OBSERVATIONS OF CEMP-*i* STARS

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University of Michigan

and

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CEMP-*s*

CEMP-*r*

CEMP-*i*

CEMP-no

CEMP-*rs*

CEMP-*r*+*s*

CEMP-*r*/*s* (= *s*/*r*)

CEMP-*s*

CEMP-*r*

CEMP-*i*

CEMP-no

CEMP-*rs*

CEMP-*r+s*

CEMP-*r*/*s* (= *s*/*r*)

CEMP-*s*

CEMP-*r*

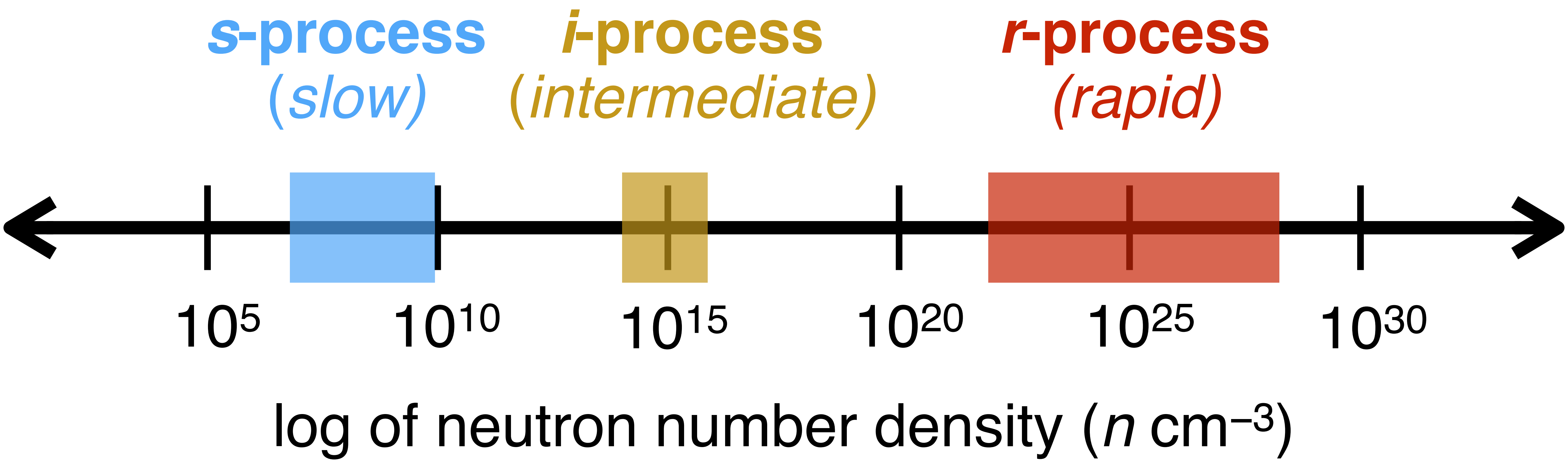
CEMP-*i*

CEMP-no

CEMP-*rs*

CEMP-*r*+*s*

CEMP-*r*/*s* (= *s*/*r*)


s-process
(slow)
i-process
(intermediate)
r-process
(rapid)
10^5
10^10
10^15
10^20
10^25
10^30
log of neutron number density (n cm^-3)

THE ASTROPHYSICAL JOURNAL, **212**:149–158, 1977 February 15

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

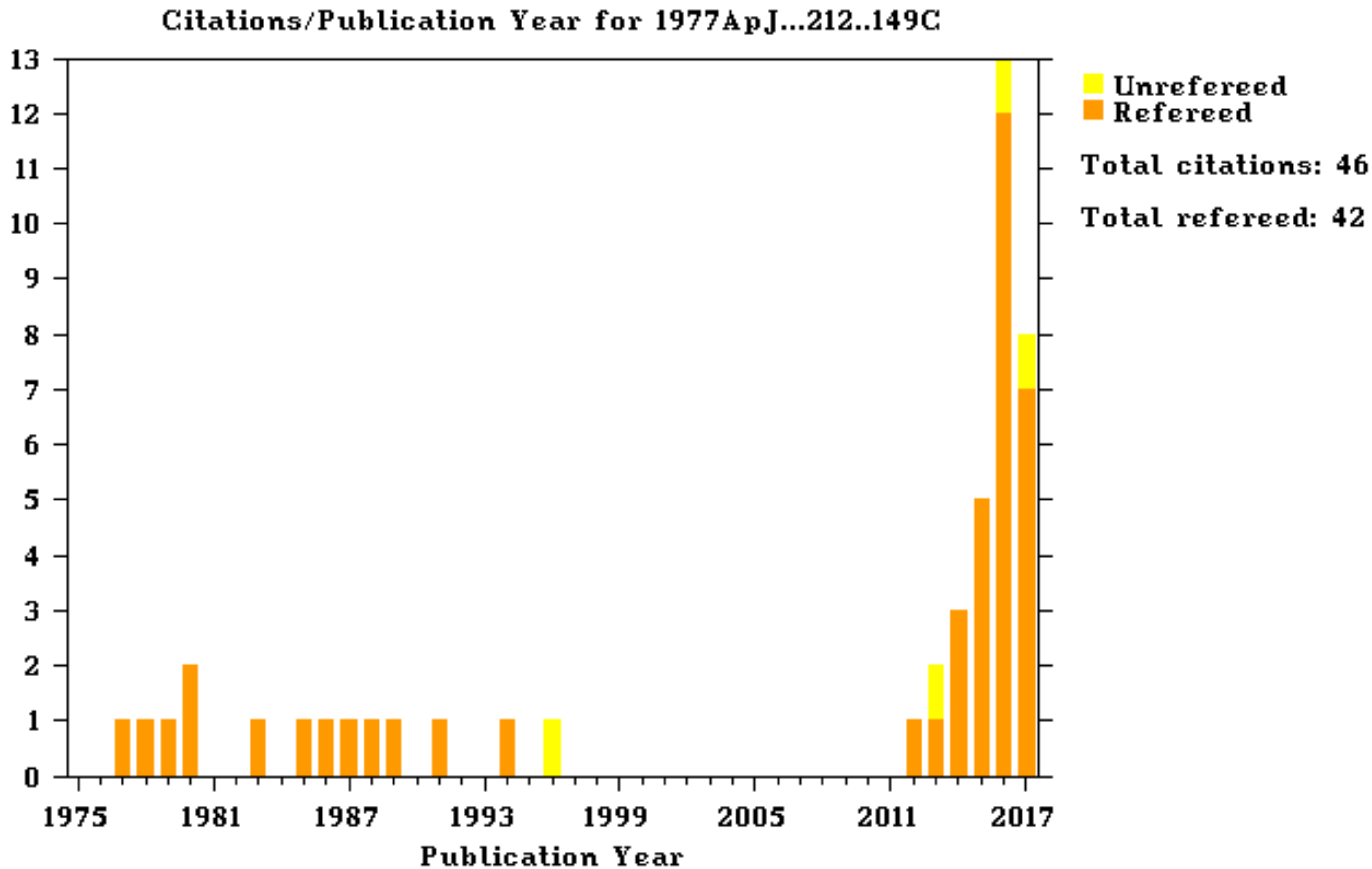
JOHN J. COWAN AND WILLIAM K. ROSE
Astronomy Program, University of Maryland, College Park
Received 1976 June 28

ABSTRACT

We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the $^{14}N(n, p)^{14}C$ reaction. If substantial portions of this intershell region are mixed out into the envelopes of red giants, then ^{14}C may be detectable in evolved stars.

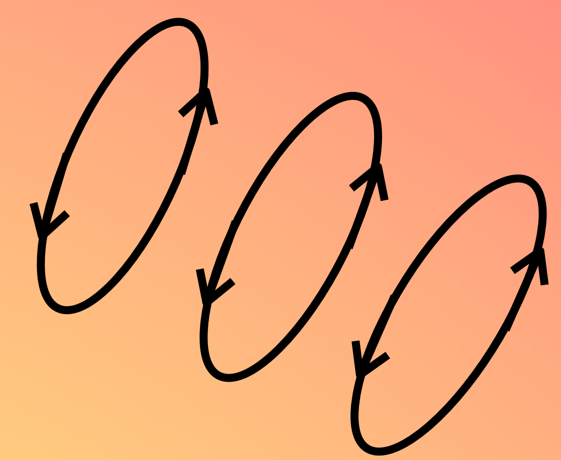
We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) may operate in evolved red giants. The neutrons are principally produced by the $^{13}C(\alpha, n)^{16}O$ reaction.

In all cases studied we find substantial enhancements of ^{17}O. These mixing models offer a plausible explanation of the observations of enhanced ^{17}O in the carbon star IRC 10216. For certain physical conditions we find significant enhancements of ^{15}N in the intershell region.

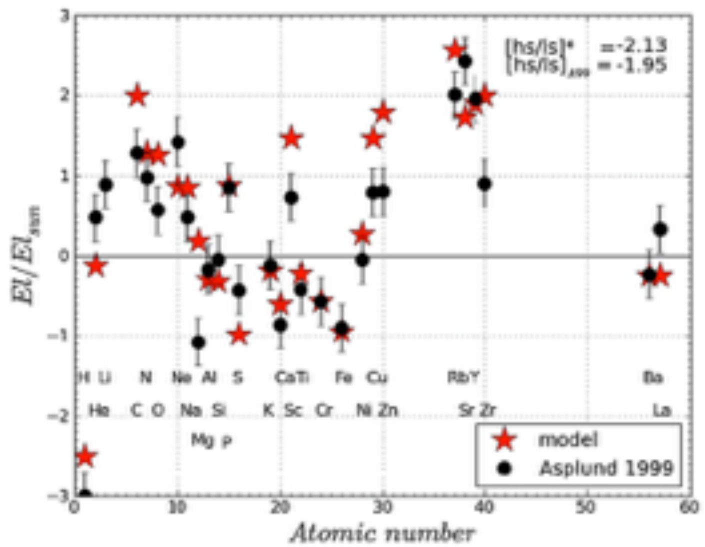

Citations/Publication Year for 1977ApJ...212..149C
Unrefereed
Refereed
Total citations: 46
Total refereed: 42
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1975
1981
1987
1993
1999
2005
2011
2017
Publication Year

$\tau_\beta = 9.6$ min

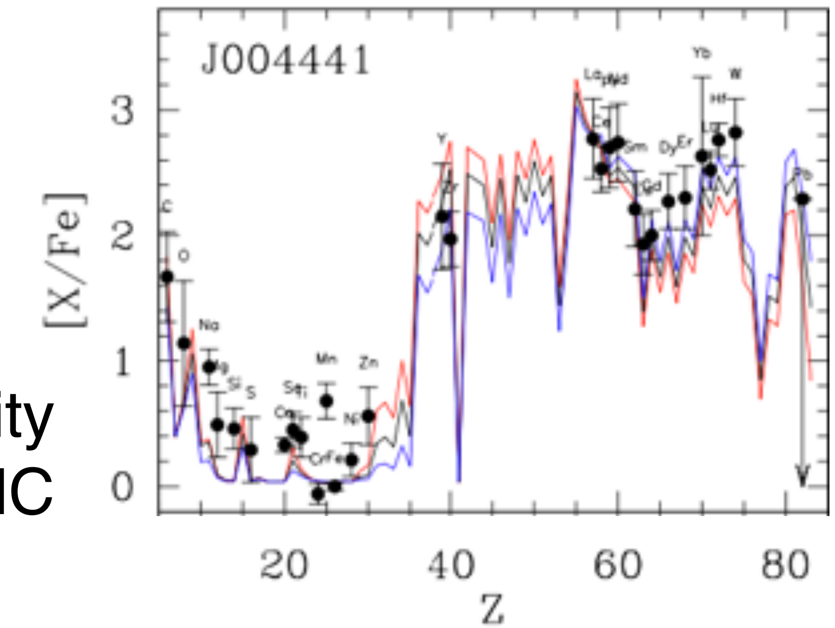
$^{12}C\,(p,\gamma)\,^{13}N\,(\beta^{+}\nu)\,^{13}C\,(\alpha,n)\,^{16}O$



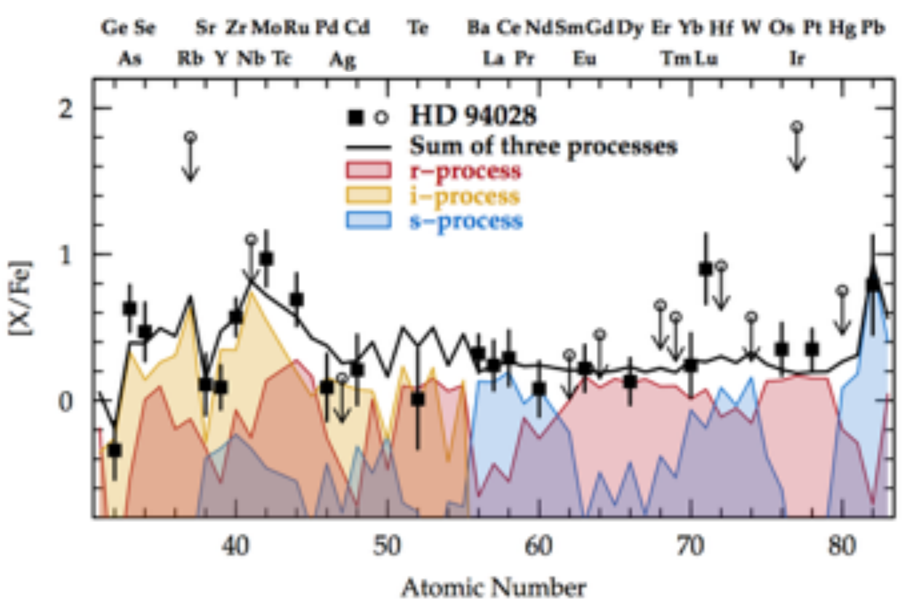
$\tau_{convection} \approx 10\text{-}20$ min



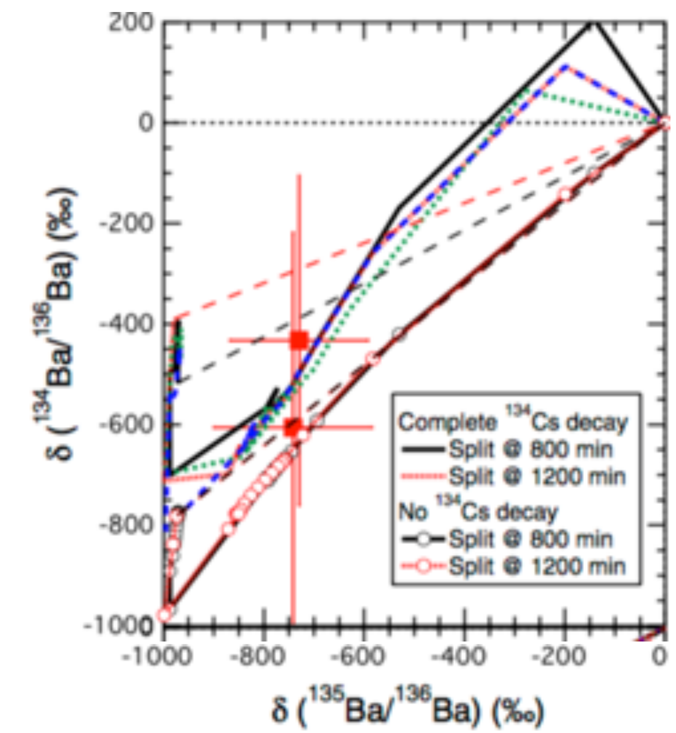
V4334 Sgr ("Sakurai's Object"), a post-AGB star



a low-mass, low-metallicity post-AGB star in the SMC



a low-metallicity main sequence star



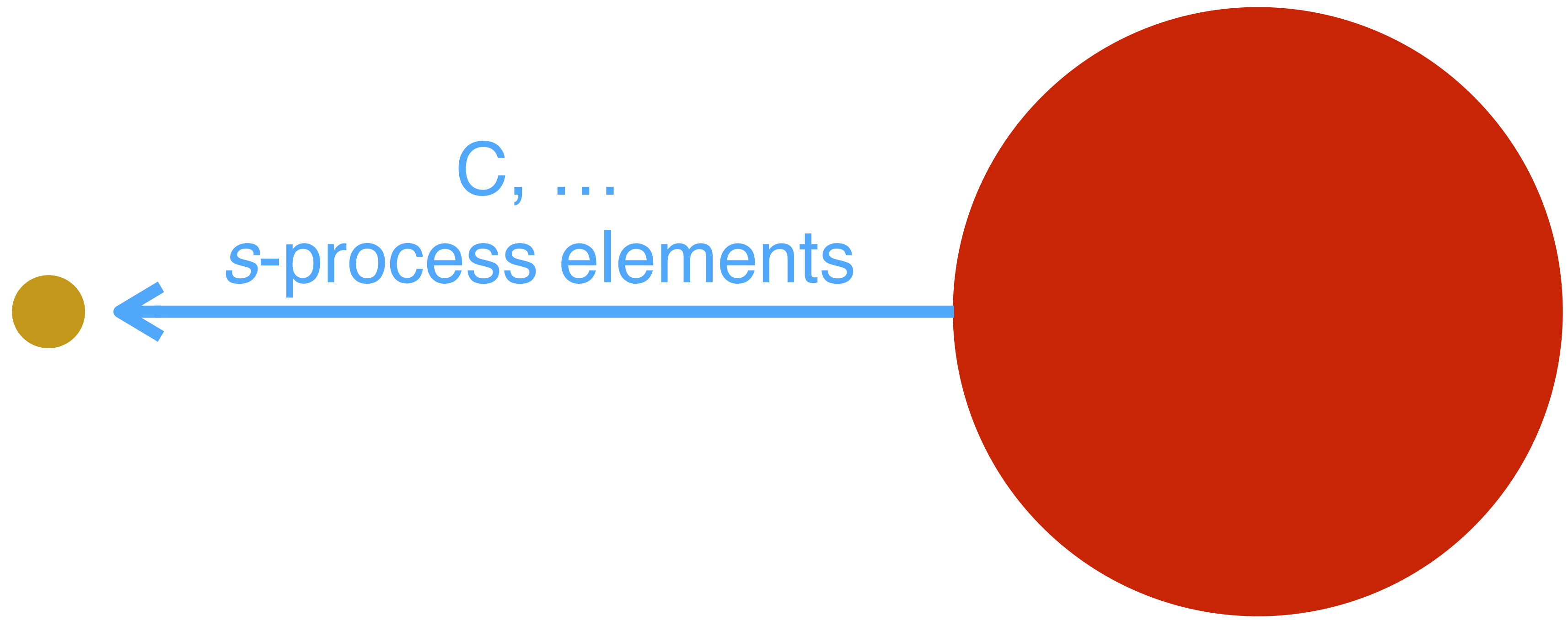
sub-solar ^{134}Ba/^{136}B ratios in pre-solar SiC grains

Herwig et al., Astrophys. J., 727, 89 (2011)
Roederer et al., Astrophys. J., 821, 37 (2016)
Lugaro et al., Astron. Astrophys., 583, A77 (2015)
Liu et al., Astrophys. J., 786, 66 (2014)

But these are not really today's subject,

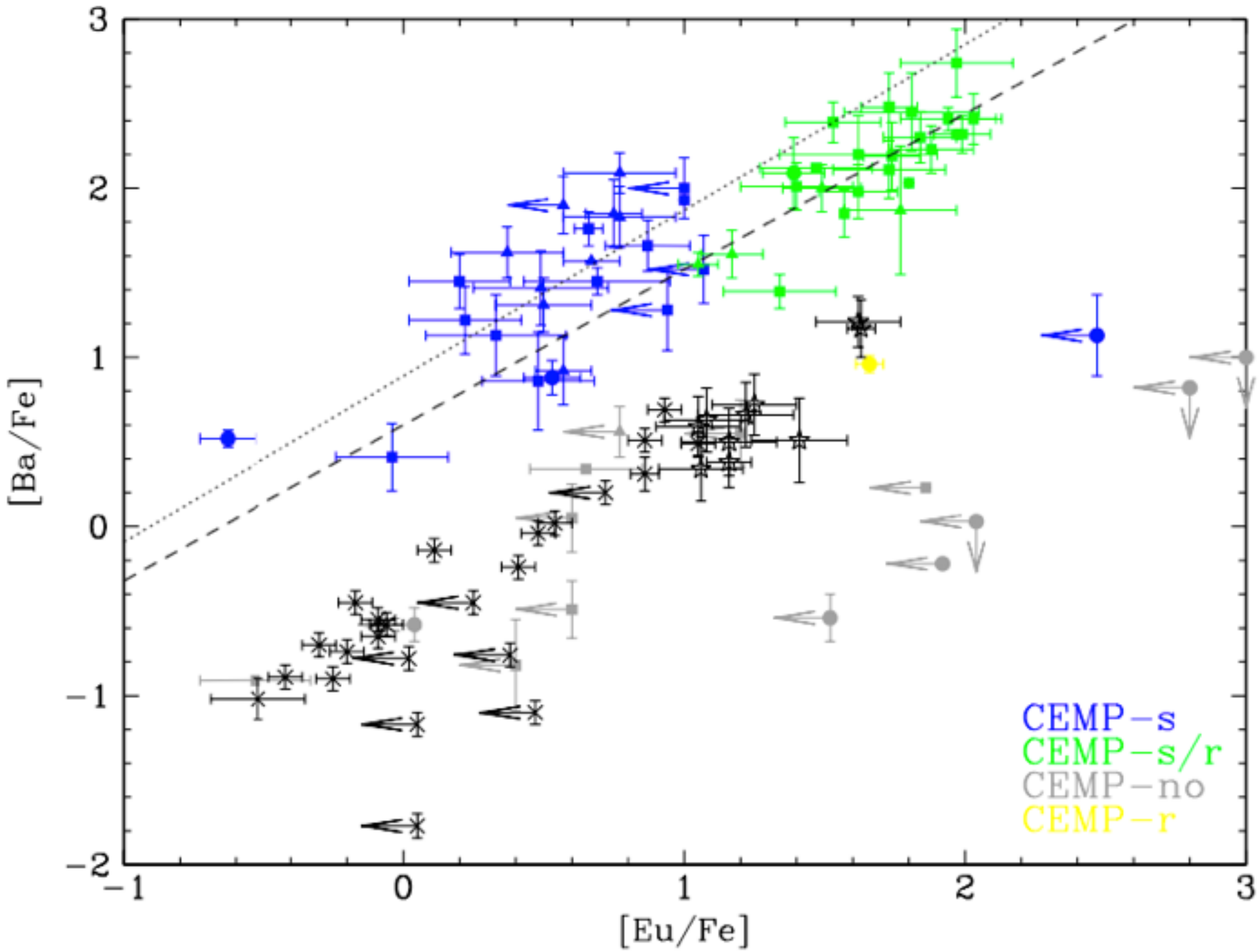
CEMP-*i* stars.

The accepted formation scenario of **CEMP-*s*** stars:



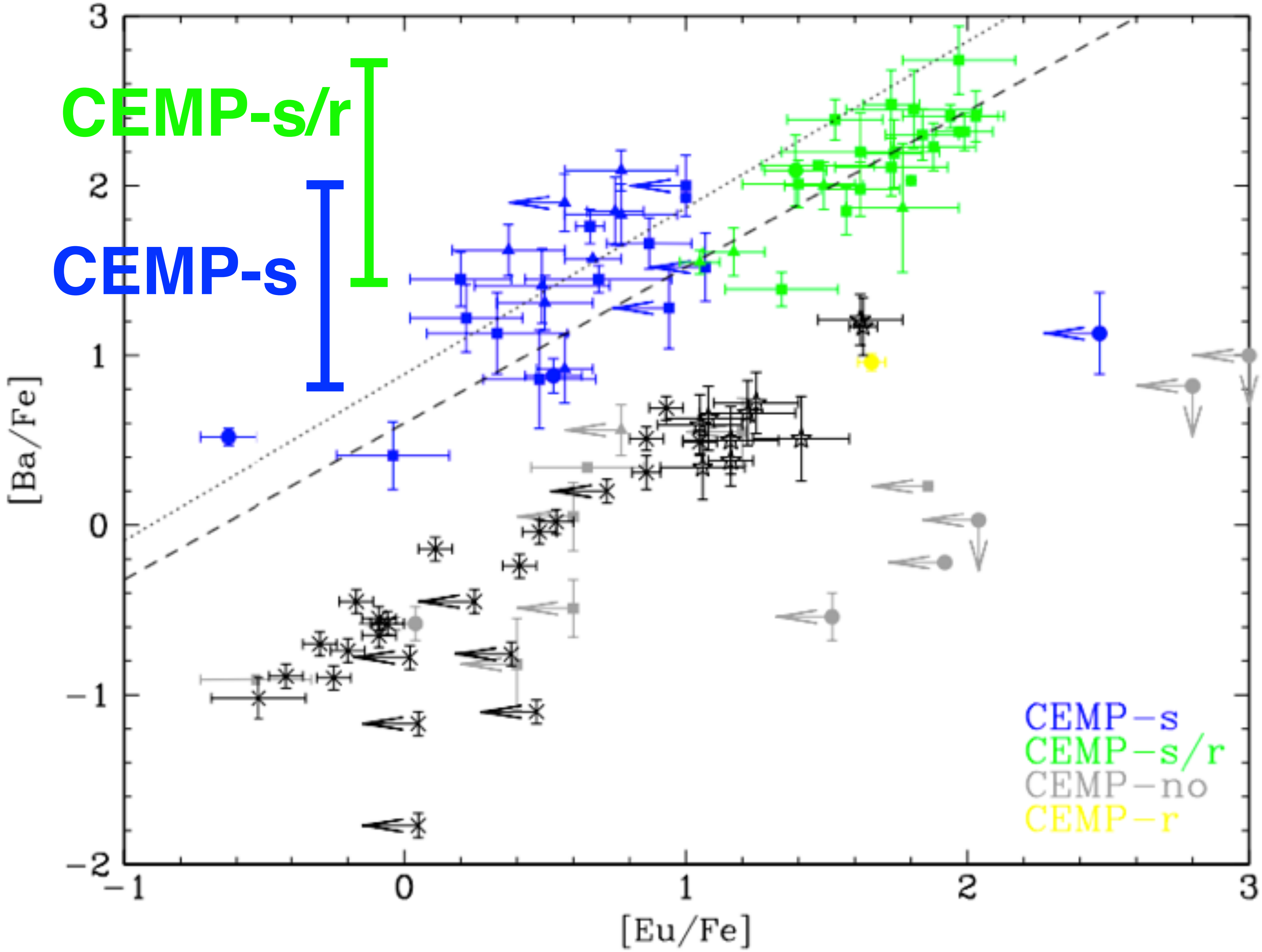
unevolved companion
(observed today as the CEMP-s star)

evolved AGB star
(not directly detected today)



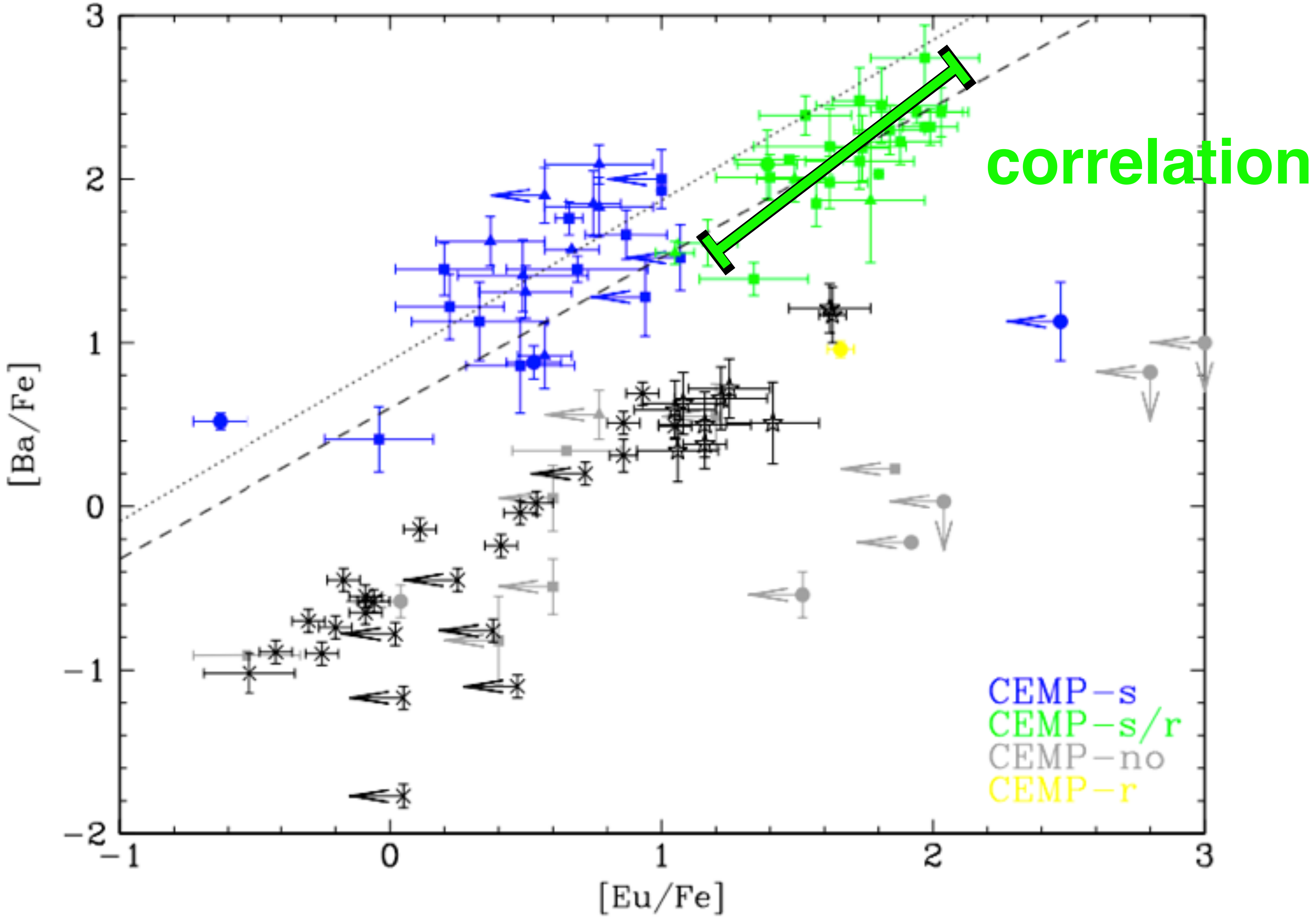
Lugaro et al., Astrophys. J., 747, 2 (2012)

(1) The [Ba/Fe] distributions of the CEMP-*s* and CEMP-*s*/*r* are different.



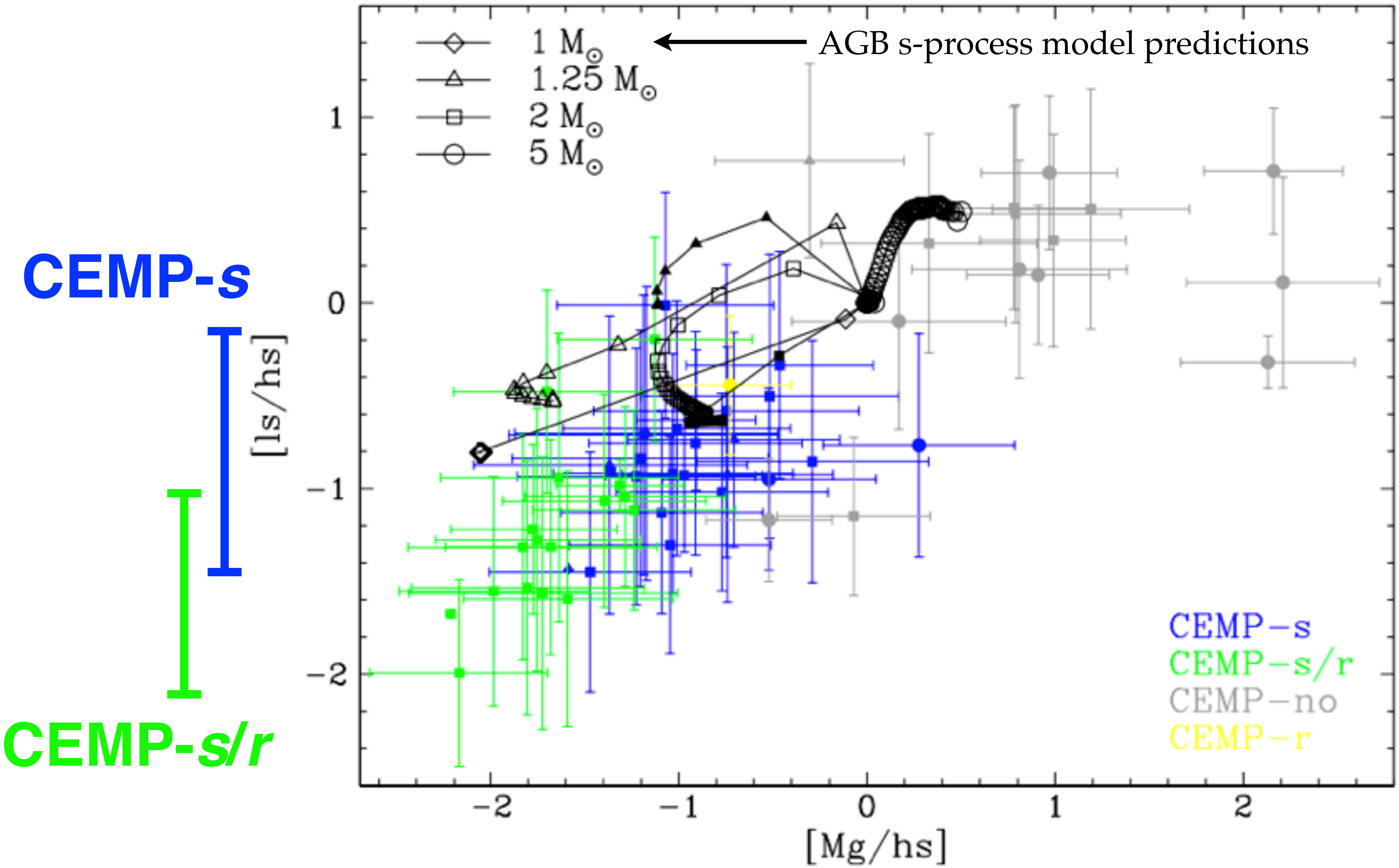
Lugaro et al., Astrophys. J., 747, 2 (2012)

(2) The [Ba/Fe] and [Eu/Fe] ratios are correlated in the CEMP-*s*/*r* stars.



Lugaro et al., Astrophys. J., 747, 2 (2012)

(3) The [ls/hs] distributions in the CEMP-*s* and CEMP-*s/r* stars are different.



Lugaro et al., Astrophys. J., 747, 2 (2012)

A&A 451, 651–670 (2006)
DOI: 10.1051/0004-6361:20054470

Astronomy & Astrophysics

The Hamburg/ESO R-process enhanced star survey (HERES)⋆,⋆⋆

III. HE 0338–3945 and the formation of the *r* + *s* stars

(here, r+s is equivalent to r/s)

K. Jonsell[1], P. S. Barklem[1], B. Gustafsson[1], N. Christlieb[2], V. Hill[3], T. C. Beers[4], and J. Holmberg[5]

ABSTRACT

We have derived abundances of 33 elements and upper limits for 6 additional elements for the metal-poor ([Fe/H] = −2.42) turn-off star HE 0338–3945 from high-quality VLT-UVES spectra. The star is heavily enriched, by about a factor of 100 relative to iron and the Sun, in the heavy *s*-elements (Ba, La, ...). It is also heavily enriched in Eu, which is generally considered an *r*-element, and in other similar elements. It is less enriched, by about a factor of 10, in the lighter *s*-elements (Sr, Y and Zr). C is also strongly enhanced and, to a somewhat lesser degree, N and O. These abundance estimates are subject to severe uncertainties due to NLTE and thermal inhomogeneities which are not taken into detailed consideration. However, an interesting result, which is most probably robust in spite of these uncertainties, emerges: the abundances derived for this star are very similar to those of other stars with an overall enhancement of all elements beyond the iron peak.
We have defined criteria for this class of stars, *r* + *s* stars, and discuss nine different scenarios to explain their origin. None of these explanations is found to be entirely convincing. The most plausible hypotheses involve a binary system in which the primary component goes through its giant branch and asymptotic giant branch phases and produces CNO and *s*-elements which are dumped onto the observed star. Whether the *r*-element Eu is produced by supernovae before the star was formed (perhaps triggering the formation of a low-mass binary), by a companion as it explodes as a supernova (possibly triggered by mass transfer), or whether it is possibly produced in a high-neutron-density version of the *s*-process is still unclear. Several suggestions are made on how to clarify this situation.

The Astrophysical Journal, 831:171 (14pp), 2016 November 10

THE INTERMEDIATE NEUTRON-CAPTURE PROCESS AND CARBON-ENHANCED METAL-POOR STARS

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[2] Argelander-Institut für Astronomie, University of Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
[3] Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1121 Budapest, Hungary
[4] Monash Centre for Astrophysics, Monash University, VIC3800, Australia
[5] Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA
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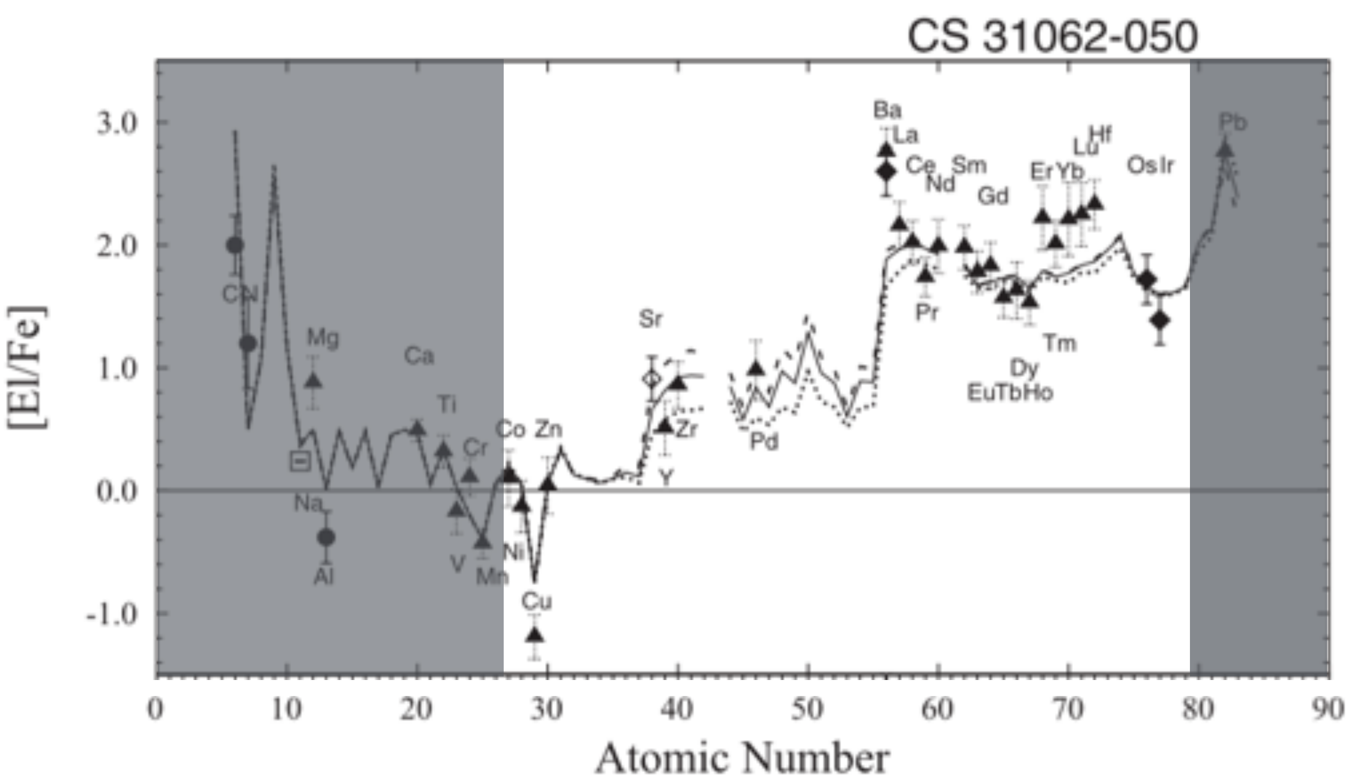
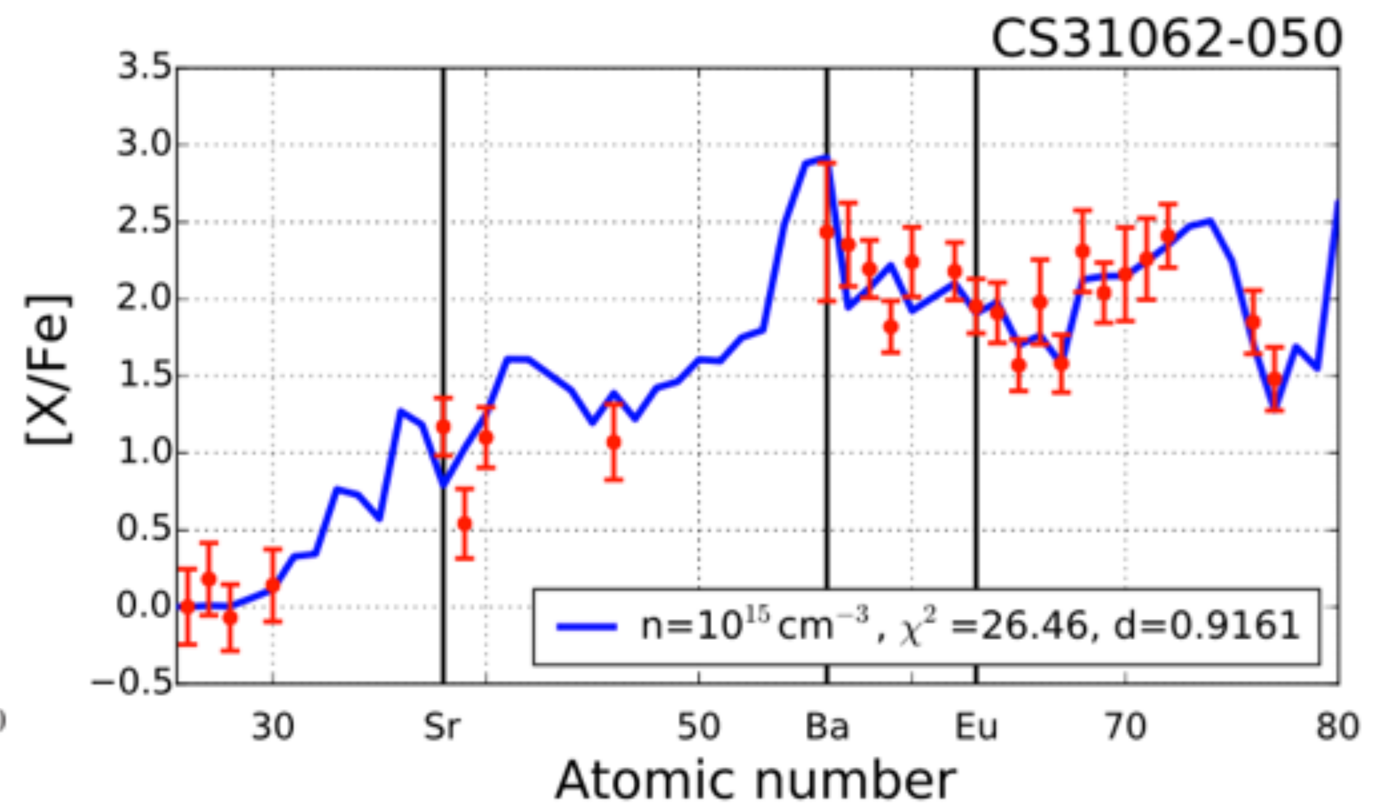
ABSTRACT

Carbon-enhanced metal-poor (CEMP) stars in the Galactic Halo display enrichments in heavy elements associated with either the *s* (slow) or the *r* (rapid) neutron-capture process (e.g., barium and europium, respectively), and in some cases they display evidence of both. The abundance patterns of these CEMP-*s*/*r* stars, which show both Ba and Eu enrichment, are particularly puzzling, since the *s* and the *r* processes require neutron densities that are more than ten orders of magnitude apart and, hence, are thought to occur in very different stellar sites with very different physical conditions. We investigate whether the abundance patterns of CEMP-*s*/*r* stars can arise from the nucleosynthesis of the intermediate neutron-capture process (the *i* process), which is characterized by neutron densities between those of the *s* and the *r* processes. Using nuclear network calculations, we study neutron capture nucleosynthesis at different constant neutron densities *n* ranging from 10^7–10^{15} cm^{-3}. With respect to the classical *s* process resulting from neutron densities on the lowest side of this range, neutron densities on the highest side result in abundance patterns, which show an increased production of heavy *s*-process and *r*-process elements, but similar abundances of the light *s*-process elements. Such high values of *n* may occur in the thermal pulses of asymptotic giant branch stars due to proton ingestion episodes. Comparison to the surface abundances of 20 CEMP-*s*/*r* stars shows that our modeled *i*-process abundances successfully reproduce observed abundance patterns, which could not be previously explained by *s*-process nucleosynthesis. Because the *i*-process models fit the abundances of CEMP-*s*/*r* stars so well, we propose that this class should be renamed as CEMP-*i*.

fit with AGB *s*-process model and initial *r*-process enhancement

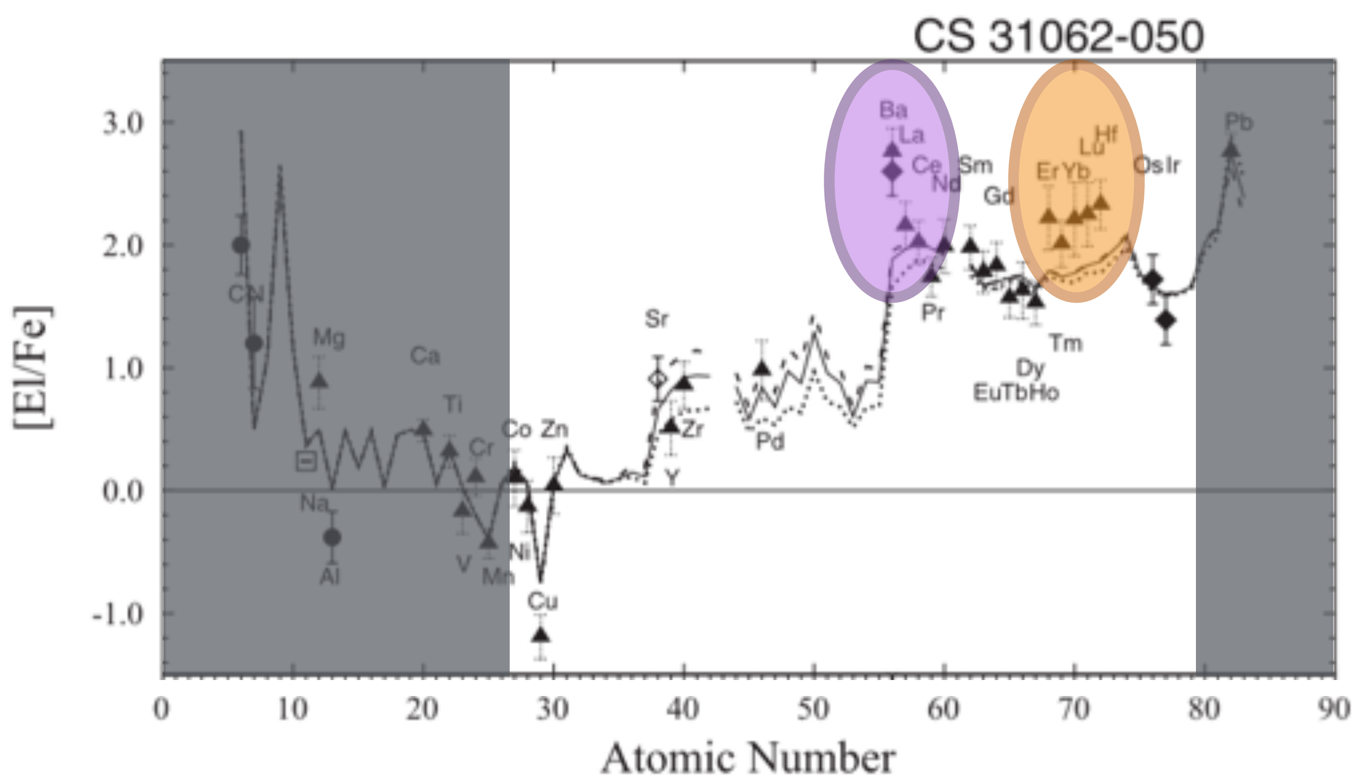


fit with one-zone *i*-process model

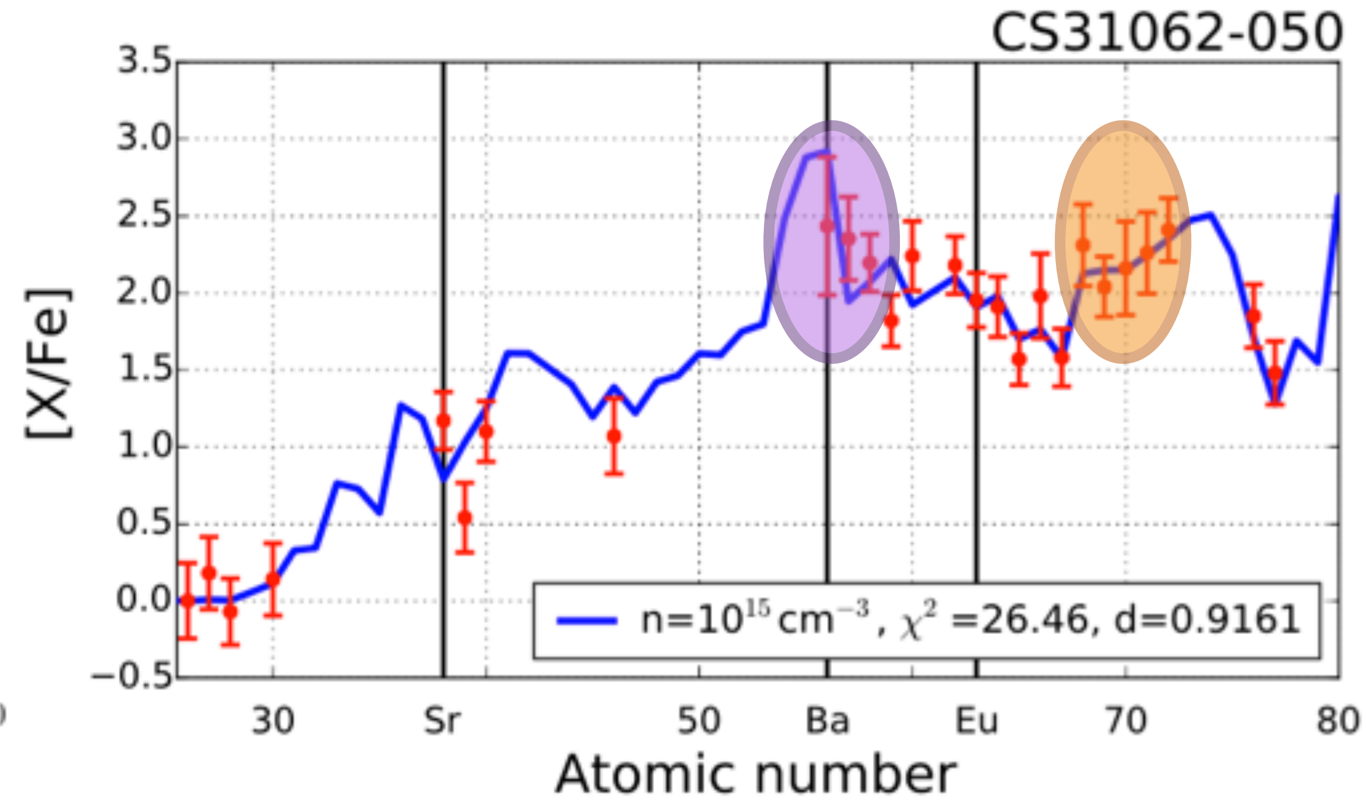


Bisterzo et al., Mon. Not. R. Astron. Soc., 422, 849 (2012)

Hampel et al., Astrophys. J., 831, 171 (2016) fit with AGB *s*-process model and initial *r*-process enhancement



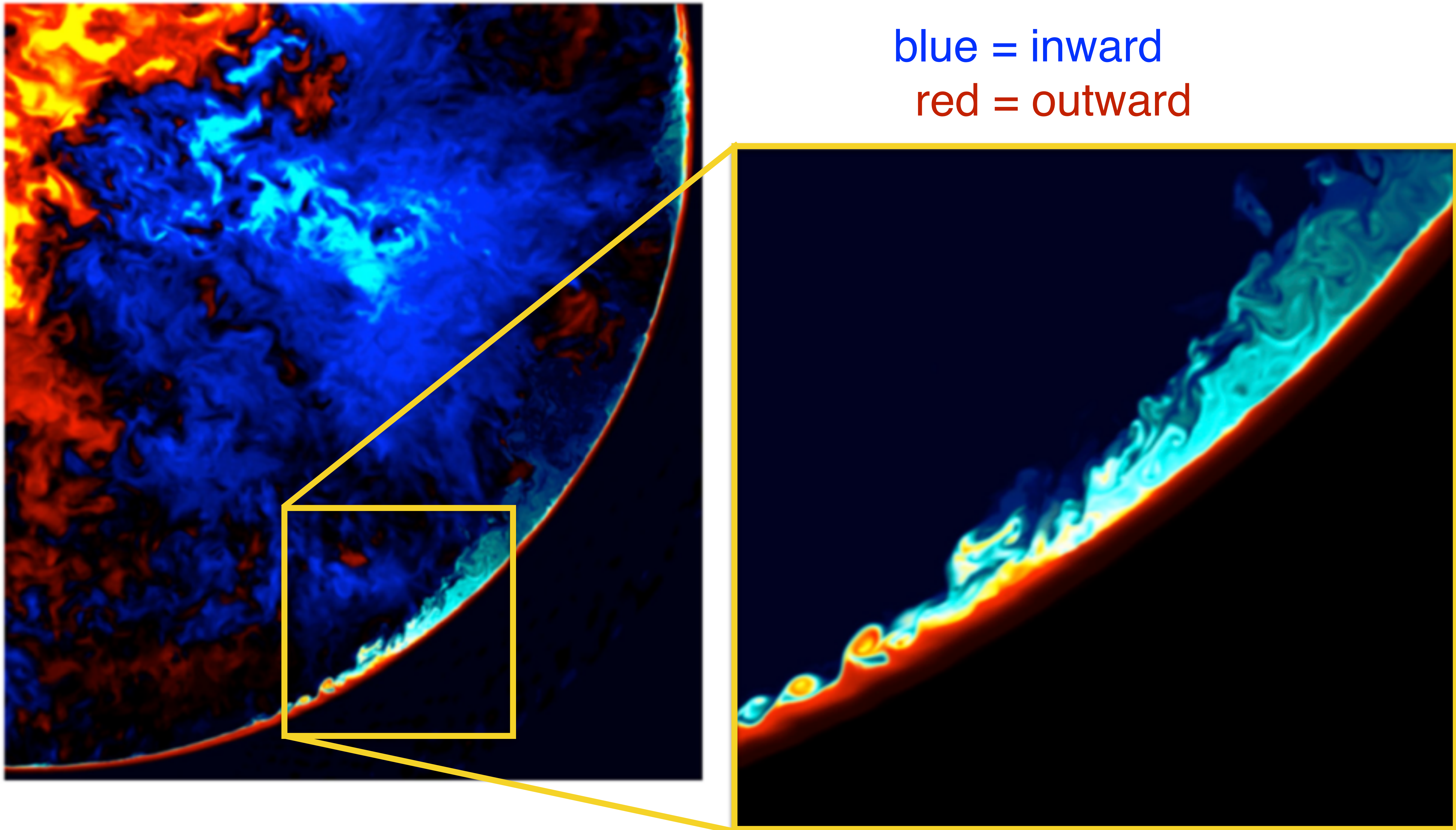
fit with one-zone *i*-process model



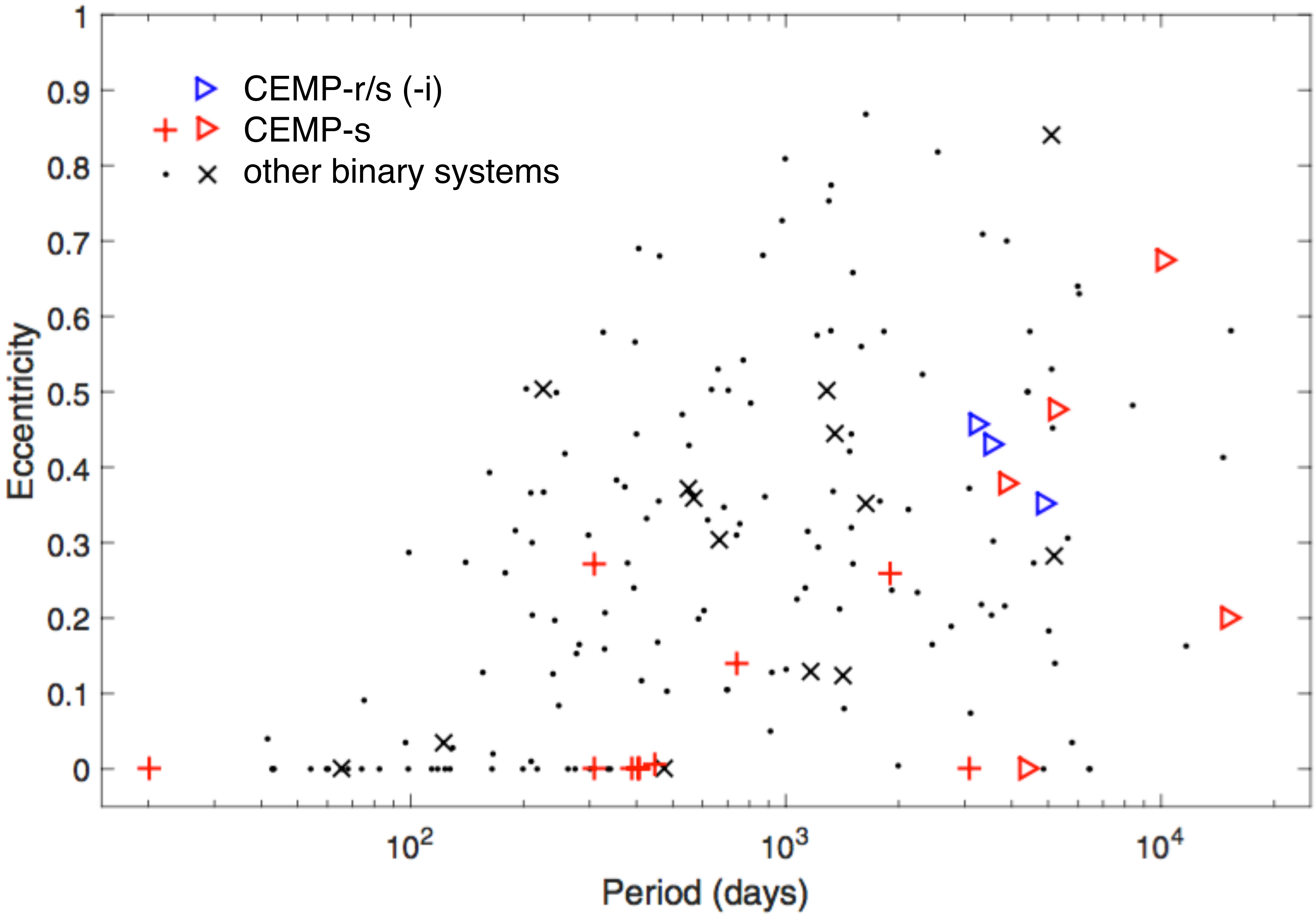
Bisterzo et al., Mon. Not. R. Astron. Soc., 422, 849 (2012)

Hampel et al., Astrophys. J., 831, 171 (2016)

blue = inward
red = outward

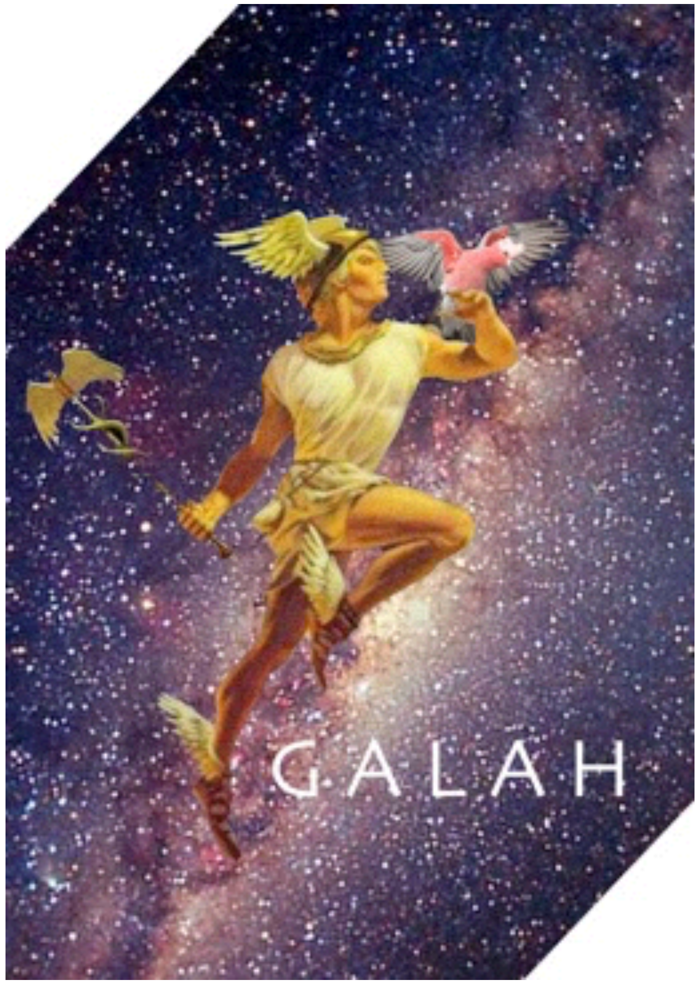


Woodward et al., Astrophys. J., 798, 49 (2015)



Hansen et al., Astron. Astrophys., 588, A3 (2016)

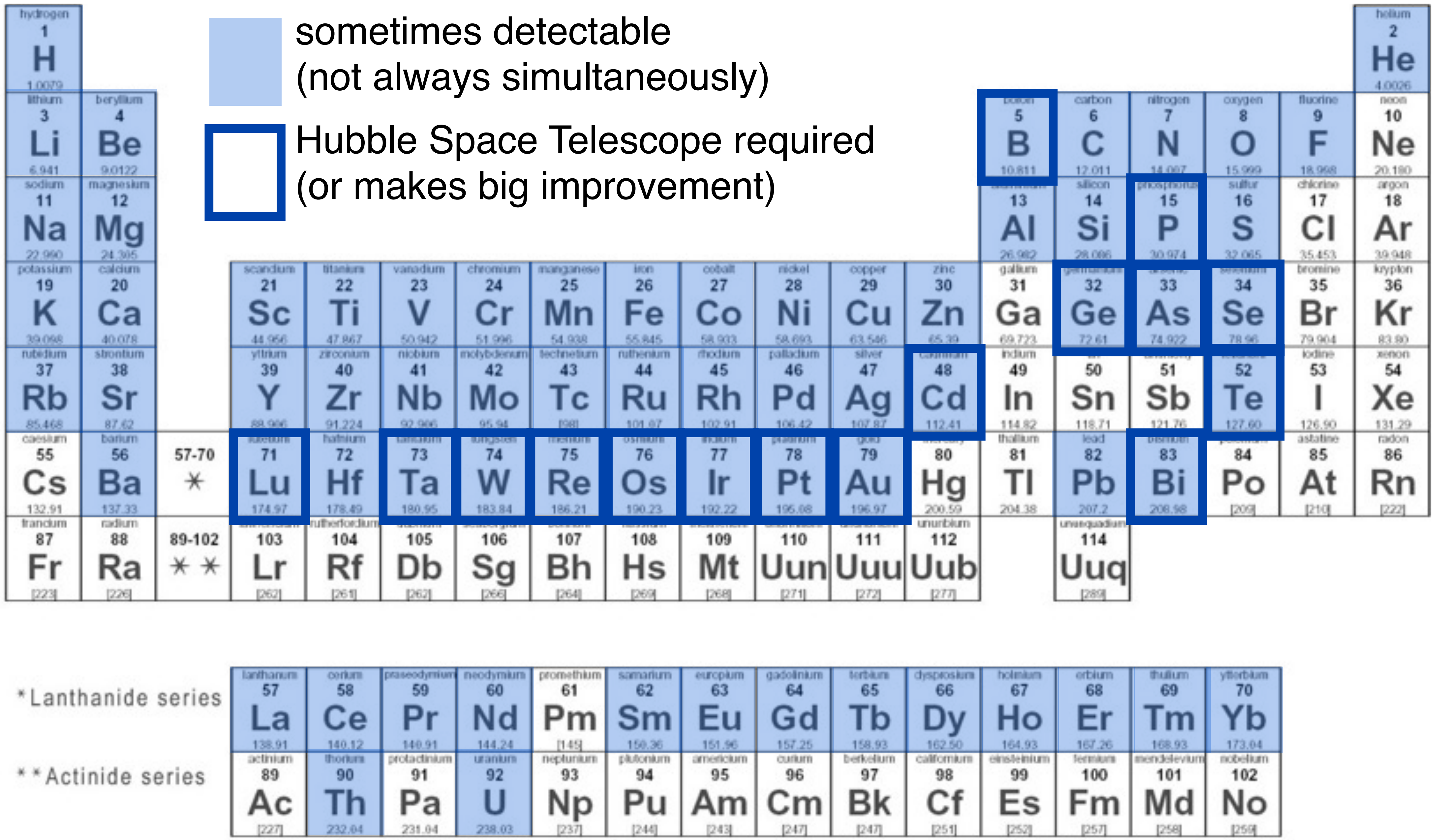
Surveys that may identify more CEMP-*i* stars:



Best and Brightest
(K. Schlaufman & A. Casey)

The CFHT "Pristine" Survey
(E. Caffau, E. Starkenburg, N. Martin, K. Venn, K. Youakim, et al.)

4MOST at ESO's VISTA Telescope



sometimes detectable
(not always simultaneously)
Hubble Space Telescope required
(or makes big improvement)
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba 57-70 Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra 89-102 Lr Rf Db Sg Bh Hs Mt Uun Uuu Uub Uuq
*Lanthanide series
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb
**Actinide series
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No

A minimal set of abundance discriminants to identify CEMP-*i* stars:

[C/Fe] > +1.0
(or > +0.7?
or luminosity
criteria?)

0.0 < [Ba/Eu] < +0.5

criteria: basically like CEMP-r/s from Beers & Christlieb, Ann. Rev. Astron. Astrophys., 43, 531 (2005)

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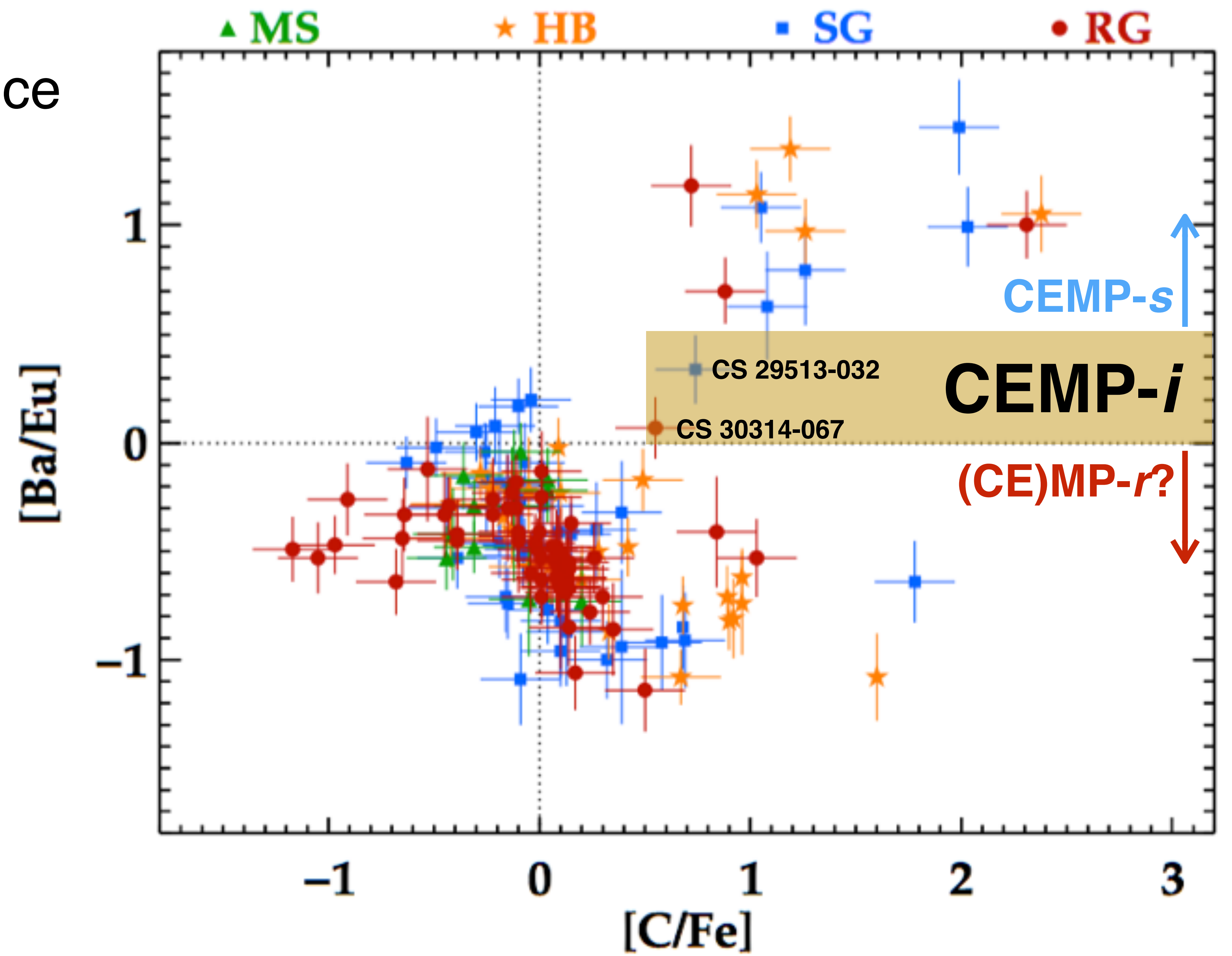
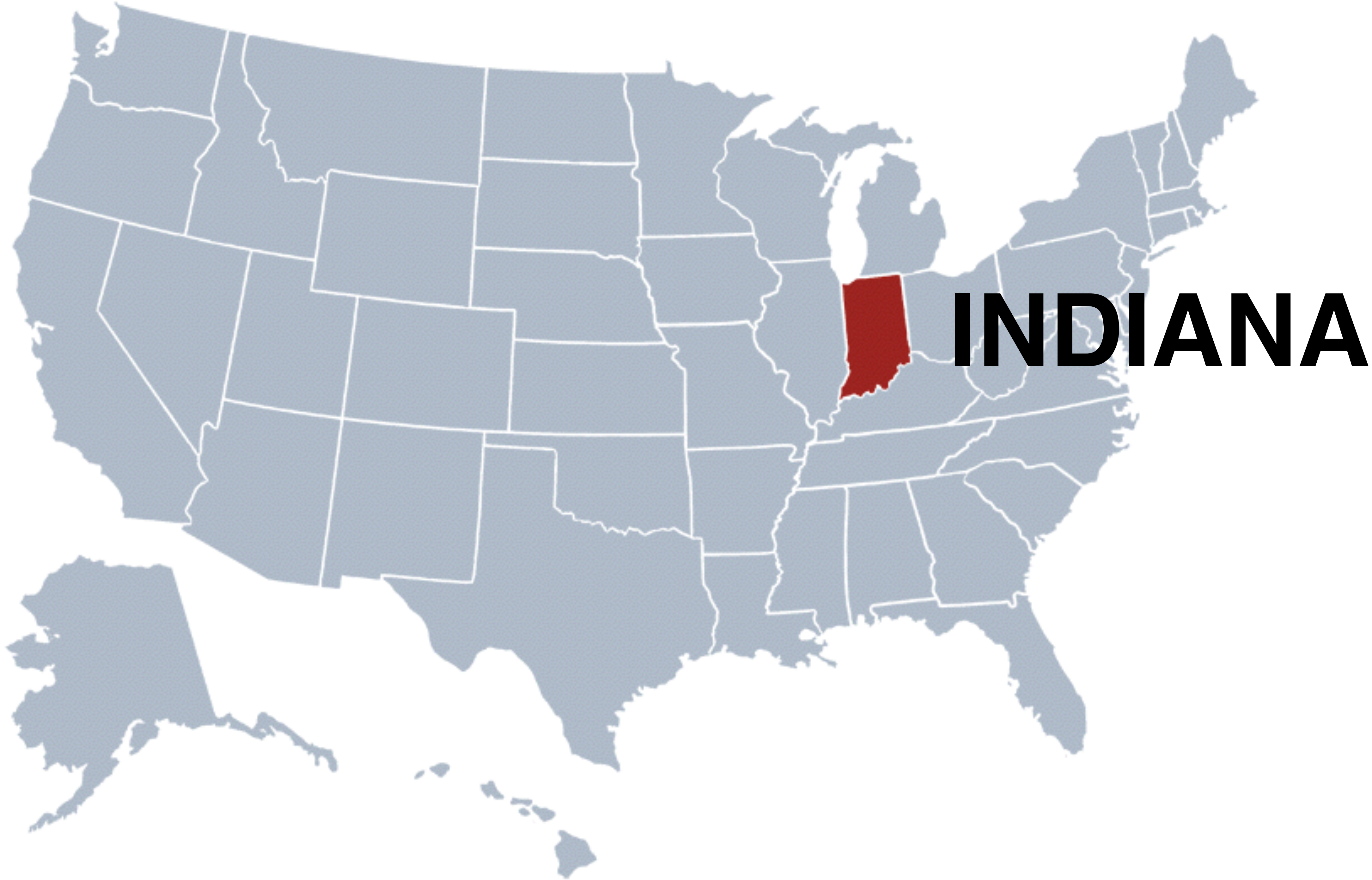
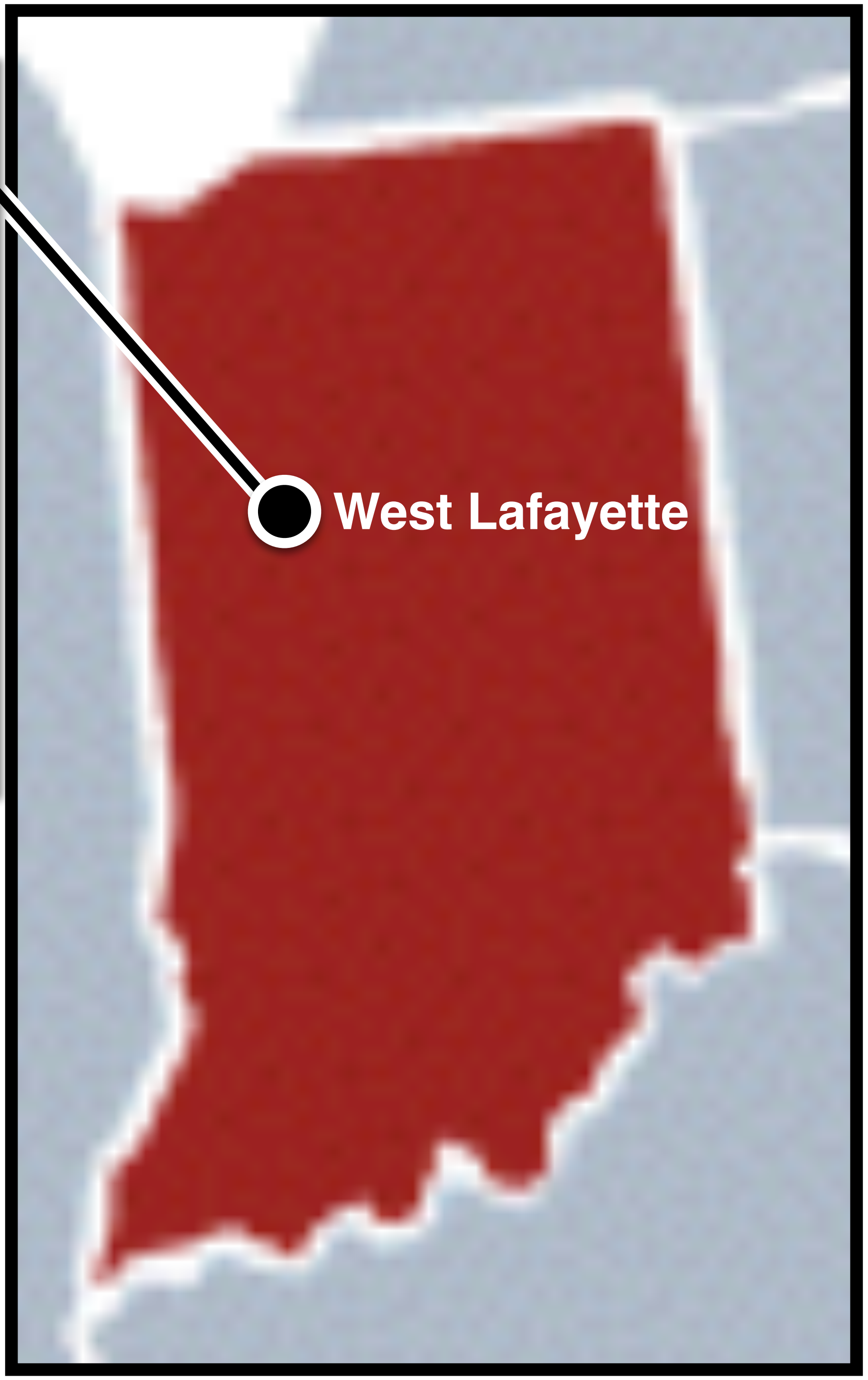


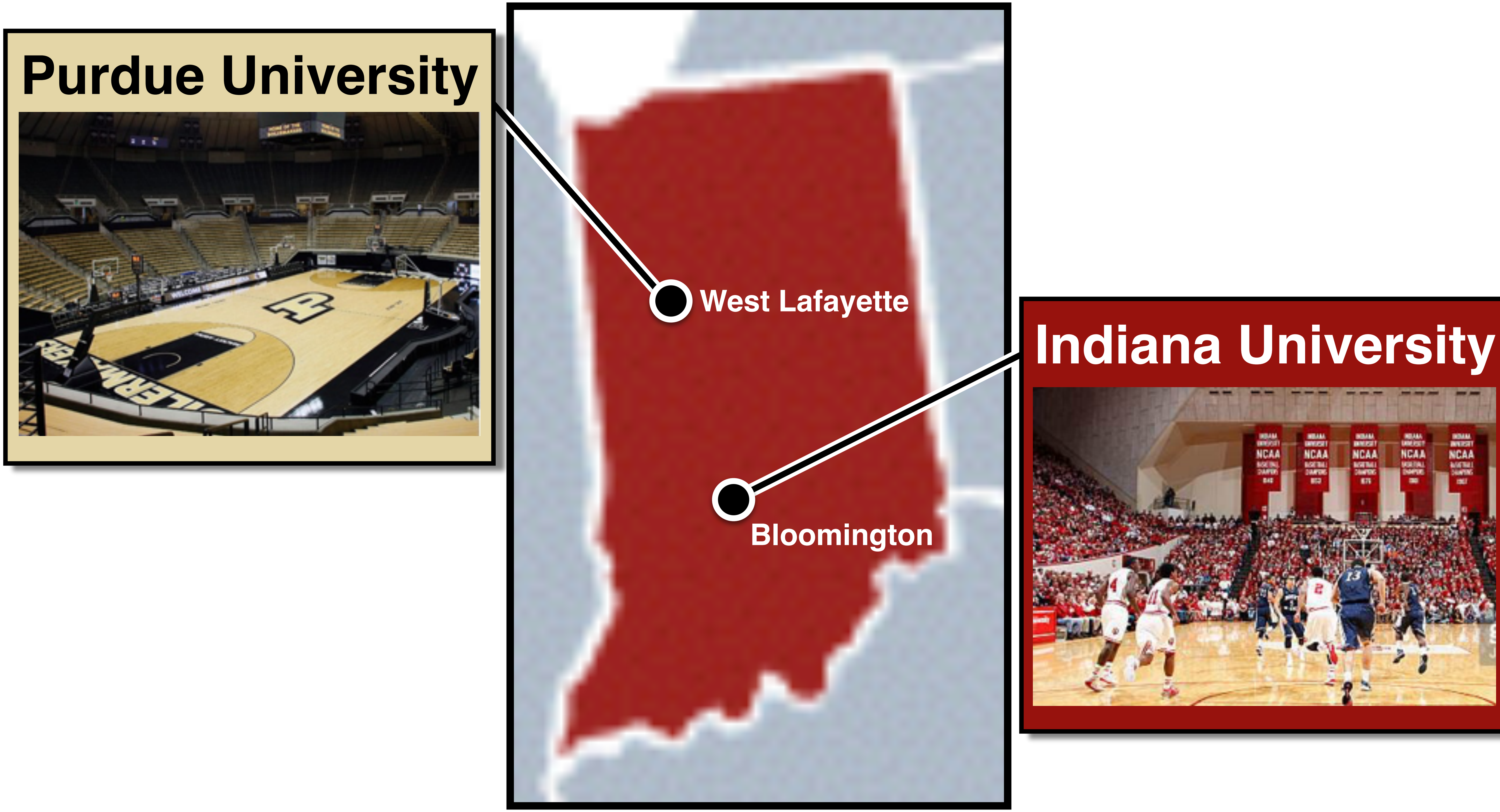
criteria: basically like CEMP-r/s from Beers & Christlieb, Ann. Rev. Astron. Astrophys., 43, 531 (2005)
figure: based on data in Roederer et al., Astron. J., 147, 136 (2014)

[redacted]


INDIANA

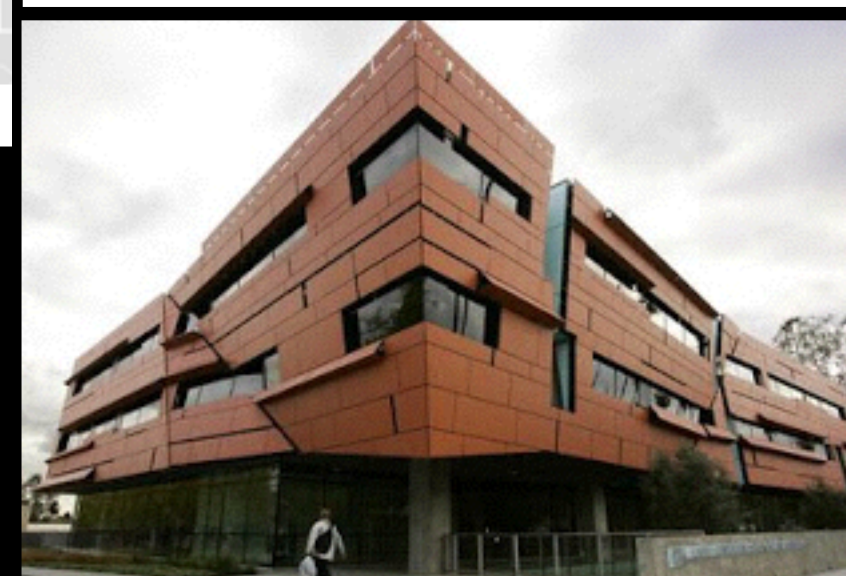
Purdue University



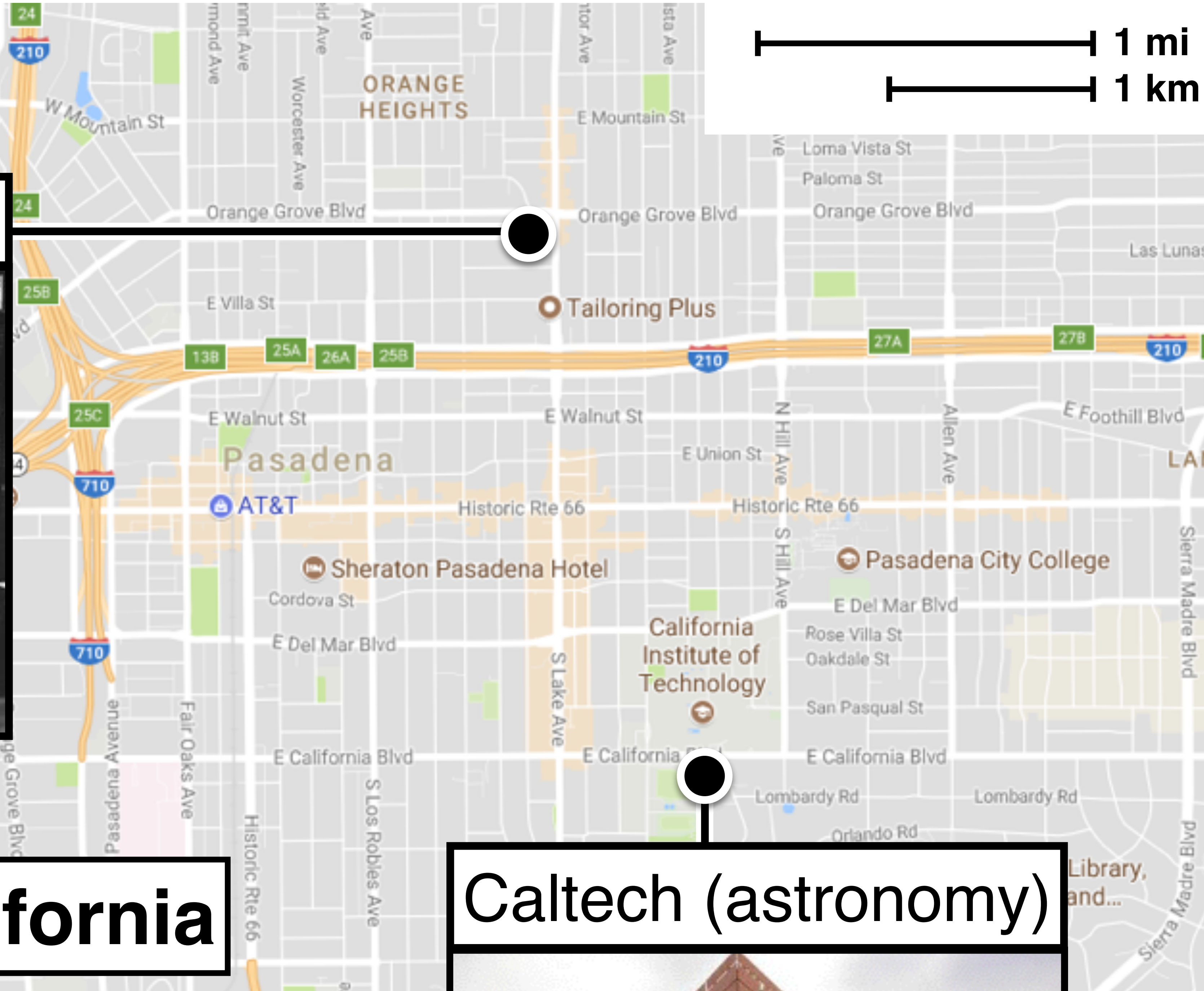

Purdue University
West Lafayette
Indiana University
NCAA
NCAA
NCAA
NCAA
NCAA
Bloomington

Pasadena, California

Caltech (astronomy)

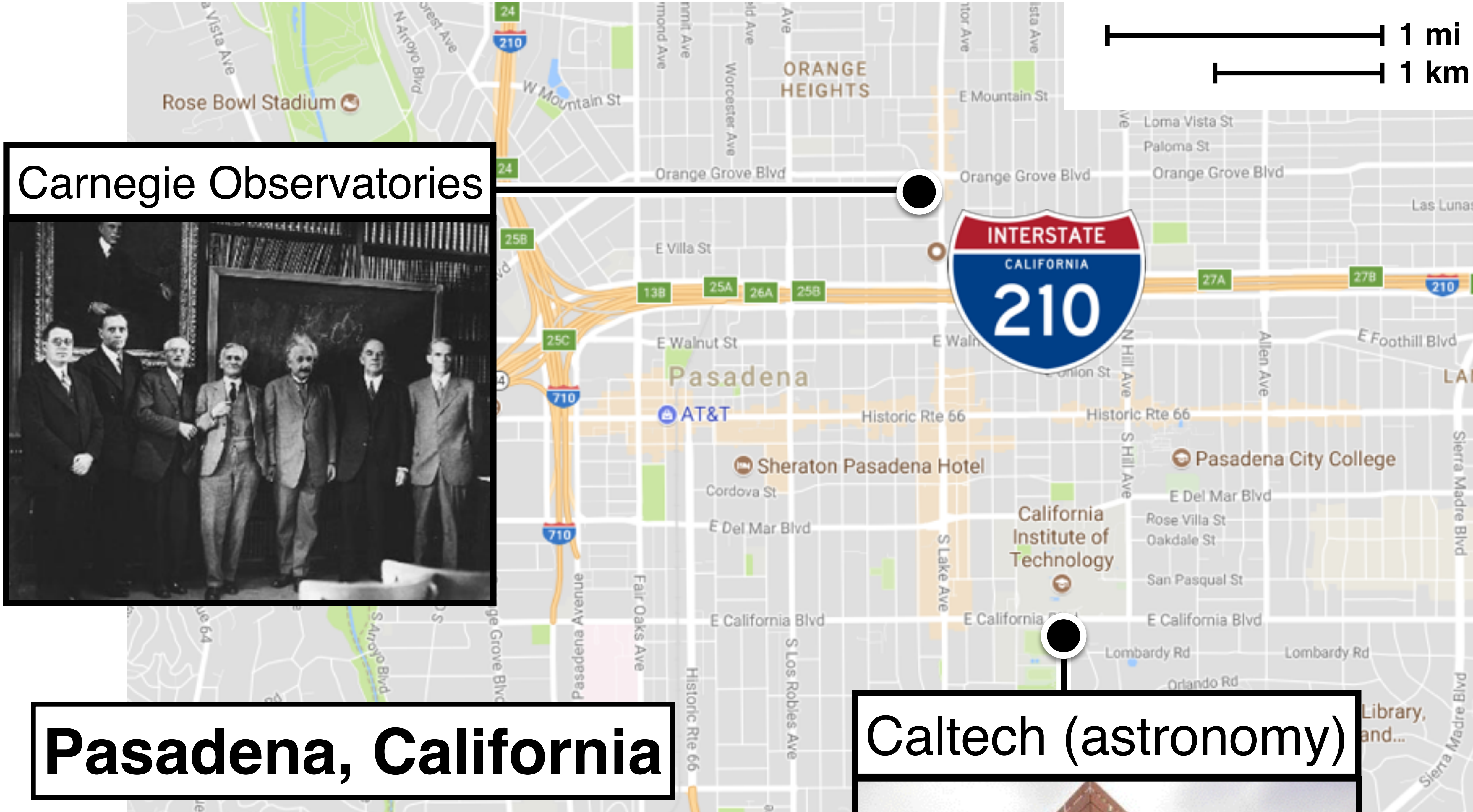


Pasadena, California



Carnegie Observatories

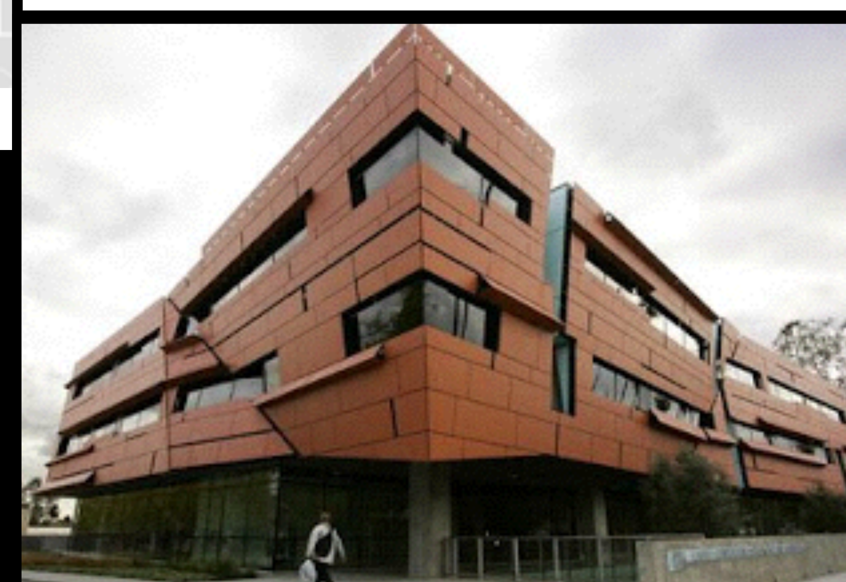
Caltech (astronomy)



Carnegie Observatories

Pasadena, California

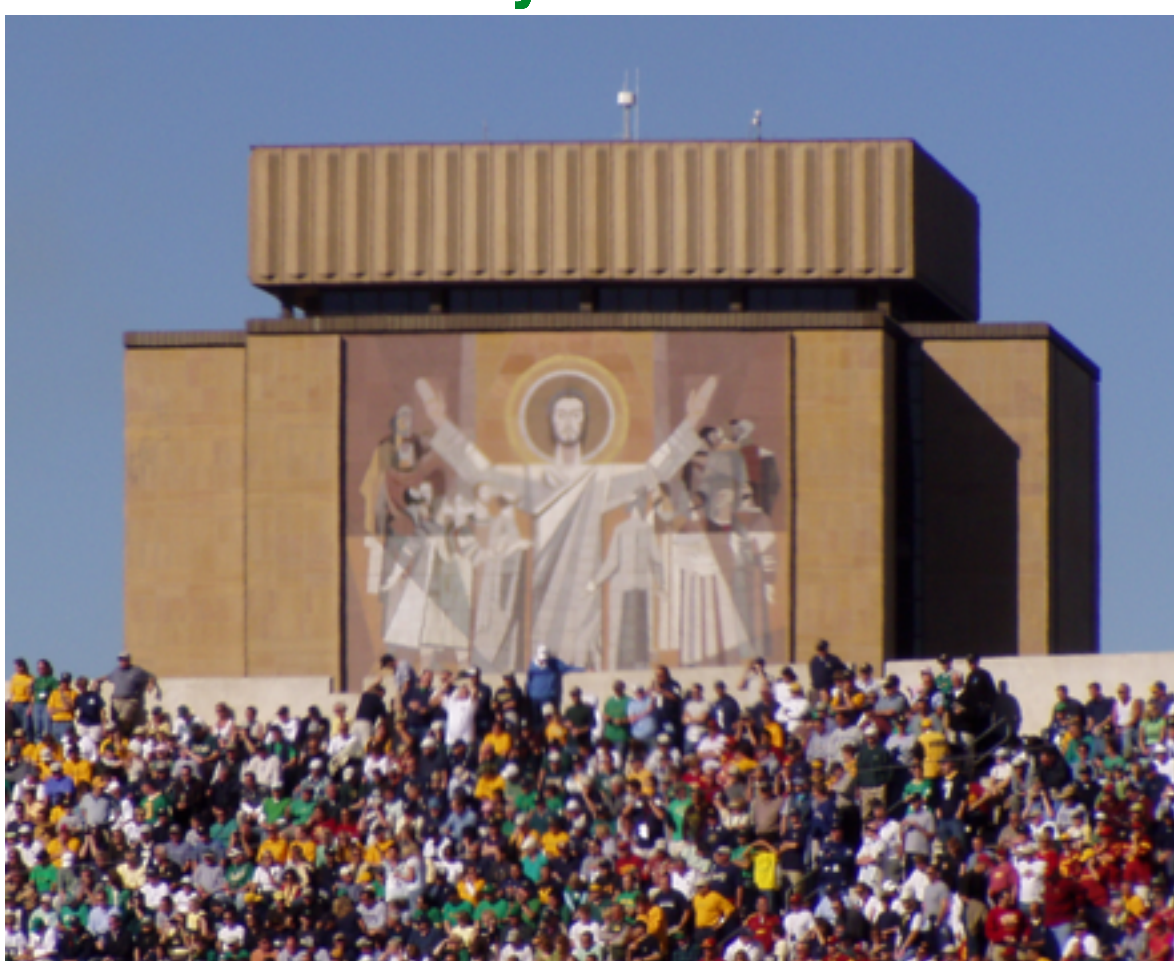
Caltech (astronomy)



GALACTIC ARCHAEOLOGY

football at
Michigan State University

football / "Touchdown Jesus"
at the University of Notre Dame



football at the University of Michigan

Timothy C Beers beers@pa.msu.edu via astro.as.utexas.edu
to Ian

Hi Ian --

WOW WOW WOW WOW WOW ! Great news indeed :) [redacted].
[redacted]

[redacted]

Cheers,

Tim


Michigan St. U.
U. Notre Dame
U. Michigan
Purdue U.
T. Ohio St. U.
Indiana U.