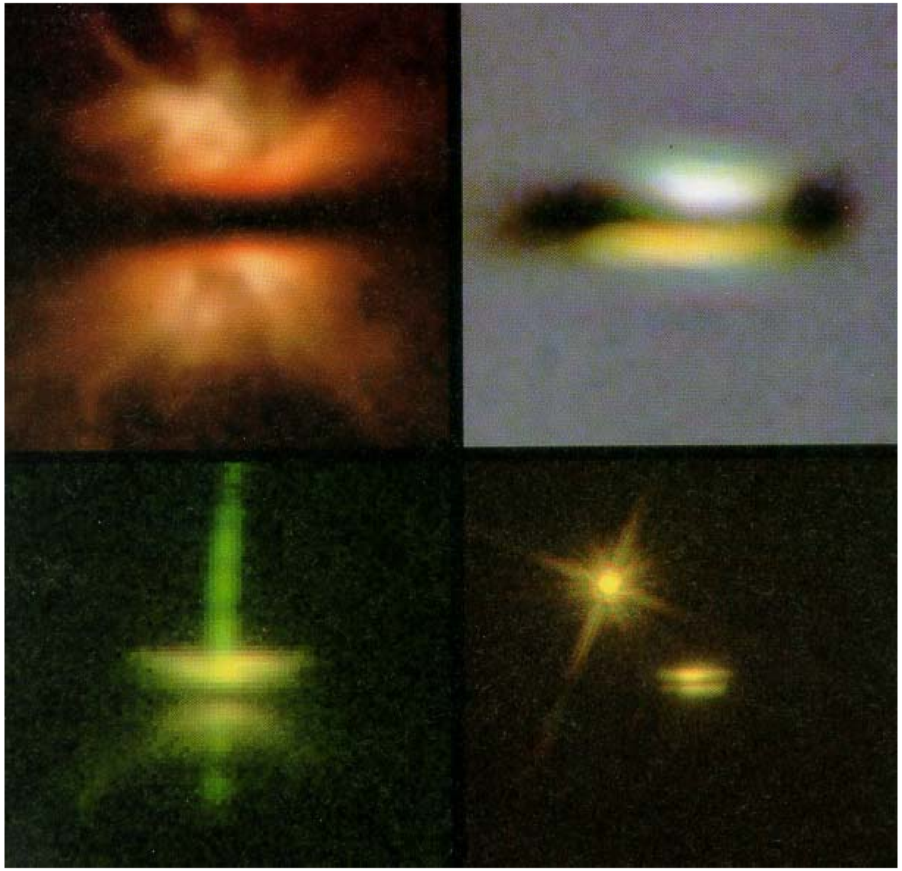
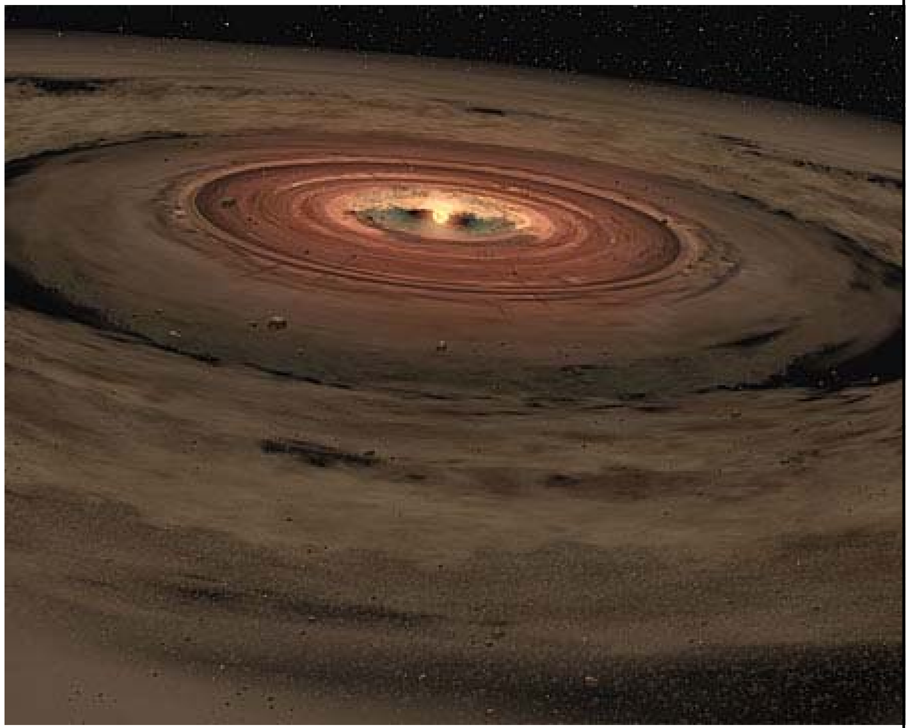
Timescales of the Protoplanetary Disk

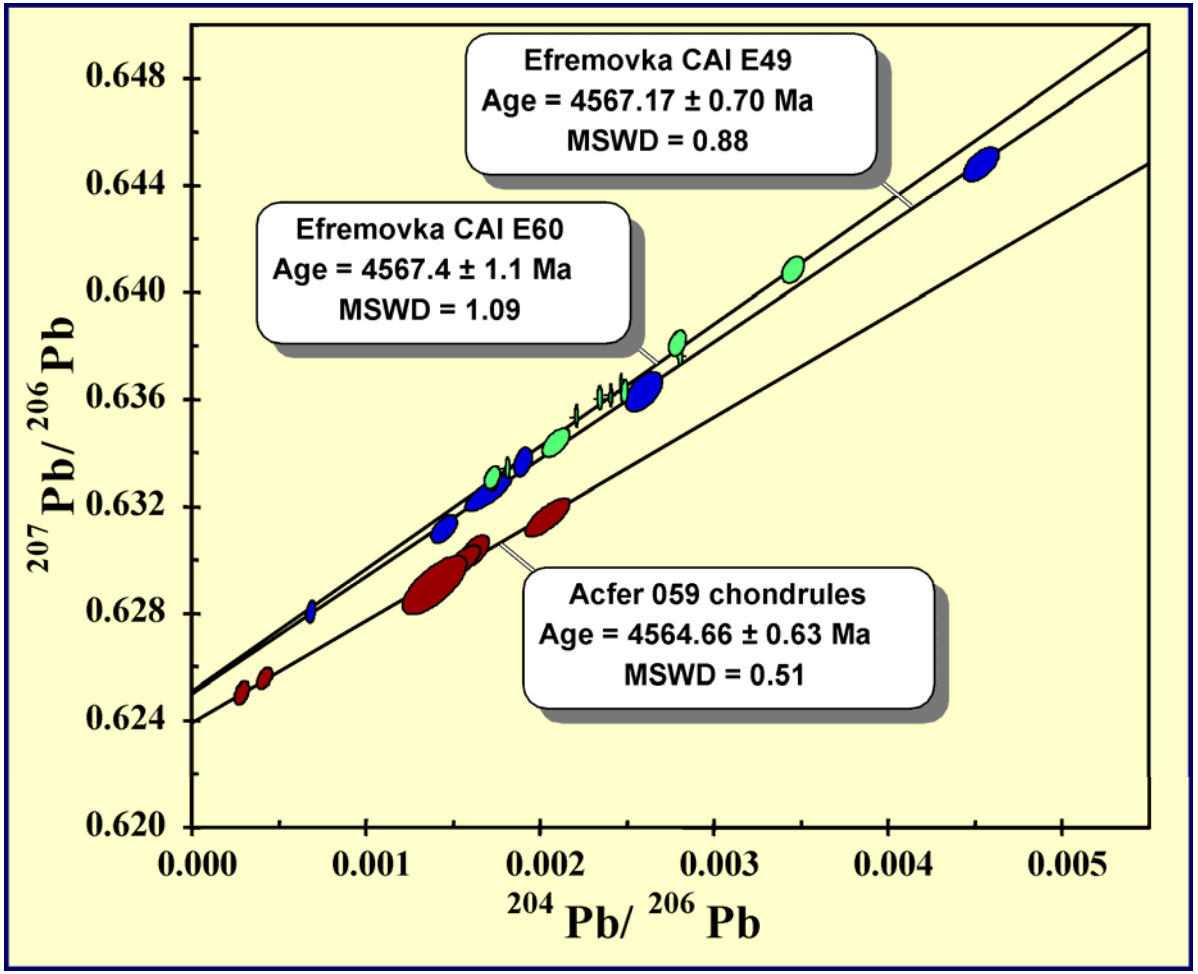
Sara Russell





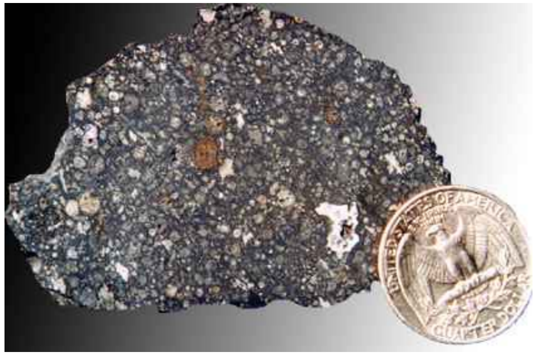
How can we determine a chronology of our protoplanetary disk?

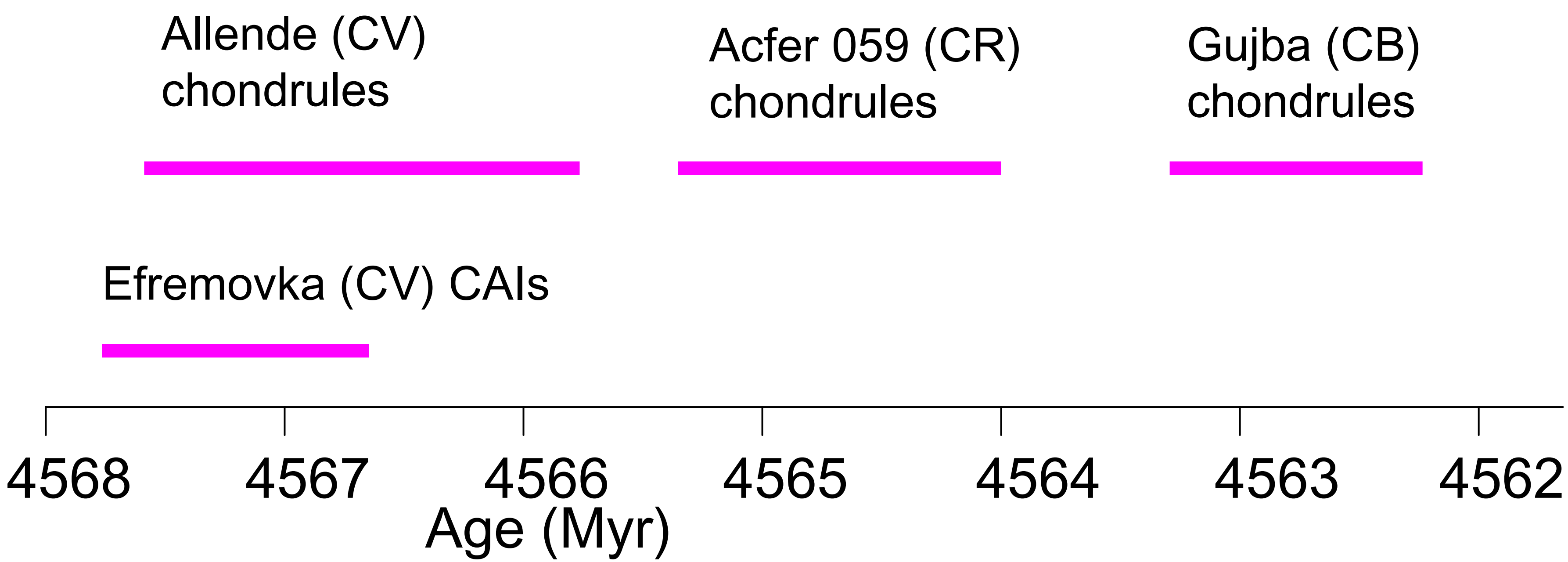
- Absolute age determinations (e.g. Pb-Pb; see previous lecture)
- Short-lived isotopes
- Petrographical constraints
- Dynamical considerations
- Observations of other protoplanetary systems



Amelin et al. 2002

- Pb-Pb age differences between chondrite types:





(Amelin et al., 2002; 2005)

Short-lived isotopes

- What short-lived isotopes are known to have been present in the early solar system?
- How are these measured?
- How did they form?
- How were they distributed within the protoplanetary disk?
- What can we learn from them about chronology?

Short-lived isotopes ($T_{1/2}$<20Myr)

Isotope	Half life (Myr)	Initial abundance	Reference
^{10}Be	1.5	$^{10}Be/^{9}Be=9\times10^{-4}$	Chassidon et al.
^{26}Al	0.75	$^{26}Al/^{27}Al=5\times10^{-5}$	Lee et al. 1976
^{36}Cl	0.3	$^{36}Cl/^{35}Cl\sim3\times10^{-6}$	Murty et al. 1997
^{41}Ca	0.15	$^{41}Ca/^{40}Ca=1.4\times10^{-8}$	Srinivasan and Goswami 1994
^{53}Mn	3.7	$^{53}Mn/^{55}Mn=4.3\times10^{-5}$	Lugmair and Shukuluykov, 1998
^{60}Fe	1.5	$^{60}Fe/^{56}Fe=6\times10^{-8}$	Mostefaoui et al. 2003
^{107}Pd	6.5	$^{107}Pd/^{108}Pd=4\times10^{-5}$	Kelly and Wasserburg, 1979
^{182}Hf	9.4	$^{182}Hf/^{180}Hf=2\times10^{-4}$	Halliday, 2000
^{129}I	16	$^{129}I/^{127}I=1.4\times10^{-4}$	Gilmour et al., 2001

Types of meteoritic object

Isotope	**CAI**	**Chondrule**	**Achondrite**
^{10}Be	√	?	
^{26}Al	√	√	√
^{41}Ca	√		
^{53}Mn	√	√	√
^{60}Fe	?	√	√
^{107}Pd			√
^{129}I	√	√	√
^{182}Hf			√

There are additional short-lived isotopes that are unconfirmed and their initial abundance is currently uncertain, e.g.

^{7}**Be** ($t_{1/2}$ = 57 days) (Chaussidon et al. 2004)

^{97}**Tc** ($t_{1/2}$ = 2.6 Myr) (Yin& Jacobsen 1998)

^{99}**Tc** ($t_{1/2}$ = 0.21 Myr) (Yin et al. 1992)

^{135}**Cs** ($t_{1/2}$ = 2.3 Myr) (Hidaka et al. 2001)

^{205}**Pb** (t1/2 = 16 Myr) (Nielsen et al. 2004)

Initial abundance of ^{26}Al in chondrules and CAIs

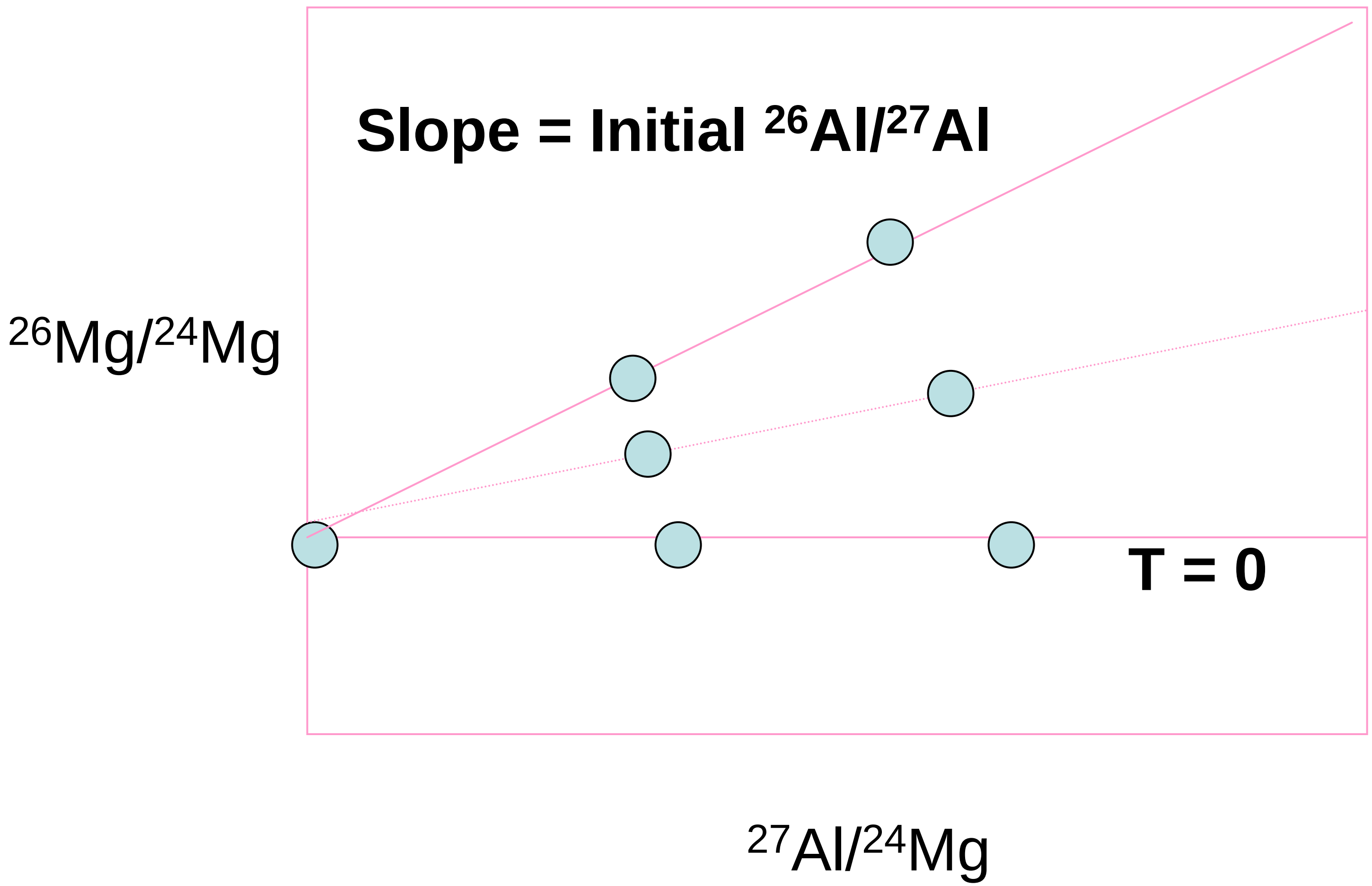
- ^{26}Al has a half life of 0.73 Myr, decays to ^{26}Mg.

$$^{26}Mg = \left(^{26}Mg\right)_0 + \left(^{26}Al\right)_0$$

$$\left(\frac{^{26}Mg}{^{24}Mg}\right) = \left(\frac{^{26}Mg}{^{24}Mg}\right)_0 + \left(\frac{^{26}Al}{^{24}Mg}\right)_0$$

$$\left(\frac{^{26}Mg}{^{24}Mg}\right) = \left(\frac{^{26}Mg}{^{24}Mg}\right)_0 + \left(\frac{^{26}Al}{^{27}Al} x \frac{^{27}Al}{^{24}Mg}\right)_0$$

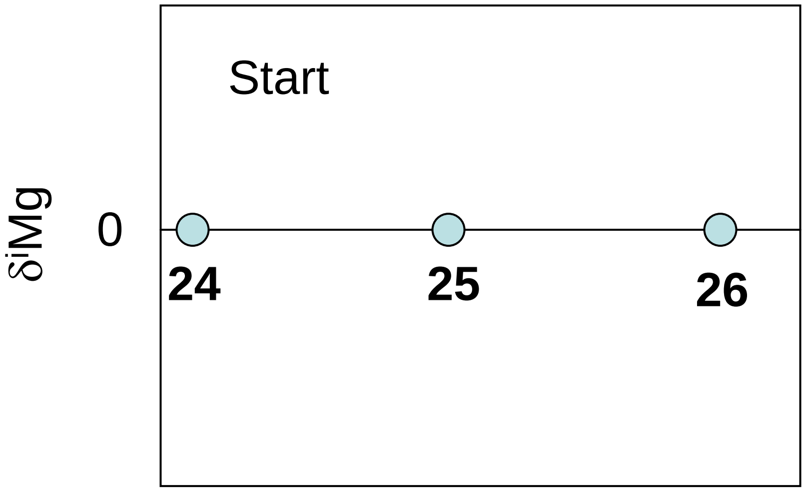
- Excess of ^{26}Mg correlated to ^{26}Al/^{27}Al indicates initial presence of ^{26}Al, and *in situ* decay of this isotope



Need to distinguish between *internal isochrons* (date time of last crystallisation) and *whole rock data* (dates time of elemental fractionation)

Fractionation of Magnesium

- Mg has three stable isotopes: ^{24}Mg (most abundant), ^{25}Mg, ^{26}Mg.
- Various cosmochemical and geological processes can cause mass fractionation



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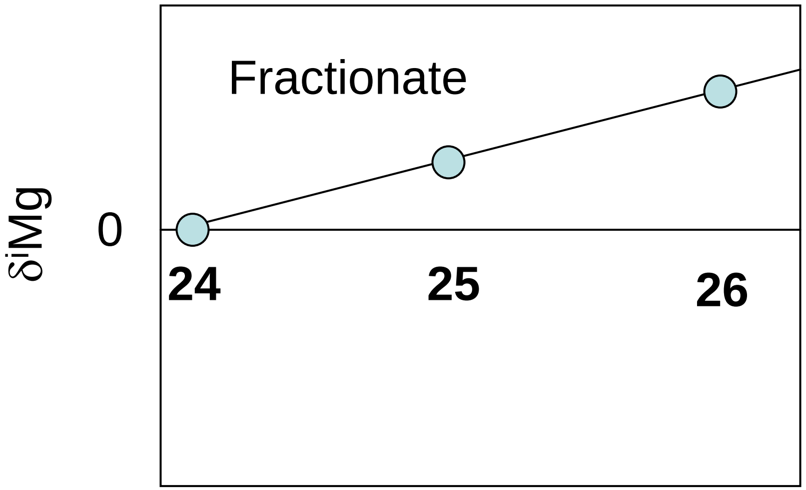

Fractionation of Magnesium

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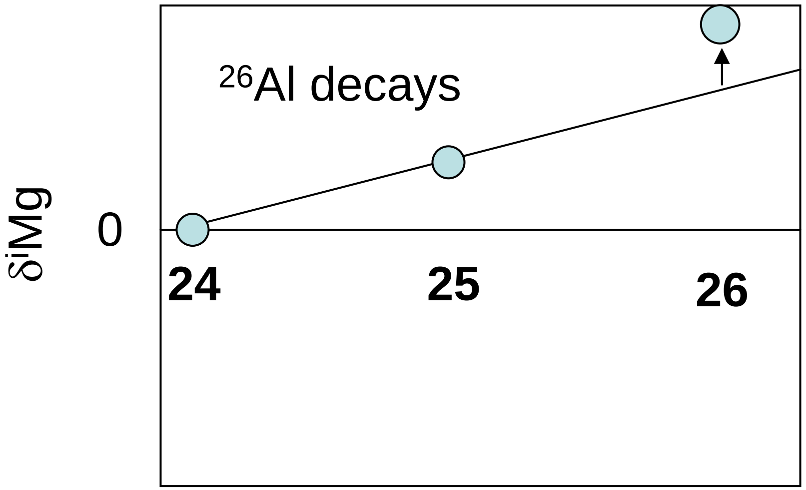
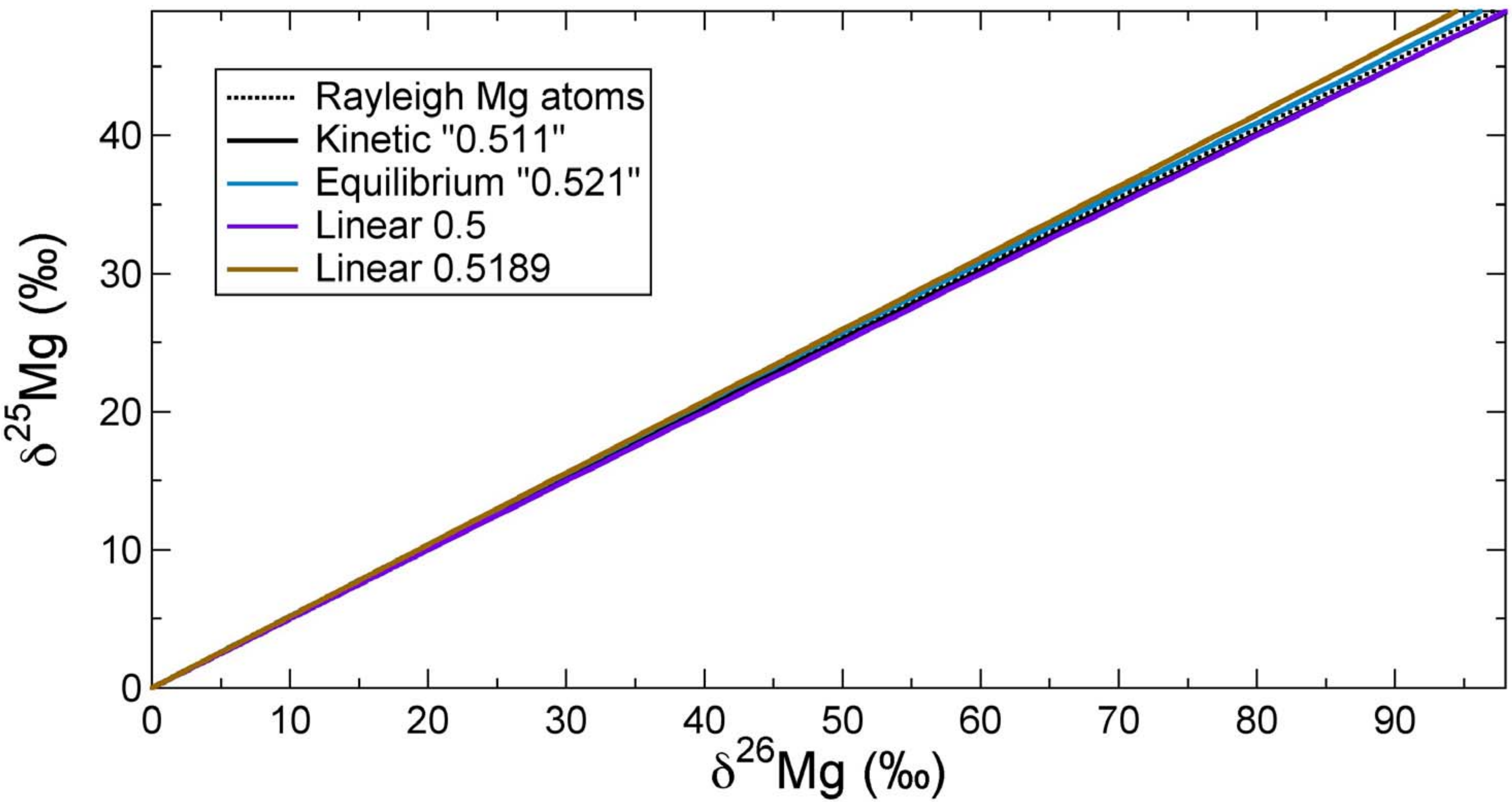
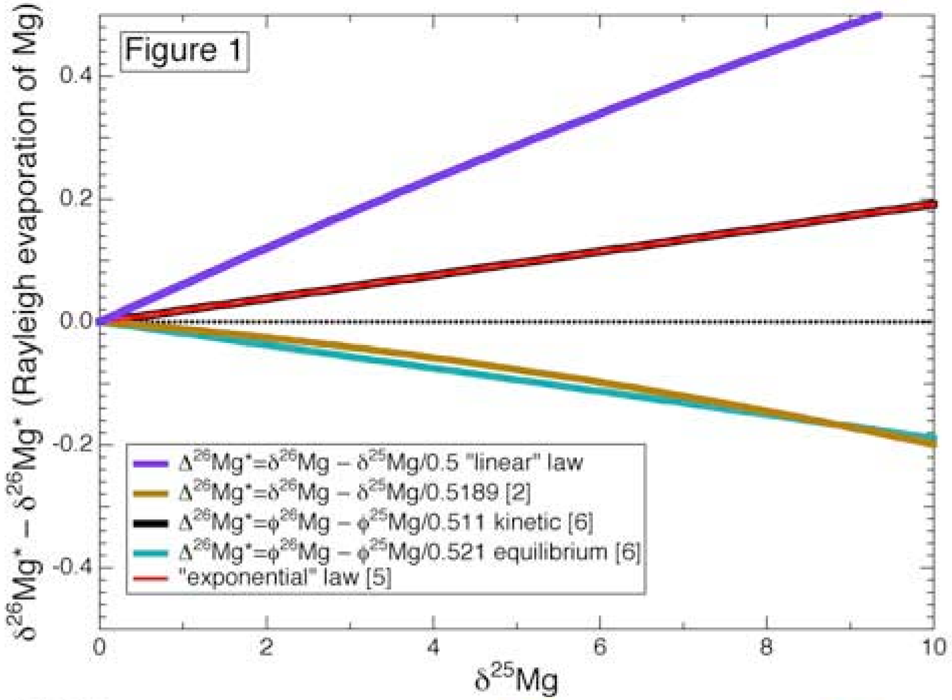
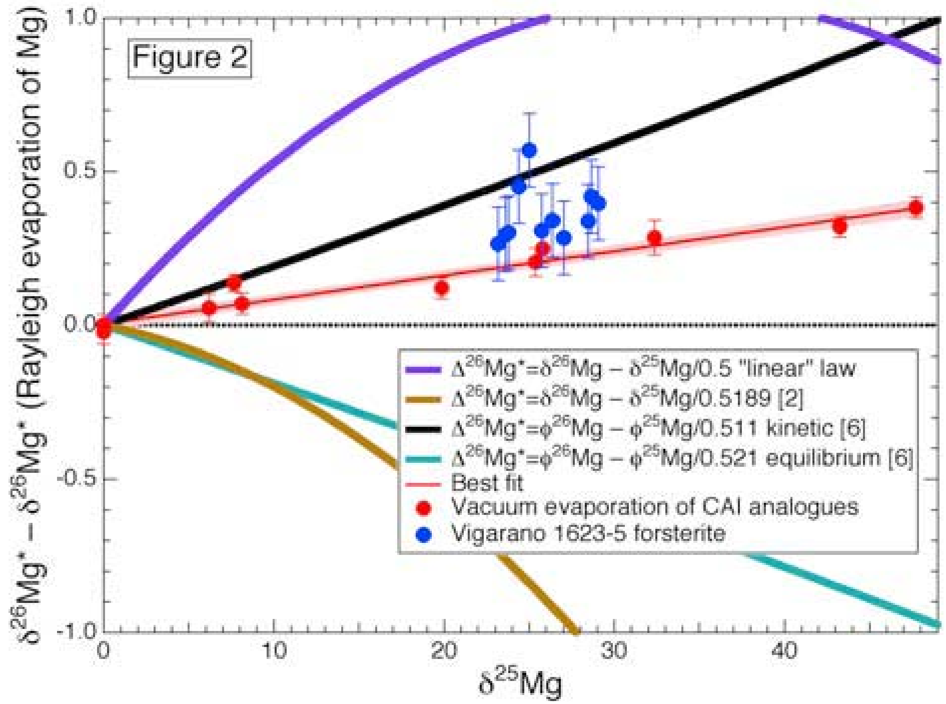


Fractionation law used can be critical in determining the amount of excess of ^{26}Mg from decay of ^{26}Al



$$\delta^{25}\mathrm{Mg} = 1000\left(\frac{{}^{25}\mathrm{Mg}/{}^{24}\mathrm{Mg}_{\mathrm{samp}}}{{}^{25}\mathrm{Mg}/{}^{24}\mathrm{Mg}_{\mathrm{std}}} - 1\right)$$



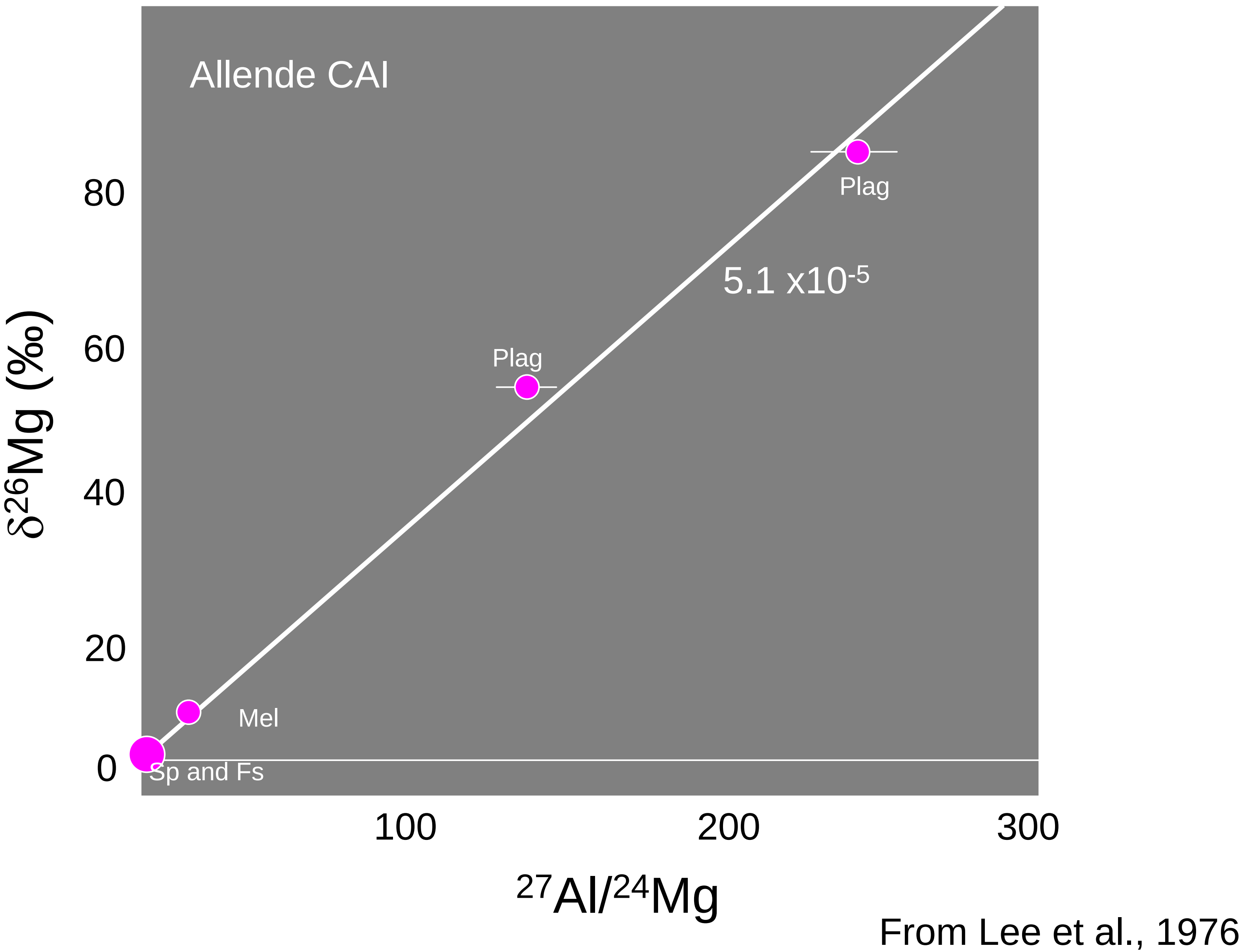


From Davis et al., LPSC 2005

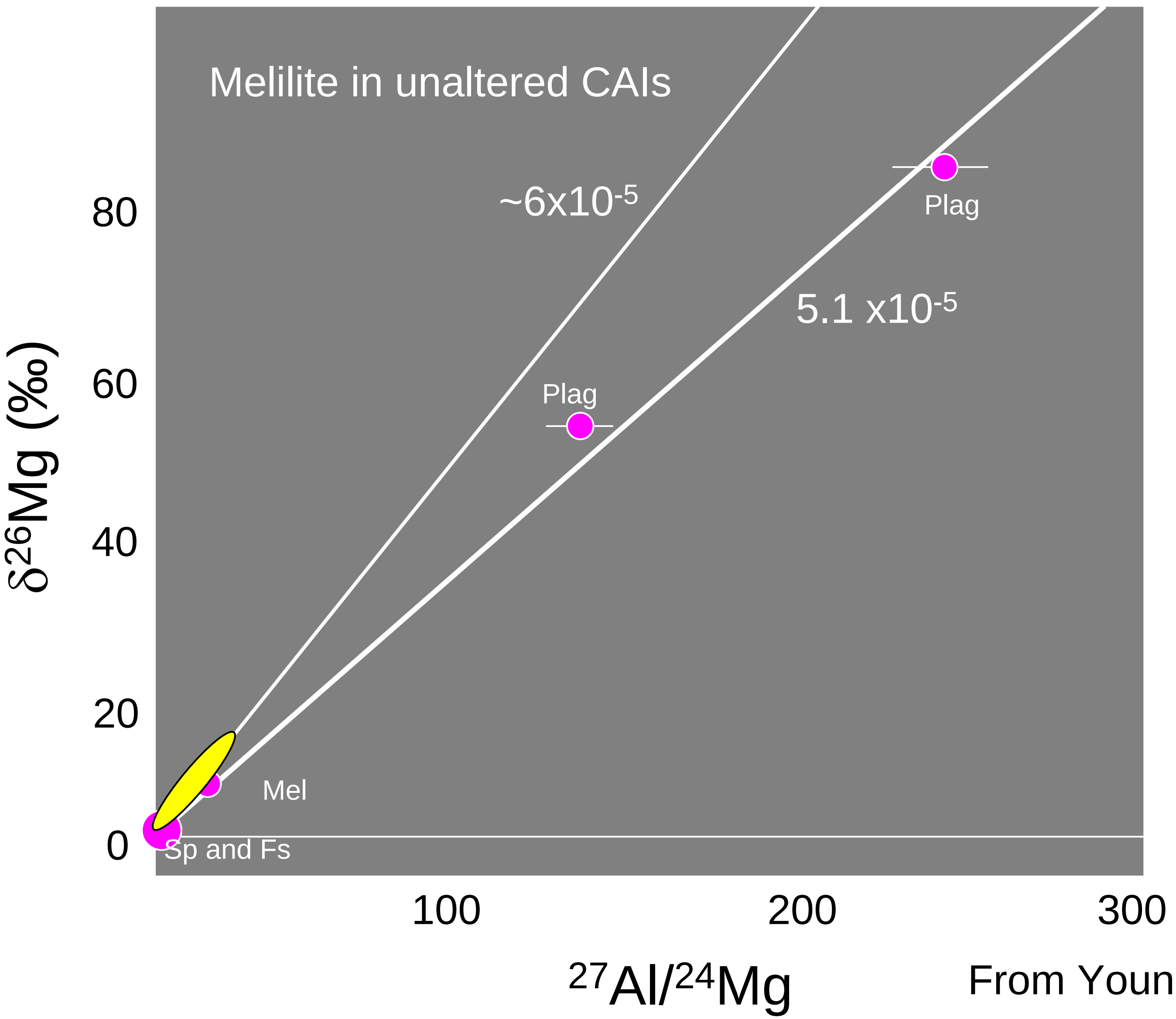
Assumptions

- Initial homogeneity of parent isotopes
- Initial homogeneity of daughter isotopes
- Evolution in a closed system
- No post-formational redistribution of isotopes

Ideally a high ratio of parent/daughter – allows larger effects to be seen

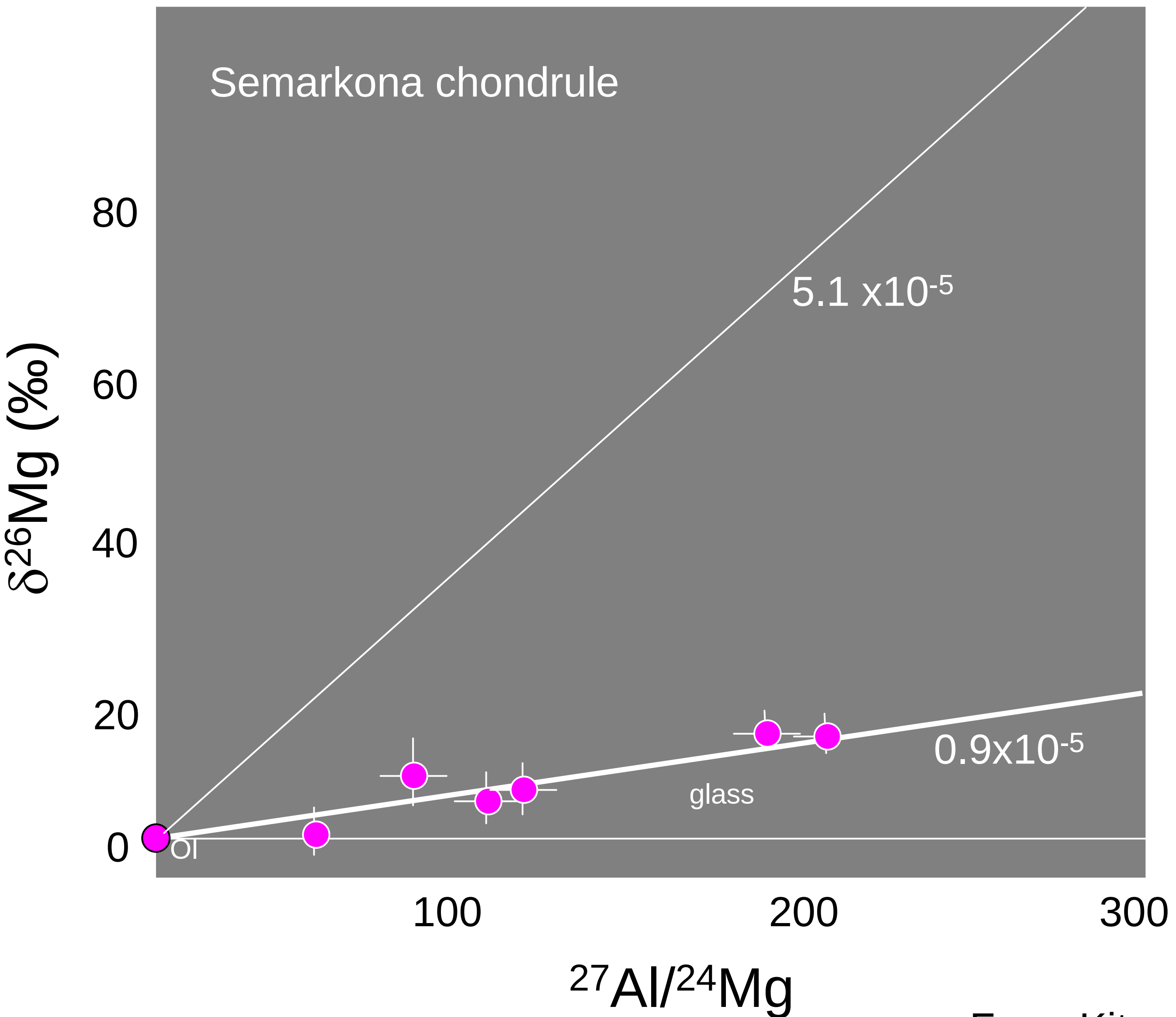


Allende CAI
80
60
40
20
0
δ26Mg (‰)
Plag
5.1 x10-5
Plag
Mel
Sp and Fs
100
200
300
27Al/24Mg
From Lee et al., 1976



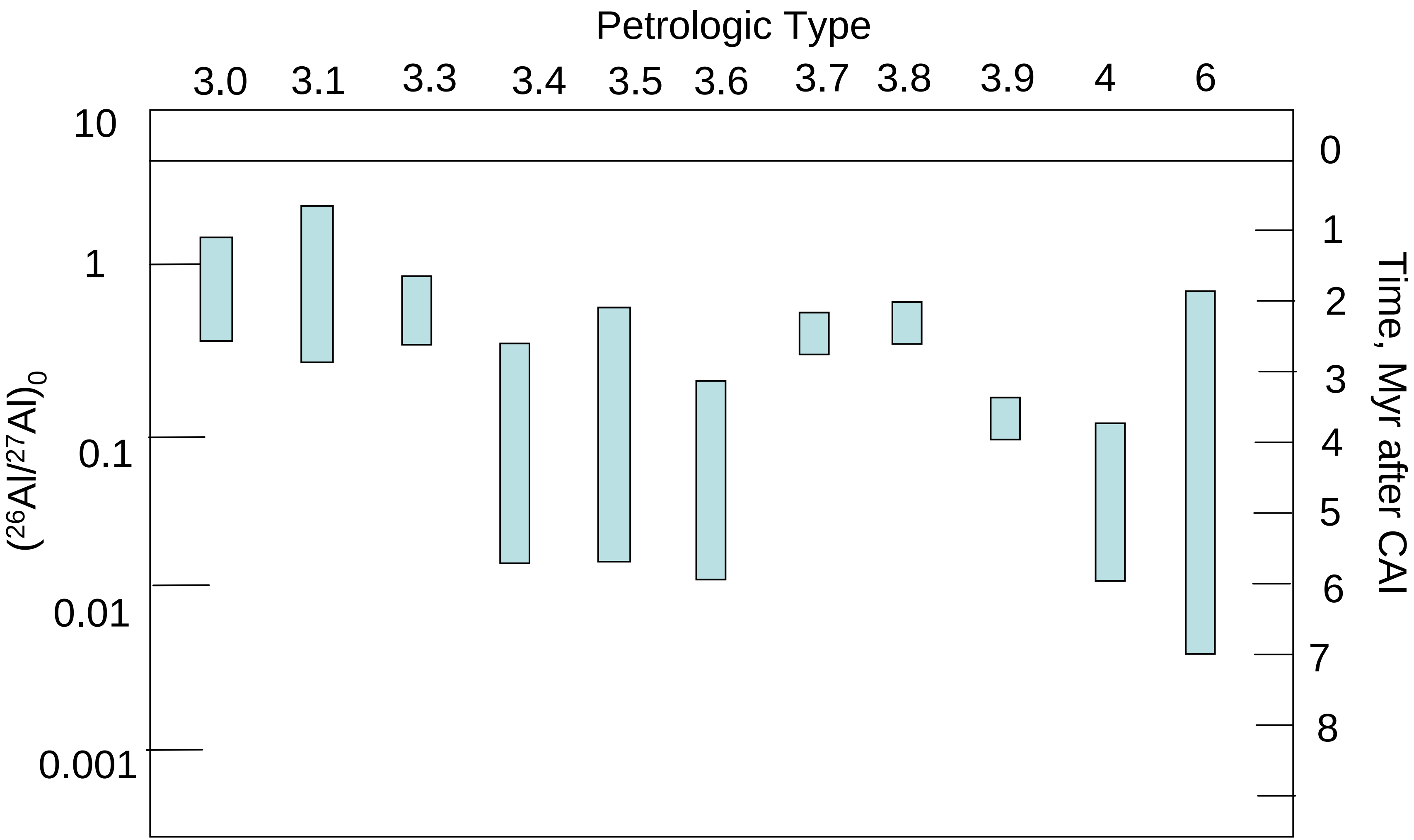
From Young et al., 2005

Range indicates several Kyr history of reheating after formation

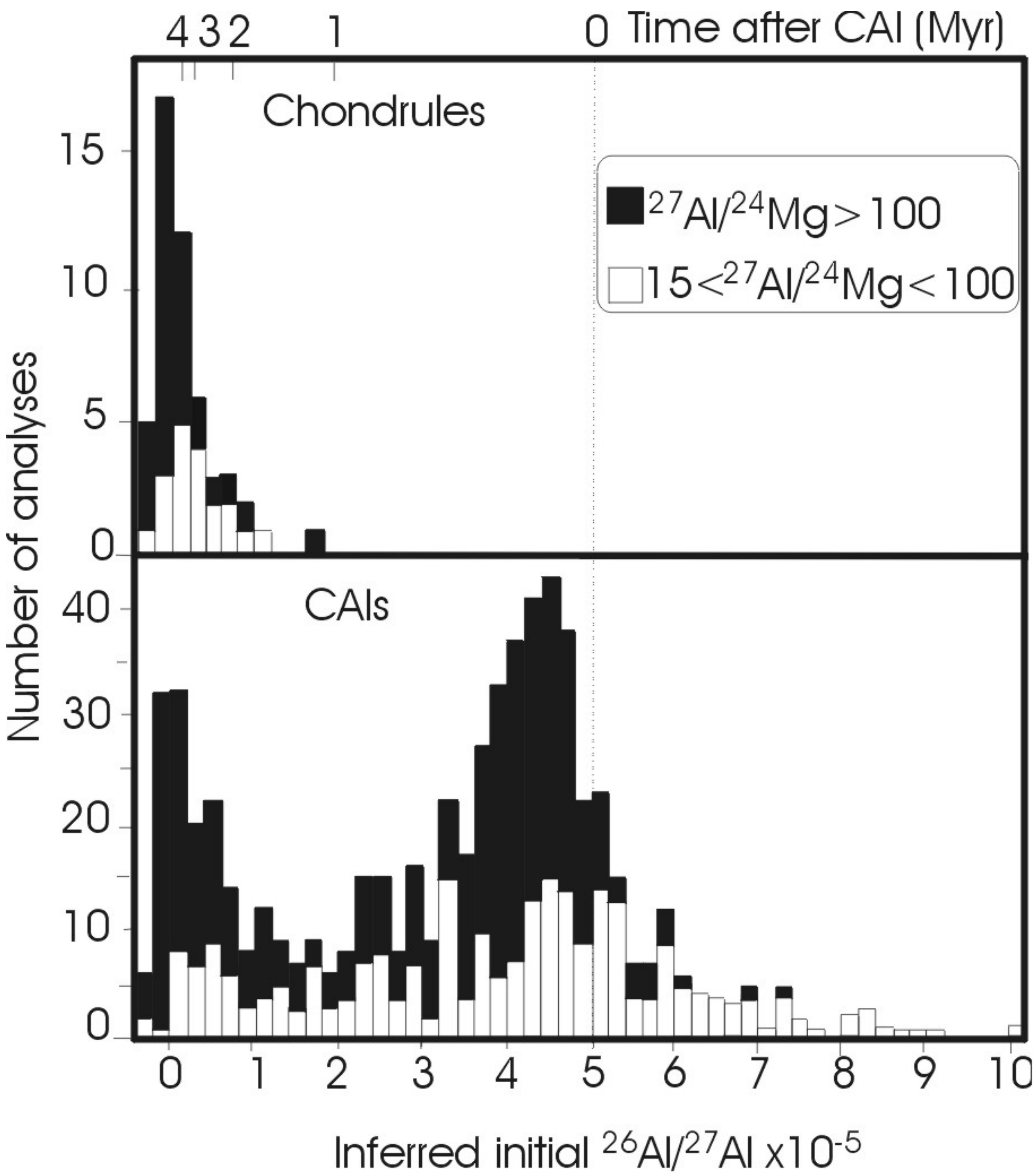


From Kita et al., 2000

Effects of metamorphism



From Huss et al. 2001



4 3 2 1 0 Time after CAI (Myr)
Chondrules
$^{27}Al/^{24}Mg > 100$
$15 < ^{27}Al/^{24}Mg < 100$
CAIs
Number of analyses
0 5 10 15
0 10 20 30 40
0 1 2 3 4 5 6 7 8 9 10
Inferred initial $^{26}Al/^{27}Al$ x10^{-5}

Clues to formation of CAIs and chondrules from ^{26}Al data

- Some single objects contain regions that differ in initial $^{26}Al/^{27}Al$ – this surely represents a time difference, with these objects having an extended nebular history
- CAIs tend to have contained more ^{26}Al than chondrules when they formed- may represent a difference in formation time between chondrules and CAIs, with chondrules forming up to ~>2 Myr earlier.
- This assumes that ^{26}Al was initially homogeneous in the CAI-chondrule forming reservoirs
- Assumption of initial homogeneity will be discussed by Sasha Krot in the next talk.

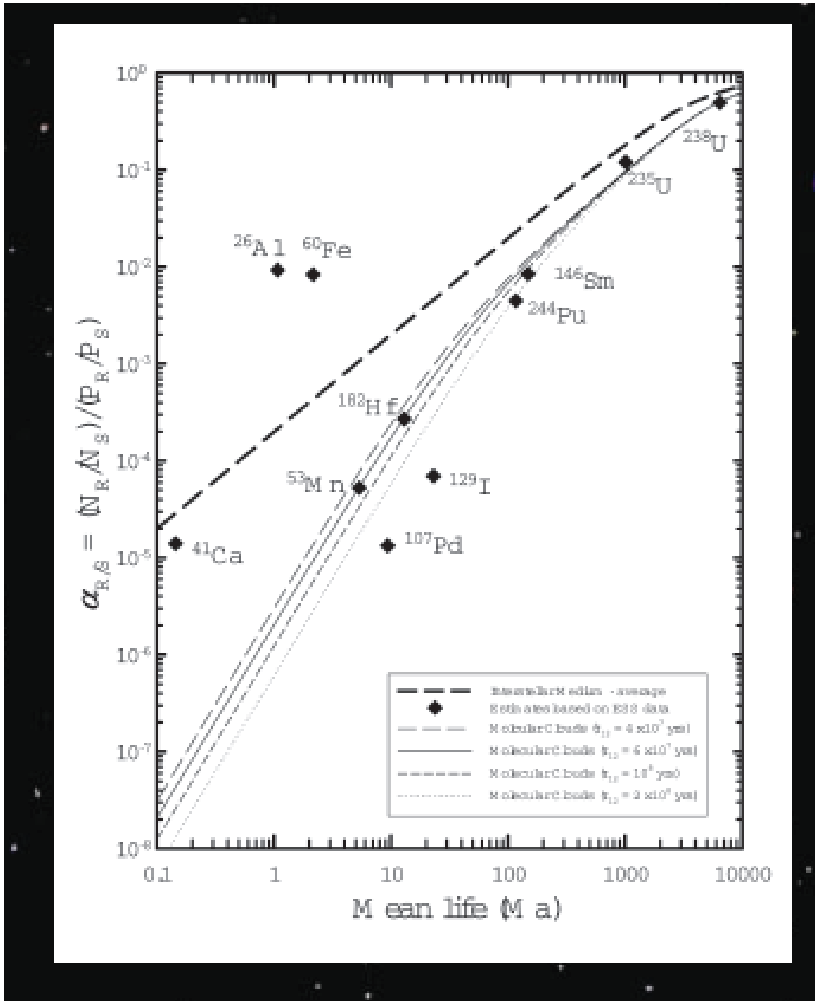
Formation of short lived isotopes

Can the abundance of short-lived isotopes be explained by normal abundance levels in the galaxy? (In this case then it is likely that they were homogeneously distributed)

R/S	T (Ma)	Initial ab.	Gal. Evolution
^{41}Ca/^{40}Ca	0.1	1×10^{-8}	no
^{26}Al/^{27}Al	0.7	5×10^{-5}	no
^{10}Be/^{9}Be	1.5	9×10^{-4}	?
^{60}Fe/^{56}Fe	1.5	5×10^{-7}	?
^{53}Mn/^{55}Mn	3.7	4×10^{-5}	?
^{107}Pd/^{108}Pd	6.5	[4×10^{-5}]	yes
^{182}Hf/^{180}Hf	9.4	[2×10^{-4}]	yes
^{129}I/^{127}I	16.7	[1×10^{-4}]	yes

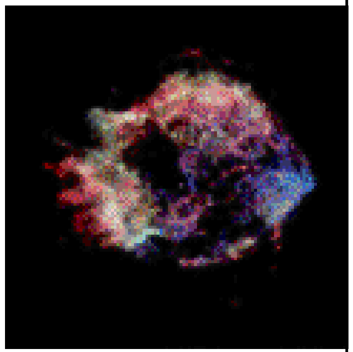
Ongoing Galactic Nucleosynthesis

- ^{129}I relatively overproduced
- Could explain abundance of ^{182}Hf, ^{107}Pd, perhaps ^{53}Mn
- Cannot explain abundance of ^{41}K, ^{26}Al
- The abundance of ^{60}Fe formed by galactic nucleosynthesis is a matter of controversy



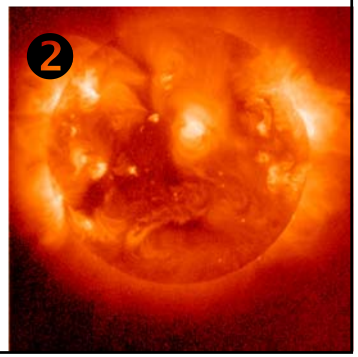
The origin of short-lived radionuclides

- Because of their short half-lives (~Ma), some short-lived radionuclides have been synthesised
  - ➲ <u>Just before</u> or <u>during</u> solar system formation



❶ Stellar model

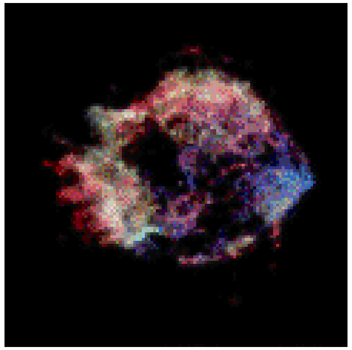
- ☆ Synthesis in a nearby evolved star
- ☆ Seeding of the molecular cloud ❶



❷ Irradiation model

- ☆ *In situ* irradiation of solar system gas/dust

Stellar origin for extinct short-lived radionuclides



- Wolf Rayet Star: Can produce: ^{41}Ca, ^{26}Al (Arnould et al. 1997)
- AGB stars: Can produce ^{41}Ca, ^{26}Al, ^{60}Fe (Busso et al. 1999)

  These two formation sites are unlikely to be the main producers of short-lived isotopes because they are not typically intimately associated with star-forming regions,as is required especially for ^{41}Ca.

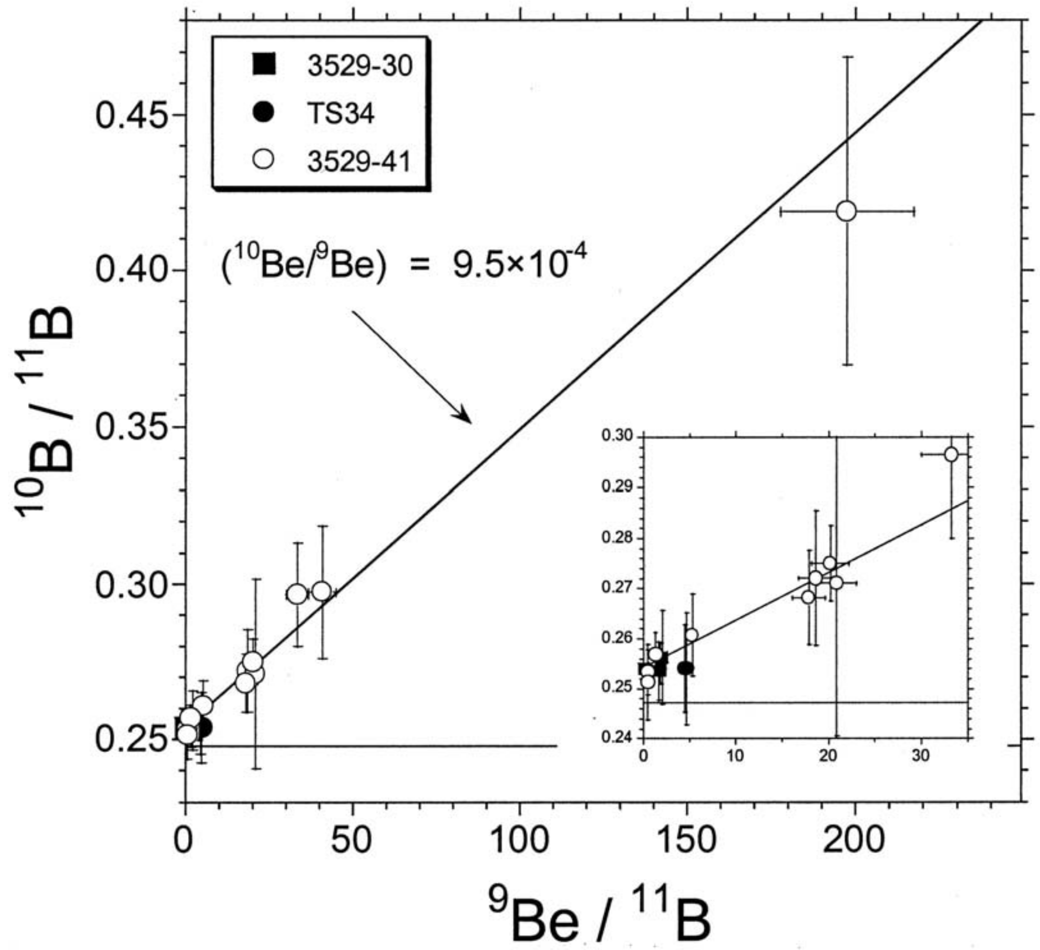
- **Supernovae**: ^{41}Ca, ^{26}Al, ^{60}Fe, ^{53}Mn, ^{182}Hf, etc.

Relative abundances of most short-lived isotopes formed in supernovae match meteoritic values reasonably [e.g. Meyer and Zinner, 2006]. Solar system input would be ~10^{-4} supernova ejecta.

Supernova probably occurred ~1 parsec away, ~ 1 Myr before solar system formation

BUT...

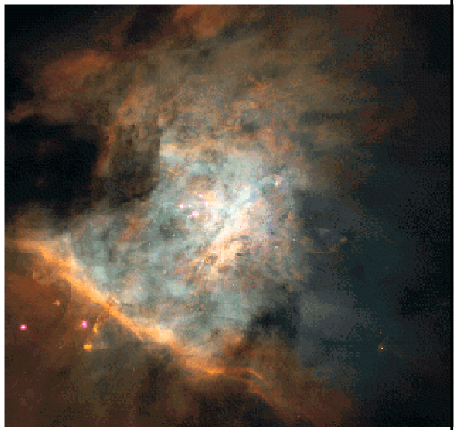
- ☆ Molecular core enclosed in a supernova remnant unusual
- ☆ Requires synchronized explosion [triggered formation]
- ☆ **^{10}Be not produced in stars**



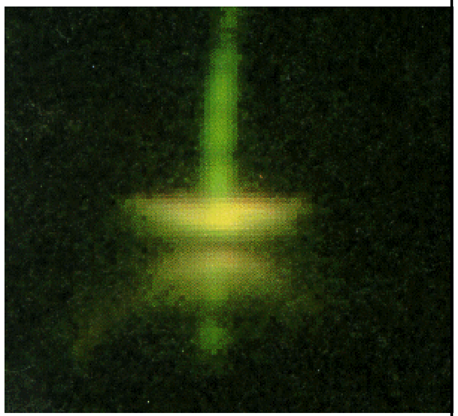
^{10}Be - A “smoking gun”? Not formed in any stars- formed by irradiation processes only

Where was ^{10}Be formed?

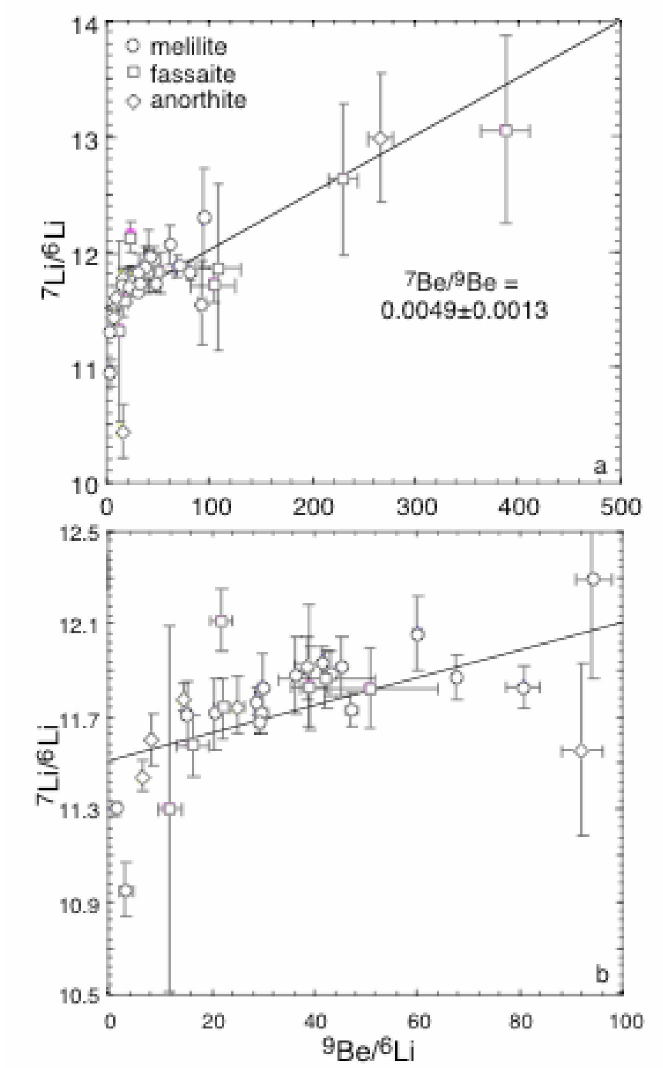
- **In the progenitor molecular cloud core**
  - ☆ Trapped galactic cosmic rays (Desch et al. 2004)
  - ☆ Requires long time to accumulate enough ^{10}Be and specific conditions
  - ☆ Would produce homogeneous $^{10}Be/^{9}Be$ in solar system



- **Close to the protosun** (Lee et al. 1998)
  - ☆ In the context of the **x-wind** model (Shu et al. 1996)
  - ☆ **X-wind** throws dustballs from 0.06 AU
  - ☆ High abundance of irradiated products then transported to asteroidal distances by stellar wind



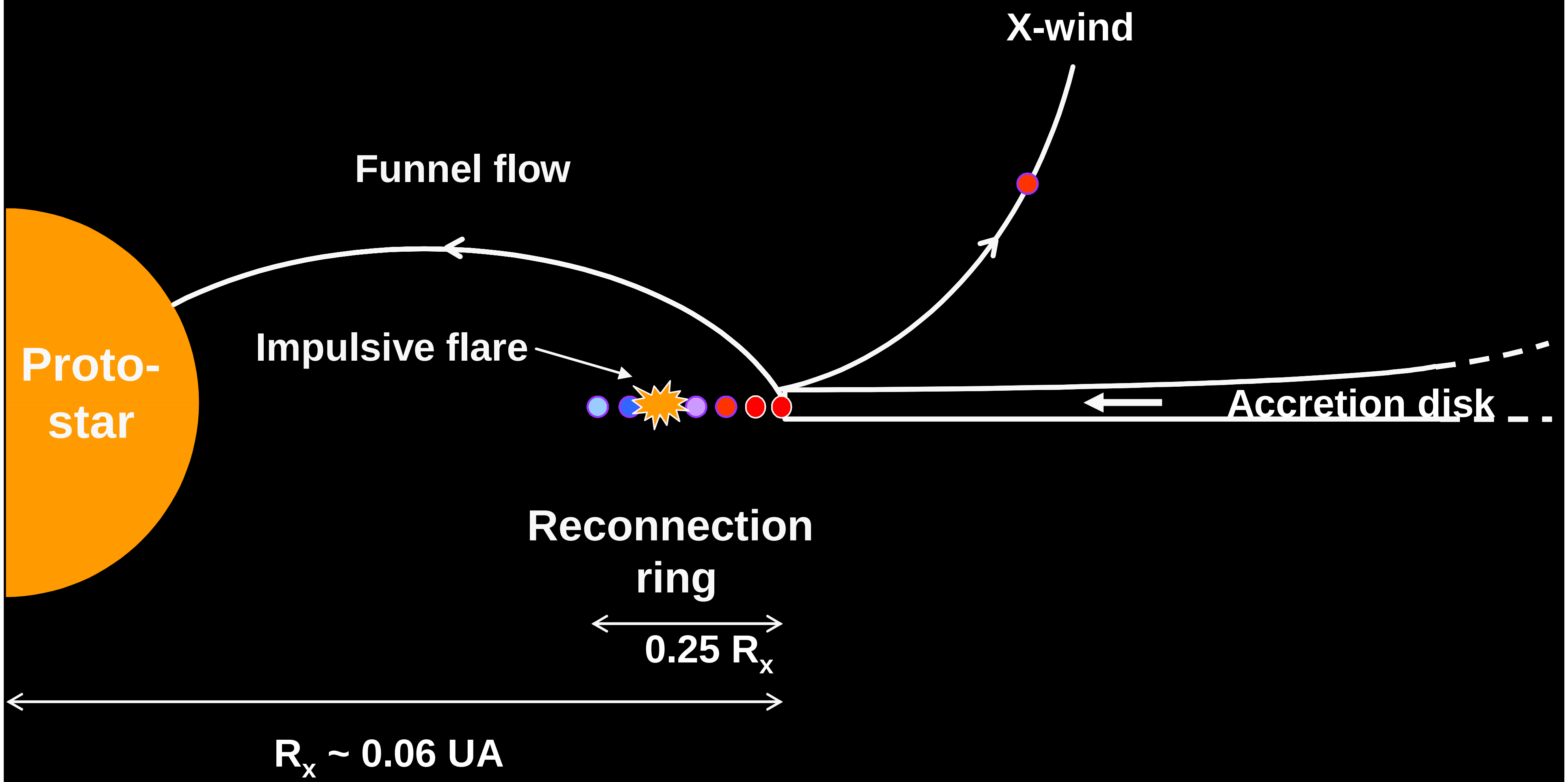
Beryllium-7- has a half life of only 57 days



Chaussidon et al., 2004

Results need confirmation…

Irradiation model



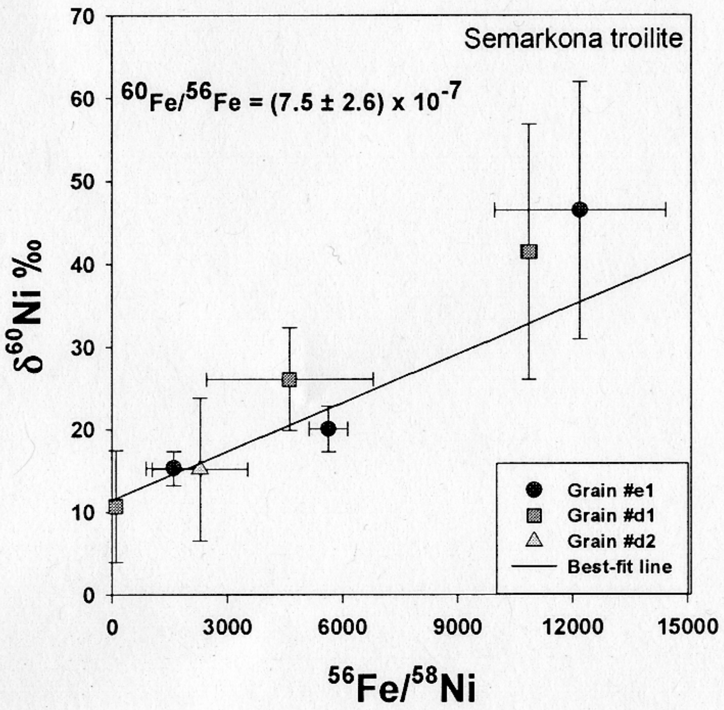


Figure 1. $\delta^{60}Ni$ as a function of $^{56}Fe/^{58}Ni$ for three troilite aggregates in the Semarkona matrix. ^{56}Fe and ^{58}Ni are calculated from measured ^{54}Fe and ^{60}Ni. Errors are 2σ.

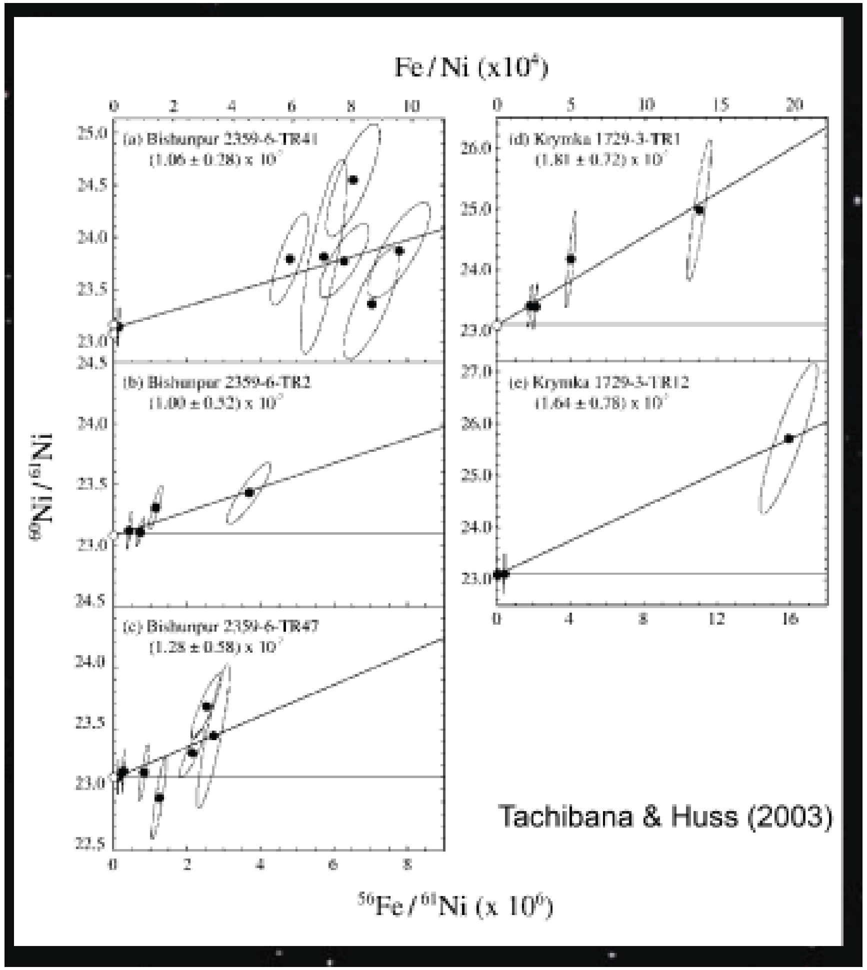
From Mostefaoui et al., 2003

^{60}Fe- ANOTHER smoking gun? This one may require a supernova input if abundant in high enough concentrations

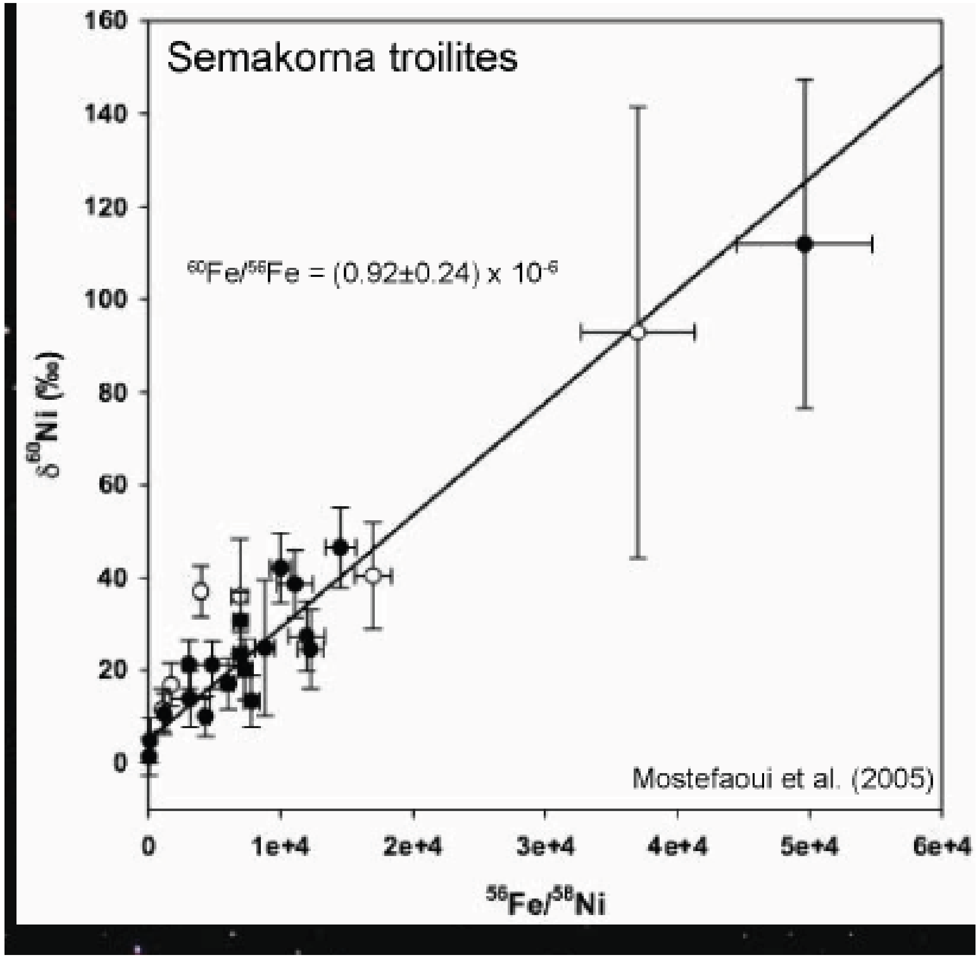
What was the initial ^{60}Fe abundance in the solar system?

•Tachibana and Huss measured troilite and reported initial ^{60}Fe/^{56}Fe = 1-2 x10^{-7}
•Assuming these grains formed with chondrules, ~2 Myr after CAIs, gives initial ^{60}Fe/^{56}Fe = ~3-5 x10^{-7}

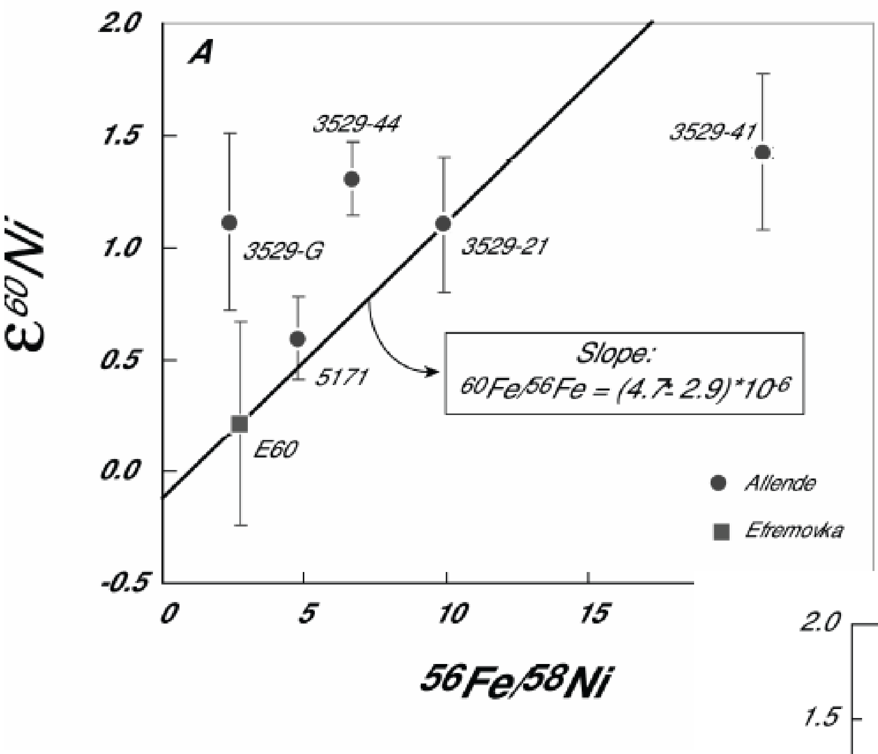
•Tachibana et al. (2006) measured Ni isotopes in pyroxene-bearing chondrules and reported ^{60}Fe/^{56}Fe = ~2-4 x10^{-7}



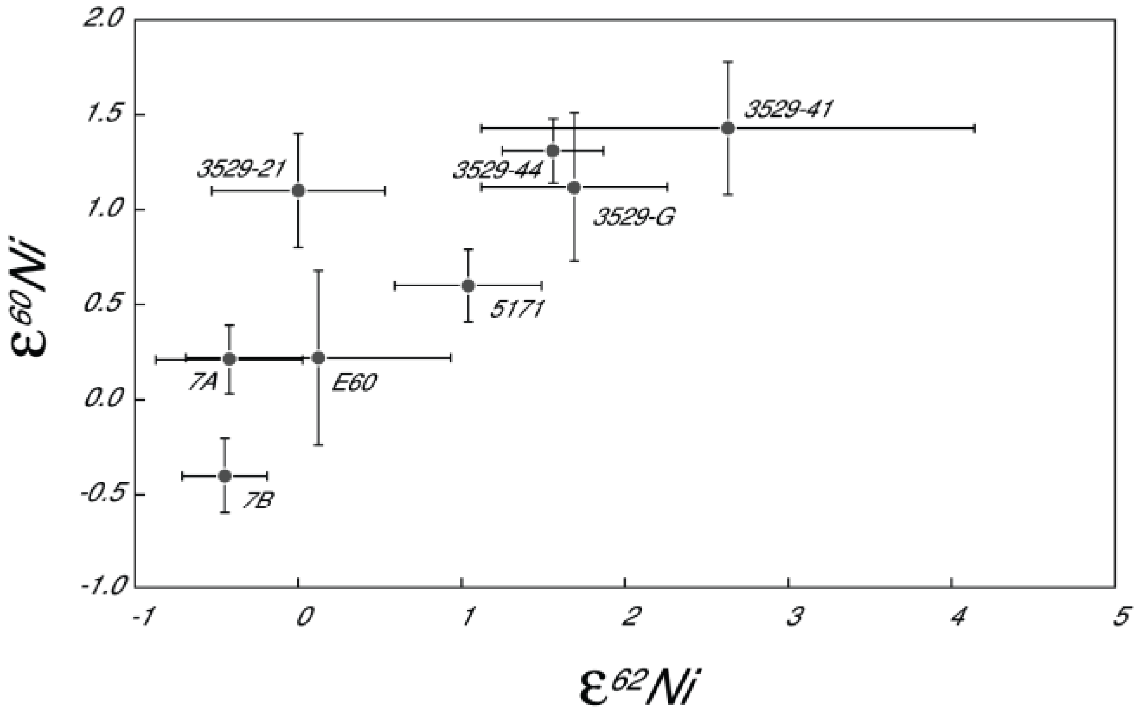
• Mostefaoui et al. suggested that most troilite is found next to metal, and this may disrupt the Fe-Ni system. They analysed isolated troilite grains and reported $^{60}Fe/^{56}Fe$ = ~1 x10^{-6}



An abundance this high cannot be explained by galactic evolution but would required input from a recent supernova.



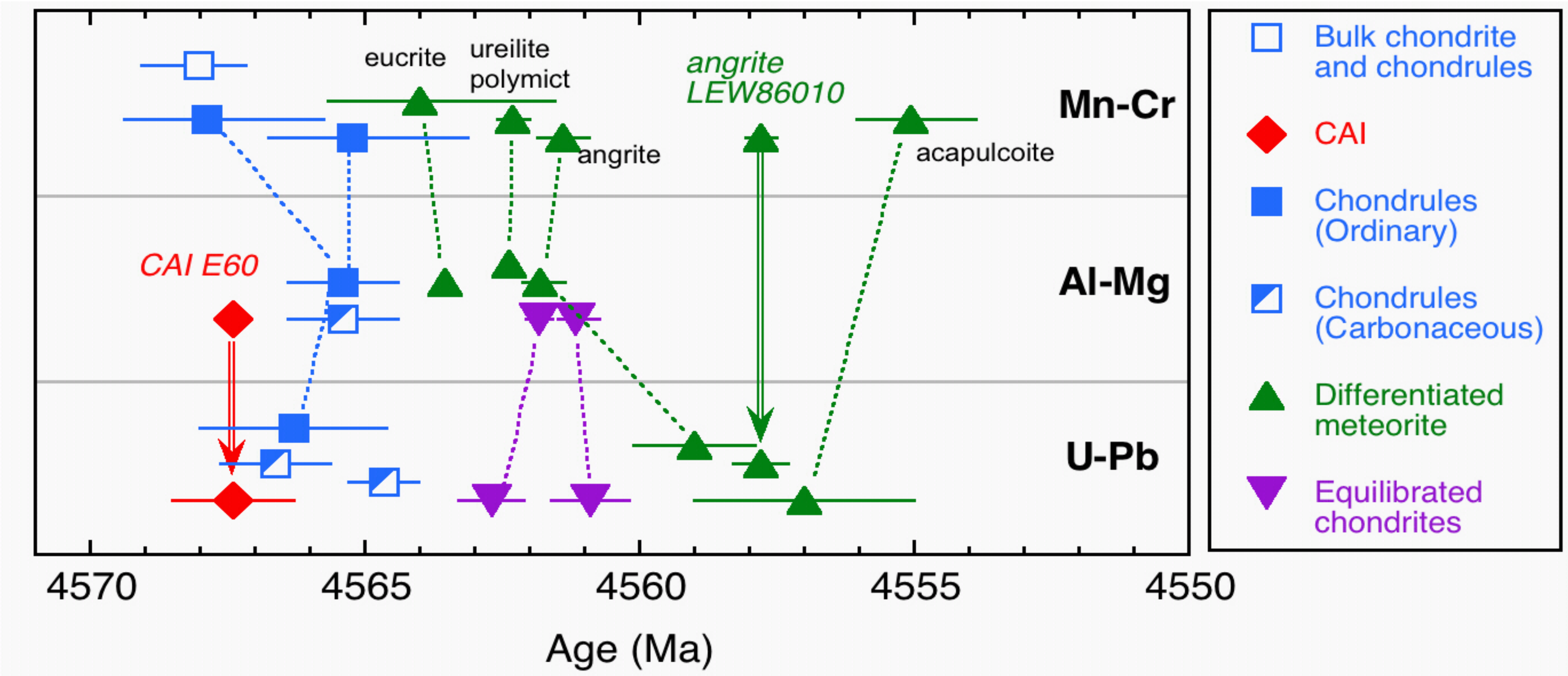
Quitte et al. (2006) measured 60Fe in CAIs, and obtained an initial $^{60}Fe/^{56}Fe$ = ~5 $\times 10^{-6}$
But also observed nucleosynthetic anomalies



Conclusions- Short-lived isotopes

- There is strong evidence that at least eight short-lived isotopes (with half-lives of less than 10Myr) were present in the early solar system
- Galactic continuous evolution can explain some of these isotopes
- ^{10}Be, ^{26}Al, ^{41}Ca and ^{53}Mn are overabundant in the solar system and these isotopes are found in CAIs.
- Probably multiple formation sites were necessary to produce these isotopes

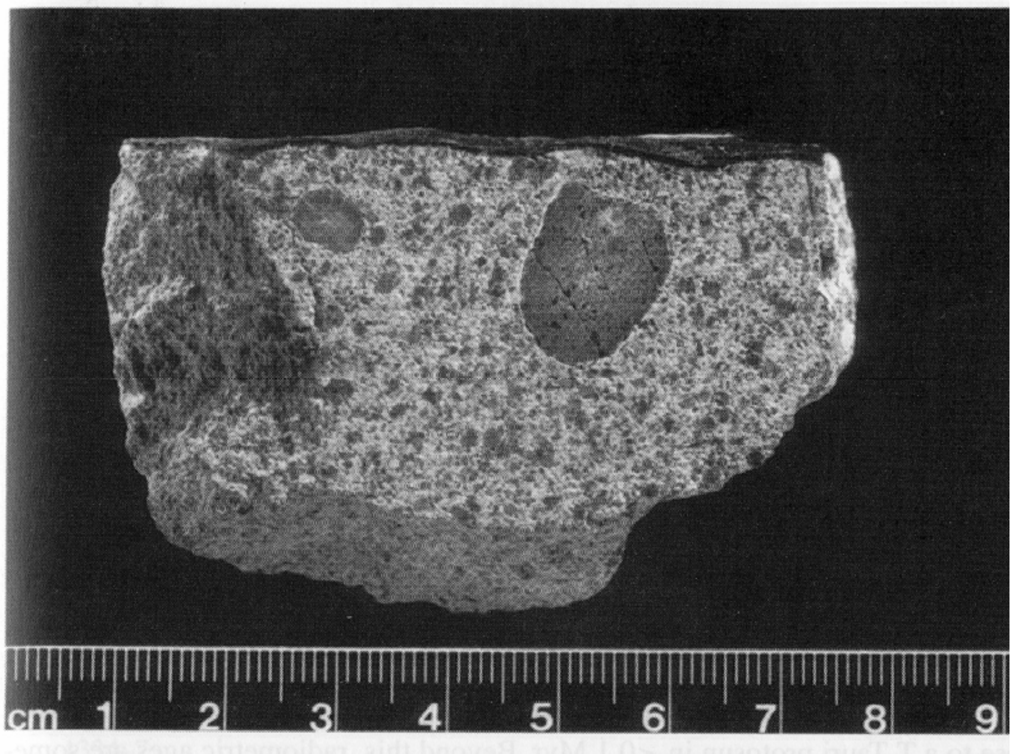
Summary of ages produced by short-lived isotope chronometers and Pb-Pb chronometer



From Kita et al

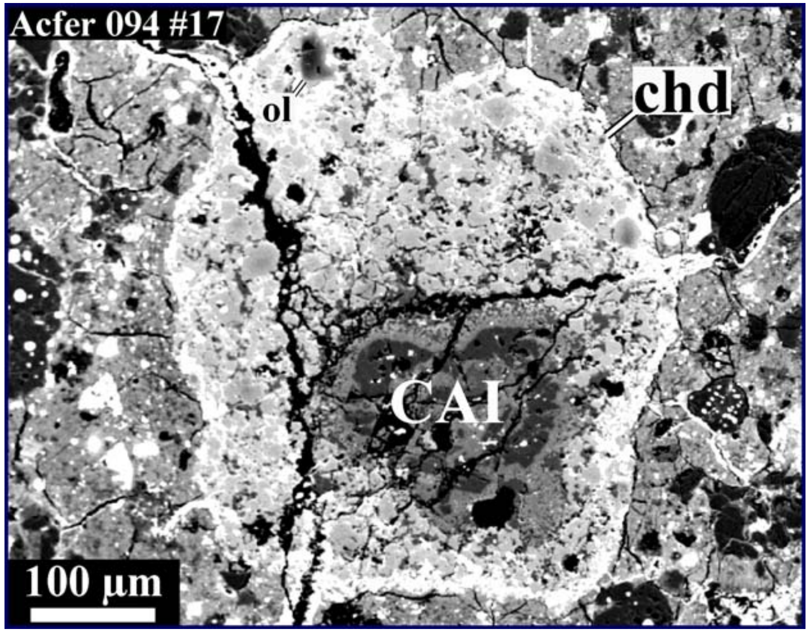
Formation of planetesimals

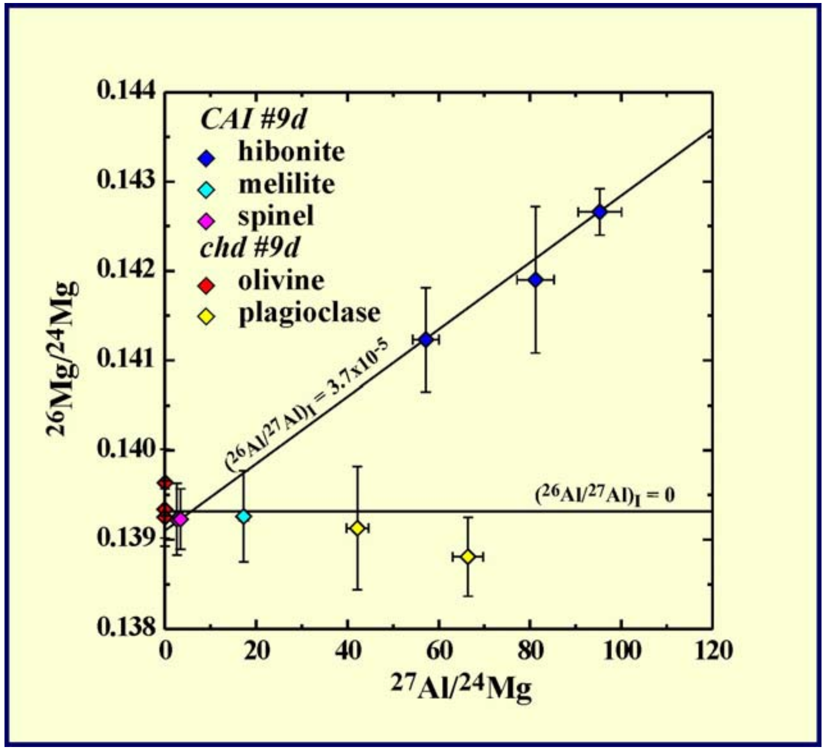
Differentiation of the first planetesimals occurred very rapidly, perhaps even around the time of CAI formation (see Wadhwa et al. 2006)



The ordinary chondrite Barwell contains an igneous clast that pre-dates the chondrite and yields a very ancient age of 4567±1 Myr (Hutchison et al. 2004)

Relict refractory inclusions in chondrules



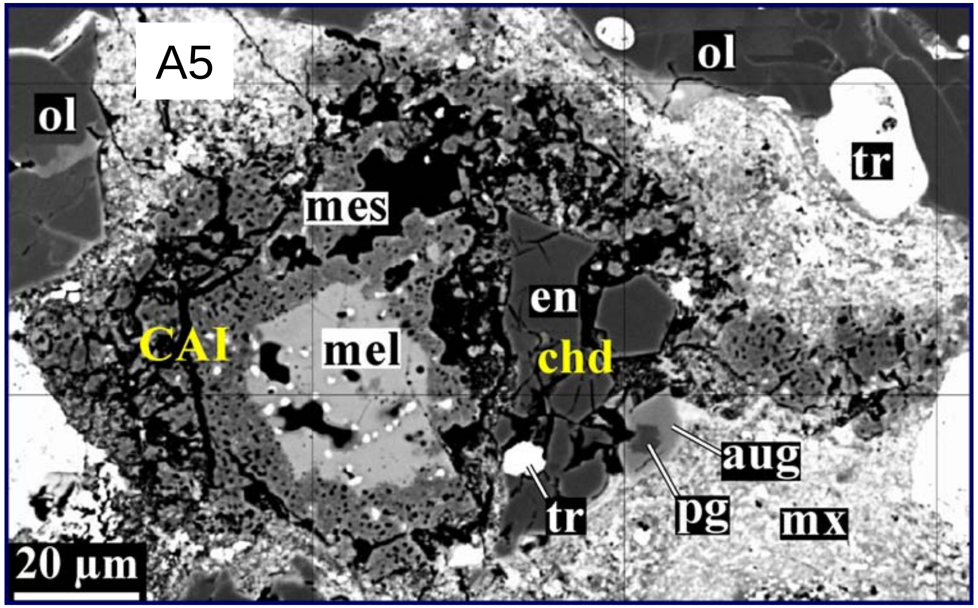


- Rare in Fe-Mg chondrules
- Common in Al-rich chondrules
- Melted to various degrees
- Formed <u>before</u> host chondrules & melted during chondrule formation
- Implies formation of CAIs first, and that they were present when Al-rich chondrules formed

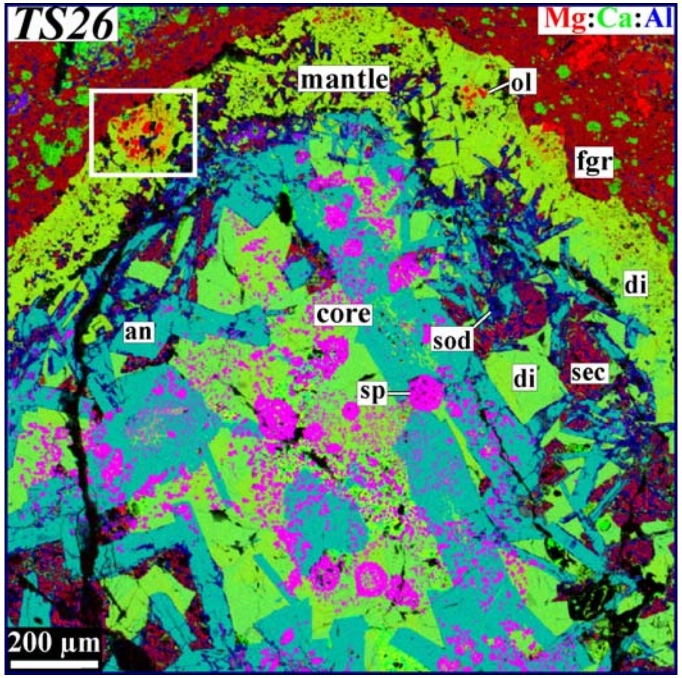
Krot et al. (2006) ApJ, 639, 1227

Relict chondrules in refractory inclusions

- Much rarer!



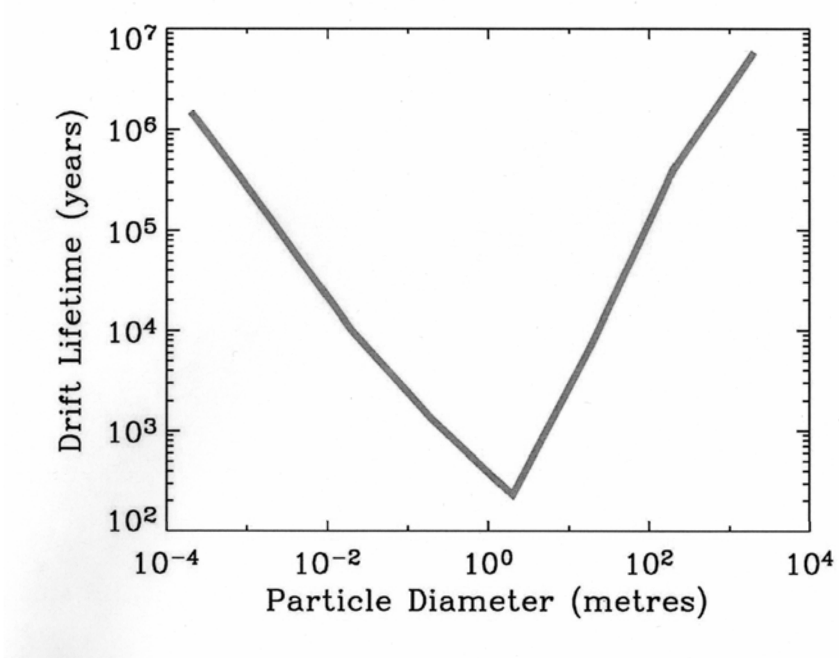
CAI A5 – Petrology ambiguous
Itoh et al. (2001)



TS26- Chondrule in the CAI mantle- this probably remelted during the chondrule forming event and trapped the chondrule (Krot et al. 2006)

Dynamical considerations

- Dust formed in a protoplanetary disk will be affected by its environment:
- Radiation pressure forces gas outwards
- Poynting-Robertson drag pulls dust inwards
- Can dust survive long enough to accrete into planets on a million-year timescale?



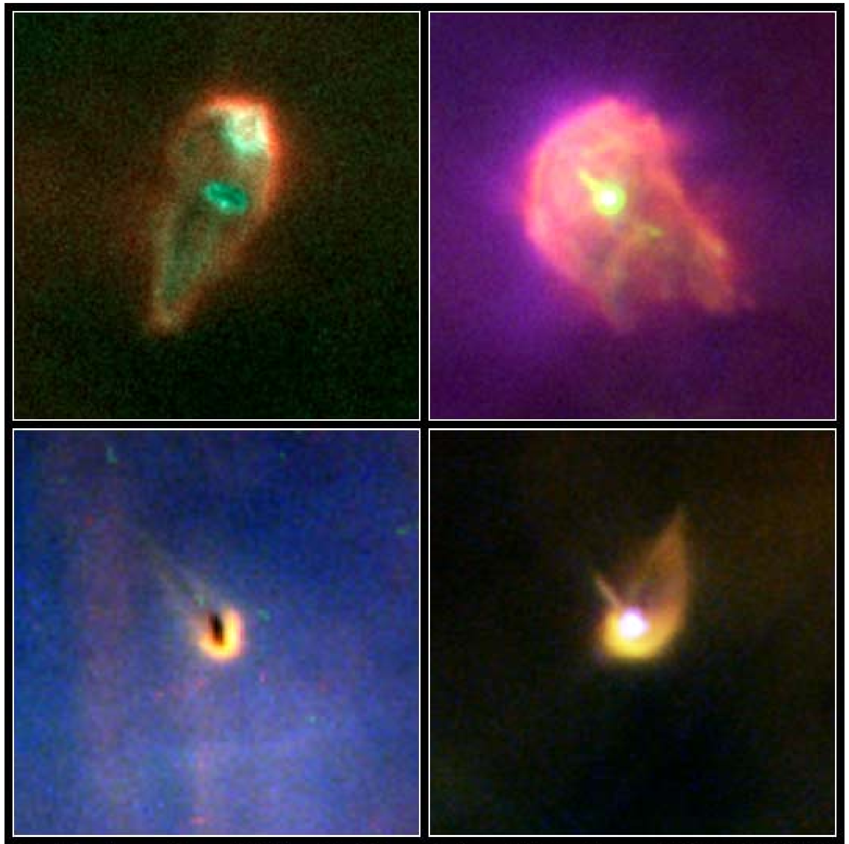
Non-turbulent nebula

- Models show that accretion would be expected to occur very quickly –kilometre-sized bodies would form in ~10^4 years
- This is incompatible with the isotope data, and also if this were true then would expect more differentiated asteroids to exist because there would be more heating by short-lived isotopes
- Only possible solution is if CAIs were stored in small (<30km) planetesimals and recycled

Turbulent, diffusive nebula

- If the nebula was turbulent:
  - Particles would be diffused into a thick, low density layer in which growth would be much slower.
  - This makes planet building harder
  - Radial diffusion likely to happen for particles the size of CAIs and chondrules
  - The ‘x-wind’ may also allow a mechanism for particles that have drifted inwards to be recycled to asteroidal distances
    - See Cuzzi and Weidenschilling, 2006 and Weidenschilling and Cuzzi, 2006.

Observations of disks

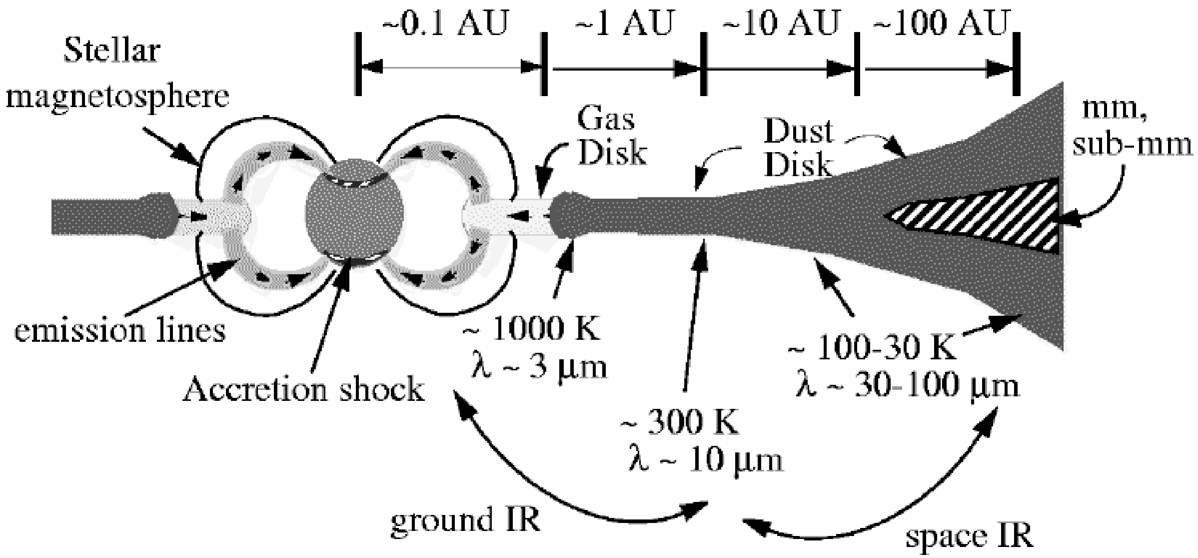


Protoplanetary Disks in the Orion Nebula **HST** • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University) • STScI-PRC01-13

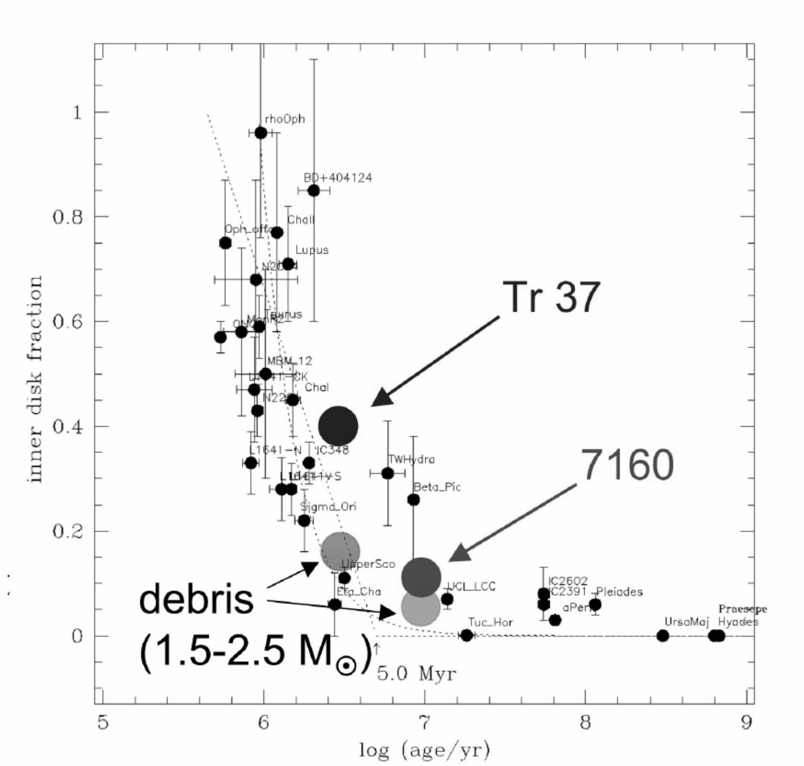
Typical T-Tauri disk showing observation mechanisms.

Most of disk is made of gas, but this is difficult to observe.
IR spectra typically sees only the surface of the dusty disk, while mm and sub-mm sees the cold dust disk far from the star.



Observational constraints

- Initially around 80% of stars have dust disks
- After 3 Myr about 50% of stars still have dust disks
- After 6 Myr most disks have disappeared
- Probably the disk has accreted into bodies too large to be easily observed
  - See Haisch et al. (2001)



Conclusions

- All available data point to a protoplanetary disk lifetime of a few million years:
- Pb-Pb dates suggest a lifetime of >~4Myr, later events may reflect impact processes
- ^{26}Al also points to a several million year disk lifetime.
- Preserving nebular-formed solids for this amount of time is possible, as long as they are prevented from falling into the Sun, by turbulence, stellar winds, or storage in primary asteroidal bodies.
- Observations of young stellar objects suggest that there is a wide variation in disk lifetimes, but ~3-5 Myr is average.
- CAIs are the oldest well dated objects that formed in the solar system. Their formation probably occurred over a relatively short timeframe. Chondrule formation probably began soon after (or at the same time as) CAIs, and continued for several millions of years.

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