

# Probing Exoplanetary Compositions using White Dwarf Stars



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# White dwarfs

Stellar remnants – core of low mass stars

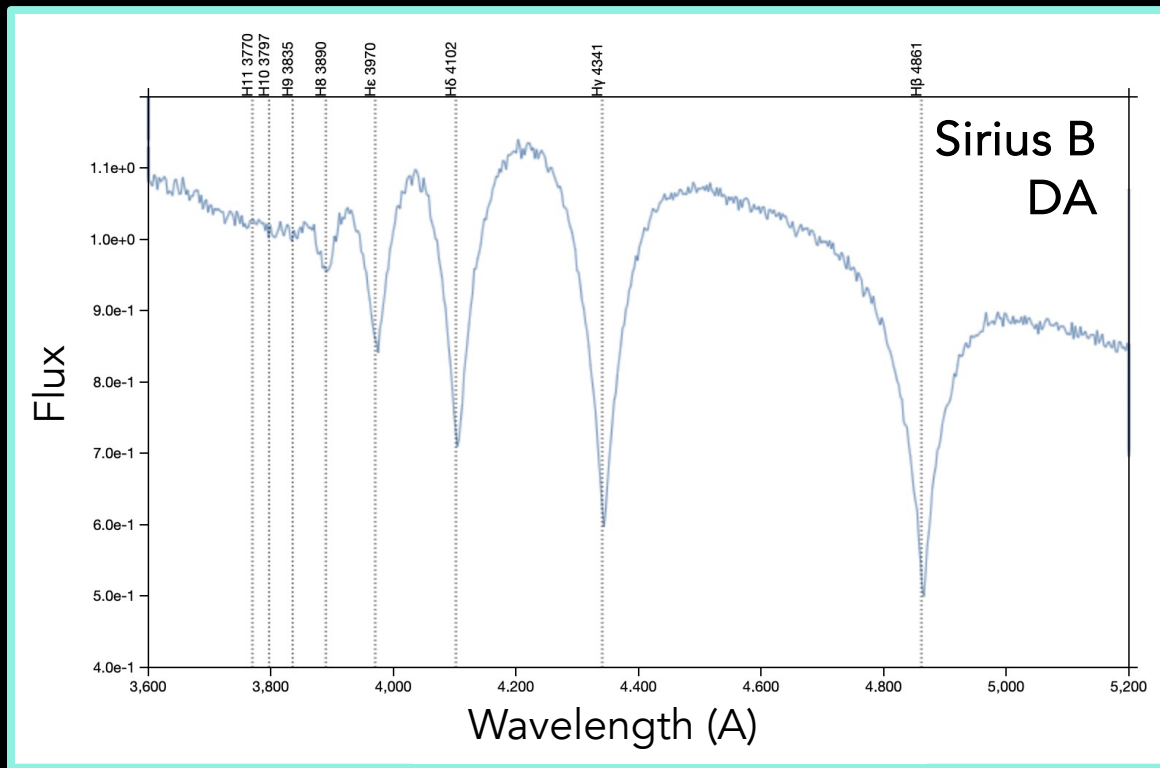
Very dense - Mass of  $\sim 0.6 M_{\odot}$  packed into the radius of the Earth

High surface gravities



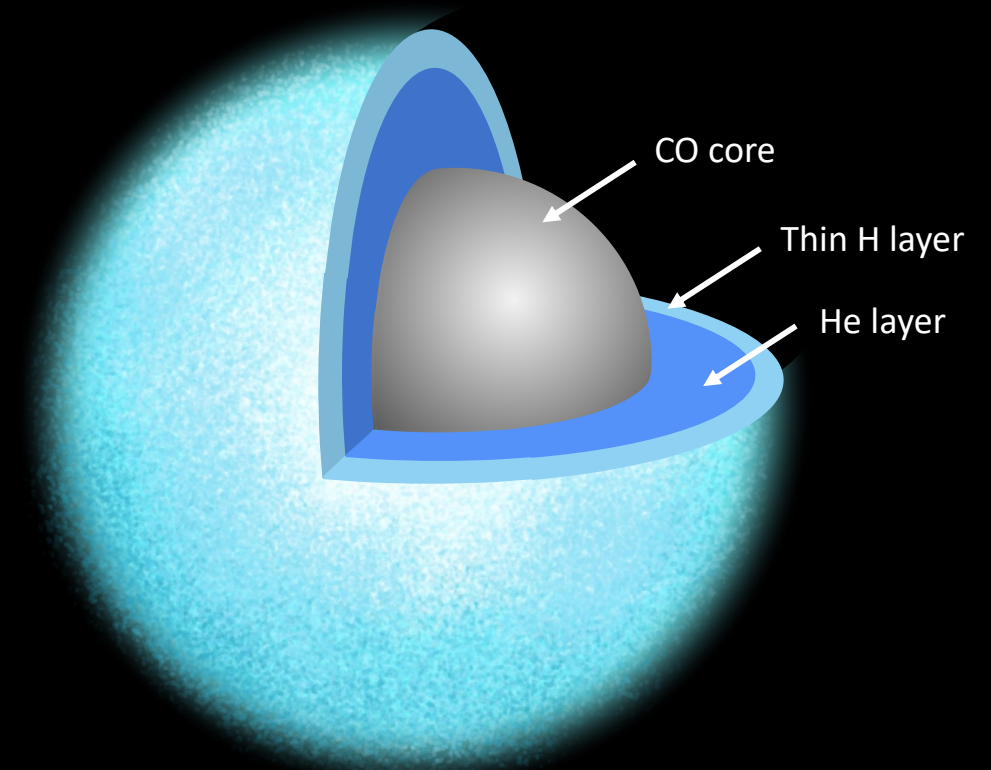
# White dwarfs

White dwarfs should have clean atmospheres (just H or He) due to their high surface gravity



From MWDD

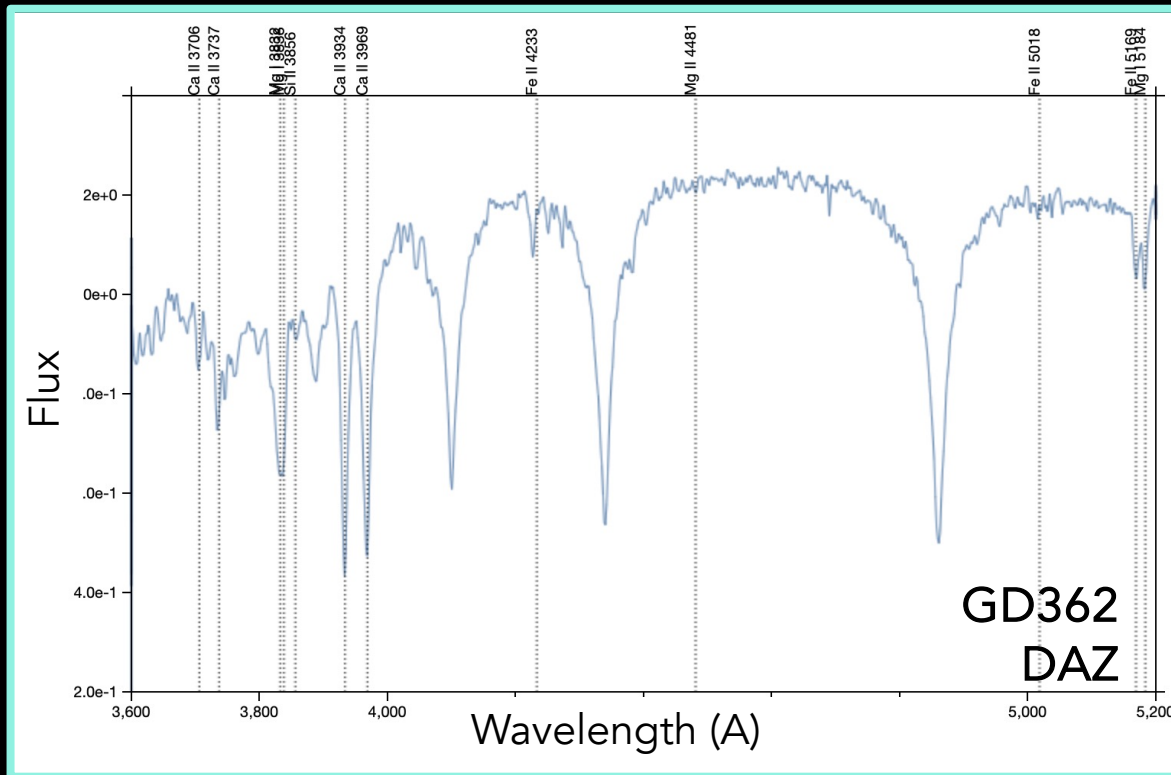
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Xu, Rogers, Blouin (2024)

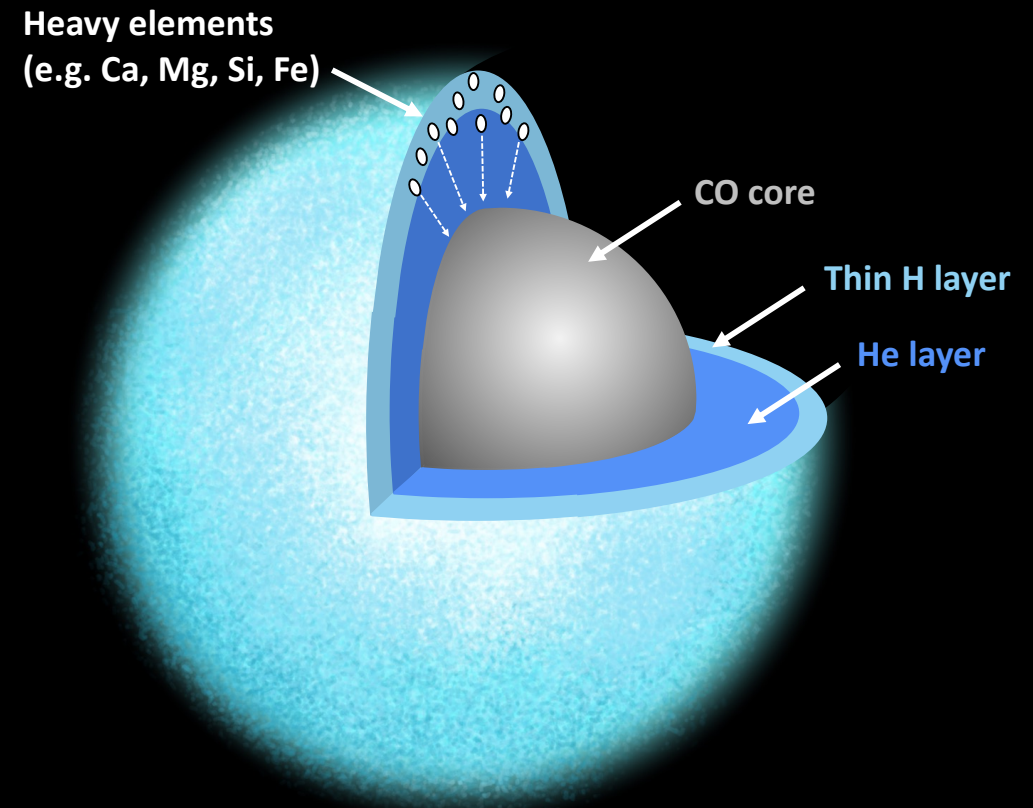
# White dwarfs

Heavy elements have been observed in the atmospheres of ~30% of white dwarfs -> must be ongoing accretion



From MWDD

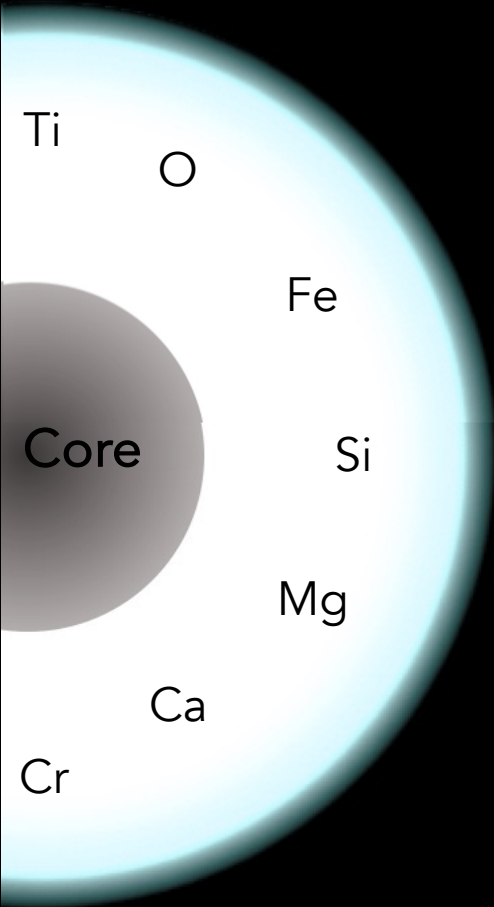
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Xu, Rogers, Blouin (2024)



# Polluted white dwarf



Infer the **bulk composition** of the accreted material

Most WDs show material that is **dry and rocky**  
 – bulk Earth like composition

1 H Hydrogen 1.00784(7)(4)																	2 He Helium 4.002602(2)						
3 Li Lithium 6.941(2)	4 Be Beryllium 9.0121831(2)																	5 B Boron 10.806(10.821)	6 C Carbon 12.0096(12.0116)	7 N Nitrogen 14.00643(14.00723)	8 O Oxygen 15.99903(15.99977)	9 F Fluorine 18.998403163(6)	10 Ne Neon 20.1797(6)
11 Na Sodium 22.98976928(2)	12 Mg Magnesium 24.304(6)																	13 Al Aluminum 26.9815386(8)	14 Si Silicon 28.0855(8)	15 P Phosphorus 30.973761998(5)	16 S Sulfur 32.059(5.078)	17 Cl Chlorine 35.446(35.457)	18 Ar Argon 39.948(1)
19 K Potassium 39.0983(1)	20 Ca Calcium 40.078(4)	21 Sc Scandium 44.955912(2)	22 Ti Titanium 47.88(7)	23 V Vanadium 50.9415(1)	24 Cr Chromium 51.9961(6)	25 Mn Manganese 54.938044(1)	26 Fe Iron 55.845(2)	27 Co Cobalt 58.933194(5)	28 Ni Nickel 58.6934(4)	29 Cu Copper 63.546(3)	30 Zn Zinc 65.38(2)	31 Ga Gallium 69.723(1)	32 Ge Germanium 72.630(8)	33 As Arsenic 74.921595(6)	34 Se Selenium 78.9718(8)	35 Br Bromine 79.904(1)	36 Kr Krypton 83.798(2)						
37 Rb Rubidium 85.4678(3)	38 Sr Strontium 87.62(1)	39 Y Yttrium 88.90584(2)	40 Zr Zirconium 91.224(2)	41 Nb Niobium 92.90637(2)	42 Mo Molybdenum 95.95(1)	43 Tc Technetium <98>	44 Ru Ruthenium 101.07(2)	45 Rh Rhodium 102.90550(2)	46 Pd Palladium 106.42(1)	47 Ag Silver 107.8682(2)	48 Cd Cadmium 112.414(4)	49 In Indium 114.818(1)	50 Sn Tin 118.710(7)	51 Sb Antimony 121.760(1)	52 Te Tellurium 127.60(3)	53 I Iodine 126.90447(3)	54 Xe Xenon 131.29(6)						
55 Cs Cesium 132.90545196(3)	56 Ba Barium 137.327(7)	57-71 Lanthanides	72 Hf Hafnium 178.49(2)	73 Ta Tantalum 180.94788(2)	74 W Tungsten 183.84(1)	75 Re Rhenium 186.207(1)	76 Os Osmium 190.23(3)	77 Ir Iridium 192.221(7)	78 Pt Platinum 195.084(6)	79 Au Gold 196.966569(4)	80 Hg Mercury 200.592(3)	81 Tl Thallium 204.382(204.385)	82 Pb Lead 207.2(1)	83 Bi Bismuth 208.9804(1)	84 Po Polonium <209>	85 At Astatine <210>	86 Rn Radon <222>						
87 Fr Francium <223>	88 Ra Radium <226>	89-103 Actinides	104 Rf Rutherfordium <261>	105 Db Dubnium <262>	106 Sg Seaborgium <271>	107 Bh Bohrium <272>	108 Hs Hassium <277>	109 Mt Meitnerium <278>	110 Ds Darmstadtium <281>	111 Rg Roentgenium <282>	112 Cn Copernicium <285>	113 Uut Ununtrium unknown	114 Fl Flerovium <289>	115 Uup Ununpentium unknown	116 Lv Livermorium <293>	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown						
57 La Lanthanum 138.90547(7)	58 Ce Cerium 140.116(1)	59 Pr Praseodymium 140.90786(2)	60 Nd Neodymium 144.242(3)	61 Pm Promethium <145>	62 Sm Samarium 150.36(2)	63 Eu Europium 151.964(1)	64 Gd Gadolinium 157.25(3)	65 Tb Terbium 158.92535(2)	66 Dy Dysprosium 162.500(1)	67 Ho Holmium 164.93033(2)	68 Er Erbium 167.256(3)	69 Tm Thulium 168.93423(2)	70 Yb Ytterbium 173.054(5)	71 Lu Lutetium 174.967(1)									
89 Ac Actinium <227>	90 Th Thorium 232.03772(6)	91 Pa Protactinium 231.03688(2)	92 U Uranium 238.02891(3)	93 Np Neptunium <237>	94 Pu Plutonium <244>	95 Am Americium <243>	96 Cm Curium <247>	97 Bk Berkelium <247>	98 Cf Californium <251>	99 Es Einsteinium <252>	100 Fm Fermium <257>	101 Md Mendelevium <258>	102 No Nobelium <259>	103 Lr Lawrencium <260>									

See Klein et al. (2021) for references

# Polluted white dwarfs are mass spectrometers for exoplanets



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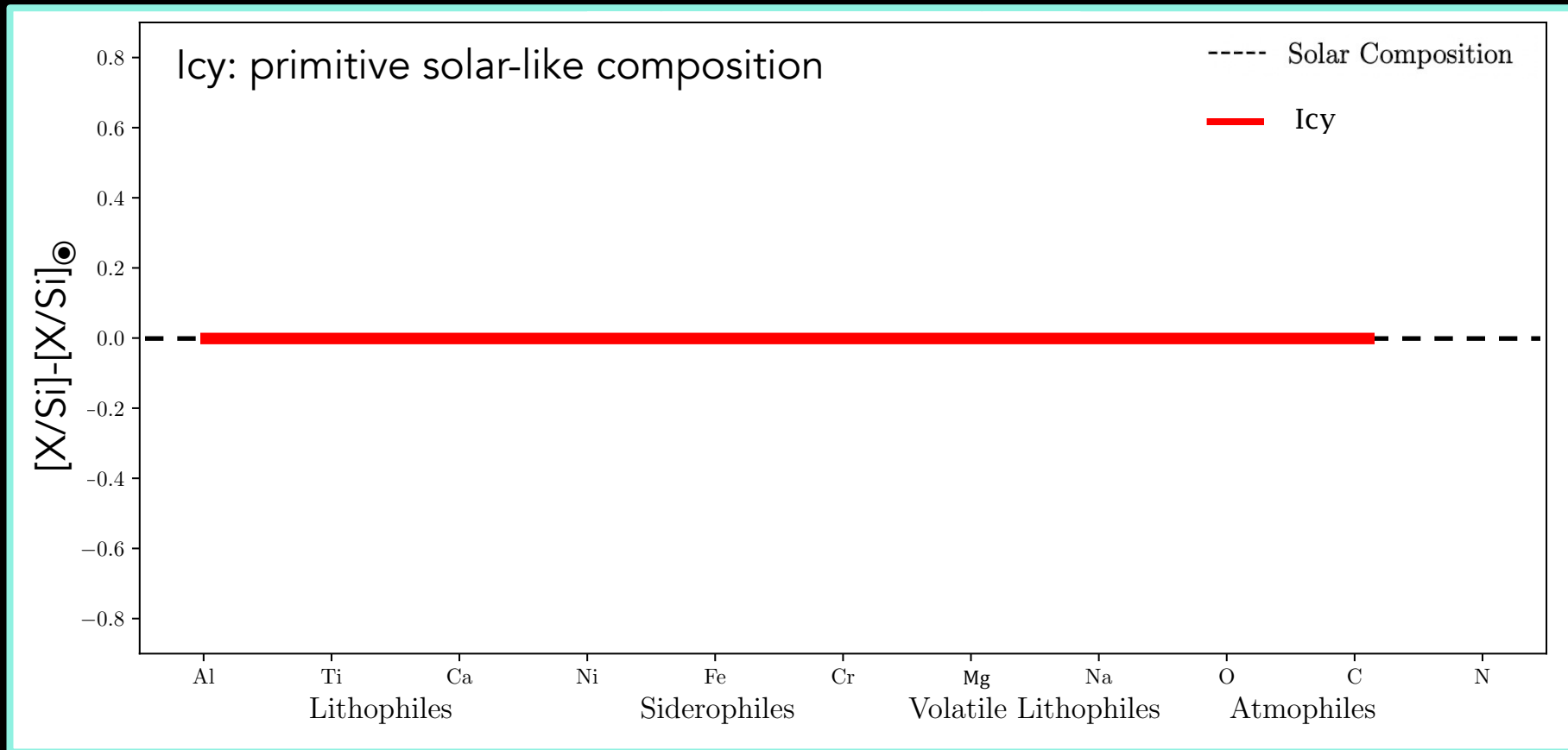


**Aim: Increase the number of exoplanetary bodies with measured bulk compositions**

*'Seven white dwarfs with circumstellar gas discs I: White dwarf parameters and pollutant abundances'* – Rogers et al. 2024a

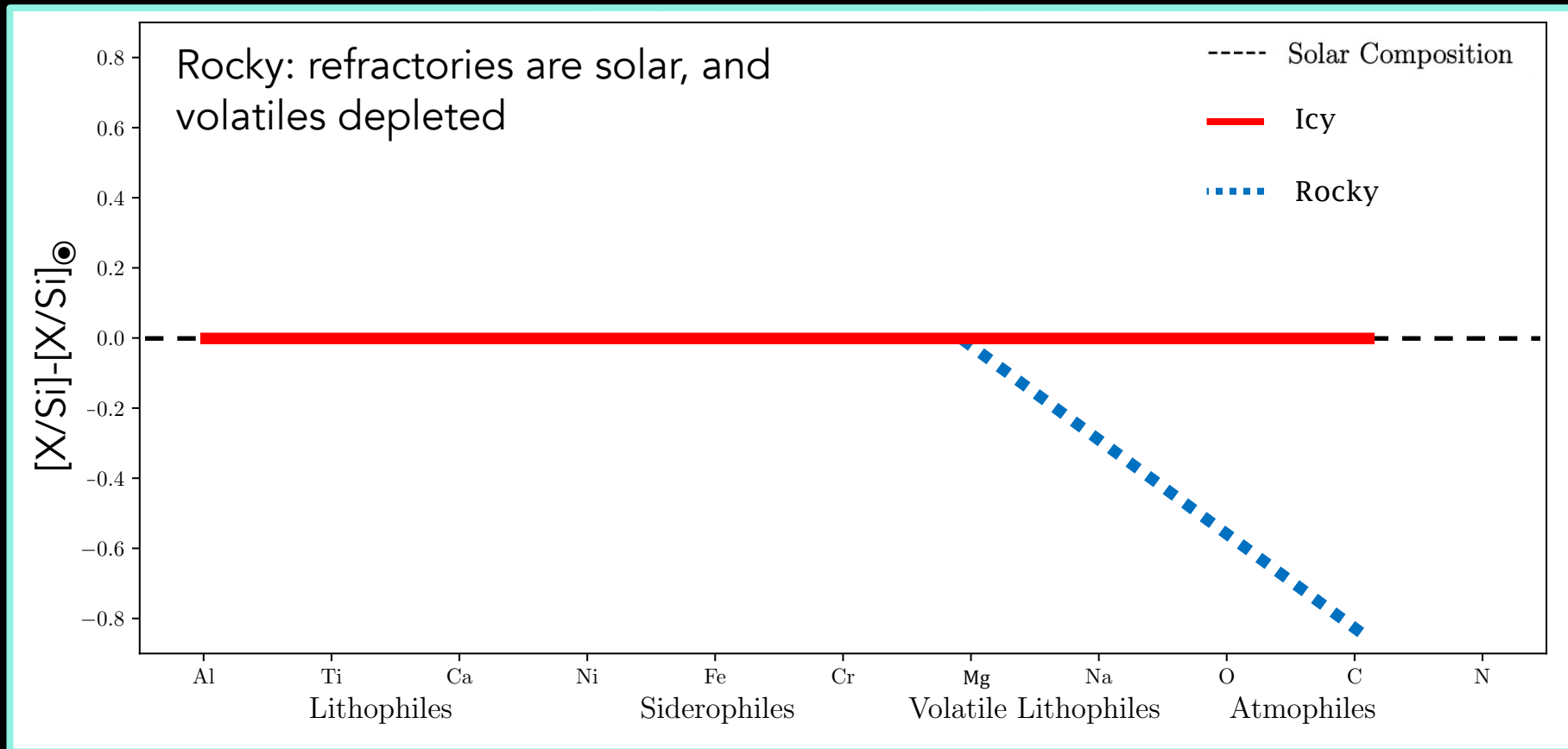
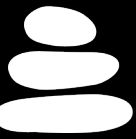
*'Seven white dwarfs with circumstellar gas discs II: Tracing the composition of exoplanetary building blocks'* – Rogers et al. 2024b

# Composition Analysis



→ See Buchan et al. (2021)  
Increasing volatility/decreasing condensation temperature

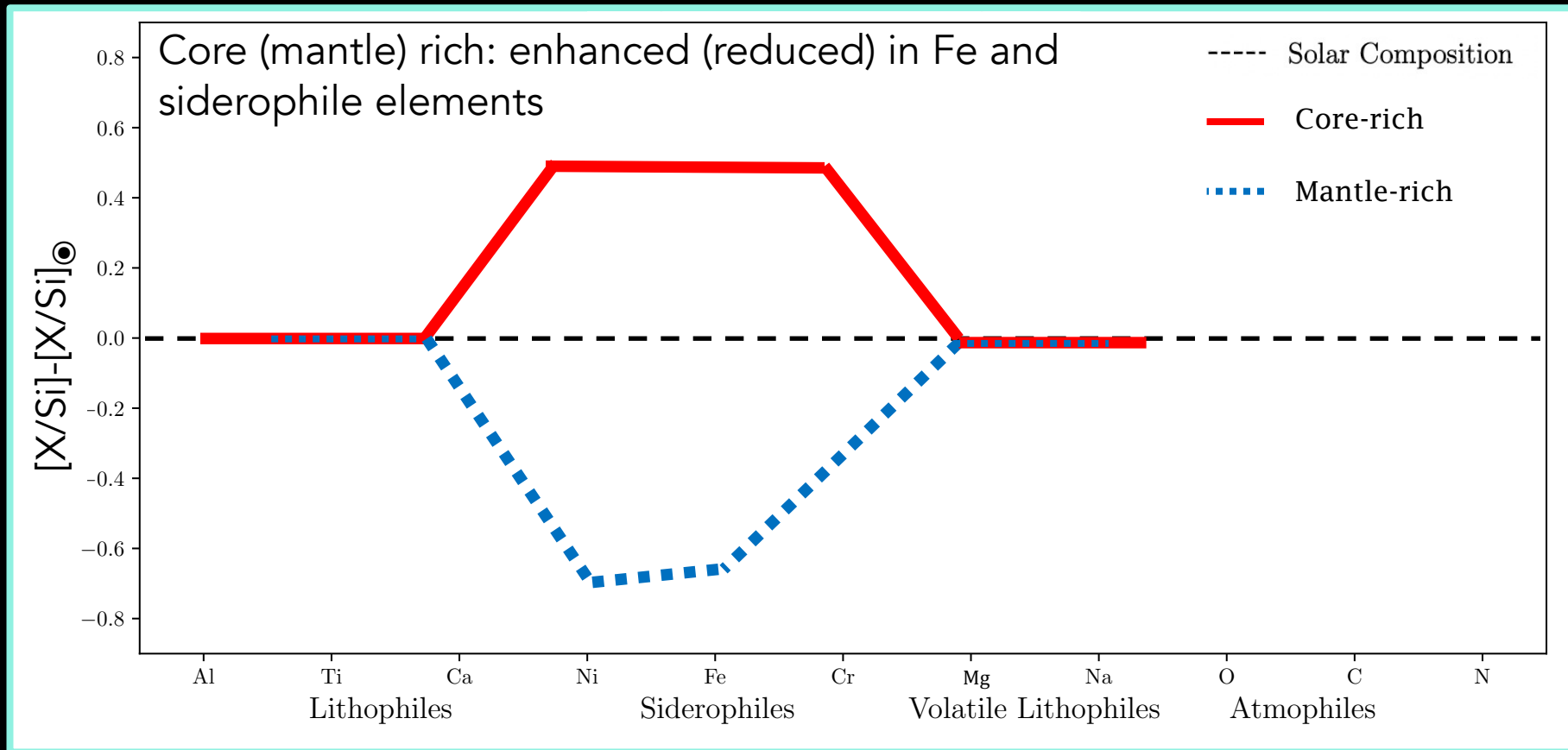
# Composition Analysis



→  
Increasing volatility/decreasing condensation temperature

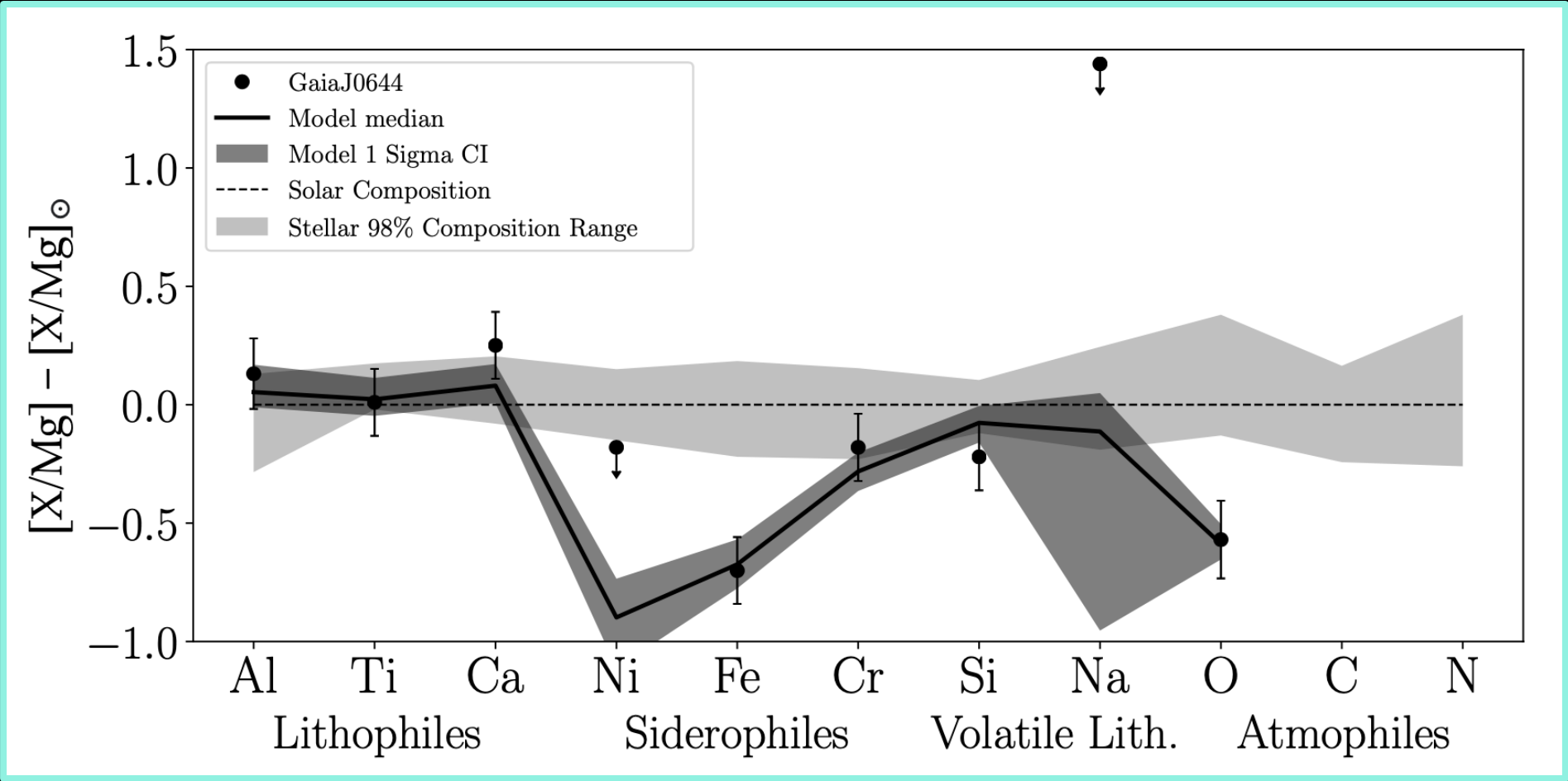


# Composition Analysis



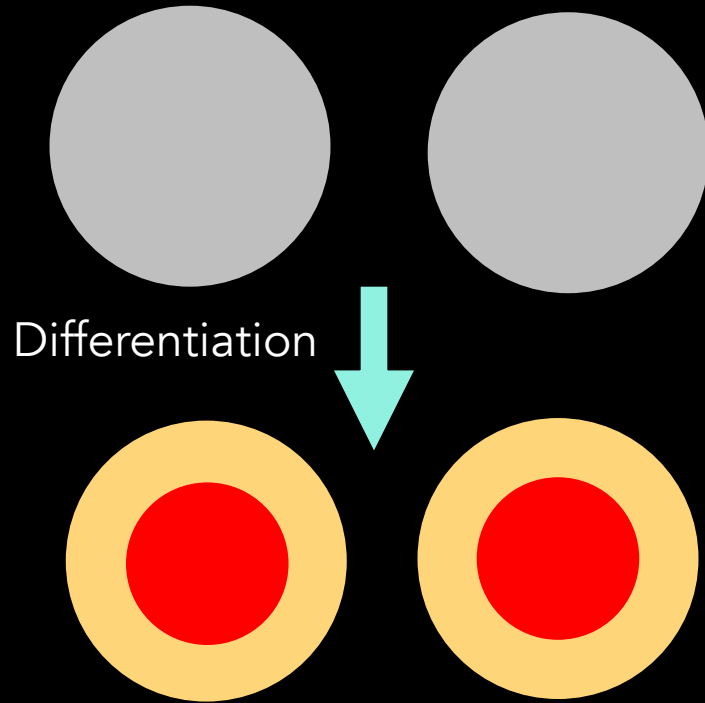
Increasing volatility/decreasing condensation temperature

# Abundance pattern showing a mantle rich fragment being accreted



Increasing volatility/decreasing condensation temperature

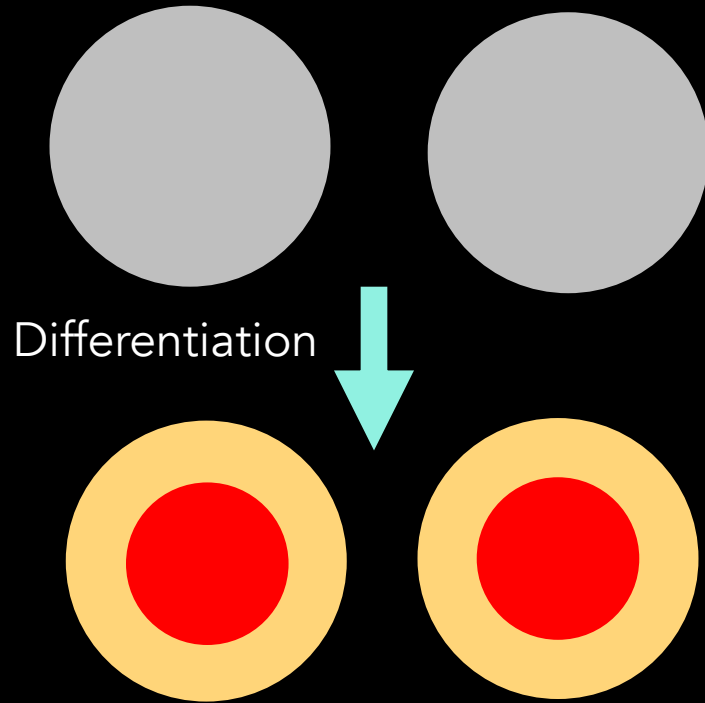
# Differentiation and Collisions



Internal heating causes Fe and siderophilic elements to migrate to the core

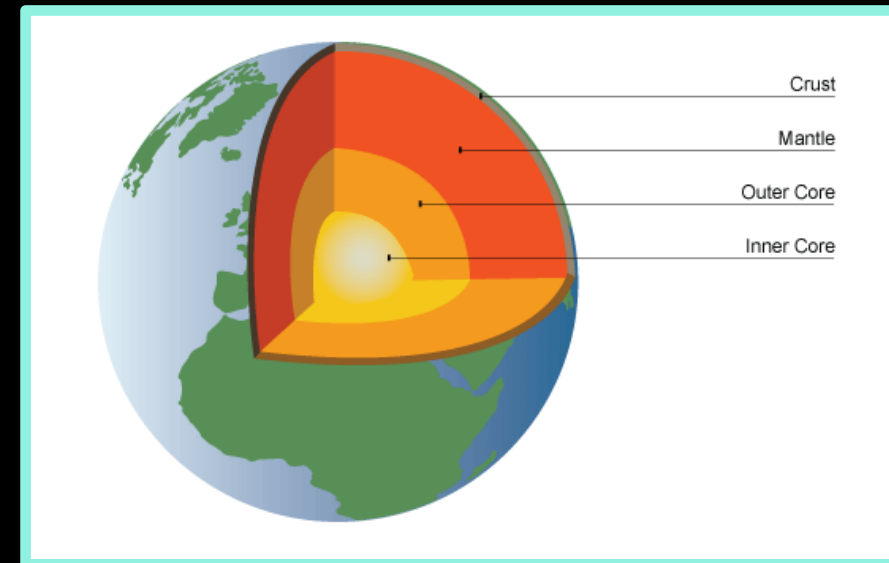
This causes differentiated bodies -> Fe-rich core and Fe-poor mantle

# Differentiation and Collisions

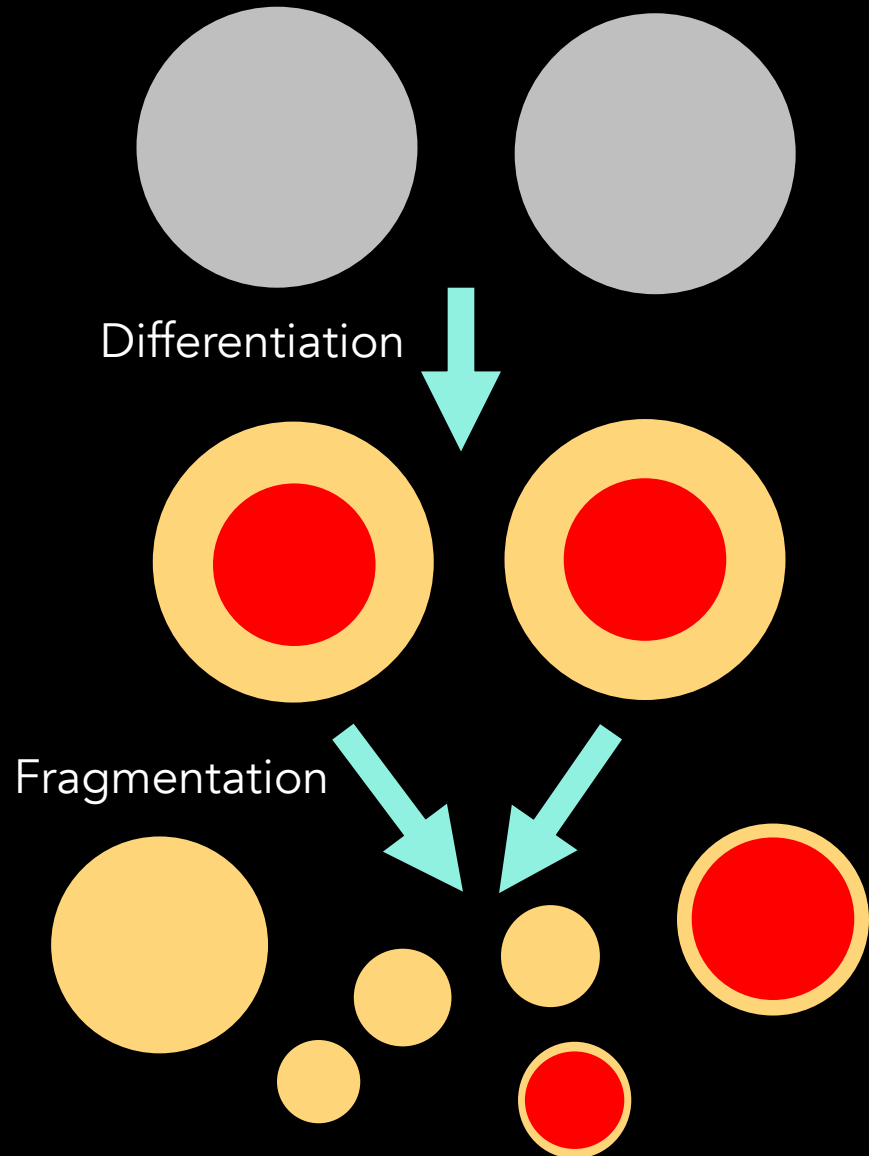


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# Differentiation and Collisions

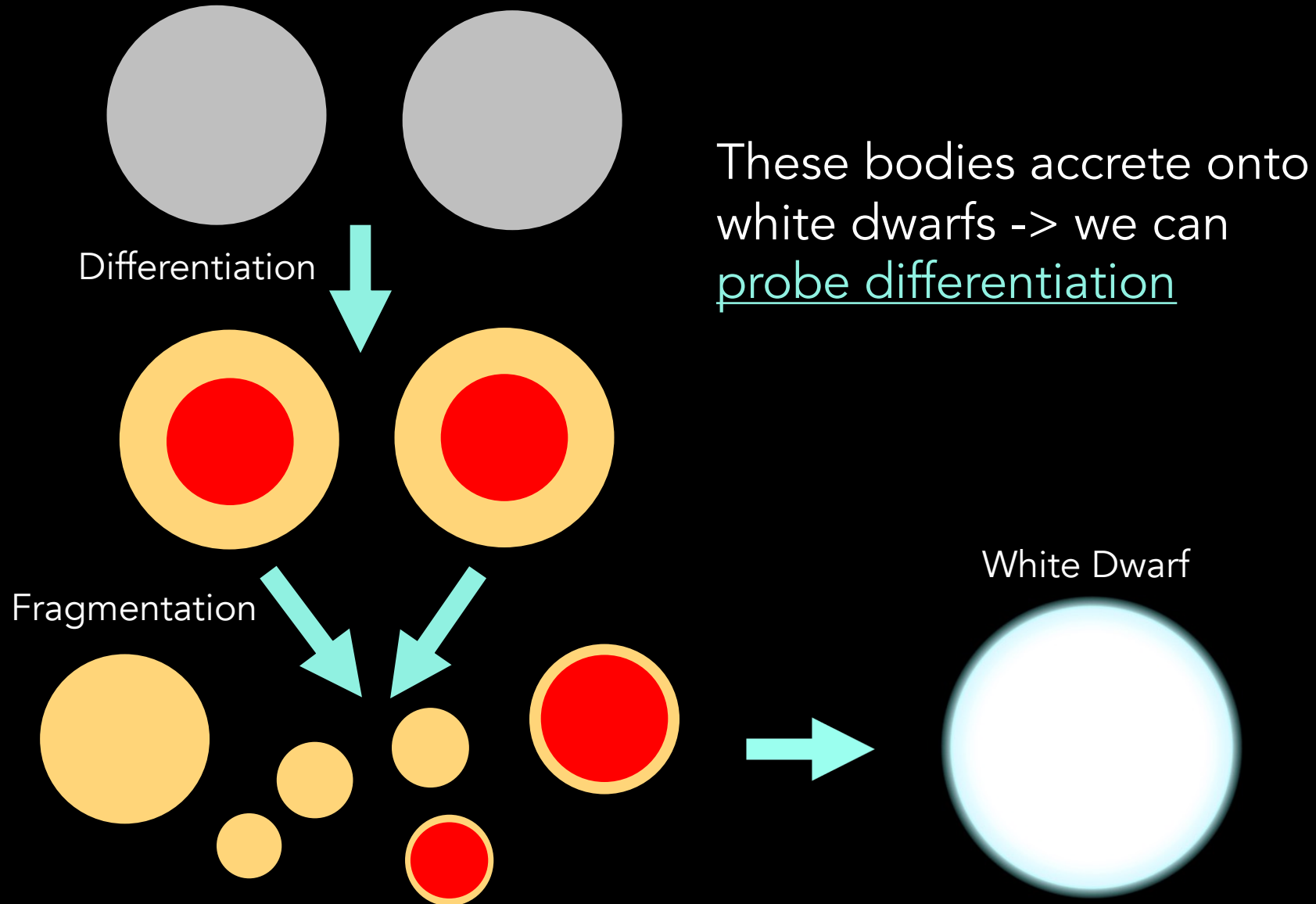


Collisions can cause fragmentation which leads to planetesimals that are: core-dominated or mantle-dominated

Note: asynchronous accretion can also lead to core or mantle rich pollutant – Brouwers et al. (2023a)

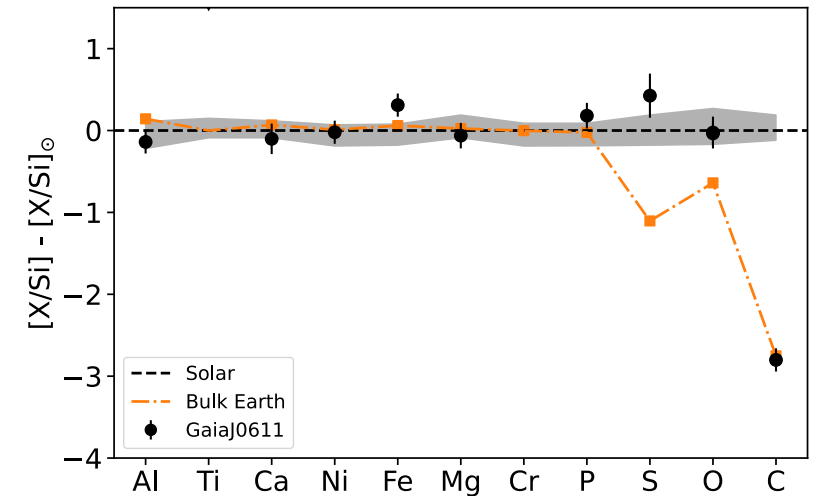
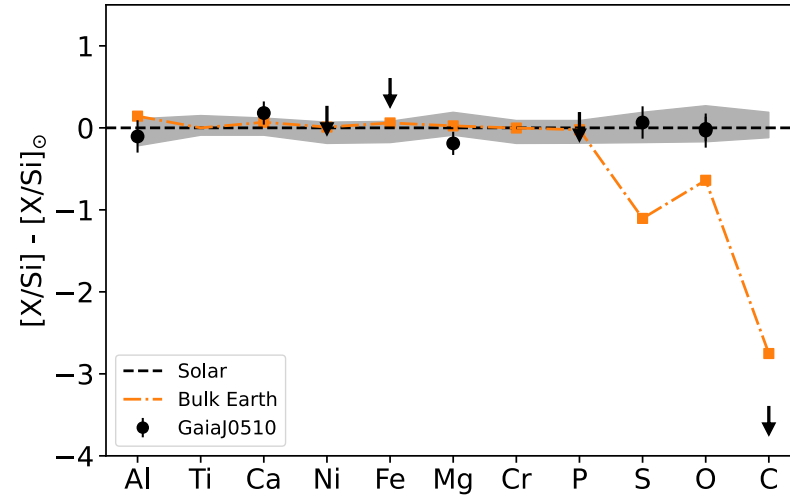
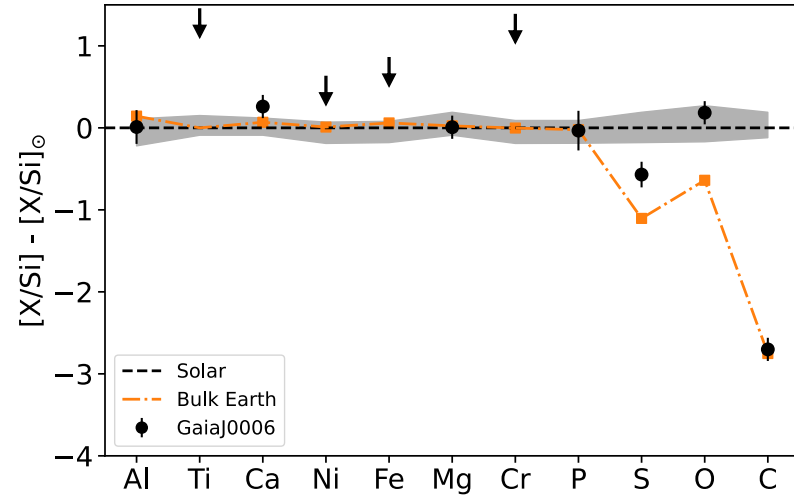


# Differentiation and Collisions



# Abundance Patterns of 3 WDs in the sample

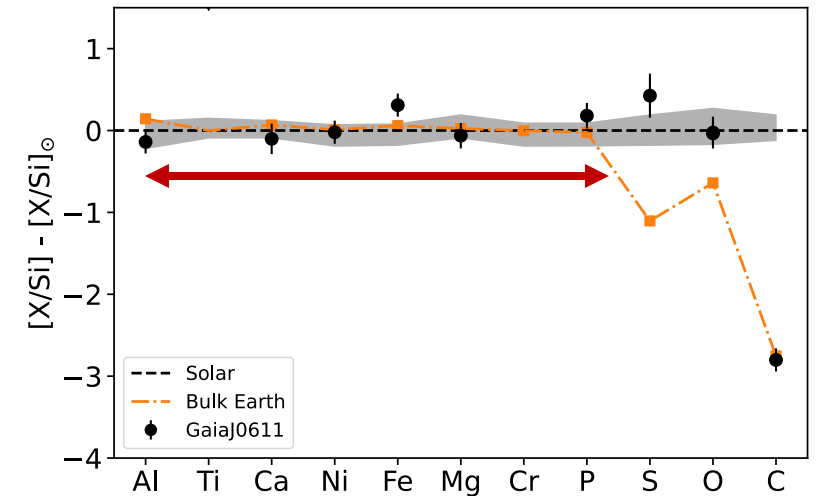
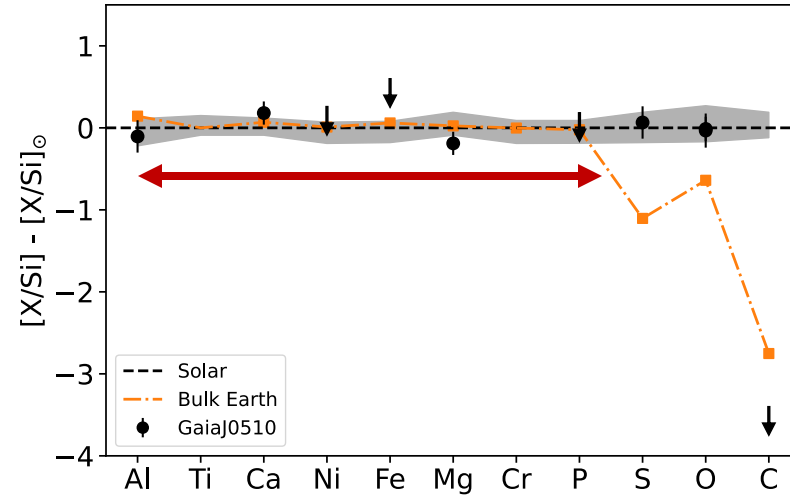
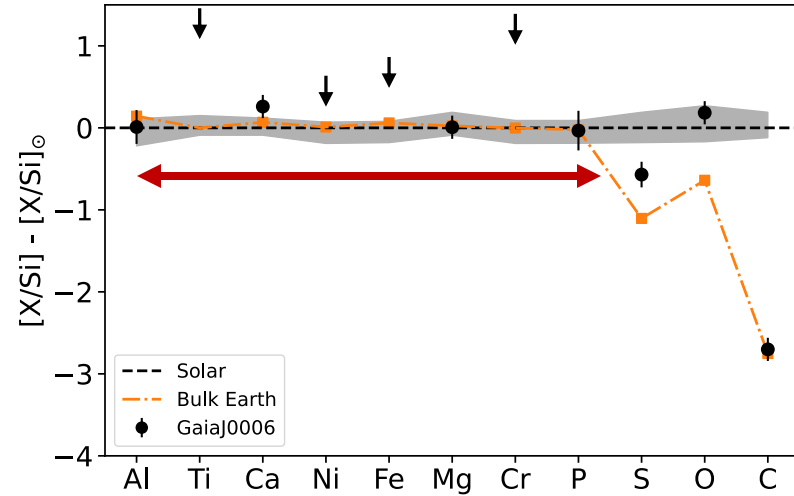
Upper limits denoted with arrows



Increasing volatility/decreasing condensation temperature

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Upper limits denoted with arrows

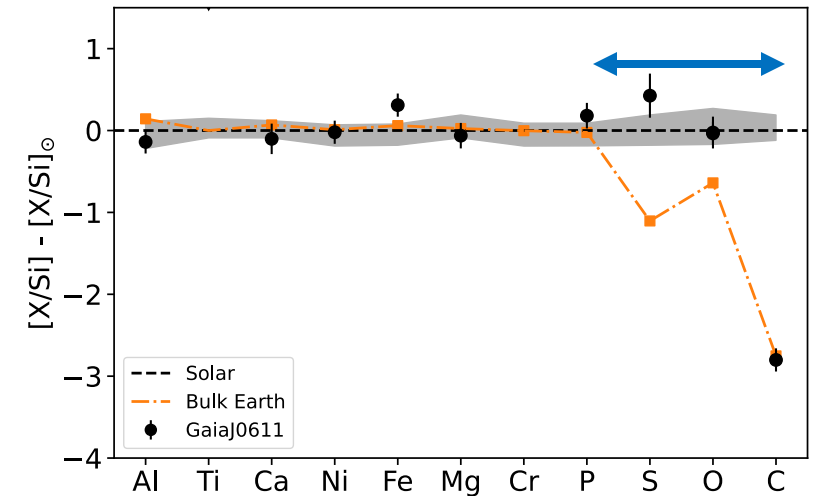
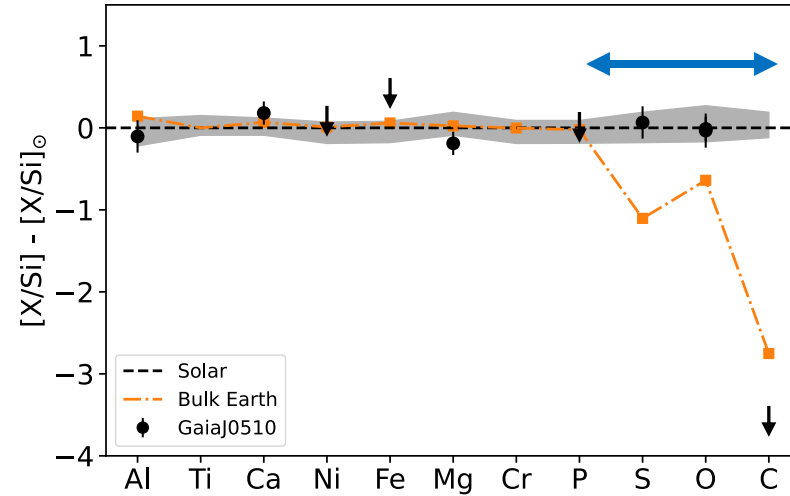
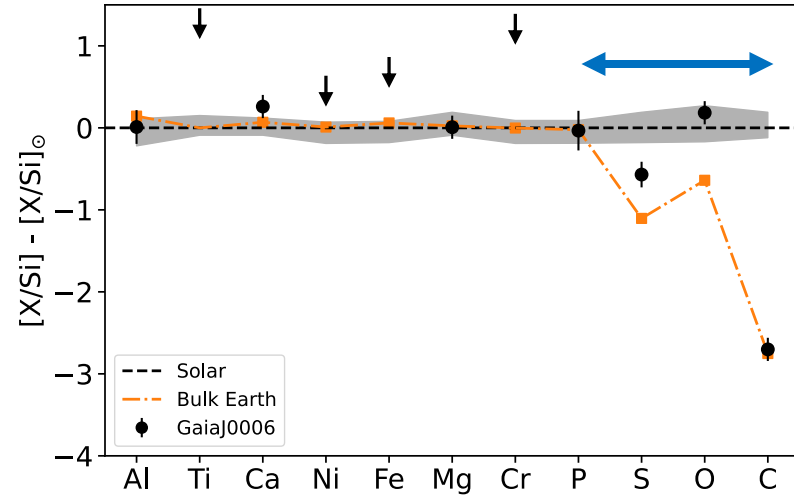


Increasing volatility/decreasing condensation temperature

The more **refractory elements** roughly match **solar/Bulk Earth composition**.

# Abundance Patterns of 3 WDs in the sample

Upper limits denoted with arrows

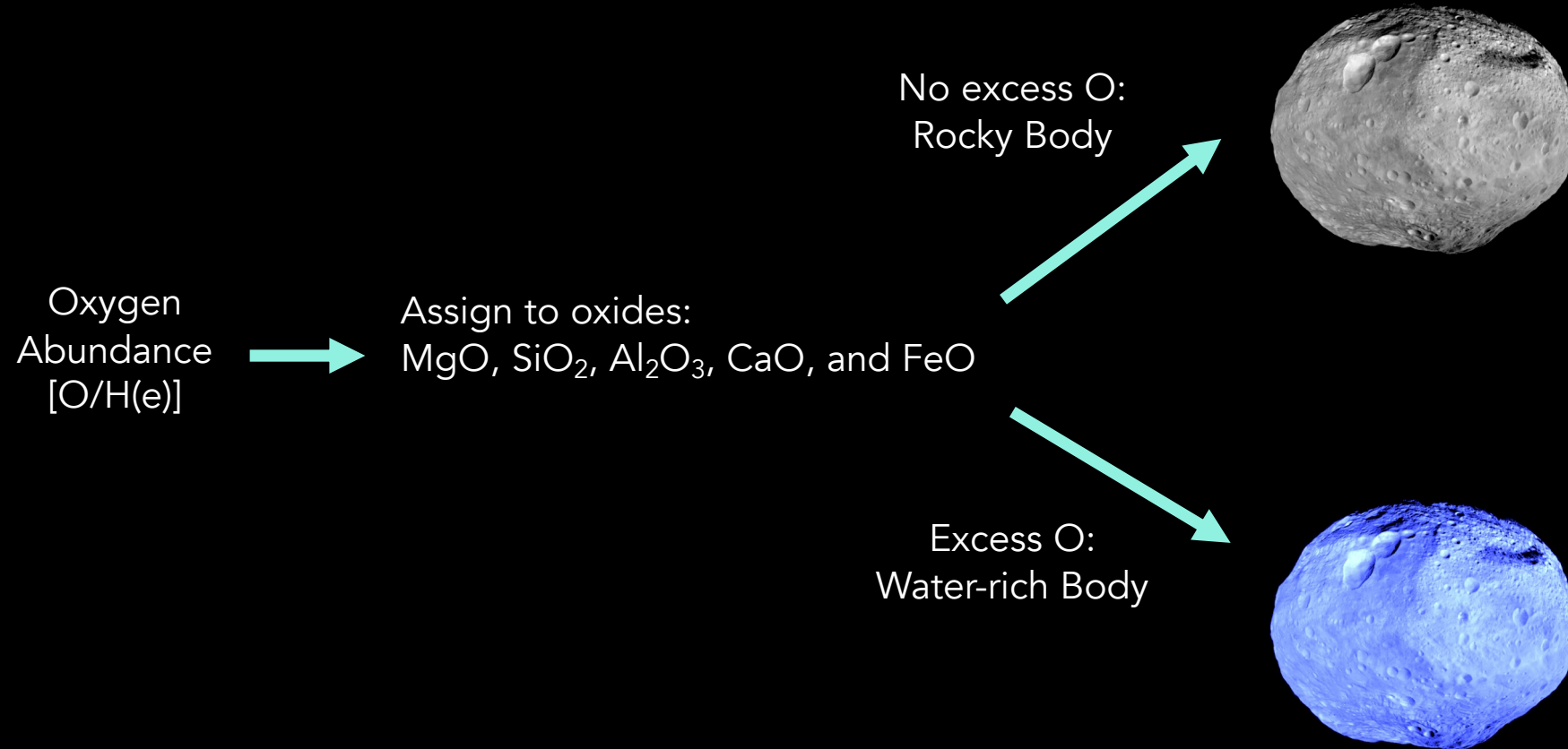


Increasing volatility/decreasing condensation temperature

More volatile elements:

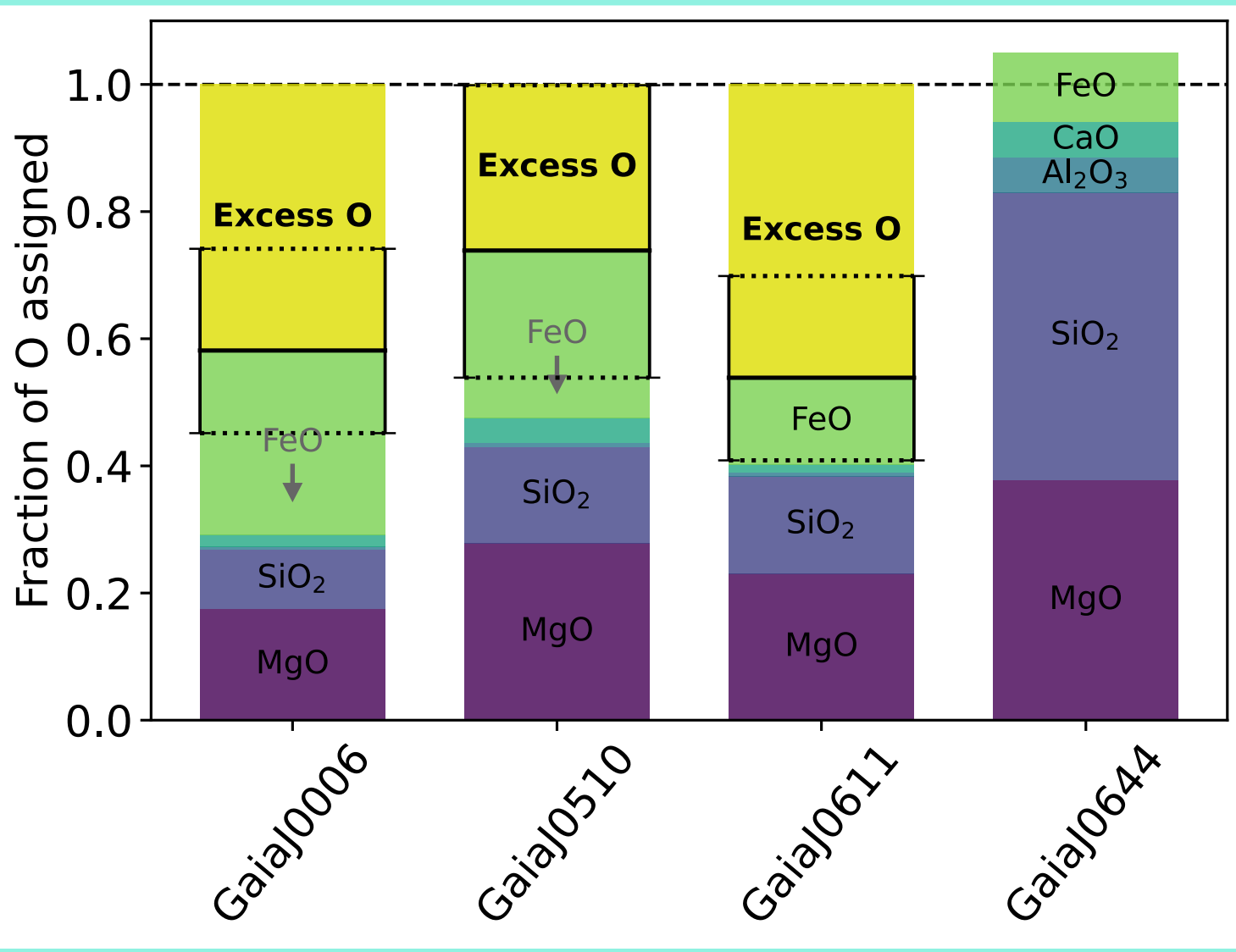
- Oxygen is enhanced compared to Bulk Earth.
- Carbon similar to Bulk Earth.

# Oxygen Budgeting





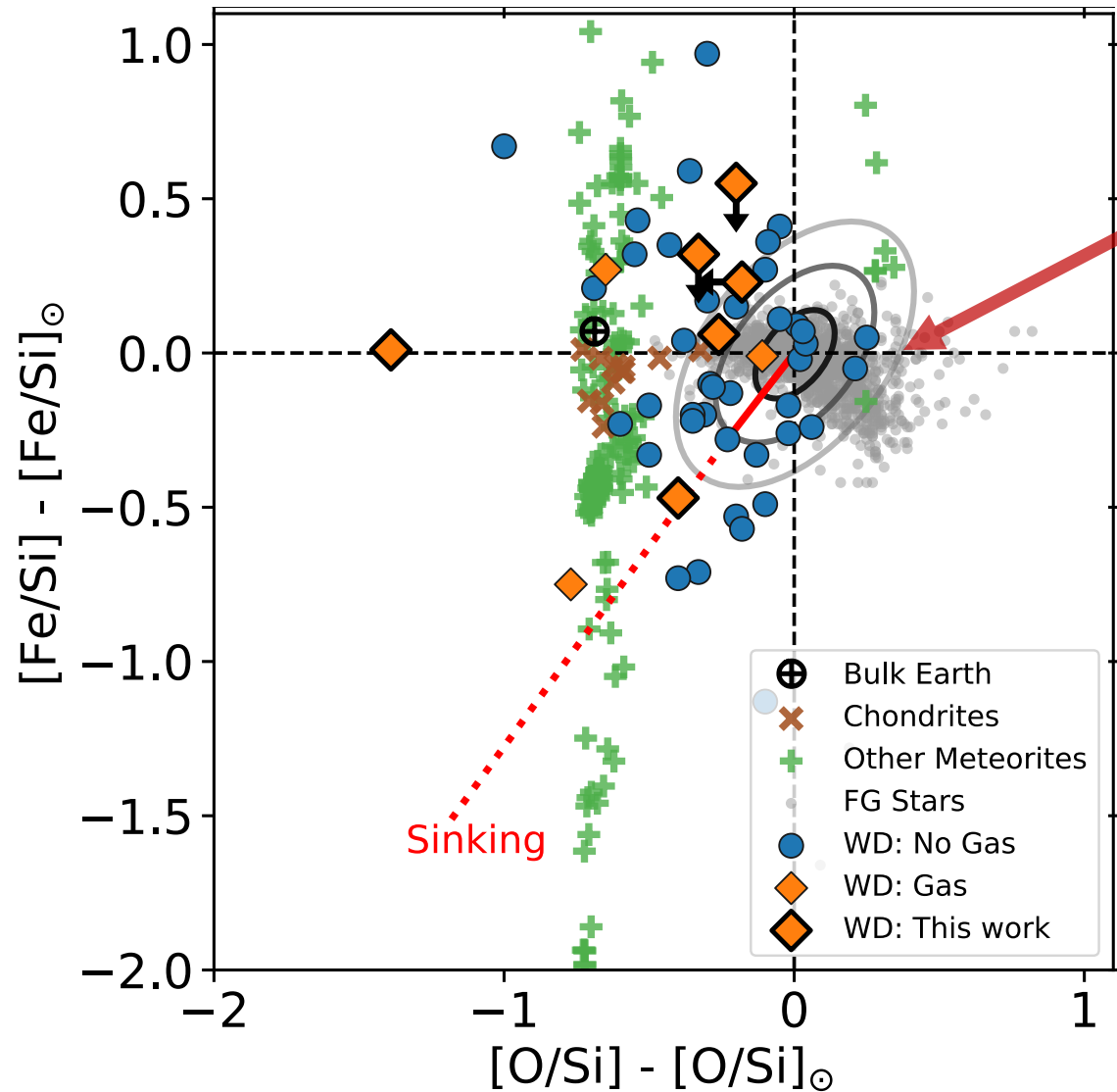
# Oxygen Excess



3 with solar/sub-solar O:  
abundances have excess  
oxygen

1 where metals in oxide  
form (mantle rich)

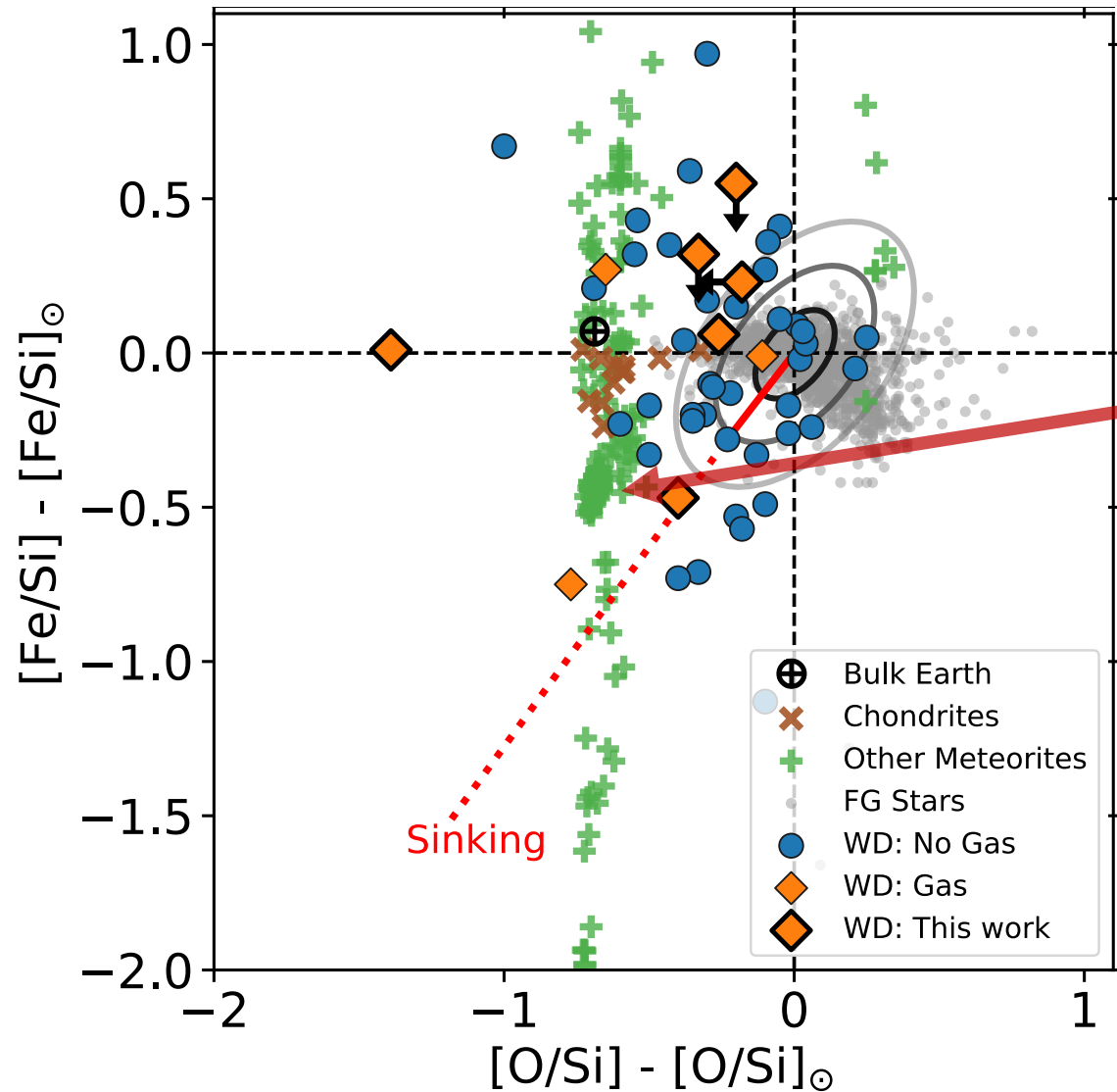
# Abundances in context



Grey scatter plot: FG stars – range of possible initial compositions

Hinkel et al. (2014)

# Abundances in context

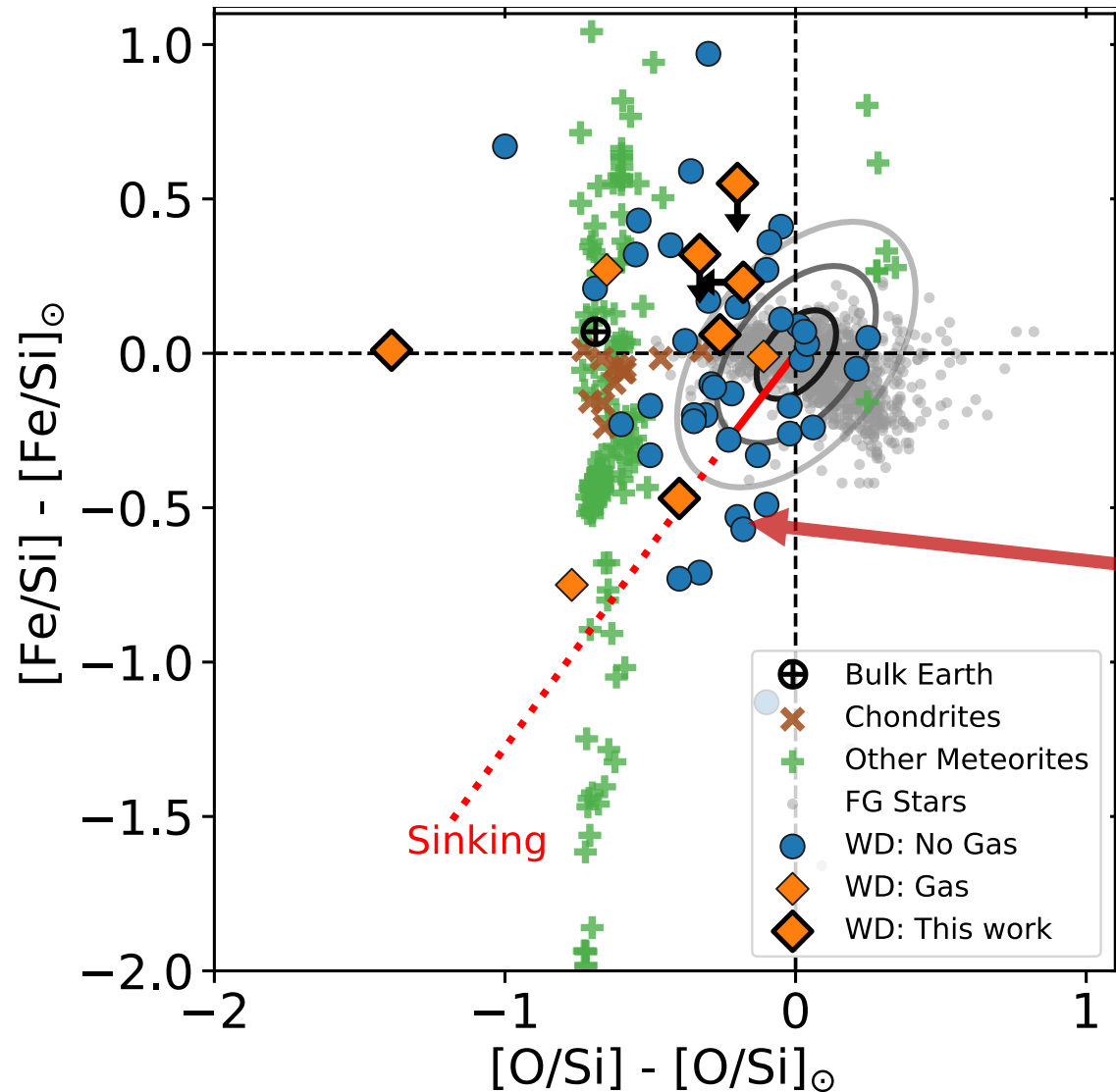


Grey scatter plot: FG stars – range of possible initial compositions

Hinkel et al. (2014)

Green and brown data show abundances of meteorites in the solar system

# Abundances in context



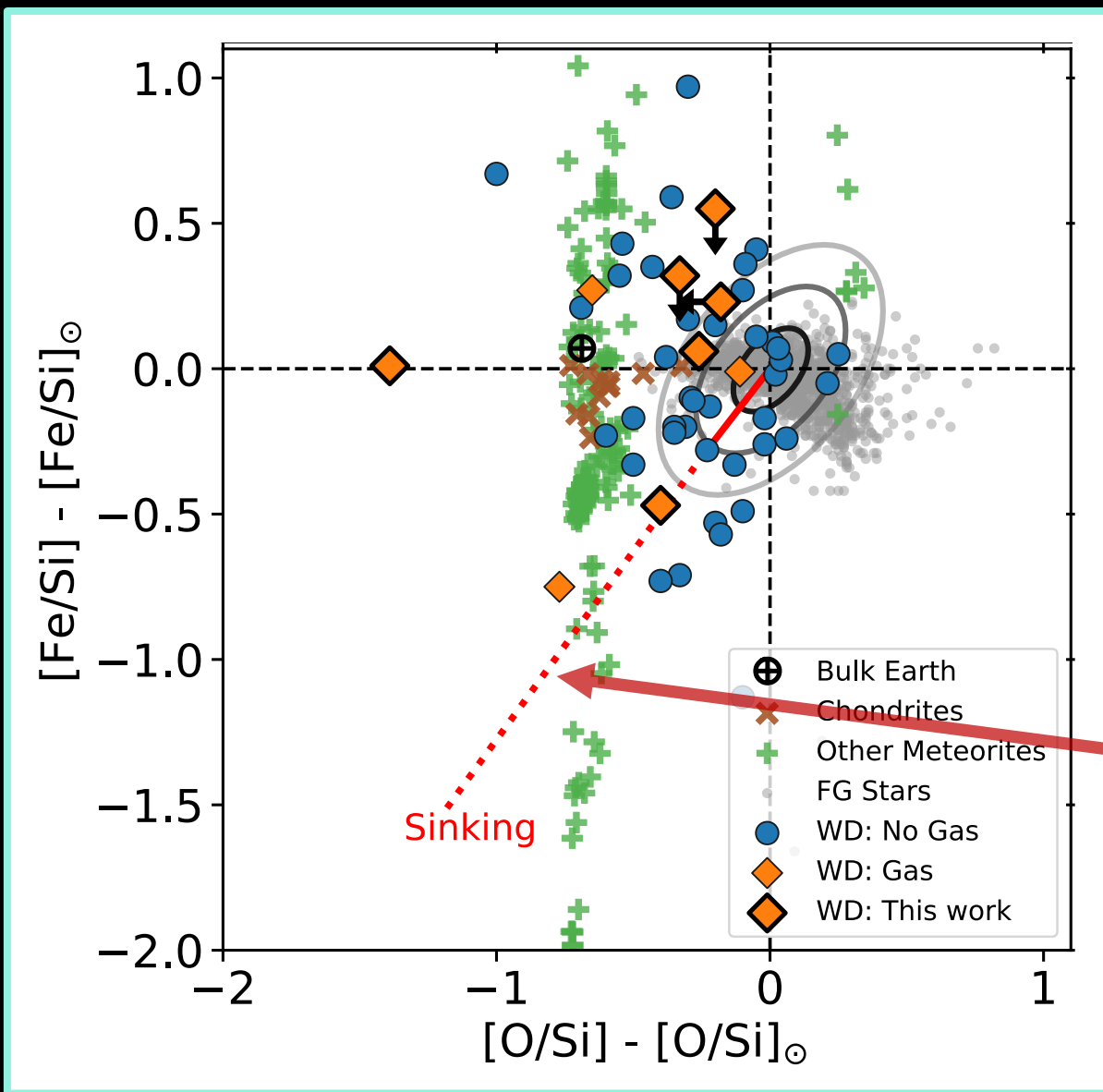
Grey scatter plot: FG stars – range of possible initial compositions

Hinkel et al. (2014)

Green and brown data show abundances of meteorites in the solar system

Orange and blue data are the polluted white dwarf abundances

# Abundances in context



Grey scatter plot: FG stars – range of possible initial compositions

Hinkel et al. (2014)

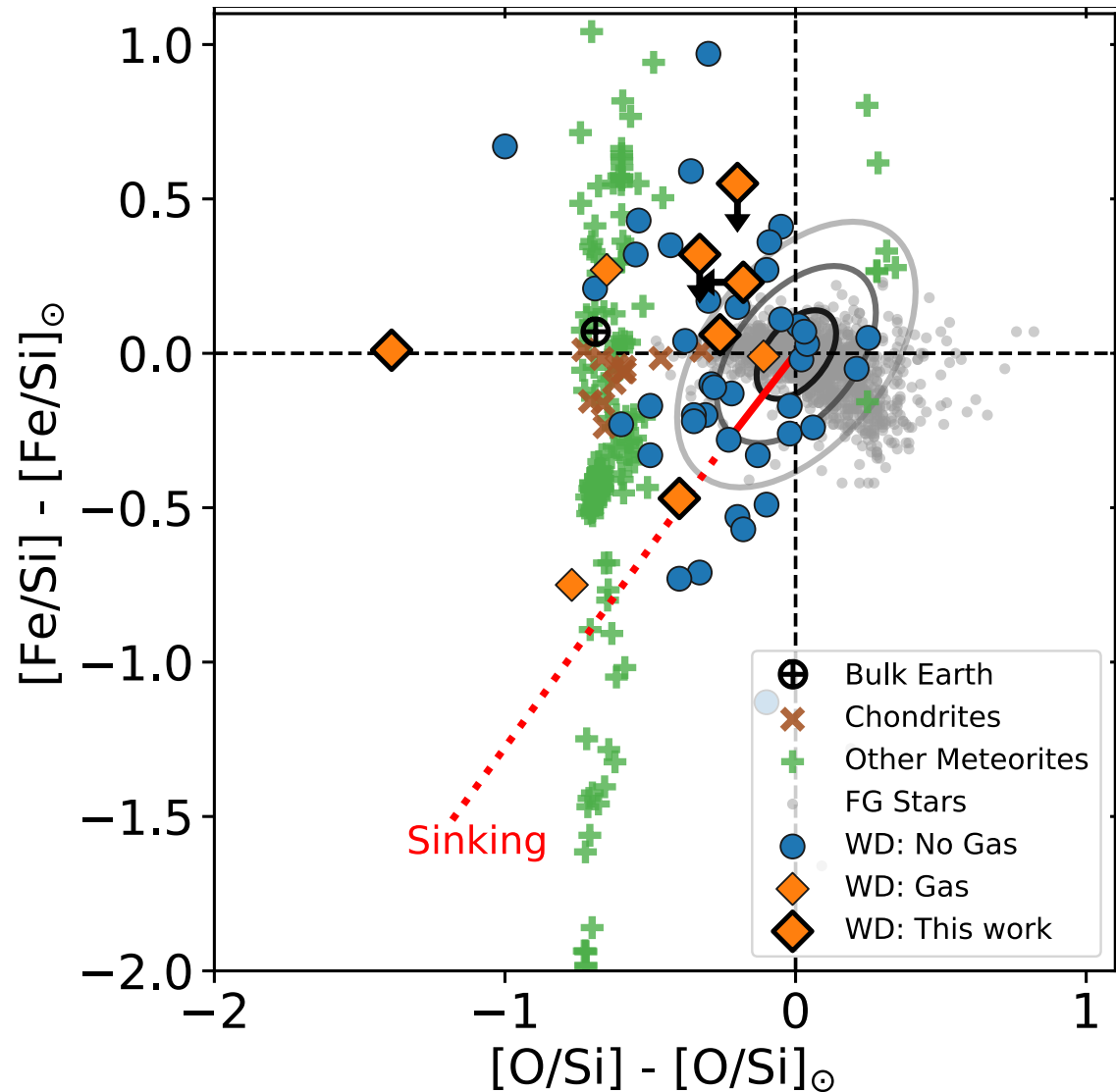
Green and brown data show abundances of meteorites in the solar system

Orange and blue data are the polluted white dwarf abundances

Red lines show how abundances can be affected by sinking in the white dwarf photosphere

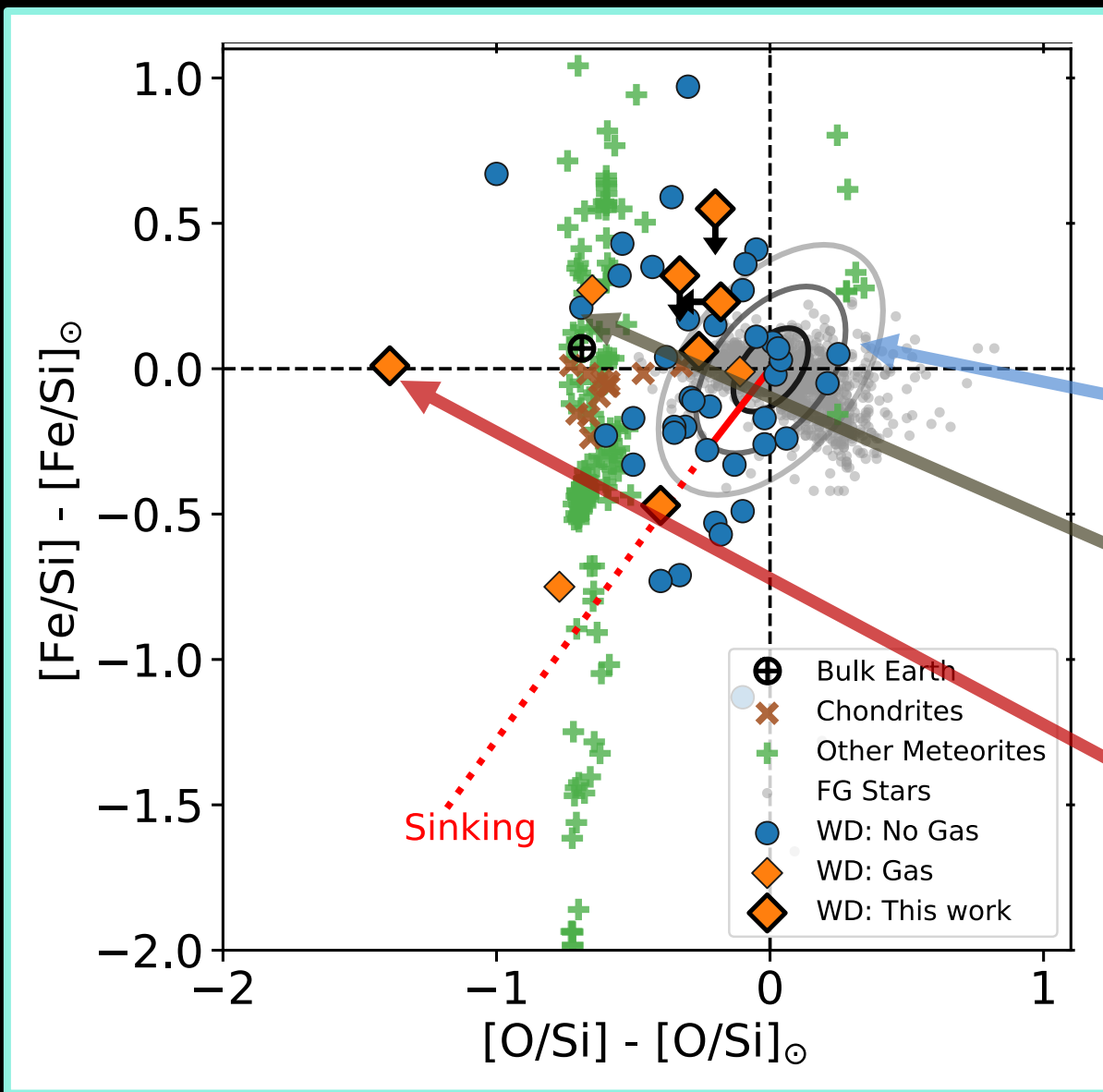


# Abundances in context



$[\text{O}/\text{Si}]$  – assess whether pollutant was oxygen rich – most WDs trace stellar and solar system compositions

# Abundances in context



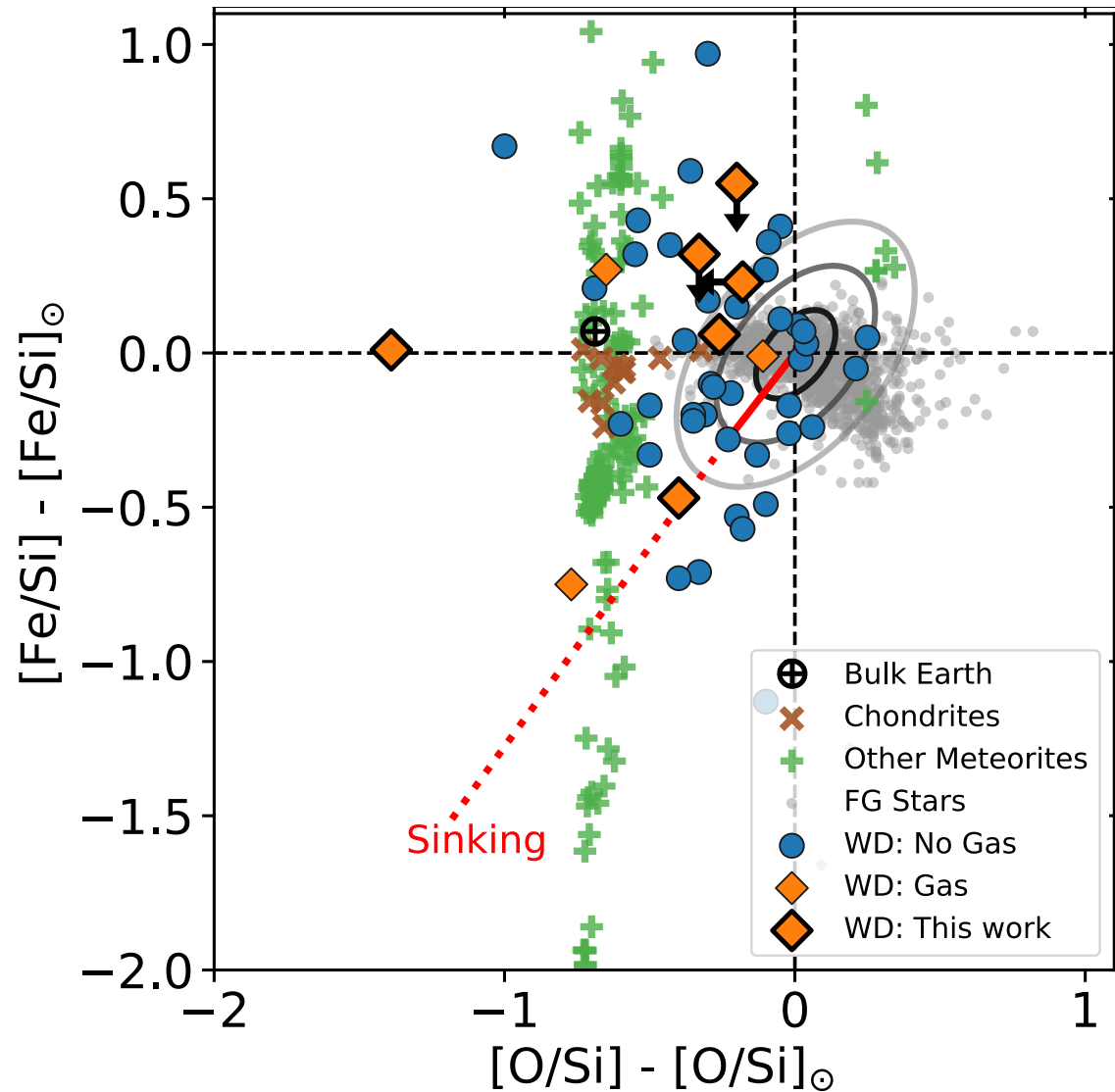
$[\text{O}/\text{Si}]$  – assess whether pollutant was oxygen rich – most WDs trace stellar and solar system compositions

Stellar levels of O

Bulk Earth levels of O

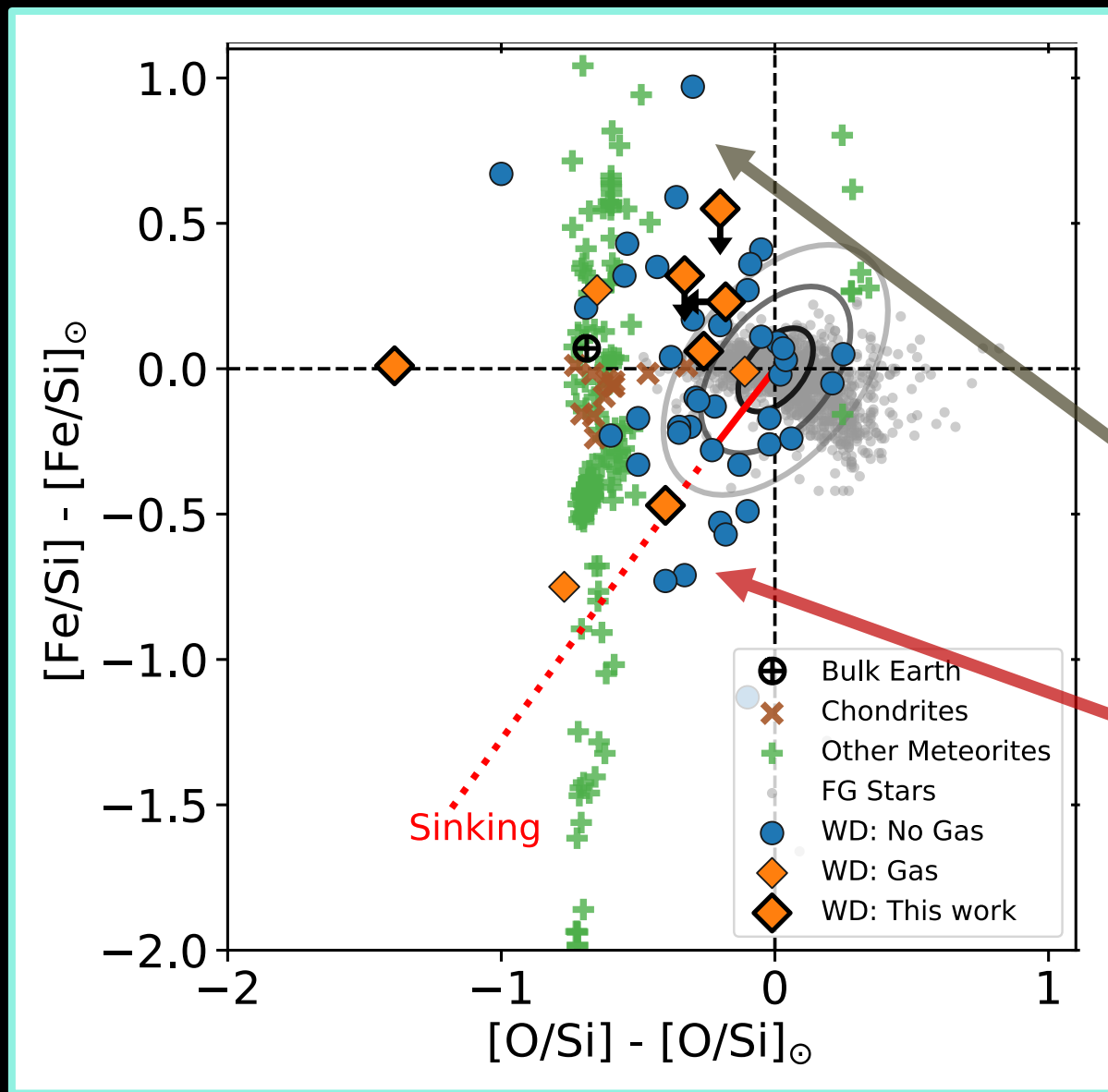
Extreme O depletion

# Abundances in context



$[\text{Fe}/\text{Si}]$  – assess whether pollutant was core-rich or mantle-rich

# Abundances in context



$[\text{Fe}/\text{Si}]$  – assess whether pollutant was core-rich or mantle-rich

Range of Fe content consistent with meteorites in the SS

Enhanced Fe – core-rich?

Depleted Fe – mantle-rich?

# Summary

## Using polluted white dwarfs to probe bulk composition

- Polluted white dwarfs can act as mass spectrometers to infer the bulk composition of exoplanetary material.
- Rogers et al. (2024 a,b):
  - Discovered a new white dwarf accreting mantle like material
  - Discovered 3 new white dwarfs accreting oxygen rich (water rich) material
- At the point where we can start to study large populations of bulk exoplanetary material – find that most resemble the bulk composition of Solar System bodies



Laura Rogers

