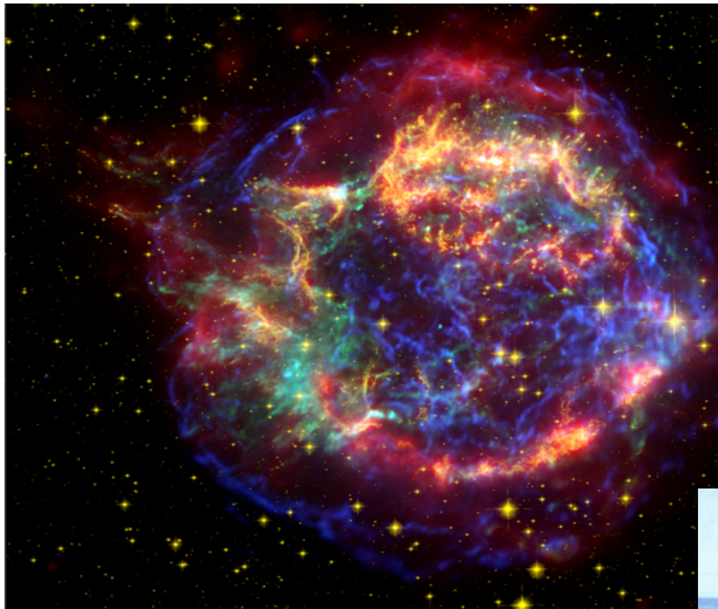
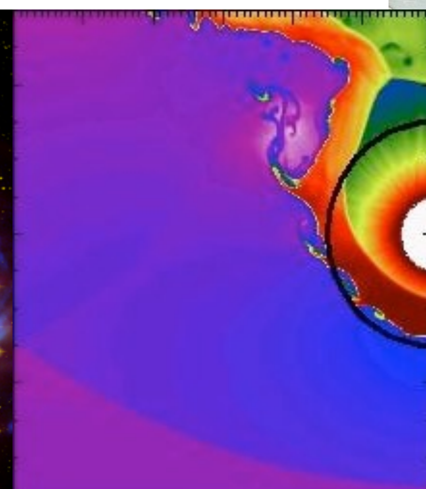
When Stars Attack!

In Search of Near-Earth Supernova Explosions





Brian Fields

Astronomy & Physics, U Illinois

Greetings Illini!

- Alumni
- Parents

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ILLINOIS

Nearby Supernova Collaborators

Themis Athanassiadou

Scott Johnson

Kathrin Hochmuth

John Ellis CERN

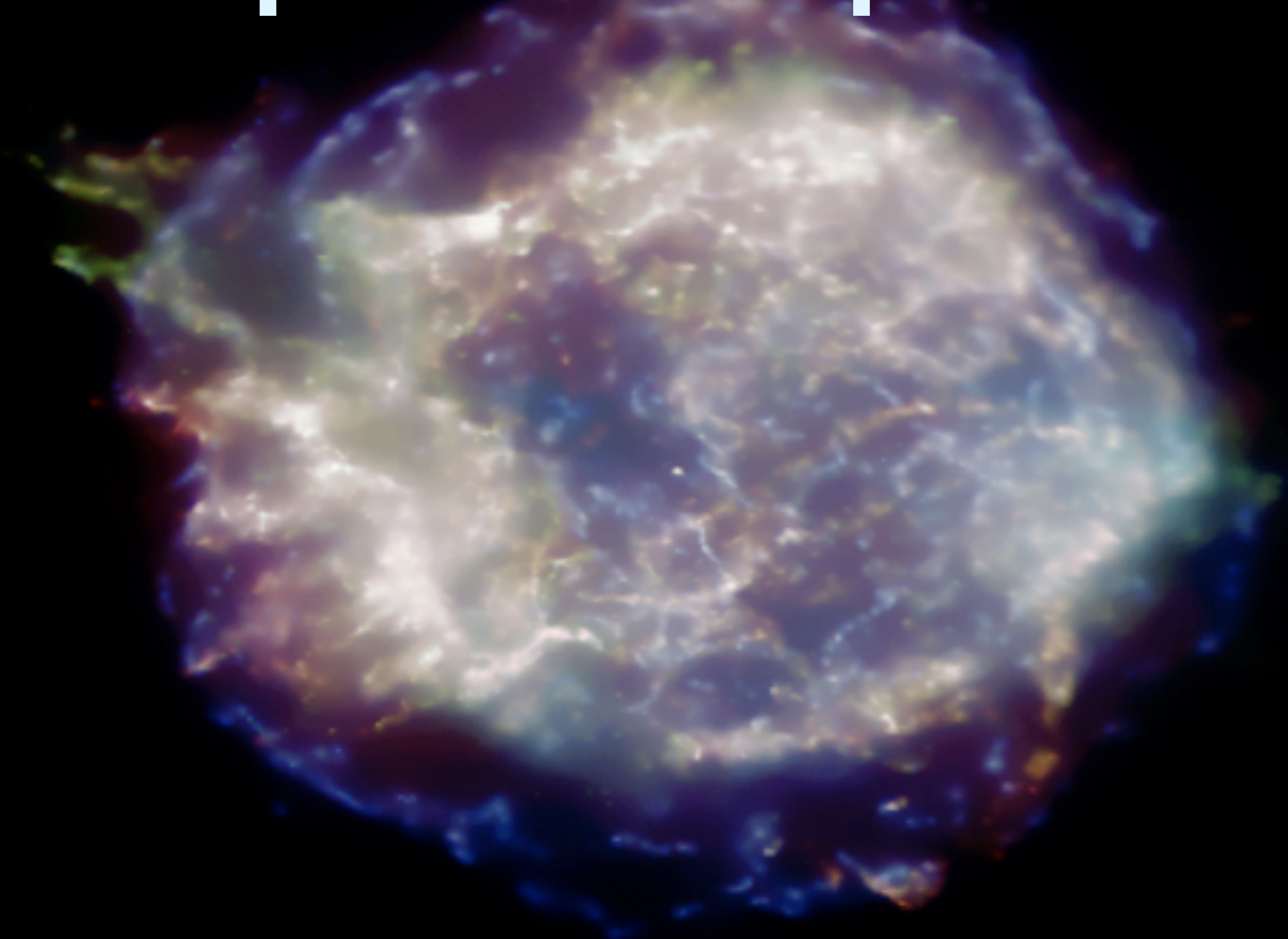
Brian Fry U. Illinois

When Stars Attack!

In Search of Near-Earth Supernova Explosions

- ★ **Supernova Explosions**
  the deaths of massive stars
- ★ **Nearby Supernovae**
  a unique laboratory...and a unique threat
- ★ **The Smoking Gun**
  supernova radioactivities on Earth
- ★ **Geological Signatures**
  sea sediments as telescopes

Supernova Explosions

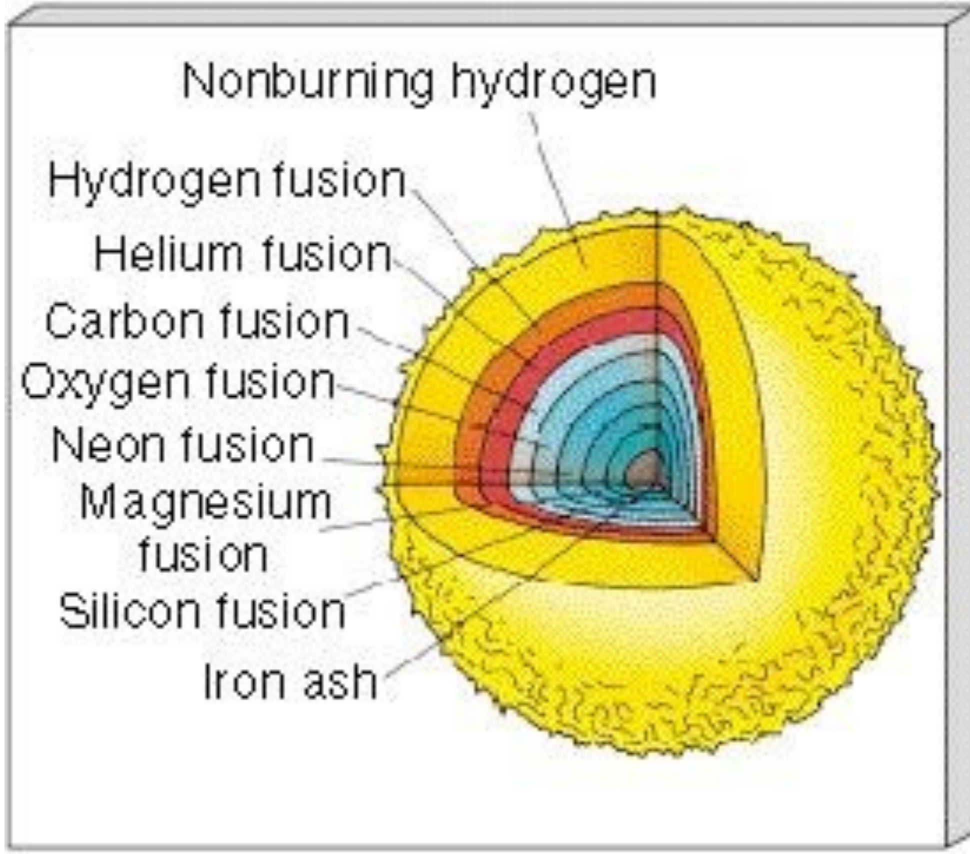


Core-Collapse Supernovae

Symphonies of the Fundamental Forces

Lives of Massive Stars (> 8-10 M_{sun})

- ★ Begin burning $H \rightarrow He$
- ★ Then, at accelerating pace
  - repeated cycles of ash ⇨ fuel
  - ever-heavier elements in core
- ★ "onion skin" structure



When core ^{56}Fe: max binding

- ★ core fusion stops: support by degen e^-
- ★ When $M_{\text{Fe core}} > M_{\text{Chandra}} \sim 1.4 M_{\text{sun}}$
  unstable ⇨ gravitational collapse
- ★ Core "bounce" at nuke density
- ★ "Neutrino bomb" ignited: ~ few 10^{53} erg
  Koshiba & Kamiokande
- ➡ Shock launched: ~10^{51} erg
  Explosion!

Supernovae and Nucleosynthesis

- both hydrostatic and explosive
- main products:
  - ✓ alpha nuclei: ^{12}C, ^{16}O, …, ^{40}Ca
  - ✓ Fe peak
- medium-lived radioactivities: ^{60}Fe, ^{26}Al, ^{53}Mn, ^{146}Sm(?)
- ^{60}Fe: made by neutron captures

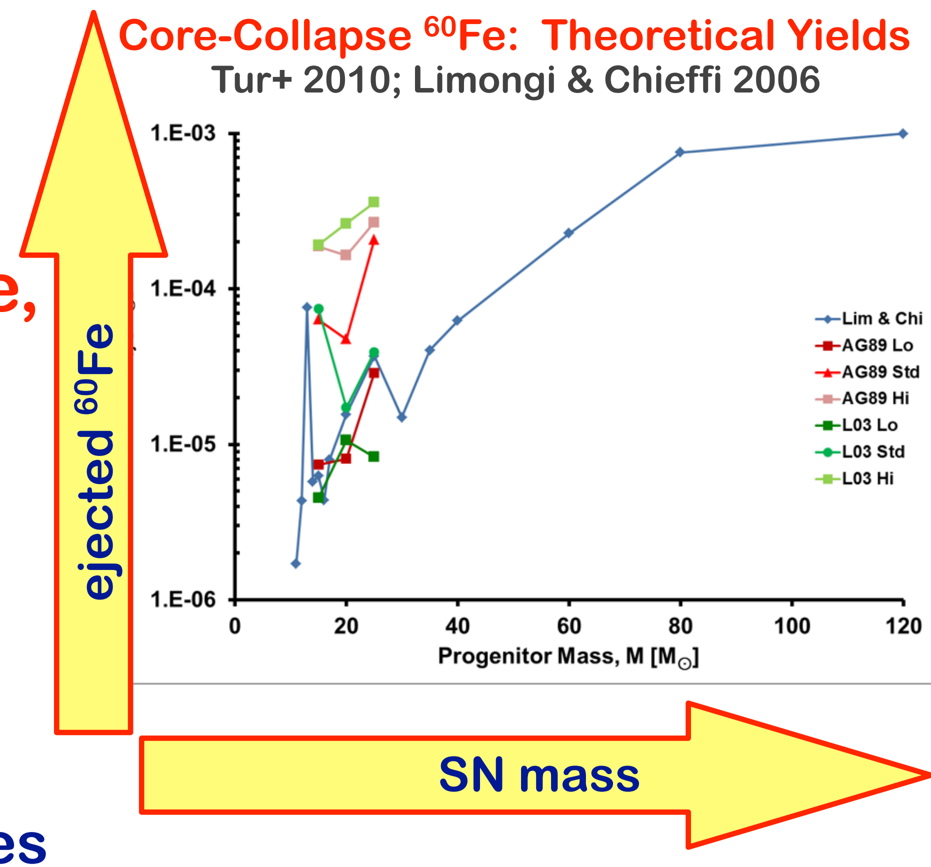
  "weak s-process"

$$^{59}\mathrm{Fe}(n,\gamma)^{60}\mathrm{Fe}$$

  large theoretical uncertainties in yield

  sensitive to stellar evolution, nuke rates

  accuracy ~order of magnitude
- r-process? ^{182}Hf, ^{244}Pu



Live Radioactivities and Nearby Supernovae

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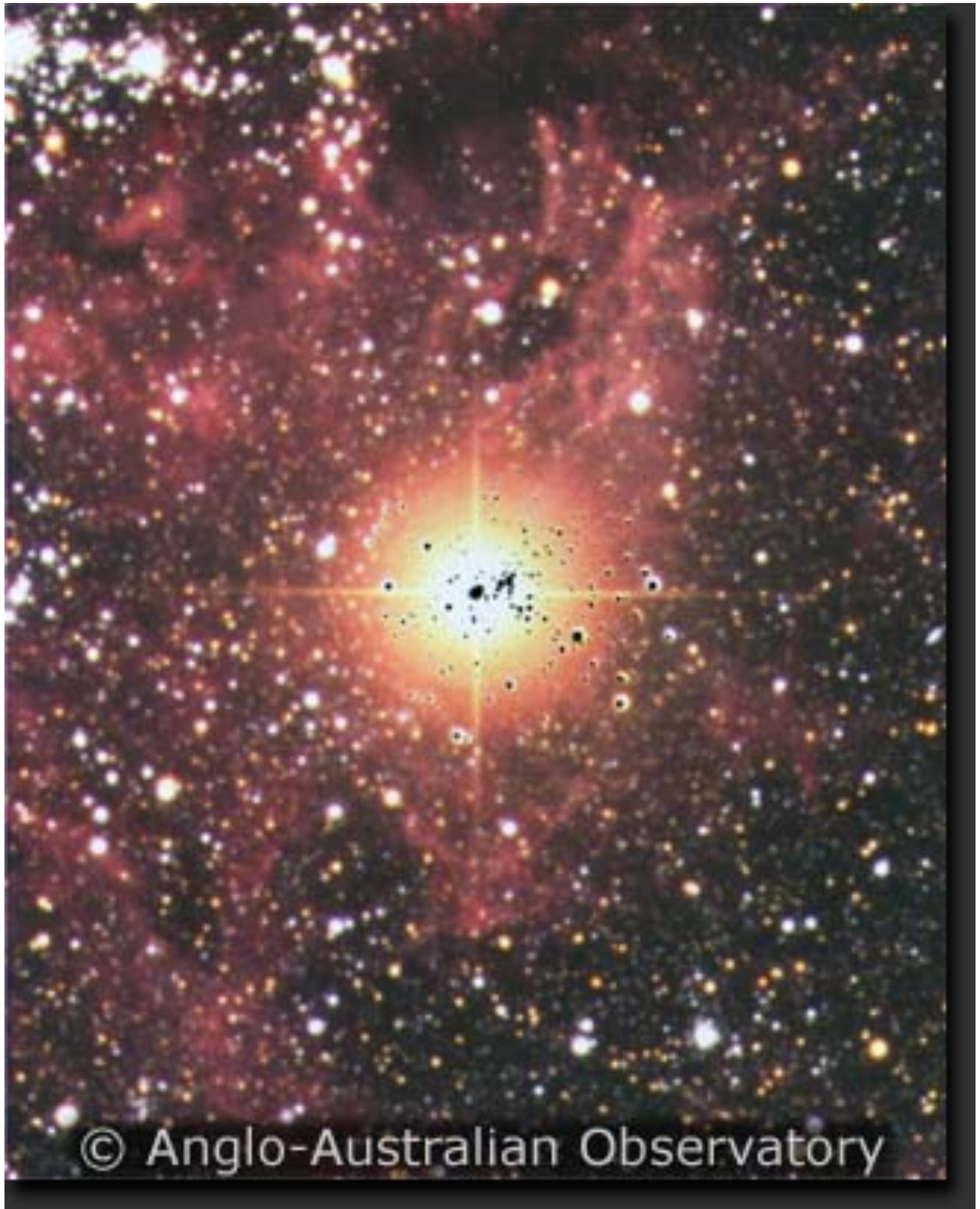
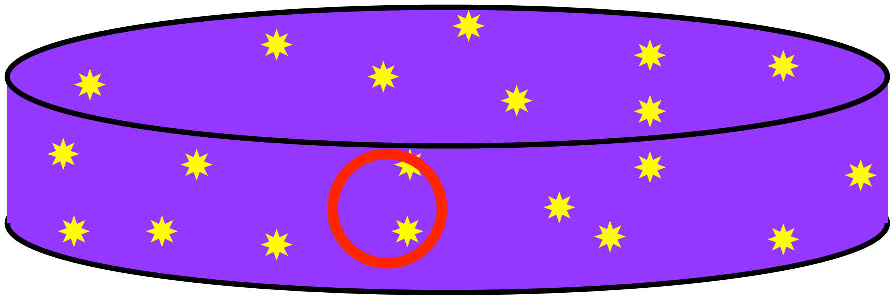
Nearby Supernovae



Cosmic WMD: Rates

- ★ How often? Depends on how far! Shklovskii 68
- ★ Rate of Supernovae inside **d**:
  - – Galactic supernova rate today: $\mathcal{R}_{\rm SN}$



$h \sim 100$ pc

$$\lambda(< d) = \frac{V_{\rm disk}(< d)}{V_{\rm disk,total}} \mathcal{R}_{\rm SN} = (10\ {\rm Myr})^{-1} \left(\frac{d}{30{\rm pc}} \right)^3$$

  - – corrections: spiral arms, molecular clouds, exponential disk… Talbot & Newman 77
  - – multiple events < few pc in the last 4.5 Gyr!

Nachbarsternsupernovaexplosionsgefahr

or

Attack of the Death Star!

Ill efects if a supernova too close

possible source of mass extinction

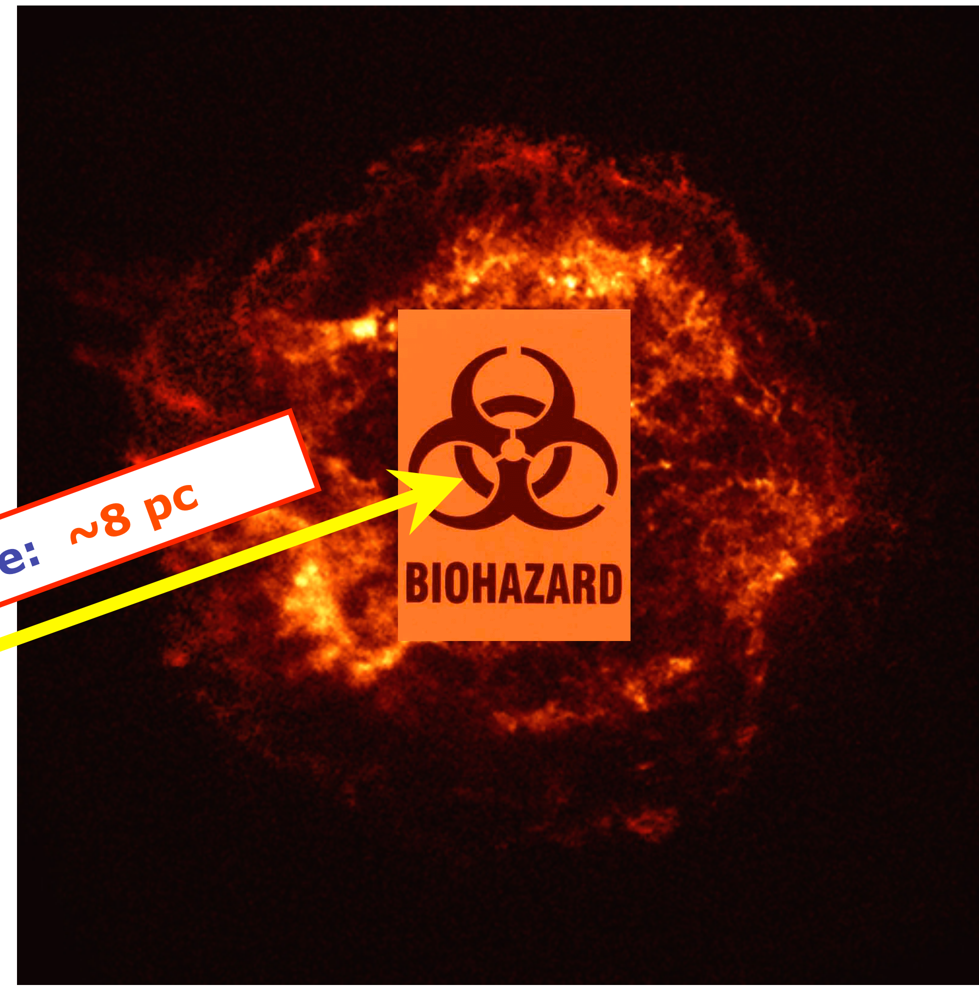
- Shklovskii; Russell & Tucker 71; Ruderman 74; Melott talk

Ionizing radiation

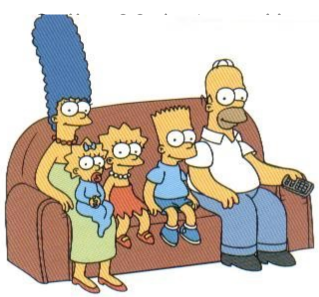
- initial gamma, X, UV rays
  subsequent diffusive cosmic rays
- destroy ozone in atmosphere
  Ruderman 74; Ellis & Schramm 94
- solar UV kills bottom of food chain
  Crutzen & Bruhl 96; Gehrels etal 03;
  Melott & Thomas groups; Smith, Sclao, & Wheeler 04

Neutrinos

- neutrino-nucleon elastic scatteri
  “linear energy transfer”
  ⇨ DNA damage
)2

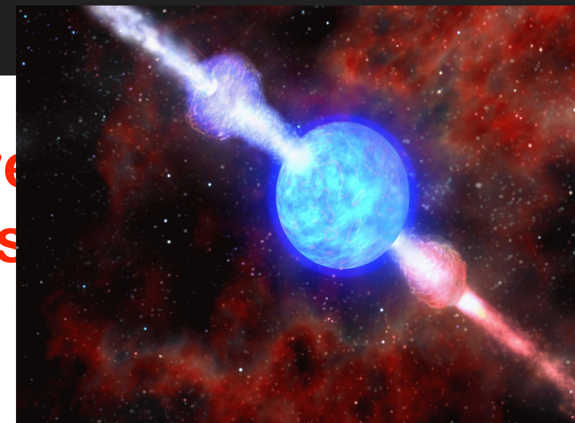


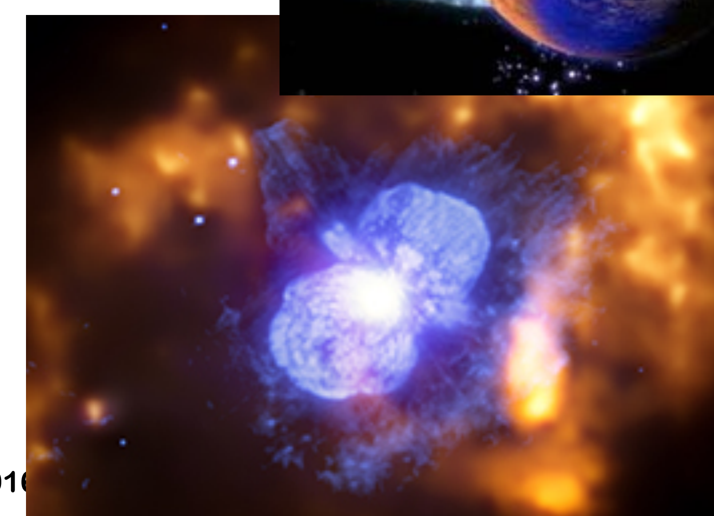
Minimum safe distance: ~8 pc



The Hits Keep Coming:
Gamma-Ray Bursts

Melott, Thomas; Dermer & Holmes





- ★ Gamma-ray bursts also delive intense ionizing radiation dos
  - tightly beamed
  - relativistic jet
  - ultra-high energy cosmic rays?
- ★ Ozone removal if Earth in beam
  - kill radius ~ 1000 pc = 1 kpc
  - but in-beam events rare
- ★ Net lethality ~ same as SN!
- ★ Nearest GRB candidate: eta Carinae
  - distance: 2.3 kpc
  - could explode as GRB-producing “hypernova”

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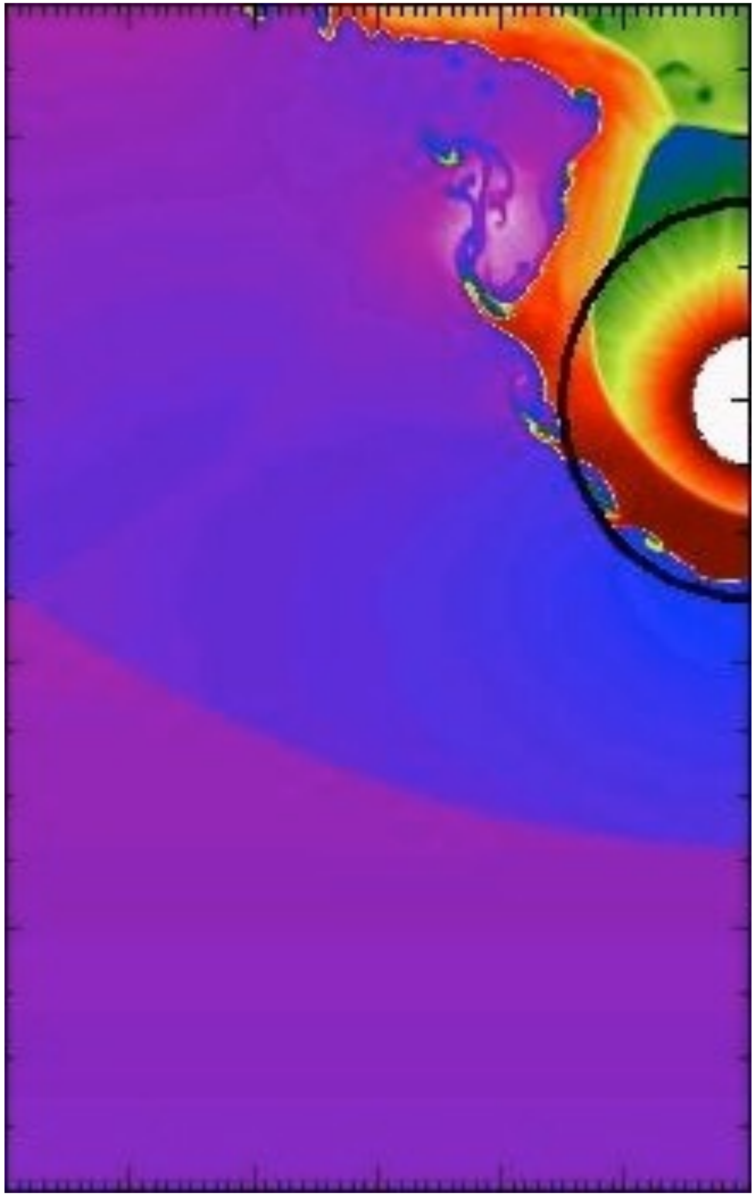


The Smoking Gun

David Schramm

1945-1997

The Smoking Gun: Supernova Debris on the Earth

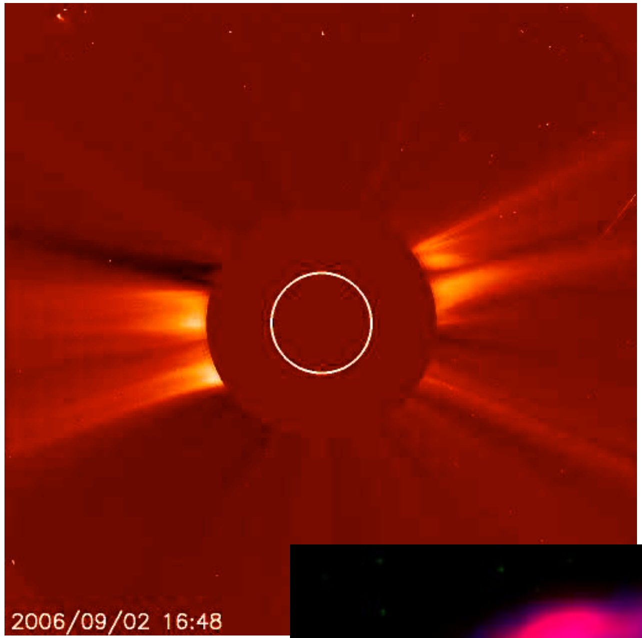
Ellis. BDF. & Schramm 1996

Explosion launched at ~few% c
Slows as plows thru interstellar matter

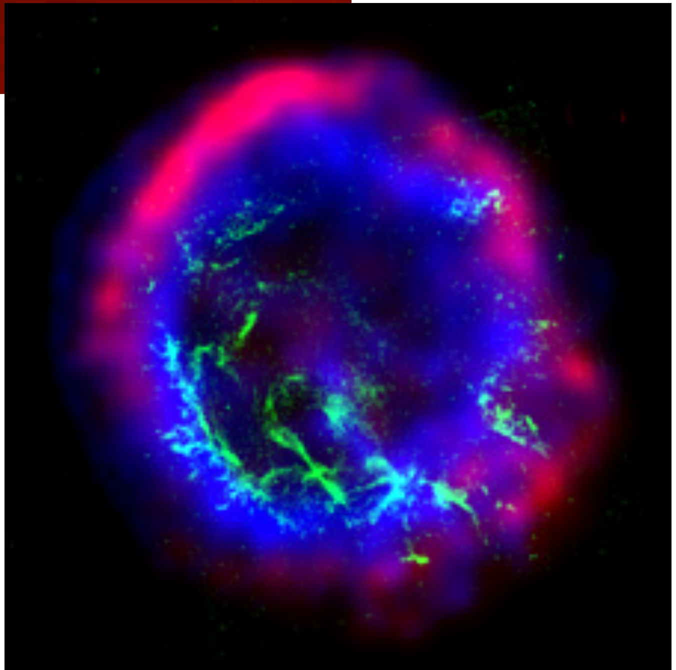
Earth "shielded" by solar wind

If blast close enough:
- ✓ overwhelms solar wind
- ✓ SN material dumped on Earth
- ✓ Accumulates in natural "archives"
  sea sediments, ice cores

Q: How would we know?
Need observable SN "fingerprint"
→ Nuclear Signature
- X Stable nuclides: don't know came from SN
- ✓ Live radioactive isotopes: none left on Earth
  If found, must come from SN!



SOHO

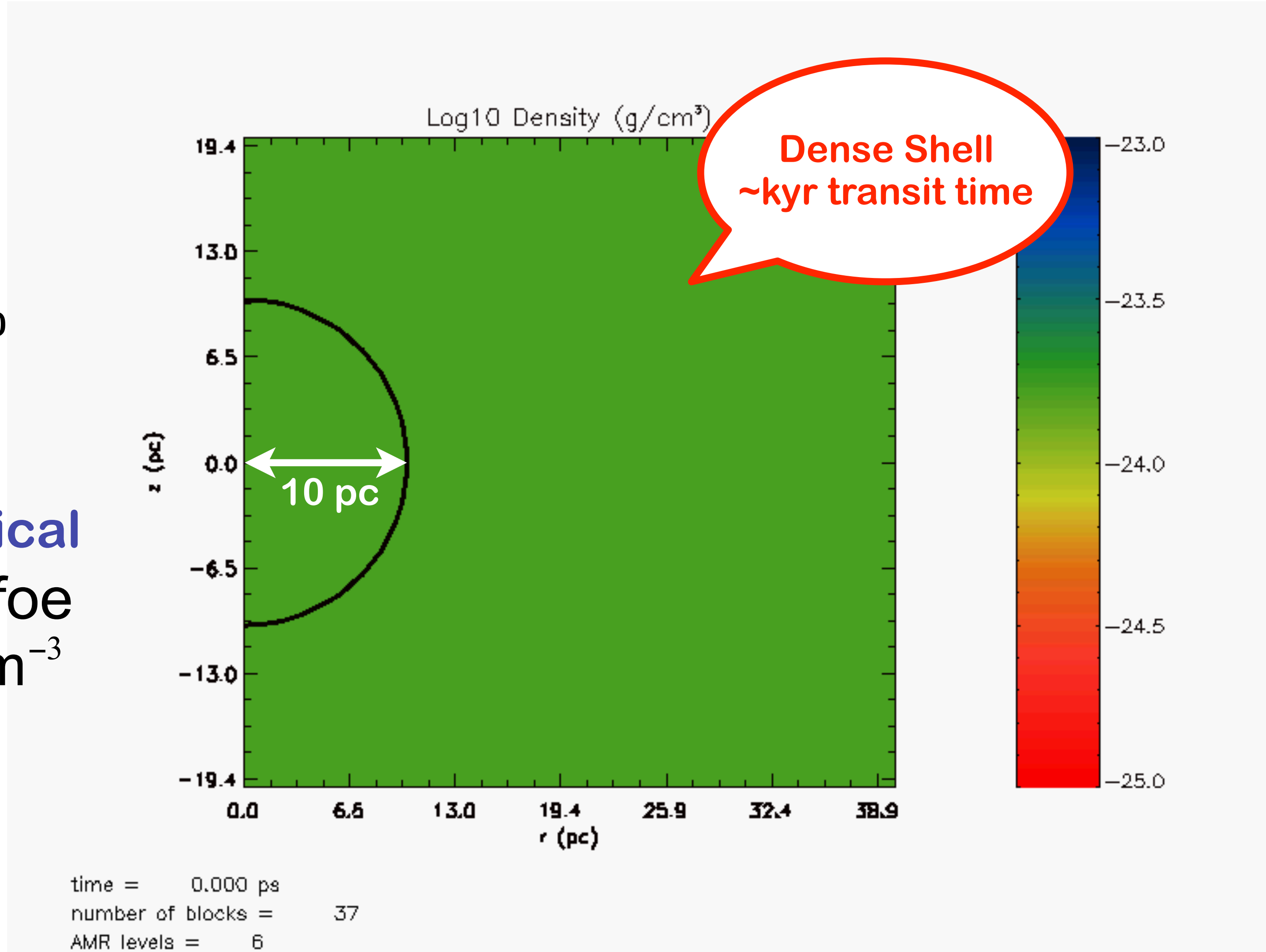


Chandra

The Fury of Aerial Bombardment:
Supernova Blast Passage--Global View
BDF, Athanassiadou, Johnson 2008

Supernova Remnant Evolution

- **Simulation:**
  FLASH Fryxell et al 2000
  Adaptive Mesh Refinement
- **geometry: cyindrical**
- $E_{\text{init}} = 10^{51}\,\text{erg} \equiv 1\,\text{foe}$
  $n_{\text{ISM}} = 1\,\text{particle cm}^{-3}$



Supernova Blast Impact on the Solar System

BDF, Athanassiadou, & Johnson 2006

Simulation:

FLASH Fryxell et al 2000

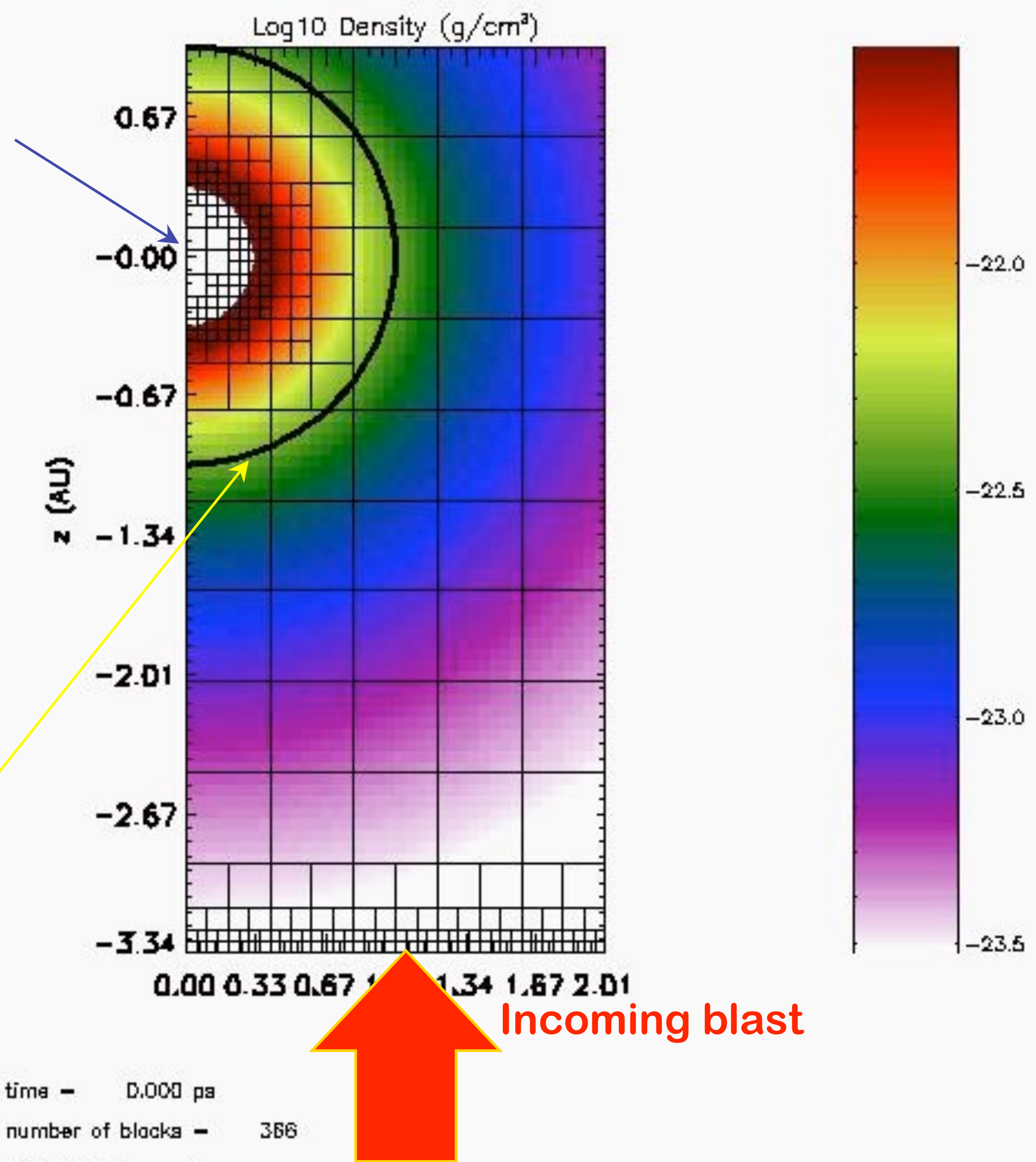
Blast Properties:

SN at 10 pc

Geometry:

Cylindrical

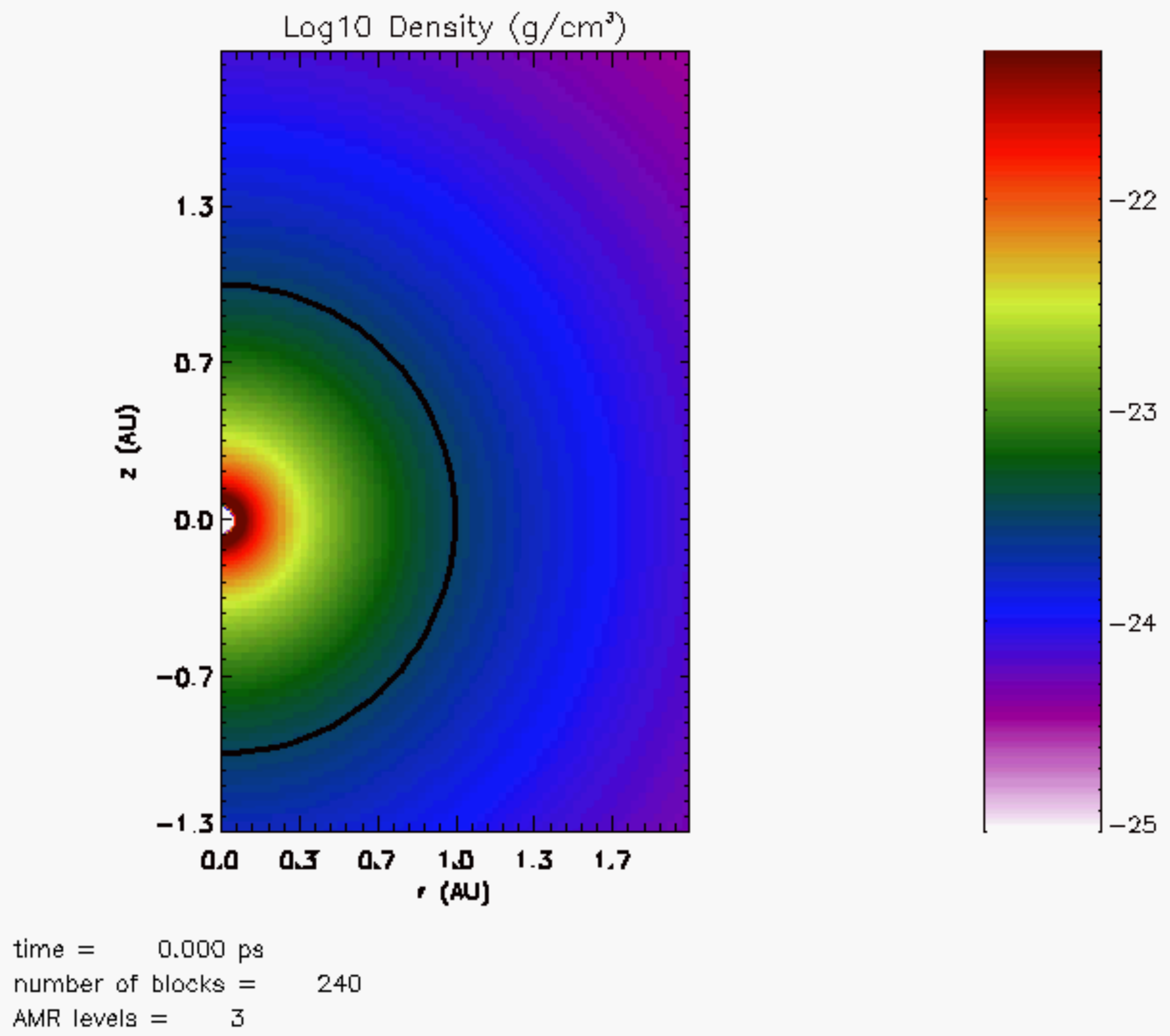
Sun



1 AU =
Earth's orbit

Incoming blast

BDF, Athanassiadou, & Johnson 2008



Now in 3-D!

It's a squid!

Athanassiadou et al in prep

Debris Delivery via Dust

Athanassiadou & BDF 11; Fry & BDF in prep

What if $d_{\rm SN} > 10\ {\rm pc}$ ⇨ $r_{\rm shock} > 1\ {\rm AU}$?

- gas-phase SN debris excluded from Earth

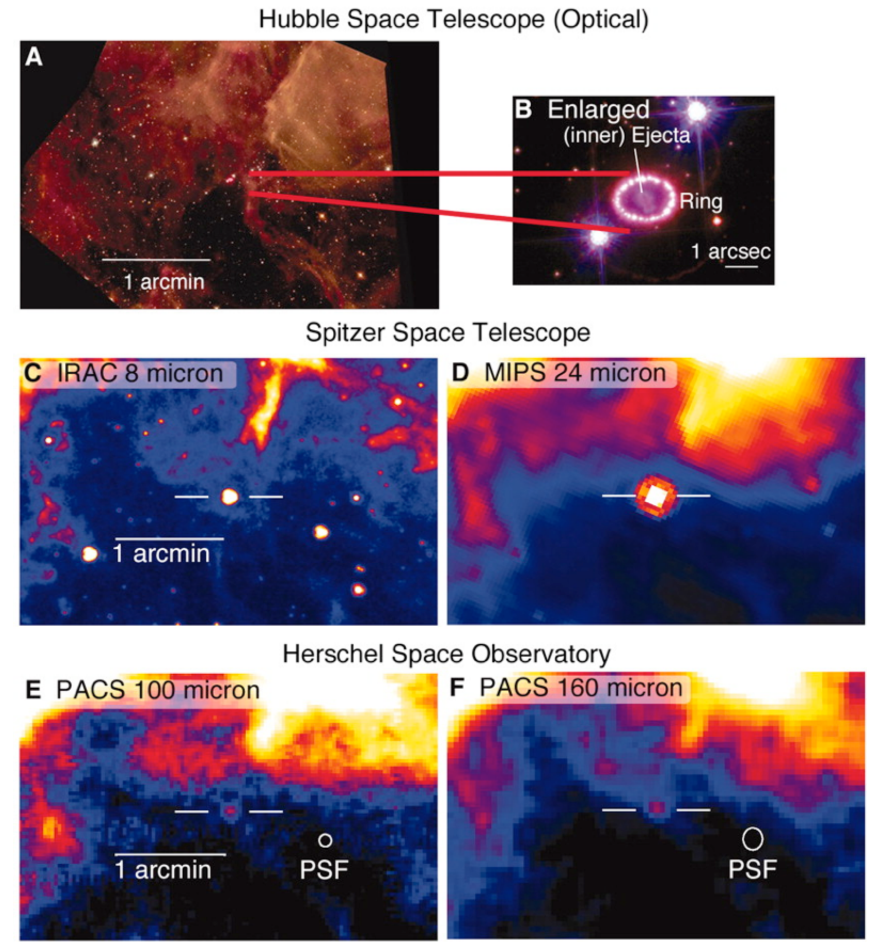
But SN radioisotopes all are refractory elements ⇨ dust grains

SN1987A:

- ~100% (!) of Fe in dust after 20 years

SN dust reaches Earth even if gas does not

- dust decouples from gas at shocks
- grains incident on heliosphere feel gravity, radiation pressure, magnetic fields
- for $v_{\rm dust} > 100\ {\rm km\ s^{-1}} \gg v_{\rm esc}$ nearly ballistic trajectory
- radioisotope delivery efficiency set by dust survival fraction



SN1987A dust: Matsuura+ 2011

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Geological Signatures

Deep Ocean Crust

Knie et al. (1999)
ferromanganese (FeMn) crust

Pacific Ocean

growth: ~ 1 mm/Myr

AMS ⇒ live ^{60}Fe, $\tau = 2.2\,\mathrm{Myr}$!

Expect: one radioactive layer

1999: ^{60}Fe in multiple layers!?

- detectable signal exists
- but not time-resolved

^{60}Fe Confirmation
Knie et al (2004)

Advances

New crust from new site

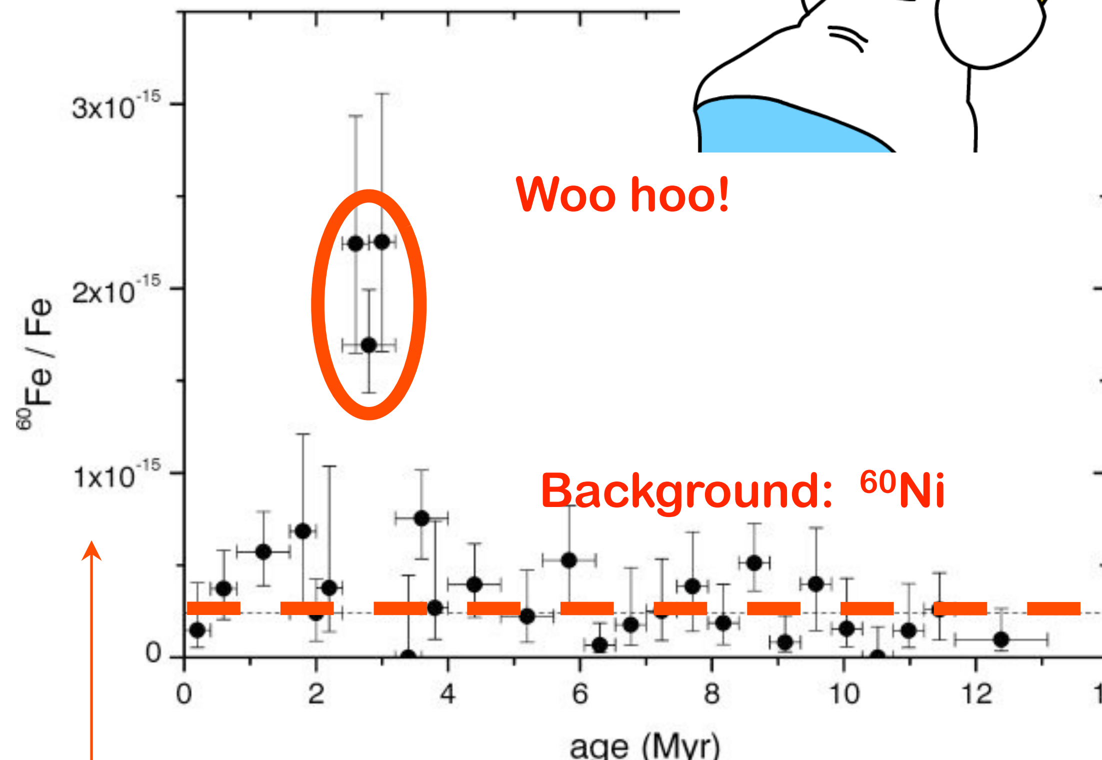
- ✓ Better geometry (planar)
- ✓ better time resolution
- ✓ ^{10}Be ⇨ radioactive timescale

Isolated Signal

$$t = 2.8 \pm 0.4 \text{ Myr}$$

A Landmark Result

- ★ Isolated pulse identified
- ★ Epoch quantified
- ★ Consistent with original crust



Note fantastic AMS sensitivity!

Whodunit?

Fry, BDF, & Ellis 2015

Turn the problem around:

$$N_{60,\mathrm{obs}} \sim M_{\mathrm{ej},60} e^{-t/\tau} / d^2$$

$$d \sim \sqrt{\frac{N_{\mathrm{obs}}}{M_{60}(M_{\mathrm{SN}})}}$$

"radioactivity distance" from ^{60}Fe yield

What makes ^{60}Fe?

- core-collapse supernovae
- ~~Type Ia supernovae~~
- ~~AGB stars~~
- ~~kilonovae~~

SN distance:

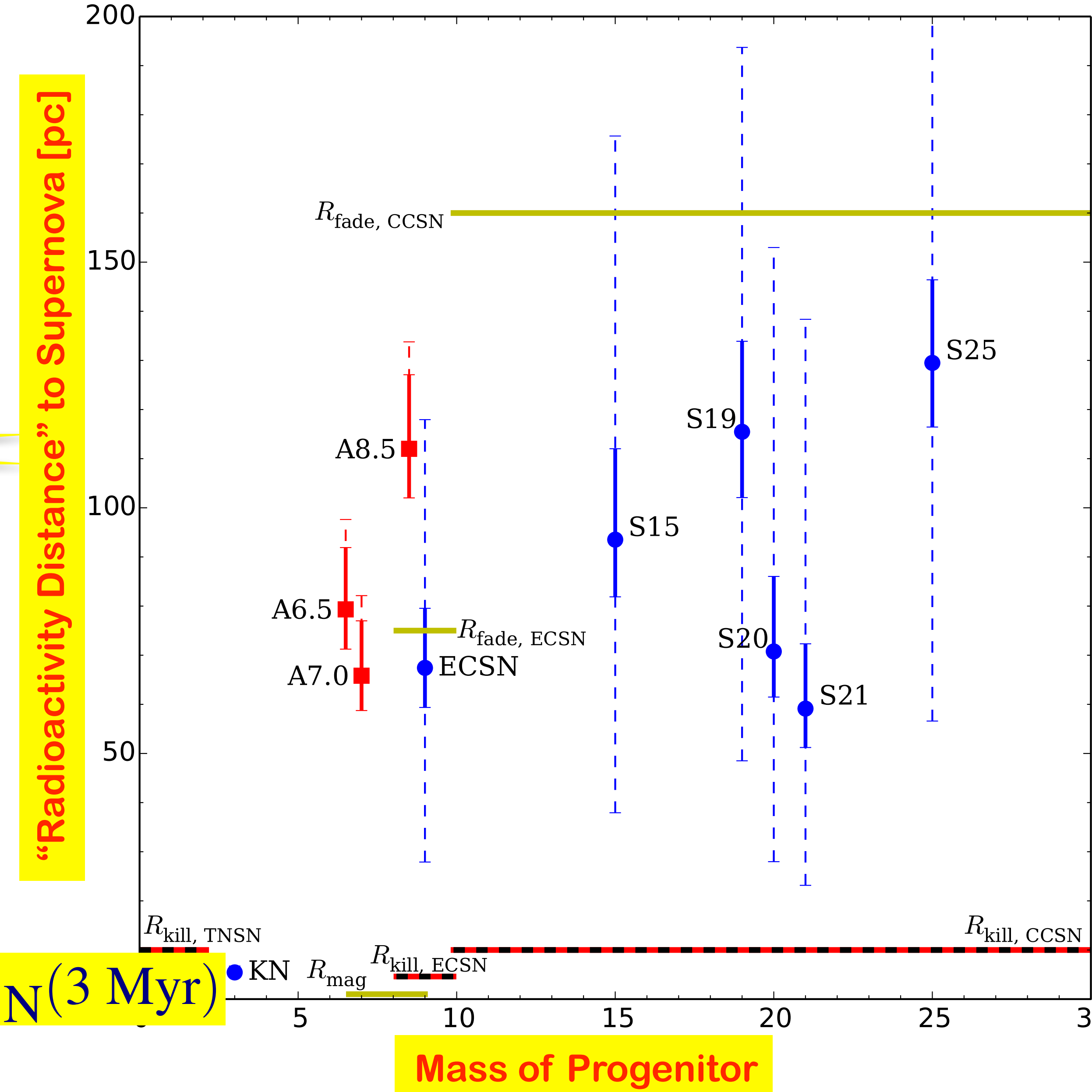
$$d(\mathrm{SN}) \sim 20 - 100\ \mathrm{pc}$$

Encouraging:

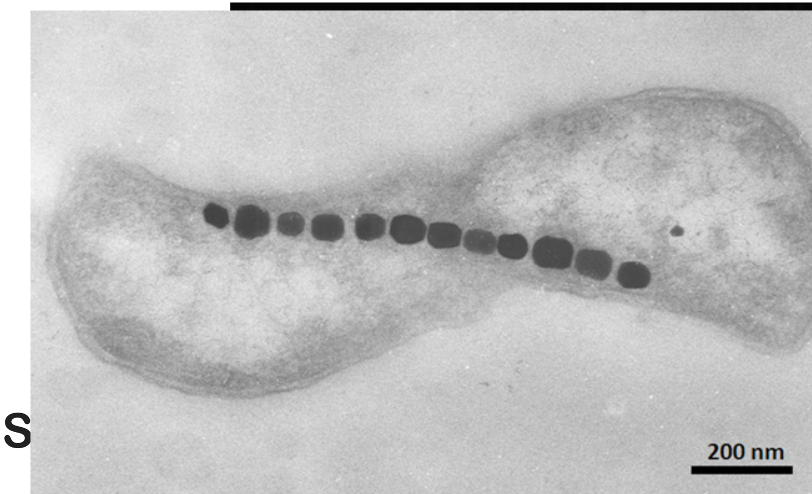
★ astronomical distances not built in!

★ $d(^{60}\mathrm{Fe}) \approx d(\mathrm{SN} \rightarrow \mathrm{Earth}) \approx d_{\mathrm{SN}}(3\ \mathrm{Myr})$

⇨ nontrivial consistency!

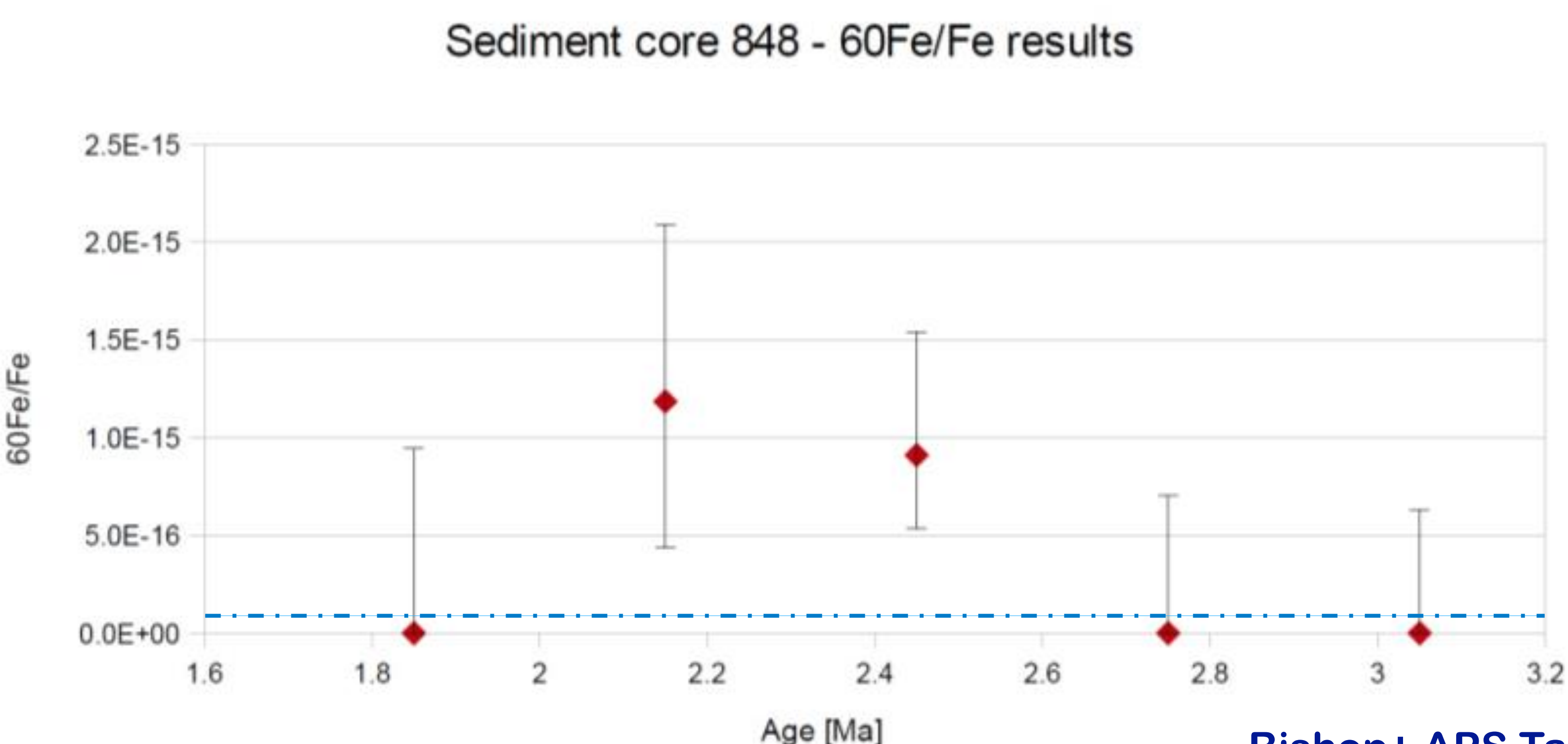


Other Signals?



Radioactive Fossil Bacteria S. Bishop APS

- -magnetotactic bacteria synthesize mage
  nanoparticles (Fe_3O_4)
- -incorporate & concentrate ocean Fe



f lunar

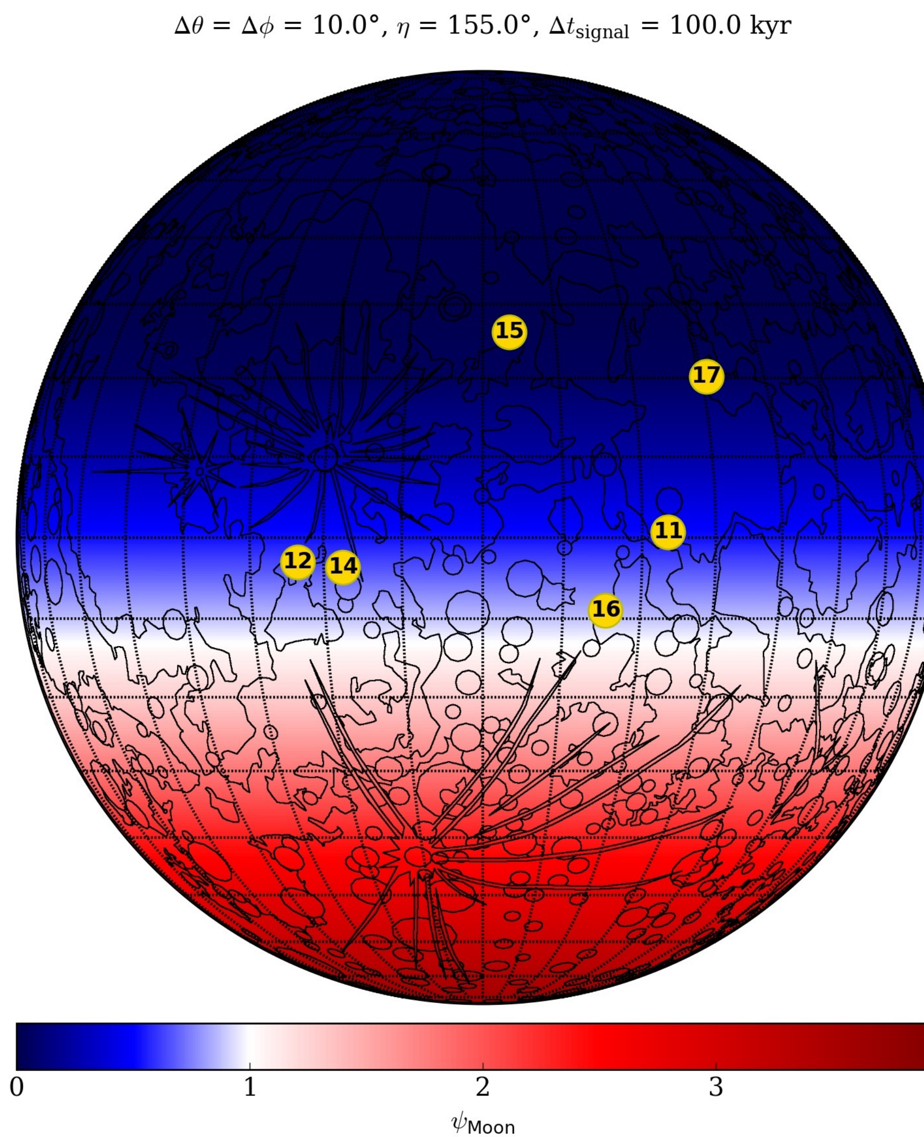
ollo 12 (1969)

Bishop+ APS Talk 2013

Whodunit?
The Moon as a Telescope

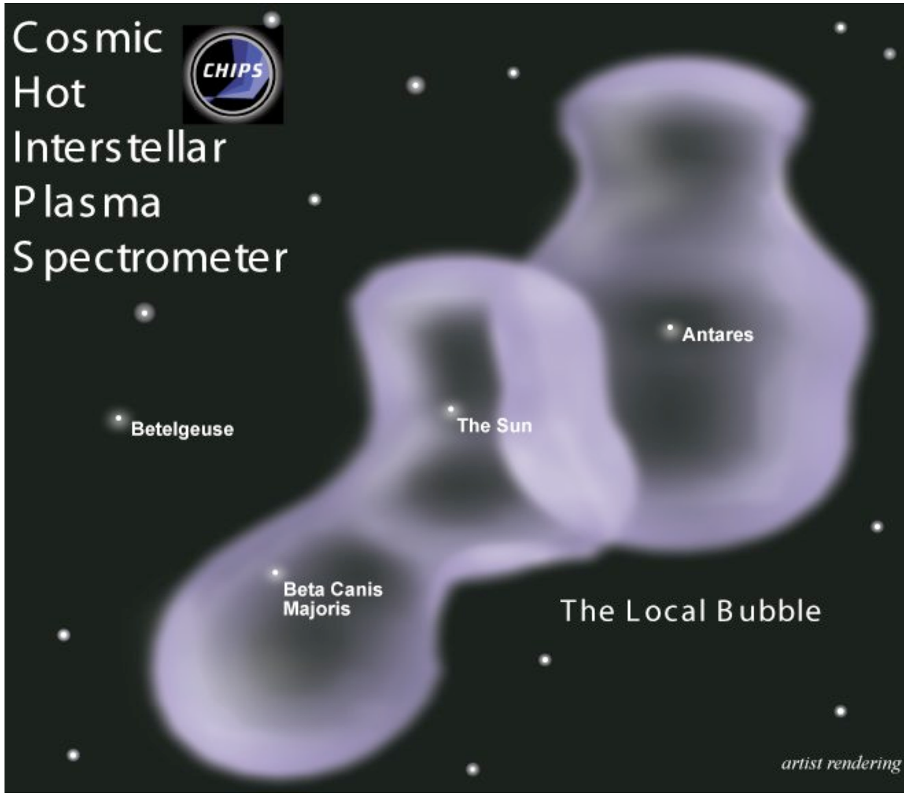
Fry, BDF, & Ellis (2016)

- ★ ^{60}Fe dust grains nearly undeflected in Solar Systen
- ★ Earth:
  - stratosphere scrambles
- ★ Moon is airless:
  - encodes direction!
  - ^{60}Fe pattern points to source!



Aftermath: The Local Bubble?

- The Sun lives in region of hot, rarefied gas
  - The Local Bubble
  - hot cavity ~50 pc ⇨ huge
  - seen via foreground absorption in nearby starlight
- Nearby SN needed
  - we live inside SN remains
  - bubble models require >> 1 SN in past 10 Myr Smith & Cox 01
  - ^{60}Fe event from nearest massive star cluster? Benitez et al 00



A Near Miss?

$d > d_{\mathrm{kill}} \sim 10$ pc ...but barely:

"near miss"

- ¿ cosmic ray winter?
- ¿ bump in extinctions?

Image: Mark Garlick
www.markgarlick.com

If true:

implications for astrobiology

tightens Galactic habitable zone

Outlook

- ★ Live ^{60}Fe seen in several deep-ocean crusts
- ★ Signal isolated to ~2-3 Myr ago
- ★ Source of Local Bubble?

Birth of “Supernova Archaeology"
Implications across disciplines:
  nucleosynthesis, stellar evolution, bio evolution, astrobiology
Nuclear & particle physics central

Future Research

- better model of SN penetration of heliosphere
- improved SN nucleosynthesis
- more, different samples:
  - ✓ other isotopes
  - ✓ other media (fossil bacteria)
  - ✓ other sites (lunar cores?)
- other epochs?   Mass extinction correlations?
- stay tuned...

Assault on the Heliosphere: Lessons

Hydrodynamic collision:

✓ Supernovae < few 10 pc
penetrate inside ~few AU

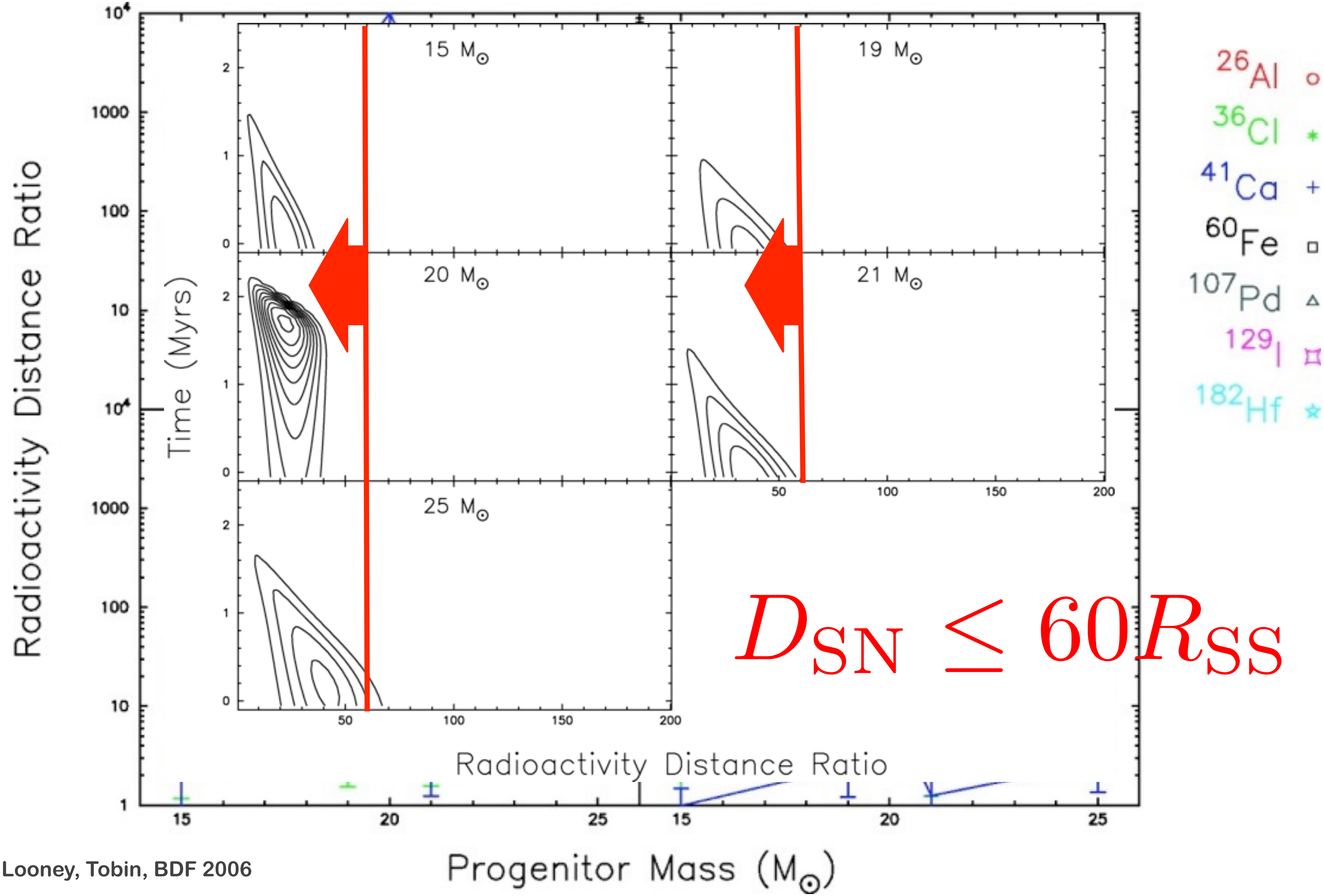
✓ Why? Happy(?) accident

➡ Ram pressures $\rho v^2(\mathrm{SN}, 10\mathrm{pc}) = \rho v^2(\mathrm{SW}, 1\mathrm{AU}) = 2\ \mathrm{nPa}$

For today:

- Take seriously possibility of SN ejecta ⇒ Earth
- Look for observable consequence

Radioactive Supernova



$$D_{\rm SN} \leq 60 R_{\rm SS}$$

Looney, Tobin, BDF 2006

Terrestrial Signatures of Nearby SNe

Ellis, BDF, Schramm 96

Observables

- Signature: Isotope Anomalies
- Medium: Gelogical Sediments “Natural Archives”
  - Ice Cores
  - Sea Sediments
- Measure: Specific concentration

$$\frac{n_i}{\rho_{\rm sed}} \sim \frac{M_{\rm SNeject,\mathit{i}}/d^2}{(\rm sed\ rate)\Delta t_{\rm dep}}$$

$$= 5 \times 10^7 \ {\rm atoms\ g^{-1}} \left(\frac{X_{ej,i}}{10^{-5}} \right) \left(\frac{1\ {\rm kyr}}{\Delta t_{\rm dep}} \right) \left(\frac{10\ {\rm pc}}{d} \right)^2$$

The Future:
Supernova Tsunami

- ★ **By LSST: ~1,000,000 core-collapse events each year!**
- ★ **Cosmic Supernova Rate by direct counting**
  - rate measured to 10% out to z~1
    - tradeoff: redshift range (scan depth) vs SN counts (sky co
  - largest uncertainty: dust obscuration
- ★ **Core-collapse come for free!**
  - survey characteristics tuned to SN Ia
  - automatically well-suited for SN II