Cosmic Observations for Nuclear Astrophysics

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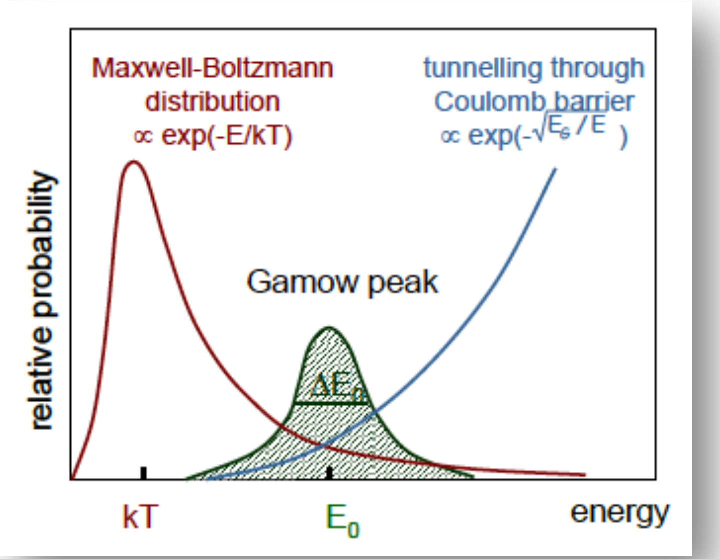
with contributions by

Cristina Chiappini, Norbert Christlieb, Peter Hoppe

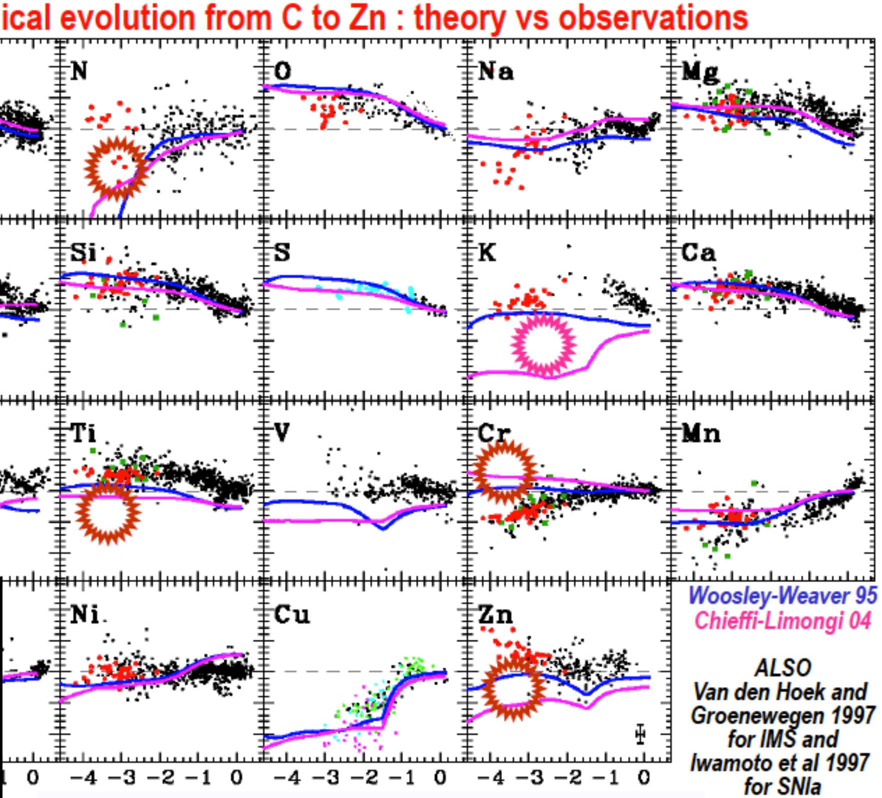
Contents

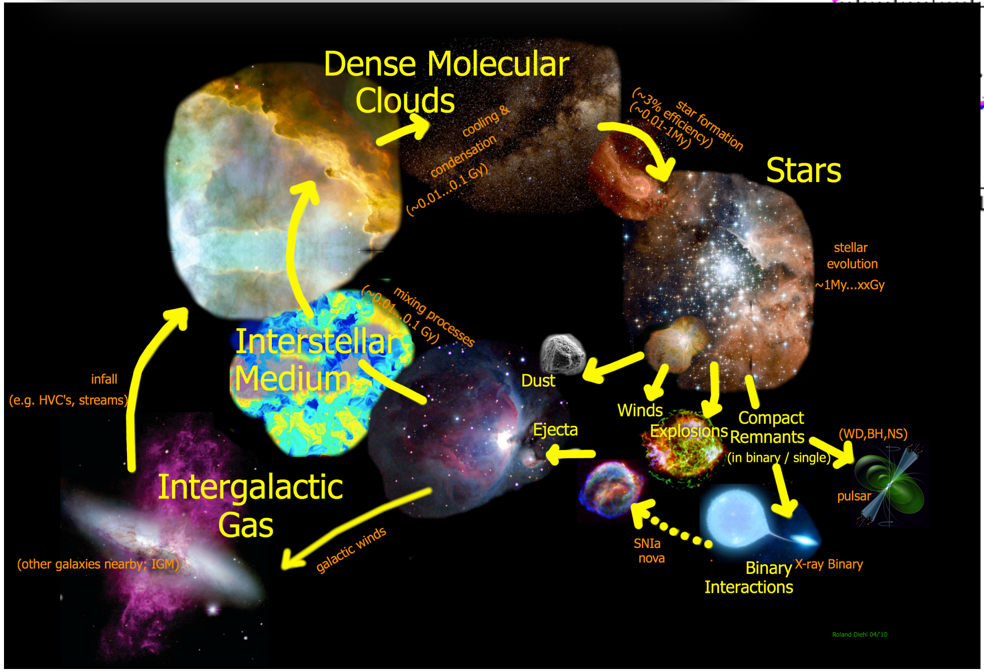
- The astrophysical quests
- Astronomical messengers
- Examples across messenger categories
  - Cosmic abundances (direct, indirect)
  - Cosmic objects (where nuclear physics is key)
- Prospects and Challenges

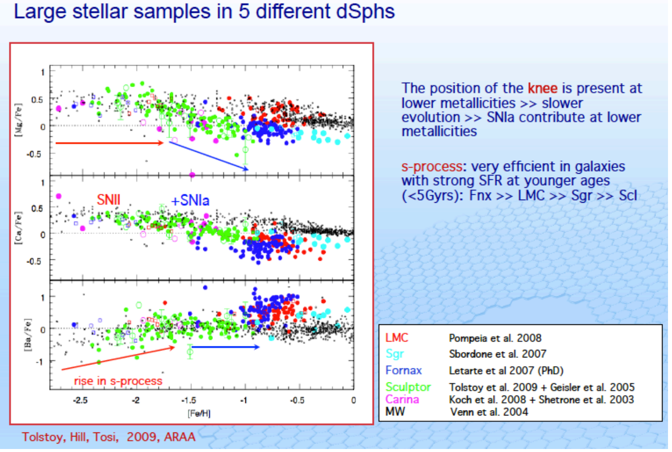
Nuclear Astrophysics: Physics and Astronomy



Chemical evolution from C to Zn : theory vs observations







Large stellar samples in 5 different dSphs

The position of the knee is present at lower metallicities >> slower evolution >> SNIa contribute at lower metallicities

s-process: very efficient in galaxies with strong SFR at younger ages (<5Gyrs): Fnx >> LMC >> Sgr >> Scl

LMC	Pompeia et al. 2008
Sgr	Sbordone et al. 2007
Fornax	Letarte et al 2007 (PhD)
Sculptor	Tolstoy et al. 2009 + Geisler et al. 2005
Carina	Koch et al. 2008 + Shetrone et al. 2003
MW	Venn et al. 2004

Tolstoy, Hill, Tosi, 2009, ARAA

Nuclear Astrophysics: History & Status

- Understanding cosmic / astrophysical objects:

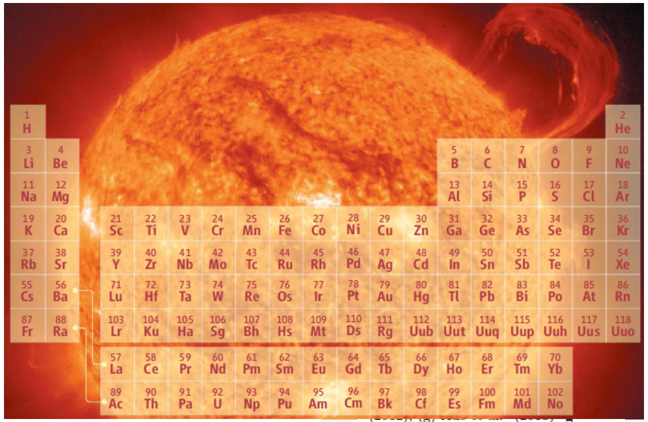
…>50 years of research…

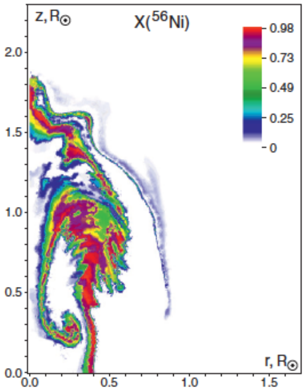
→ Current status:

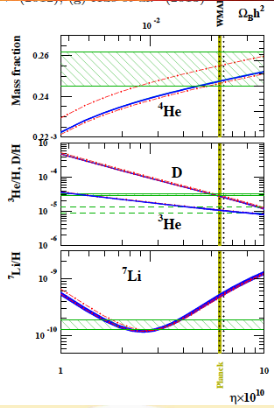
- Basic "processes" defined & confirmed
- Basic role of nuclear physics and nuclear reactions incorporated
- Research focus drifted to other astrophysical questions
  - cosmology, black holes, galaxies, dark components, planets

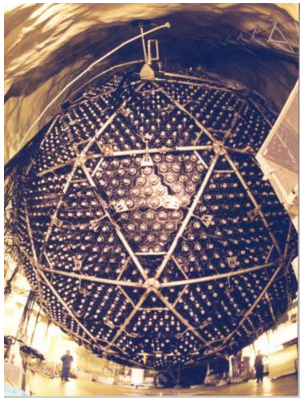
Nuclear Astrophysics: New Perspectives

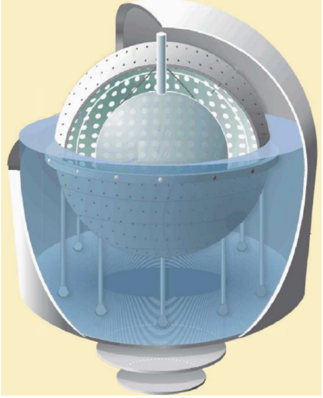
- Recent new findings & puzzles:
  - – solar abundances: δ~30%!
  - – solar model debated (seismic data)
  - – giant stars (late stages) unclear
  - – supernovae: more variety of models
  - – better abundances
    → BBN Li? Many r-processes?
- New perspectives:
  - – abundance surveys, massive data
  - – complementing messengers
    - opt/IR/sub-mm/X/gamma/GW/ν's











New perspectives from recent findings

- Current quests & themes …

Stellar Structure and Evolution

- Model Dependencies
  - Giant Stars (He Burning)
    - *Martins & Palacios 2013*

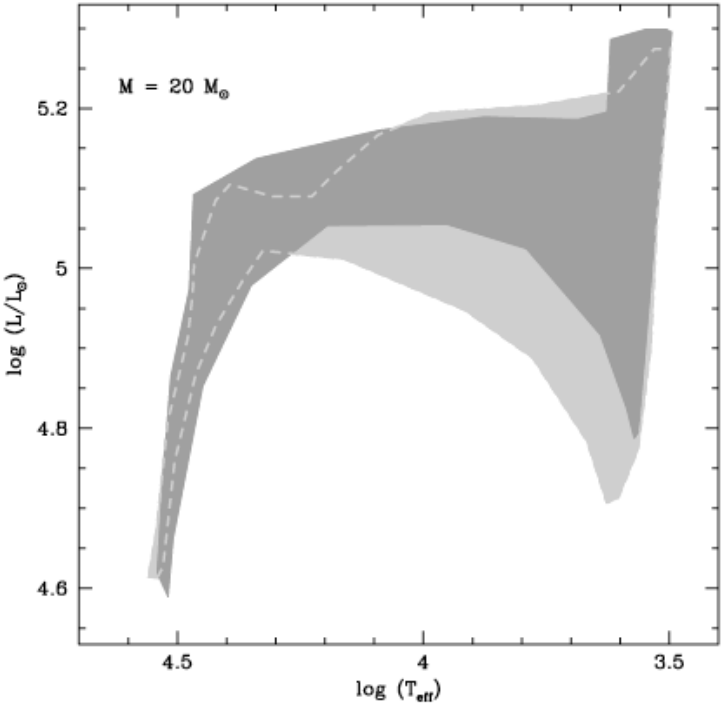
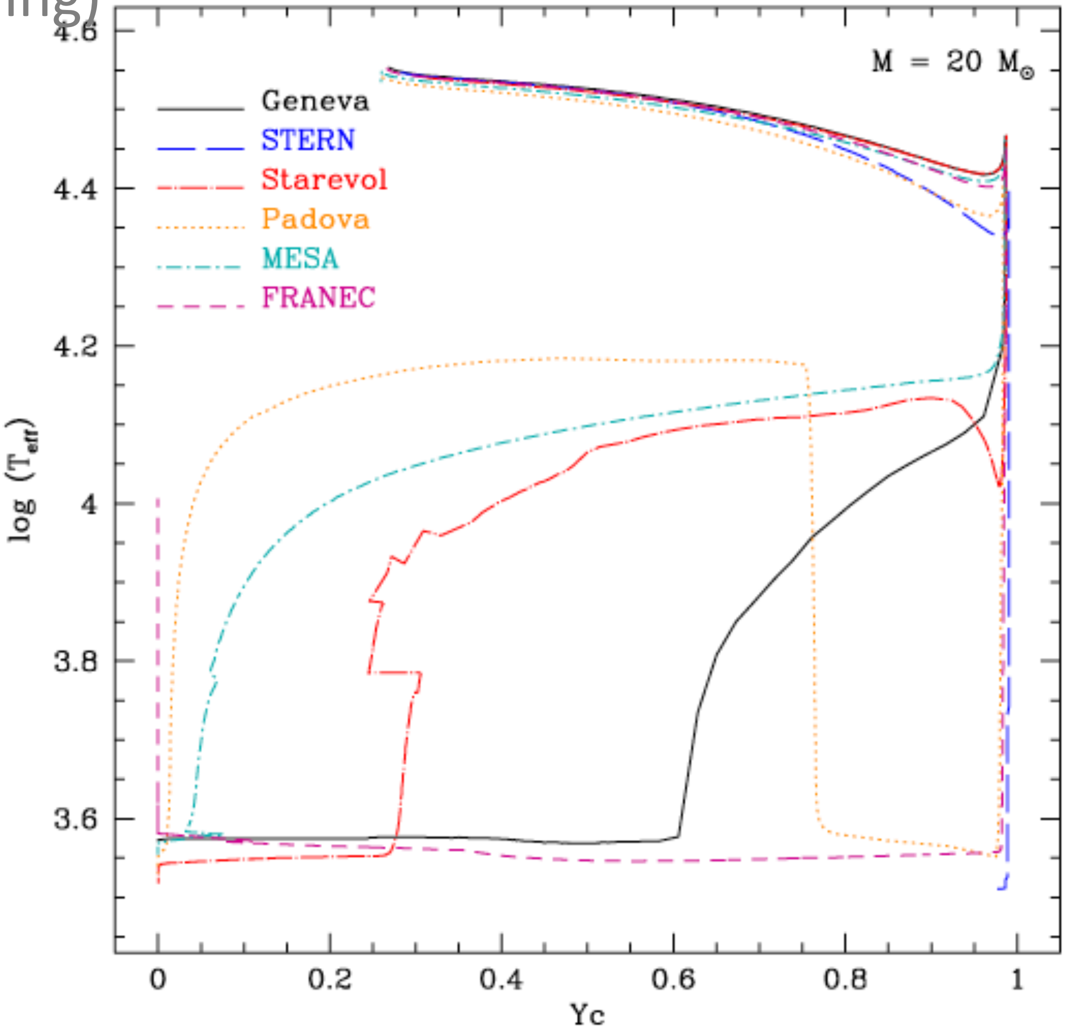


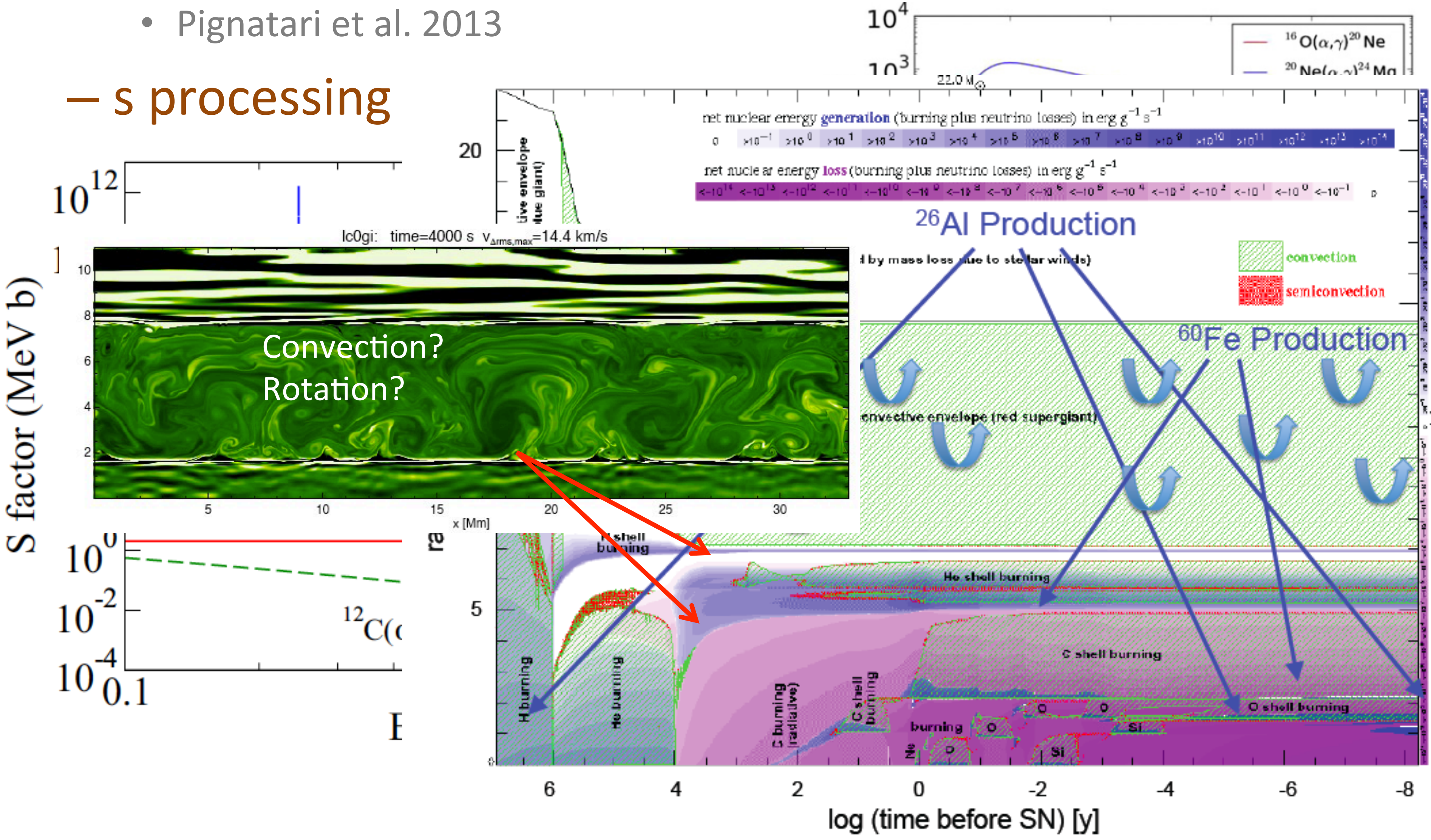
Fig. 7. Uncertainty on the location of the evolutionary path for a 20 $M_\odot$ stellar model with (dark grey envelope) and without (light grey delimited by dashes lines) rotation. We have considered tracks generated by five different codes (Geneva, STERN, FRANEC, MESA and Starevol) with similar (yet not exactly the same) initial rotation rates.



Nuclear Reactions in Massive Star Shells

- Complex & different dependencies for the key reactions
  - Pignatari et al. 2013

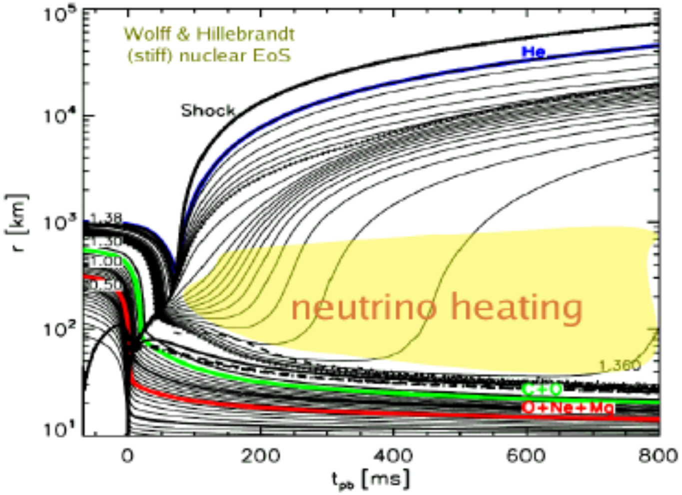
– s processing



Core-Collapses: Supernova Explosions (?)

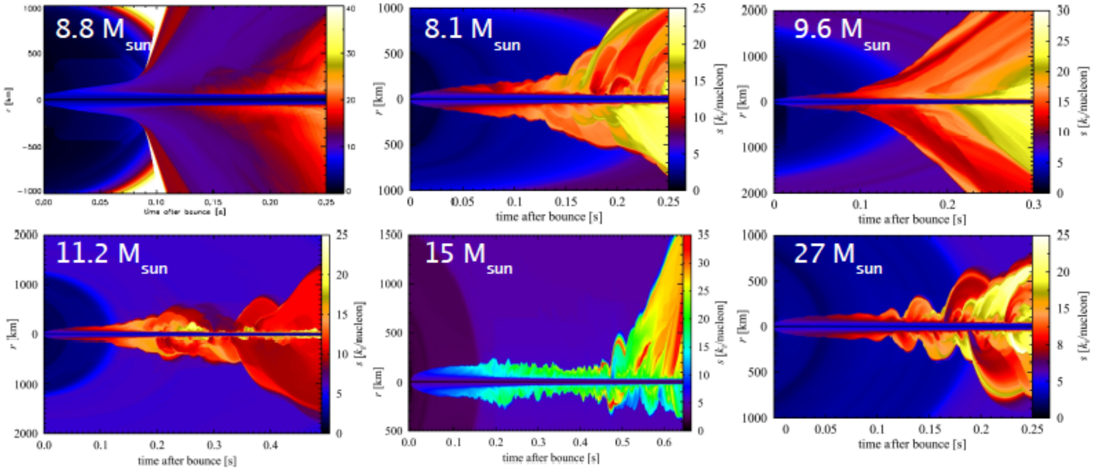
- 1D Simulations → SNe (EC) from ~8-10 $M_\odot$ Stars
- 2D Simulations → SNe for 10-25 $M_\odot$ Stars, by x Groups
  - SASI, n's, G modes → 3D-effects
- 3D Simulations → ???

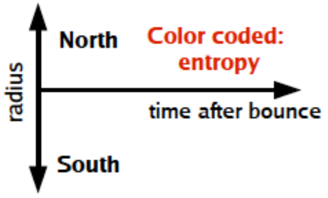
"Electron-capture supernovae"
or "ONeMg core supernovae"

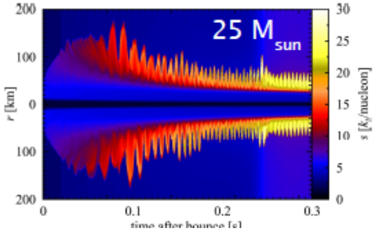


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

Fischer et al. 2010

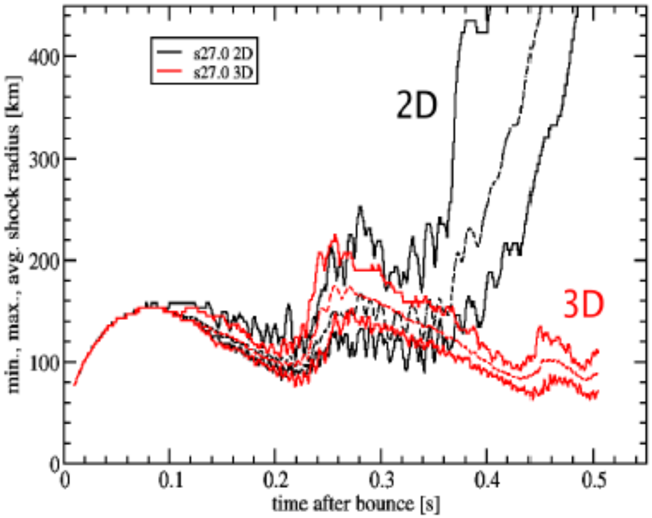






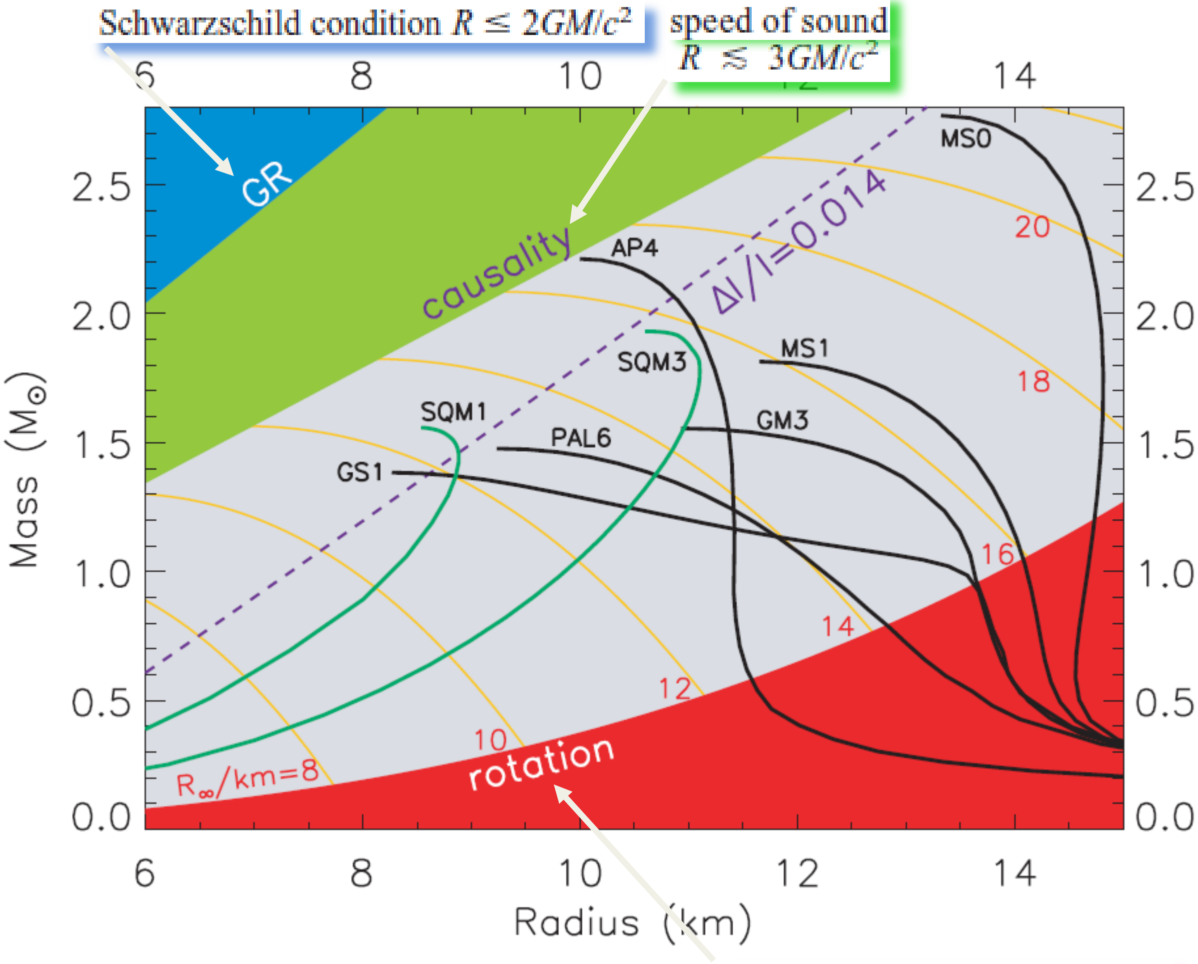
Bernhard Müller, THJ, et al. (ApJ 756, ApJ 761, arXiv:1210.6984

Basic confirmation of previous explosion models for 11.2 and 15 M_{sun} stars by Marek & THJ (2009)



Understanding Neutron Stars

- Stability
  - Pressure from Degenerated n
  - Rotation
- Constraints
  - $v_{Fermi} < c$
  - $v_{Sound} < c$
  - $v_{Surf} < v_{Kepler}$
- Issues
  - n Phases
    - Lattices/Rods
    - Hyperons
    - Pairings, Condensates

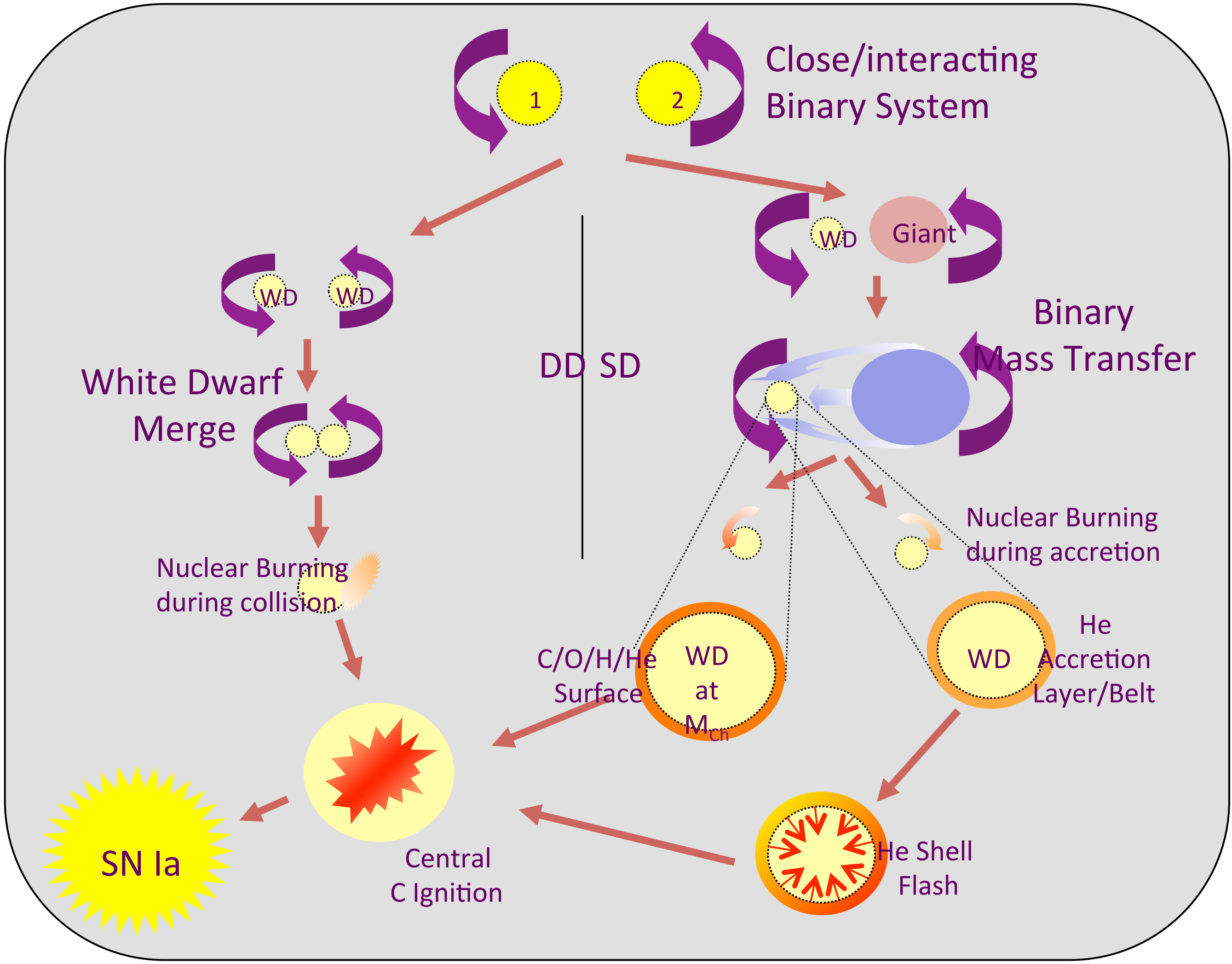


Schwarzschild condition $R \leq 2GM/c^2$

speed of sound $R \lesssim 3GM/c^2$

$$\nu_K = (2\pi)^{-1}\sqrt{GM/R^3} = 1833(M/M_\odot)^{1/2}(10\ \mathrm{km}/R)^{3/2}\ \mathrm{Hz}$$

SNIa – ‘standard’ sources?



Close/interacting Binary System

DD SD

White Dwarf Merge

Nuclear Burning during collision

Binary Mass Transfer

Nuclear Burning during accretion

C/O/H/He Surface

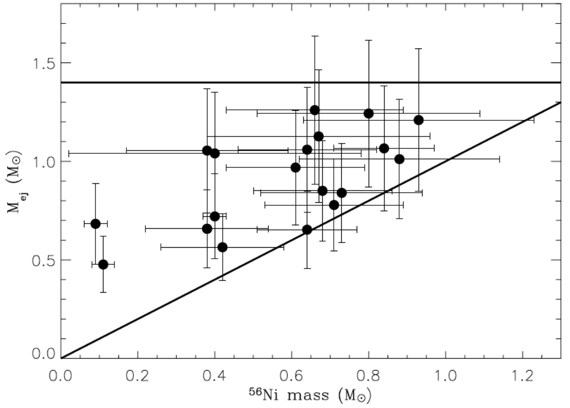
He Accretion Layer/Belt

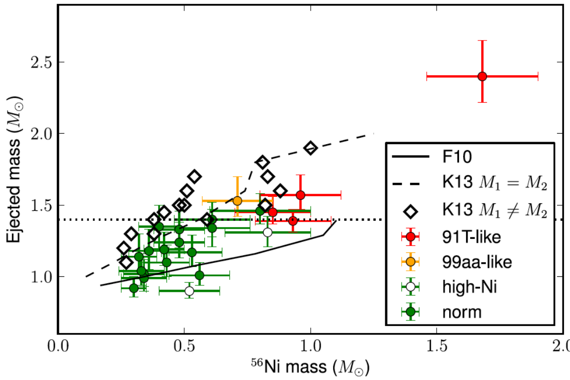
He Shell Flash

Central C Ignition

SN Ia

- Varying amounts of radioactive ^{56}Ni?

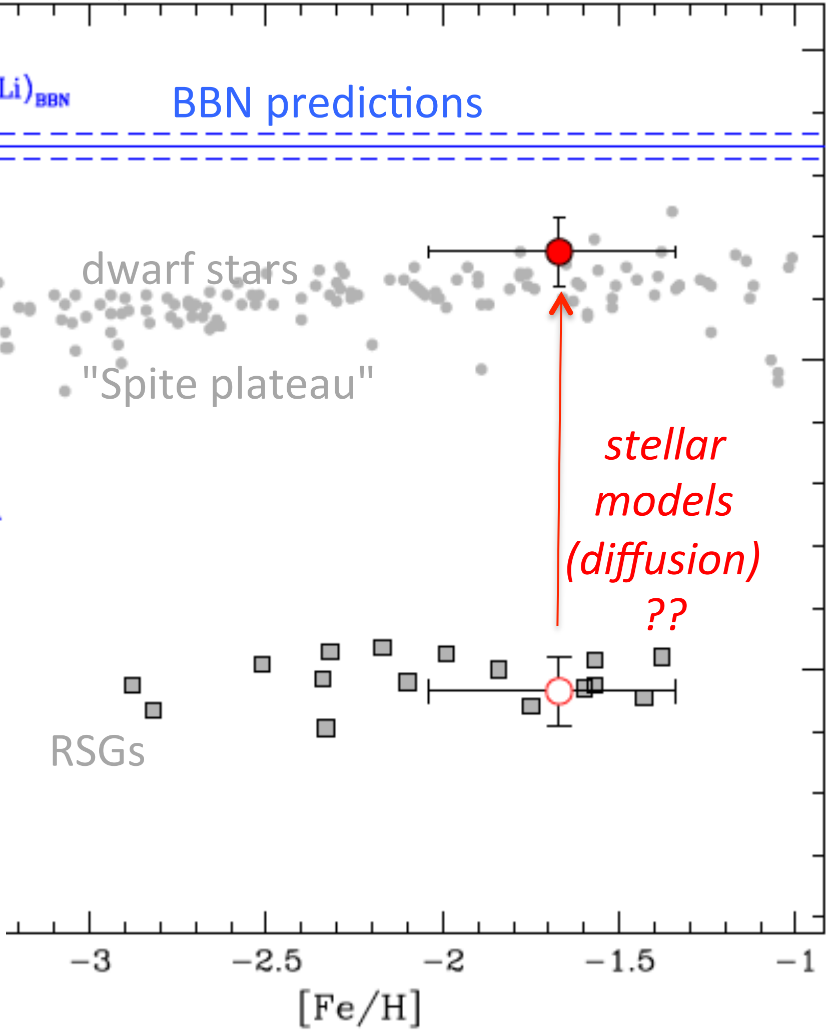




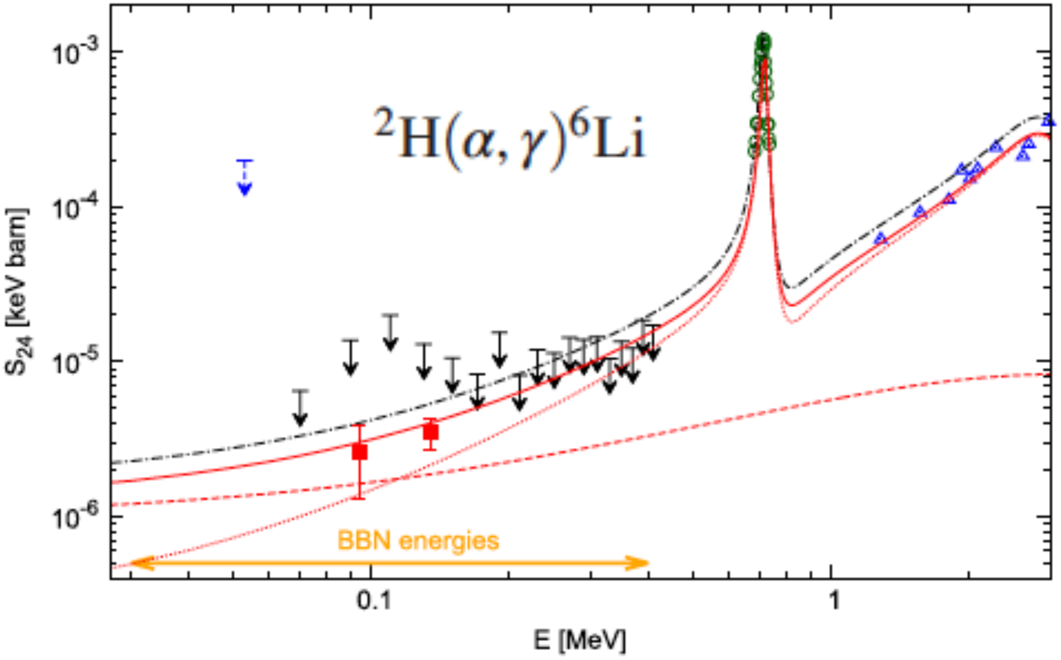
Li abundance issues

- BBN predicts Li abundance; conflict to observations?
  - stellar processing
    → apparent Li reduced?
  - ^{6}Li/^{7}Li: ~2 10^{-5} (BBN)
    or ~10^{-2} (stars)??
  - BBN ^{6}Li production correct?

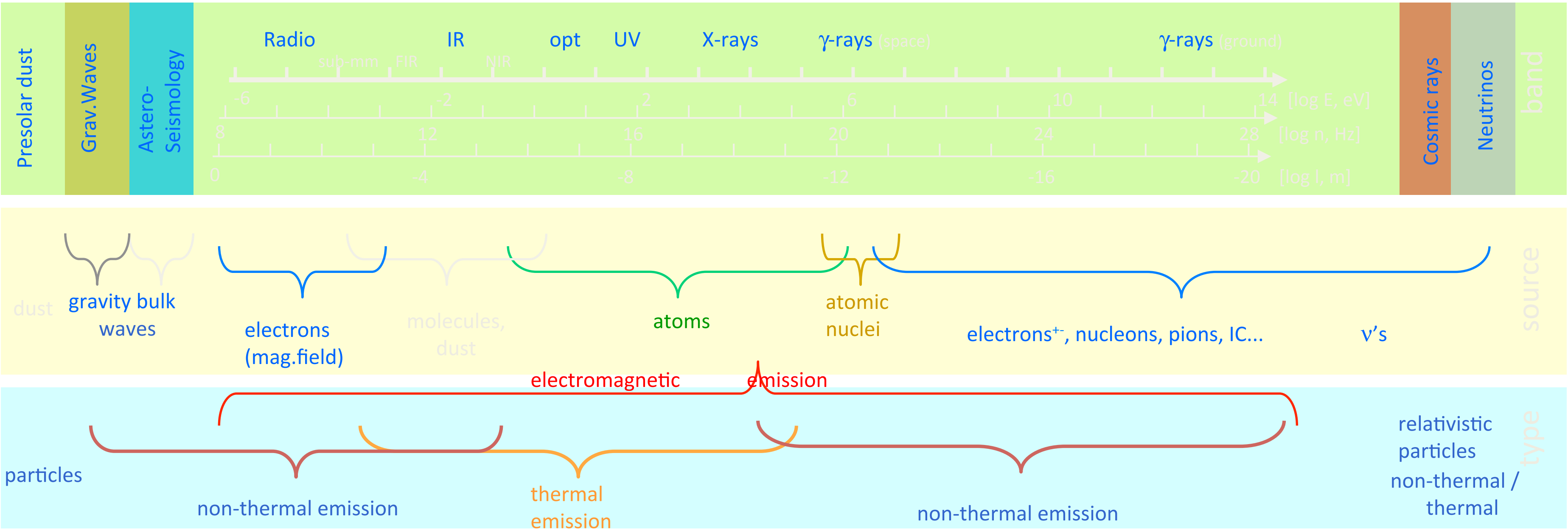
Coc et al. 2013; Mucciarelli et al 2014



Anders et al., PRL 2014



Astronomy : The Variety of Astrophysical Messengers



– Astronomy with photons/e.m. radiation is complemented by new "messengers →

- Presolar grains, cosmic rays: material samples from the cosmos
- Neutrinos: High-energy process is cosmic objects
- Gravitational Waves: Interactions of compact stars

Recent cosmic-observation examples for NA

- Selected examples across the various astronomical windows and messengers …

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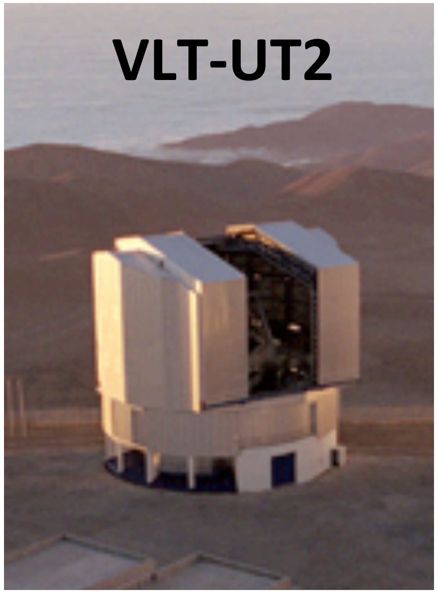

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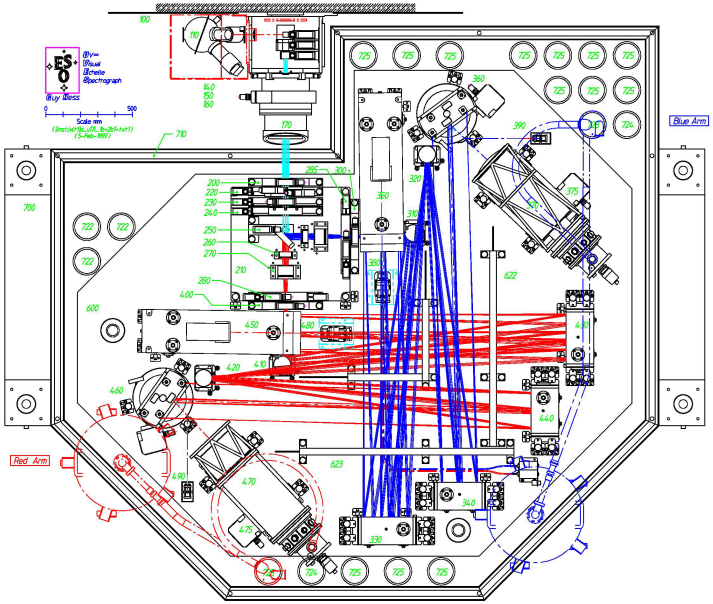

UVES

(two-arm cross-dispersed Échelle spectrograph)

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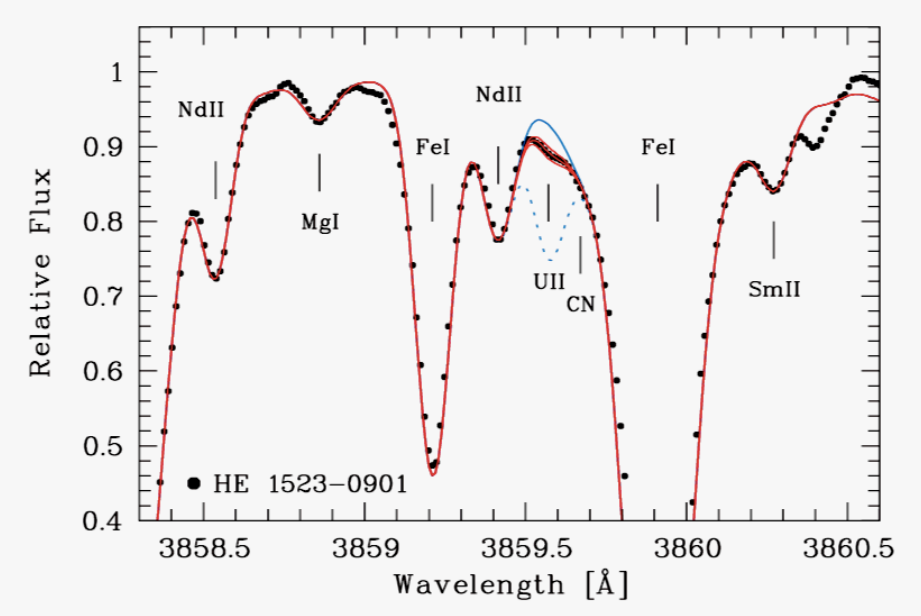
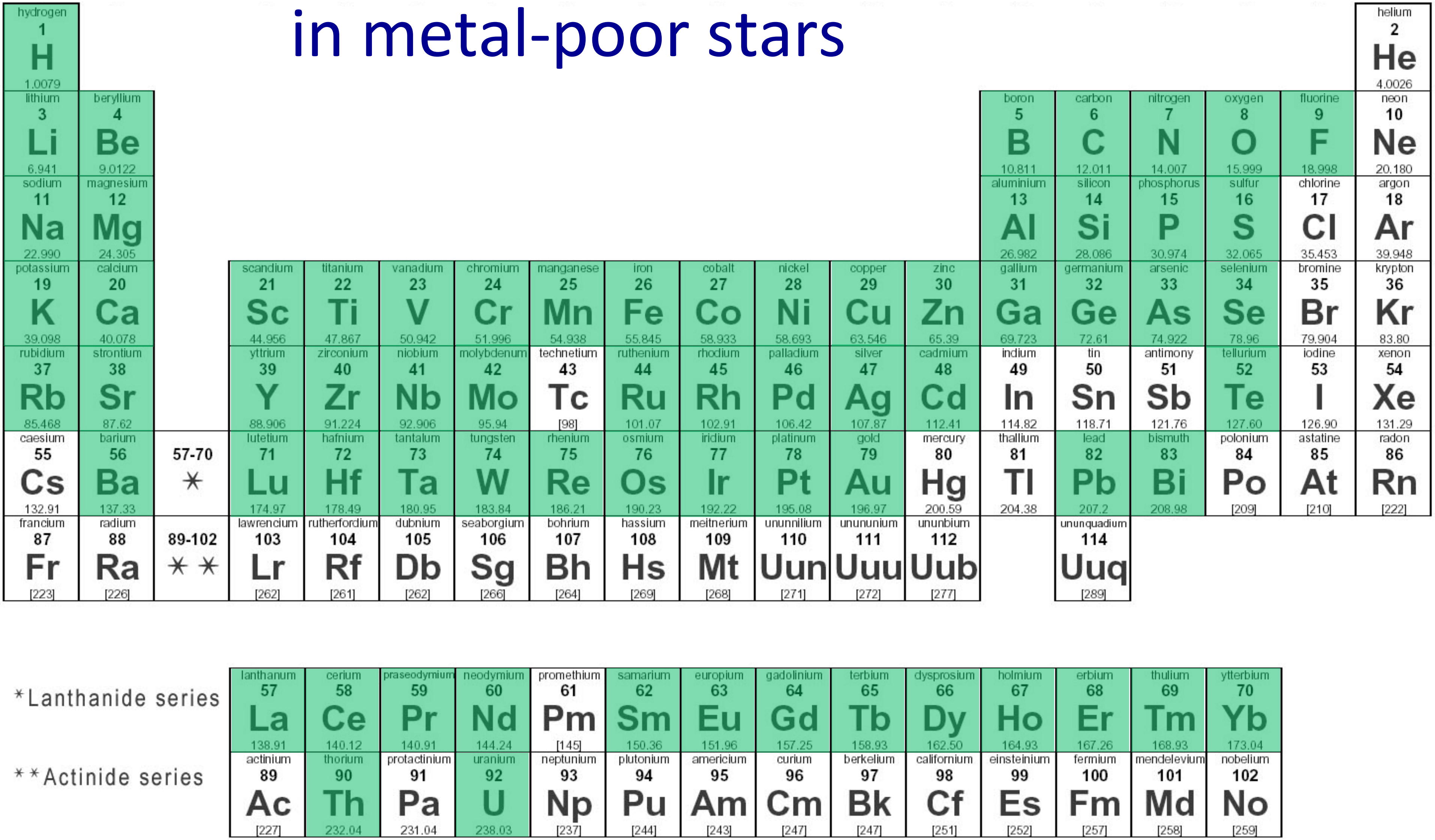


Elements measured in metal-poor stars

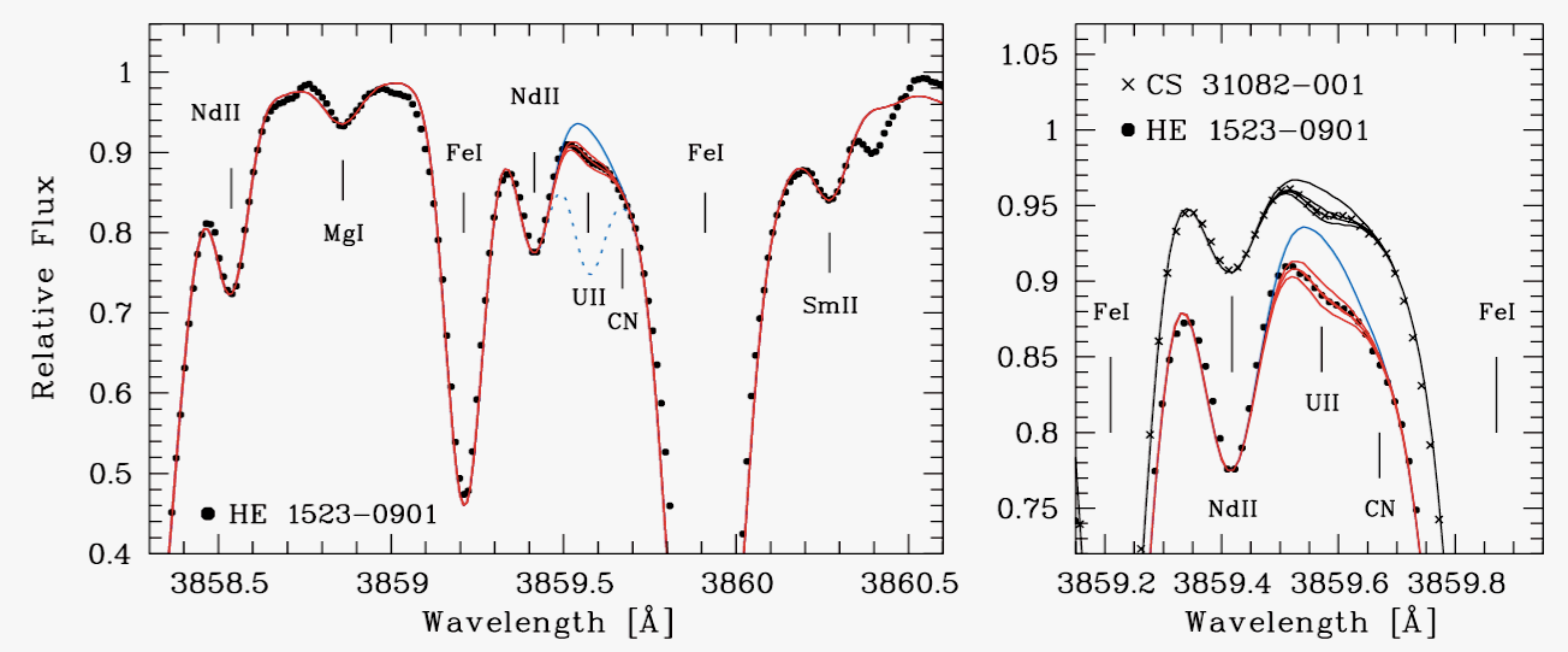


🟩 hydrogen 1 H 1.0079																	helium 2 He 4.0026
🟩 lithium 3 Li 6.941	🟩 beryllium 4 Be 9.0122											🟩 boron 5 B 10.811	🟩 carbon 6 C 12.011	🟩 nitrogen 7 N 14.007	🟩 oxygen 8 O 15.999	🟩 fluorine 9 F 18.998	neon 10 Ne 20.180
🟩 sodium 11 Na 22.990	🟩 magnesium 12 Mg 24.305											🟩 aluminium 13 Al 26.982	🟩 silicon 14 Si 28.086	🟩 phosphorus 15 P 30.974	🟩 sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
🟩 potassium 19 K 39.098	🟩 calcium 20 Ca 40.078		🟩 scandium 21 Sc 44.956	🟩 titanium 22 Ti 47.867	🟩 vanadium 23 V 50.942	🟩 chromium 24 Cr 51.996	🟩 manganese 25 Mn 54.938	🟩 iron 26 Fe 55.845	🟩 cobalt 27 Co 58.933	🟩 nickel 28 Ni 58.693	🟩 copper 29 Cu 63.546	🟩 zinc 30 Zn 65.39	🟩 gallium 31 Ga 69.723	🟩 germanium 32 Ge 72.61	🟩 arsenic 33 As 74.922	🟩 selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
🟩 rubidium 37 Rb 85.468	🟩 strontium 38 Sr 87.62		🟩 yttrium 39 Y 88.906	🟩 zirconium 40 Zr 91.224	🟩 niobium 41 Nb 92.906	🟩 molybdenum 42 Mo 95.94	technetium 43 Tc [98]	🟩 ruthenium 44 Ru 101.07	🟩 rhodium 45 Rh 102.91	🟩 palladium 46 Pd 106.42	🟩 silver 47 Ag 107.87	🟩 cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	🟩 tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	🟩 barium 56 Ba 137.33	57-70 *	🟩 lutetium 71 Lu 174.97	🟩 hafnium 72 Hf 178.49	🟩 tantalum 73 Ta 180.95	🟩 tungsten 74 W 183.84	🟩 rhenium 75 Re 186.21	🟩 osmium 76 Os 190.23	🟩 iridium 77 Ir 192.22	🟩 platinum 78 Pt 195.08	🟩 gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	🟩 lead 82 Pb 207.2	🟩 bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]			

*Lanthanide series	🟩 lanthanum 57 La 138.91	🟩 cerium 58 Ce 140.12	🟩 praseodymium 59 Pr 140.91	🟩 neodymium 60 Nd 144.24	promethium 61 Pm [145]	🟩 samarium 62 Sm 150.36	🟩 europium 63 Eu 151.96	🟩 gadolinium 64 Gd 157.25	🟩 terbium 65 Tb 158.93	🟩 dysprosium 66 Dy 162.50	🟩 holmium 67 Ho 164.93	🟩 erbium 68 Er 167.26	🟩 thulium 69 Tm 168.93	🟩 ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	🟩 thorium 90 Th 232.04	protactinium 91 Pa 231.04	🟩 uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Detection of Uranium

Frebel et al. (2007, ApJ 660, L117)



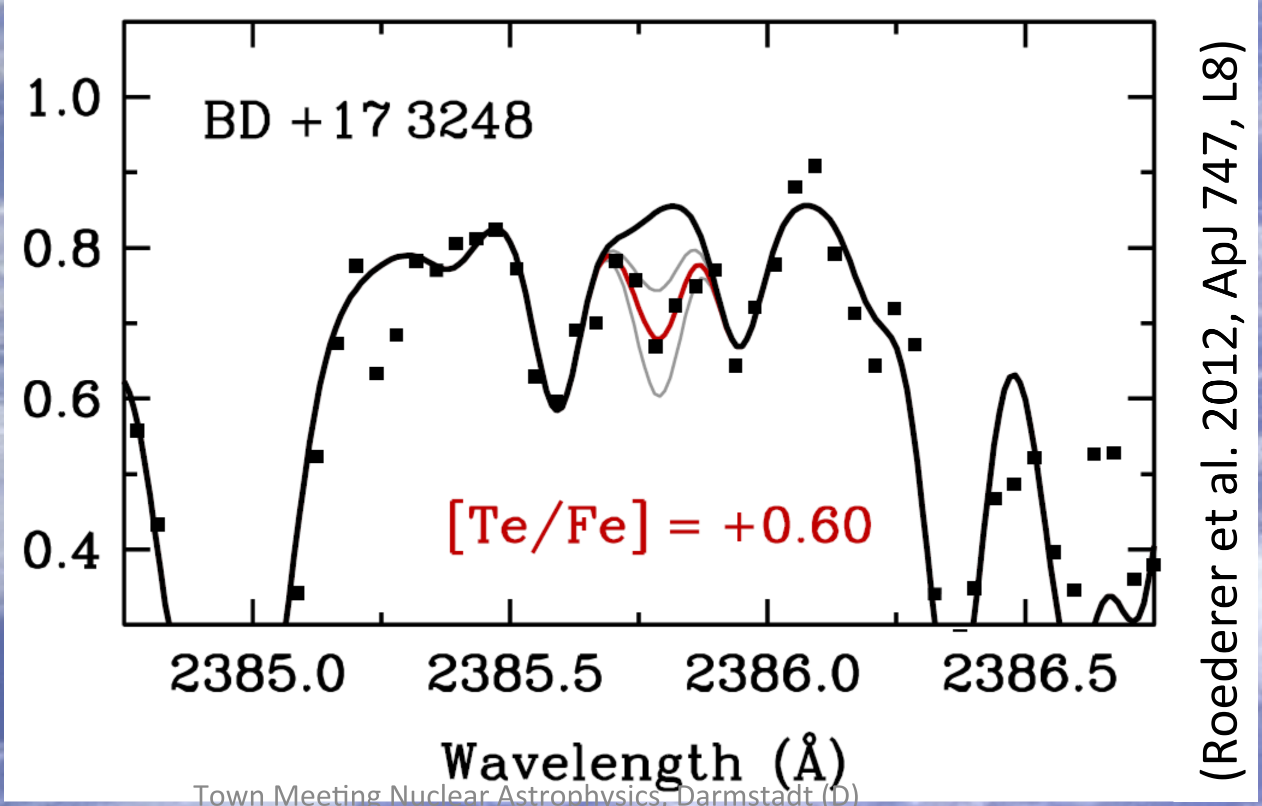
Log ε(U) = -2.06

Q: How many atoms of uranium per hydrogen atom are there in this star?

A: log ε(U) = $\log_{10}(N_U/N_H) + 12 = -2.06$ => 1 in ~10^{14}!

…but very high spectral resolution ($R = \lambda/\delta\lambda > 60{,}000$) and signal-to-noise ratio ($S/N > 500$) needed, therefore limited to bright stars.

HST observations of Te



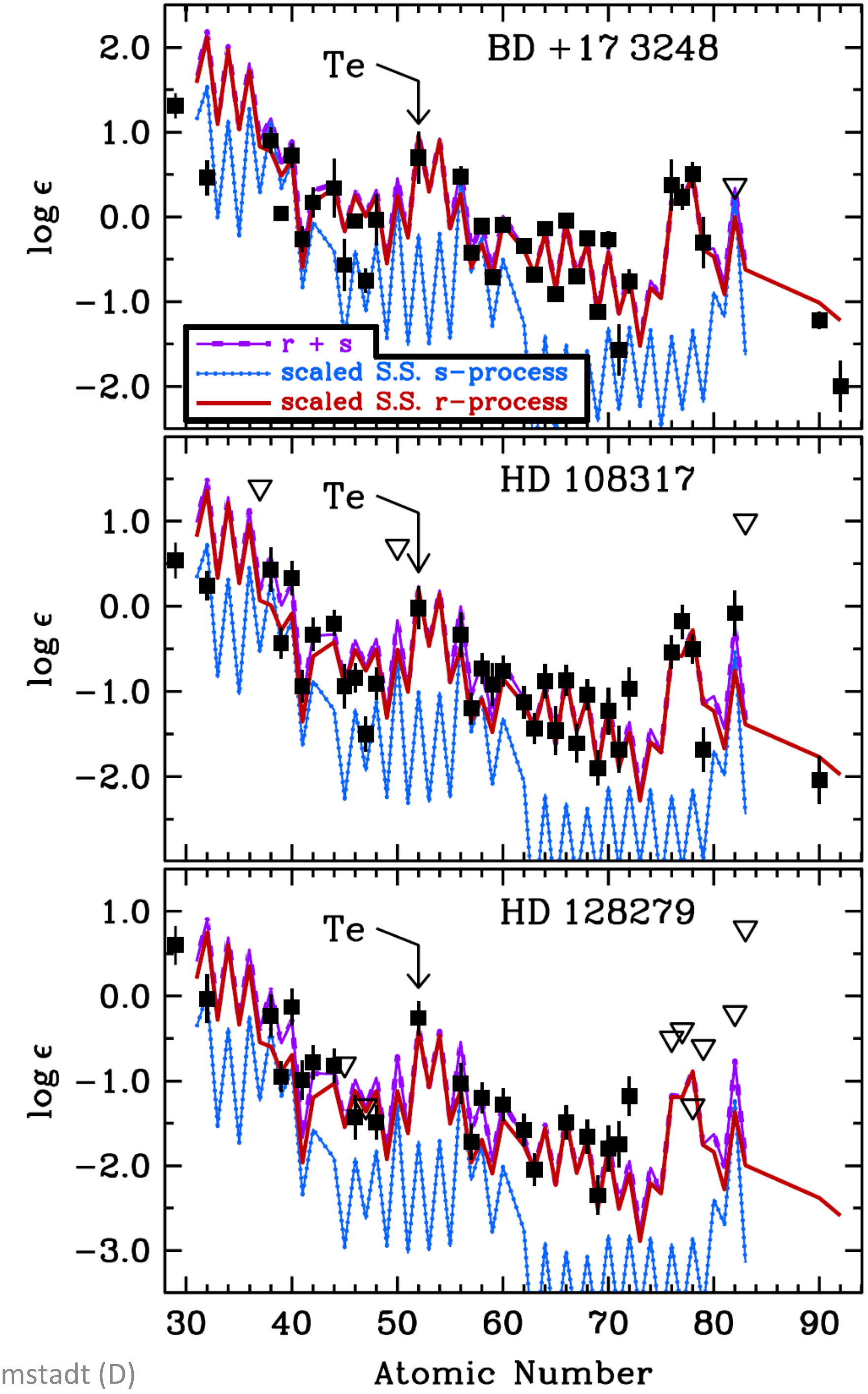
(Roederer et al. 2012, ApJ 747, L8)

Tellurium

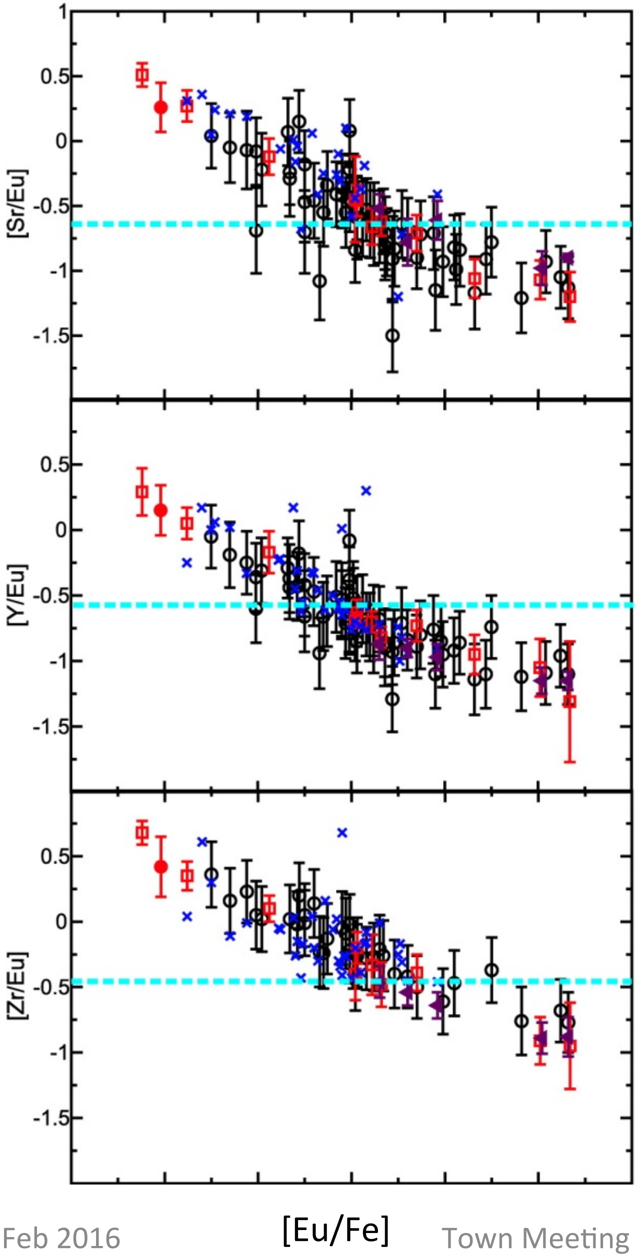
- *Roederer et al. (2012, ApJ 747, L8):*

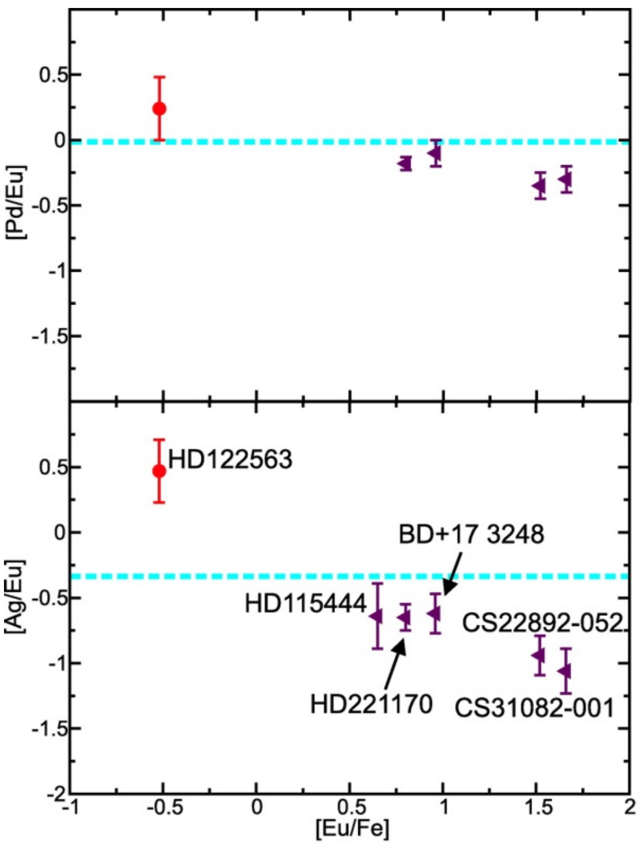
  Observed Te abundances match scaled Solar “r-process” abundance pattern well.

The stars
observe
from space
you shall!



Light neutron-capture elements

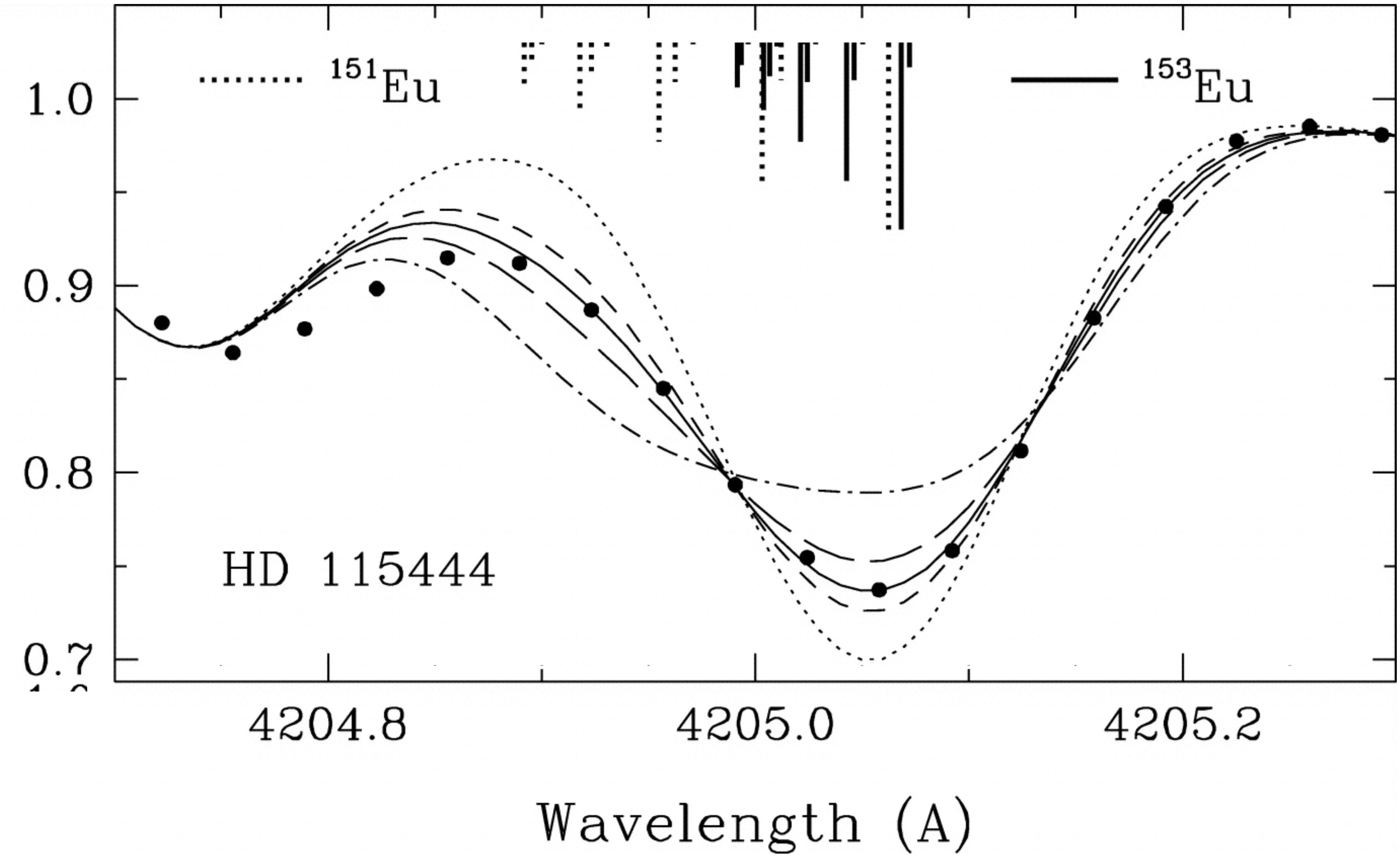




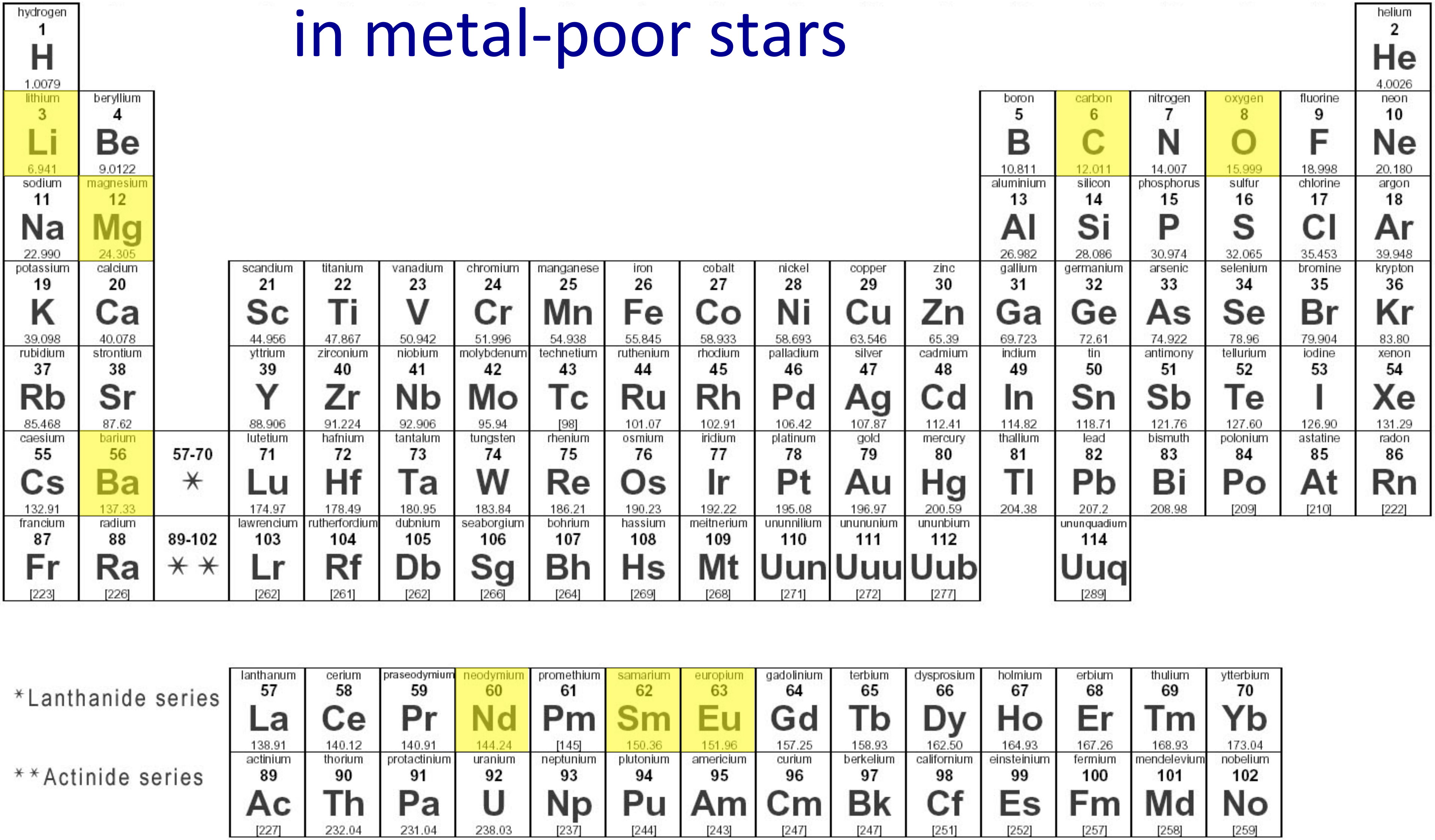
Montes et al. (2007, ApJ 671, 1685)

Conclusion: the light (38 < Z < 47) and heavy (Z > 47) neutron-capture elements were produced in two different nucleosynthesis processes.

Europium isotopic ratio



Isotopic ratios measured in metal-poor stars



hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
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*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
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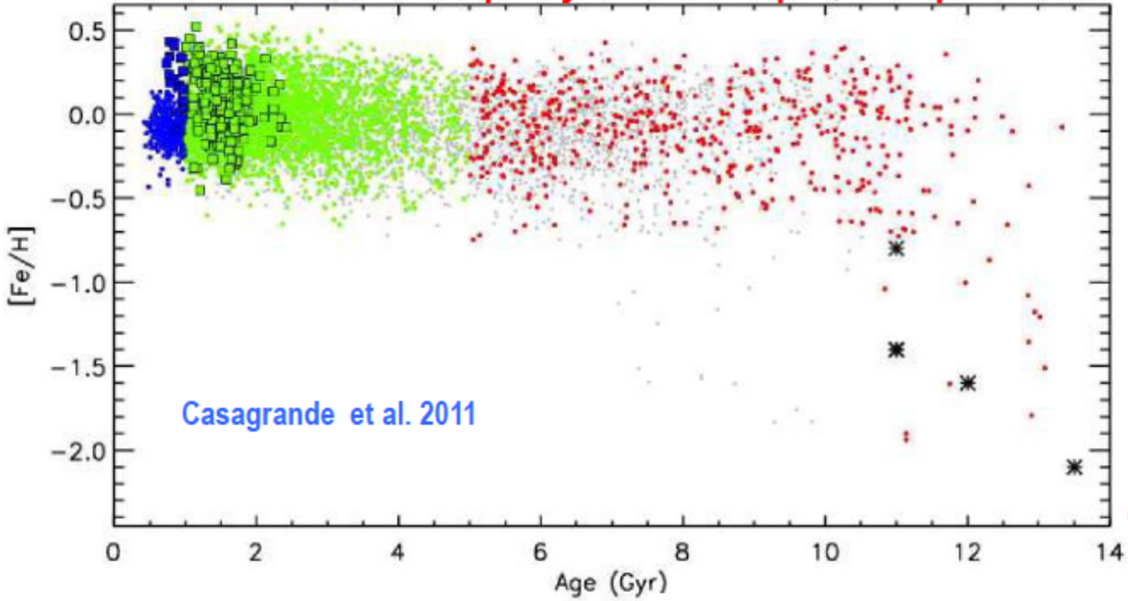
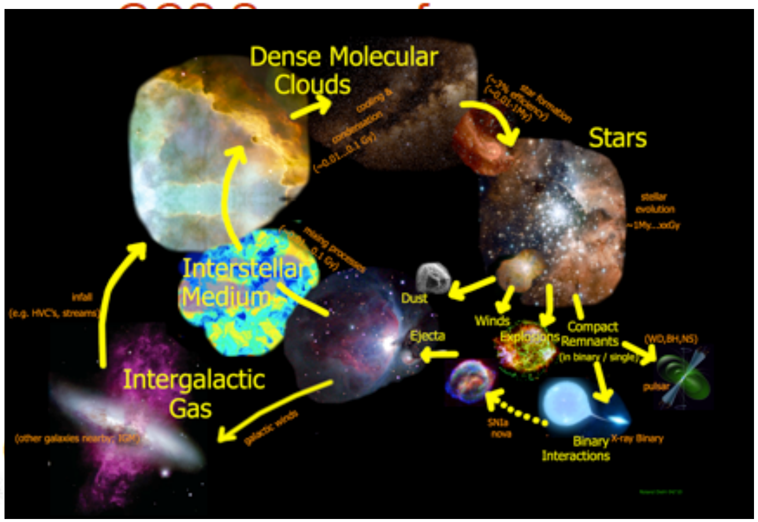
Compositional Evolution – a Challenge

Inadequacy of the simple, independent-ring models

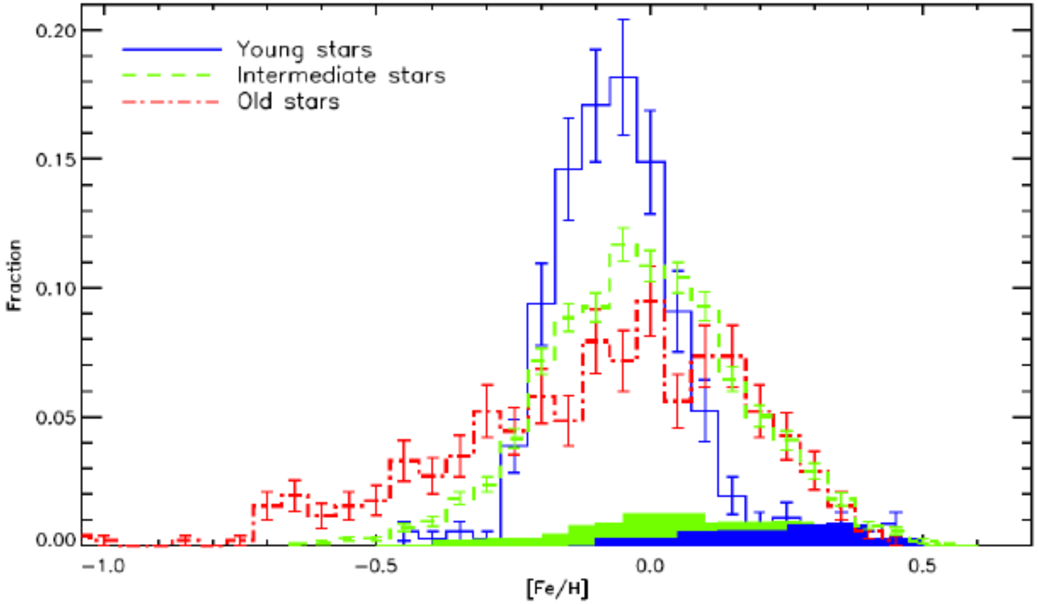


- *From Lecture Series at Universe Cluster by Nikos Prantzos, Nov'14*



Old stars of both *high* and *low* metallicities

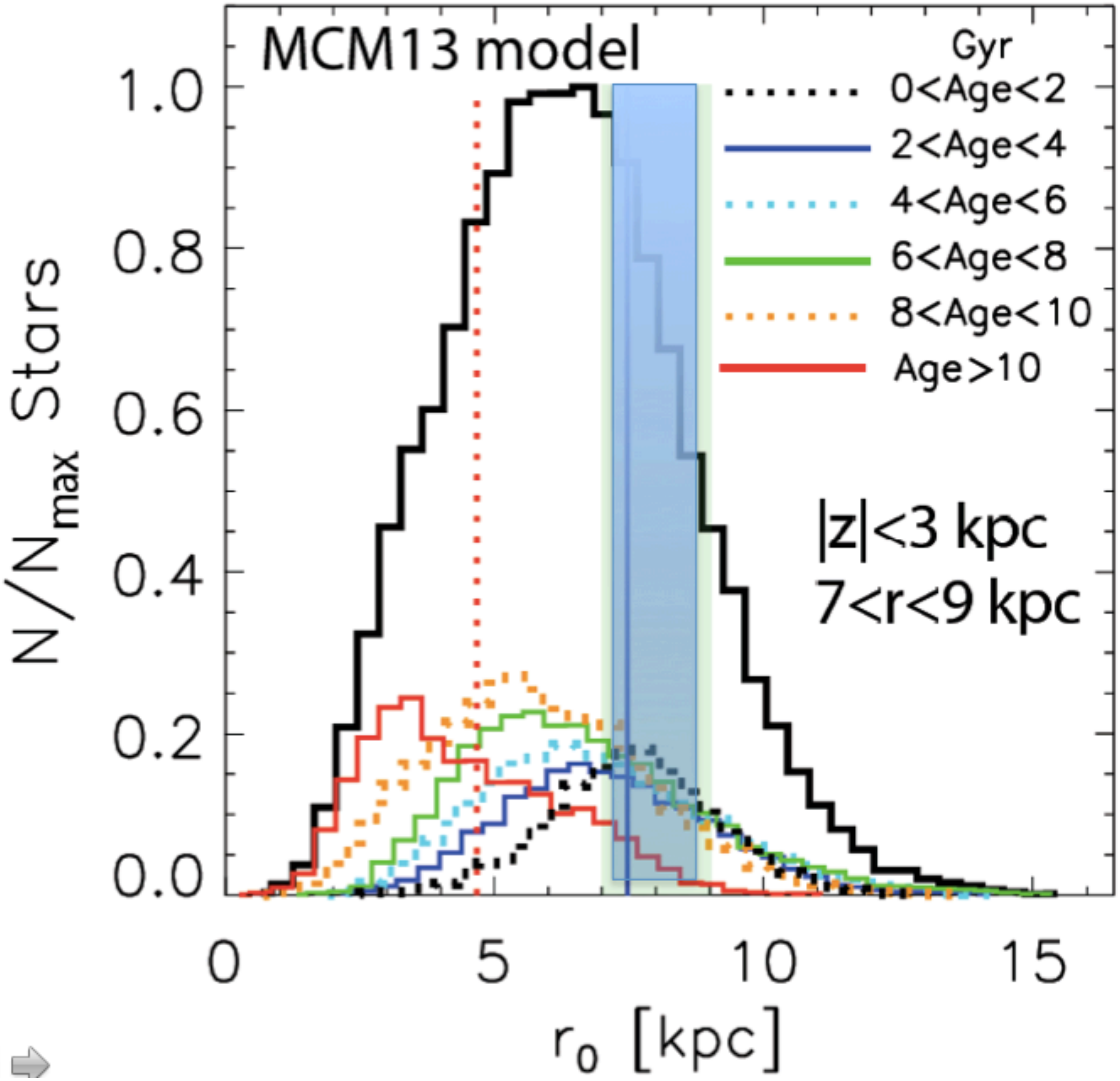
Inadequacy of the simple (independent ring) model (*Edvardsson et al. 1993, Haywood 2006*)



Chemodynamical Modeling: Radial Migration

Mosaic of stars born at different $R_{initial}$ at different times

- New Approach: Chemodynamical model of the MW (Minchev, Chiappini, Martig 2013, 2014)



r_0 = Birth Radii in kpc

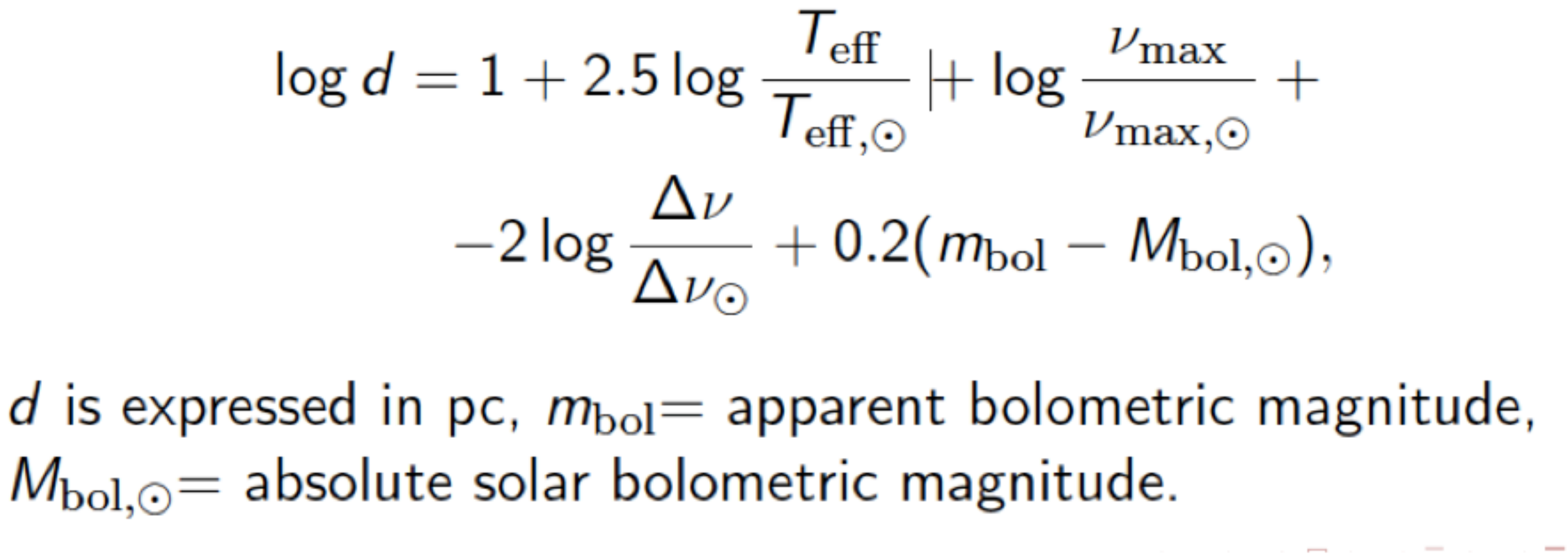
Input chemistry:
Thin disk only

Self-consistent dynamics:

N-body simulation in
cosmological framework:
early mergers,
gas infall,
bar,
spirals,
radial migration

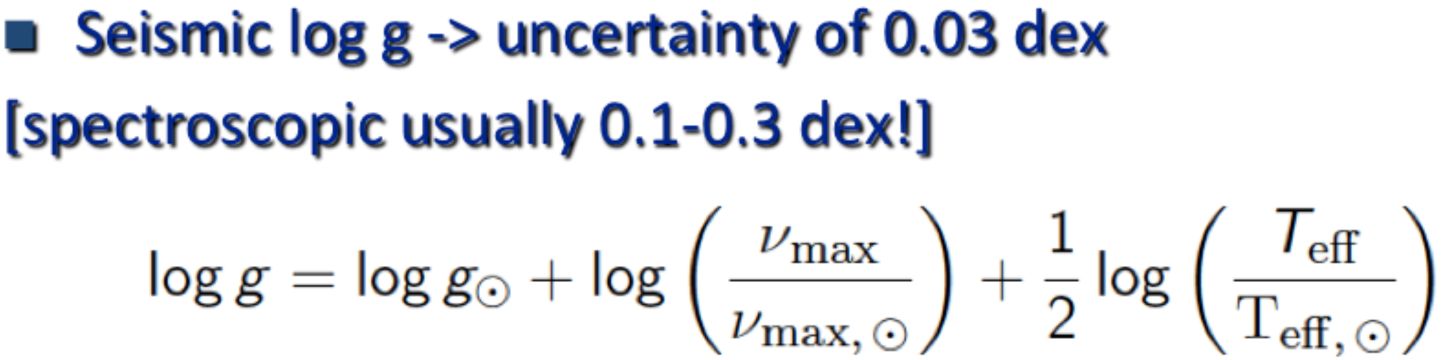
Help from Asteroseismology: Distances!

- Uncertainties in distances ~ 15 %; <5% for high quality data



$$\log d = 1 + 2.5 \log \frac{T_{\rm eff}}{T_{\rm eff,\odot}} | + \log \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} + -2 \log \frac{\Delta\nu}{\Delta\nu_\odot} + 0.2(m_{\rm bol} - M_{\rm bol,\odot}),$$

d is expressed in pc, $m_{\rm bol}$= apparent bolometric magnitude, $M_{\rm bol,\odot}$= absolute solar bolometric magnitude.



- **Seismic log g -> uncertainty of 0.03 dex**

[spectroscopic usually 0.1-0.3 dex!]

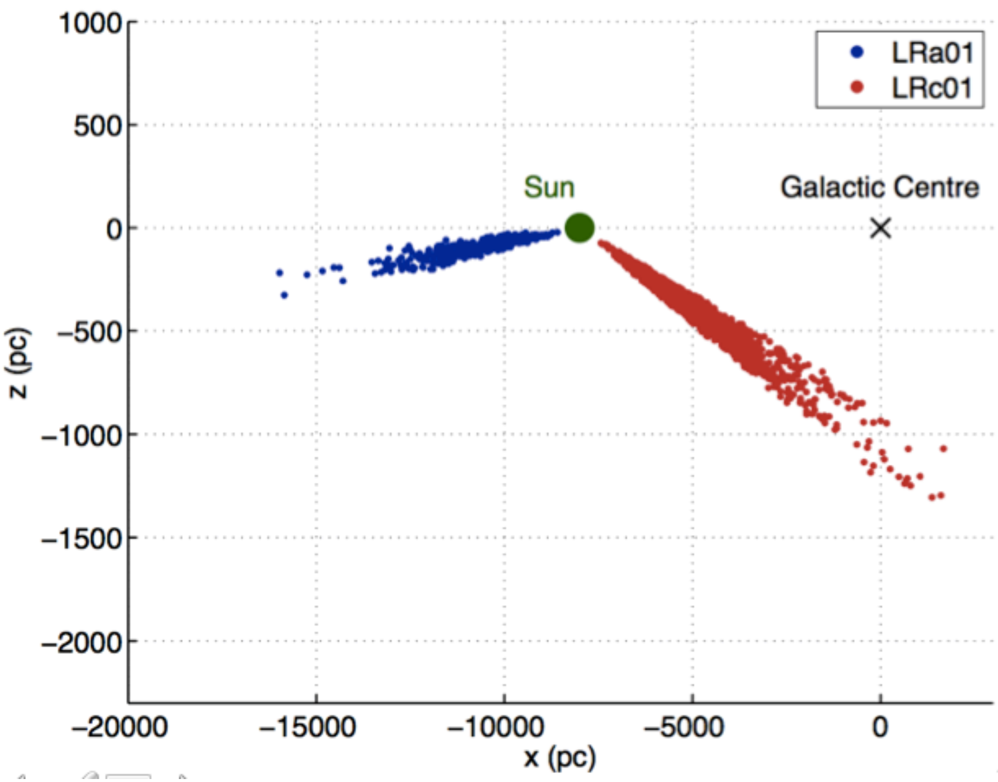
$$\log g = \log g_\odot + \log\left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) + \frac{1}{2}\log\left(\frac{T_{\rm eff}}{\mathrm{T}_{\rm eff,\odot}}\right)$$

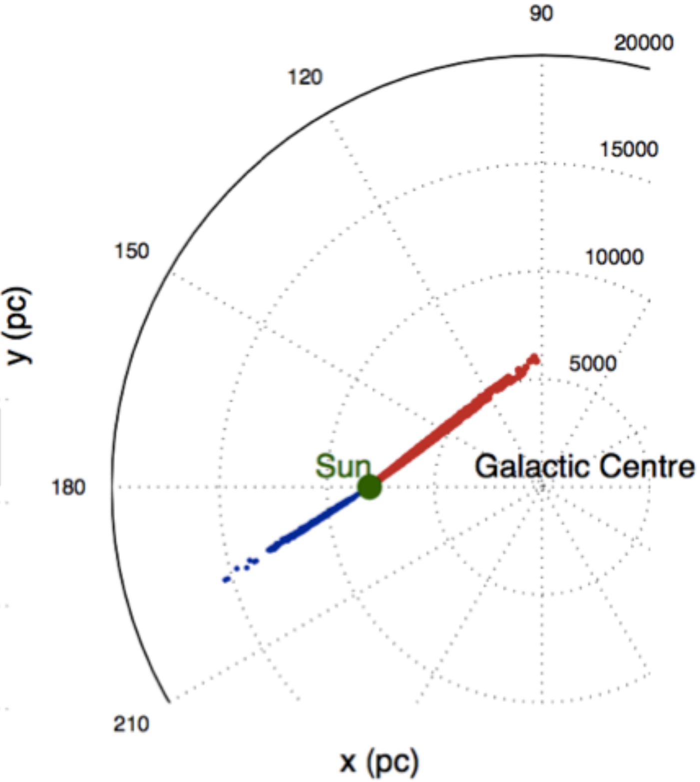
Help from Asteroseismology: Distances!

CoRoT

First use of asteroseismology to determine precise distances for a large (~2000) sample of field stars (giants) spread across nearly 15 kpc of the Galactic disc.

Different Mass Distributions -> Age vertical gradient





Miglio, Chiappini, Morel, Barbieri, Chaplin, Girardi, Montalban, Noels, Valentini, Mosser, Baudin, Casagrande, Fossati, Silva Aguirre & Baglin 2013, MNRAS 429, 423
[LRa01+Lrc01 analysis]

Molecular Gas: $^{13}C/^{12}C$

– Radiation from

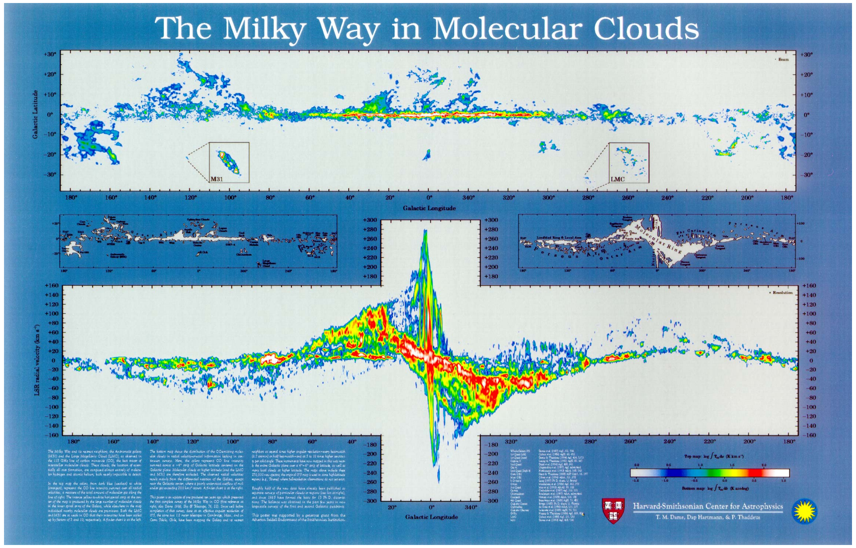
• Electronic Transitions	~2 eV	optical
• Vibrational Transitions	~0.2 eV	NIR
• Rotational Transitions	10^{-16} eV	Radio

– Optical Depth (from dust absorption)

$$\tau_{radio} << \tau_{optical}$$

- Mostly Radio Measurements

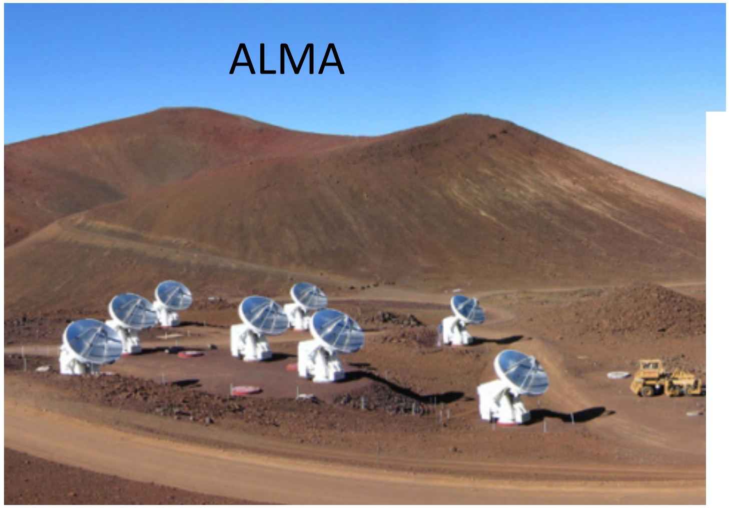
$$\nu = \frac{j\hbar}{2\pi\mu r_0^2}$$



e.g.: ^{12}CO

m=6.859 amu, r_o=1.128 10^{-8} cm ,
rotational transitions =>
j=1->j=0: 115 GHz 2.61 mm
230 1.3
345 0.87
equidistant levels

Sub-mm



Ar isotope

ratio measurements

In star forming regions

Schilke+2014

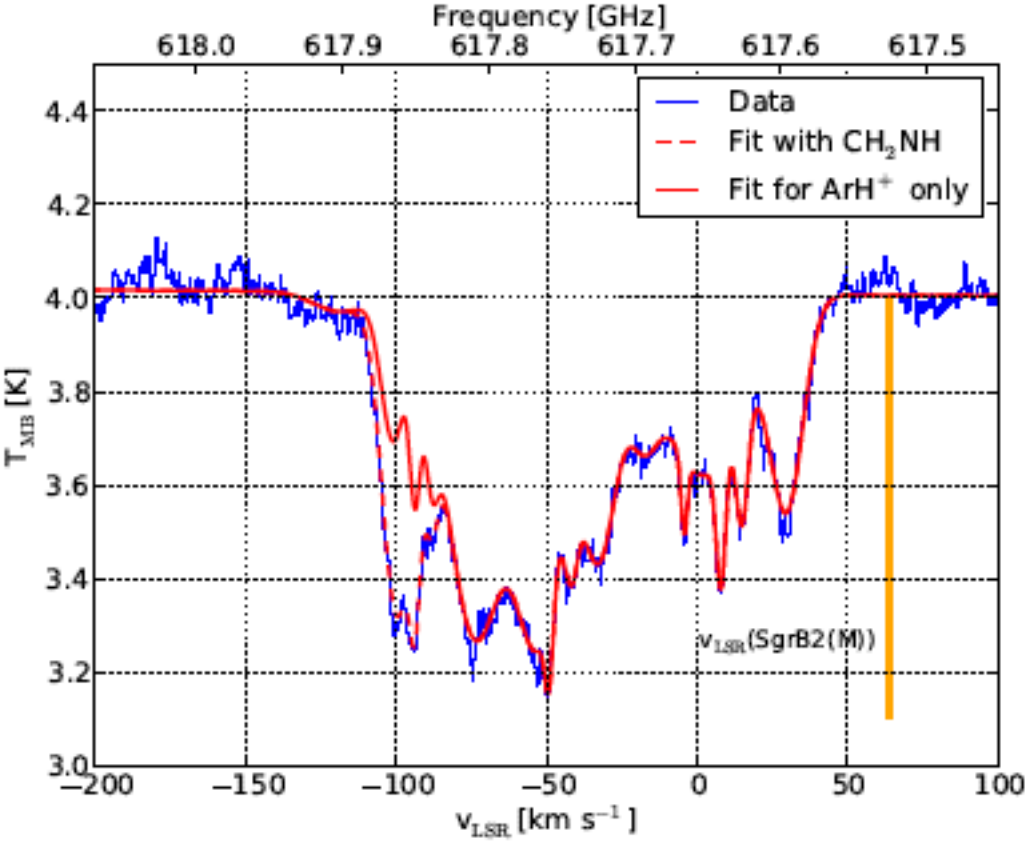


Fig. 1. Spectrum of ^{36}ArH$^+$(1–0) toward SgrB2(M), with fit including the H_2CNH line blending at –110 km s^{-1} (see Fig. 3) as a dashed red line, and fit of ^{36}ArH$^+$ only in red. Note the lack of absorption at the source velocity 64 km s^{-1}, indicated by the vertical orange marker.

X rays

- Type I X-ray bursts:
  - Nuclear ignition on the surface of a neutron star

Maahmodifar&Strohmeyer (2015)

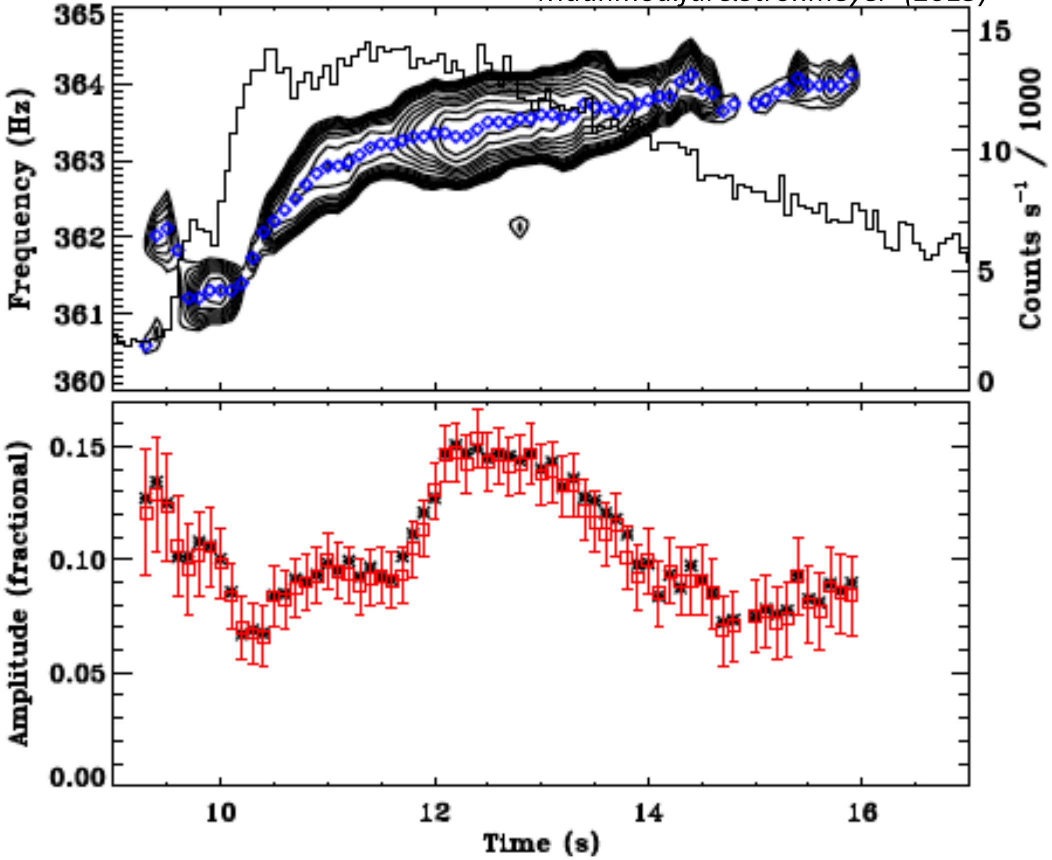
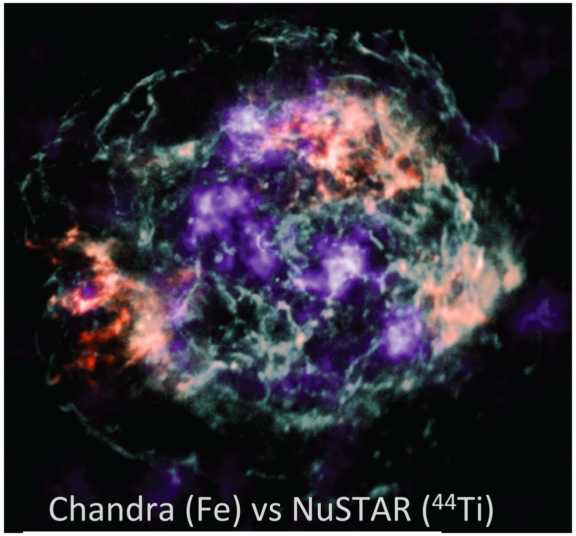


FIG. 1.— Dynamic power spectrum overplotted on the PCA light curve (top) for the Sept. 20, 1997 burst from 4U 1728-34, and the fractional amplitude of oscillations during the burst (bottom).

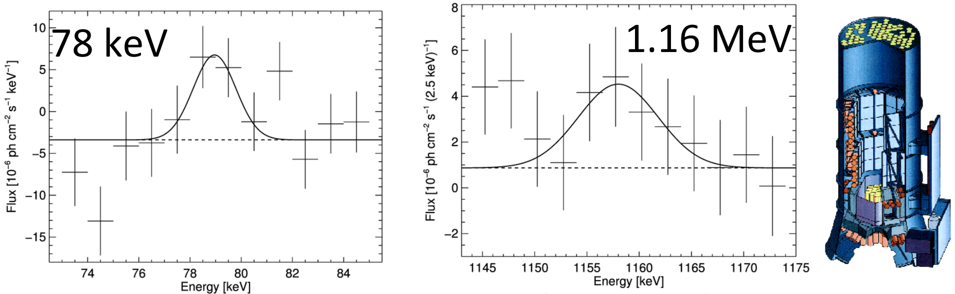
Flame propagation
on the
neutron star surface
→ characteristic oscillations

rp process network

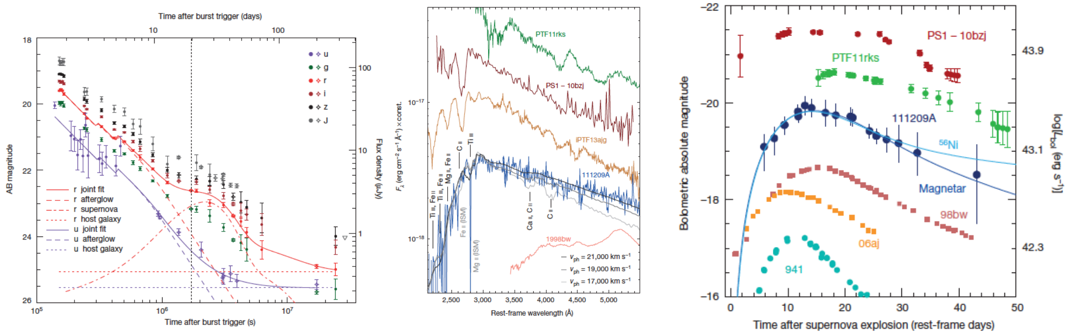
Core collapse supernova variety


Chandra (Fe) vs NuSTAR (^{44}Ti)

- Inner Ejecta: ^{44}Ti lines from Cas A
  - First mapping of radioactivity at 68,78 keV in a SNR ever
    - ^{44}Ti Image differs from Fe!!
  - Spectroscopy of X- and gamma-ray lines
    - Consistent Doppler broadening
    - Hint for particle acceleration
- GRBs and ccSNe:
  - Ultralong GRB, featureless SN spectrum
  - a magnetar energy source (rather than ^{56}Ni)



Siegert et al. (A&A 2015)

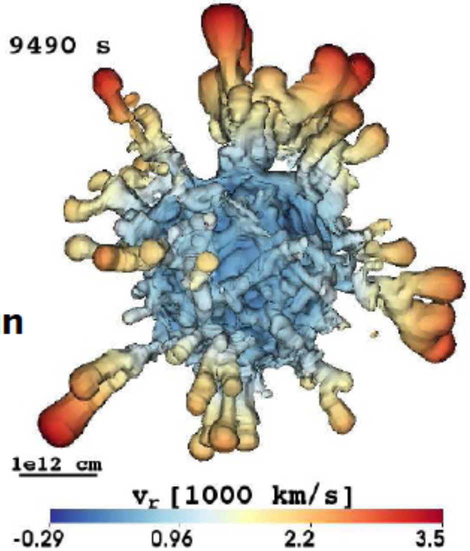


Greiner et al. (Nat 2015)

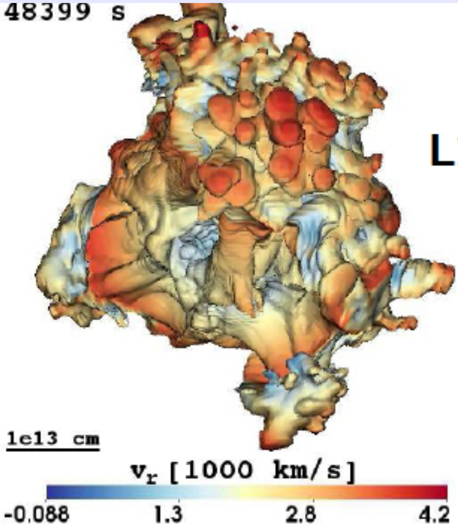
Core-collapse explosions

- Mixing instabilities in 3D SN models: → asphericities

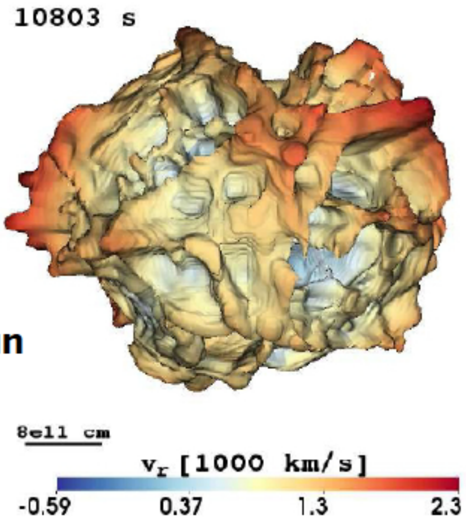
Wongwathanarat, Müller & Janka '15



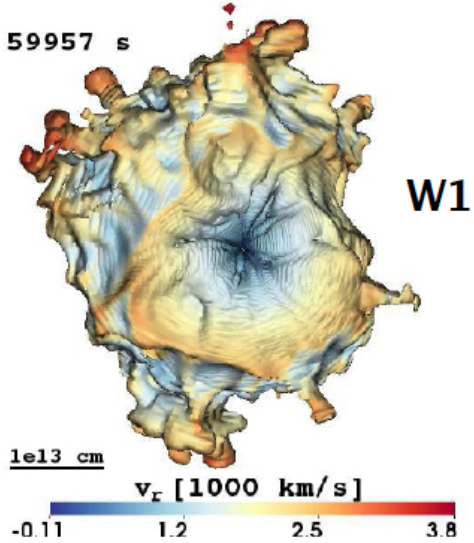
B15: 15 M_{sun}



L15: 15 M_{sun}



N20: 20 M_{sun}



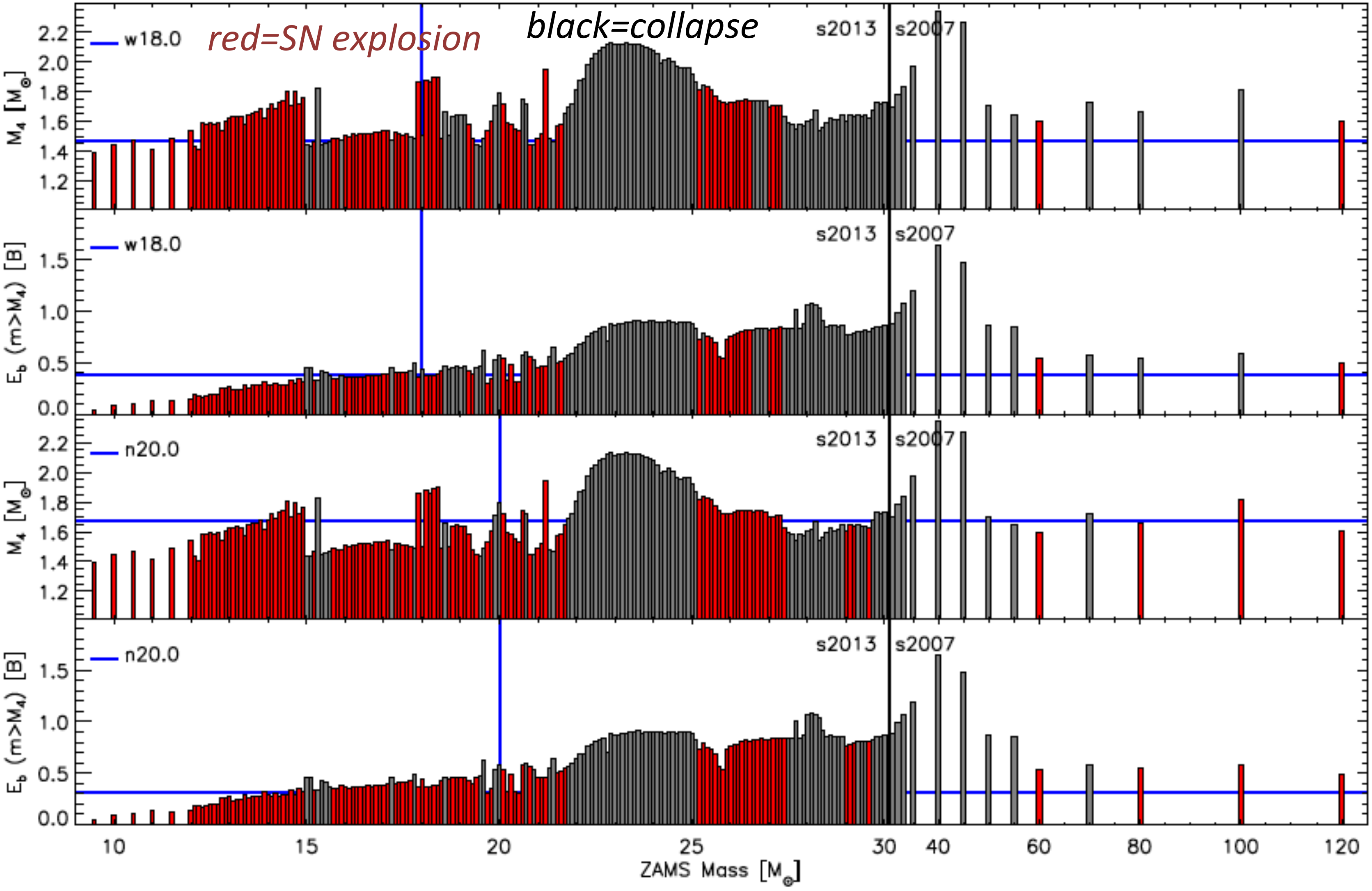
W15: 15 M_{sun}

  - Cover time from bounce +15msec to ~4 days in one simulation

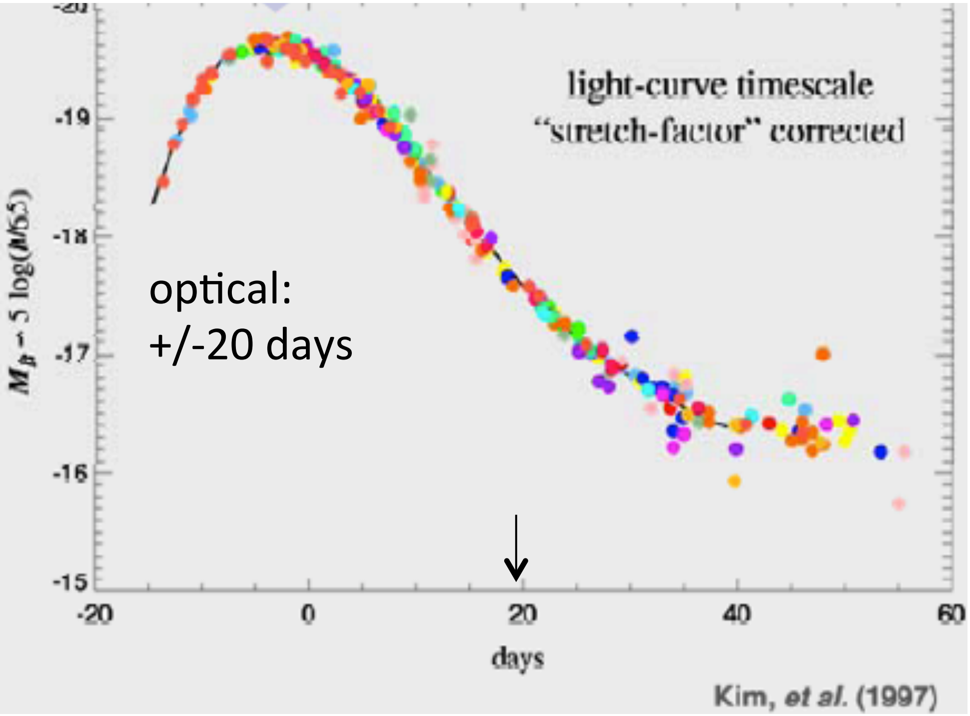
Systematics across mass range

- “Explodability” : understanding systematics

Ertl+ 2015; Sukhbold+2015

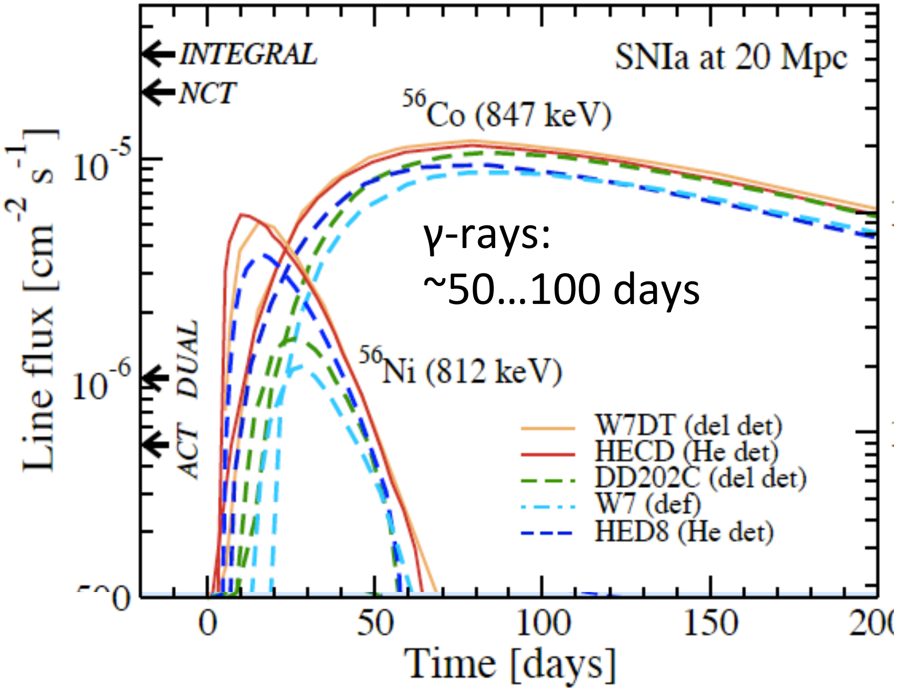


SNIa Light: Radioactivity → Optical Emission



optical:
+/-20 days

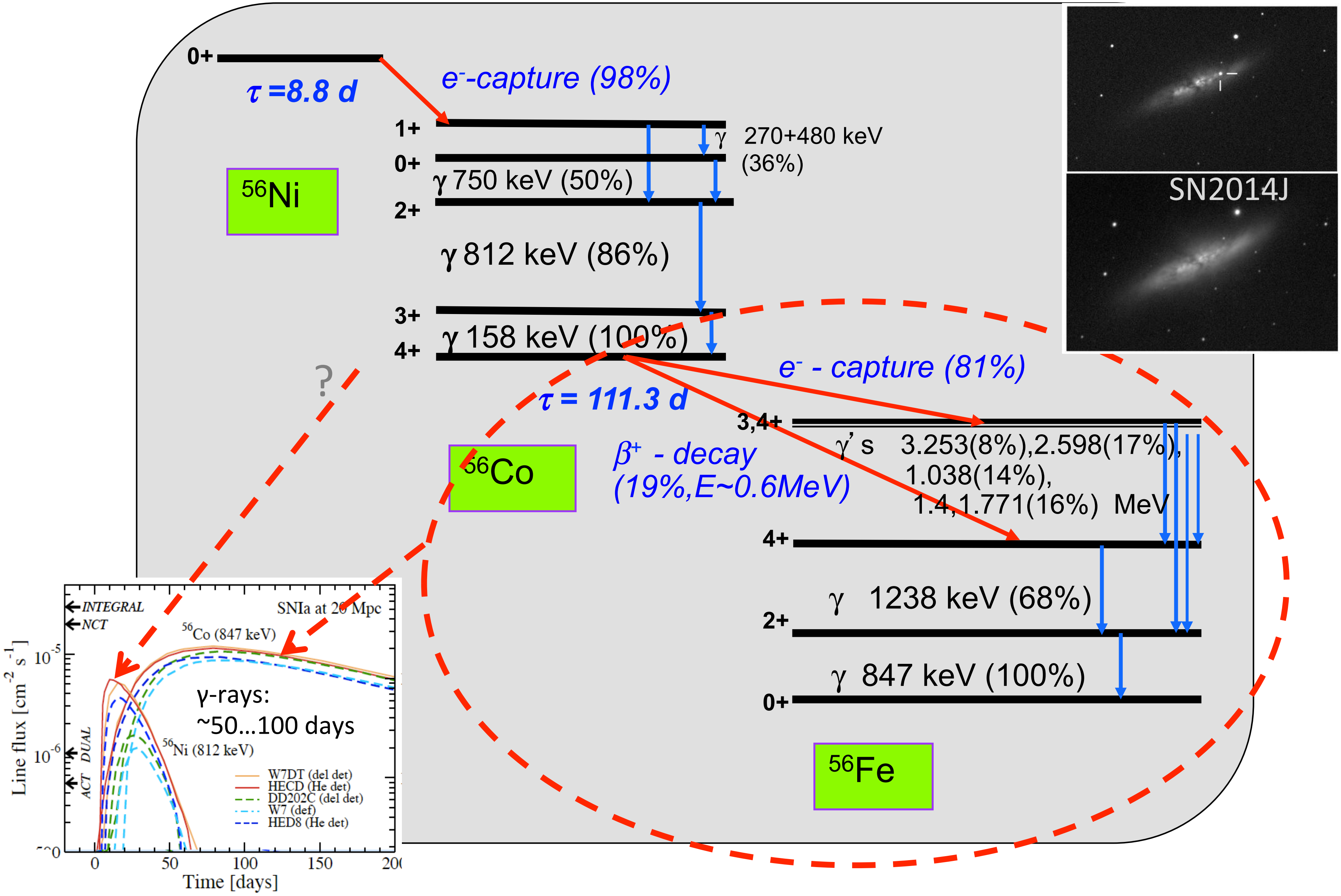
Kim, *et al.* (1997)



γ-rays:
~50...100 days

- ^{56}Ni decay gamma-rays and e^+ are initially fully absorbed (→ light), and leak out later

^{56}Ni Decay Chain and Gamma-Rays



0+

τ =8.8 d

e^--capture (98%)

1+

0+

2+

γ 270+480 keV (36%)

γ 750 keV (50%)

γ 812 keV (86%)

3+

4+

γ 158 keV (100%)

^{56}Ni

?

τ = 111.3 d

^{56}Co

e^- - capture (81%)

β^+ - decay (19%,E~0.6MeV)

3,4+

γ' s 3.253(8%),2.598(17%), 1.038(14%), 1.4,1.771(16%) MeV

4+

γ 1238 keV (68%)

2+

γ 847 keV (100%)

0+

^{56}Fe

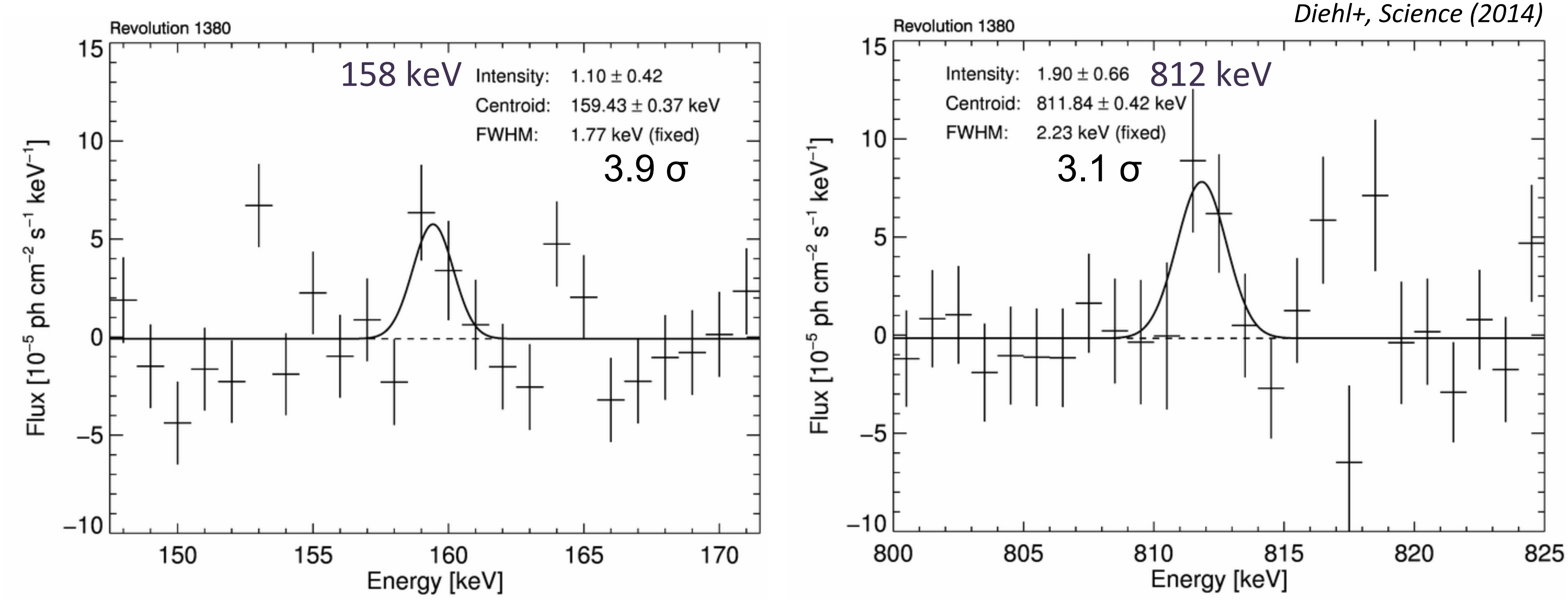
SN2014J

γ-rays: ~50...100 days

SN2014J: Early ^{56}Ni

- Spectra from the SN position
  - Detections of the two strongest lines expected from ^{56}Ni with the INTEGRAL Spectrometer 'SPI'

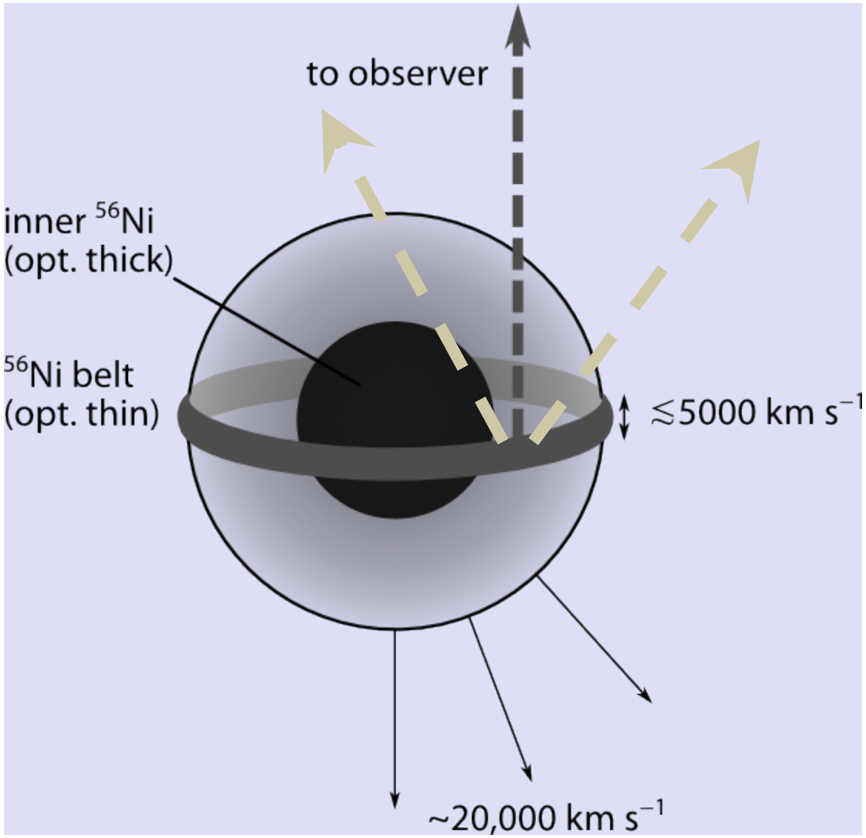
Diehl+, Science (2014)



  - ^{56}Ni mass estimate (backscaled to explosion): ~0.06 $M_\odot$

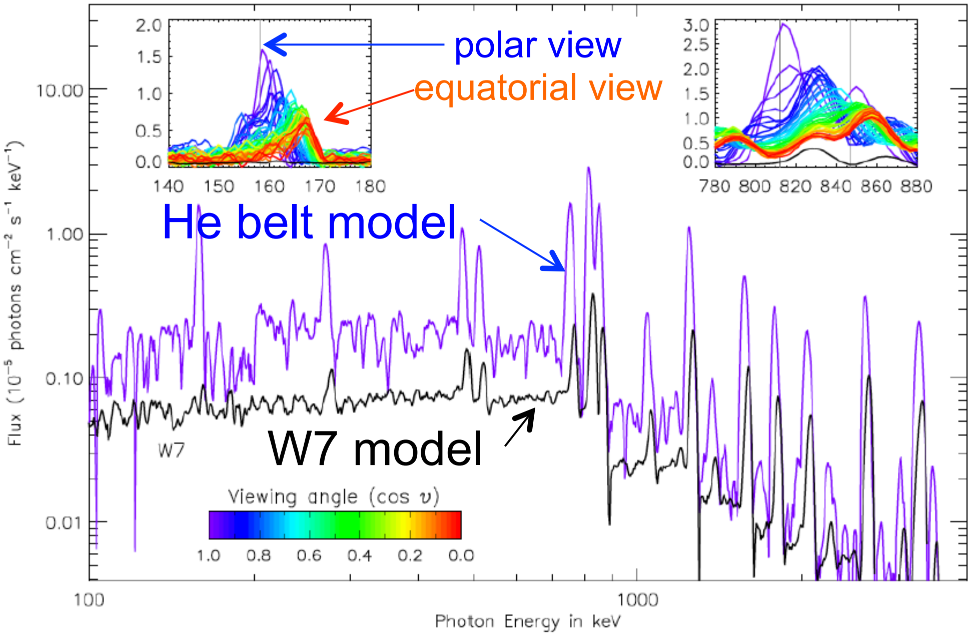
SN2014J: An unusual (triggered) explosion?

- A belt of He accreted from the companion star → He explosion, triggering the SNIa explosion of the CO white dwarf ($M<M_{ch}$)



Simulating how an exploding belt of accreted He would be observed in gamma-rays:
Polar viewing → unshifted lines
Equatorial viewing → blue shift

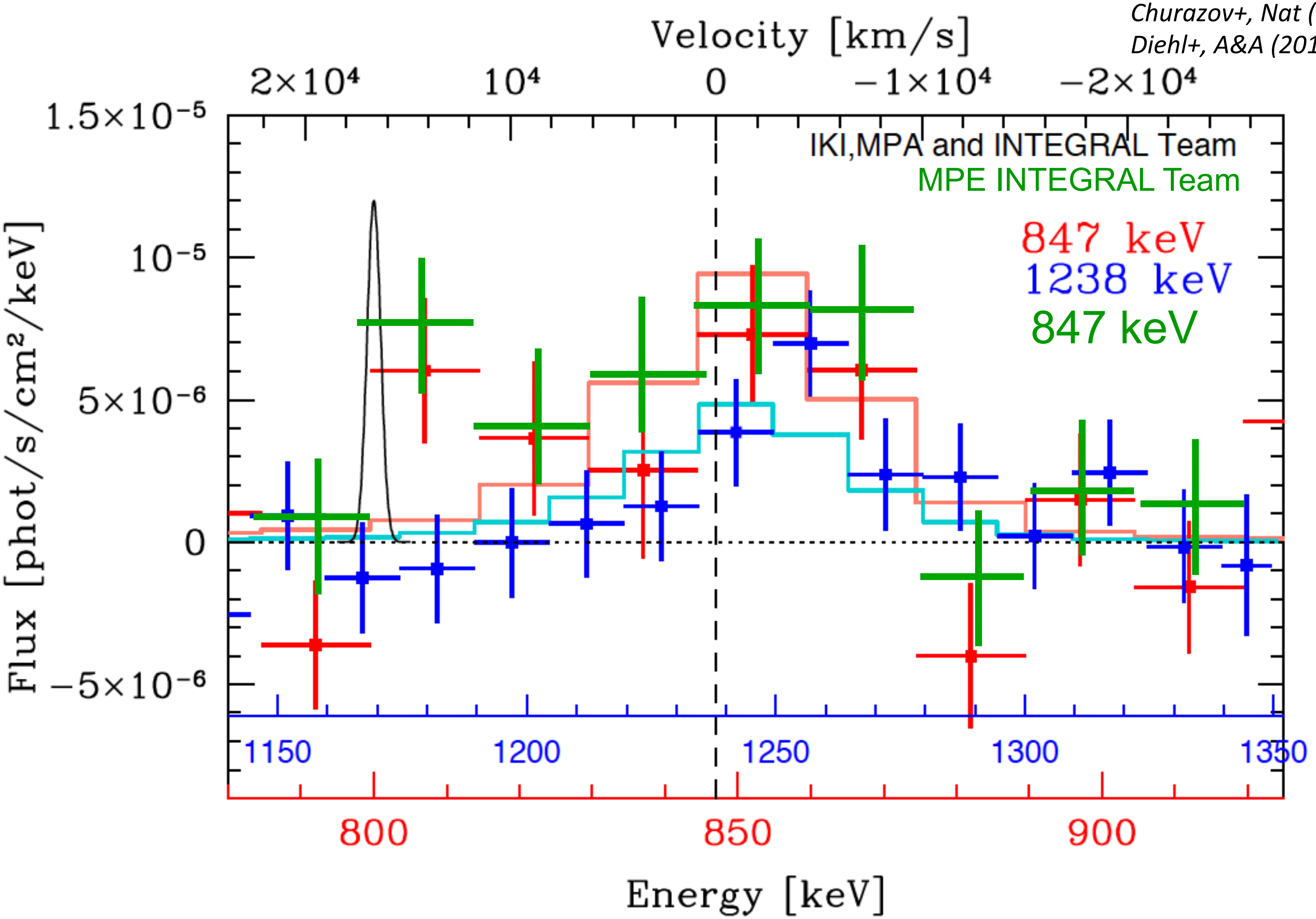
Markus Kromer



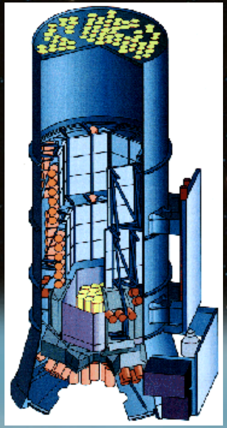
Longterm Data: Broad Lines from ^{56}Co!

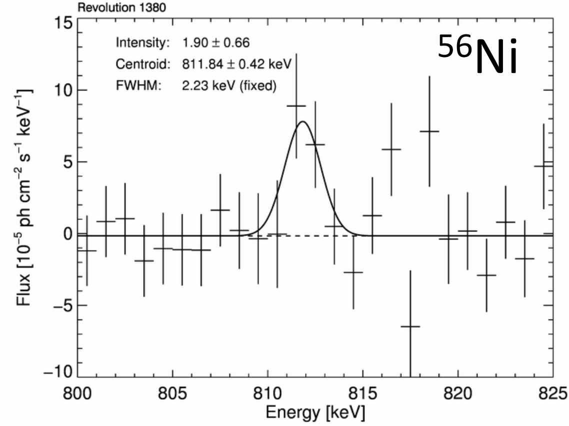
- INTEGRAL Obs from 31 Jan till 26 Jun 2014

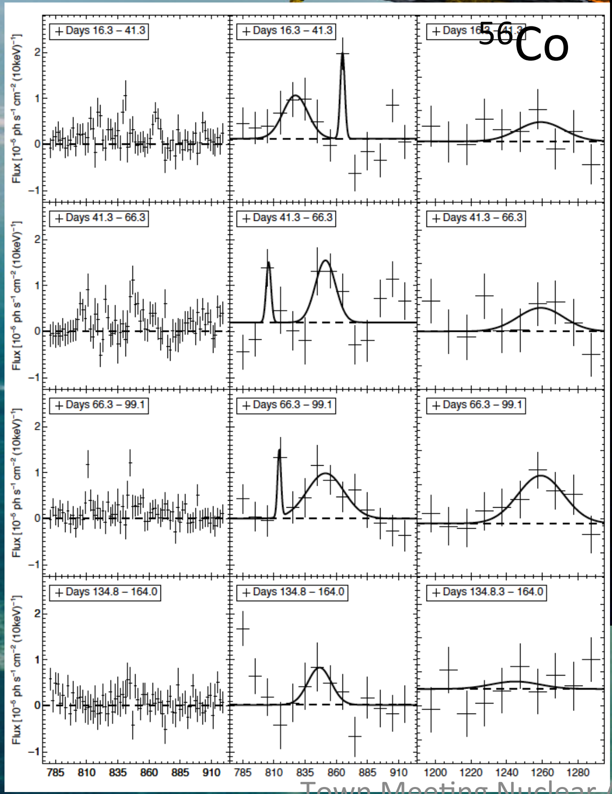
Churazov+, Nat (2014)
Diehl+, A&A (2015)

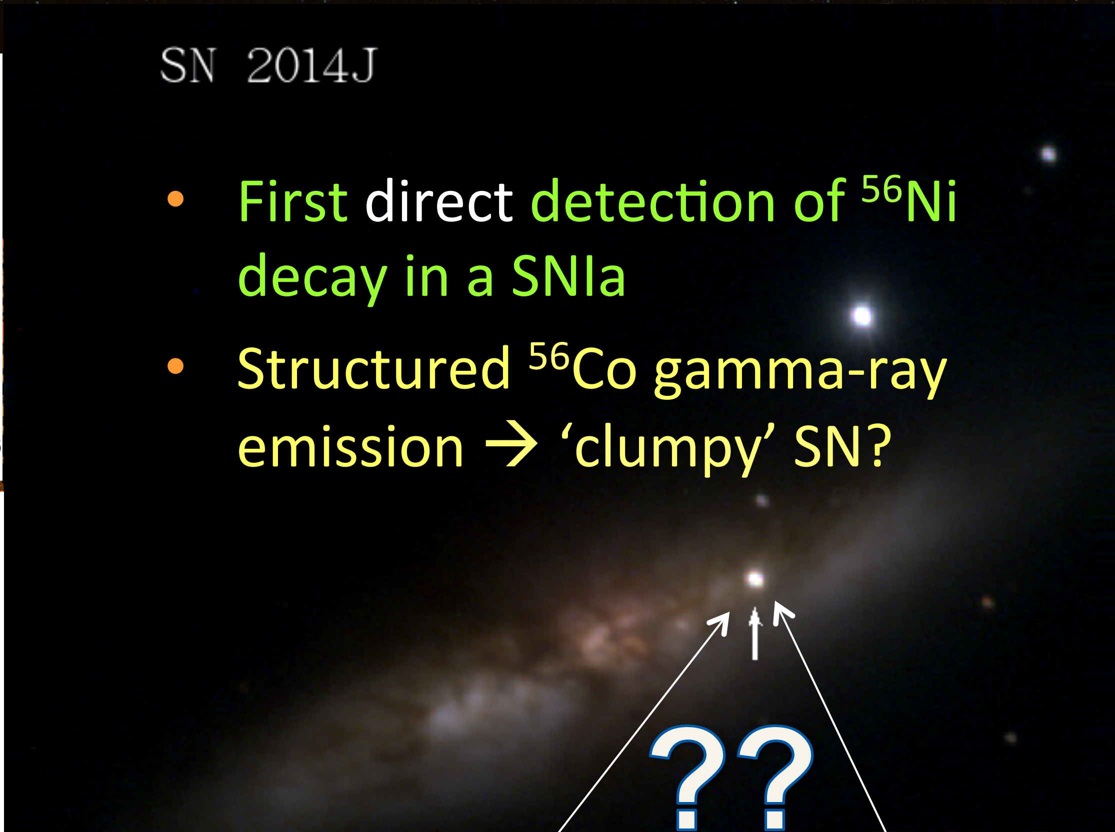


Gamma-Rays from a Supernova Ia: SN2014J

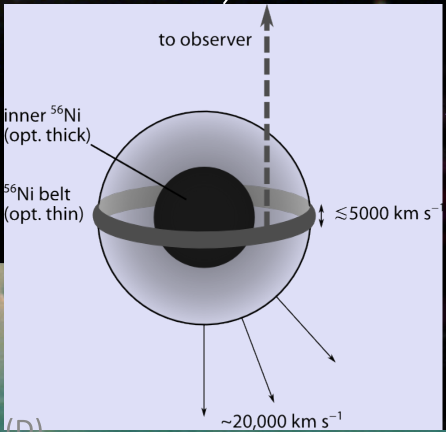


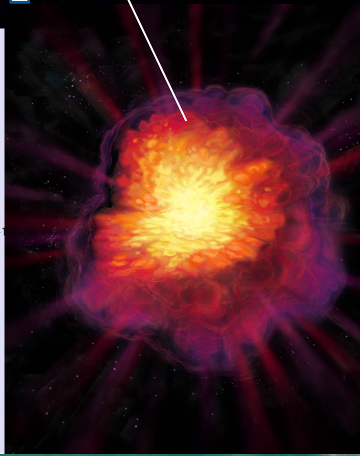




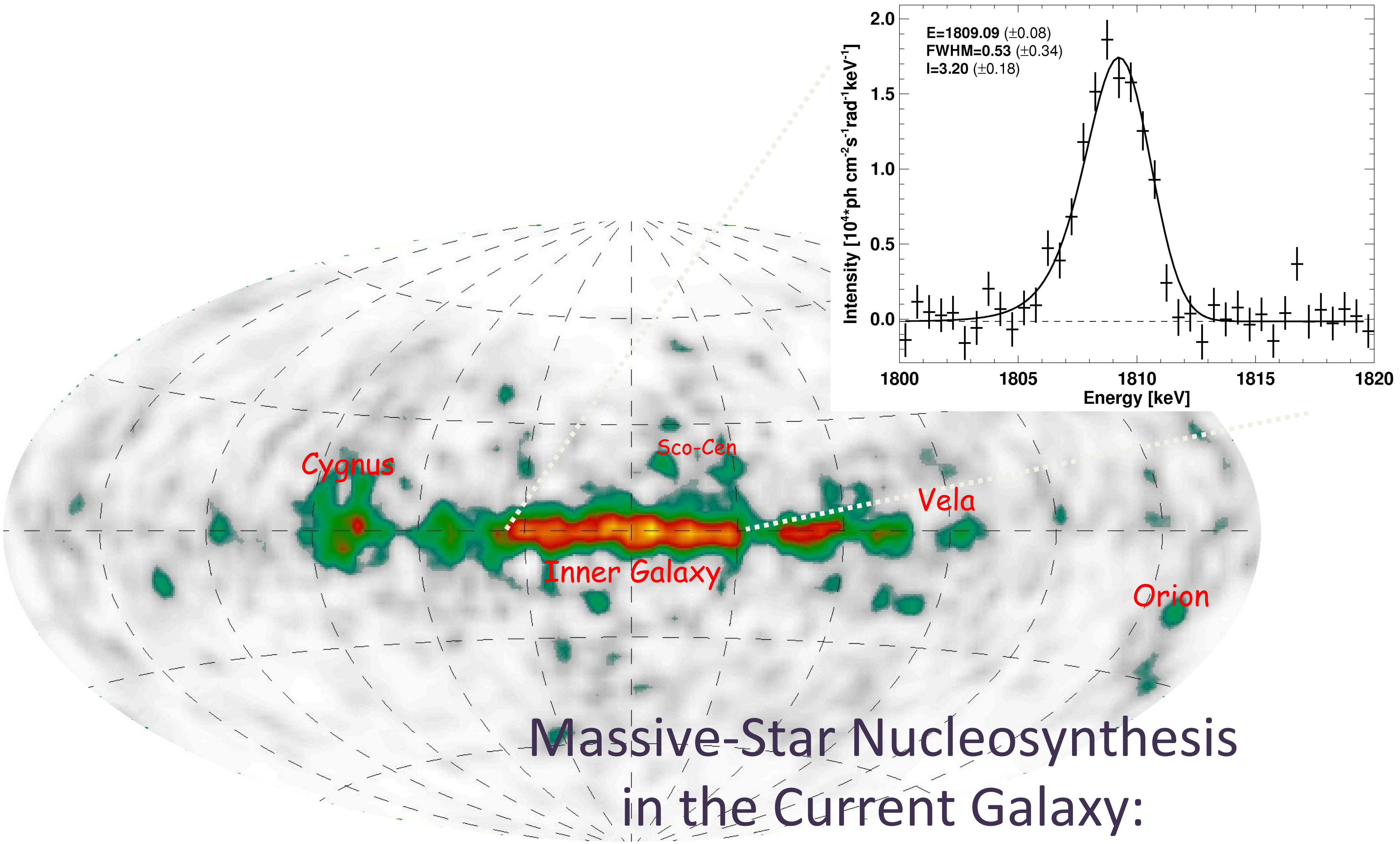


- First direct detection of ^{56}Ni decay in a SNIa
- Structured ^{56}Co gamma-ray emission → 'clumpy' SN?





^{26}Al in our Galaxy: γ-ray Image and Spectrum

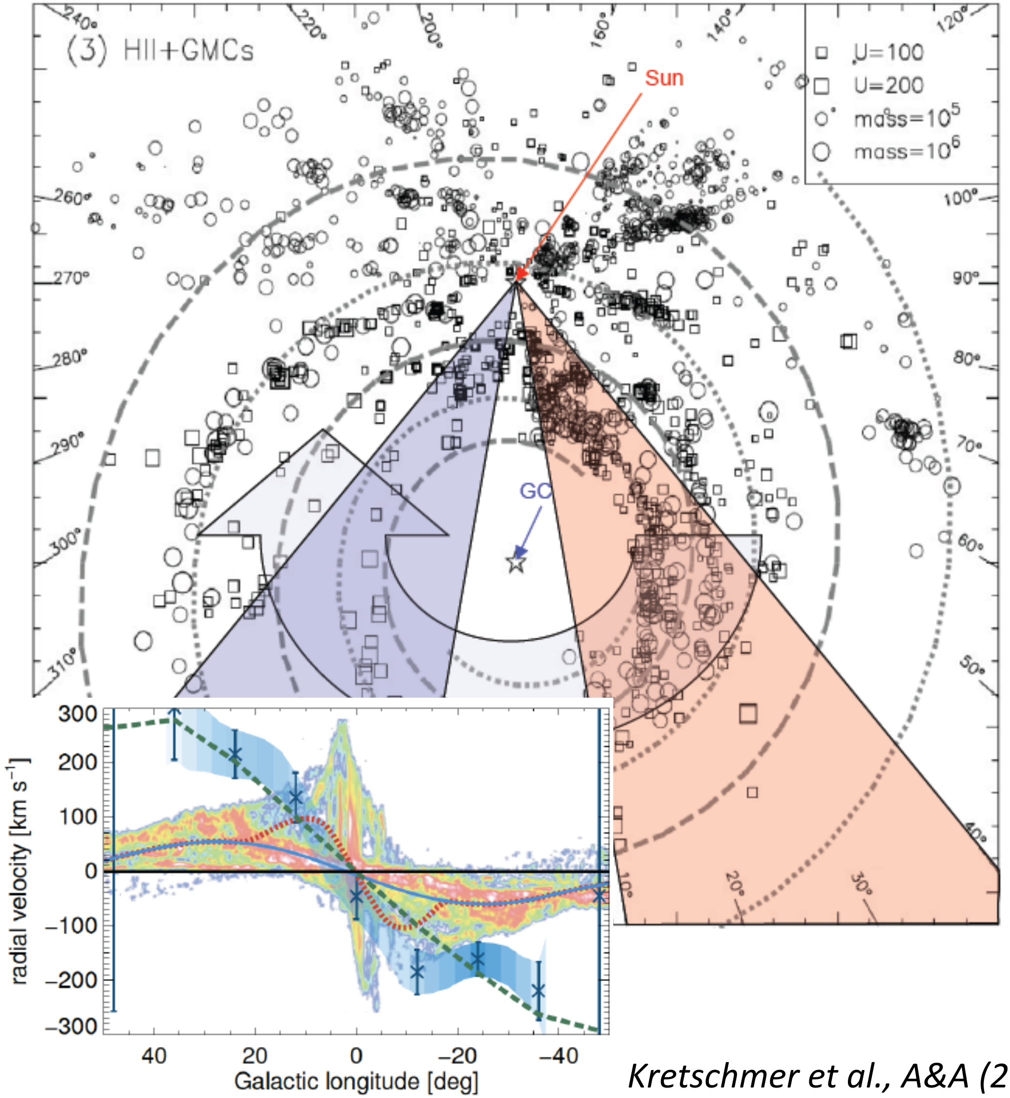


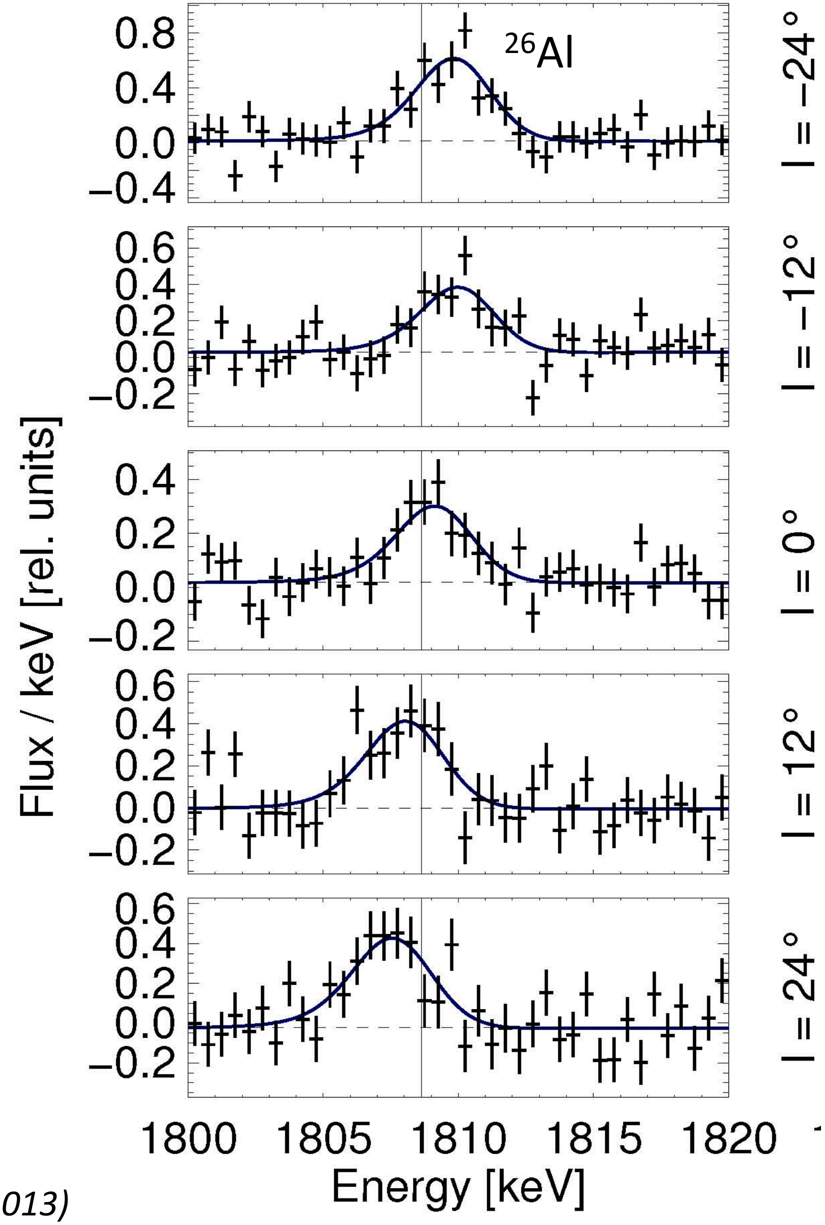
Massive-Star Nucleosynthesis
in the Current Galaxy:

Current Enrichment (~My) from ^{26}Al γ-rays

Ejecta Dynamics in our Galaxy: Superbubbles

- Large-scale velocity excess

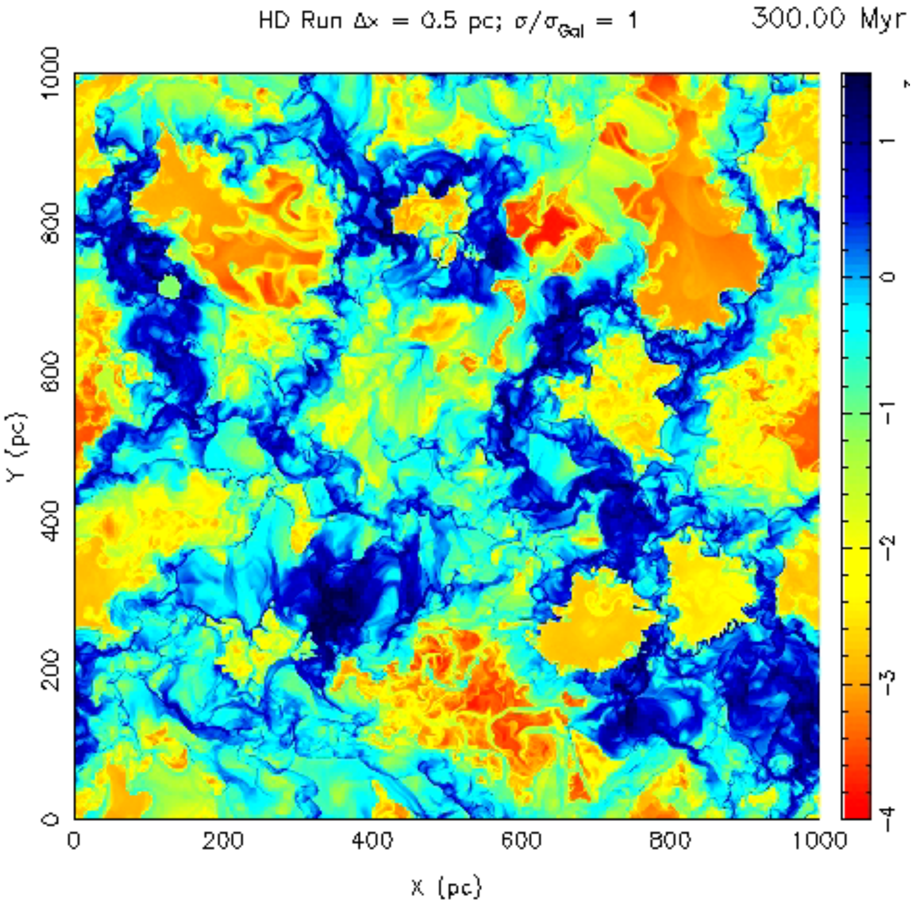


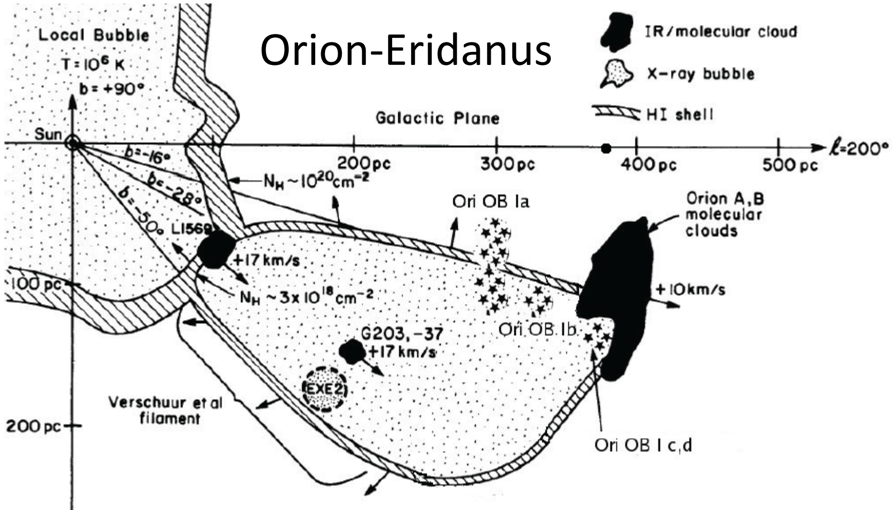


Kretschmer et al., A&A (2013)

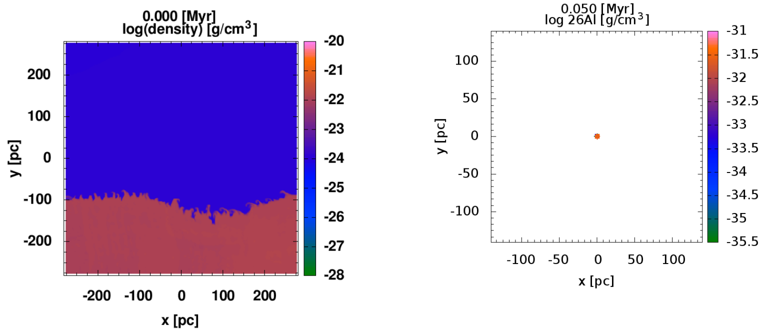
Dynamics of the Interstellar Medium

- ISM is Highly-Dynamic → Ejecta are traced by radioactivity γ-rays
  - Study Specific Regions in Detail (Cygnus, Orion, Scorpius-Centaurus, Carina)



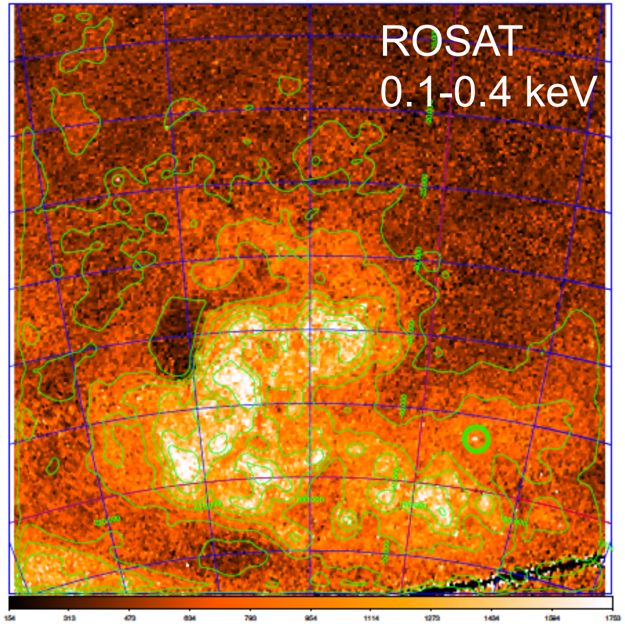


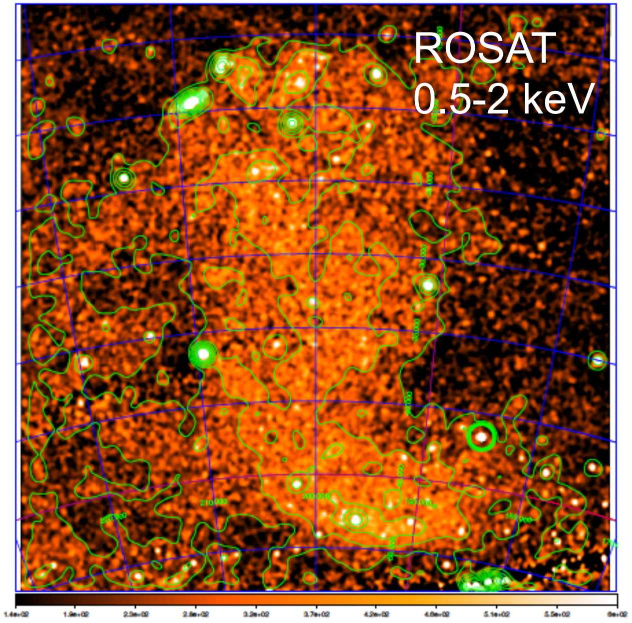
K. Fierlinger+, MNRAS (2015)

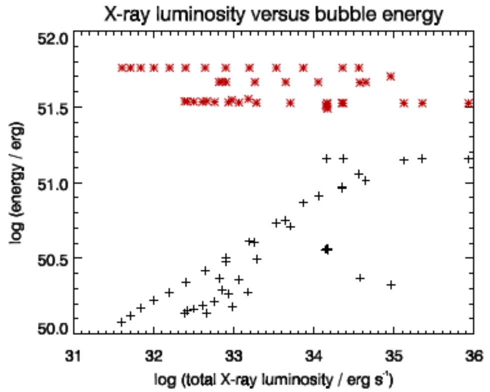


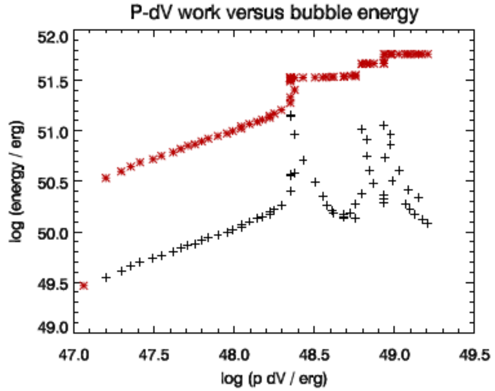
Understanding the Eridanus Superbubble

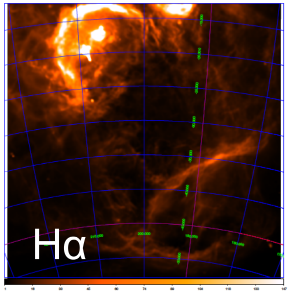
- X-ray Emission, size, ^{26}Al

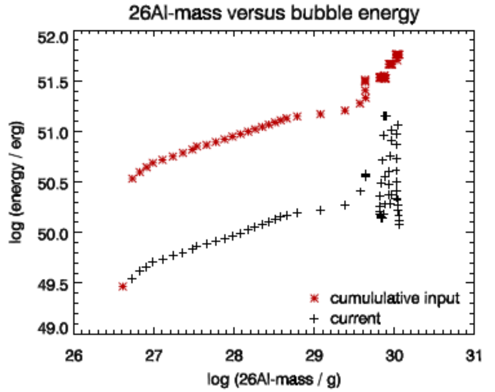










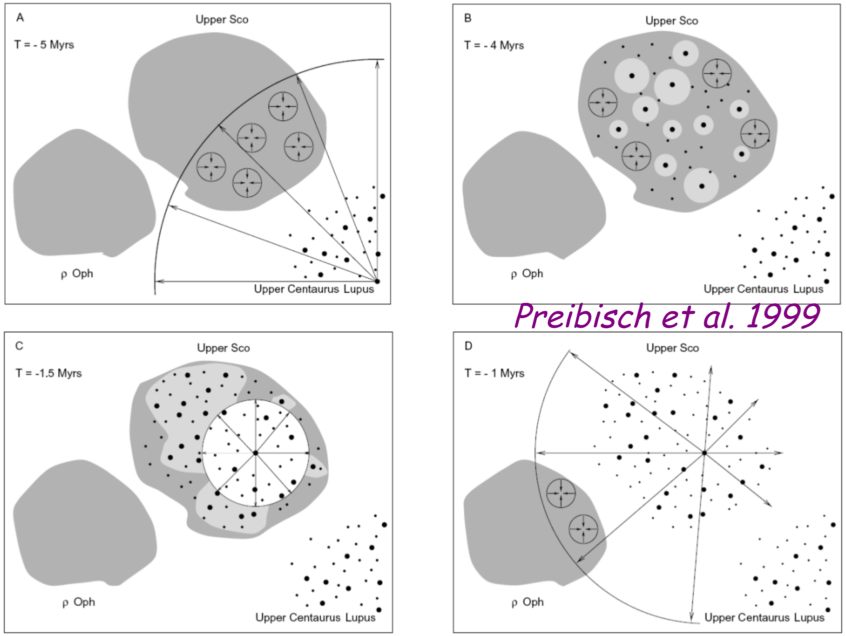


  - Temporal X-ray brightenings after SN energy injections
  - spatial oscillations of X brightness

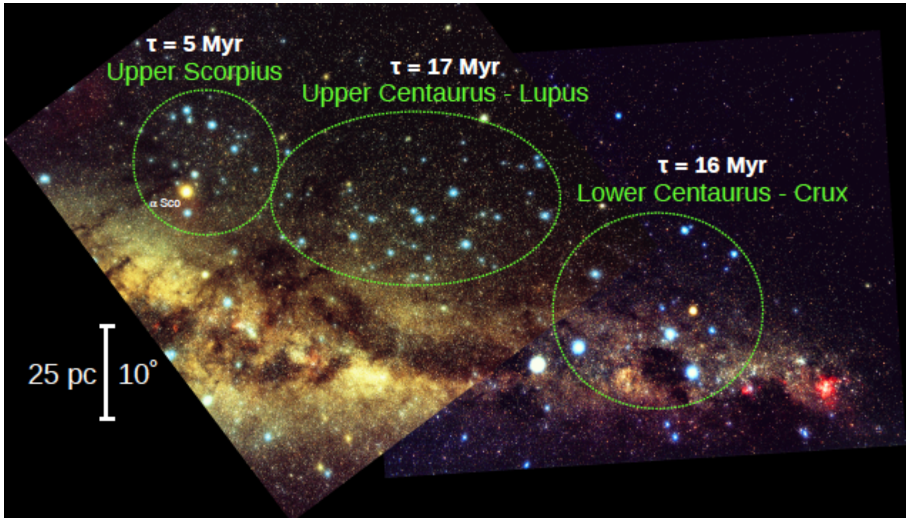
Krause+ 2014

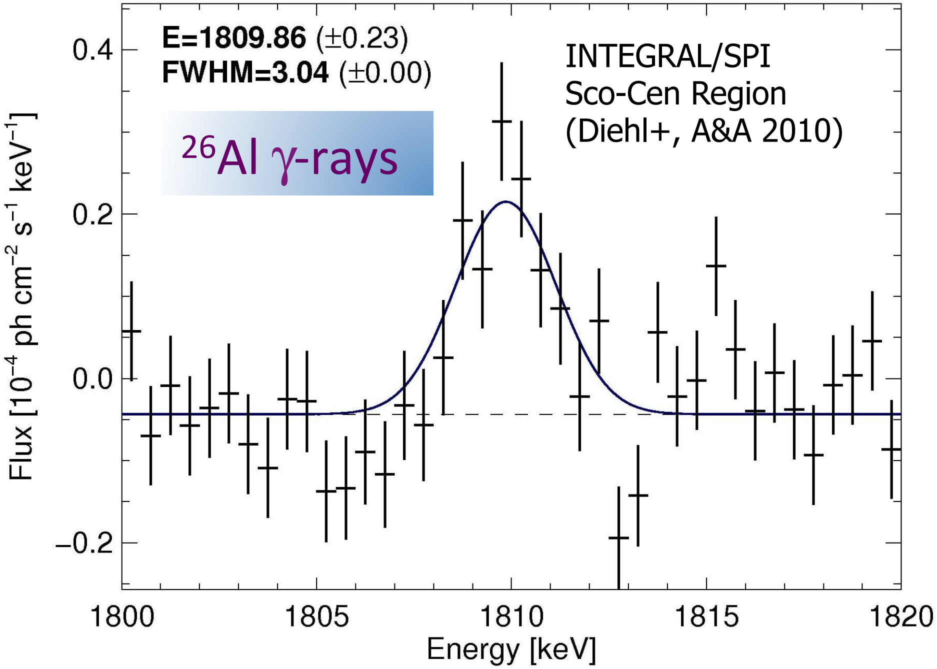
The Sco-Cen Association: Triggered Star Formation?

- Nearest OB Association (~120pc)
  - subgroups of ages 5, 16, 17 My
- Extended, Triggered Star Formation?



Preibisch et al. 1999



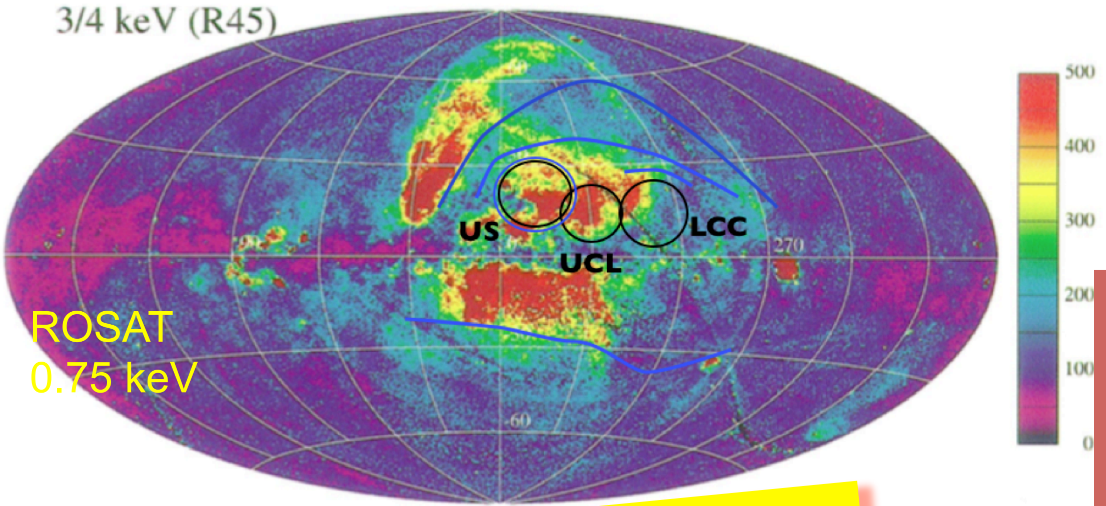


☆ **Compare Data with Population Synthesis**

R. Voss, RD, et al., 2009, 2010, 2011

- ☆ **Observed ^{26}Al Emission**
- ☆ **Stellar Groups Ages & Richness**
- ☆ **ISM Shell/Cavity Observables**

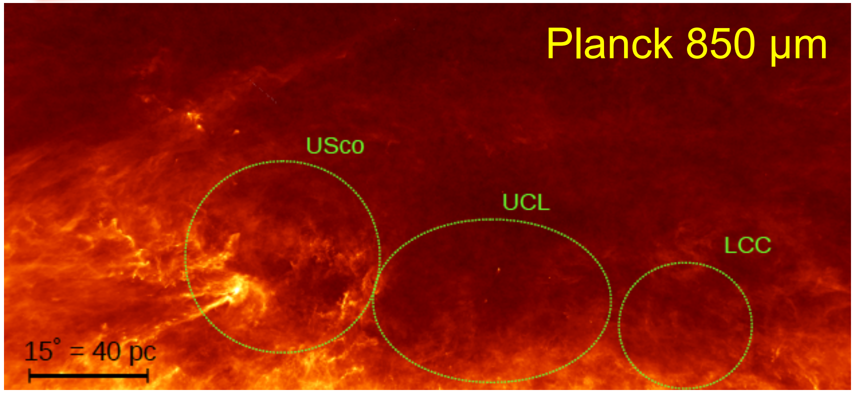
Scorpius-Centaurus Groups

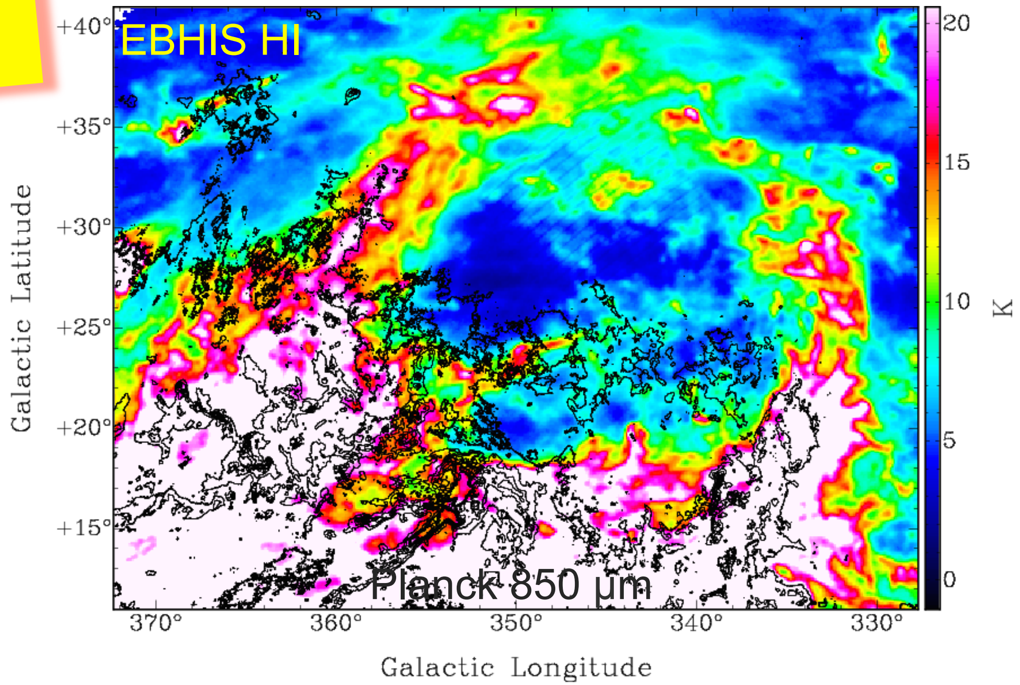


Studies at different wavelengths and observables…X-rays dust, HI

Using new ages, star counts, and the cluster-mass/most-massive-star relation →

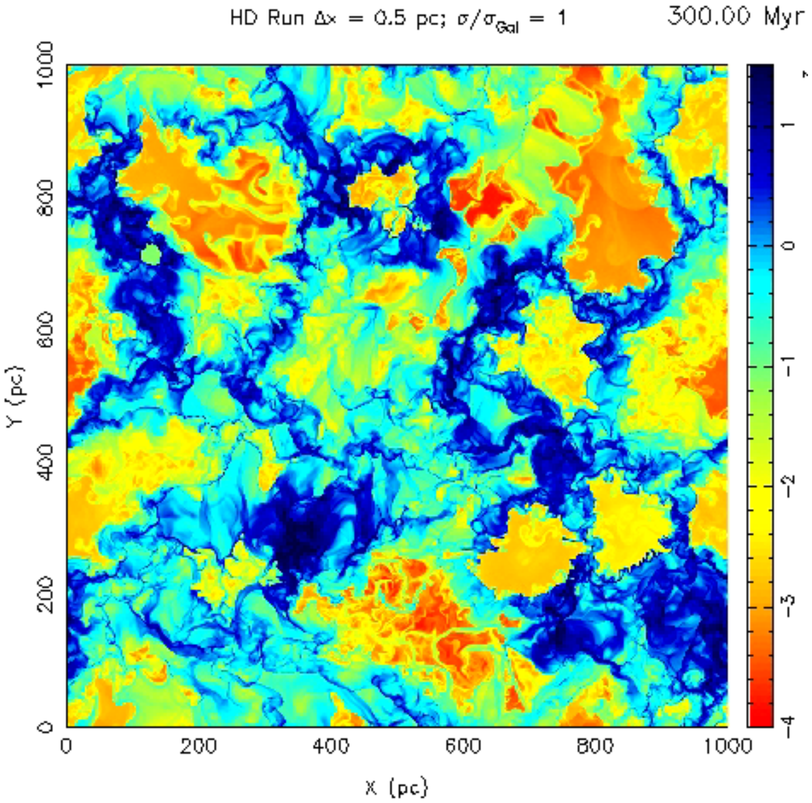
Illustration of multi-wavelength approach:
Need to model the ^{26}Al spatial distribution
In order to search for its gamma-rays

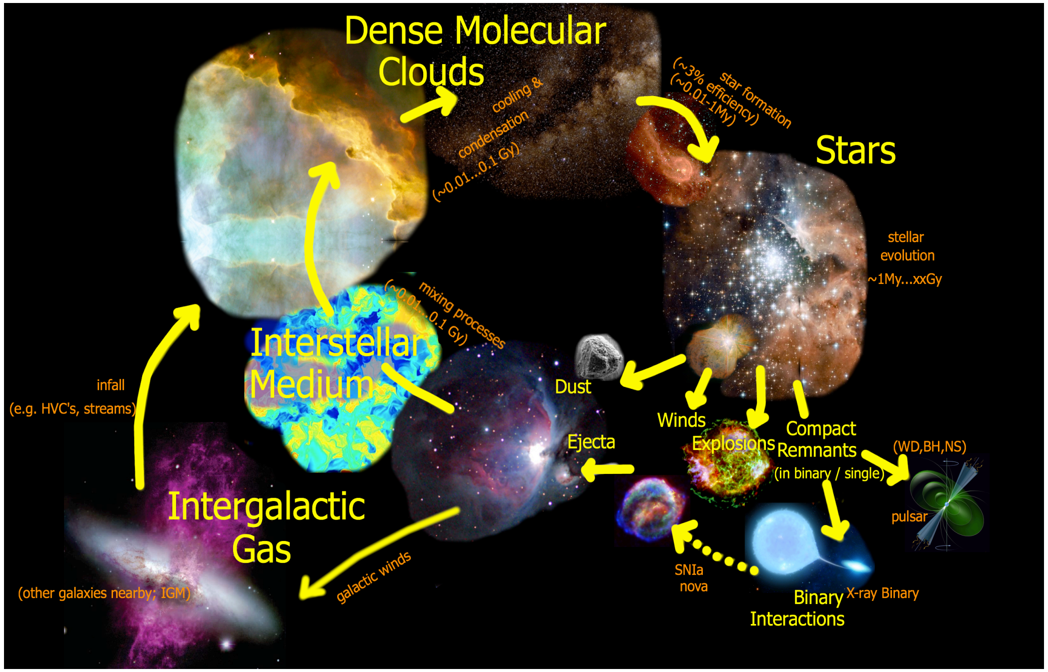




Dynamics of the Interstellar Medium

- Ejecta will mix into newly-forming stars (e.g. our Sun)





CR Primary Composition near Knee

– ... is quite uncertain / controversely discussed

  - here: Tokuno+ 2008

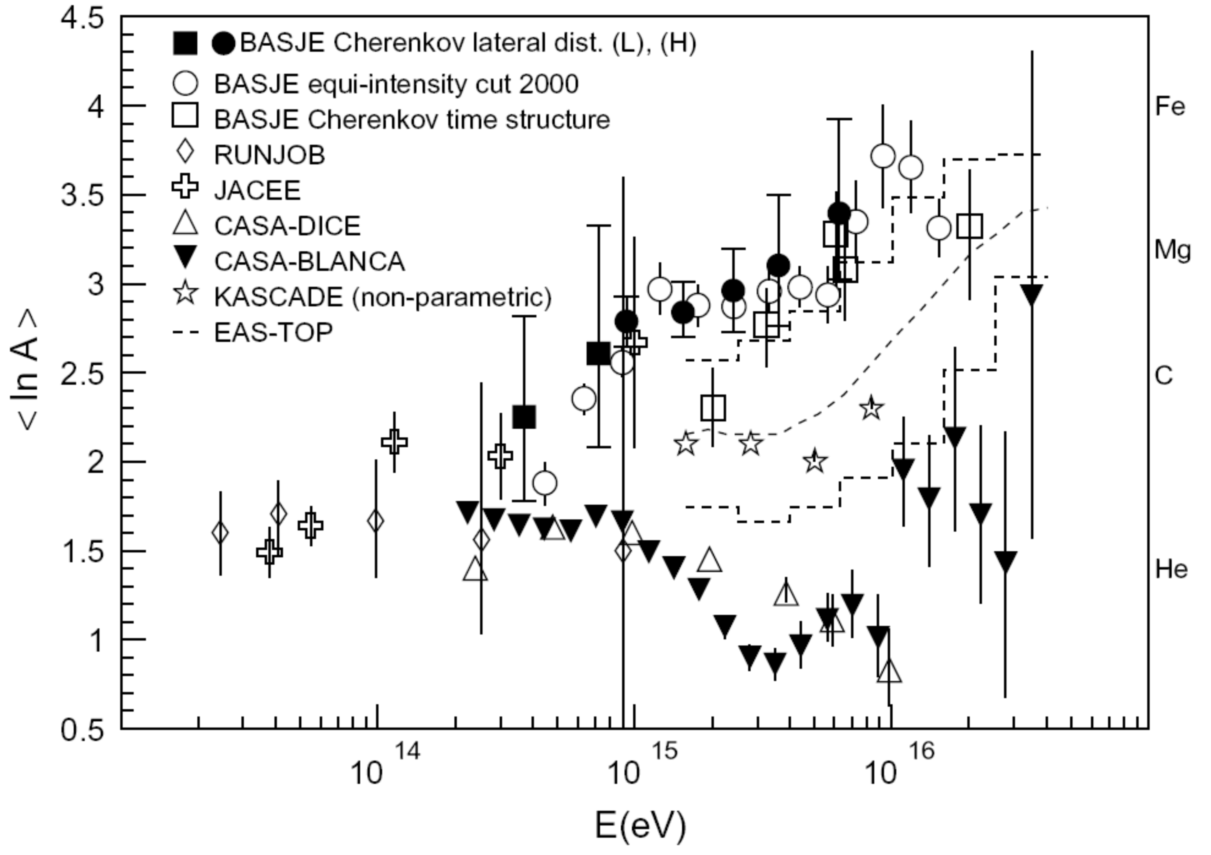


Fig. 15. The present result of the mean logarithmic mass ⟨ln*A*⟩ compared with the results of other experiments BASJE [1,8], CASA-BLANCA [9], CASA-DICE [10], KASCADE(non-parametric) [11], EAS-TOP [19], and direct measurements (JACEE [6] and RUNJOB [7]).

CR Spectra for Different Species

- from near-Earth Measurements *(PT May 2011)*

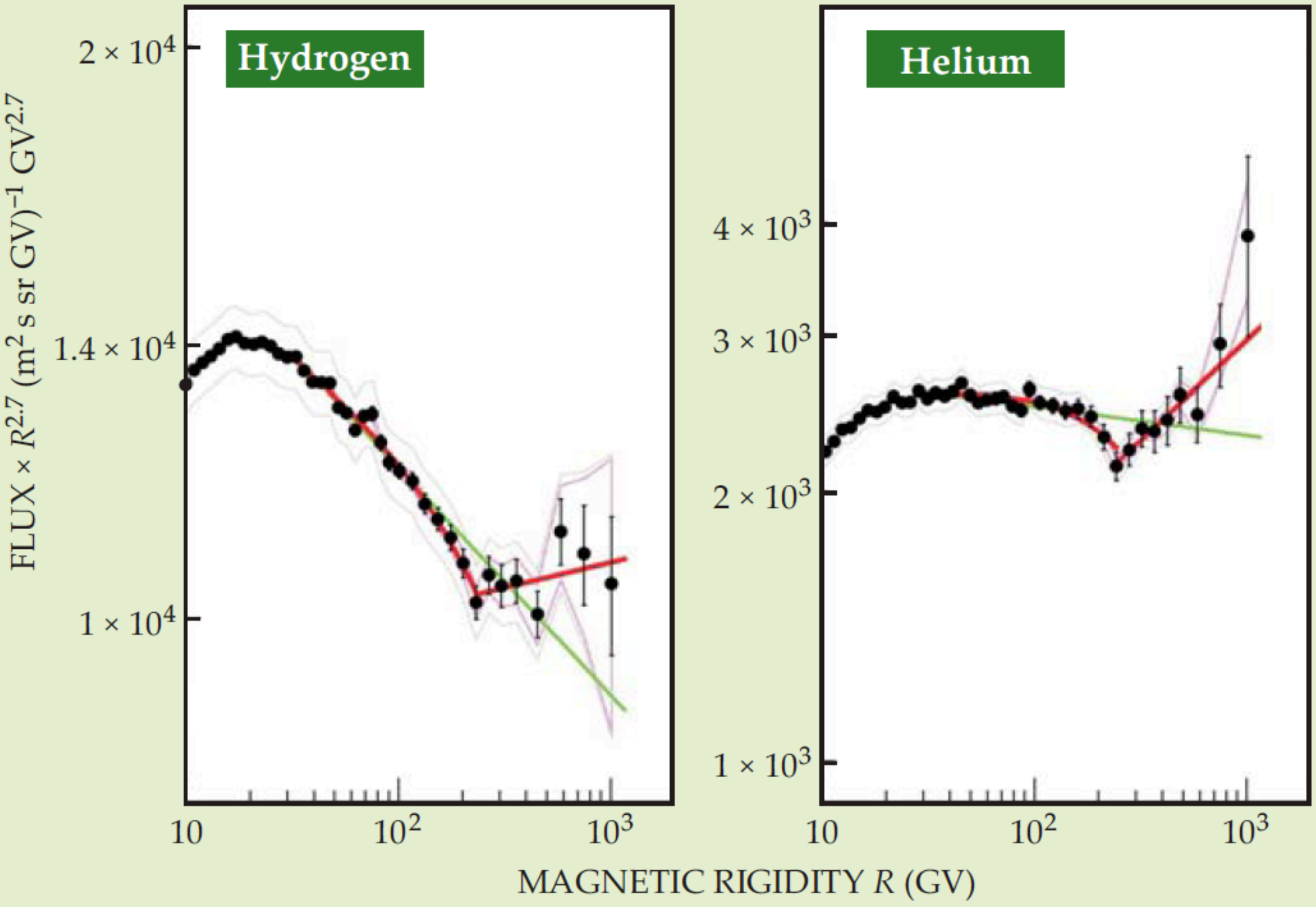
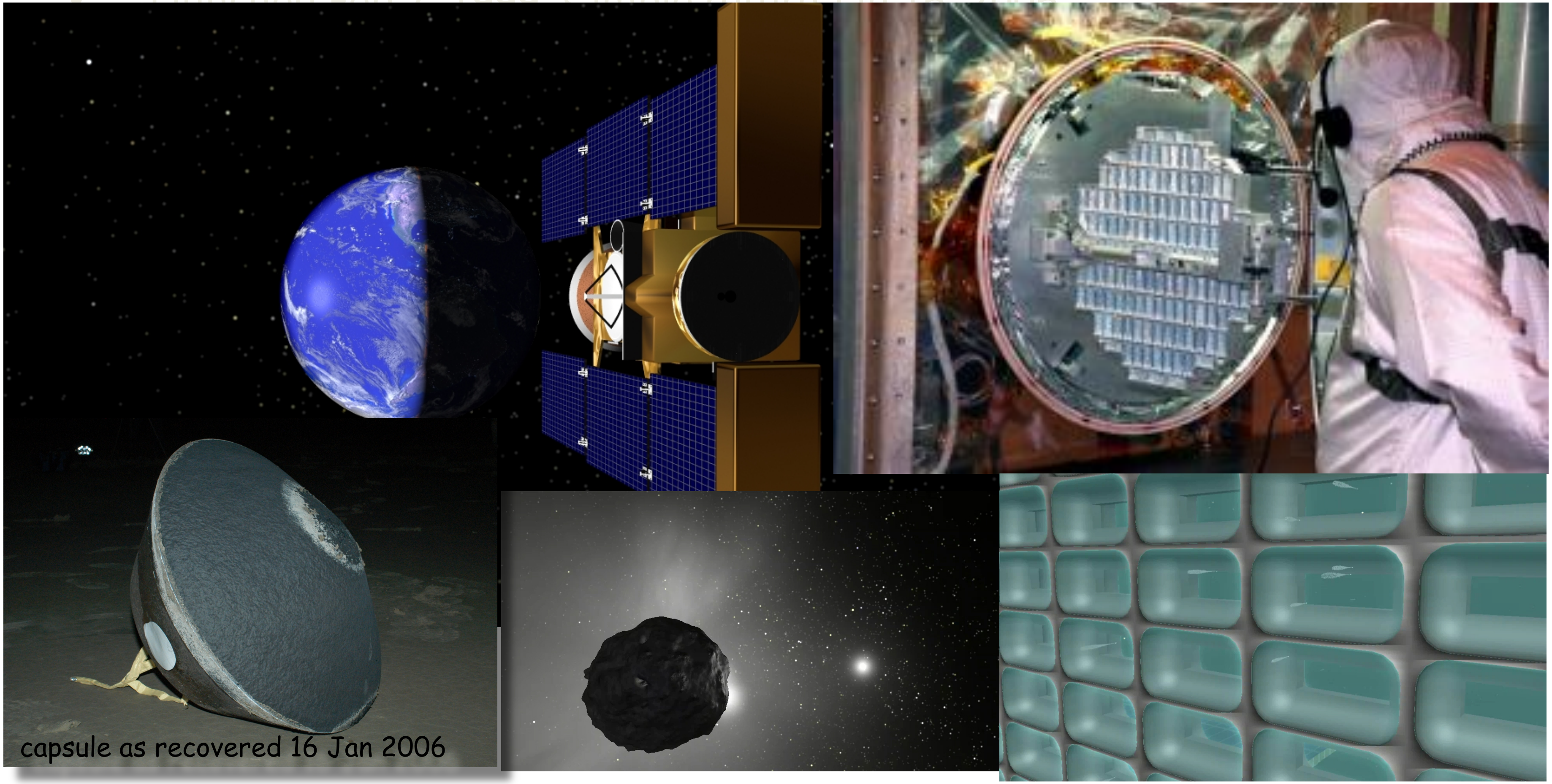


Figure 3. The hydrogen and helium spectra measured by PAMELA both reveal sharp breaks at $R \approx 240$ GV. The straight green and red lines, showing power-law fits below and above the breaks, emphasize the curvature away from the power-law fit just before the breaks. (Adapted from ref. 2.)

Stardust Mission: Collecting Interplanetary Dust

- Aerogel Layers Deposited in Interplanetary Space
- Sample Return for Analysis in Terrestrial Laboratory
  - "Stardust" Mission: Sample Return from Comet Wild
  - launched Feb 7, 1999; sample return Jan 16, 2006



Sample-Return Analyses

- Compare Crater Morphologies with Laboratory-Made Craters (Using Meteorite Grains)

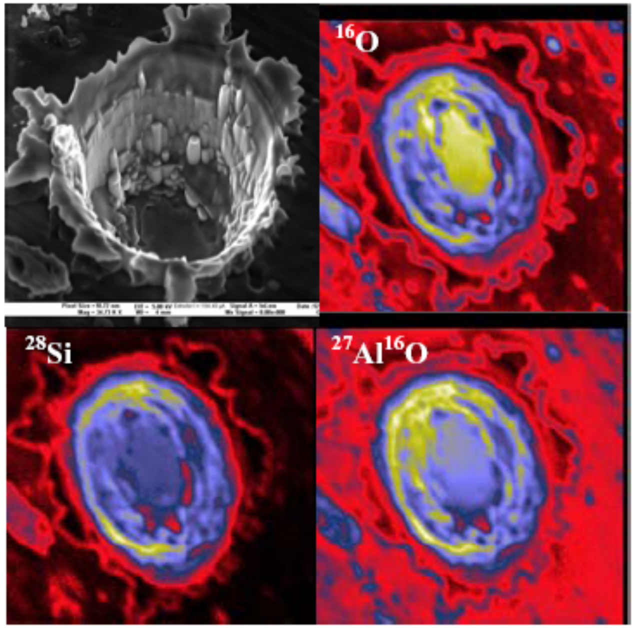


Figure 3. SEM image (after NanoSIMS analysis) and NanoSIMS ion images of ^{16}O, ^{28}Si, and ^{27}Al^{16}O of a crater produced by an Allende projectile. Field of view is 8 x 8 μm^2 in the ion images (from ref. 10).

- Analyze Samples Grains with Mass Spectrometers

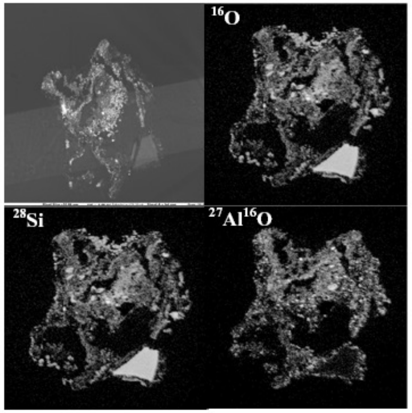


Figure 4. SEM image and NanoSIMS ion images of ^{16}O, ^{28}Si, and ^{27}Al^{16}O of ultra-microtome section E237-7f-s3g6-E. Field of view is 32 x 32 μm^2 in the ion images.

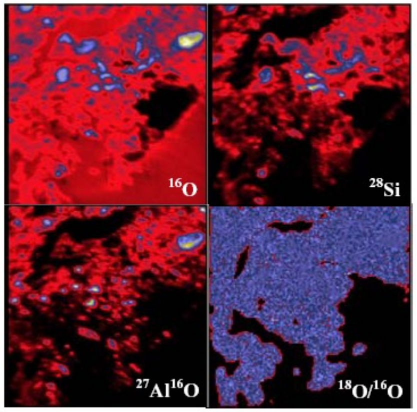


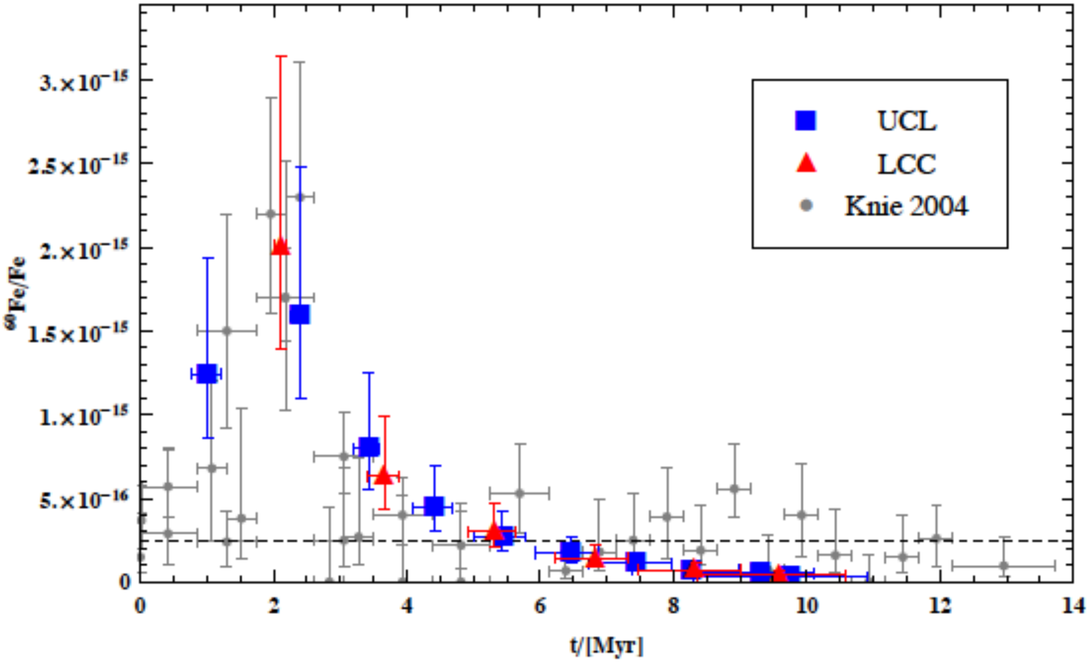
Figure 5. NanoSIMS ion images of ^{16}O, ^{28}Si, ^{27}Al^{16}O, and ^{18}O/^{16}O of a 10 x 10 μm^2-sized sub-area of ultra-microtome section E237-7f-s3g6-E.

Supernova Ejecta from a Nearby Event

- ^{60}Fe Clearly Seen in Oceanfloor Samples

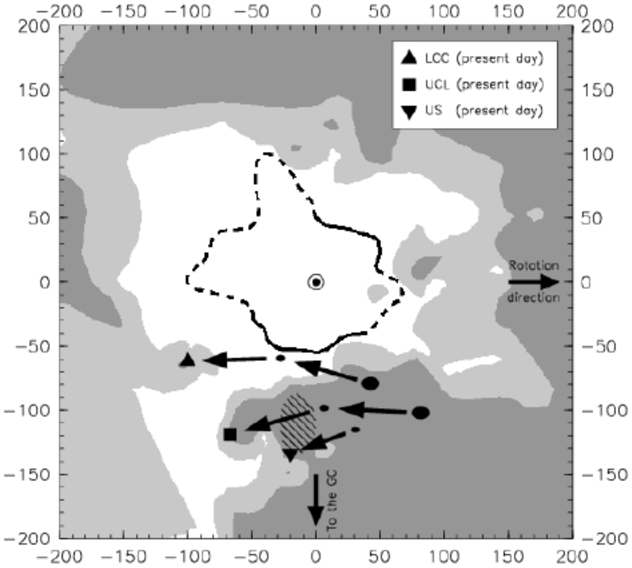
→ SN ~2-3 My ago

Knie et al. 2004; Fitousi et al. 2008; Feige 2014; Fimiani et al. 2015



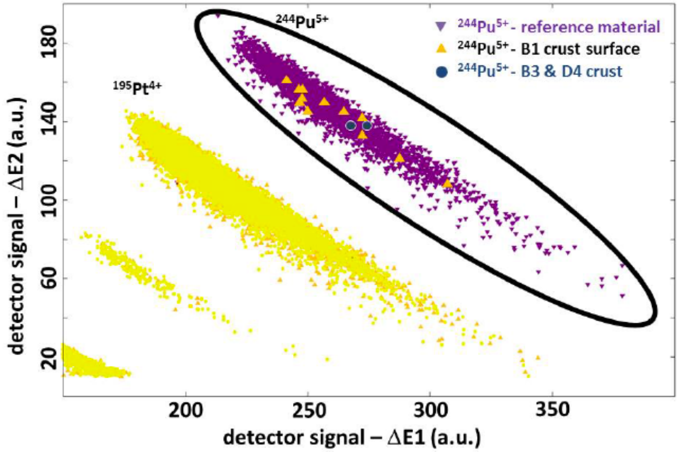
The computed data (UCL: blue, LCC: red) plotted over the ^{60}Fe measurements (black points) with an ISM density of $n = 1$ atom/cm^3.

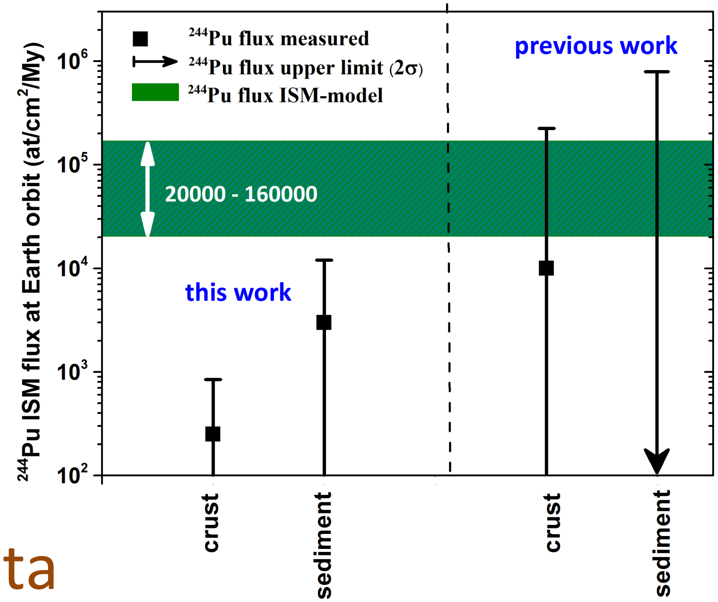
Feige+ 2014



r process ejecta on Earth?

- If r process occurs nowadays → interstellar material should bring this to Earth
  - search for typical r-process isotopes in sediments with AMS
    - *A. Wallner+Nat. 2015*

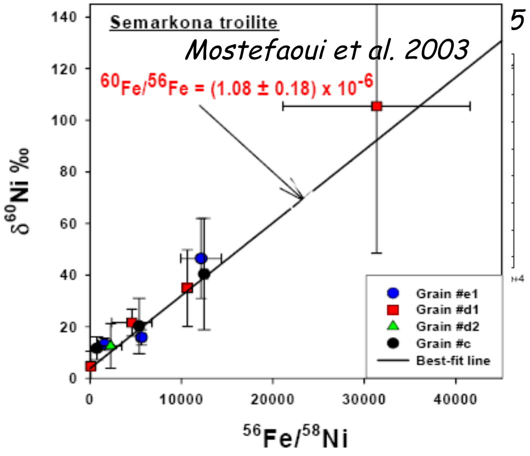


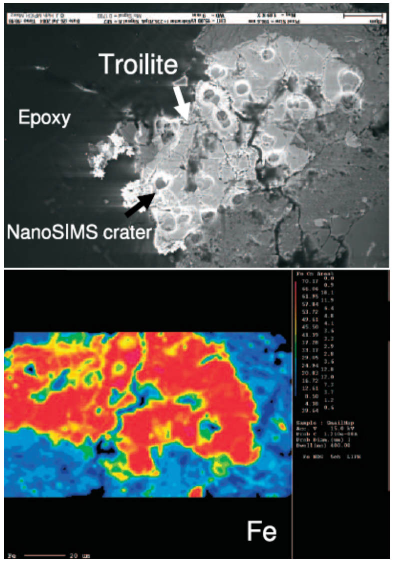


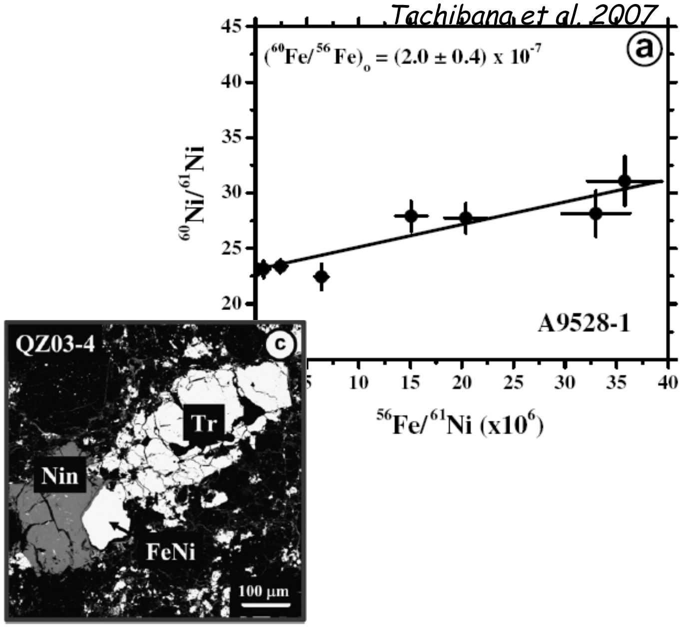
  - no signs of current r-process ejecta

^{60}Fe in Solar-System Meteorites

- ^{60}Ni Excesses wrt. Ni Isotopes Detected in Meteorites
  - ^{60}Fe/^{56}Fe ~ 3 10^{-7} … 1 10^{-6}



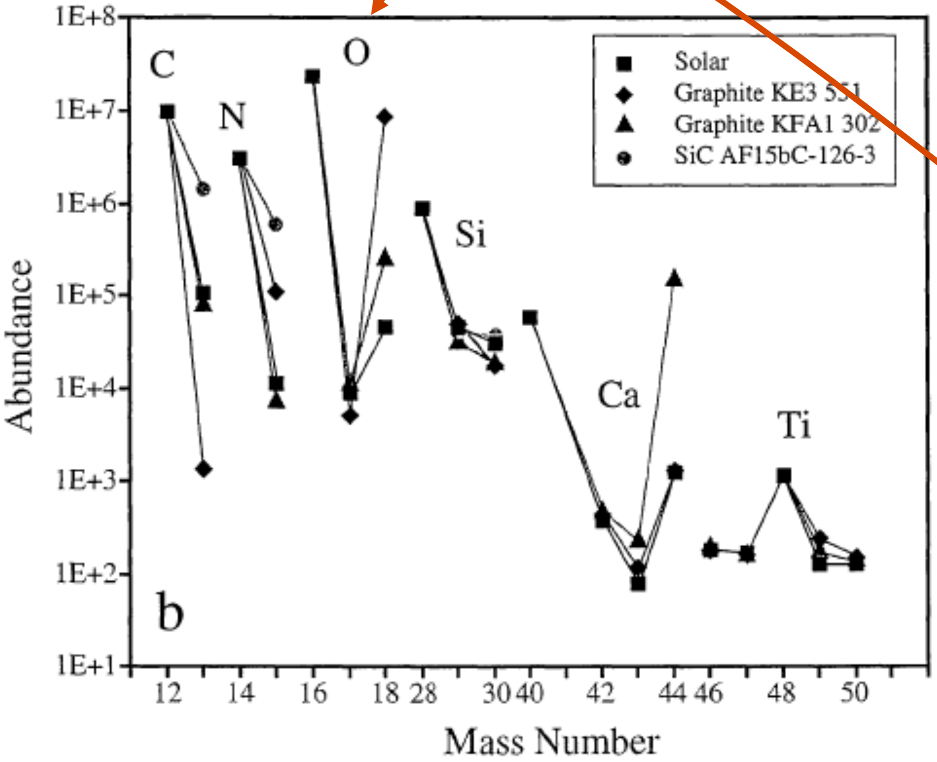


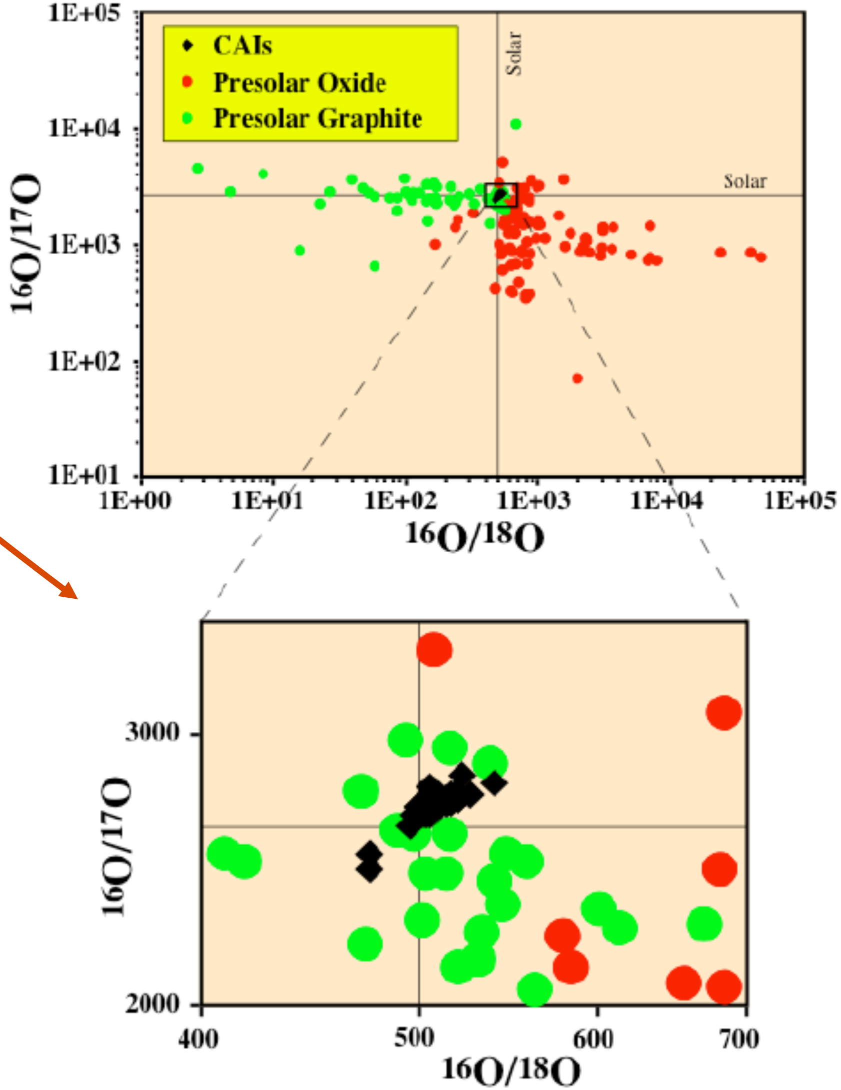


- ISM Abundance Ratio?
  - ^{26}Al & ^{60}Fe from ISM γ's & SAD ^{27}Al,^{56}Fe -> ~ 1.4 10^{-7}
- The "Disk Area" of a Newly-Formed Stellar System is ~10 My
- Chondrules are Formed ~Myrs *after* Decoupling of SolarSys from ISM
  - When, Exactly, Does Chondrule Formation Occur?
  - Was ^{60}Fe a Significant Heat Source of Chondrules?
  - Has there been 'late' SN Enrichment?

Detection of Presolar Grains

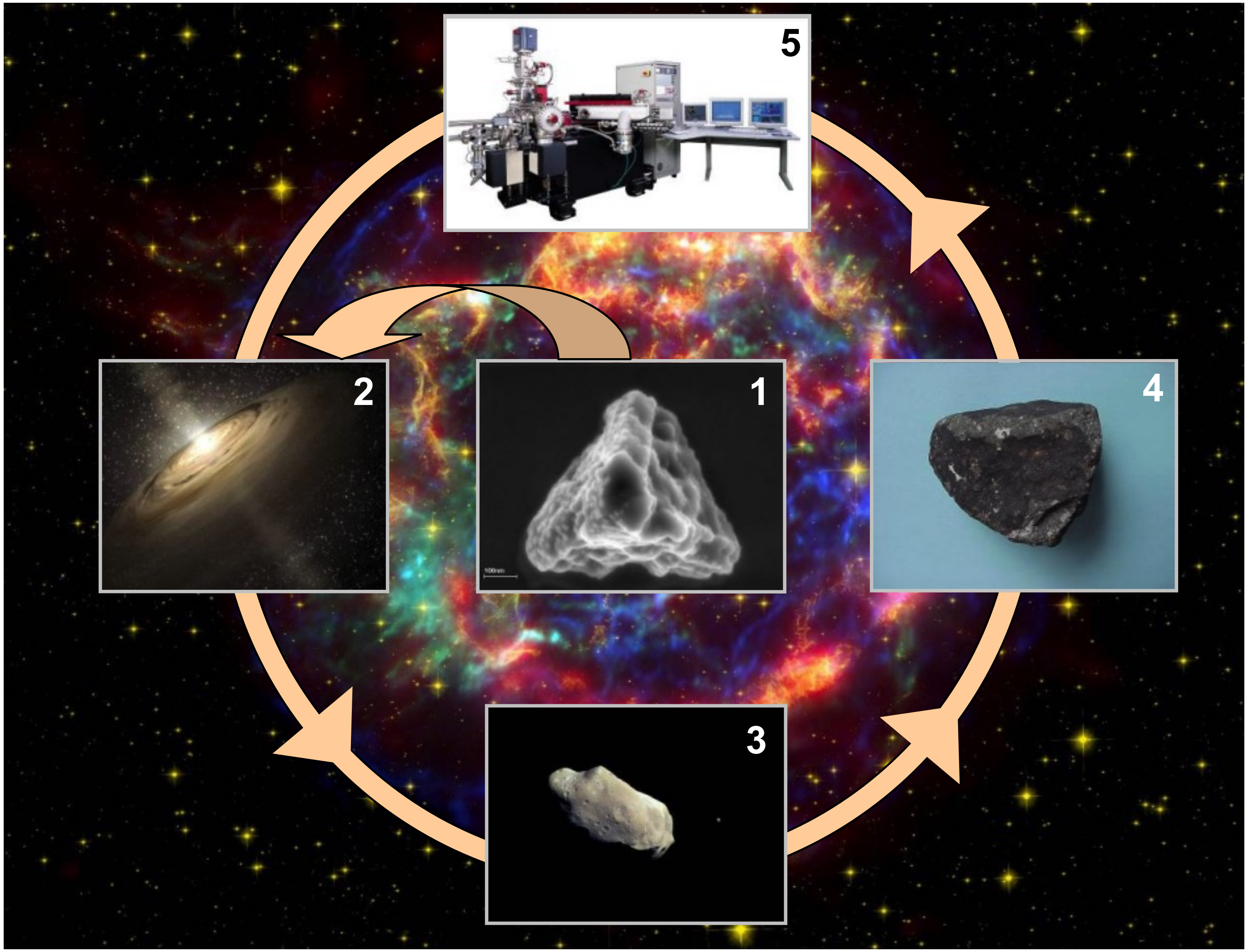
- Huge (compared to solar-sample variances) Isotopic Abundance Anomalies
  - C or O Isotopes
    - Solar Variation ~10%
    - Total Range ~10^5





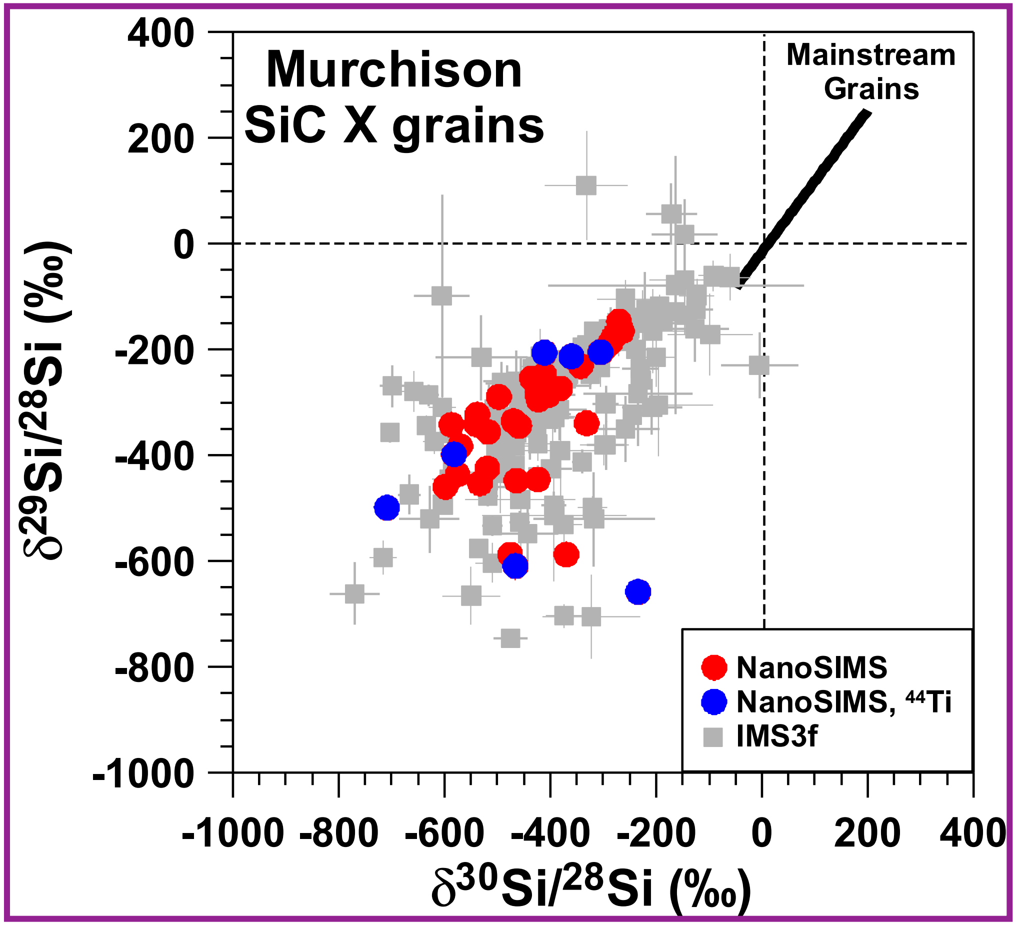
Isotopic Studies of Presolar Grains in the Laboratory

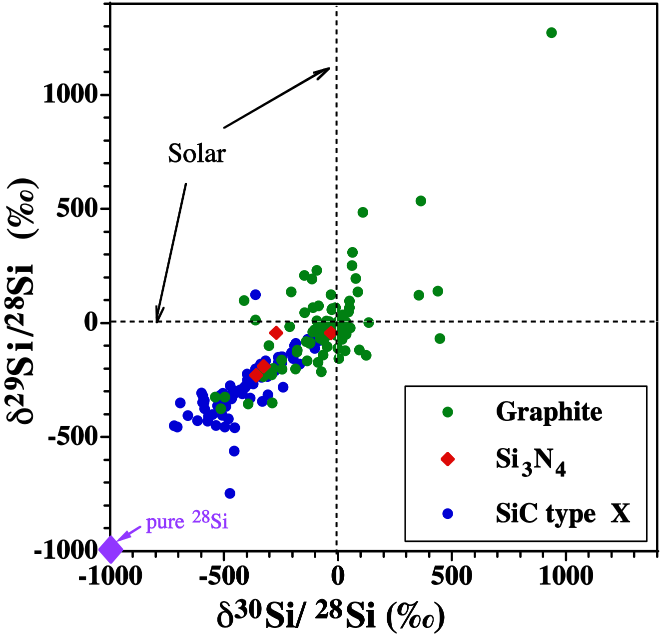
Peter Hoppe, MPI for Chemistry



Presolar Grains = Samples of Stardust in the Laboratory

Stardust: Presolar "X" Grains





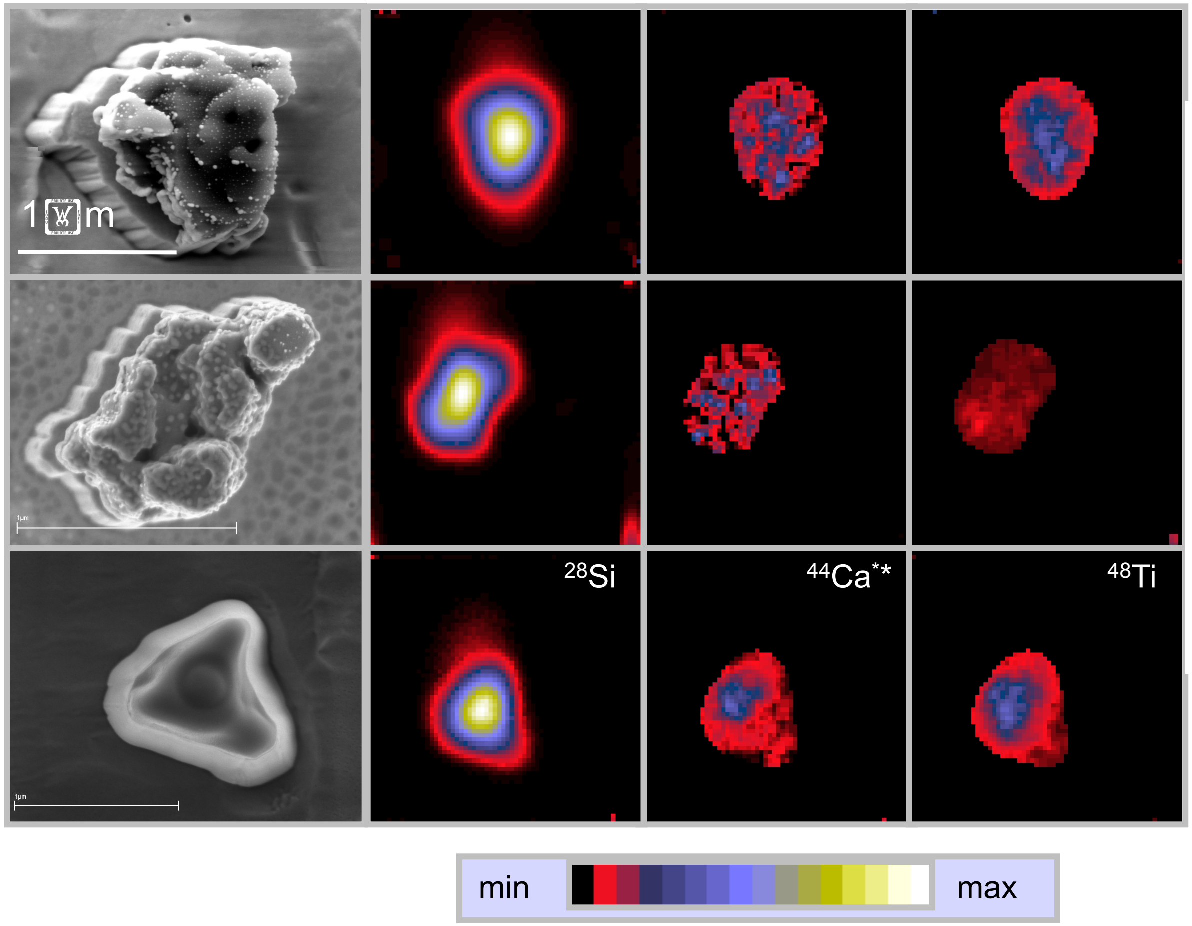
$\delta^{i}\mathrm{Si}/^{28}\mathrm{Si}$ (‰) = $((^{i}\mathrm{Si}/^{28}\mathrm{Si})_{\mathrm{Grain}}/(^{i}\mathrm{Si}/^{28}\mathrm{Si})_{\mathrm{Solar}} - 1)\times 1000$

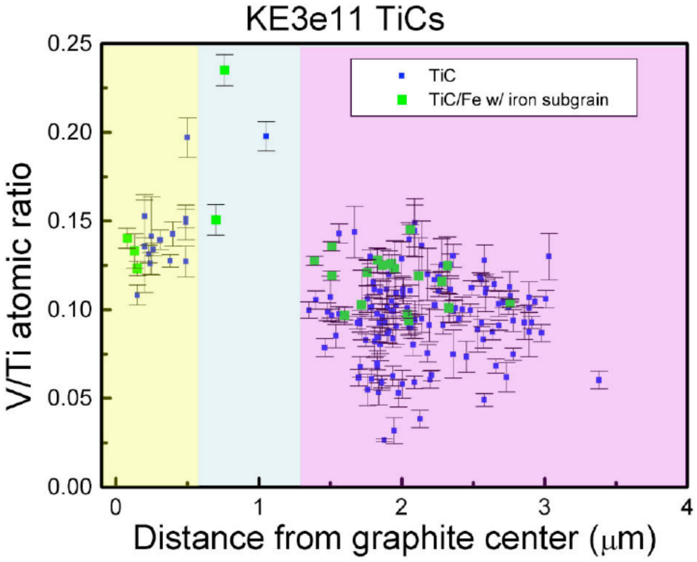
- “Mainstream” SiC Grains from C-rich Stars→ AGB Stars
- SiC X grains are a rare type of presolar SiC
- Isotopic signatures: Excesses in ^{12}C (most grains), ^{15}N, and ^{28}Si, large amounts of ^{26}Al and presence of ^{44}Ti (some grains)
- cc SN are the most likely stellar sources

^{44}Ti in Presolar Grains: Morphology on Fine Scales

Localized ^{44}Ti subgrains,
Correlated with ^{48}Ti

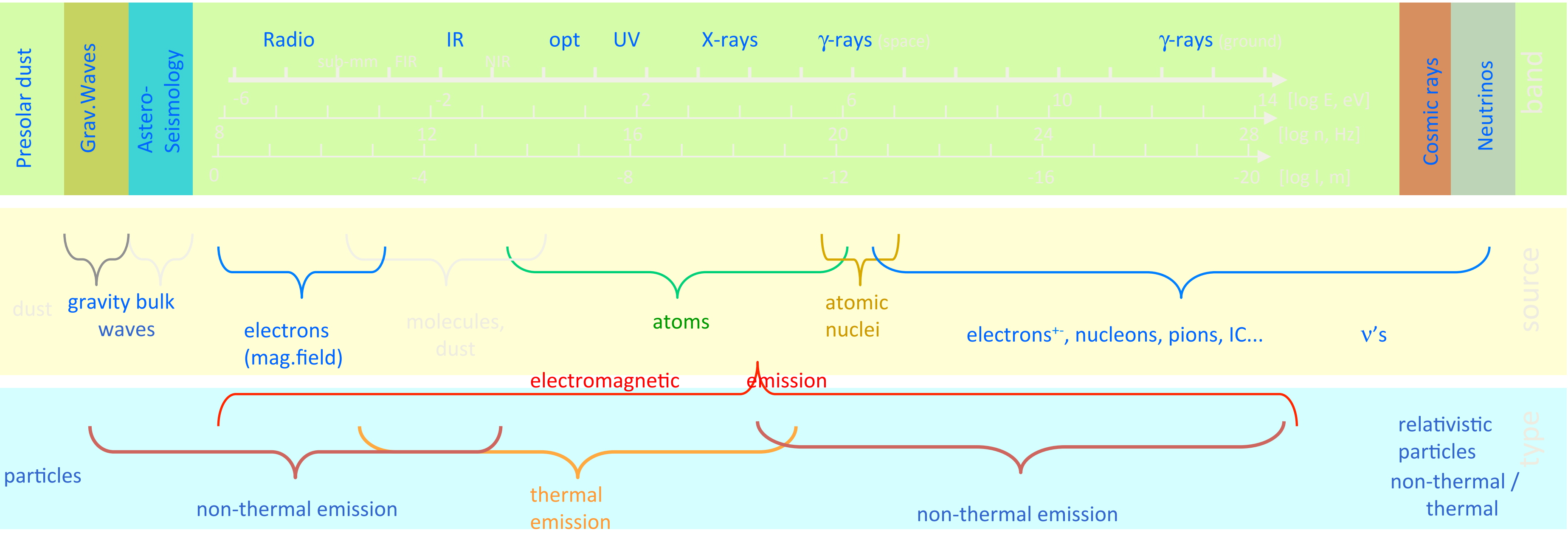
in SiC X Grains





→ grain growth and condensation within SN envelope

Astronomy : The Variety of Astrophysical Messengers



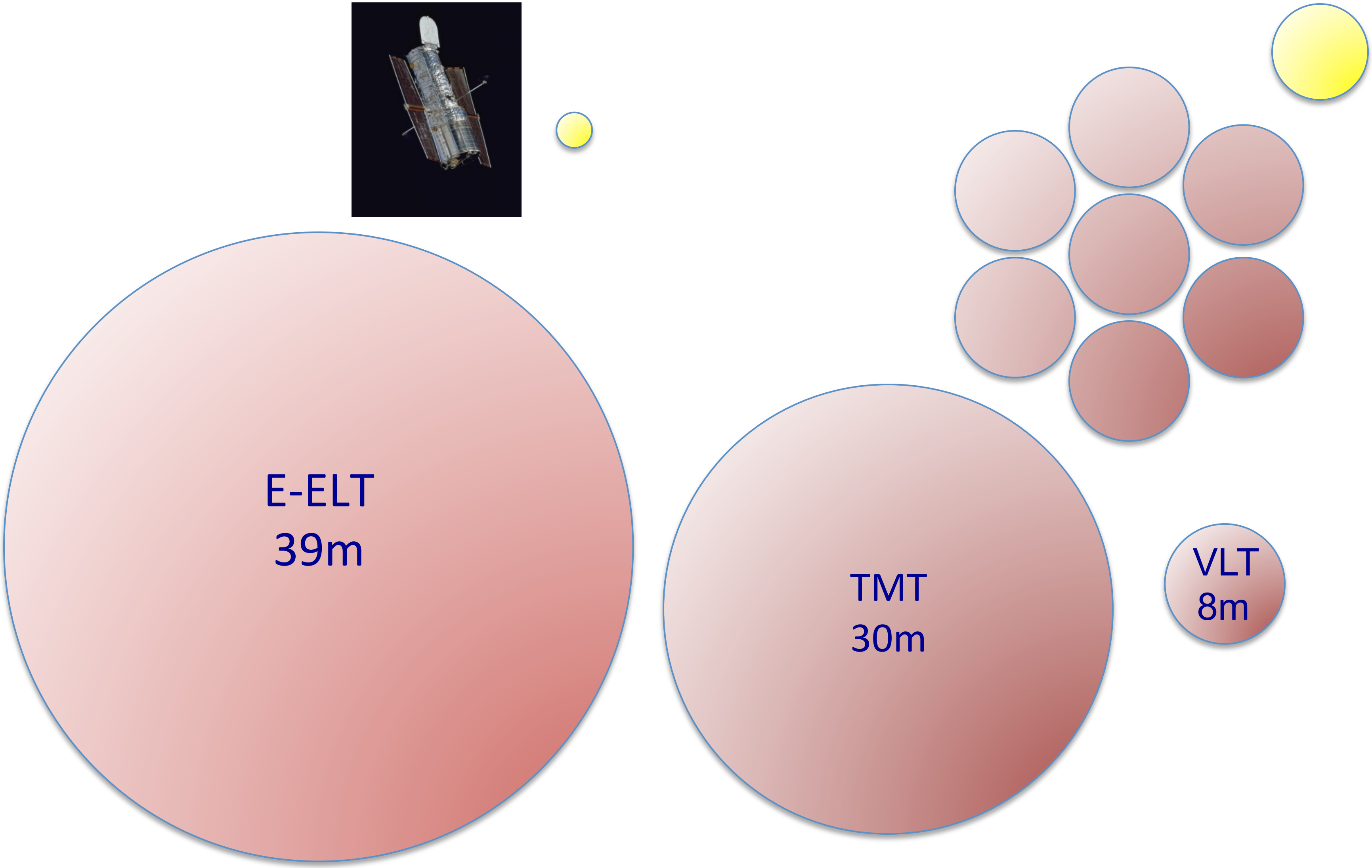
- Astronomy with photons/e.m. radiation is complemented by new "messengers →
  - Presolar grains, cosmic rays: material samples from the cosmos
  - Neutrinos: High-energy process is cosmic objects
  - Gravitational Waves: Interactions of compact stars

Prospects and Challenges

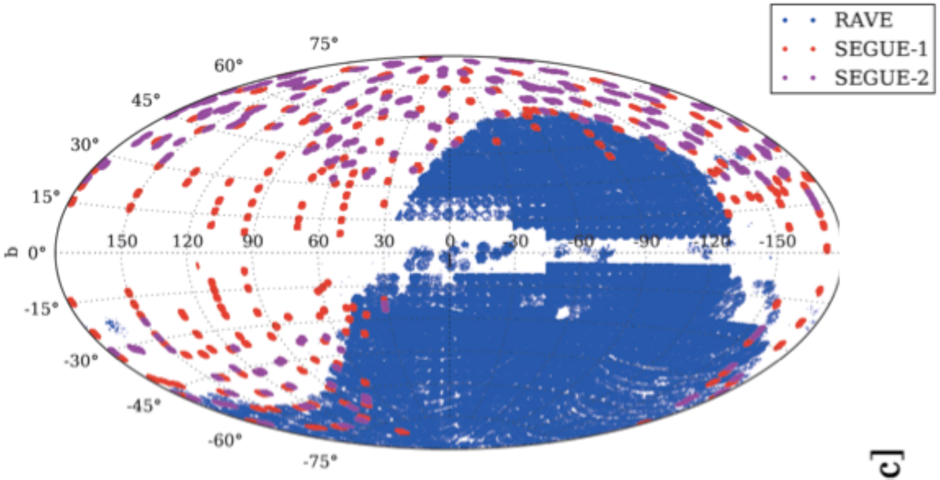
30m-class telescope projects

- **European Extremely Large Telescope (E-ELT)** **`www.eso.org/sci/facilities/eelt/`**
  - ESO
  - 798 hexagonal primary mirror segments of 1.4 m <=> *D* = 39 m
  - Site: Cerro Armazones, Chile
  - First Light: “mid-2020ies”
- **Thirty Meter Telescope (TMT; `www.tmt.org`)**
  - USA + Canada + China + Japan
  - 492 hexagonal primary mirror segments of 1.4 m <=> *D* = 30 m
  - Site: Mauna Kea, Hawai’I
  - First Light: 2022?
- **Giant Magellan Telescope (GMT; `www.gmto.org`)**
  - USA + Australia + Korea
  - 7 round mirrors of 8.4 m <=> *D* = 22 m
  - Site: Las Campanas, Chile
  - First Light: “2022”

Telescope primary mirrors

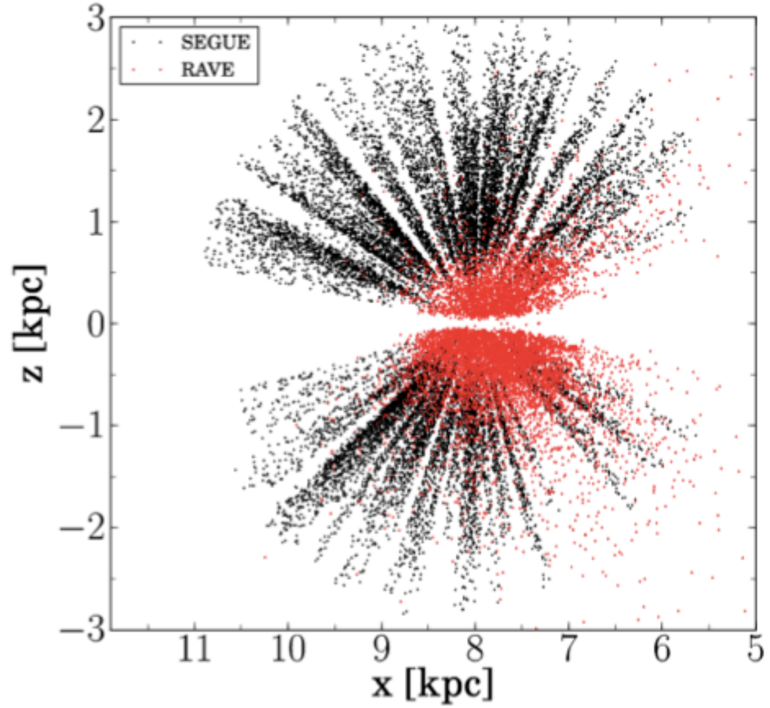


Surveys: Abundance data from stars

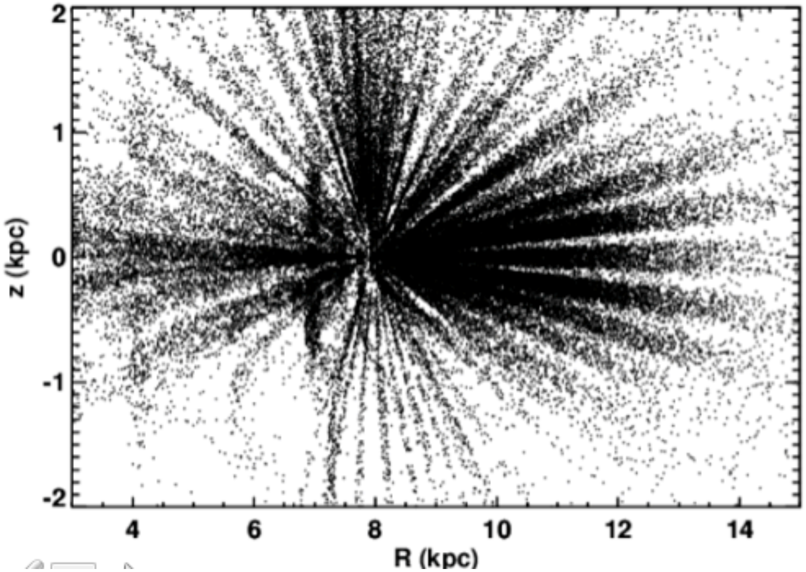


SEGUE dwarfs

RAVE giants

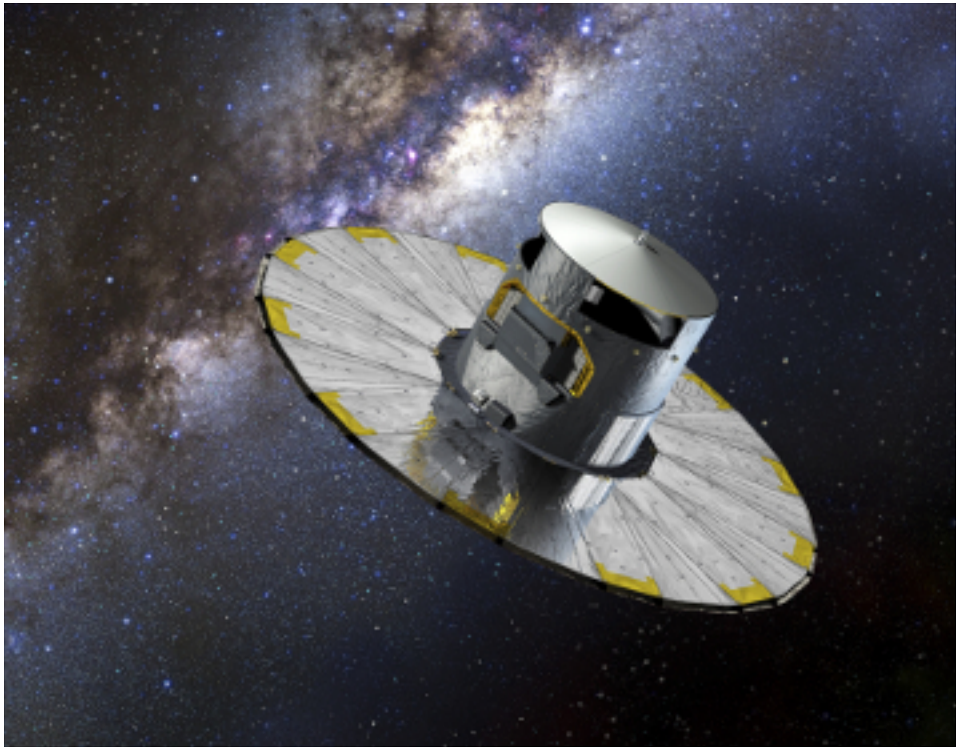


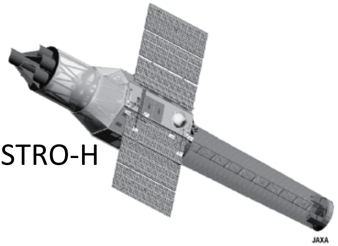
APOGEE – DR12



Gaia and other surveys: massive data

- New facilities built for other purposes (cosmology, dark energy) also produce a rich database of stellar abundance data!
  - Need processing & abundance analysis facilities, classifications, quantitative analysis, …





ASTRO-H

plus: ALMA, NOEMA/IRAM, SOFIA, NICER, ATHENA…

→ Abundance and source constraints as by-products

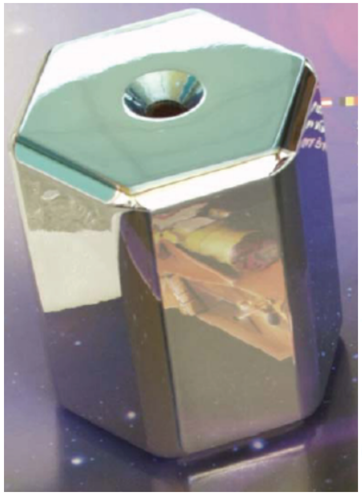
Current Nuclear Gamma-Ray Line Telescopes

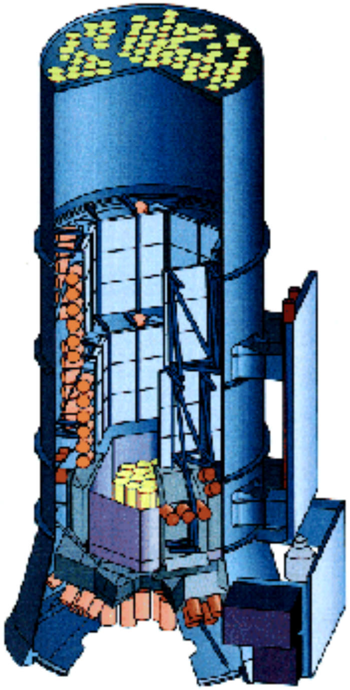
– INTEGRAL Observatory

2002-(2016+..202x)

ESA

Ge Detectors





– NuSTAR (<80 keV!)

2012- …

NASA

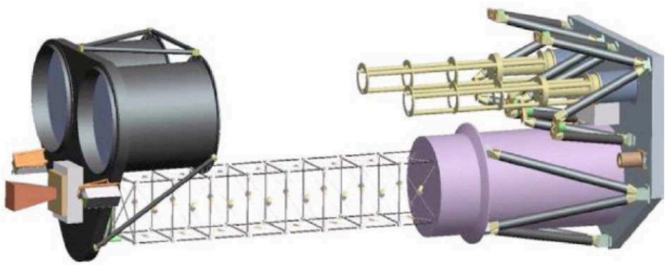
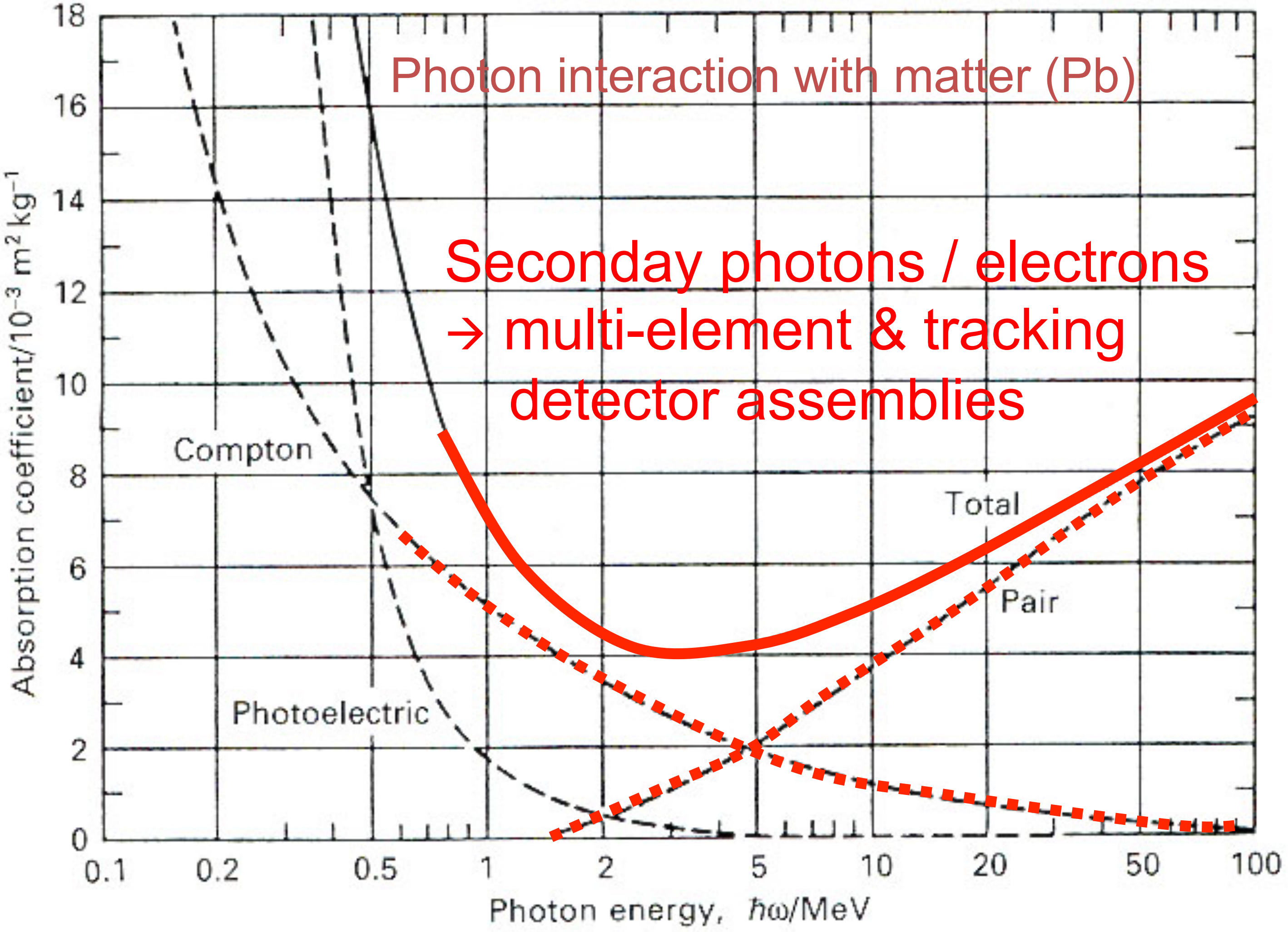


Fig. 1. NuSTAR telescopes in deployed configuration

Astronomical Gamma-Ray Telescopes:
Interaction of High-Energy Photons with Matter

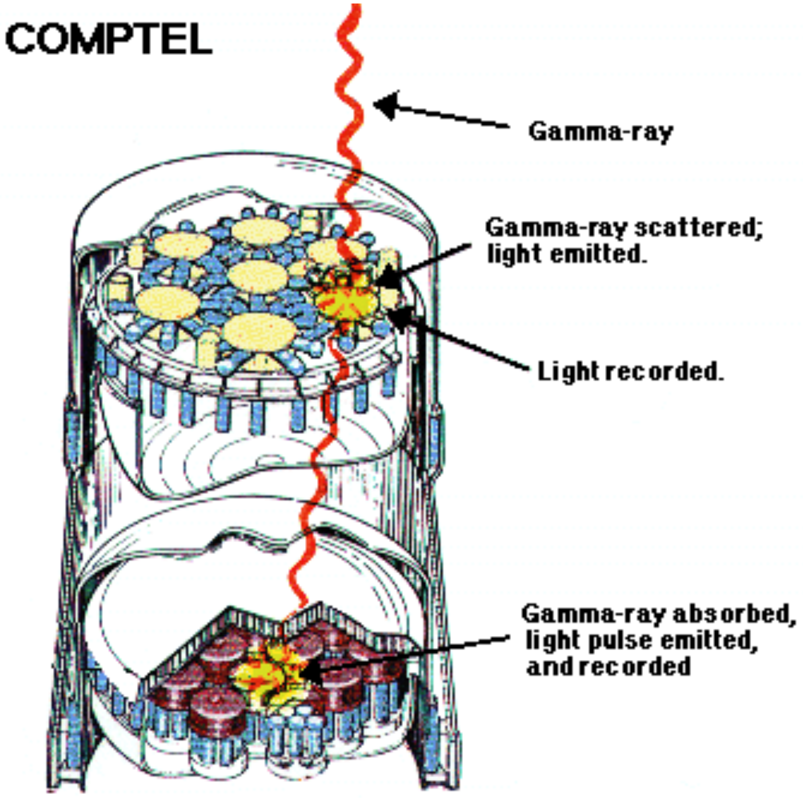


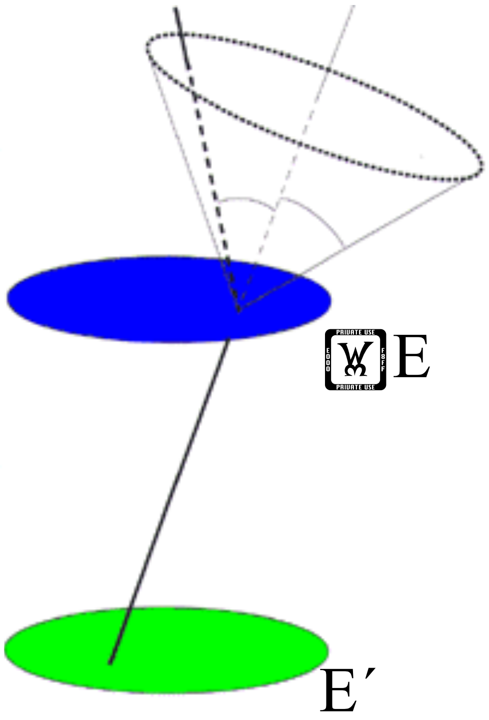
Seconday photons / electrons
→ multi-element & tracking detector assemblies

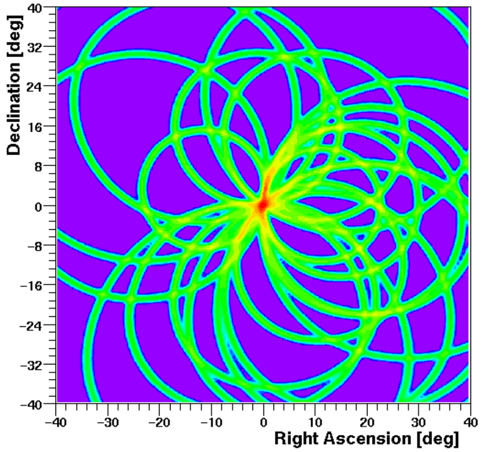
-> Secondary Particles … → e.m. cascade

Compton Telescope

Compton Scattering: Coincidence Experiments





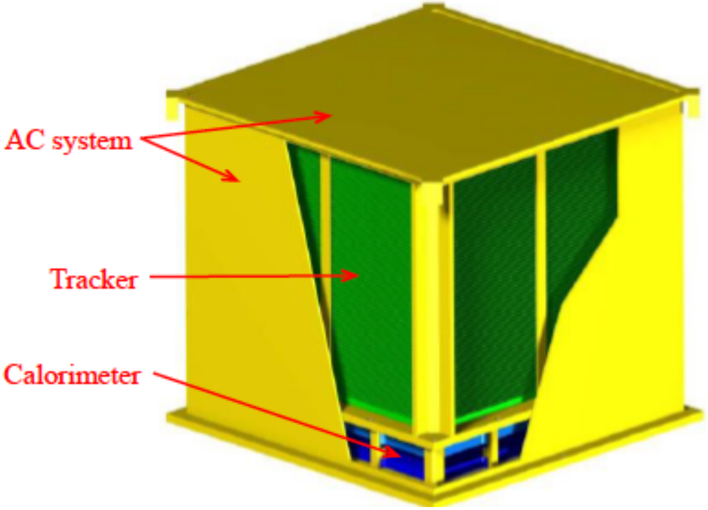


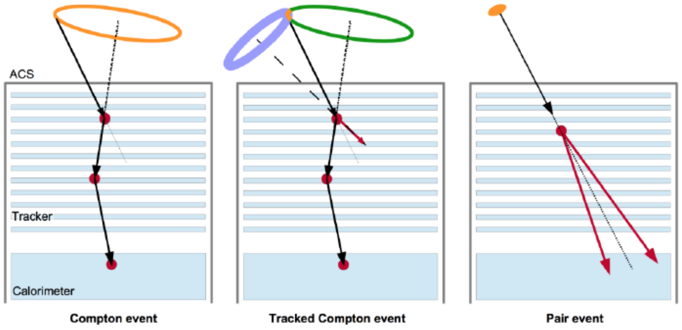
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

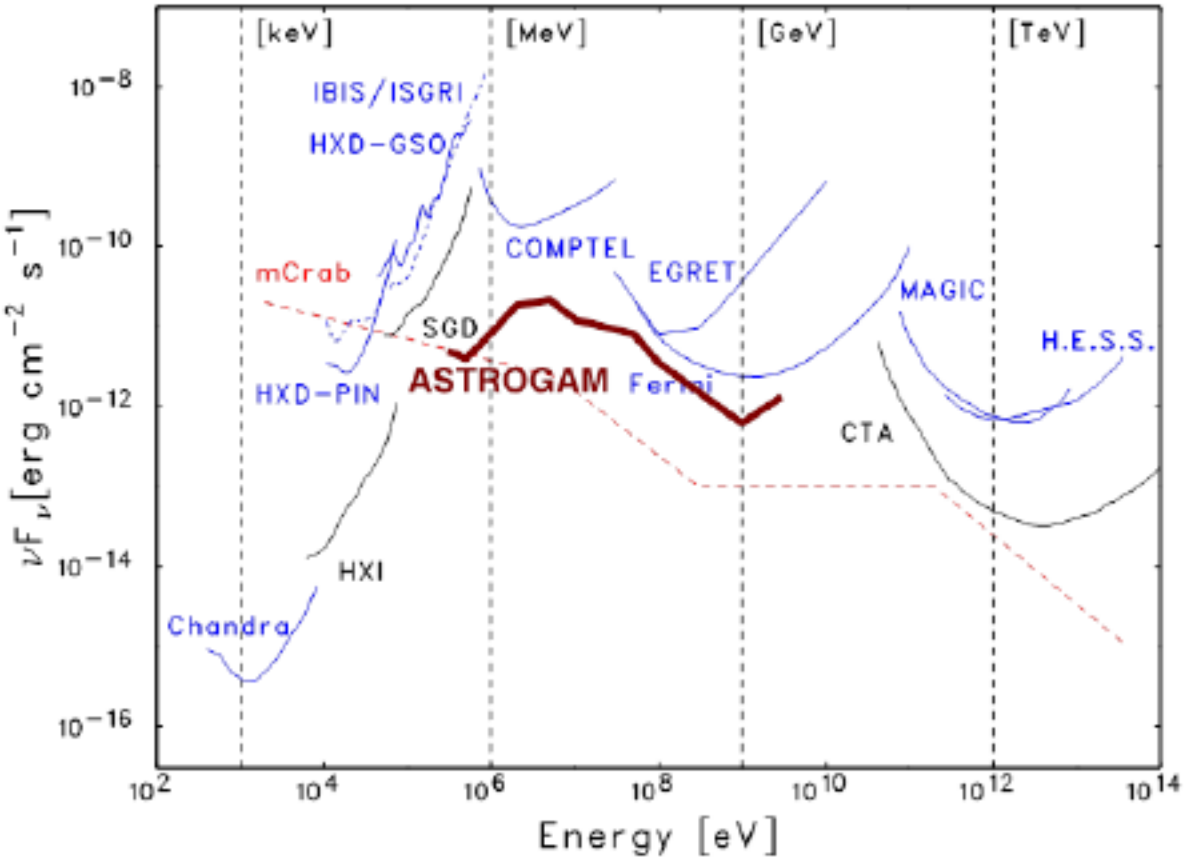
$$\varphi_{geometric} = \arccos\left\{1 + m_e c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma - \Delta E} \right)\right\}$$

Nuclear-range Telescope Proposals

- ESA M-class missions → "Astrogam" (2015)







- Not selected, though scientific value appreciated

Laboratory Isotope Studies of Presolar (Stardust) Grains

- Provide opportunity to study isotopic compositions of dust from individual stars in the laboratory with unrivaled precision
- Permit to track nucleosynthetic processes in parent stars (AGB stars, supernovae, novae)
- Coordinated high spatial resolution isotope measurements (<100 nm) by NanoSIMS and RIMS (CHILI, University of Chicago) opens a new window to nuclear astrophysics

Summary

- Astronomical messenger variety has increased substantially, wrt. cosmic nuclear processes
- Nucleosynthesis sites/sources are recognized as complex (3D) objects
- Links to astrophysical theory are key to data interpretations in many areas
- Nuclear reaction rates are (one of … key) ingredients to astrophysical source models
- Diversity of links nuclear ←→ astro -physics
- Need communication/collaboration platforms!