

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

2021

Tea-Talk

Image credit: livescience.com

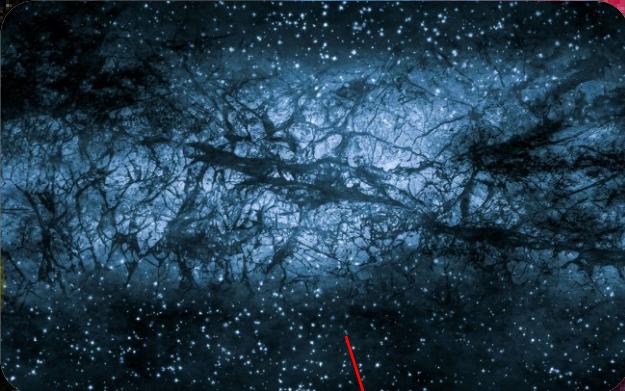
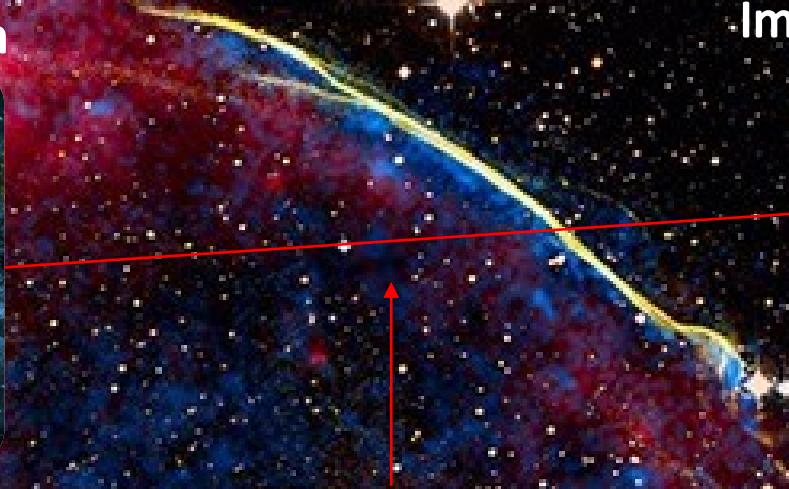


Image credit: forbes.com



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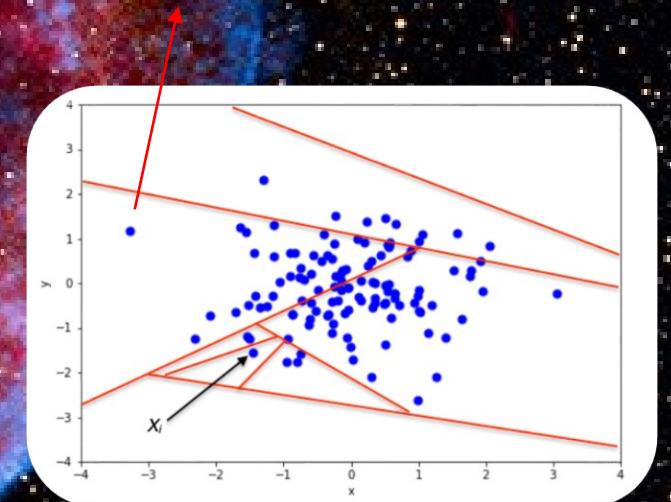


Image credit: wikipedia.com

Self-Introduction



Dr. S-C. Leung



CUHK - Physics
2nd Year M.Phil. Student



Prof. M-C. Chu



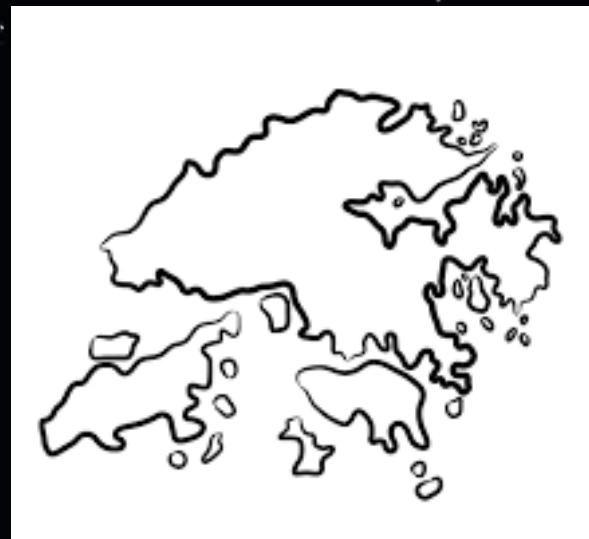
Dr. L-M. Lin



Mentor

Me

Supervisors



Introduction And Motivation

Dark Matter Astronomy

Image credit: astrobites.org

Image credit: Rubin et al. 1970

Non-Visible Matter?

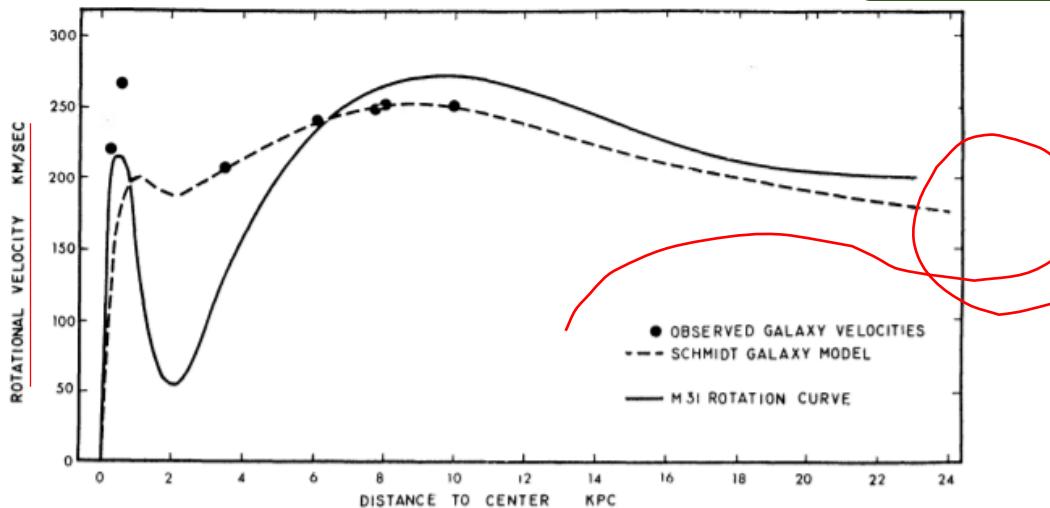
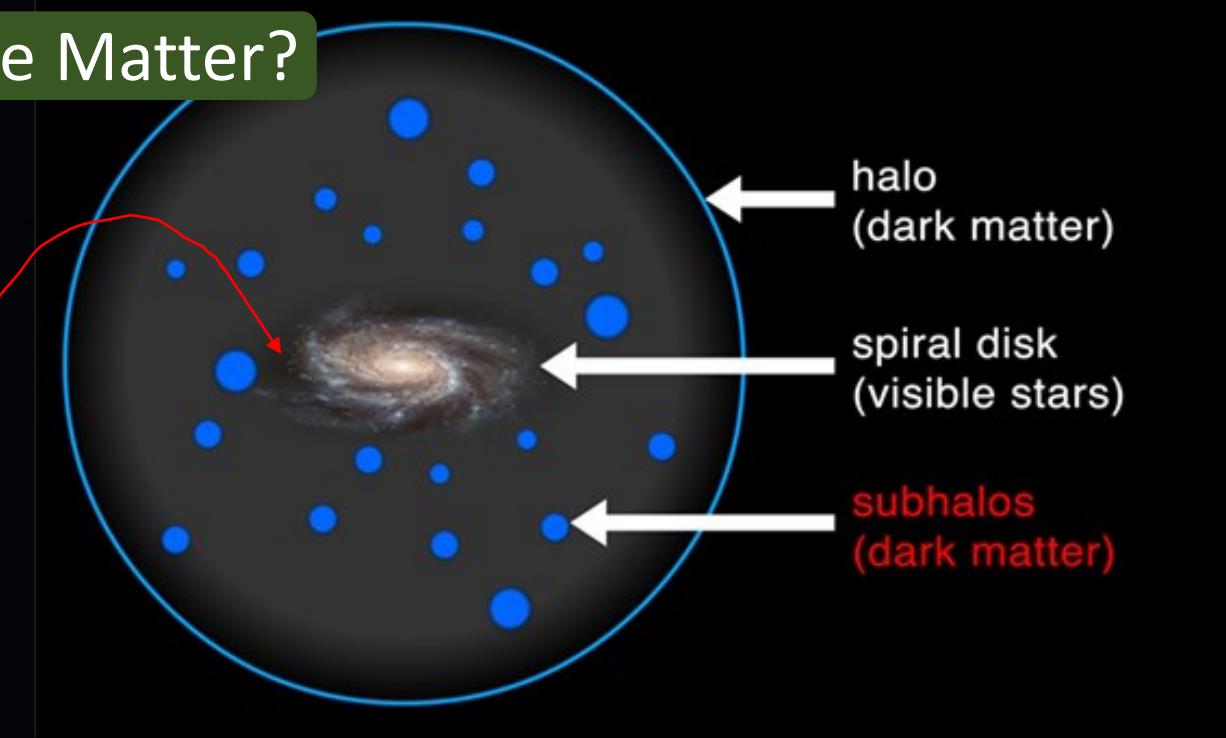


FIG. 15.—Comparison of rotation curves for M31 and the Galaxy, as a function of distance from the center. Solid line, rotation curve for M31 (Fig. 9); dashed line, rotation curve from Schmidt model of the Galaxy. Filled circles, observed rotational velocities for the Galaxy (Rougoor and Oort 1960; Schmidt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

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



- 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,*}

^aDépartement AGO-IFPA, Université de Liège, 4000 Belgium

^bEISLAB, Luleå Tekniska Universitet, 971 87 Luleå, Sweden

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

Come back to this
later

Image credit: Leung et al. 2013

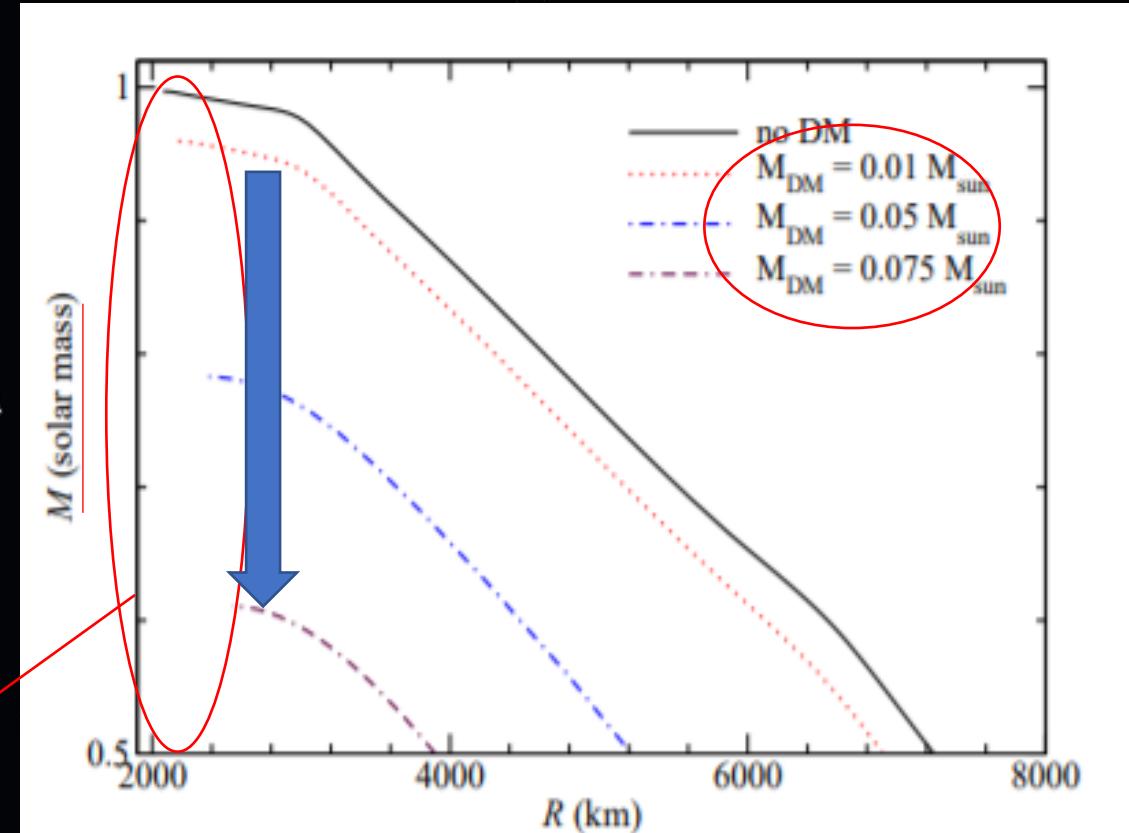


FIG. 3: Same as Fig. 1, but for $m_{DM} = 1$ GeV.

Dark Matter Admixed Type Ia Supernovae

Image credit: astronomy.swin.edu.au

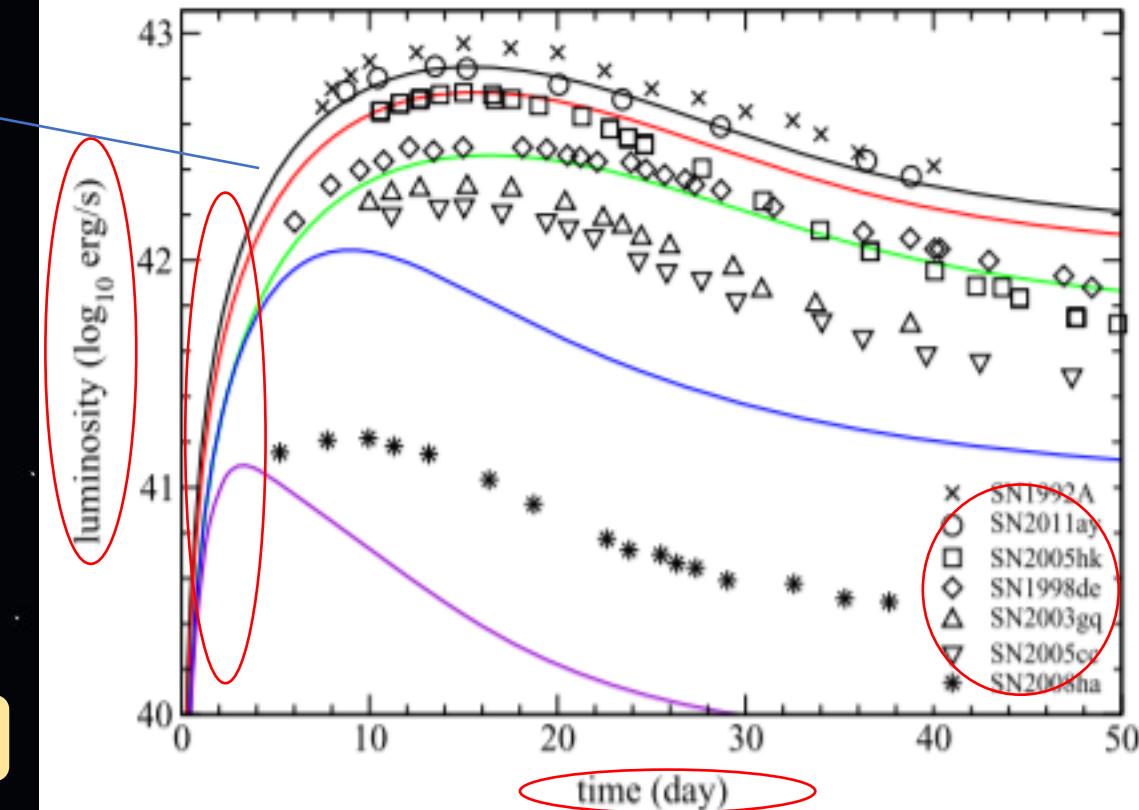


Bright Transient

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

Bolometric

Image credit: Leung et al. 2015



What if we alter these assumptions?

- Assumptions:

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

Methodology

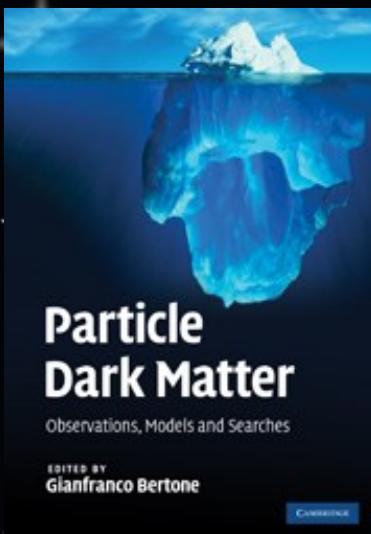
Hydro-Static Equilibrium Structures

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

$$\frac{dp_i}{dr} = -\frac{G(m_1(r) + m_2(r))}{r^2} \rho_i$$
$$\frac{dm_i}{dr} = 4\pi r^2 \rho_i$$

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 $\sim 10 \text{ GeV}$ → Point gravitational source
- Representative mass $\sim 0.1 \text{ GeV}$ → Generalise light DM particles

Some Examples

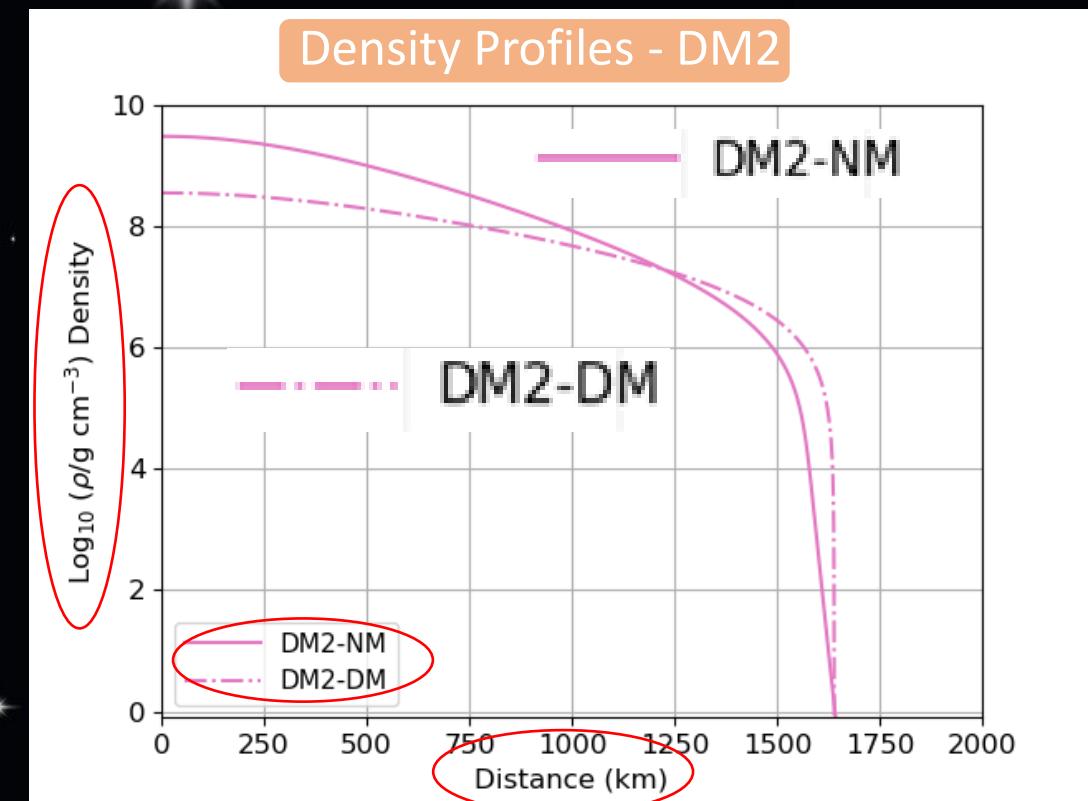
Progenitors

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!



Image credit: Chapman



Model The Explosion

- One-dimensional, finite volume version of
- Eulerian grid-based hydro-code
- 5th Order reconstruction method
- Two-fluids motion coupled through gravity
- Contains 7 major isotope:
 - He4, C12, O16, Ne20, Mg24, Si28, Ni56
- Simulation duration – 5s



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

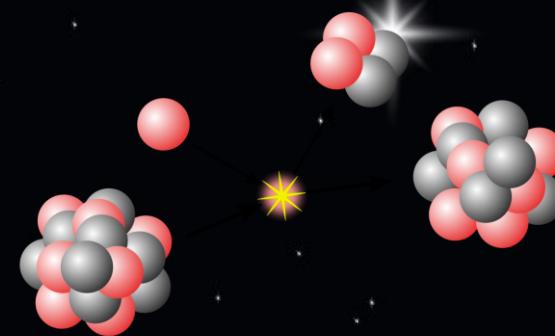
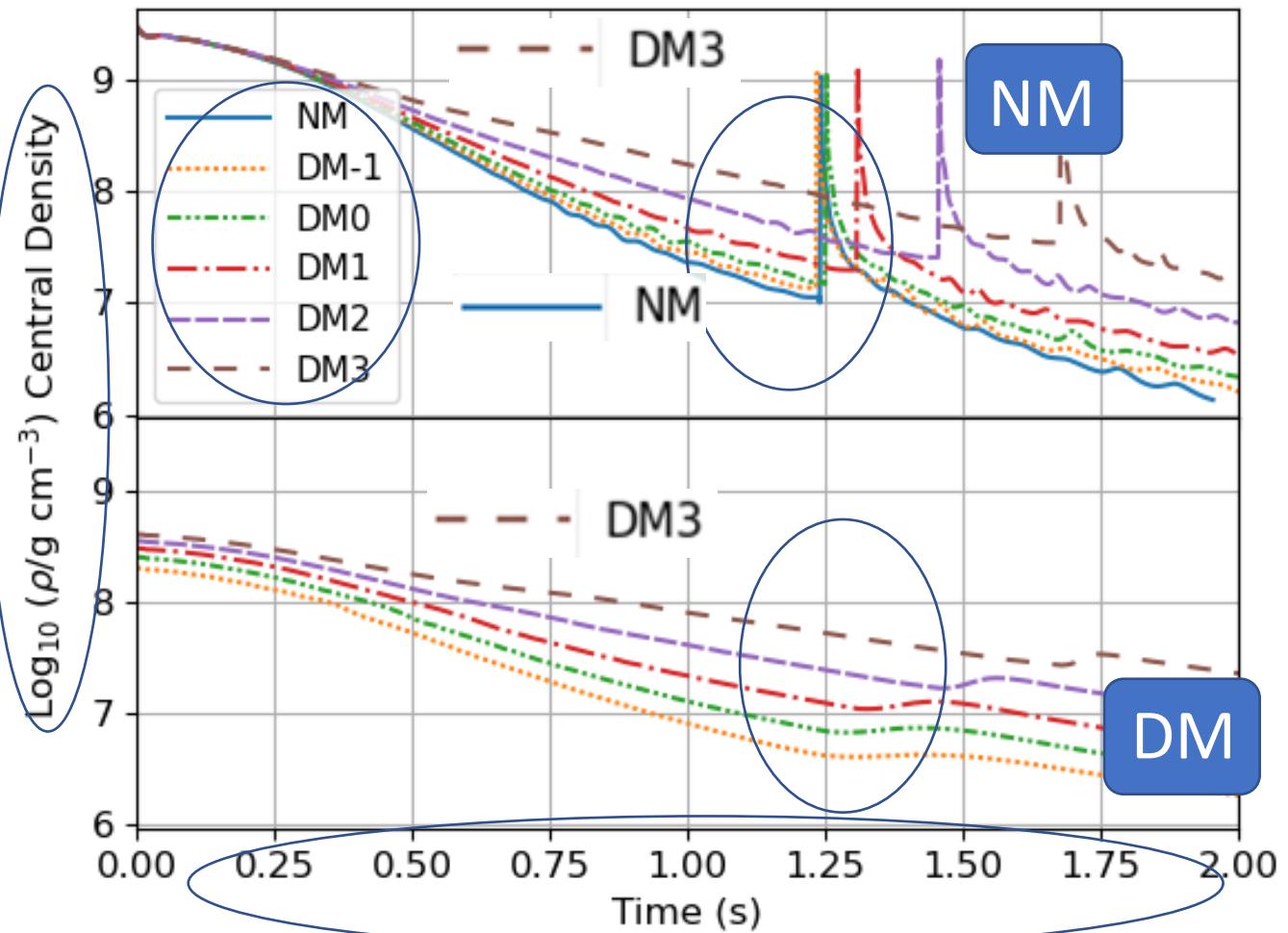


Image credit: Wikipedia.com

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
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Results And Discussions

Global Hydrodynamic Quantities



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

Model	NM	DM-1	DM0	DM1	DM2	DM3	DM3
$\text{NM } \rho_c (10^9 \text{ g cm}^{-3})$	3.0	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	

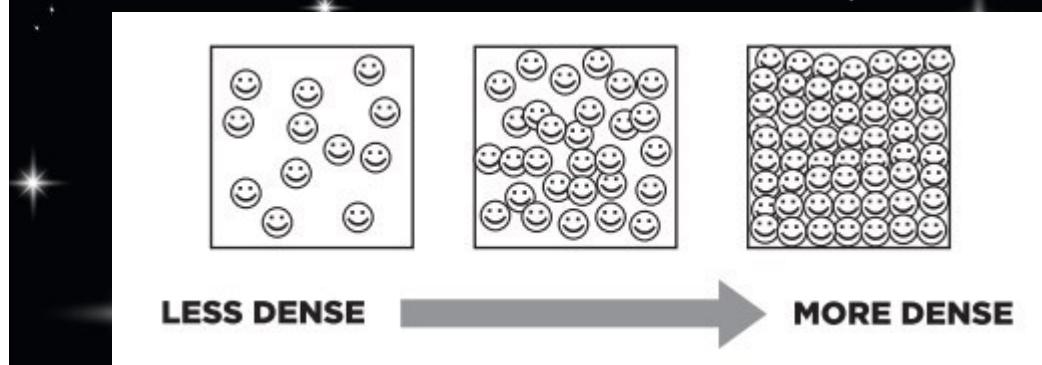
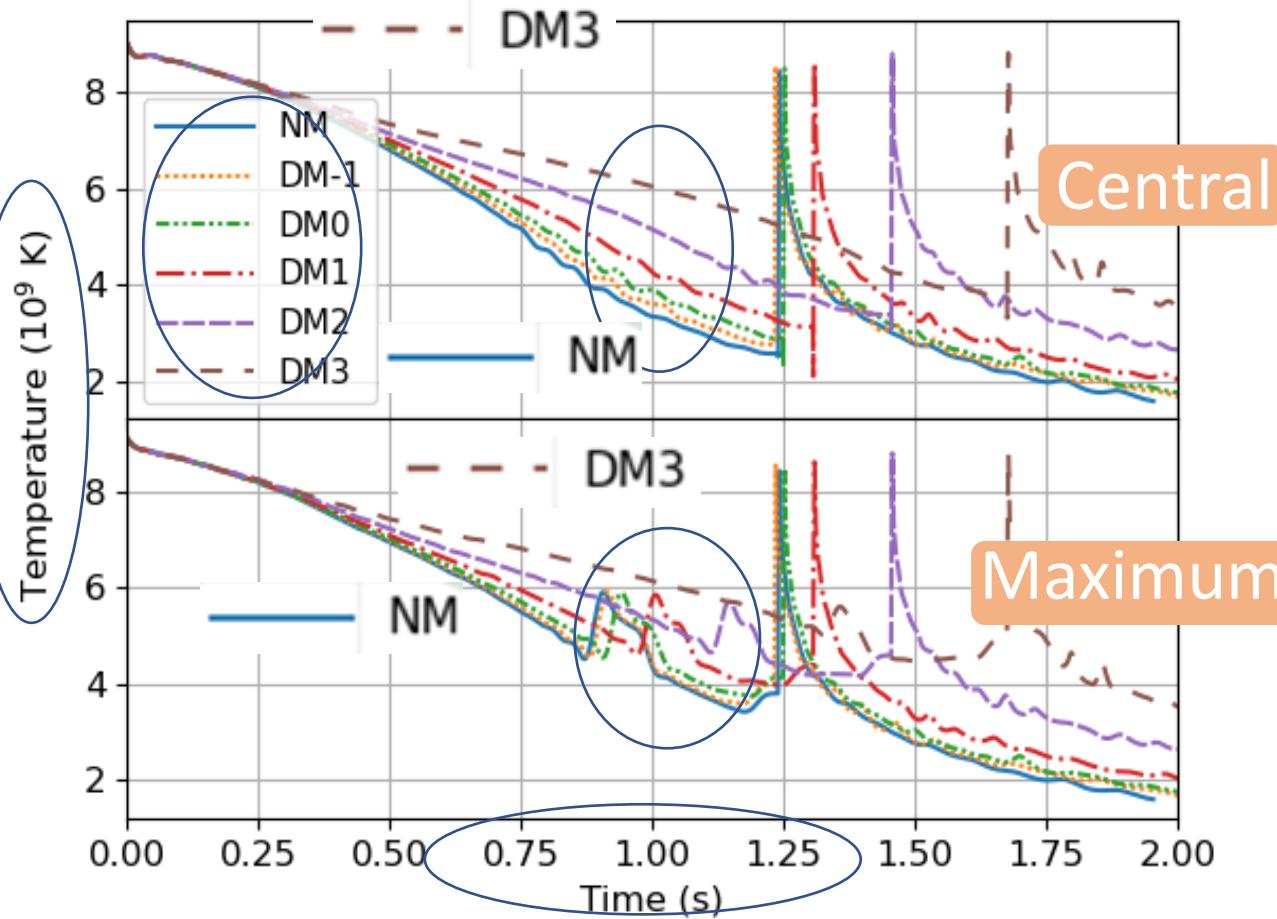


Image credit: scienceworld.ca

Global Hydrodynamic Quantities

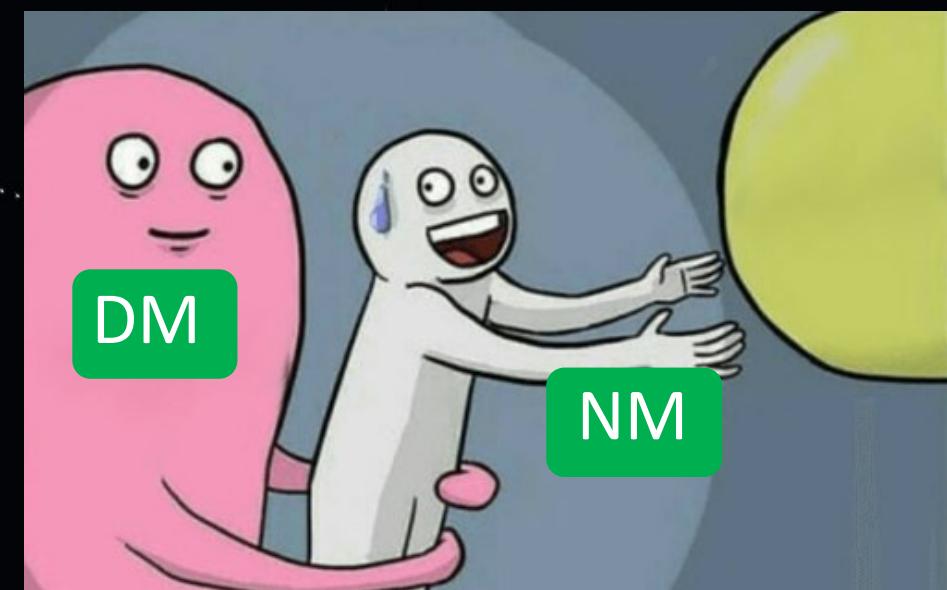
- DM gravitational force **prohibit** the expansion of NM

NM Temperature



- More DM:
- NM **is hotter**

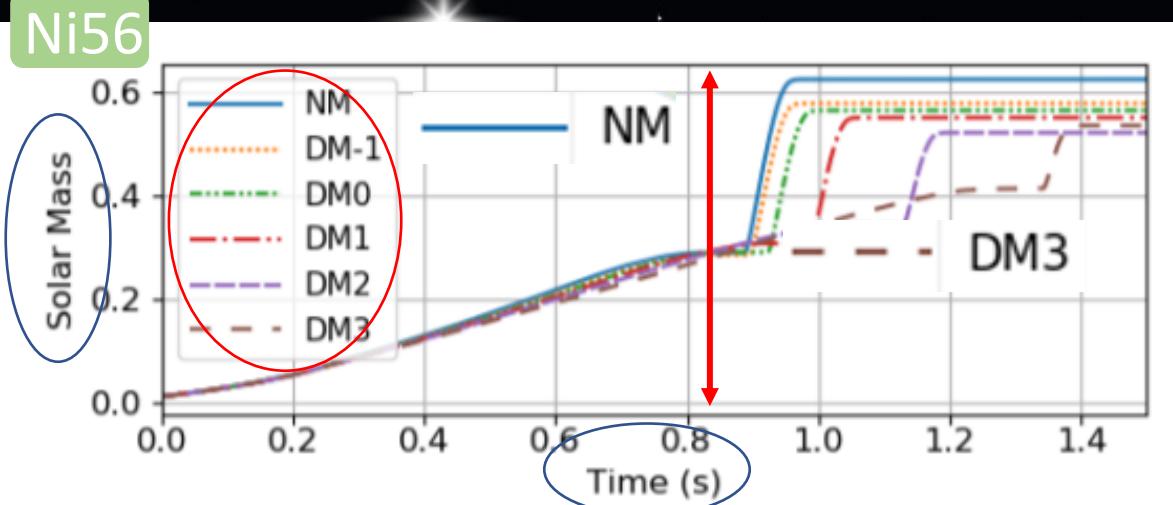
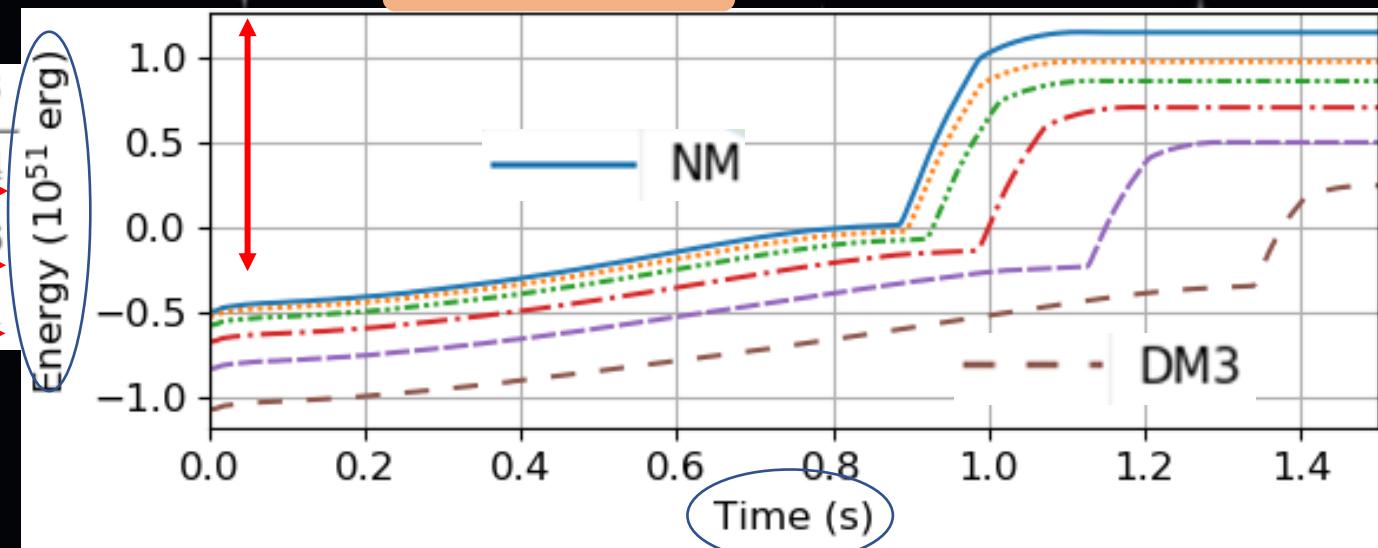
Model	NM	DM-1	DM0	DM1	DM2	DM3
$NM \rho_c (10^9 \text{ g cm}^{-3})$	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass (M_\odot)	-	0.067	0.120	0.201	0.322	0.494
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Ni56 And Energy Production

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

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



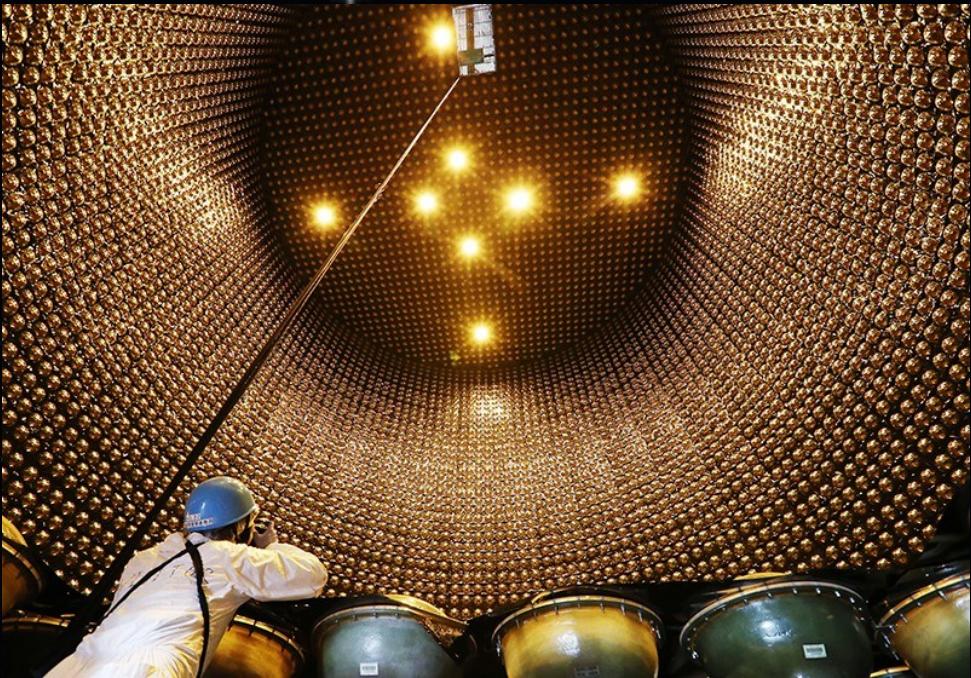
Model	NM	DM-1	DM0	DM1	DM2	DM3
$\text{NM } \rho_c$ (10^9 g cm $^{-3}$)	3.0	3.0	3.0	3.0	3.0	3.0
DM Mass (M_{\odot})	-	0.067	0.120	0.201	0.322	0.494
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Important Consequences on Light Curves

Supernova Observables

Supernova Neutrinos

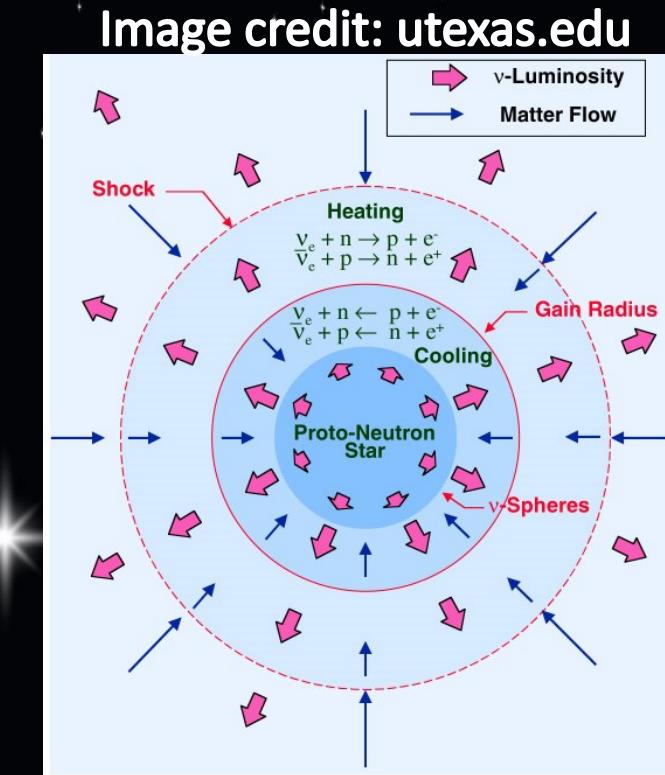
Image credit: nature.com



Super Kamiokande, Japan

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

Detect



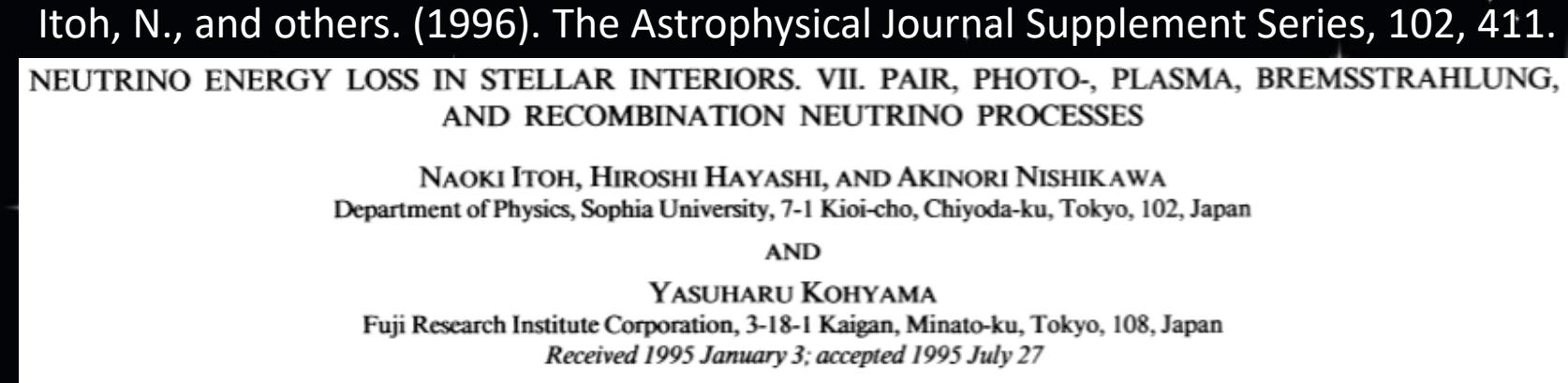
Core-Collapse Supernovae

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



- Thermal emission of neutrinos

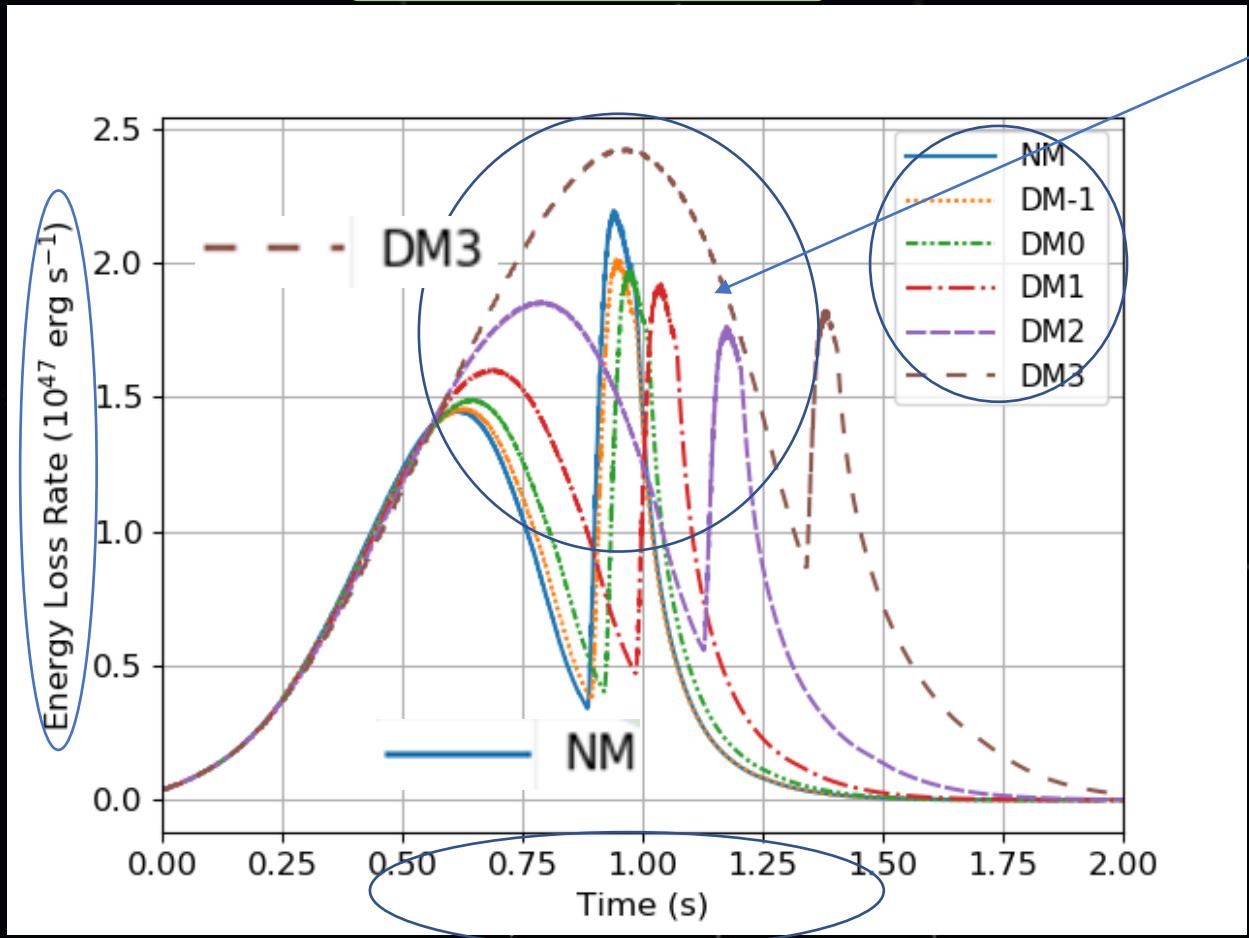
1. Pair-Production
2. Photoneutrino
3. Plasmon neutrino
4. Bremsstrahlung
5. Recombination



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
Model	NM	DM-1	DM0	DM1	DM2	DM3
$\text{NM } \rho_c (10^9 \text{ g cm}^{-3})$	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, Memphis	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

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

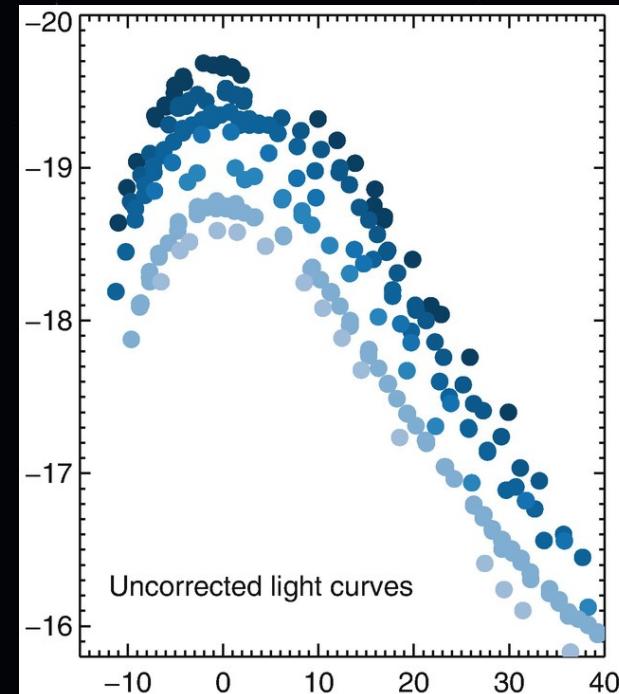
SNEC Code

- Input
- Density, Mass, Velocity of the NM

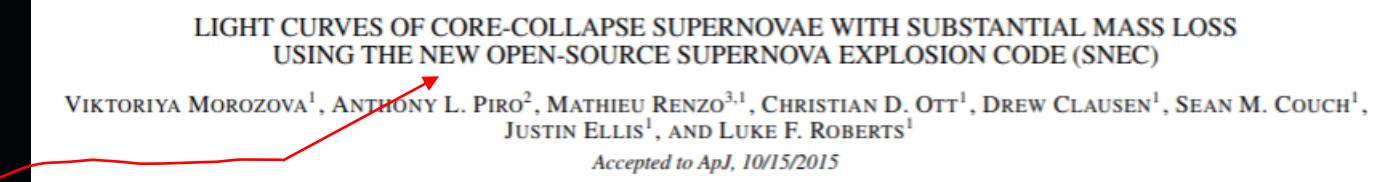
- Isotopes:

- He4, C12, O16, Ne20, Mg24, Si28, **Ni56**

Image credit: Handbook of Supernovae



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



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

Image credit: symmetrymagazine.org



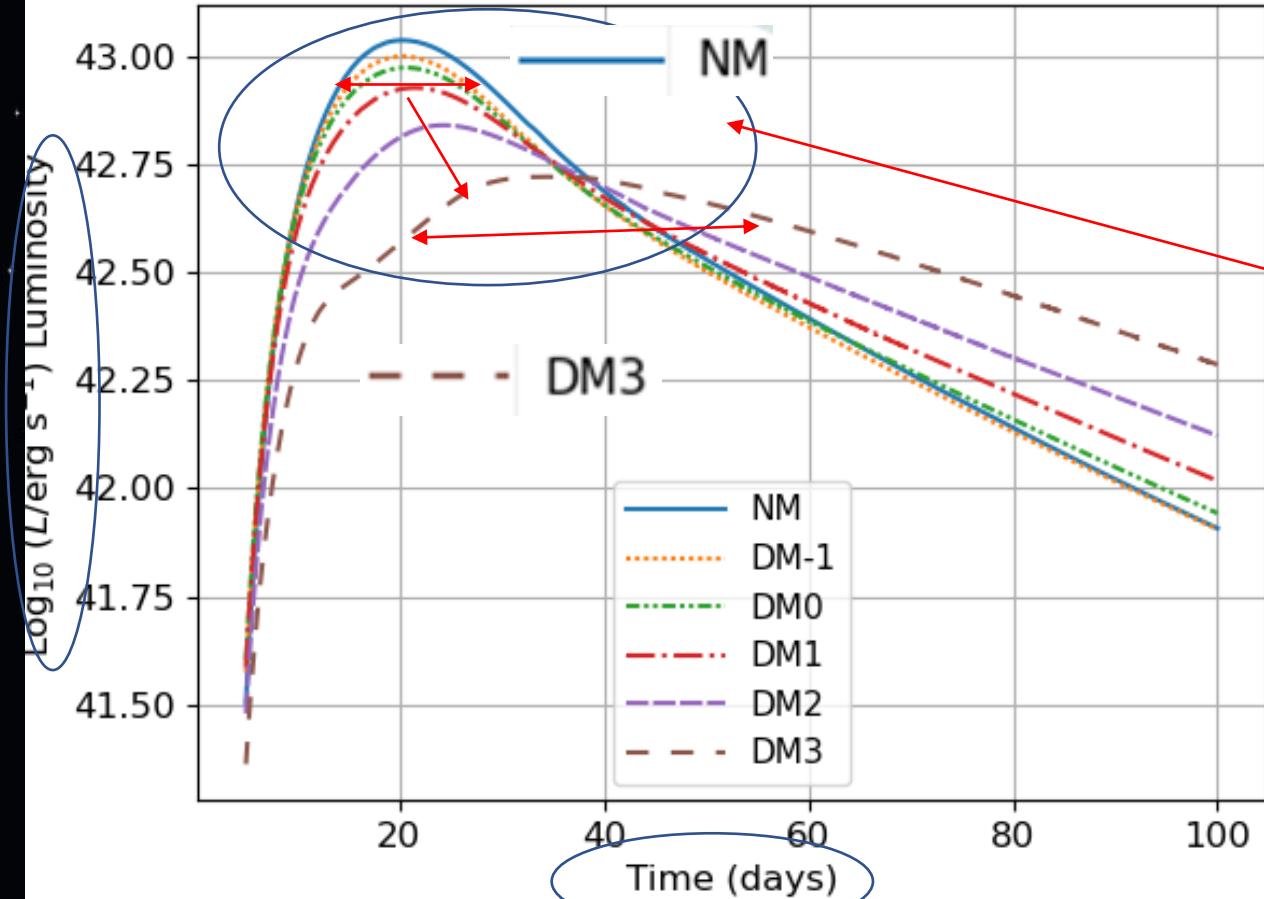
- DM is much smaller in size than NM
- DM act as monopole gravity source

$$g_{DM} = -\frac{GM}{r^2}$$

LSST

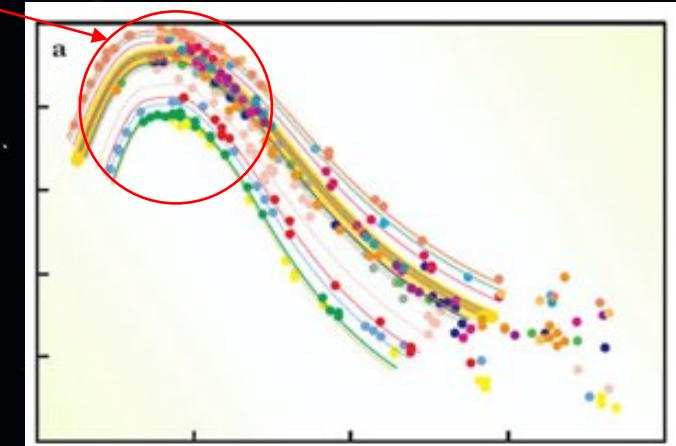
Supernova Light Curves

Bolometric Luminosity



Model	NM	DM-1	DM0	DM1	DM2	DM3
$\text{NM } \rho_c (10^9 \text{ g cm}^{-3})$	3.0	3.0	3.0	3.0	3.0	3.0
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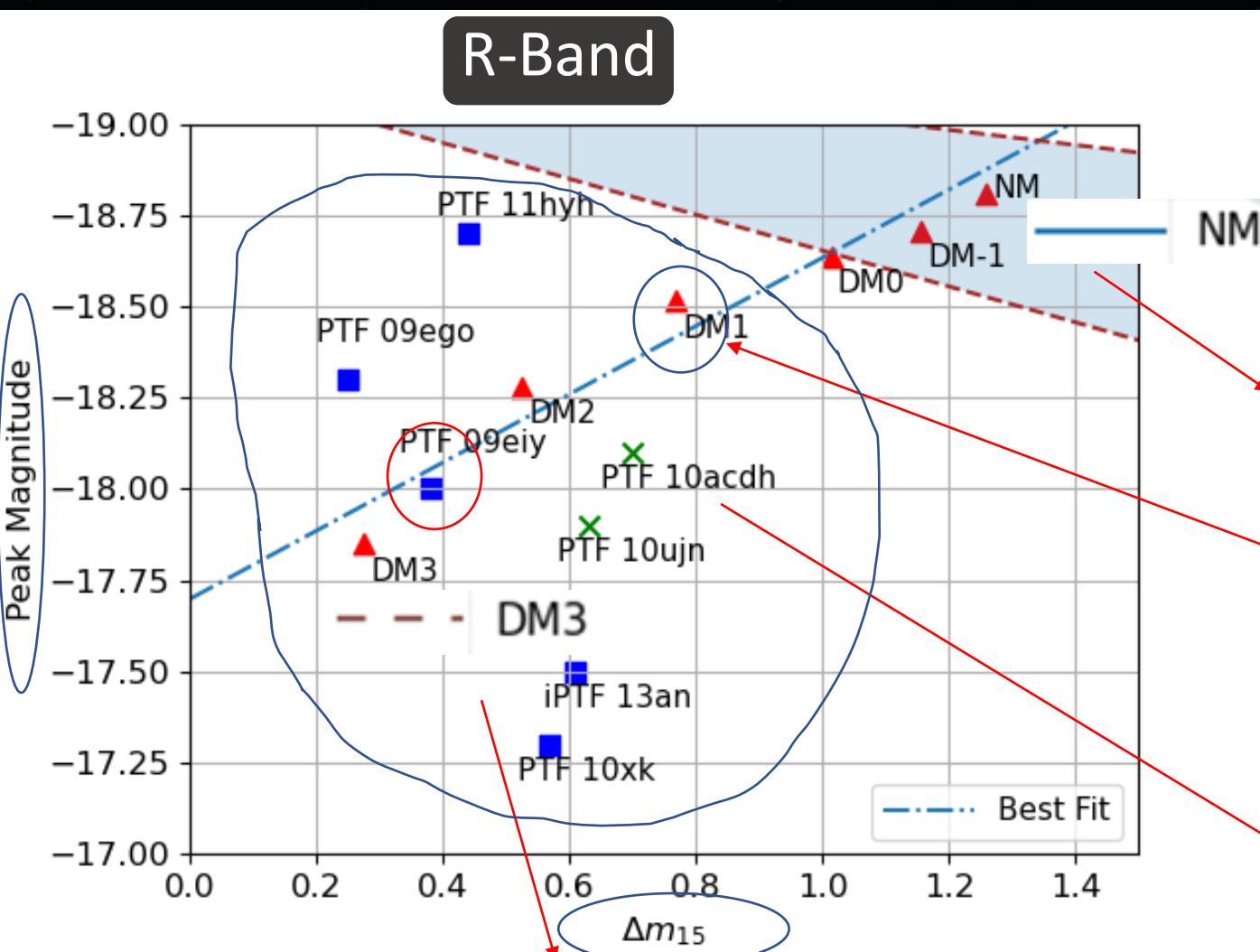
- More DM:
- Dimmer light curves
- Broader light curves
- Go against the usual Phillips relation ... ?



Even complex realistic models do not reproduce the Phillips relation

What can be inferred from our results?

Supernova Light Curves



Model	NM	DM-1	DM0	DM1	DM2	DM3
$NM \rho_c (10^9 \text{ g cm}^{-3})$	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
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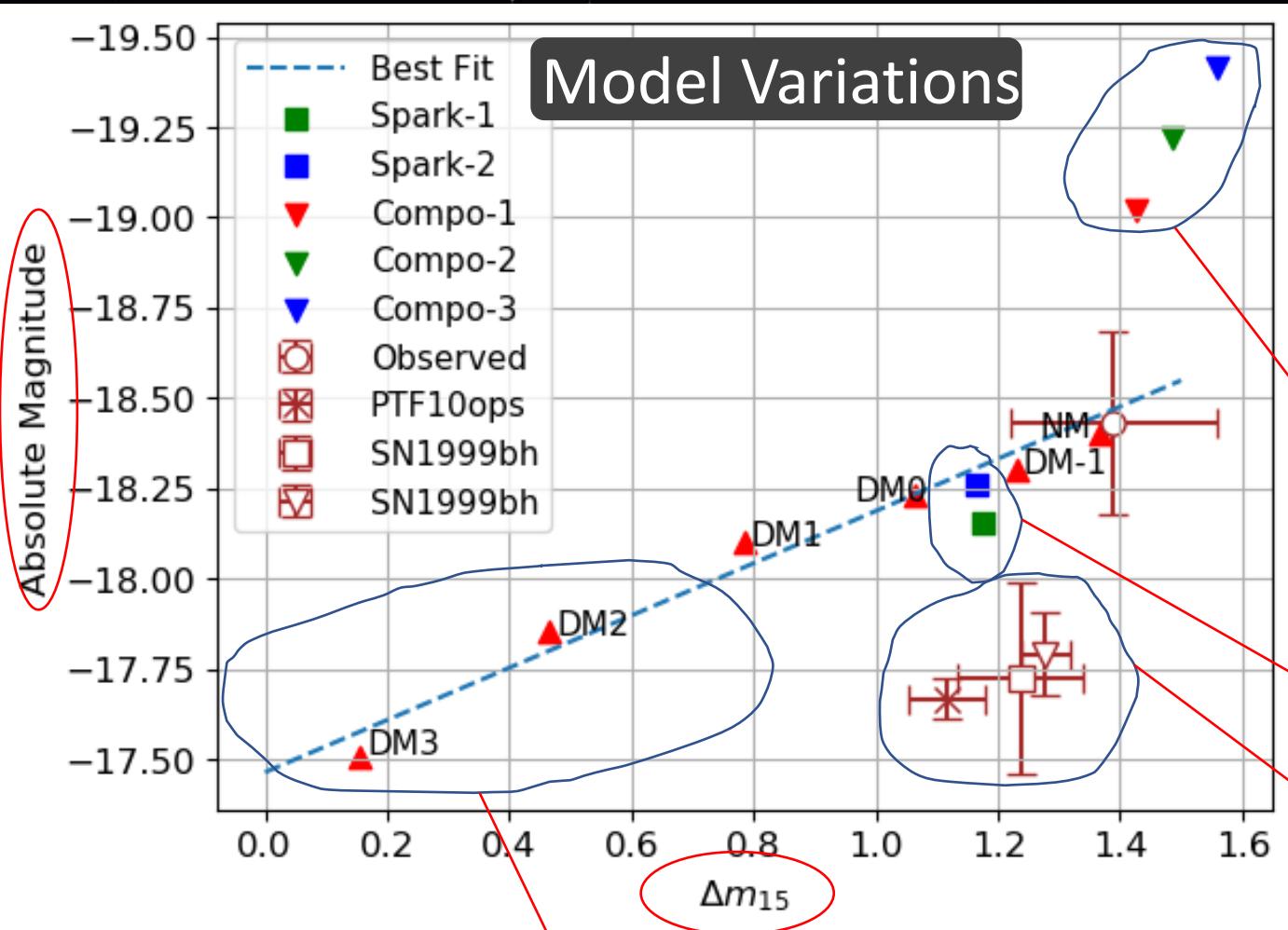
- Observed R-Band Phillips relation
- Best-fit line for all DM models

Peculiar supernovae detected by PTF

Slightly Dimmer

Slowly Declining

Supernova Light Curves



Model	NM	NM	DM-1	DM0	DM1	DM2	DM3
$NM \rho_c (10^9 \text{ g cm}^{-3})$	3.0	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	

- Model variations → deviations from the Phillips relation
- Only DM models located at the **low m** and **small Δm_{15}** space?
- Varying initial WD compositions
- Varying explosion conditions
- Explained by other explosion mechanisms

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



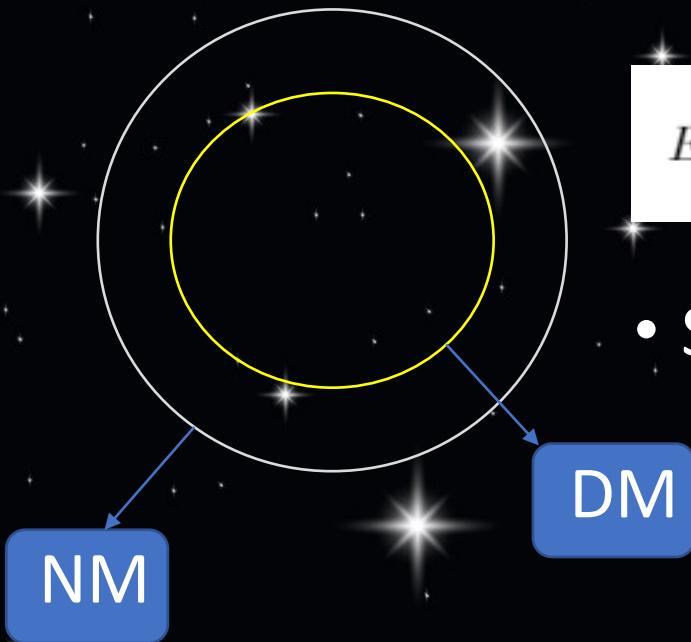
Appendix

Admixing Solar Mass Scale DM

- Inherit a DM component during the star is formed

- Total energy (DM + NM)

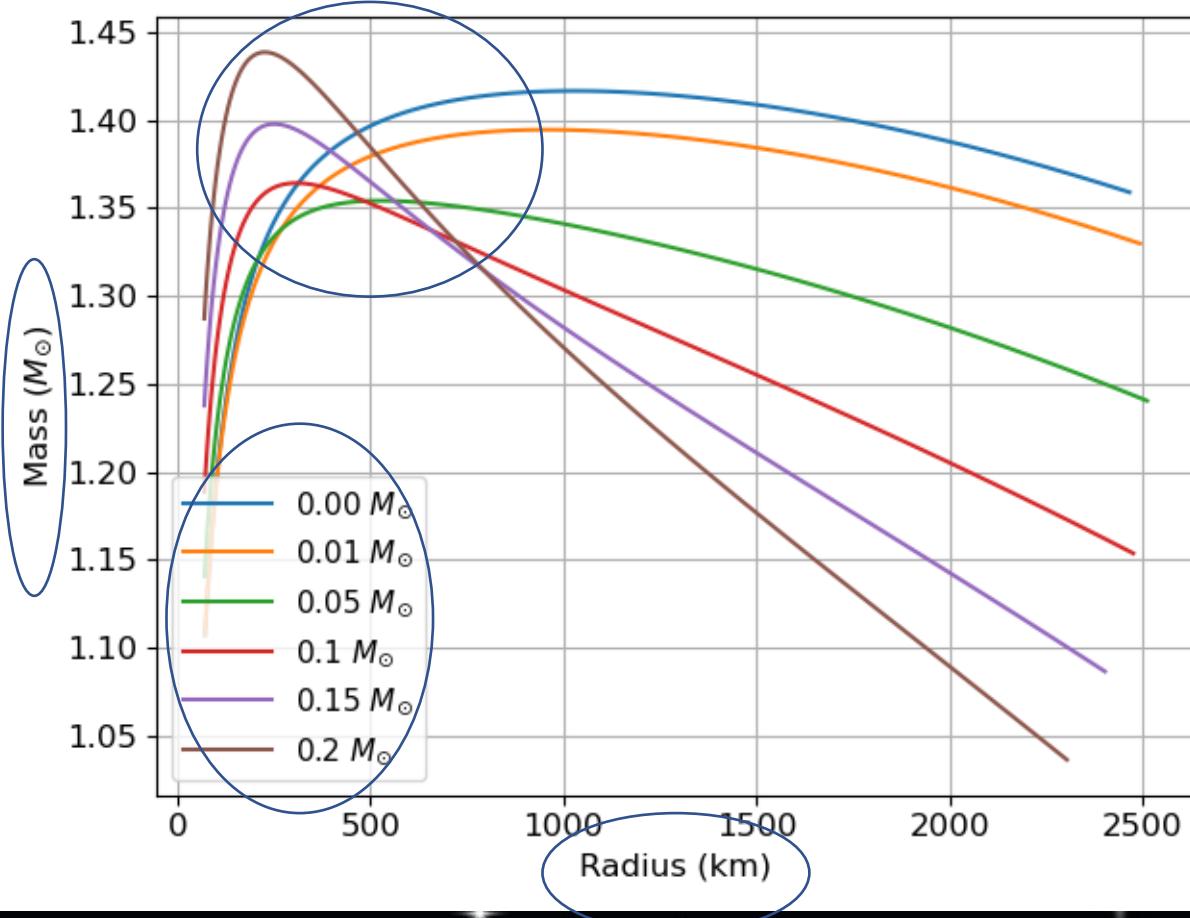
$$E = -\left(\frac{3}{5}\frac{GM_1^2}{R_1} + \frac{3}{5}\frac{GM_2^2}{R_2} + \frac{3}{2}\frac{GM_1M_2}{R_1} - \frac{3}{10}\frac{GM_1^2R_1^2}{R_1^3}\right) + \frac{3}{2}NkT + \frac{1}{2}M_1v_1^2.$$



- Solve for DM radius R_1 and density ρ_1

- Particular solution: $(1.71 \times 10^8 \text{ cm}, 3860 \text{ GeV/cm}^3)$
 - Large but possible

The increase in total mass

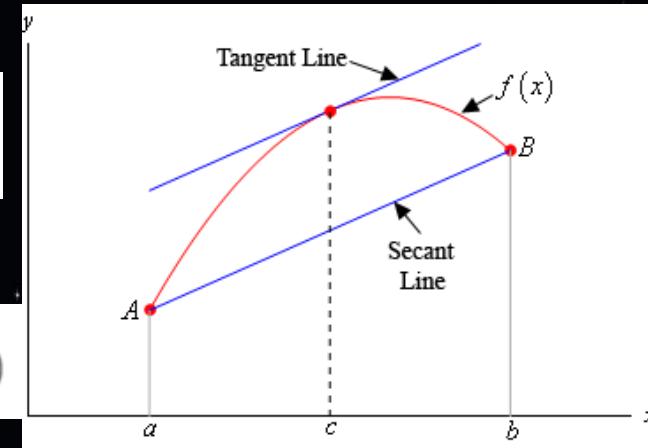


- Also true in the GR scenario

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

Total mass of NM and DM

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



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

$$M_{\text{DM}} \gg M_{\text{NM}},$$

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

- 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

$$\frac{dp_i}{dr} = -\frac{G(m_1(r) + m_2(r))}{r^2} \rho_i$$
$$\frac{dm_i}{dr} = 4\pi r^2 \rho_i$$

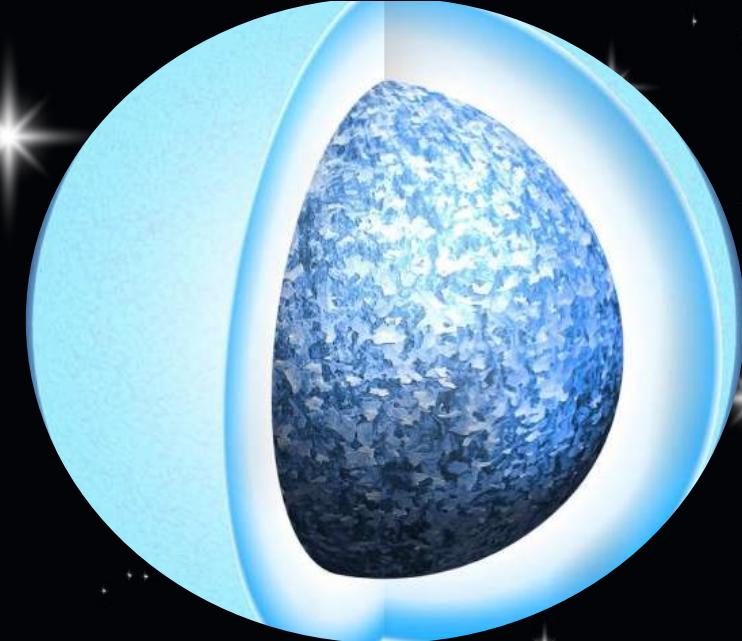


Image credit: phys.org

- Global stellar parameters such as Masses and Radii

Exploding a white dwarf!

Deflagration



Image credit: reddit.com

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

Detonation



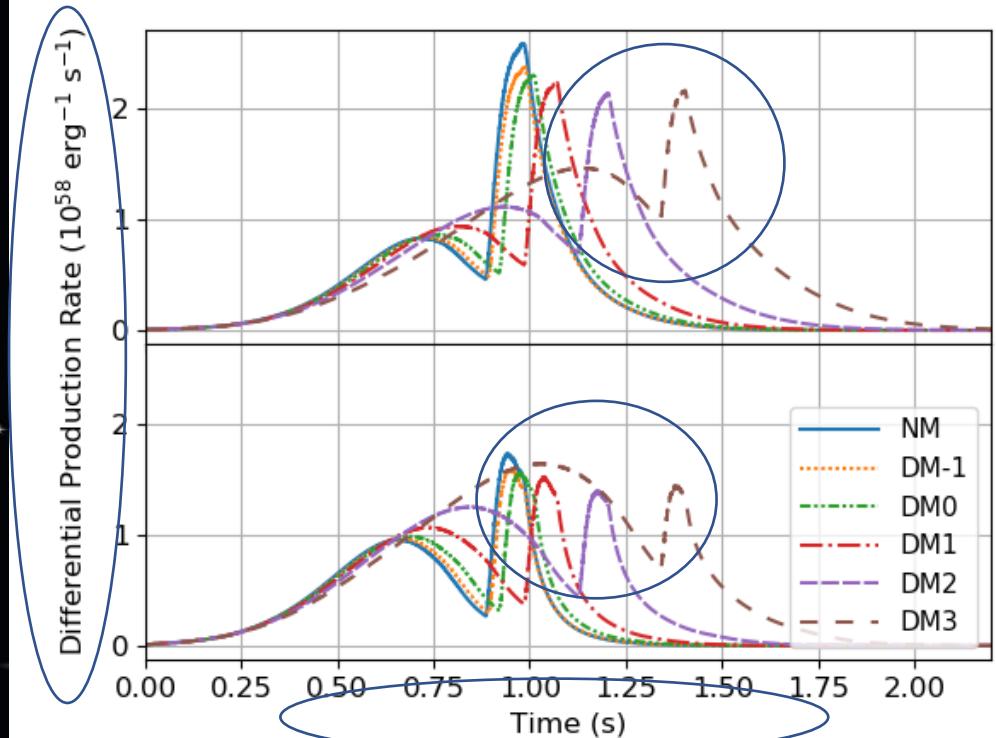
Image credit: CNN

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

Start out as deflagration → detonation

Thermo-neutrinos Production

Neutrino Spectra



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

1 MeV

DM models produce more energetic neutrinos

2 MeV

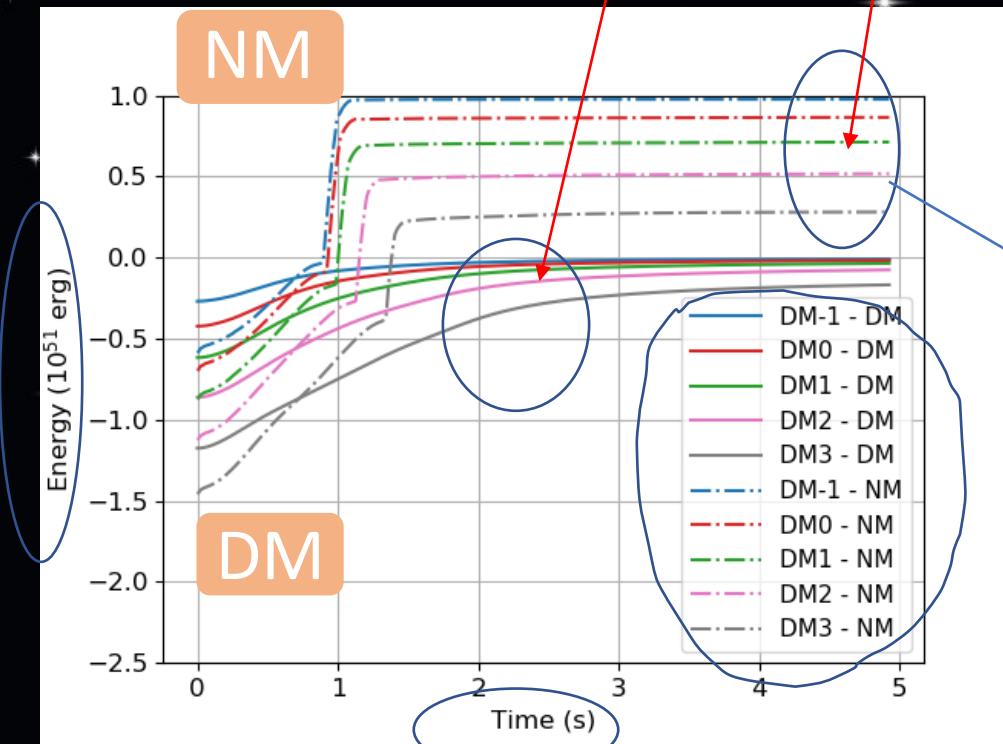
Model	NM	DM-1	DM0	DM1	DM2	DM3
1 MeV (10^{52})	1.232	1.176	1.204	1.316	1.595	2.191
2 MeV (10^{52})	1.944	1.911	1.993	2.253	2.875	4.303
3 MeV (10^{52})	1.264	1.265	1.329	1.521	1.981	3.076
4 MeV (10^{52})	0.605	0.612	0.643	0.737	0.959	1.505
5 MeV (10^{52})	0.249	0.254	0.266	0.302	0.389	0.607
Total (10^{52})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

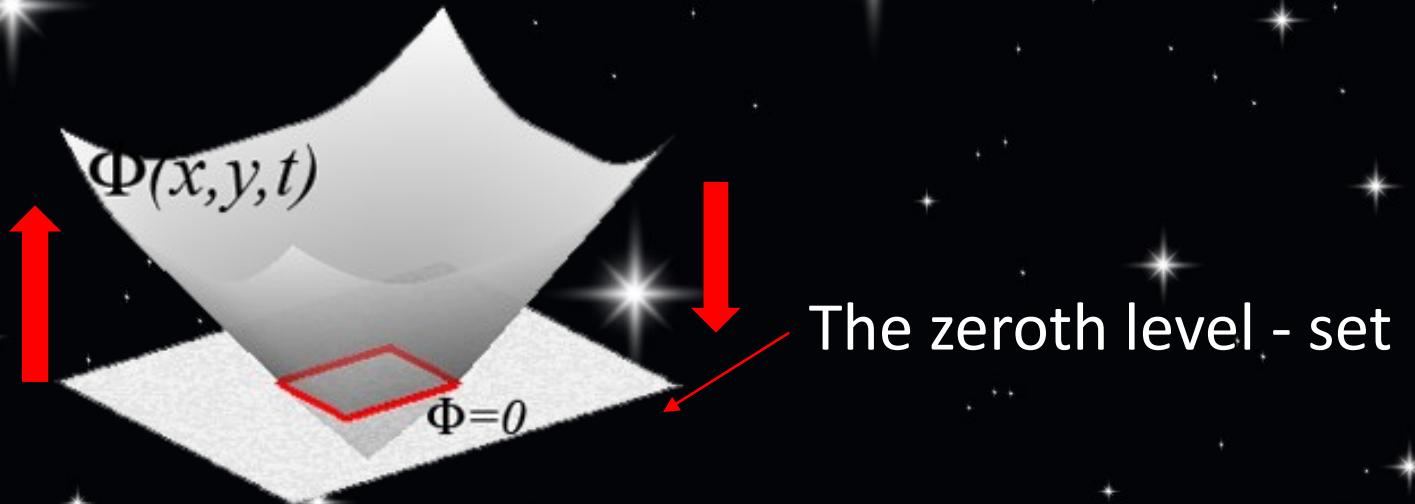


Image credit: profs.etsmtl.ca

- In a mathematical way...

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