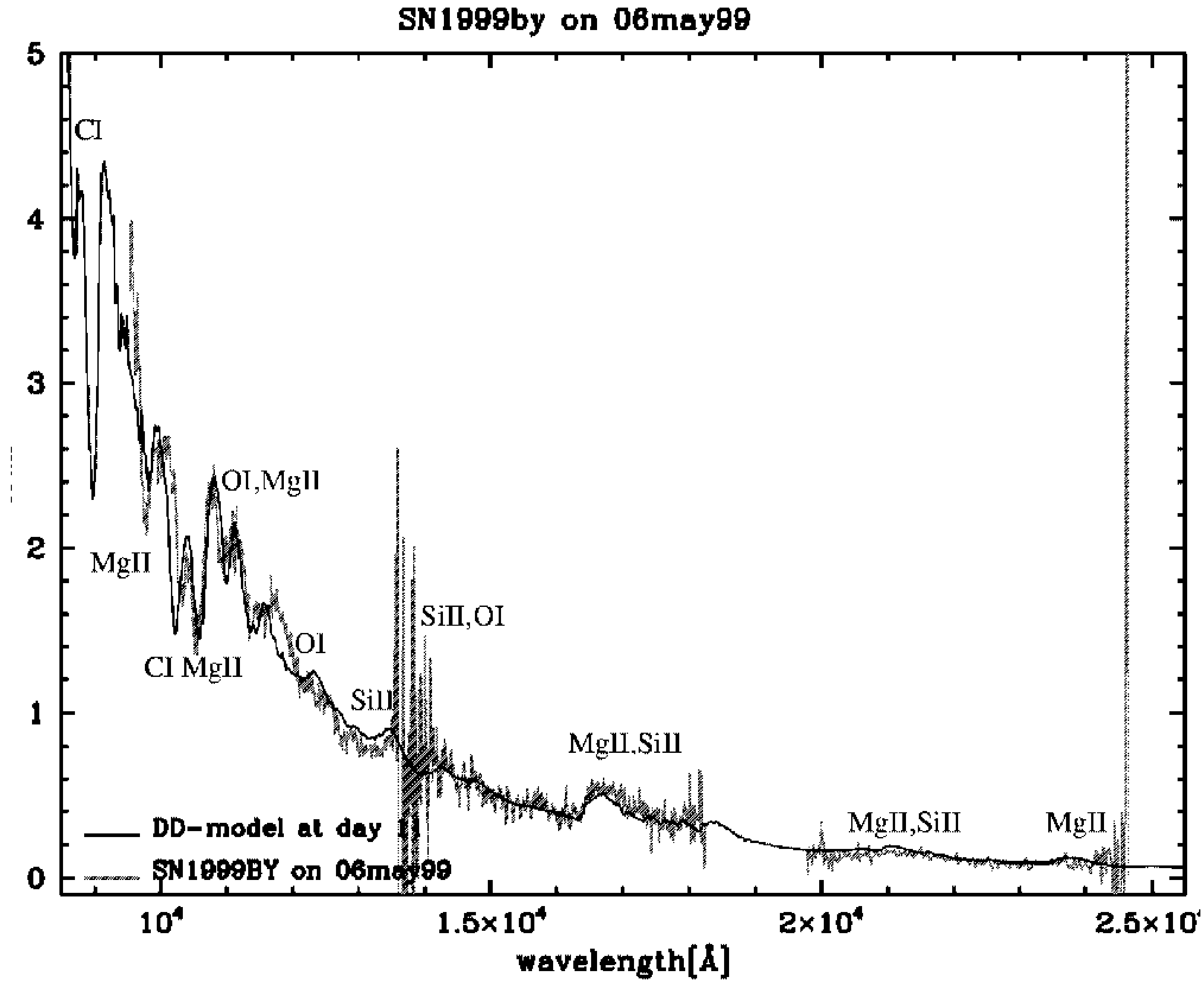


1d models, DDT, Layered structure

- Velocity=A*Radius
- T = T(R)

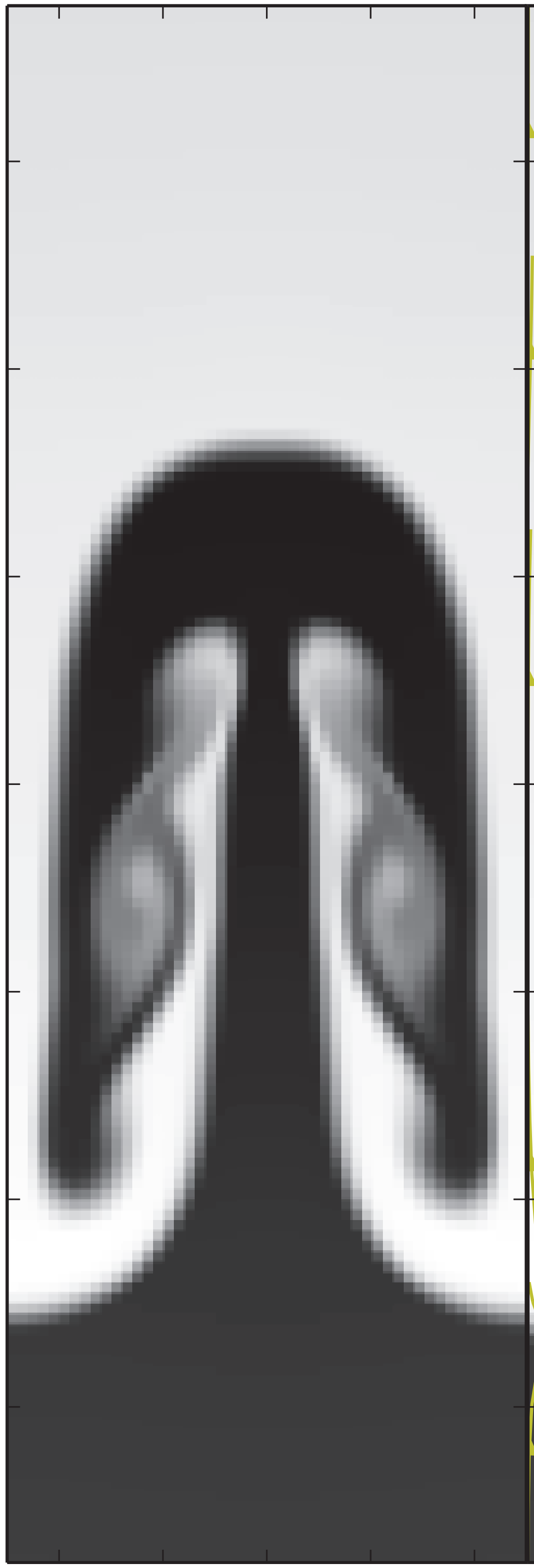


Resultant Spectra



One dimension works pretty well.

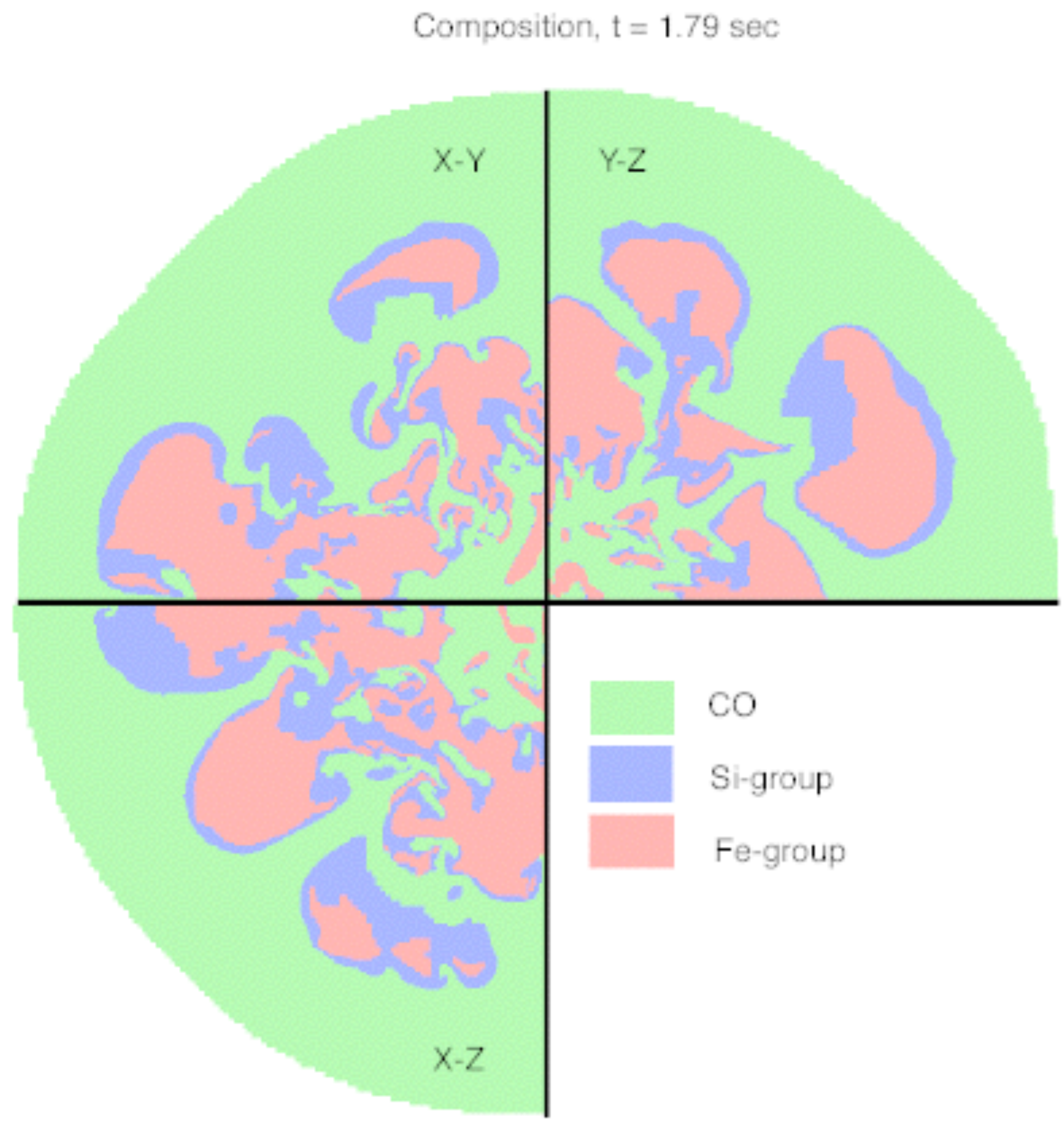
- But, stars aren't one dimensional
- And we know that there are instabilities: Rayleigh-Taylor being the most problematic.
- Low density accelerating into High Density,
    - Bubbles go up,
    - Spikes go down
    - Secondary Kelvin Helmholtz makes Mushrooms



(enzo-project.org)

3D models

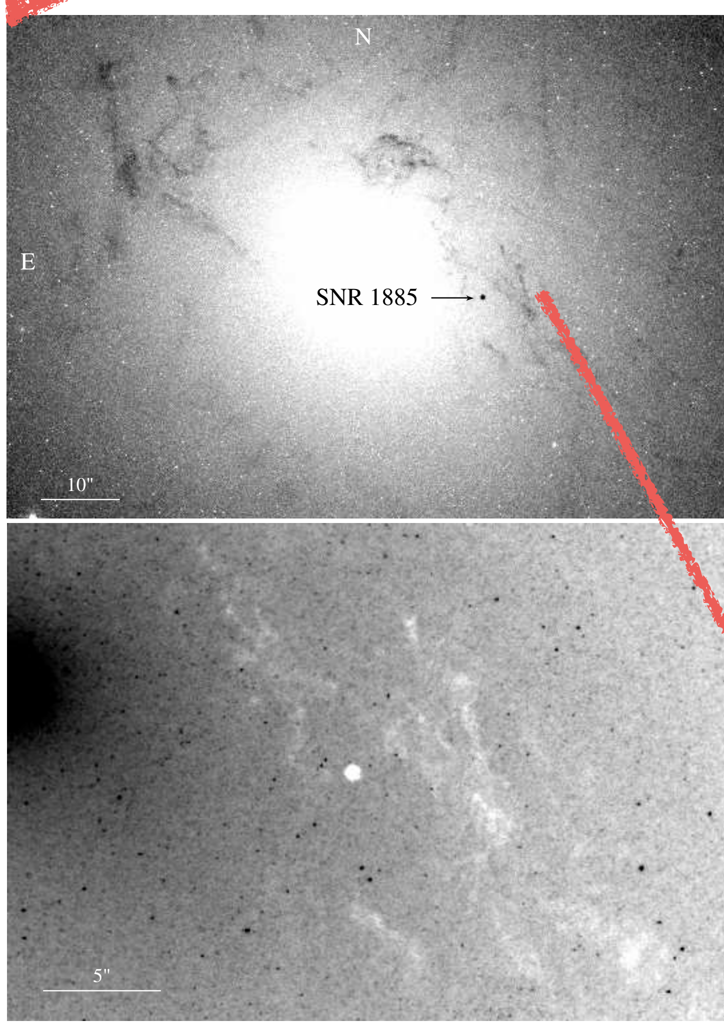
- Rayleigh Taylor
- Tremendous Mixing.
- Pulls Carbon (not burned) down to the center



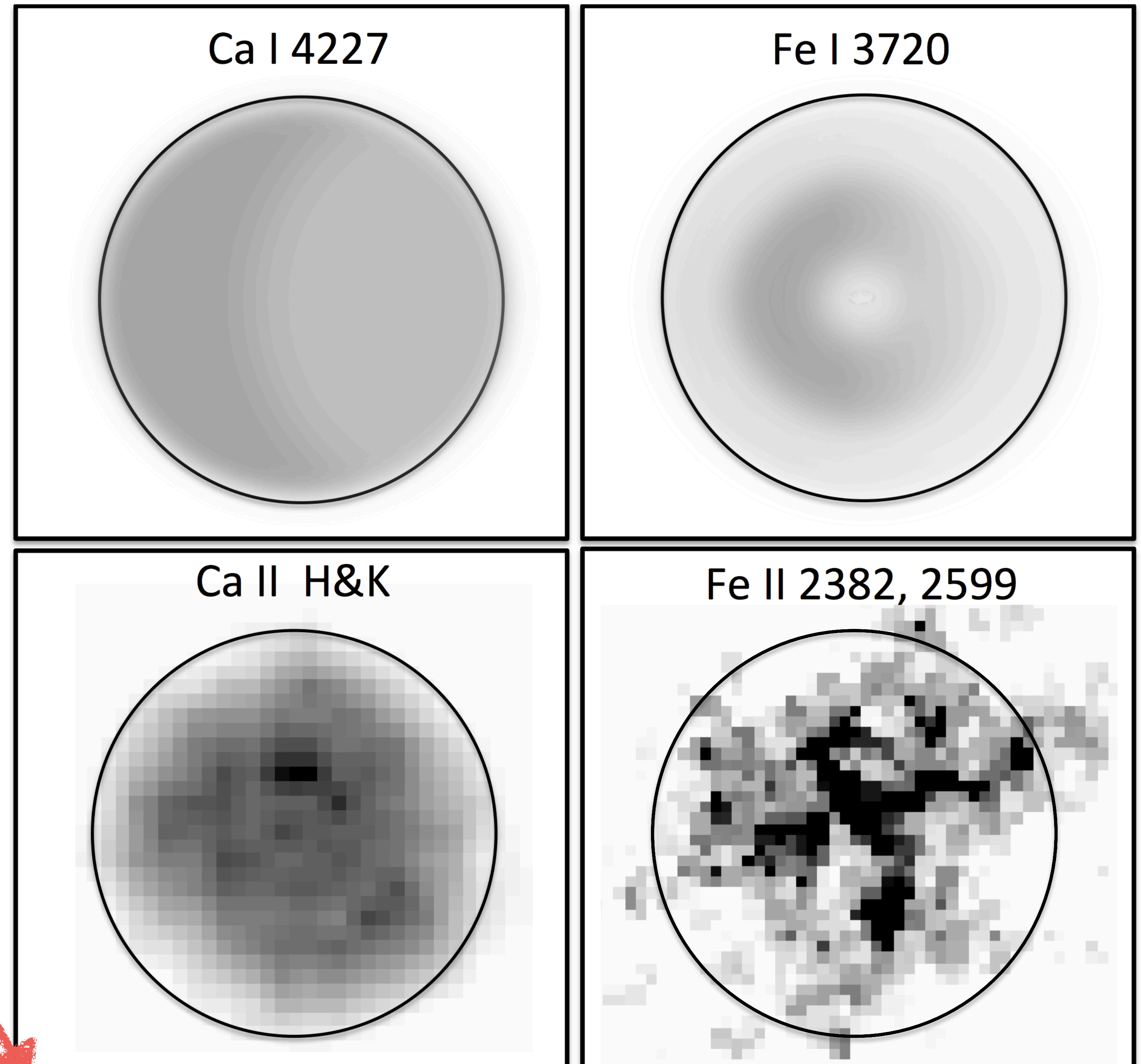
(Khokhlov 2000)

What does the sky show?

Andromeda!



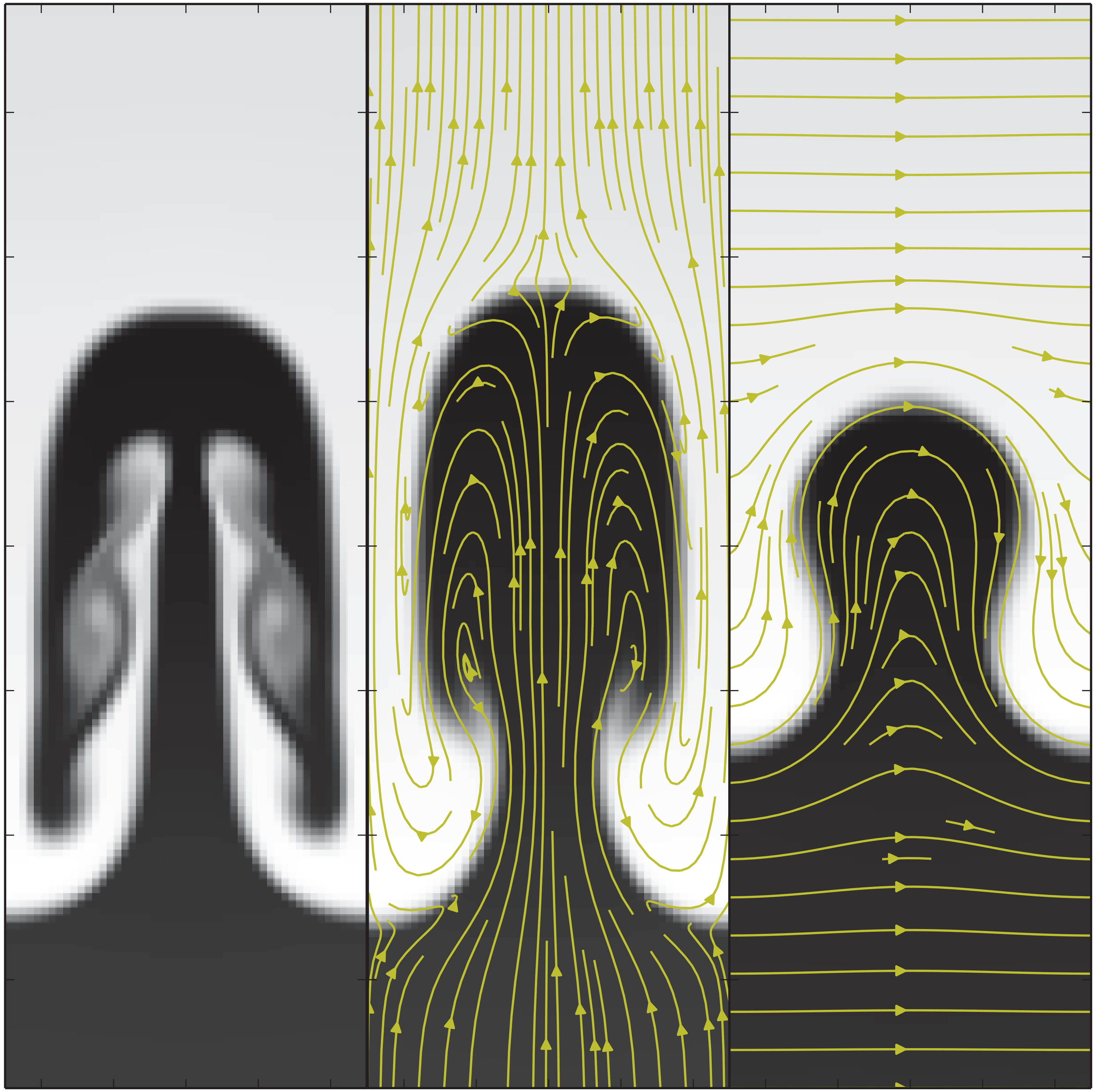
Calcium is mixed: shouldn't be
But there's some RT.



(Fesen et al 2016)

Magnetic Fields are cool.

- It’s know that Magnetic Fields suppress RT.
- Like rebar, fields have tension and pressure
- And White Dwarfs are plasma, and most stars host magnetic fields.



(enzo-project.org)

MHD Equations

- Hydro
- Energy input from Burning
- With Magnetic Fields
  - Tension
  - Pressure
  - Like vorticity

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + \mathbf{I}P - \frac{\mathbf{B}\mathbf{B}}{8\pi} \right) = -\rho \mathbf{g}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P)\mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = -\rho \mathbf{v} \cdot \mathbf{g} + \dot{Q}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

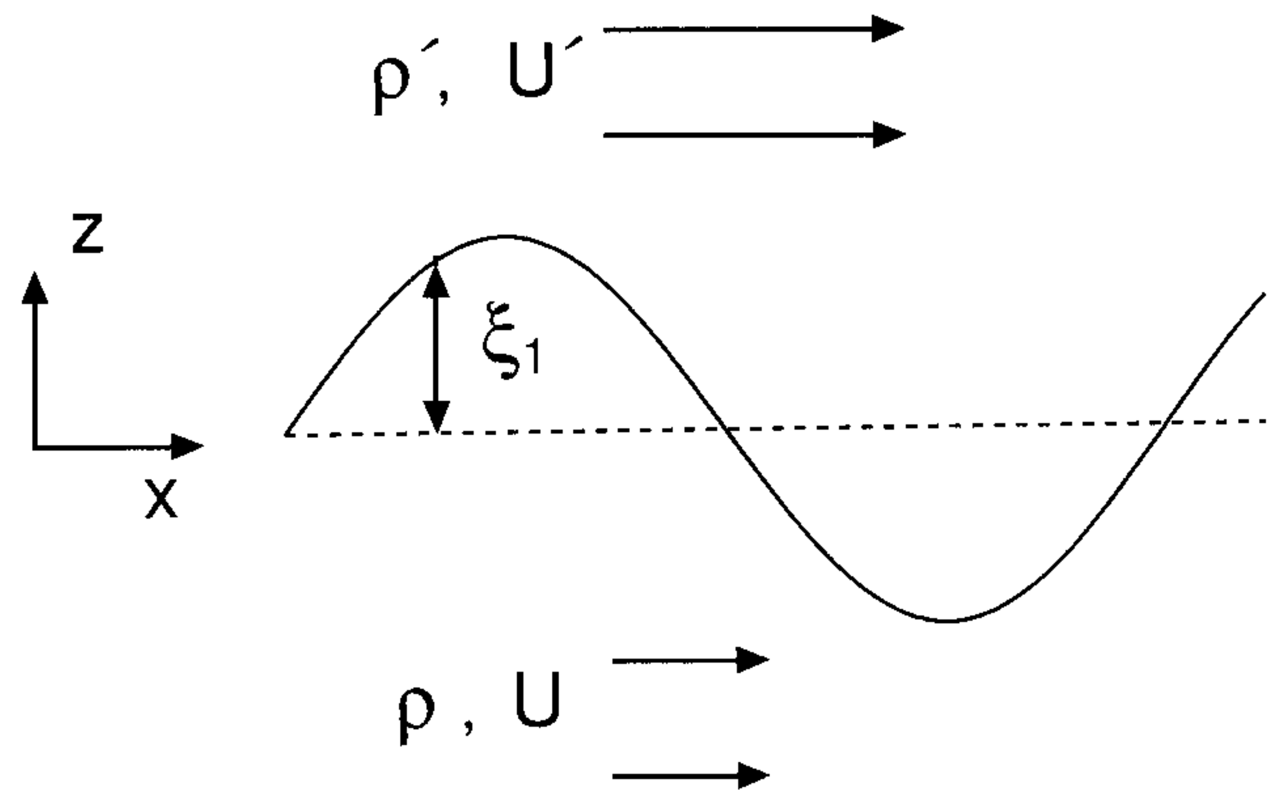
Outline

- RT linear theory
  - All modes reduced.
  - Some modes stabilized
  - Depends on field strength
- Sweet movies.
- Need to understand the non-linear effects.

Linear Theory

- (the light is better over here)
  (Surface gravity waves, infinitely deep)

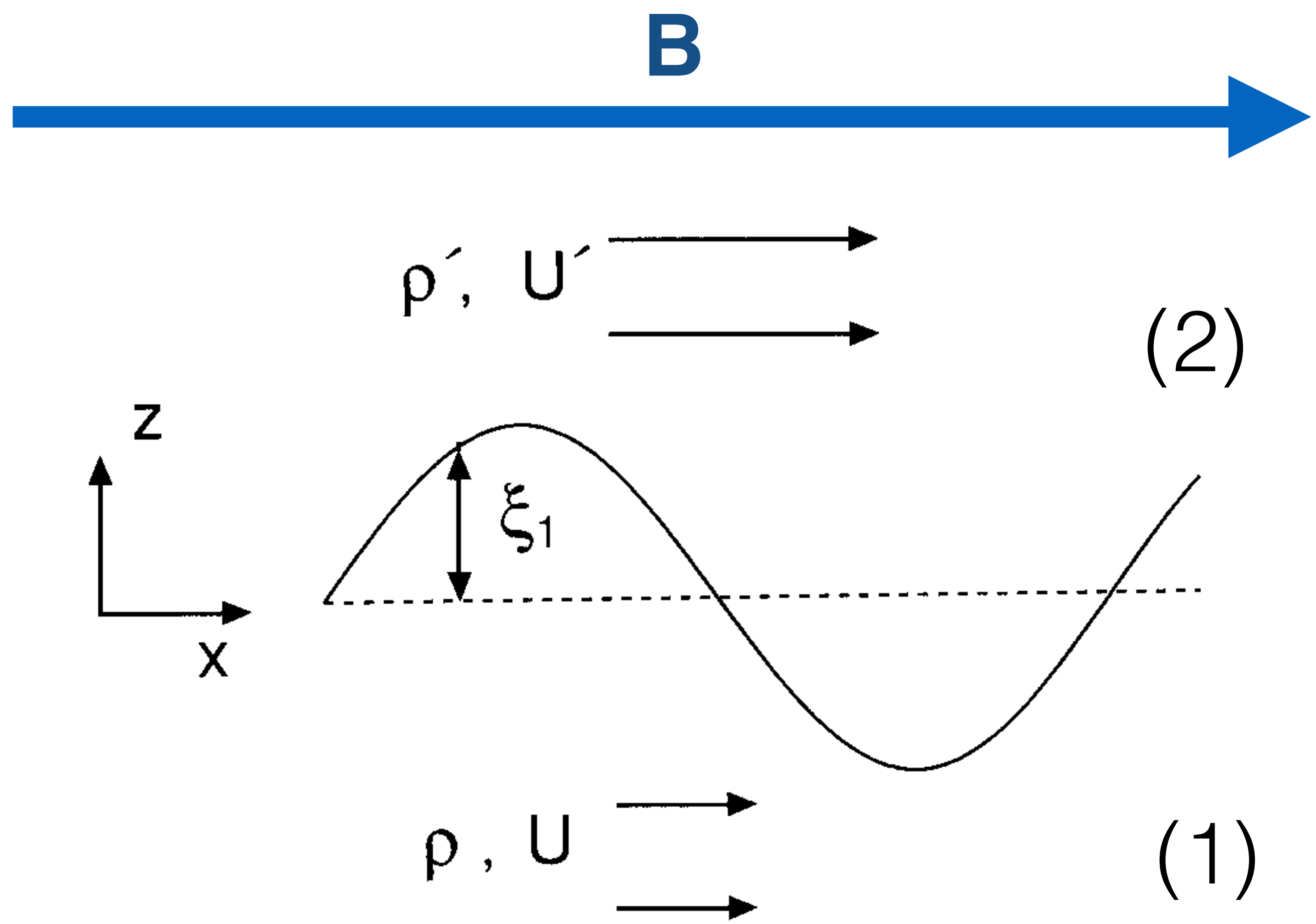
$$\frac{\omega}{k} = \pm\sqrt{\frac{g}{k}\frac{\rho-\rho'}{\rho+\rho'}}.$$



Linear Theory

- With field along plane: stability!
(notation change: Omega is the growth rate, 2 is on top)

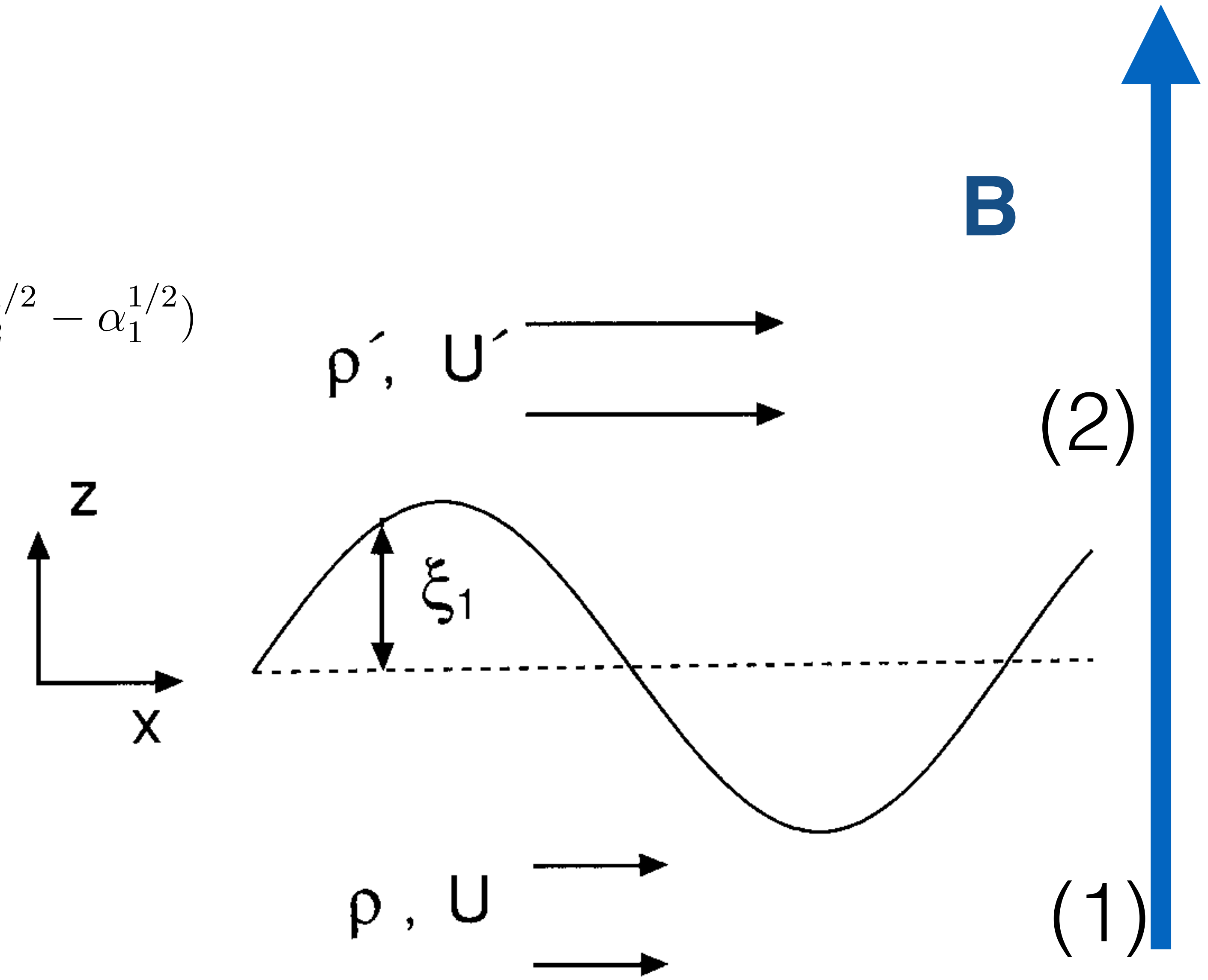
$$\Omega_\perp^2 = \mathrm{g}k\left(\frac{\rho_2-\rho_1}{\rho_2+\rho_1} - \frac{B^2\cos^2(\mathbf{B},\mathbf{k})}{2\pi(\rho_2+\rho_1)g}k\right)$$

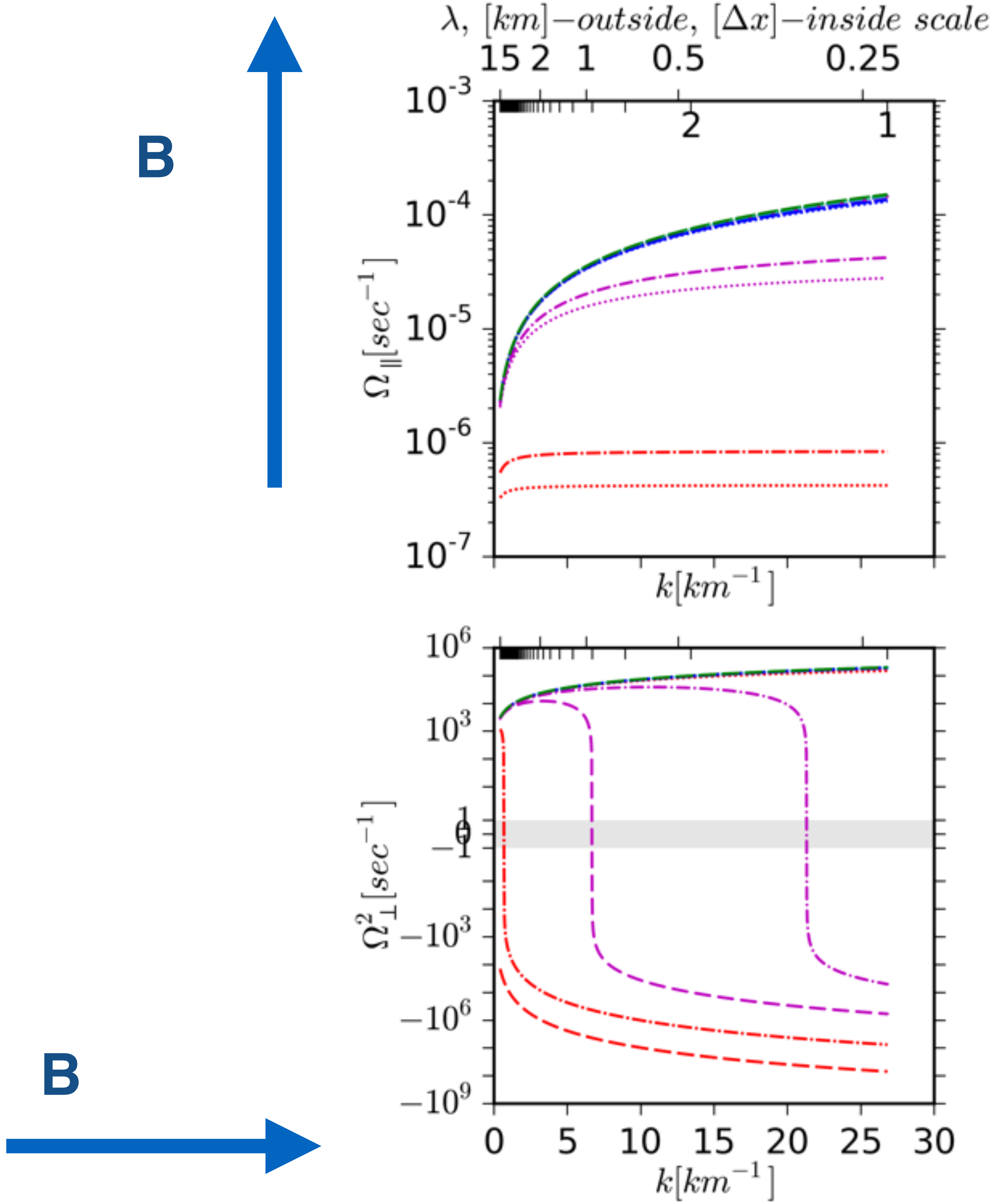


Linear Theory

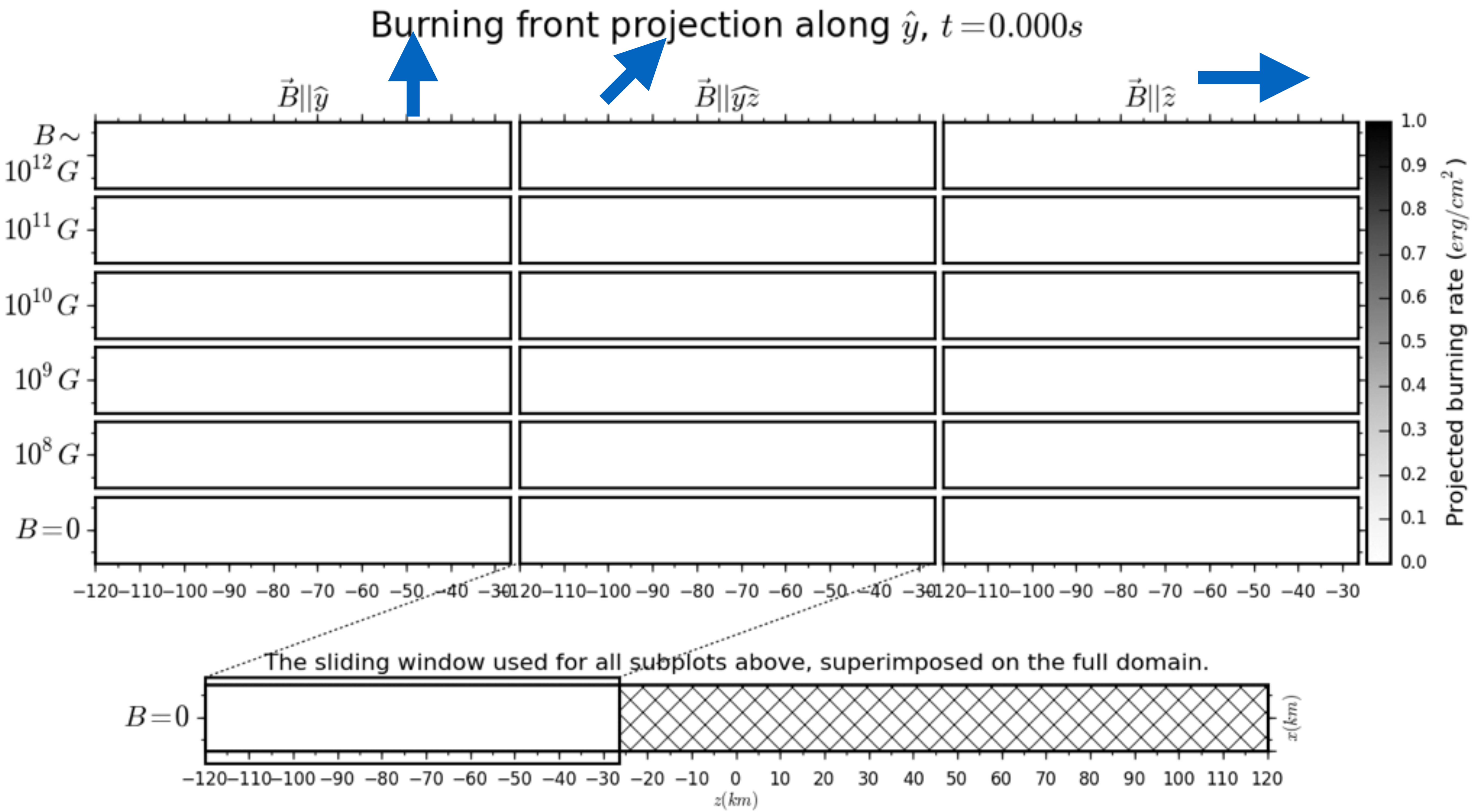
- With field perpendicular to: growth rate reduced! (eta = Omega * units)

$$\eta^3 + 2\kappa(\alpha_2^{1/2} + \alpha_1^{1/2})\eta^2 + \kappa(2\kappa + \alpha_1 - \alpha_2)\eta - 2\kappa^2(\alpha_2^{1/2} - \alpha_1^{1/2})$$



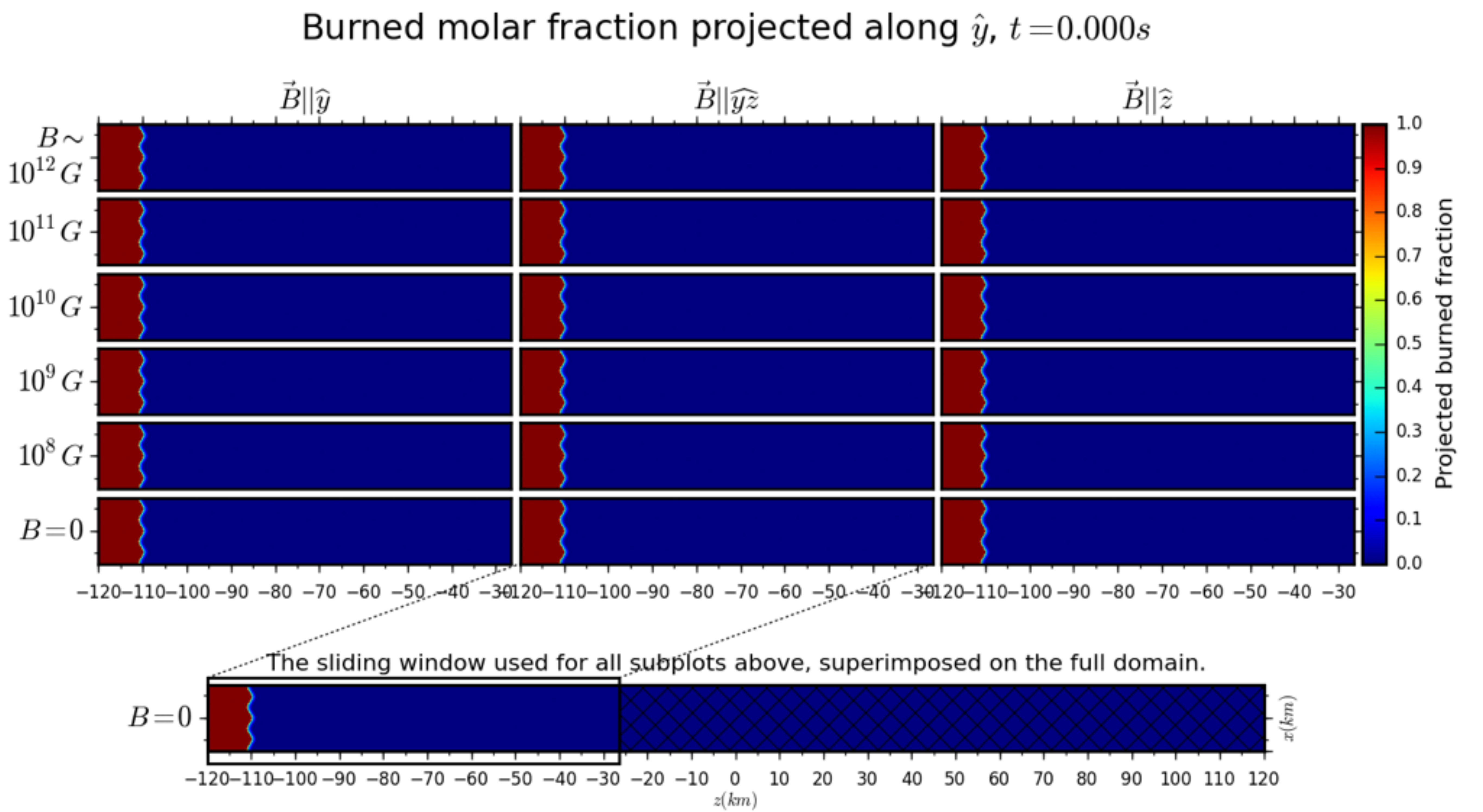

B
λ, [km]−outside, [Δx]−inside scale
15 2 1 0.5 0.25
2
1
10^-3
10^-4
10^-5
10^-6
10^-7
Ω_∥[sec^-1]
k[km^-1]
10^6
10^3
1
0
−1
−10^3
−10^6
−10^9
Ω²_⊥[sec^-1]
0 5 10 15 20 25 30
k[km^-1]
B

Burning Rate



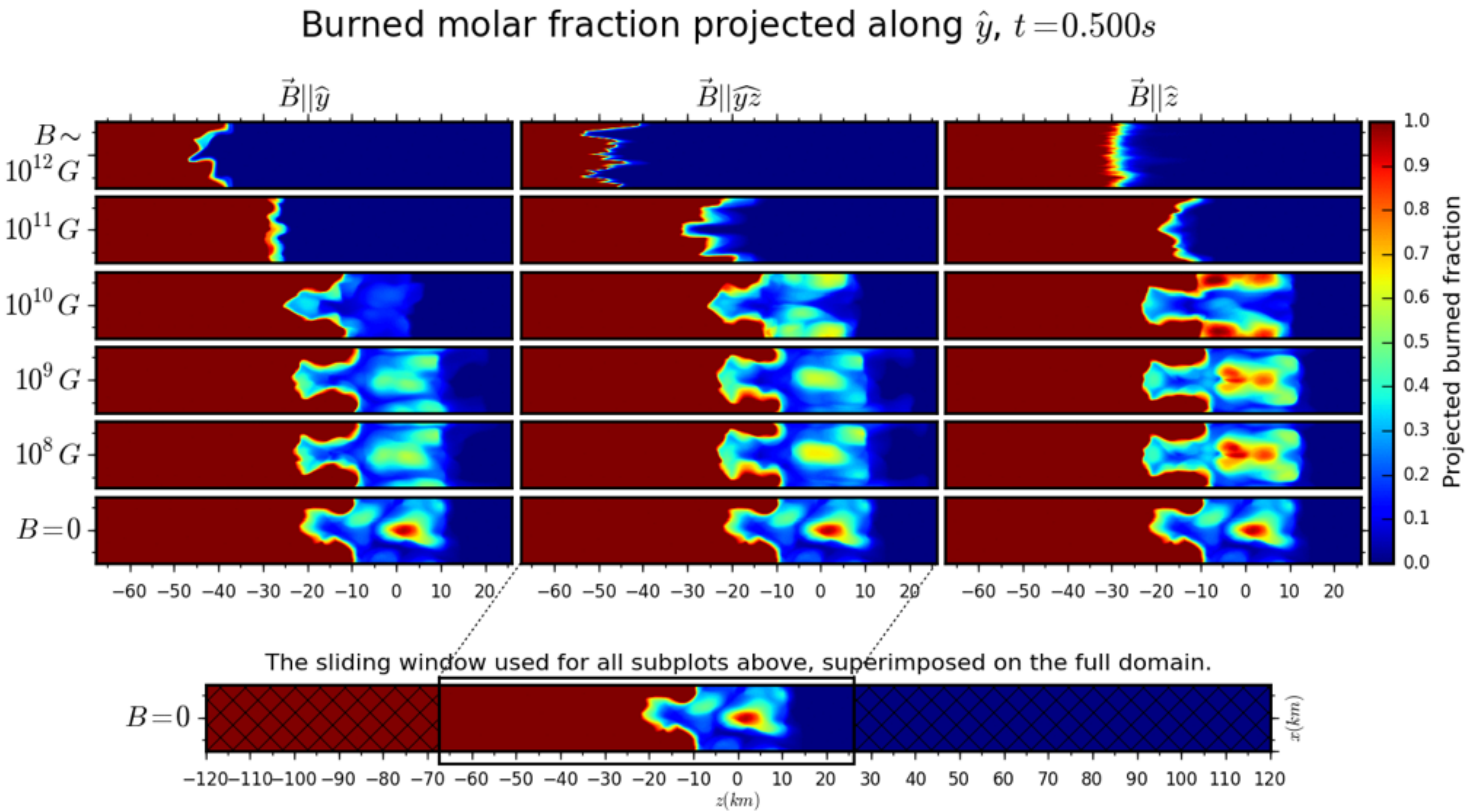
(note to self: Qdot-bw.gif)(gif should auto-play, give it a second)

Burned Fraction



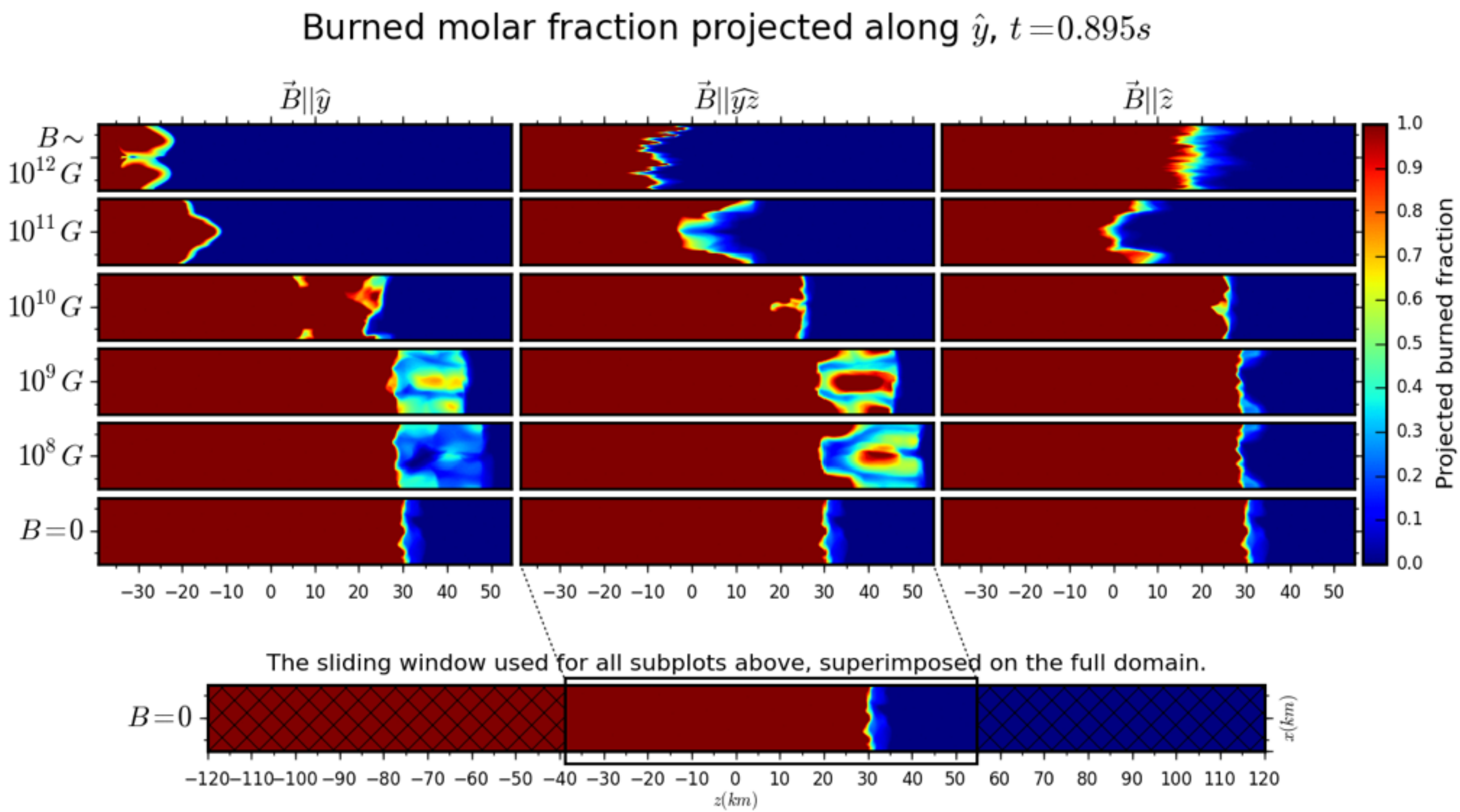
(not a gif)

Burned Fraction



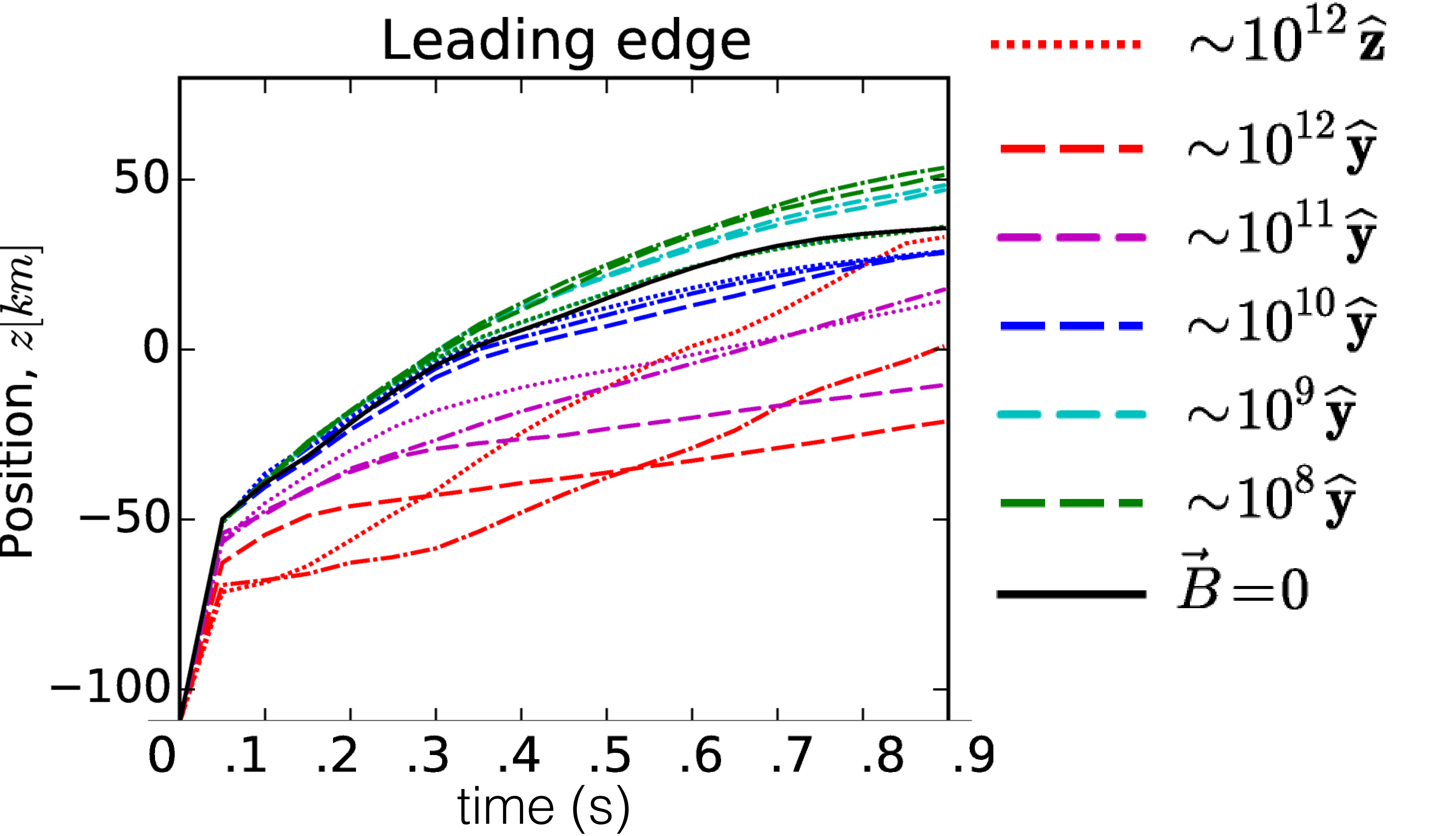
(not a gif)

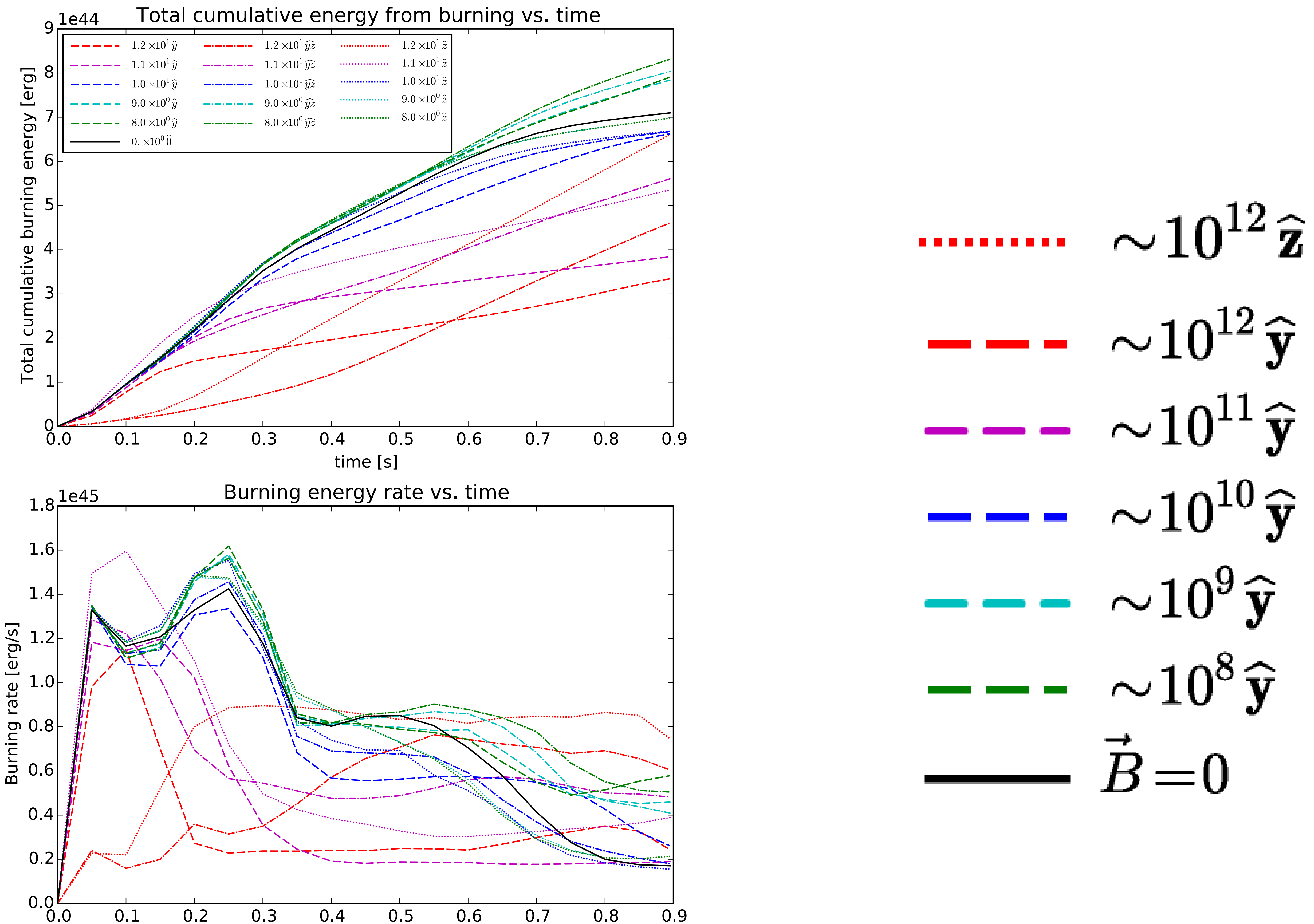
Burned Fraction



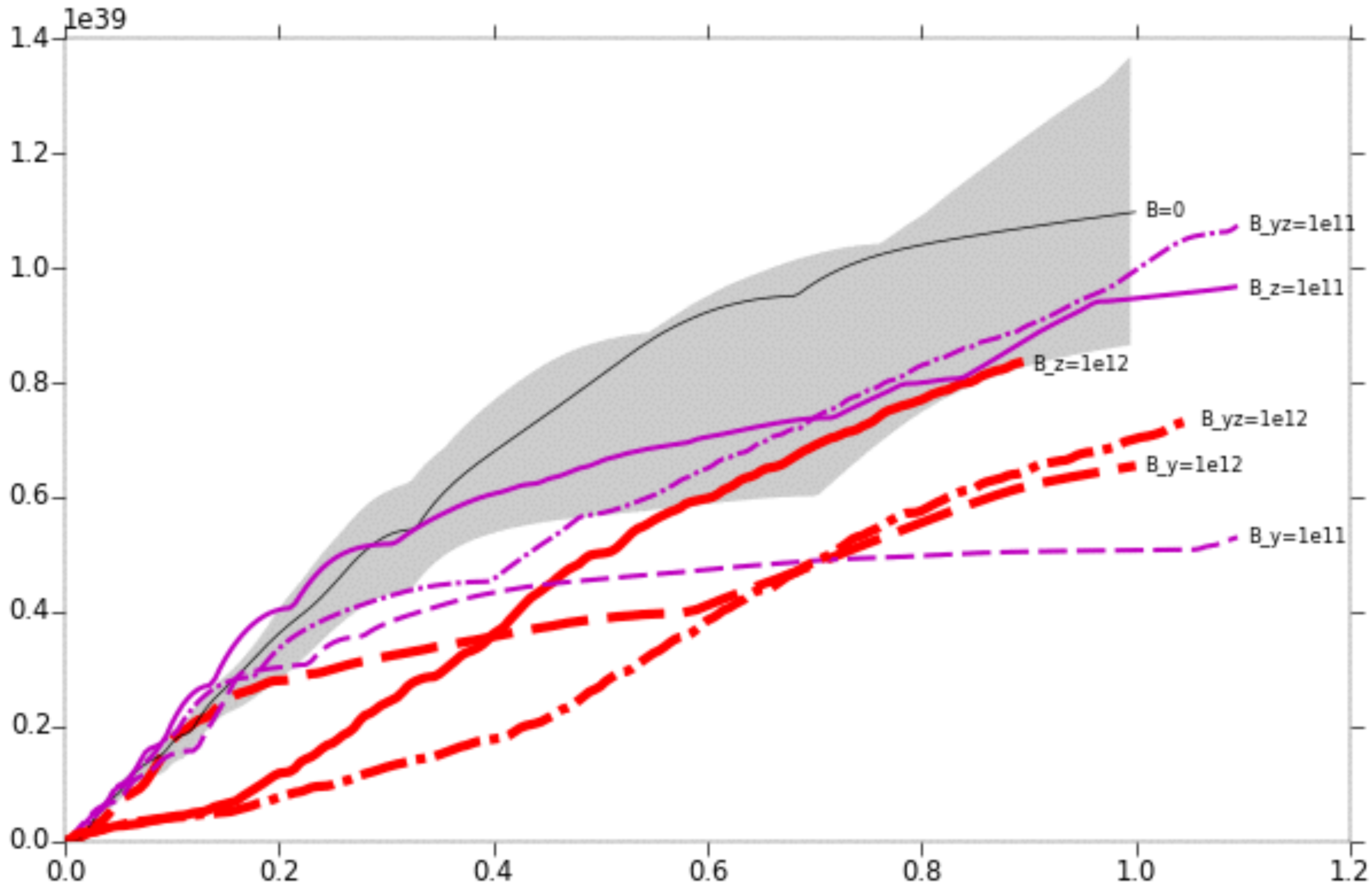
(not a gif)

Front Position



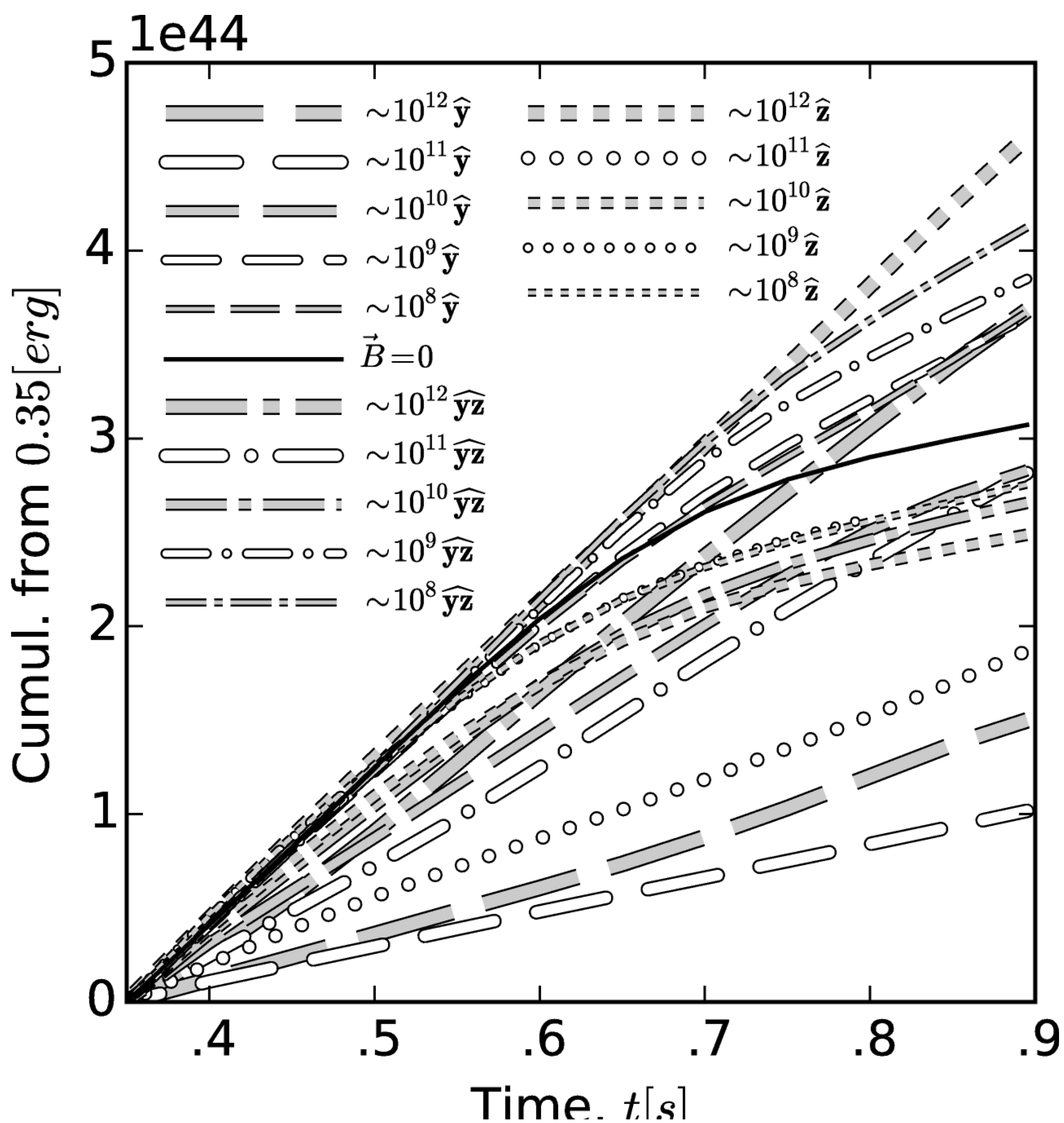

Total cumulative energy from burning vs. time
1e44
Total cumulative burning energy [erg]
time [s]
$1.2 \times 10^1 \,\widehat{y}$
$1.1 \times 10^1 \,\widehat{y}$
$1.0 \times 10^1 \,\widehat{y}$
$9.0 \times 10^0 \,\widehat{y}$
$8.0 \times 10^0 \,\widehat{y}$
$0. \times 10^0 \,\widehat{0}$
$1.2 \times 10^1 \,\widehat{yz}$
$1.1 \times 10^1 \,\widehat{yz}$
$1.0 \times 10^1 \,\widehat{yz}$
$9.0 \times 10^0 \,\widehat{yz}$
$8.0 \times 10^0 \,\widehat{yz}$
$1.2 \times 10^1 \,\widehat{z}$
$1.1 \times 10^1 \,\widehat{z}$
$1.0 \times 10^1 \,\widehat{z}$
$9.0 \times 10^0 \,\widehat{z}$
$8.0 \times 10^0 \,\widehat{z}$
Burning energy rate vs. time
1e45
Burning rate [erg/s]
$\sim 10^{12}\,\widehat{\mathbf{z}}$
$\sim 10^{12}\,\widehat{\mathbf{y}}$
$\sim 10^{11}\,\widehat{\mathbf{y}}$
$\sim 10^{10}\,\widehat{\mathbf{y}}$
$\sim 10^{9}\,\widehat{\mathbf{y}}$
$\sim 10^{8}\,\widehat{\mathbf{y}}$
$\vec{B} = 0$

Cumulative energy from burning.
The shaded area is the envelope of the lower B runs.

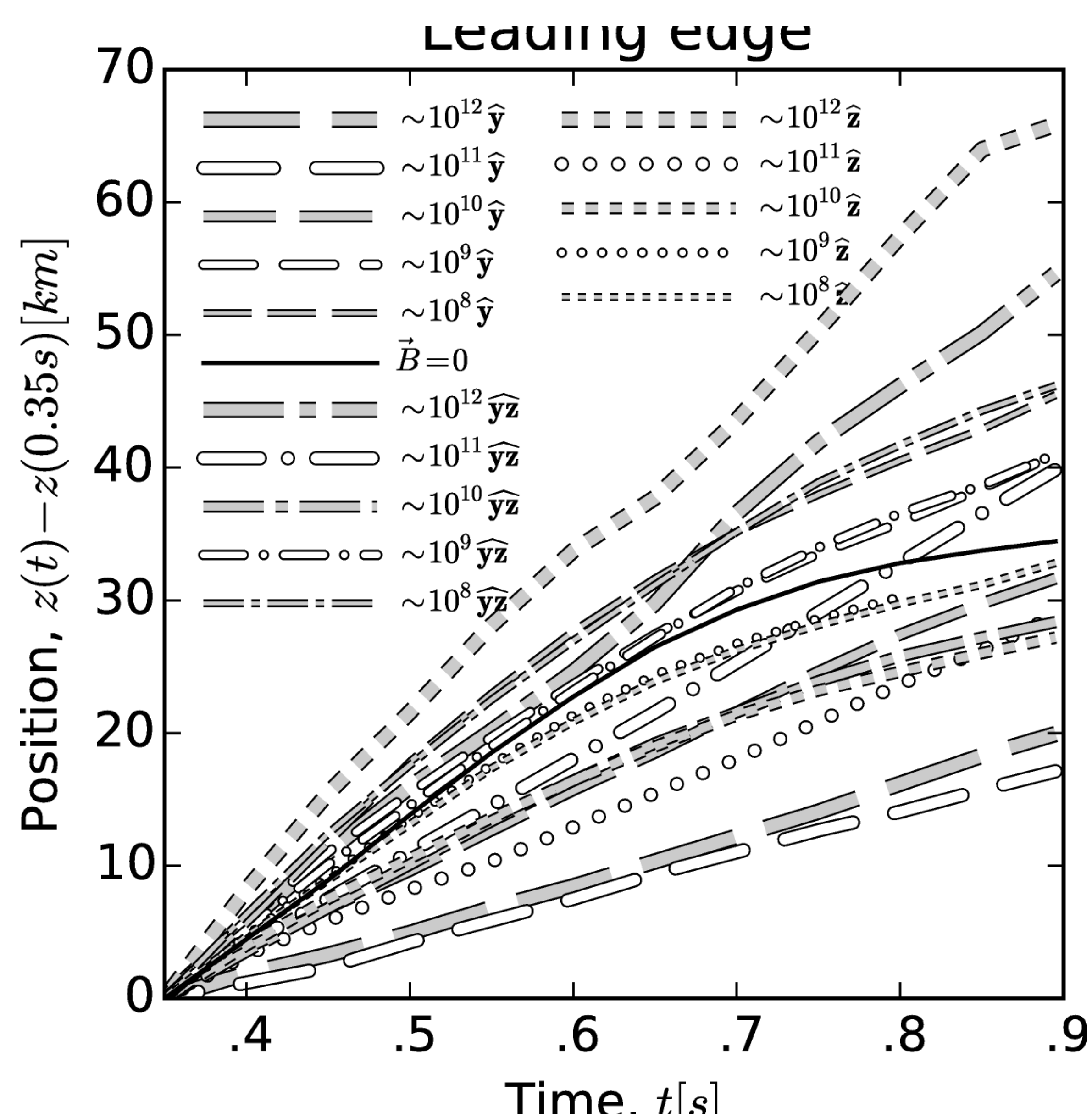


After Initial Transient

- Non-monotonic behavior belies complexity: front surface area



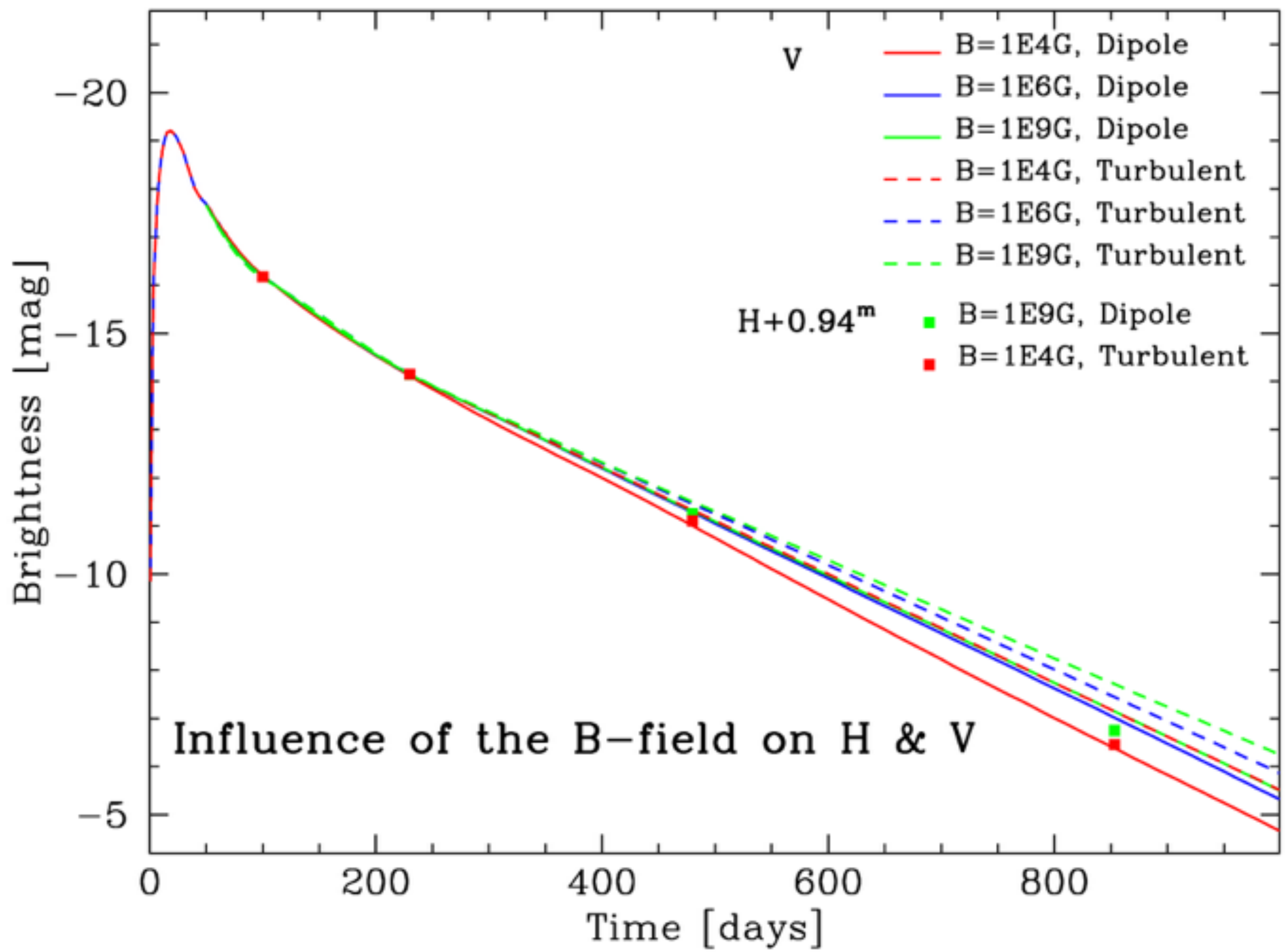
(a) Cumulative burning starting from $0.35\,s$



(b) Front position starting from $0.35\,s$

Light Curve

- Larger magnetic field traps positrons in the center, causing more ^{56}Ni, and a brighter curve at very late times



Summarize

- Supernovae are important for measuring the basic properties of the universe.
- Understanding the fine details requires understanding the burning.
- 1d simulations are successful at predicting brightness-decline relation, spectra
- Magnetic processes can possibly aid in suppression of mixing seen in 3d simulations; may alter front velocities in non-monotonic manner.