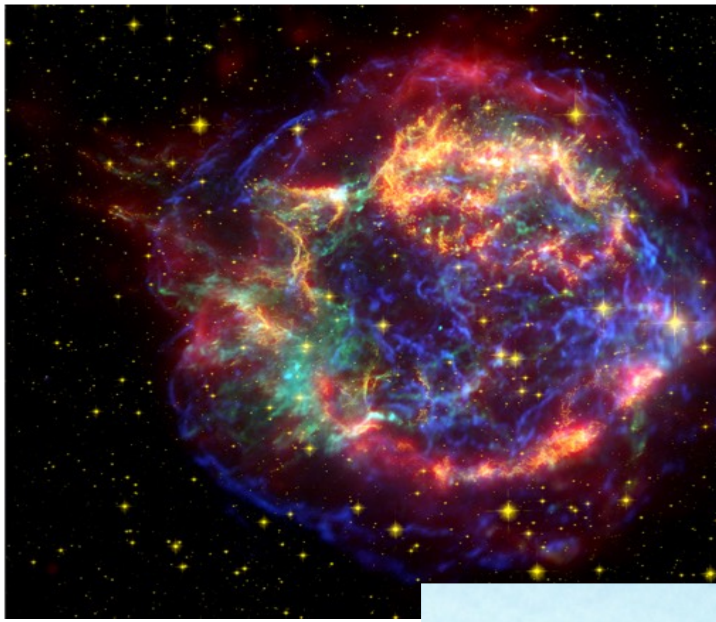
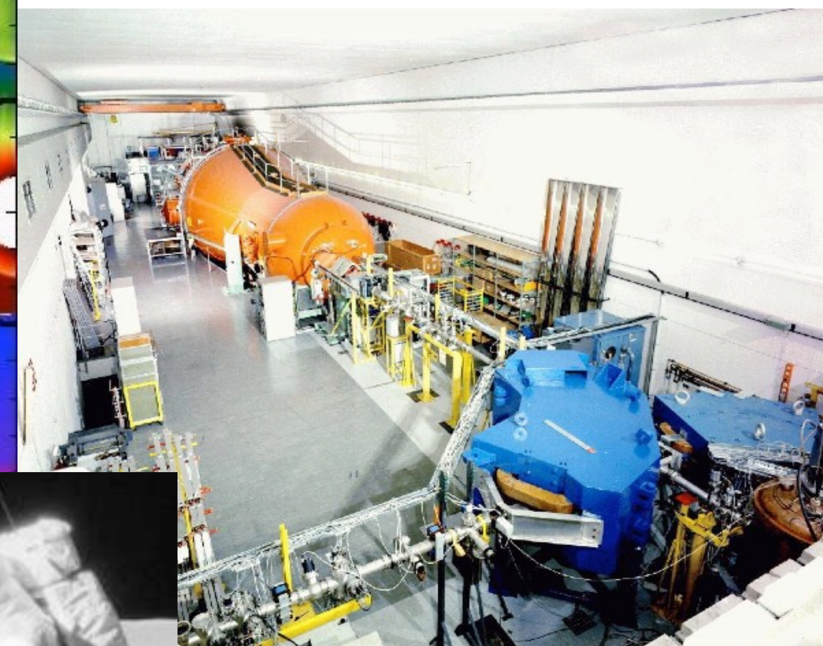
When Stars Attack!

Near-Earth Supernova Explosions
Revealed by Deep-Ocean and Lunar Radioactivity



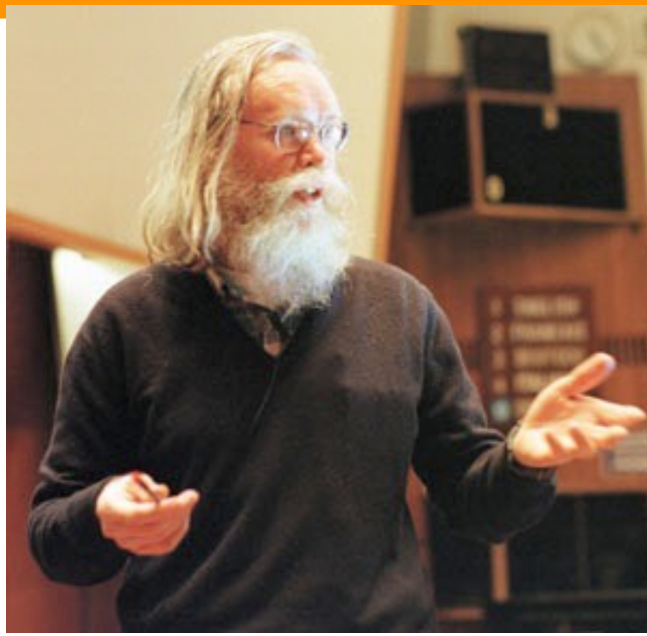


Brian Fields

Astronomy & Physics, U Illinois

ECT* Indirect Methods in Nuclear Astrophysics, Nov 7 2018

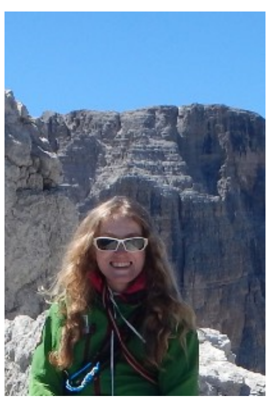
Team Nearby Supernovae



John Ellis

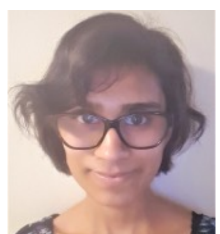
Themis Athanassiadou

Brian Fry

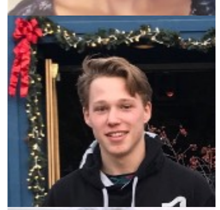


Kathrin Hochmuth

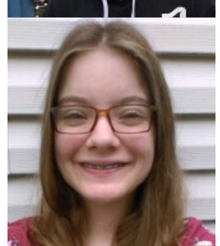
Scott Johnson



Ashvini Krishnan



Danylo Sovgut



Alexandra Trauth

Adrienne Ertel

Jesse Miller

When Stars Attack!
Near-Earth Supernova Explosions Revealed

- ★ **Supernovae & Radioisotopes**
  massive star explosions as radioactive ion beams
- ★ **Nearby Supernovae**
  a unique laboratory...and a unique threat
- ★ **The Smoking Gun**
  supernova radioactivities on Earth
- ★ **Geological Signatures**
  telescopes probing prehistoric supernovae

Supernova Radioactivities

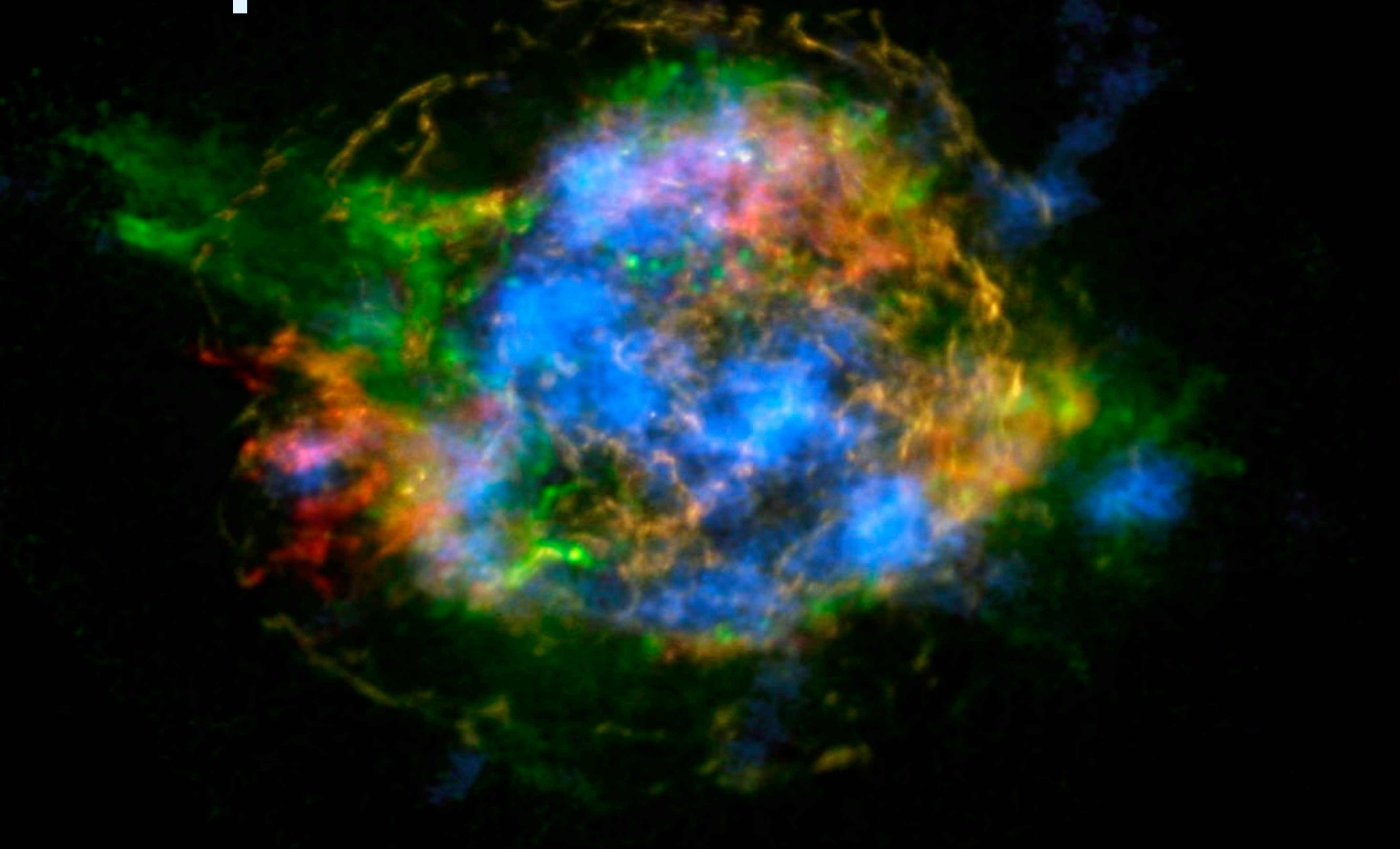


Image: Chardra & NuSTAR

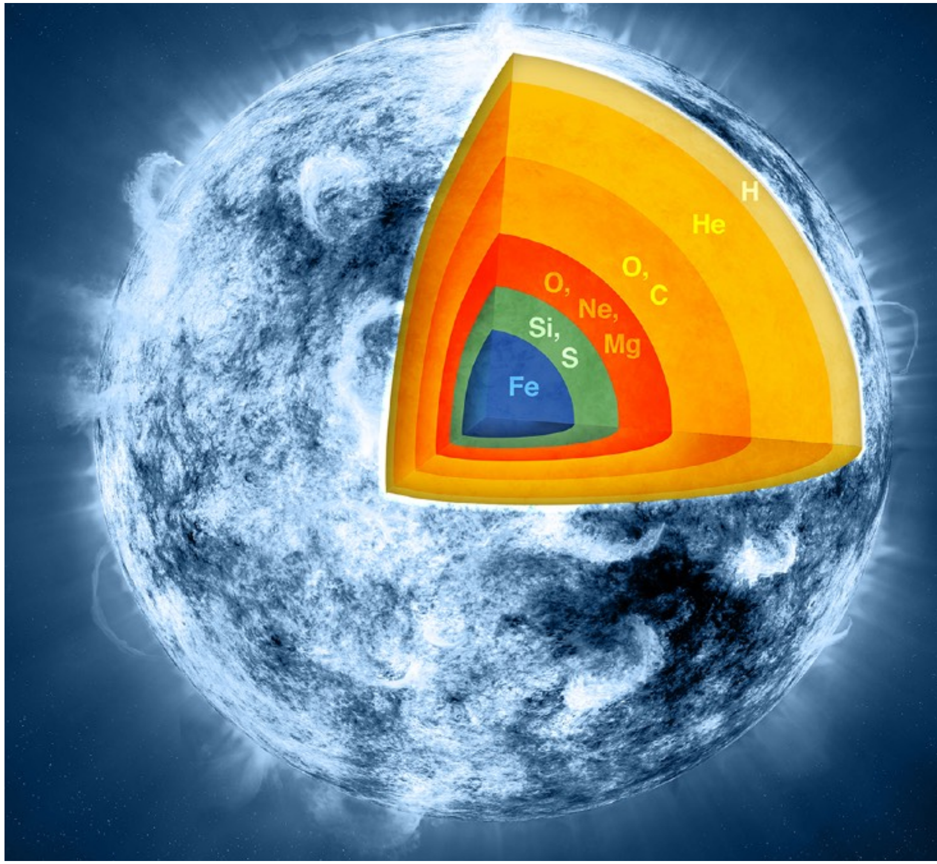
Core-Collapse Supernovae

Twitter Version

A star's life is a struggle against gravity

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

- ★ Begin burning $\mathrm{H} \rightarrow \mathrm{He}$
- ★ Then, at accelerating pace
  - repeated cycles of ash ⇨ fuel
  - ever-heavier elements in core



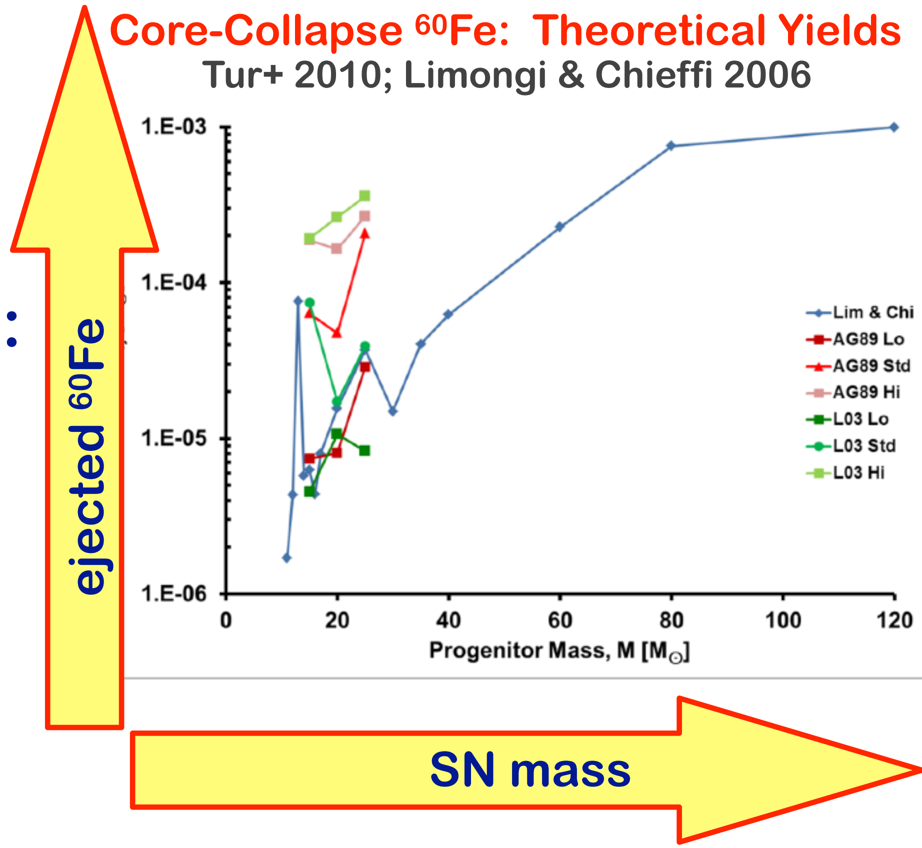
When core ^{56}Fe: max binding

- ★ 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 1987
- ➡ Shock launched: ~10^{51} erg

Explosion!

Supernovae are Element Factories

- hydrostatic and explosive nucleosynthesis
- main products:
  - ✓ alpha nuclei: ^{12}C, ^{16}O, …, ^{40}Ca, ^{44}Ti
  - ✓ Fe peak
- medium-lived (> Myr) radionuclides: $\boxed{^{60}\text{Fe},}$ ^{26}Al, ^{41}Ca, ^{53}Mn, ^{97,98}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

  and to He burn rates: $3\alpha \rightarrow {}^{12}\mathrm{C}$ $\quad {}^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ $\quad {}^{12}\mathrm{C}(^{12}\mathrm{C},n)^{23}\mathrm{Mg}$

  Tur, Heger, Austin, West 2010, 2017; Bucher+ 2015

  accuracy ~order of magnitude

  $^{59}\mathrm{Fe}(n,\gamma)^{60}\mathrm{Fe}$ thanks Peter Mohr!
- r-process? ^{182}Hf, ^{244}Pu

Live Radioactivities and Nearby Supernovae

★ **Supernova Explosions**

the deaths of massive stars

★ **Nearby Supernovae**

a unique laboratory...and a unique threat

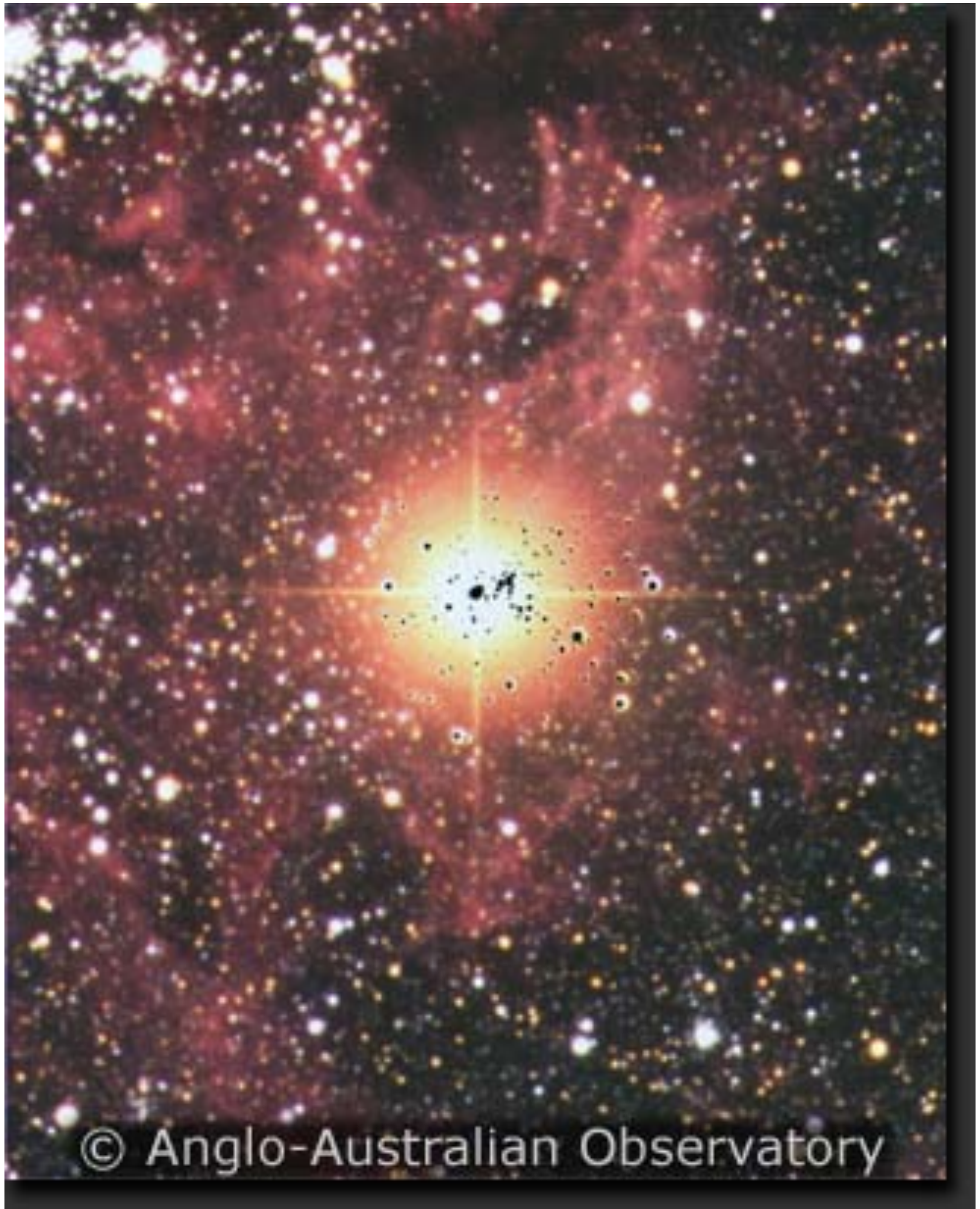
★ **The Smoking Gun**

supernova radioactivities on Earth

★ **Geological Signatures**

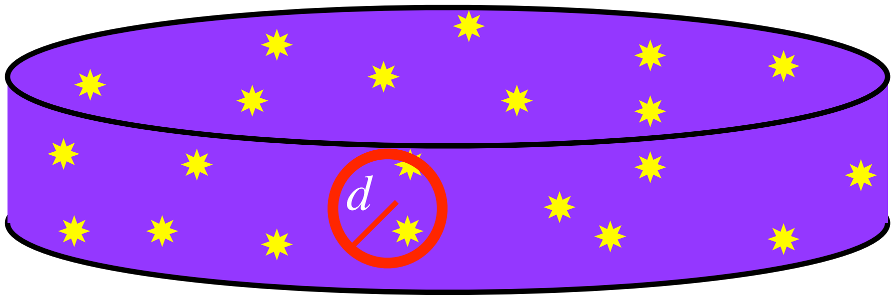
sea sediments as telescopes

Nearby Supernovae



Cosmic WMD: Rates

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



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

  - exponential disk: solar circle rate ~5x smaller
    Krishnan, Sovgut, Trauth, BDF 2018 in prep
  - also: spiral arms, molecular clouds Talbot & Newman 77
  - 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

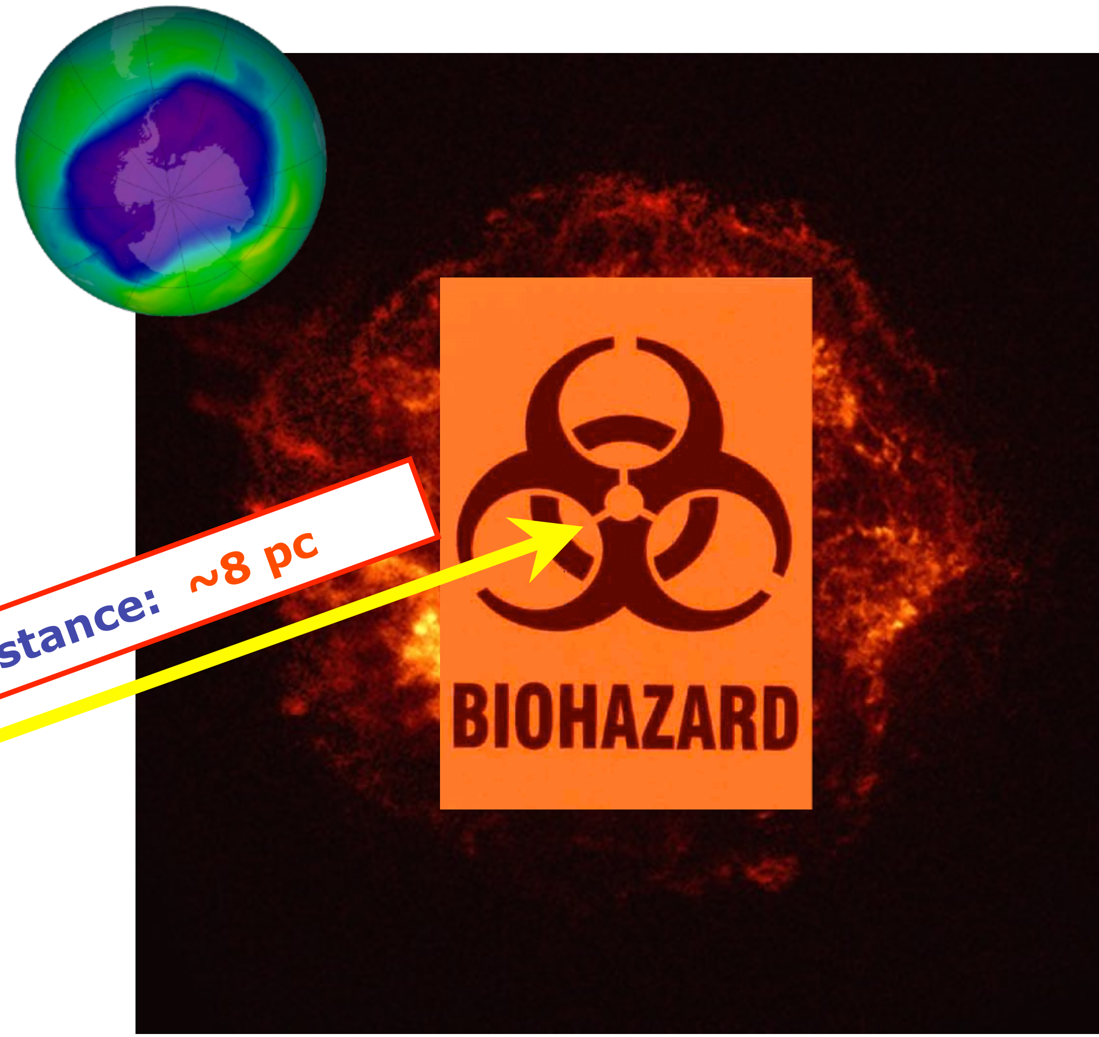
  Ruderman 74; Ellis & Schramm 94

- 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



Minimum safe distance: ~8 pc

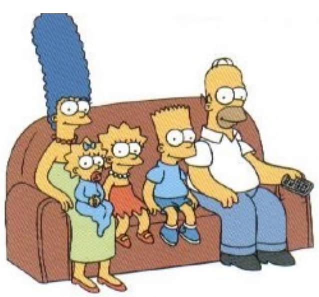
Neutrinos

- neutrino-nucleon elastic scatterin

  “linear energy transfer”

  ⇨ DNA damage

  02



Live Radioactivities and Nearby Supernovae

★ **Supernova Explosions**

the deaths of massive stars

★ **Nearby Supernovae**

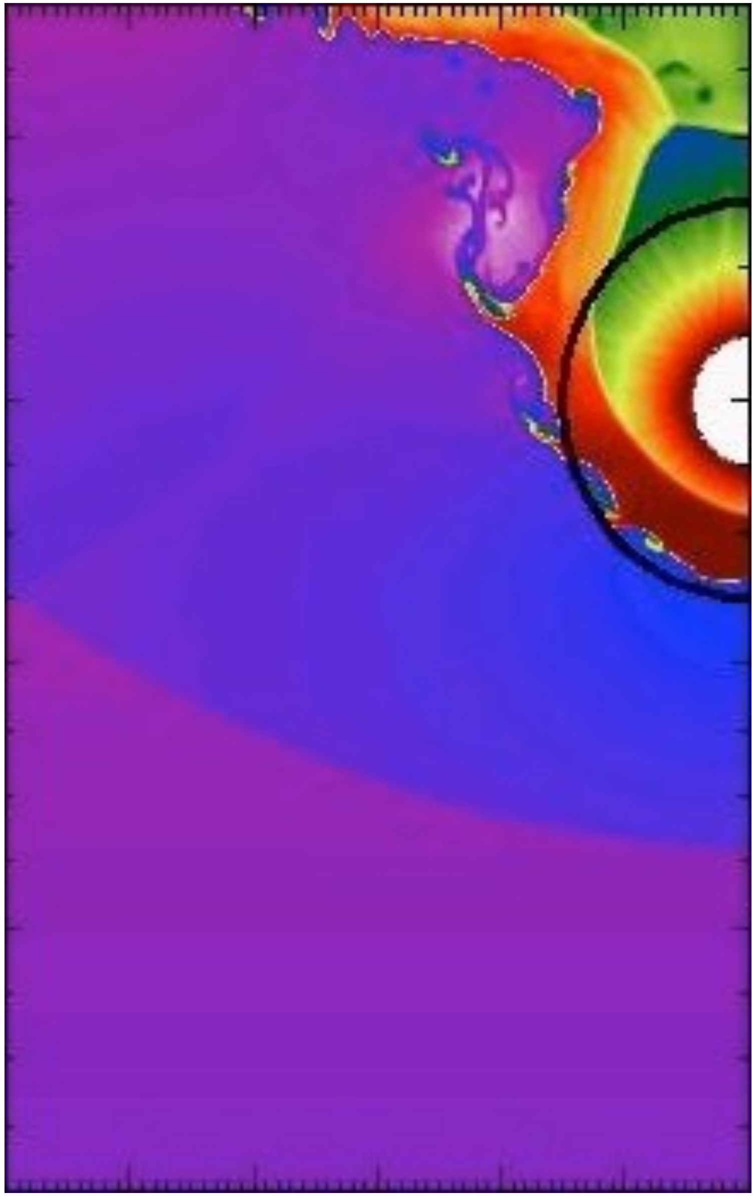
a unique laboratory...and a unique threat

★ **The Smoking Gun**

supernova radioactivities on Earth

★ **Geological Signatures**

sea sediments as telescopes



The Smoking Gun

Nearby Supernovae Rain Ejecta on Earth

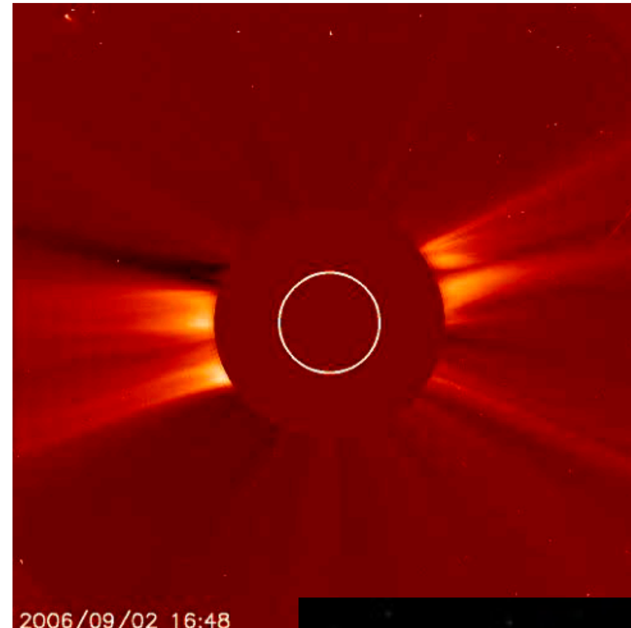
Ellis, BDF, & Schramm 1996; BDF, Athanassiadou, & Johnson 2008; Fry, BDF, Ellis 2015

SN eject plows thru interstellar matter

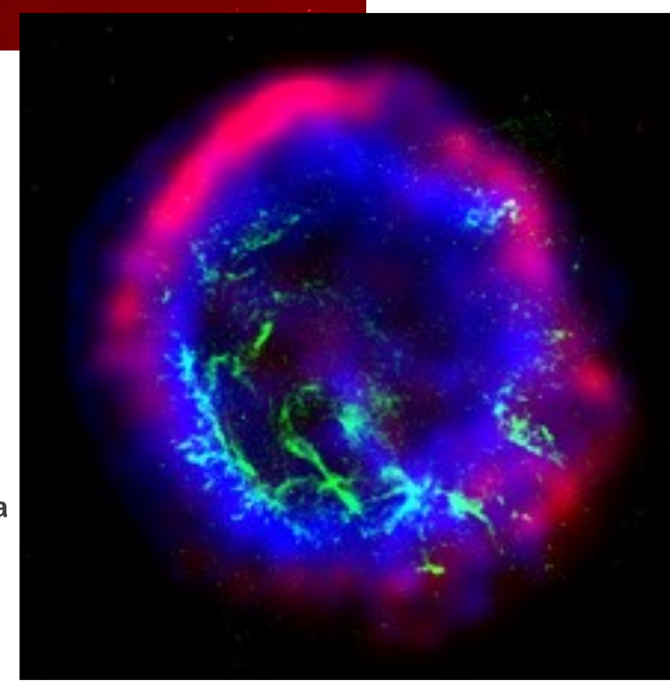
Earth shielded by solar wind

If blast close enough:

- plasma pushes to inner Solar System
- dust decouples, rains on Earth
- SN dust accumulates in deep ocean



SOHO



Chandra

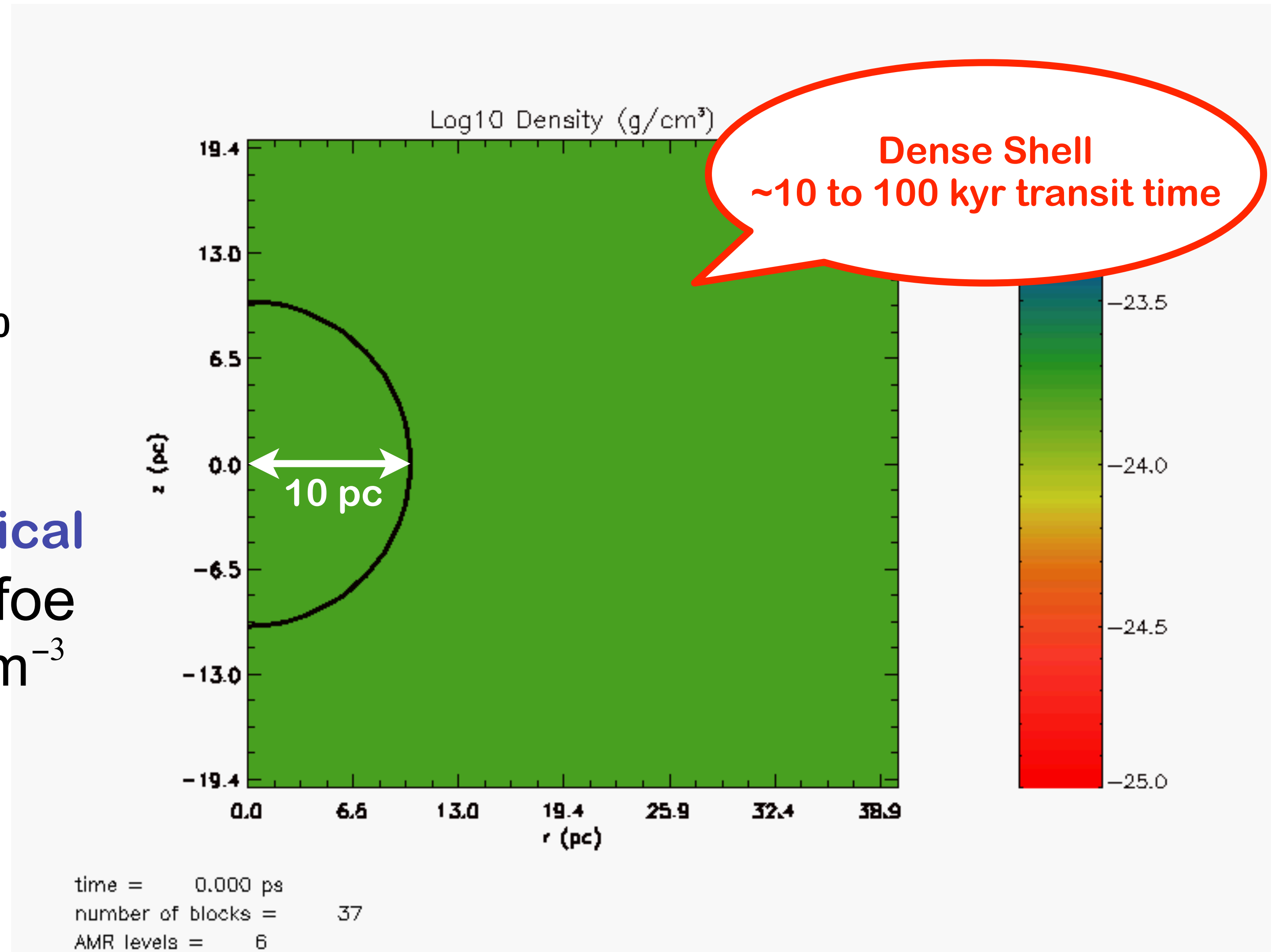
The Fury of Aerial Bombardment:
Supernova Blast Passage--Global View
BDF, Athanassiadou, Johnson 2008

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

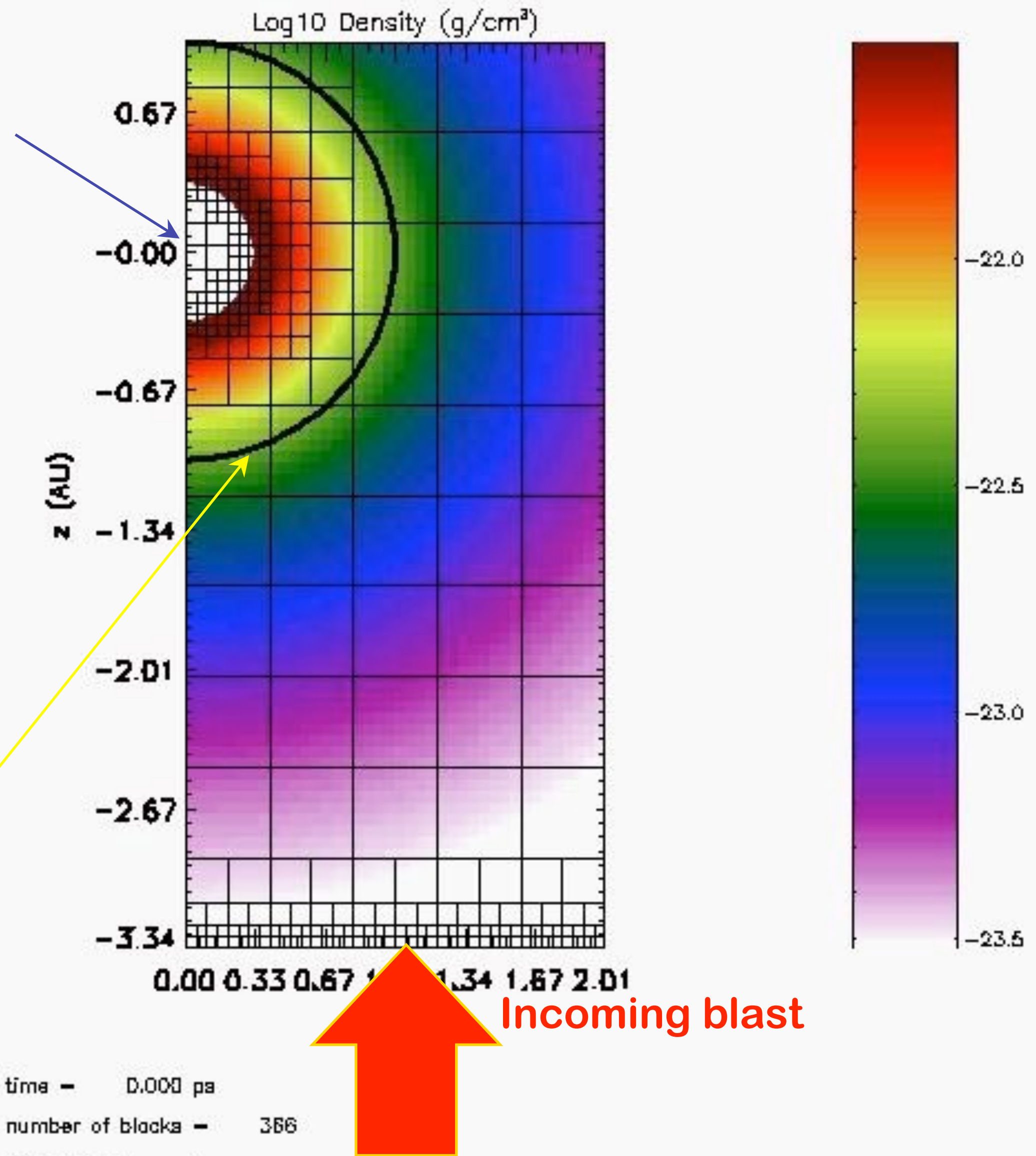
Blast Properties:

SN at 10 pc

Geometry:

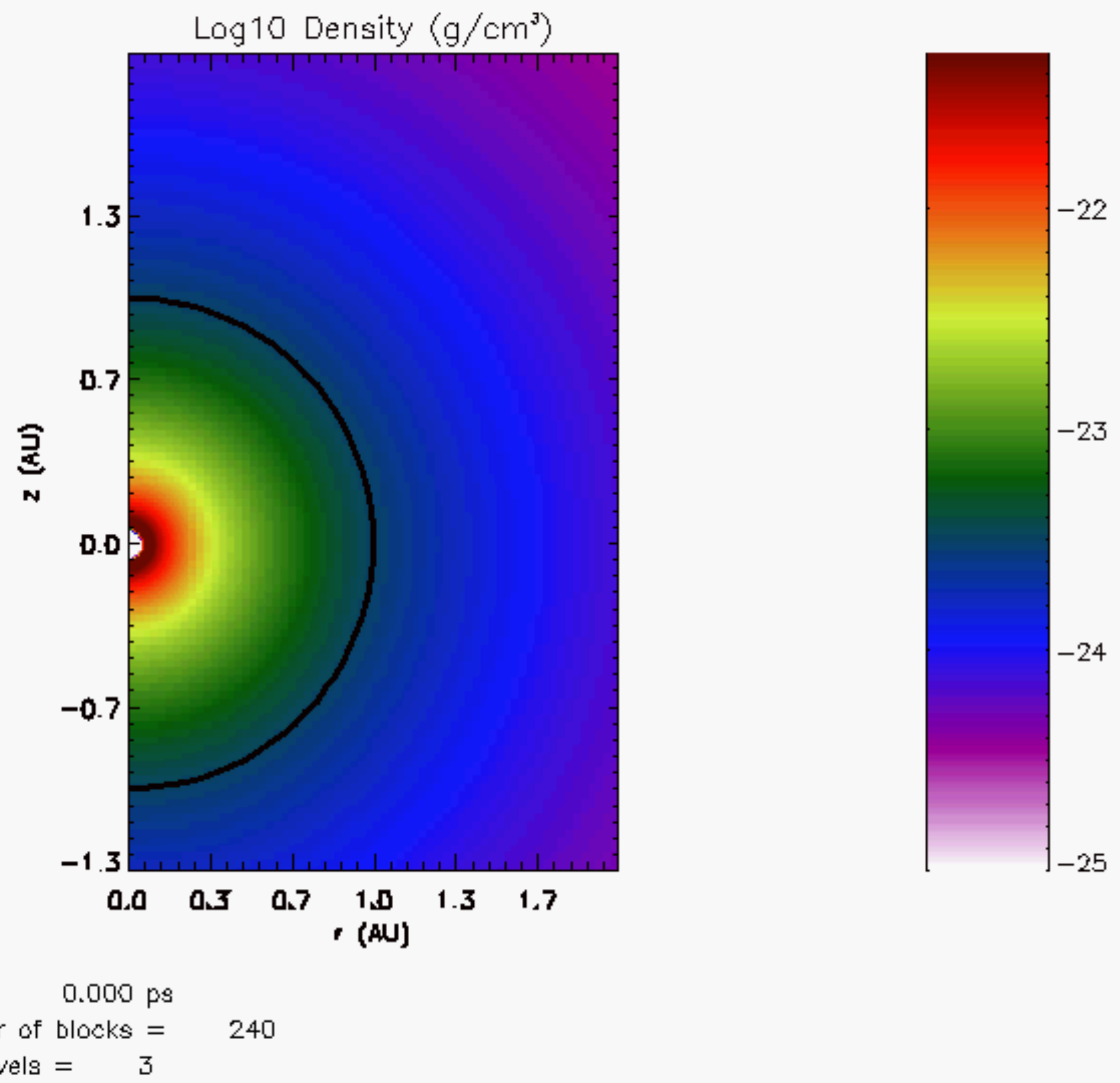
Cylindrical

Sun



1 AU =
Earth's orbit

BDF, Athanassiadou, & Johnson 2008



Now in 3-D!

It’s a squid!

Athanassiadou et al in prep

Debris Delivery via Dust

Athanassiadou & BDF 11; Benitez+ 02; Fry, BDF, & Ellis 2015,2016

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

- gas-phase SN debris excluded from Earth

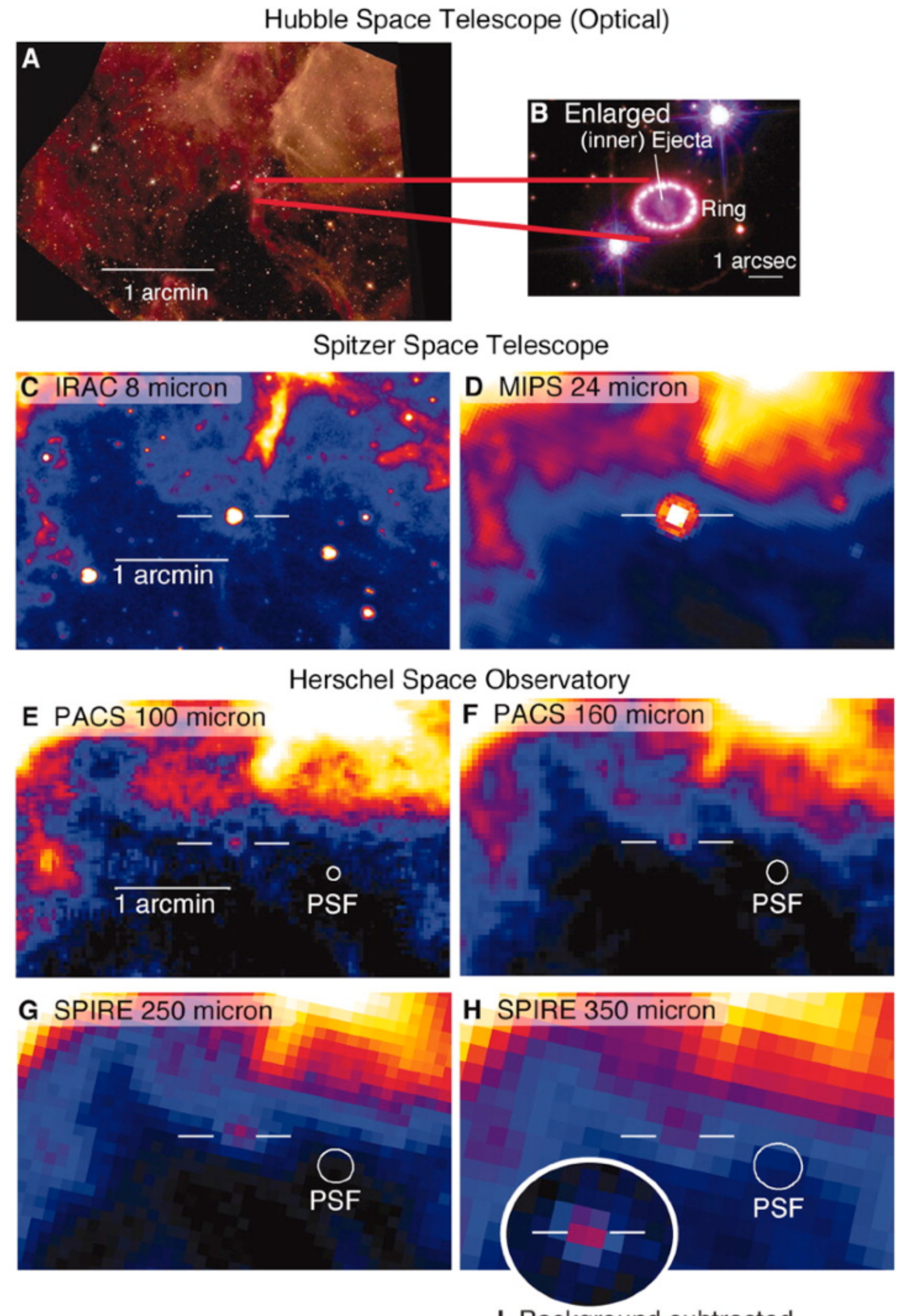
But SN radioisotopes all are refractory elements $\Rightarrow$ **dust grains**

SN1987A:

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

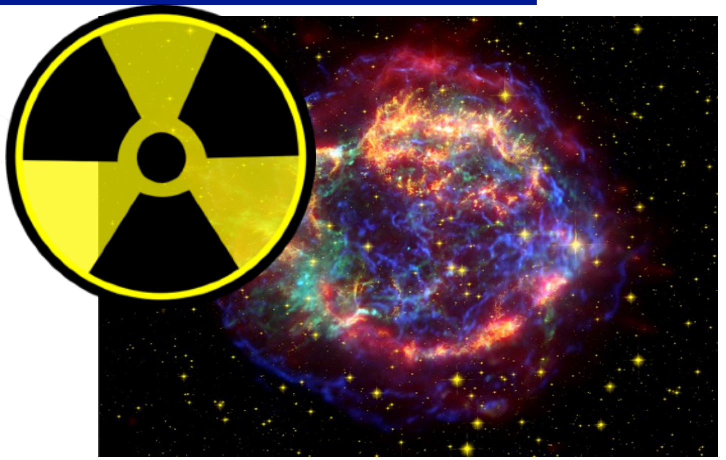
SN dust reaches Earth even if gas does not

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



The Smoking Gun: Radioactivity

Ellis, BDF, & Schramm 1996;   BDF, Athanassiadou, & Johnson 2008;   Fry, BDF, Ellis 2015



Q: How would we know?

Need observable SN "fingerprint"
→ Nuclear Signature

★ Stable nuclides: don't know came from SN
★ Live radioactive isotopes: none left on Earth
If found, must come from SN!

^{60}Fe $t_{1/2} = 2.6\ \mathrm{Myr}$

also, e.g., ^{26}Al, ^{97}Tc, ^{244}Pu?

Live Radioactivities and Nearby Supernovae

- ★ **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**
  - telescopes probing prehistoric supernovae

Geological Signatures

Deep Ocean Crust

Knie et al. (1999)

ferromanganese (FeMn) crust

Pacific Ocean

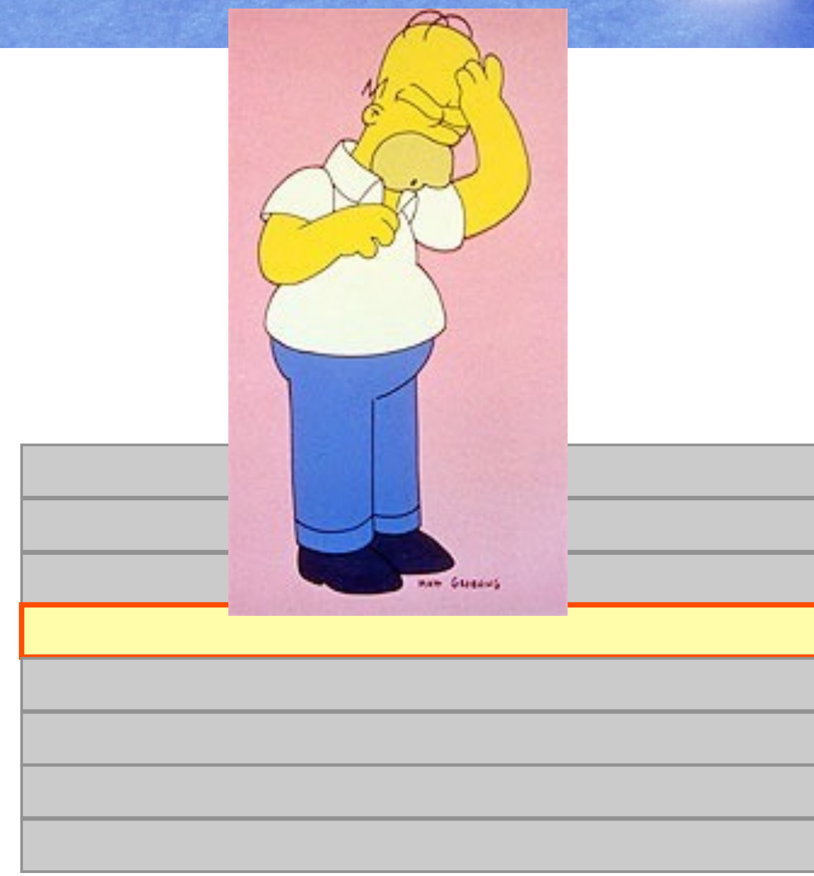
growth: ~ 1 mm/Myr

AMS ⇨ live ^{60}Fe, $t_{1/2} = 2.6\ \mathrm{Myr}$!

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

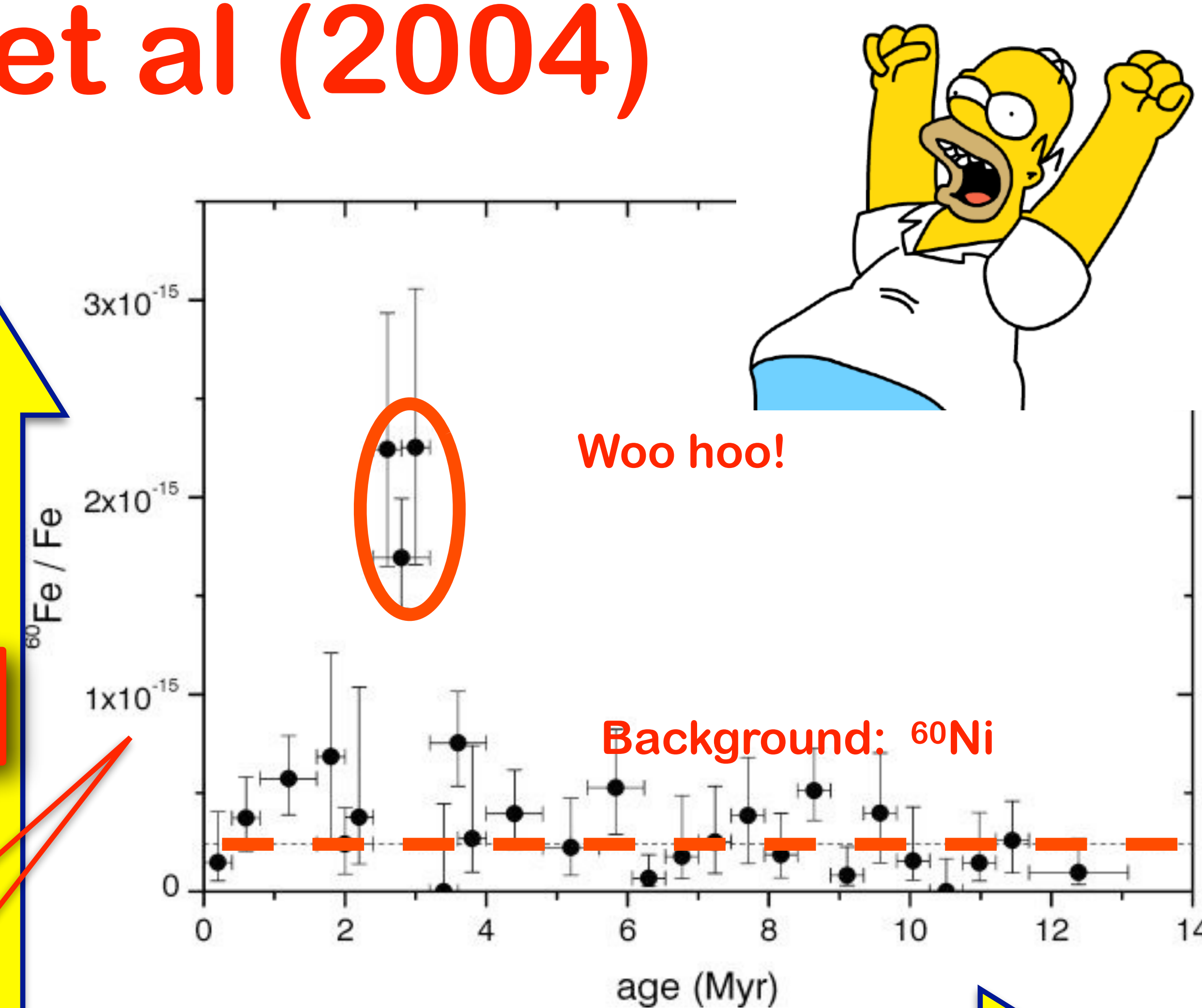
- ✓ Better geometry (planar)
- ✓ better time resolution
- ✓ ^{10}Be ⇨ radioactive timesc

Isolated Signal

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

A Landmark Result

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



time before present [Myr]

Note fantastic AMS sensitivity!

Explosion Distance

Ellis, BDF, Schramm 1996; BDF & Ellis 1999; BDF, Hochmut & Ellis 2005; Fry, BDF, & Ellis 2015

Observable: surface density/fluence:

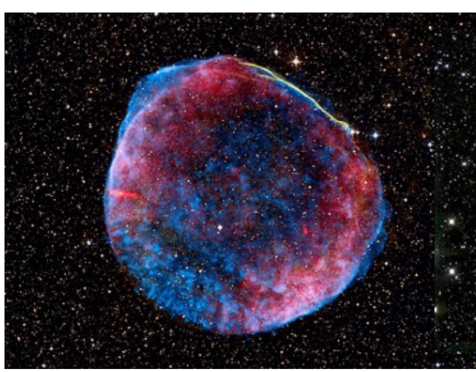
$$N_{60,\mathrm{obs}} \sim \frac{M_{60,\mathrm{eject}}}{D^2}$$

Turn the problem around:

"radioactivity distance" from ^{60}Fe yield

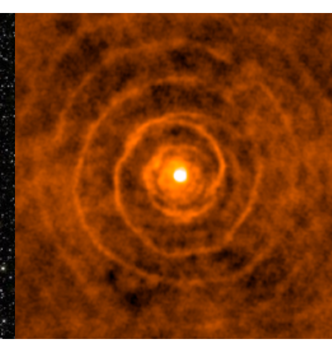
$$D \sim \sqrt{M_{60,\mathrm{eject}} / N_{60,\mathrm{obs}}}$$

^{60}Fe Suspects:



core-collapse supernova

Type Ia supernova



AGB star

NS merger

impactor

Whodunit?

Fry, BDF, & Ellis 2015

"radioactivity distance" from ^{60}Fe yield

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

What makes ^{60}Fe?

- core-collapse supernovae
- ~~Type Ia supernovae~~
- ~~AGB stars~~
- ~~kilonovae~~
- ~~impactor~~ Wallner+ 16; Miller & BDF 18

SN distance:

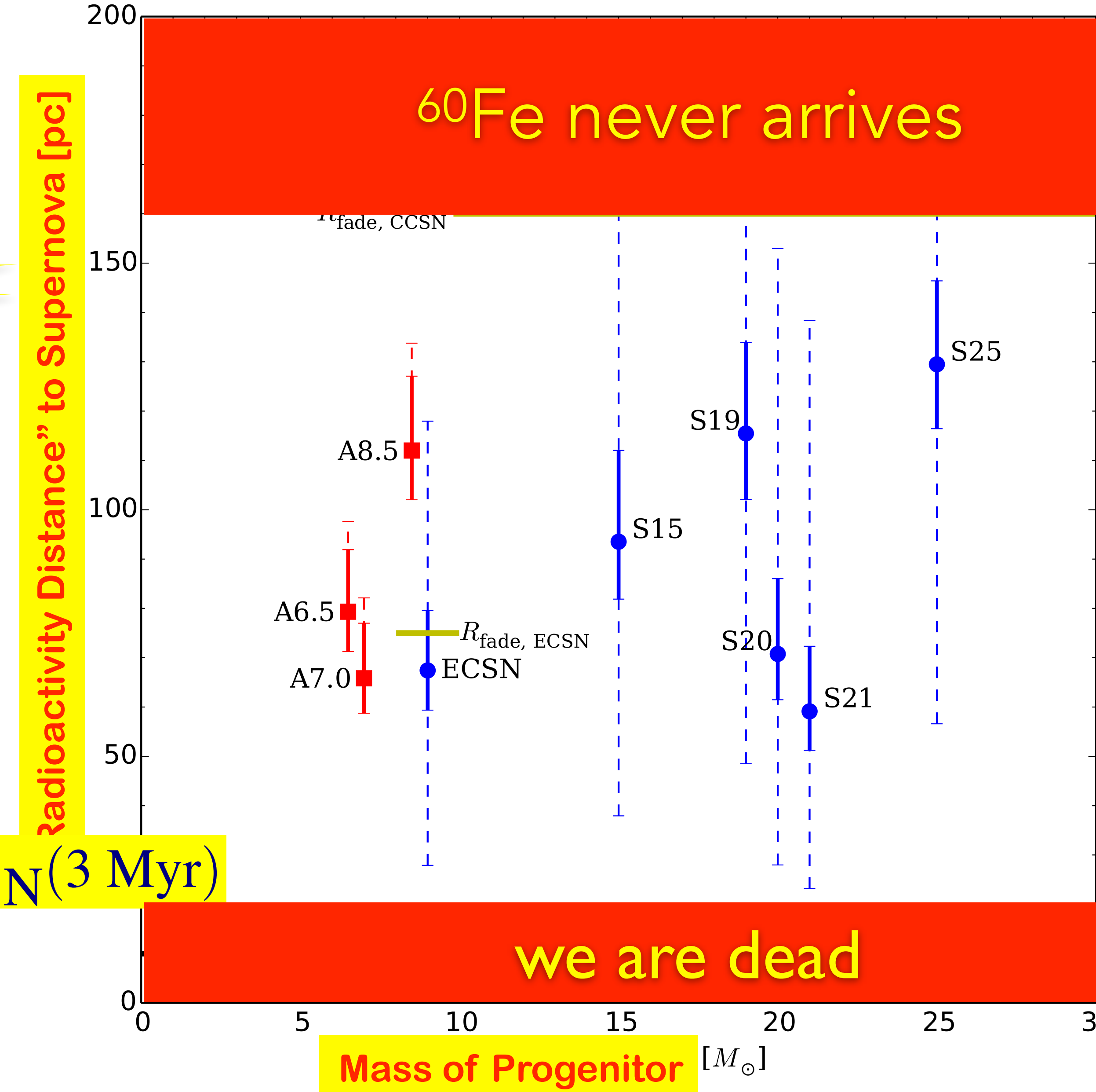
$$d(^{60}\mathrm{Fe}) \sim 30 - 150 \ \mathrm{pc}$$

Encouraging:

★ astronomical distances not built in!

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

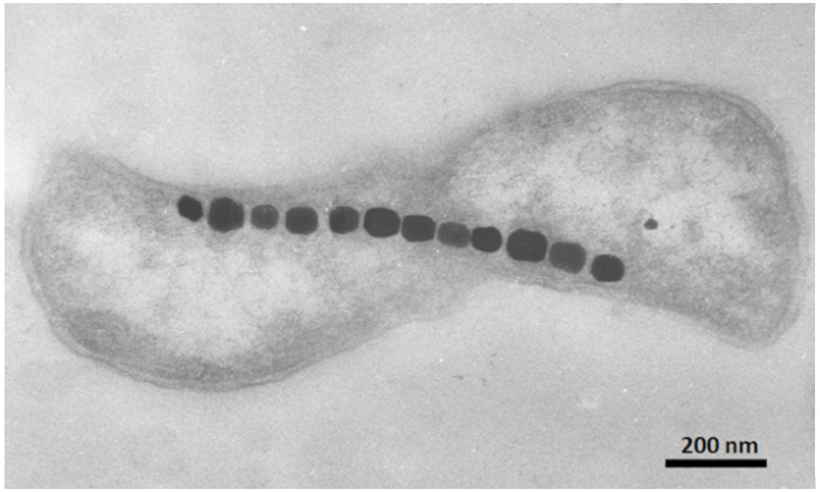
⇨ nontrivial consistency!

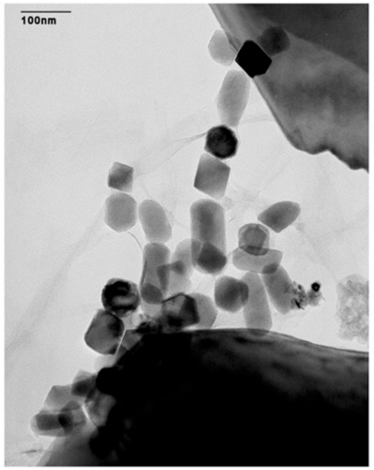


2016+

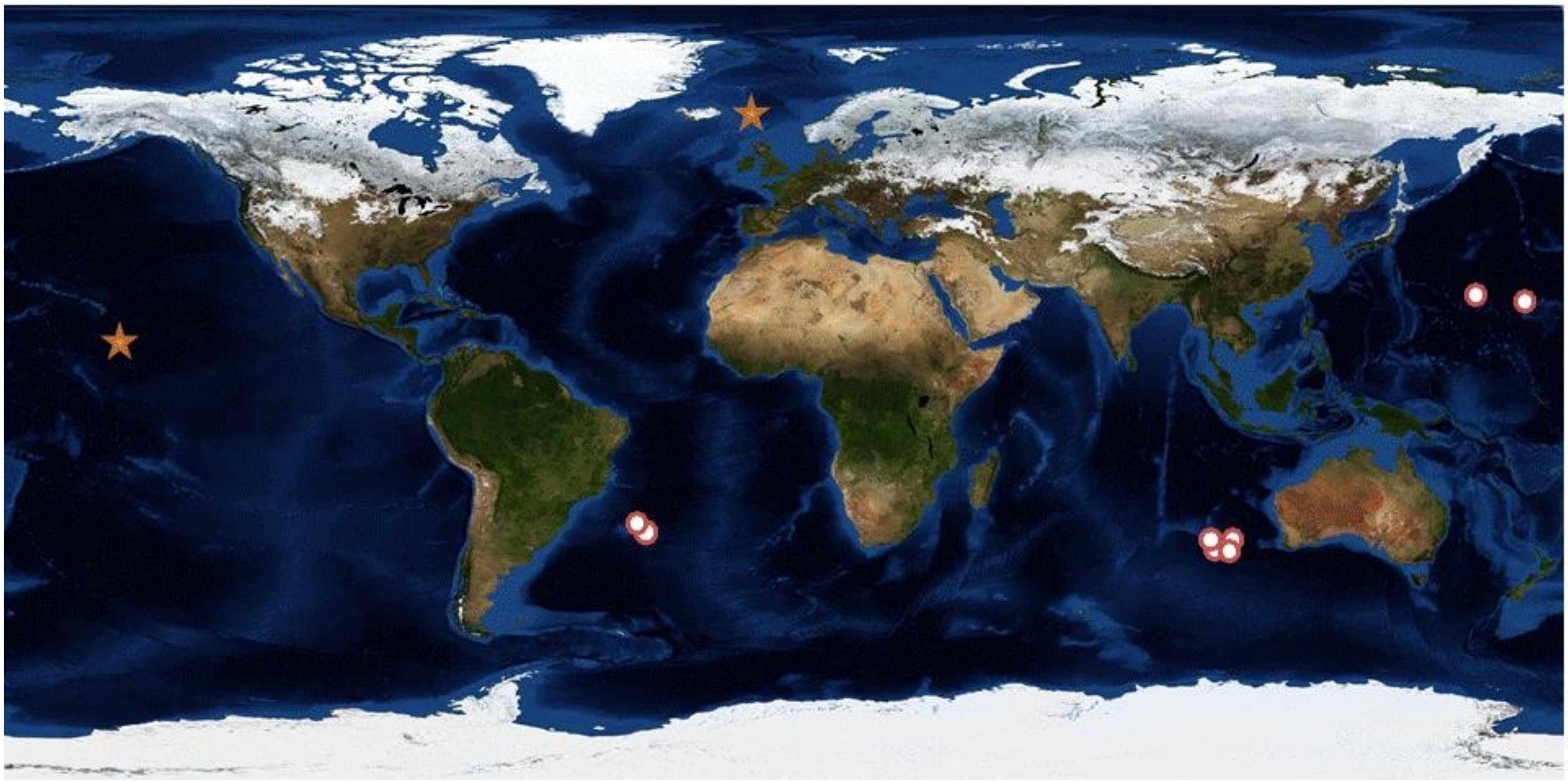
New Data, New Probes, New Sites

- ★ **New crust data** Wallner+ 2016
  - consistency check
- ★ **Ocean sediment data** Ludwig+ 2016; Wallner+ 2016
  - faster growth rate ~ 1 mm/kyr
  - much improved time resolution
  - magnetic microfossils!
- ★ **Lunar cores!** Fimiani+ 2016
  - ^{60}Fe excess over cosmic-ray production
- ★ **Cosmic rays** Binns+ 2016
  - ^{60}Fe detected, requires local source

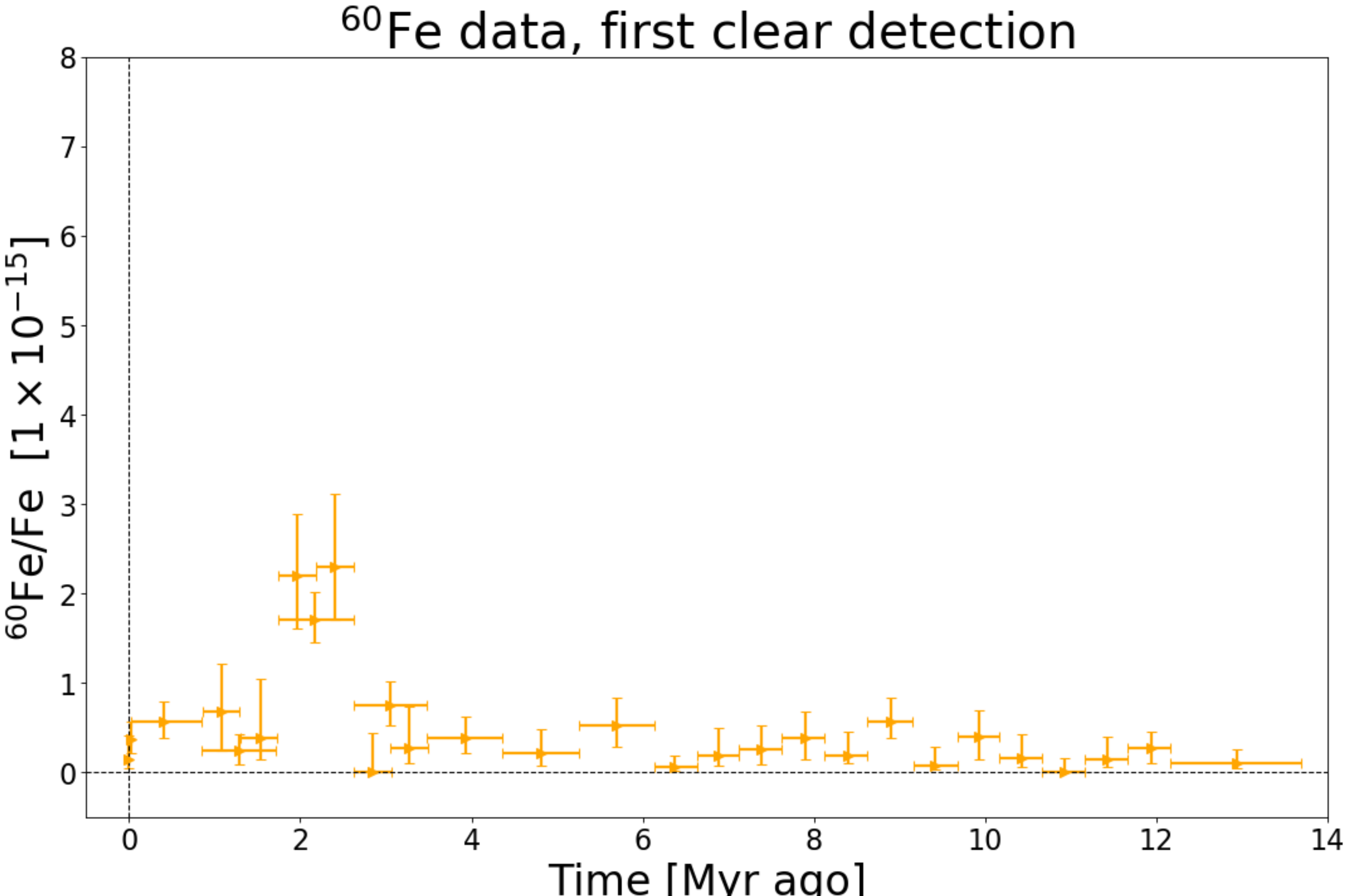




^{60}Fe Sample Sites

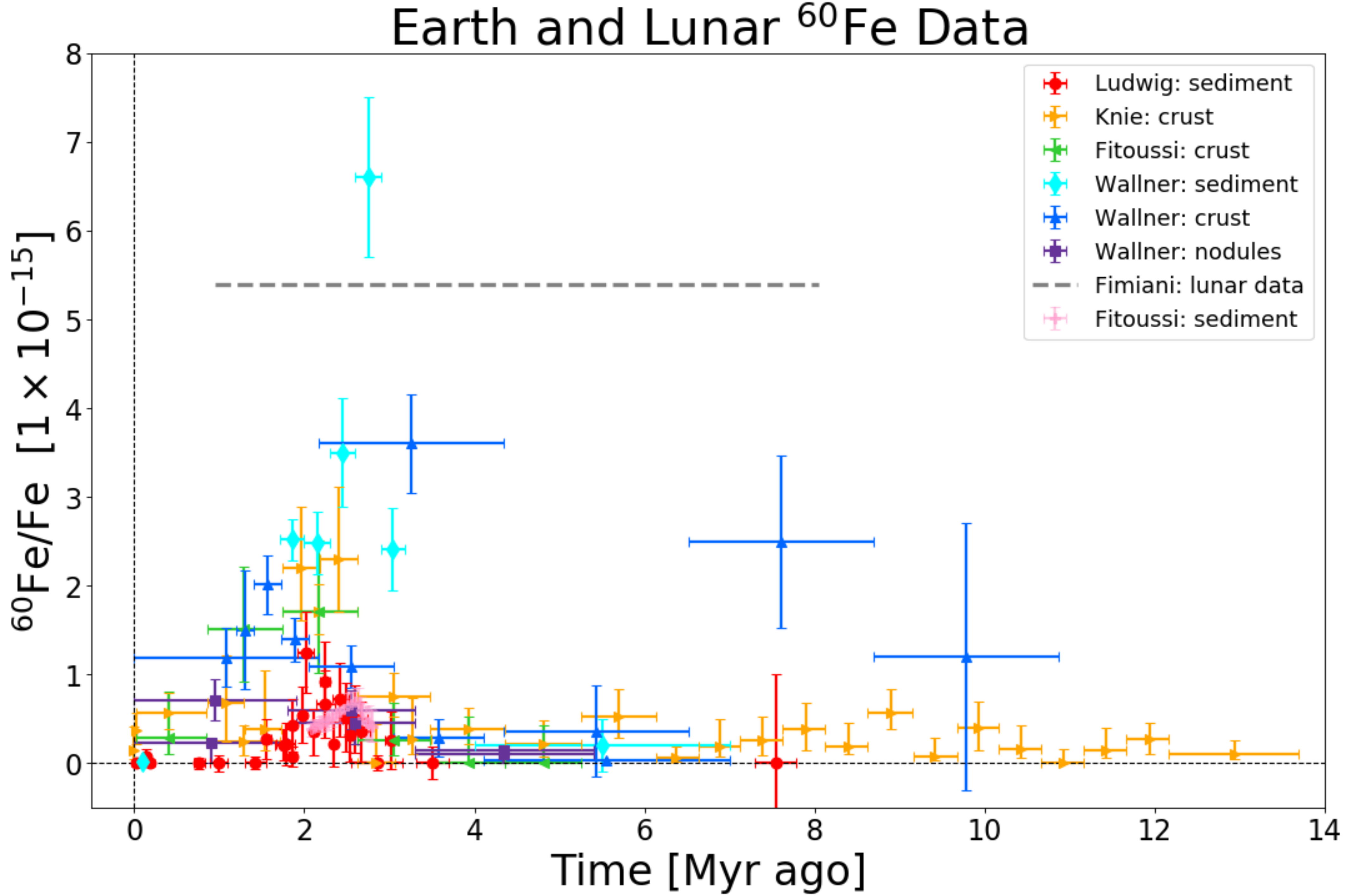


BEFORE



^{60}Fe data, first clear detection
^{60}Fe/Fe $[1 \times 10^{-15}]$
Time [Myr ago]
0
2
4
6
8
10
12
14
1
3
5
7

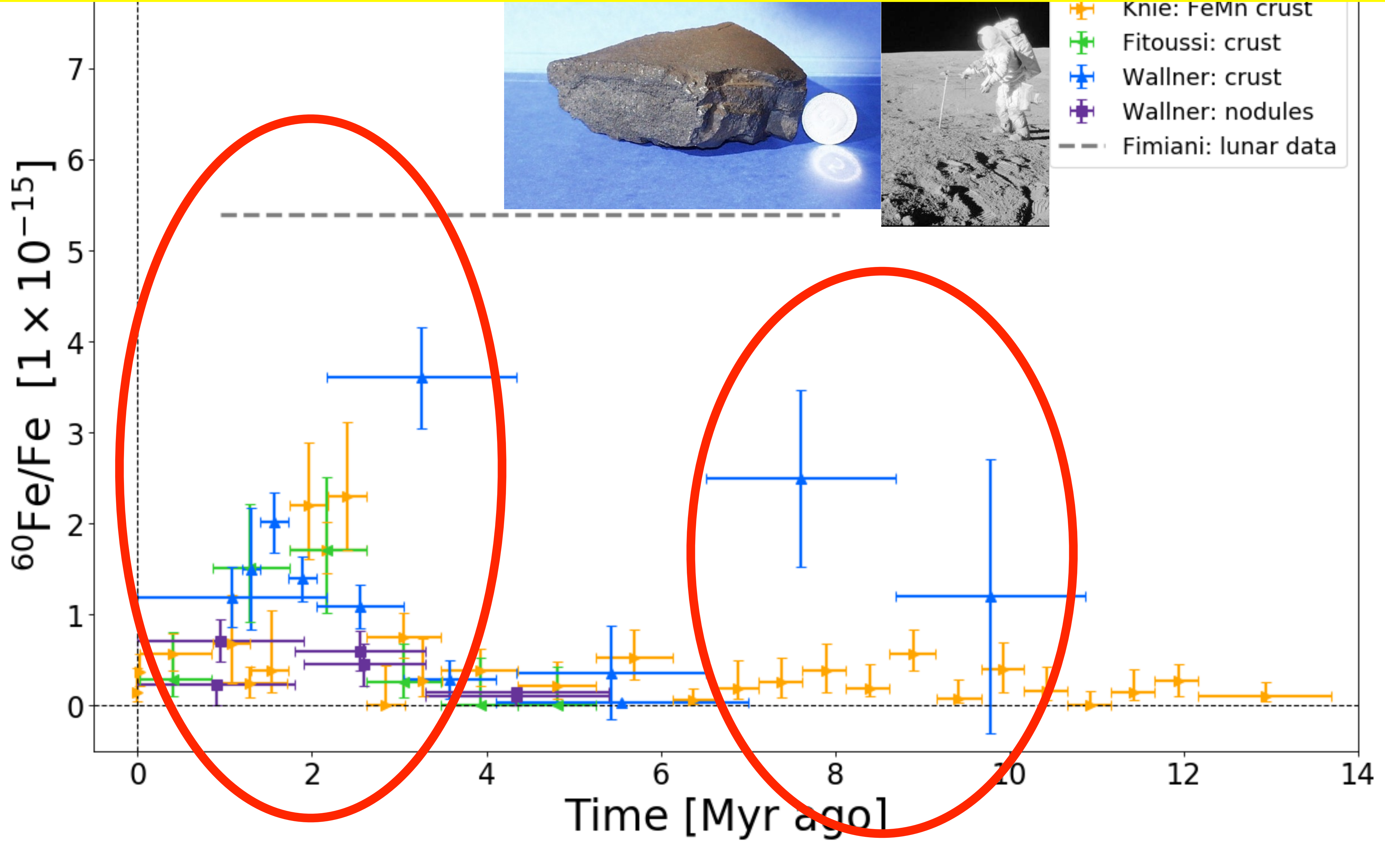
AFTER



Earth and Lunar ^{60}Fe Data
^{60}Fe/Fe [1×10^{-15}]
Time [Myr ago]
Ludwig: sediment
Knie: crust
Fitoussi: crust
Wallner: sediment
Wallner: crust
Wallner: nodules
Fimiani: lunar data
Fitoussi: sediment
0
1
2
3
4
5
6
7
8
10
12
14

★confirmation of ^{60}Fe crust signal at 2-3 Myr

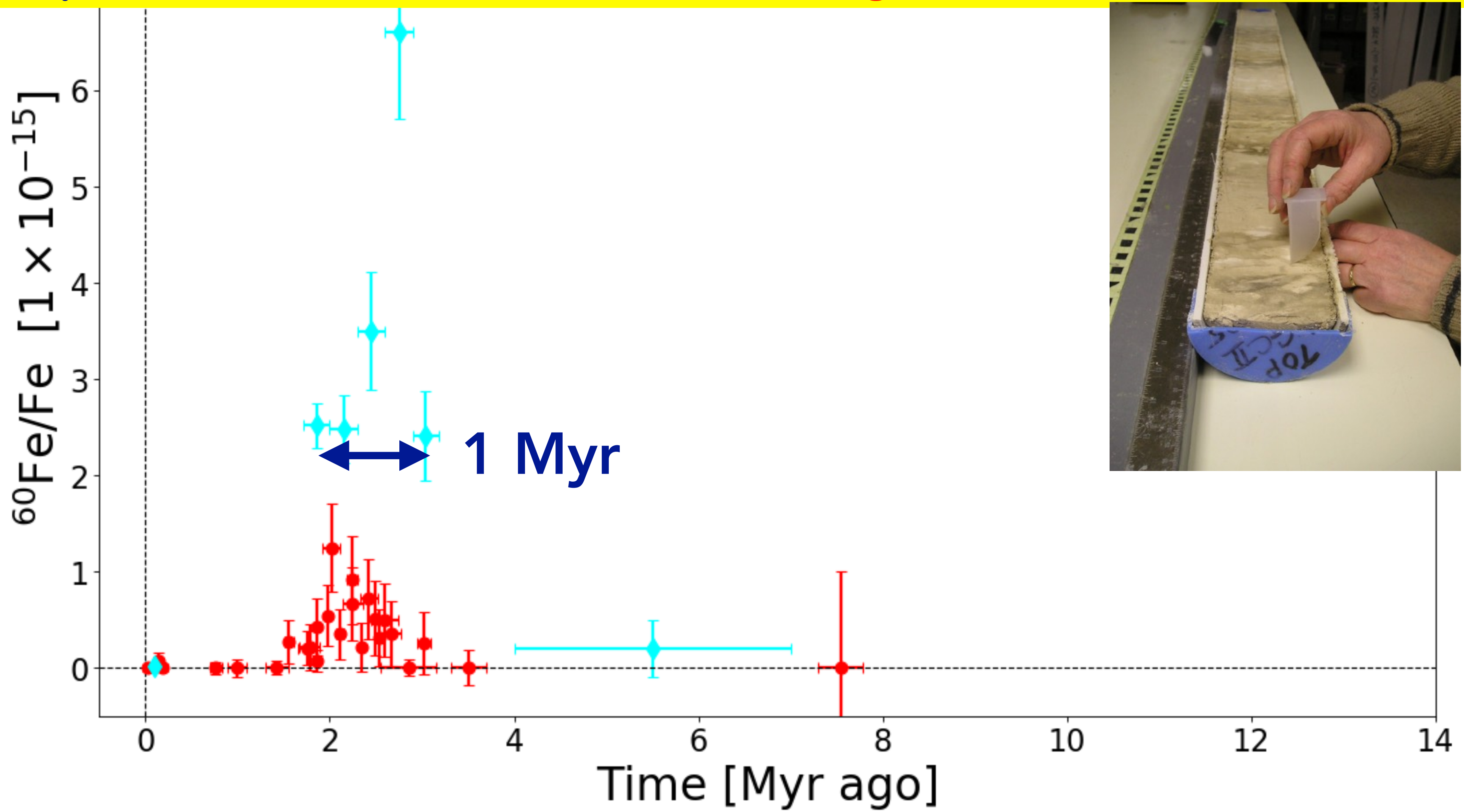
★another signal at ~8 Myr? ...now confirmed



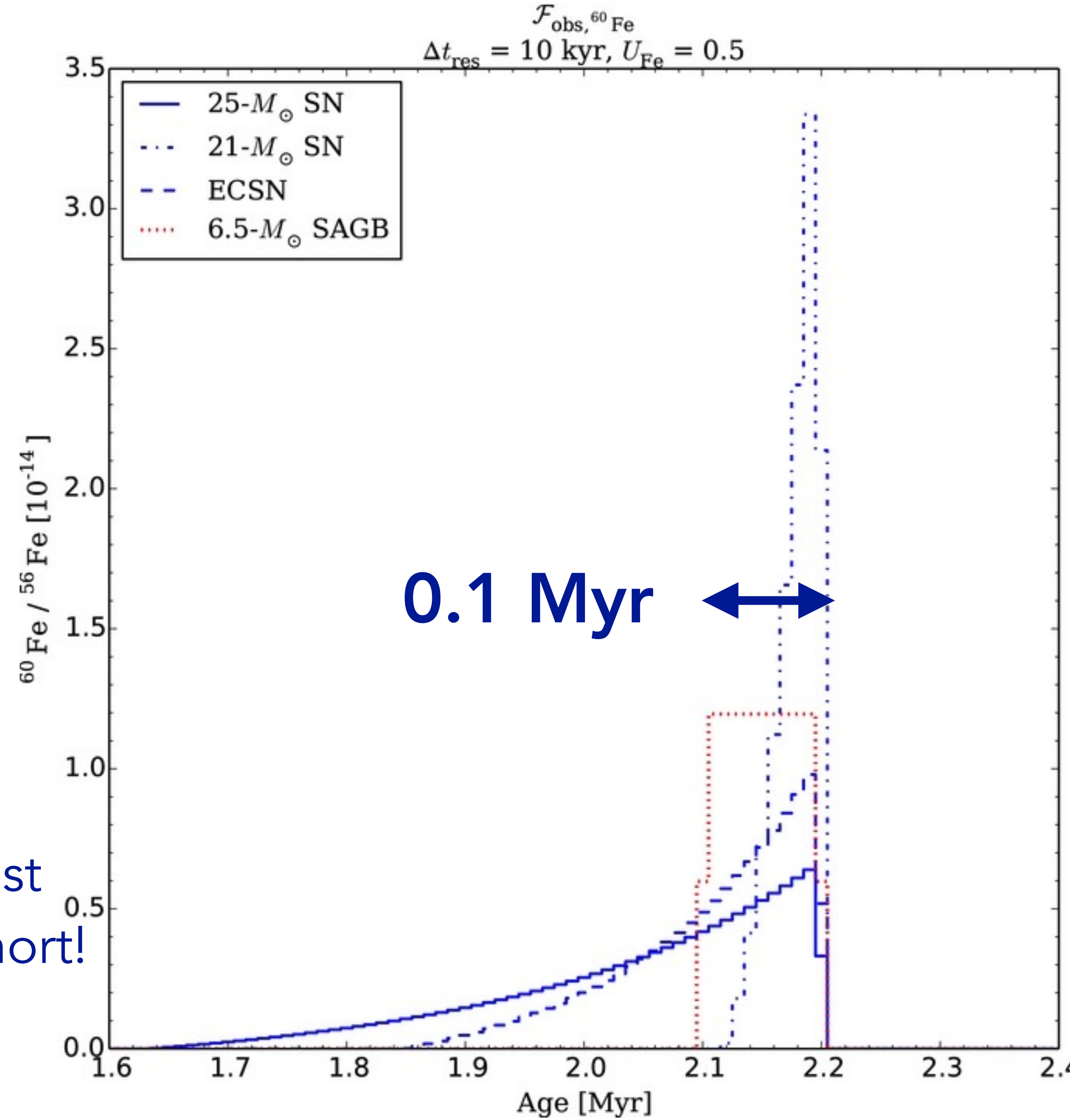
★^{60}Fe flux duration ~1 Myr

★far exceeds Sedov prediction!?! Fry+ 2015

★probes dust evolution & dynamics? Fry, Ertel + 2017



^{60}Fe Time Profile: Sedov Models

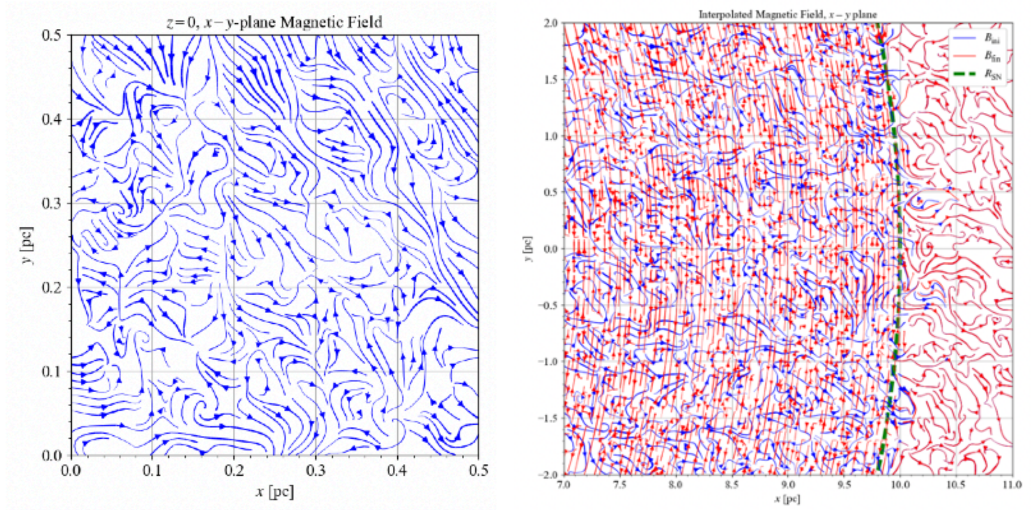


Fry, BDF, Ellis 2015

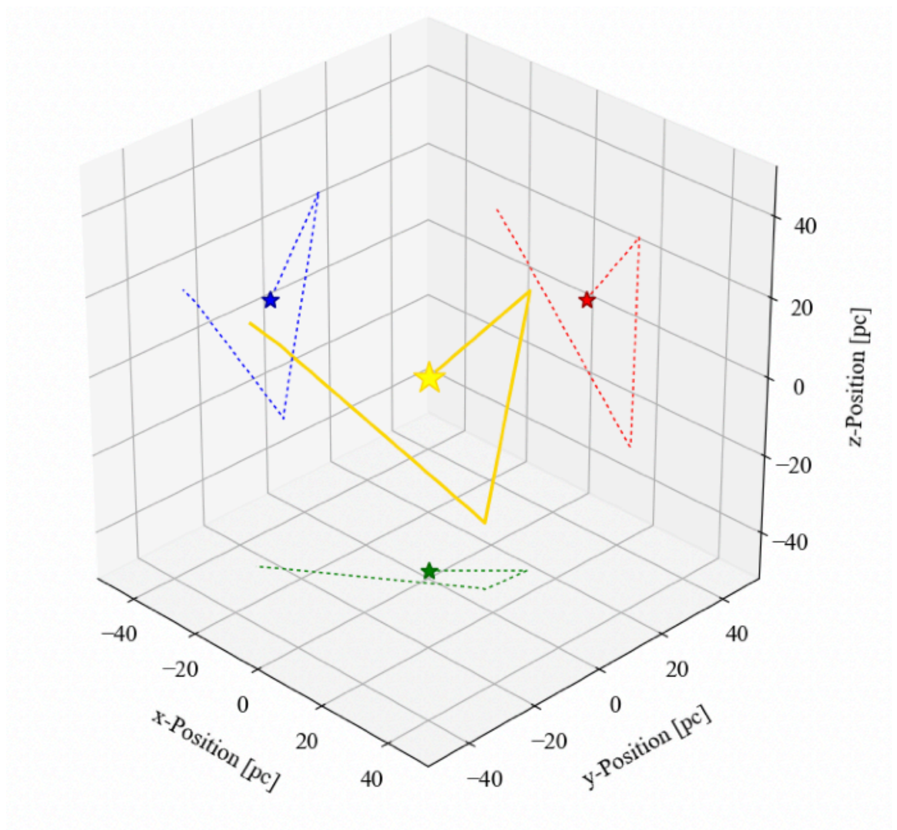
- assumes dust carried in blast
- ~0.1 Myr timescale: too short!

^{60}Fe Probes Supernova Dust

Fry, BDF, Ellis 2017; Fry, Ertel, Fields, Ellis 2017

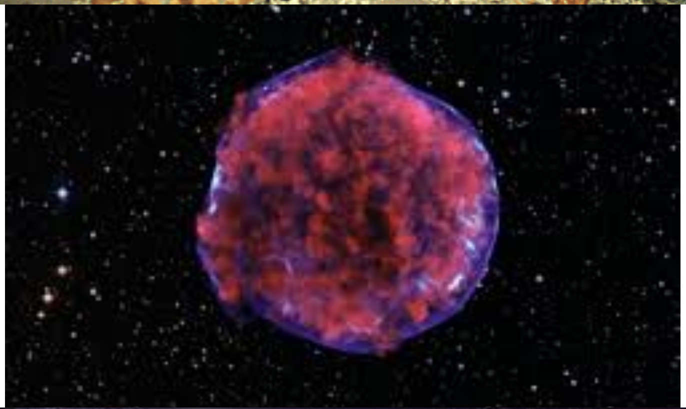


- ★ ^{60}Fe dust moves in magnetized SNR
- ★ decouples from blast
- ★ reflected by shocked ISM fields
- ★ bounces inside SNR
- ★ timescale probes dust drag & sputtering!



Plutonium-244

Bishop talk; r-process sessions



- ★ **half-life** $t_{1/2}(^{244}\mathrm{Pu}) = 80\ \mathrm{Myr}$
  - gateway to mass extinctions
- ★ **made in r-process**
  - binary neutron star mergers: kilonovae!
  - a component from core-collapse SN?
- ★ **detection would confirm:**
  - (some) SN are r-process factories!
- ★ **Results:**
  - see Bishop talk!

CONCLUSION

THIS IS A THING

new probe for astronomy, astrophysics, geology, biology…

Neil de Grasse Tyson
Cosmos Finale Episode

FeMn nodule!

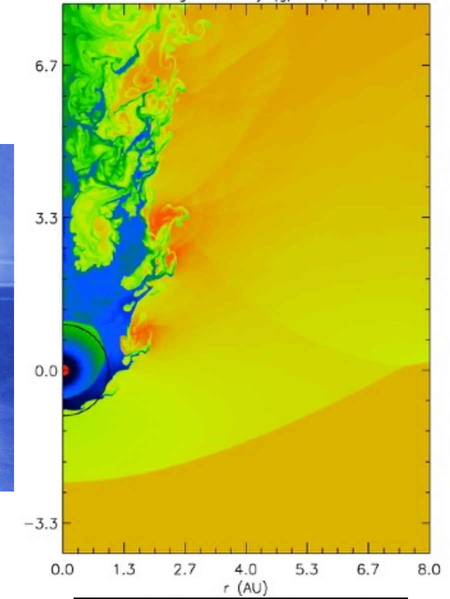
The difference between

seeing nothing but a pebble

and reading the history of the cosmos
inscribed inside it

is Science.

Outlook



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

- ★ signal in deep ocean crusts, nodules, sediments find
- ★ confirmed pulse ~2-3 Myr ago
- ★ now strong evidence for pulse at ~7 Myr
- ★ ^{60}Fe pulse duration ~1 Myr ?!?
- ★ evidence for lunar signal—directionality?
- ★ ^{244}Pu detection announced
- ★ Source of Local Bubble?

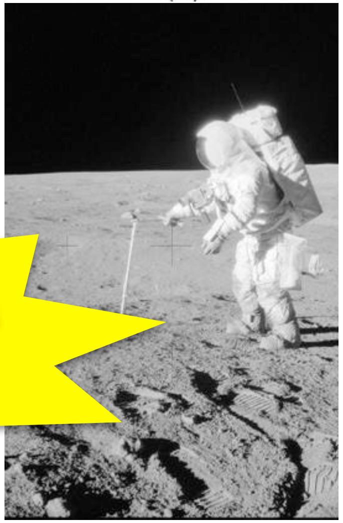
Birth of "Supernova Archaeology"

Convergence among disciplines:

astro (nucleosynthesis, cosmic dust, stellar evolution, local bubble)

beyond: geology, bio evolution, astrobiology

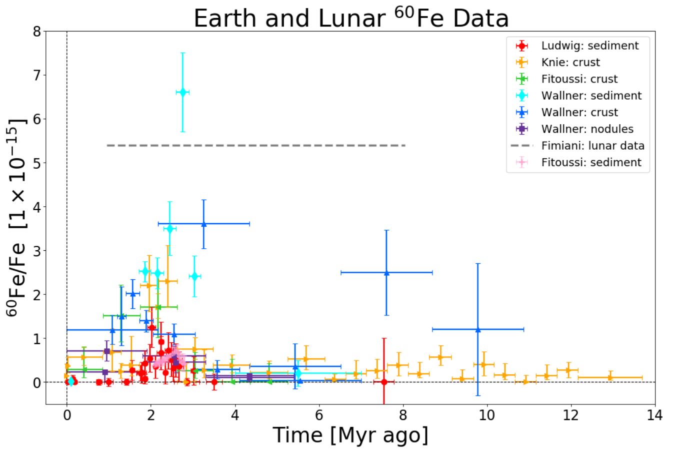
Close similarities to SN injection model of presolar radioactivities



Congratulations Shawn!

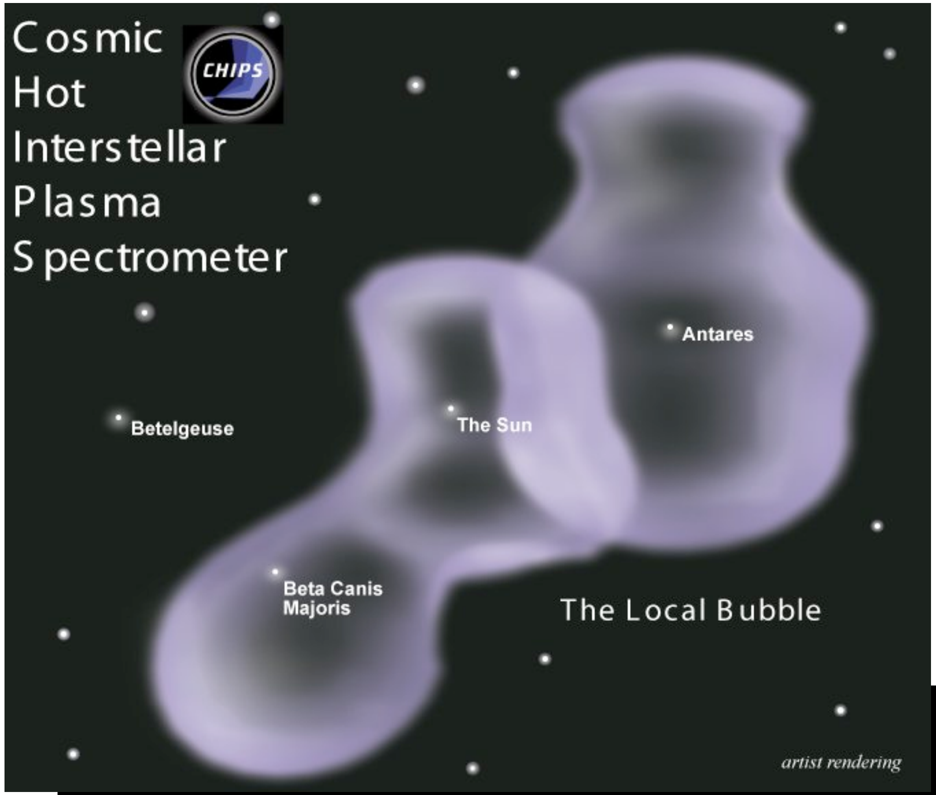
Future Research

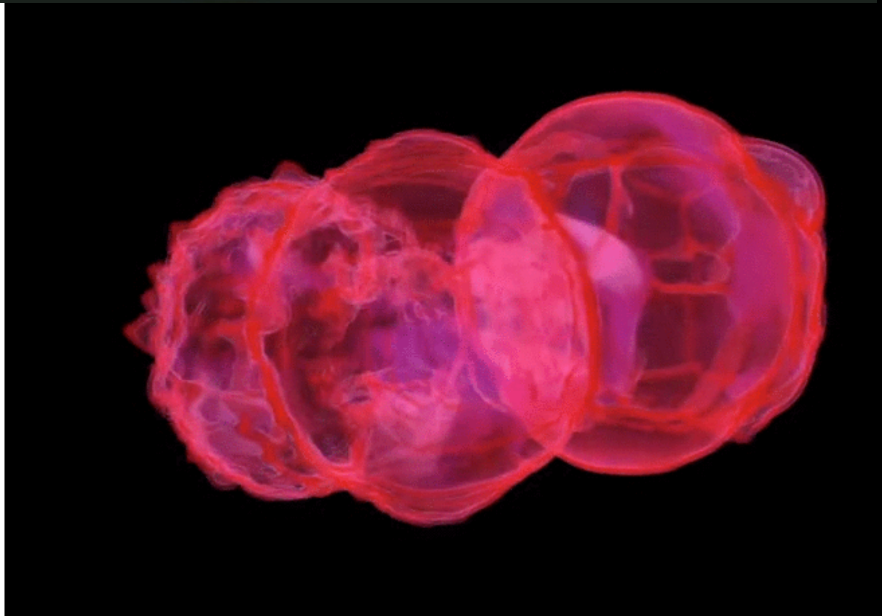
- Supernova(e) origin and direction
  - ★ lunar distribution
  - ★ cosmic-ray anisotropies, ^{60}Fe excess
  - ★ neutron star/pulsar correlation
  - ★ dust production, evolution, dynamics
- more, different samples:
  - ✓ other isotopes (reactions and nucleosynthesis!)
    - e.g., ^{26}Al, ^{41}Ca, ^{53}Mn, $^{97,98}Tc$. Now also: ^{244}Pu!!!
  - ✓ other media (fossil bacteria)
  - ✓ other sites: back to the Moon!
- other epochs? Mass extinction correlations?
- stay tuned!



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 from near star cluster? Benitez et al 02
  - – Bubble wall as source of ~1 Myr ^{60}Fe pulse width? Breitschwerdt+ 2016; 2017





A Near Miss?

Thomas+ 2016, Knie+ 2004, BDF+ 2005

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

"near miss"

Image: Mark Garlick www.markgarlick.com

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

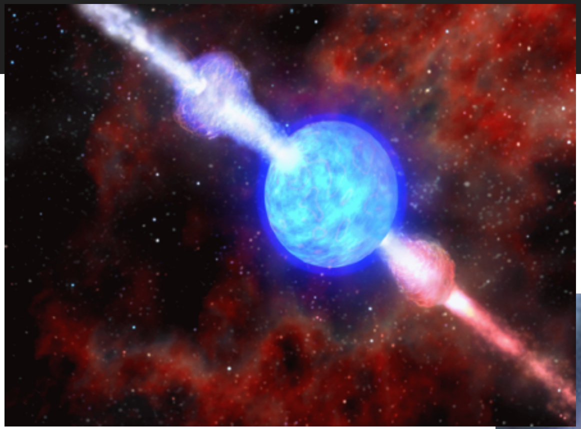
If true:

implications for astrobiology

tightens Galactic habitable zone

The Hits Keep Coming:
Gamma-Ray Bursts

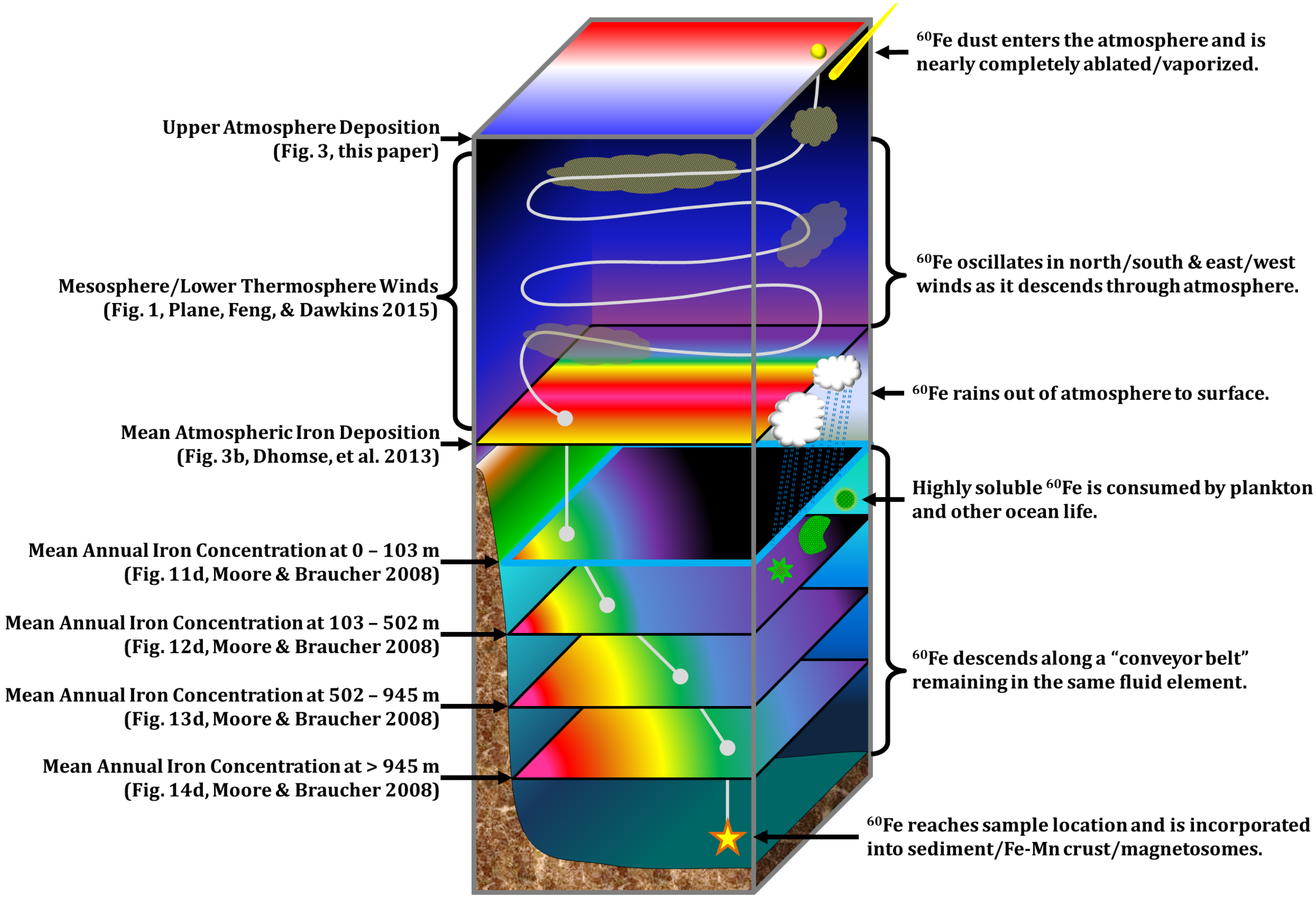
Melott, Thomas; Dermer & Holmes



- ★ Gamma-ray bursts also deliver intense ionizing radiation dose
  - – 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"
  - – but non-lethal even if aimed at us Thomas et al 2008

Radioactive Iron Rain

Frv. BDF. Ellis 2016

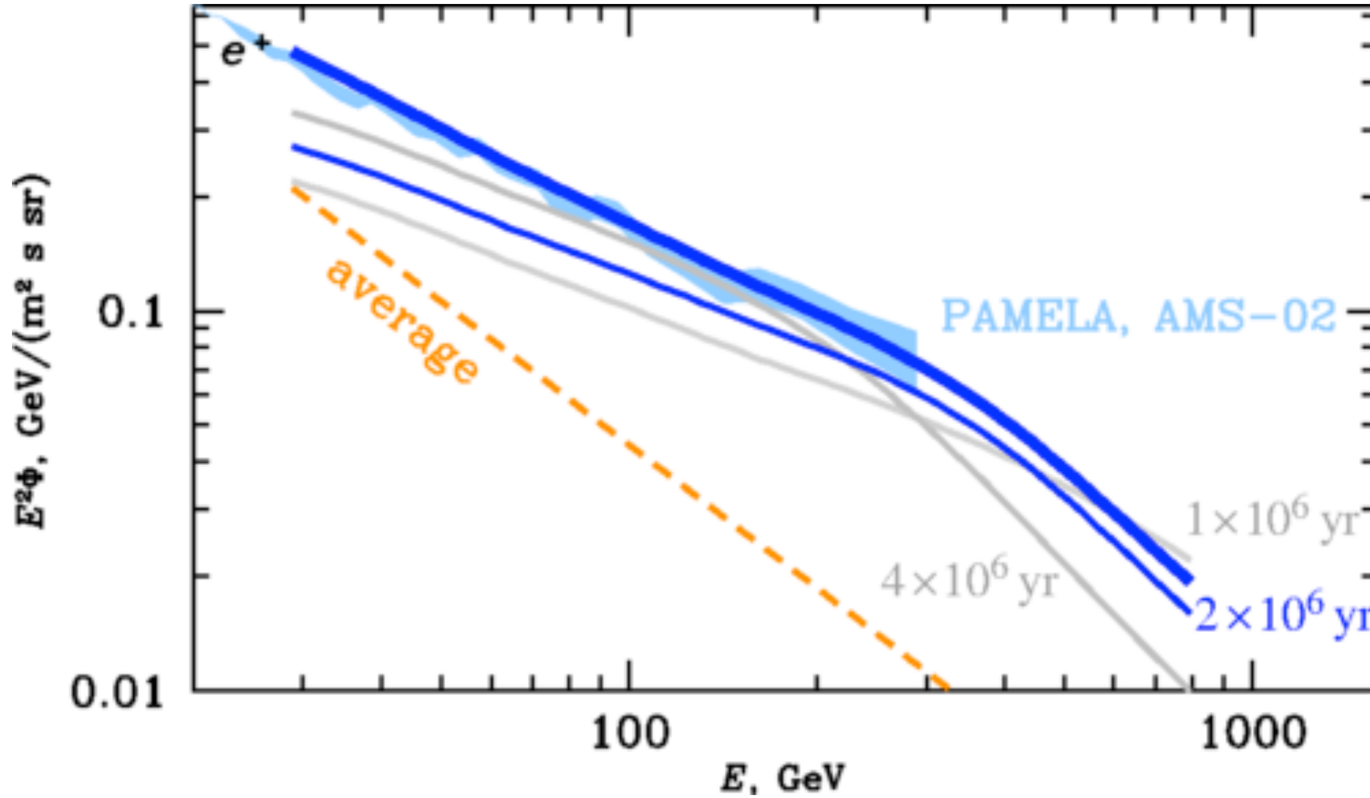


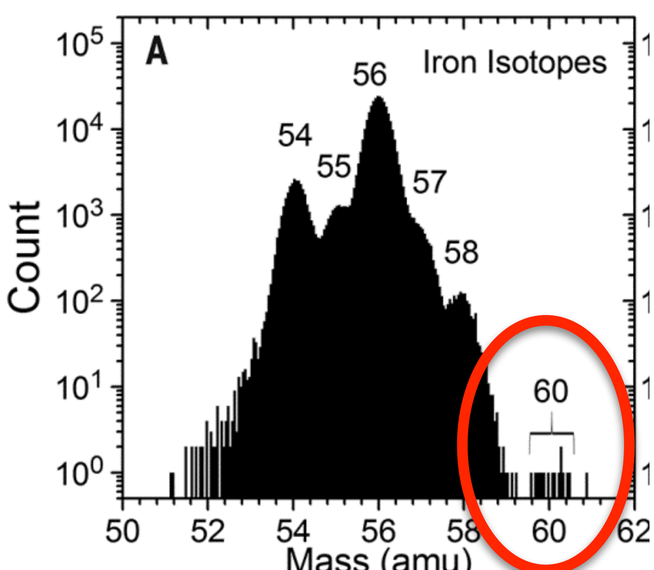
Cosmic-Ray Corroboration?

★ 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

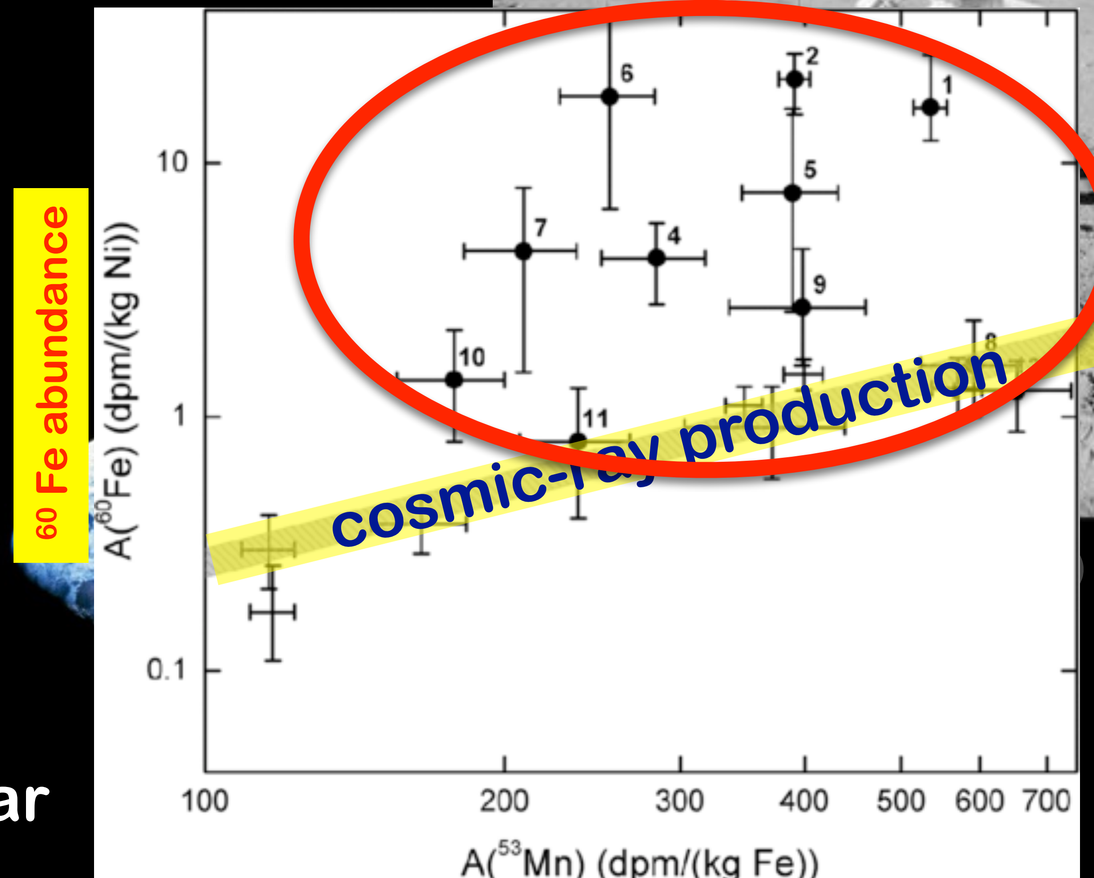
- requires local & recent source

The Moon!

Lunar Soil

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

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

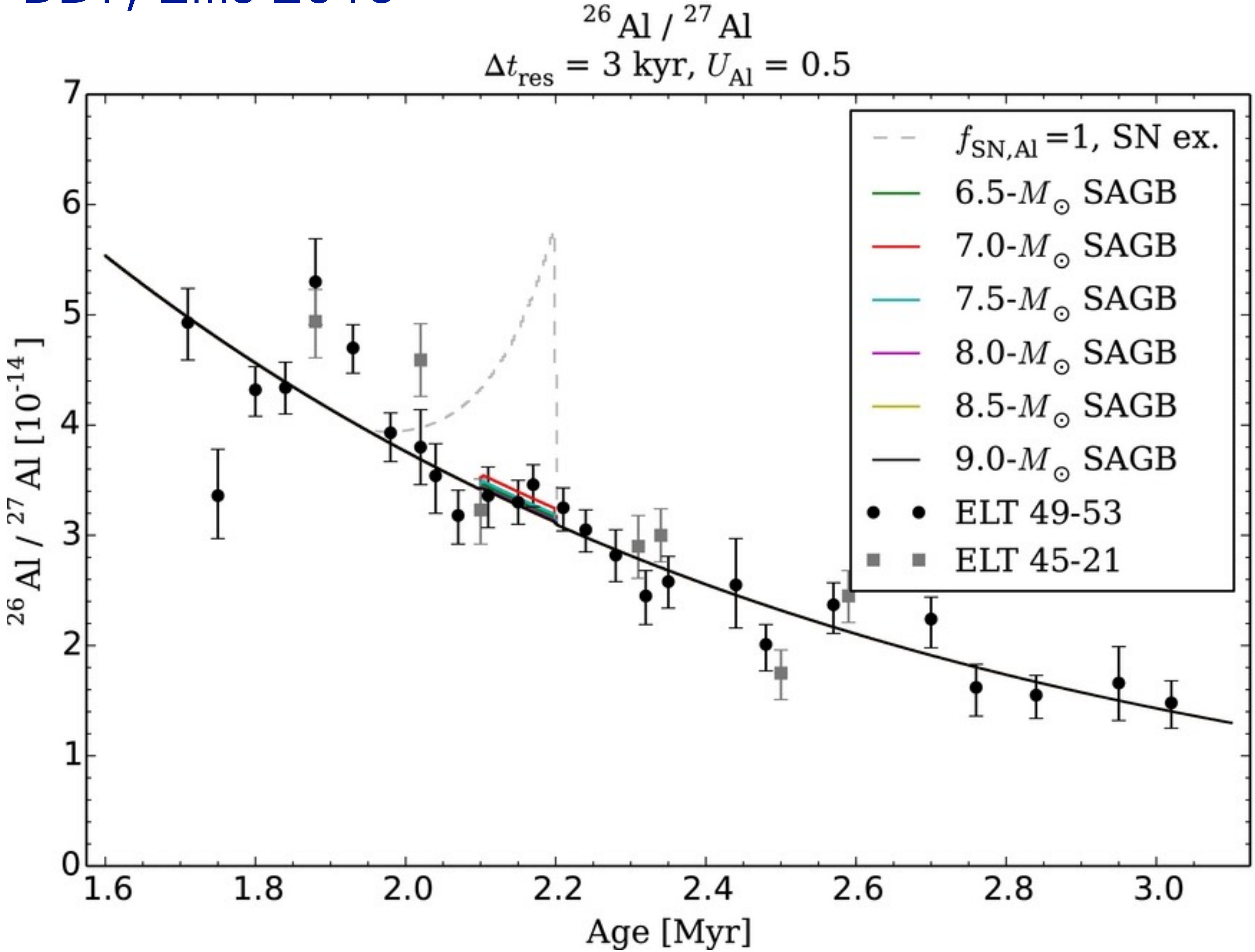


radioactive ^{53}Mn abundance

Fimiani+ 2016 PRL

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

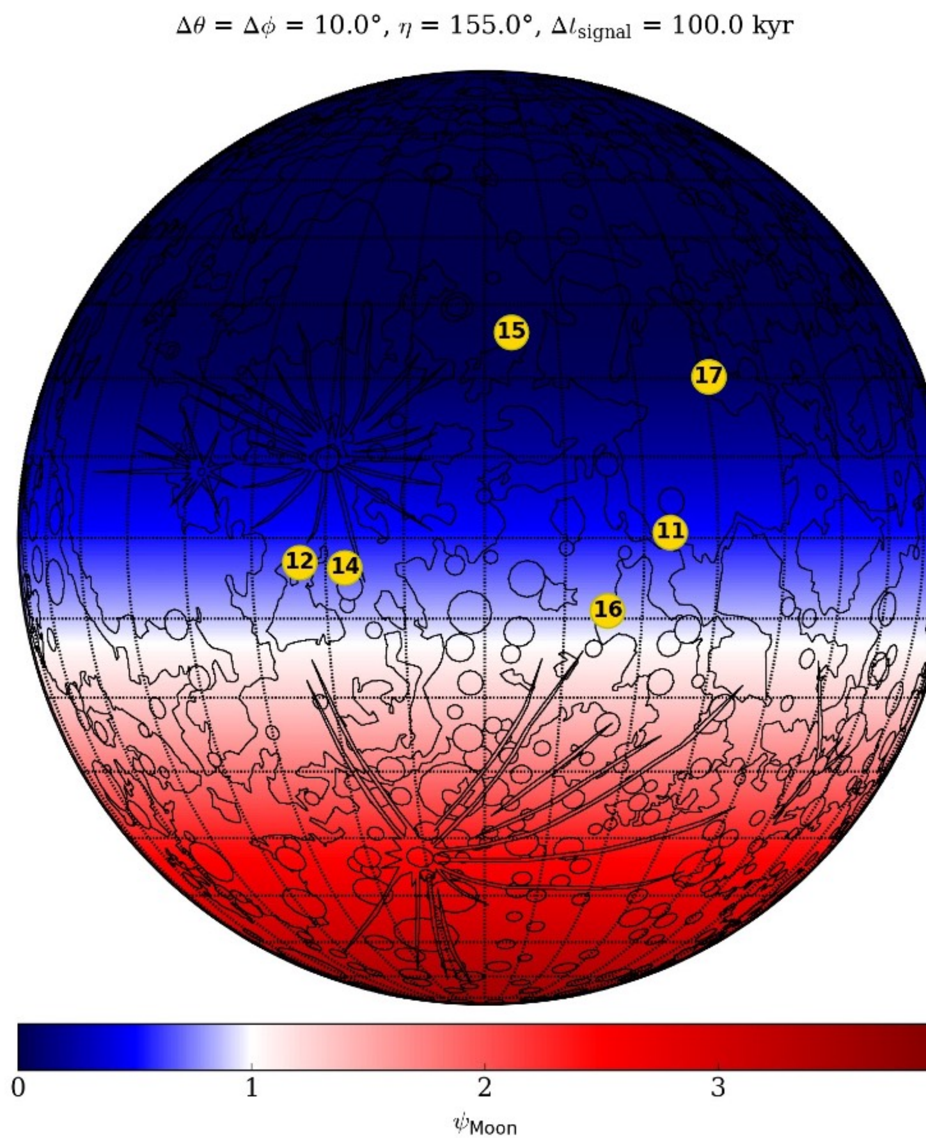
Fry, BDF, Ellis 2015



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!



Fry, BDF, Ellis 2017