Title: Radioactive Iron Rain: Evidence of a Recent Nearby Supernova Explosion

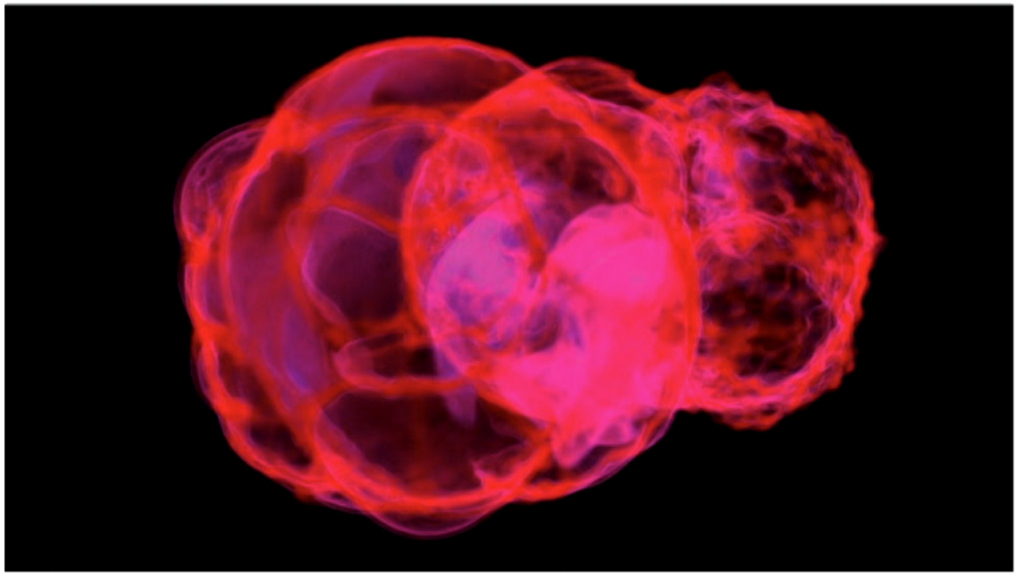
Date: Feb 07, 2017 01:00 PM

URL: http://pirsa.org/17020094

Abstract: <p>A very close supernova explosion could have caused a mass extinction</p>

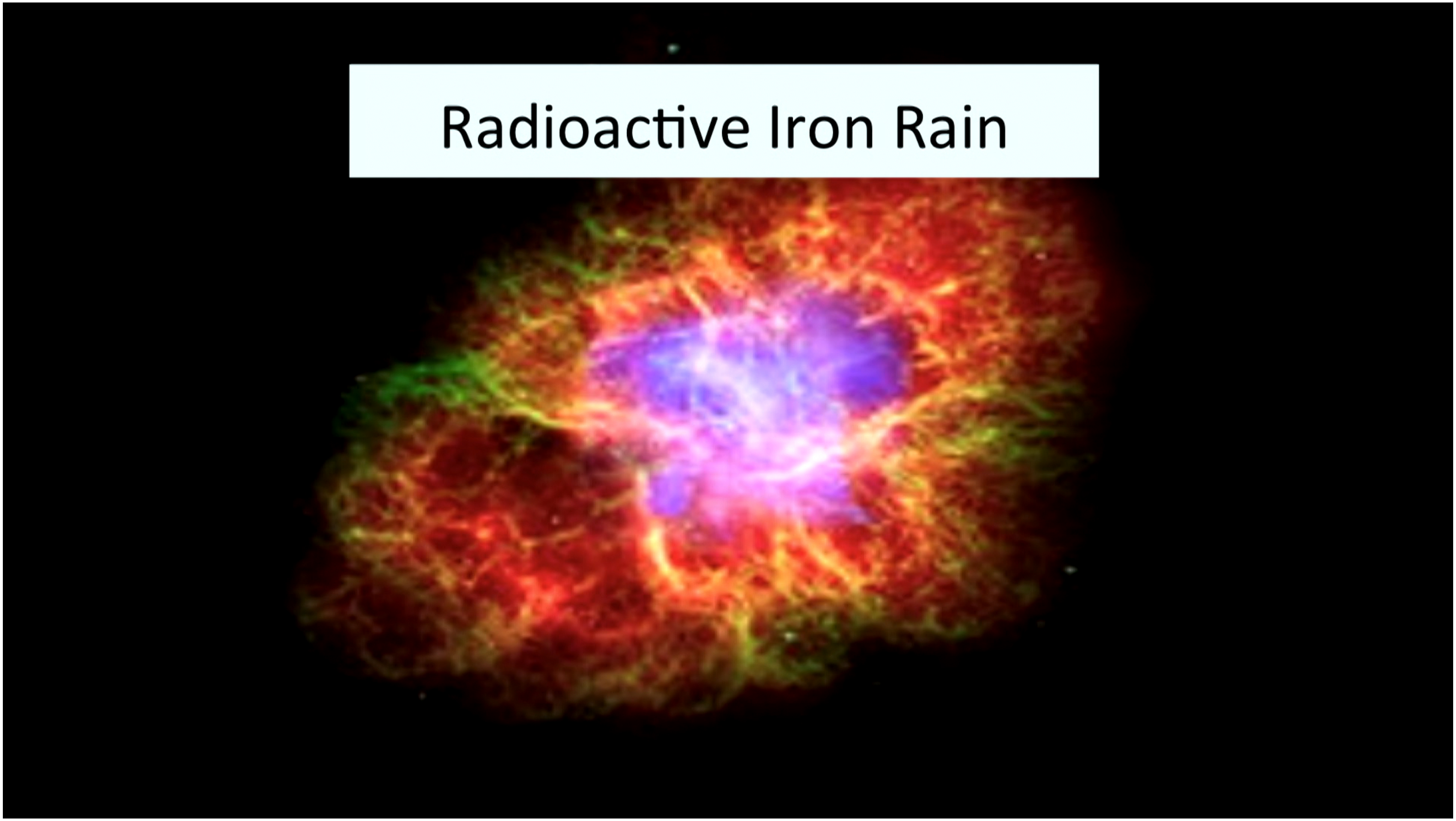
<p>of life in Earth. In 1996, Brian Fields, the late Dave Schramm and the
speaker proposed looking for unstable isotopes such as Iron 60 that could
have been deposited by a recent nearby supernova explosion. A group from
the Technical University of Munich has discovered Iron 60 in deep-ocean
sediments and ferromanganese crusts due to one or more supernovae that
exploded O(100) parsecs away about 2.5 million years ago. These results
have recently been confirmed by a group from the Australian National
University, and the Munich group has also discovered supernova Iron 60 in
lunar rock samples and in microfossils of magnetotactic bacteria.
This colloquium will discuss the data and their interpretation
in terms of supernova models, and the possible implications for
life on Earth.</p>

Science AAAS



A simulation of iron-60 atoms dispersed by multiple supernovae close to the solar system 2.2 million years ago. Some of that iron still lies at the bottom of the oceans and on the moon. Michael Schulreich

Earth barraged by supernovae millions of years ago, debris found on moon

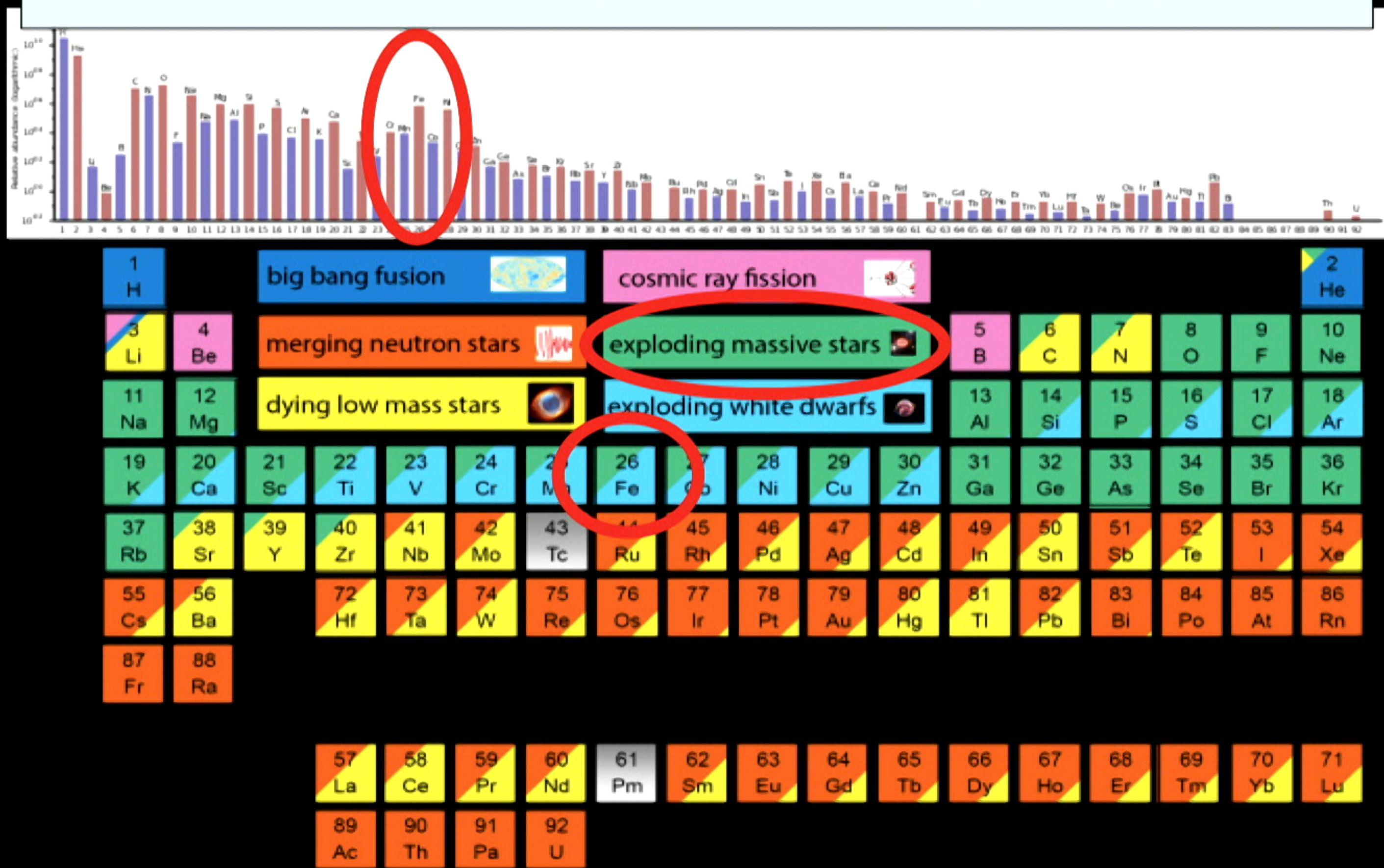

Radioactive Iron Rain

Radioactive Iron Rain

The discovery of ^{60}Fe from a nearby supernova explosion

~ 2.5 million years ago

Terrestrial Element Abundances

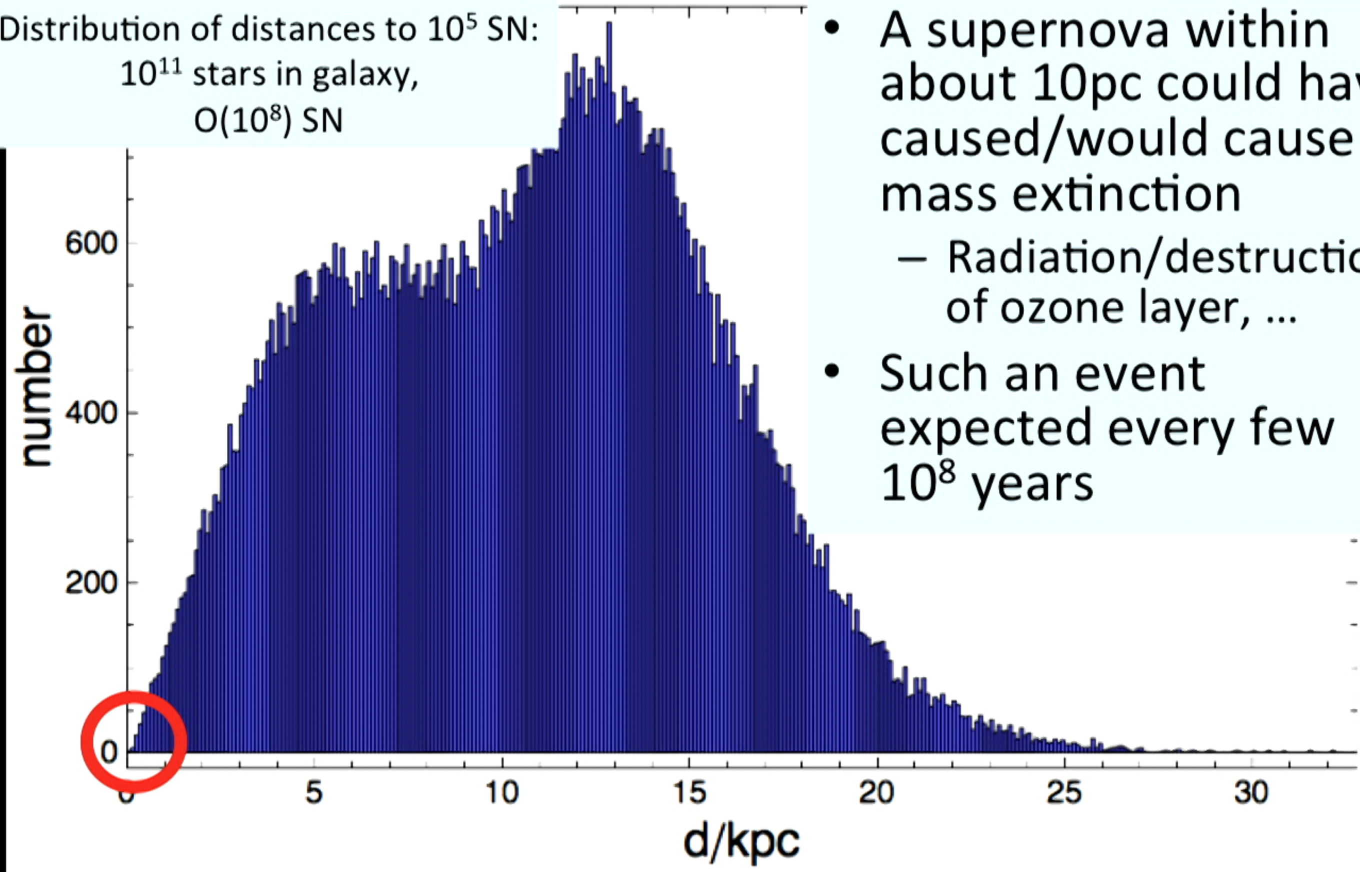


Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova

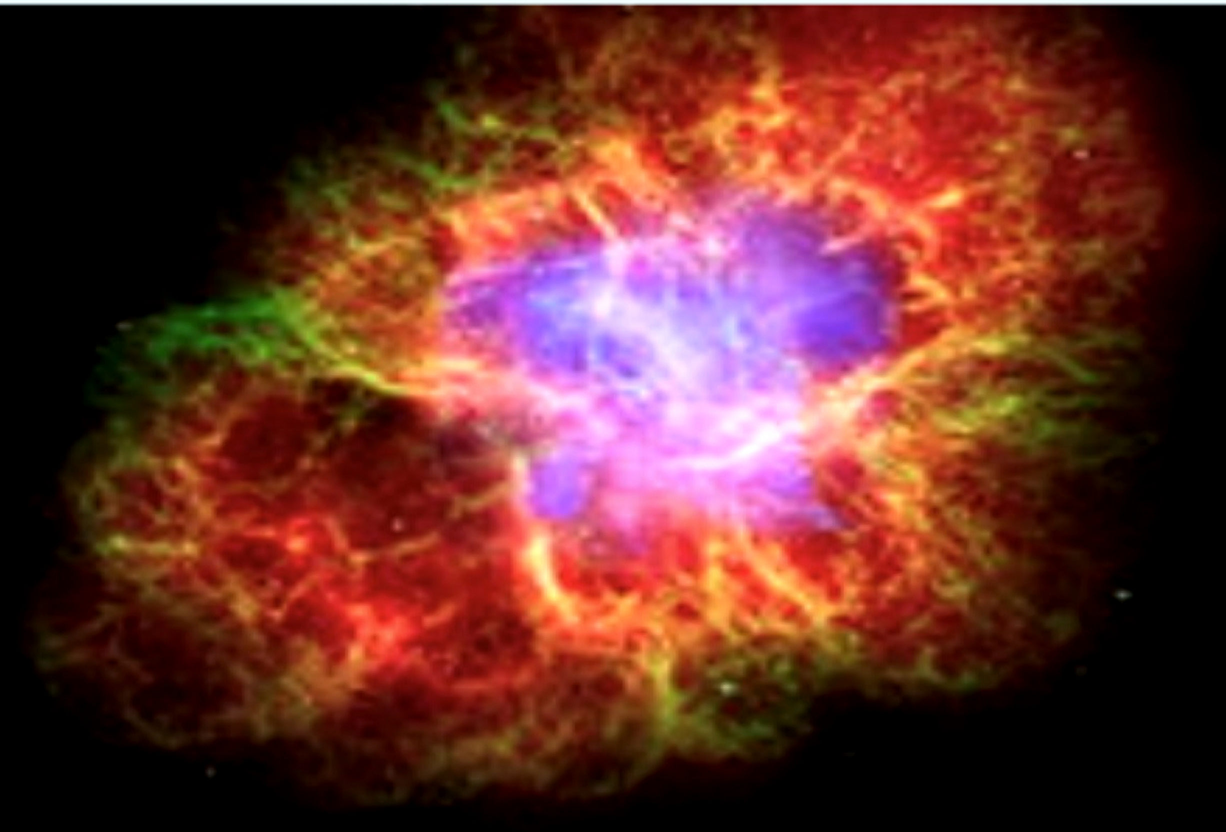
A Killer Supernova Explosion?

Distribution of distances to 10^5 SN:
10^{11} stars in galaxy,
$O(10^8)$ SN



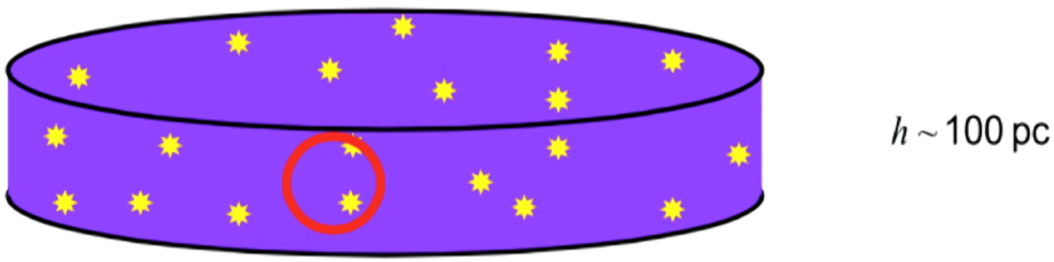
- A supernova within about 10pc could have caused/would cause a mass extinction
  - Radiation/destruction of ozone layer, …
- Such an event expected every few 10^8 years

A Killer Supernova Explosion?



A Killer Supernova Explosion?

– **Galactic supernova rate today:** $\mathcal{R}_{\rm SN}$



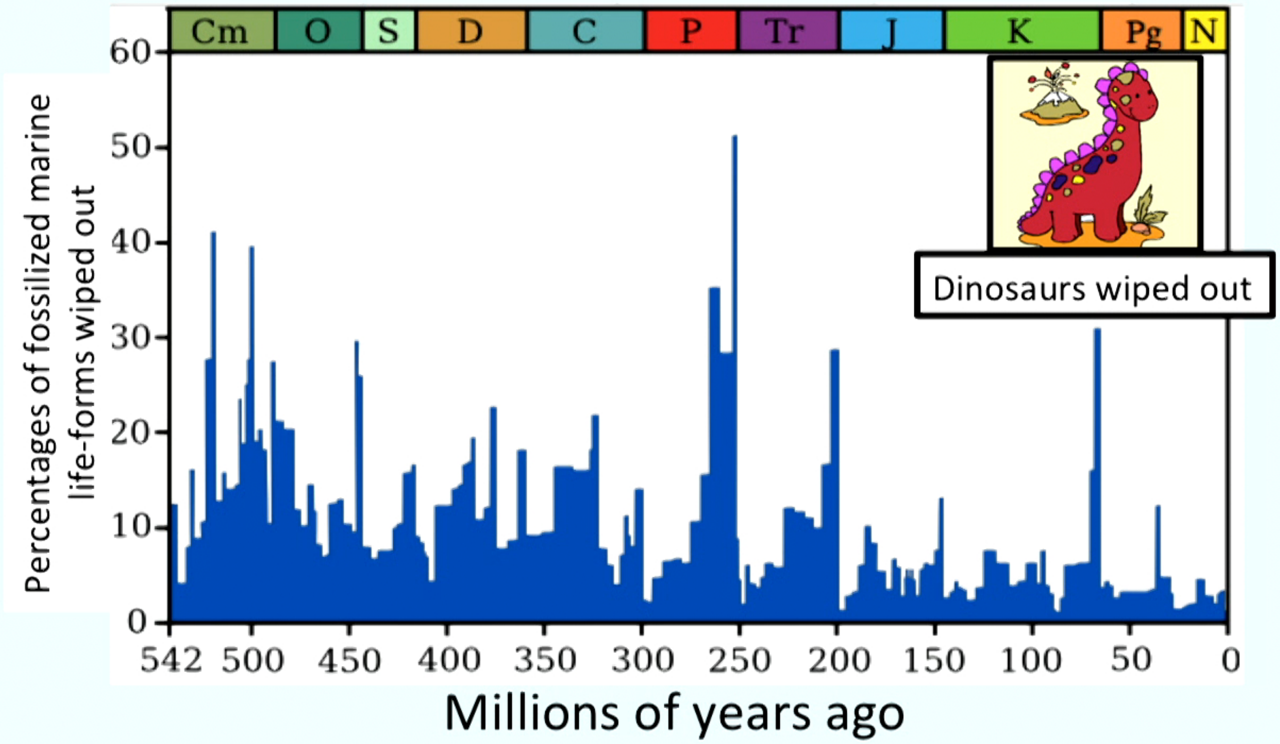
$$\lambda(< d) = \frac{V_{\rm disk}(< d)}{V_{\rm disk,total}} \mathcal{R}_{\rm SN} = (10\ {\rm Myr})^{-1} \left(\frac{d}{30{\rm pc}}\right)^3$$

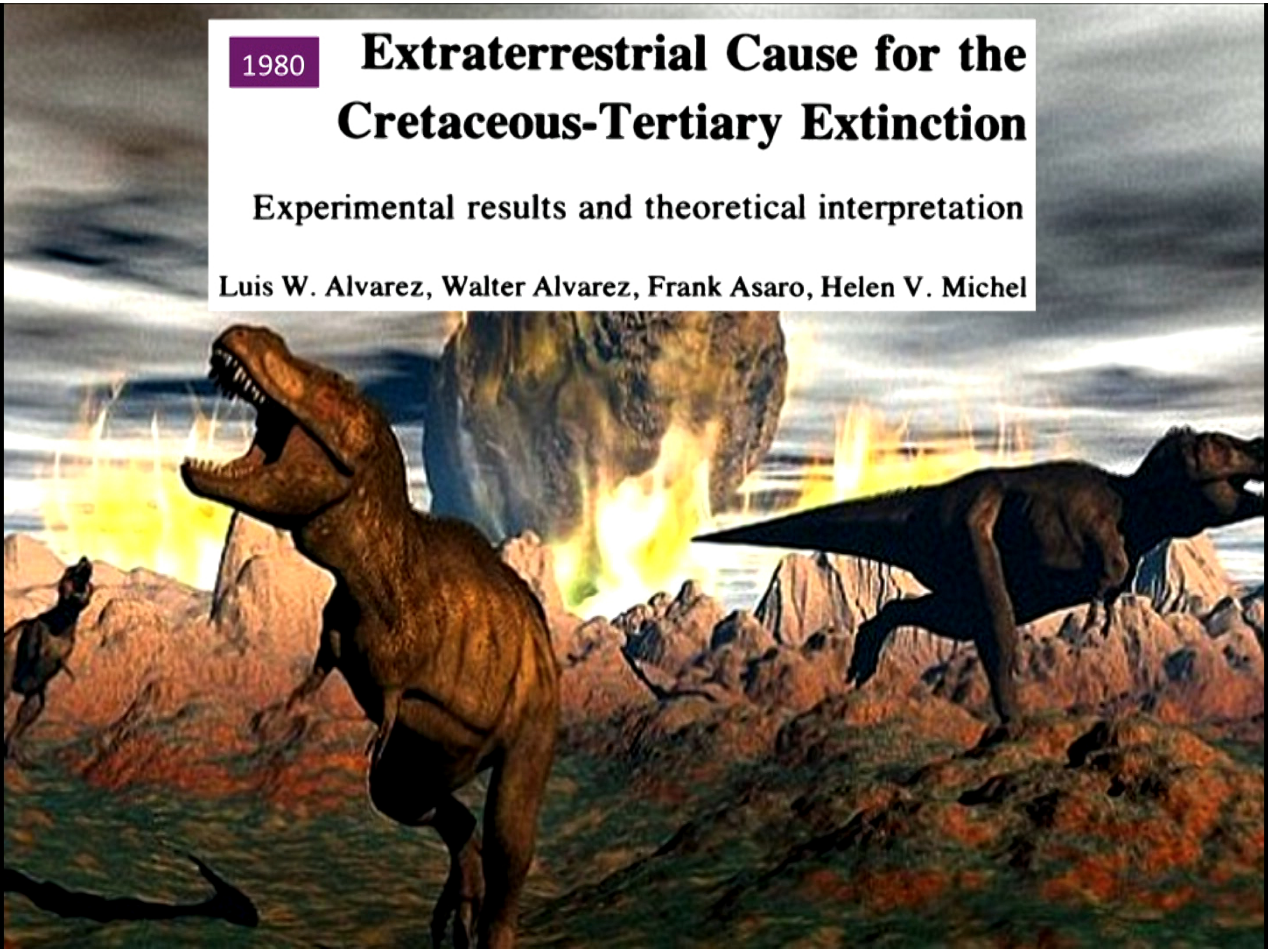
– **corrections: spiral arms, molecular clouds, exponential disk...** Talbot & Newman 77

– **multiple events < 10 pc in the last 4.5 Gyr!**

Mass extinctions

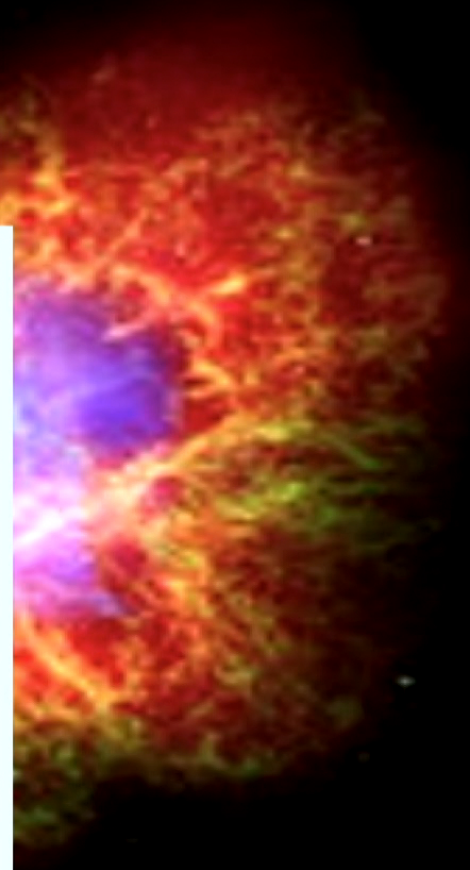
- Many mass extinction events in Earth's history




1980
Extraterrestrial Cause for the Cretaceous-Tertiary Extinction
Experimental results and theoretical interpretation
Luis W. Alvarez, Walter Alvarez, Frank Asaro, Helen V. Michel

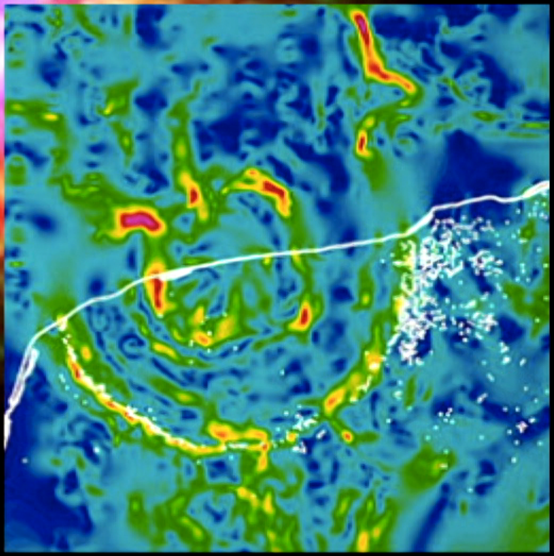
A Killer Asteroid Impact

- Alvarez, Alvarez, Asaro & Michel searched for evidence of a SN
- Found Iridium layer
- Not accompanied by Plutonium 244: “not SN”



A Killer Asteroid Impact

- Alvarez, Alvarez, Asaro & Michel searched for evidence of a SN
- Found Iridium layer
- Not accompanied by Plutonium 244: "not SN"
- Due to asteroid impact



Effects of a Nearby Supernova

JE & Schramm, astro-ph/9303206

- Flash of gamma rays
  - Optical light not harmful for biosphere
- Increased flux of cosmic rays
  - Neutral: $7.4 \times 10^6 \left(\frac{10}{D_{pc}}\right)^4$ ergs/cm$^2 \cdot$ y
  - Charged: $6.6 \times 10^5 \left(\frac{10}{D_{pc}}\right)^2$ ergs/cm^2 for $3.D_{pc}{}^2$y
  - Cf, usual cosmic rays: 9.10^4 ergs/cm^2/y
  - Increased NO production, destruction of ozone
    - Bad for land life, plankton & marine life
- Deposition of dust
  - Small effect on sunlight, **observable signature?**

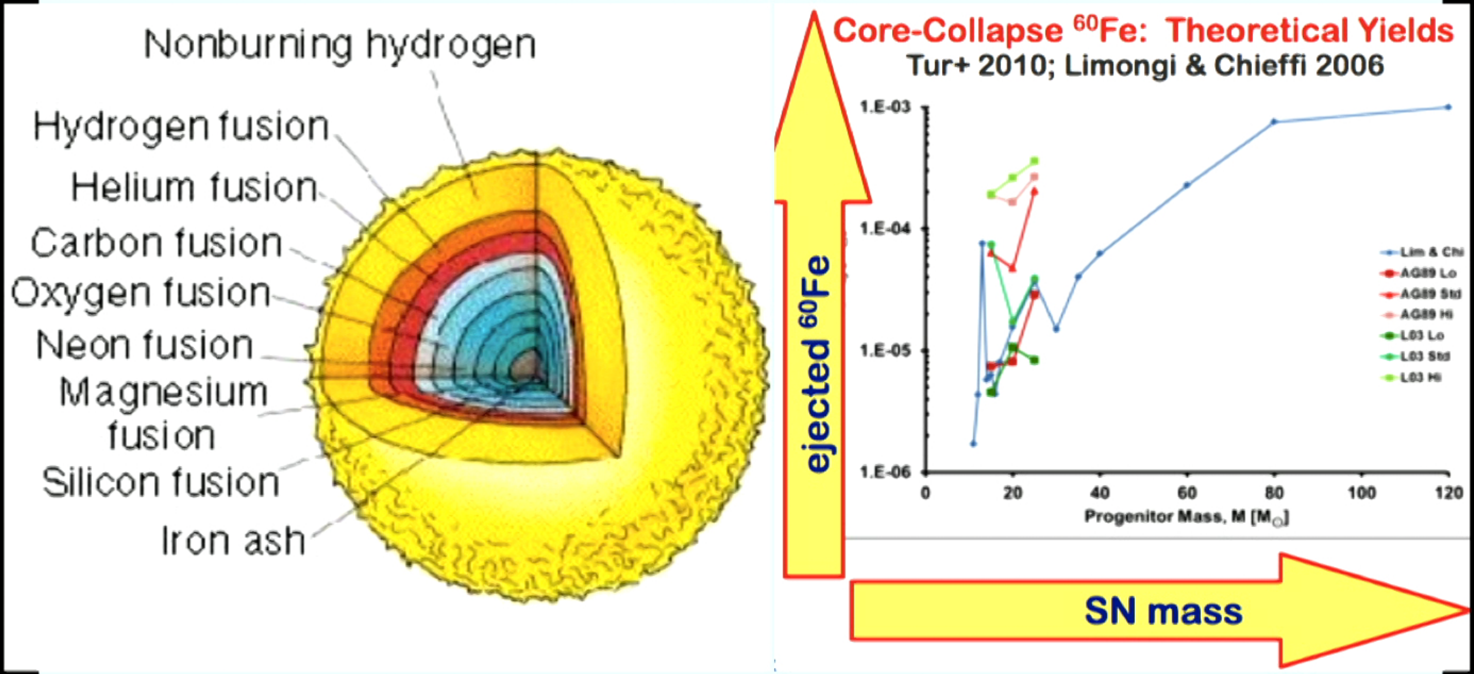
David Schramm

1945-1997


Look for Radioactive Rain

^{60}Fe Production in Supernova Cores

- Stellar fusion terminates with an iron core



- Followed by collapse, explosive energy release

JE, Schramm & Fields, astro-ph/9605128

Unstable Isotope Signatures

- Interested in lifetimes < few 10^8 years: candidates ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{59}Ni, ^{60}Fe, ^{129}I, ^{146}Sm, ^{244}Pu
- ^{10}Be anomalies reported in ice cores from ~ 35 and 60 kiloyears ago, also deep-ocean sediments
- Could have been produced directly by supernova
  - Or swept up by supernova shock front
  - Also possible cosmogenic backgrounds
- Made calculations for SN @ 20pc

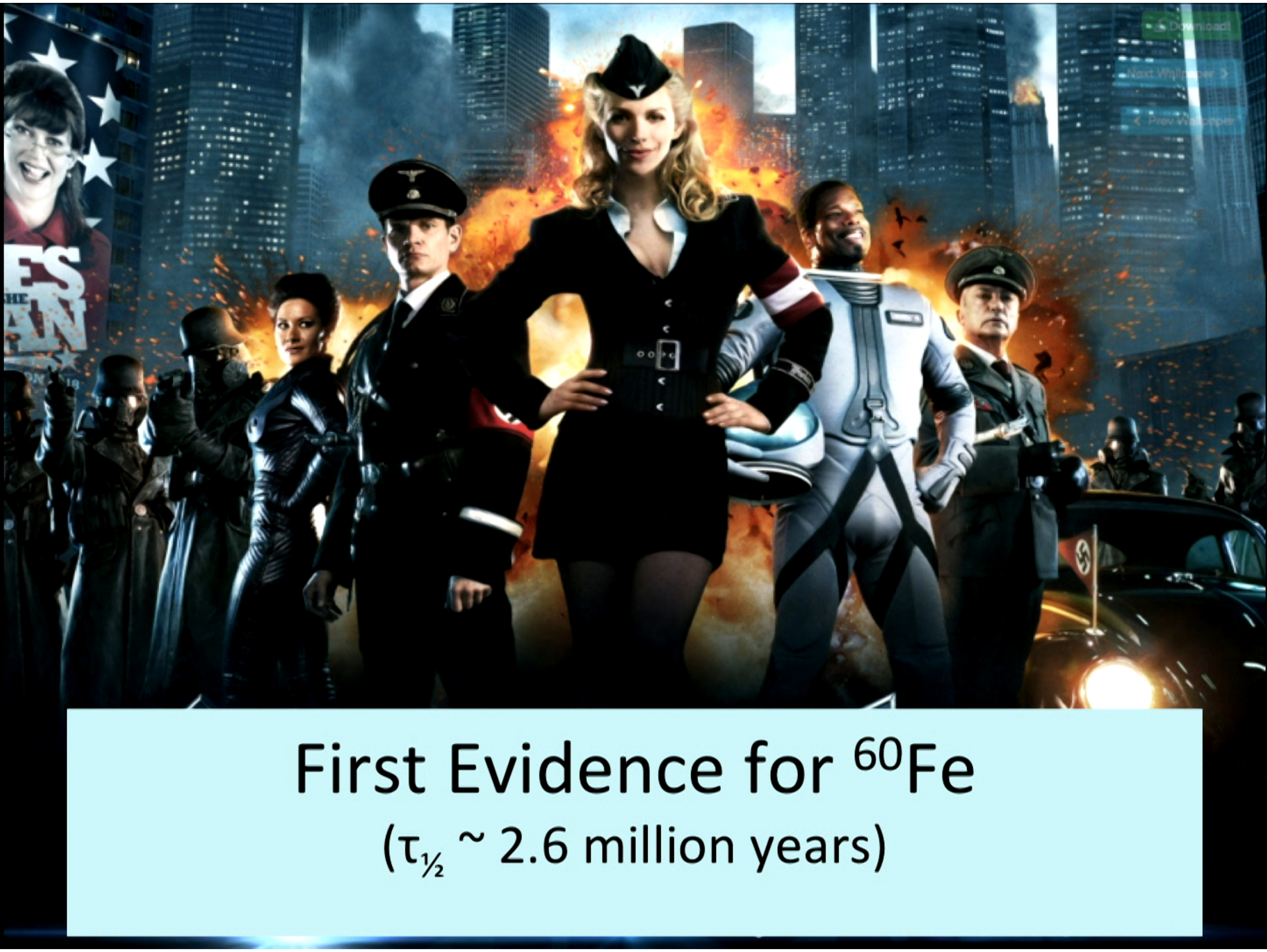
JE, Schramm & Fields, astro-ph/9605128

Calculations of Unstable Isotopes

- Interested in lifetimes < few 10^8 years

Isotope	SN ejecta	Swept	Cosgen.	TOT. SIGNAL	Cosgen. bgd.	Rad. bgd.	TOT. BGD.
^{10}Be	—	—	1.9×10^6	1.9×10^6	2.2×10^6	—	2.2×10^6
^{26}Al	8.4×10^6	9.3×10^4	3.1×10^3	8.4×10^6	3.5×10^3	—	3.5×10^3
^{36}Cl	4.8×10^6	2.2×10^4	6.6×10^4	4.9×10^6	7.5×10^4	—	7.5×10^4
^{41}Ca	1.5×10^6	6.7×10^3	1.4	1.5×10^6	1.6	—	1.6
^{53}Mn	2.3×10^7	1.3×10^6	0.7	2.4×10^7	0.79	—	0.79
^{59}Ni	1.0×10^7	$1.2 \times 10^{[illegible]}$	—	1.0×10^7	$1.6 \times 10^{[illegible]}$	[illegible]	1.6×10^{-3}
^{60}Fe	1.2×10^6	5.4×10^3	1.4	1.2×10^6	1.6	—	1.6
^{129}I	6.9×10^3	1.70×10^3	1.4	8.6×10^3	1.6	1.1	2.7
^{146}Sm	0.32	0.50	—	0.82	—	6.7	6.7
^{244}Pu	69	86	—	1.6×10^2	—	—	—

- Calculations for SN @ 20pc



First Evidence for ^{60}Fe

($\tau_{1/2}$ ~ 2.6 million years)

Accelerator Mass Spectrometry

- Used to analyze ferromanganese crusts & deep-ocean sediments

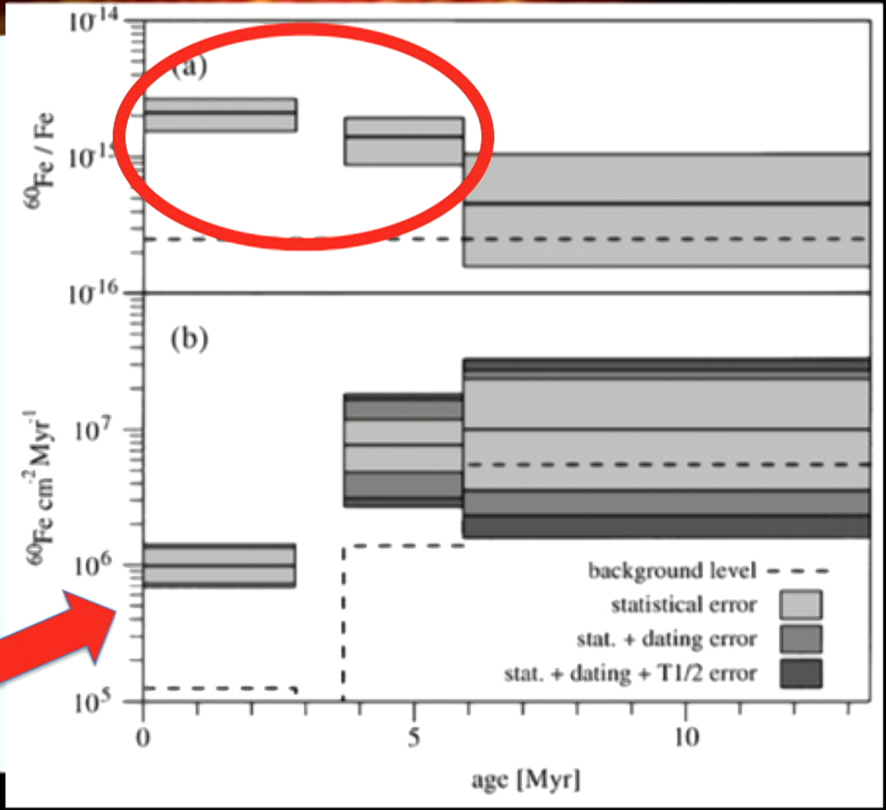
Accelerator Mass Spectrometry

- Used to analyze ferromanganese crusts & deep-ocean sediments

Knie et al (TUM), PRL 83, 18 (1999)

First Indication for SN ^{60}Fe on Earth

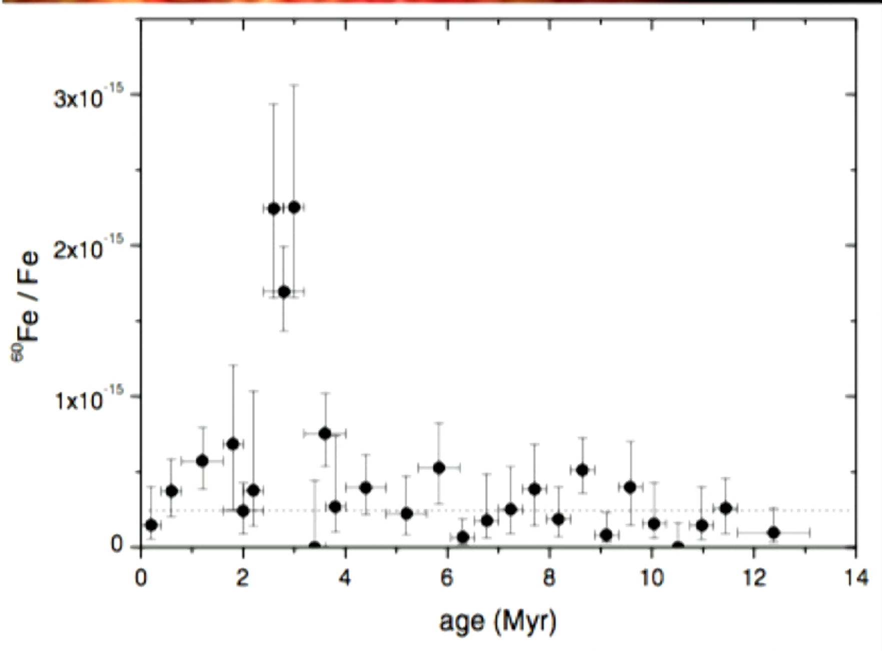
- Excess of ^{60}Fe in deep-ocean ferromanganese crust
- Deposited during last ~ 5 M years
- Strongest signal < 3 M years



Knie et al (TUM), PRL 93, 171103 (2004)

Follow-up on SN ^{60}Fe Anomaly

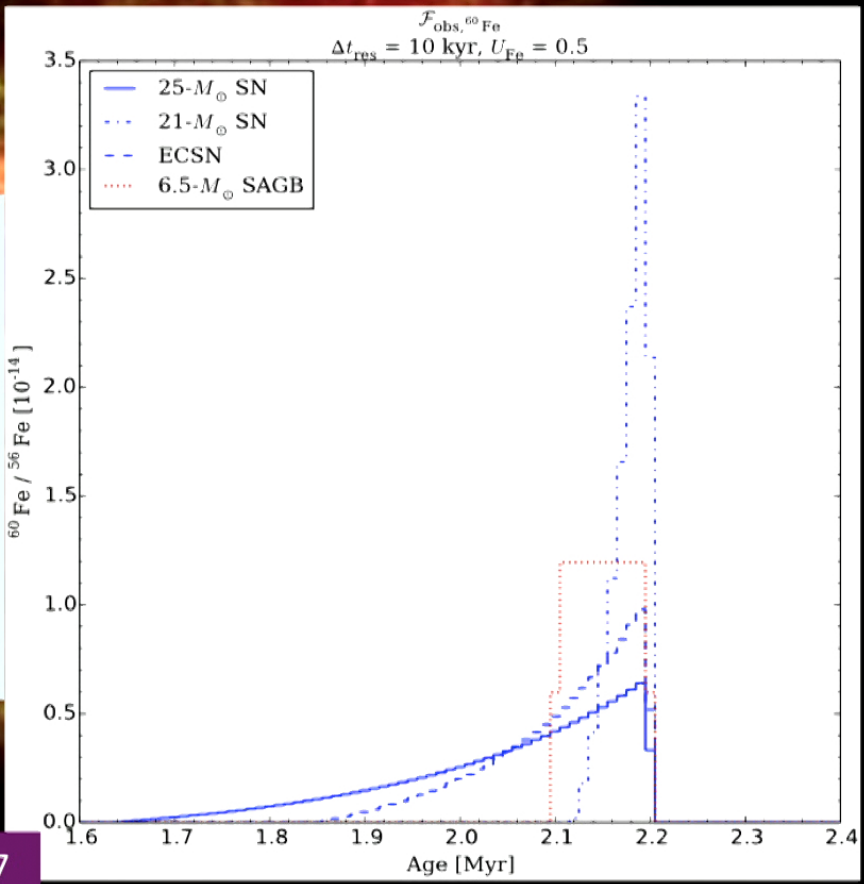
- Confirm excess of ^{60}Fe in deep-ocean ferromanganese crust



Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

Time Profile of ^{60}Fe Deposition

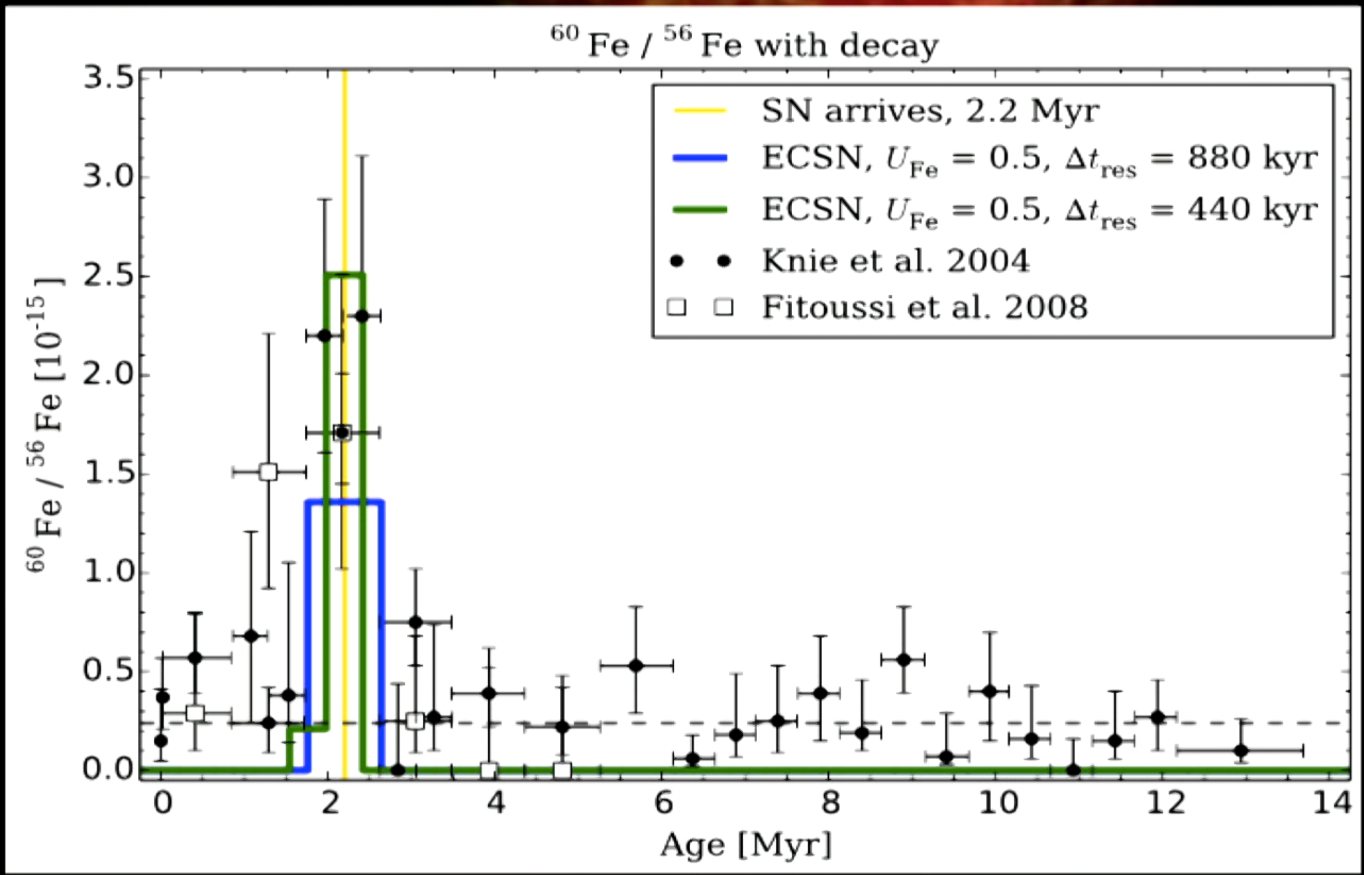
- Dispersion during propagation through the interstellar medium
- Sedov profile



See also Fields & JE, astro-ph/9811457

Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

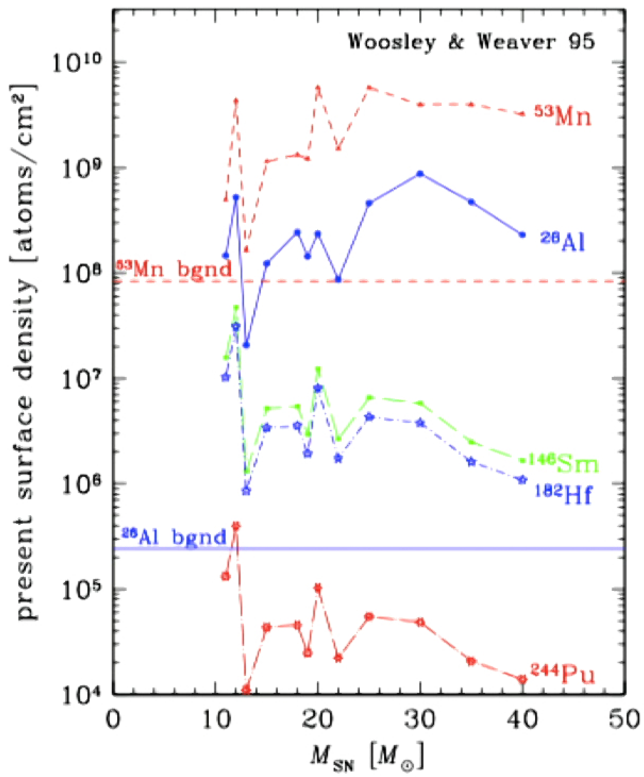
Comparison with ^{60}Fe Data

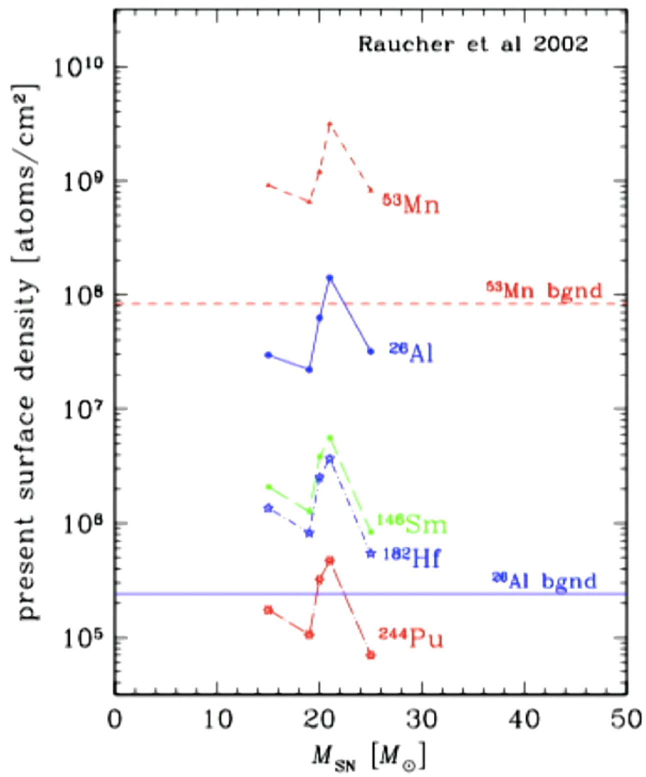


Fields, Hochmuth & JE, astro-ph/0410525

Estimated Yields of Other Isotopes

- Depend on SN model: prospects with ^{53}Mn, ^{26}Al?





Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

Estimated Yields of Other Isotopes

- Depend on mass, type of SN progenitor

Progenitor	15-$M_\odot$ CCSN[a]	19-$M_\odot$ CCSN[a]	20-$M_\odot$ CCSN[a]	21-$M_\odot$ CCSN[a]	25-$M_\odot$ CCSN[a]	8-10-$M_\odot$ ECSN[b]
^{26}Al	2.6×10^{-5}	3.2×10^{-5}	3.0×10^{-5}	4.6×10^{-5}	7.0×10^{-5}	4.4×10^{-8}
^{53}Mn	1.8×10^{-4}	2.1×10^{-4}	1.3×10^{-4}	2.3×10^{-4}	3.6×10^{-4}	1.1×10^{-6}
^{60}Fe	6.6×10^{-5}	1.1×10^{-4}	3.6×10^{-5}	2.5×10^{-5}	1.5×10^{-4}	3.6×10^{-5}
^{41}Ca	4.3×10^{-6}	2.7×10^{-5}	4.3×10^{-4}	6.9×10^{-6}	3.2×10^{-5}	2.0×10^{-7}
^{93}Zr	1.3×10^{-8}	4.7×10^{-8}	9.8×10^{-9}	5.9×10^{-8}	1.5×10^{-7}	N/A[d]
^{97}Tc	4.8×10^{-11}	4.2×10^{-11}	1.9×10^{-10}	1.3×10^{-10}	8.3×10^{-11}	N/A[d]
^{107}Pd	4.1×10^{-10}	8.4×10^{-10}	4.6×10^{-10}	1.4×10^{-9}	1.4×10^{-9}	N/A[d]
^{146}Sm	3.9×10^{-10}	6.3×10^{-12}	3.4×10^{-10}	8.5×10^{-10}	1.2×10^{-9}	N/A[d]
^{182}Hf	1.4×10^{-10}	1.5×10^{-9}	2.5×10^{-10}	5.5×10^{-10}	4.3×10^{-10}	N/A[d]
^{244}Pu[c]	2.0×10^{-11}	2.2×10^{-10}	3.7×10^{-11}	8.1×10^{-11}	6.3×10^{-11}	N/A[d]
Progenitor	6.5-$M_\odot$ SAGB[e]	7.0-$M_\odot$ SAGB[e]	7.5-$M_\odot$ SAGB[e]	8.0-$M_\odot$ SAGB[e]	8.5-$M_\odot$ SAGB[e]	9.0-$M_\odot$ SAGB[e]
^{26}Al	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	8.0×10^{-6}	1.0×10^{-5}	1.1×10^{-5}
^{53}Mn	0	0	0	0	0	0
^{60}Fe	5.0×10^{-6}	3.0×10^{-6}	4.0×10^{-6}	9.0×10^{-6}	1.4×10^{-5}	1.4×10^{-5}

Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

Estimated Yields of Other Isotopes

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^{53}Mn	1.8×10^{-4}	2.1×10^{-4}	1.3×10^{-4}	2.3×10^{-4}	3.6×10^{-4}	1.1×10^{-6}
^{60}Fe	6.6×10^{-5}	1.1×10^{-4}	3.6×10^{-5}	2.5×10^{-5}	1.5×10^{-4}	3.6×10^{-5}
^{41}Ca	[illegible] $\times 10^{-6}$	2.7×10^{-5}	4.3×10^{-4}	6.9×10^{-6}	[illegible]	2.0×10^{-7}
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^{53}Mn	0	0	0	0	0	0
^{60}Fe	5.0×10^{-6}	3.0×10^{-6}	4.0×10^{-6}	9.0×10^{-6}	1.4×10^{-5}	1.4×10^{-5}

- Core-collapse or electron-capture?

Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

Estimated Yields of Other Isotopes

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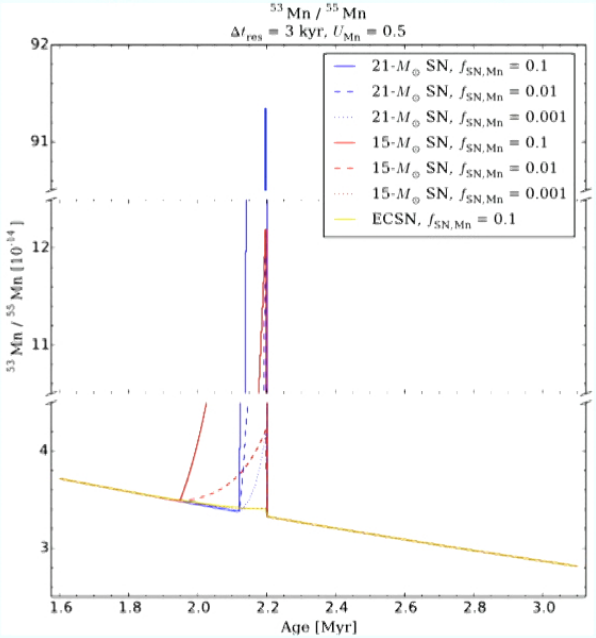
^{60}Fe	5.0×10^{-6}	3.0×10^{-6}	4.0×10^{-6}	9.0×10^{-6}	1.4×10^{-5}	1.4×10^{-5}

- Core-collapse or electron-capture?

Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

Estimated Yields of Other Isotopes

- Core-collapse SN would have given large ^{53}Mn signal: not seen, so electron-capture SN?



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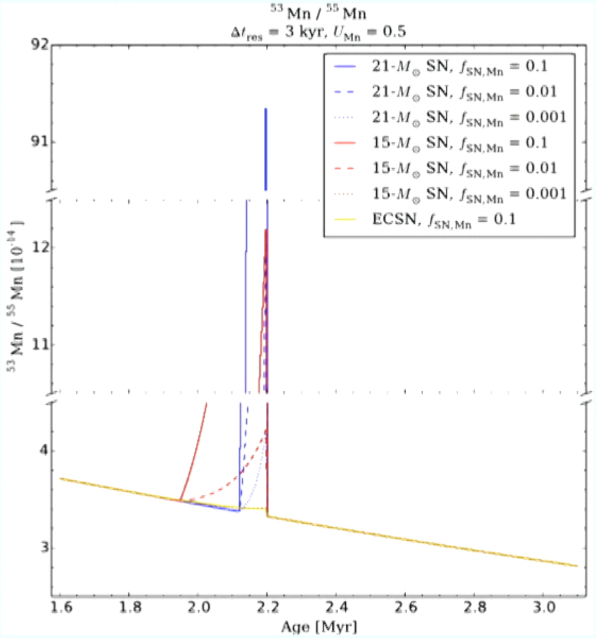

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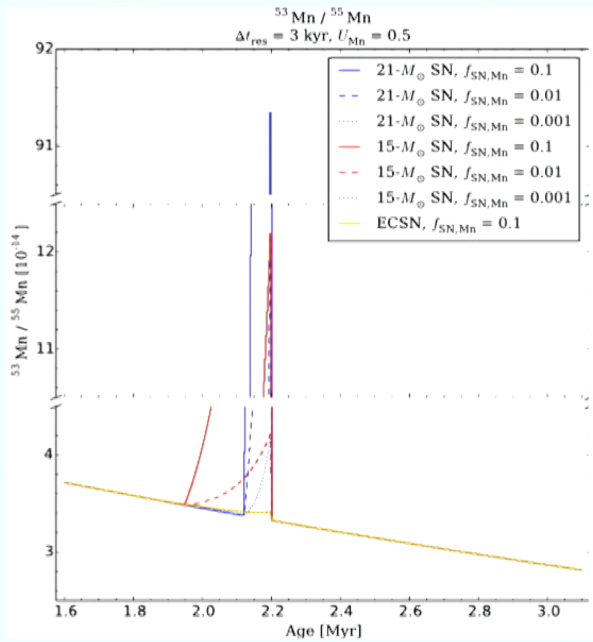
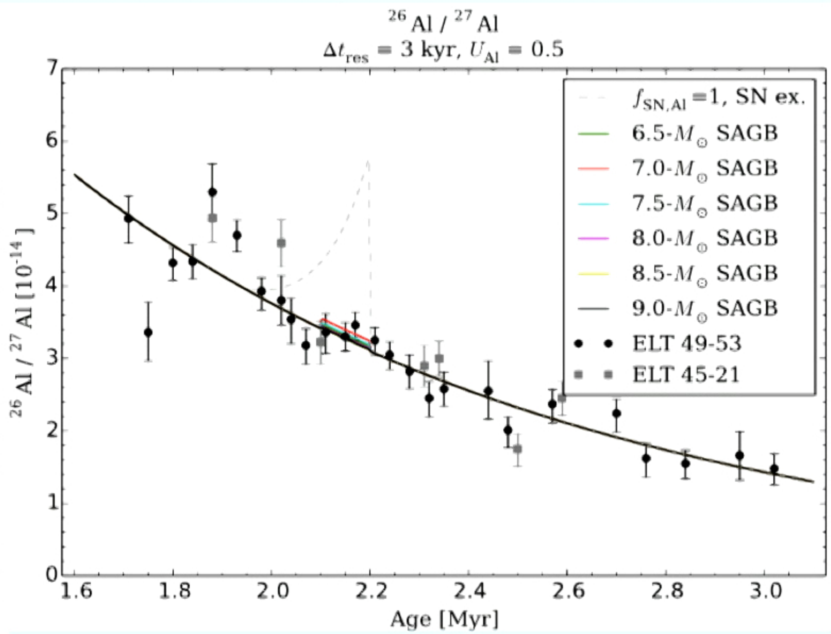


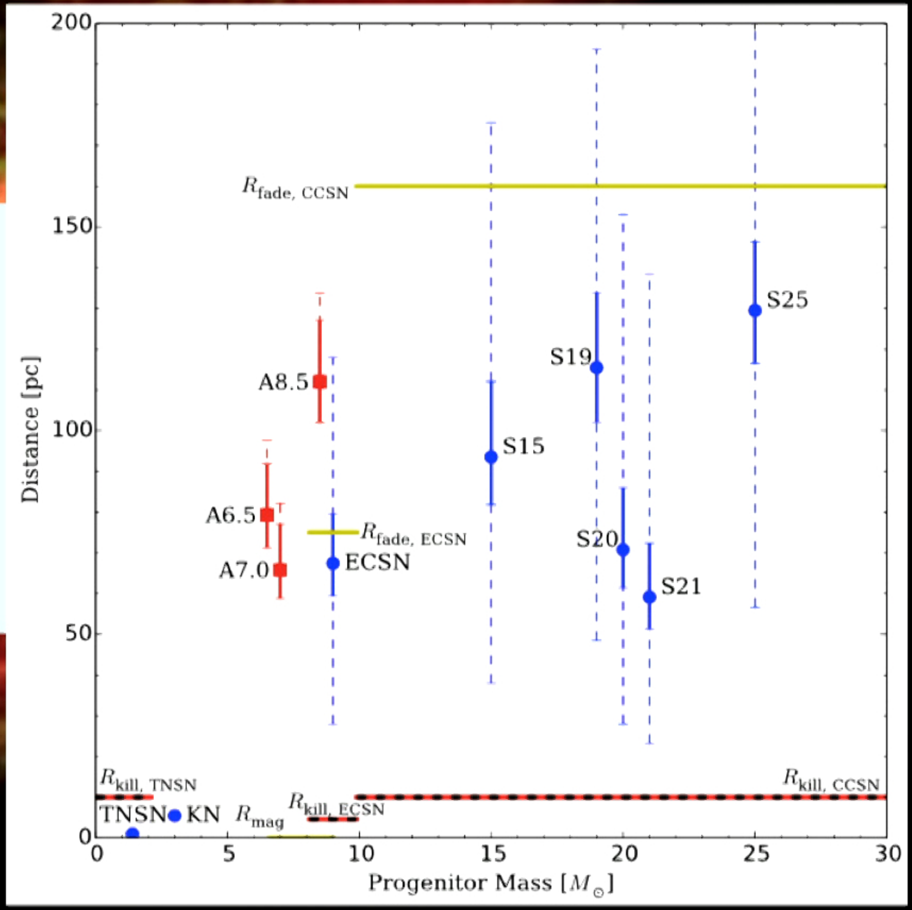


- Electron-capture SN: expect small ^{26}Al signal

Fry, Fields & JE, arXiv:1405.3210 [astro-ph.SR]

Would this SN have been Dangerous?

- Estimated distance ~ 50 to 150 pc, well beyond "kill radius"




Confirmation by new Data

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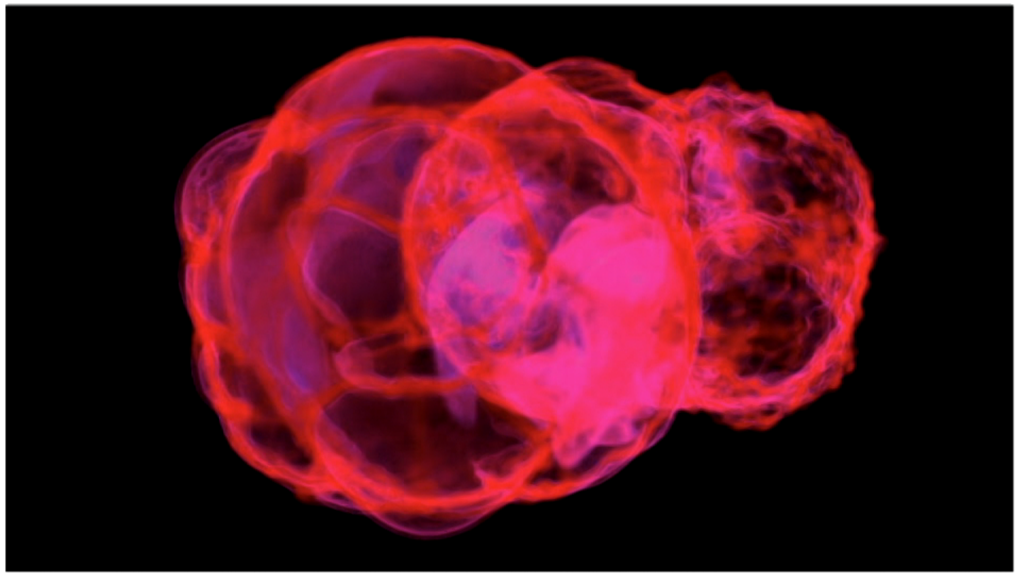


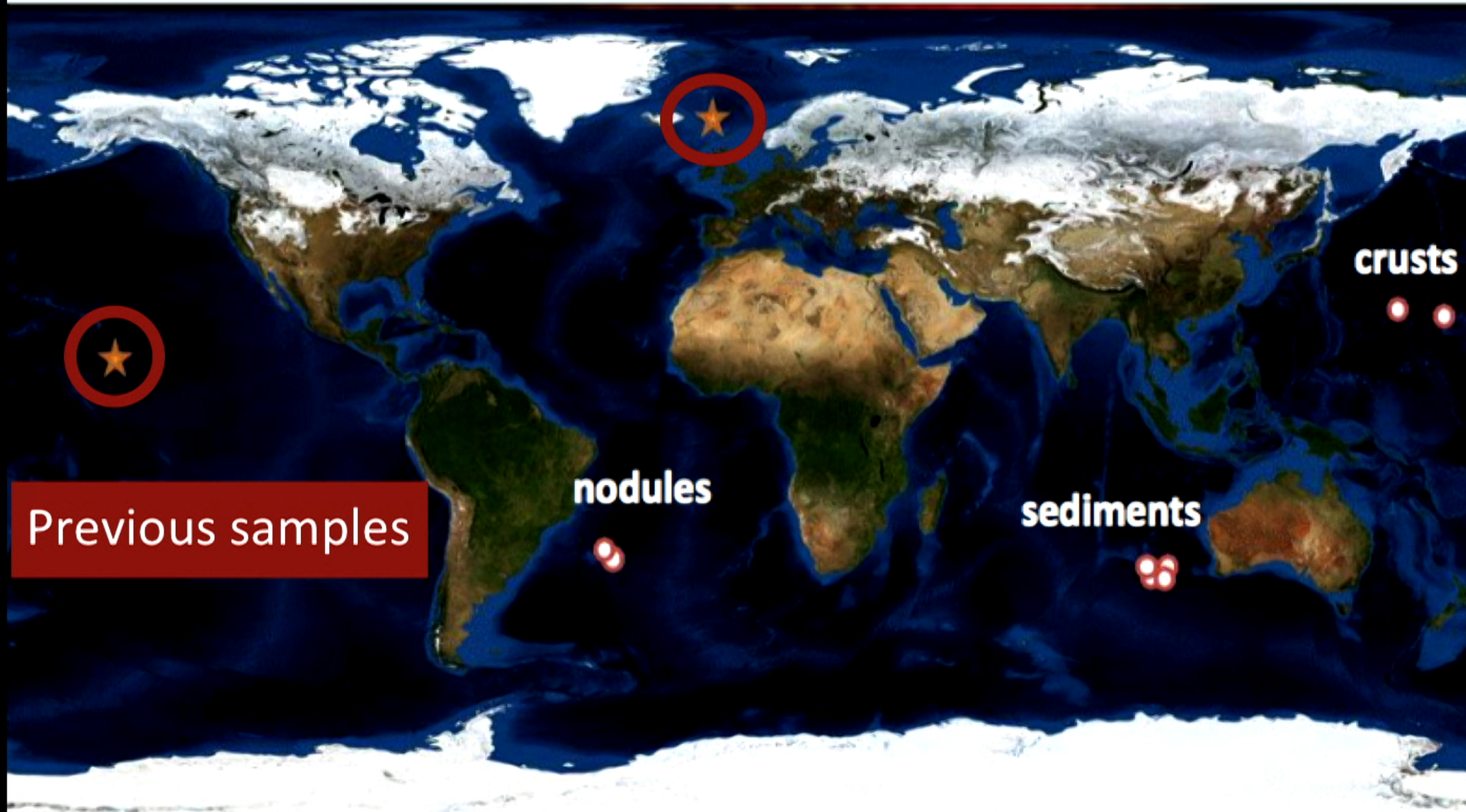
A simulation of iron-60 atoms dispersed by multiple supernovae close to the solar system 2.2 million years ago. Some of that iron still lies at the bottom of the oceans and on the moon.

Michael Schulreich

Earth barraged by supernovae millions of years ago, debris found on moon

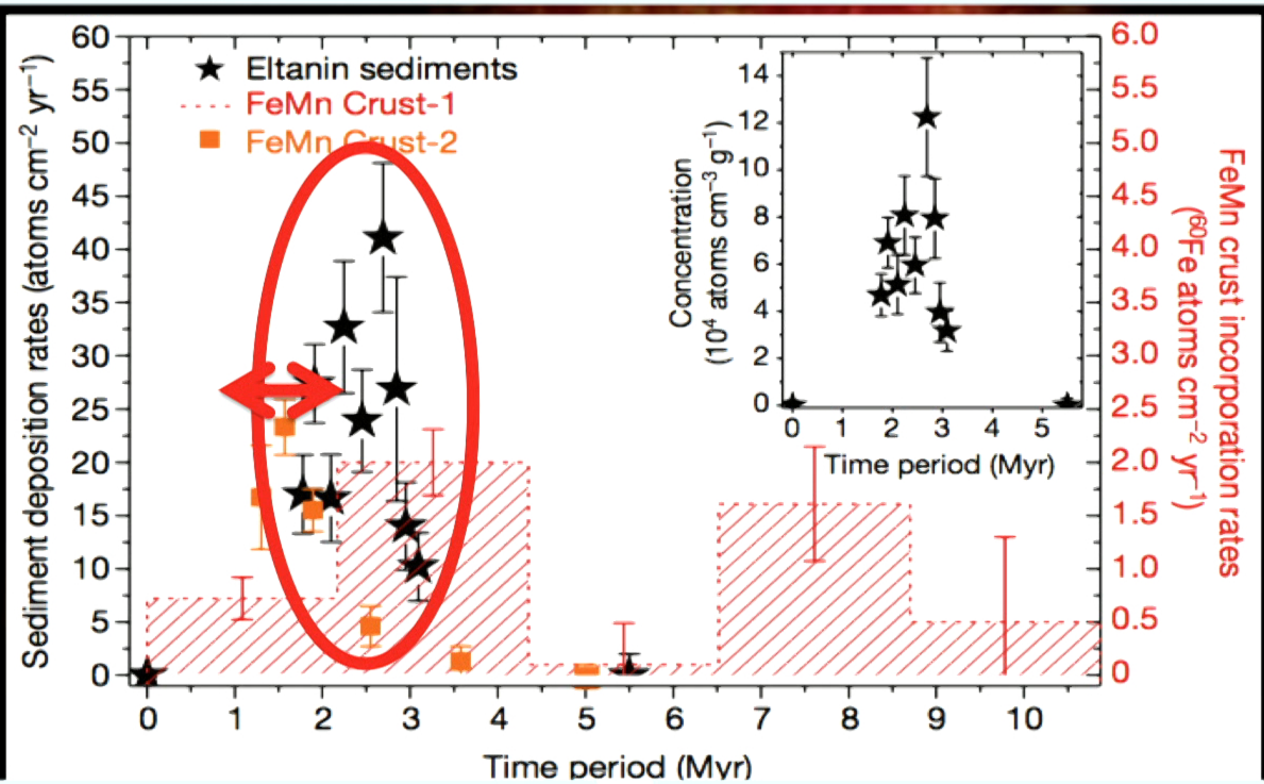
Wallner et al (ANU), Nature 532, 69 (2016)

Locations of ^{60}Fe Measurements



Wallner et al (ANU), Nature 532, 69 (2016)

Time Profile of ^{60}Fe Signal



>1 SN ~ 2.5 M years ago?

+ SN ~ 7 to 8 M years ago?

Wallner et al (ANU), Nature 532, 69 (2016)

^{60}Fe Measurements in Sediments

Table 1 | Averaged ^{60}Fe/Fe atom ratios from AMS measurements at ANU of the sediment samples

Sediment cores	Sediment samples	Time period (Myr)	^{60}Fe counts detected	^{60}Fe/Fe (10^{-15} atoms per atom)	Background- and decay-corrected ^{60}Fe/Fe (10^{-15} atoms per atom)	Fe concentration (10^{-2} grams per gram)	^{60}Fe concentration (10^{4} atoms per gram)	^{60}Fe deposition rates (atoms cm^{-2} yr^{-1})	^{60}Fe deposition (10^{6} atoms cm^{-2} per layer)
45–21/50–02	5	<0.2	2	0.06 ± 0.04	0.02 ± 0.02	0.30 ± 0.10	<0.2	<0.2	NA
49–53/45–21	14	1.71–2.0	123	1.67 ± 0.15	2.52 ± 0.23	0.23 ± 0.01	6.0 ± 0.6	22.8 ± 2.3	6.5 ± 0.7
49–53/45–21/50–02	11	2.0–2.3	51	1.51 ± 0.21	2.48 ± 0.35	0.24 ± 0.01	6.7 ± 1.0	24.8 ± 3.6	7.4 ± 1.1
49–53/45–21/50–02	7	2.3–2.6	33	1.96 ± 0.34	3.50 ± 0.61	0.17 ± 0.01	6.5 ± 1.2	27.1 ± 5.0	8.1 ± 1.5
49–53/45–16	7	2.6–2.9	54	3.40 ± 0.46	6.61 ± 0.90	0.16 ± 0.01	10.3 ± 1.5	34.8 ± 5.2	10.4 ± 1.5
49–53/45–16	6	2.9–3.18	27	1.18 ± 0.23	2.41 ± 0.47	0.13 ± 0.01	3.4 ± 0.7	11.4 ± 2.4	3.0 ± 0.6
45–16	2	~4–7*	1	0.11 ± 0.11	0.20 ± 0.30	0.14 ± 0.01	<0.4	<1	NA
Commercial iron	99	Background	7	0.042 ± 0.015	NA	NA	NA	NA	NA

Wallner et al (ANU), Nature 532, 69 (2016)

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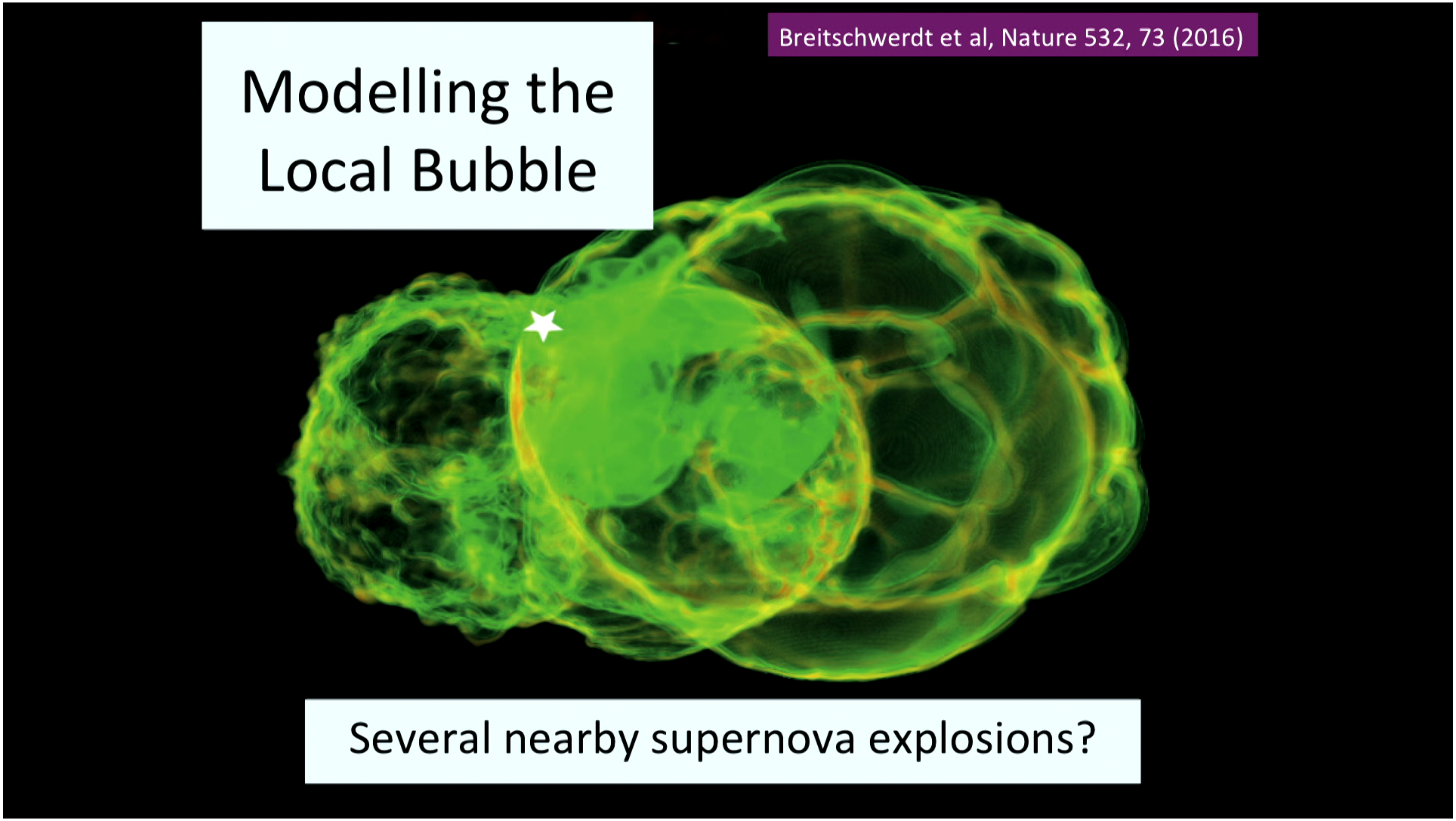
Wallner et al (ANU), Nature 532, 69 (2016)

^{60}Fe Data from Different Locations

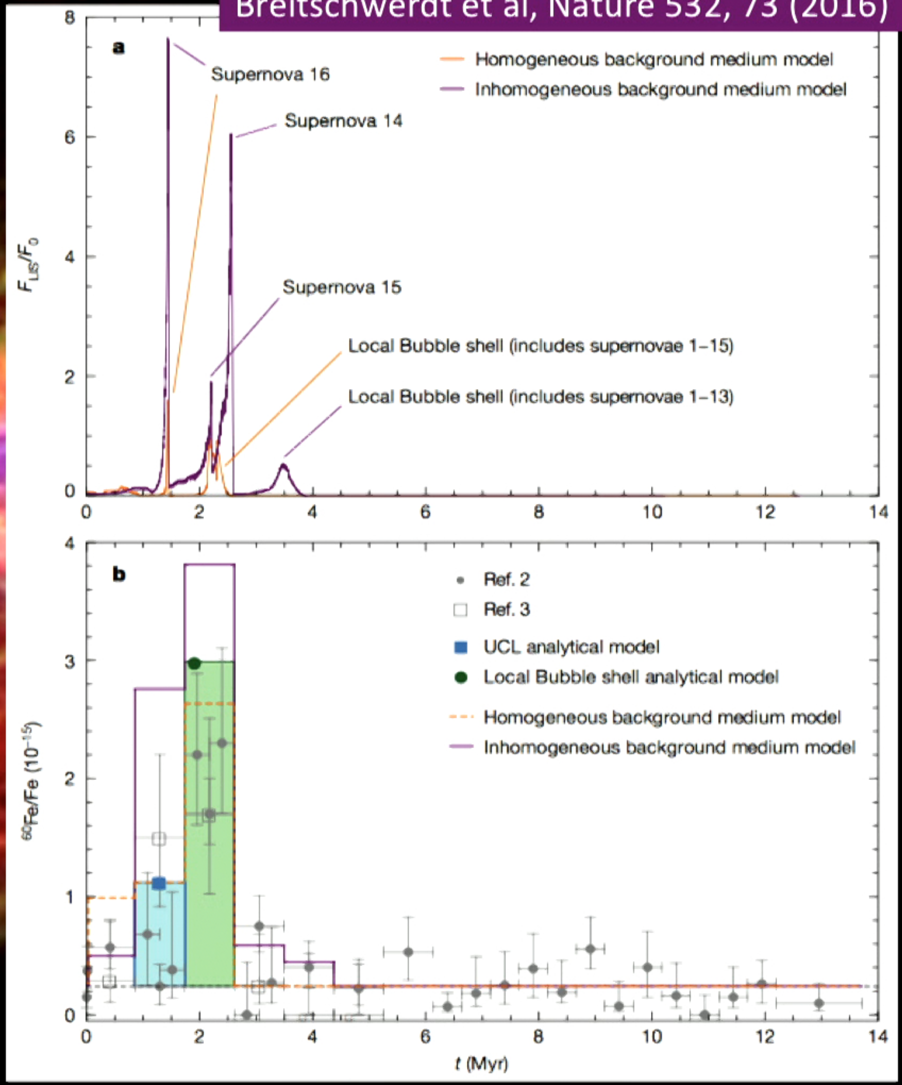
Deep-sea archive	Cores	Location	Time period (Myr)	^{60}Fe detector events	^{60}Fe deposition (10^6 atoms cm^{-2})
Sediment	4	Indian Ocean	1.71–3.18	288	35.4 ± 2.6
FeMn Crust-1	2	Pacific Ocean	0–4.35	97	5.9 ± 0.8
FeMn Crust-1			6.52–8.70	26	3.5 ± 1.4
FeMn Crust-2			1.2–3.1	94	2.2 ± 0.2
FeMn nodules	2	Atlantic Ocean	1.8–3.3	13	0.6 ± 0.2
			0–3.3	20	1.4 ± 0.5
FeMn Mona Pihoa[10]	1	Pacific Ocean	0–5.9	21	$\sim 9^{+11}_{-6}$‡
FeMn 237KD[11]	1	Pacific Ocean	1.74–2.61*	69	1.5 ± 0.4*
Lunar material[22]	4	Moon	Integral	†	~ 10


Breitschwerdt et al, Nature 532, 73 (2016)
Modelling the Local Bubble
Several nearby supernova explosions?

Modelling ^{60}Fe Profile

- Better fit with > one SN (width of signal)?

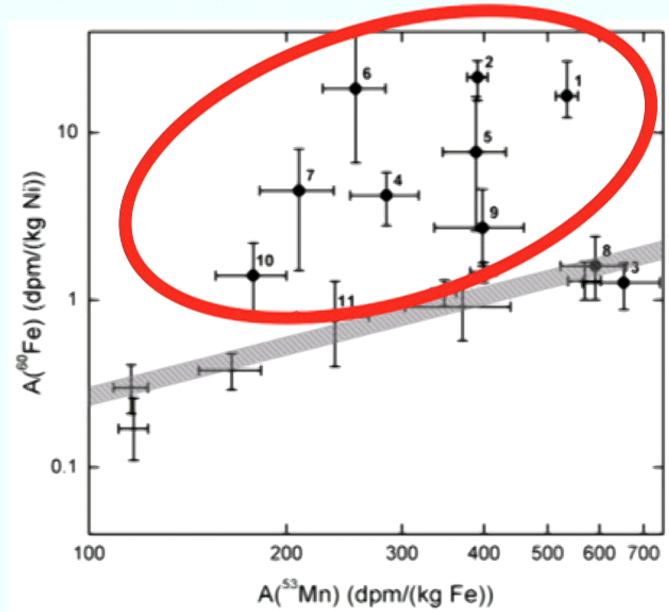
Breitschwerdt et al, Nature 532, 73 (2016)



Fimiani et al (TUM), PRL 116, 151104 (2016)

Apollo Lunar Rock Samples

- Several sample return missions

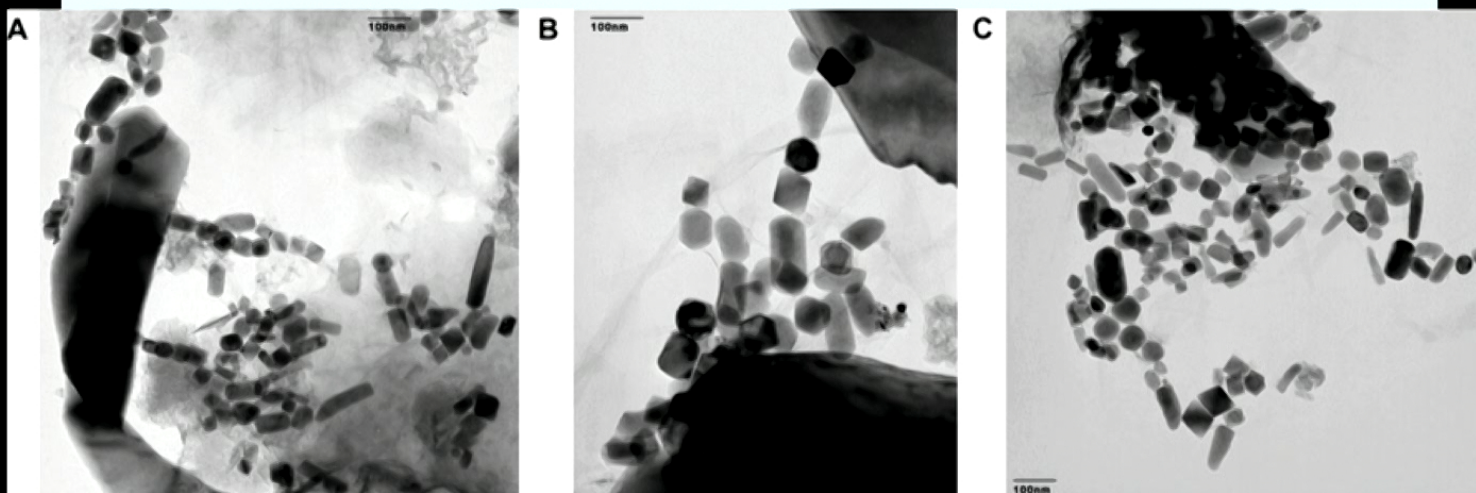


- Significant excess of ^{60}Fe in several samples
- No timing information

Ludwig et al (2016), www.pnas.org/cgi/doi/10.1073/pnas.1601040113

^{60}Fe in Magnetotactic Bacteria

- Bacteria that orient along magnetic field lines
- Live near water/sediment interface

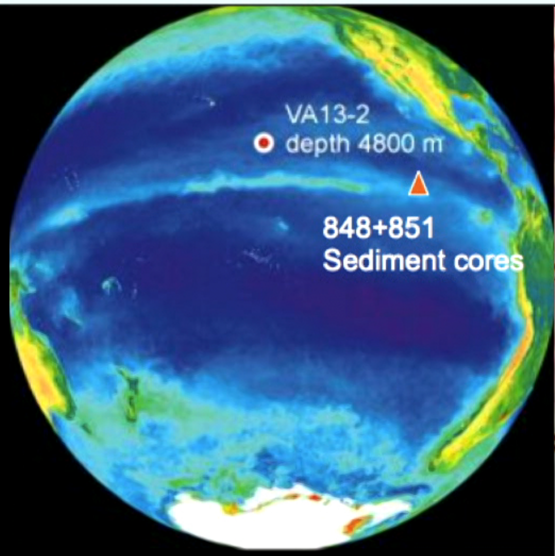


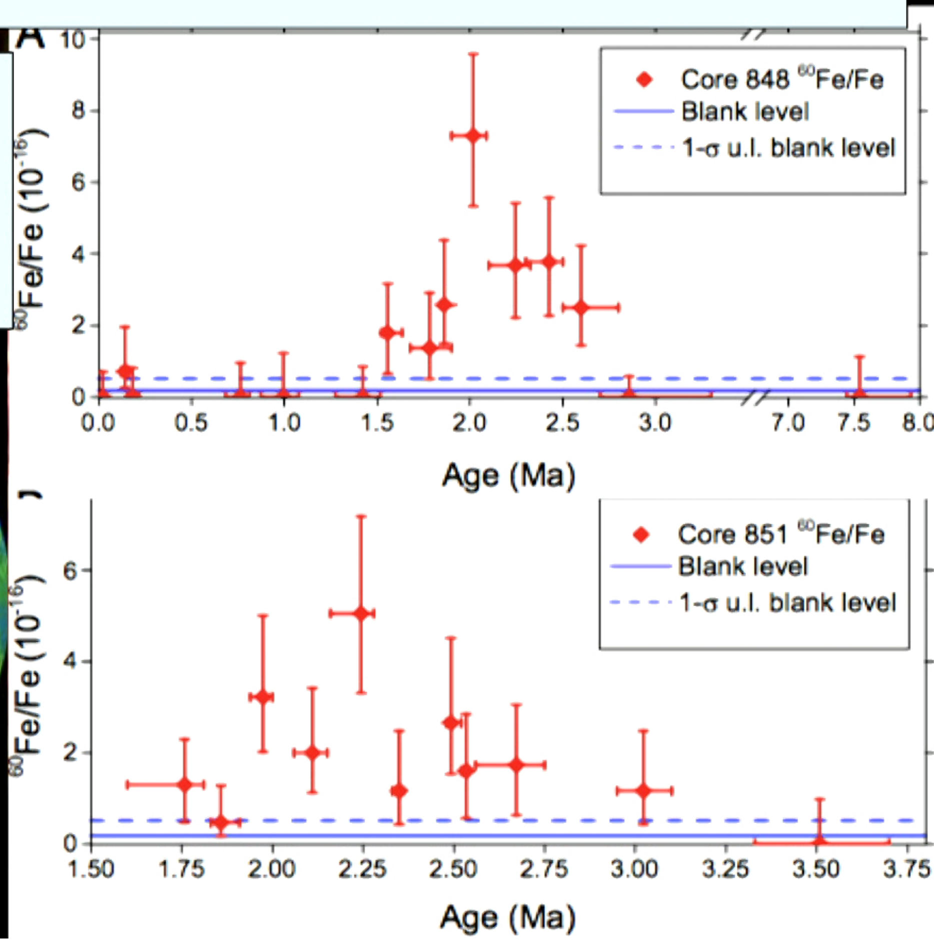
- Magnetite crystals identified in sediments

Ludwig et al (2016), www.pnas.org/cgi/doi/10.1073/pnas.1601040113

^{60}Fe in Magnetotactic Bacteria

- ^{60}Fe signal found in two sediment samples





Ludwig et al (2016), www.pnas.org/cgi/doi/10.1073/pnas.1601040113

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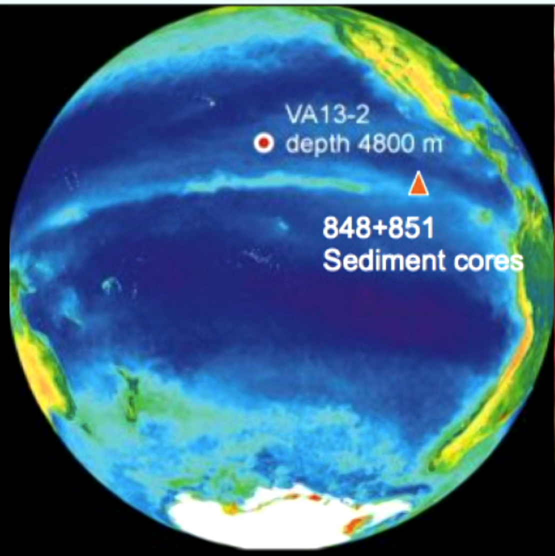

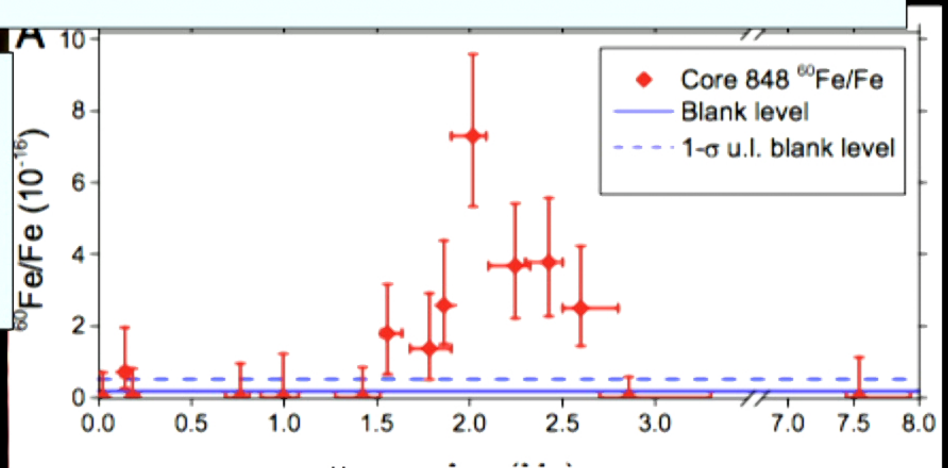

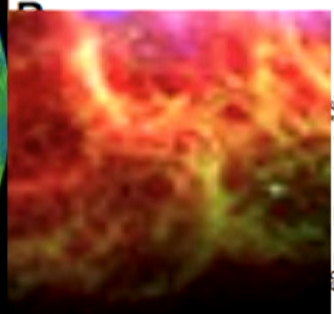

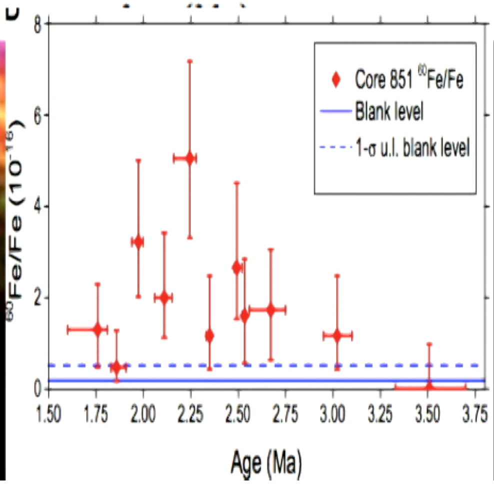

Wallner et al, Nature Comms DOI: 10.1038/ncomms6956 (2015)

Search for Live SN Plutonium

- Expect to produce ^{244}Pu ($\tau_{½}$ = 81 My) in r-process nucleosynthesis
  - SN or neutron-star mergers?
- Amount in deep-ocean sediments < expected production by SN

Wallner et al, Nature Comms DOI: 10.1038/ncomms6956 (2015)

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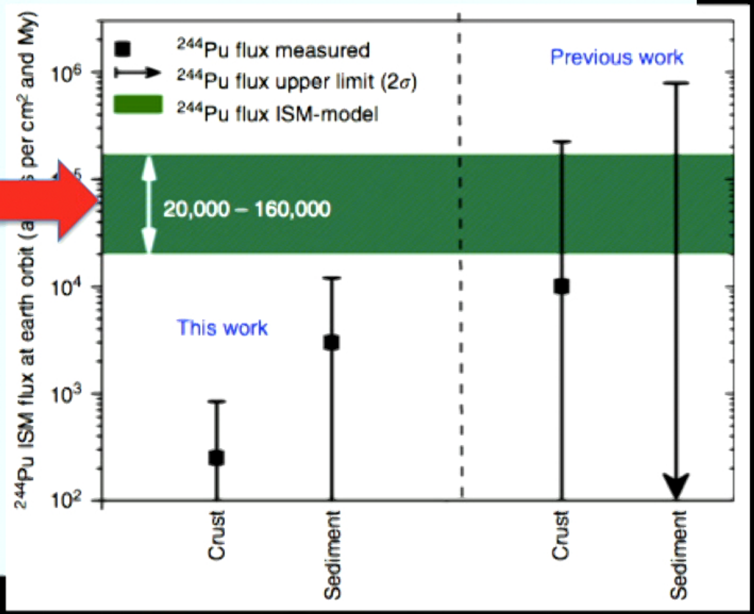
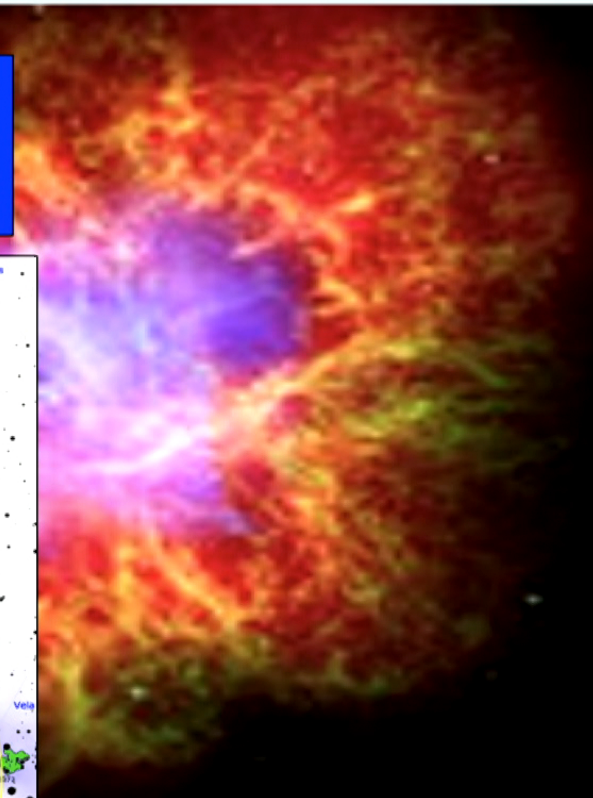
- r-process nucleosynthesis sites infrequent, rare?

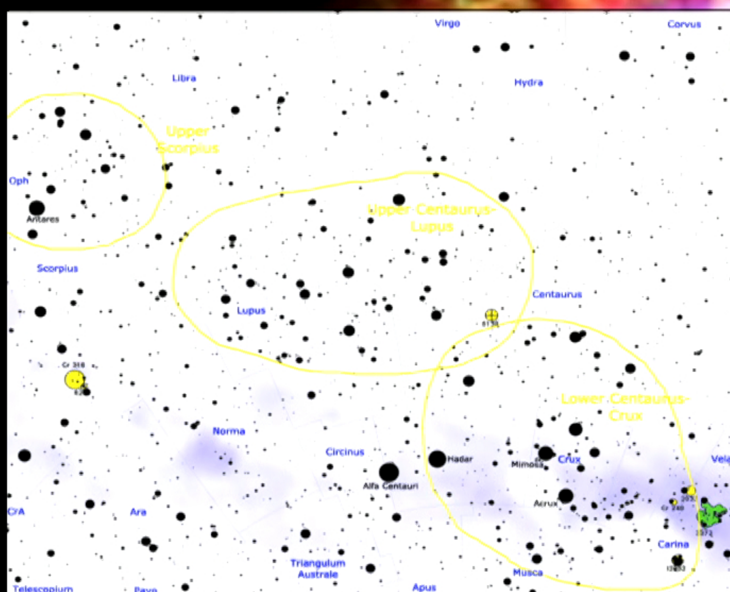


Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

Candidate origins of 60Fe Signal



Scorpio-Centaurus Association (Sco-Cen)



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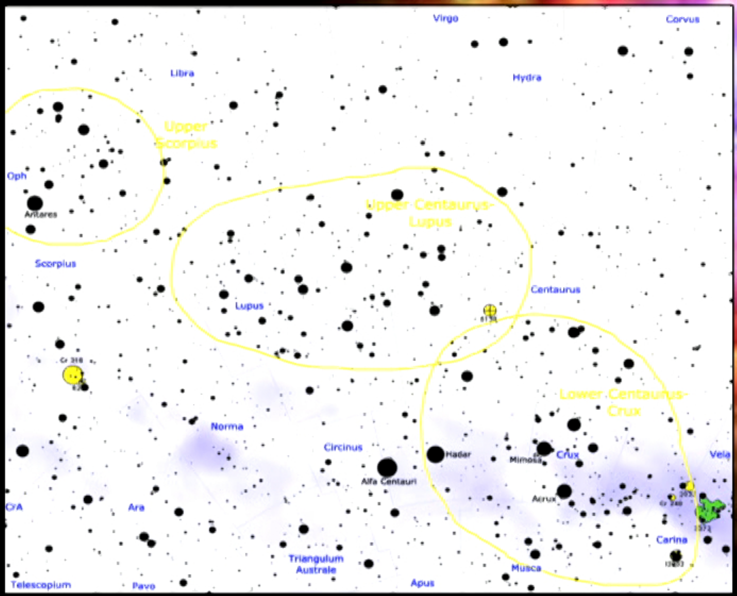
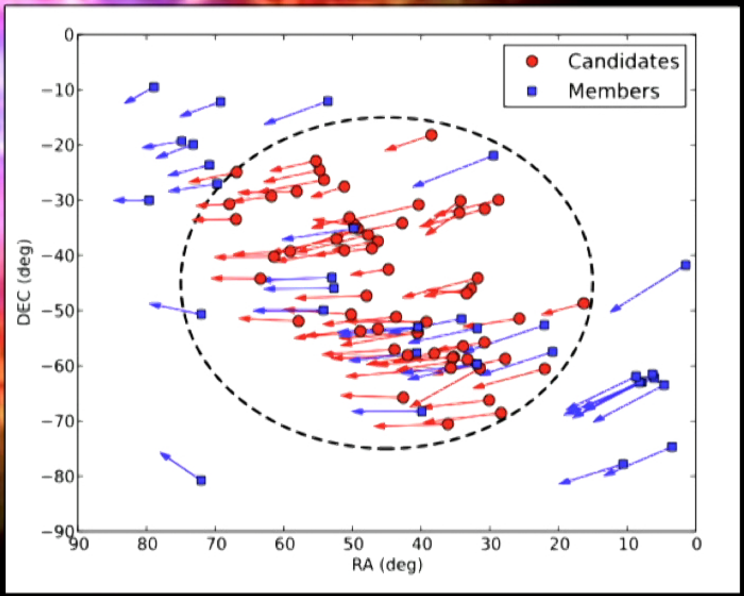


Tucana-Horologium Association (Tuc-Hor)



Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

Where was the SN?

- Implied source distance

  (depending on uptake fraction of $^{60}Fe = U_{crust}$):

Case	Standard	High	Low
$\psi_{\rm Knie} = 0.43$	$U_{\rm crust} = 0.5$	$U_{\rm crust} = 1.0$	$U_{\rm crust} = 0.1$
$8-10$-$M_\odot$ ECSN	46^{+10}_{-6} pc	45^{+10}_{-6} pc	35^{+8}_{-5} pc
15-$M_\odot$ CCSN	64^{+14}_{-8} pc	61^{+14}_{-8} pc	47^{+11}_{-6} pc
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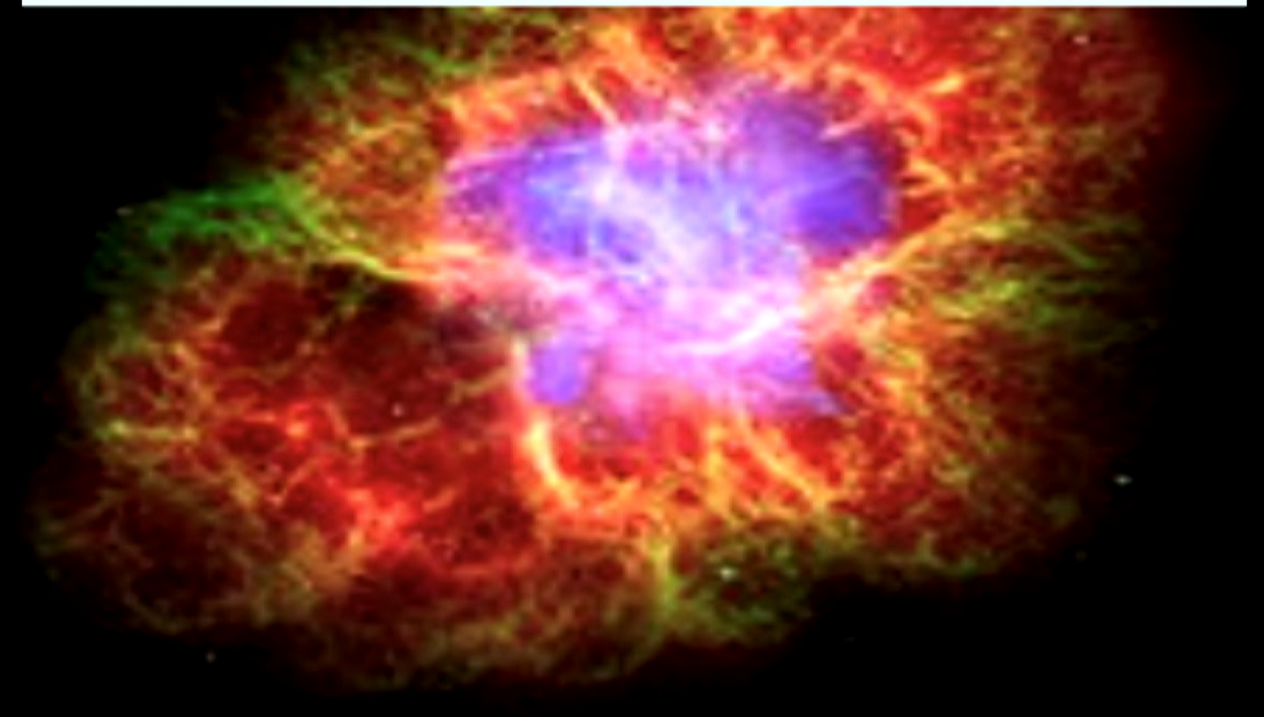
Radioactive Iron Astronomy?

Dust Trajectories through the Heliosphere



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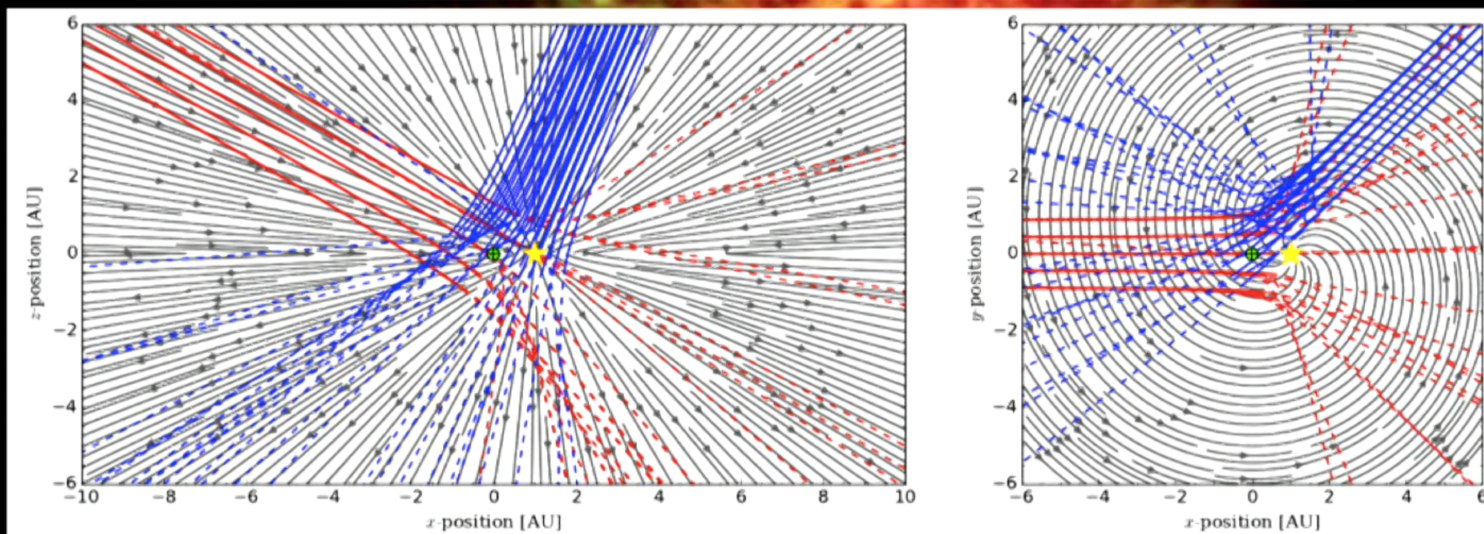
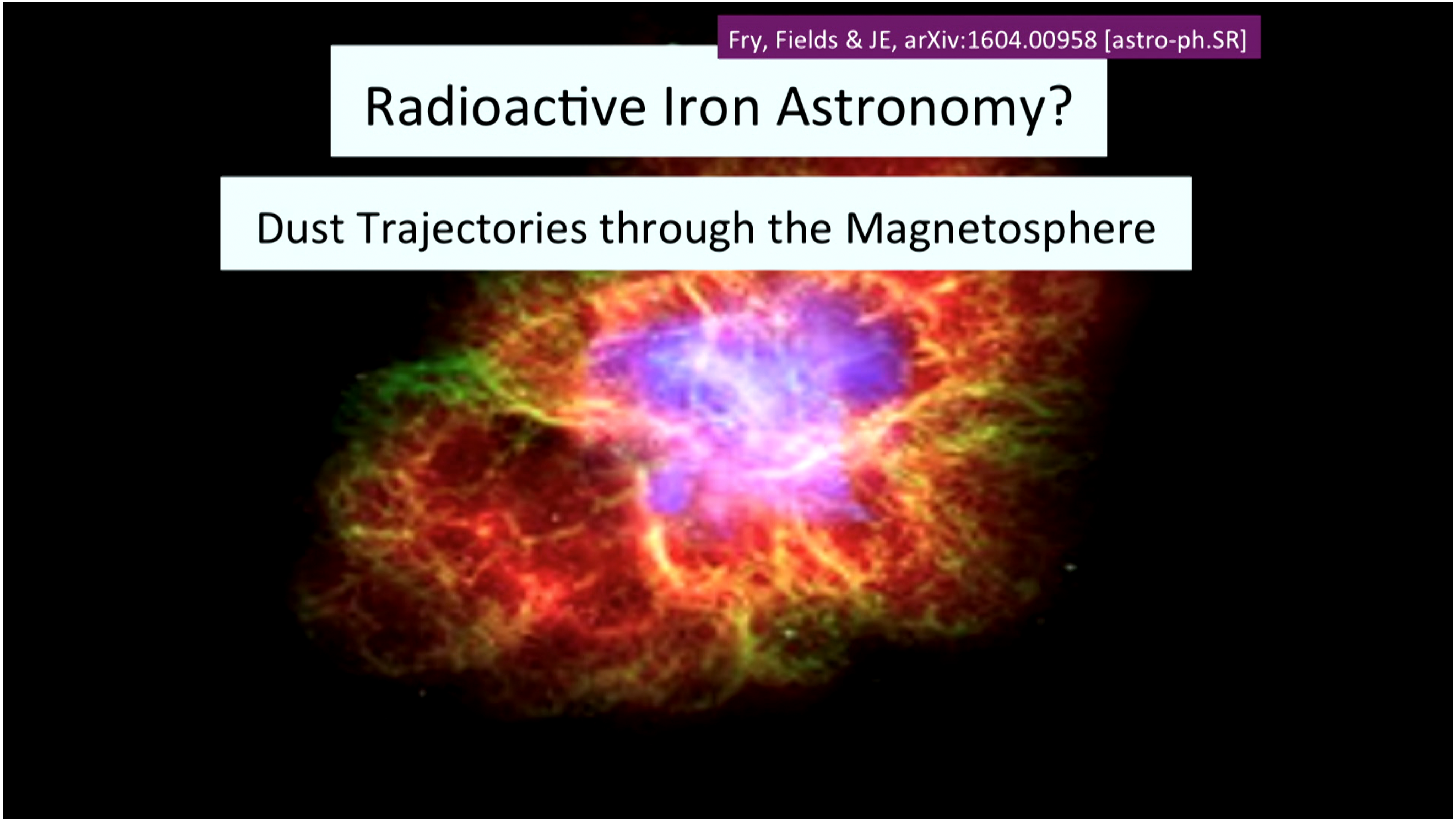


Directionality retained

before the SN dust reaches the Earth: ———

(trajectories after passing the Earth: ----------)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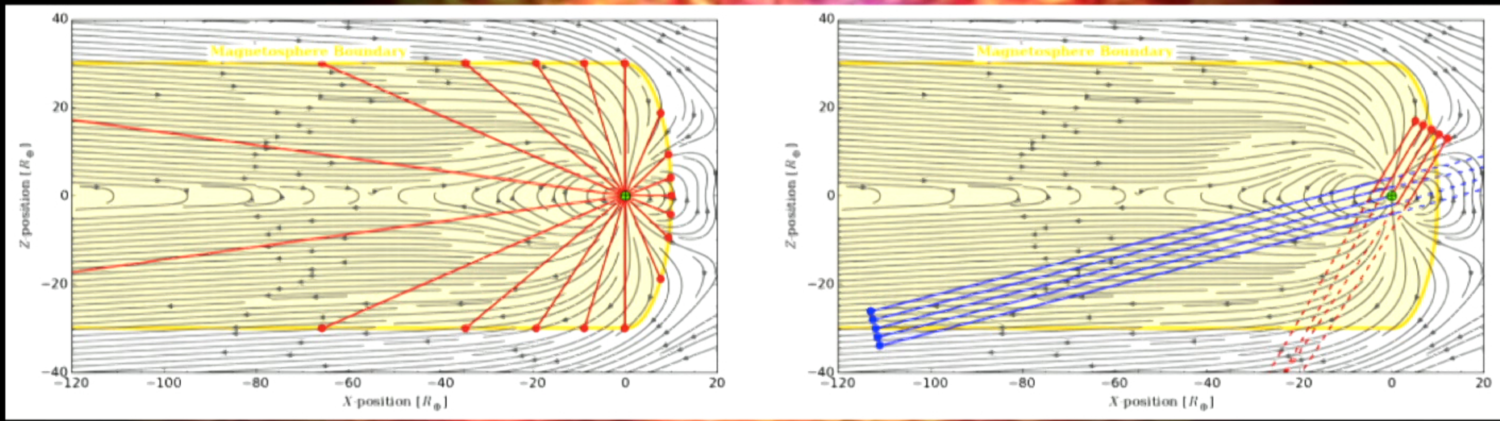
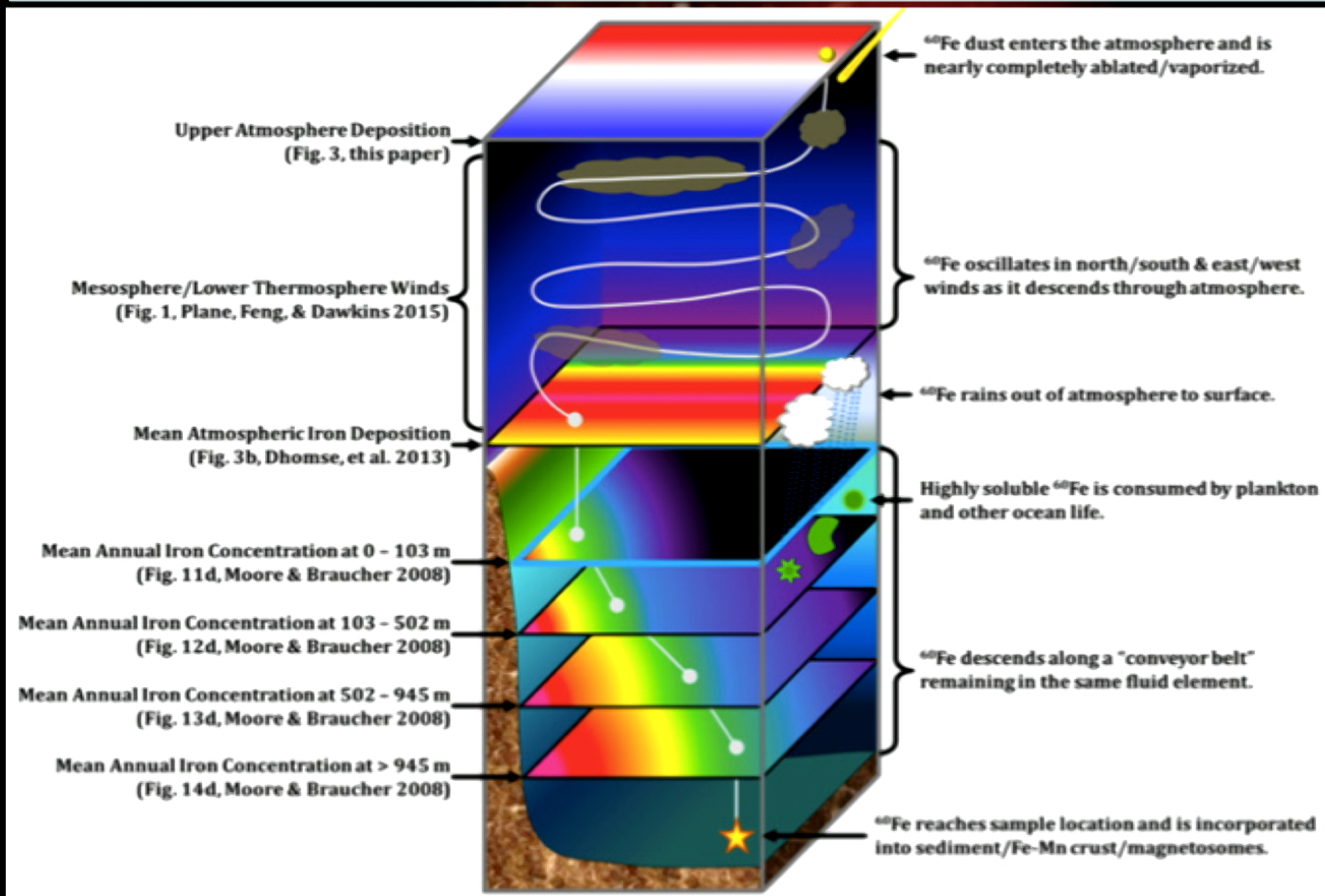


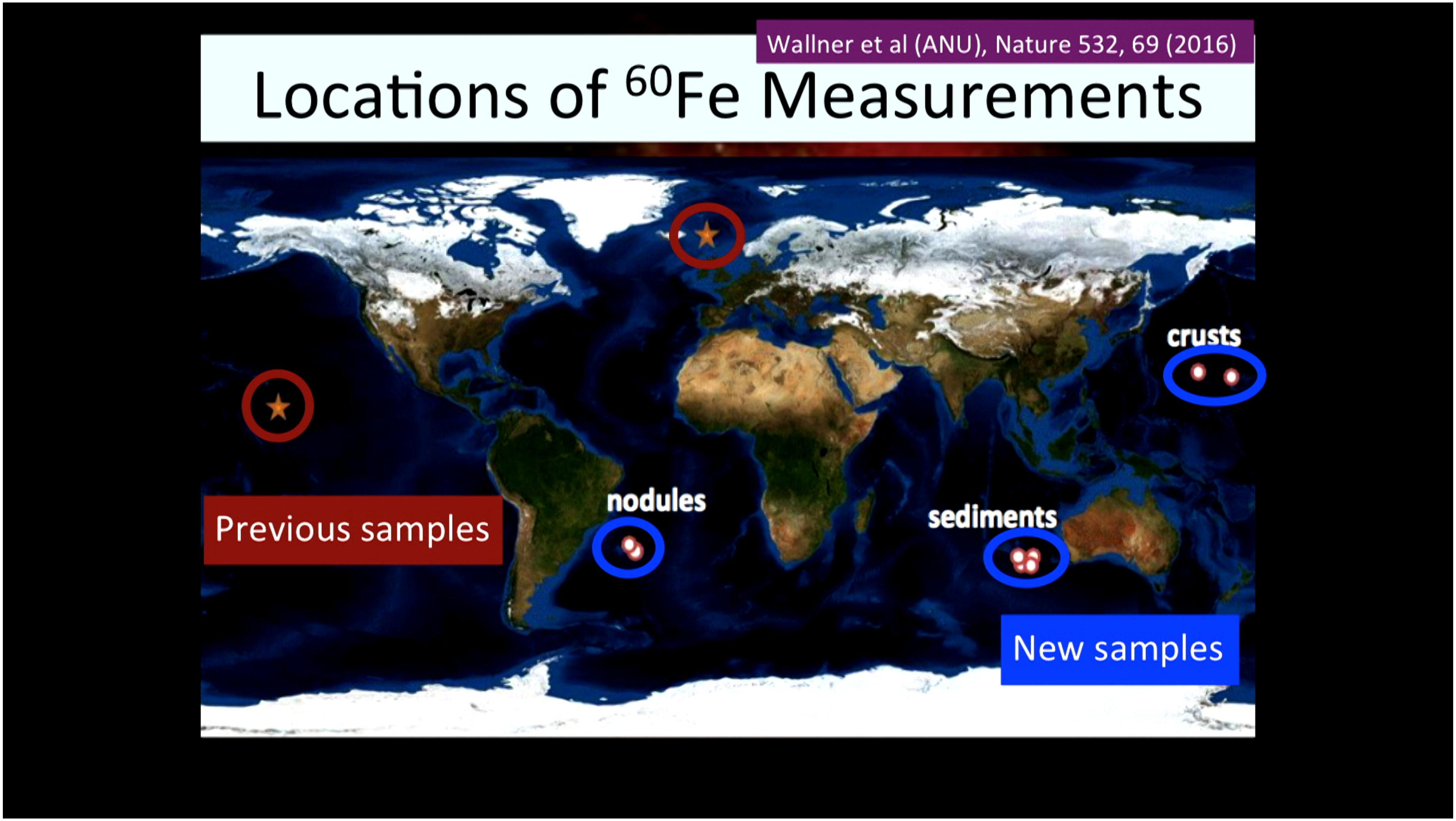
Directionality retained
before the SN dust reaches the Earth: ———
also after passing the Earth: ----------

But

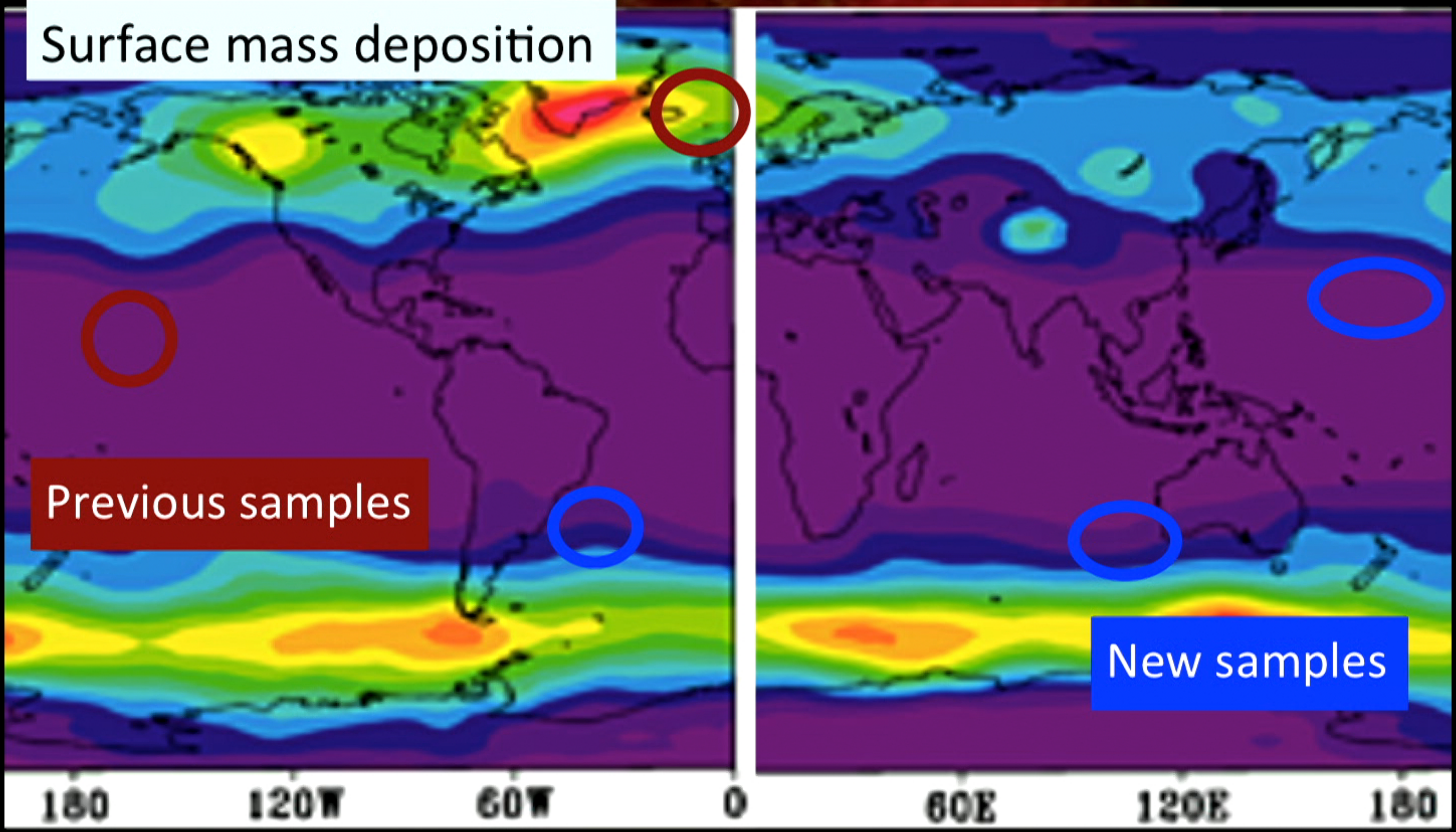
Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

The Terrestrial Journey of ^{60}Fe




Wallner et al (ANU), Nature 532, 69 (2016)
Locations of 60Fe Measurements
crusts
nodules
sediments
Previous samples
New samples

Locations of ^{60}Fe Measurements



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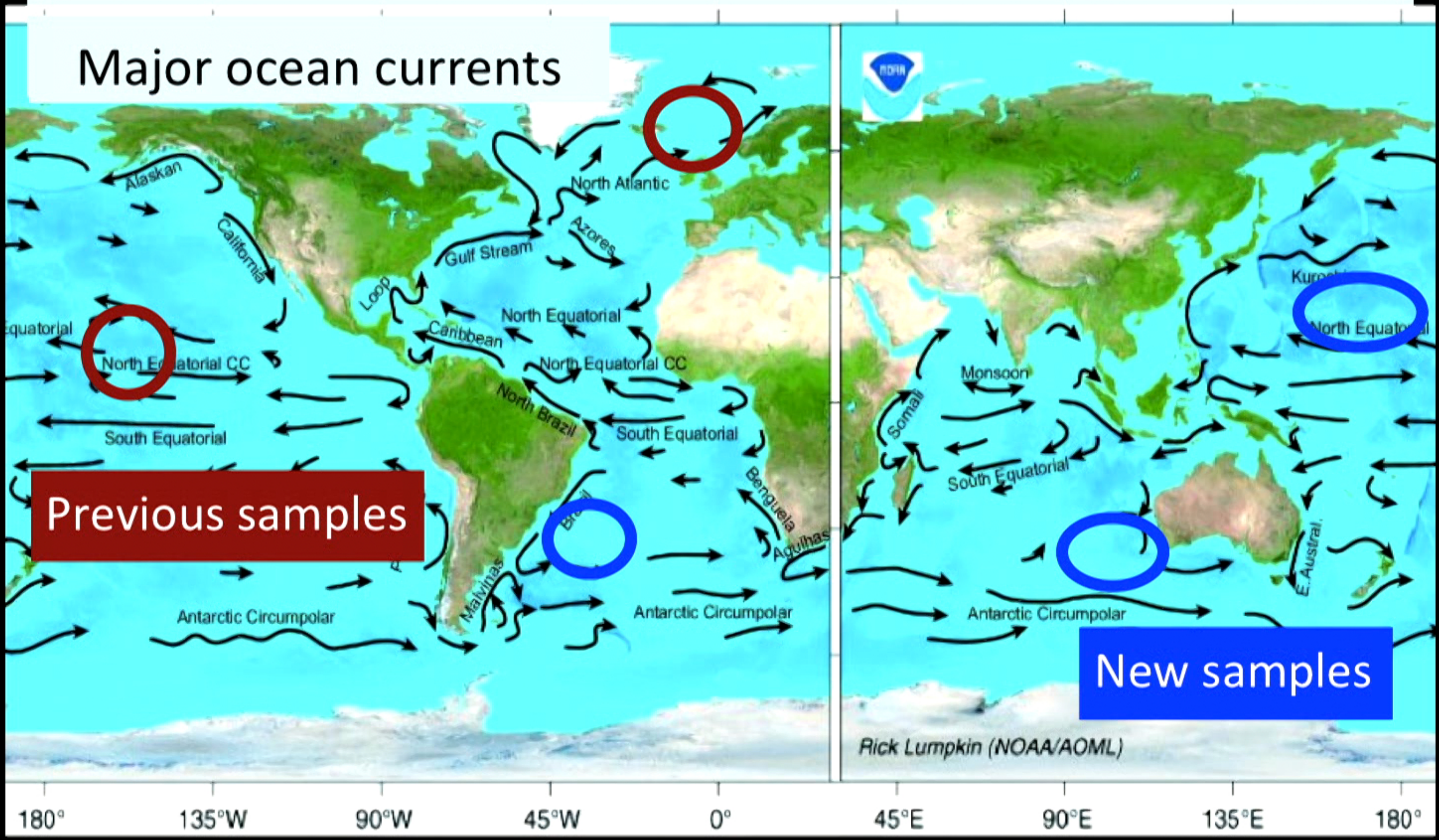

However

Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

^{60}Fe Distribution on the Moon

- Signal smeared out in longitude, not latitude

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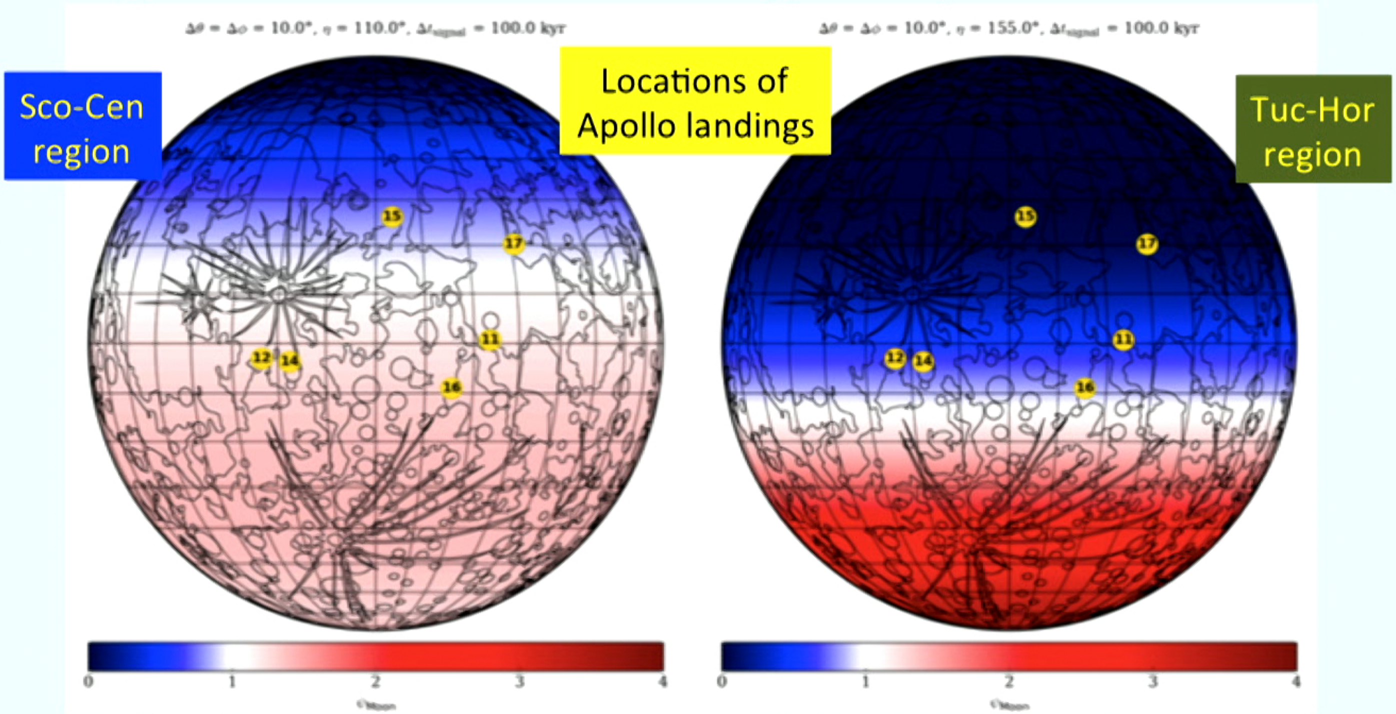

- Calculations for two possible SN locations

Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

Lunar Latitude Distributions

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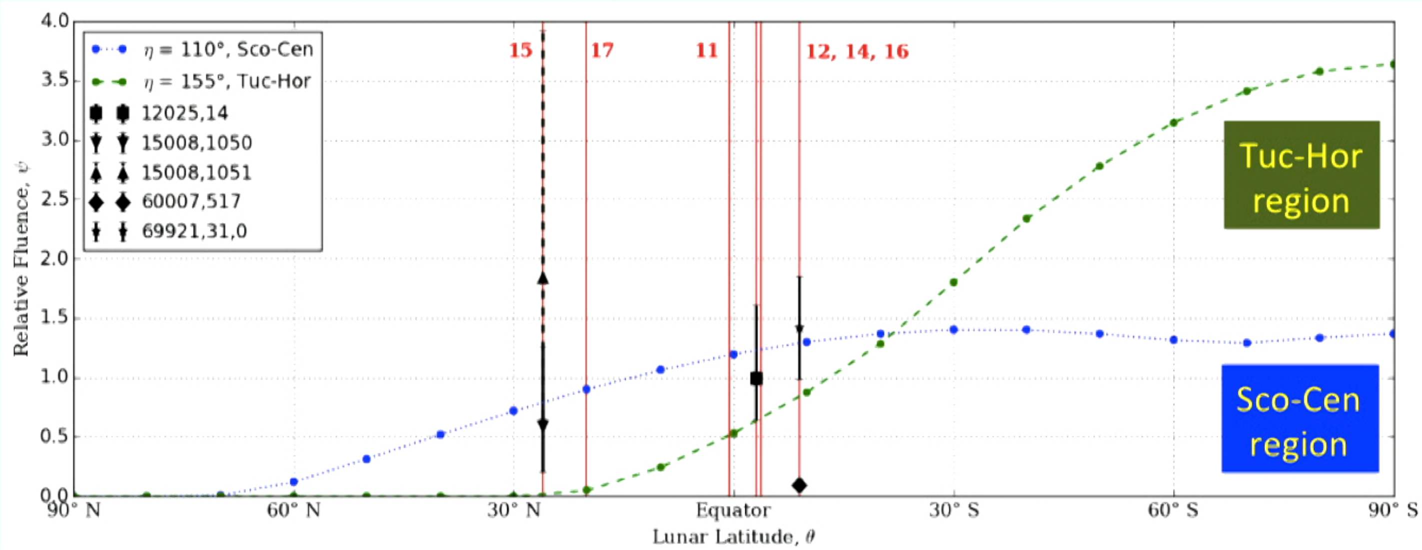

Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

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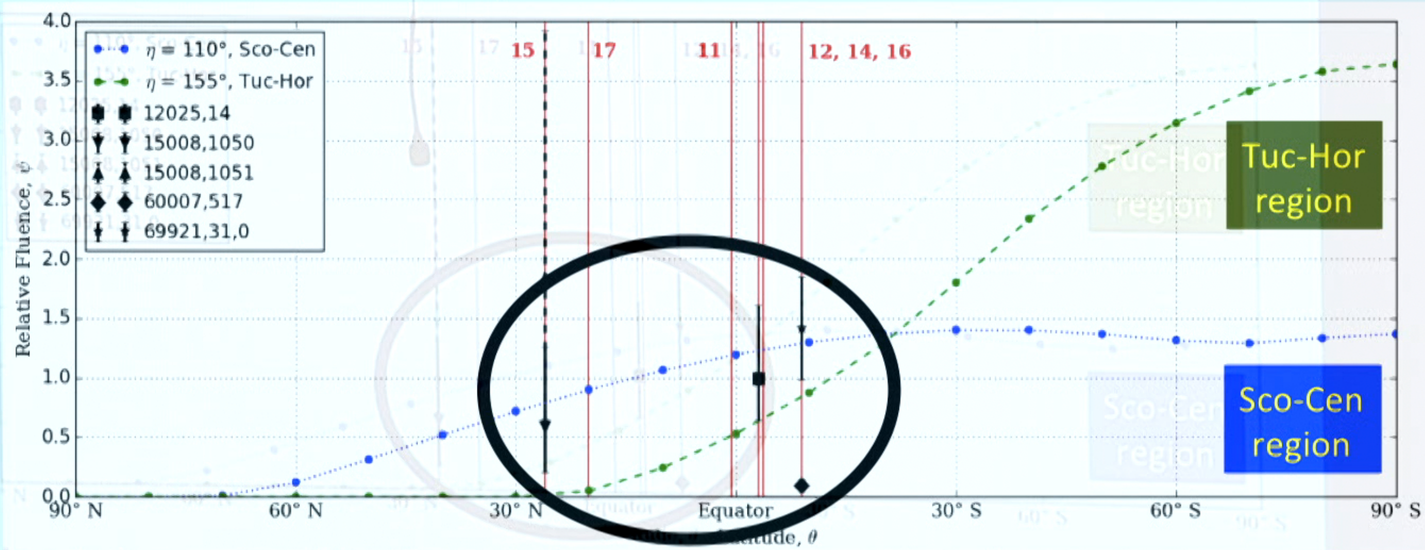

- Showing results from Apollo sample returns
- **Future sample return missions could distinguish?**

Fry, Fields & JE, arXiv:1604.00958 [astro-ph.SR]

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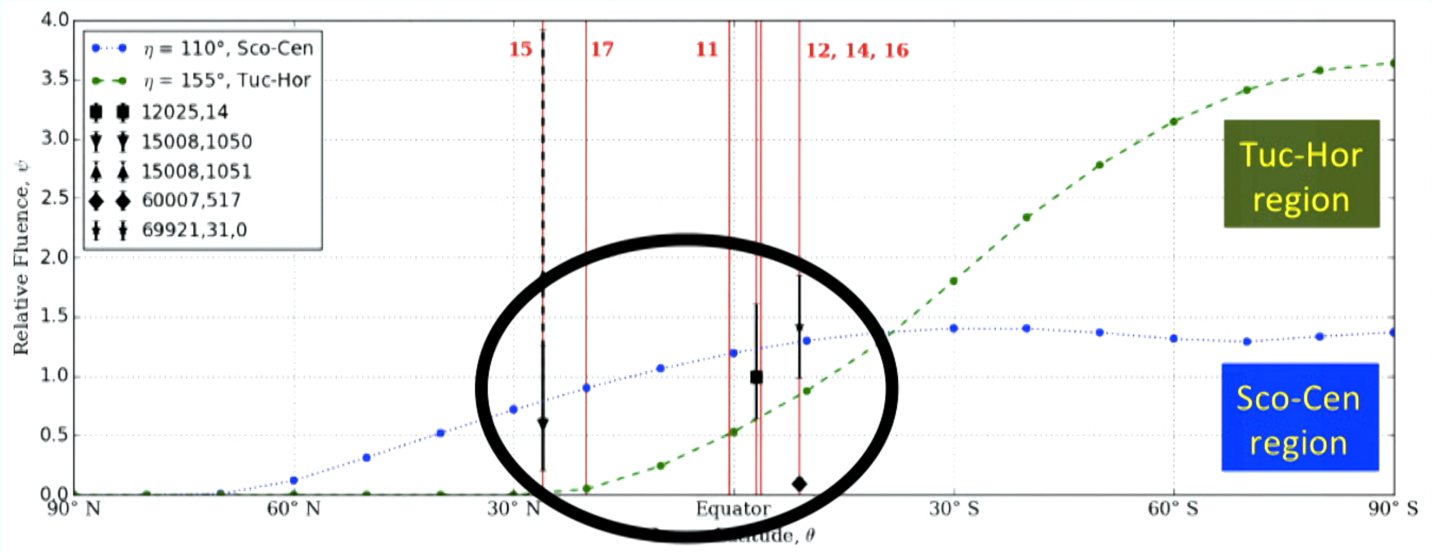
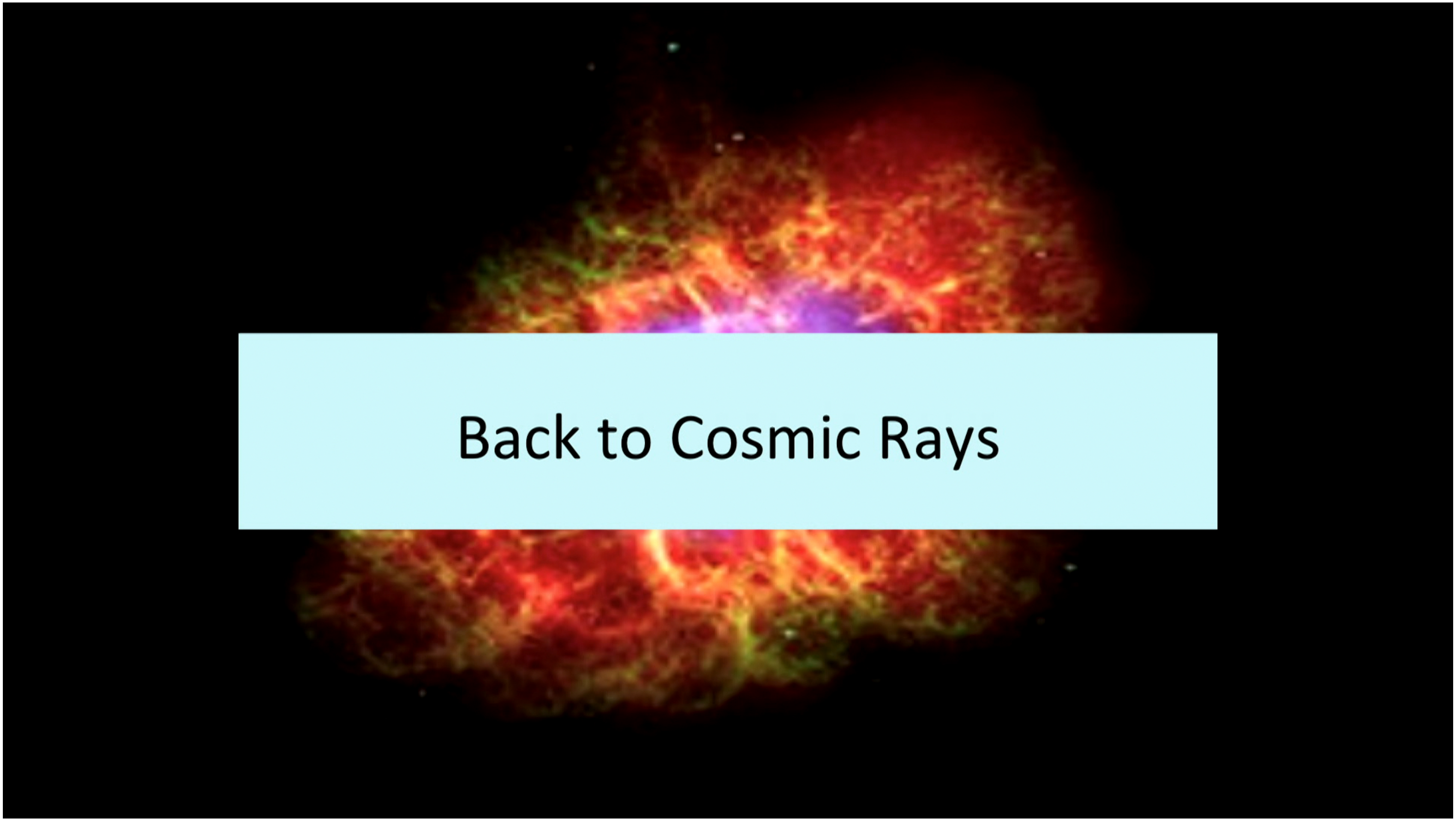


- Showing results from Apollo sample returns
- **Future sample return missions could distinguish?**
- Want high latitudes, controlled sampling

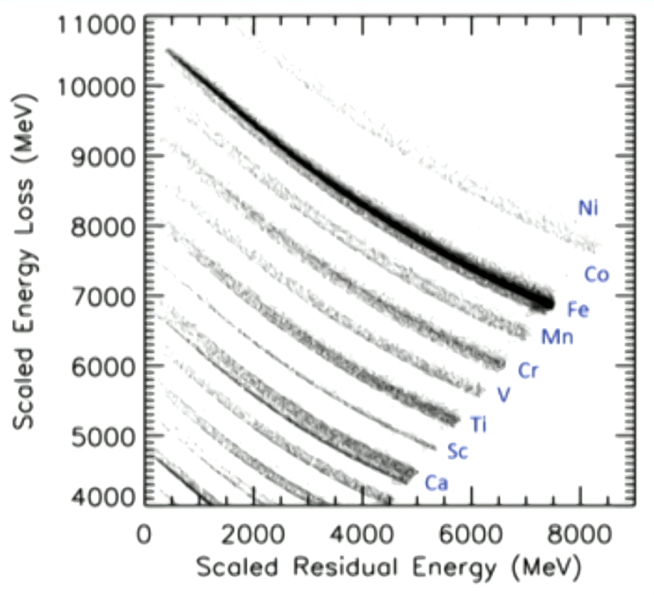


Back to Cosmic Rays

Binns et al, Science 10.1126/science.aad6004 (2016)

Observation of ^{60}Fe in Cosmic Rays

- Clear separation between different isotopes



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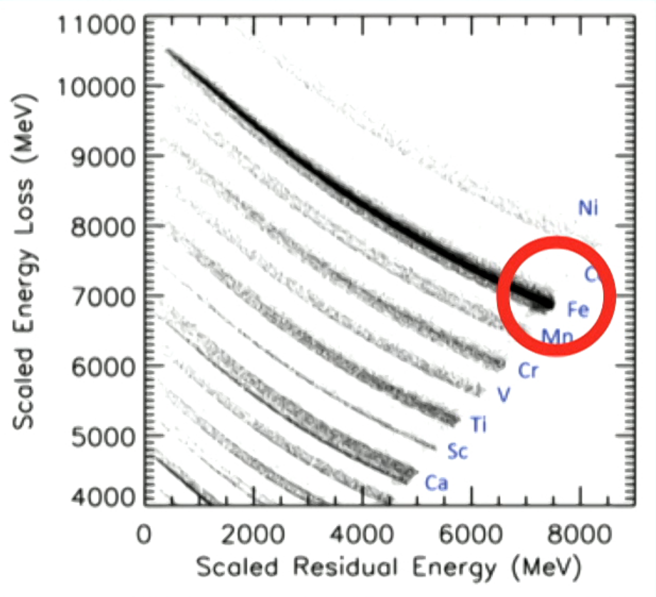

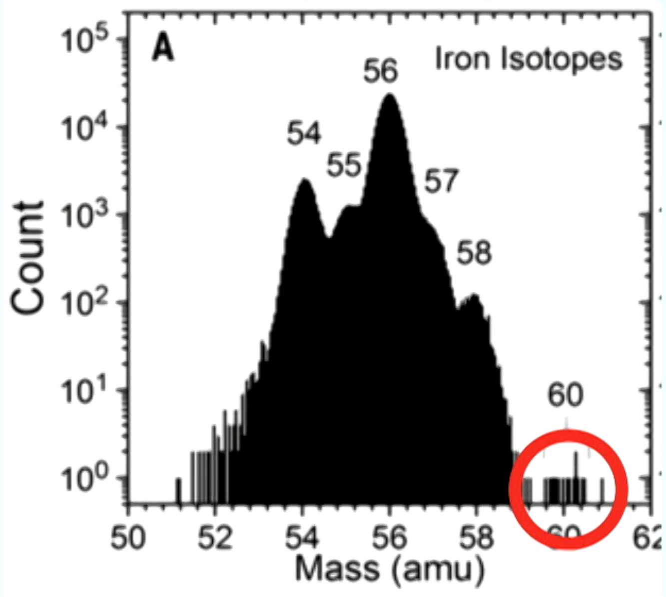

- 15 ^{60}Fe vs. $(7.5 \pm 2.9) \times 10^5$ ^{56}Fe
- Independent evidence for recent SN(e)

Kachelriess, Neronov & Semikoz, arXiv:1504.06472 [astro-ph.HE]

Other Evidence from Cosmic Rays?

- Excesses of cosmic rays due to SN ~ 2M years ago?

Kachelriess, Neronov & Semikoz, arXiv:1504.06472 [astro-ph.HE]

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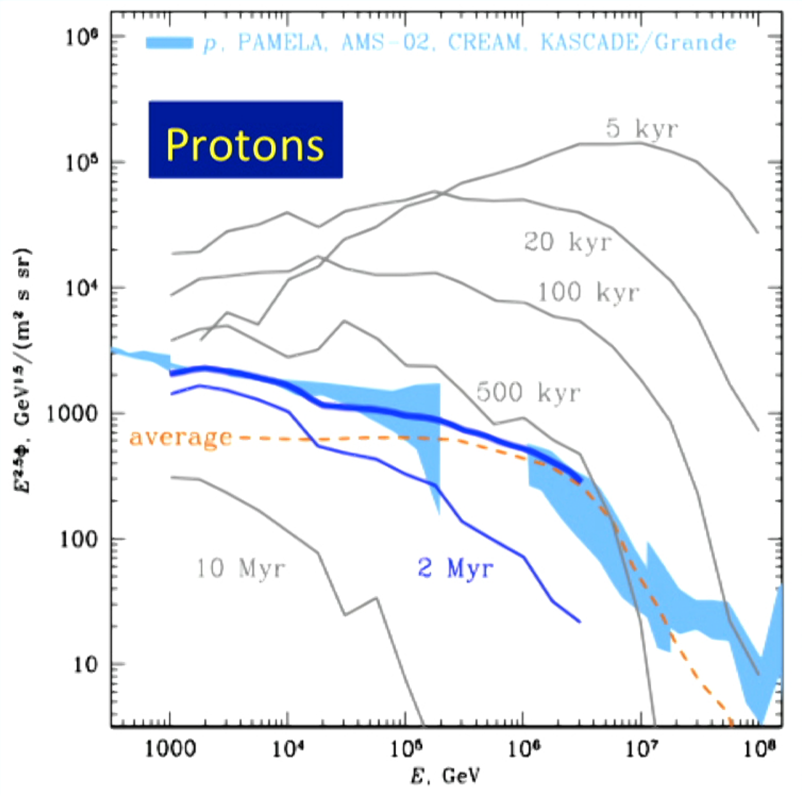

Kachelriess, Neronov & Semikoz, arXiv:1504.06472 [astro-ph.HE]

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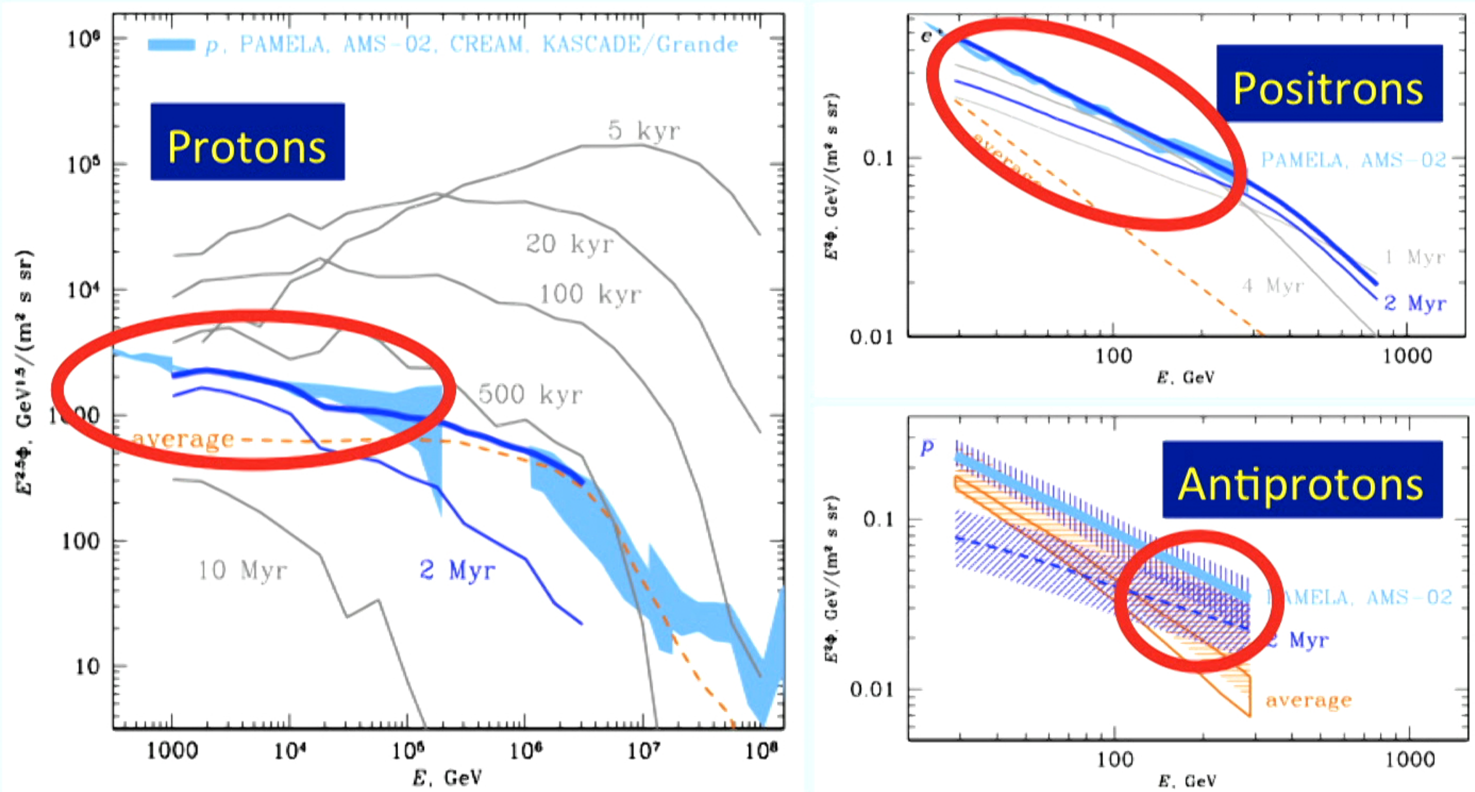
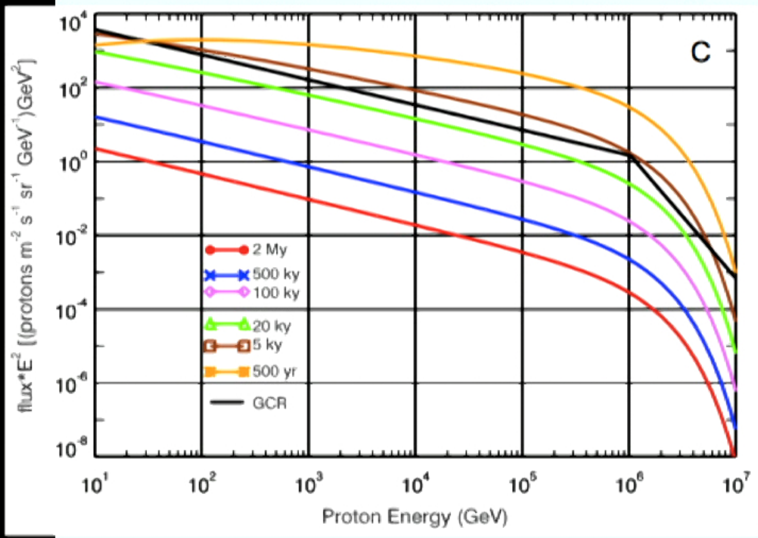


Thomas et al, arXiv:1605.04926 [astro-ph.HE]

Cosmic Ray Flux from Nearby SN

- Enhanced cosmic-ray flux for ~ 5000 years



Thomas et al, arXiv:1605.04926 [astro-ph.HE]

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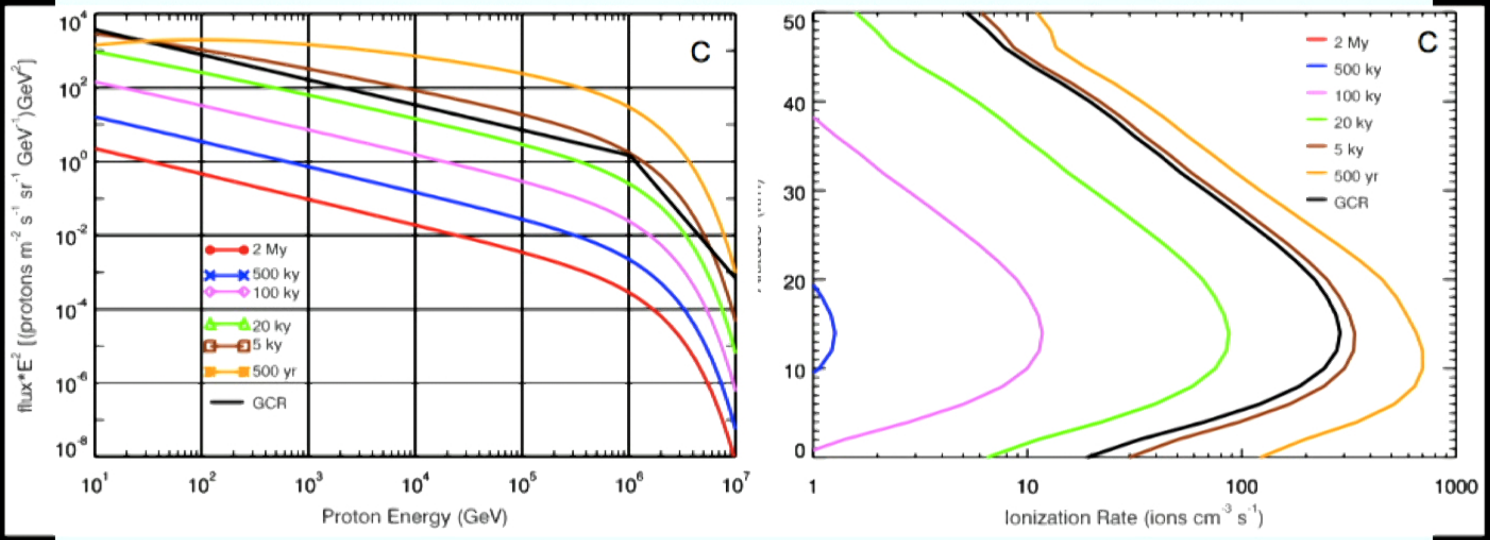
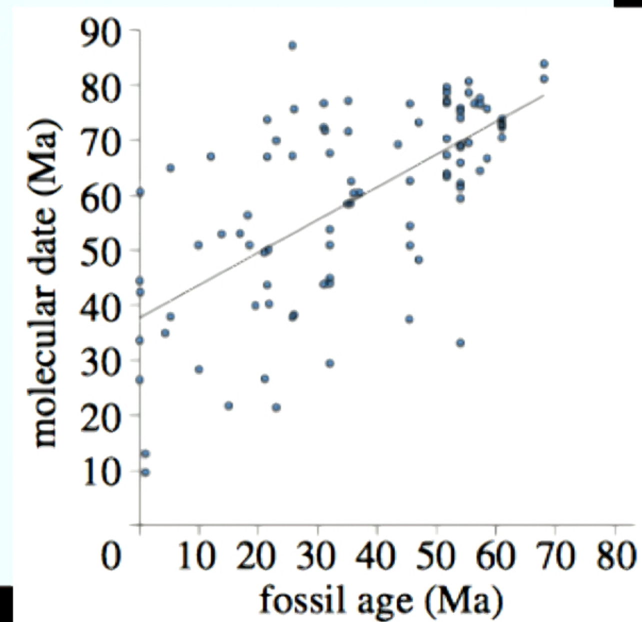


- Increased ionization rate
- **Enhanced mutation rate?**

Ksepka, Ware & Lamm, Proc. Roy. Soc. B281 20140677 (2014)

Biological Effects of Nearby SN?

- Compare fossil ‘clock’ with molecular ‘clock’ based on DNA mutations
- Discrepancy seen in the data on birds
- Seems >> estimated effect of cosmic rays
- Affaire à suivre!



Summary

- **First discovery of effect on Earth of an interstellar event: ^{60}Fe on ocean floors**
- Also seen in lunar samples
- Indications of recent nearby supernova explosion also in cosmic rays
- No threat to life on Earth
- How to look for previous SN explosion that might have caused a mass extinction?
- ^{235}U? ($\tau_{1/2}$ ~ 700 million years)