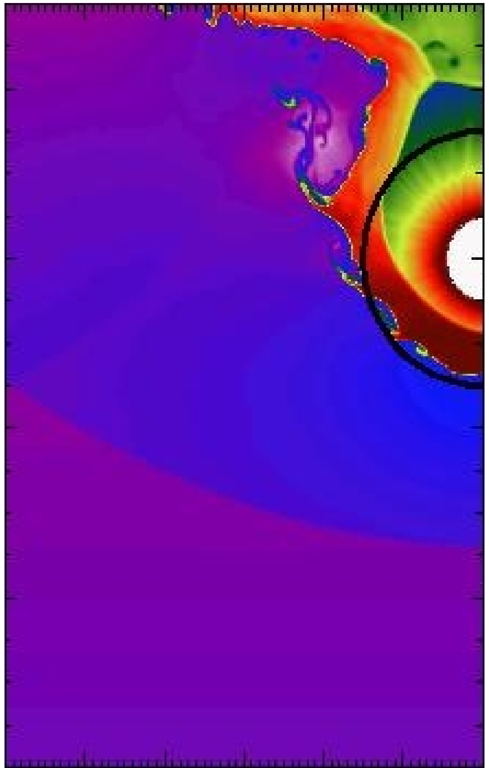
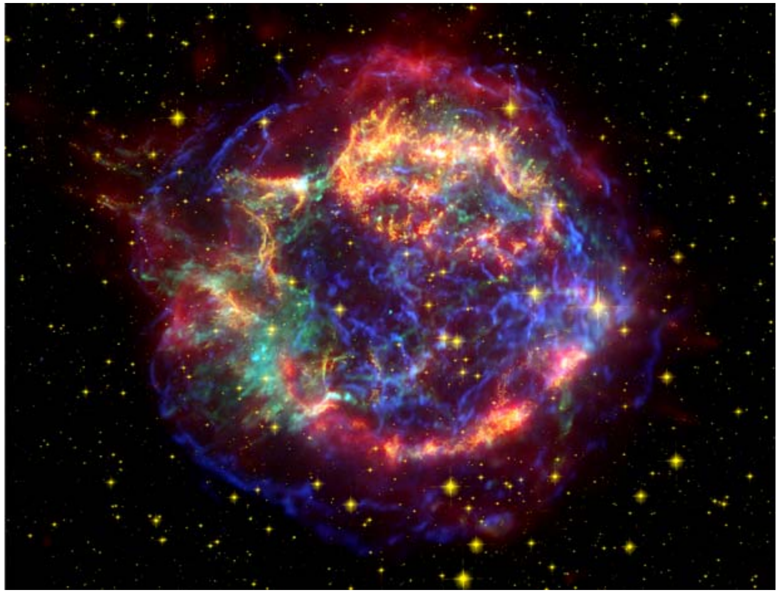
When Stars Attack!

Live Radioactivities as Signatures of Nearby Supernovae





Brian Fields

Astronomy & Physics, U Illinois

NIC-IX, CERN, June 2006

June 2, 2006

from Nuclei in the Cosmos...
to Nuclei in a Sea Sludge...

Collaborators

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Scott Johnson	
Kathrin Hochmuth	Technical U. Munich
John Ellis	CERN

Live Radioactivities and Nearby Supernovae

- **Nearby Supernovae**

  a unique laboratory…and a unique threat

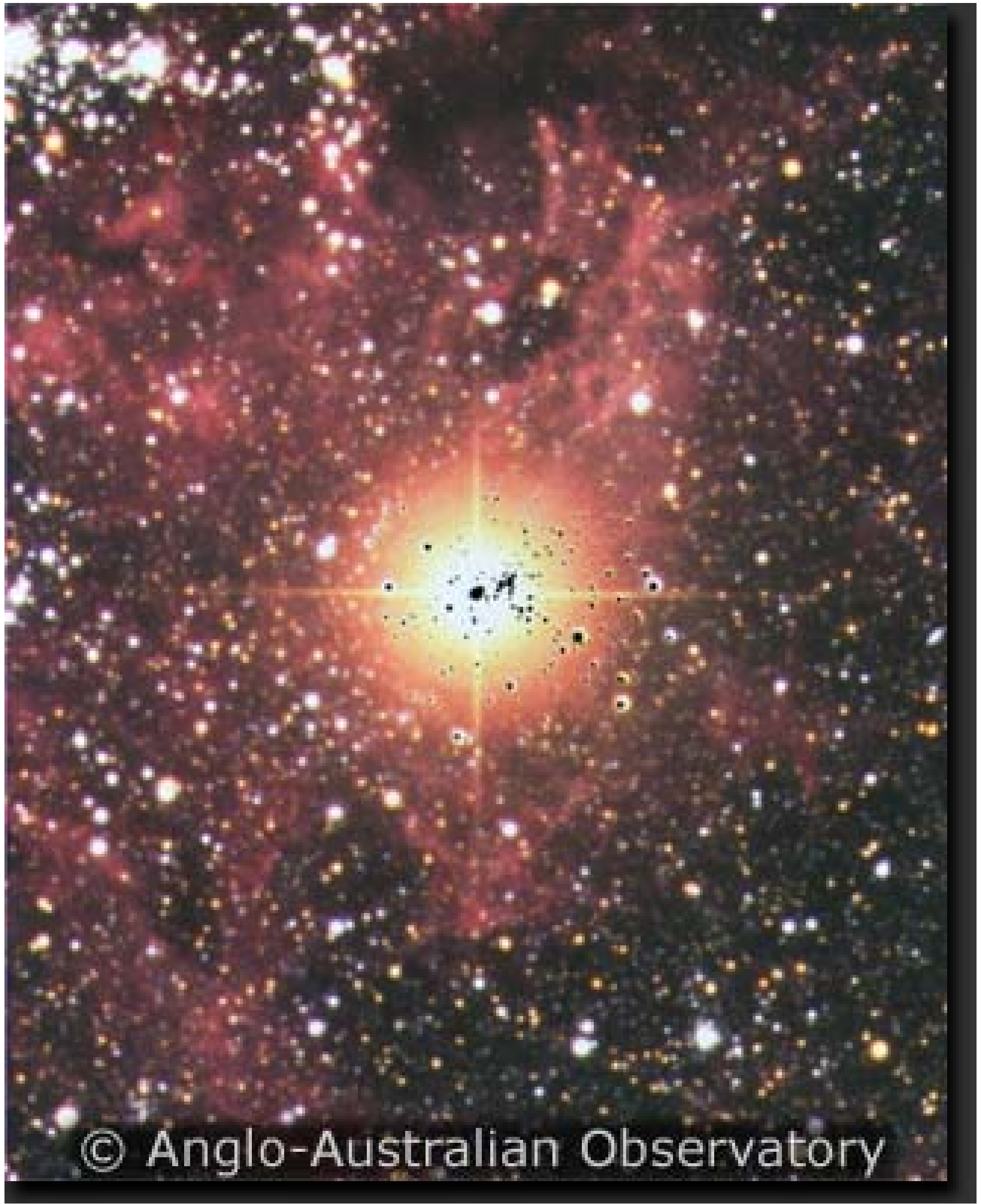
- **The Smoking Gun**

  supernova radioactivities on Earth

- **Geological Signatures**

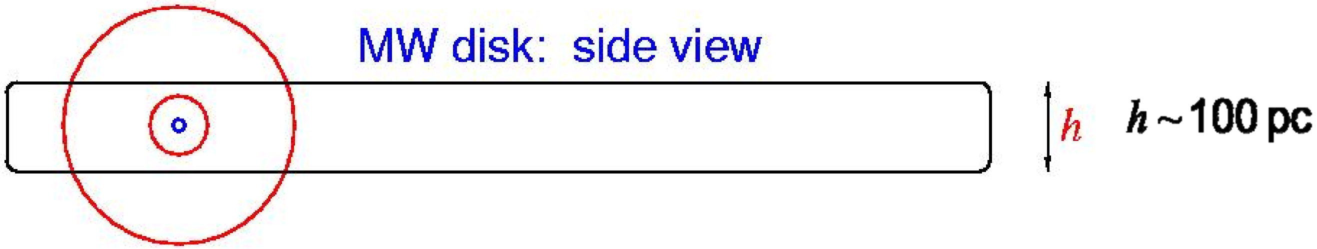
  sea sediments as telescopes

Nearby Supernovae



Cosmic WMD: Rates

- How often? Depends on how far! Shklovskii 68
- Rate of Supernovae inside d:
  - Galactic supernova rate today: $\mathcal{R}_{\rm SN}$
  - in homog. disk, scale height



$$\lambda(< d) = \frac{V_{\rm disk}(< d)}{V_{\rm disk,total}} \mathcal{R}_{\rm SN} = (0.3\ {\rm Myr})^{-1} \left(\frac{d}{100{\rm pc}} \right)^3$$

  - 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 of a supernova too close

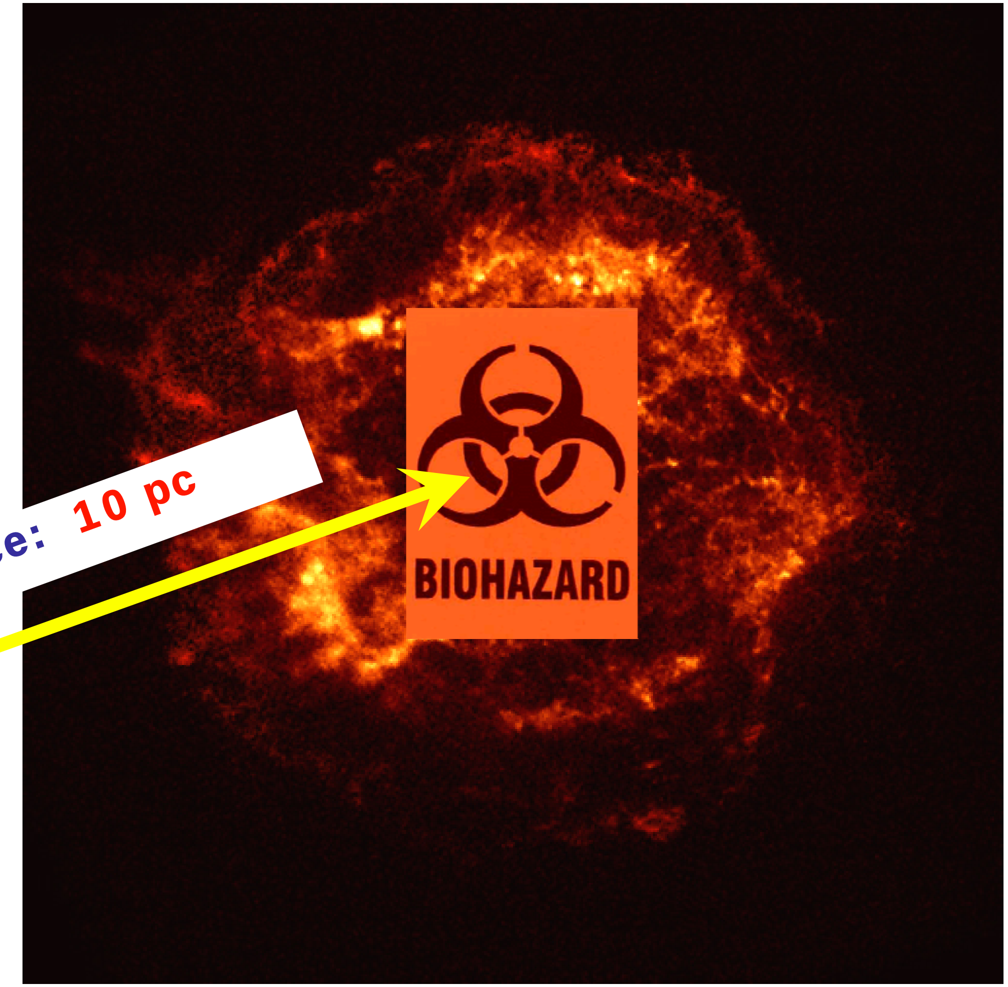
possible source of mass extinction

- Shklovskii; Russell & Tucker 71; Ruderman 74

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
  but true hazard unclear
  Crutzen & Bruhl 96; Gehrels etal 03;
  Smith, Sclao, & Wheeler 04
- seeds cloud formation? Svensmark 98 cosm… winter? BDF & Ellis 99

Minimum safe distance: 10 pc

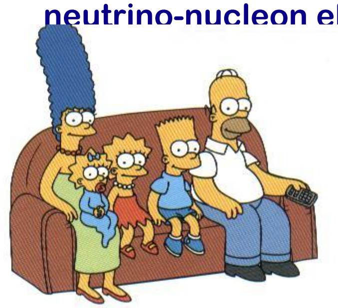


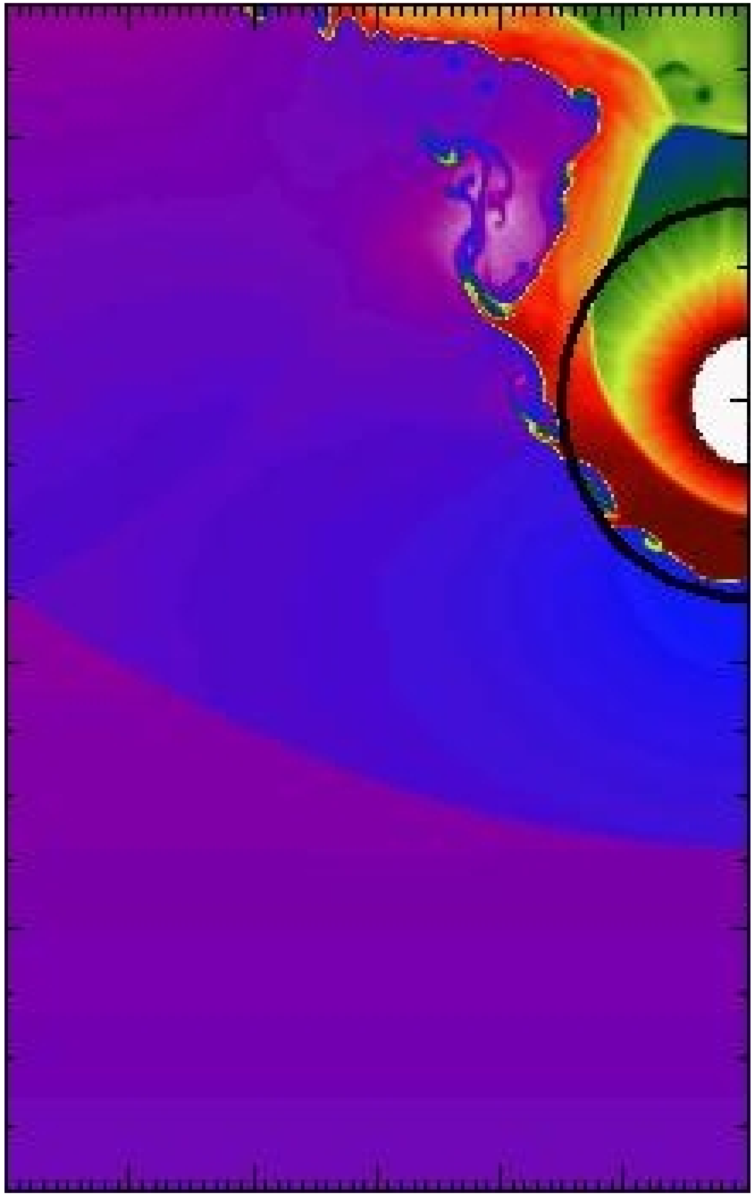
Neutrinos

- neutrino-nucleon elastic scatt…ing:

…er

…02





The Smoking Gun

The Smoking Gun:
Supernova Debris on the Earth

Ellis, BDF, & Schramm 1996

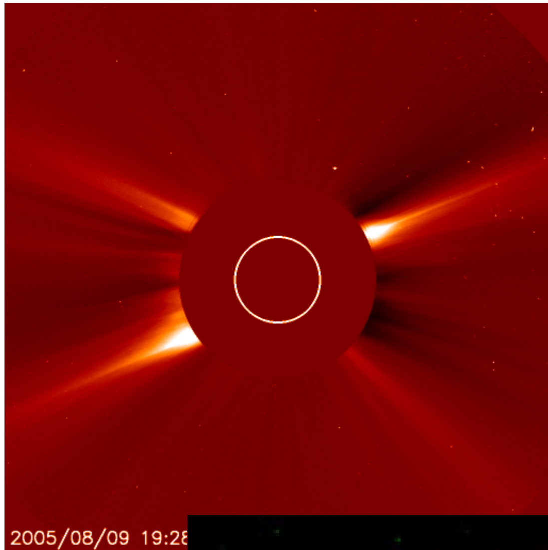
Explosion launched at ~few% c

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

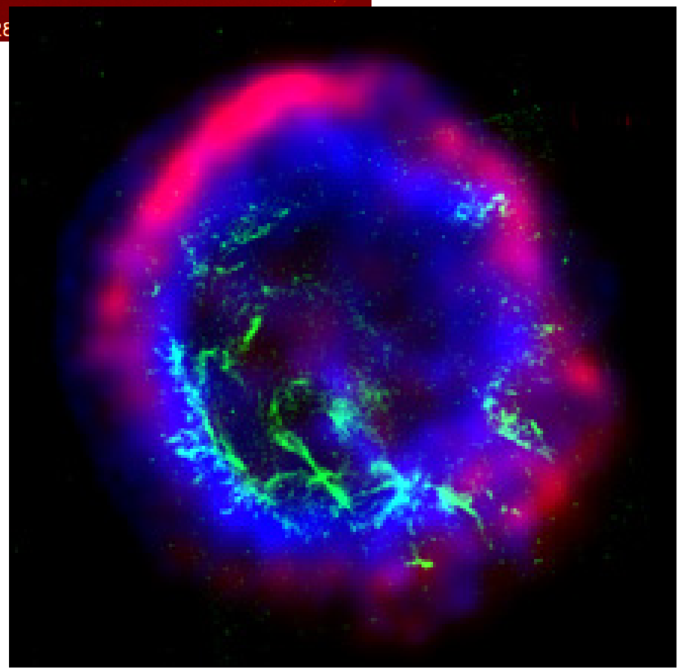


Q: How would we know?

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!



Supernova Blast Impact on the Solar System

BDF, Athanassiadou, & Johnson 2006

Simulation:

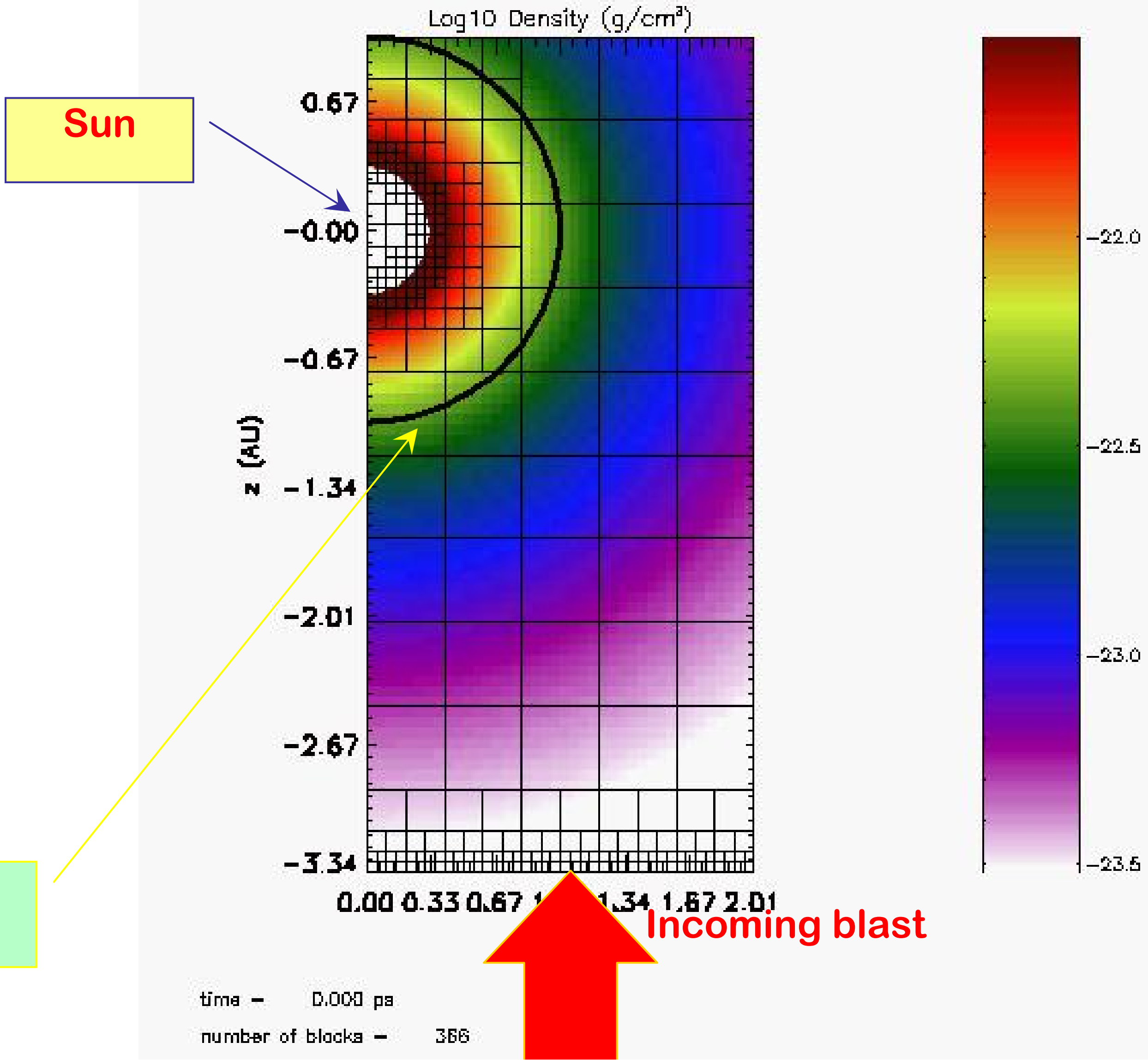
FLASH Fryxell et al 2000

Blast Properties:

SN at 10 pc

Geometry:

Cylindrical



BDF, Athanassiadou, & Johnson 2006

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Assault on the Heliosphere:
Lessons

Results preliminary, but already clear:

- ✓ Supernovae < few 10 pc
  penetrate inside ~few AU
- ✓ Why? Happy(?) accident
  - Ram pressures $\rho v^2(\mathrm{SNR}, \sim 10\mathrm{pc}) \approx \rho v^2(\mathrm{SW}, \sim 1\mathrm{AU})$

Since $r_{\text{shock-Sun}} \sim 1\mathrm{AU}$ careful simulation warranted

- ❖ 3-D, dust, ions vs neutrals, B fields...
- ❖ "vanilla" model is worst case:
  most effects "beneficial" for matter deposition

For today:

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

Geological Signatures

Deep Ocean Crust

Knie et al. (1999) Korschinek talk
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)

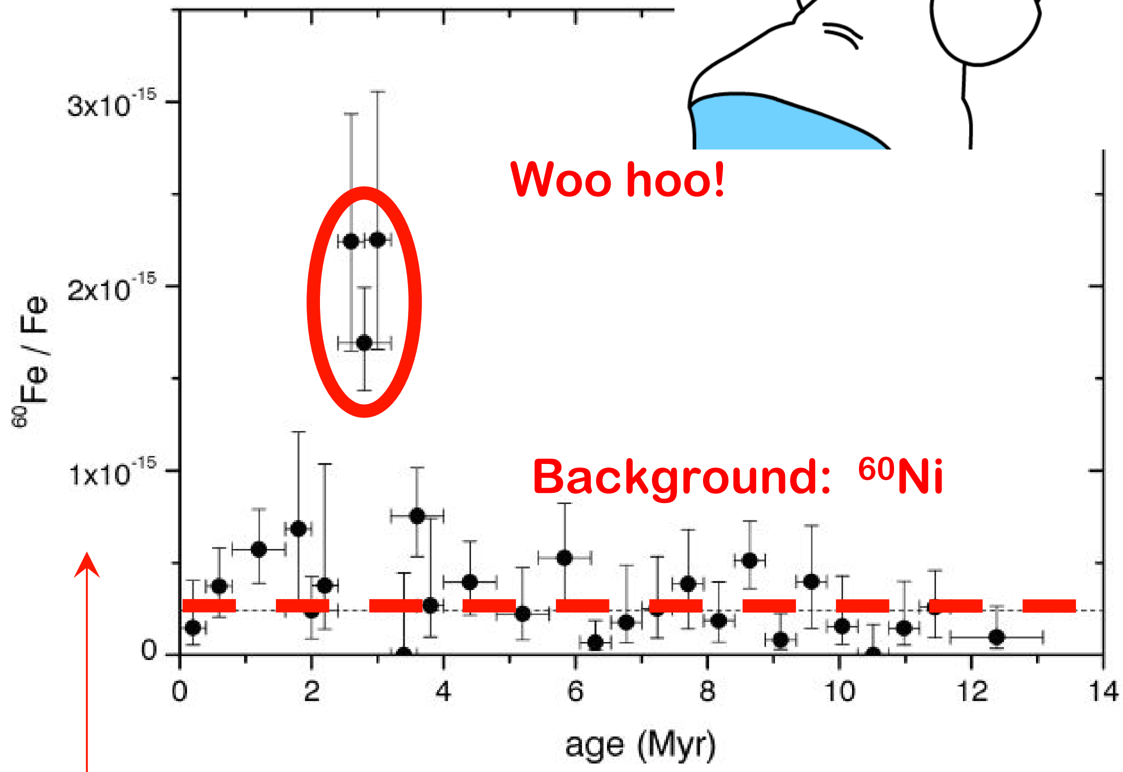
Advances Korschinek talk; Knie & Wallner poster

New crust from new site

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

Isolated Signal

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



Note fantastic AMS sensitivity!

A Landmark Result

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

Sea Sludge as a Telescope

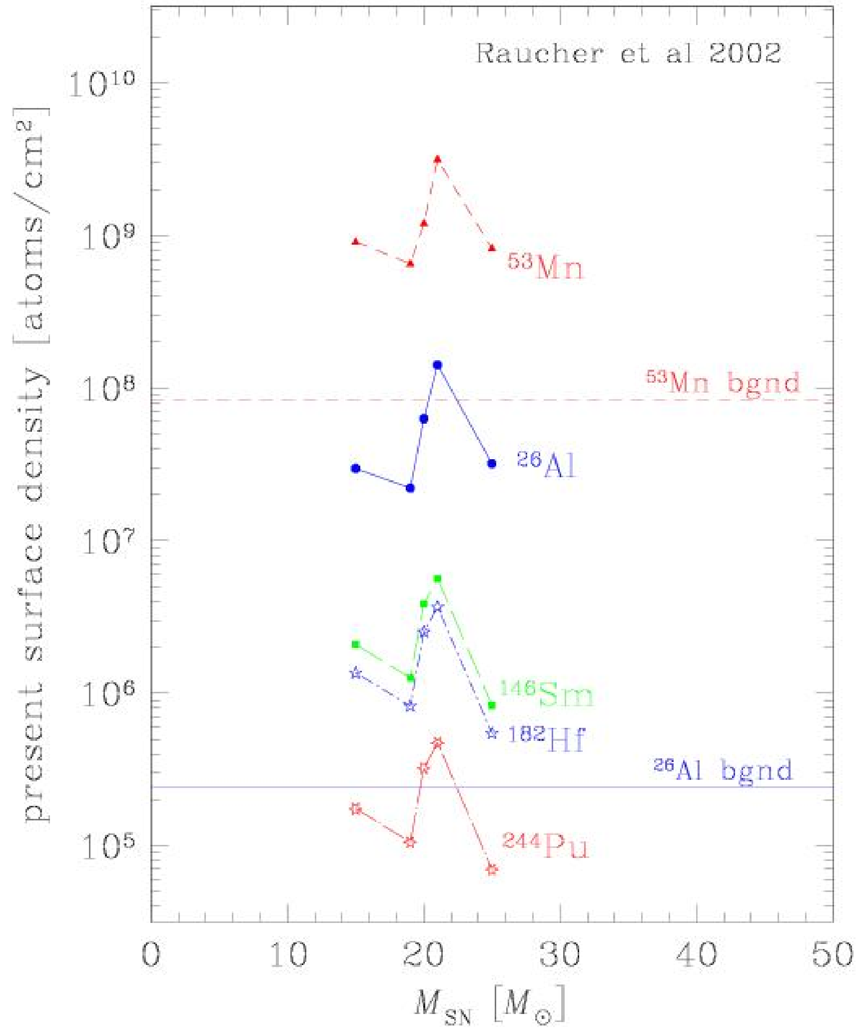
Given ^{60}Fe:
Other isotopes fixed by SN mass
Indep of SN distance!

$$N_i = \frac{M_{ej,i}(M_{SN})/A_i}{M_{ej,60}(M_{SN})/60} N_{60}$$

Probes SN mass, nucleosynthesis

Expect observable signals:
^{10}Be, ^{26}Al, ^{53}Mn
If r-process made:
^{182}Hf, ^{244}Pu

Wallner et al 2002: single ^{244}Pu atom(!)
If real: SN are r-process site!



Outlook

Summary and Conclusions

- Live ^{60}Fe seen in several deep-ocean crusts
- Signal isolated to ~2-3 Myr ago

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
  - ✓ other sites (lunar cores?)
- other epochs? Mass extinction correlations?
- stay tuned...

Implications: SN Distance

Turn the problem around:

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

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

In principle:

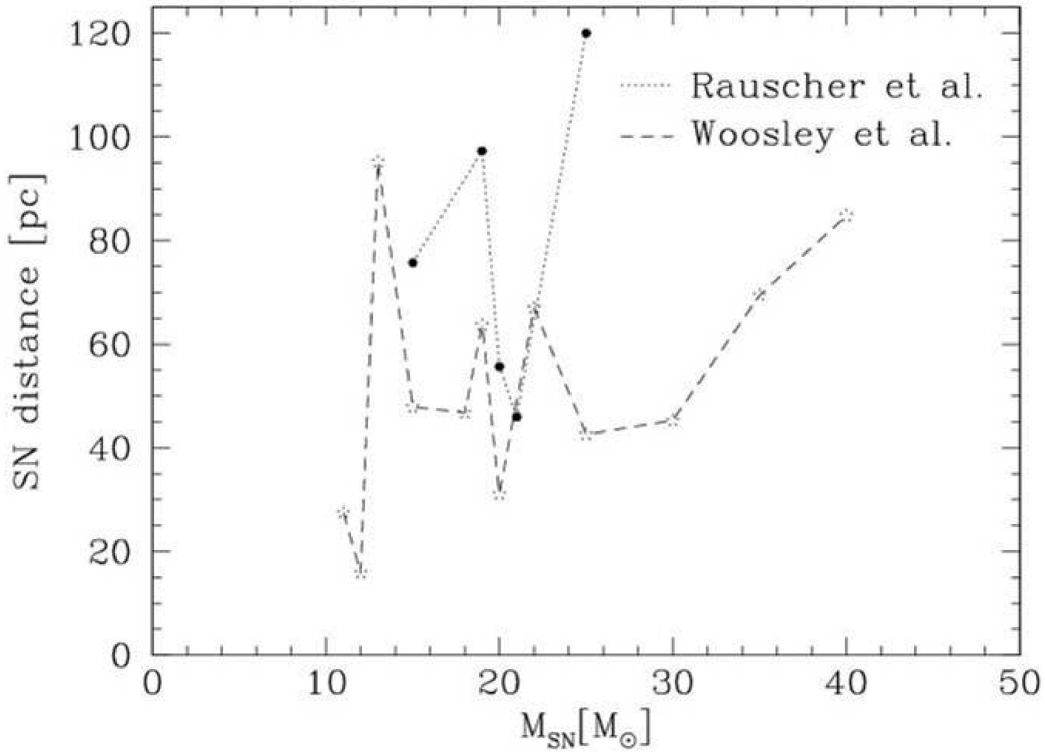
- Multiple isotopes ⇨ SN mass

In practice:

- ^{60}Fe mass dependence non-monotonic, model-dependent
- Need other isotopes

For now:

$$d \sim 20-100 \ \text{pc}$$



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A Near Miss?

$d > d_{\text{kill}} \sim 10\ \text{pc}$ ...but barely: "near miss"

¿ cosmic ray winter?

¿ bump in extinctions?

If true: implications for astrobiology

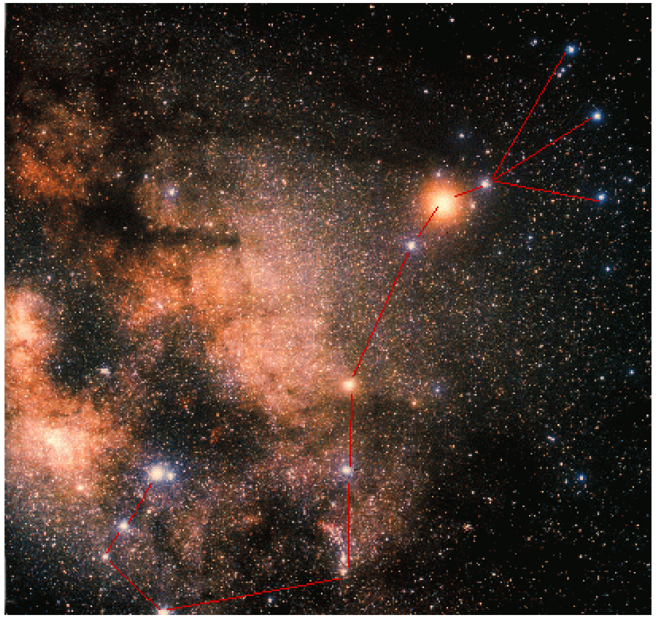
tightens Galactic habitable zone

^{60}Fe & ^{53}Mn in Deep Ocean Crust

Whodunit?

If SN: nearby, recent

- Cluster of newborn massive stars (OB association) may still exist
- maybe source of Local Bubble? (hot, rarefied gas surrounding solar system)?



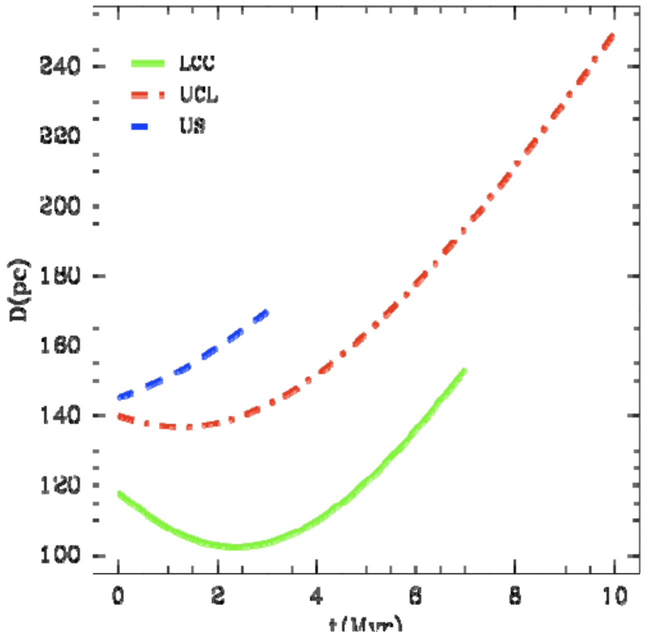
Sco-Cen OB Association

Benitez et al 2000

~120 pc away now

Kinematics: closest appraoch

100 pc (~ 40 pc at 2σ)



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

$$\Lambda_i = \frac{n_i}{\rho_{\text{sed}}} \sim \frac{M_{\text{ej},i} / d^2}{(\text{sed rate})\Delta t_{\text{dep}}}$$

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