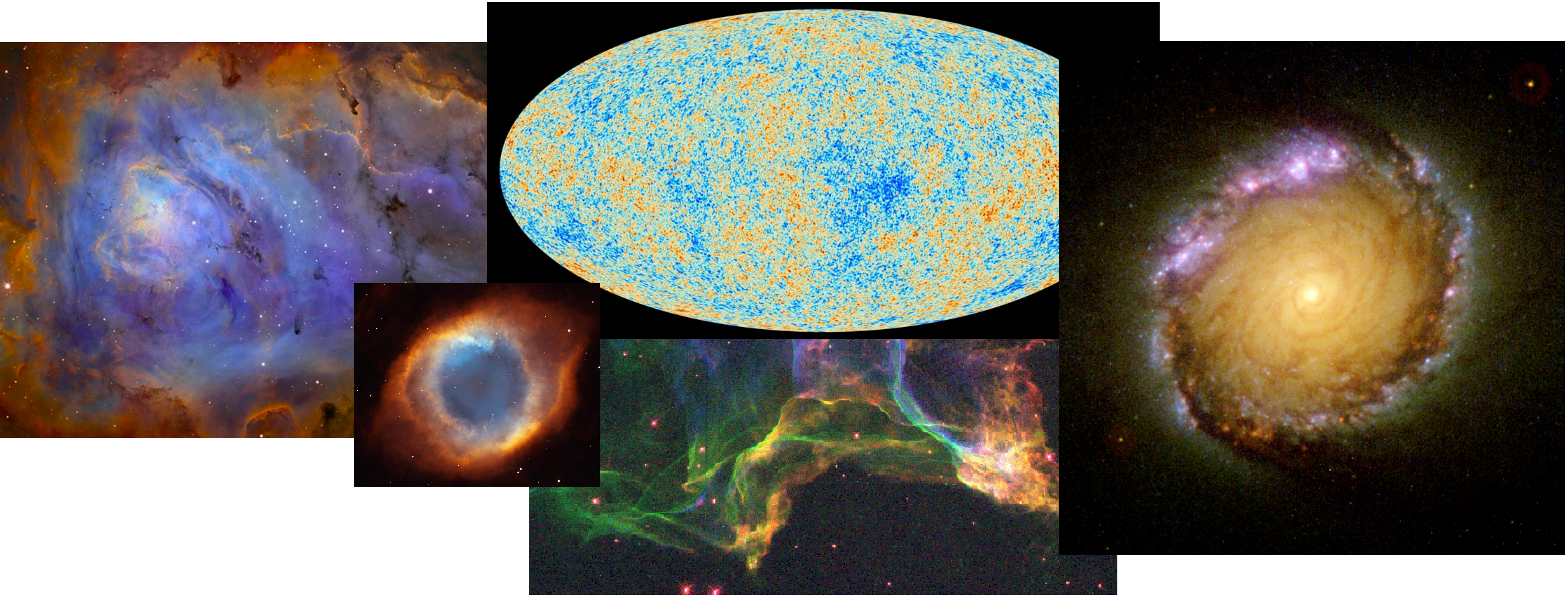
Nuclear Astrophysics

The Cosmic History of Baryonic Matter



Brian Fields

U. of Illinois

TALENT School, MSU, May 2014

Overview

We are in a golden age for nuclear astrophysics

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Objective:

to understand the distribution, composition, and history of cosmic baryons (both visible and dark) in terms of microphysical processes

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Present status: turning point

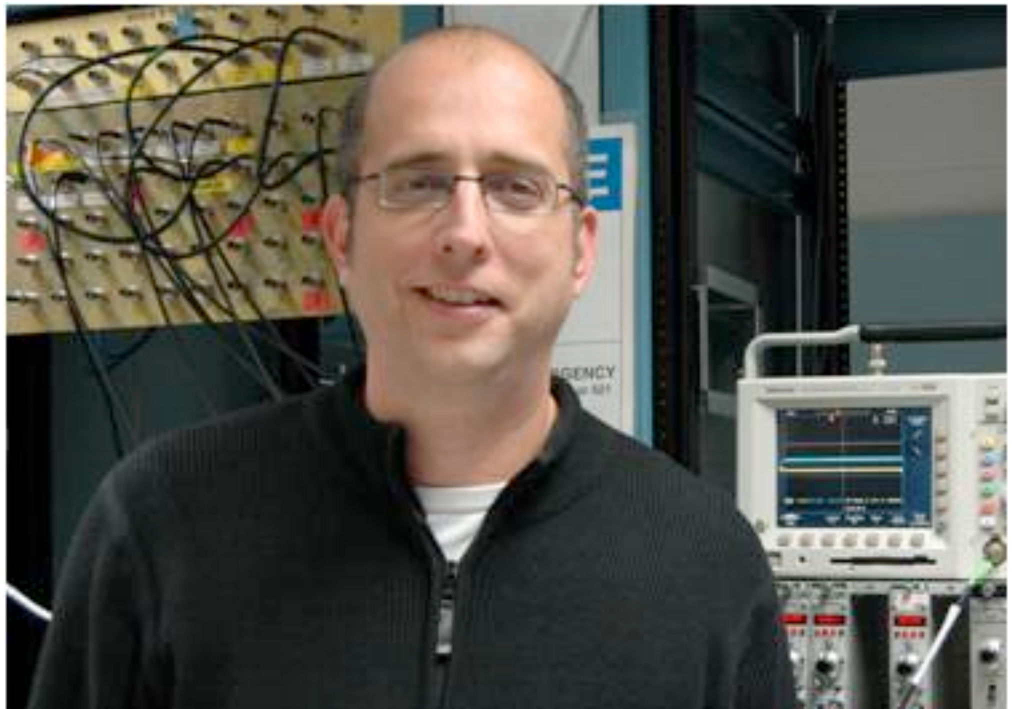
major 20th century successes–tools, techniques, results lay foundations to answer 21st century questions

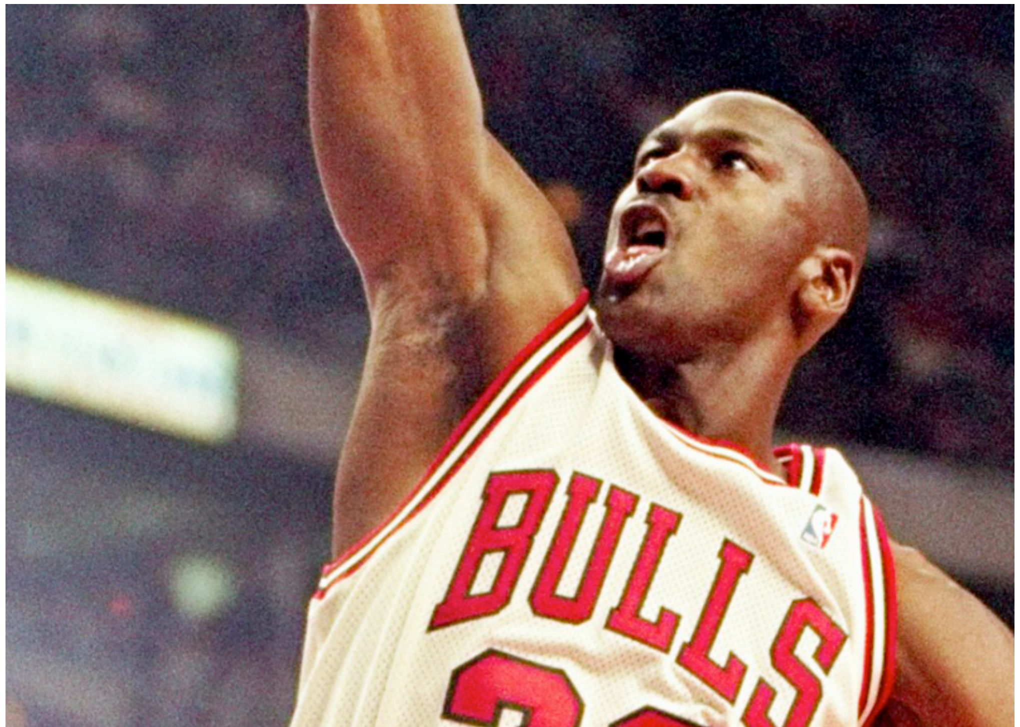
Nuclear Astrophysics:
Frontier Physics

Yesterday: NSF Announces JINA Threepeat

- Recognition of vitality of nuke astro
- $$$ = love/respect
- Guarantees visibility & activity

Give it up for Hendrik Schatz, PI





Whirlwind Tour:
Preview of Coming Attractions

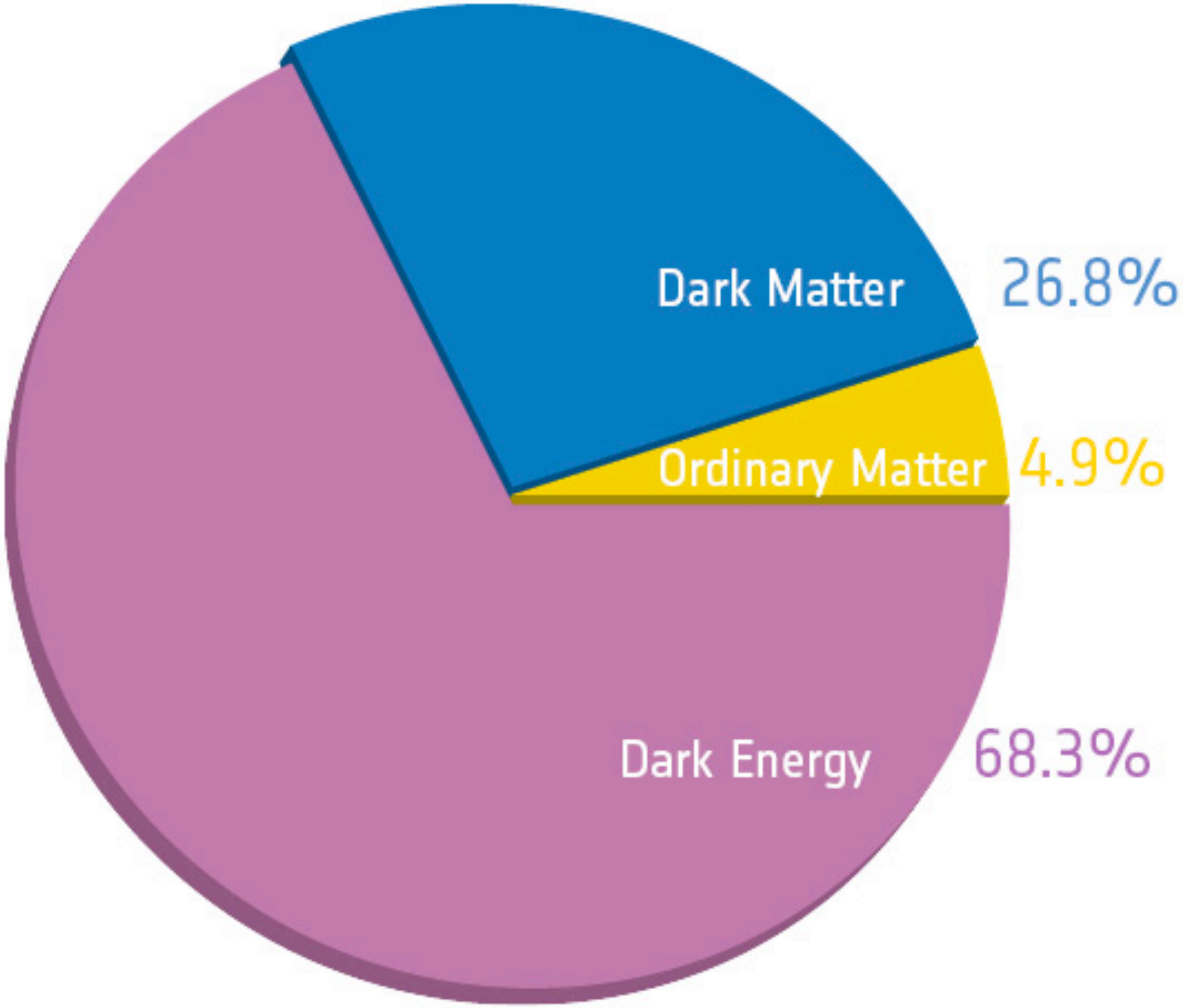
Slices of the Cosmic Pie

We want to use physics to understand the nature and history of cosmic matter

To place in context: (looking ahead to results we haven’t derived)

- Q: what are the main components of the universe today?
- Q: which is the dominant component, and by how much?

The Cosmic Pie Chart



Q: lessons?

Observables for Nuclear Astrophysics

To be a science: must have empirical evidence

→ need observable data to reveal/test cosmic matter history

Seek observables which:

- probe nature of cosmic constituents
- reveal history of cosmic matter
- indicate nuke/particle interactions have taken place

Q: What are some? (no peeking at notes)

Q: Compare observables list to cosmic pie chart. Comments?

Observables for Nuclear Astrophysics

Observable	Example
laboratory terrestrial matter	chart of nuclides
lab. extraterrestrial matter	meteorites, moonrocks
other extraterrestrial matter	cosmic rays
photons: low-energy	cosmic microwave background
medium energy	solar, stellar, galactic spectra
high energy	gamma rays
neutrinos	solar neutrinos
gravitational radiation	neutron star mergers
dark matter	direct detection, annihilations
dark energy	cosmic acceleration

Note: the dominant cosmic components today are the hardest to track observationally!

How do we even know that nuclear physics is the key to baryonic history?

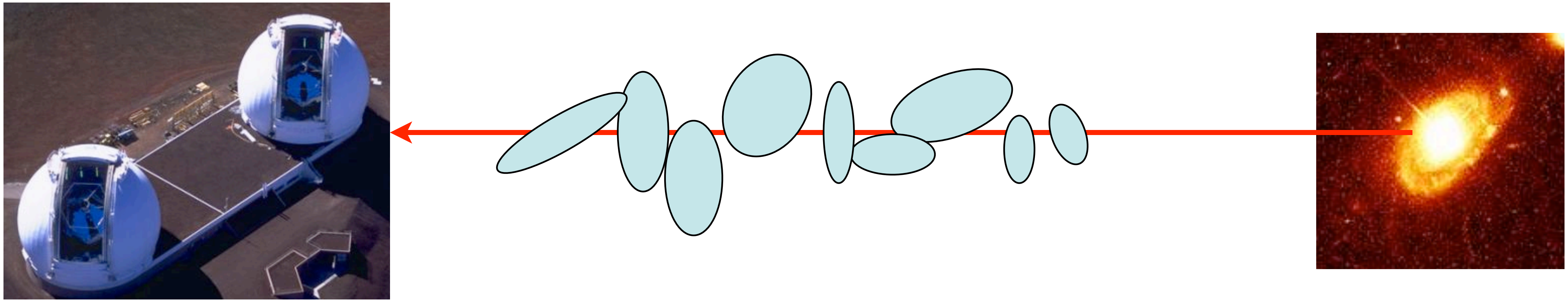
Q: theorists?

Q: observers/experimentalists?

Unveiling the Distant Universe

Unveiling the Distant Universe

- **High-redshift quasar=light bulb**
- **Intervening H gas absorbs at** $\mathrm{Ly}\alpha(n = 1 \rightarrow n = 2)$



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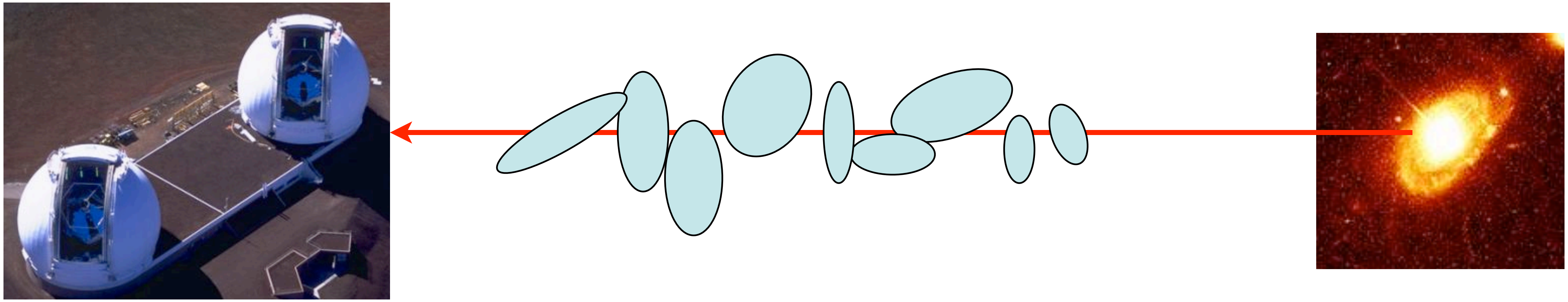

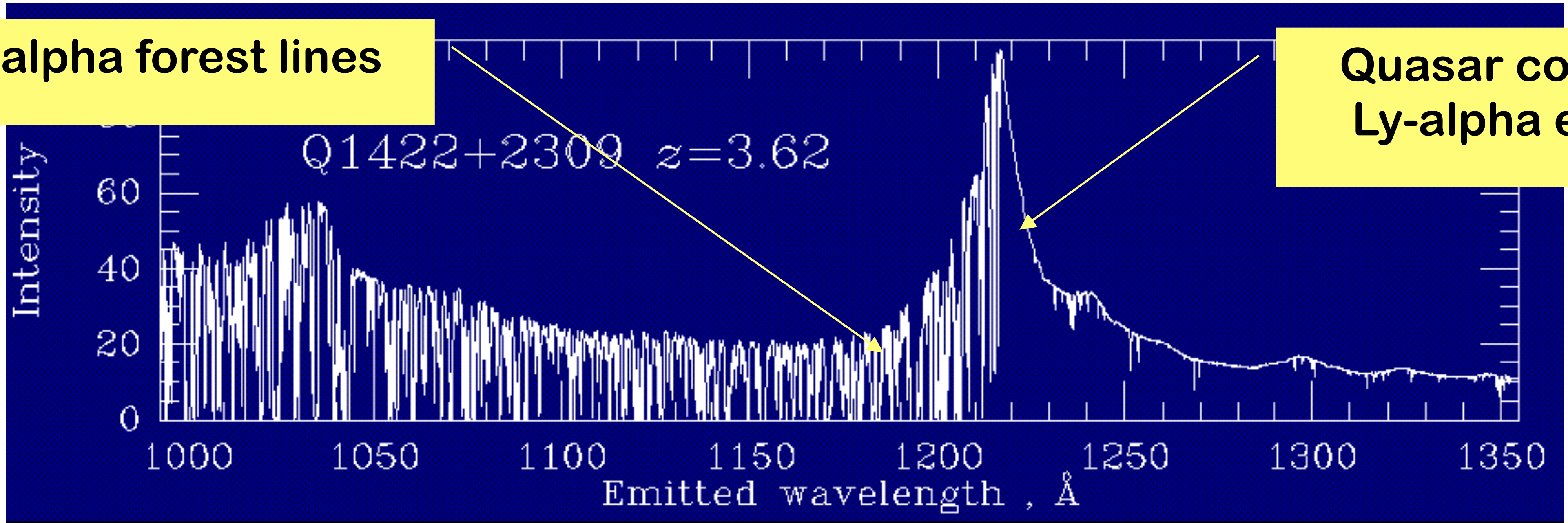

Ly-alpha forest lines

Quasar continuum, Ly-alpha emission

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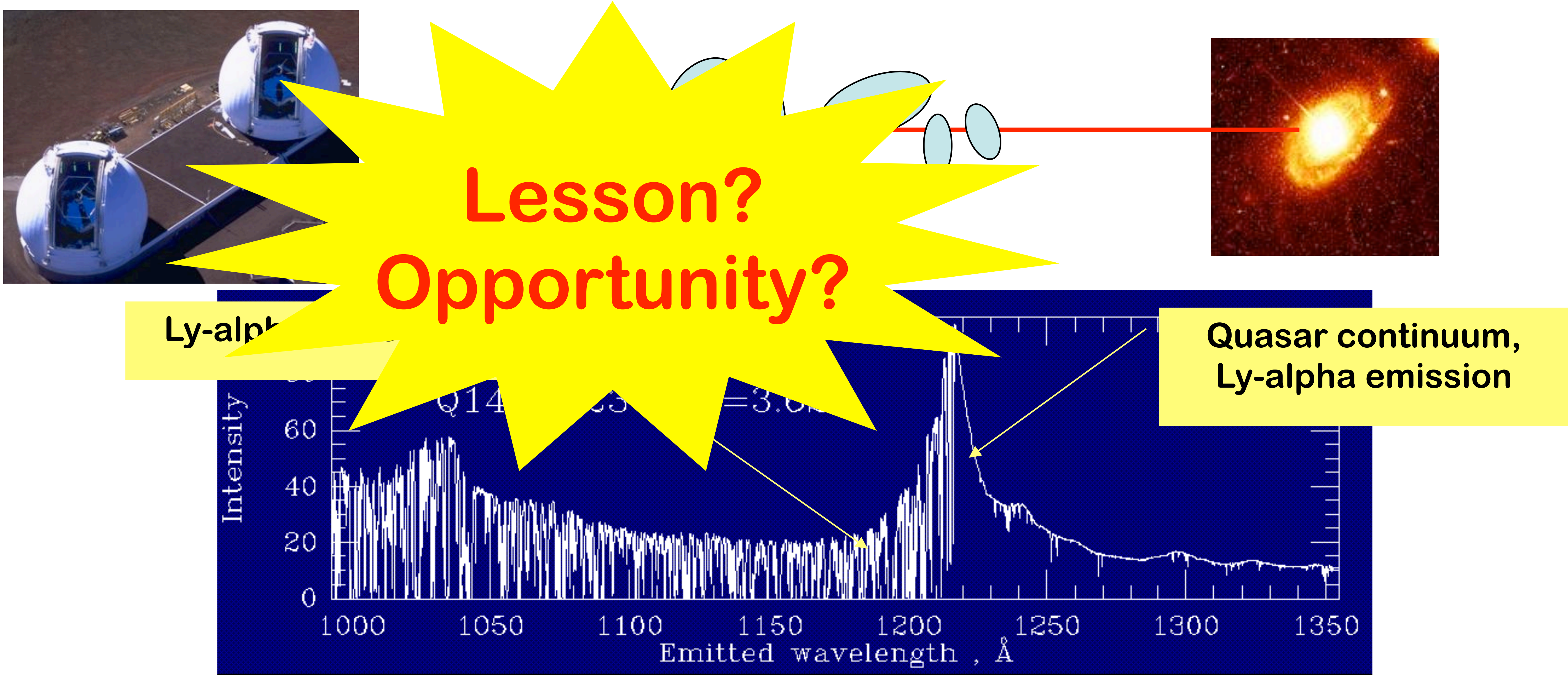


Lesson?
Opportunity?

Ly-alph

Quasar continuum, Ly-alpha emission

Cosmic Deuterium Observed

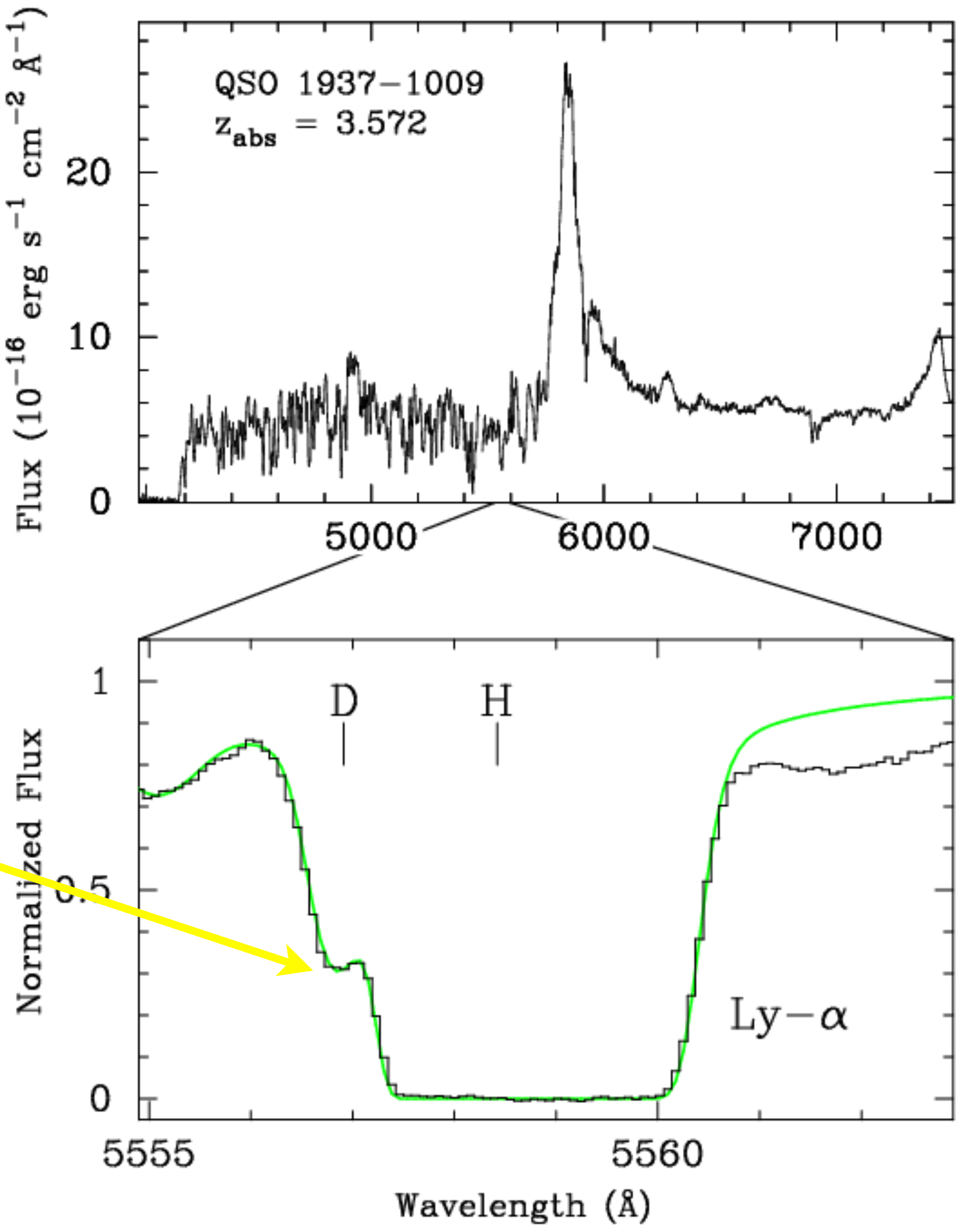
Deuterium Ly-alpha shifted from H:

$$\begin{aligned} E_{\mathrm{Ly}\alpha} &= \frac{1}{2}\alpha^2 \mu_{\mathrm{reduced}} \\ \frac{\delta\lambda_{\mathrm{D}}}{\lambda_{\mathrm{D}}} &= -\frac{\delta\mu_{\mathrm{D}}}{\mu_{\mathrm{D}}} = -\frac{m_e}{2m_p} \\ c\delta z &= 82\ \mathrm{km/s} \end{aligned}$$

Get D directly at high-z!

Lessons?

- deuterium in place very early
- stars destroy D: must be primordial
- will see: D/H is sensitive baryometer

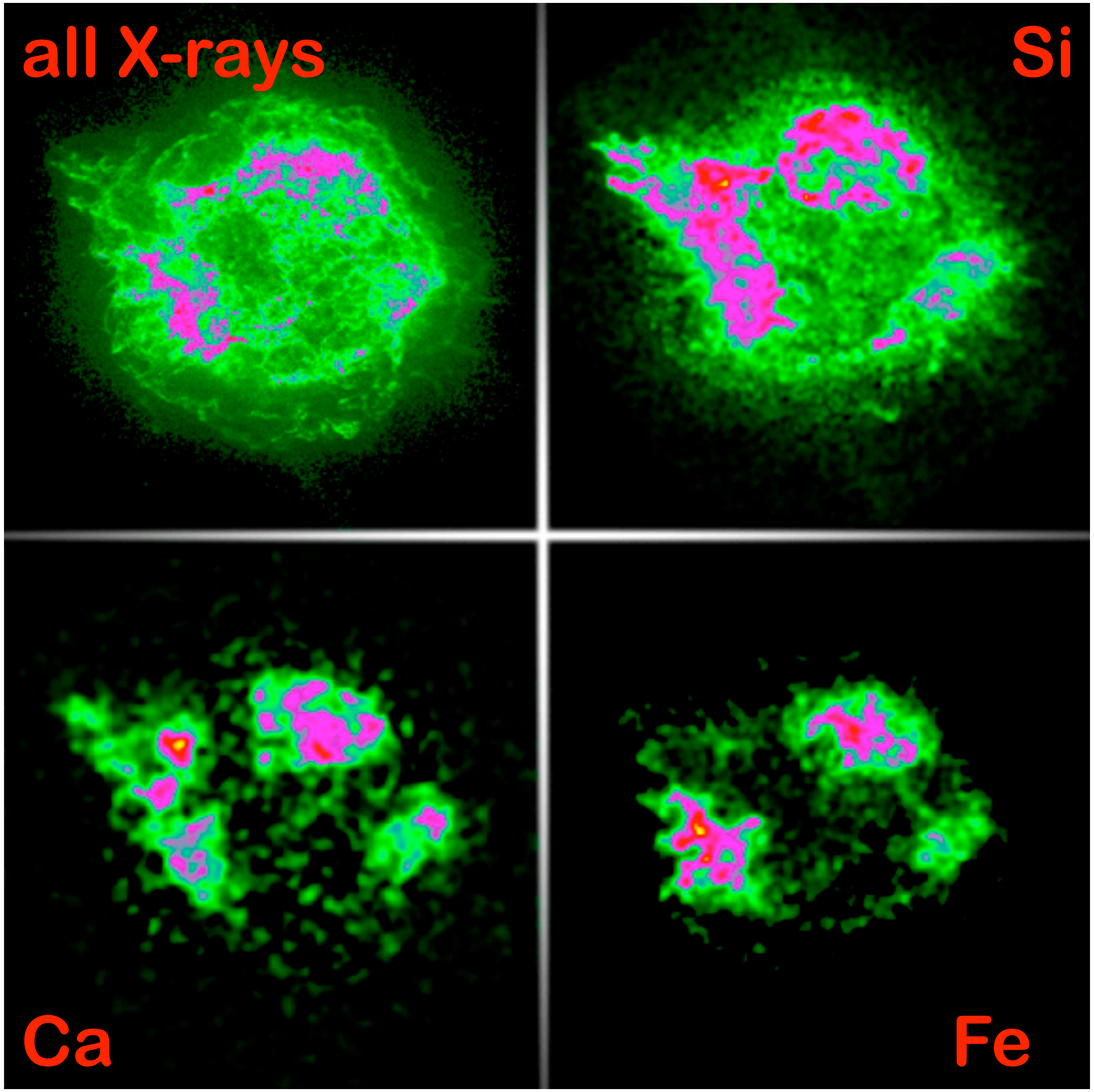


Tytler & Burles

Stellar Nucleosynthesis: Supernovae

supernova explosions produce most of the diversity of heavy elements

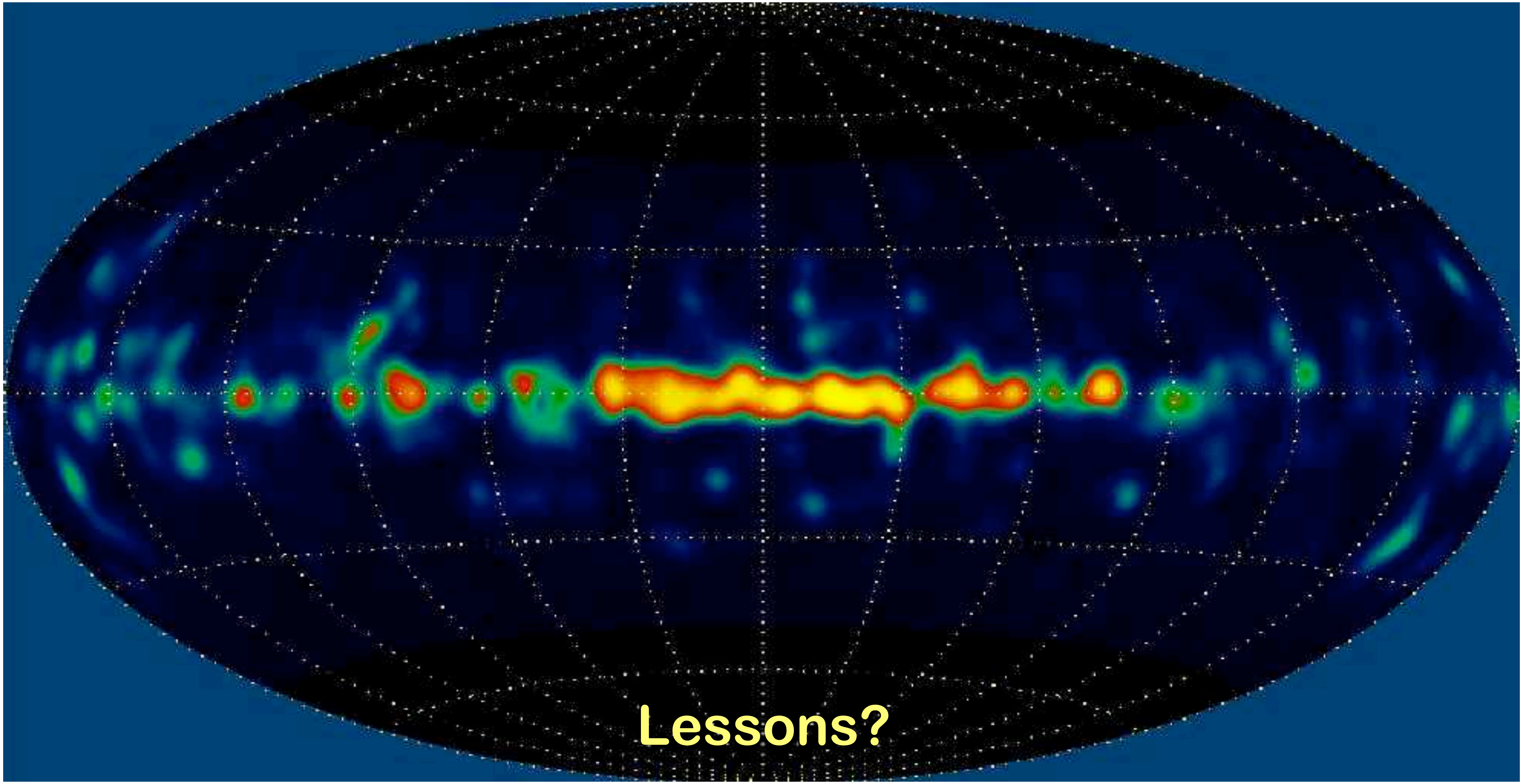
- will look at in detail



SN remnant Cas A in X-rays (Chandra)

The Radioactive Sky

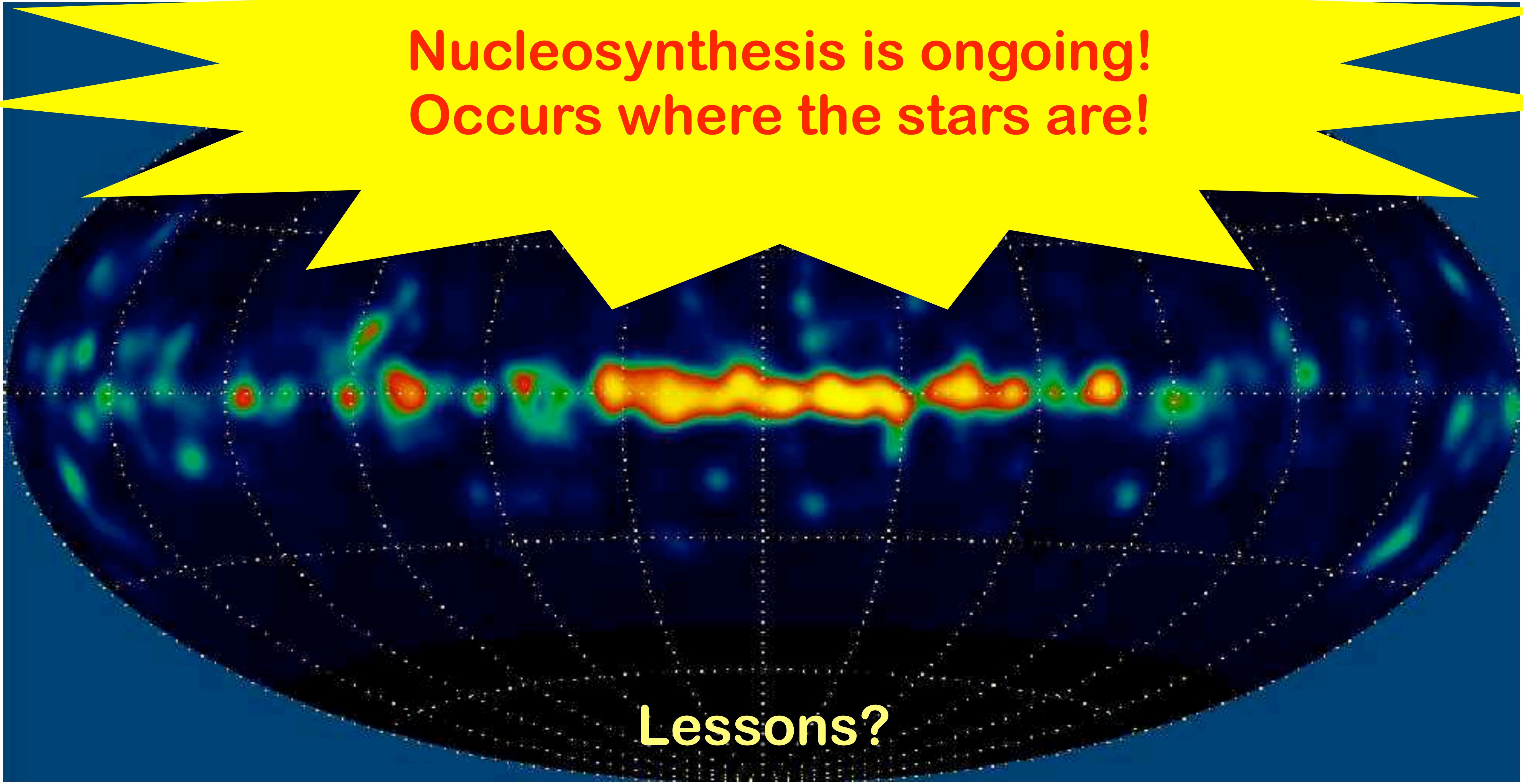
$$^{26}\mathrm{Al} \xrightarrow{0.7\ \mathrm{Myr}} {}^{26}\mathrm{Mg}^* \rightarrow {}^{26}\mathrm{Mg}^{\mathrm{gs}} + \gamma_{1.8\ \mathrm{MeV}}$$


Lessons?

The Sky at 1.8 MeV, Galactic Coordinates (Comptel)

The Radioactive Sky

^{26}Al 0.7



Nucleosynthesis is ongoing!
Occurs where the stars are!

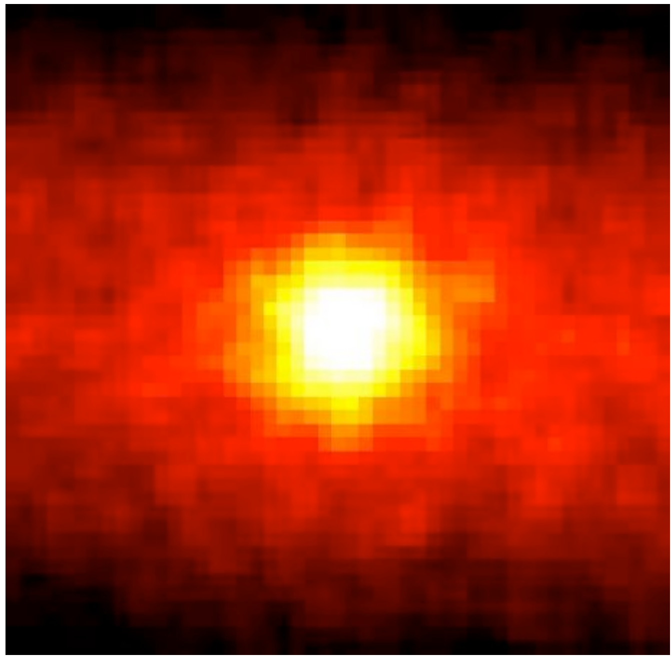
Lessons?

The Sky at 1.8 MeV, Galactic Coordinates (Comptel)

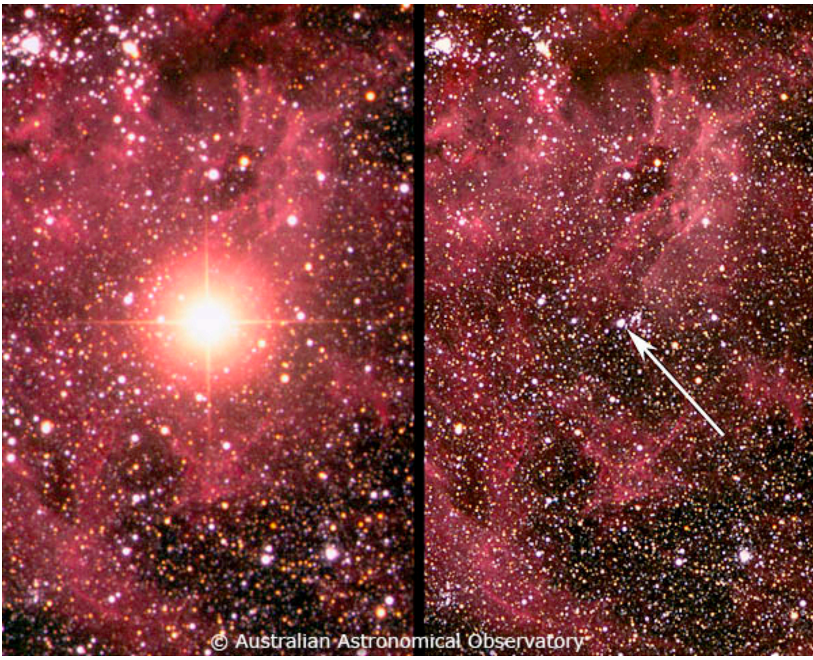
Messengers Beyond Photons: Neutrinos

Barely there but at the heart of it all!

Solar Neutrinos



Supernova Neutrinos



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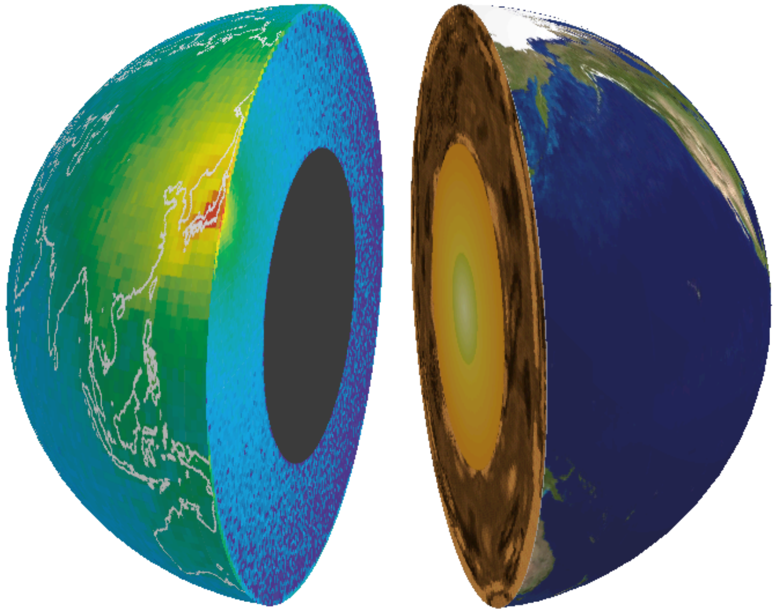
Terrestrial Neutrinos



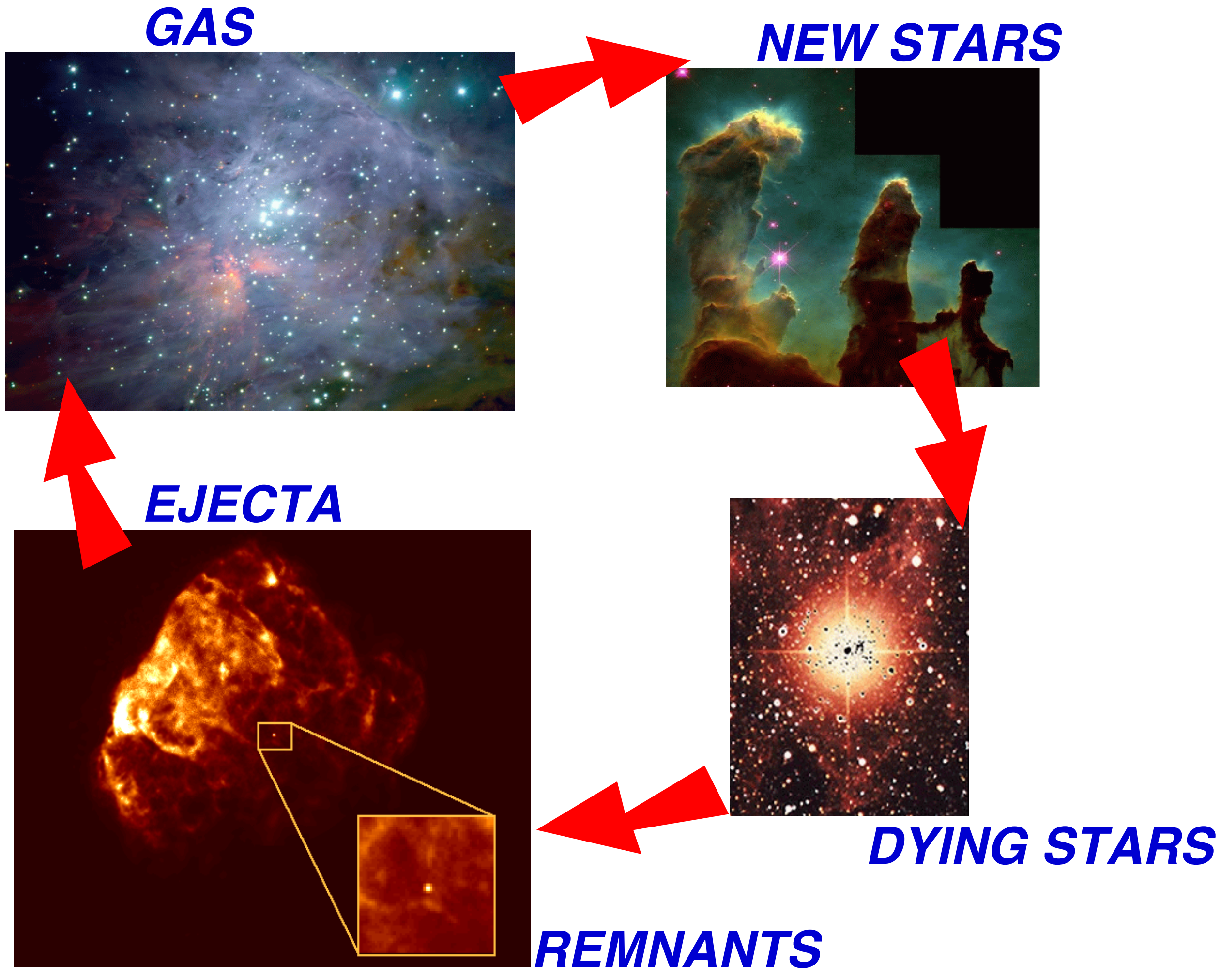
Cosmological Neutrinos (CNB)

– tell me if you know how to detect these!

Baryonic History:
Galactic Chemical Evolution

The Basic Idea

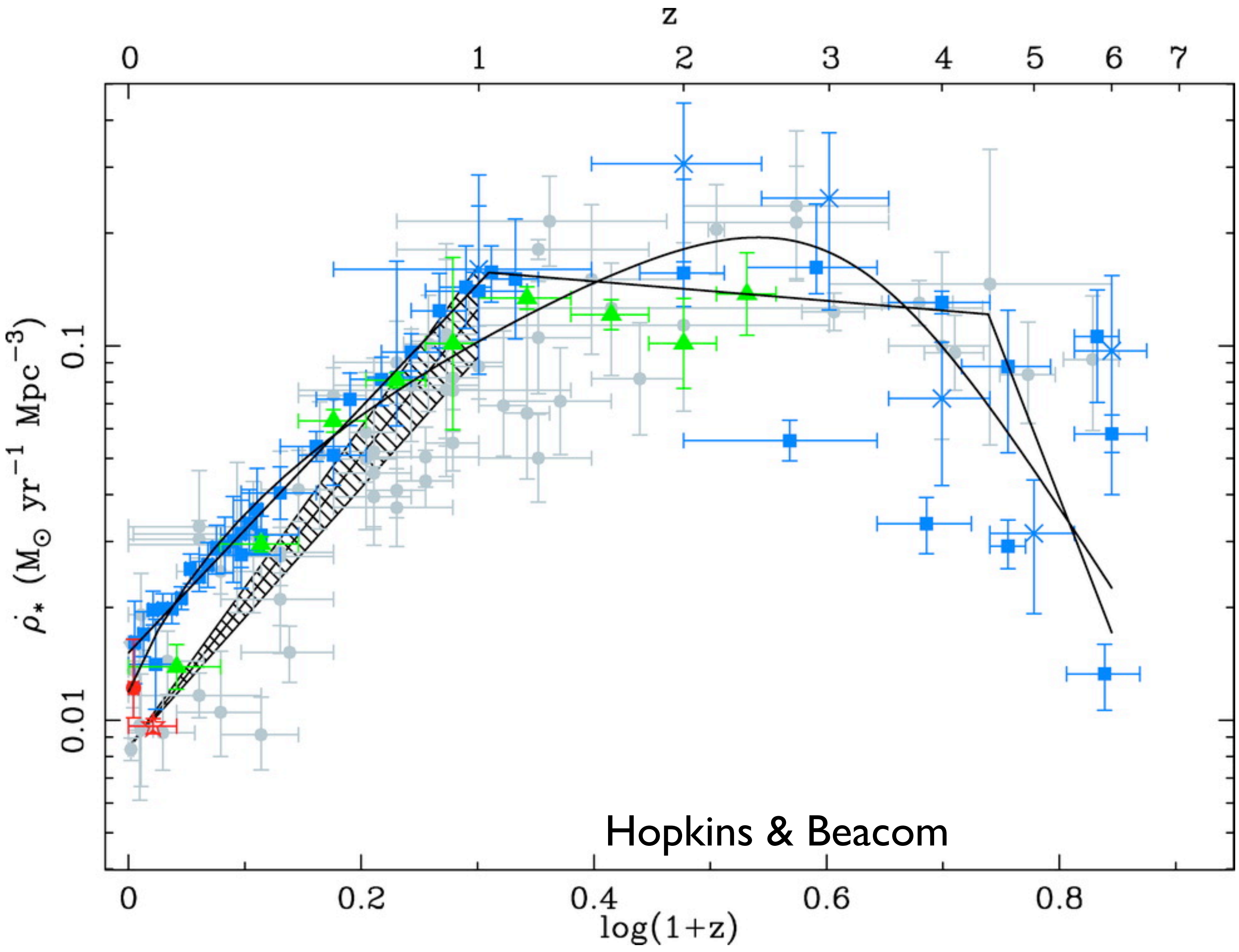
- consider a star forming system;
  - e.g., our Galaxy, other galaxies, or a protogalactic subhalo
- baryons cycle thru stars: abundances altered by nuke processing
- every parcel of baryonic matter records the nucleosynthetic history of cosmic & stellar events



Cosmic Star Formation History: Present Data

Cosmic average star formation rate per comoving volume

Q: Trends?



Cosmic Star Formation Rate
Present Data

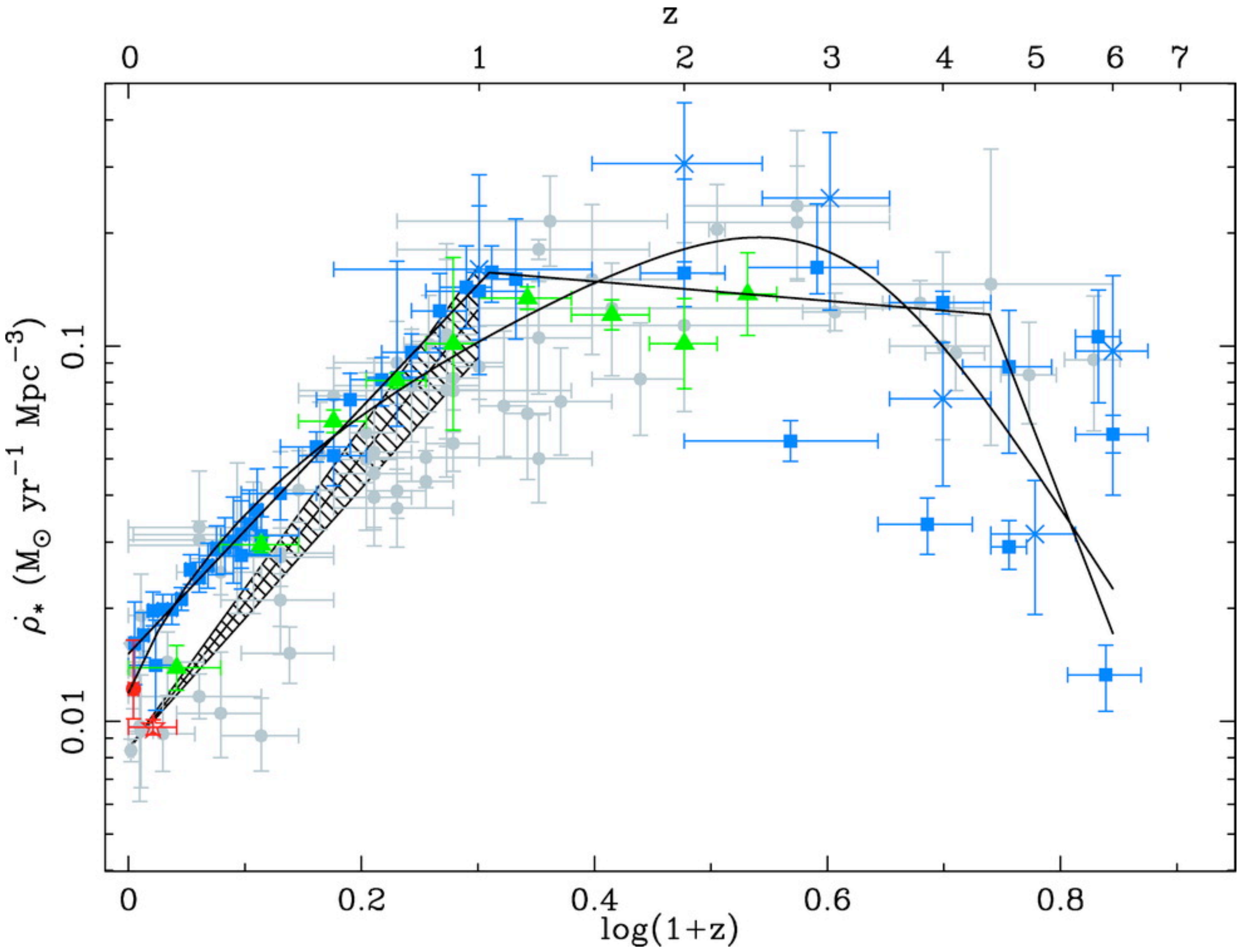
Cosmic average star formation rate per comoving volume

Clear trend:

- rate much higher at redshift z~1-2: t~4 Gyr ago

Not so clear:

- normalization
- high-redshift behavior



Hopkins & Beacom

Baryons: Praise Them or Bury Them?

recall: baryon →3 bound quarks →proton, neutron → nuclei → atoms

baryons comprise

- a tiny fraction of cosmic matter today
- and an even smaller fraction of total cosmic mass-energy

and (at least some) baryons are not exotic with (fairly) well-understood physics

Q: so what's the use of studying cosmic baryons?

In Defense of Baryons

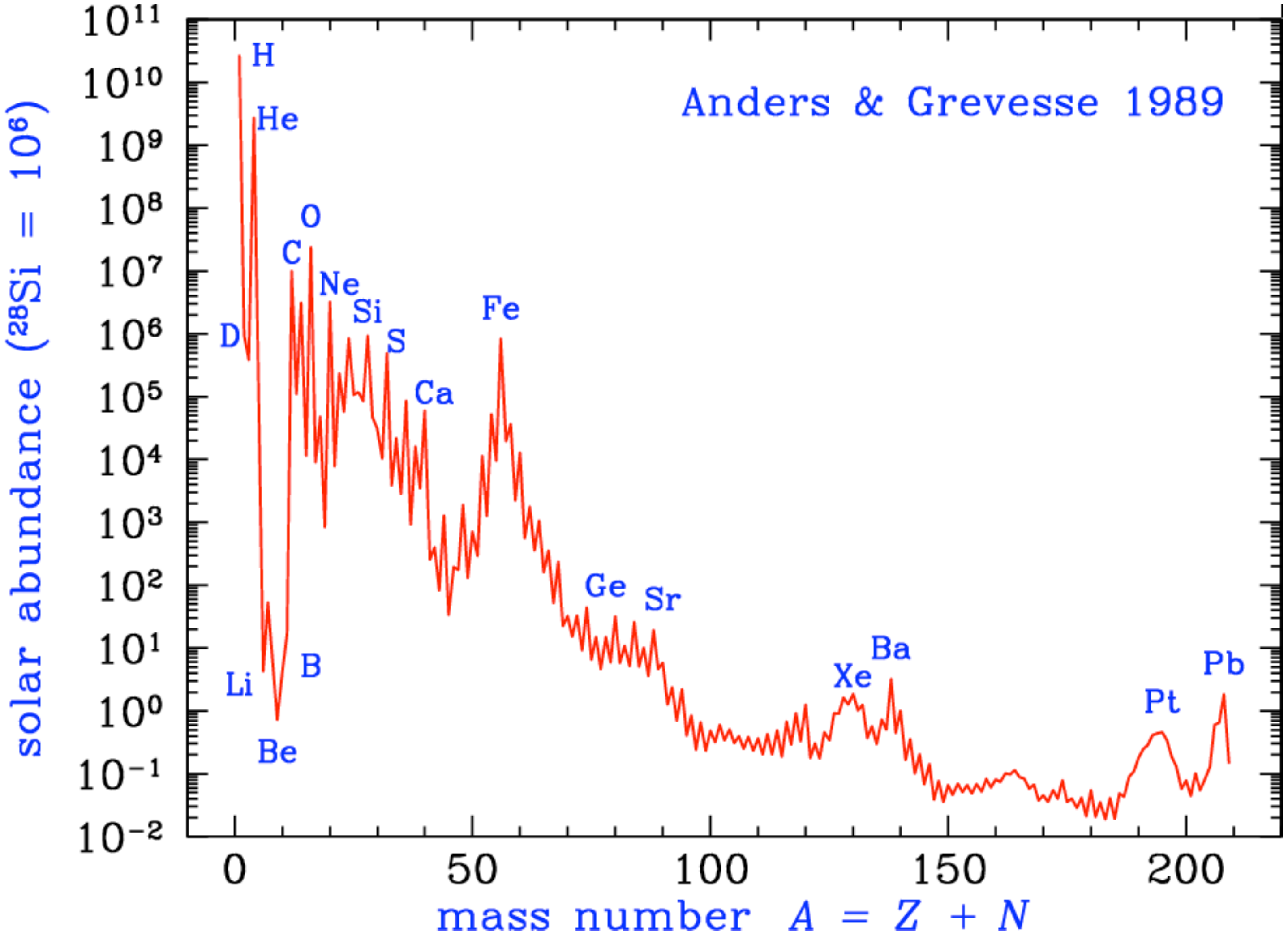
- ★ because we know much about baryonic physics
  - both micro (particle, nuclear, atomic)
  - and macro (hydrodynamics, condensed matter)

- ★ baryons show how particle properties are manifest in cosmo/astro context
  - good training for dark matter, dark energy

- ★ lessons:
  - detailed picture of how baryonic microphysics determines cosmic properties and shapes cosmic events
  - see how unexpected and complex phenomena emerge

- ★ we are baryons!

Abundances



Anders & Grevesse 1989
solar abundance (^{28}Si = 10^6)
mass number $A = Z + N$
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
50
100
150
200
H
He
O
C
Ne
Si
S
Fe
D
Ca
Ge
Sr
Ba
Xe
Pb
Pt
B
Li
Be

Central Baryonic Observable: Abundances

a key tracer of cosmic particle history and
the key tracer of cosmic nuclear history
is baryonic composition ⇒abundances

Q: where can we measure abundances?
Q: where most accurate? most interesting?

Observable Abundances

Sun , solar system

MW Galaxy:

- stars, ISM, cosmic rays

External galaxies:

- ISM, stars

Intergalactic medium at high, low redshift

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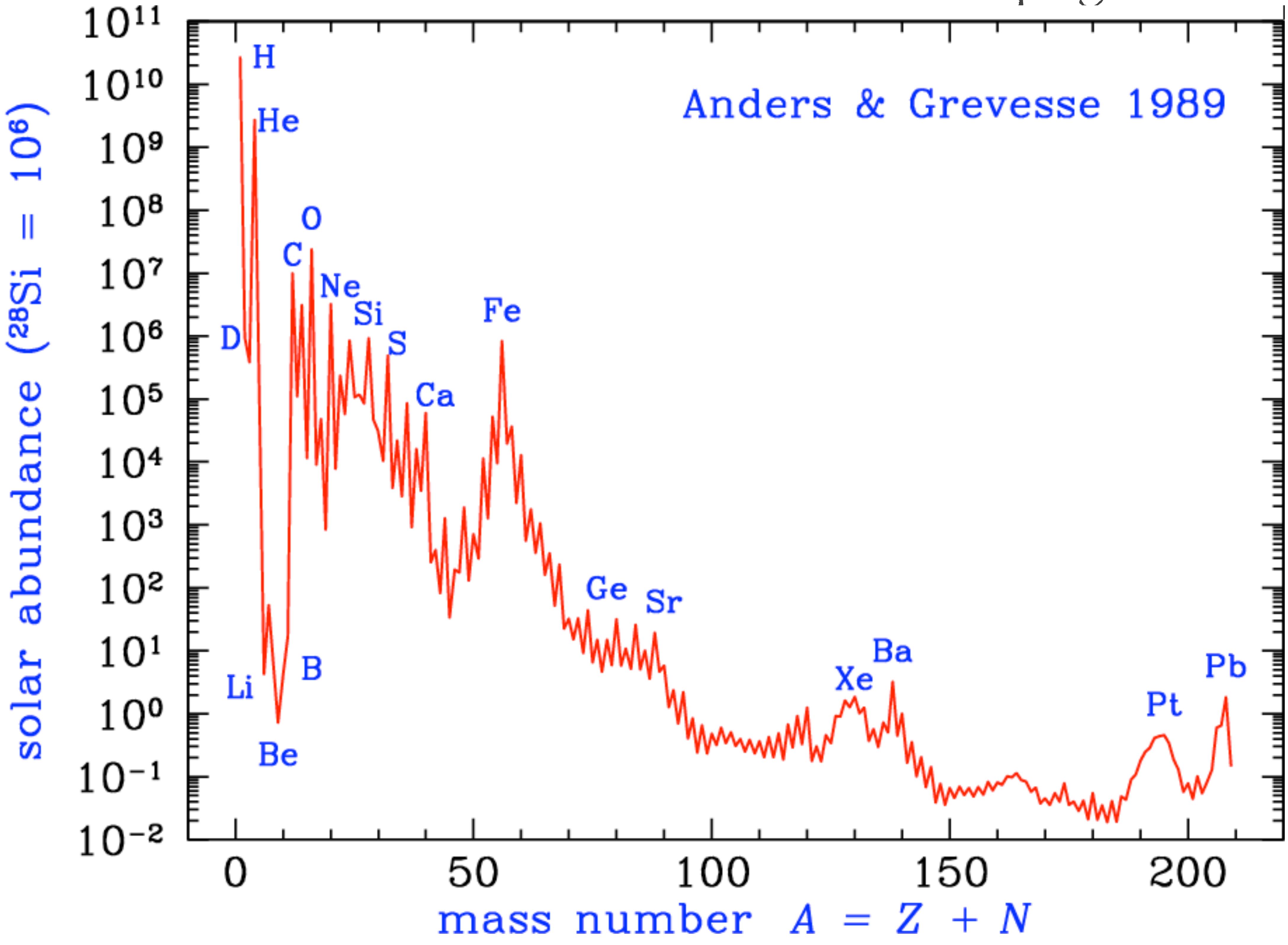
Solar System Abundances

Rosetta Stone of Nuclear Astrophysics



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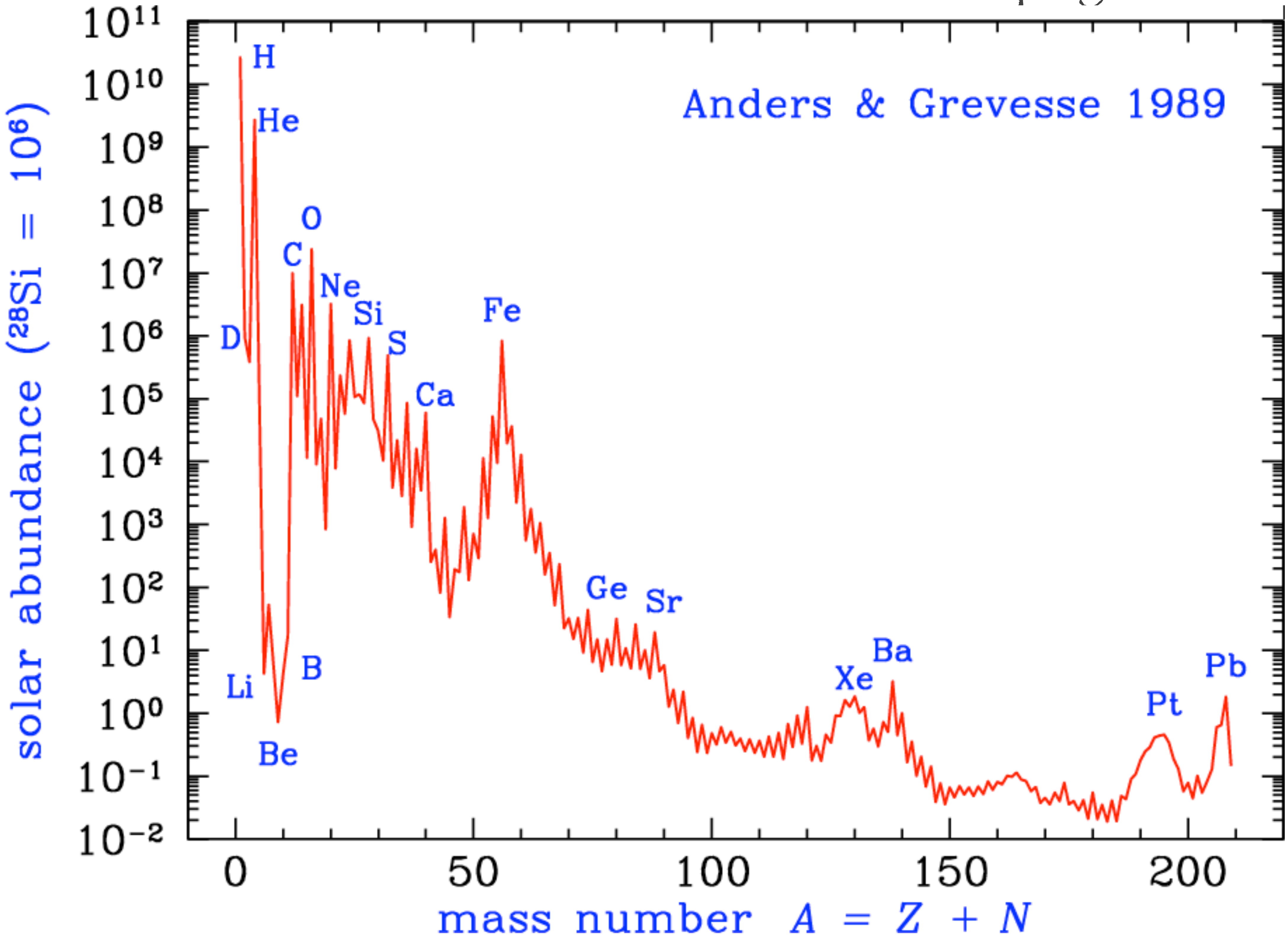


Q: physical significance? trends/features? lessons?

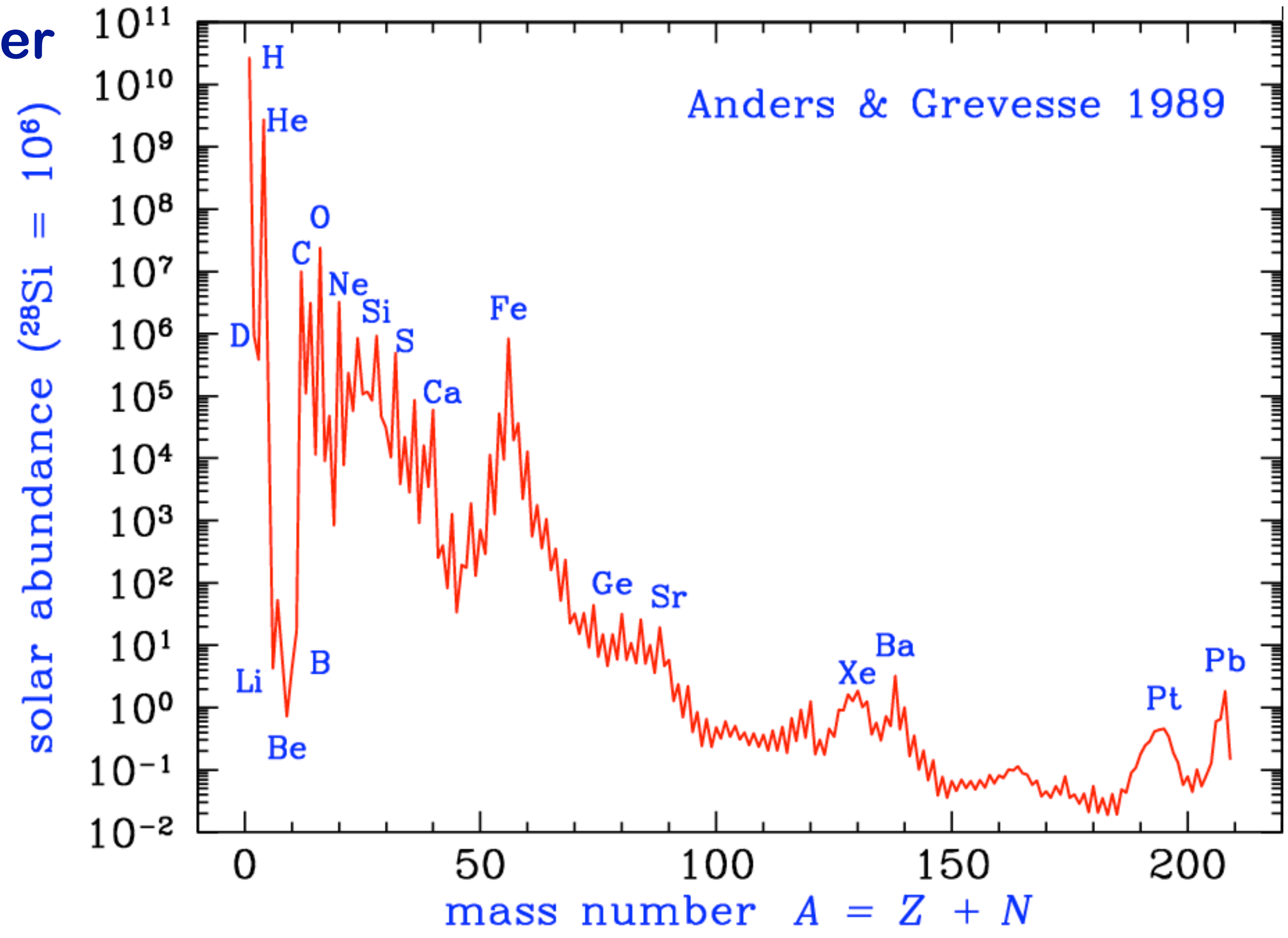
Solar System Abundances

Rosetta Stone of Nuclear Astrophysics

sums cumulative nucleosynthesis up to birth of solar system

nuclear physics written into the matter around us

- odd-even effect
- max binding at ^{56}Fe
- min binding for D, Li, Be, B



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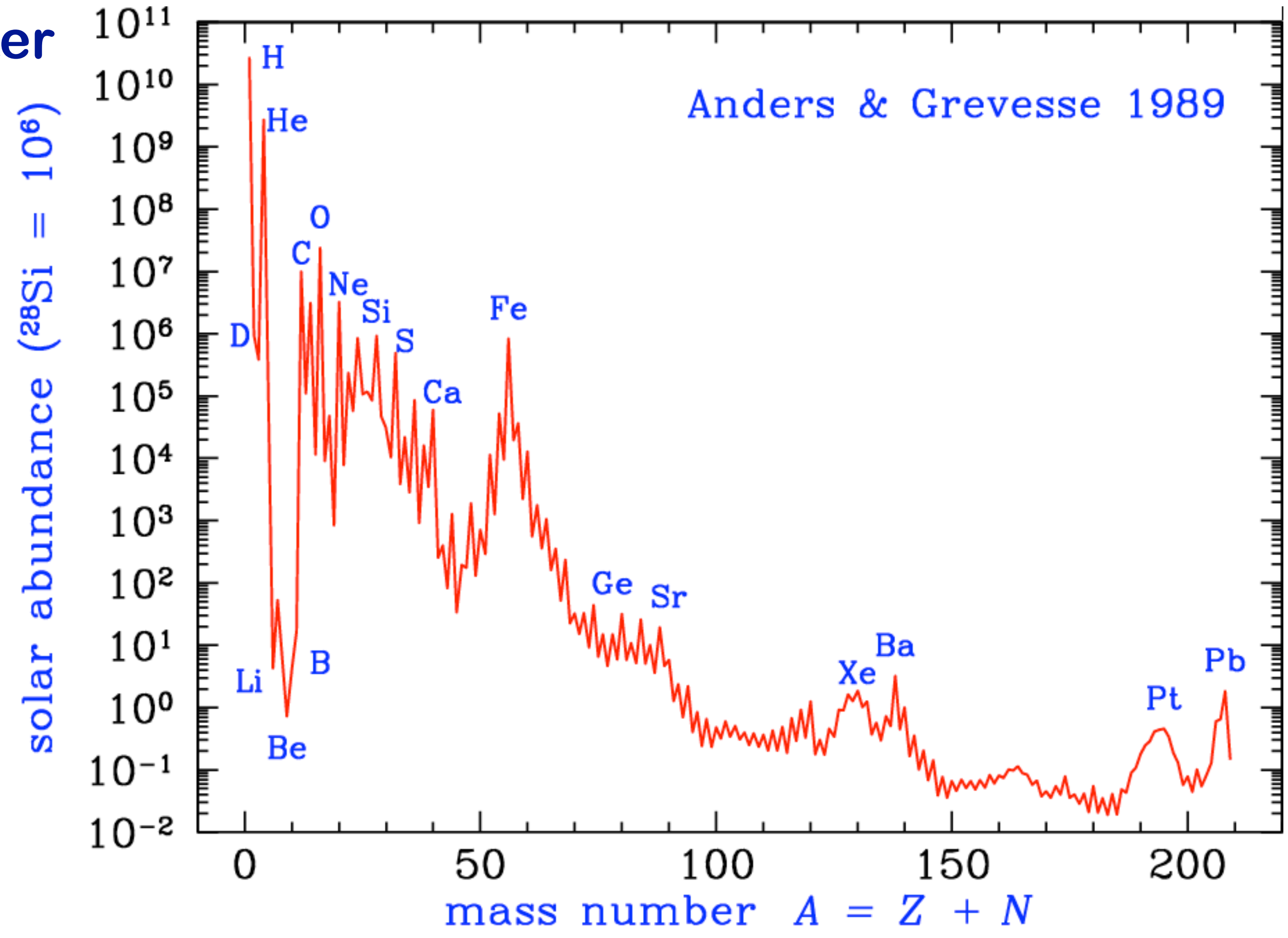
multiple processes at work



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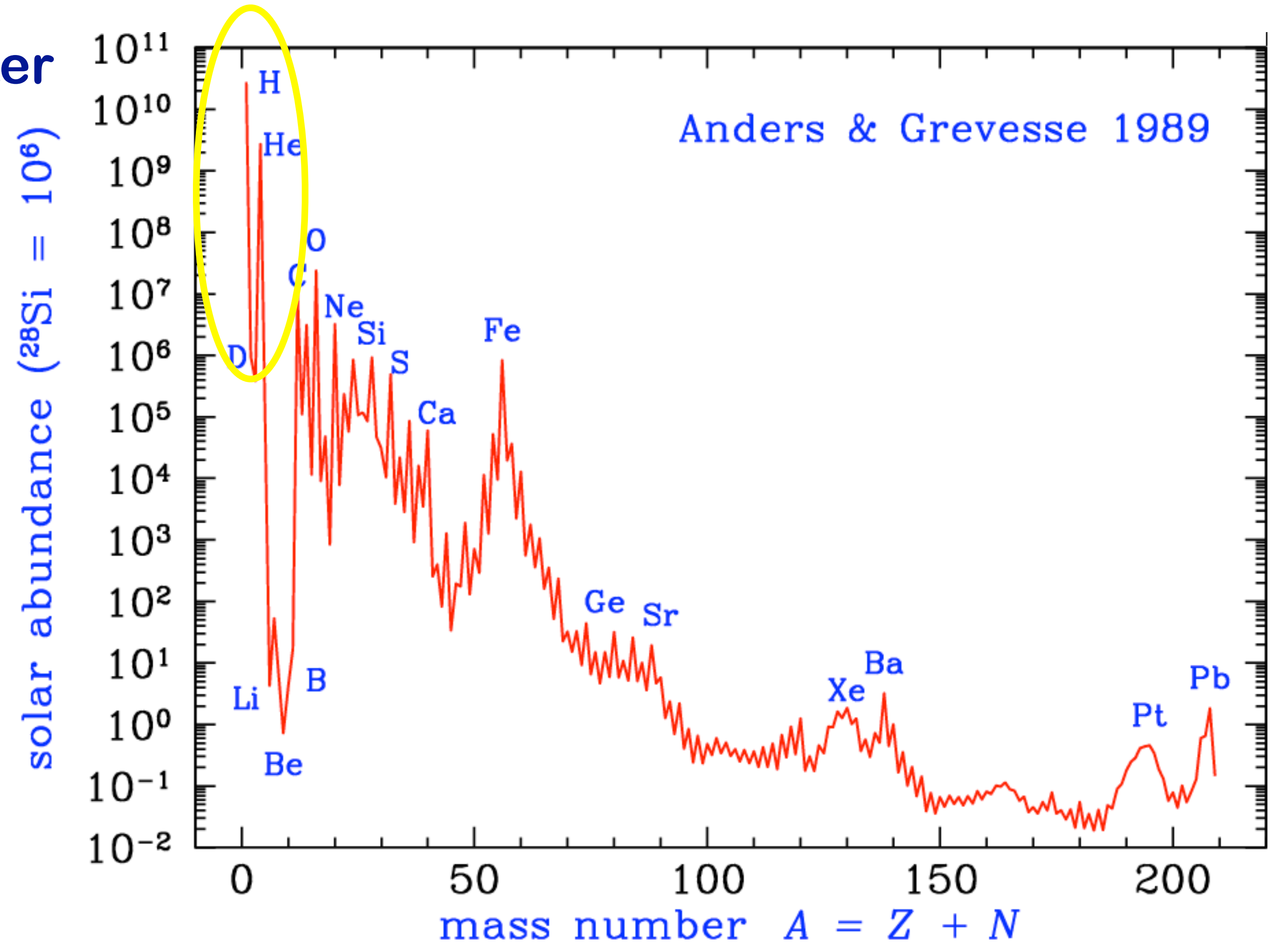

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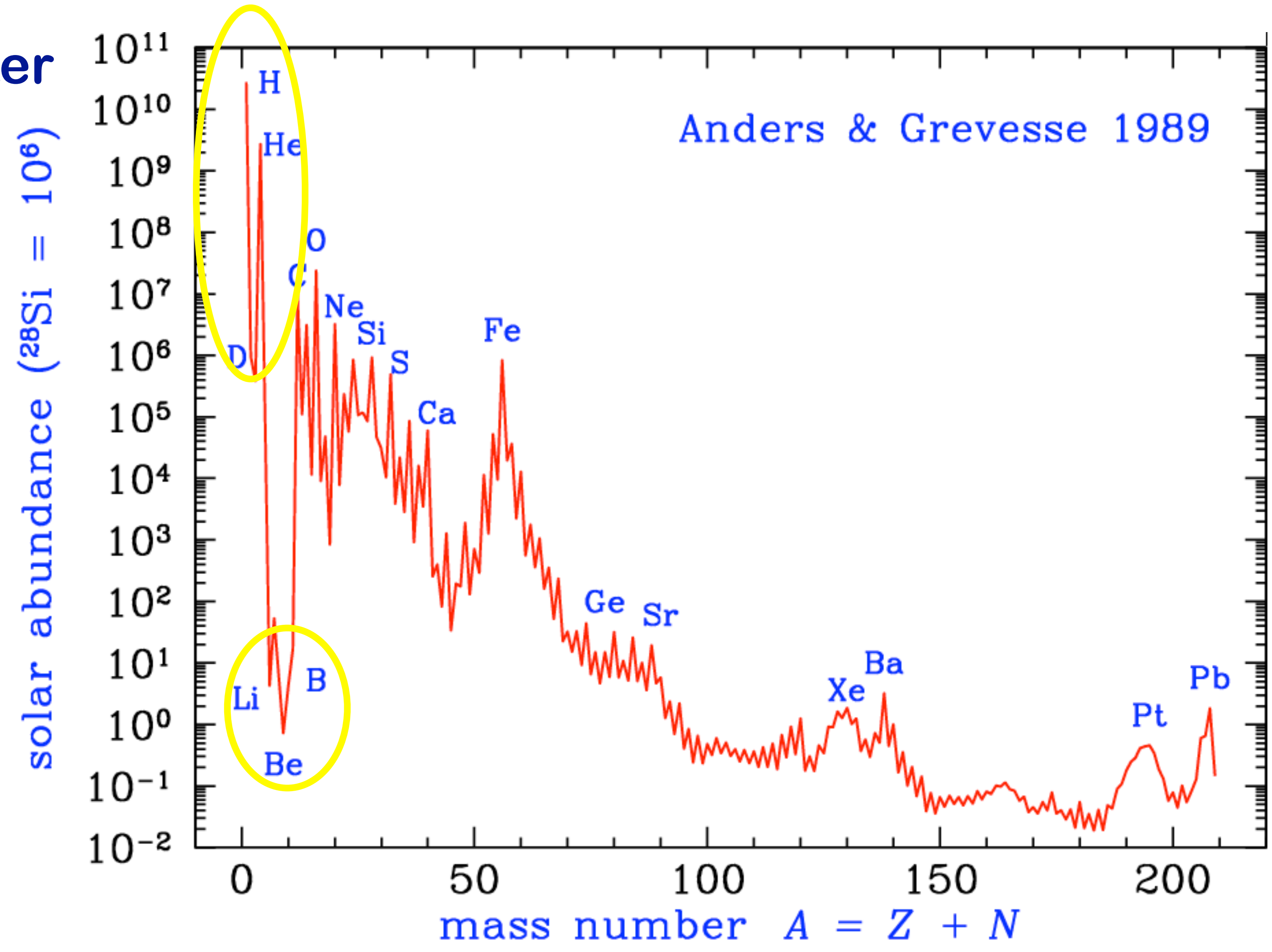

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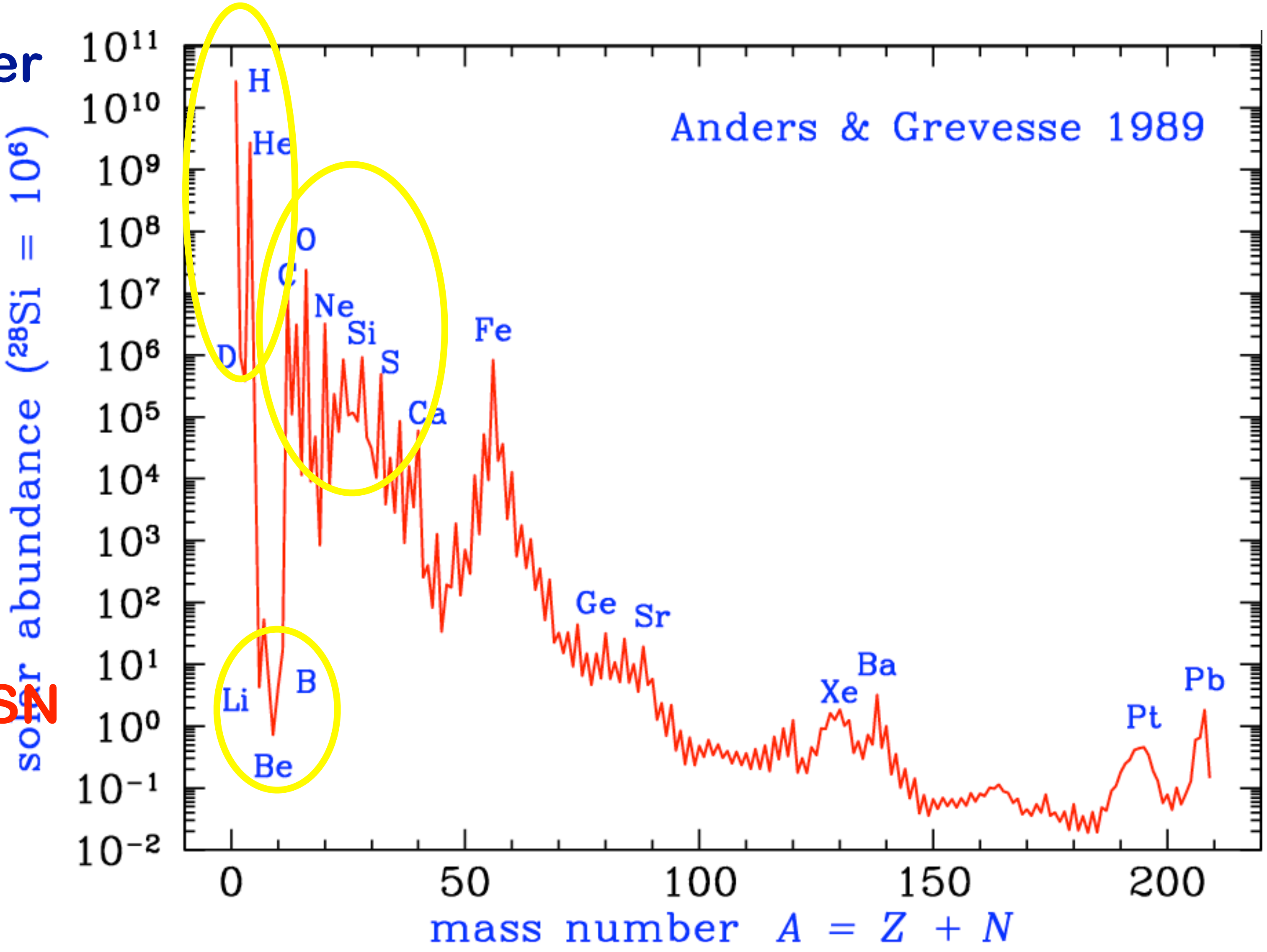

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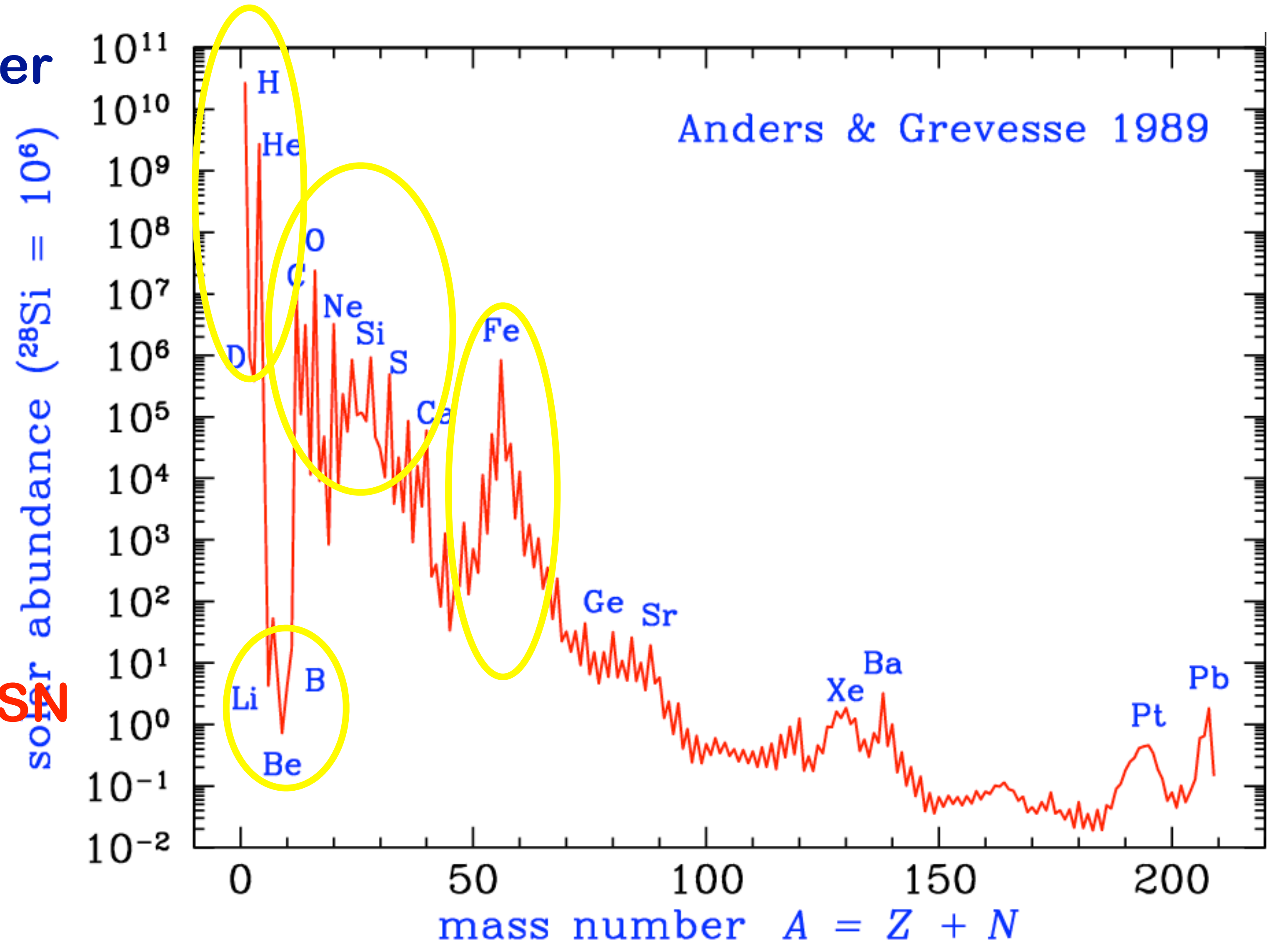

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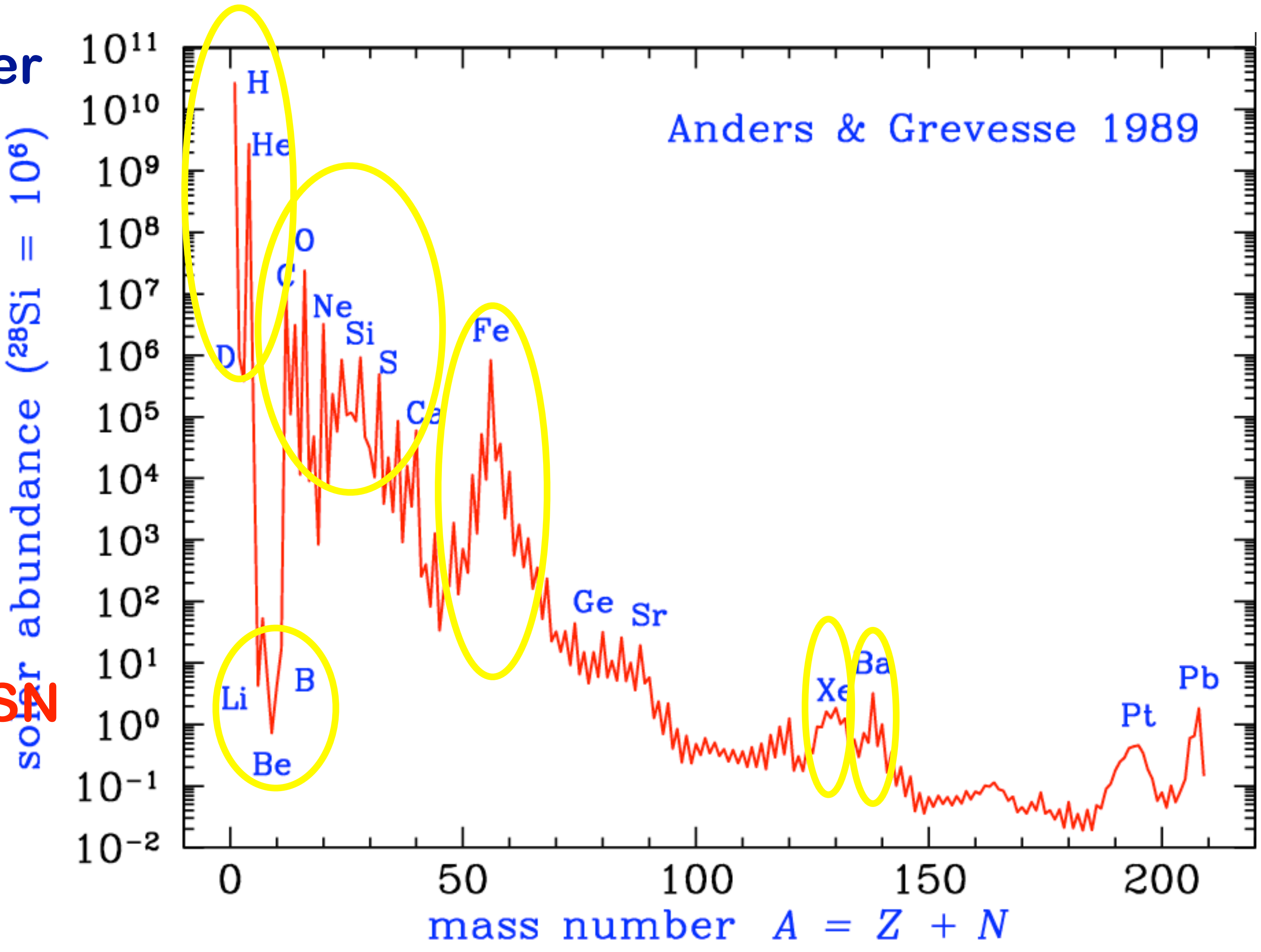

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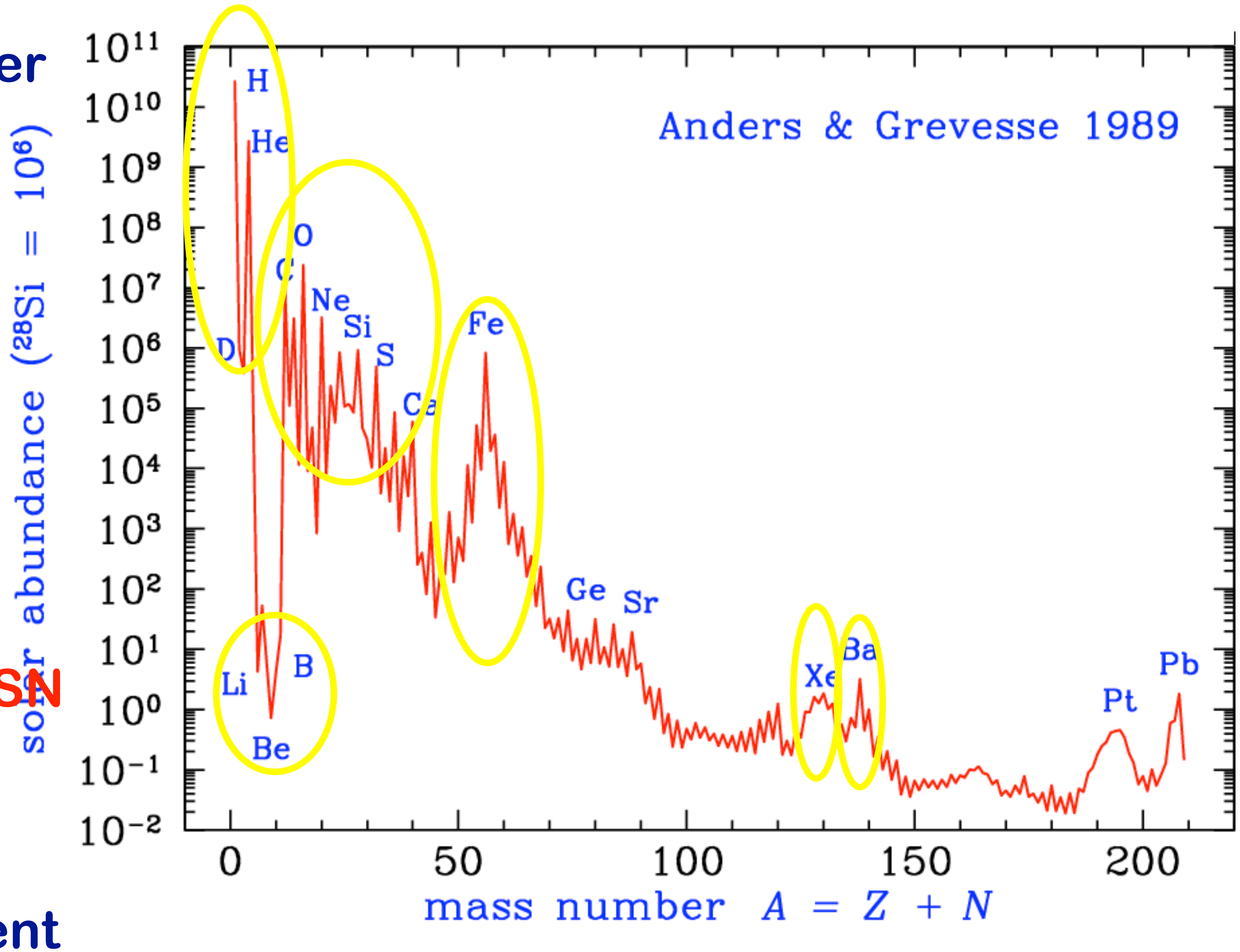
integrated yields and rates for different sources must give these



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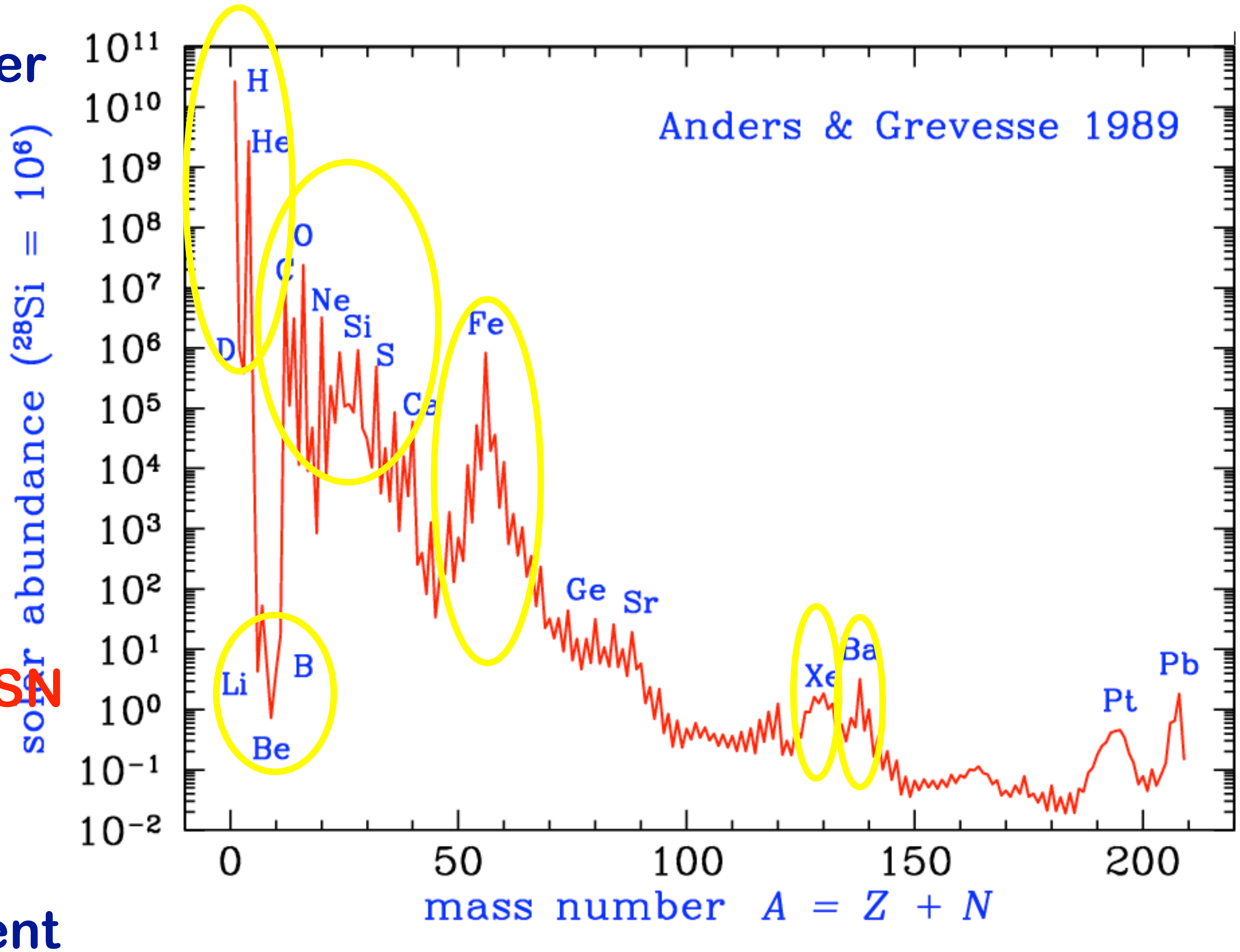

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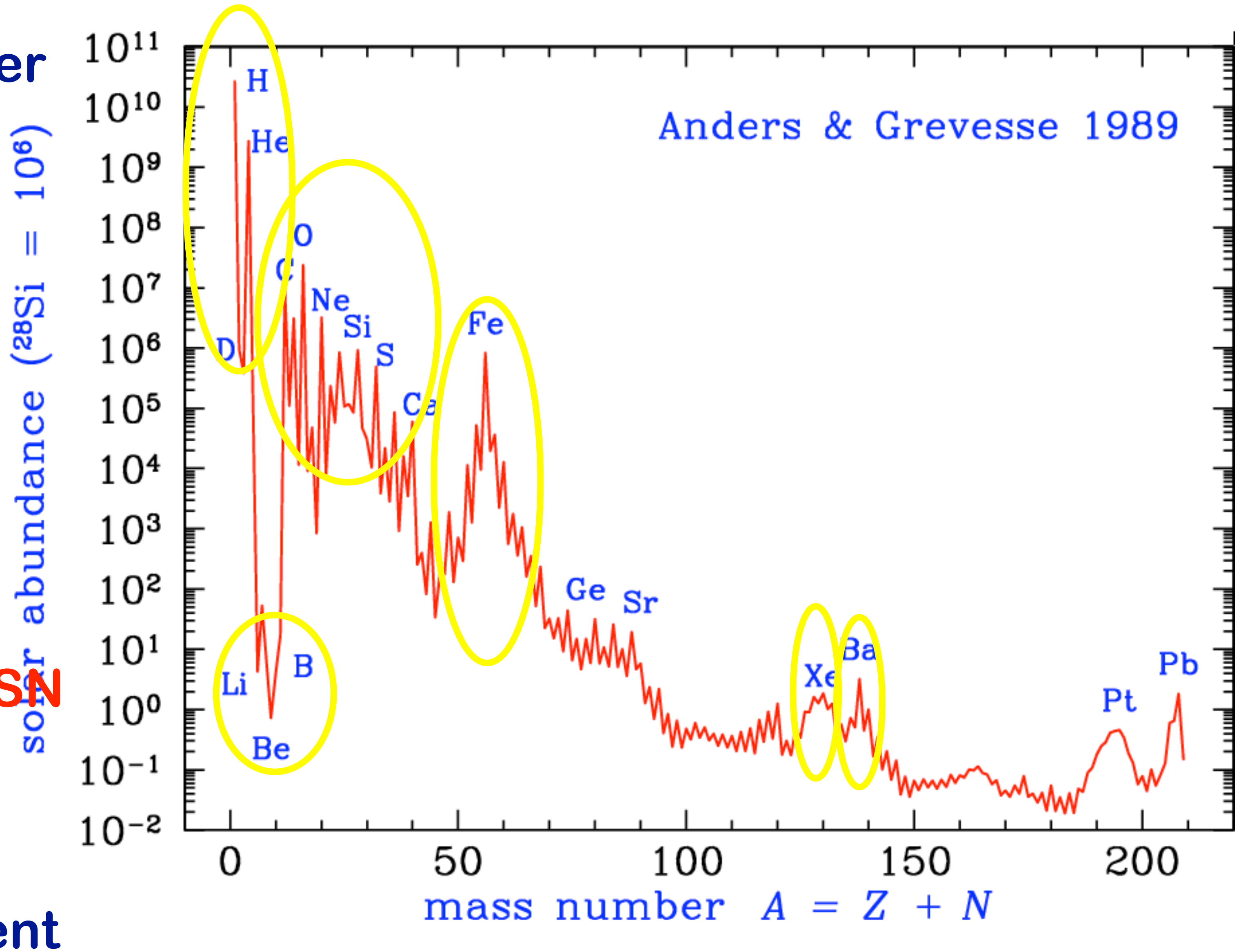

Q: where measured?

Measuring Solar System Abundances

Sun

- photosphere
- only elemental abundances (sum over isotopes) Q: why?

Meteors

- most primitive: carbonaceous chondrites
- much more precise abundances, and get isotope info
- but only measure “refractory” elts (condense readily)
- can’t measure “volatile” (gaseous/hard to condense) e.g., H, He, C, N, O, Ne, Ar

Q: so how can we put both on same scale?

Q: what is physical significance of SS abs?

Solar Abundances: Physical Significance

Strictly:

- SS abundances ⇒ matter at Sun birth
- record of all nuclear processing and mixing of that material

Broadly:

- Sun ~ typical Pop I (Milky Way disk) star
- expect similar patterns in nearby disk stars

Practically:

- serve as benchmark, fiducial standard
- (much as Sun is a standard, e.g., L⊙ and M⊙)

Quantifying Abundances

see Arnett, Ch. 1

composition quantified via

- abundance ≡ ratio of species i to some standard

usually “species” = element or isotope

in choosing how to quantify: want abundance changes to

- reflect nuclear/high-energy transformations,
- but to be invariant under compression   Q: why?

Densities

consider a sample of (bayronic) matter

- (total) mass density: ρ
- mass density of species i: ρ_i
- number density of species i: n_i

note: $\sum_i \rho_i = \rho$

$\rho_i = m_i n_i$, $m_i =$ mass of one nucleus/atom

these quantify sample composition

but: not good as abundance measures

Q: why?

Q: what would be better?

compression invariance ⇒ take *ratio*

of density to density of conserved quantity:

- mass density (if non-relativistic)
- baryon number density n_B

again: "baryon" = proton or neutron

a nucleus with N neutrons, Z protons

has **baryon number** $A = N + Z$

and baryon number density $n_{B,i} = A_i n_i$

Useful (theoretical) abundance measures of species

mass fraction: $\boxed{X_i = \rho_i / \rho}$

mole fraction: $\boxed{Y_i = n_i / n_B}$

note: traditional astronomers mass fraction shorthand:

$X_{\rm H} = X$

$X_{\rm He} = Y$

$X_{\rm other} = Z$ *"metallicity"*

e.g., famous "metals" like C, N, O, ...

normalization: $X + Y + Z = 1$

observe/infer: solar system value

$X_\odot \simeq 0.70$, $Y_\odot \simeq 0.28$, $Z_\odot \simeq 0.02$

but for astrophysical sources,

can't directly measure n_i or ρ_i

Q: what do we measure?

direct astrophysical composition observables: **spectra**
from emission/absorption lines, measure column densities
$N_i \simeq \int_{\mathrm{mfp}} n_i \, d\ell$

observers report ratios $N_i/N_j \simeq n_i/n_j$
Q: what assumed in $\simeq$ *?*

usually normalize to H (most abundant)
$\mathcal{A}_i/\mathrm{H} \equiv N_i/N_{\mathrm{H}} \simeq n_i/n_{\mathrm{H}}$
e.g., solar system mean $(\mathrm{Fe/H})_\odot = 3.2 \times 10^{-5}$

For SS isotopes: arbitrarily normalize to Si (10^6)

DISCUSSION

THIS IS YOUR SCHOOL!

Survey: background

- nuclear theory
- nuclear experiment
- astronomy observation
- astrophysics theory
- other

What do you want to learn?

- concepts
- tools
- connections