Exploding Dark Matter Admixed White Dwarfs An Alternative Explanation for Peculiar Supernovae?

2021

Tea-Talk

The Chinese University of Hong Kong

Image credit: Nasa.gov

Image credit: livescience.com

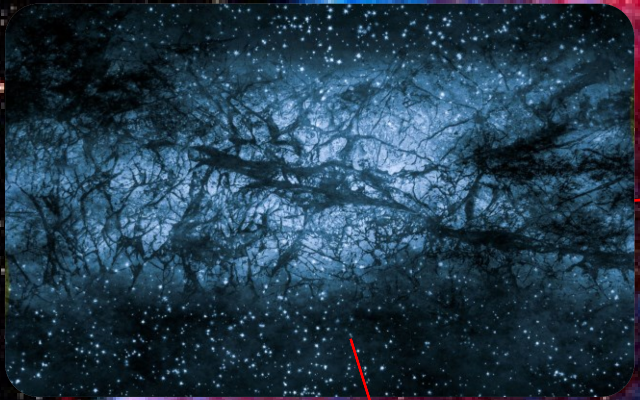


Image credit: forbes.com

Exploding Dark Matter Admixed White Dwarfs

An alternative explanation for Peculiar Supernovae?

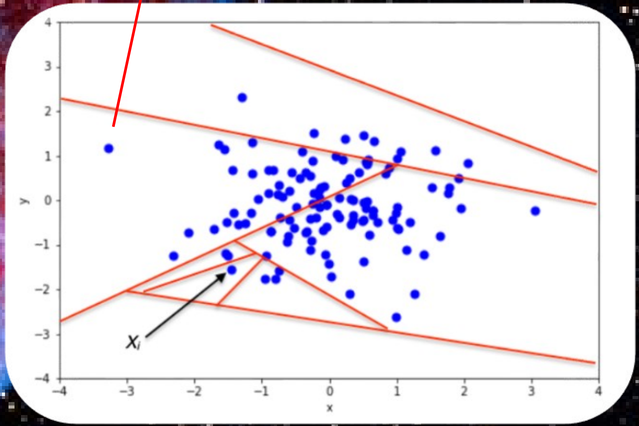


Image credit: wikipedia.com

Self-Introduction

Dr. S-C. Leung

Mentor

Prof. M-C. Chu

Supervisors

Dr. L-M. Lin

Me

CUHK - Physics

2nd Year M.Phil. Student

Introduction And Motivation

Image credit: universetoday.com

Dark Matter Astronomy

Image credit: Rubin et al. 1970

Non-Visible Matter?

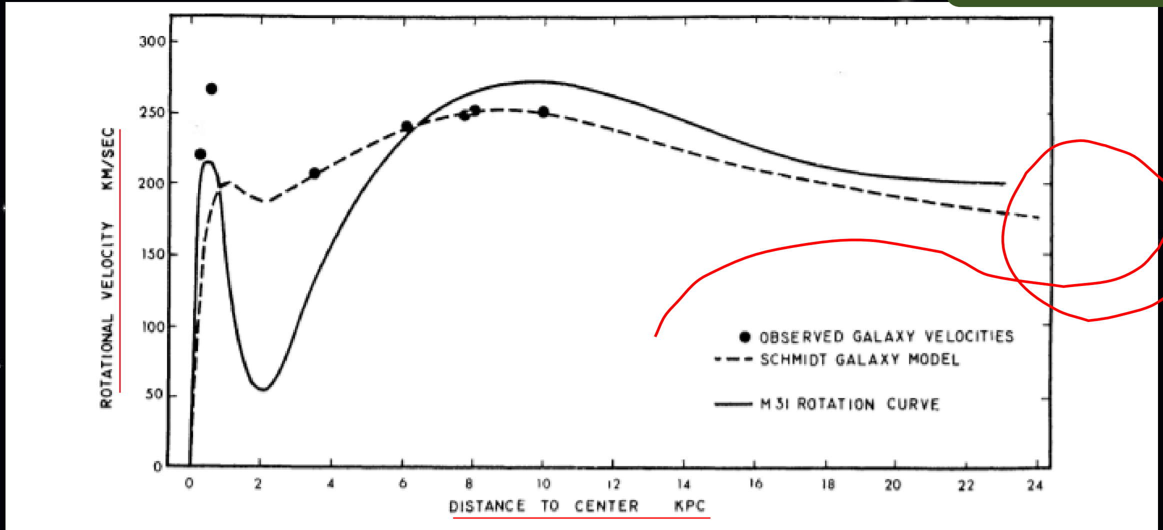
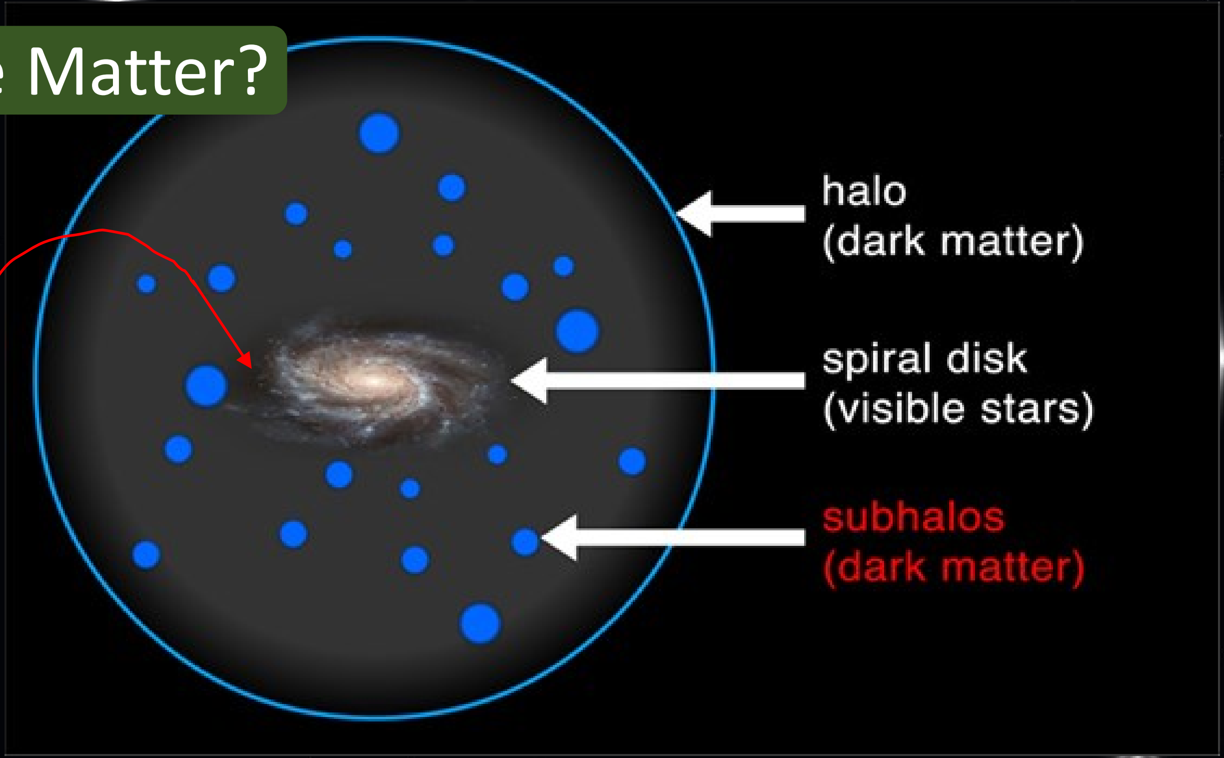


FIG. 15.—Comparison of rotation curves for M31 and the Galaxy, as a function of distance from the center. *Solid line*, rotation curve for M31 (Fig. 9); *dashed line*, rotation curve from Schmidt model of the Galaxy. *Filled circles*, observed rotational velocities for the Galaxy (Rougoor and Oort 1960; Schmidt 1965).

- Rubin et al. in 1970 discovered anomalous Galactic rotational velocity

Image credit: astrobites.org



- Dark matter (DM) and “normal” matter (NM) form Galactic bound systems

Can they form stellar-scale bound systems?

Dark Matter Admixed Stars

Sandin, F., & Ciarcelluti, P. (2009). Astroparticle Physics, 32(5), 278-284.

Effects of mirror dark matter on neutron stars

Fredrik Sandin [a,b], Paolo Ciarcelluti [a,*]

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- Visionary research paper by Sandin et al. 2009
  - DM and NM as fluids forming hybrid stars

Come back to this later

Image credit: Leung et al. 2013

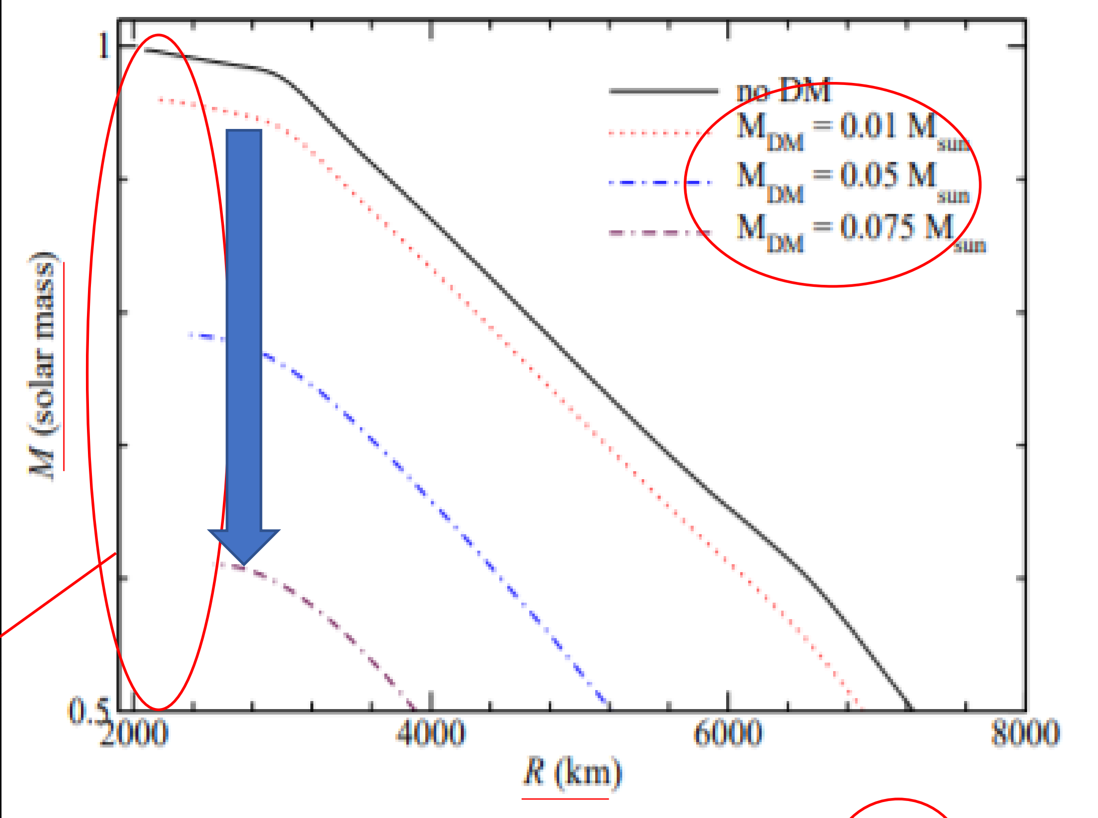


FIG. 3: Same as Fig. 1, but for $m_{DM} = 1$ GeV.

- Leung et al. 2013 studied DM admixed white dwarfs
  - Assume heavy DM particles (> 1 GeV)
  - Degenerate Fermionic DM (Spin - $\frac{1}{2}$)
- DM component is much smaller in size than NM

NM Mass Decreases

Dark Matter Admixed Type Ia Supernovae

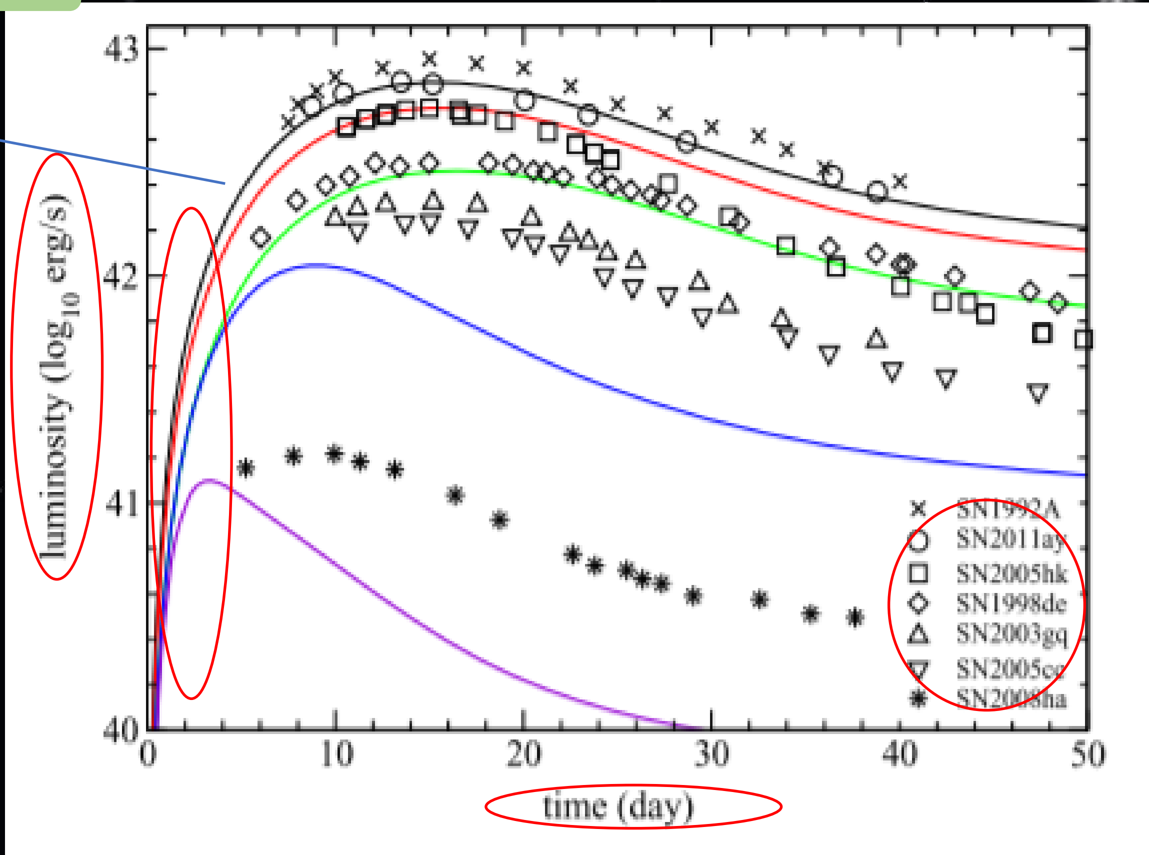
Image credit: astronomy.swin.edu.au

- Type Ia supernova – Explosion of a white dwarf
  - Mass decrease → less fuel → dimmer
- Dimmer light curves → Sub-luminous supernovae

Bright Transient

Bolometric

Image credit: Leung et al. 2015



- Assumptions:

1. Large DM particle mass (1 GeV)
2. DM component is stationary (point gravity source)
3. DM total mass O(10^{-2}) $M_\odot$

What if we alter these assumptions?

Methodology

Photo credit: universetoday.com

Hydro-Static Equilibrium Structures

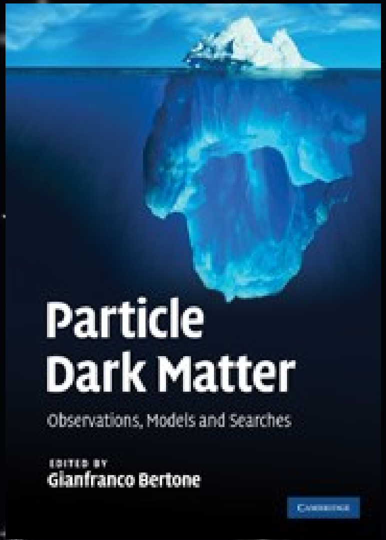
- DM and NM as separate fluids. Interact through gravity only:

$$\frac{dp_i}{dr} = -\frac{G\left(m_1(r) + m_2(r)\right)}{r^2}\rho_i$$

$$\frac{dm_i}{dr} = 4\pi r^2 \rho_i$$

Mass
Radius

- For i = 1(DM) and i = 2(NM). Combined gravity.
- Degenerate Fermionic spin $\frac{1}{2}$ DM. DM particle mass 0.1 GeV



- DM particle mass ~ 10 GeV → Point gravitational source
- Representative mass ~ 0.1 GeV → Generalise light DM particles

Some Examples

Progenitors

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015
DM Radius (km)	-	975	1160	1380	1640	1920
NM Radius (km)	1930	1890	1830	1740	1650	1560

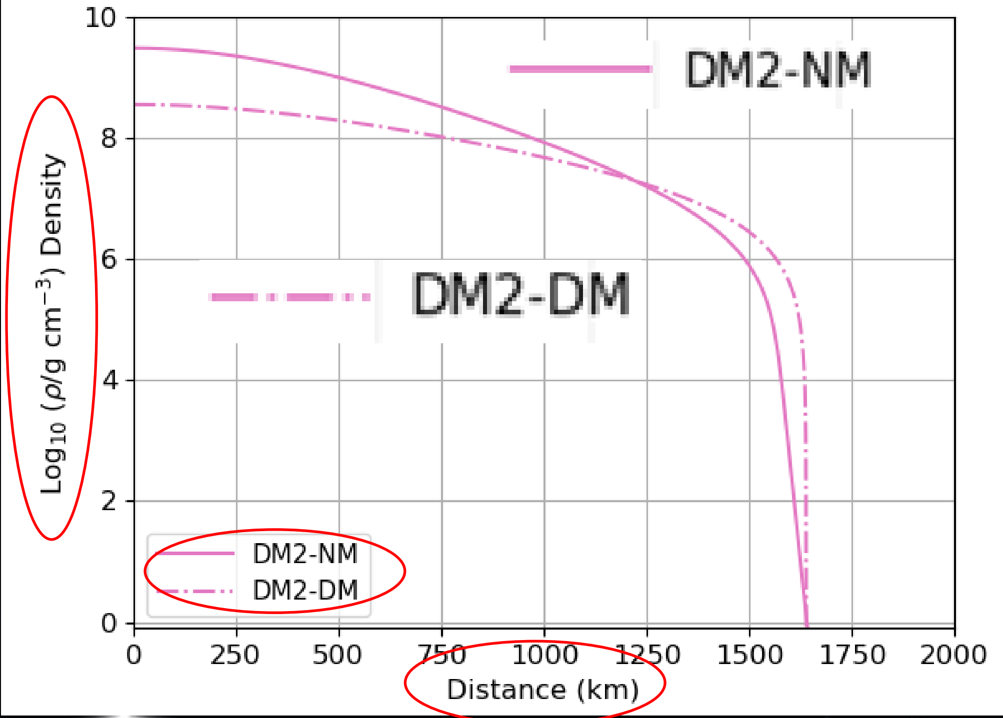
- A Common choice for white dwarfs about to explode
- NM mass reduced. DM mass increased.
- TOTAL mass is increased (DM3 – 1.509 $M_\odot$)
- Solar mass scale DM!
- Extended component of DM – not stationary!

DM

NM

Image credit: Chapman

Density Profiles - DM2



Model The Explosion

- One-dimensional, finite volume version of
- Eulerian grid-based hydro-code
- 5th Order reconstruction method
- Two-fluids motion coupled through gravity

Leung, S. C., Chu, M. C., & Lin, L. M. (2015). MNRAS, 454(2), 1238-1259.

A new hydrodynamics code for Type Ia supernovae

S.-C. Leung,* M.-C. Chu and L.-M. Lin

Department of Physics and Institute of Theoretical Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong S.A.R., China

- Contains 7 major isotope:
    - He4, C12, O16, Ne20, Mg24, Si28, Ni56

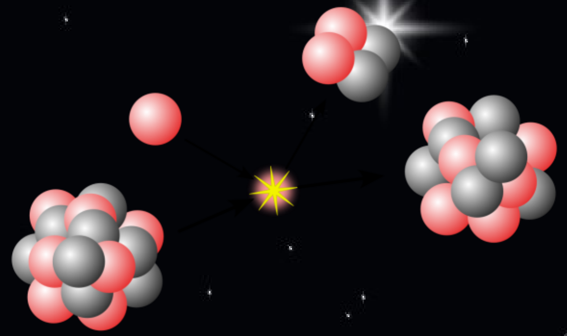


Image credit: Wikipedia.com

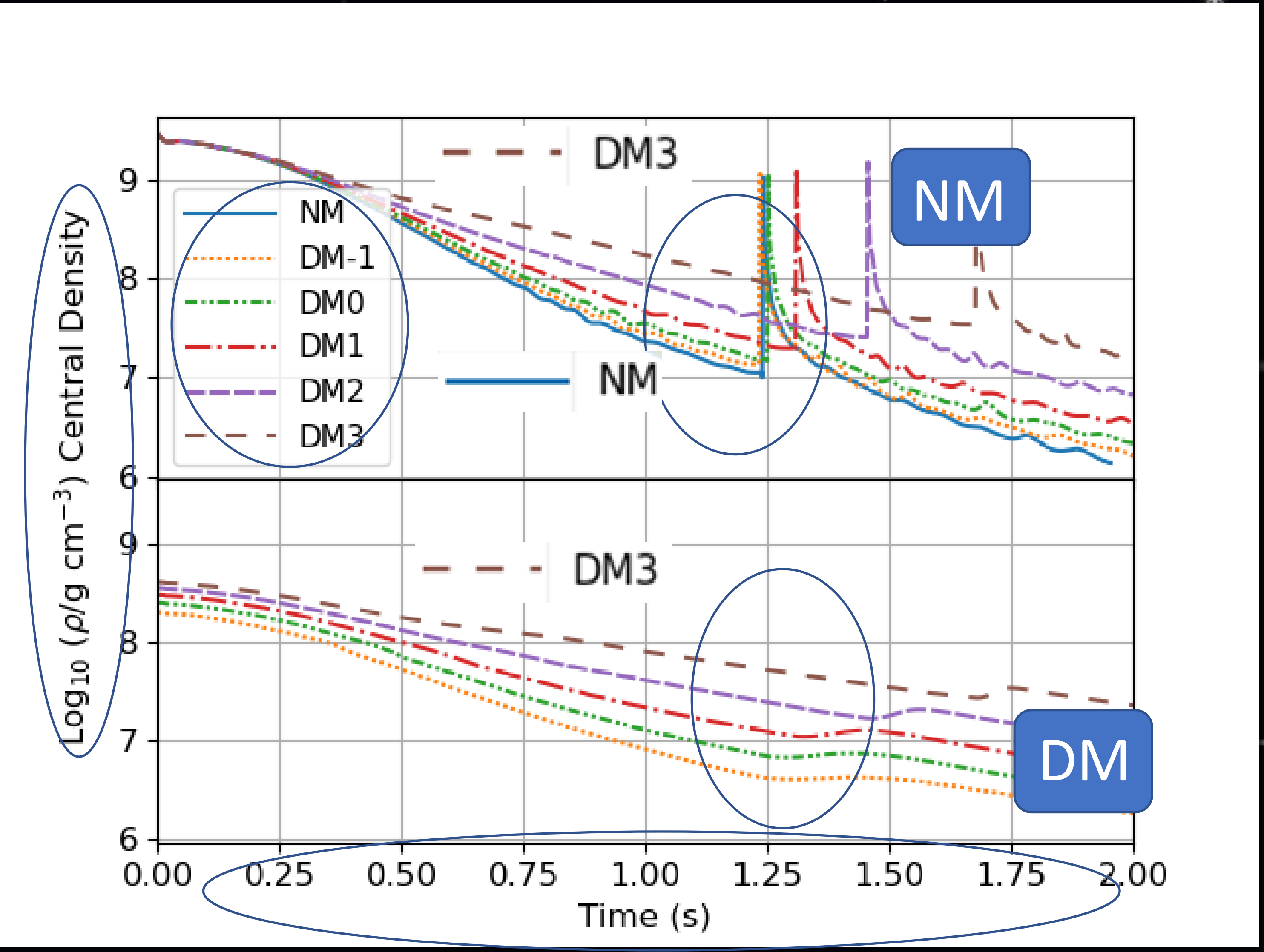
- Simulation duration – 5s

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

Results And Discussions

Photo credit: universetoday.com

Global Hydrodynamic Quantities



- More DM:
- The NM is denser
- Both fluids expands slower …

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

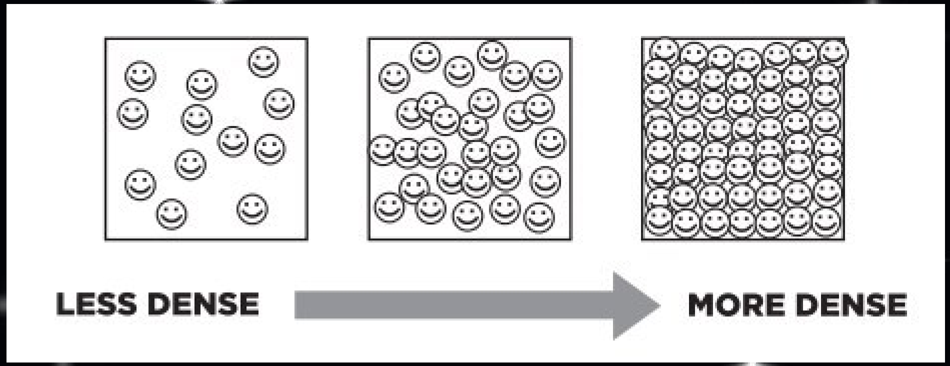
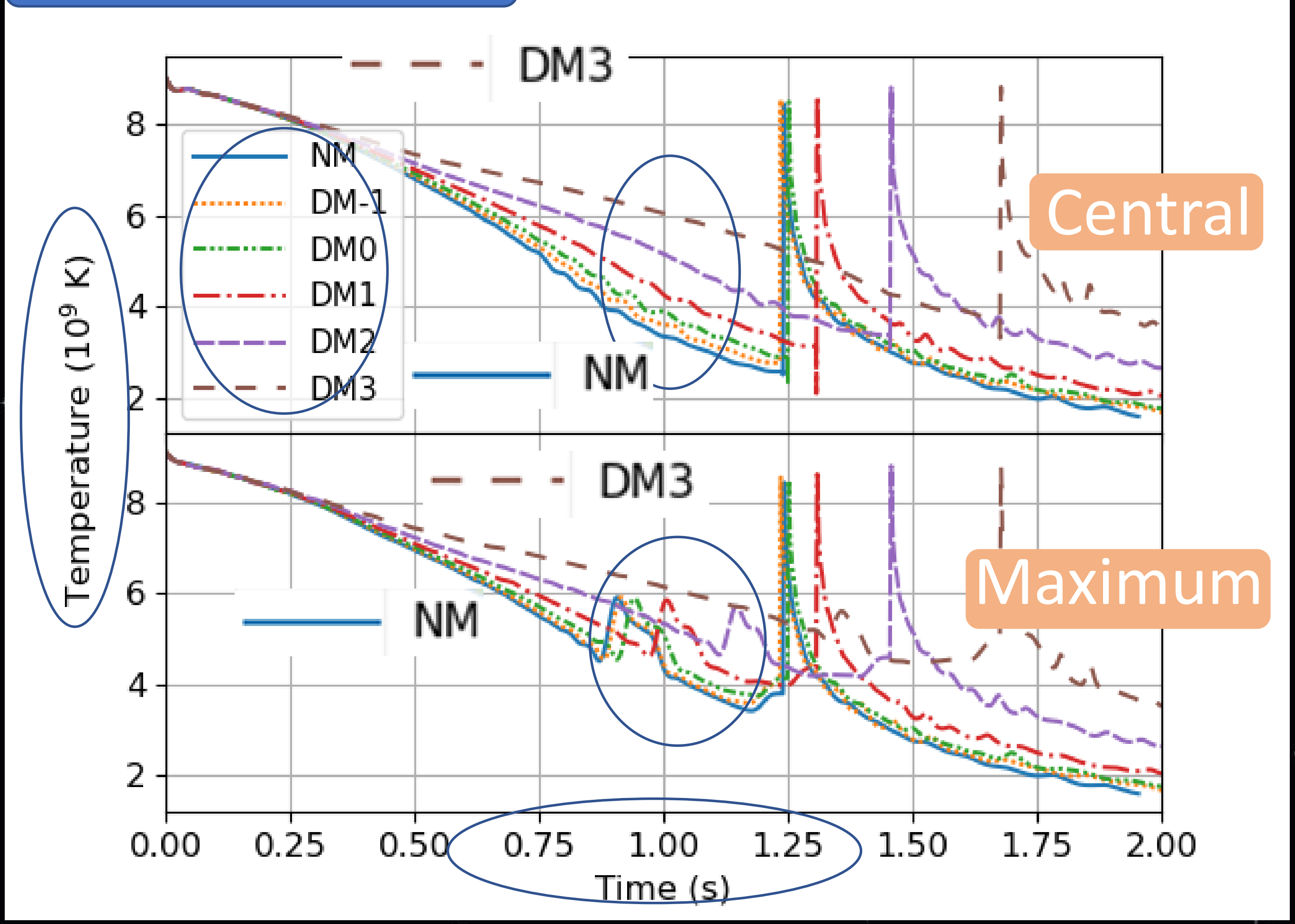


Image credit: scienceworld.ca

Global Hydrodynamic Quantities

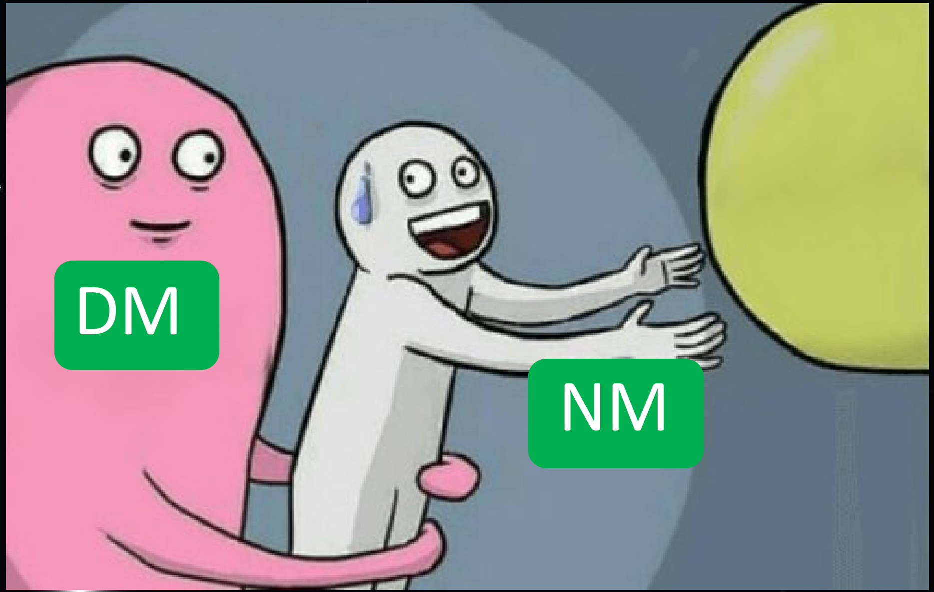
- DM gravitational force prohibit the expansion of NM

NM Temperature



- More DM:
- NM is hotter

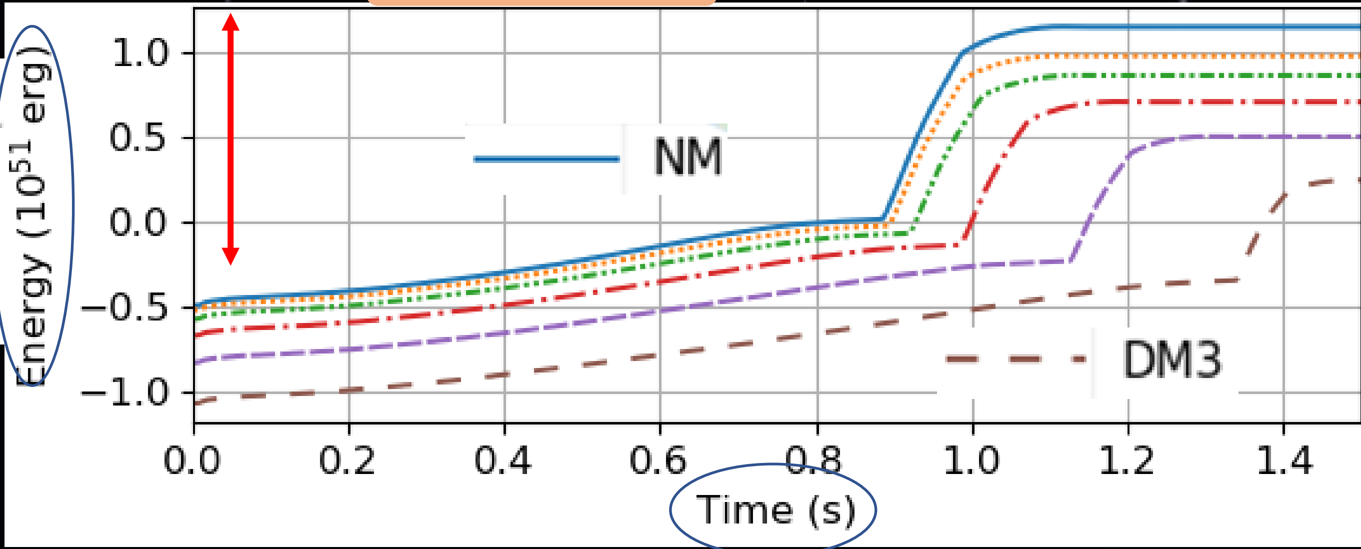
Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015



Ni56 And Energy Production

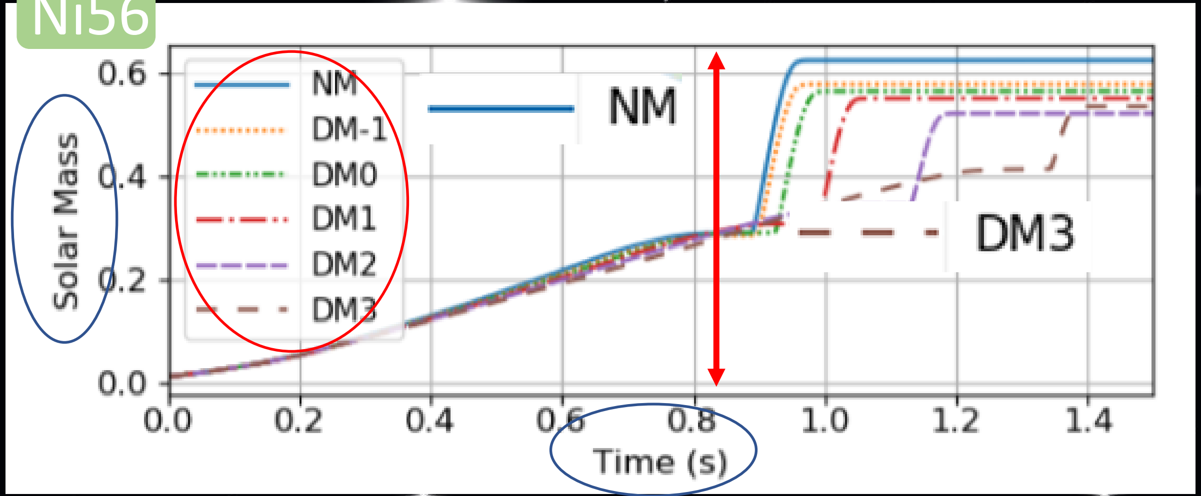
Model	NM	DM-1	DM0	DM1	DM2	DM3
^{56}Ni Mass ($M_\odot$)	0.623	0.577	0.563	0.549	0.520	0.534
^{56}Ni Fraction	0.453	0.465	0.476	0.488	0.488	0.526
Energy (10^{51} erg)	1.650	1.503	1.442	1.383	1.336	1.321

Total Energy



- More DM:
- Less energy produced
- Ni56 mass fractions increased
- Dense and hot environment favors producing Ni56

Ni56



Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

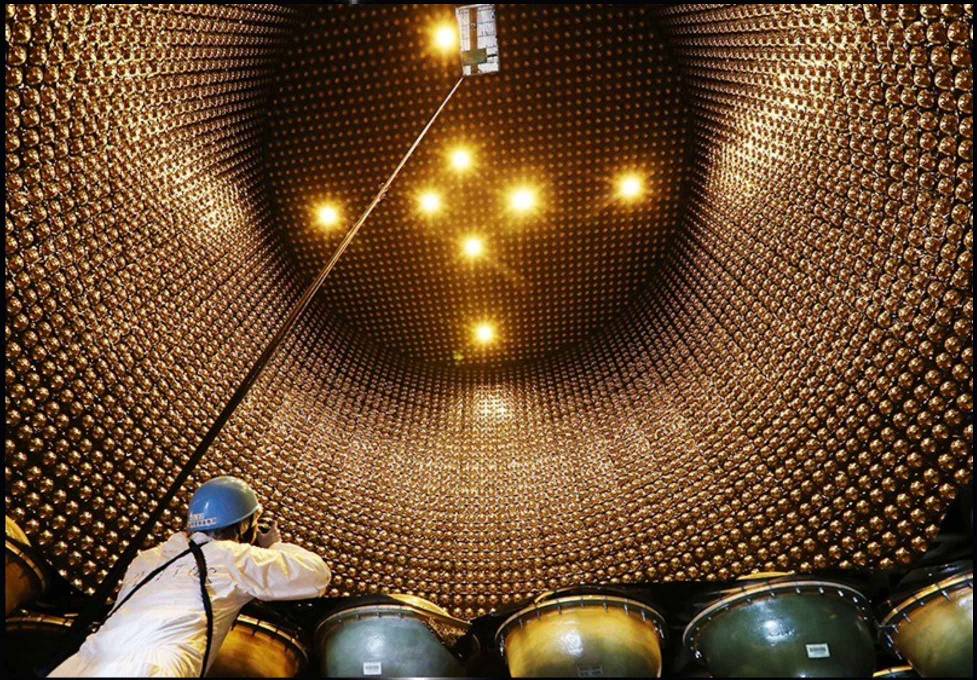
Important Consequences on Light Curves

Supernova Observables

Photo credit: universetoday.com

Supernova Neutrinos

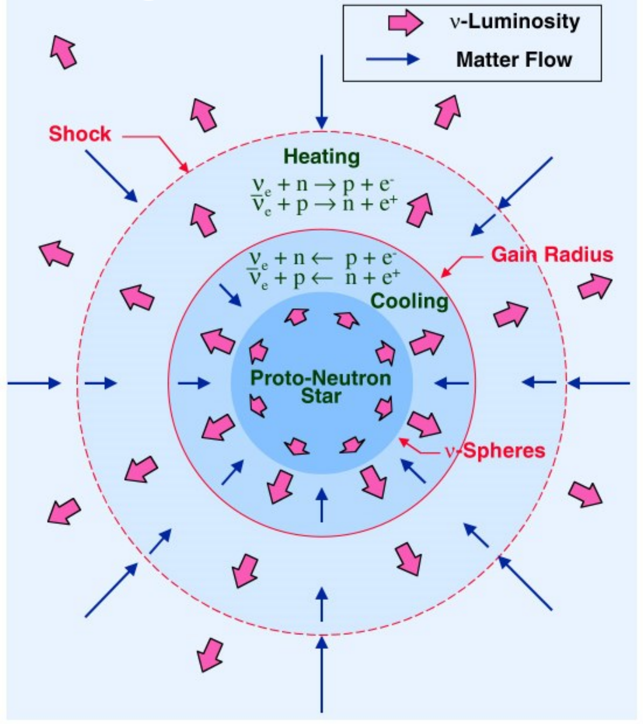
Image credit: nature.com



Super Kamiokande, Japan

Detect

Image credit: utexas.edu



Core-Collapse Supernovae

- Supernova neutrinos from CCSN – Strong
- Supernova neutrinos from Type Ia – Weaker
- Still worth to study if DM is admixed

Wright, W. P., and others. (2016). Physical Review D, 94(2), 025026.

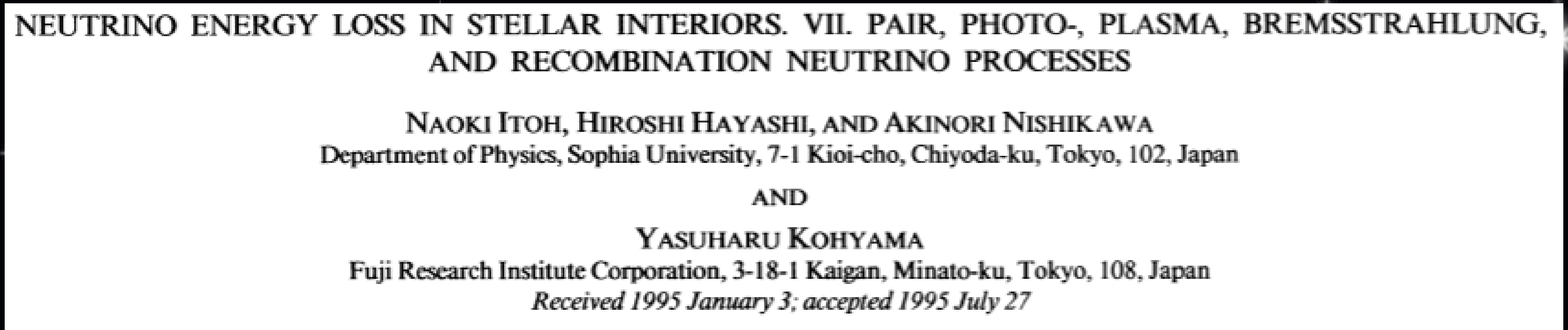
Neutrinos from type Ia supernovae: the deflagration-to-detonation transition scenario

Warren P. Wright,[1,*] Gautam Nagaraj,[1,†] James P. Kneller,[1,‡] Kate Scholberg,[2,§] and Ivo R. Seitenzahl[3,4,¶]

Thermo-neutrinos Production

- Used package from cococubed.asu.edu of Timmes et al.
- Based on the work by

Itoh, N., and others. (1996). The Astrophysical Journal Supplement Series, 102, 411.



NEUTRINO ENERGY LOSS IN STELLAR INTERIORS. VII. PAIR, PHOTO-, PLASMA, BREMSSTRAHLUNG, AND RECOMBINATION NEUTRINO PROCESSES

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Department of Physics, Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo, 102, Japan

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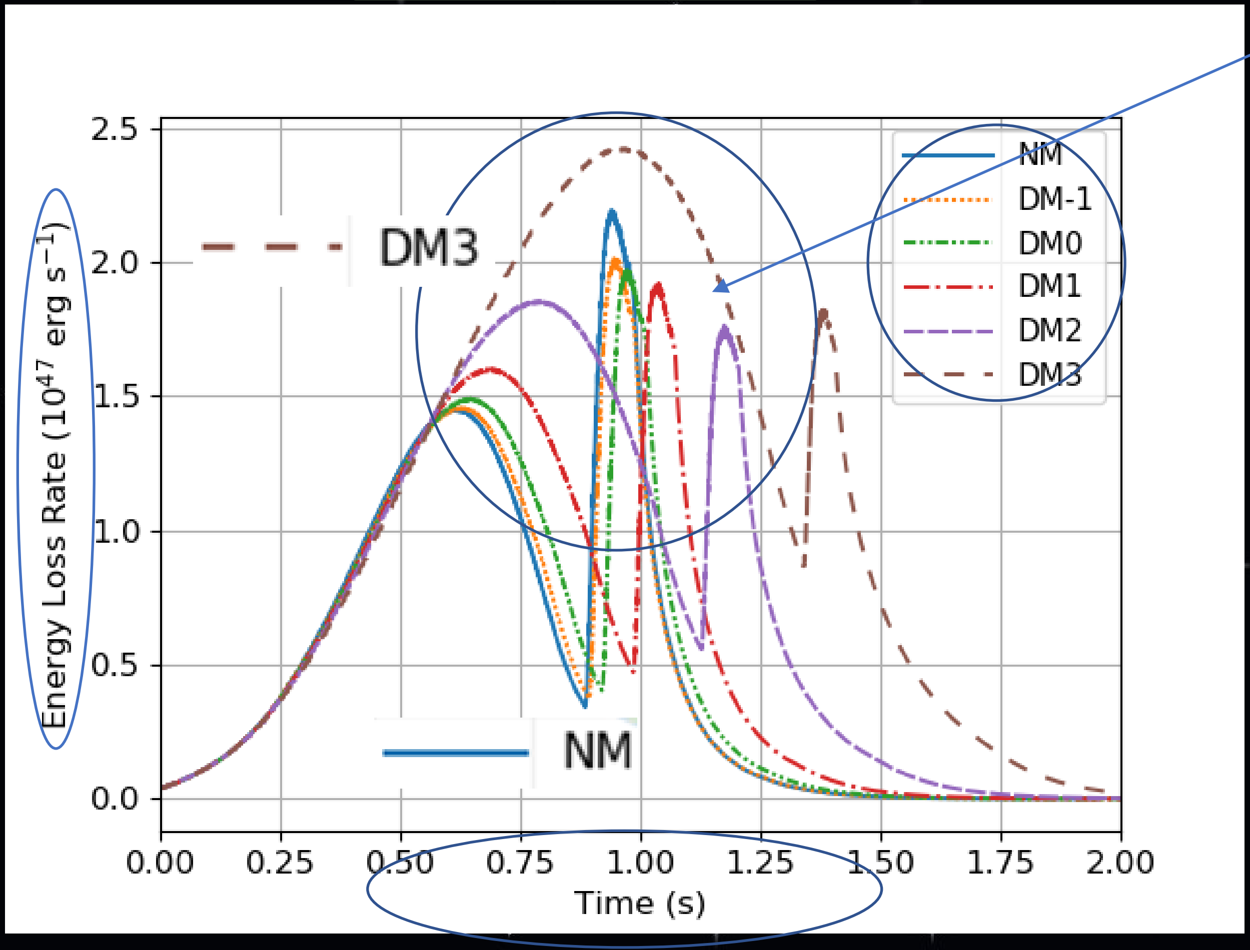
Received 1995 January 3; accepted 1995 July 27

- Thermal emission of neutrinos
  1. Pair-Production
  2. Photoneutrino
  3. Plasmon neutrino
  4. Bremsstrahlung
  5. Recombination

Image credit: space.com

Thermo-neutrino Production

Neutrino Energy Lost



- Total energy lost $\int f(t)dt$
- More DM → More energy loss due to thermo-neutrino production

Model	NM	DM-1	DM0	DM1	DM2	DM3
Energy (10^{47} erg)	0.970	0.958	0.998	1.234	1.426	2.133

NM DM3

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

- Hot and dense environment favors thermo-neutrino production

Thermo-neutrino Production

Image credit: hyper-k.org

Estimated Total Event Count

-	NM	DM-1	DM0	DM1	DM2	DM3
Hyper-K, Memphys	3.3	3.3	3.4	3.8	4.9	7.3
Glacier	4.2	4.1	4.3	4.9	6.2	9.3
LENA (ES0)	2.9	2.9	3.0	3.4	4.3	6.4
LENA (PES)	12.0	11.8	12.3	13.9	17.7	26.5

NM DM3

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

- Total neutrino detected scales linearly with total neutrino production

$$N \propto N_\nu \propto \text{Energy Lost}$$

- Could have notable differences only for large DM admixtures

Supernova Light Curves

SNEC Code

- Input
- Density, Mass, Velocity of the NM
- Isotopes:
  - He4, C12, O16, Ne20, Mg24, Si28, Ni56

Morozova, V., and others. (2015). *The Astrophysical Journal*, *814*(1), 63.

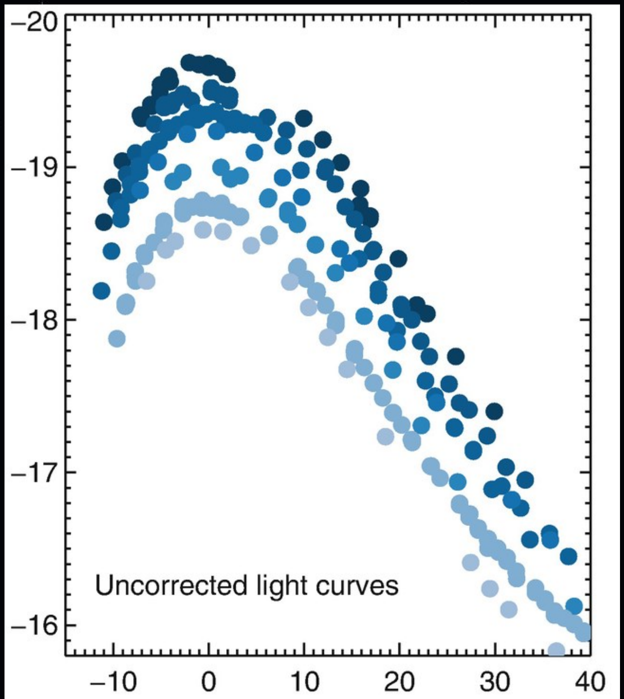
LIGHT CURVES OF CORE-COLLAPSE SUPERNOVAE WITH SUBSTANTIAL MASS LOSS USING THE NEW OPEN-SOURCE SUPERNOVA EXPLOSION CODE (SNEC)

VIKTORIYA MOROZOVA[1], ANTHONY L. PIRO[2], MATHIEU RENZO[3,1], CHRISTIAN D. OTT[1], DREW CLAUSEN[1], SEAN M. COUCH[1], JUSTIN ELLIS[1], AND LUKE F. ROBERTS[1]

Accepted to ApJ, 10/15/2015

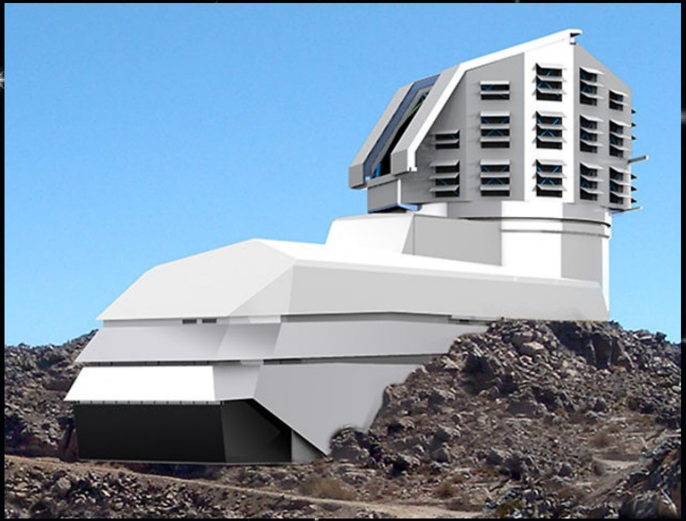
- 1D Local Thermodynamic Equilibrium
- Lagrangian grid-based radiative-hydro

Image credit: Handbook of Supernovae



- DM is much smaller in size than NM
- DM act as monopole gravity source
- $g_{DM} = -\frac{GM}{r^2}$

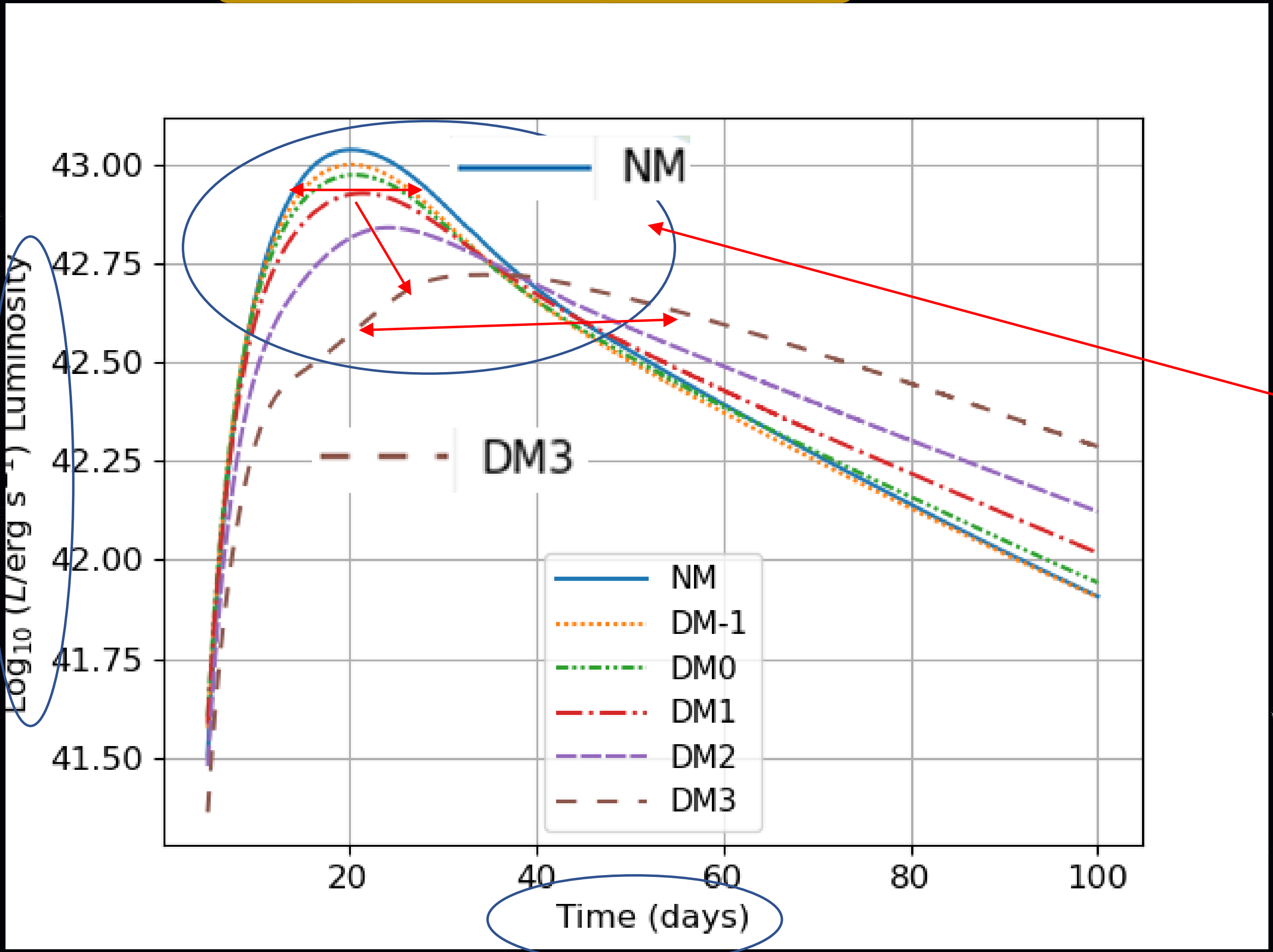
Image credit: symmetrymagazine.org



LSST

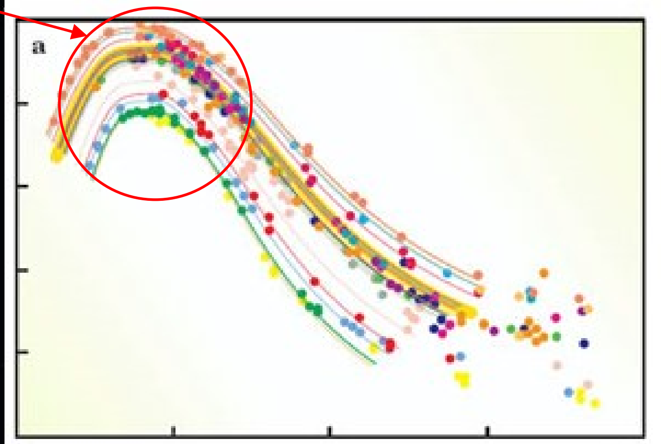
Supernova Light Curves

Bolometric Luminosity



Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

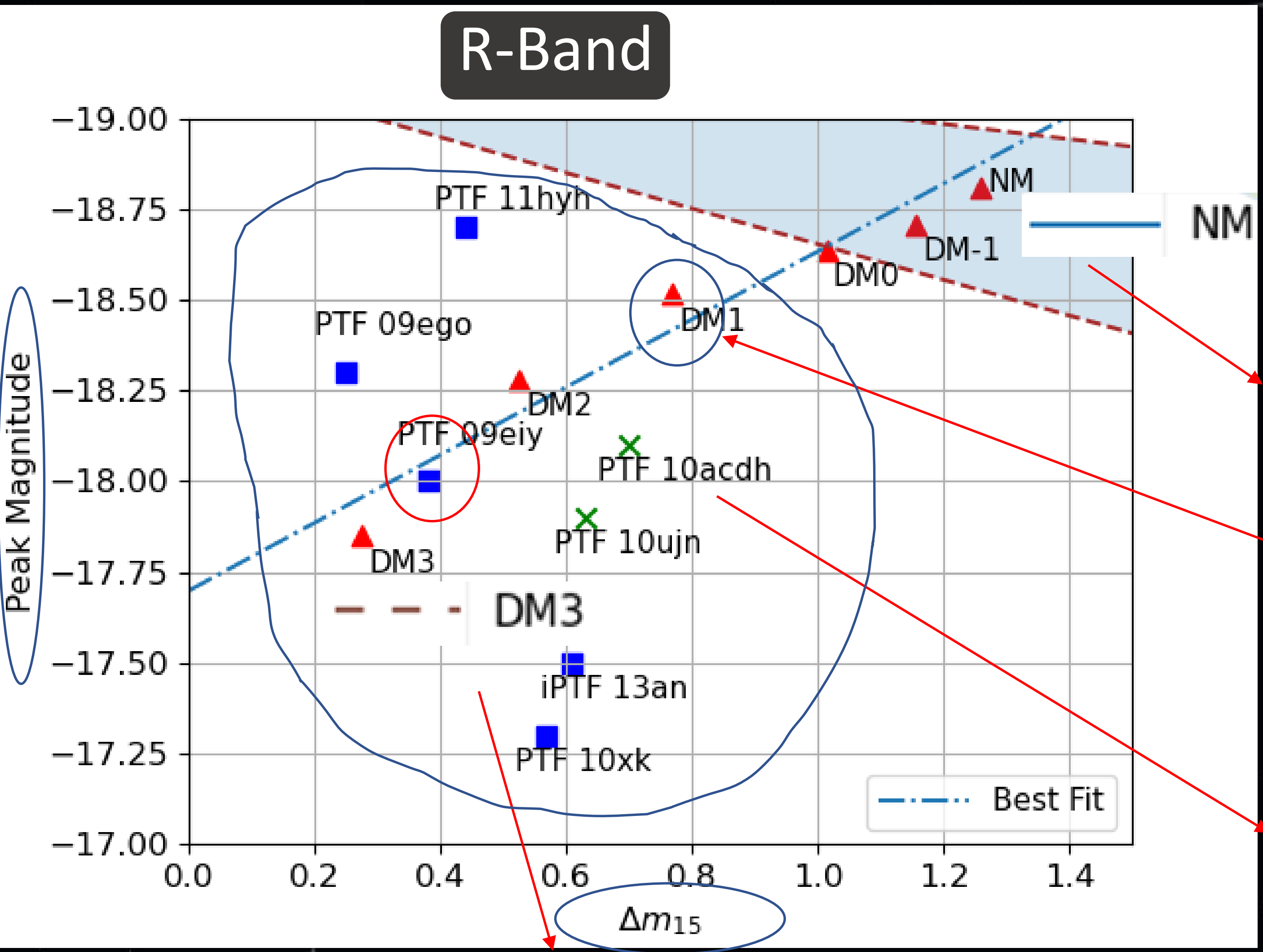
- More DM:
- Dimmer light curves
- Broader light curves
- Go against the usual Phillips relation … ?



Even complex realistic models do not reproduce the Phillips relation

What can be inferred from our results?

Supernova Light Curves



NM DM3

Model	NM	DM-1	DM0	DM1	DM2	DM3
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DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

- Observed R-Band Phillips relation
- Best-fit line for all DM models

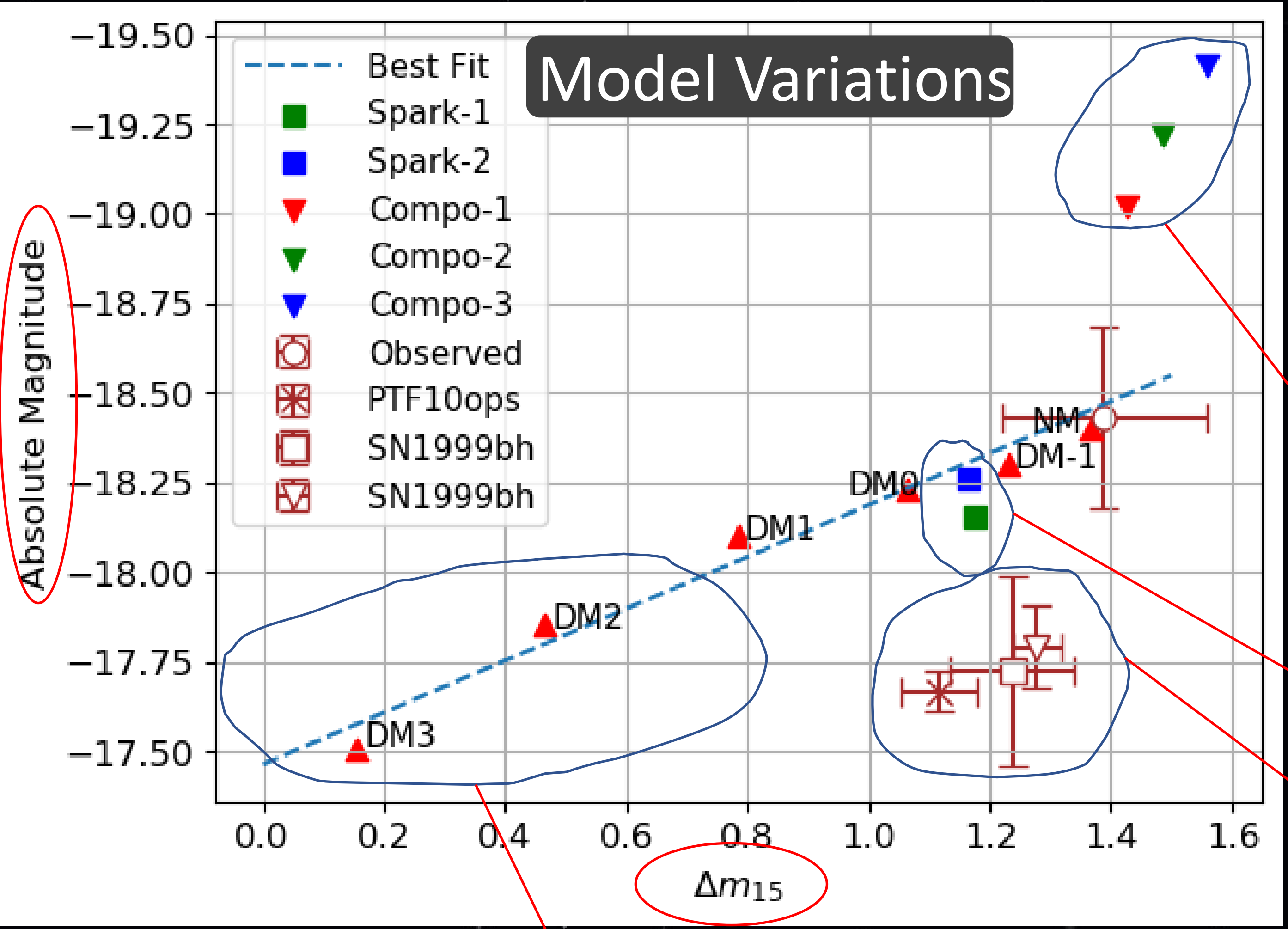
Peculiar supernovae detected by PTF

- Parameter spaces with slightly lower m but very small Δm_{15}

Slightly Dimmer

Slowly Declining

Supernova Light Curves



NM — DM3

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM ρ_c (10^9 g cm^{-3})	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass ($M_\odot$)	-	0.067	0.120	0.201	0.322	0.494
NM Mass ($M_\odot$)	1.374	1.242	1.183	1.124	1.067	1.015

- Varying initial WD compositions
- Varying explosion conditions
- Explained by other explosion mechanisms

- Model variations → deviations from the Phillips relation
- Only DM models located at the low m and small Δm_{15} space?

DM admixed models could explain SOME peculiar supernovae

Conclusion

- We performed 1-D spherically symmetric simulations of DM-admixed Type Ia Supernovae
  - The DM component is extended and comparable to that of the NM
- More DM admixtures would lead to stronger thermo-neutrino production
- DM models produce dimmer and wider light curves which could help explain certain peculiar supernovae

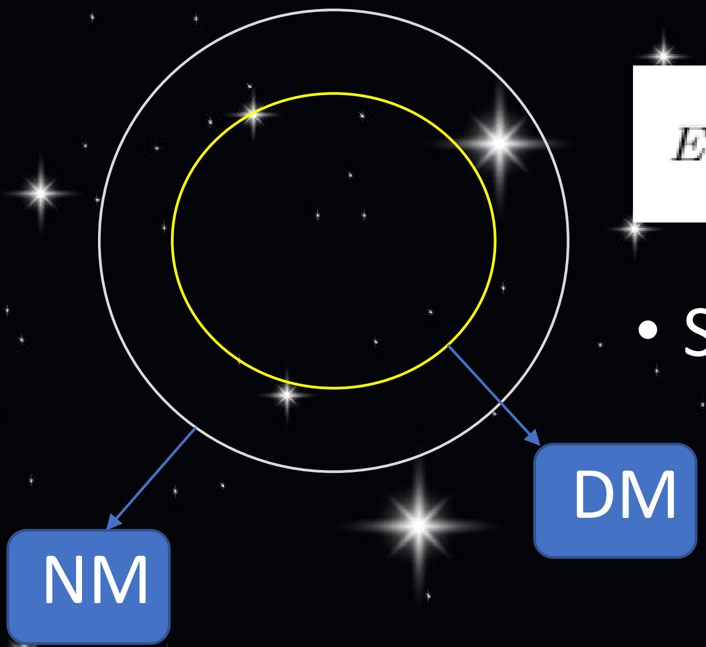
Thank You

Appendix

Photo credit: universetoday.com

Admixing Solar Mass Scale DM

- Inherit a DM component during the star is formed



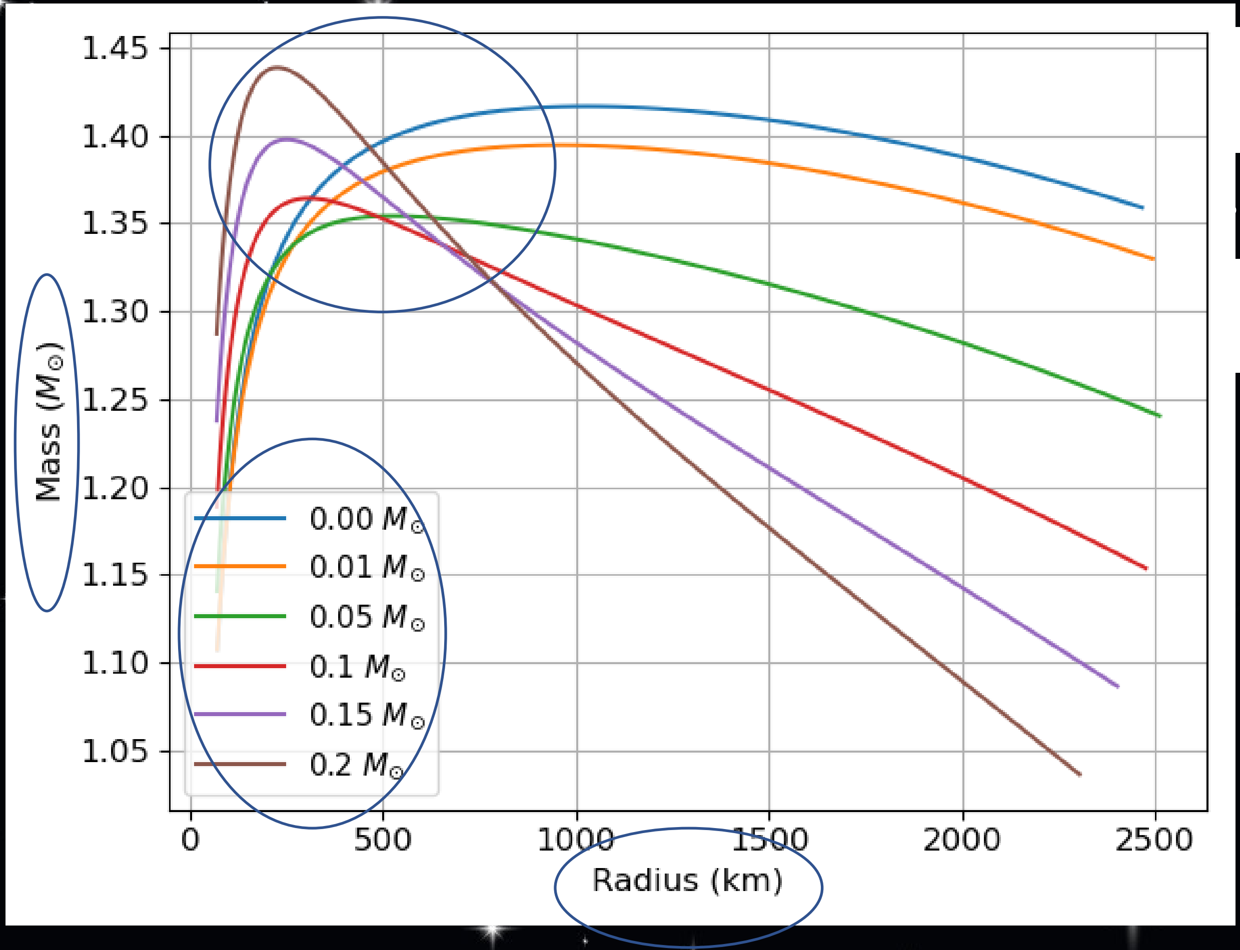
- Total energy (DM + NM)

$$E = -\left(\frac{3}{5}\frac{GM_1^2}{R_1} + \frac{3}{5}\frac{GM_2^2}{R_2} + \frac{3}{2}\frac{GM_1M_2}{R_1} - \frac{3}{10}\frac{GM_1^2R_1^2}{R_1^3}\right) + \frac{3}{2}NkT + \frac{1}{2}M_1v_1^2.$$

- Solve for DM radius R_1 and density ρ_1

- Particular solution: (1.71×10^8cm, 3860 GeV/cm3)
- Large but possible

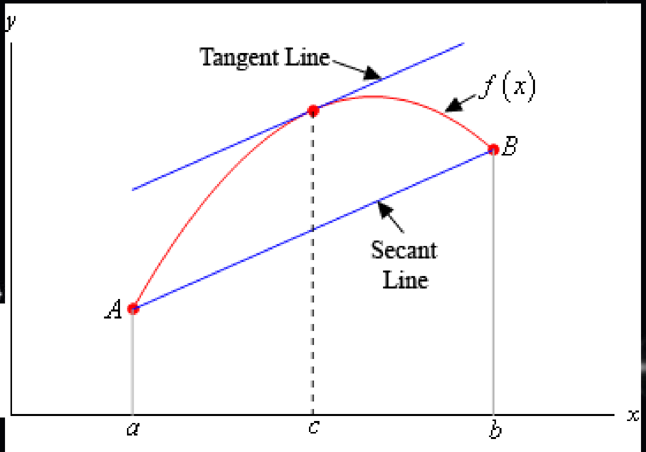
The increase in total mass



$$M_{\rm total} = M_{\rm NM}(M_{\rm DM}) + M_{\rm DM}$$

Total mass of NM and DM

$$M_{\rm NM}(M_{\rm DM}) + M_{\rm DM} = M_{\rm NM}(0)$$



- Total mass equals to initial mass without DM
- This equation always has solution
- Mean-value theorem → local minimum

$$M_{\rm DM} \ggg M_{\rm NM},$$

$$M_{\rm total} \approx M_{\rm DM}$$

- Also true in the GR scenario
- At large DM mass the total mass scales linearly with DM mass

Initial Conditions

- DM – Ideal generate Fermi Gas EOS (c.f. Shapiro et al.)
- Temperature – Isothermal $10^8 K$ (electron conduction)
- Finite temperature stellar EOS Helmholtz
- Initial composition – equal portion of C12 and O16

$$\frac{dp_i}{dr} = -\frac{G\left(m_1(r) + m_2(r)\right)}{r^2}\rho_i$$

$$\frac{dm_i}{dr} = 4\pi r^2 \rho_i$$

- Global stellar parameters such as Masses and Radii

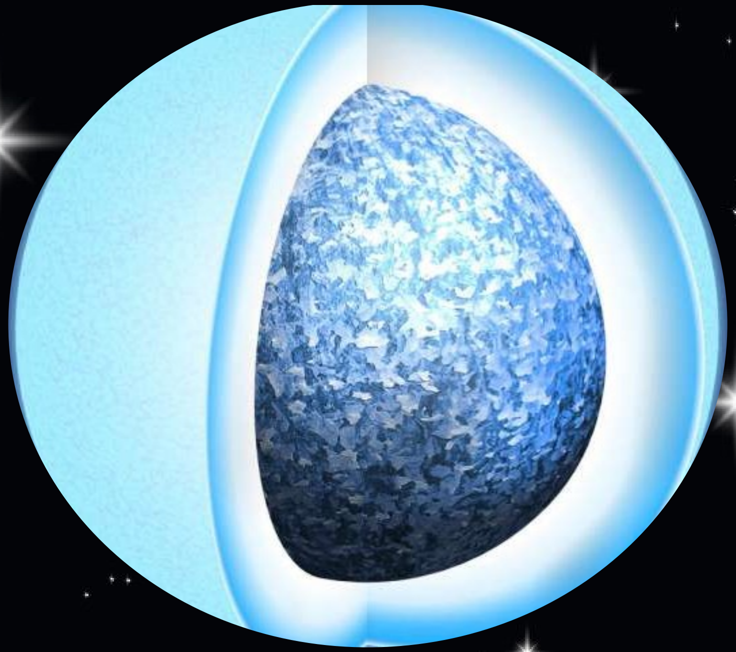


Image credit: phys.org

Exploding a white dwarf!

Deflagration

Image credit: reddit.com

- Propagate sub-sonically
- Through heat transfer process
- Depends on micro-physics
- Release less energy

Detonation

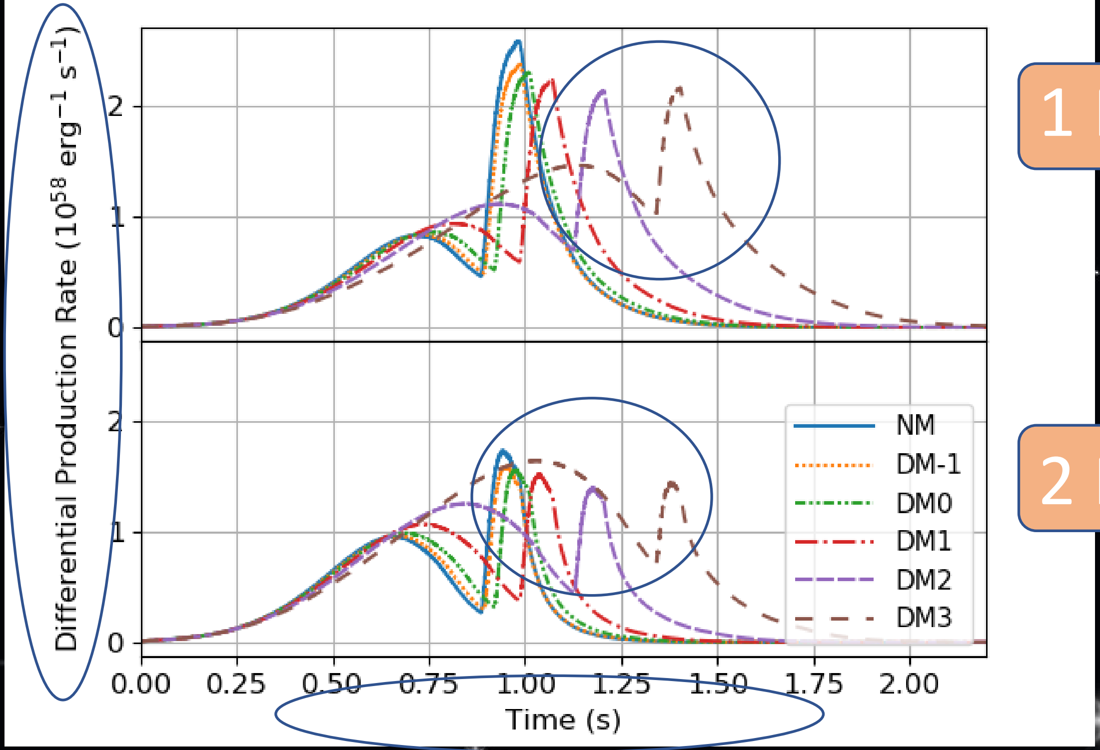
Image credit: CNN

- Propagate super-sonically
- Through generations of shocks
- Depends on hydrodynamics
- Release more energy

Start out as deflagration → detonation

Thermo-neutrinos Production

Neutrino Spectra



1 MeV

2 MeV

- Total production $\sim \int \int f(\epsilon, t) dt d\epsilon$

DM models produce more energetic neutrinos

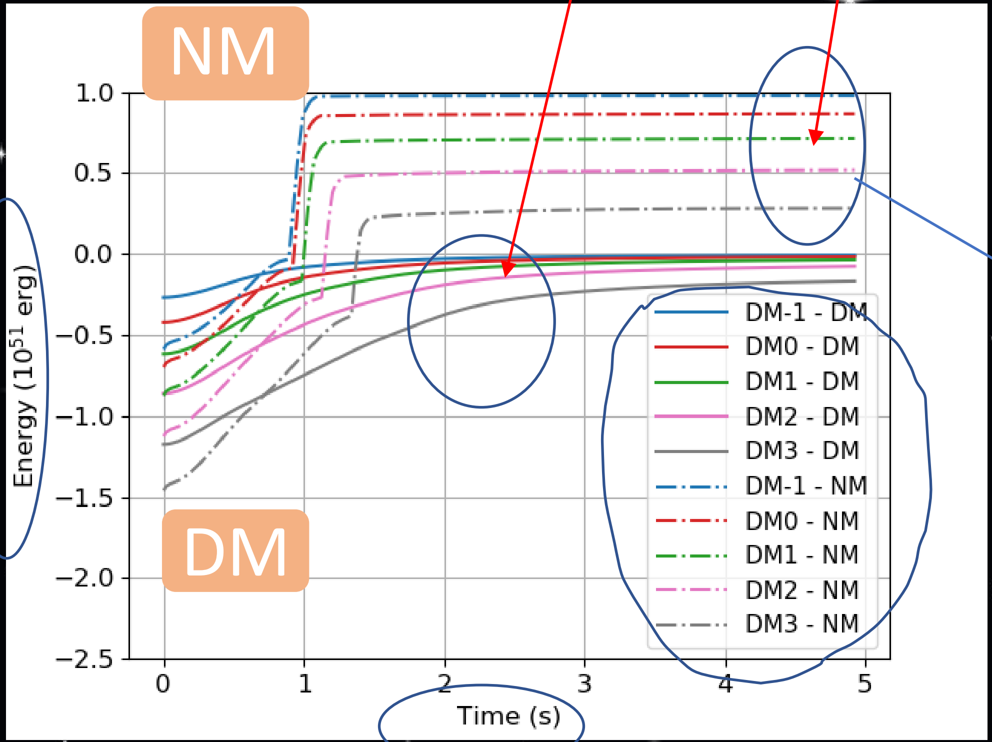
Model	NM	DM-1	DM0	DM1	DM2	DM3
1 MeV (10^{52})	1.232	1.176	1.204	1.316	1.595	2.191
2 MeV (10^{52})	1.944	1.911	1.993	2.253	2.875	4.303
3 MeV (10^{52})	1.264	1.265	1.329	1.521	1.981	3.076
4 MeV (10^{52})	0.605	0.612	0.643	0.737	0.959	1.505
5 MeV (10^{52})	0.249	0.254	0.266	0.302	0.389	0.607
Total (10^{52})	5.294	5.218	5.434	6.129	7.800	11.682
Ratio	1.000	0.986	1.027	1.158	1.473	2.207

- Hot and dense environment favors thermo-neutrino production

Individual Energy At The End of Simulation

Model	NM	DM-1	DM0	DM1	DM2	DM3
NM Energy (10^{51} erg)	1.512	0.977	0.865	0.713	0.517	0.281
DM Energy (10^{50} erg)	-	−0.091	−0.178	−0.355	−0.758	−1.680

- Kinetic + thermal + gravitational



- NM energy is positive at the end
- DM energy is negative at the end (bound)

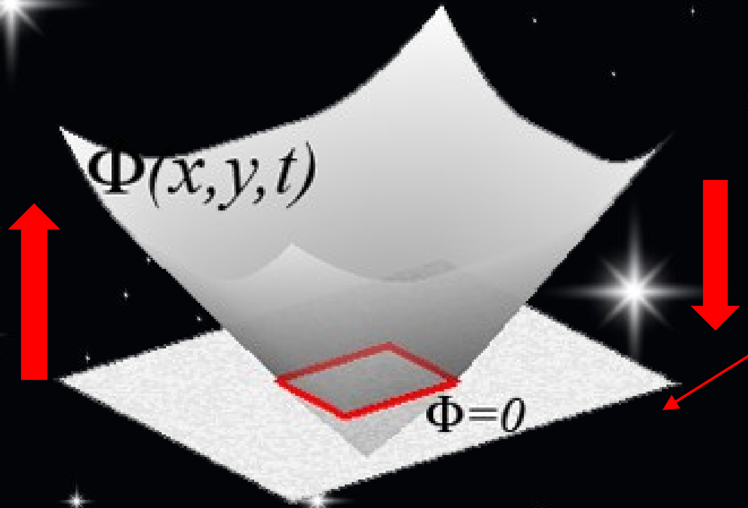
- Asymptotically flat – decoupled

- Different time scales! (free-fall vs explosion)
- Energy transfer through gravity is inefficient

Level-set method as a flame capturing method

- The surface is the zeroth level – set of a scalar field Φ

Motion of surface governed by motion of Φ



The zeroth level - set

Image credit: profs.etsmtl.ca

- In a mathematical way…

$$\{\vec{x}(t) | \Phi(\vec{x}(t), t) = 0\}$$