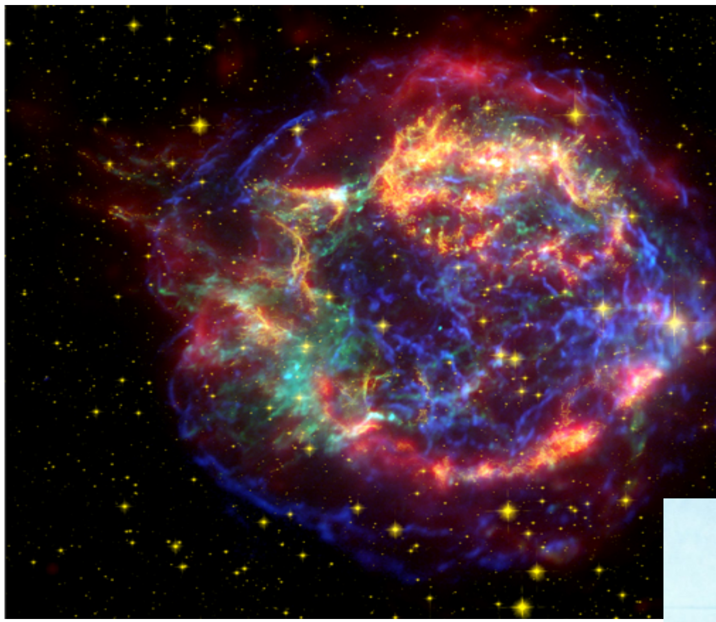
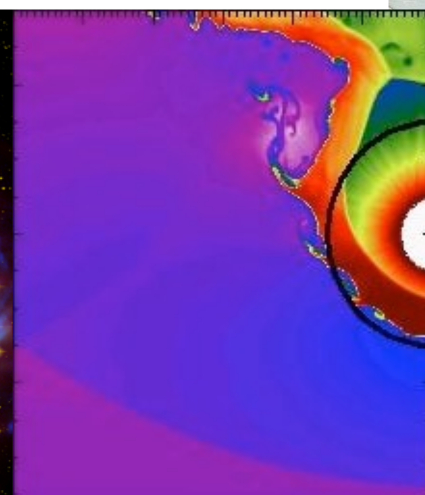
When Stars Attack!

Recent Near-Earth Supernovae Revealed by ^{60}Fe



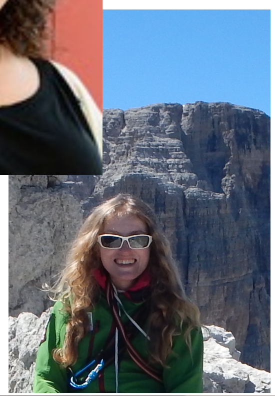


Thank You Organizers!

Brian Fields
Astronomy & Physics, U Illinois

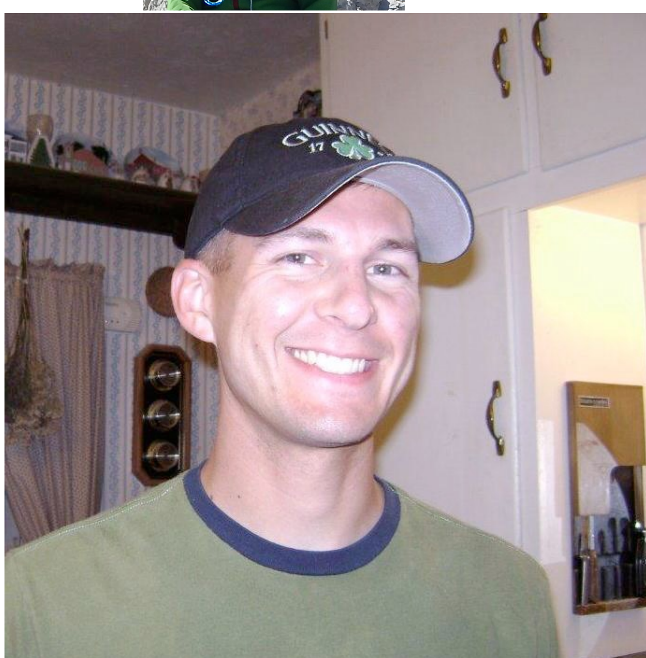
Nearby Supernova Collaborators

Themis Athanassiadou



Scott Johnson

Kathrin Hochmuth



John Ellis CERN

Brian Fry

Recent Near-Earth Supernovae Revealed by ^{60}Fe

★ **Supernovae are Radioactivity Factories**

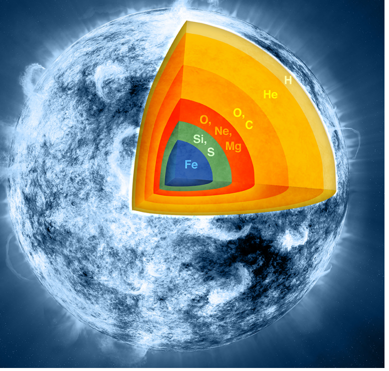
if near: a unique laboratory…and a unique threat

★ **The Smoking Gun**

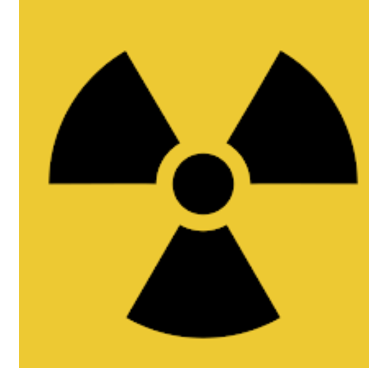
supernova radioactivities on Earth

★ **Geological Signatures**

sea sediments as telescopes



Supernovae are Radioactivity Factories



- **medium-lived radioactivities: ^{60}Fe, ^{26}Al, ^{53}Mn, ^{41}Ca, ^{97}Tc(?), ^{146}Sm(?)**

- **^{60}Fe: made by neutron captures**

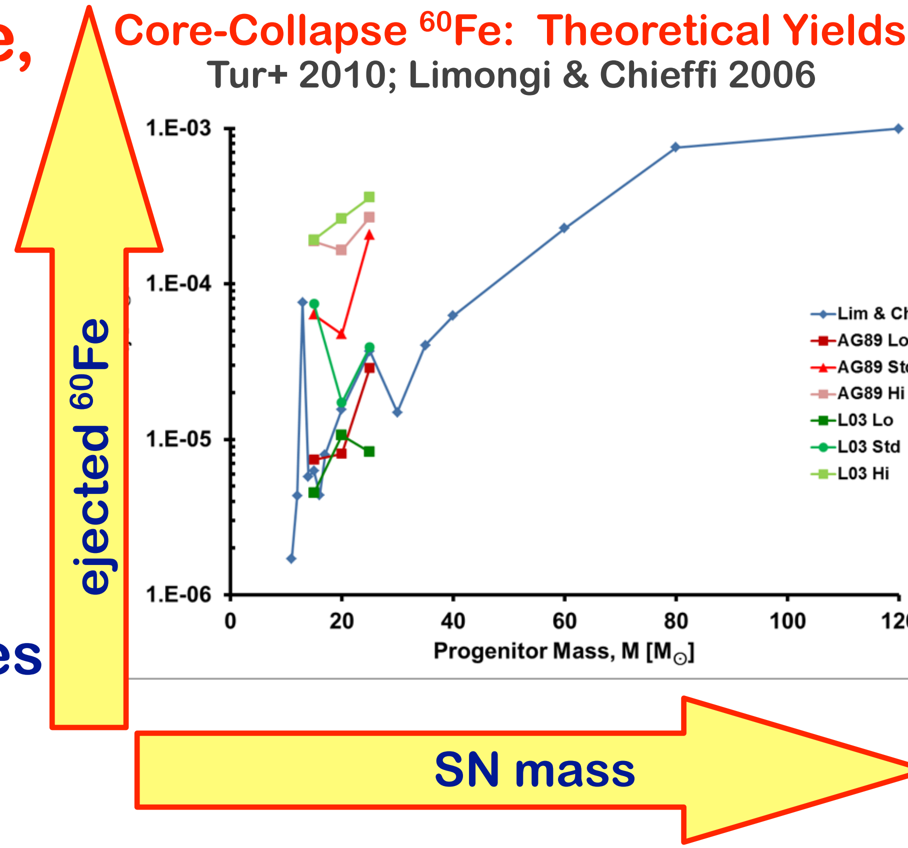
  "weak s-process"

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

  large theoretical uncertainties in yield

  sensitive to stellar evolution, nuke rates

  accuracy ~order of magnitude



- **r-process? ^{182}Hf, ^{244}Pu**

The Smoking Gun: Supernova Debris on the Earth

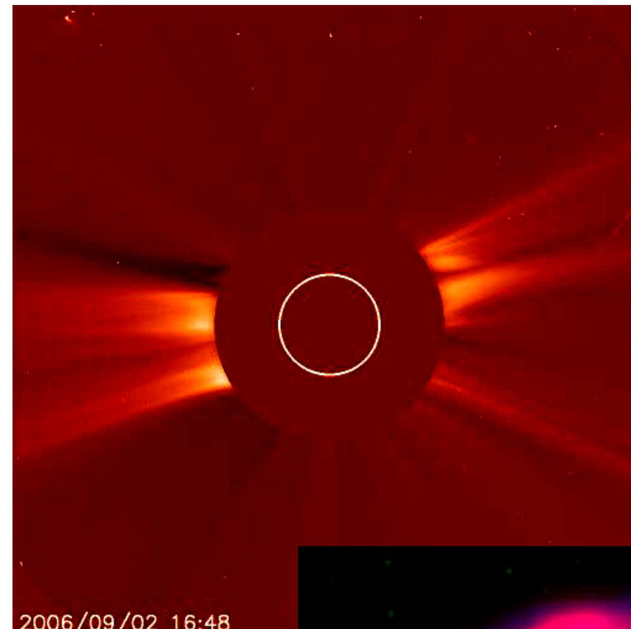
Ellis, BDF, & Schramm 1996

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



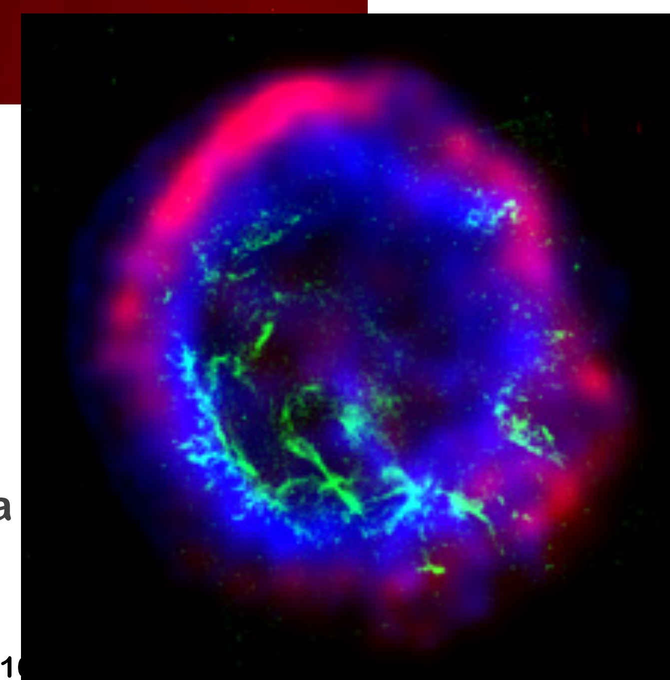
SOHO

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! also Korschinek+ 96

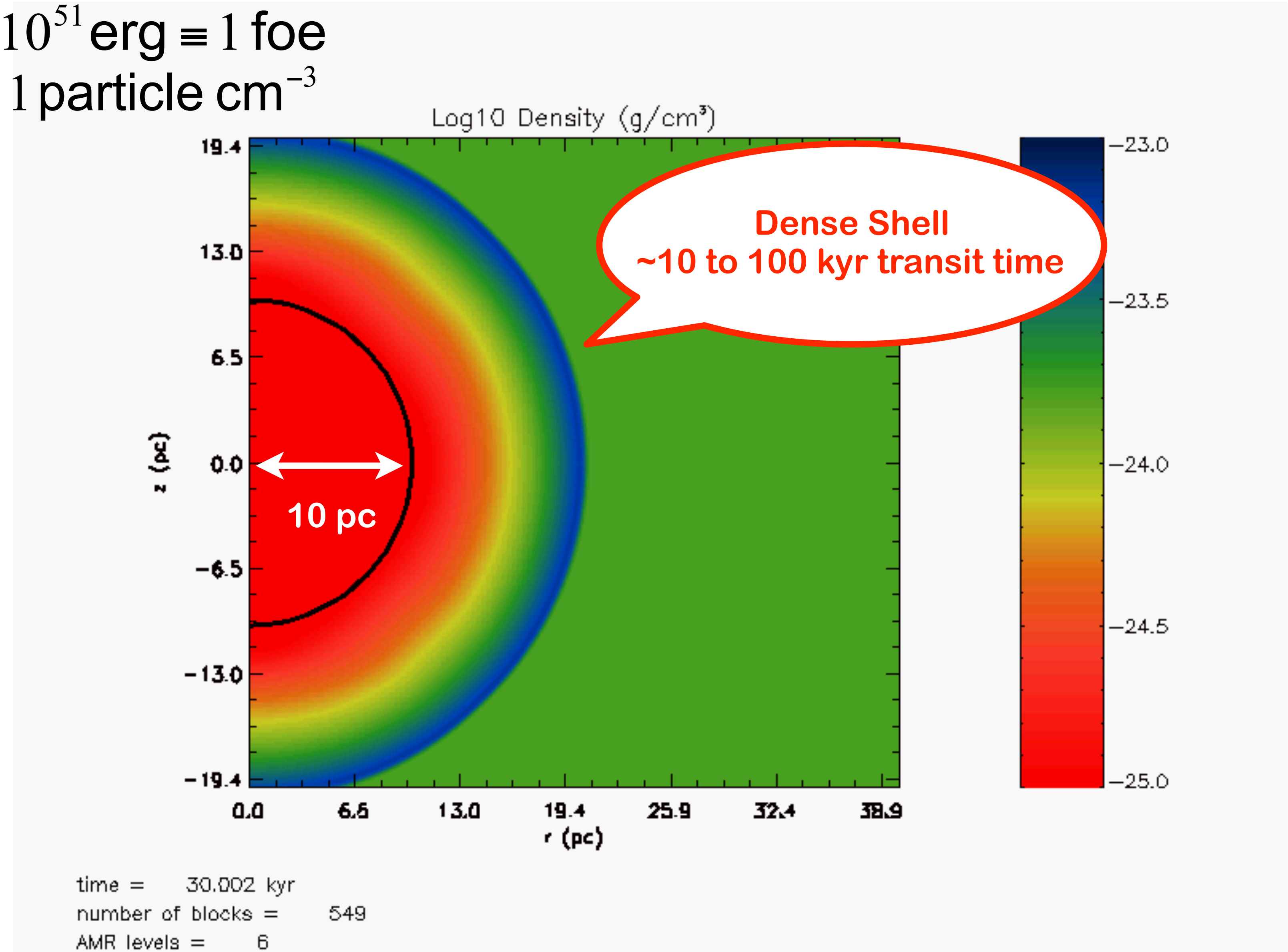
Chandra



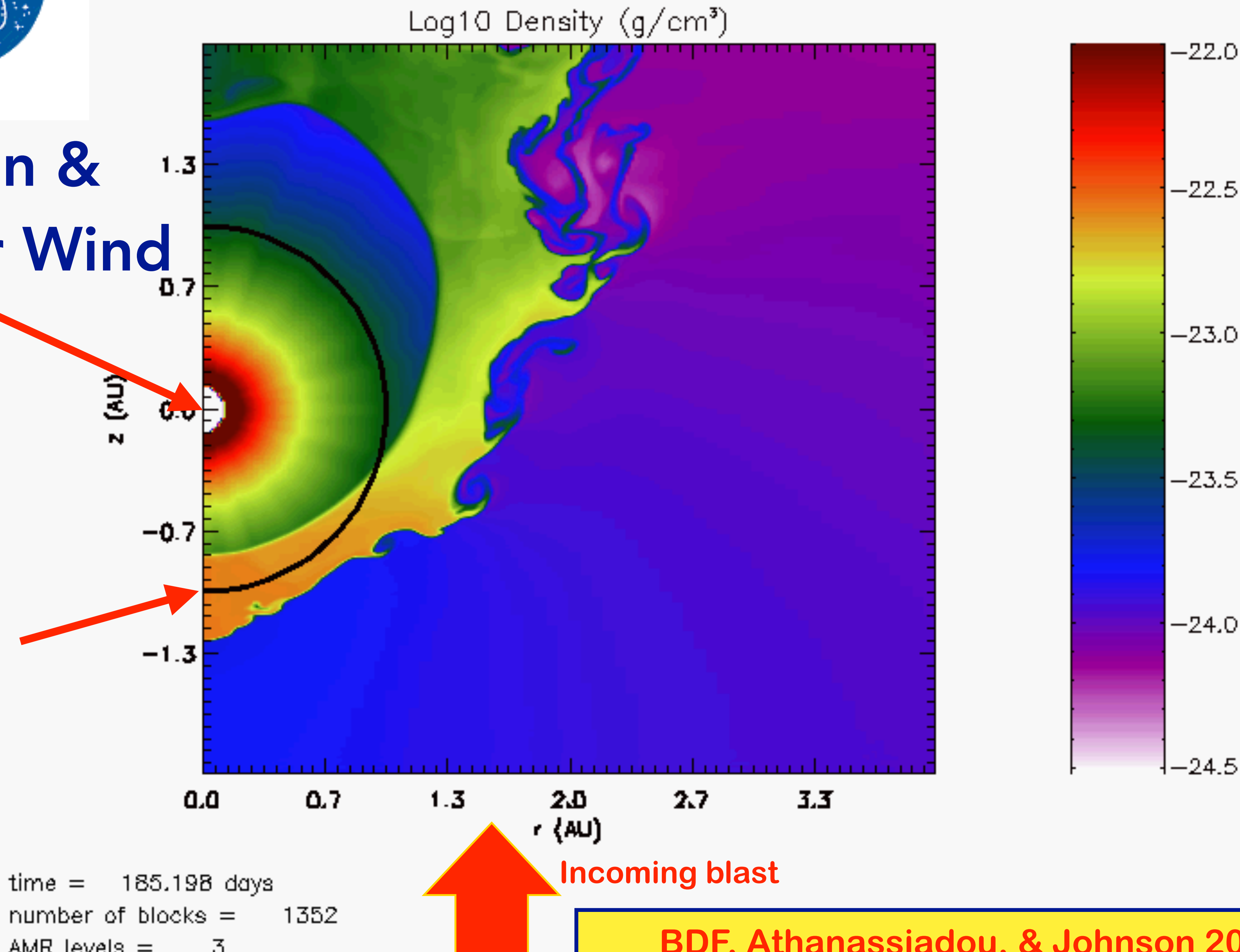
The Fury of Aerial Bombardment:
Supernova Blast Passage--Global View
BDF, Athanassiadou, Johnson 2008

$E_{\rm init} = 10^{51}\,\text{erg} \equiv 1\,\text{foe}$

$n_{\rm ISM} = 1\,\text{particle cm}^{-3}$

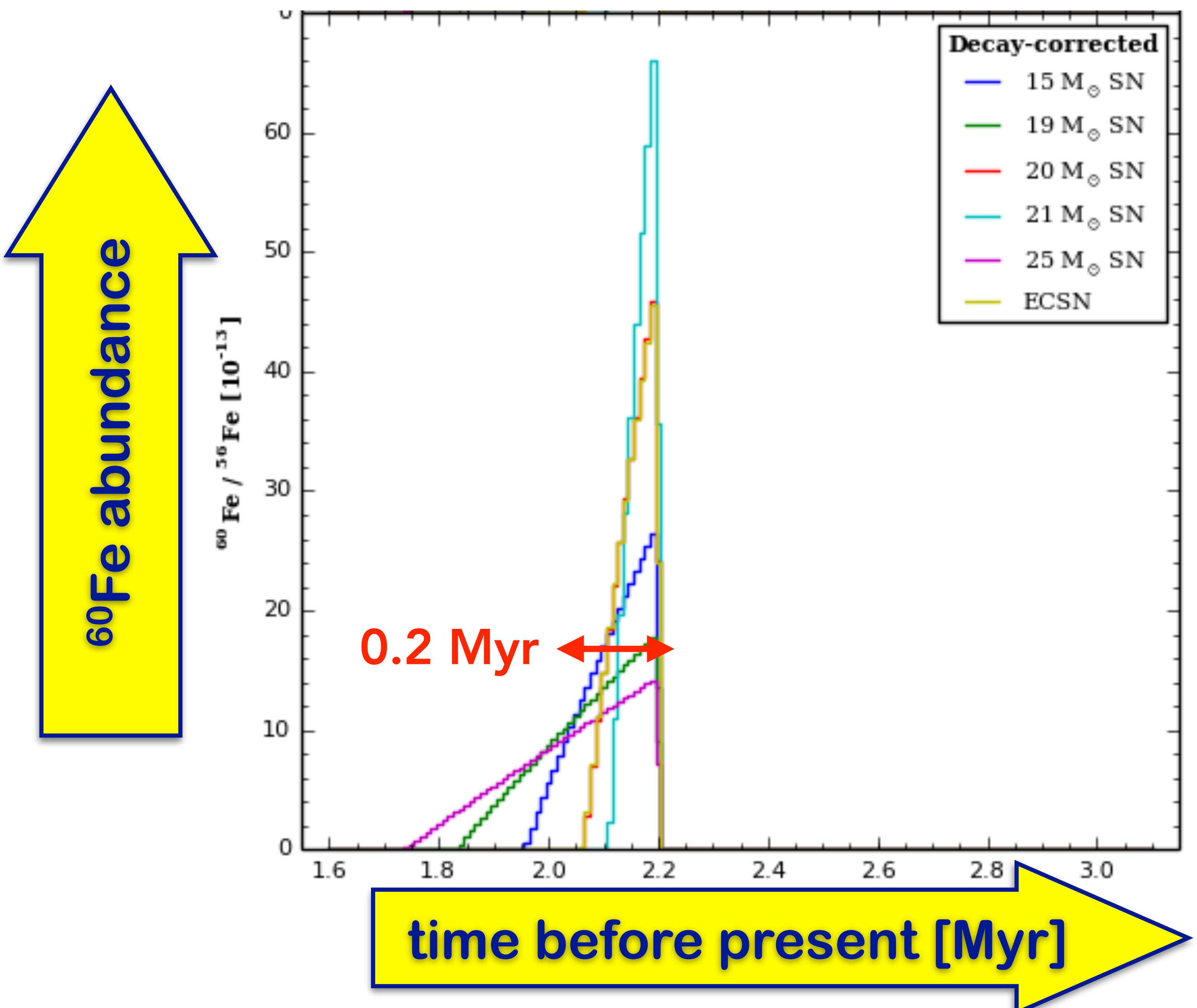


Supernova at 20 pc: Zoom to Solar System Impact



BDF, Athanassiadou, & Johnson 2008

^{60}Fe Time Profile: Sedov SN



Fry, BDF, Ellis 2015

Debris Delivery via Dust

Athanassiadou & BDF 11; Benitez+ 02; Fry, BDF, & Ellis 2016

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

- gas-phase SN debris excluded from Earth

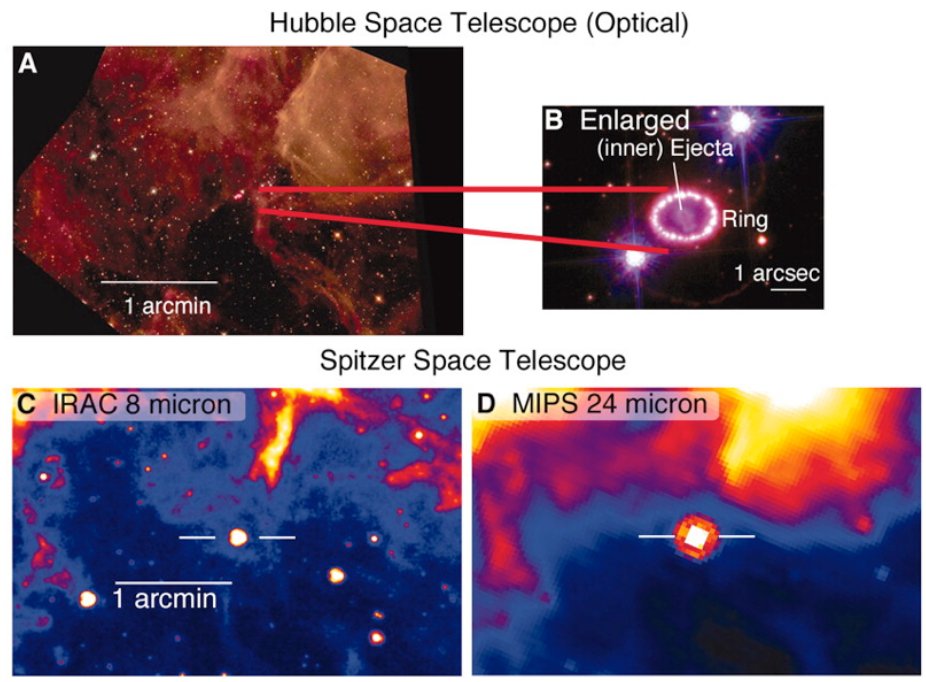
But SN radioisotopes all are refractory elements $\Rightarrow$ dust grains

SN1987A:

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

SN dust reaches Earth even if gas does not

- dust decouples from gas at shocks
- radioisotope delivery efficiency set by dust survival fraction



SN1987A dust: Matsuura+ 2011

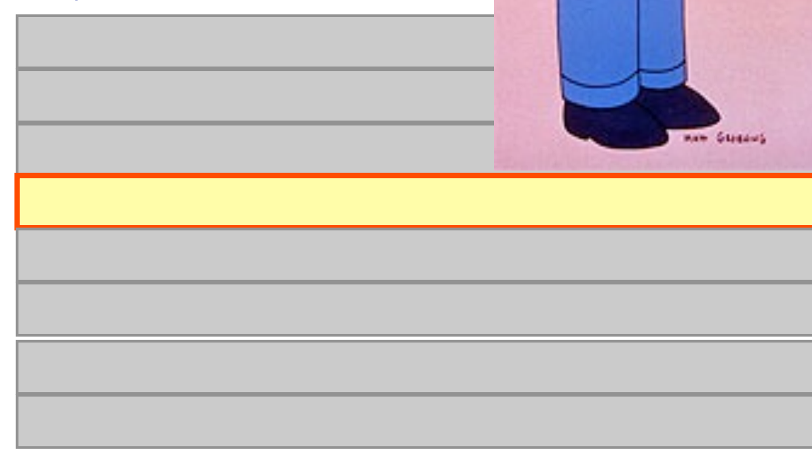
Geological Signatures

Deep Ocean Crust

Knie et al. (1999)

- ferromanganese (FeMn) crust
- Pacific Ocean
- growth: ~ 1 mm/Myr

AMS ⇨ live ^{60}Fe, $\tau_{60} = 2.6\ \mathrm{Myr}$!



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

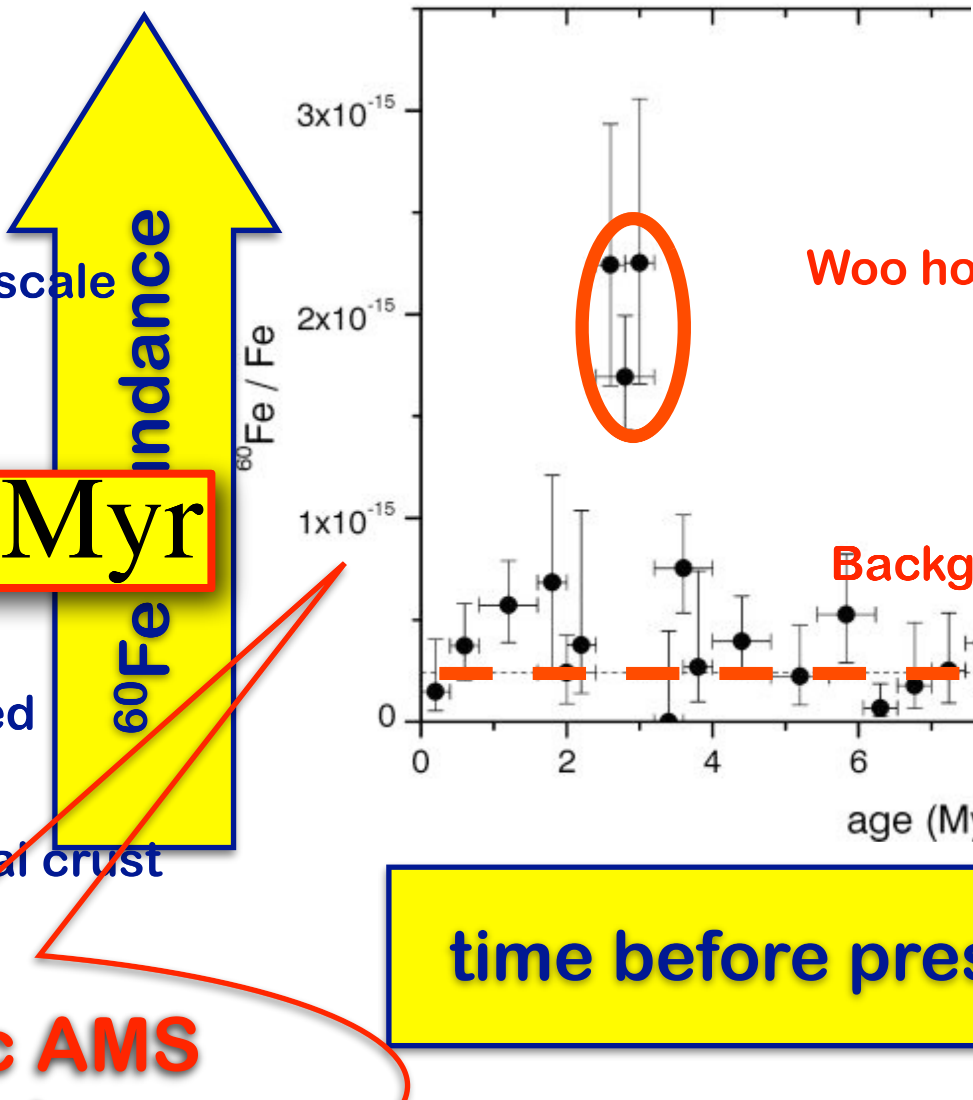
- √ Better geometry (planar)
- √ better time resolution
- √ ^{10}Be ⇨ radioactive timescale

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:

$$N_{60,\mathrm{obs}} \sim \frac{M_{60,\mathrm{eject}}}{D^2}$$

$$D \sim \sqrt{M_{60,\mathrm{eject}} / N_{60,\mathrm{obs}}}$$

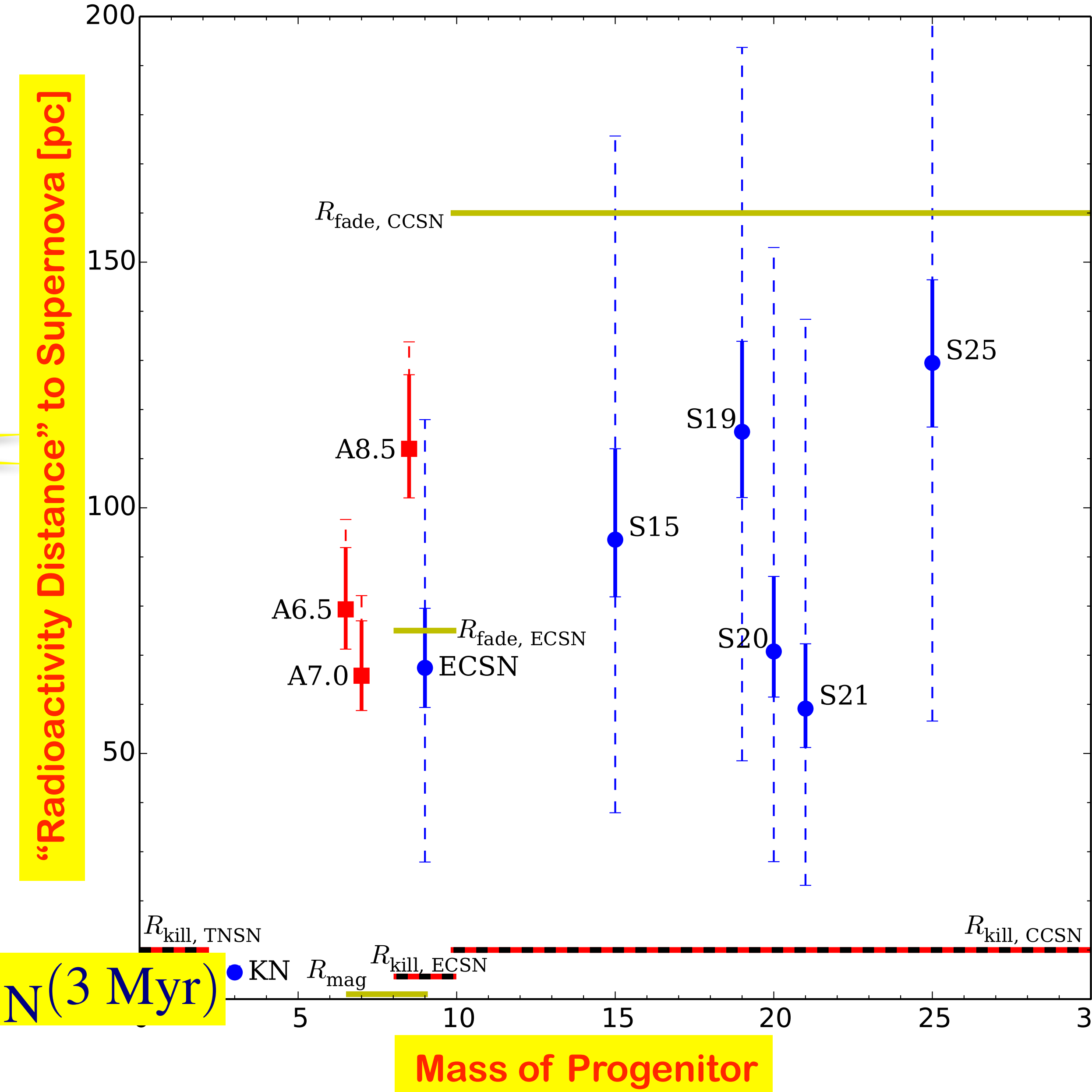
"radioactivity distance" from ^{60}Fe yield

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!

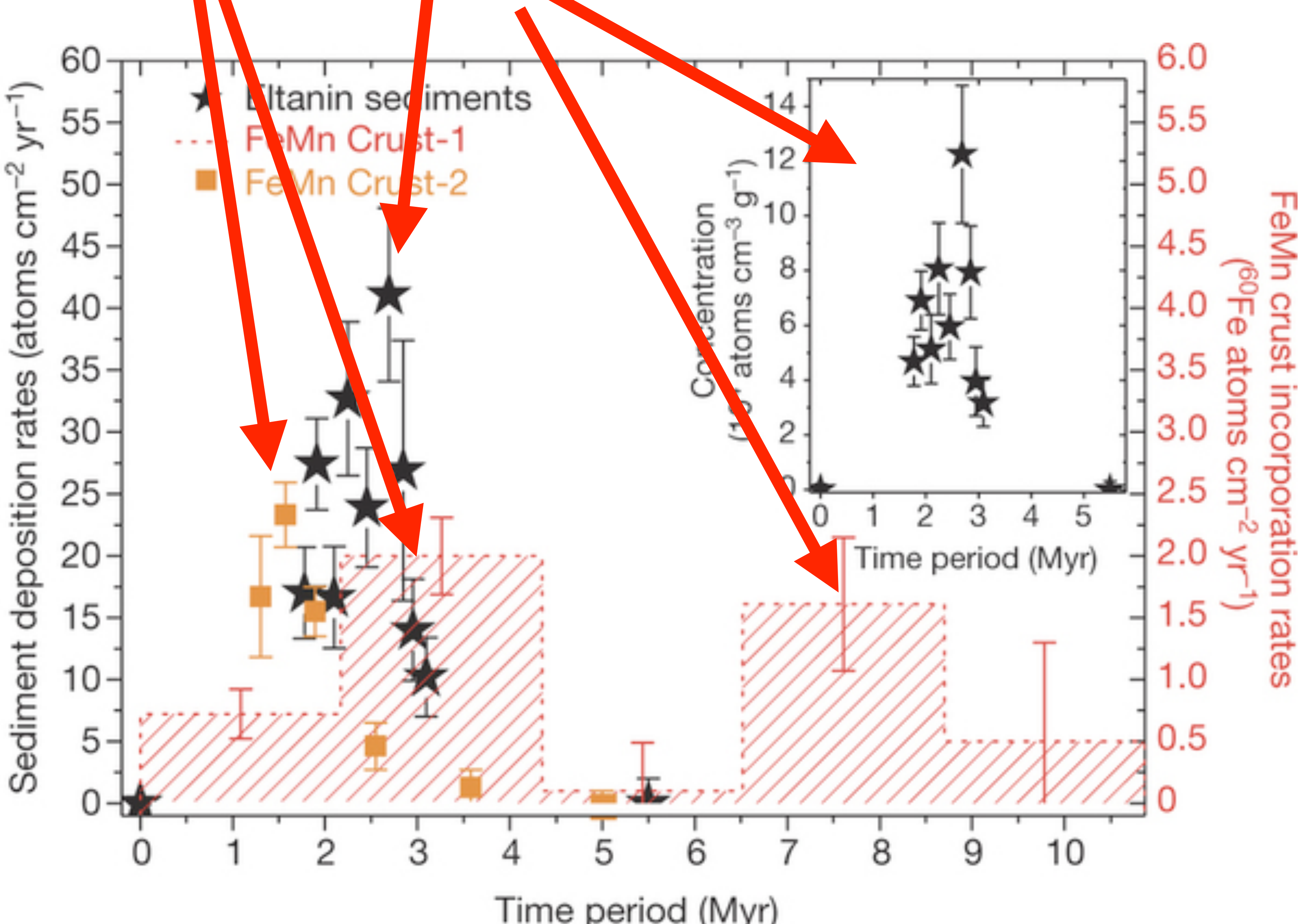
★ $d(^{60}\mathrm{Fe}) \approx d(\mathrm{SN} \to \mathrm{Earth}) \approx d_{\mathrm{SN}}(3\ \mathrm{Myr})$

⇨ nontrivial consistency!


2016

Wallner+ 2016 Nature

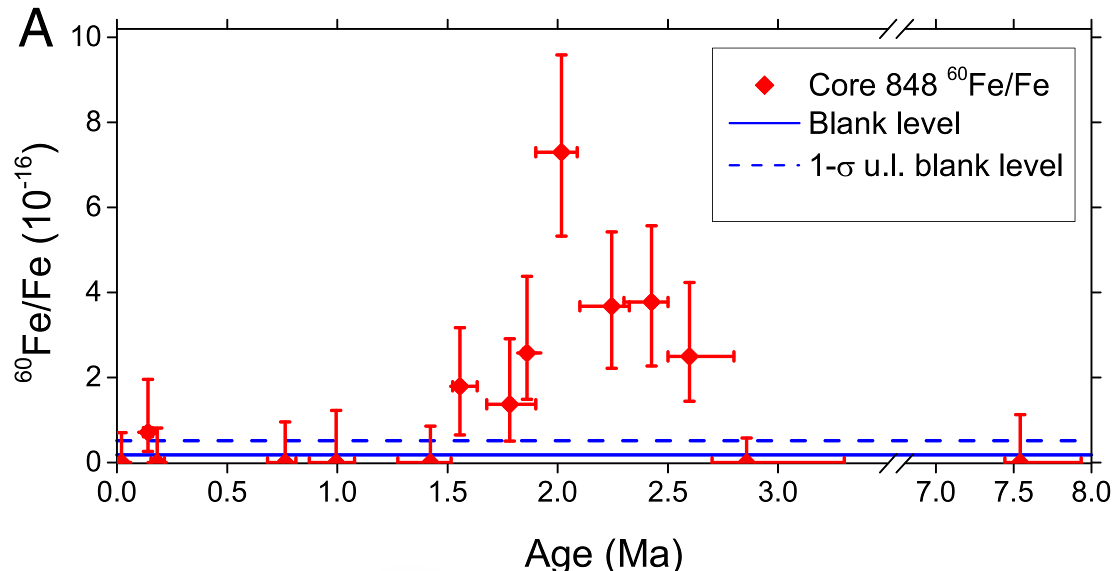
- ★ confirmation of 60Fe crust signal at ~3 Myr
- ★ sedimentary time profile: ~1 Myr width?!
- ★ indication of second ^{60}Fe pulse ~8 Myr

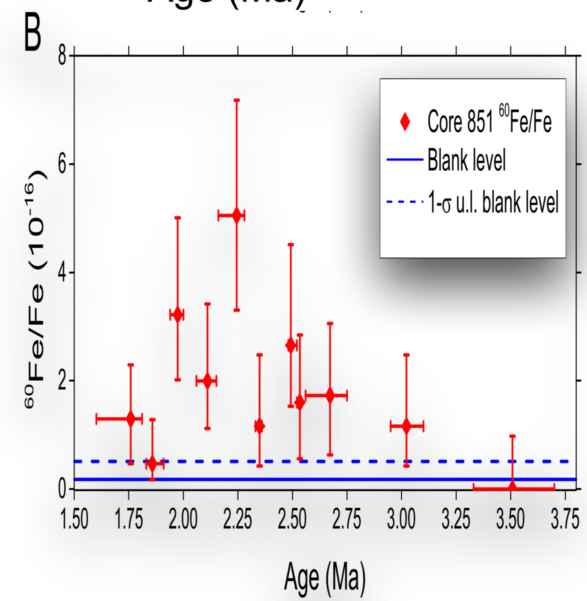


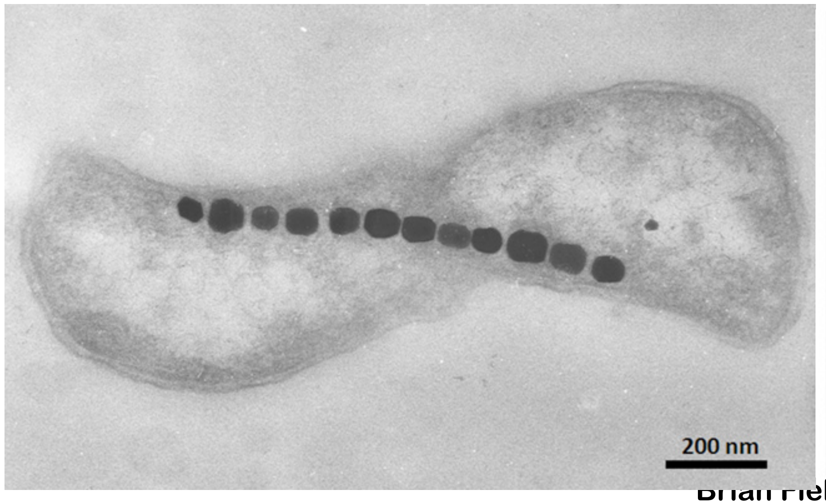
Radioactive Fossil Bacteria

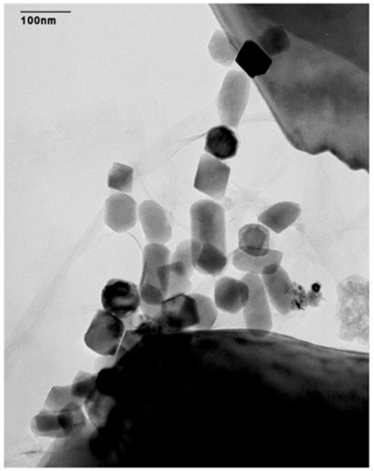
Ludwig, Bishop, et al 2016

- Deep-ocean sediments
- Select small grains of magnetite Fe_3O_4
- Fossilized remains of magnetotactic bacteria







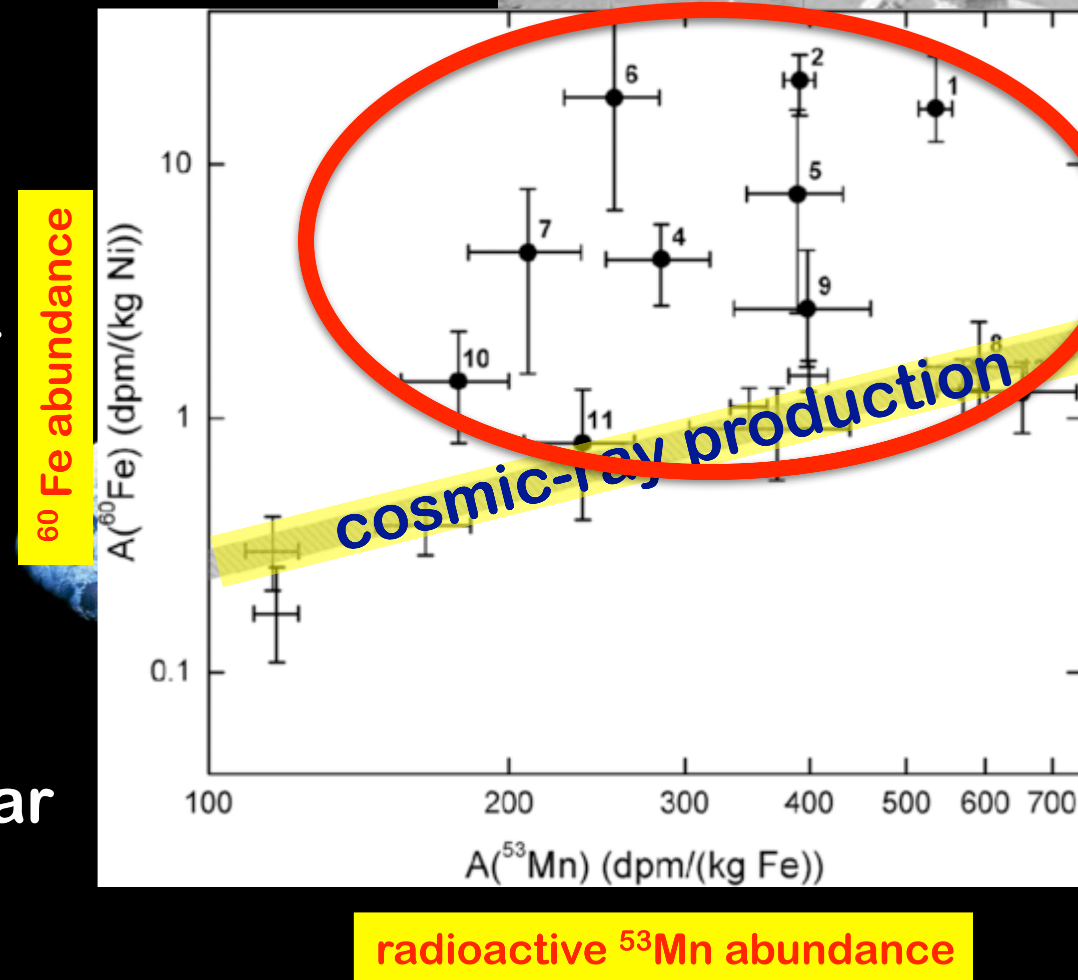


The Moon!

Lunar Soil

- ★ consistency check for deep-ocean signal
- ★ but: nontrivial background: cosmic-ray activation of lunar regolith

$$\mathrm{CR} + \mathrm{Ni} \rightarrow {}^{60}\mathrm{Fe} + \cdots$$
$$\mathrm{CR} + \mathrm{Fe} \rightarrow {}^{53}\mathrm{Mn} + \cdots$$



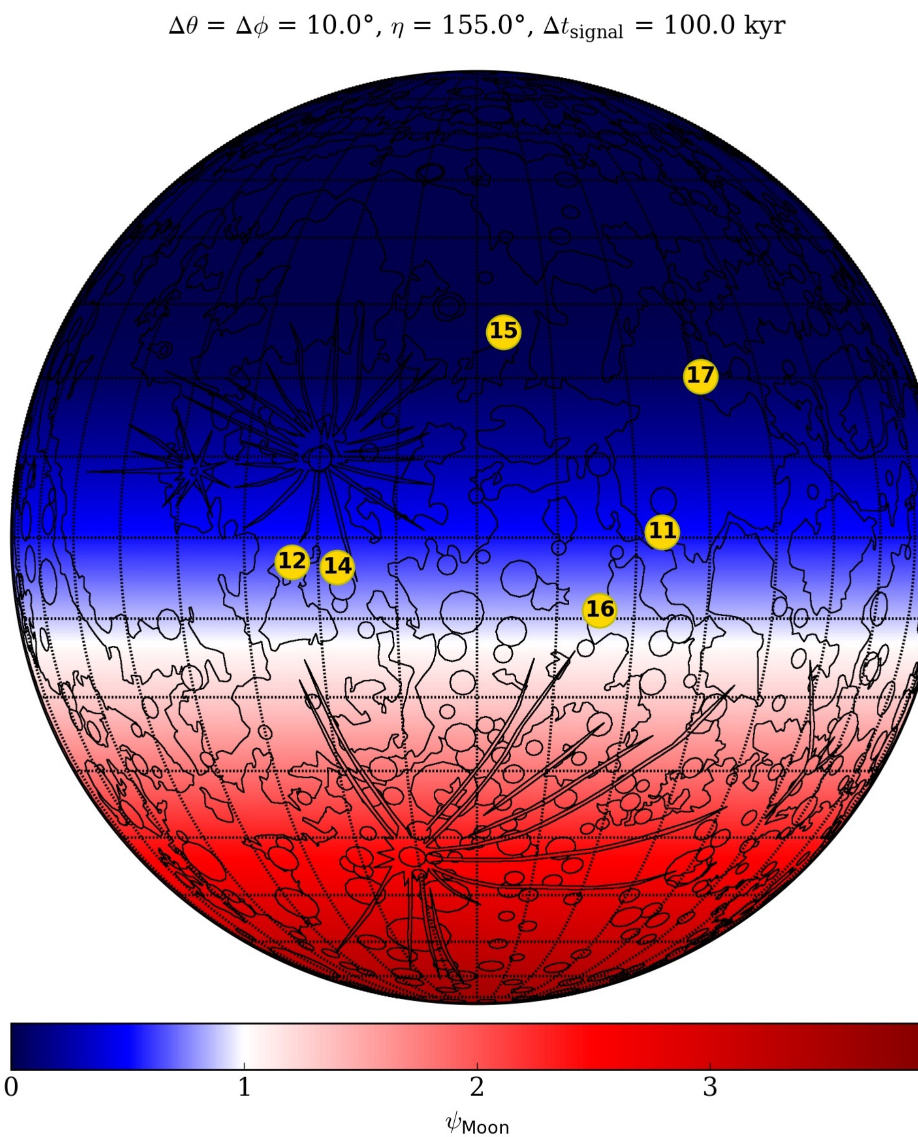
Fimiani+ 2016 PRL

- ★ ^{60}Fe excess in top layer of lunar drill core
- ★ signal (surface density) consistent with deep ocean

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!

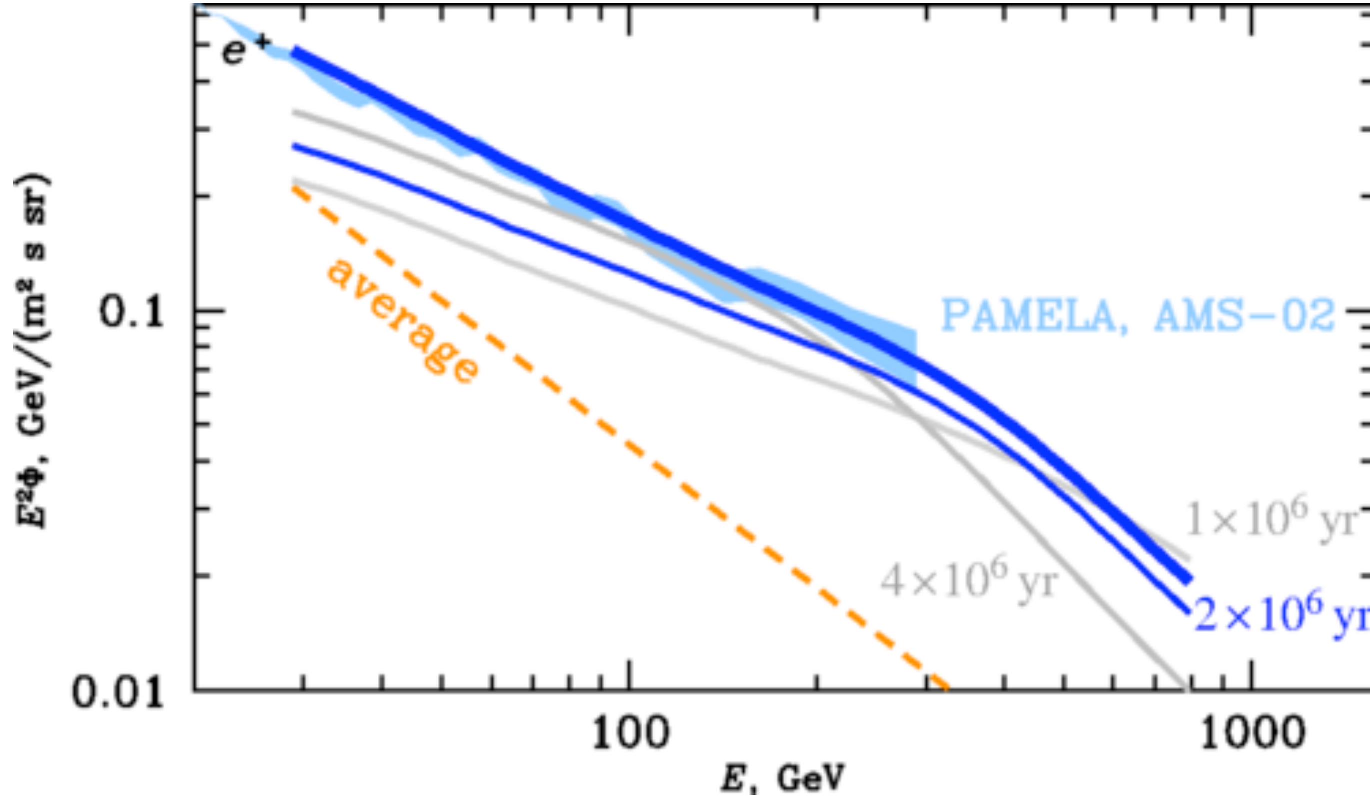


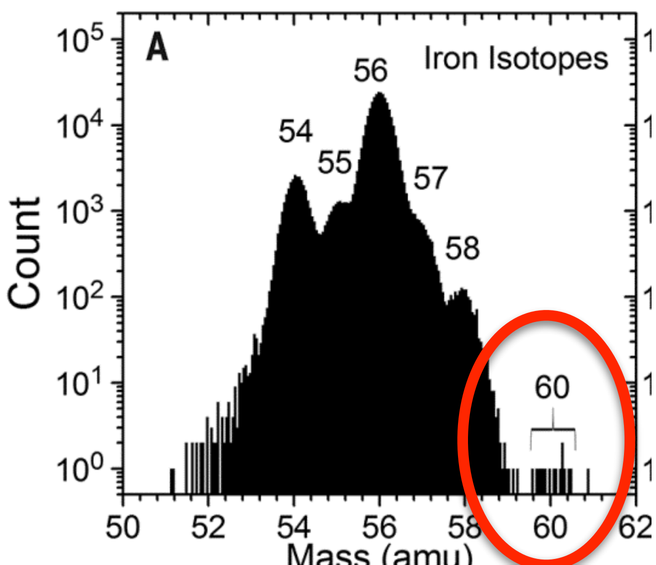
Cosmic-Ray Corroboration?

★ excess of antiprotons & positrons

Kachelriess, Neronov, & Semikoz 2015

- requires local & recent source
- d~100 pc
  t~2-4 Myr





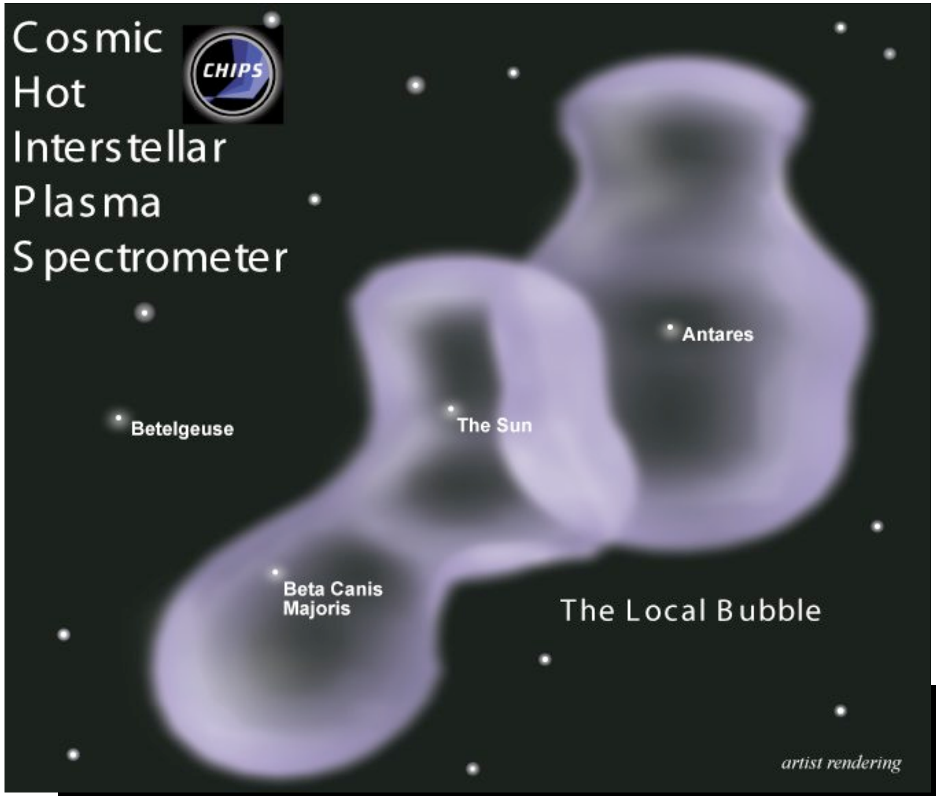
★ ^{60}Fe detected in cosmic rays

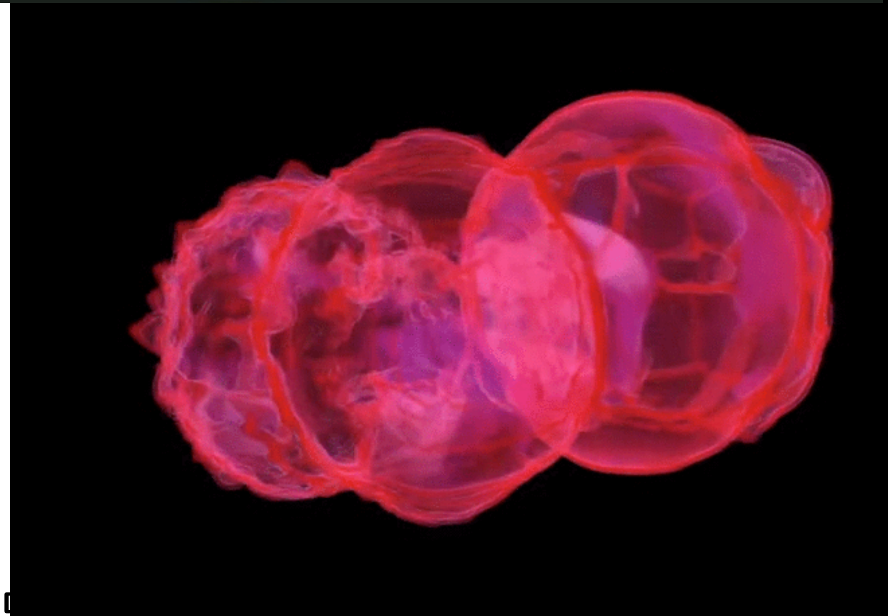
Binns+ 2016, Binns talk

- requires local & recent source

Aftermath: The Local Bubble

- ★ **The Sun lives in region of hot, rarefied gas**
  - The Local Bubble
  - hot cavity ~50 pc ⇒ huge
- ★ **Nearby SN needed**
  - we live inside SN remains
  - bubble requires >> 1 SN in past 10 Myr Smith & Cox 01
  - ^{60}Fe event from nearest massive star cluster? Benitez et al 00
  - Bubble wall as source of ~1 Myr ^{60}Fe pulse width? Breitschwerdt+ 2016, Lallement and Schulreich talks





A Near Miss?

Thomas+ 2016, Knie+ 2004, BDF+ 2005

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

"near miss"

Image: Mark Garlick
www.markgarlick.com

- ¿ TeV cosmic-ray boost: 20x muon irradiation
- ¿ cosmic-ray winter?
- ¿ bump in extinctions?

If true:

implications for astrobiology

tightens Galactic habitable zone

Outlook

Live ^{60}Fe seen globally and on the Moon

- ★ signal in deep ocean crusts, nodules, sediments find
- ★ confirmed pulse ~2-3 Myr ago
- ★ evidence for pulse at ~8 Myr
- ★ evidence for lunar signal
- ★ Source of Local Bubble?

Birth of “Supernova Archaeology"

Implications across disciplines:

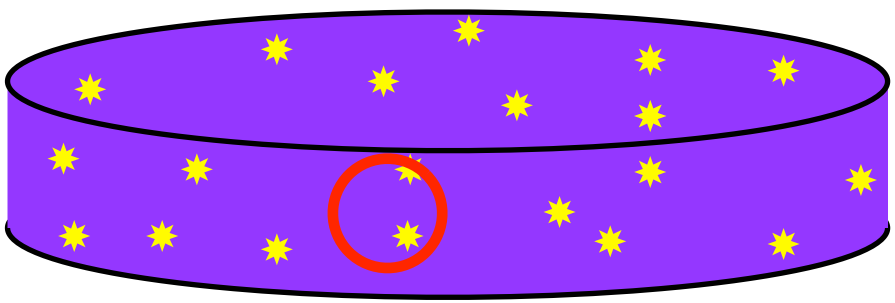
cosmic rays, nucleosynthesis, stellar evolution, bio evolution, astrobiol

Future Research

- Supernova(e) origin and direction
  - ★ lunar distribution
  - ★ cosmic-ray anisotropies
  - ★ neutron star/pulsar correlation
- more, different samples:
  - ✓ other isotopes
  - ✓ other media (fossil bacteria)
  - ✓ other sites: Moon!
- other epochs? Mass extinction correlations?
- stay tuned… BDF Euro sabbatical AY 2017-2018

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 < 10 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 group

Ionizing radiation

- initial gamma, X, UV rays destroy stratospheric ozone

  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

- cosmic rays arrive with blast, double whammy
- ionization damage, muon radiation

Neutrinos

- neutrino-nucleon elastic scatterin

  "linear energy transfer"

  ⇨ DNA damage

  02

Minimum safe distance: ~8 pc