Dark Matter-Admixed White Dwarfs and their Thermonuclear Explosions – Alternative Probe to Astronomical Dark Matter

Physics Student Conference

21.9.2019

We are only small part of the universe….

Are the visible object represent all of the universe?

Could something not been seen yet plays a role in the universe?

We can find a way to observe them!

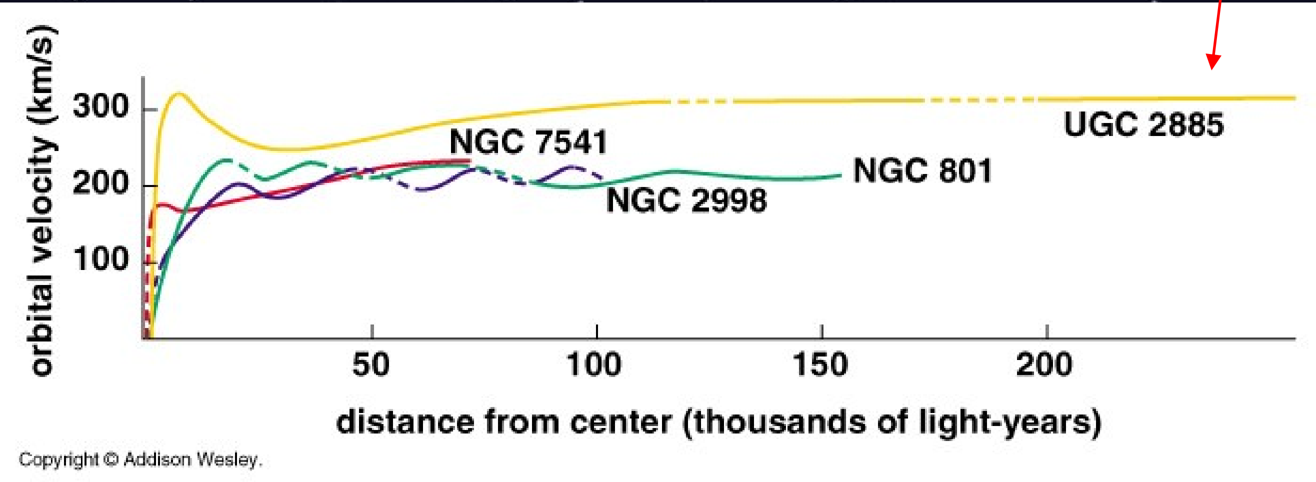
Hubble Deep Field Picture From

https://www.spacetelescope.org

The Dark Matter Problem

- Rotational velocity curves of galaxies shows asymptotically flatness
- Extended well beyond the visible region
- Maybe some “Dark” Matter (DM) exist?

Typical Galaxies Rotational Velocity Curve
Taken From https://www.arizona.edu/



Such DM could be accreted by stars

How would they affect the stars?

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Outline Of Our Presentation

- Introduction and motivation – DM as the unseen of the universe
- Equilibrium structure of dark matter admixed white dwarf
- Thermonuclear explosions of dark matter admixed white dwarf
- Seeing in the future – Improvements on current explosions model
- An overall summary

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Equilibrium Structure Of Dark Matter Admixed White Dwarf

The white dwarf concept picture taken from https://www.theverge.com

Previous Literature Results

- Assumed spin $\frac{1}{2}$ ideal fermi gas DM
- DM particle mass over $1GeV/c^2$
- Spherical Symmetric white Dwarfs/Neutron Star

DM Admixed White Dwarfs (DMAWD)

- DM core surrounded by normal matter (NM)
- ???

DM Admixed Neutron Stars (DANS)

- DM core surrounded by NM or vice versa
- Comparable DM And NM Mass And Radius

What would happen if lighter DM accreted into White Dwarf?

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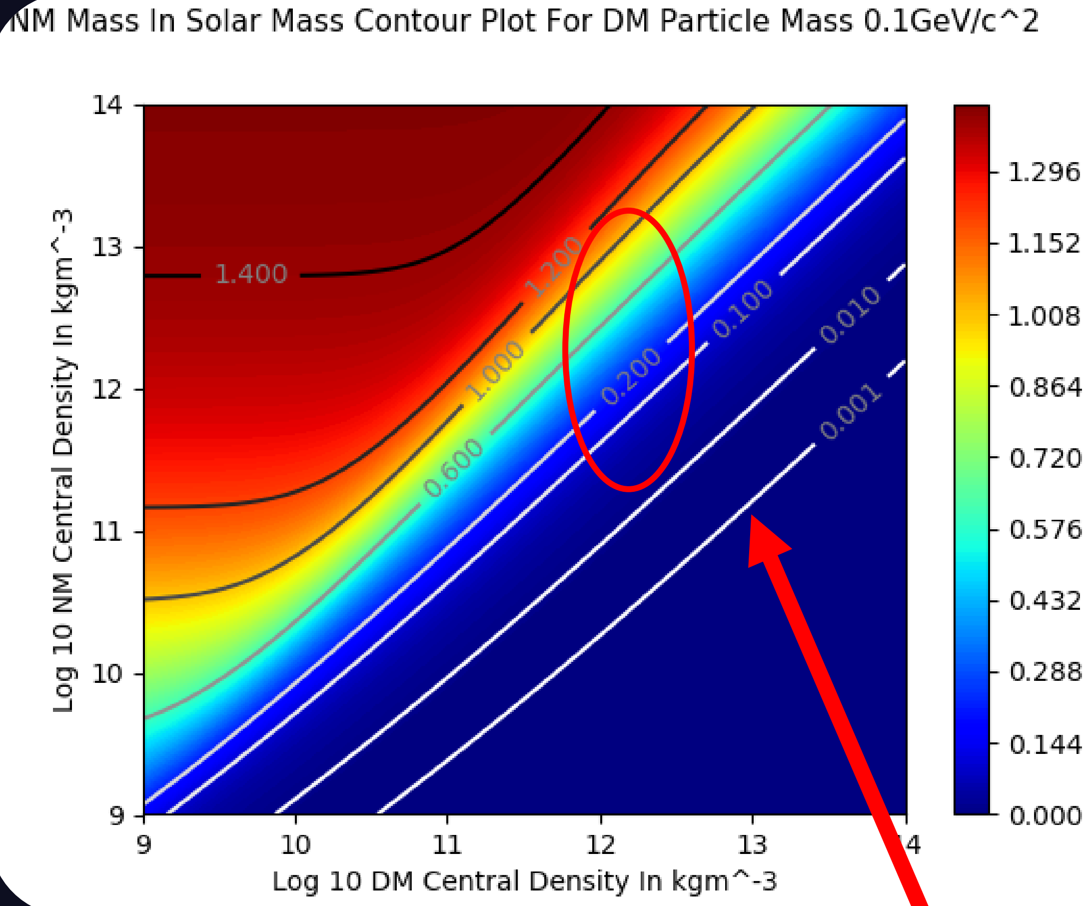
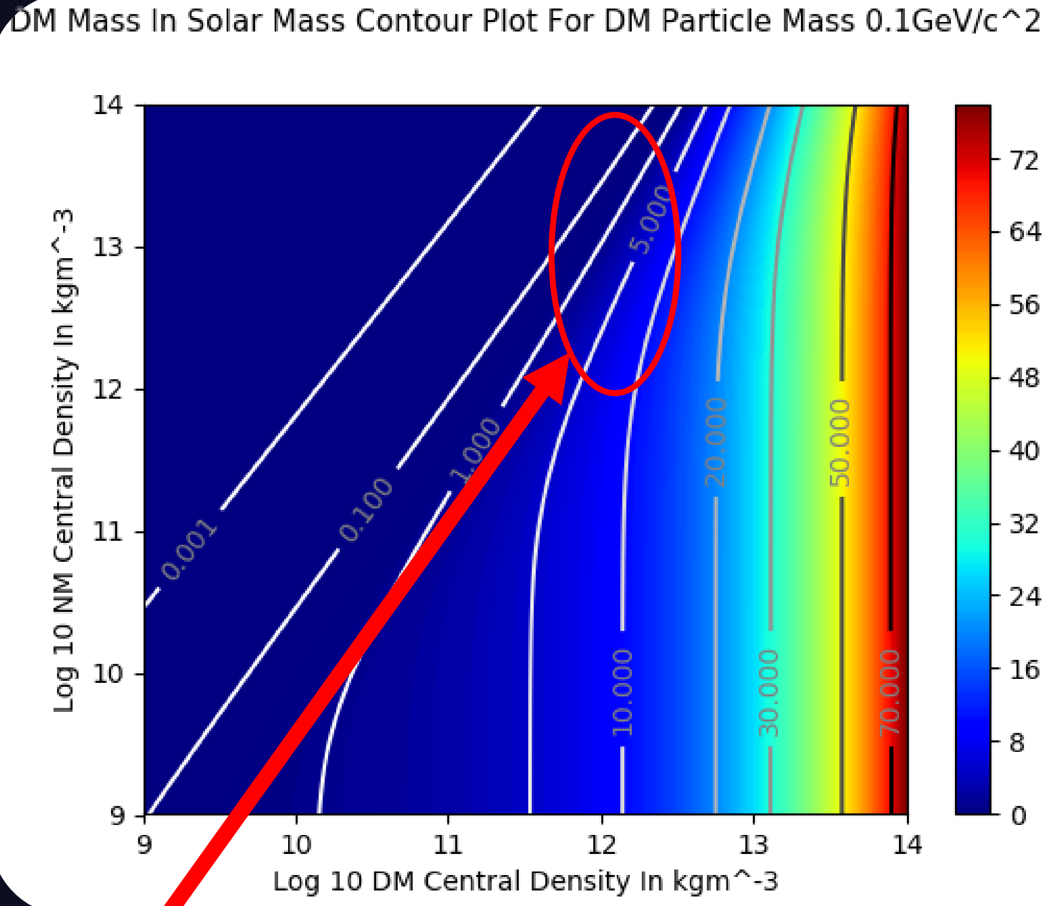
NM and DM Masses Contour Plot





Closely packed contour lines where colors changes significantly

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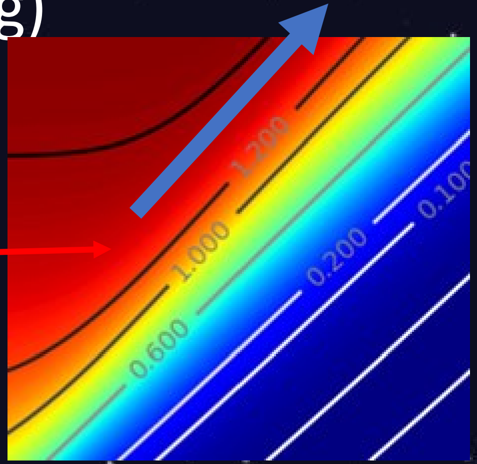
Closely Packed Contours And Its Effect

- Conserve NM mass, the DMAWD should lie on constant NM mass line
- When accreted DM mass small, almost no changes (NM dominating)
- Accreted DM mass increase, goes along contour lines…
- NM central density increase and radius decrease rapidly…



Accreted DM increase NM central density significantly
Recall that typical Type Ia supernova density ~ $10^{9} gcm^{-3}$
A Type Ia supernova with lower NM mass?

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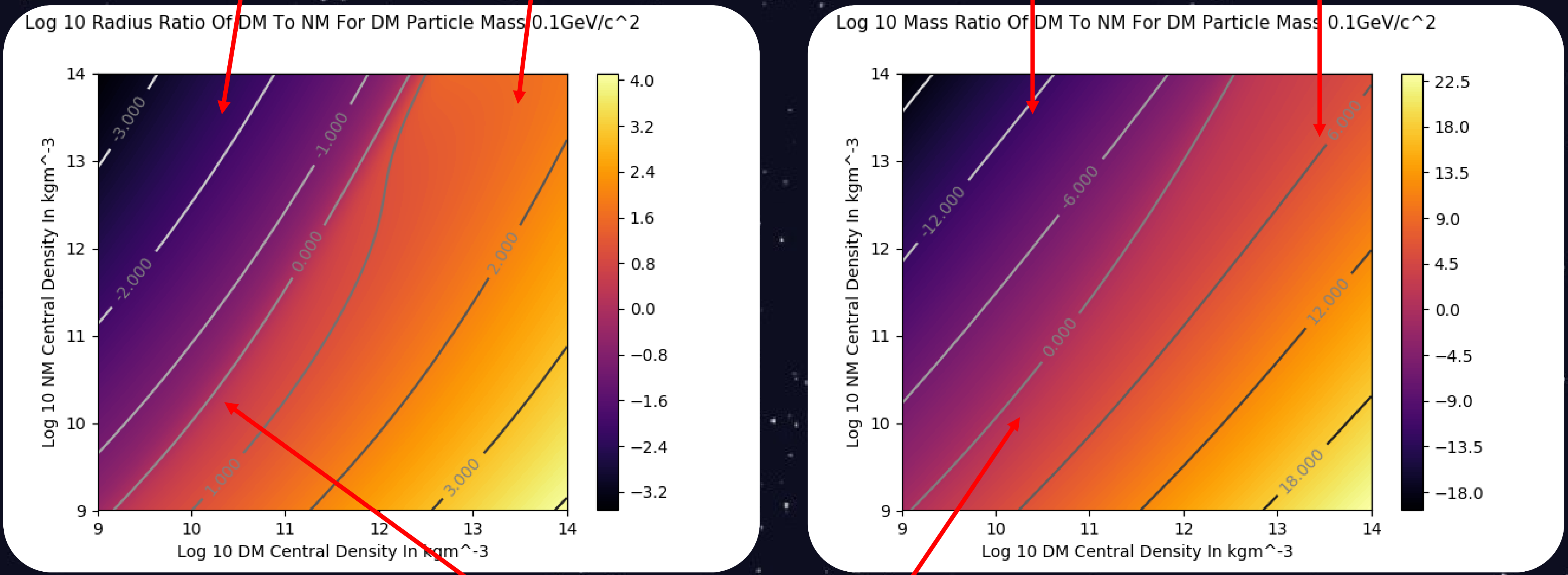
NM / DM Radii and Masses Ratio Contour Plot

DM(NM) more massive then NM(DM) → DM(NM) surrounding NM(DM)



The contour line 0 represent masses or radii are equal

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What Can Be Known From The Ratio Plot?

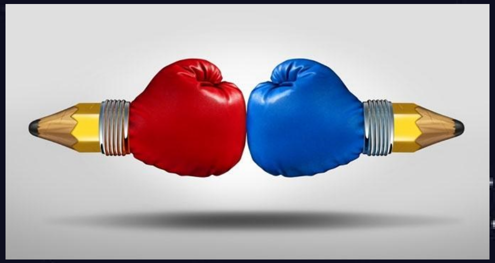
Some other class of DMAWD…

DMAWD having …

1. DM surrounding NM core
2. Comparable order of DM and NM radii and masses

Not found previously

Such DMAWD could also exist so that NM central density ~ Type Ia
What would happen if a Type Ia explosions happen ?



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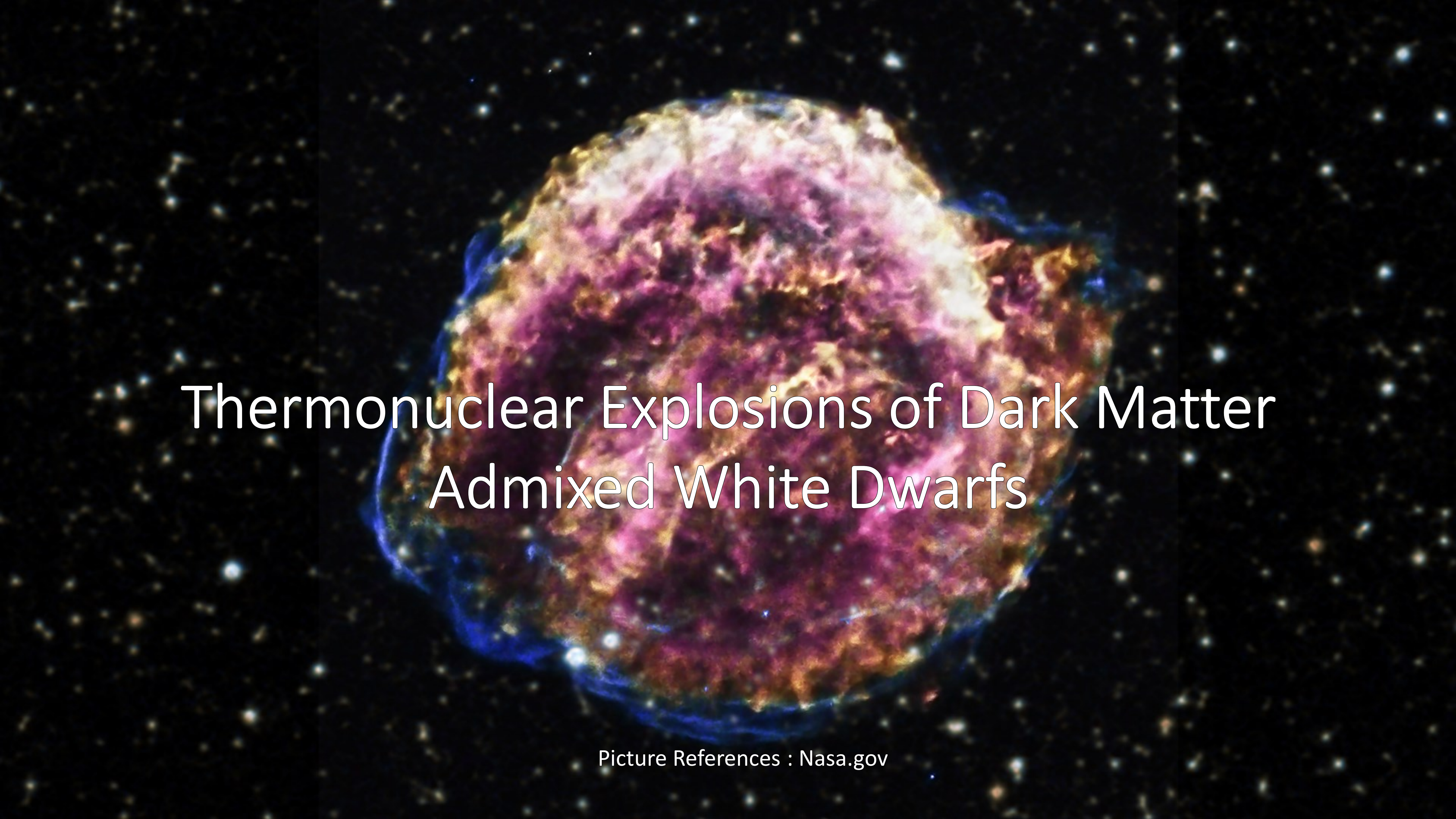
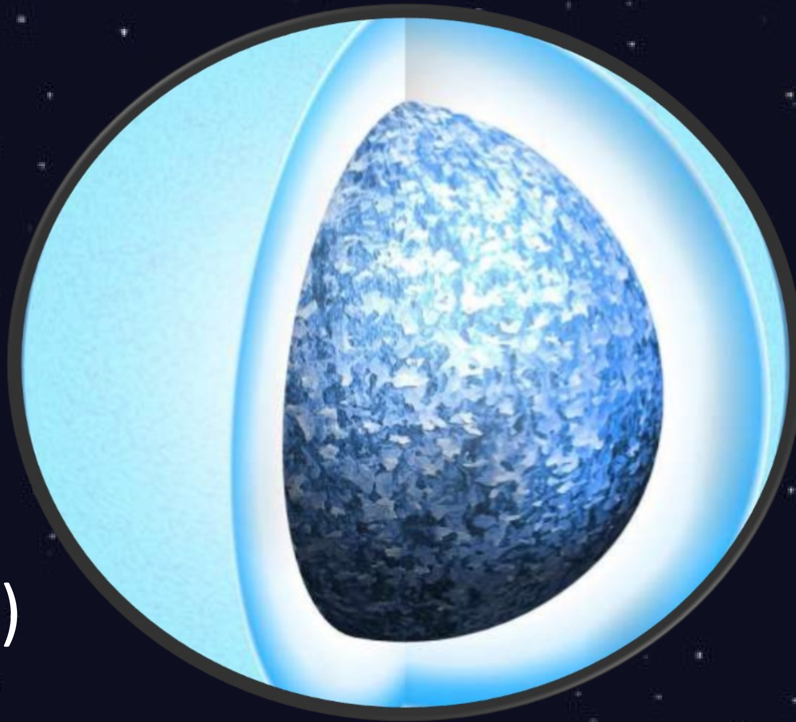

Thermonuclear Explosions of Dark Matter
Admixed White Dwarfs
Picture References : Nasa.gov

Setup Of Our Simple Type Ia Model

- One - dimensional
- Pure Carbon – 12 White Dwarf
- Immediate conversion $14C12 \rightarrow 3Ni56$
- Central Density - $3 \times 10^{12}\mathrm{kgm}^{-3}$
- Temperature – Isothermal $10^{8}K$ (electron conduction)
- Stellar equation of state by Timmes et al.
- Pure deflagration model
- $\vec{v}_n = \beta c_s$, c_s is the local sound speed

Serve to compare with previous literature (Woosley, Holfich…)



Picture References : Phys.org

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Dark Matter Admixed SNeIa

- DM squeeze lower NM mass to high central density
- Sub-Luminous SNeIa? Leung et al. perform stationary DM simulation
- Extend to movable DM?

	Parameters						
	DM Mass	NM Mass	DM Radius	NM Radius	DM Central Density	NM Central Density	DM Movable
DF10	$0.009M_\odot$	$1.37M_\odot$	370km	$1830km$	$3\times10^{10}\text{kgm}^{-3}$	$3\times10^{12}\text{kgm}^{-3}$	No
DF11	$0.07M_\odot$	$1.25M_\odot$	960km	$1780km$	$2\times10^{11}\text{kgm}^{-3}$	$3\times10^{12}\text{kgm}^{-3}$	Yes
DF12	$0.20M_\odot$	$1.13M_\odot$	1380km	$1650km$	$3\times10^{11}\text{kgm}^{-3}$	$3\times10^{12}\text{kgm}^{-3}$	Yes

- Deflagration speed $0.75c_s$, initial position enclose $10^{-4}M_\odot$
- Lower NM mass - Less Nickel-56 or energy being produced?
- How would the DM behaved?

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DM Admixed SNeIa Model DF10 – DF12

Simulations Results

	Nickel-56 Mass	Energy Production	DM Unbinding Time	NM Unbinding Time
DF9	$0.58M_\odot$	1.47×10^{44}J	-	0.12s
DF10	$0.58M_\odot$	1.47×10^{44}J	-	0.12s
DF11	$0.54M_\odot$	1.36×10^{44}J	1.05s	0.11s
DF12	$0.52M_\odot$	1.30×10^{44}J	0.95s	0.13s

- More DM admixed ➡ less NM mass
- Hence less Nickel-56 and energy
- DM unbinding time later than NM
- DM freely expanding after NM exploded
- Reason – A weaker gravitational interaction between NM and DM

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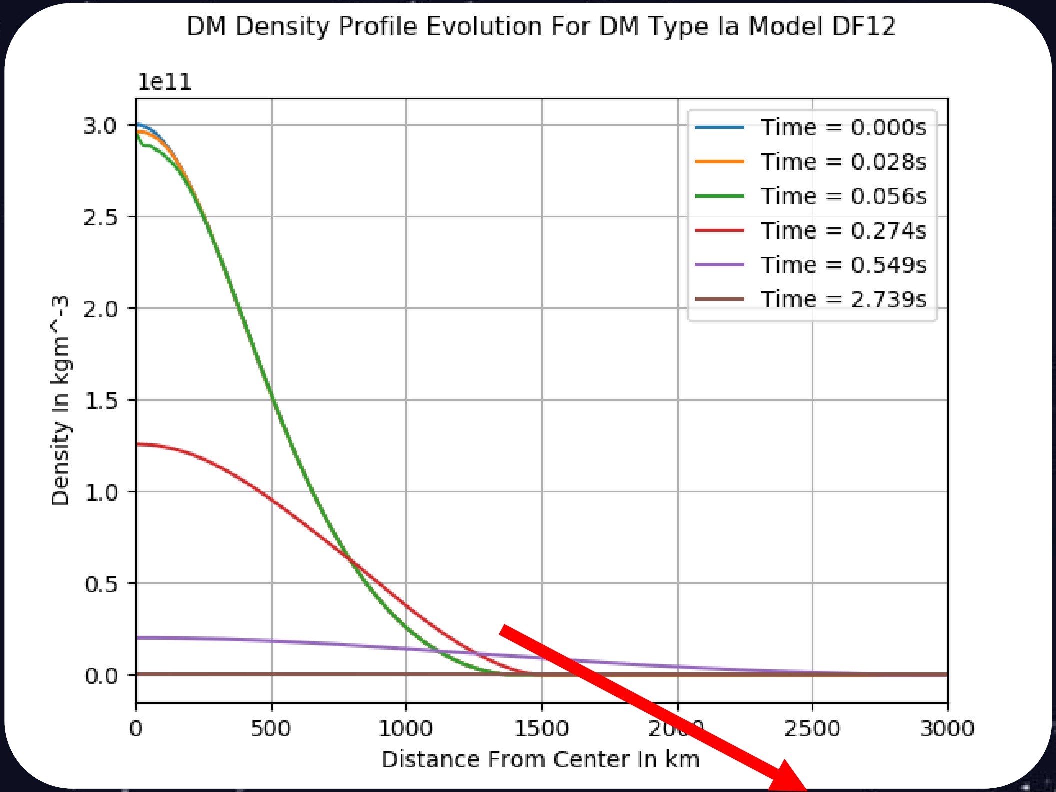
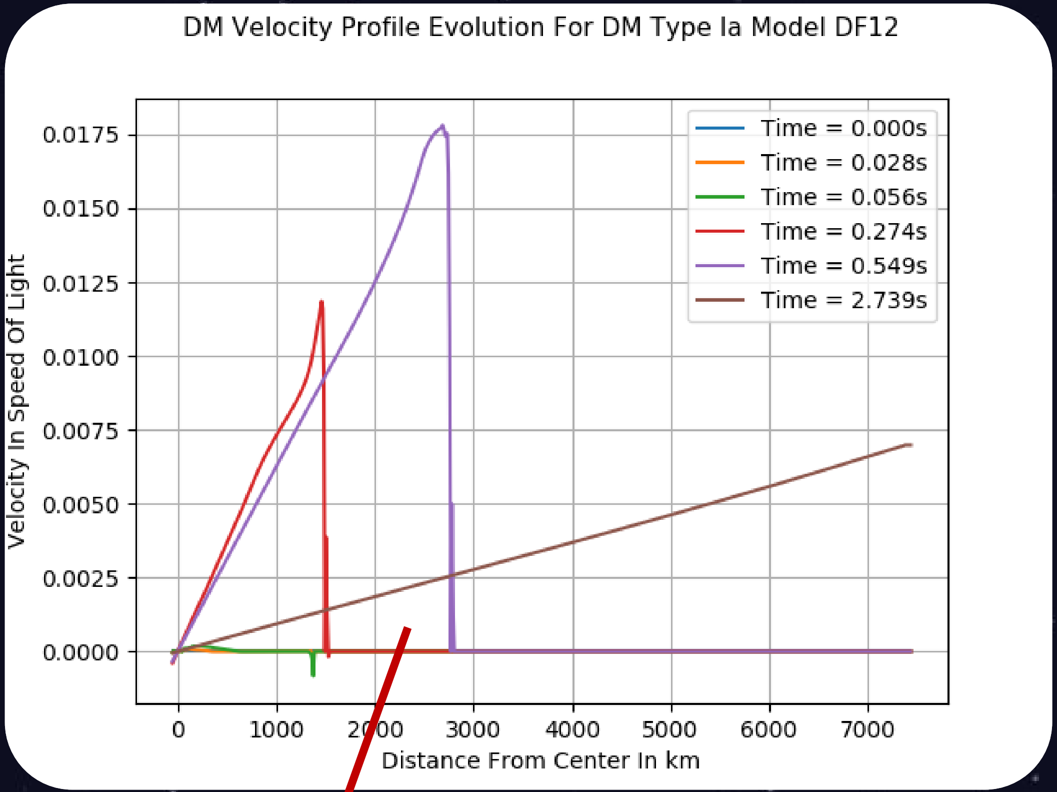
Density and Velocity Profiles For DM





- DM density decreasing, NO inversion
- Velocity profile radially increasing – Free expansion

NM explosion is able bring along DM

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Extension To Higher DM Central Density

Higher DM Central Density → More DM Mass

↓

Higher NM Central Density + Less NM Mass

What if DM mass or radius start to be comparable
Or even over dominate that of NM?

Would a DM star left behind? Worth to explore

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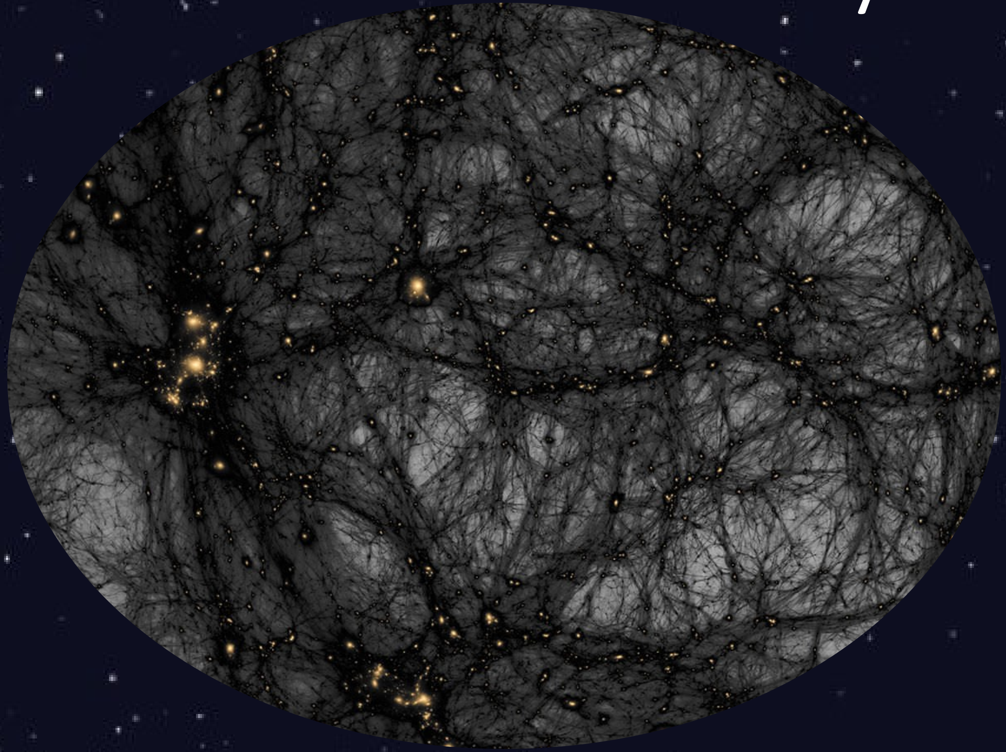
A Small Summary



- We discover two new class of DMAWD equilibrium structure
- We simulate a simple thermonuclear explosions of DMAWD
- With less NM mass comes with less Ni-56 produced – Sub luminous
- DMAWD with more massive DM worth to explore – Observable?

Picture References : Universe Today

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SNeIa Model DF1 – DF9

These meet the requirement $0.5M_{\odot}$ Nickel-56 And 10^{44}J energy

Simulations Results	DF1	DF2	DF3	DF4	DF5	DF6	DF7	DF8	DF9
Initial deflagration Position ($M_{\odot}$)	0.01	0.001	0.0001	0.01	0.001	0.0001	0.01	0.001	0.0001
Deflagration Speed (c_s)	0.25	0.25	0.25	0.50	0.50	0.50	0.75	0.75	0.75
Unbinding Time (s)	0.15	0.24	0.29	0.09	0.14	0.16	0.07	0.10	0.12
Ni56 Mass ($M_{\odot}$)	0.24	0.22	0.21	0.43	0.41	0.41	0.59	0.58	0.58
Energy Released (10^{44} J)	0.66	0.65	0.62	1.12	1.09	1.08	1.48	1.47	1.47

- Differentiated by deflagration speed and front location
- Different Nickel-56, energy production, unbinding time

Faster propagation OR Further initial position

More energy + Nickel-56 + earlier unbinding → More energetic explosion

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Appendix – Supplementary To Main Slide

Constructing DMAWD Model

Hydrostatic Equilibrium Equation Of DM and NM

$$\frac{dP_1(r)}{dr} = -\frac{\rho_1(r)G}{r^2}(M_1(r) + M_2(r))$$

$$\frac{dP_2(r)}{dr} = -\frac{\rho_2(r)G}{r^2}(M_1(r) + M_2(r))$$

$$\frac{dM_1(r)}{dr} = 4\pi r^2 \rho_1$$

$$\frac{dM_2(r)}{dr} = 4\pi r^2 \rho_2$$

- With M the mass, ρ the density, P the pressure, r the radius
- Subscript 1 and 2 belongs to DM and NM respectively
- DM and NM only acts through gravity
- Solving these sets of coupled equation with RK4 scheme

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Assumption In Model Construction

- White dwarfs would have general relativity parameter

$$\frac{GM_{total}}{Rc^2} \sim 10\text{^}(-4)$$

- Safe to assume Newtonian gravity in most case
- DM particle mass ranging from $0.1GeV/c^2$ to $0.3GeV/c^2$
- DM and NM central Density ranging from 10^9 to 10^{14}
- Make sure they are degenerate

Make contour plots of DM/NM Mass And Radius

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How Do We Classify Thermonuclear Explosion?

Deflagration

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

Detonation

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

- Their burning region (front) separate ash and fuels
- Very thin in astrophysical contexts ($10^{-3} cm$ vs $\sim 10^{3} km$)

Good to approximate them as a discontinuous surface

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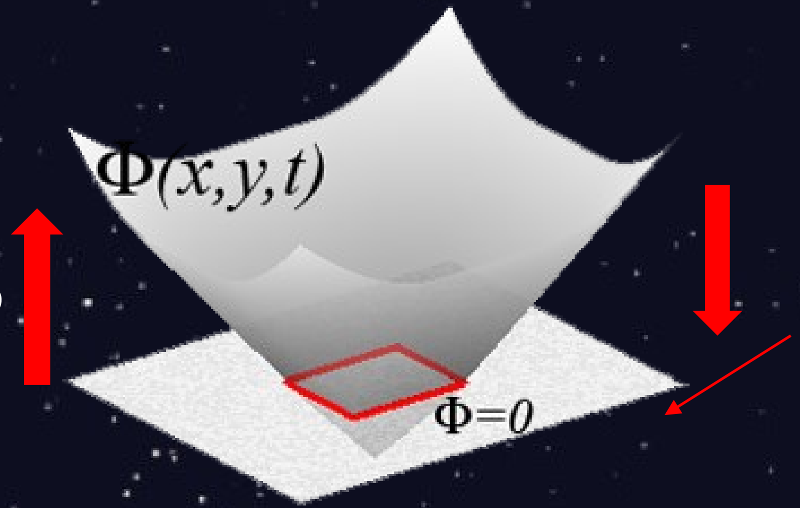
The Level – Set Surface Capturing Method

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

Motion of surface governed by motion of Φ



The zeroth level - set

Picture References : profs.etsmtl.ca

- In a mathematical way…

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

- Immediate advantage – Topological change handled naturally

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Limitations – Unrealistic Nuclear Reaction

- We need high deflagration speed to produce sufficient Nickel-56
- $>0.5c_s$ vs $0.3c_s$ as pointed by Woosley, Hoflich et al….
- Reinecke et al. say that immediate conversion to Ni56 not realistic…

$$14C12 \rightarrow 3Ni56$$
$$Ni56 \longleftrightarrow alpha\ particle$$

- Nuclear statistical equilibrium shift towards Ni56 later
- Effect – less energetic explosion initially, more time to burn $C12$…
- How about other elements? E.g. Intermediate mass elements?

A large nuclear network between elements is needed

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Limitations – Deflagration speed? DDT?

- Deflagration speed in local sound speed is unphysical?
- How about other choice of speed? But...

Laminar deflagration speed couldn't produce explosions

- Convective deflagration speed? Turbulence deflagration speed?
- Act to "accelerate" deflagration front
- Prompt Explosion - How about a transition detonation?

Deflagration to detonation transition(DDT) – One explosion model

- However, DDT in open system is still debatable...

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Limitations – Light Curve + Microphysics

- Other important benchmark – Light curve + Neutrino emission
- Light curve – a radiative transfer equation?
- Special relativistic hydro-dynamics? (The velocity is so high)
- Amount Nickel – 56 and other iron peak elements?
- Need electron capture module, reduce iron peak elements.
- NSE module to calculate elements in burnt region?

Still a long way to go to produce a good model…

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Appendix - deflagration/detonation speed?

- Timmes et al. solved energy equation to obtain…

$$\vec{v}_n = 92.0\left(\frac{\rho}{2\times 10^9}\right)^{0.805}\left[\frac{X_{c12}}{0.5}\right]^{0.889} \quad kms^{-1}$$

- Problems – Too slow for explosions
- Solutions – Accelerate it
- By means of turbulence, convection…

$\vec{v}_n$ turbulence parameterized in fractal dimension?

- More realistic – Go to higher dimension
- Handle turbulence more carefully

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Appendix - Why not pure detonation model?

- Pure detonation – burn much material at high density
- Too much iron peak elements
- Much less intermediate mass elements (Silicon, magnesium…)
- Some also argued that…
- Pure detonation is not possible to initiate

> It is commonly argued that the initiation of detonations in degenerate C-O mixtures is impossible (e.g. Nomoto et al. 1976, 1984; Mazurek et al. 1977; Woosley et al. 1980). The argument was that constant volume explosions in C-O mixtures generate only weak shock waves, which cannot trigger a detonation.

Picture References : Khokhlov et al.

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Appendix – What is DDT?

Pure detonation – Too much Ni56

Pure deflagration – Too weak

How about combine both?

- Khokhlov first proposed DDT
- Initially, a slow deflagration expand stars
- At critical condition, transit to detonation
- Observed on terrestrial combustion

What condition?(Density? Temperature?...)
Still unclear!

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Appendix – What is Timmers EOS?

White dwarf – degenerate electron in finite temperature

- Needs finite temperature EOS with contribution from electron…
- Include pressure, density, specific energy from…

Electron, positron, photo, ideal gas ions

- A finite temperature EOS
- Solved by calculating the fermi integral exactly
- Included in terms of a free energy table
- Interpolate the free energy table – Get thermo variables…

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