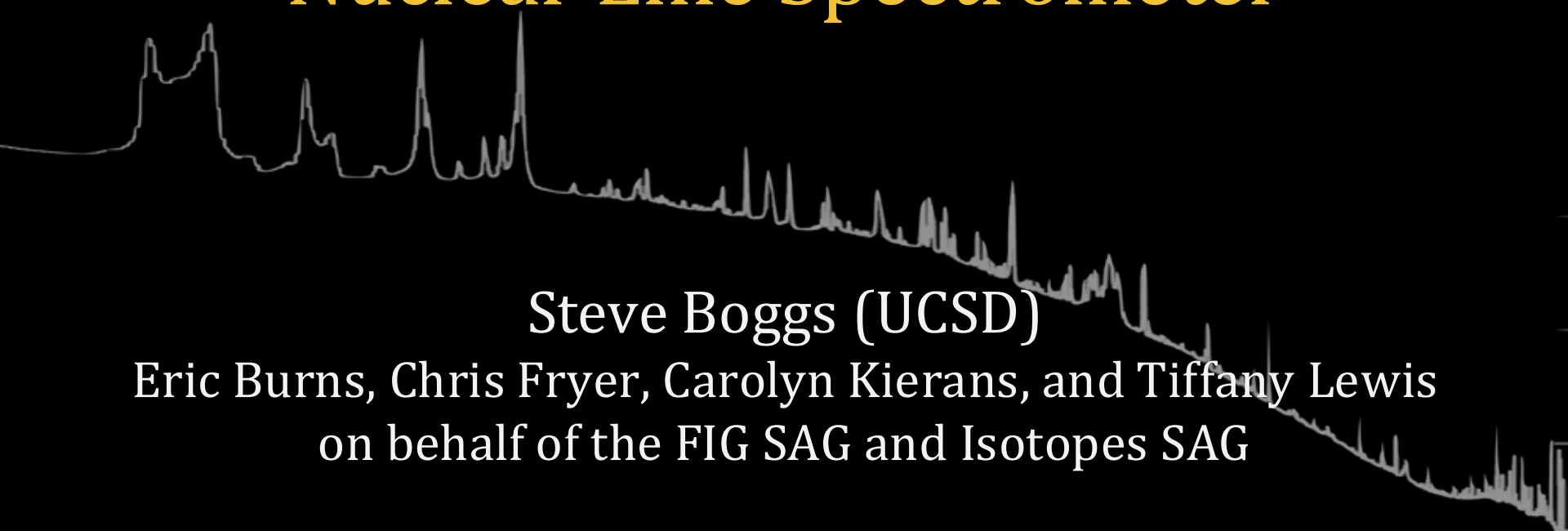


Origin of the Isotopes: The Case for a Next-Generation Nuclear Line Spectrometer



Steve Boggs (UCSD)

Eric Burns, Chris Fryer, Carolyn Kierans, and Tiffany Lewis
on behalf of the FIG SAG and Isotopes SAG

Outline

Introduction to gamma-ray line astronomy

Measurements that have been made in the past

Introduction to the MeV Gap and COSI

3 main science questions for a next-generation mission:

1. Type 1a SN
2. CCSN
3. Nova

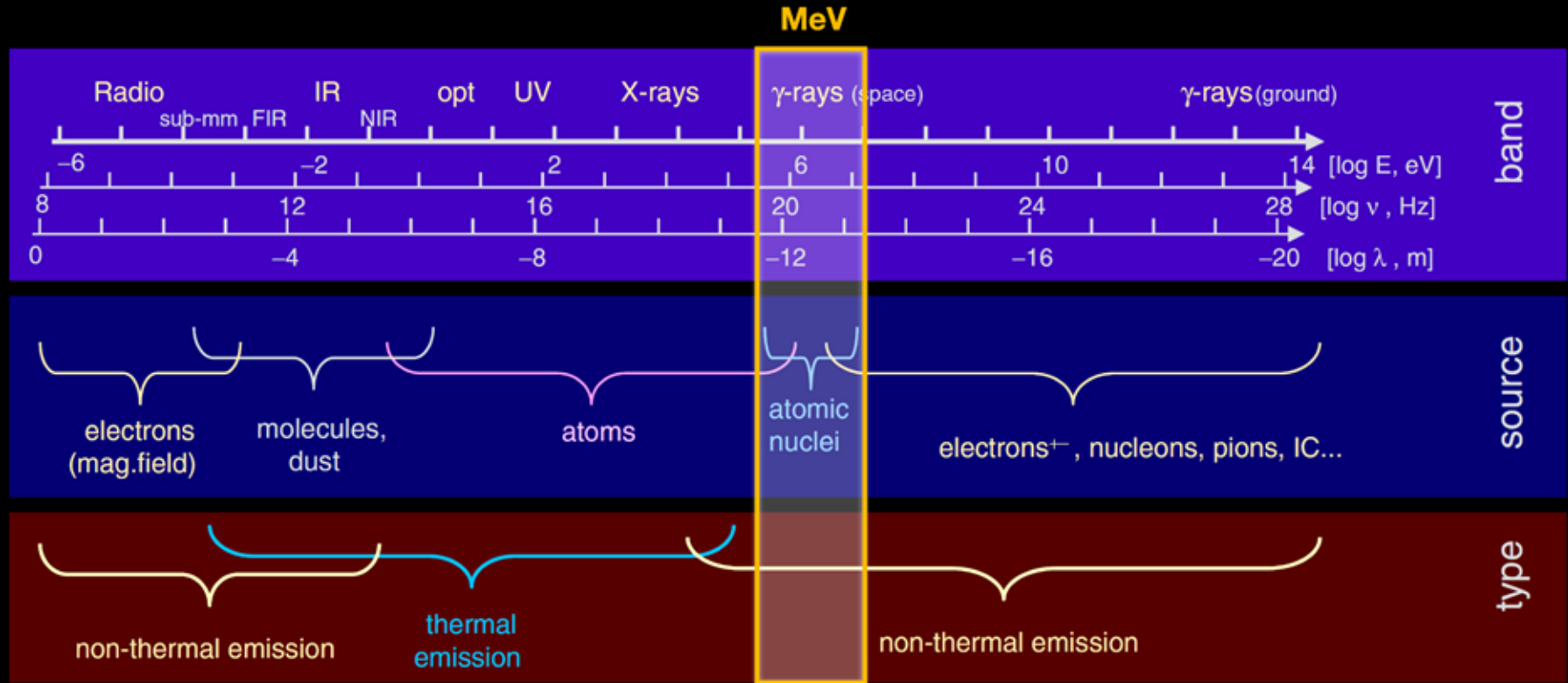
General requirements for a future mission
(~sensitivity, observing profile, energy res.)

Isotopes SAG aims to deliver
a report this calendar year.

More information and
signup here:



A Unique Window in the Electromagnetic Spectrum



MeV gamma-rays probe nuclear processes in astrophysical objects:

- radioactive decay
- nuclear de-excitation
- positron annihilation

Different Isotopes Probe Different Objects

Element Origins

Big Bang

Cosmic Ray Fission

Exploding Massive Stars

Exploding White Dwarfs

Merging Neutron Stars

Dying Low Mass Stars

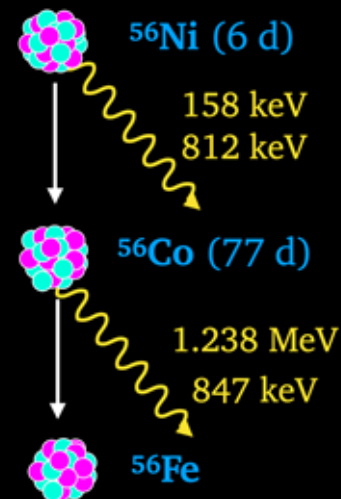
1 H																	2 He			
3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg													13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr			
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe			
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn		
87 Fr	88 Ra																			
						57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
						89 Ac	90 Th	91 Pa	92 U											

Image Credit: Jennifer Johnson/SDSS

Image Credit: Jennifer Johnson/SDSS

Catching Element Formation in the Act*

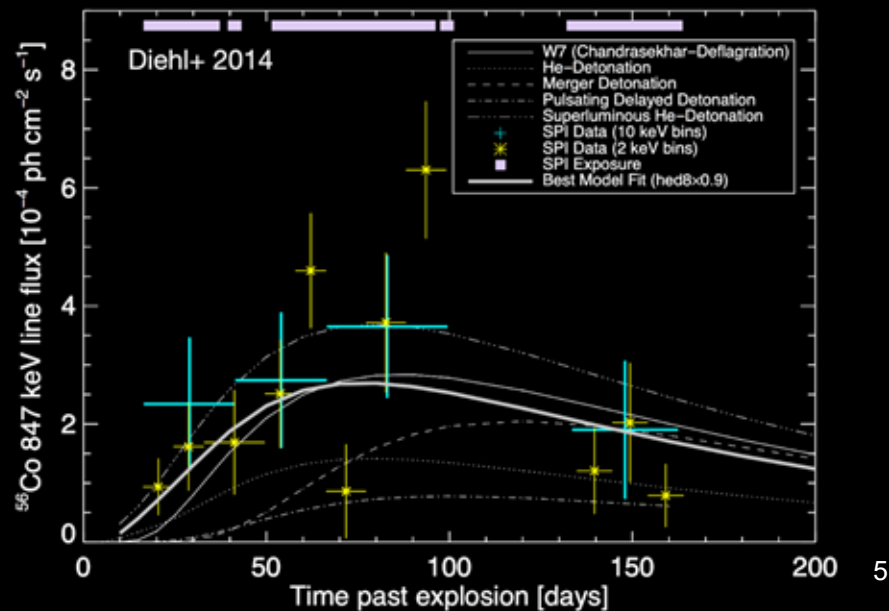
*Timmer et al. 2019



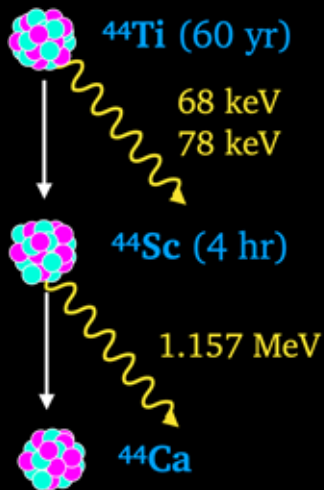
^{56}Ni is produced in large quantities in Type 1a SN which powers the ~month-long lightcurve

- the nature of the explosion and its progenitor is unknown
- different ^{56}Ni distributions give variations in the light curve
- detected in SN2014J (SN1a) and SN1987A (ccSN)

Early-time gamma-ray emission indicates ^{56}Ni on the surface, but result has low significance

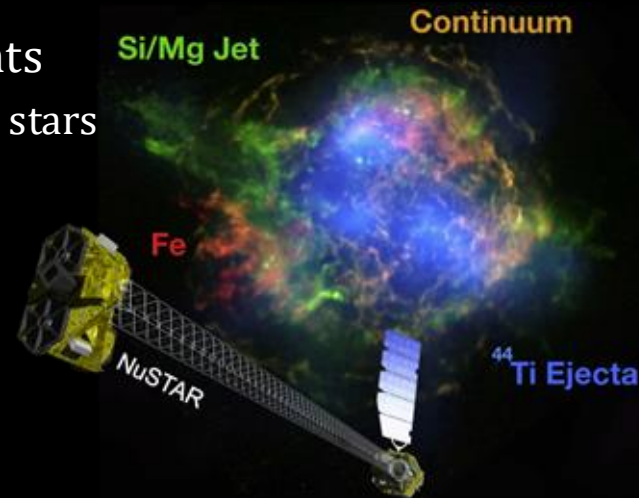
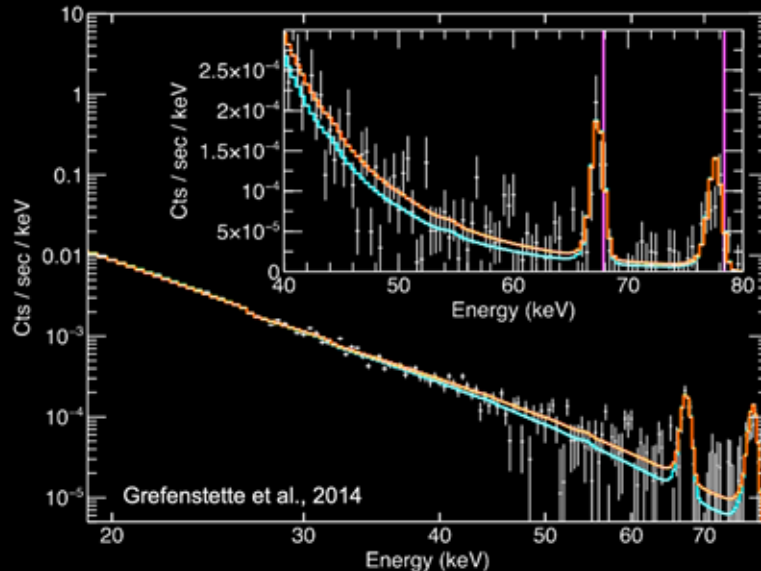


^{44}Ti - Probing the Heart of Supernova



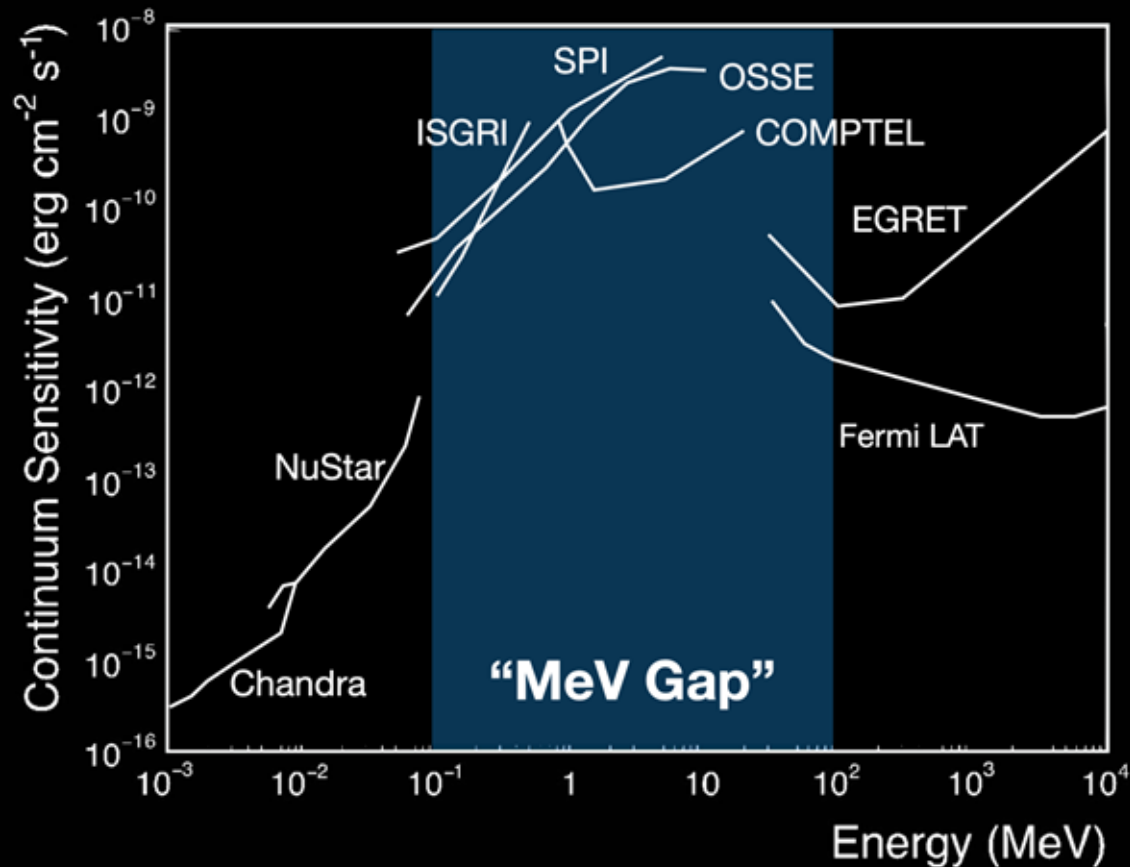
^{44}Ti is a tracer of young supernova remnants

- produced in innermost layers of collapsing stars
- synthesis is sensitive to local conditions
- detected in Cas A and SN1987A (ccSN)



Measured redshift and spatial distribution indicate asymmetric explosion, confirming convection-enhanced engine

The MeV range remains underexplored



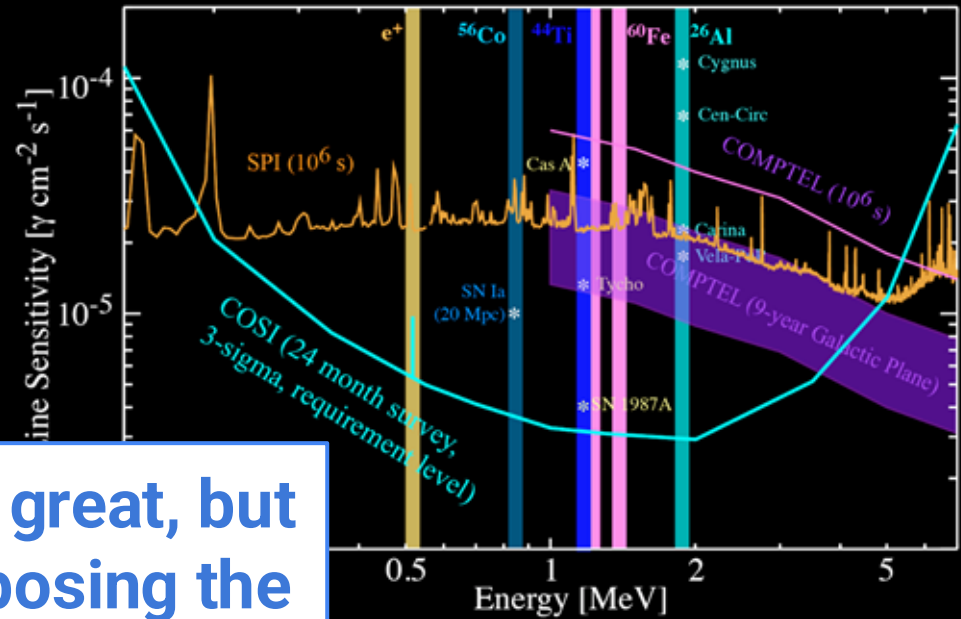
The upcoming Compton Spectrometer and Imager

COSI is NASA's next
Small Explorer mission
scheduled to launch
in August 2027



**COSI will be great, but
it is only exposing the
tip of the iceberg!**

COSI is **optimized for line sensitivity** to
enable all-sky images of nucleosynthesis lines



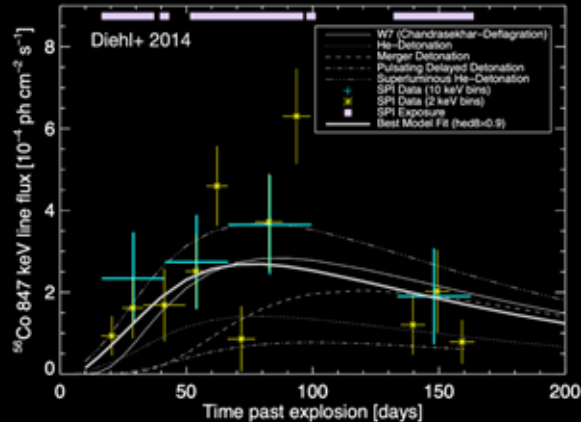
Understanding the Nature of Thermonuclear Supernovae

Why is it Important?

Type 1a SN are foundational standard candles for dark energy cosmology

What is the problem?

The standardization is empirical, not physical. Changes from progenitors or engine variation may cause systematic errors



How can gamma-rays help?

- Temporal evolution of ^{56}Ni can discriminate progenitors in individual events.
- Observations of ^{57}Ni can differentiate between single-degenerate and double-degenerate models as yield is set by neutron fraction

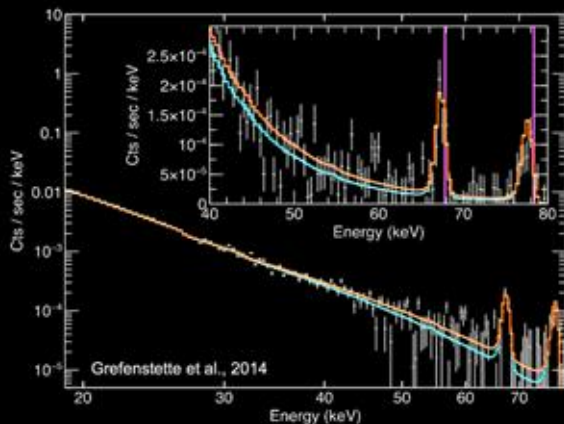
Understanding the Core-Collapse Supernova Engine

Why is it Important?

CCSN are key for cosmic feedback, forge heavy elements, form compact objects, produce various transients, and probe hot, dense matter

What is the problem?

Current models do not capture the nature of stellar convection or the structure progenitor properties.



How can gamma-rays help?

- Larger sample of ^{44}Ti and ^{56}Ni measurements, with line profiling to determine velocity distribution, places strong constraints on SN engines and progenitors

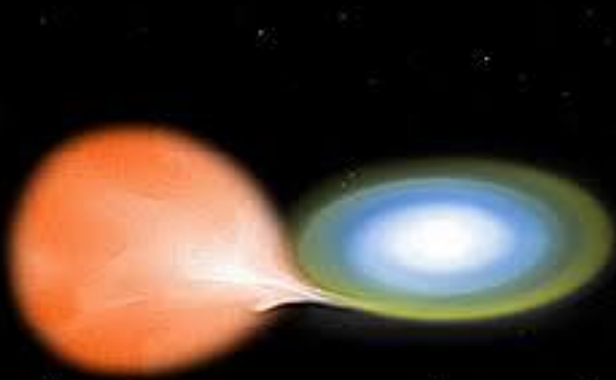
Probing Novae

Why is it Important?

Galactic transients enable study of accretion, nucleosynthesis, and reactive flows.

What is the problem?

Observed elemental yields require mixing with surface, but how this occurs is not fully understood. It is unknown if the explosion causes a net gain or loss of mass, which is critical for understanding Type Ia SN progenitors



How can gamma-rays help?

- Nuclear lines (${}^7\text{Be}$, ${}^{13}\text{N}$, ${}^{18}\text{F}$, ${}^{22}\text{Na}$, and ${}^{26}\text{Al}$) identify properties of the turbulent/reactive flows, and the nuclear reactions occurring

Requirements to Understand the Origin of the Isotopes

Observations of gamma-ray decay lines are critical to understanding stellar explosions and their progenitors

Narrow-line sensitivities 10–30× better than COSI are required to build a sample with high SNR to sufficiently constrain models.

- Sensitivity of $1\text{--}3\times 10^{-7}$ ph/s/cm²
- Line profiling requires ~1% energy resolution (detection does not)

There is no one-size-fits-all mission, and different approaches have different advantages!

