Supernovae

Peak brightness: $10^8 - 10^{10}\ L_\odot$

Duration : $10 - 200$ days

$\bar{E}_{rad} \sim 10^{49}$ erg

$\bar{E}_{kin} \sim 10^{51}$ erg

~1-2 per 100 years in MW (last: 1604)

~1000 found per year up to $z \sim 2$

Classification purely observational from absorption lines in maximum light spectrum. 4 major classes:

- With hydrogen: Type II ~ 55%
- Without hydrogen: Type I

With helium
Type Ib

No helium, strong Si
Type Ia
~25%

No He, weak Si
Type Ic

Ic + Ib ~ 20%

But: SNe Ia on average much brighter

Magnitude limited: Ia 79%, II 17%, Ibc 4%

Type Ia Supernovae

- No bound remnant detetable (BH, NS, Star)
- No detection of the progenitor system, stronges limits for SN 2011fe in M101 (20 million Lyrs distance):
  - optical : $L \lesssim L_\odot$
  - X-ray : $\dot{M} \lesssim 10^{-10} \frac{M_\odot}{yr}$

  But: for most SNe Ia limits are much less strict
- No star in remnant (possible companion?)
- No radio emission from SN : expansion into empty space (no wind before SN)
- Spectra show IGES (Fe, Co, Ti) and IMEs (Si, S, Mg, Ca) plus C, O

  No hydrogen/helium ~~at also~~ at all ($X_H \lesssim 10^{-3}$)
- Found in all kinds of galaxies, no recent star formation required

↳ Thermonuclear explosion of CO WD

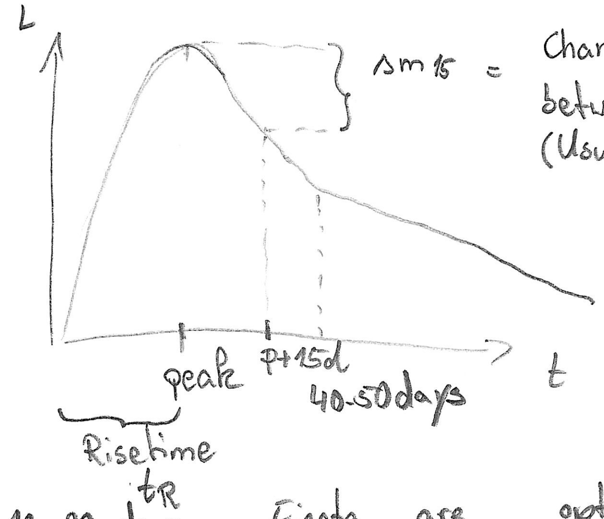
But : Isolated WD's are inert

→ Binary system . Companion? (a. Progenitor system)

What triggers the explosion?

SN Ia Observables

Lightcurve:



Δm_{15} = Change in brightness between peak and peak +15d. (Usually peak in M_B)

Rise time: 10-20 days. Ejecta are optically thick, γ-rays from decay of ^{56}Ni scattered around, stored in ejecta. Brightness increases as opacity of outer layers decreases and more photons diffuse outwards.

Spectra dominated by absorption lines of C, O, Mg, Ne, S, S

Around maximum: Energy deposition by rad. decay equals luminosity. Afterwards L decreases (opacity decreases, E-deposition also, stored photons empty)

(Arnett's law)

At max: $L \overset{\sim 1}{\approx \alpha} \underset{\uparrow}{R(t_R)} M_{Ni}$

Radioactive luminosity per unit M_{Ni} evaluated at peak

$$R(t_R) = \left[7.74 \cdot 10^{43} e^{-\frac{t_R}{8.8d}} + 1.43 \cdot 10^{43} e^{-\frac{t_R}{111d}}\right] \frac{erg}{s\,M_\odot}$$

→ Estimate for M_{Ni}: Normal SNe Ia 0.4 - 1.0, peak around 0.7 $M_\odot$

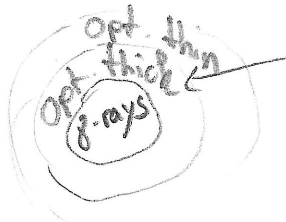
Extreme cases: 0.1 $M_\odot$ (SN1991bg), 2.0 $M_\odot$ (SN2009dc)

After ~ 40 days decay of ^{56}Co takes over

(after) Maximum spectra: Absorption lines of S, Si, Ca, Fe, Co

Late time: Around 100 days after explosion ejecta are fully transparent. γ-rays from decay escape, but e^+ from subdom. channel of ^{56}Co decay excites material
Nebular spectra: emission lines of Fe, Co, from center of the ejecta

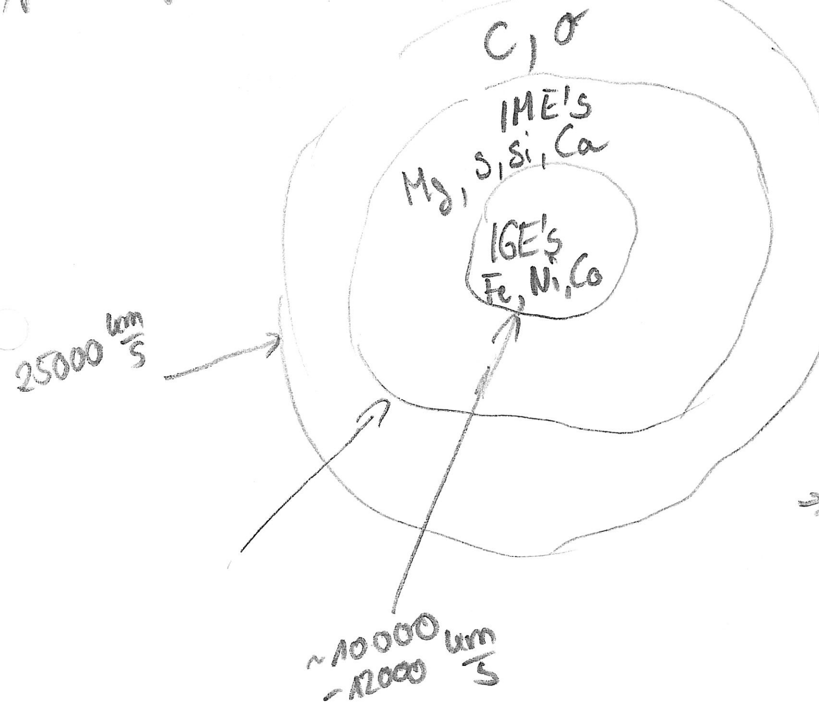
Spectra:



Absorption lines from transition region, blackbody below

„Photosphere" recedes with time → See radial composition changes in spectra

Typical ejecta:



Ejecta in homologous expansion.
Every atom travels independently with constant

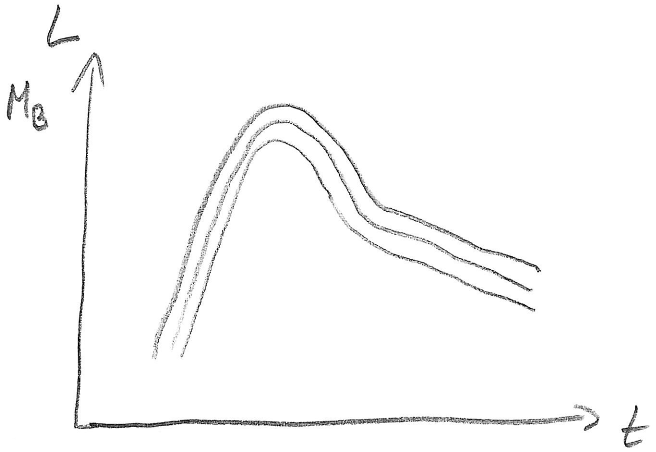
$$\vec{v} \Rightarrow \vec{x}(t) = \cancel{\vec{x}_0} + \vec{v} \cdot t$$

Negligible

⇒ Radial expansion, frozen in velocity space

But: Mixing, 3D structure (overlap)

Compare LC's:



→ $\Delta m_{15}(B)$ correlates tightly with M_B (peak brightness in B-band)

Luminosity - width relation (Phillips relation)

$$M_B = -21.7 + 2.70 \, \Delta m_{15}(B) \qquad \sigma = 0.36$$

→ Standardizable candles, measure width of LC's to infer intrinsic brightness → Distance measurements

Physical explanation:

- brighter explosion → more ^{56}Ni
- more ^{56}Ni → higher T in ejecta, higher ionisation states of Fe, Co, Ni
- Higher ionisation of Fe → less effective redistribution of flux to longer wavelength (→IR)
- Hotter ejecta → more opacity → slower change in lightcurves

Reactive Euler equations:

Cons. of mass: $$\frac{\partial \rho}{\partial t} = -\nabla(\rho\vec{v})$$

Cons. of momentum: $$\frac{\partial(\rho\vec{v})}{\partial t} = -\vec{\nabla}(\rho\vec{v}\otimes\vec{v}) - \nabla P + \rho\nabla\phi$$

Cons. of energy: $$\frac{\partial \rho e_{tot}}{\partial t} = -\vec{\nabla}(\rho e_{tot}\vec{v}) - \nabla(P\vec{v}) + \rho\vec{v}\nabla\phi + \rho S$$

Self-gravity: $$\Delta\phi = 4\pi G\rho$$

Nuclear reactions: $$\frac{\partial \rho\vec{X}}{\partial t} = -\nabla(\rho\vec{X}\vec{v}) + \vec{r}$$

X: mass fractions of species

$\vec{r} = f(\rho, T, \vec{X})$ reaction rates

$S = f(r)$ energy generation

Equation of state: $$P, T = f_{EOS}(\rho, \underset{\uparrow \text{internal energy}}{u}, X)$$

Special case of Navier-Stokes equations for negligible viscosity. Reynolds number: $Re(l) = \frac{\rho l |v(l)|}{\underset{\leftarrow \text{viscosity}}{\eta}}$

For astrophysics typically $Re \gtrsim 10^{10}$ → good approximation!

Nuclear flames

Discontinuities separating fuel and ash

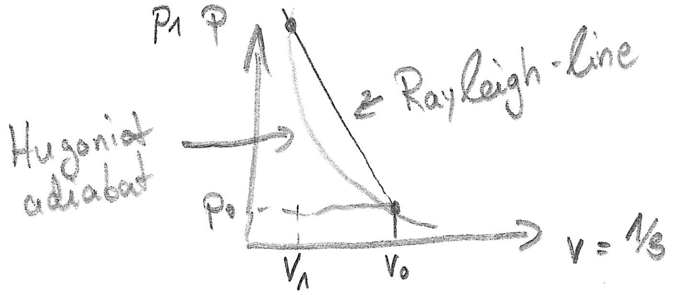
→ "weak" solutions, use integral form of equations

→ Jump conditions to conserve quantities over discontinuities

Pure hydro with mass flux over discontinuity (shock):

$$-\varrho_0^2 D^2 = \frac{P-P_0}{V-V_0} , \quad \cancel{P-P_0} \quad V = \frac{1}{\varrho} \quad \Bigg| \quad \mathcal{H}(P,\varrho) = u - u_0 + \frac{1}{2}\frac{P+P_0}{V-V_0}$$

Rankine - Hugoniot jump conditions

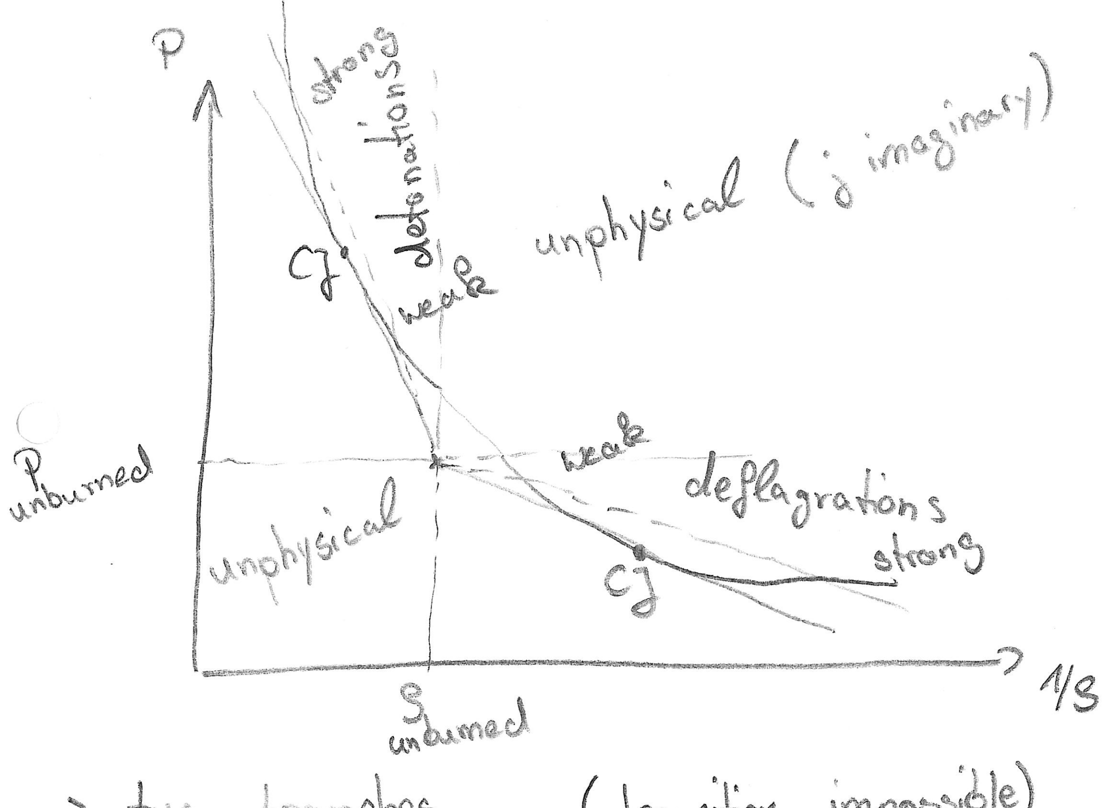


Add nuclear reactions (energy generation in ~~fly.~~ ashes):

$$\overset{\text{mass flux}}{\rightarrow} -\dot{j}^2 = \frac{P_{\text{burned}} - P_{\text{unburned}}}{\varrho^{-1}_{\text{burned}} - \varrho^{-1}_{\text{unburned}}}$$ Rayleigh criterion

Energy balance:

$$\mathcal{H}(P,\varrho) = u(P,\varrho) + \overset{\text{energy release}}{Q} - u_{\text{unburned}} + \frac{1}{2}\frac{P+P_{\text{unburned}}}{\varrho^{-1} - \varrho^{-1}_{\text{unburned}}}$$ Hugoniot curve



→ two branches (transition impossible)

1) detonations ($P_{\text{burned}} > P_{\text{unburned}}$, $\varrho^{-1}_{\text{burned}} < \varrho^{-1}_{\text{unburned}}$)

2) deflagrations: ($P_{\text{burned}} < P_{\text{unburned}}$, $\varrho^{-1}_{\text{burned}} > \varrho^{-1}_{\text{unburned}}$)

CJ: Chapman - Jouget points: burned material moves with speed of sound

Detonations:

More with ~ c_s of ash, supersonic w.r.t. fuel

Shock wave driven by energy release from nuclear burning behind the shock.

Not susceptible to fluid instabilities, propagates faster!

Deflagrations:

Propagate subsonically by heat conduction

Speed determined by balance of heating and conduction

~~[illegible] pressur~~

Typical laminar speed in $10^9 \frac{g}{cm^3}$ C/O : $10 \frac{km}{s}$,

$10^7 \frac{g}{cm^3}$: $10^{-2} \frac{km}{s}$

Typical sound speed: $10^4 \frac{km}{s}$

→ Burning a WD takes a long time

But: susceptible to hydrodynamic instabilities

- Kelvin - Helmholtz instability:
  Shear flow, always unstable

- Rayleigh - Taylor instability:
  Unstable if lower density material below higher density material

→ Turbulence (ash less dense, rises, instabilities)

Turbulent flame speed > 30% c_s !

Back to M_{Ch} - WD; flame just formed:

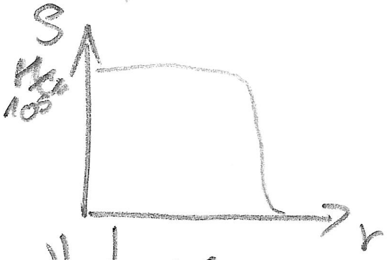
- As a detonation
  → The whole WD is burned at pre-runaway densities

$\rho \gtrsim 10^7 \frac{g}{cm^3}$: IGEs

$10^5 \frac{g}{cm^3} \lesssim \rho \lesssim 10^7 \frac{g}{cm^3}$: IMEs

$\rho \lesssim 10^5 \frac{g}{cm^3}$: not burned

Density profile M_{Ch} - WD:



Composition of ashes only depends on fuel density!

→ Everything burned to IGEs, not what we observe!

- As a deflagration:
  Energy injection causes WD to expand during burning
  → Result depends on initial flame configuration which changes how fast the WD expands
  Most material burned at $\rho < 10^7 \frac{g}{cm}$, since turbulence needs time to develop.

  Max $M_{^{56}Ni} \sim 0.4\, M_\odot$ → not bright enough
  And: RT + KH instabilities completely mix ejecta!
  → Can only explain small peculiar subset of SNe Ia (02cx-like objects)

→ Combine burning modes

Idea: Start with deflagration, but only burn central part to ^{56}Ni / IGES. After WD expanded a bit, ignite detonation to burn outer layers to get the observed layered composition.

- Main problem: How to ignite detonation?
  - Turbulence: delayed detonation
  - Converging surface shocks: GCD (Grav. confined detonation)
  - WD pulsations: Pulsating delayed detonation

Deldet: best studied model at the moment, active research, may work but still a lot of problems.

General problems:
- How to prevent IGEs from deflagration to reach outer layers of explosion?
- How to explain observational correlations between brightness / galaxy type / age of stellar population?
- Why is there no signature of a companion?
- Are there enough M_{Ch} WDs?

How to reach M_{Ch}?

- Accretion of hydrogen with stable burning on surface of WD.

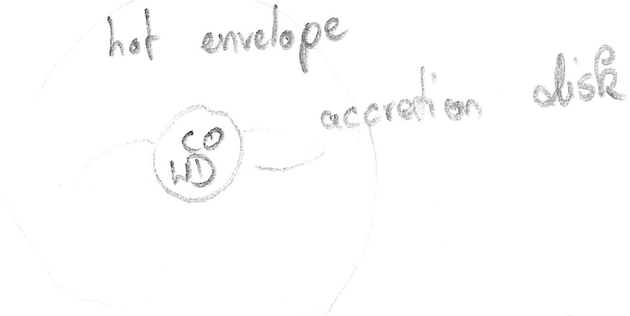
Companion: MS or RG star with hydrogen-rich envelope

→ Single degenerate scenario

- Alternative: second (CO) WD → double degenerate scenario

Standard scenario: close WD + WD binary

→ merger after long inspiral due to emission of grav. waves, less massive WD destroyed!



Accretion of C/O on primary WD grows it. When it approaches M_{Ch} (if $M_{tot} \gtrsim M_{Ch}$) → SN Ia?

Problem: When $T_{surface} \gtrsim 6 \cdot 10^8 K$ ignition of C, burns inwards by conduction, converts WD to ONeMg WD.

→ Ignition at higher density, but when $\rho > 4\ 10^9 \frac{g}{cm^3}$ e^--capture on Ne, Mg runs away → collapse to neutron star

→ No M_{Ch} explosions from double degenerate systems!

Sub-Chandrasekhar-mass scenario:

$M_{WD} < M_{Ch} \Rightarrow 0.9\,M_\odot - 1.2\,M_\odot$

$\rightarrow \rho_c \sim 10^7 \frac{g}{cm^3} - 10^8 \frac{g}{cm^3}$

Deflagration does not produce ^{56}Ni (ϱ too low)

→ only detonations are of interest.

But: how to ignite?

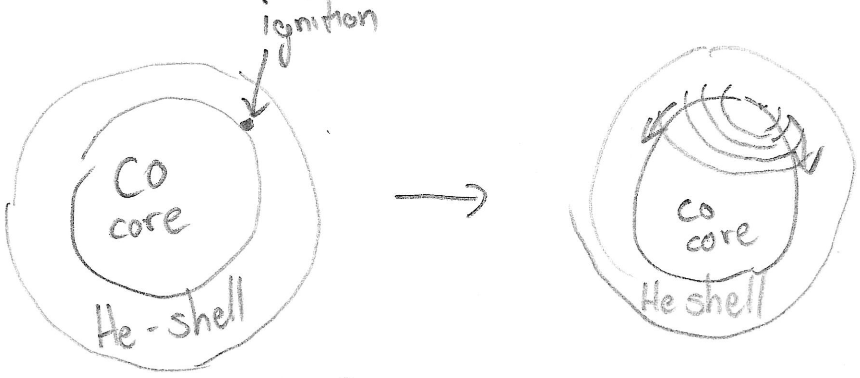
No internal ignition as for M_{Ch} WDs → external trigger

Double detonation scenario:

CO-WD accretes He-layer from companion (He-star or He-WD)

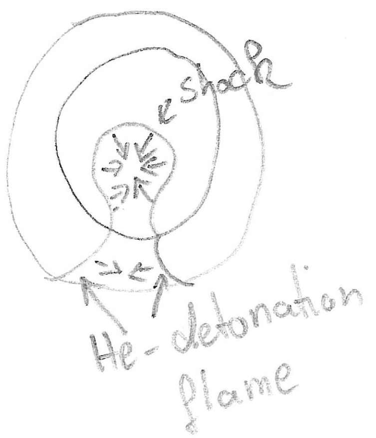
If massive enough, He-burning starts at bottom of shell, leads to convection and eventual runaway (cmp. novae!)

Assume that thermonuclear runaway ignites He-detonation:



det propagates around WD and sends shockwave into core

He-det faster than shocks in core:

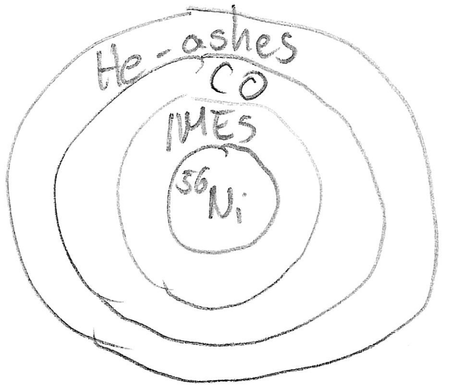


Shock in CO-core converges at single point

→ Ignition of C-detonation!

→ CO core is burned by det.

Ejecta:



Advantages:

- layered structure of IGEs/IMEs/CO → reproduce spectra/LCs well
- distribution of brightnesses of SNe Ia directly linked to masses of (primary) WDs
- If He shell detonates, C detonation seems unavoidable

Problems:

- He-ashes probably IGEs → problems with early spectra
- Formation of He-detonation unclear
- Massive primary WD's needed
  ($M_{WD} = 1.1 M_\odot \rightarrow M_{^{56}Ni} \sim 0.6 M_\odot$, but typical birth mass of CO WDs $\sim 0.6 M_\odot$ → has to grow significantly before explosion)

The double degenerate scenario revisited.

Avoid conversion to ONe WD

→ "prompt" detonation before / during merger

either by

- He-shell on primary WD ($\sim 10^{-3}$ $M_\odot$)
  Very similar to double detonation scenario, but
  He-shell much smaller → less of a problem for observables
  No convection → He-detonation ignited dynamically
  from interactions in accreation stream
  Secondary WD still around
- In the merger itself when the secondary WD hits
  the surface of the primary WD, direct
  ignition of C-detonation
  → Ignition much harder, only relevant if He-shell
  not present

Advantages:

- Avoids most problems with non-detetions of
  companion star
- Similar to Sub Ch-scenario without / very little
  Helium

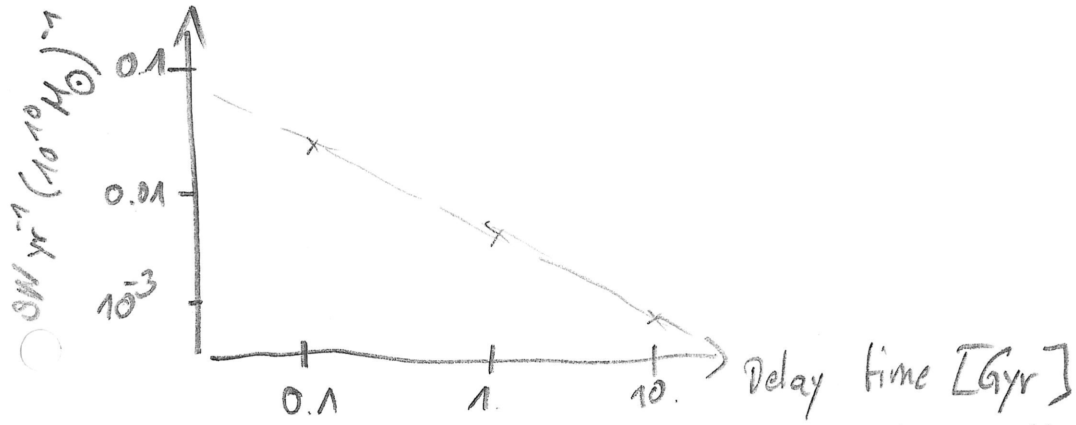
Problems:

- Ignition of first detonation unclear
- Again, enough massive primary WDs needed

Rates and delay time distributions

DTD: hypothetical $\overset{SN}{\text{rate}}$ vs. time following a brief star burst that created a unit mass of stars

Observed:



~~Normalizati~~ Slope: good agreement with t^{-1} power-law

$$\Rightarrow \quad \Psi(t) = 4 \cdot 10^{-13}\ \mathrm{yr}^{-1} \cdot M_\odot^{-1} \left(\frac{t}{1\,\mathrm{Gyr}}\right)^{-1}$$

[illegible]

$\Rightarrow$ Total rate (Integral 40 Myr $\rightarrow$ 10 Gyr) $\quad \frac{N_{SN}}{M_*} = \overset{(0.5-3.5)}{2.2} \cdot 10^{-3}\, M_\odot^{-1}$

Theoretical DTD:

DD: $t_{gw} \sim a^4$

$$\Rightarrow \frac{da}{dt} \sim t^{-3/4}$$

$\frac{dN}{da} \sim a^{\varepsilon}$ $\quad \varepsilon \sim -1$ Observed for non-interacting binaries

$$\Rightarrow \frac{dN}{dt} = \frac{dN}{da}\frac{da}{dt} \sim t^{(\varepsilon-3)/4} \sim t^{-1}$$

But: No model seems to be able to explain the observed normalization!

SD: $t \sim m^{\delta}$ Main seq. lifetime; Initial mass

IMF $\frac{dN}{dm} \sim m^{\lambda}$

$$\Rightarrow \frac{dN}{dt} = \frac{dN}{dm}\frac{dm}{dt} \sim t^{(1+\lambda-\delta)/\delta}$$

Stellar ev. models: $\delta \sim -2.5$

Salpeter IMF: $\lambda = -2.35$

$$\Rightarrow \frac{dN}{dt} \sim t^{-0.5}$$

SN Ia Theory summary:

Main problem: we don't know the progenitors

SD vs. DD prog scenario

M_{Ch} vs. Sub Ch explosion scenario