Presolar grains in meteorites - origins and nucleosynthesis

U.Ott

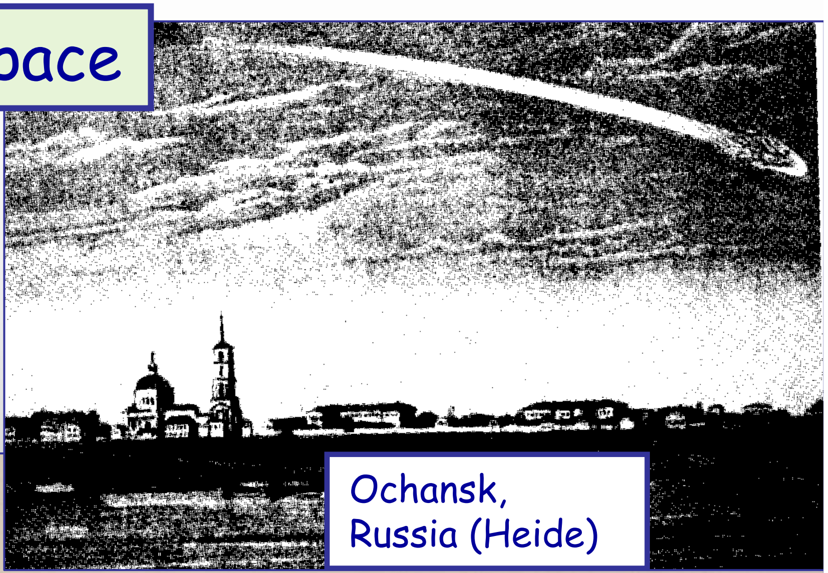
Frankfurt
December 3, 2010

Rough outline:

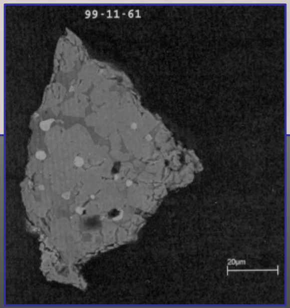
- meteorites
- recognition of isotope anomalies
- presolar grains vs. bulk and CAI isotopes
- presolar silicon carbide and the s-process
- an age for presolar SiC

Meteorites - Messengers from Space

Murchison (carbonaceous chondrite)



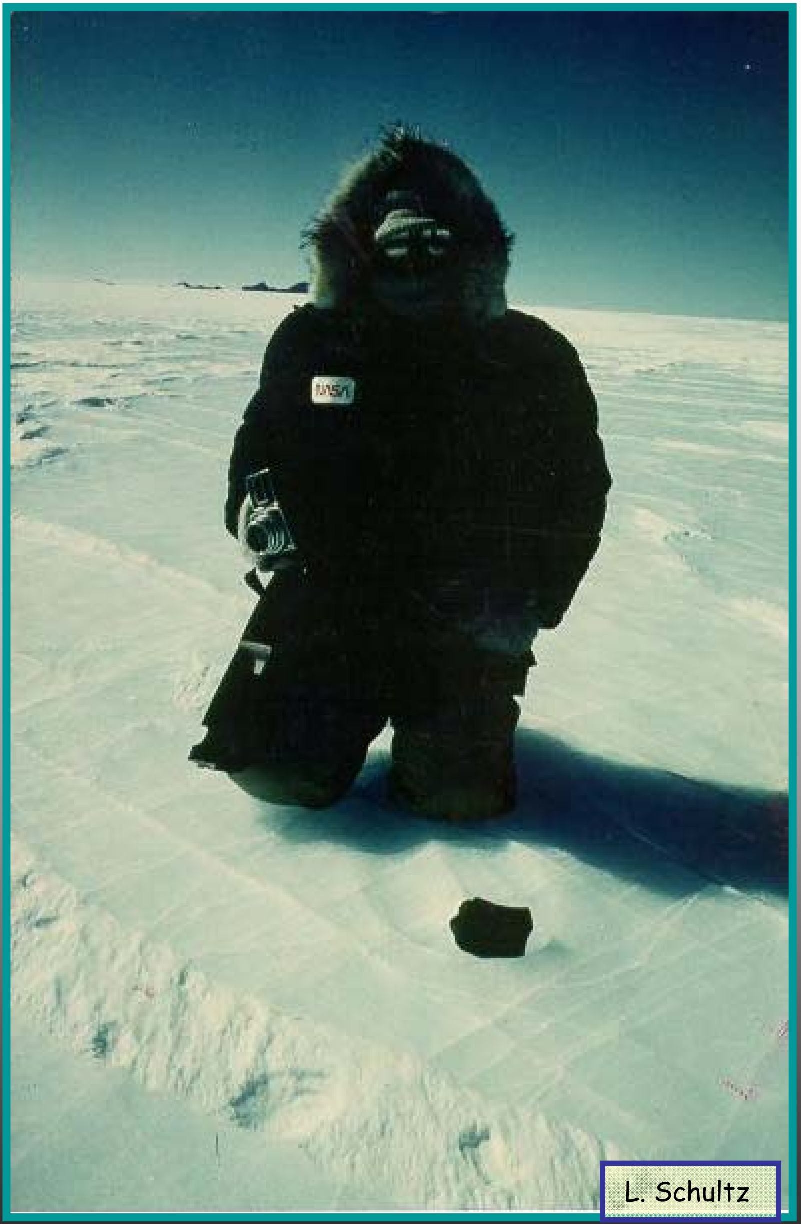
Ochansk, Russia (Heide)



micrometeorite
(from Kurat)

ALH 81032 (ordinary chondrite)

Earth: accretes ~ 40,000 tons of extraterrestrial material each year – some of it can be recovered as meteorites



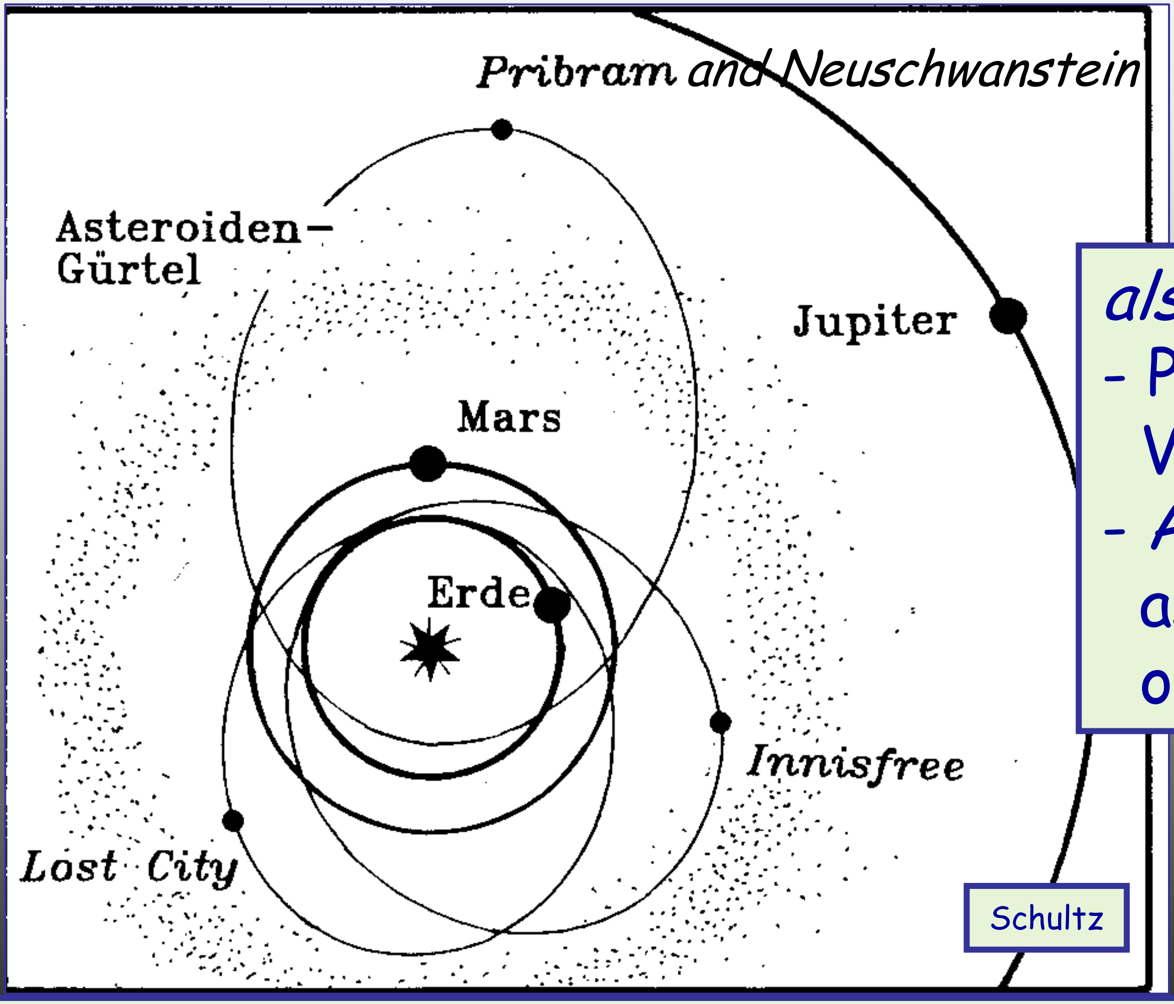
L. Schultz

falls vs. finds:

- falls = fall observed
- finds = found, have a "terrestrial age" of up to 1 Ma in places with little weathering like Antarctica

➢ join a search party !

parent bodies of meteorites
= mostly asteroids from the main belt as indicated by, e.g., the orbital characteristics of those for which a trajectory could be determined



also more recently:
- Puerto Lapice (from Vesta, presumably)
- Almahata Sitta (small asteroid – approach observed)

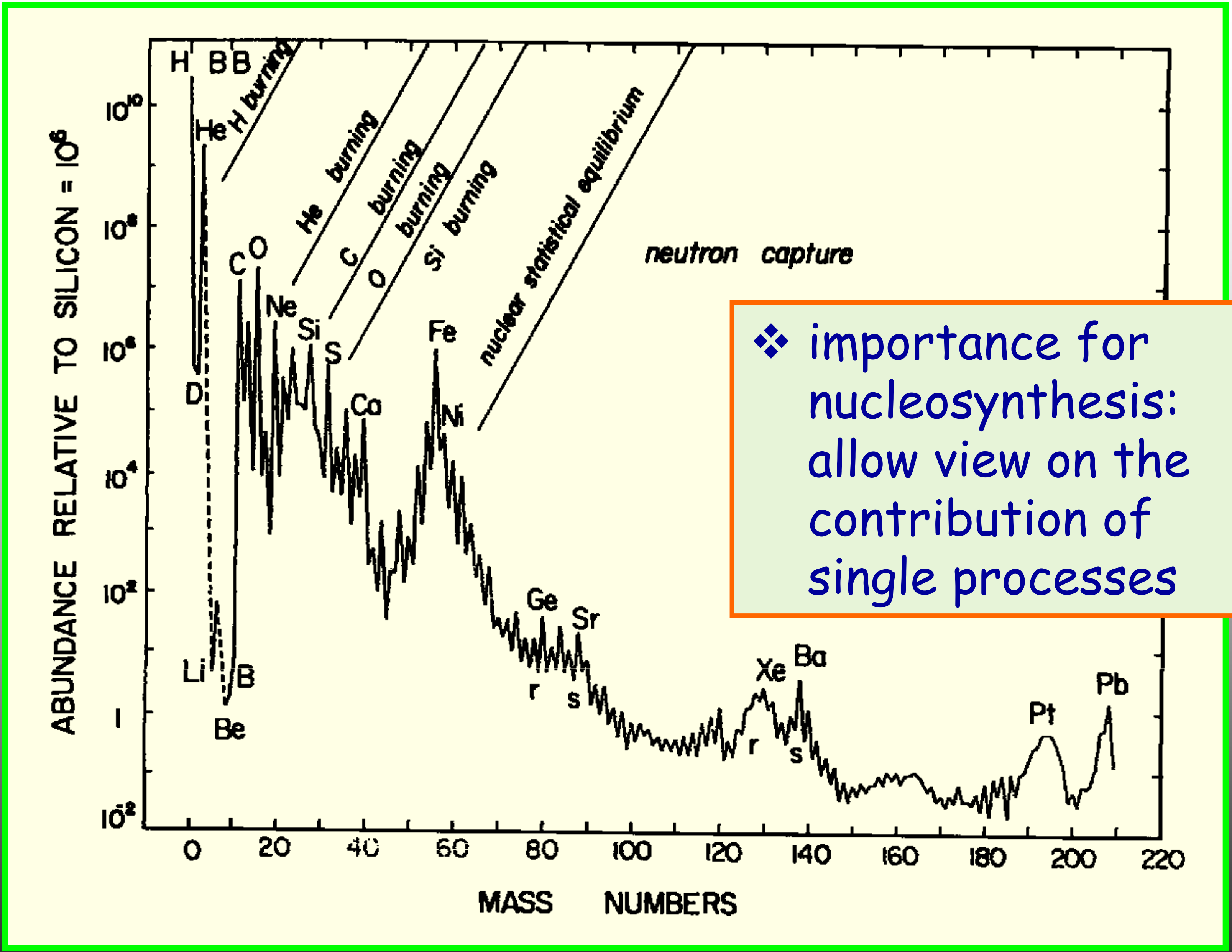
in addition some from the Moon, from Mars, from comets (?)

- (short form) **isotopic anomalies**
  = isotope *abundance* anomalies

- observed as isotopic *variations* in "primitive" matter
  → **meteorites**

- which, however, are also the best reference for ***mean*** composition of the Solar System
  (and not only of deviations thereof)
  → meteorites are important for astrophysics

- distinguish nucleosynthetic from other anomalies (radiogenic, cosmogenic, …)



- importance for nucleosynthesis: allow view on the contribution of single processes

identifying anomalies - technical:

- technique: ***mass spectrometry,*** after appropriate handling / preparation / isolation of samples
- mass spectrometric technique depending on problem: thermal ionization mass spectrometry (TIMS), inductively coupled plasma (ICP-MS), gas mass spectrometry, secondary ion mass spectrometry (SIMS), resonance ionization (RIMS) – *primary difference: in how to make ions*
- most sensitive to "foreign" additions: noble gases (because of their low abundance in rocks)
  → have played special role in the detection of presolar grains in meteorites

size + abundance matter

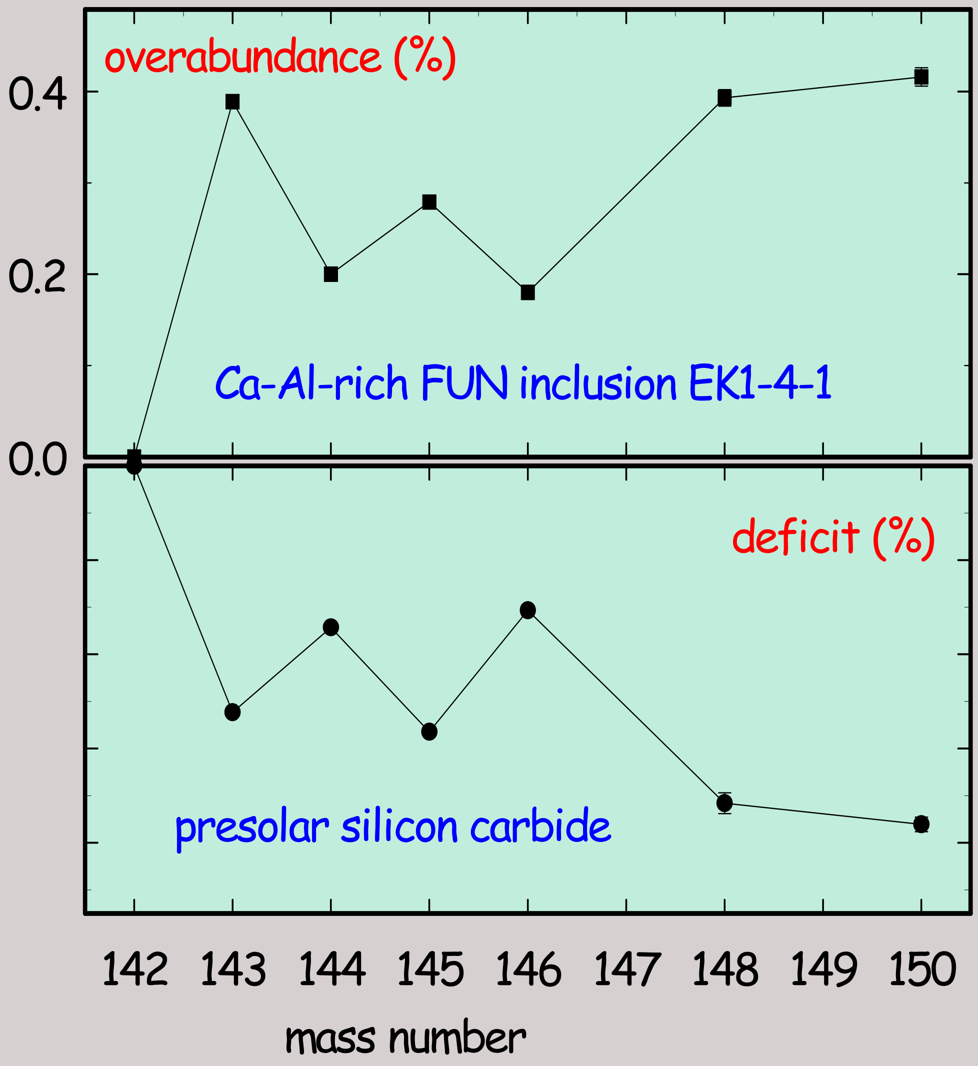
- *CV3 meteorite Axtell (Meteoritics cover)*

- *~ μm or less:*
  presolar grains

- *~ mm size:*
  - chondrules
  - CAIs (Ca-Al-rich) = first Solar System condensates

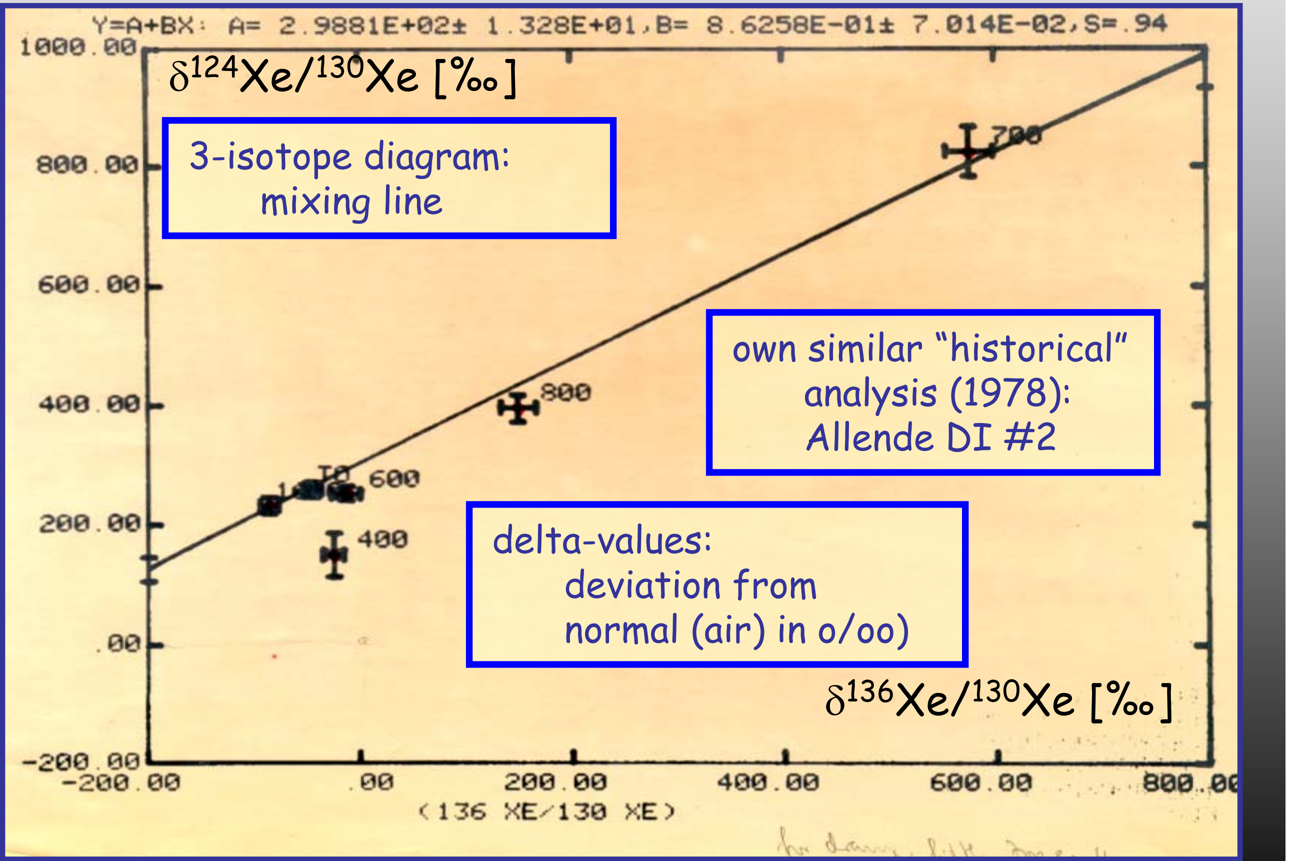
Presolar grain anomalies - stardust
vs. CAIs = formed within Solar System

- CAIs
  contain *some* material not completely homogenized isotopically with rest of Solar System; but formed within
- presolar grains
  = ***stardust***,
  record earlier stage; effects much larger



- ❖ key to identification of presolar matter in meteorites: natural low abundance of noble gases in solids; unusual isotopic structures of noble gases in presolar materials can “shine through“ even in bulk analyses
- ❖ …. 1964: Reynolds and Turner: stepwise release and analysis of xenon isotopes in carbonaceous chondrite Renazzo

- ➢ Allende meteorite: Xe released in certain temperature steps: up to ~2x relative enhancement of lightest and heaviest isotopes
- ➢ Xe-HL from presolar diamond

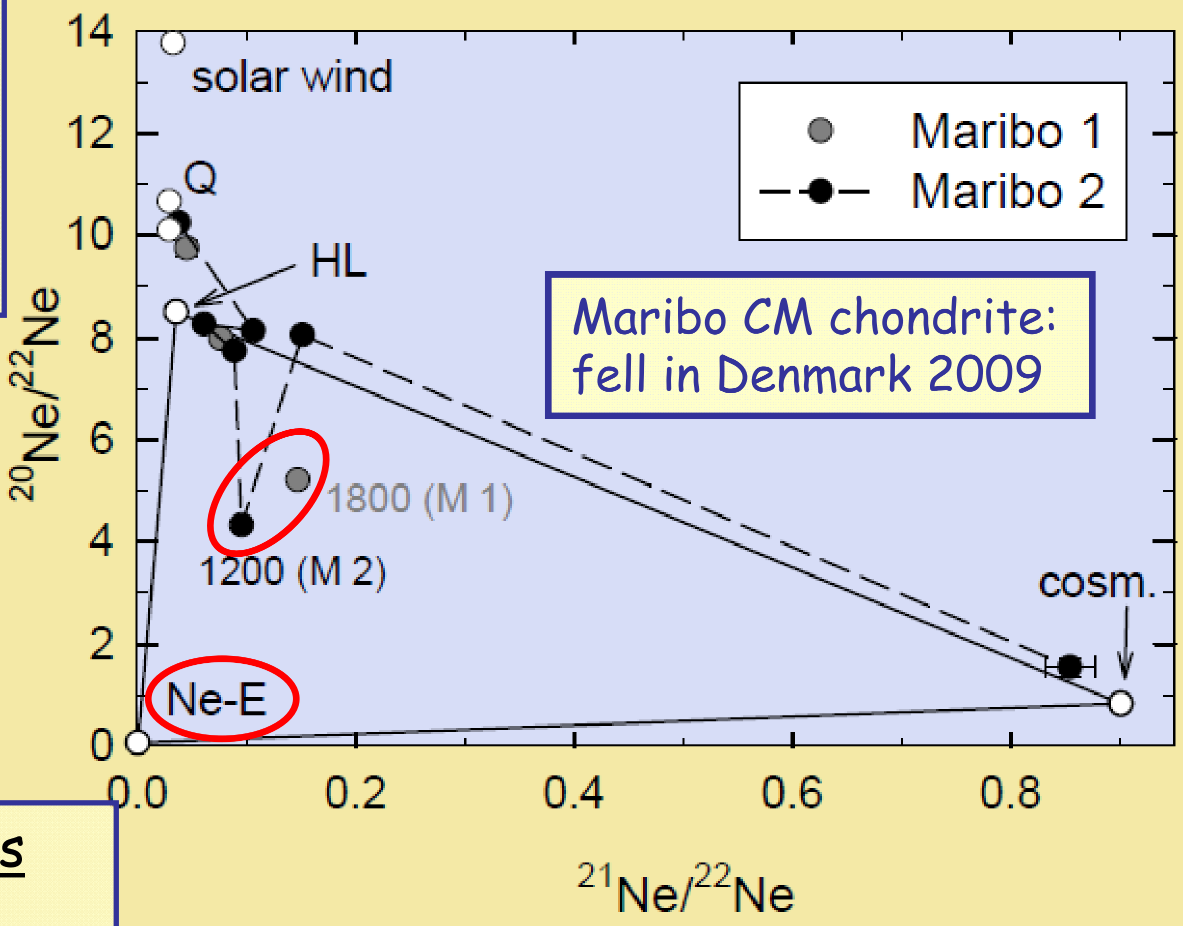


3-isotope diagram: mixing line

own similar “historical” analysis (1978): Allende DI #2

delta-values: deviation from normal (air) in o/oo

- similarly, heat a primitive CM / CI meteorite, in certain temperature steps: enhancement of ^{22}Ne



Maribo CM chondrite: fell in Denmark 2009

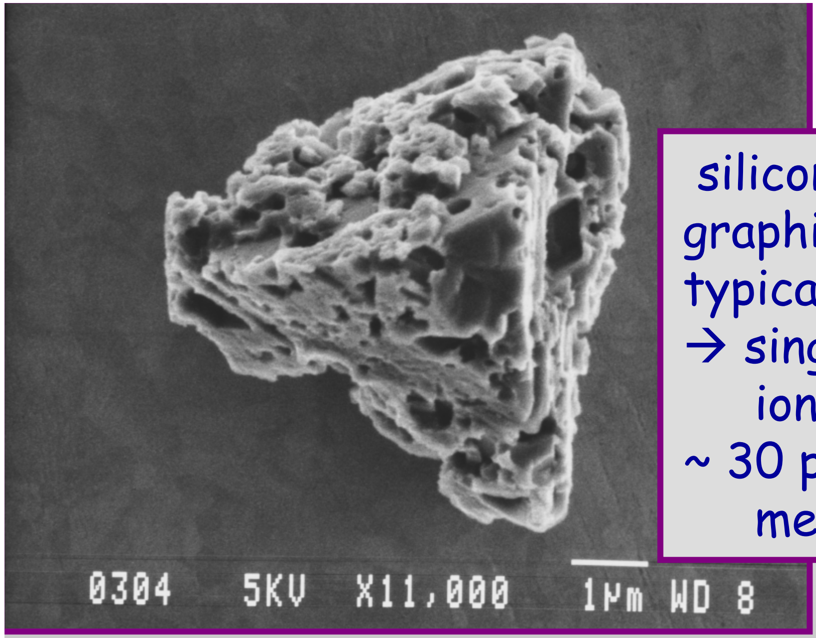
<u>characteristic noble gases</u>

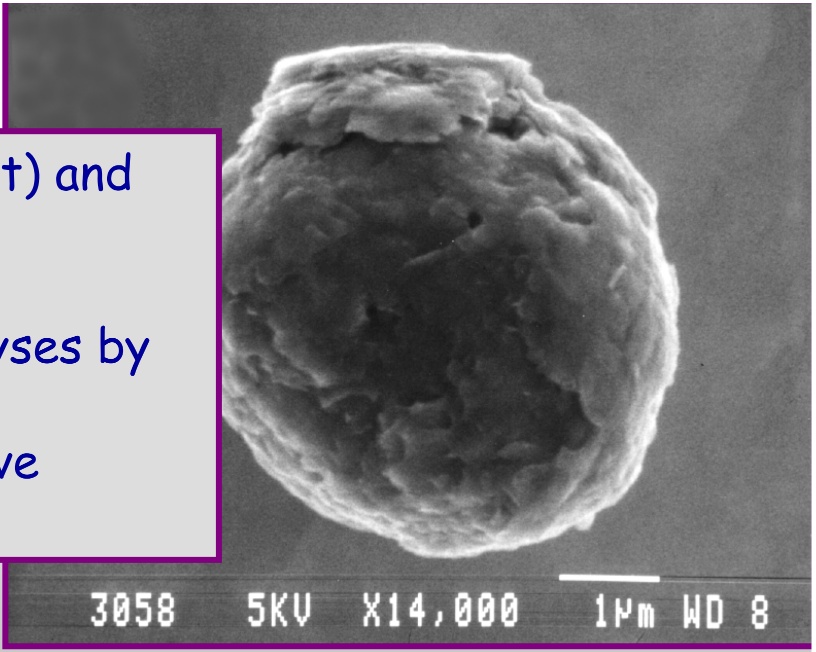
- Xenon-HL - diamonds
- Xe-S and Ne-E (almost pure ^{22}Ne) - silicon carbide (and graphite)

further characteristic of noble gas carriers: resistance to acids

Presolar grains in meteorites - **Overview**

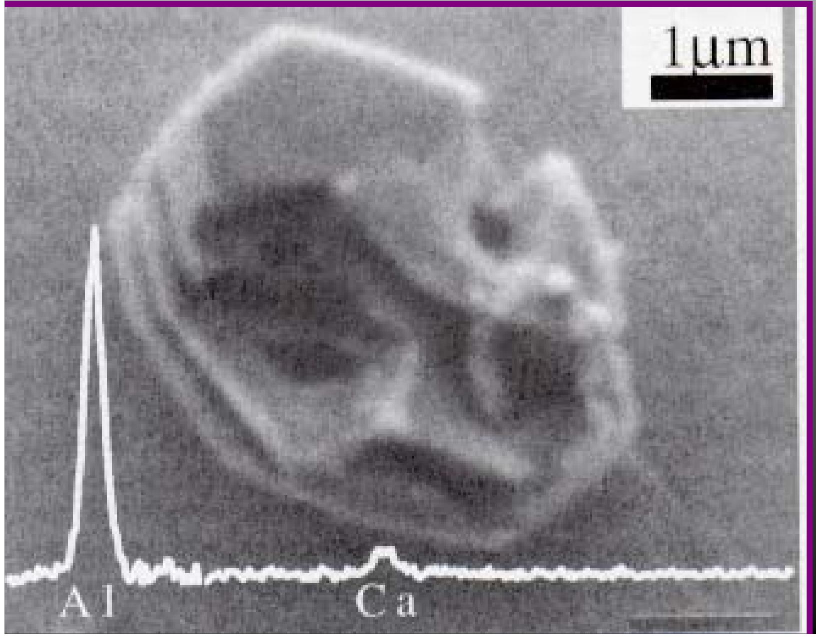
mineral	isotopic signatures	stellar source	contribution
diamond **1500 ppm**	Kr-H, Xe-HL, Te-H	supernovae	?
silicon carbide **30 ppm**	enhanced ^{13}C, ^{14}N, ^{22}Ne, s-process elements low ^{12}C/^{13}C, often enhanced ^{15}N enhanced ^{12}C, ^{15}N, ^{28}Si; extinct ^{26}Al, ^{44}Ti low ^{12}C/^{13}C, low ^{14}N/^{15}N	AGB stars J-type C stars (?) supernovae novae	> 90 % < 5 % 1 % 0.1 %
graphite **10 ppm**	enhanced ^{12}C, ^{15}N, ^{28}Si; extinct ^{26}Al, ^{41}Ca, ^{44}Ti Kr-S low ^{12}C/^{13}C low ^{12}C/^{13}C; Ne-E(L)	SN (WR?) AGB stars J-type C stars (?) novae	80 % < 10 % < 10 % 2 %
>50 ppm corundum/ spinel **> 200 ppm** silicates	enhanced ^{17}O, moderately depleted ^{18}O enhanced ^{17}O, strongly depleted ^{18}O enhanced ^{16}O similar to oxides above	RGB and AGB AGB stars supernovae	> 70 % 20 % 1 %
silicon nitride **0.002 ppm**	enhanced ^{12}C, ^{15}N, ^{28}Si; extinct ^{26}Al	supernovae	100 %



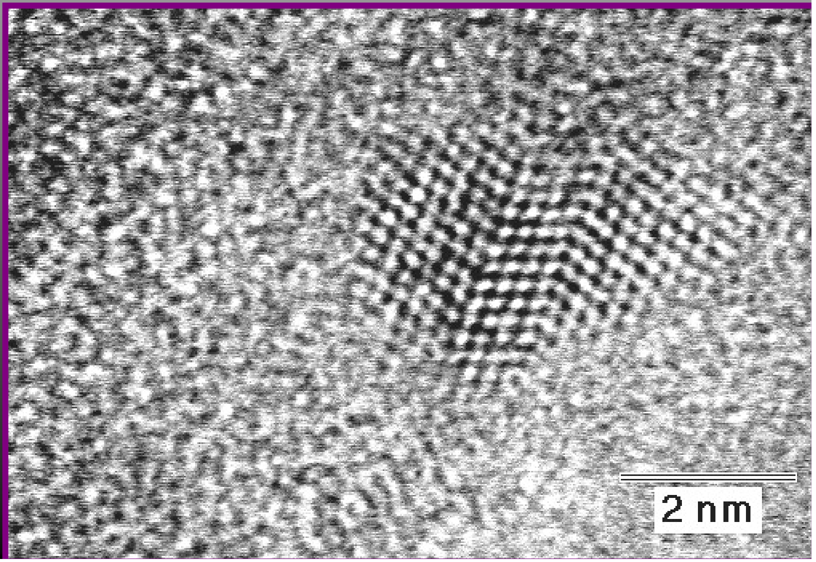


silicon carbide (left) and graphite (right);
typically µm-sized
→ single grain analyses by ion microprobe,
~ 30 ppm in primitive meteorites

hibonite: rare

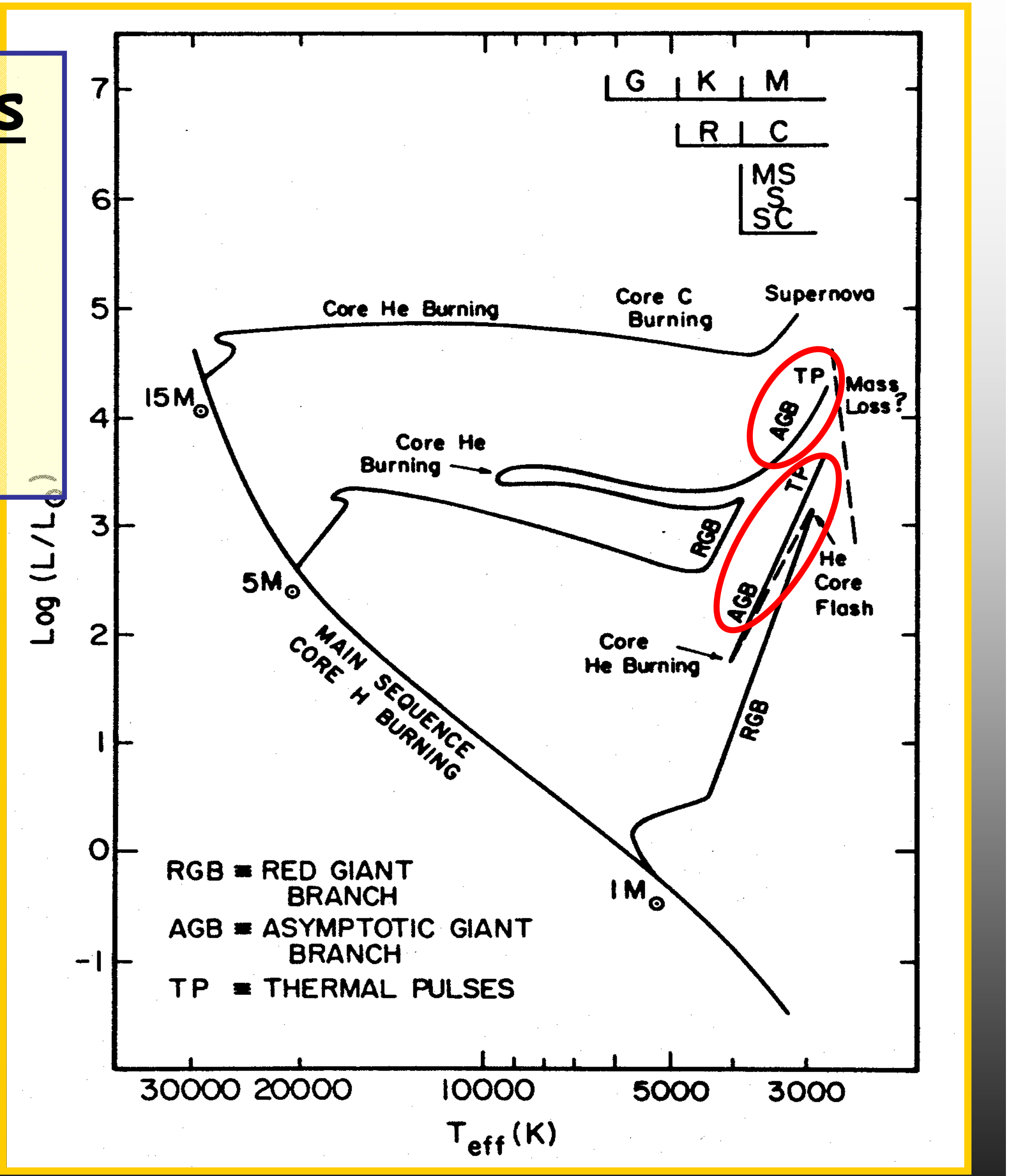


nanodiamond (TEM): ~ 1000 C atoms; abundant (~ 1.5 per mill)



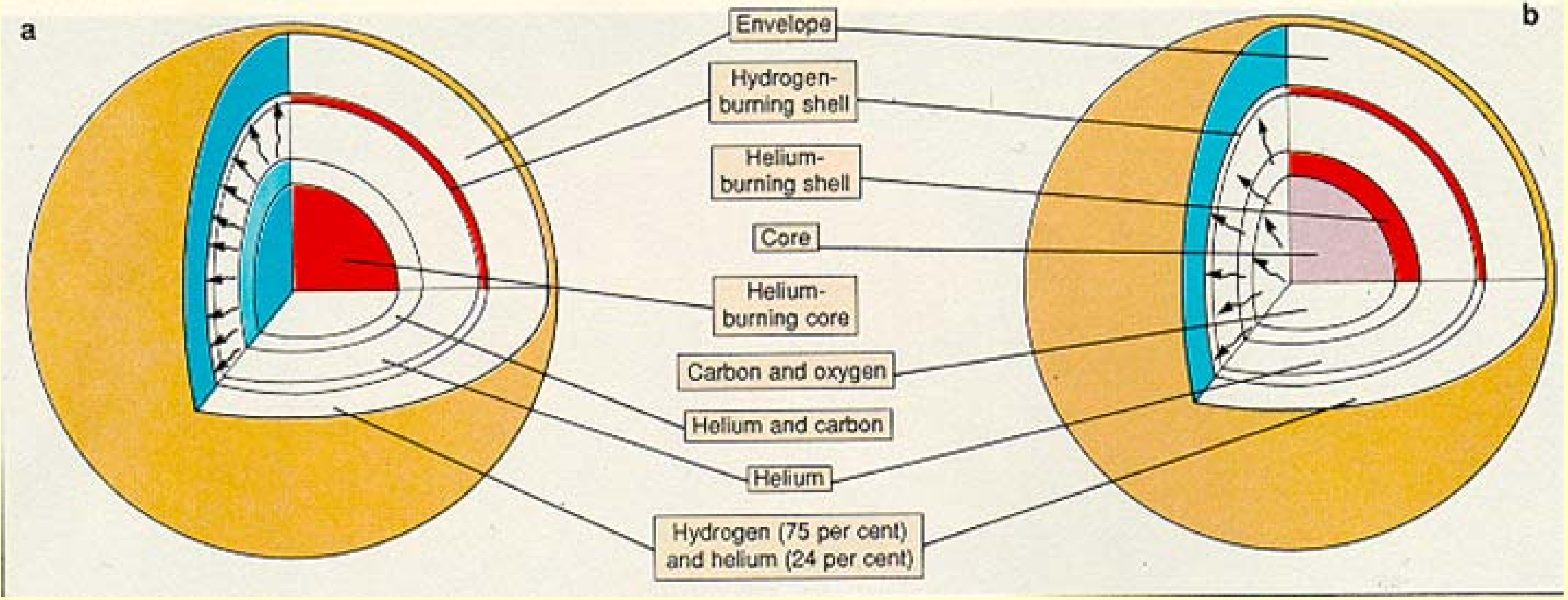
major dust factories

- *AGB stars (low mass < 8 M_{sun})*
- *and supernovae (high mass)*



Hertzsprung-Russell diagramm

➢ *AGB stars (low mass < 8 M_{sun})*



-- C-O-core (from core He burning)

-- alternate He and H burning in shells

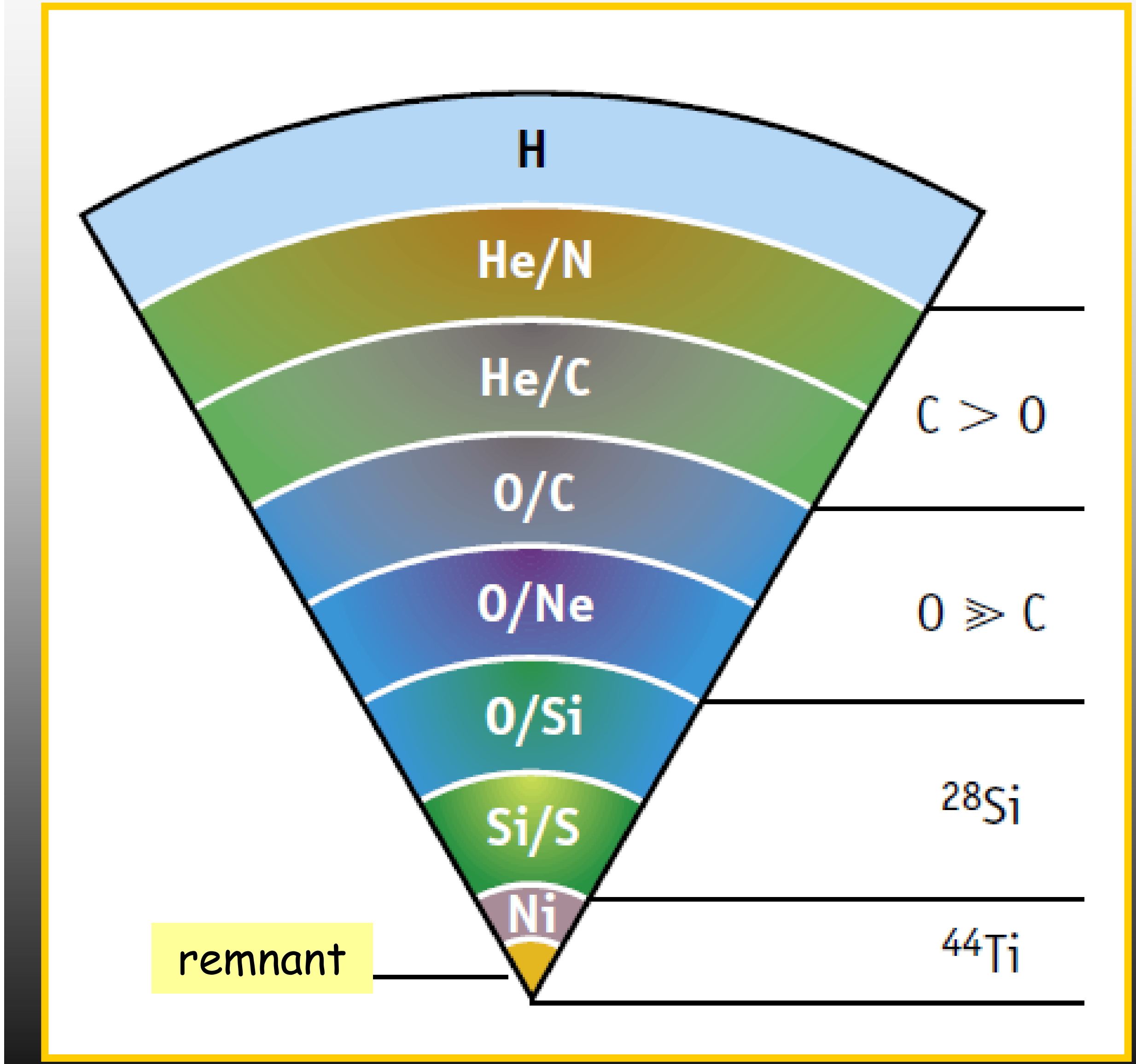
$3\,\alpha \rightarrow {}^{12}C$,

→ Ne-E (almost pure ^{22}Ne from α-captures on ^{14}N),

→ s-process

-- (3rd dredge up)→ surface; winds → grain condensation

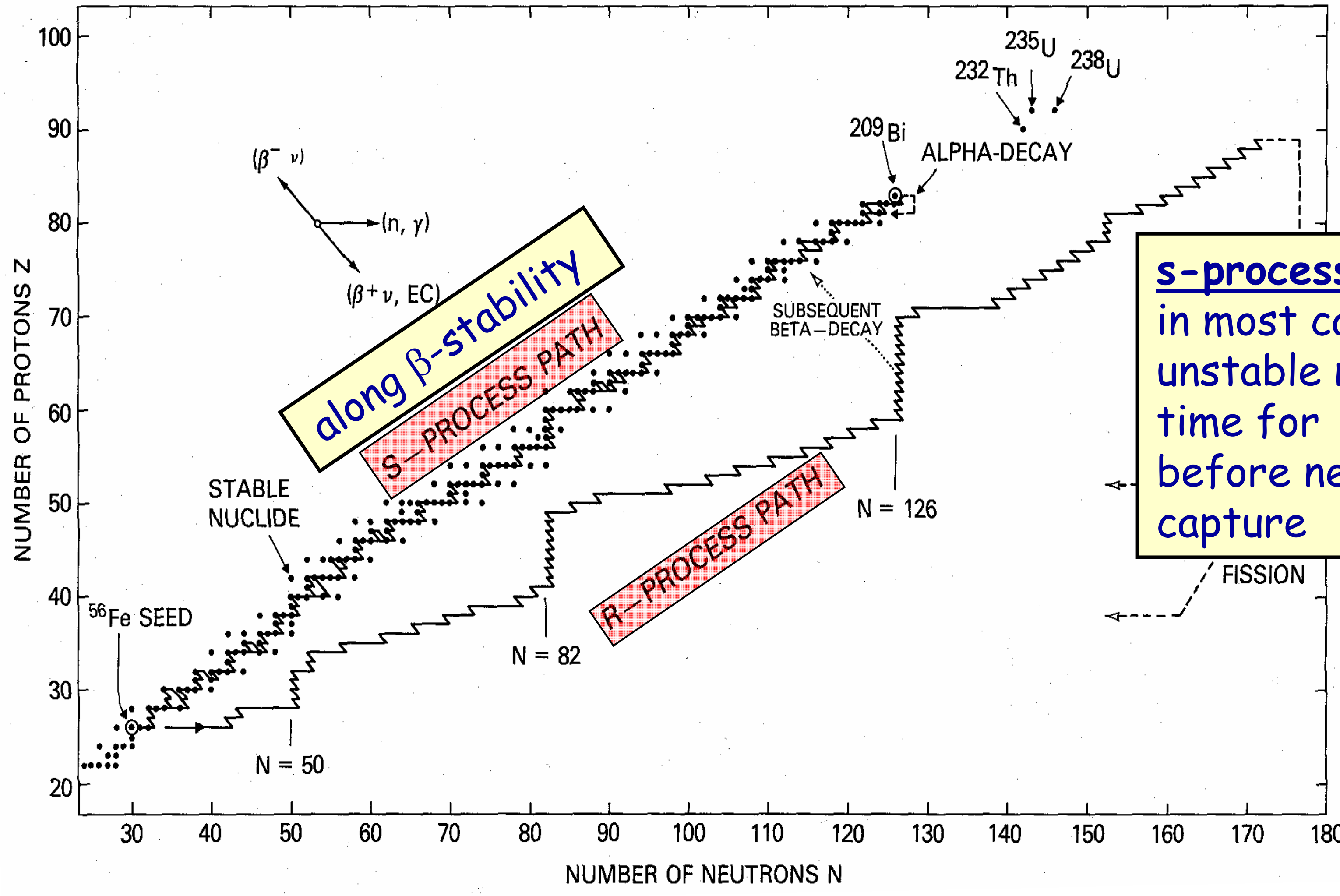
➢ supernovae (high mass > 8 M_{sun})



- higher temperatures, densities → higher burning phases
- "onion shell" structure
- explosion + explosive nucleosynthesis

main nucleosynthesis interest in heavy elements;

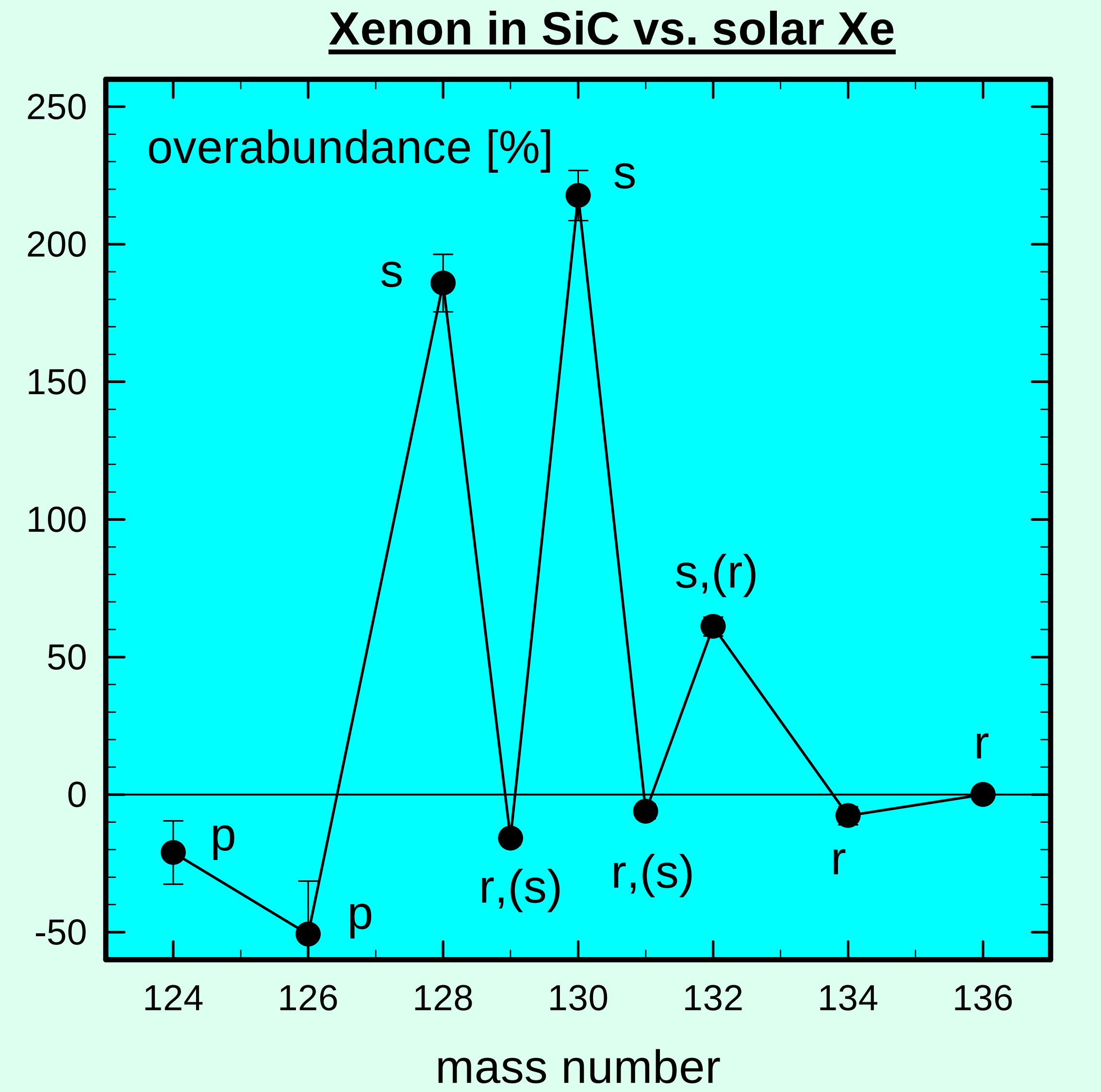
s-process (slow neutron capture) and r-process (rapid);
each source of about half of the elements heavier than Fe



s-process:
in most cases, unstable nuclei have time for β-decay before next neutron capture

Most clear-cut case: silicon carbide

- best (?) understood nucleosynthesis process: s-process
- takes place in He shell of TP-AGB stars
- most (>90%) of presolar SiC grains come from AGB stars (from single grain C, Si etc. analyses)

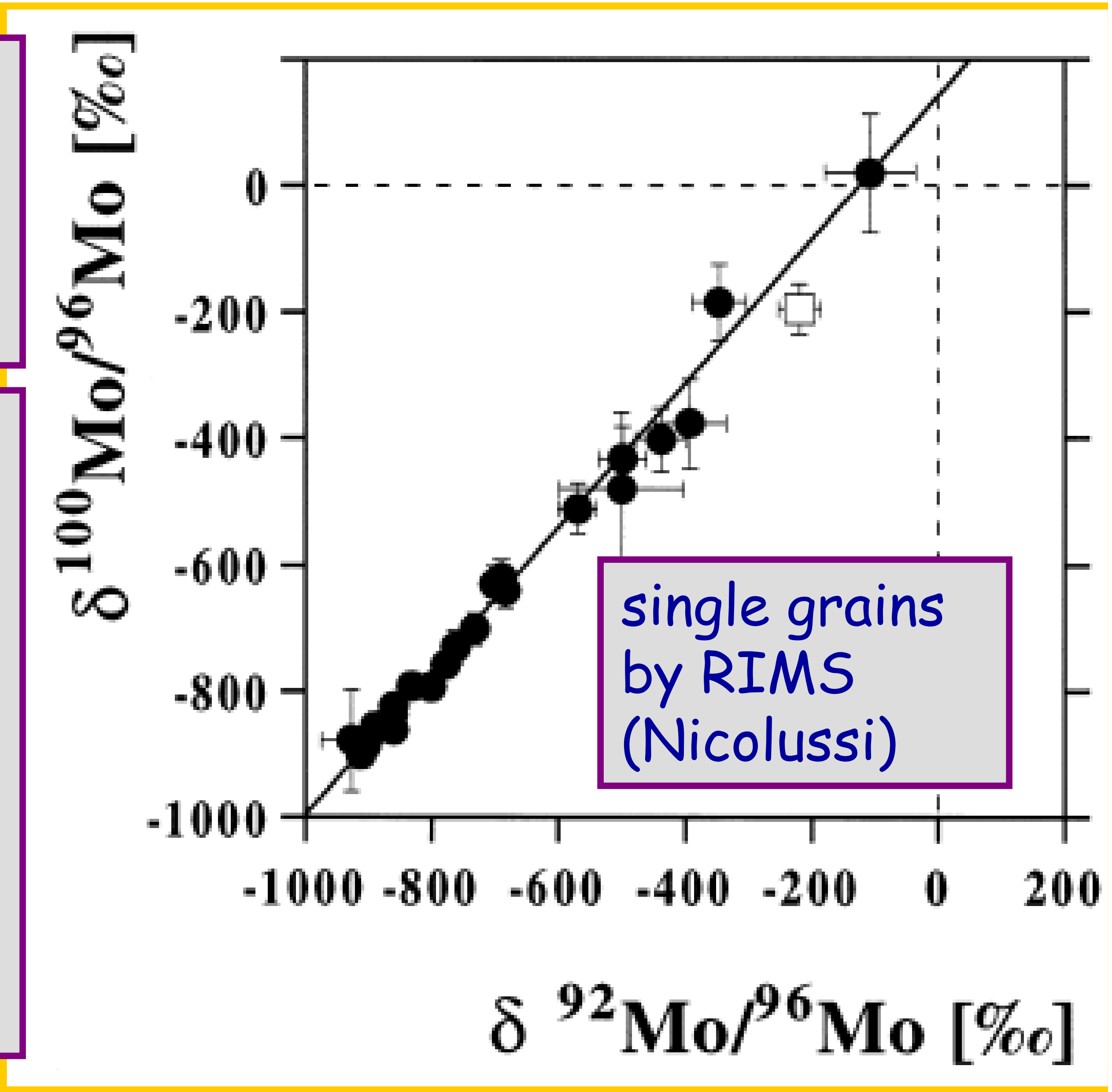


Xenon in SiC vs. solar Xe

Molybdenum in SiC

- most convincing abundant (fits chemically)

- most SiC grains: from AGB stars, s-process signature
- abundance of p-only ^{92}Mo and r-only ^{100}Mo = 0; i.e. delta-values = - 1000 ‰

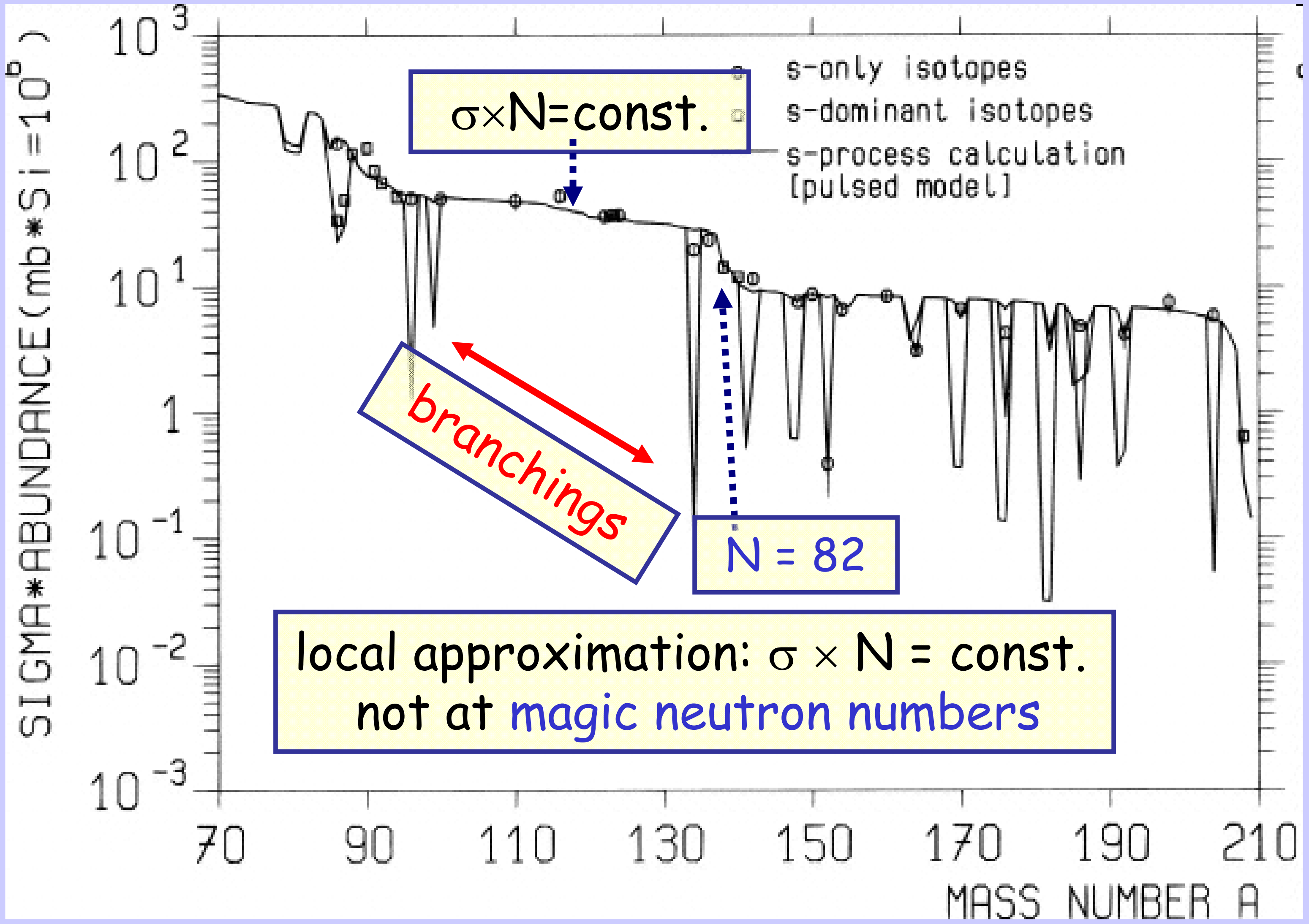


single grains by RIMS (Nicolussi)

some data on s-process by various methods

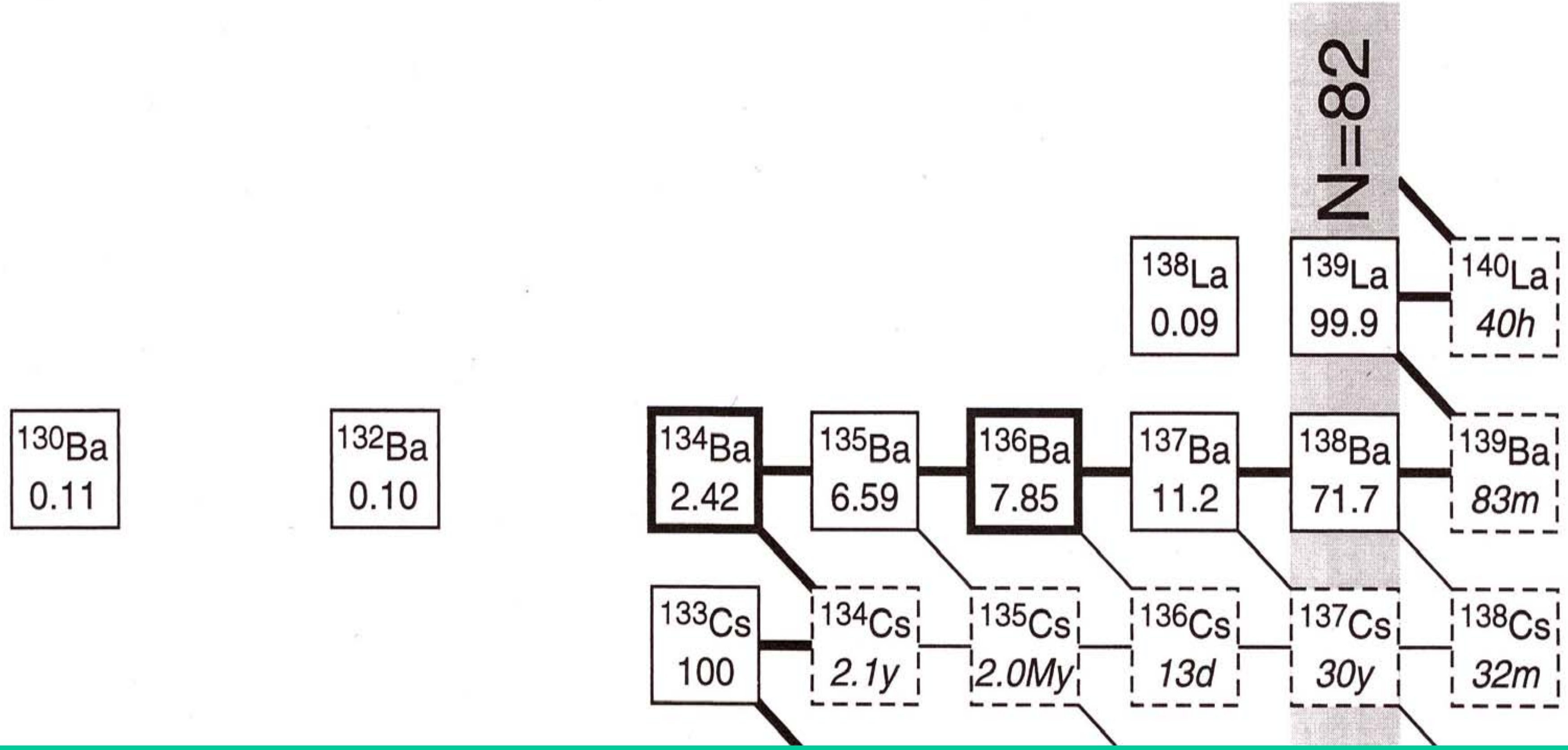
- noble gas mass spectrometry → noble gases (Kr, Xe)
- thermal ionization mass spectrometry
  → first analyses of "solid elements" (bulk SiC):
  Sr, Ba, Nd, Sm, Dy
- single grain analysis of single SiC grains by
  -- RIMS (resonance ionization mass spectrometry):
  Sr, Zr, Mo, Ru, Ba
  -- NanoSIMS (Ba)
- bulk SiC analysis by slurry ICP-MS (multi-element)

- s-process and solar system abundances: flow equilibrium almost reached
  → over large ranges valid is "local approximation"



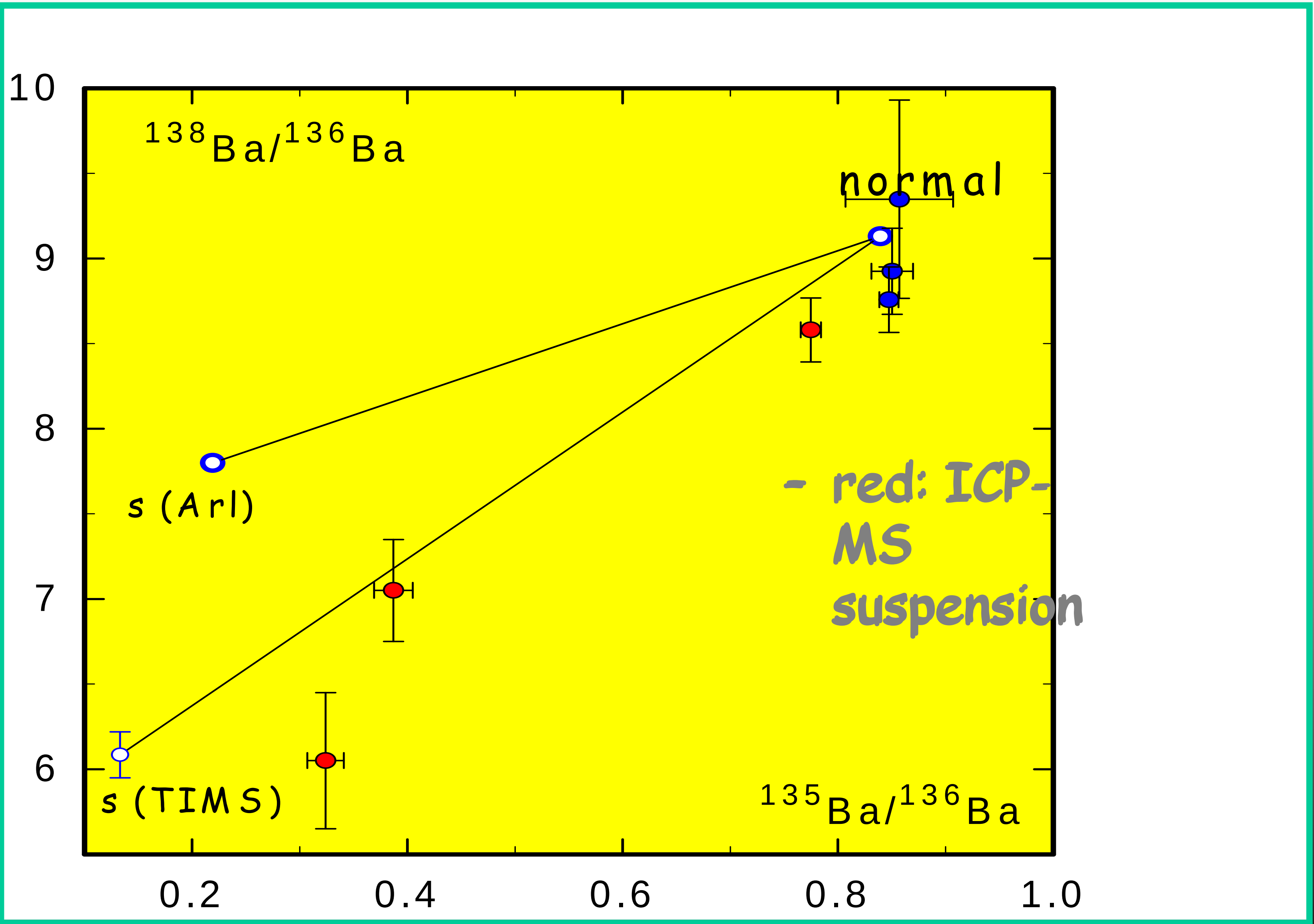
local approximation: σ × N = const.
not at magic neutron numbers

Barium

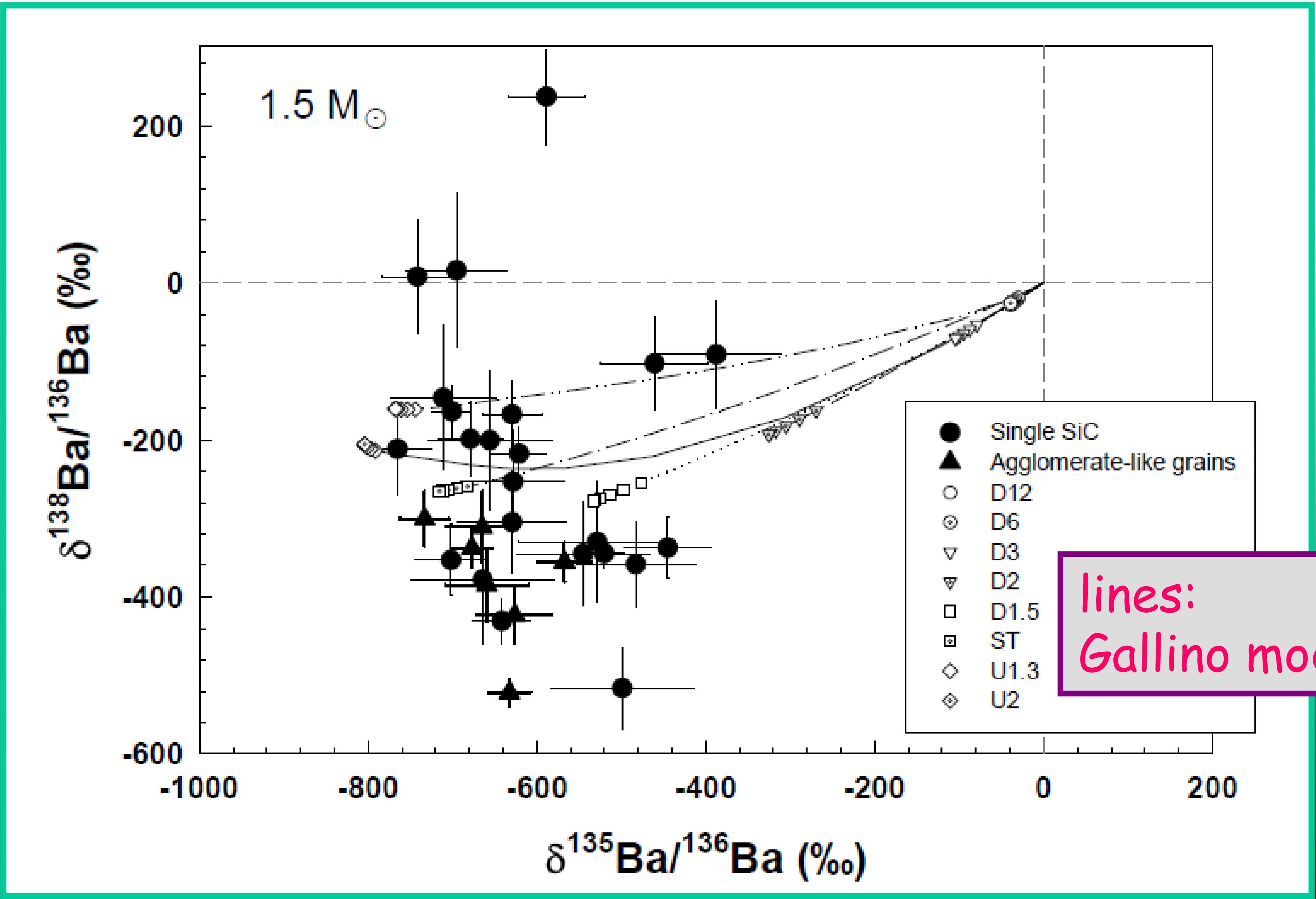


-- interesting branching at ^{134}Cs → ^{134}Ba/^{136}Ba, ^{135}Ba/^{136}Ba
-- closed neutron shell at ^{138}Ba → ^{138}Ba/^{136}Ba

well known lower than solar s-Ba ^{138}Ba/^{136}Ba: bulk SiC

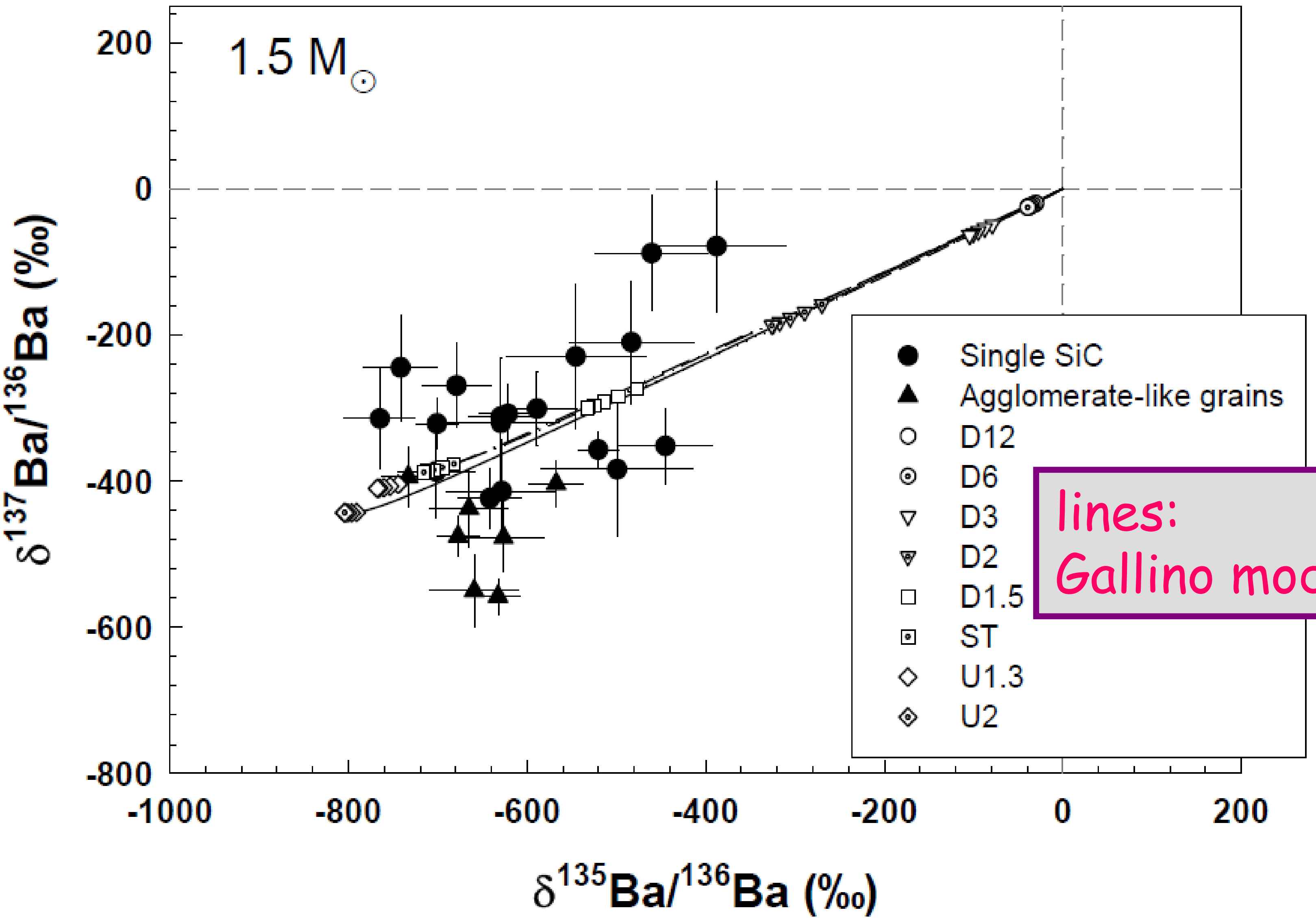


Barium single grains by NanoSIMS (Marhas): how good are the models?



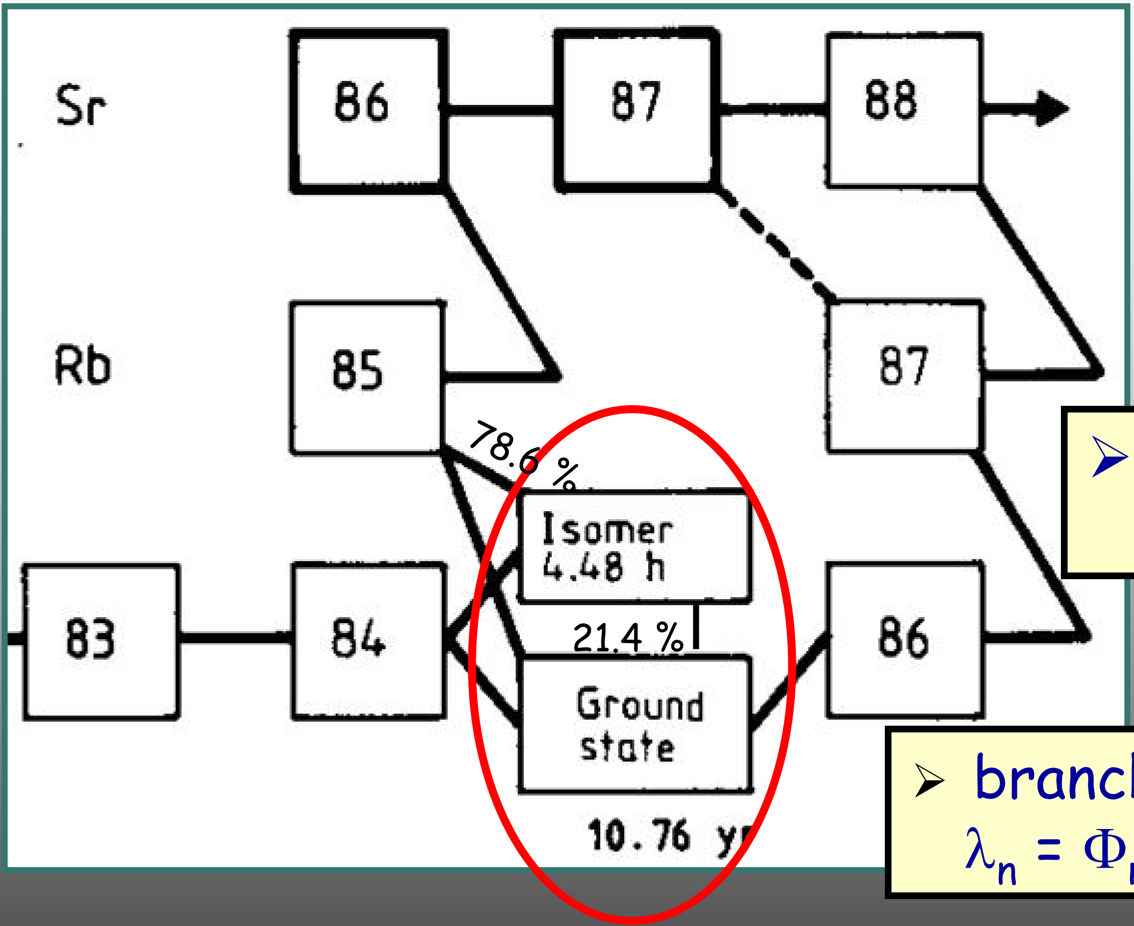
lines:
Gallino models

a closer look at ^{137}Ba



lines:
Gallino models

- branching: competition between neutron capture and β-decay; e.g. at ^{85}Kr

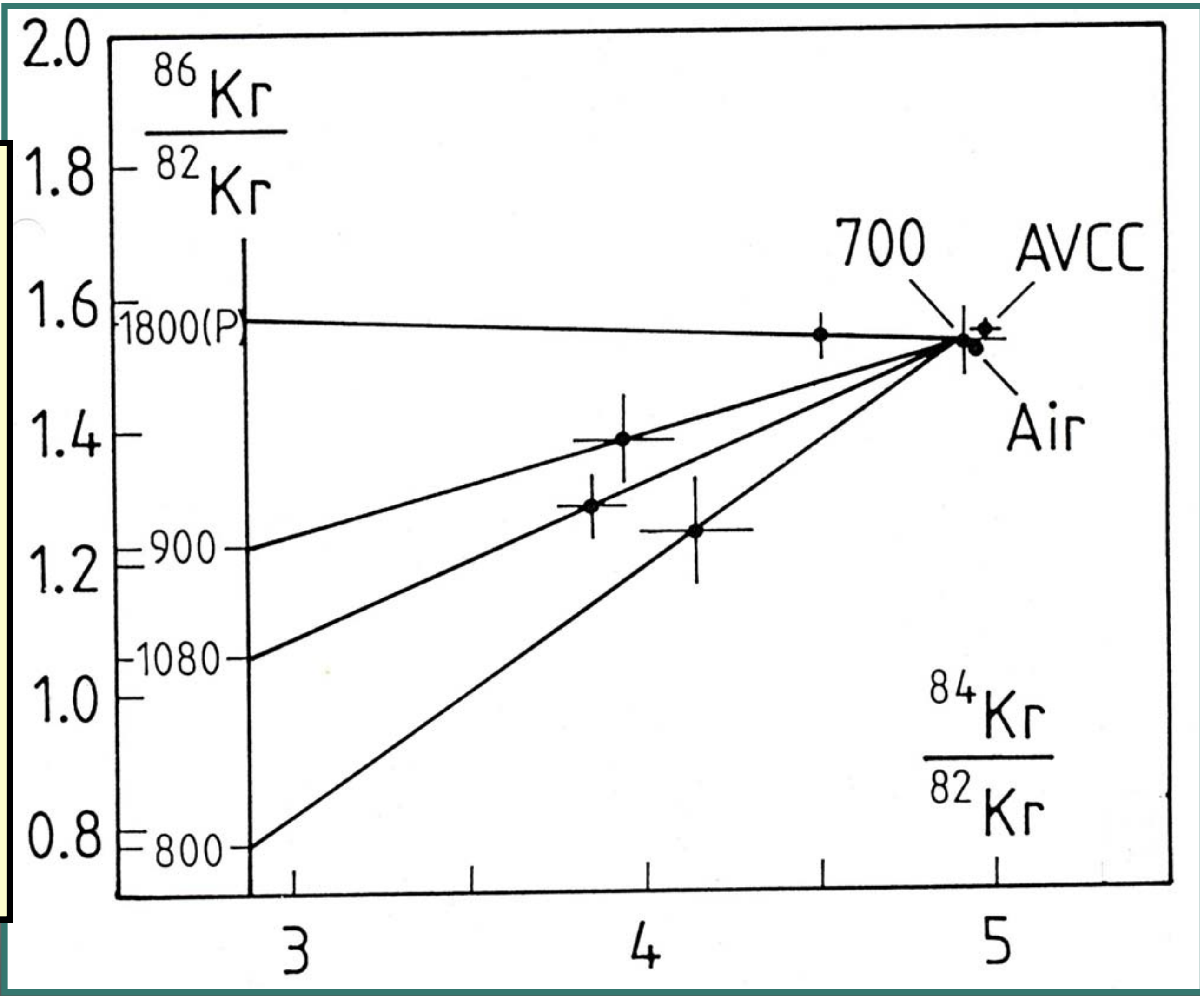


- half life of ^{85}Kr ground state: 10.76 a

- branching factor $f_n=\lambda_n/(\lambda_n+\lambda_\beta)$
  $\lambda_n = \Phi_n \sigma = n_n v_{th} \sigma$

- thus: ^{86}Kr/^{84}Kr ratio sensitive to neutron density

- stepwise combustion → variable ^{86}Kr/^{82}Kr → production at variable n densities
- timescales for n capture on the order of ^{85}Kr half life

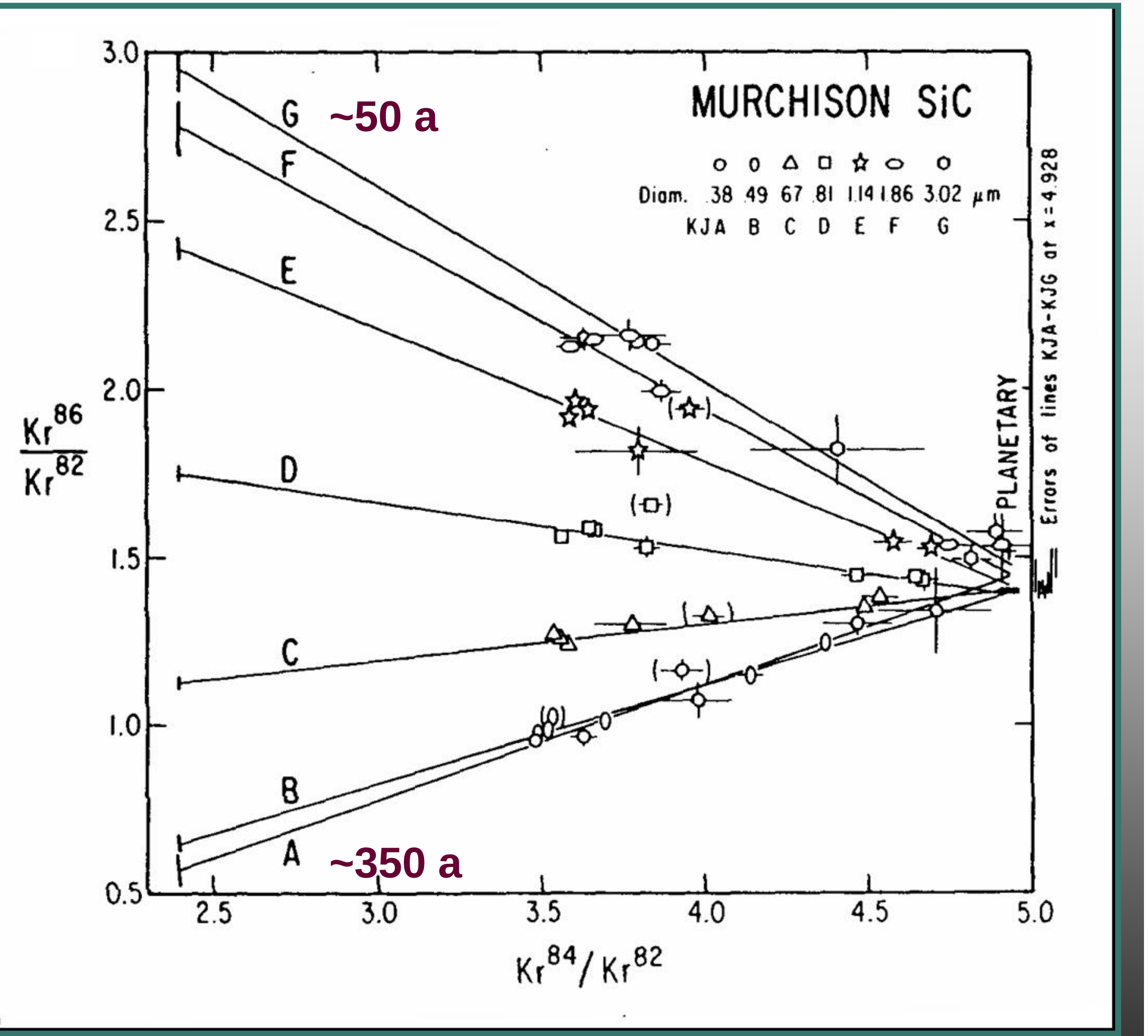


- same observation in analysis of SiC size separates (Lewis et al.)

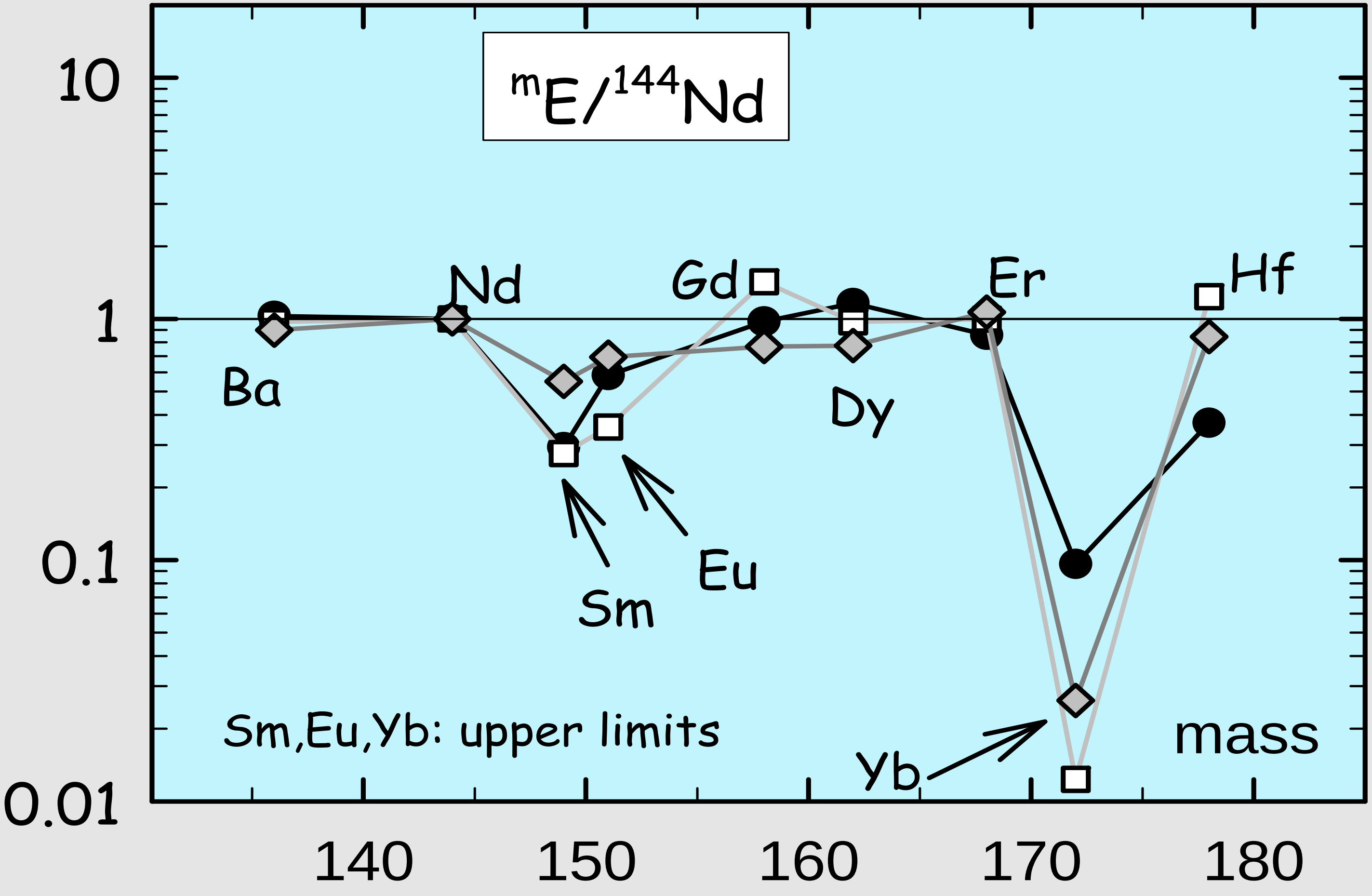
- classical model of s-process (constant neutron density, temp. etc.)

- → half life against neutron capture between **~50 a (G)** and **~350 a (A)**

- → n densities between 0.44 and 3.1 x10^8 cm^{-3}



- large overview Ba to Hf (Yin et al.) by ICP-MS solution – limited isotopeic data



overall relative elemental abundance pattern in REE region ~ predictions (exceptions Dm, Eu, Yb: volatility)

Celestial History

how to date a presolar grain…. ?

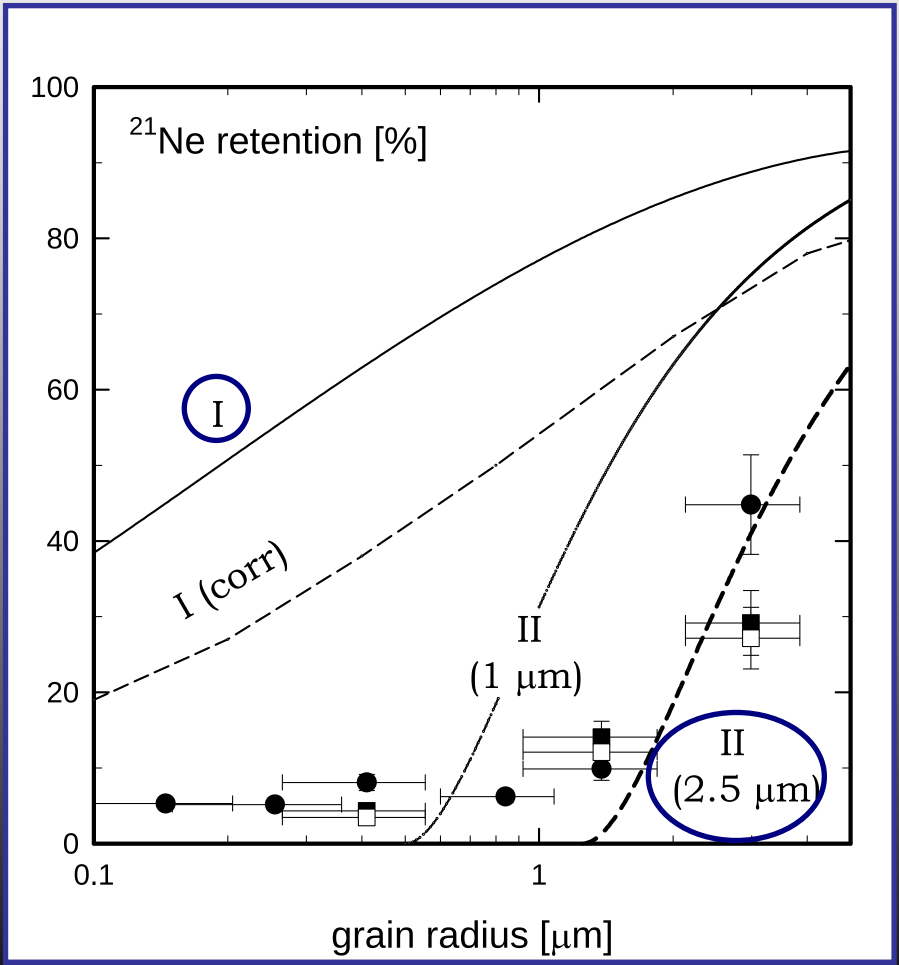
- classical approach – radioactive decay:
  D = daughter, P = parent element;
  1, 2 = isotopes;
  1= radiogenic / radioactive; 2 = stable nonradiogenic
  λ = decay constant
- then: $D1/D2 = (D1/D2)_{ini} + (P1/D2)\,(e^{\lambda t}-1)$
- problem with stardust – unusual isotopic compositions
  → what was non-radiogenic ratio $(D1/D2)_{ini}$? (for "model age")
  → or: can one possibly assume grains lie on isochrone?
- alternative (first suggested/applied by Anders and colleagues)
  - exposure to cosmic rays (→ pre-solar cosmic ray exposure age, to be added to Solar System age)
- applied to SiC, CR production of ^{21}Ne from Si target

not so easy either…

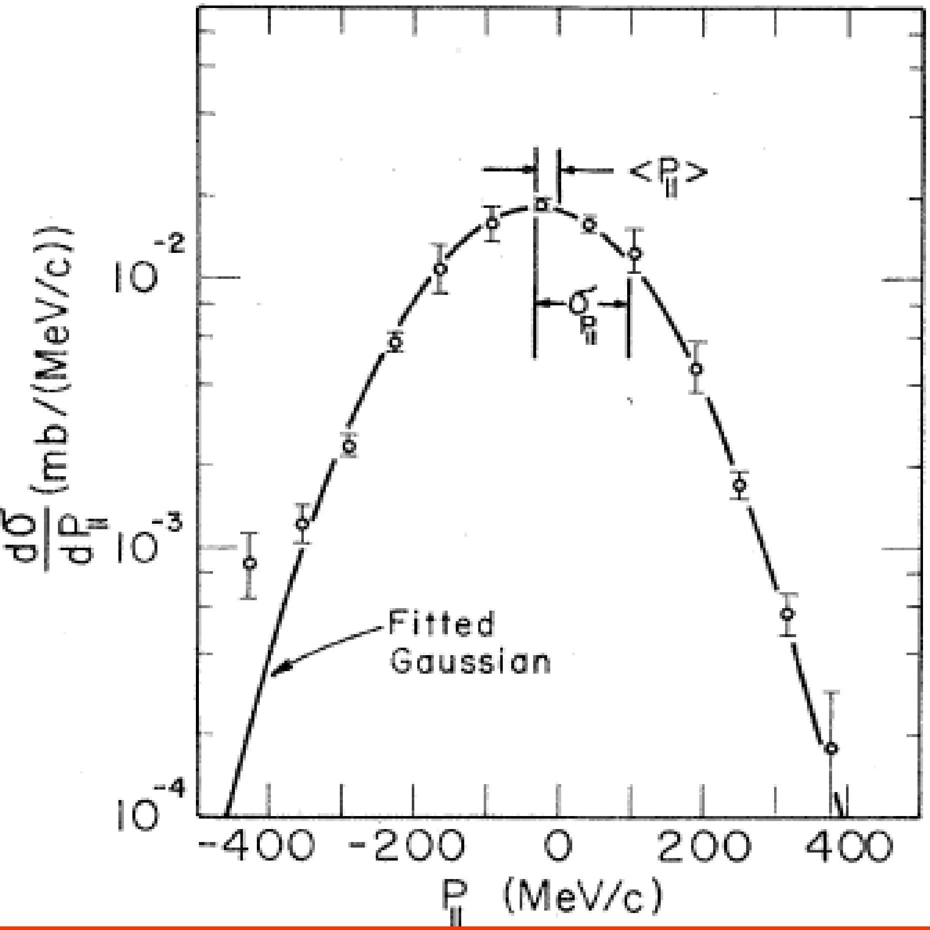
1. what is the abundance of non-cosmogenic ^{21}Ne?
2. what was the production rate (depending on flux and spectrum of cosmic rays) >4.6 Ga ago ?

3. significant error in first application (Tang and Anders 1988): recoil loss of spallation ^{21}Ne from µm-sized grains

- - used curve 1; based on an experiment of Greiner et al. (1975)
- - our experiment: mean range ~2.5 µm



The Greiner experiment

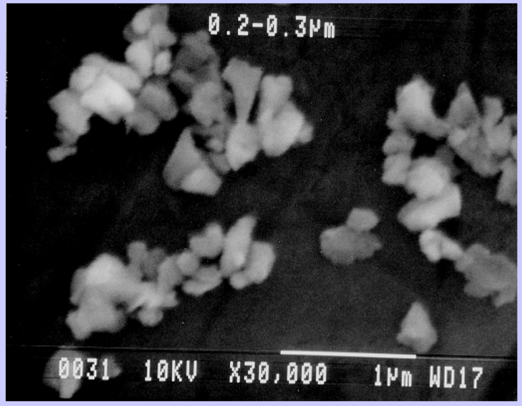


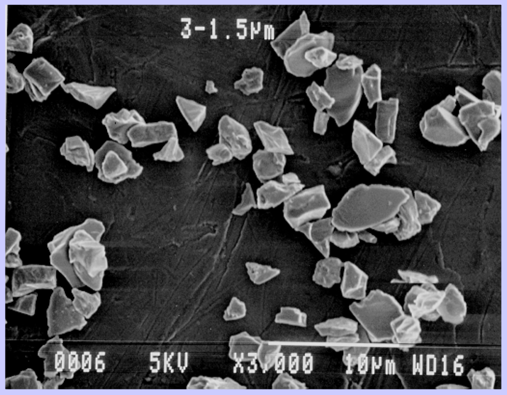
- fragmentation of C, O nuclei to produce He, Li, …
- momentum distribution ~ Gaussian isotropic in system where C,O nuclei ~ at rest
- like in grains…→ good data base for He, Li recoil
- **mistake** of Ray and Völk: averaging over momentum including direction
- however: two nuclei going into opposite direction with large momentum will be lost, even if their "average" momentum is close to zero!!!

→ fold momentum /energy distribution with energy-range relationship → recoil losses

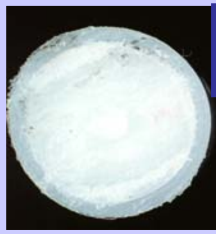
an experiment…

1. take (terrestrial) SiC grains of various sizes



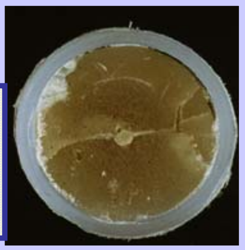


2. distribute homogeneously (and sufficiently separated) in a matrix where spallation does not produce ^{21}Ne



paraffin wax

paraffin wax with SiC



3. irradiate with energetic protons (1.6 GeV), at Saturne (Saclay) – satellite experiment
4. recover irradiated SiC, measure Ne in grains, compare with production (from ^{22}Na in SiC+paraffin)

most recent work / new possibilities - collaborations

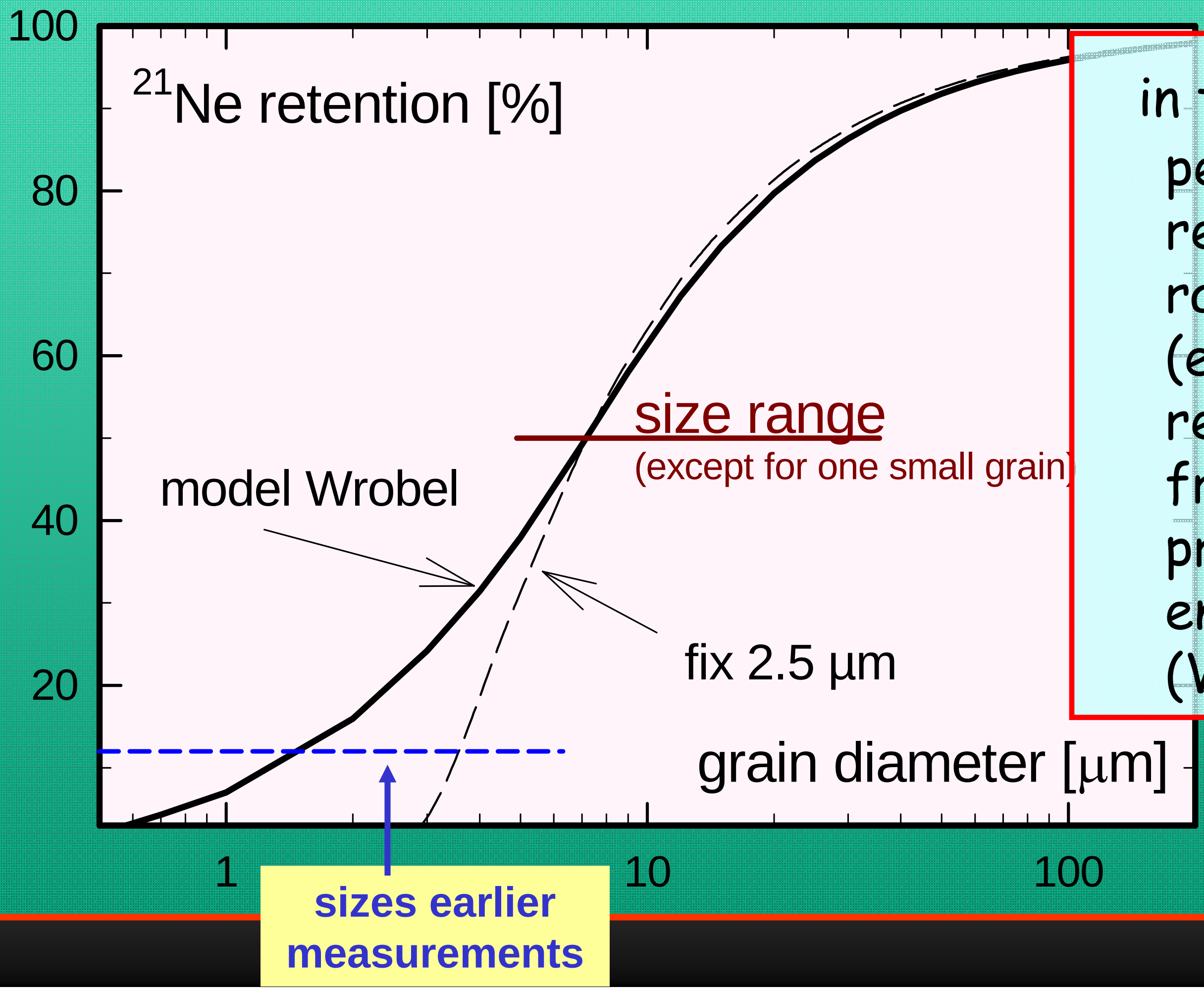
- new technology for high-sensitivity Ne analyses (ETH Zürich);
  + supply of "large" (> 5 µm) SiC grains (Chicago, St. Louis)
  → analyses of single large grains (little recoil loss)
- evidence for cosmic ray effects in such large grains also seen in Li isotopes (enhanced $^{6}Li/^{7}Li$) – St. Louis
- calculations of recoil energy *distribution*
  by **F. Wrobel** (Montpellier)

New results: Jumbo grains

large grains: 5-35 µm

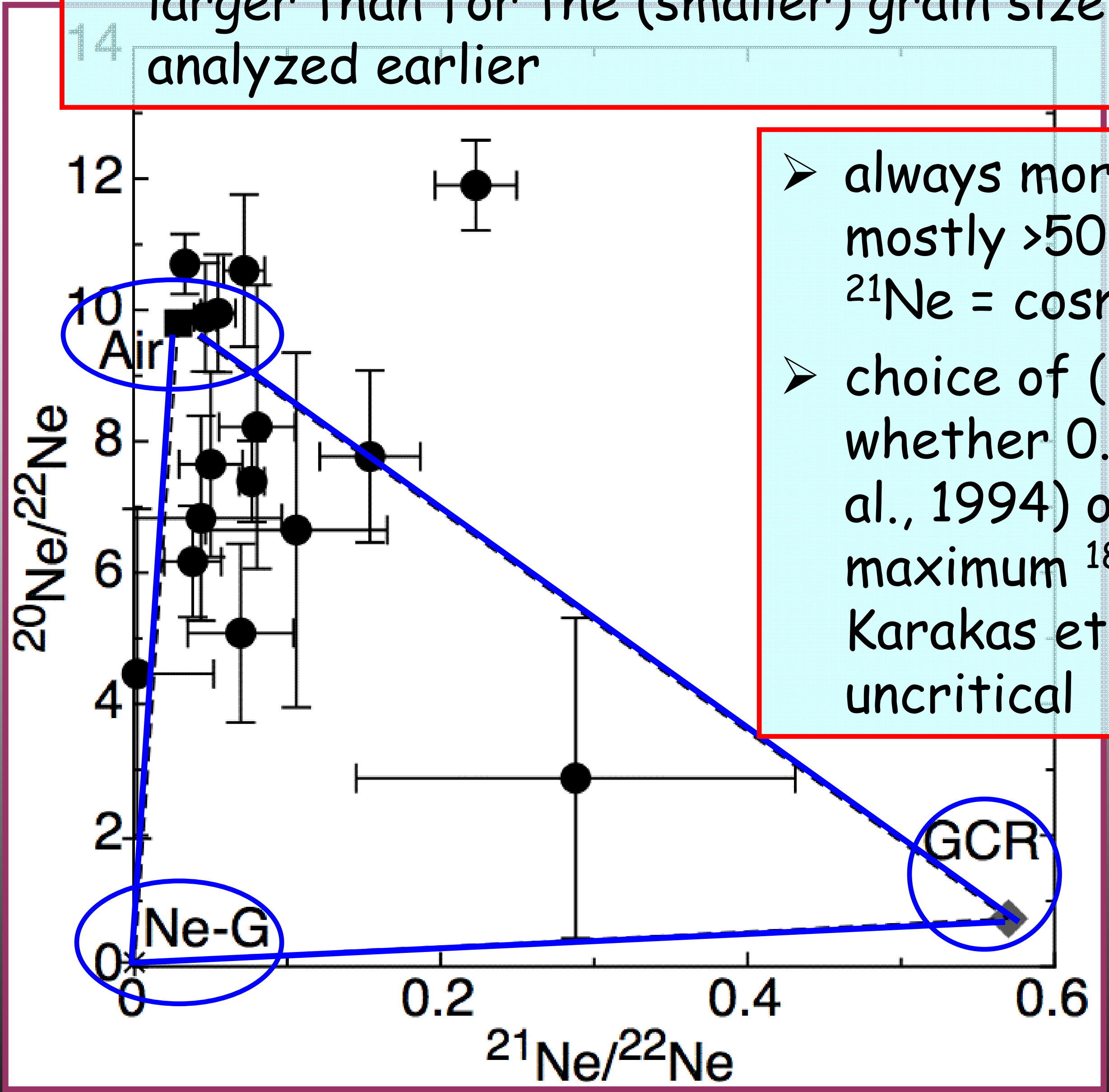
(except for one small ~ 2 µm grain; not considered here)

→ recoil correction unproblematic



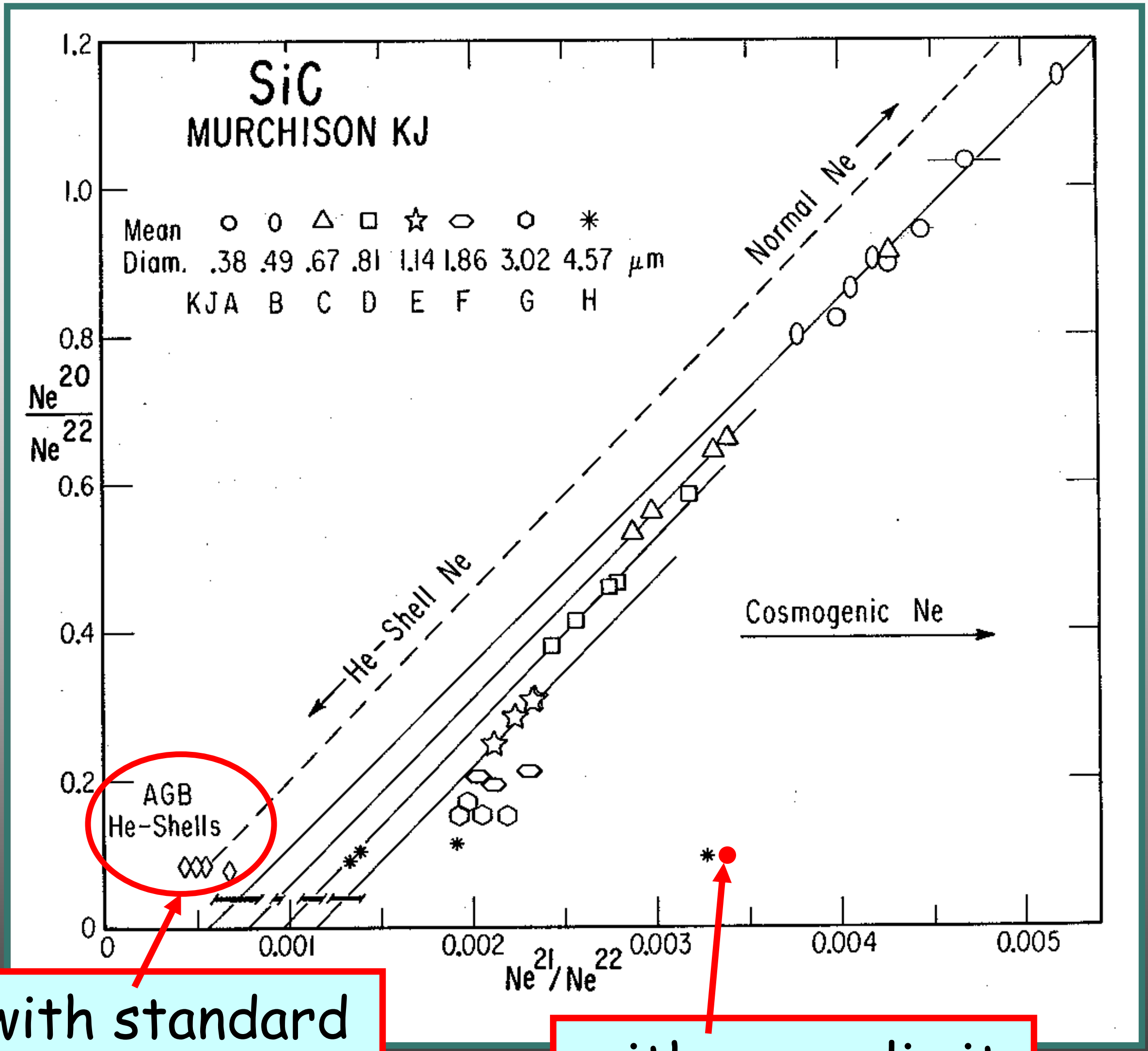
in this size range:

perfect agreement of recoil losses for fixed range of 2.5 µm (experiment, Morissey relation similar) and from theoretical predictions of recoil energy distribution (Wrobel) – ***and small*** moreover: fraction of ^{21}Ne that is cosmogenic is much larger than for the (smaller) grain size separates analyzed earlier



- always more than 30%, mostly >50 %, up to 97% of ^{21}Ne = cosmogenic
- choice of (^{21}Ne/^{22}Ne)-G, whether 0.00059 (Lewis et al., 1994) or 0.0033 (for maximum ^{18}F(α,p)^{21}Ne rate; Karakas et al, 2008) uncritical

- situation different for more typical SiC grains size separates)
- not only critical recoil losses, but also critical assumptions on stellar $^{21}Ne/^{22}Ne$

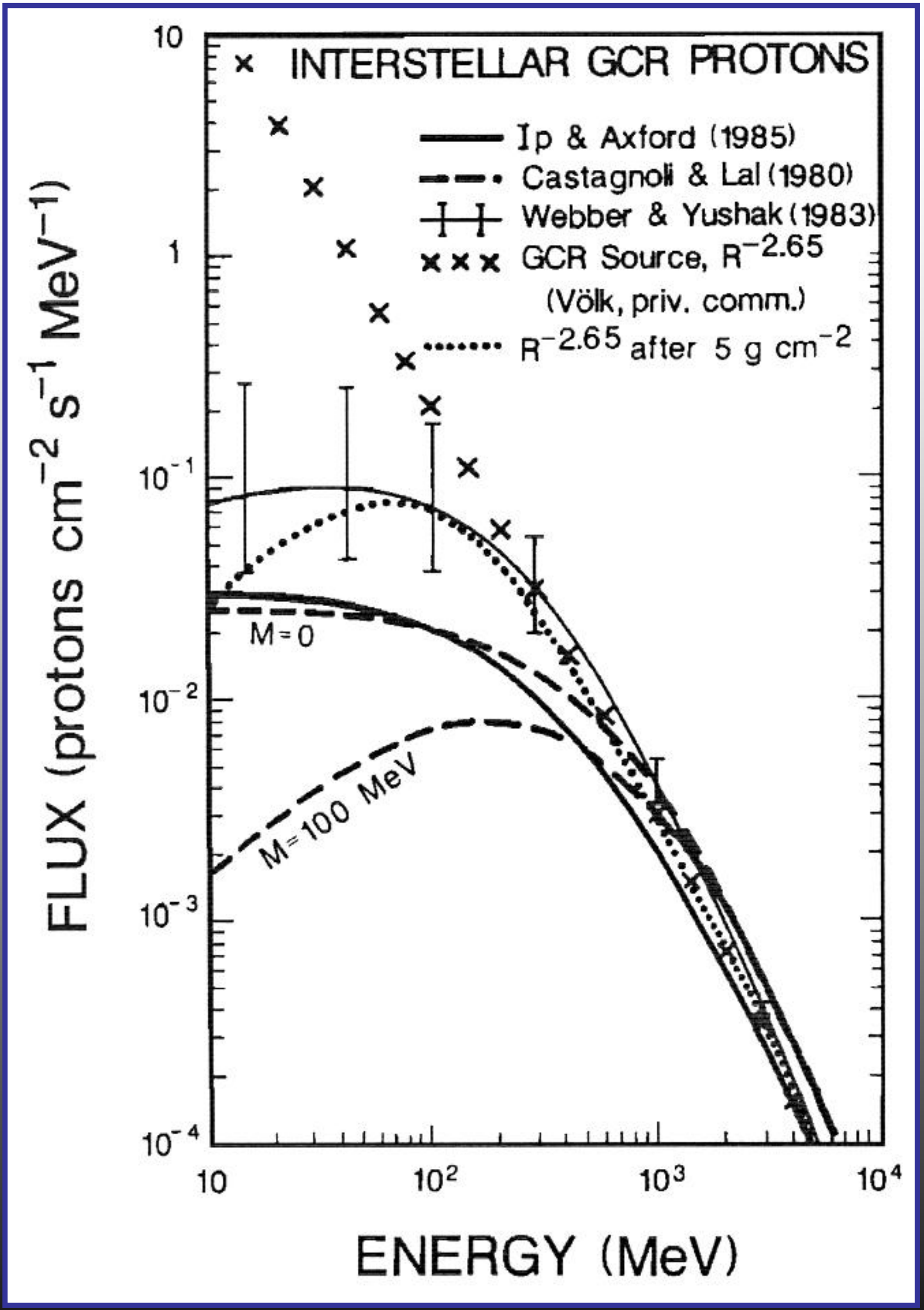


with standard rates

with upper limit for $^{18}F(\alpha,p)^{21}Ne$

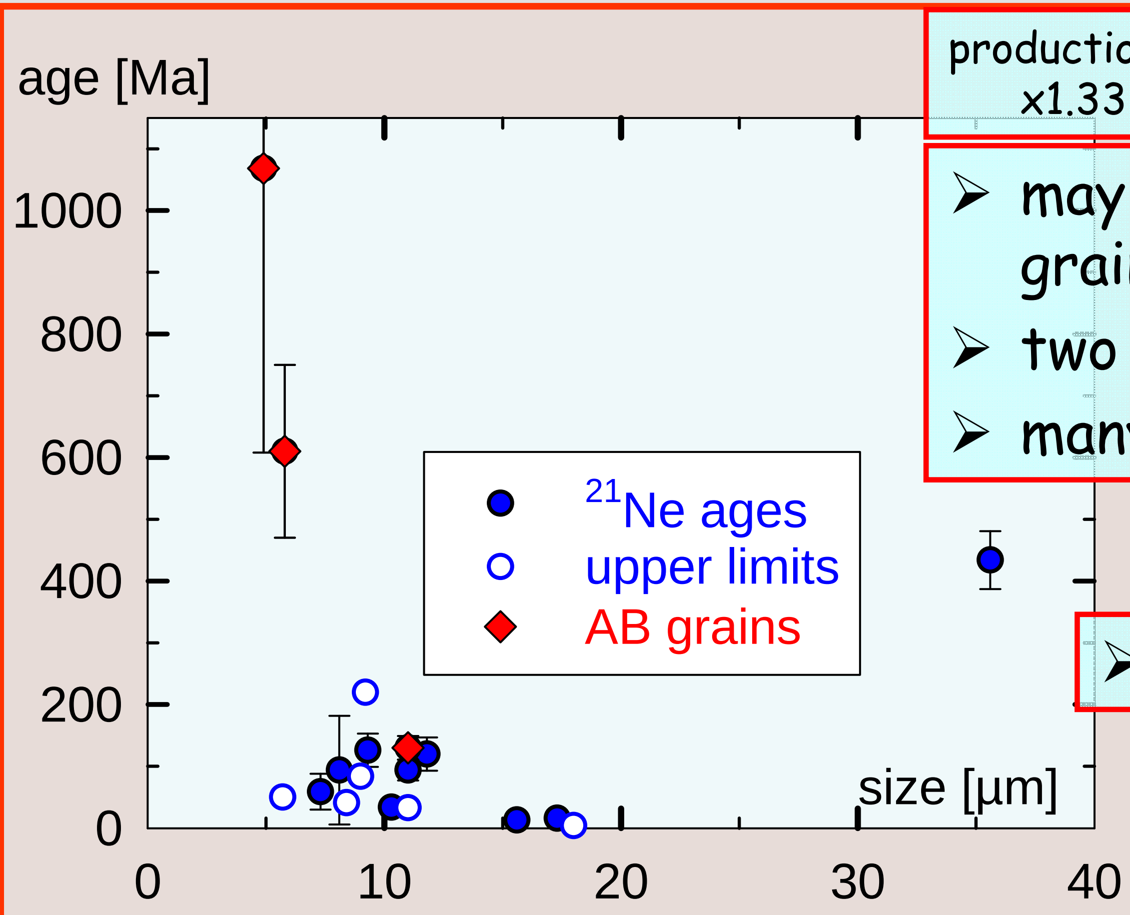
for production rates in IS space

- commonly used: predictions of Reedy (1989)
- uses for flux and spectra geometric mean of the four spectra on the right (not the “source” spectrum; from Reedy, 1987)
- additional input: nuclear cross sections
- overall uncertainty ~ 60 % (Reedy) (?)



The results

- ➢ ^{21}Ne ages mostly < 200 Ma, distinctly shorter than "expected" interstellar grain lifetimes of ~ 500 Ma
- ➢ no obvious trend with grain size



production rates from Reedy (1989),
x1.33 for α-induced reactions

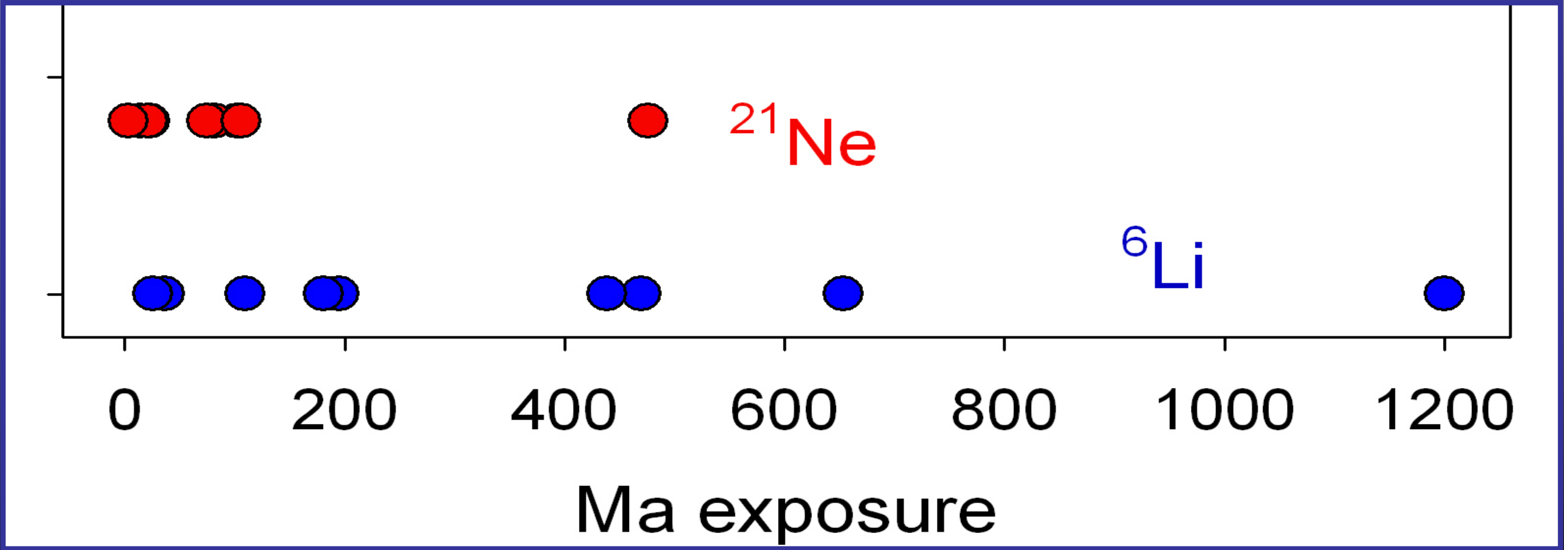
- ➢ maybe one "really old" grain at 1070±460 Ma
- ➢ two "expected" ages
- ➢ many young ages

- ➢ AB grains older?

a scenario for young grains

- starburst ~ 2 Ga before SS formation
- suggested by Clayton in connection with Si isotopes; a possible explanation for special ^{18}O/^{17}O of solar system (~5 instead of ~3.5 in ISM today)
- AGB parent stars of SiC most likely mass ~1.5-2 $M_\odot$
  → at 500 Ma before SS formation not yet in AGB phase
- first grains from these sources arrived only "shortly" before SS formed

- another suitable element: Li;
  but Li and Ne ages do not agree that well
- only one Ne age clearly higher than 100 Ma (several, not shown, with low upper limits only); whereas many Li ages of several hundred Ma, in line with "typical" ages expected for IS grains
- need same grain analyses;
  moreover: JUMBO grains are not "typical", e.g. also low in Ne-E (AG He shell)

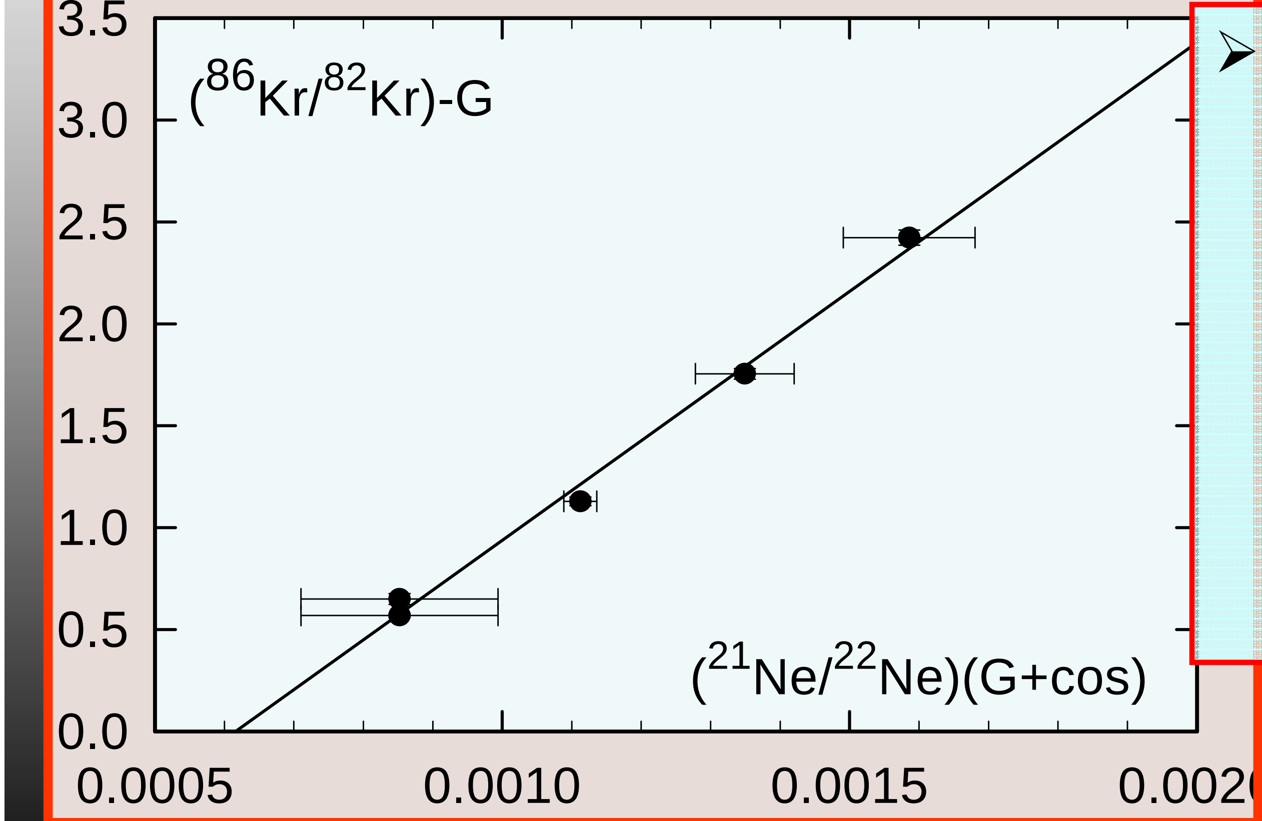


- would be nice to have ages for **the typical smaller** grains

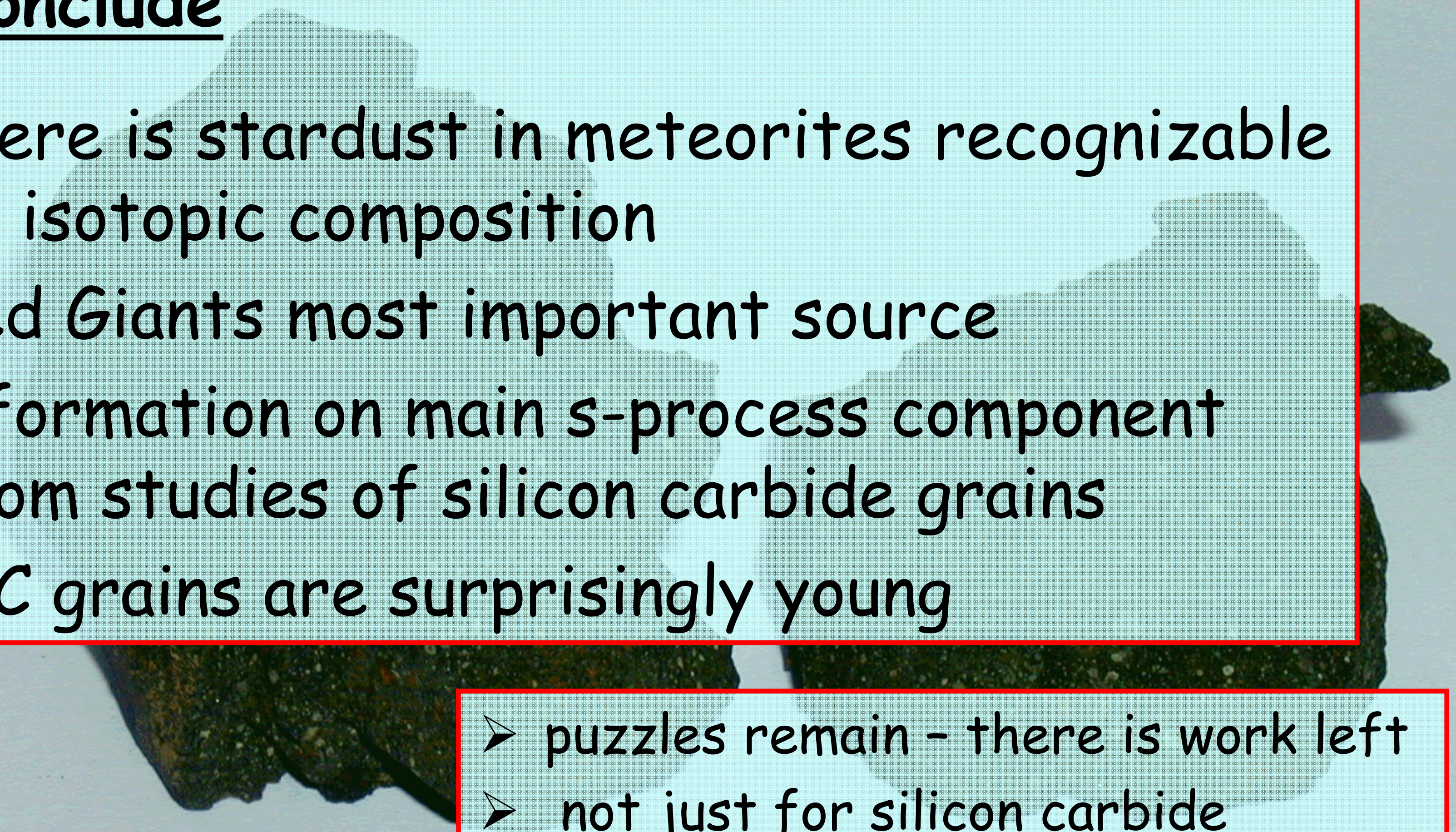
  note: Jumbos are poor in Ne-G:

  -- KJA (0.4 µm) to KJG (3.0 µm) 2000 – 40,000 (increasing with size)

  -- while Jumbos only between 0 and 1,000 (in units of 10^{-8} cc/g)



- can we possibly infer the correct **$^{21}Ne/^{22}Ne$ of the G component** in a given grain / sample using its (simultaneously measured) Kr composition as a guide?



To conclude

- there is stardust in meteorites recognizable by isotopic composition
- Red Giants most important source
- information on main s-process component from studies of silicon carbide grains
- SiC grains are surprisingly young

- puzzles remain – there is work left
- not just for silicon carbide

Thank You