STELLAR SOURCES FOR OXYGEN IN THE EARLY SOLAR SYSTEM

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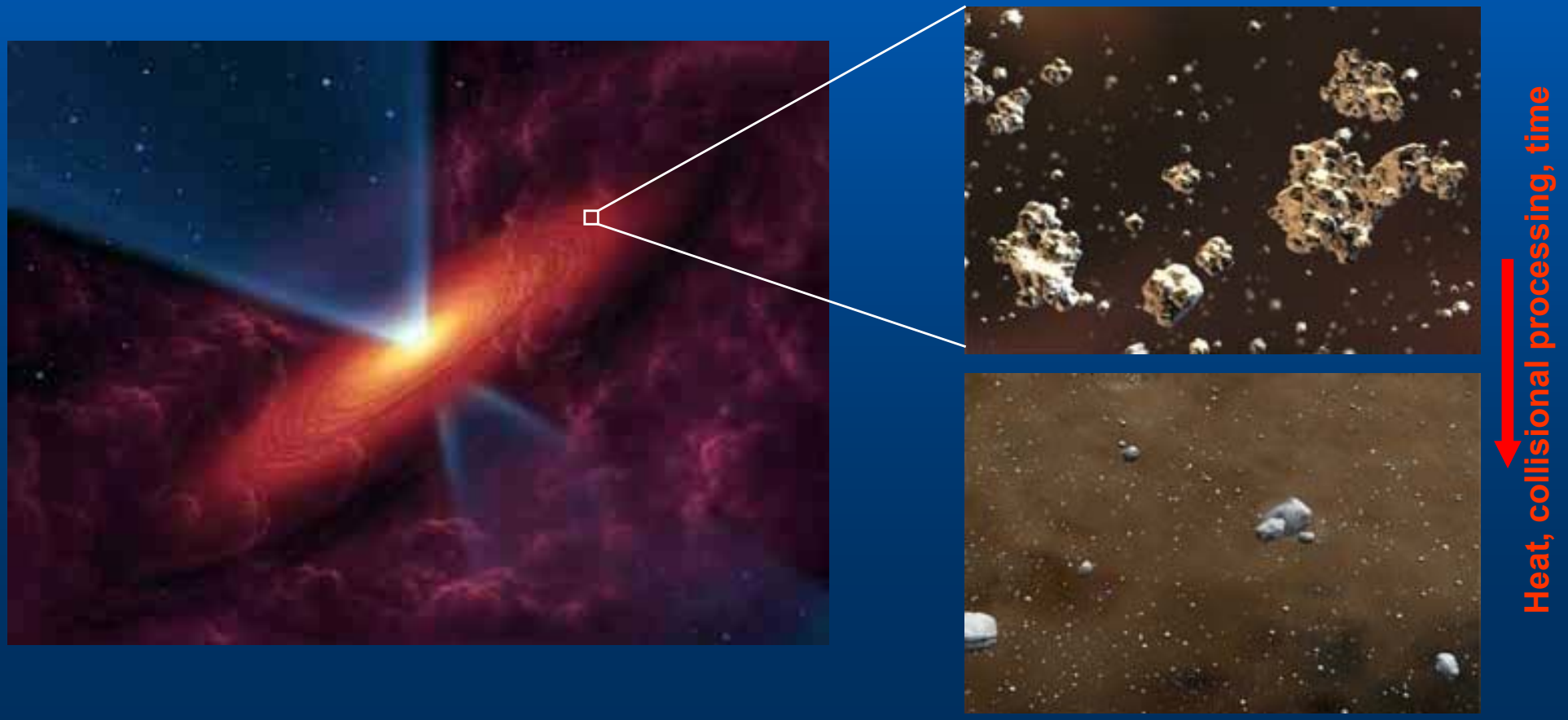
[With contribution on AGB models from D.A. García-Hernández, M. Lugaro, A. Karakas, P. García Lario, and A. Manchado.]



OUTLINE

- The stellar environment in which our solar system formed
  - Meteorite and IDP evidence of preserved stellar grains
- Stellar (presolar) products retained in primitive materials
  - Short lived nuclides (SLNs) and stellar grains
- Components of carbonaceous chondrites:
  - Astrophysical clues on the primeval solar system environment
  - C-rich chondrites
- AGB stars as sources of SLNs, stellar grains and organics:
  - Nucleosynthesis products as function of stellar mass
  - The ^{22}Ne source to explain SLNs in CAIs
- O incorporation into asteroidal and cometary bodies:
  - Clues from carbonaceous chondrites
  - Interplanetary Dust Particles
- Conclusions: the many pathways of O into the early solar

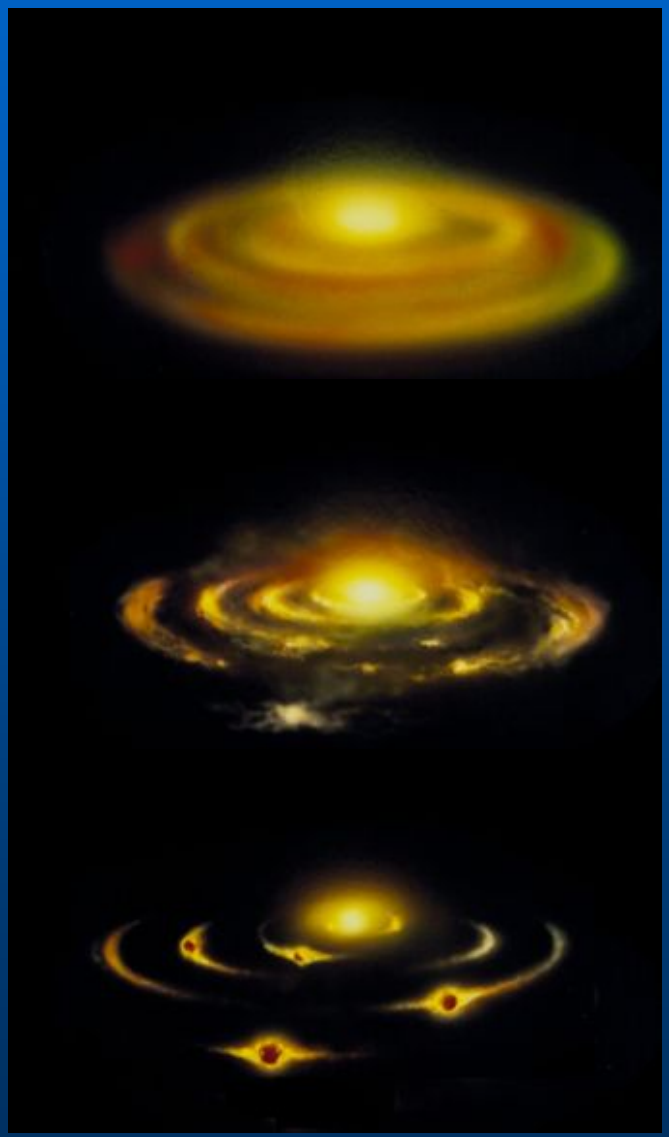
THE METEORITICAL CONFIRMATION

NGC3603, adapted from HST image (NASA)

NASA

- Solar System formation took place from the gravitational collapse of a molecular cloud (Cameron, 1962):
  - Primordial and stellar nucleosynthetic heritage from meteorite components
  - Remote observation of proplyds (Herbig, 1977) plus theoretical studies (Lynden-Bell & Pringle, 1974)
- First stellar grains in meteorites: a new age in laboratories (Bernatowicz et al., 1987)
  - Materials formed in stars during solar system formation (Anders, 1987; 1988)
    - Extreme isotopic anomalies
  - *Secondary Ion Mass Spectrometer (SIMS)* to get accurate isotopic abundances of components of meteorites (Ott, 1993; Bernatowicz & Zinner, 1997)

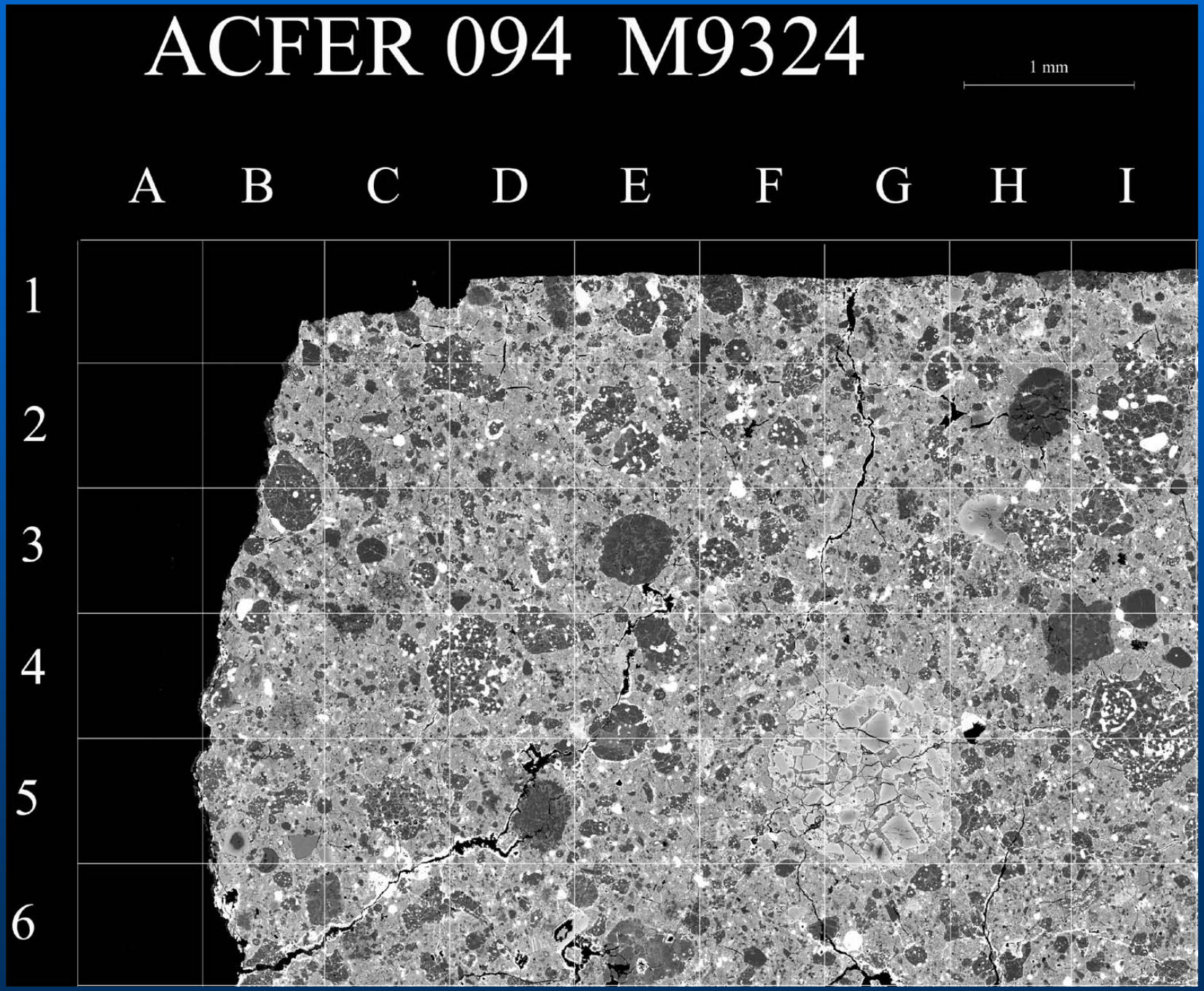
A SIMPLIFIED BIRTH SEQUENCE FOR THE SOLAR SYSTEM



First 10Myr in SS formation

- Primordial nebula collapsed ~4.57 Gyr ago
- What was the origin of the matter falling into the protoplanetary disk?
  - Not all chemical and isotopic fingerprints were erased because the nebula was not so hot as Cameron (1978) and Lewis (1980) thought.
  - Products of the chemical evolution of the galaxy
  - Primitive meteorites inherited stellar materials:
    - Isotopic anomalies and presolar grains

PRIMITIVE CHONDRITES

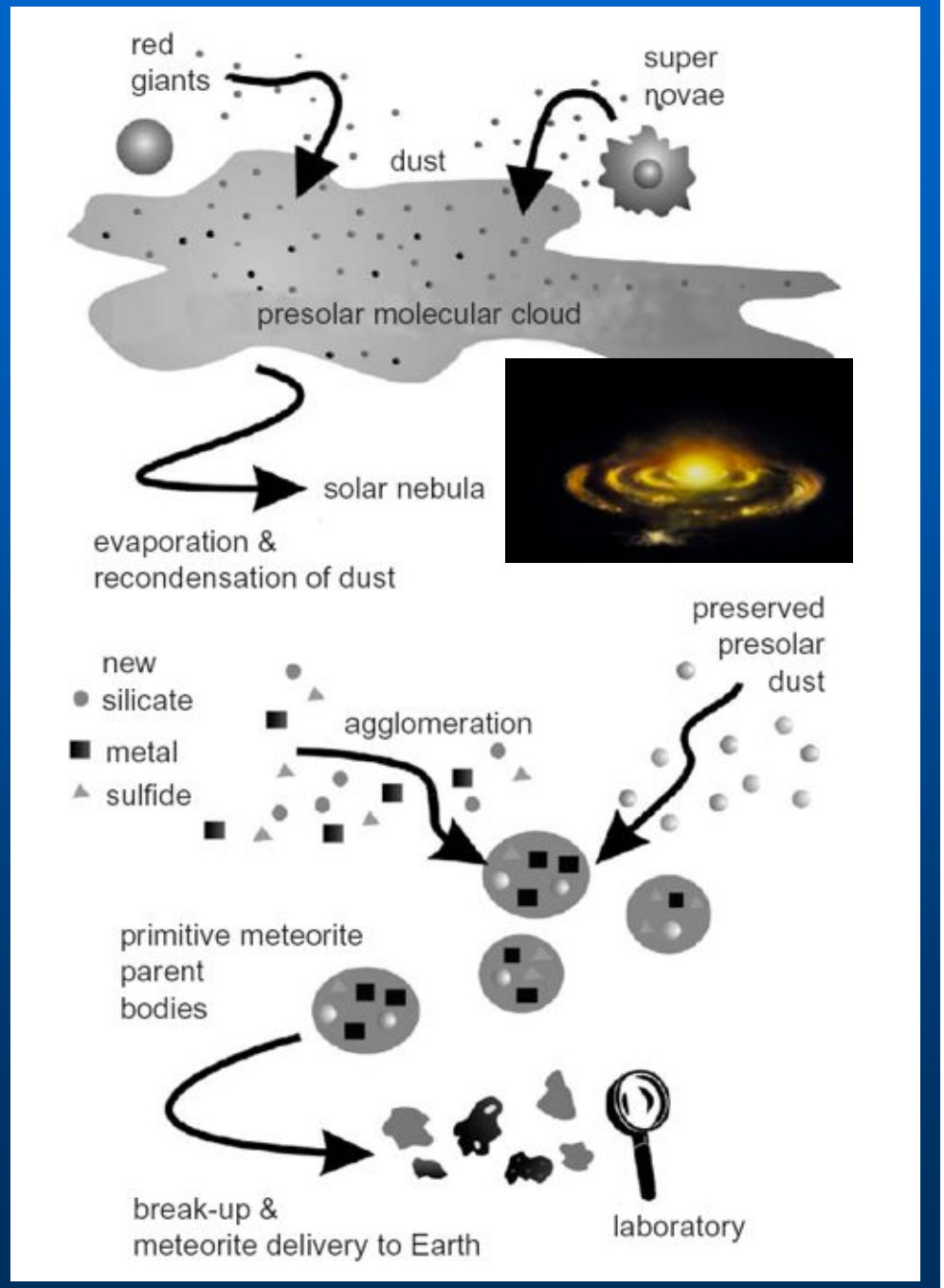


SEM image of CM-like ungrouped Acfer 094 (Trigo-Rodríguez et al., 2006)

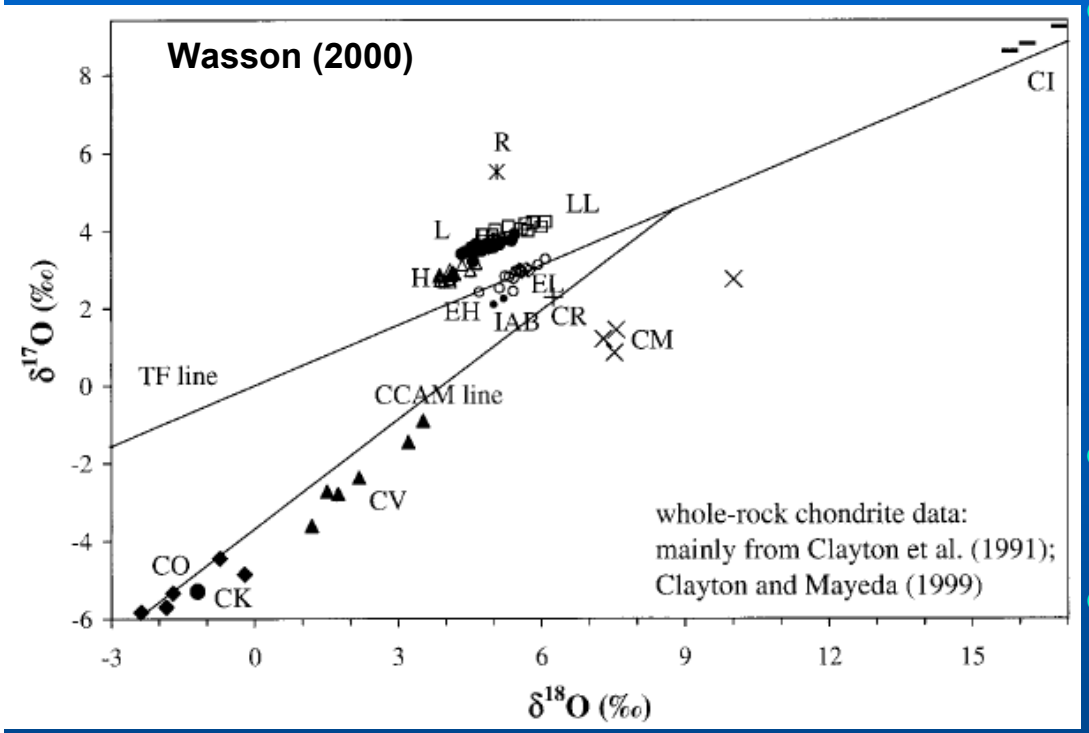
STELLAR COMPONENTS

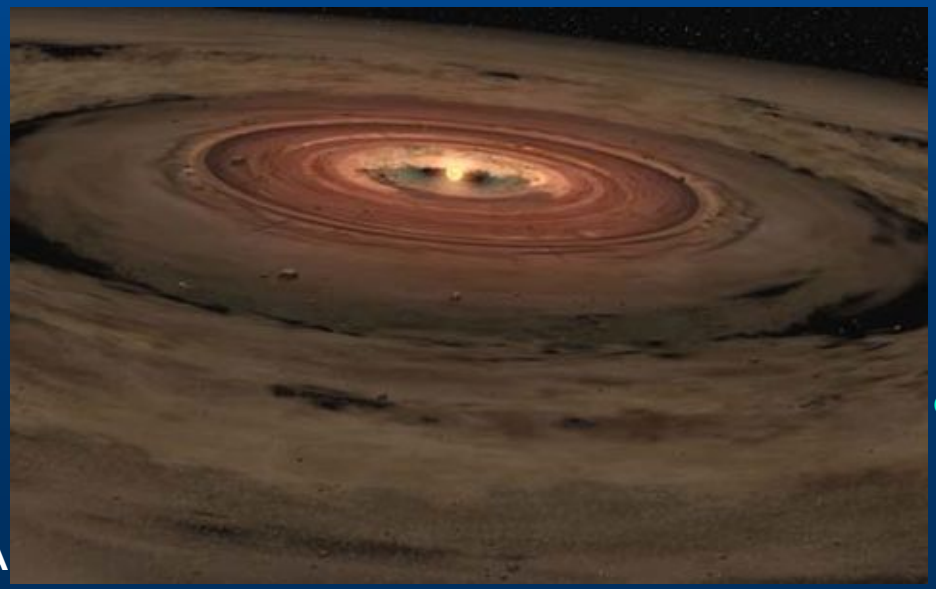
- The Sun and the protoplanetary disk formed from an environment rich in stellar products.
  - Growing evidence of the SS formation in a rich stellar cluster
- A small part of the materials were not processed in the solar nebula, and are "presolar":
  - Presolar (stellar) grains
  - Radioisotopes
    - In the components
    - Trapped in the matrix
  - Isotope anomalies
- Principal sources:
    - Circumstellar shells of red giants
    - AGBs
    - Novae and SN ejecta

Adapted from Lodders and Amari (2005)



OXIGEN ISOTOPIC CLUES





NASA

- Clayton et al. (1973) found that the O isotopic ratios are far from the line of Terrestrial fractionation (TF)

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{muestra}}{(^{18}O/^{16}O)_{SMOW}} - 1\right] \times 1000$$

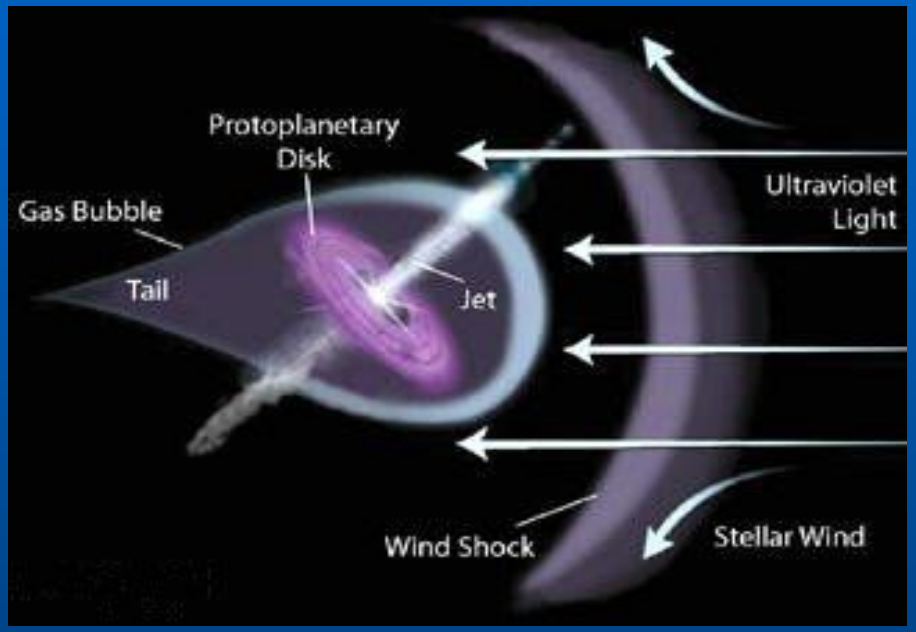
  - SMOW: *standard mean ocean water*
- The drift from TF is measured by:

$$\Delta^{17}O = \delta^{17}O - 0.52 \times \delta^{18}O$$

- So the different planetesimals as a function of their formation region and instant of formation retained different isotopic abundances (Wasson, 1972)
  - Most carbonaceous chondrites (CCs) are falling into the CCAM (anhydrous minerals of CCs)
  - Some are outside that pattern because were significantly altered by water: CM & CR
- What is the origin of those anomalies?
  - A changing environment (stellar sources)
  - CO self shielding (nebular)

SCENARIOS FOR ^{i}O ANOMALIES

- Tielens & Heidenreich (1983) first suggestion of O_2 *self shielding* in the nebula
  - Later on discarded by Navon & Wasserburg (1985)
- Subsequent analysis ruled out self-shielding of O_2 (Navon & Wasserburg, 1985)
- But Lyons y Young (2005) supported again the origin of O anomalies as due to an irradiation process:
  - CO is photodissociated by FUV (91 a 110 nm)
    - Each $C^{i}O$ molecule will absorb FUV depending of their initial column densities
  - In the model: $C^{x}O + h\nu \rightarrow C + {}^{x}O$ (x=16,17 & 18)
    - 96 chemical species and 375 reactions
  - $C^{17}O$ and $C^{18}O$ species are more resistant to FUV flux
    - Inner disk is poor in ^{16}O
    - Ices heritage of ^{17}O & ^{18}O higher abundances
  - Nebular models ($pH_2=10^{-5}$ atm): half of the O was as CO and 1/3 as H_2O
- ^{16}O-enriched CAIs discovery (Clayton et al., 1973)
  - CCAM line with slope ≈ 0.9
  - Pure ^{16}O injected from nearby SN
- Our $6M_o$ intermediate mass AGB model could also have enriched the outer disk in ^{17}O and ^{18}O-rich materials (Trigo-Rodríguez et al., 2009)
  - Before dilution with the nebula: $\Delta^{17}O \approx 4{,}500$



RADIONUCLIDES FOUND IN METEORITES

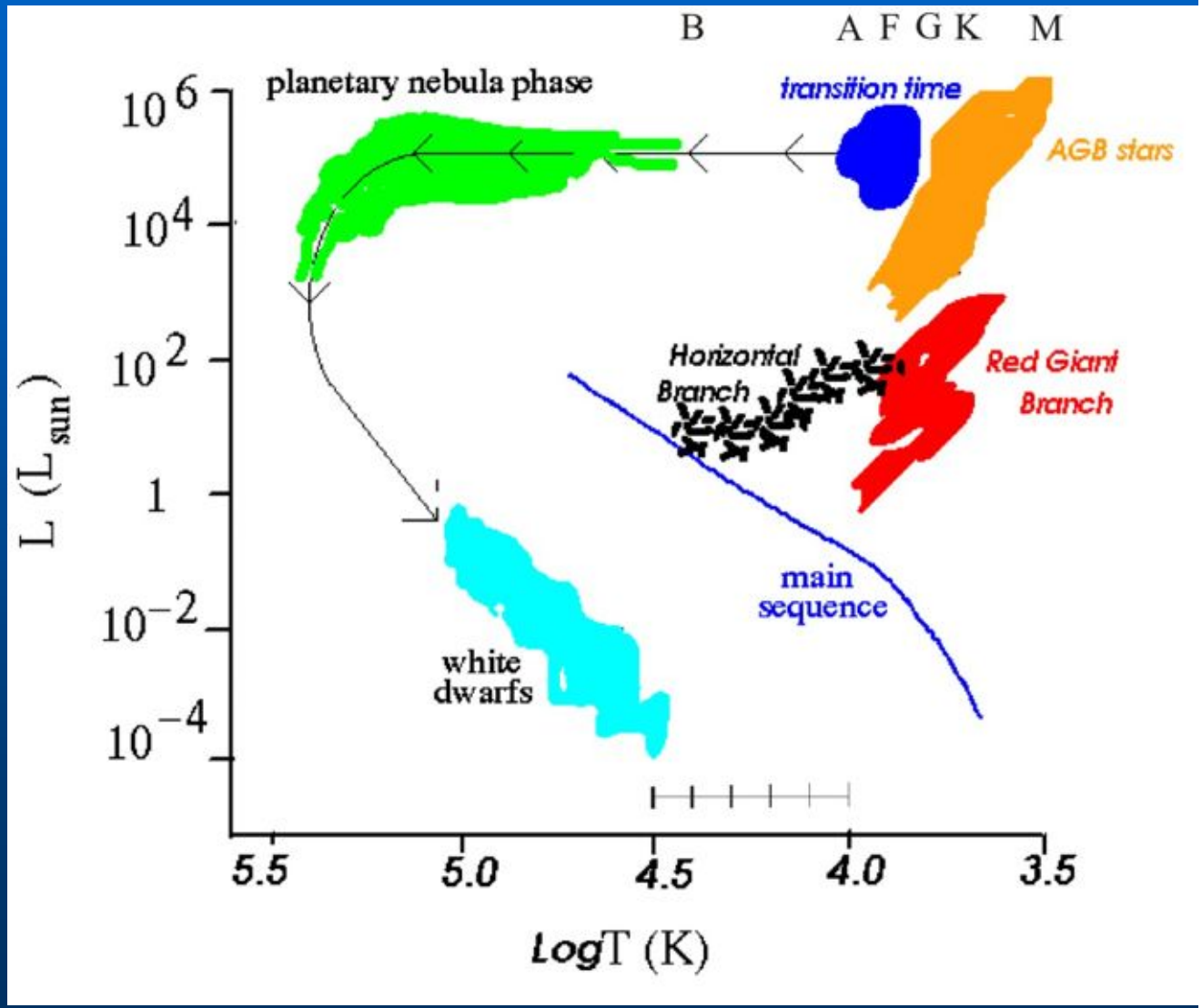
- In particular short-lived nuclides (SLN) were important for planetesimals internal heating
- They incorporated from the vapor phase into the minerals forming chondritic components

Parent	Daughter	Detected Presence	Half-Life (10^6 yr)	Likely stellar source(s)
^{10}Be	^{10}B	CAIs (McKeegan et al., 2000)	1.5	Spallation product
^{26}Al	^{26}Mg	CAIs (Lee et al.,1966) and chondrules (Galy et al. 2000)	0.73	SN, massive AGBs
^{41}Ca	^{41}K	CAIs (Srinivasan et al., 1994)	0.1	AGBs
^{53}Mn	^{53}Cr	CAIs (Birk and Allègre, 1985), chondrules, etc	3.7	AGBs
^{60}Fe	^{60}Ni	CAIs, eucrites (Shukolyukov and Lugmair, 1993)	1.5	SN, massive AGBs
^{87}Rb	^{87}Sr	CAIs	48,800	Massive AGBs

STELLAR SOURCES: AGB STARS

Asymptotic Giant Branch (AGBs): late stage of evolution of low- to intermediate-mass stars:
$1 \leq M \leq 8\ M_{\odot}$

TP phase: strong mass loss enriches the ISM with radionuclides and circumstellar dust grains!



García-Hernández, 2005

THE s-PROCESS IN AGB STARS

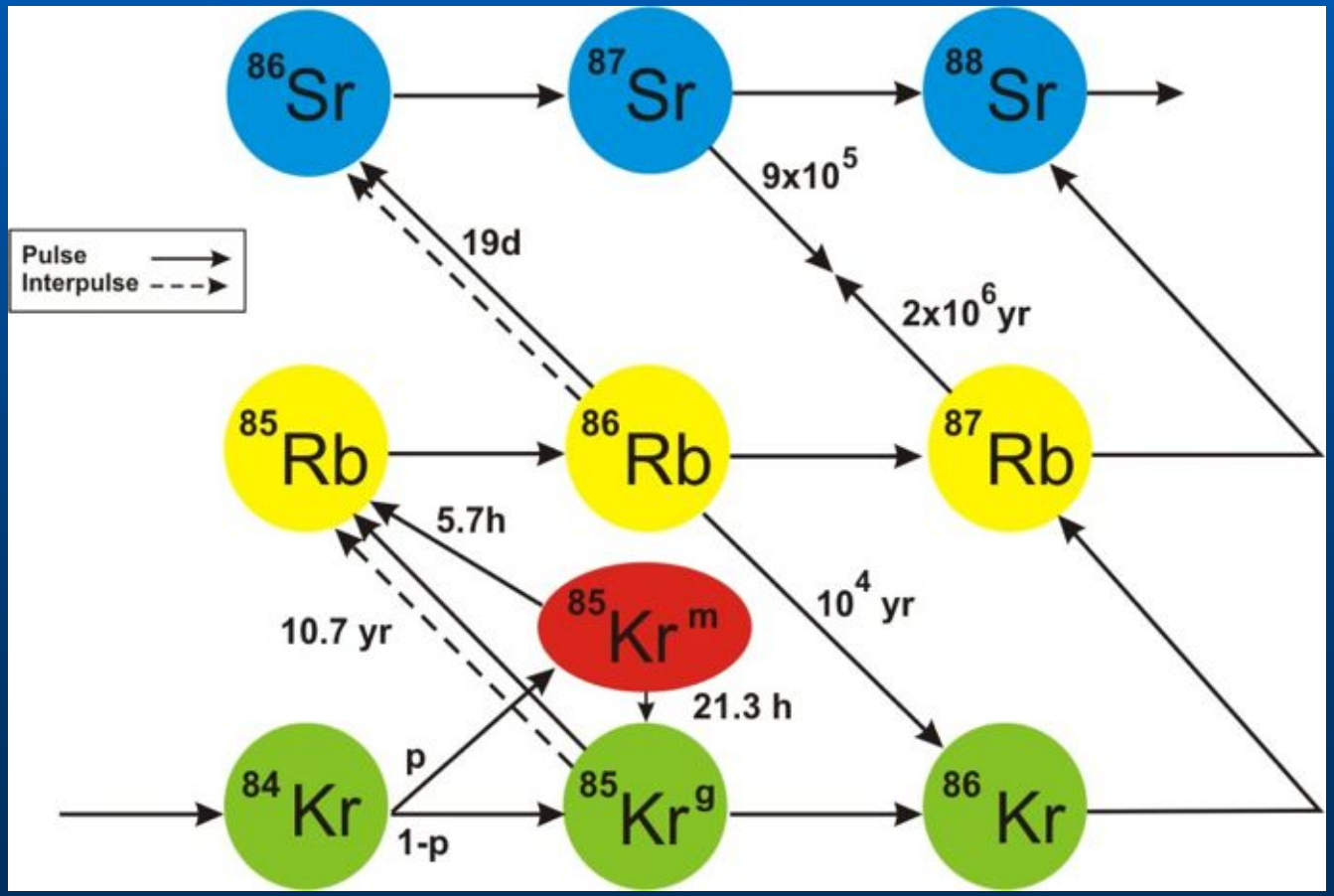
- **Free neutrons to form heavier elements (s-elements such as Rb, Zr, Sr, etc.) can be released by $^{13}C(\alpha,n)\,^{16}O$ or by $^{22}Ne(\alpha,n)^{25}Mg$ reactions** (Busso et al. 99)

- **^{13}C operates during the interpulse period. It is more efficient in 1–3 $M_\odot$ AGB stars.**
  - All previous observations of AGB stars were consistent with ^{13}C!

- **^{22}Ne is expected to be efficient in the convective thermal pulse at higher T and N_n. It should become strongly activated by Hot Bottom Burning in more massive AGB stars (M>4–5 $M_\odot$).**
  - This prediction was confirmed by accurately-reduced stellar spectra (García-Hernández et al., 2006, Science)

THE ^{22}Ne NEUTRON SOURCE

- The operation of the ^{22}Ne neutron source favors the production of the stable isotope ^{87}Rb (also of ^{60}Fe, ^{41}Ca, ^{96}Zr, ^{25}Mg, ^{26}Mg, etc.) because of the operation of a branching in the s-process path at ^{85}Kr (Beer & Macklin, 1989)



García-Hernández, 2005

A MASSIVE AGB STAR IN THE ORIGIN OF THE SOLAR SYSTEM?

- We have suggested that a 6.5 $M_{\odot}$ AGB star of solar metallicity played a role in the Solar System enrichment in short-lived nuclides (SLN)
- By comparing the SLN abundances in primitive meteorites with the isotopic pattern modeled for the surrounding environment of that AGB star
  - Our model match the abundances of ^{26}Al, ^{41}Ca, ^{60}Fe, and ^{107}Pd inferred to have been present in the solar nebula by using a dilution factor of 1 part of AGB material per 300 parts of original solar nebula material
  - Such a polluting source does not overproduce ^{53}Mn, as supernova models do, and only marginally affects isotopic ratios of stable elements

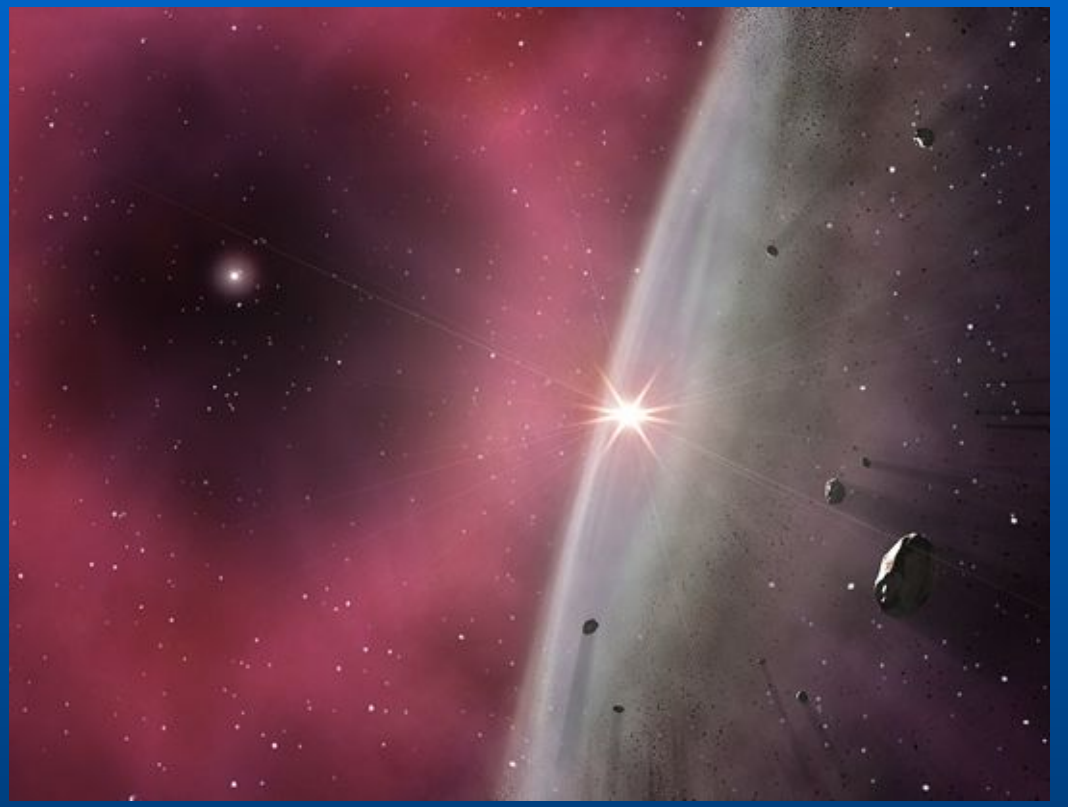


Image Gabriel Pérez Diaz (IAC)

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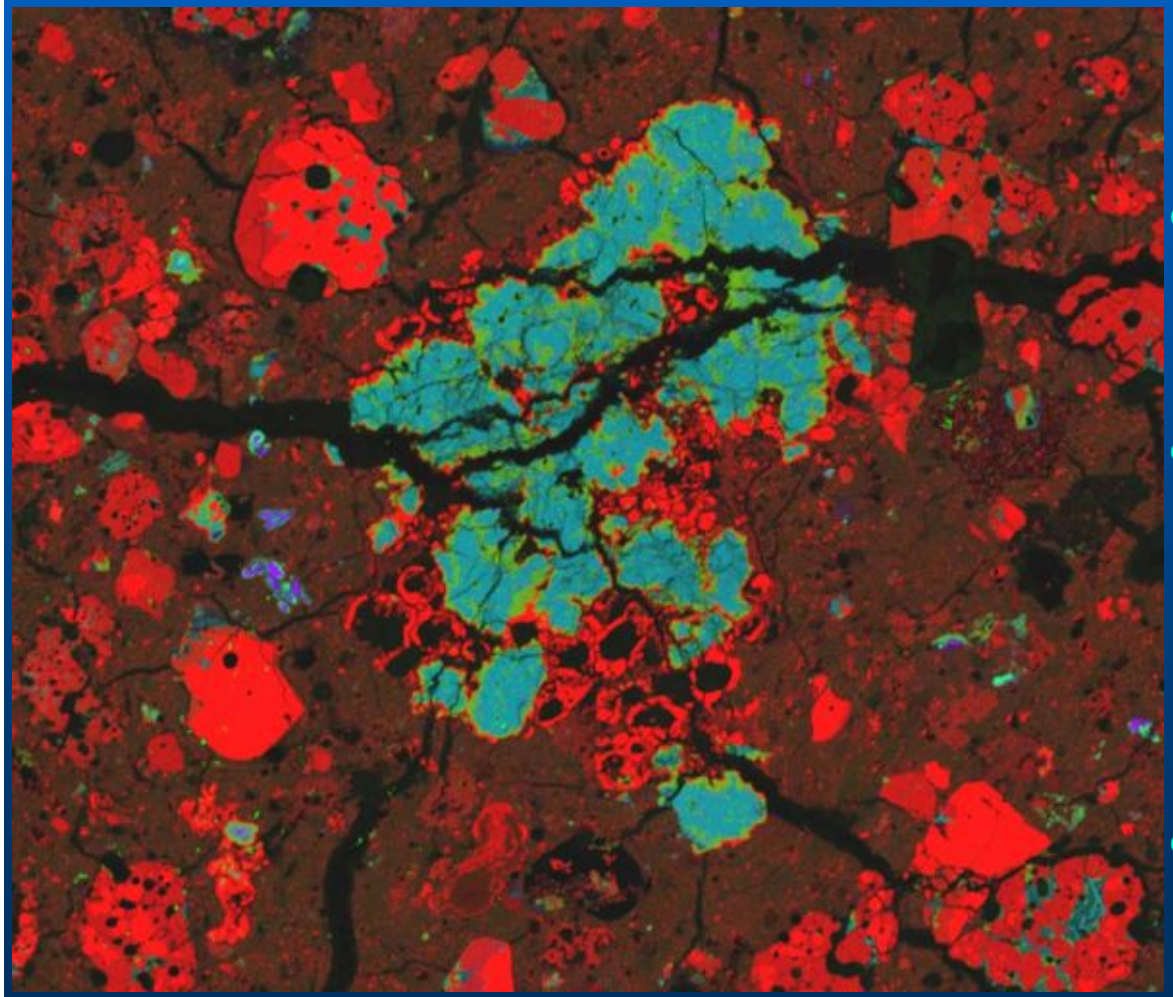
LOOKING FOR EVIDENCE IN FIRST MATERIALS...

CAIs: THE OLDEST SS MATERIALS

0.5 mm-sized CAI surrounded by chondrules and matrix In ACFER 094 (Trigo-Rodríguez et al. 2006, GCA)

RGB X-Ray mapping (each color for Mg, Ca, Al)

Note the relic aggregate-like structure

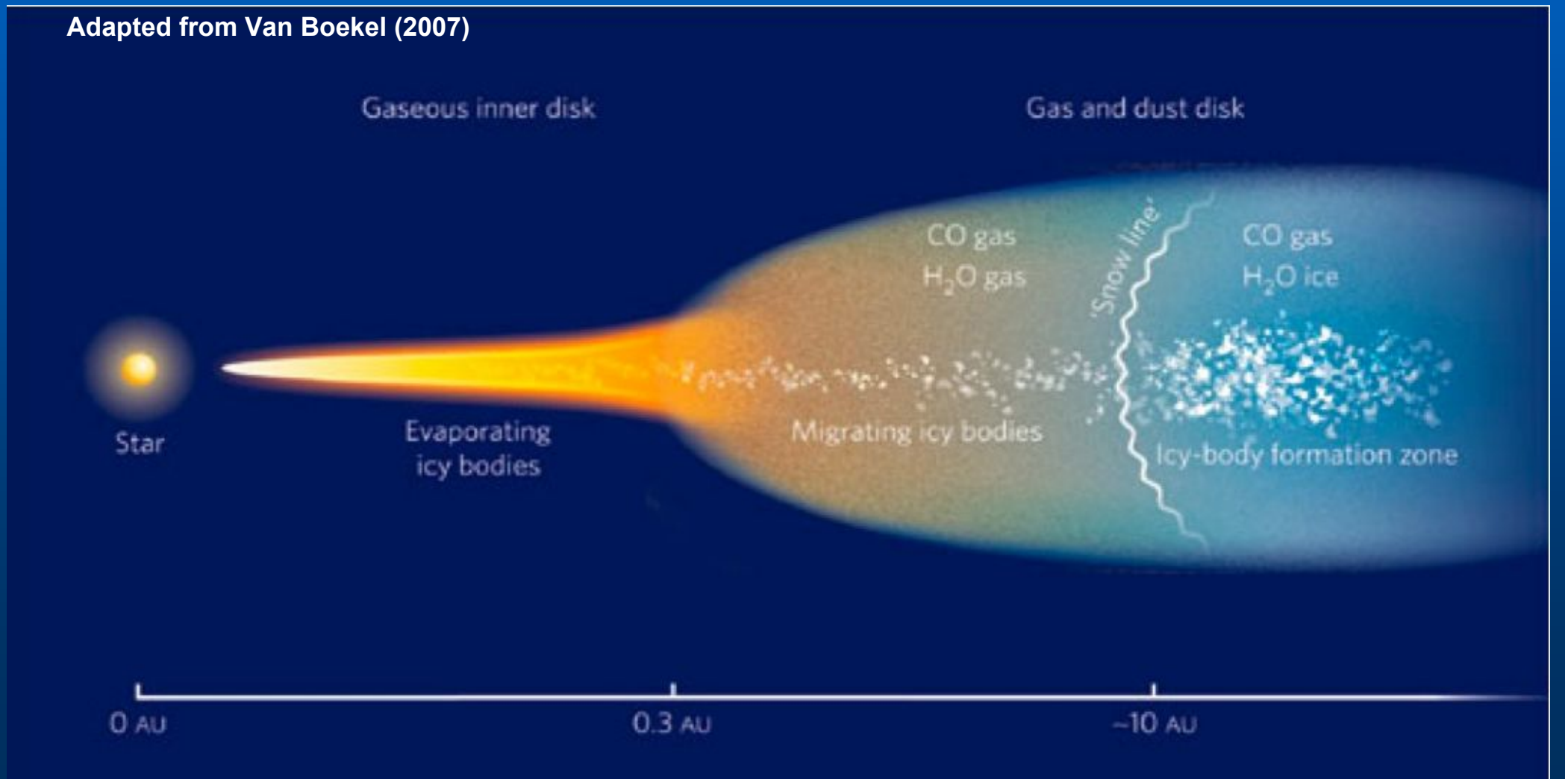


- **The Ca-Al rich Inclusions (CAIs)**
  - **The oldest SS materials: 4567±1 Myr (Amelin et al., 2002)**
  - **Formed by refractory minerals: spinel ($MgAl_2O_4$) + melilite ($Ca_2Al_2SiO_7$)+ hibonite ($CaAl_{12}O_{19}$)**
- **More accepted model:**
  - **CAIs are the resulting products of heating CI-composition dust clumps**
- **CAIs retained a variety of isotopic anomalies (they are rich in ^{16}O, ^{26}Al, ^{53}Mn, ^{41}Ca, ^{87}Rb) inherited from incompletely homogenized materials:**
  - ^{60}Fe excesses correlated with ^{96}Zr ➔ ^{22}Ne! (Quitté et al. 07)
- **It is a mere coincidence that CAIs show all the chemical anomalies expected in massive AGB stars?**

SCENARIO FOR CAI and AOI FORMATION

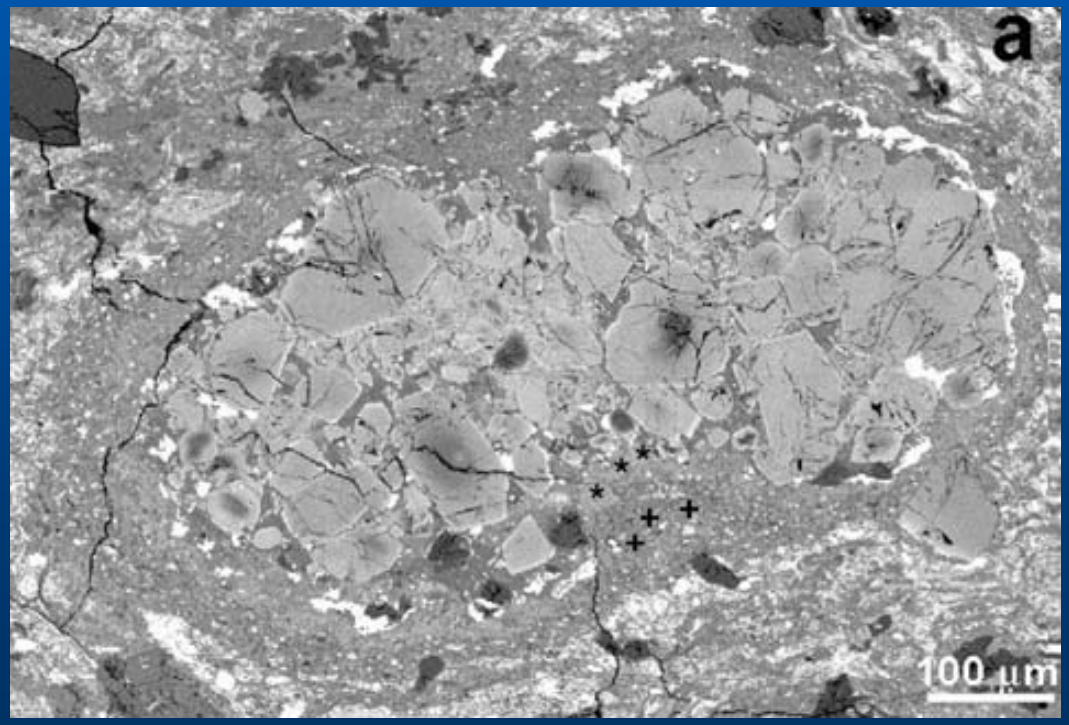
- Shu et al. (2001) suggested that CAIs can form as evaporative residues of "dustballs" in the context of his theory of magnetohydrodynamic X-winds
- Flares induced by the stressing of magnetic fields in the inner edge of the disk
  - Hard (2-10 keV) X-ray flares can lead to vaporization and melting of materials in t~30 yr

Adapted from Van Boekel (2007)

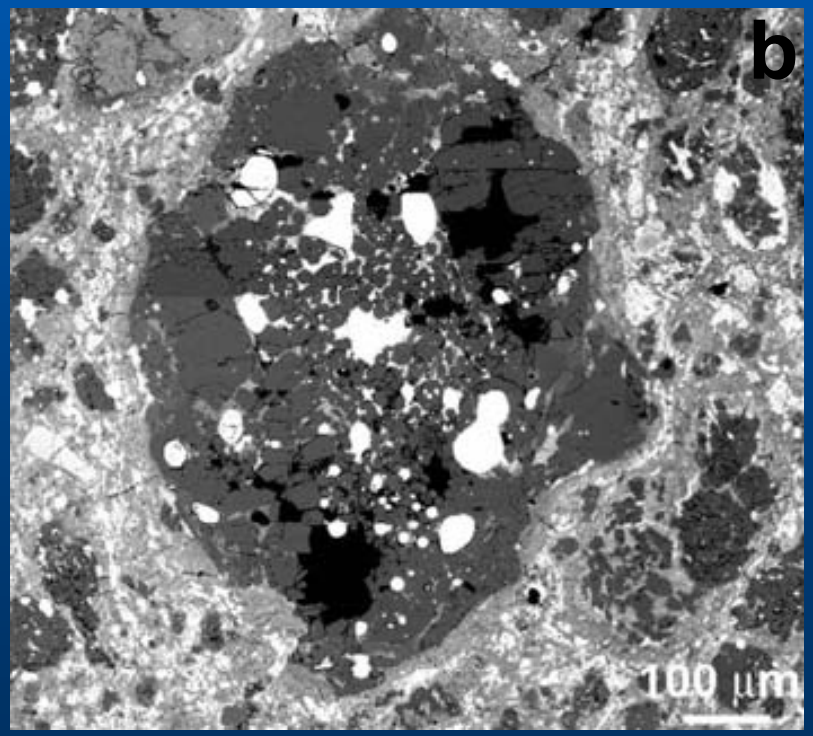


TYPES OF CHONDRULES

- Igneous-textured particles composed mainly of olivine and low-Ca pyroxene crystals set in a feldespathic glass.
- Two types that evidence different mineralogy, but also a diversified forming environment, rich and poor in O:
  - Oxygen-isotopic compositions of large individual chondrules also suggest that they formed in different reservoirs (or at different times).
  - For comparison, CAIs formed in an environment richer in ^{16}O

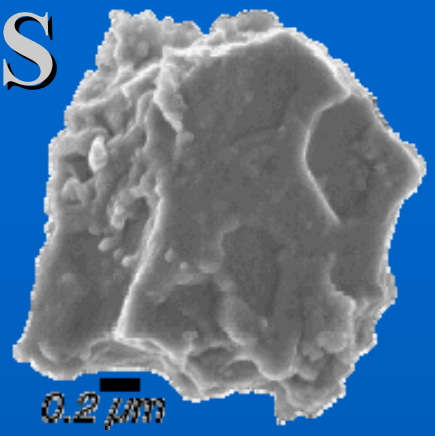


a) High-FeO (type I) chondrule



b) Low-FeO (type II) chondrule

CLUES FROM STELLAR GRAINS



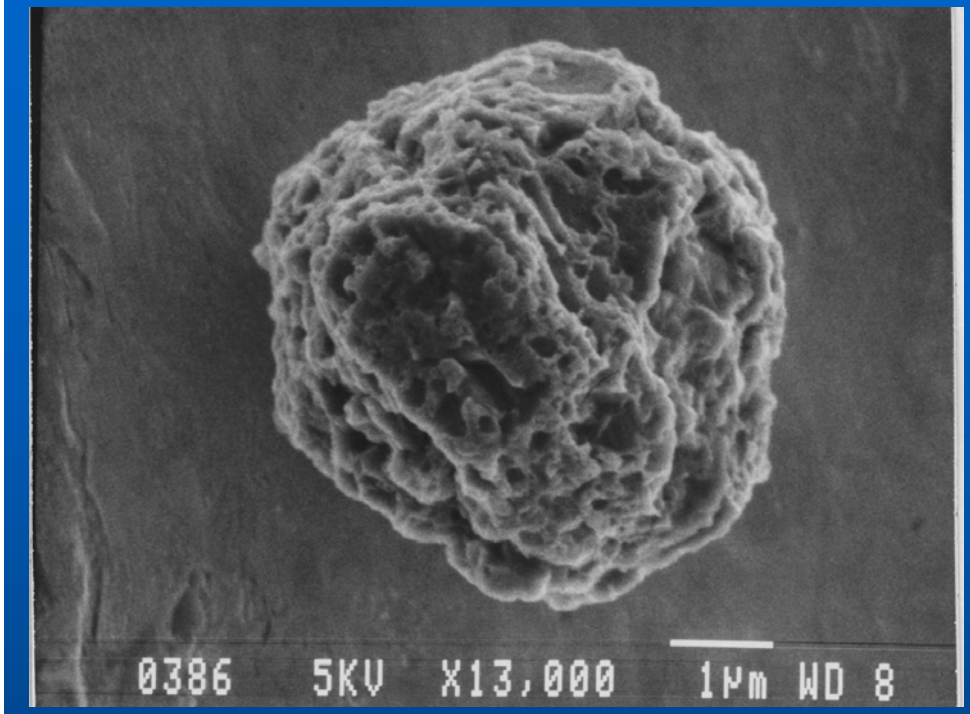
- Grains formed in stellar outflows of late-type stars and in ejecta of stellar explosions
  - Their stellar origin is identified by their anomalous isotopic compositions compared to SS materials

refractory

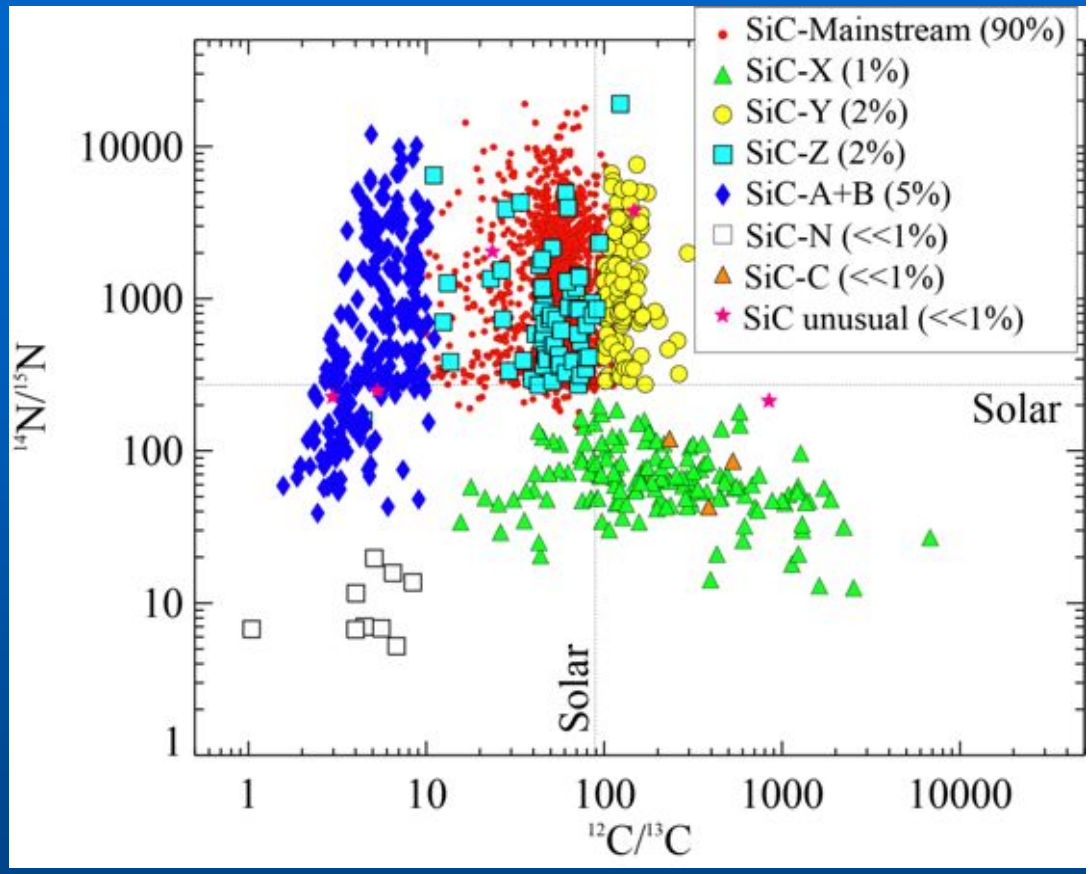
Grain type	Typical size	Abundance	Stellar sources
Diamond	2 nm	1,000 ppm	AGB?, SNe
Silicon carbide	0.1-20 μm	10 ppm	AGB, SNe, J-stars, novae
Graphite	1-20 μm	1-2 ppm	RG, AGB, SNe
Oxides	0.15 – 3 μm	1 ppm	SNe, AGB
Silicon nitride	0.3 – 1 μm	~ 3 ppb	SNe, AGB
Ti-, Fe-, Zr-, Mo-carbides	10-200 nm	< 1 ppb	SNe
Kamacite, iron	~10-20 nm	?	SNe
Olivine	0.1-0.3 μm	?	RGB, AGB, SNe?

compiled from: Zinner, (2003) and Lodders and Amari (2005)

THE ORIGIN OF SiC GRAINS



Chemically extracted SiC grain (S. Amari)

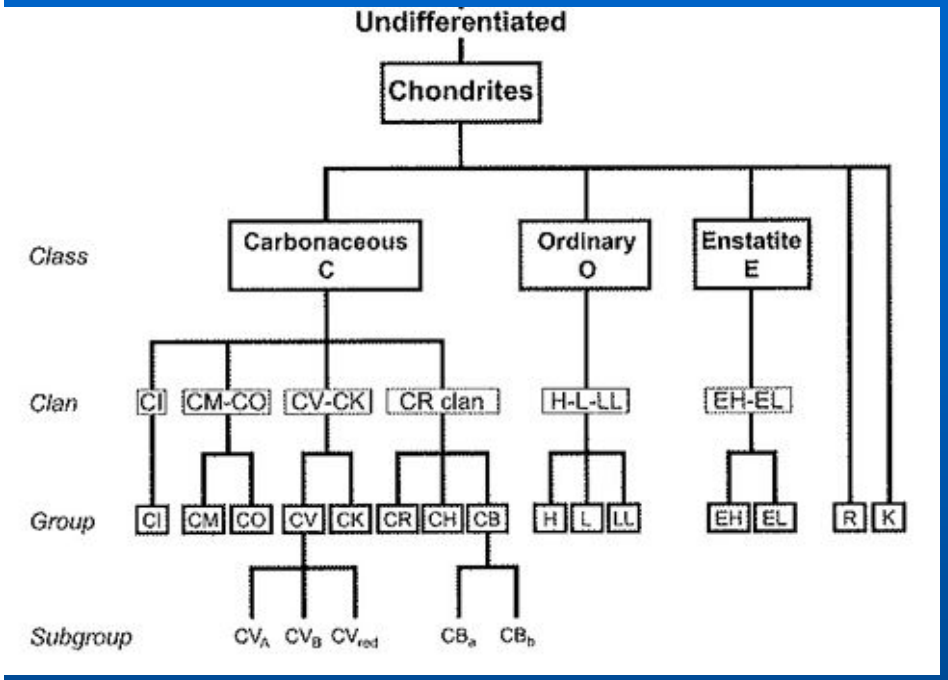


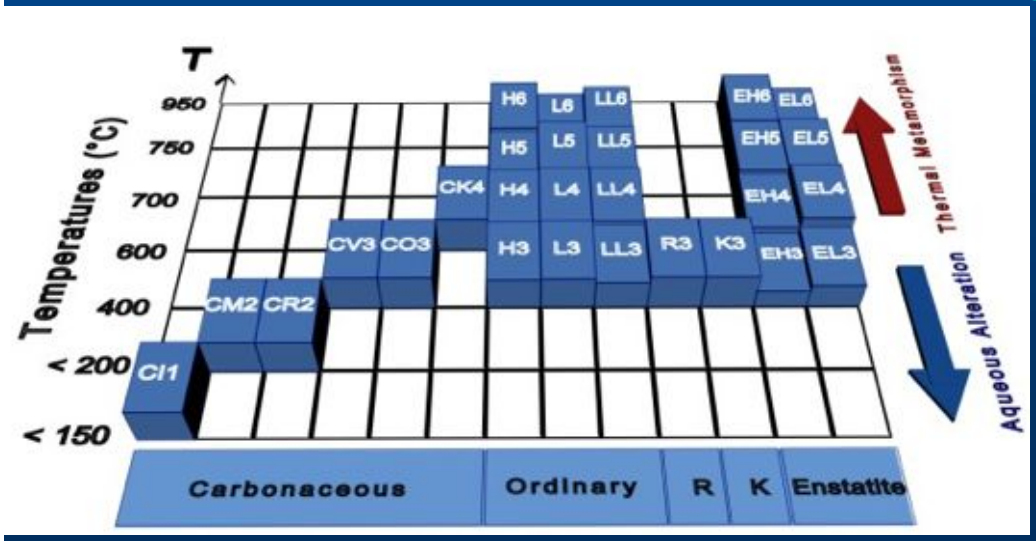
Courtesy L. Nittler

- **The different groups reveal several stellar sources:**
  - "Main stream" grains and groups Y, Z are from 1-4 solar masses AGBs
  - Y-grains would be coming from intermediate-mass AGB stars as they contain enrichments in s-elements
  - A+B grains come from J-type stars of C
  - Or from Novae: $^{12}C/^{13}C<10$ (José and Hernanz, 1998; José et al., 2001, 2004)

CHONDRITE GROUPS

Weisberg et al. (2006)

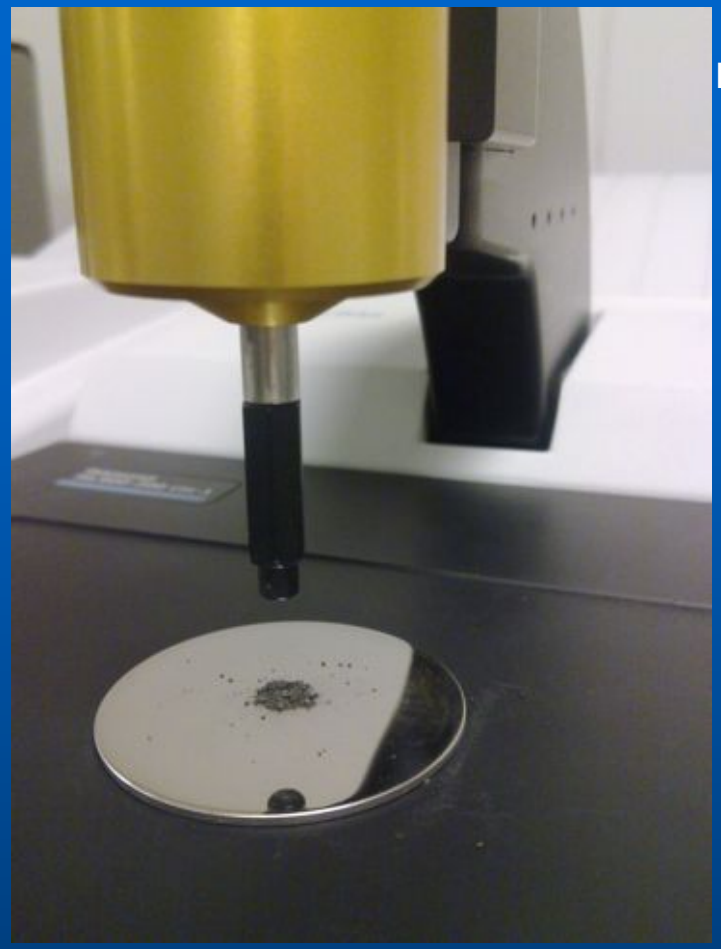


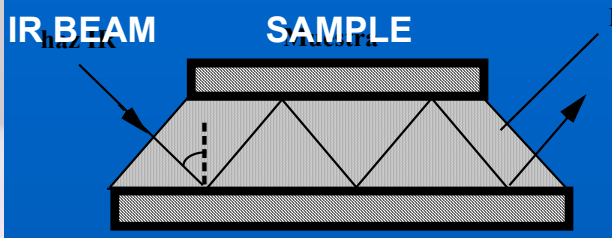


- **Different degrees of aqueous alteration and metamorphism are found**
- **The CCs can be classified according the estimated T required to produce the petrographic types (Dotto et al., 2005)**
- **At the Institute of Space Sciences (CSIC-IEEC) we work in CSIC and UPC labs focusing on the role of aqueous alteration on primitive chondrites and performing remote studies of comets**
- **Reflectance spectra are taken in the** UPC Center for Research in NanoEngineering (Prof. J. Llorca).

Dotto et al. (2005)

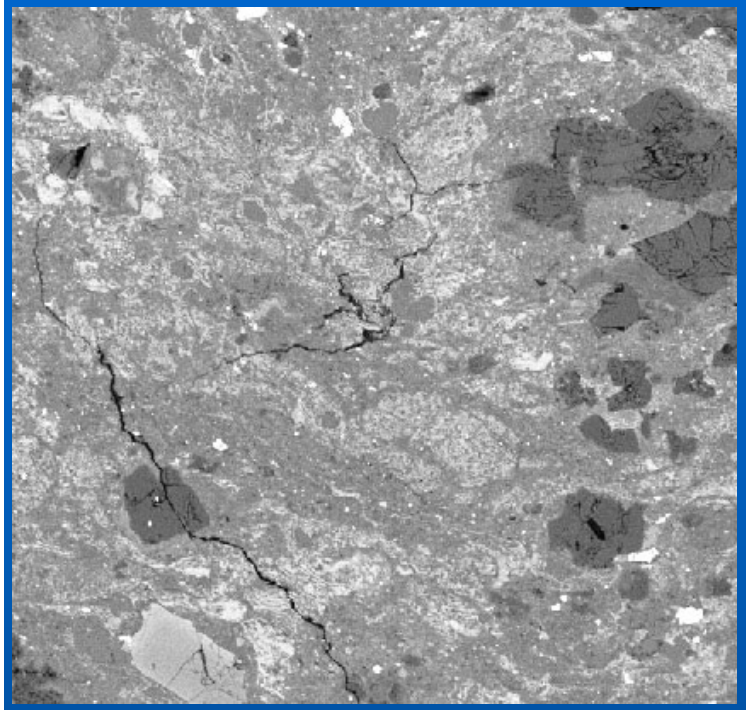
IR SPECTROMETER



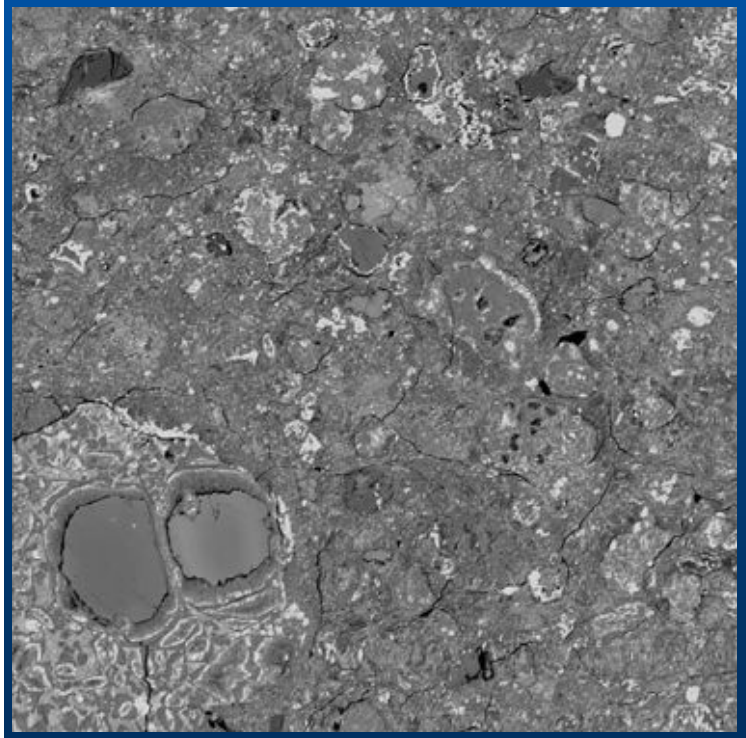


- Small chips of each meteorite were grinded using an agate mortar
- Powders were carefully located in between a diamond detector of a Smart Orbit ATR (Attenuated Total Reflectance) IR spectrometer.
- This instrument provides high resolution internal reflection spectra of meteorite powders following standard procedures and using a diamond detector

NASA ANTARCTIC CHONDRITES



Y791198 CM2

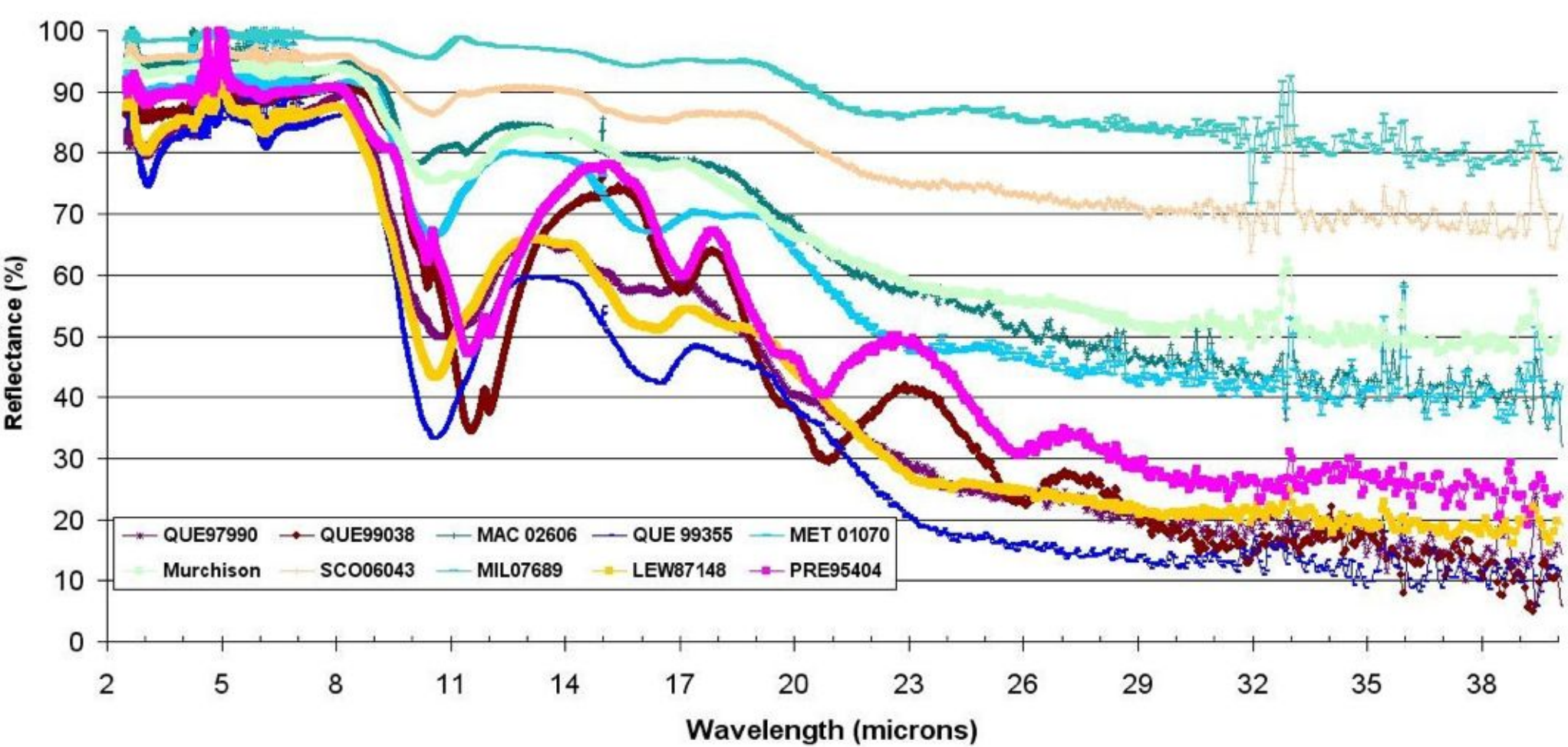


QUE93005 CM2

Meteorite	Group	Weatering grade	Year
ALH 77003	CO3.6	Ae	1977
ALH 83108	CO3.5	A	1983
ALH 84028	CV3	Ae	1984
EET 92159	CR2	B/C	1992
GRA 95229	CR2	A	1995
LAP 02342	CR2	A/B	2002
MAC 02606	CM2	A	2002
MET 01070	CM1	Be	2001
MET 01074	CV3	B	2001
MIL 07689	CM1	C	2007
PRE 95404	R3	A	1995
QUE 97990	CM2	Be	1997
QUE 99038	CM2	A/B	1999
QUE 99355	CM2	B	1999
SCO 06043	CM1	~B	2006

SPECTRA OF CM CHONDRITES

- For the CM several OH absorption bands characteristic of phyllosilicates exhibit different depths in agreement with previous studies using IR micro-spectroscopy [e.g. Beck et al. (2010), GCA 74]
- The variable depth in OH bands exhibited by some of the selected CMs is probably consequence of the degree of aqueous alteration



Trigo-Rodriguez et al. (2012), LPS XLIII, abstract #1443.

WATER+ORGANICS+CLAYS…

- Hydrothermal activity in carbonaceous asteroids promoted increasing complexity in organics present in the matrix
  - Minerals participated in the synthesis and interconversion of organic species, particularly in presence of water and N (Glavin et al., 2010)
- Clays are produced in chondrules and inclusions, by the progressive hydration from the matrix:
  - Clays to synthesize life (Cairns-Smith, 1982)
- The matrix is source of biogenic elements
- Consequently, a prebiotic synthesis could have occurred in first stages of chondritic accretion

Extraterrestrial environments to synthesize water-soluble compounds, also rich in N

- GRA 95229 (Pizzarello et al., 2011)

GRA 95229 (NASA/JSC)

CONCLUSIONS

- Materials preserved in primitive meteorites and comets provide information on protoplanetary disk forming components:
  - Minerals, organics and ices condensed all over the disk preserved O isotopic patterns in those pristine (undifferentiated) materials.
  - In front of the usual view of a SN contributing for living nuclides, other massive stars are also possible
  - AGB stars played a key role in the chemical enrichment of the solar nebula
    - Observed radionuclides in CAIs are identical to the expected for intermediate-mass AGBs
    - SiC grains are typically associated with AGB low mass stars.
    - However, why are intermediate-mass AGB condensates apparently missing?
- Recent evidence in 81P/Wild 2 materials and cometary IDPs:
  - Importance of turbulence and mixing in the early protoplanetary disk
  - Astrophysical models for the formation conditions of CAIs, chondrules, presolar grains should be revisited
- Cometary matter as source of additional information:
  - Lower degrees of thermal and aqueous alteration than primitive chondrites
- Importance of recovery of "pristine" materials in future sample-return missions:
  - Marco Polo-R presented to last call of Cosmic Vision
  - Cryogenic mission to a comet proposed to NASA (Sandford et al., 2010)

Thanks for your attention