Title: Nucleosynthesis of Heavy Elements in Neutrino-Driven Winds and Neutron-Star Mergers

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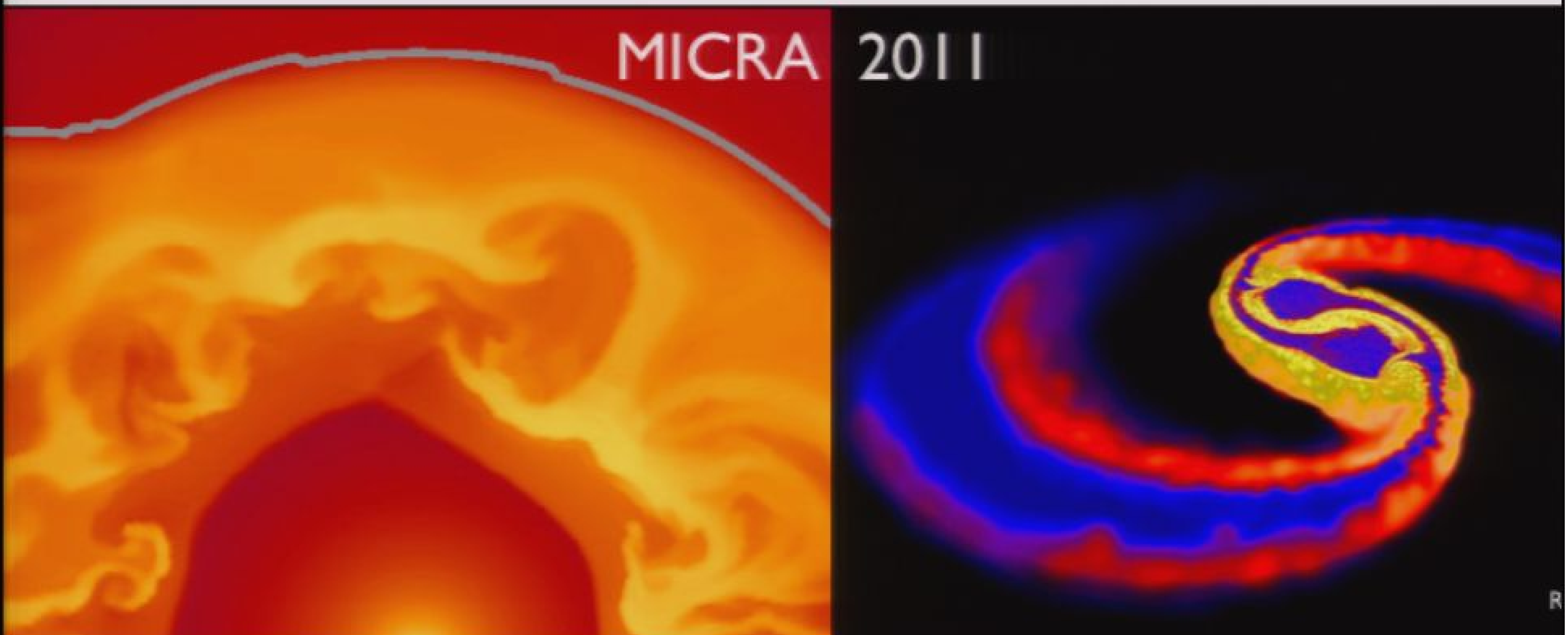
Abstract: The energy generated by the r-process can impact the dynamics of neutron star mergers. Solving a full r-process network coupled with the hydrodynamics becomes the necessary but it is computational very expensive. We have developed a simple model that can be implemented into hydrodynamic simulations and gives a very good estimate of the r-process heating.

Nucleosynthesis of heavy elements in neutrino-driven winds and neutron-star mergers

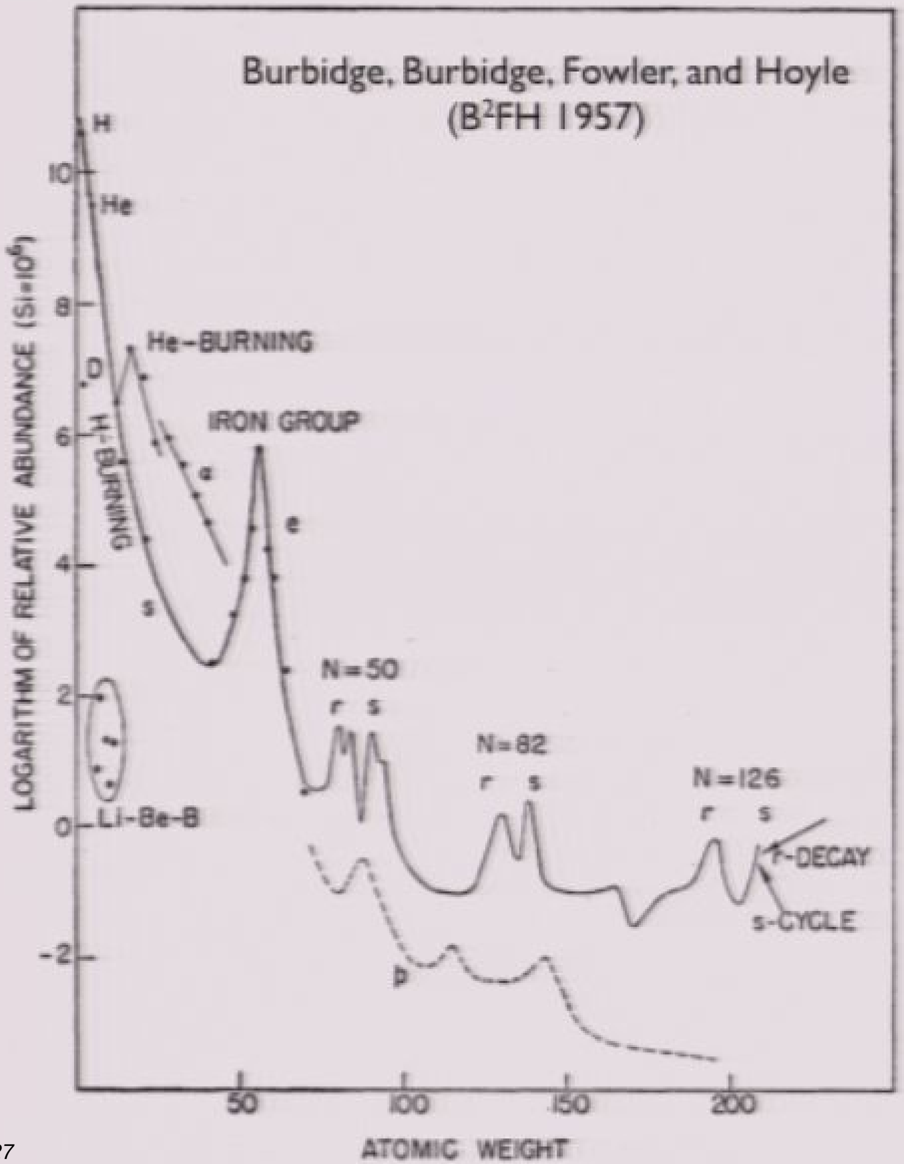


Almudena Arcones

Feodor Lynen Fellow at the University of Basel

Alexander von Humboldt

Origin of heavy elements



Abundance observations

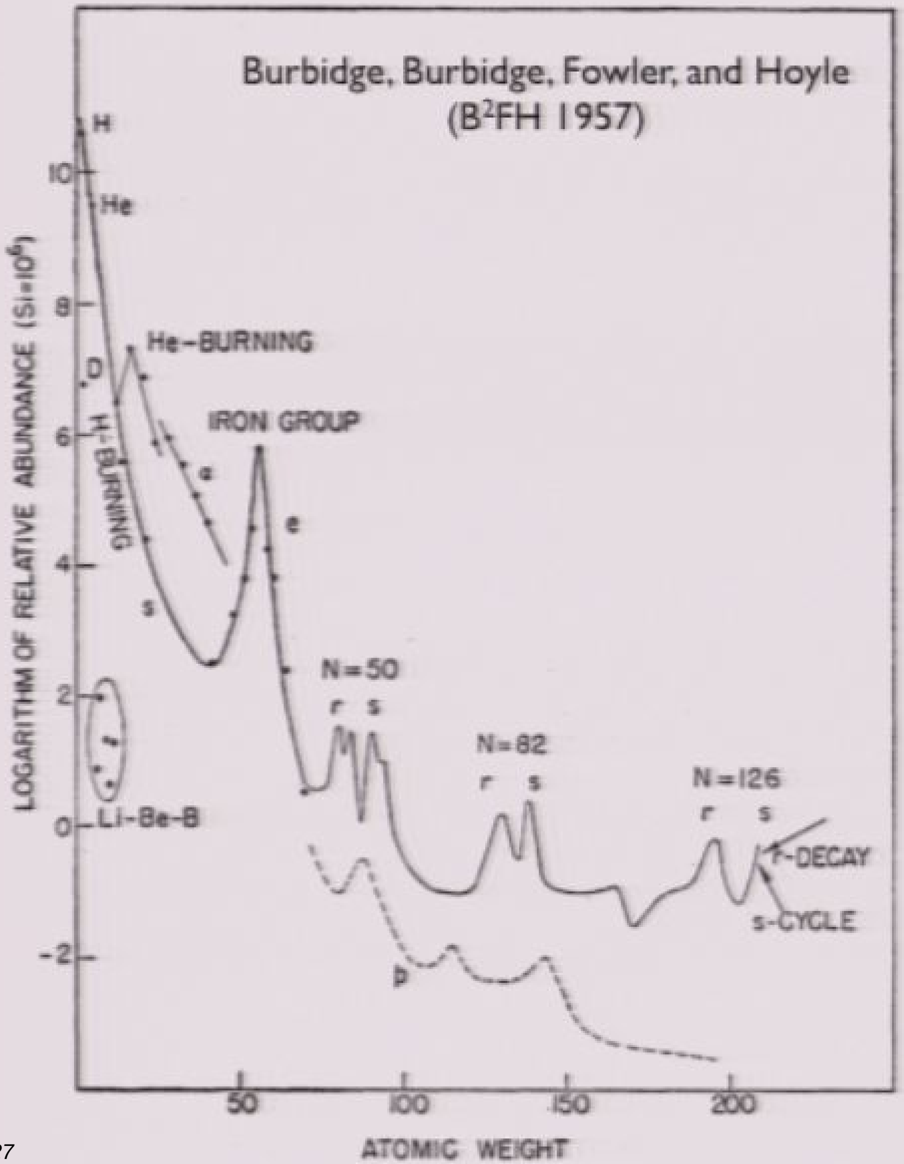
solar system
ultra metal poor halo stars

Nuclear physics and processes

peaks at neutron magic numbers

r-process, s-process,
p-process, νp-process

Origin of heavy elements



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peaks at neutron magic numbers

r-process, s-process,
p-process, νp-process

Astrophysical conditions

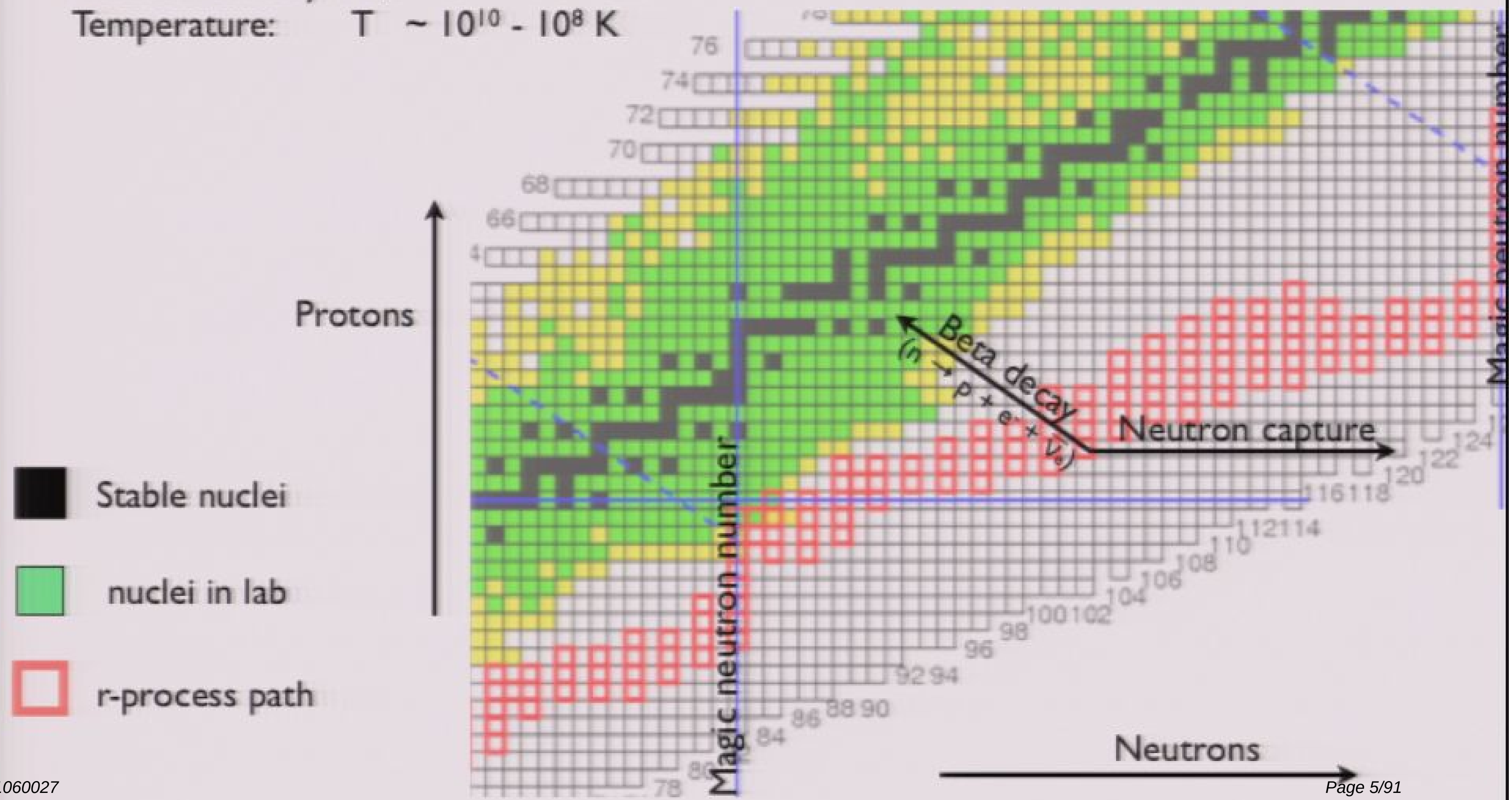
astrophysical sites

study the nucleosynthesis
based on hydrodynamical simulations

r-process

Rapid neutron capture compared to beta decay

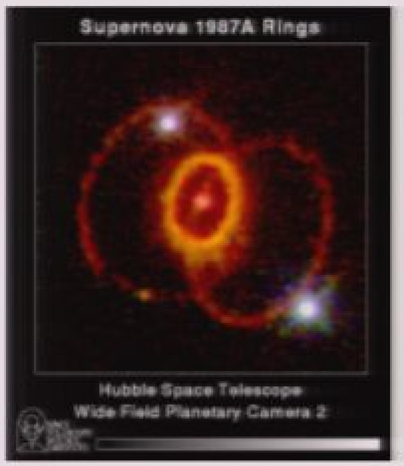
Neutron density: $N_n \sim 10^{27} - 10^{20}\ cm^{-3}$
Temperature: $T \sim 10^{10} - 10^{8}$ K



Astrophysical site(s) of the r-process

core-collapse supernovae

(B²FH 1957)



neutron star mergers

(Lattimer & Schramm 1976)

Rosswog

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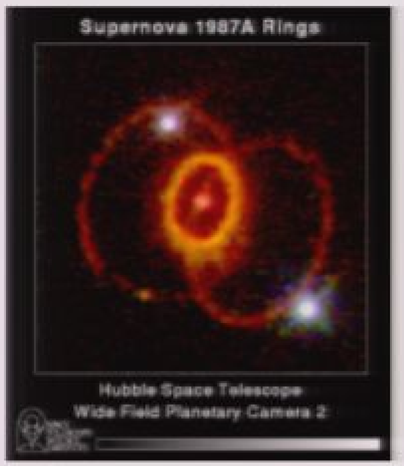
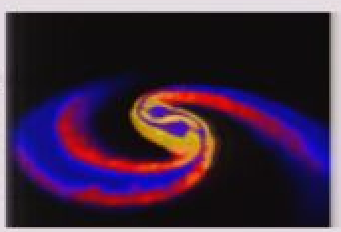


- neutrino-driven wind (Meyer et al. 1992, Woosley et al. 1994)
- prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984)
- shocked surface layers (Ning, Qian, Meyer 2007)
- jets (e.g., Nishimura et al. 2006)

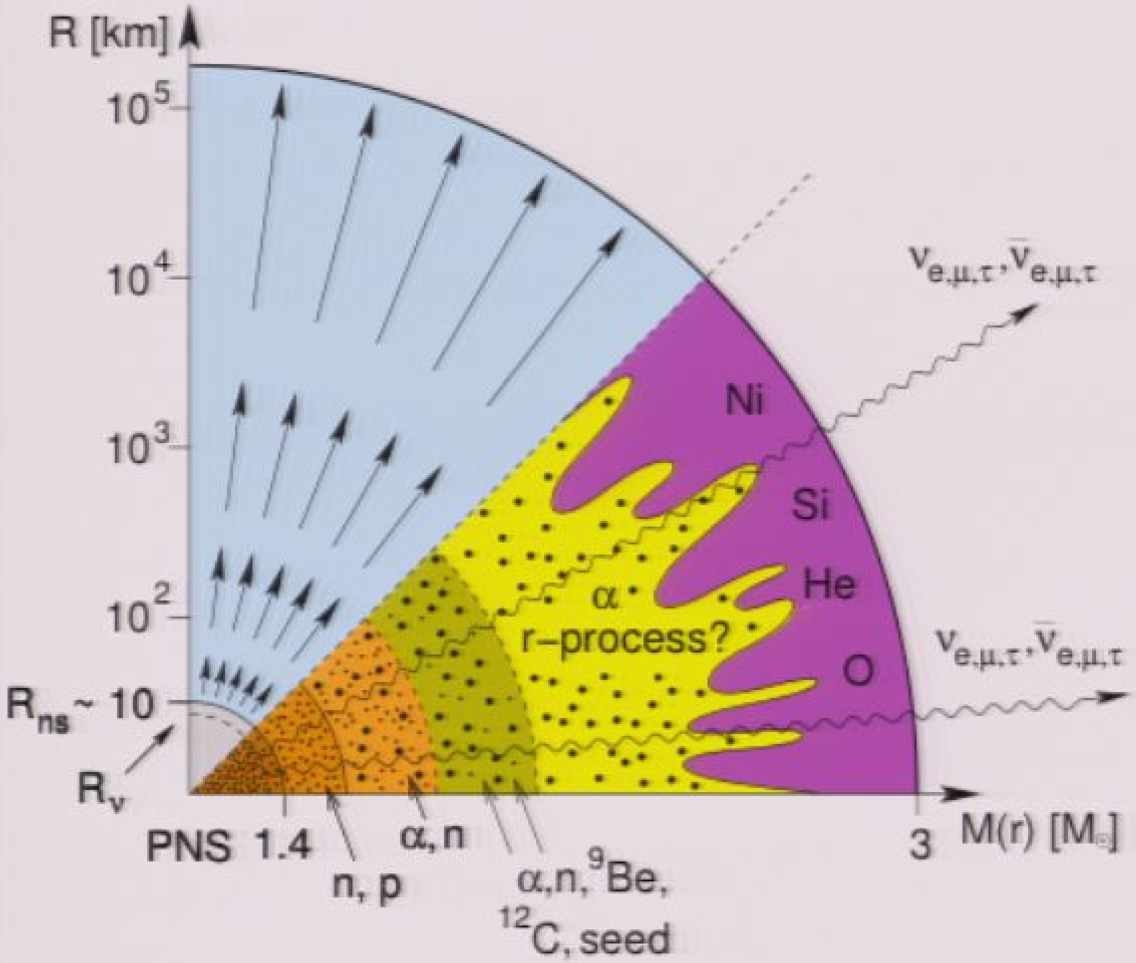
neutron star mergers

(Lattimer & Schramm 1976)



Rosswog

Nucleosynthesis in neutrino-driven winds



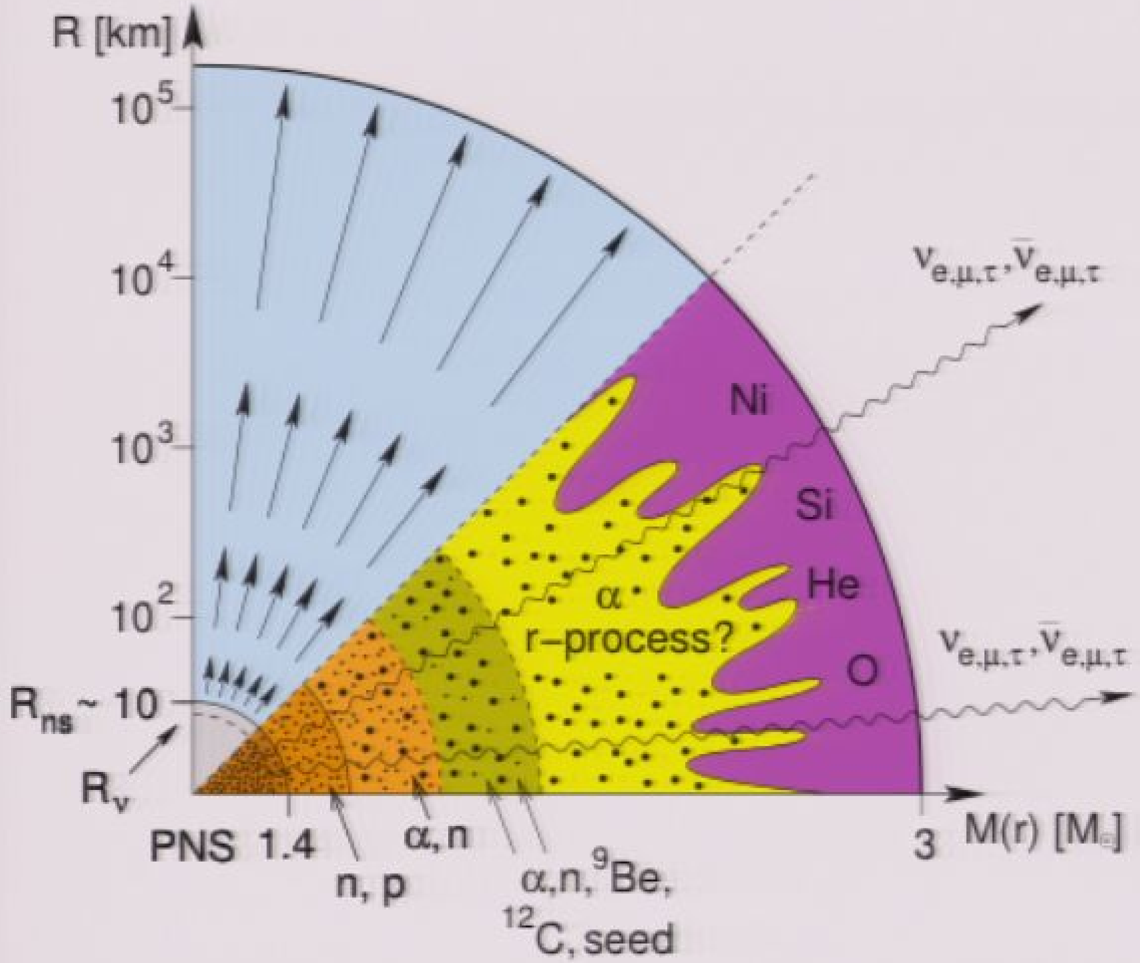
Production of heavy elements (A>13
requires high neutron-to-seed ratio
(Y_n/Y_{seed}~100).

Necessary conditions for the r-proce

- fast expansion: inhibits the alpha-process and thus the formation of seed nuclei
- neutron rich ejecta: Y_e<0.5
- high entropy is equivalent to high photon-to-baryon ratio. Photons dissociate seed nuclei into nucleon

(Meyer et al. 1992, Hoffman et al. 1997, Otsuki et al. 2000, Thompson et al. 2001...)

Nucleosynthesis in neutrino-driven winds



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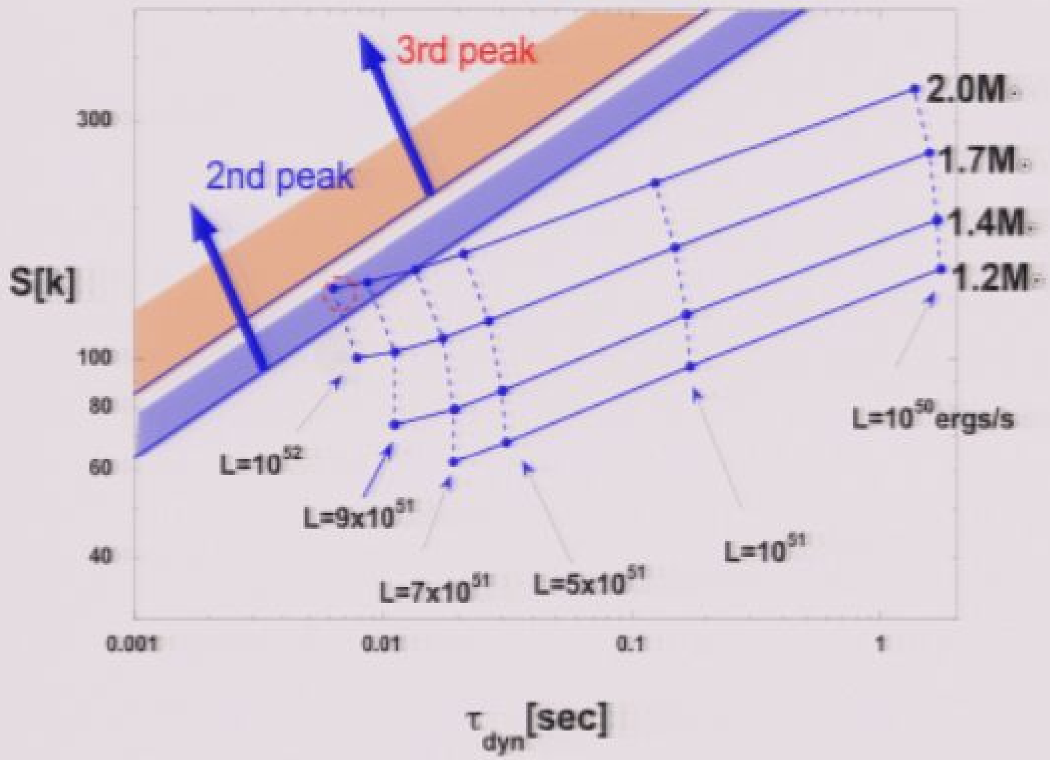
Nucleosynthesis in neutrino-driven winds

Otsuki et al. 2000



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Necessary conditions identified by steady-state models (e.g. Otsuki et al. 2000, Thompson et al. 2001) are not realized in recent simulations (Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010)

(Meyer et al. 1992, Hoffman et al. 1997, Otsuki et al. 2000, Thompson et al. 2001...)

Astrophysical site(s) of the r-process

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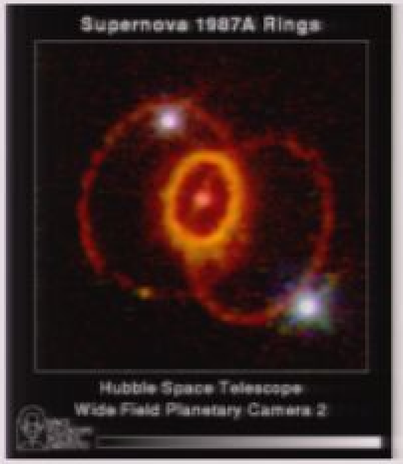

- neutrino-driven wind (Meyer et al. 1992, Woosley et al. 1994):
  proton rich (Fischer et al. 2010, Hüdepohl et al. 2010)
  entropy too low (Woosley et al. 1994 → Roberts et al. 2010)
  → multidimensional effects, neutrino collective oscillations, ...?
- prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984): excluded
- shocked surface layers (Ning, Qian, Meyer 2007): possible?
- jets: potential, very preliminary magneto hydrodynamic simulations (e.g., Nishimura et al. 2006)

Astrophysical site(s) of the r-process

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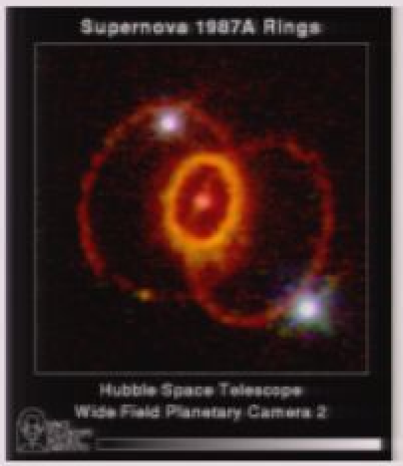

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neutron star mergers

(Lattimer & Schramm 1976)

- Right conditions for a successful r-process (Freiburghaus et al. 1999)
- No only r-process site: they do not occur early and frequently enou
  to account for the heavy elements observed in old stars and their scatter in the Galaxy (Qian 2000, Argast et al. 2004)
- r-process heating affects merger dynamics (Metzger, Arcones, Quataert, Martinez-Pinedo 2010)

Hydrodynamical simulations

Long-time hydrodynamical simulations following the ejecta from ~5ms after bounce to ~3s in 2D (Arcones & Janka 2011) and ~10s in 1D (Arcones et al. 2007).

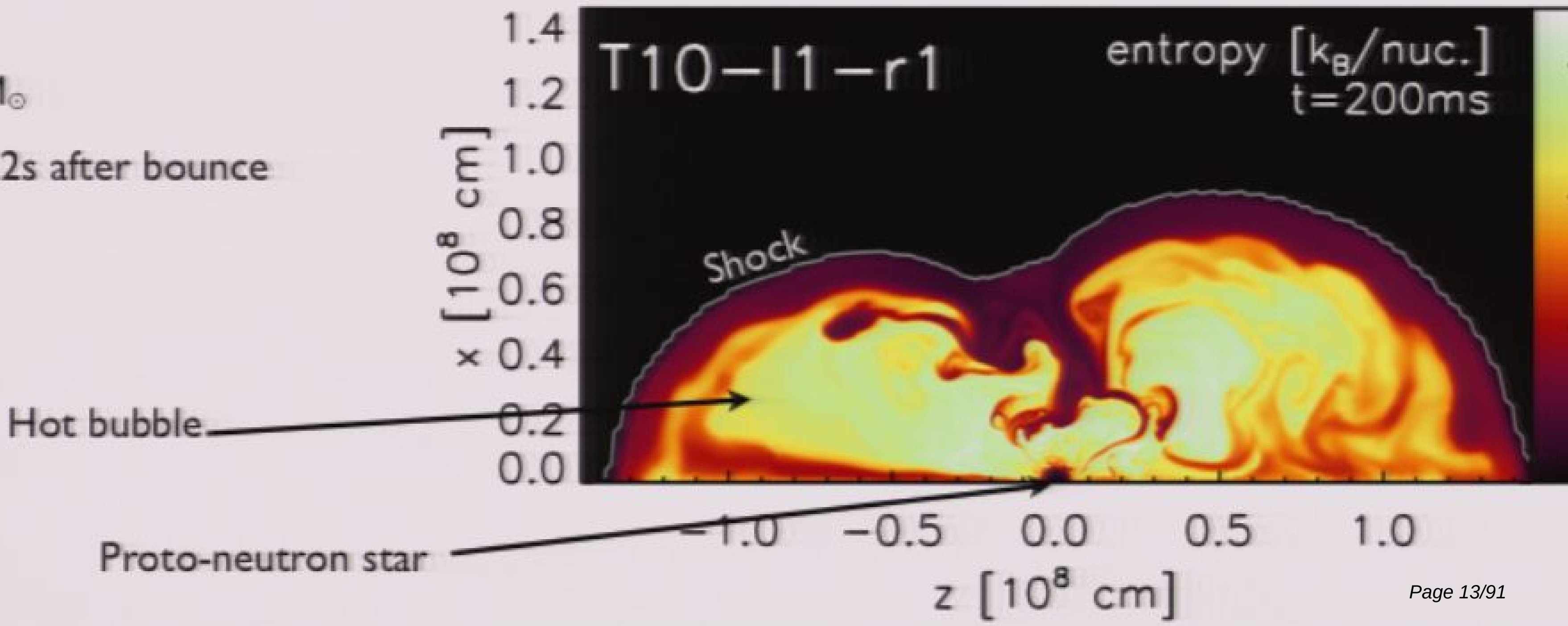
Explosion by increasing the neutrino luminosities to obtain typical explosion energies ~10^{51}erg.

Detailed study of nucleosynthesis-relevant conditions: interaction of the neutrino-driven wind and the slow supernova ejecta.

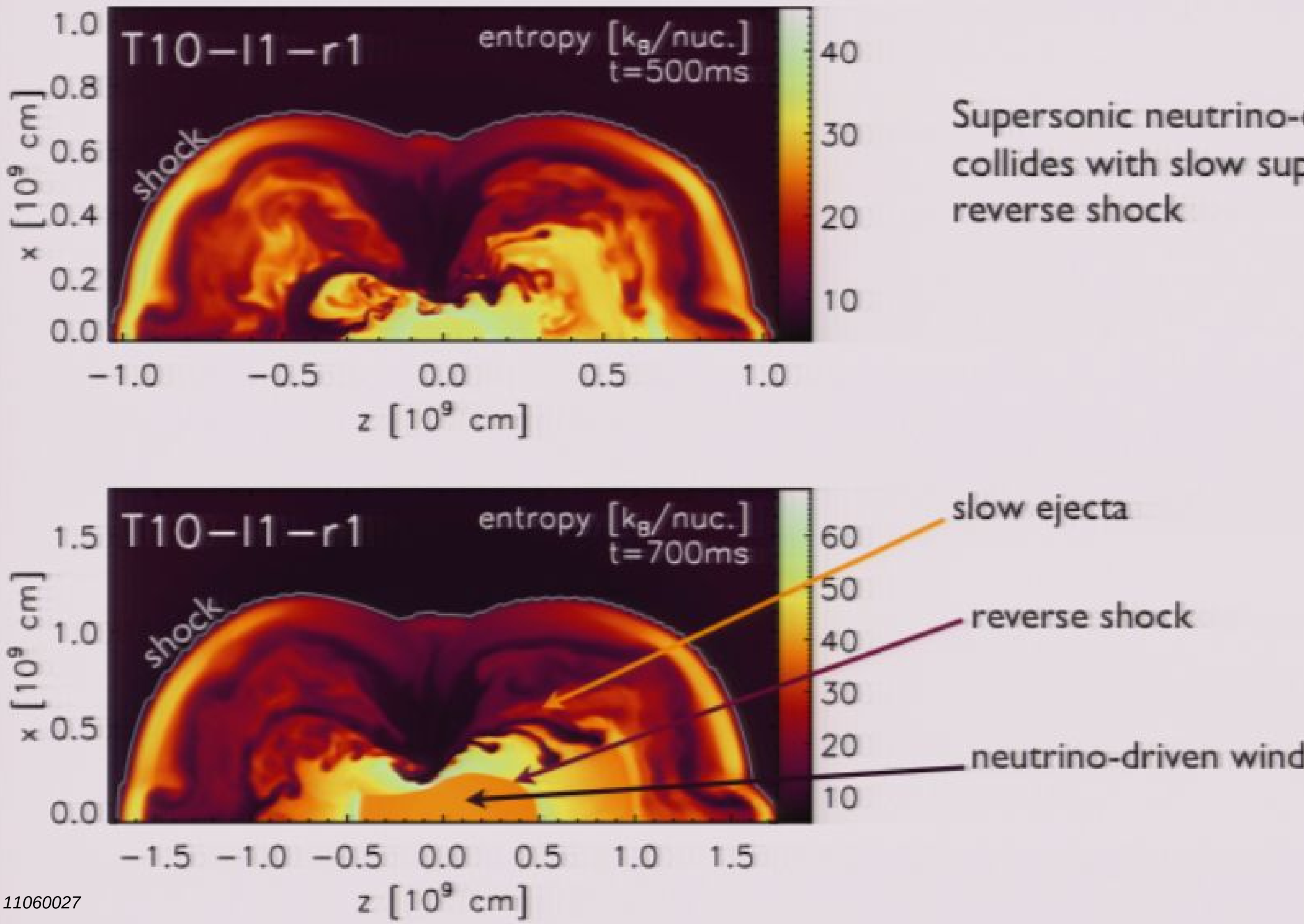
Variations of explosion energy, proto-neutron star cooling, and progenitor.

$10 M_\odot$

t=0.2s after bounce



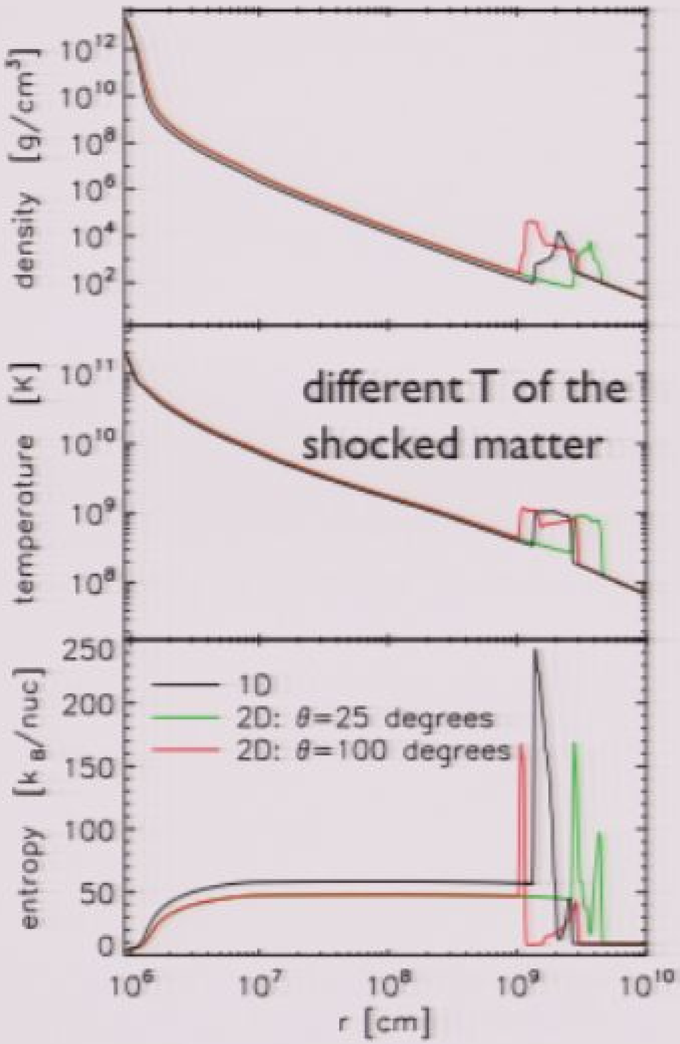
Neutrino-driven wind in 2D

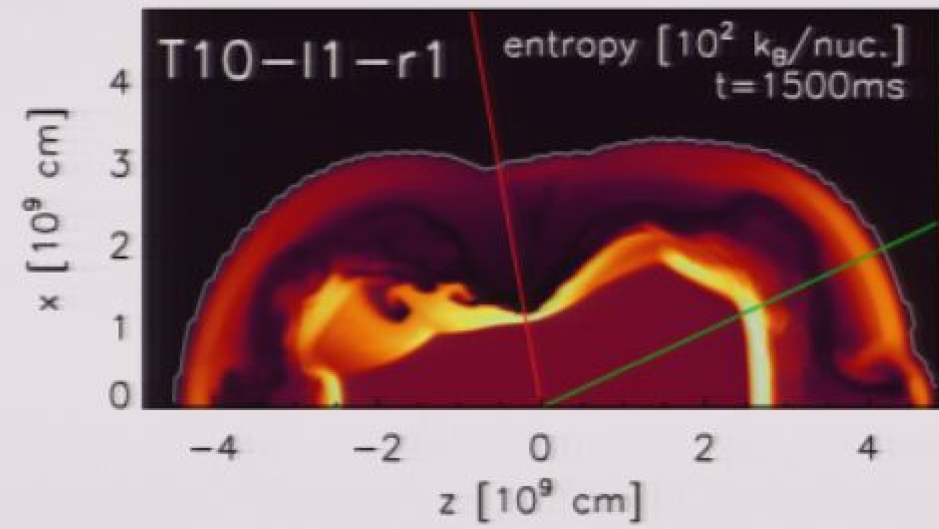


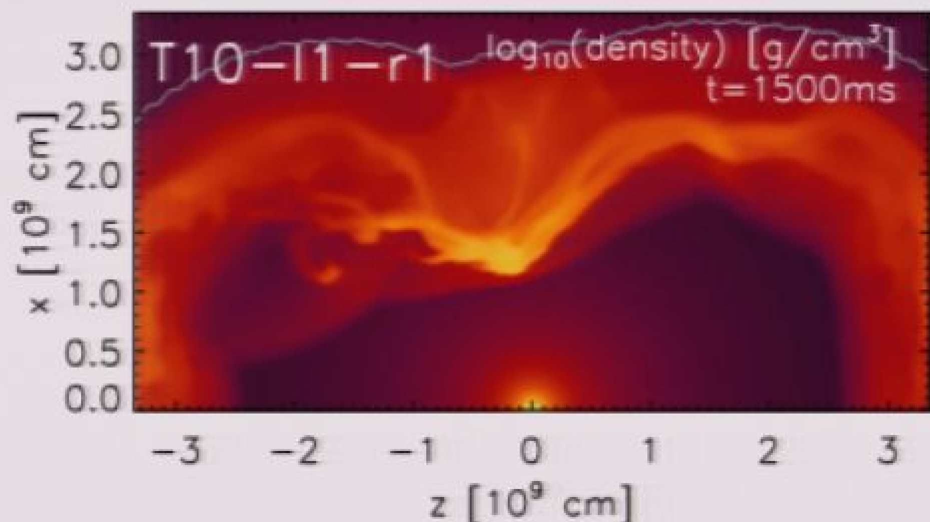
Supersonic neutrino-driven wind collides with slow supernova ejecta: reverse shock

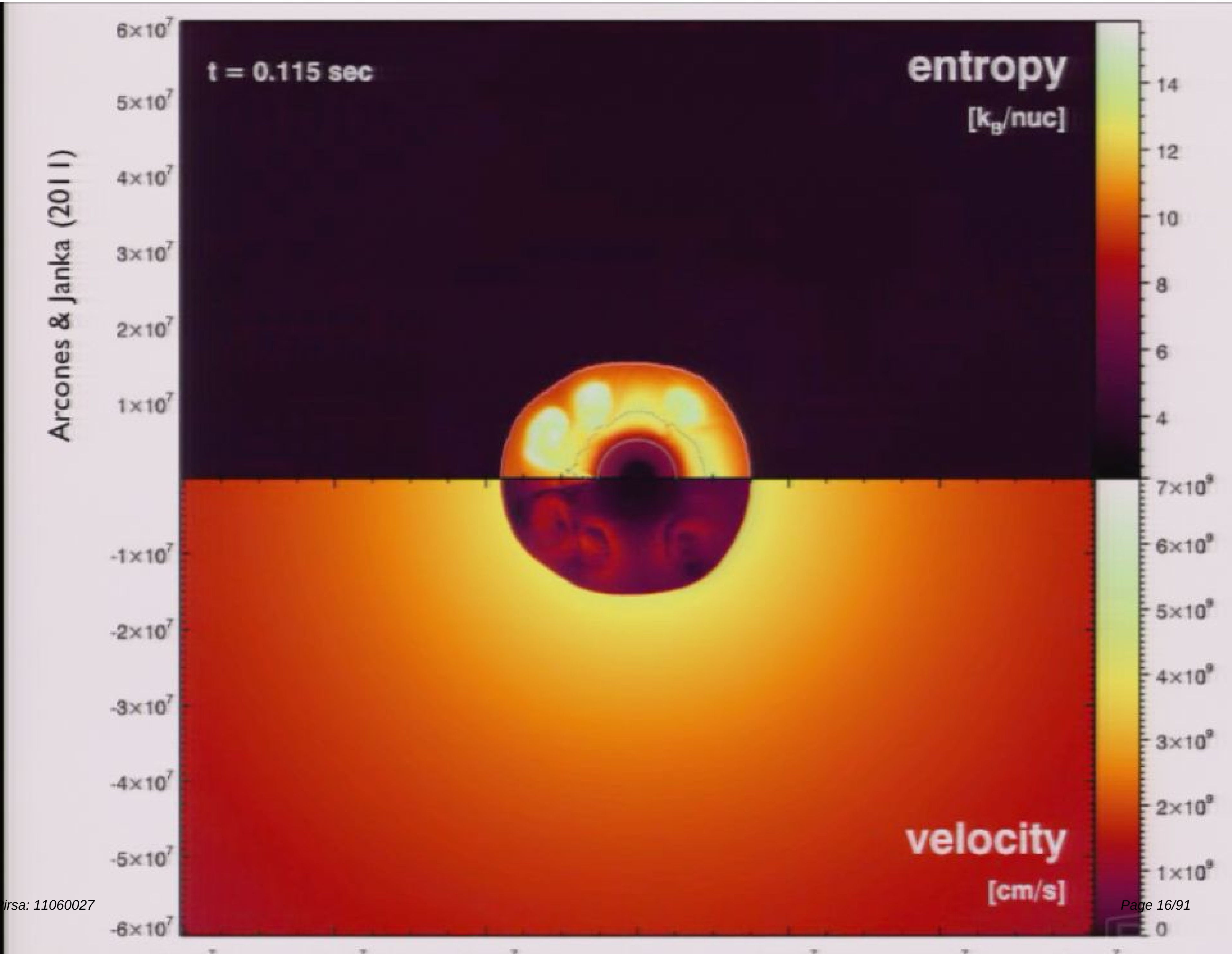
Neutrino-driven wind in 2D and 1D

Spherically symmetric wind









t = 0.115 sec
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[k_B/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
6×10^7
5×10^7
4×10^7
3×10^7
2×10^7
1×10^7
-1×10^7
-2×10^7
-3×10^7
-4×10^7
-5×10^7
-6×10^7
14
12
10
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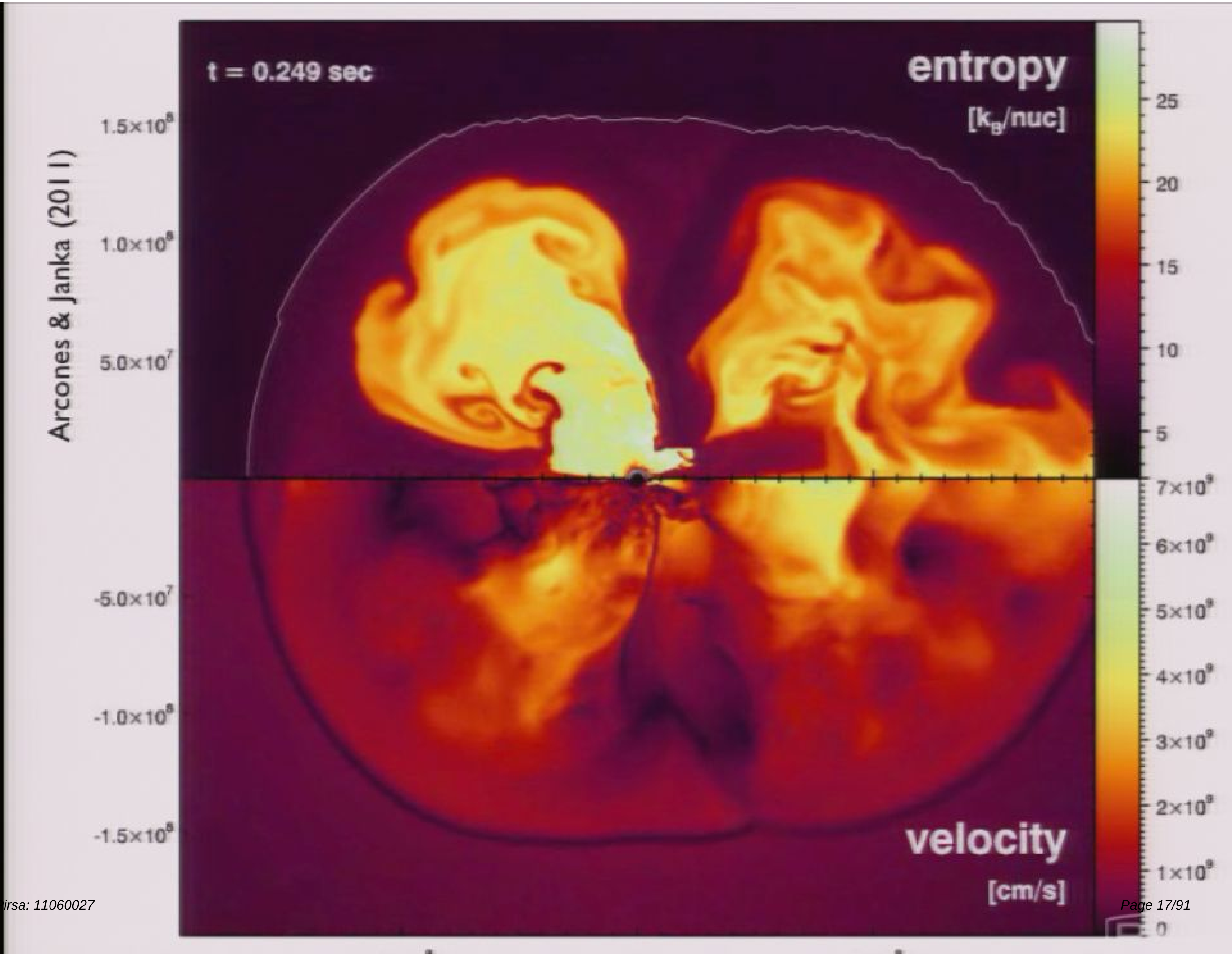
2×10^9
1×10^9
0



Arcones & Janka (2011)
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[cm/s]
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1.0×10^8
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-1.0×10^8
-1.5×10^8
25
20
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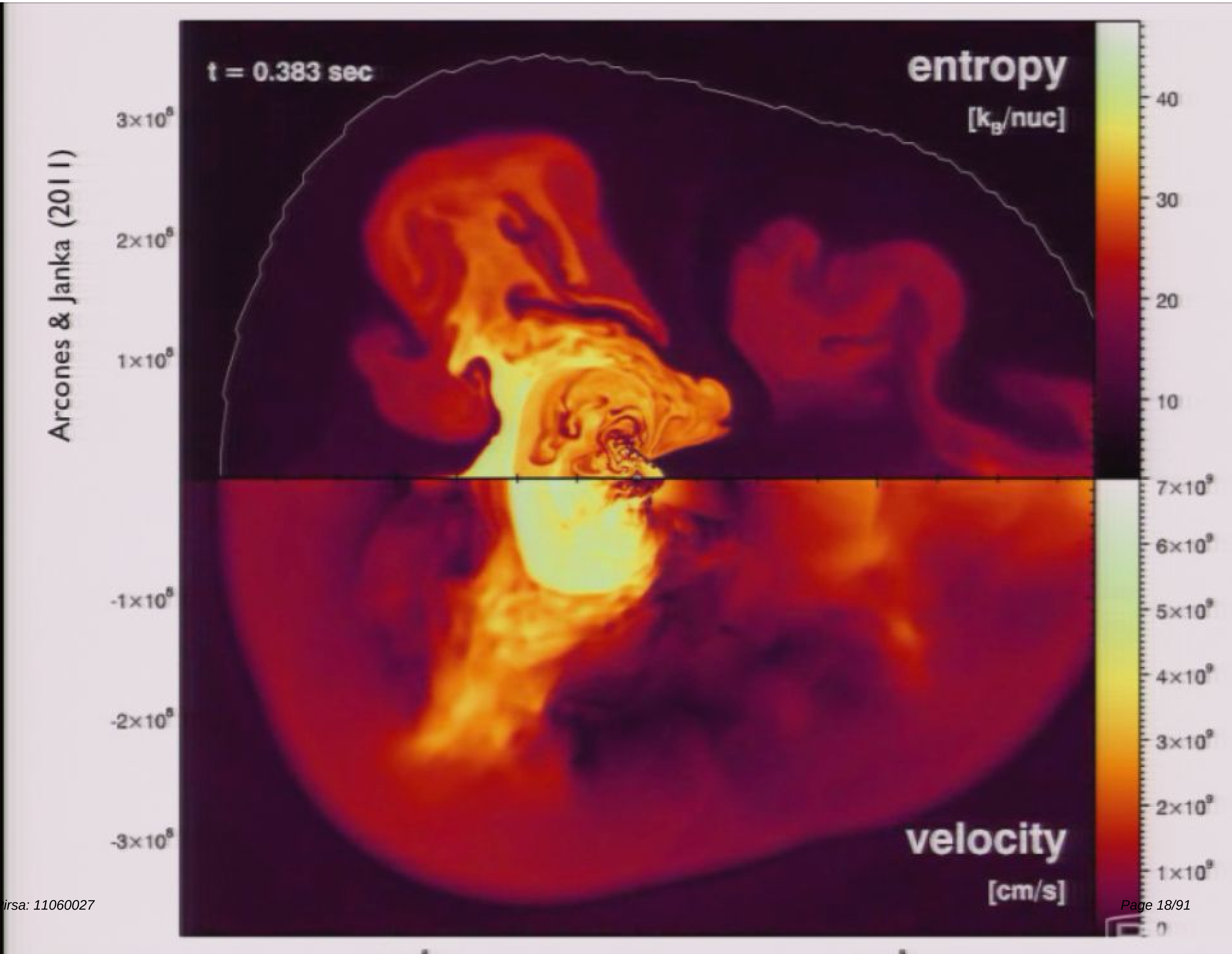
2×10^9
1×10^9
0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[k$_B$/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
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2×10⁸
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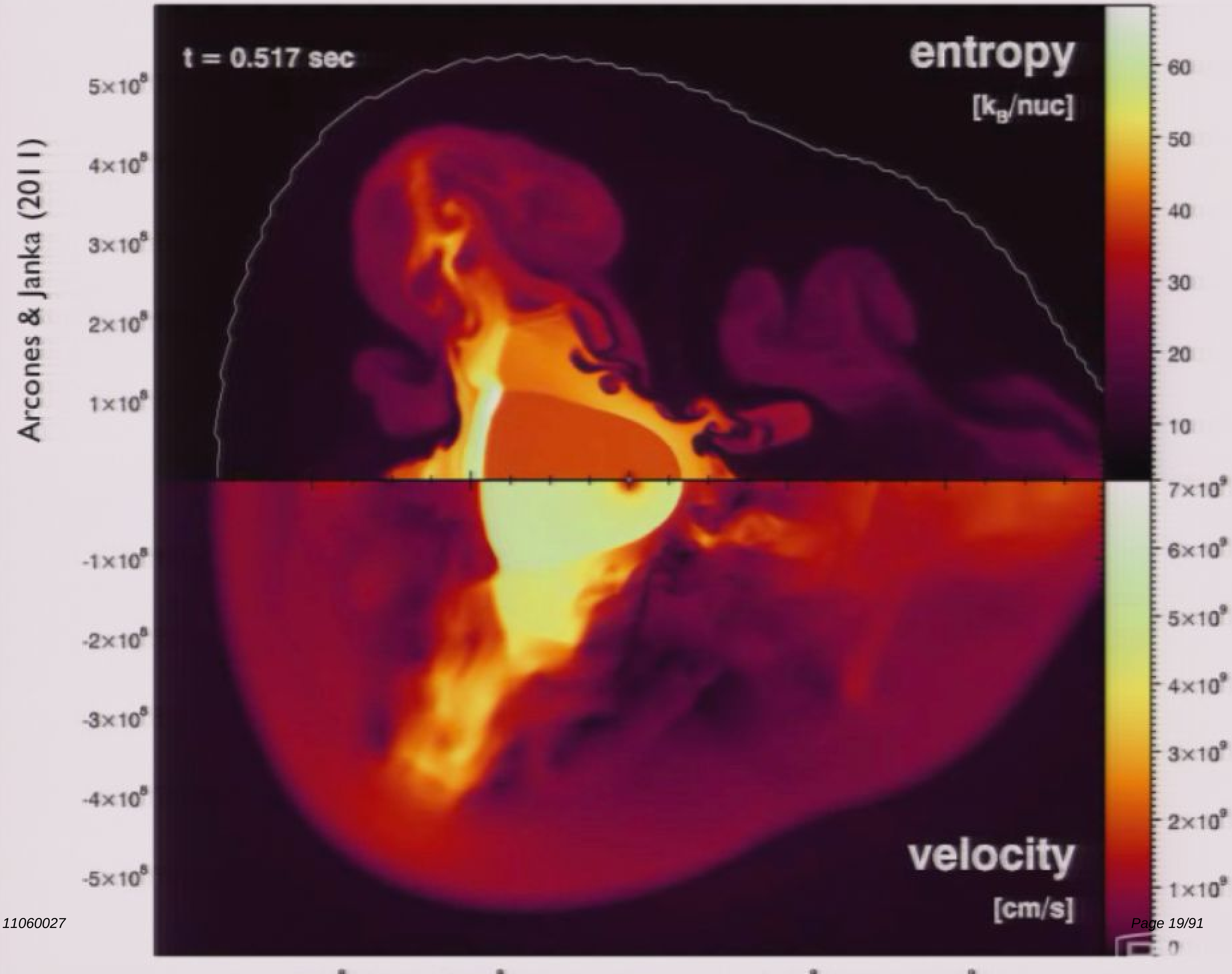
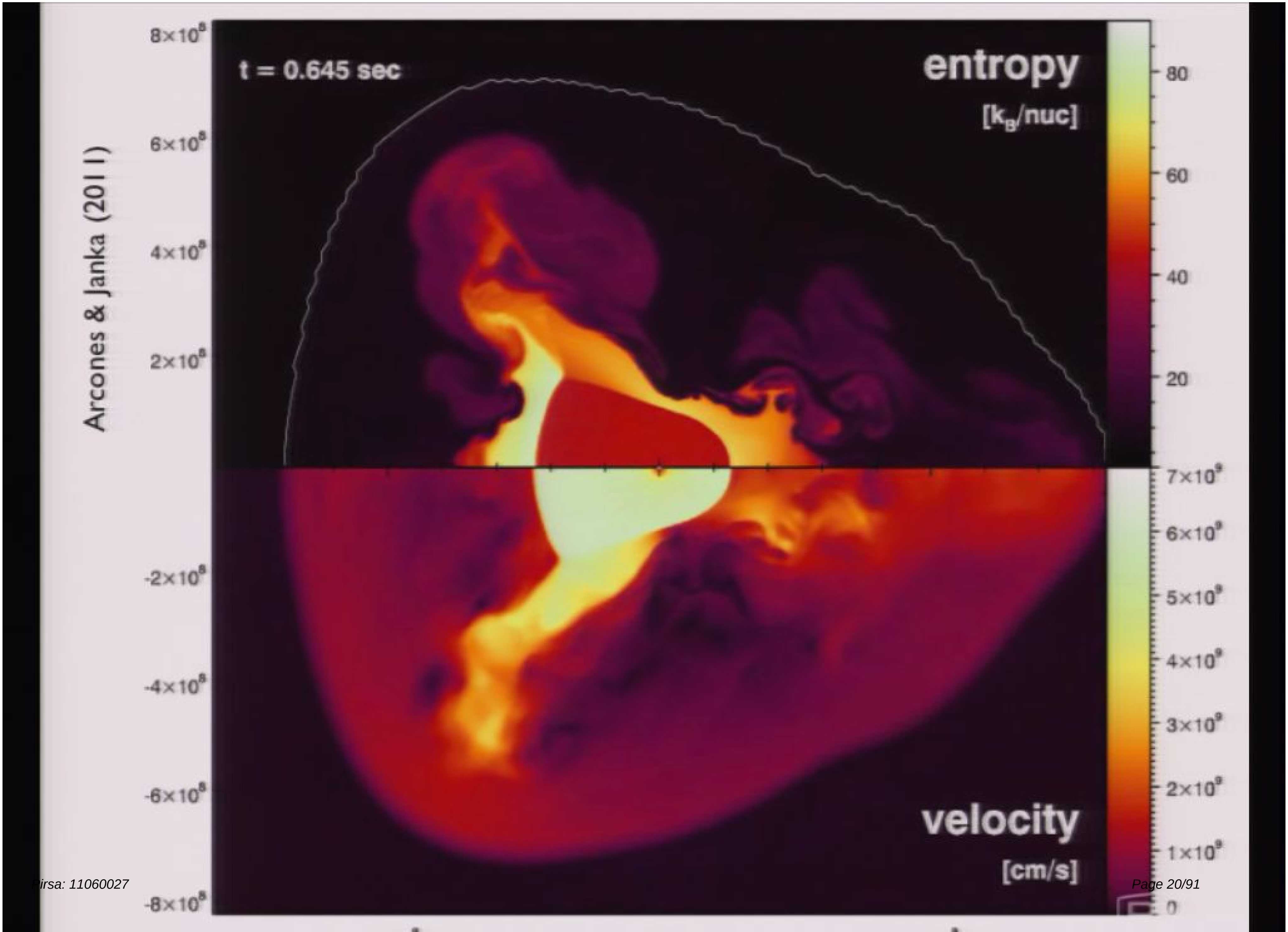
-1×10⁸
-2×10⁸
-3×10⁸
40
30
20
10
7×10⁹
6×10⁹
5×10⁹
4×10⁹
3×10⁹
2×10⁹
1×10⁹
0


t = 0.517 sec
entropy
[k_B/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
5×10⁸
4×10⁸
3×10⁸
2×10⁸
1×10⁸
-1×10⁸
-2×10⁸
-3×10⁸
-4×10⁸
-5×10⁸
60
50
40
30
20
10
7×10⁹
6×10⁹
5×10⁹
4×10⁹
3×10⁹
2×10⁹
1×10⁹
0


t = 0.645 sec
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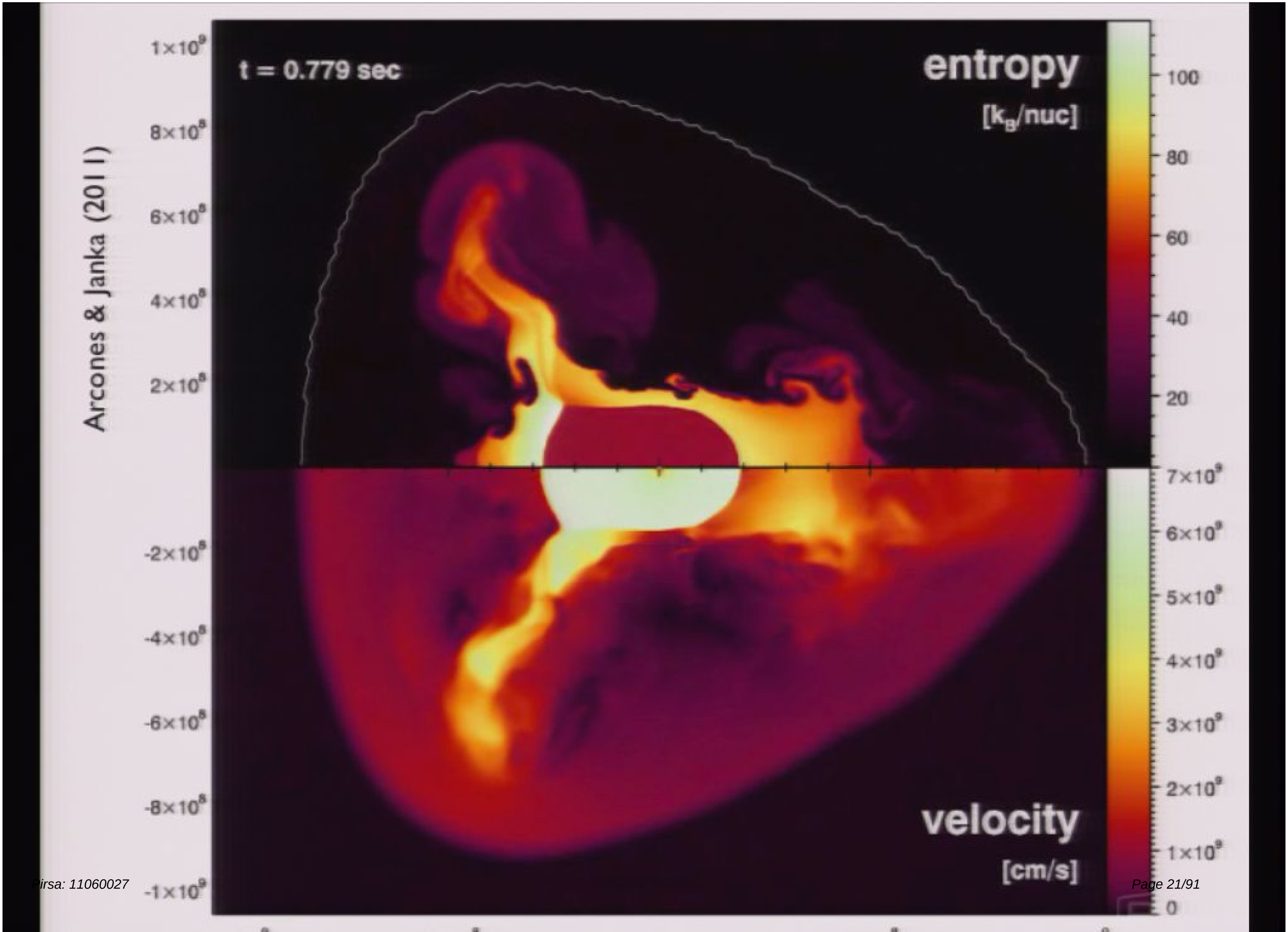
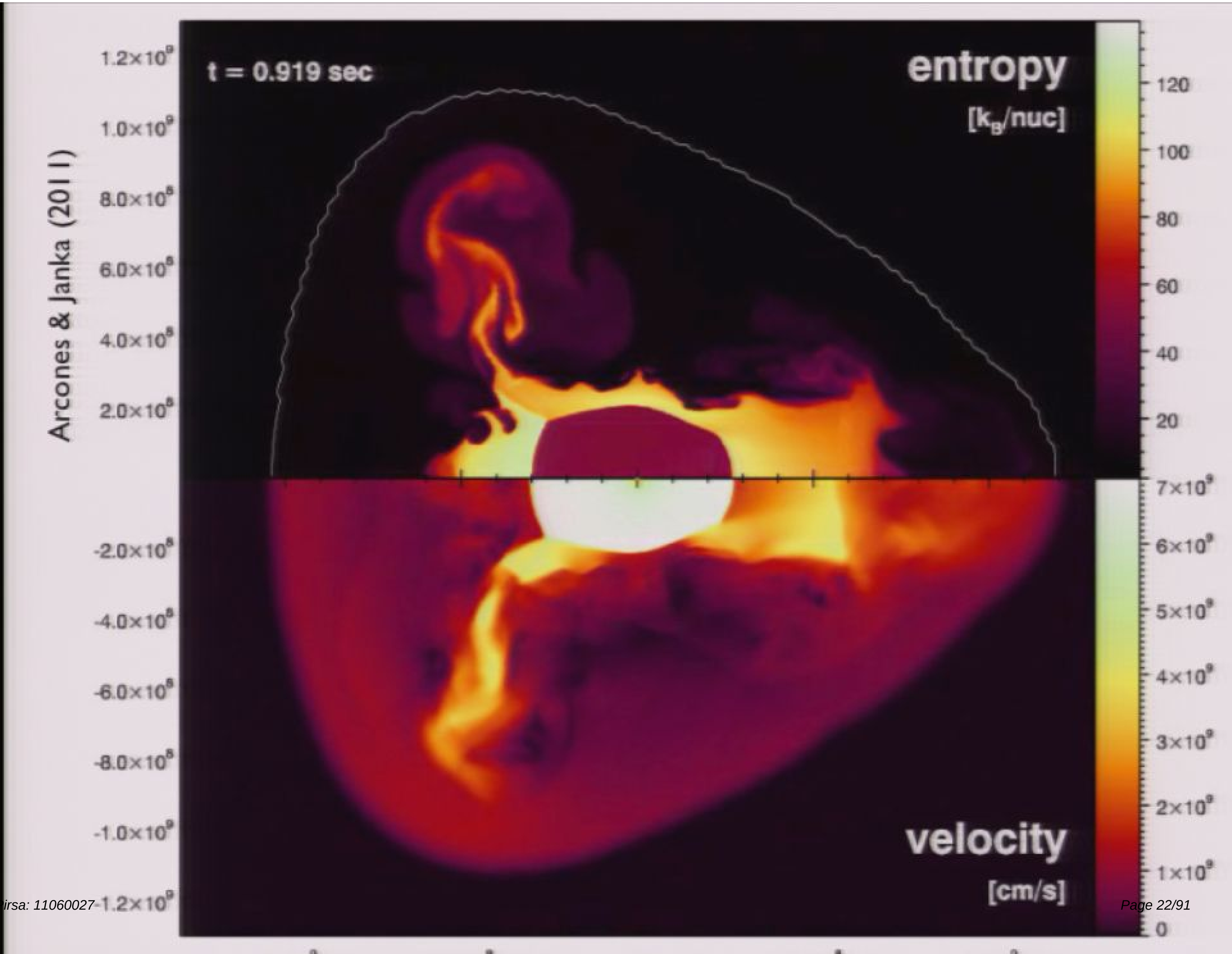
velocity
[cm/s]
Arcones & Janka (2011)
8×10^8
6×10^8
4×10^8
2×10^8
-2×10^8
-4×10^8
-6×10^8
-8×10^8
80
60
40
20
7×10^9
6×10^9
5×10^9
4×10^9
3×10^9
2×10^9
1×10^9
0


Arcones & Janka (2011)
t = 0.779 sec
entropy
[k$_B$/nuc]
velocity
[cm/s]
1×10⁹
8×10⁸
6×10⁸
4×10⁸
2×10⁸
-2×10⁸
-4×10⁸
-6×10⁸
-8×10⁸
-1×10⁹
100
80
60
40
20
7×10⁹
6×10⁹
5×10⁹
4×10⁹
3×10⁹
2×10⁹
1×10⁹
0


t = 0.919 sec
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[k_B/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
1.2×10^9
1.0×10^9
8.0×10^8
6.0×10^8
4.0×10^8
2.0×10^8
-2.0×10^8
-4.0×10^8
-6.0×10^8
-8.0×10^8
-1.0×10^9
-1.2×10^9
120
100
80
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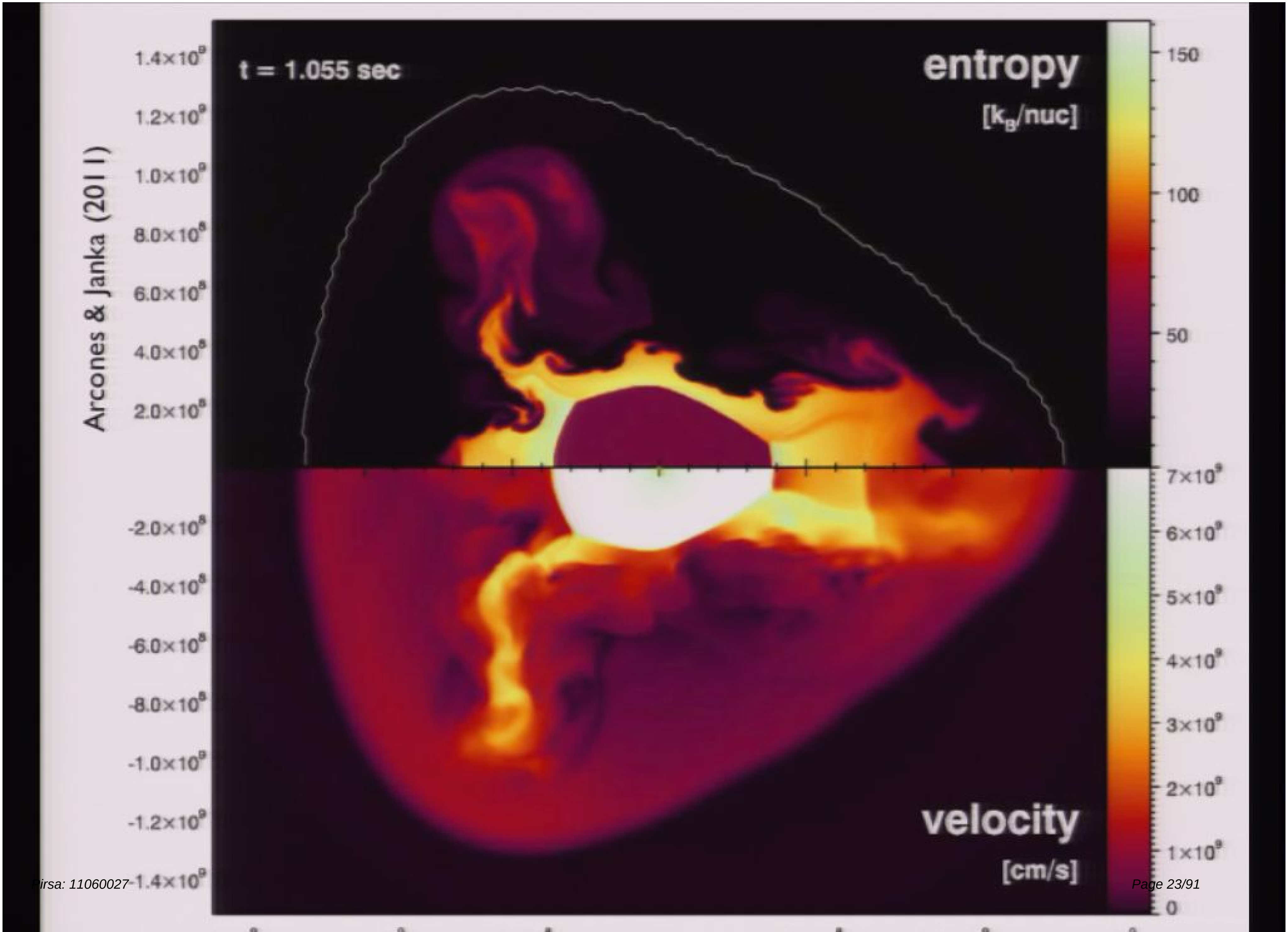
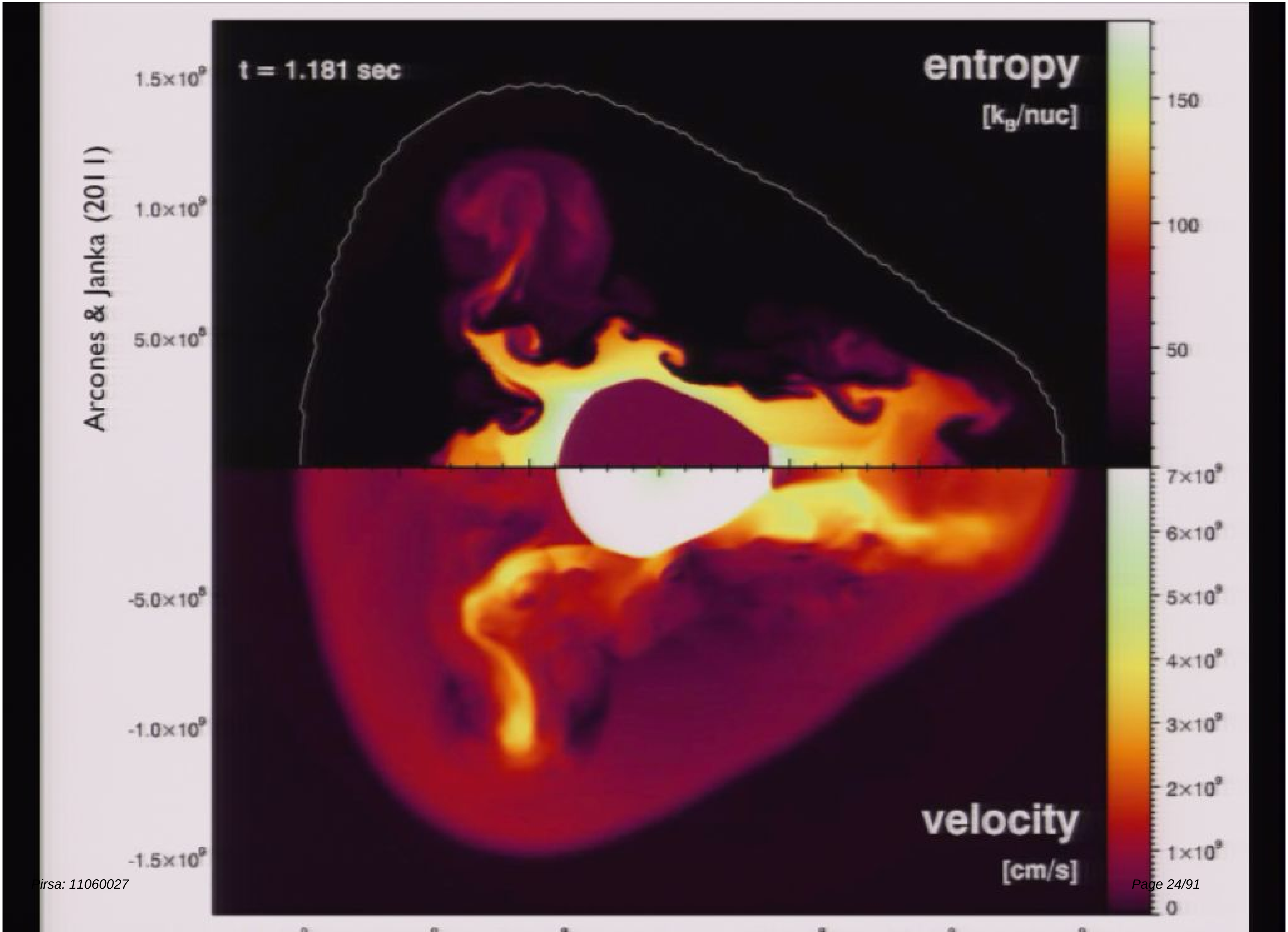
2×10^9
1×10^9
0


t = 1.055 sec
entropy
[k_B/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
1.4×10⁹
1.2×10⁹
1.0×10⁹
8.0×10⁸
6.0×10⁸
4.0×10⁸
2.0×10⁸
-2.0×10⁸
-4.0×10⁸
-6.0×10⁸
-8.0×10⁸
-1.0×10⁹
-1.2×10⁹
-1.4×10⁹
150
100
50
7×10⁹
6×10⁹
5×10⁹
4×10⁹
3×10⁹
2×10⁹
1×10⁹
0



t = 1.181 sec
entropy
[k_B/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
1.5×10⁹
1.0×10⁹
5.0×10⁸
-5.0×10⁸
-1.0×10⁹
-1.5×10⁹
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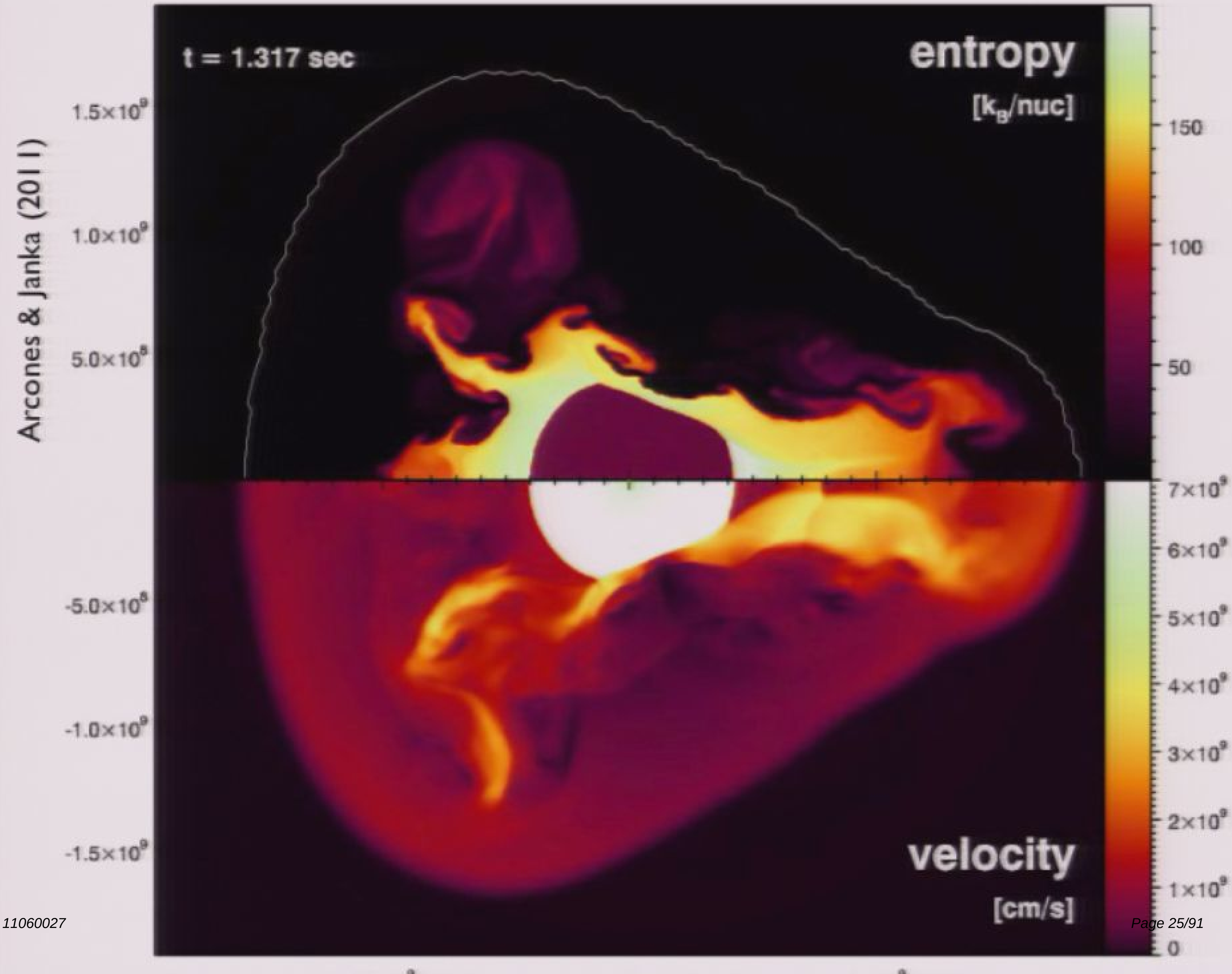
2×10⁹
1×10⁹
0


t = 1.317 sec
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[k_B/nuc]
velocity
[cm/s]
Arcones & Janka (2011)
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1.0×10^9
5.0×10^8
-5.0×10^8
-1.0×10^9
-1.5×10^9
150
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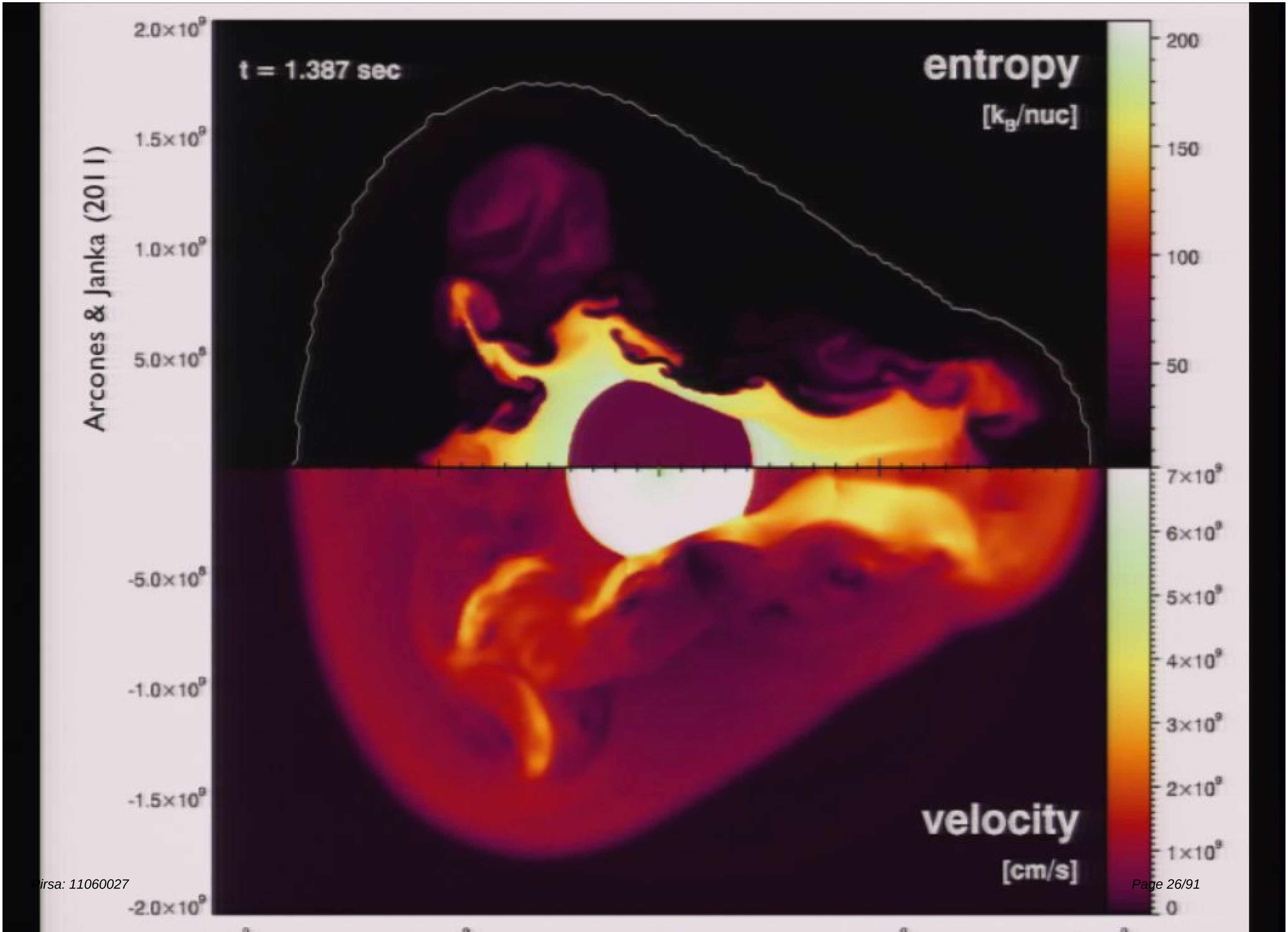
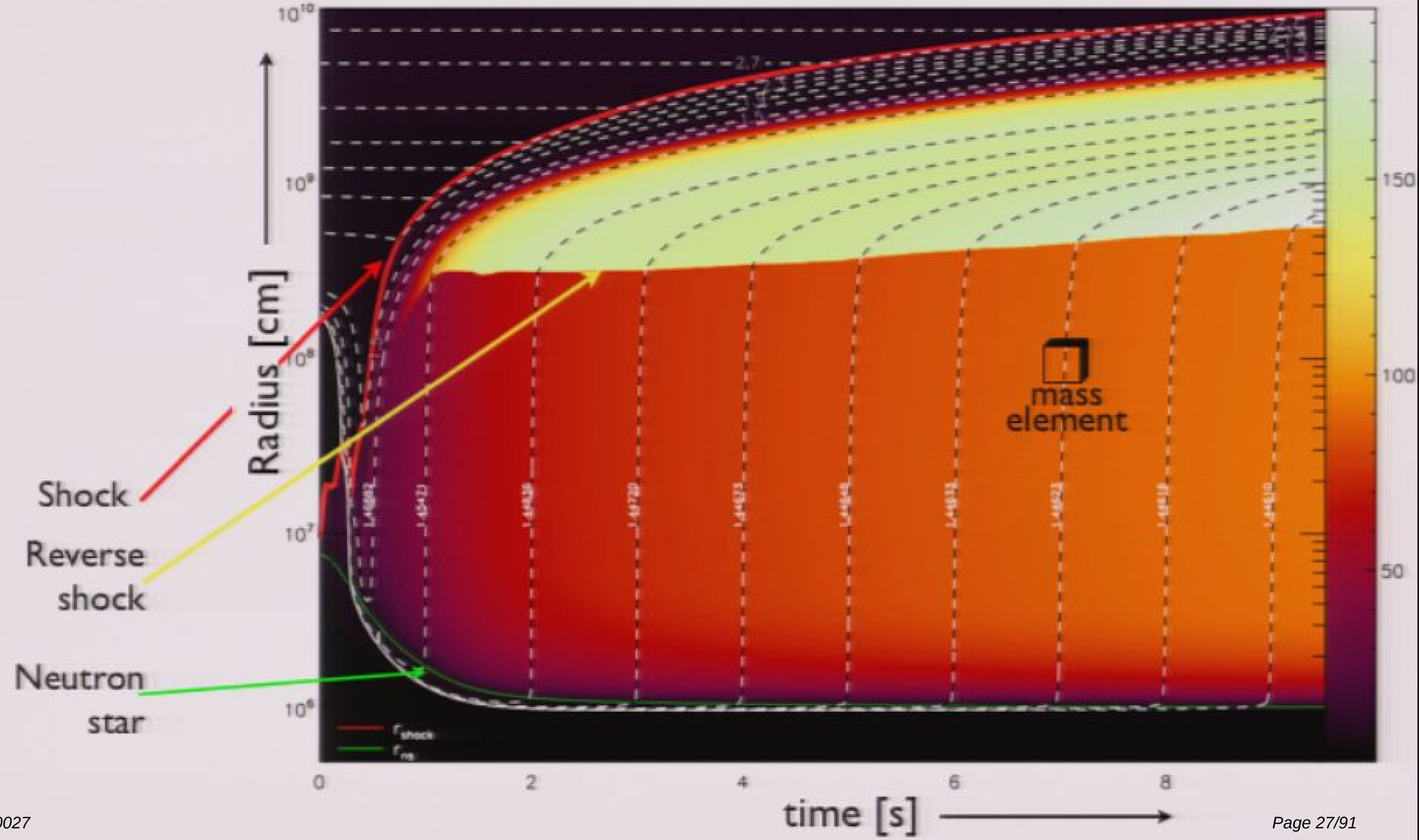
2×10^9
1×10^9
0


Arcones & Janka (2011)
t = 1.387 sec
entropy
[k_B/nuc]
velocity
[cm/s]
2.0×10⁹
1.5×10⁹
1.0×10⁹
5.0×10⁸
-5.0×10⁸
-1.0×10⁹
-1.5×10⁹
-2.0×10⁹
200
150
100
50
7×10⁹
6×10⁹
5×10⁹
4×10⁹
3×10⁹
2×10⁹
1×10⁹
0

1D simulations for nucleosynthesis studies

Arcones et al. 2007



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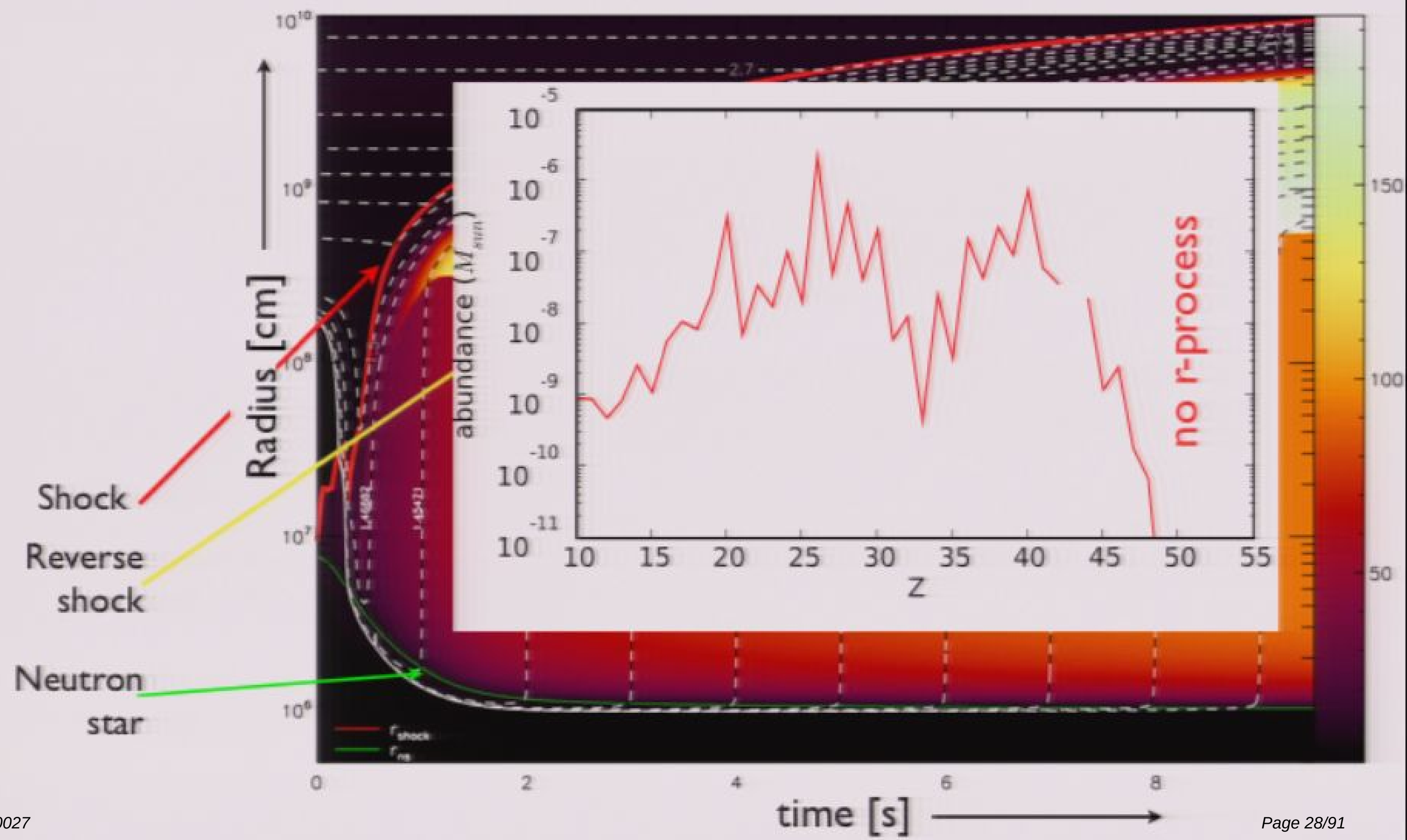
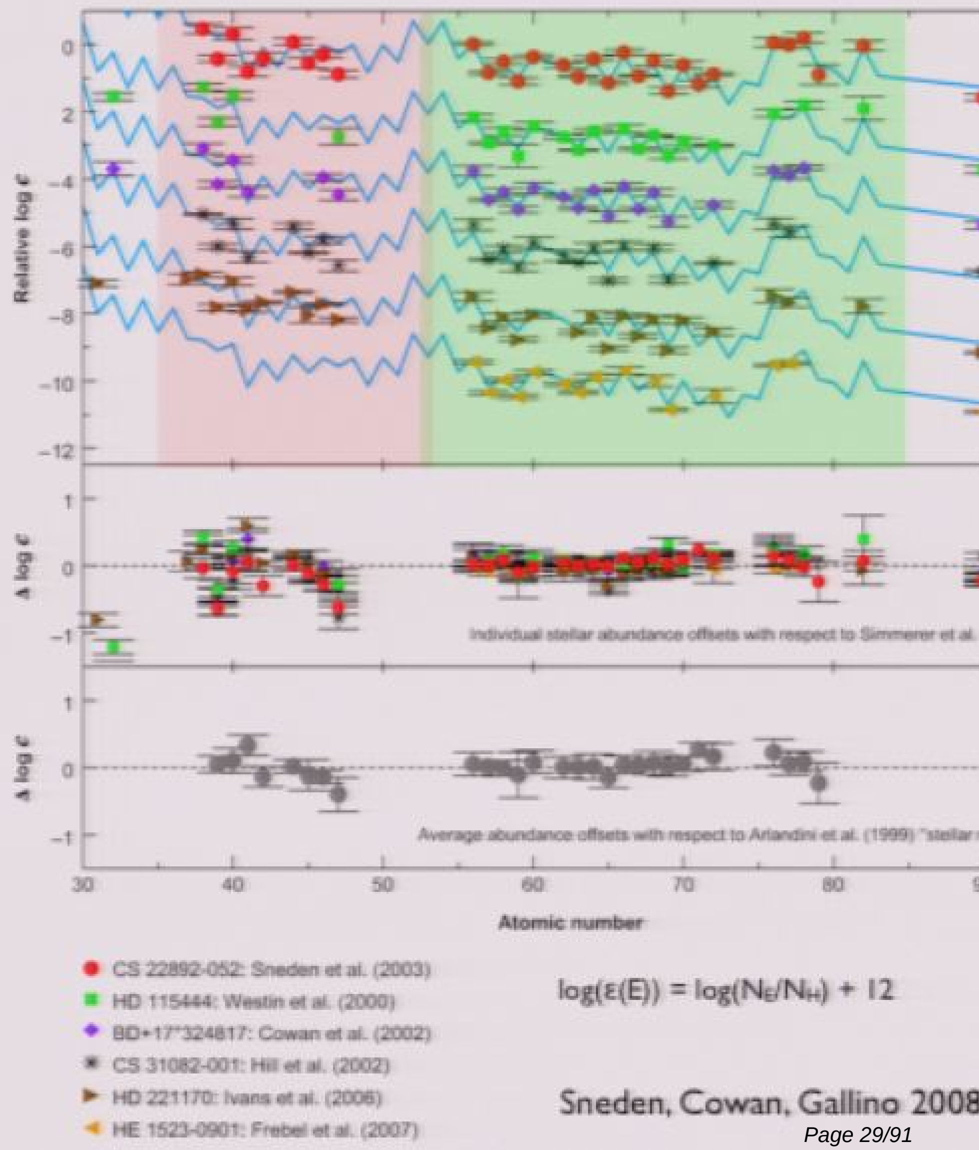


Ultra metal-poor stars = very old stars

Their atmospheres show fingerprints of only few nucleosynthesis events that enriched the interstellar medium.

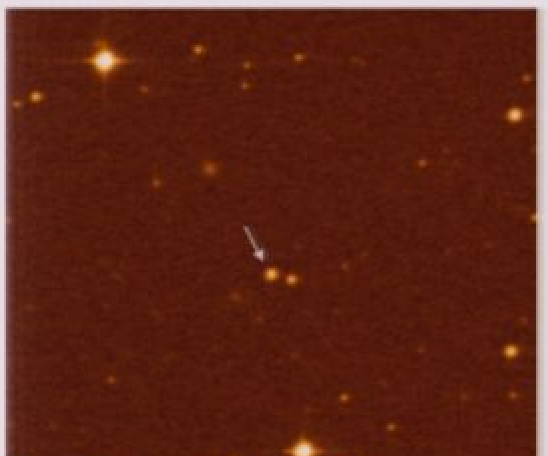
Abundances of r-process elements in:
- ultra metal-poor stars and
- solar system

Two components or sites:
- robust r-process for 56<Z<83
- scatter for lighter heavy elements Z~40



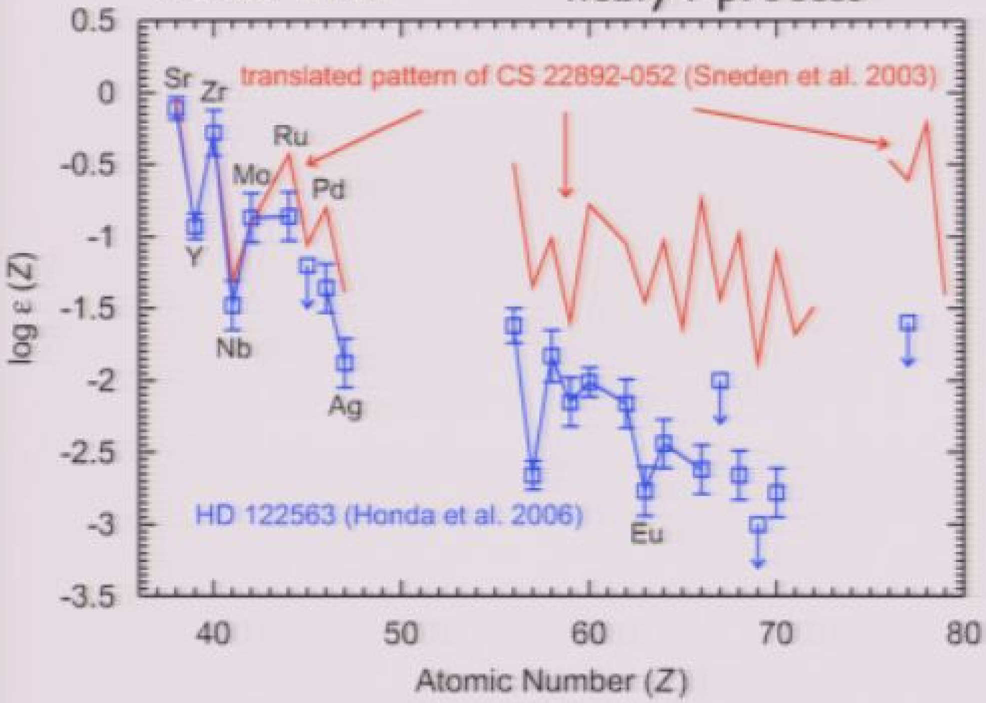
$$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$$

Sneden, Cowan, Gallino 2008



The very metal-deficient star HE 0107-5240 (Hamburg-ESO survey)

LEPP: Light Element Primary Process



Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei sugge two components or sites (Qian & Wasserburg

- stellar LEPP: neutrino-driven winds
- heavy r-process?

Travaglio et al. 2004:
solar = r-process + s-process + solar LEPP

Montes et al. 2007:
solar LEPP ~ stellar LEPP → unique

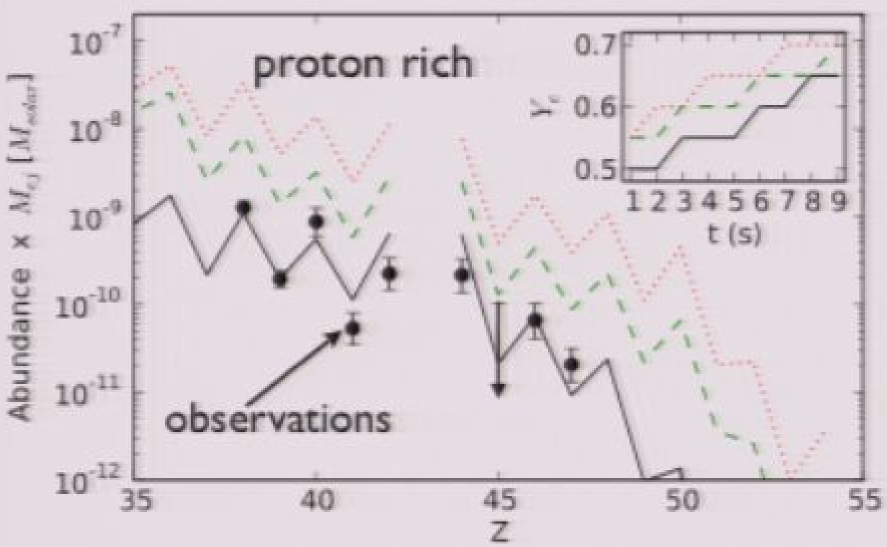
Can the LEPP pattern be produced in neutrino-driven wind simulations?

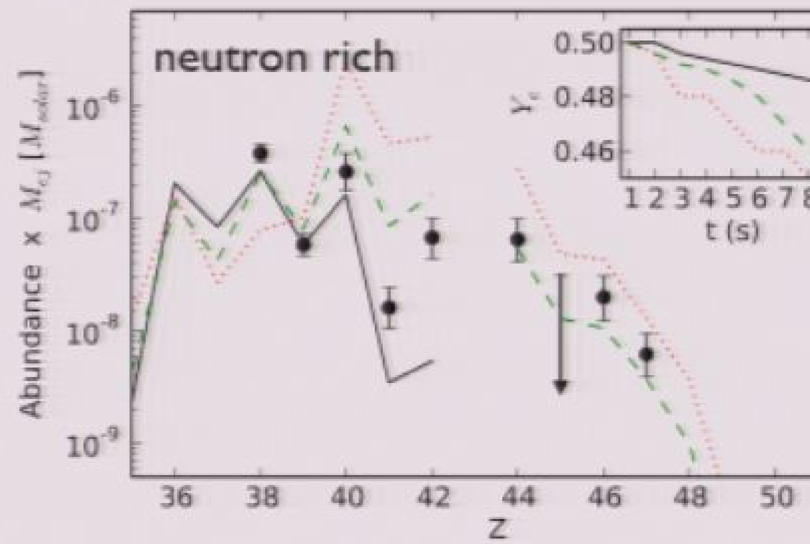
LEPP in neutrino-driven winds

(Arcones & Montes, 2011

Y_e depends on details of neutrino interactions and transport

Impact of the electron fraction: $Y_e = n_p/(n_p+n_n)$





Observation pattern can be reproduced!

Production of p-nuclei (neutron-deficient nuclei)

Overproduction at A=90, magic neu number N=50 (Hoffman et al. 1996) sugge only a fraction of neutron-rich ejecta

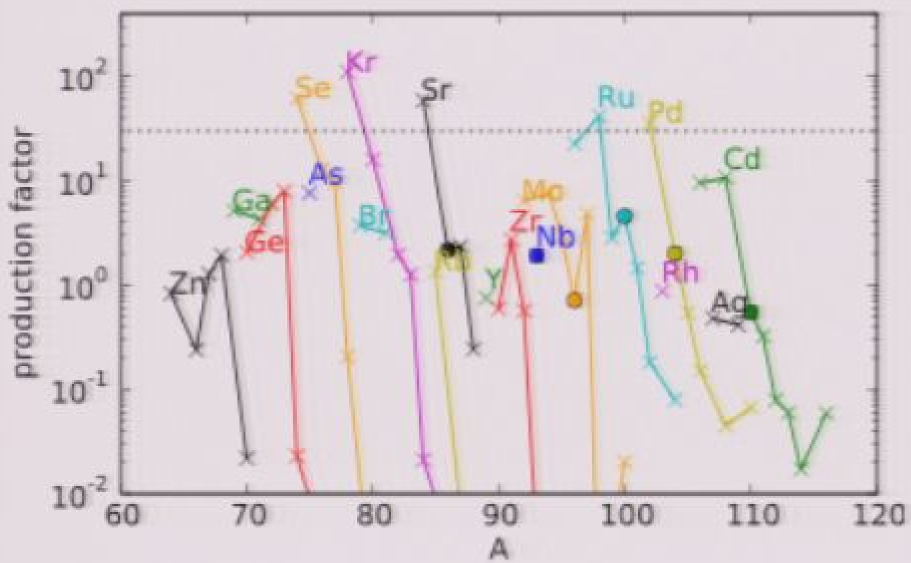
Isotopic abundances from old stars will give rise to new insights!

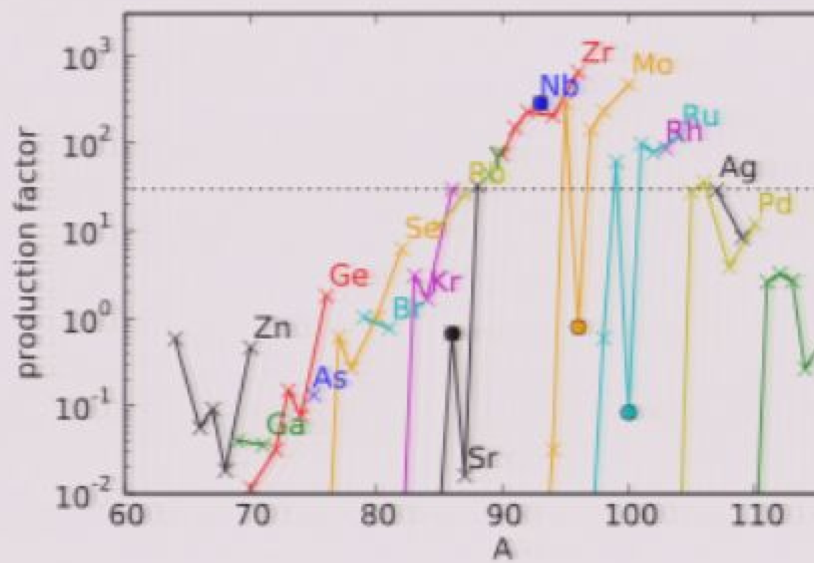
LEPP in neutrino-driven winds

(Arcones & Montes, 2011

Y_e depends on details of neutrino interactions and transport

Impact of the electron fraction: $Y_e = n_p/(n_p+n_n)$





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Overproduction at A=90, magic neu
number N=50 (Hoffman et al. 1996) sugge
only a fraction of neutron-rich ejecta

Isotopic abundances from old stars will give rise to new insights!

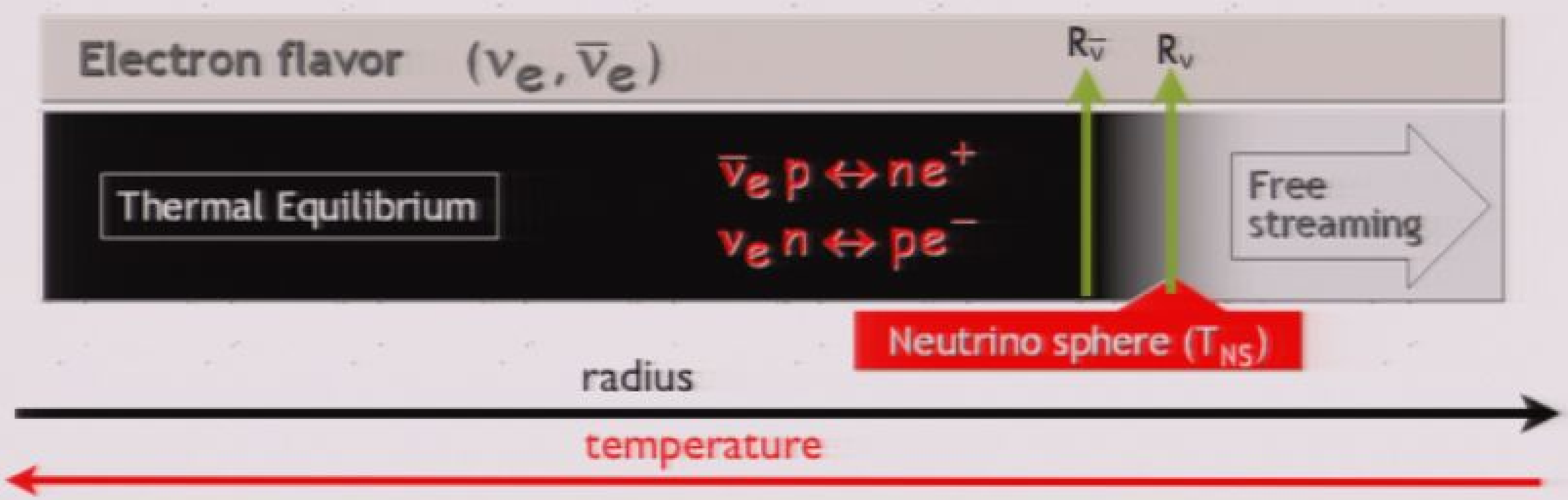
Electron fraction and uncertainties

Electron fraction depends on accuracy of the supernova neutrino transport and on details of neutrino interactions in the outer layers of the neutron star.

$$Y_e = \frac{\lambda_{\nu_e,n}}{\lambda_{\nu_e,n} + \lambda_{\bar{\nu}_e,p}} = \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\varepsilon_{\nu_e}}\right]^{-1}$$

($\Delta = m_n - m_p$)

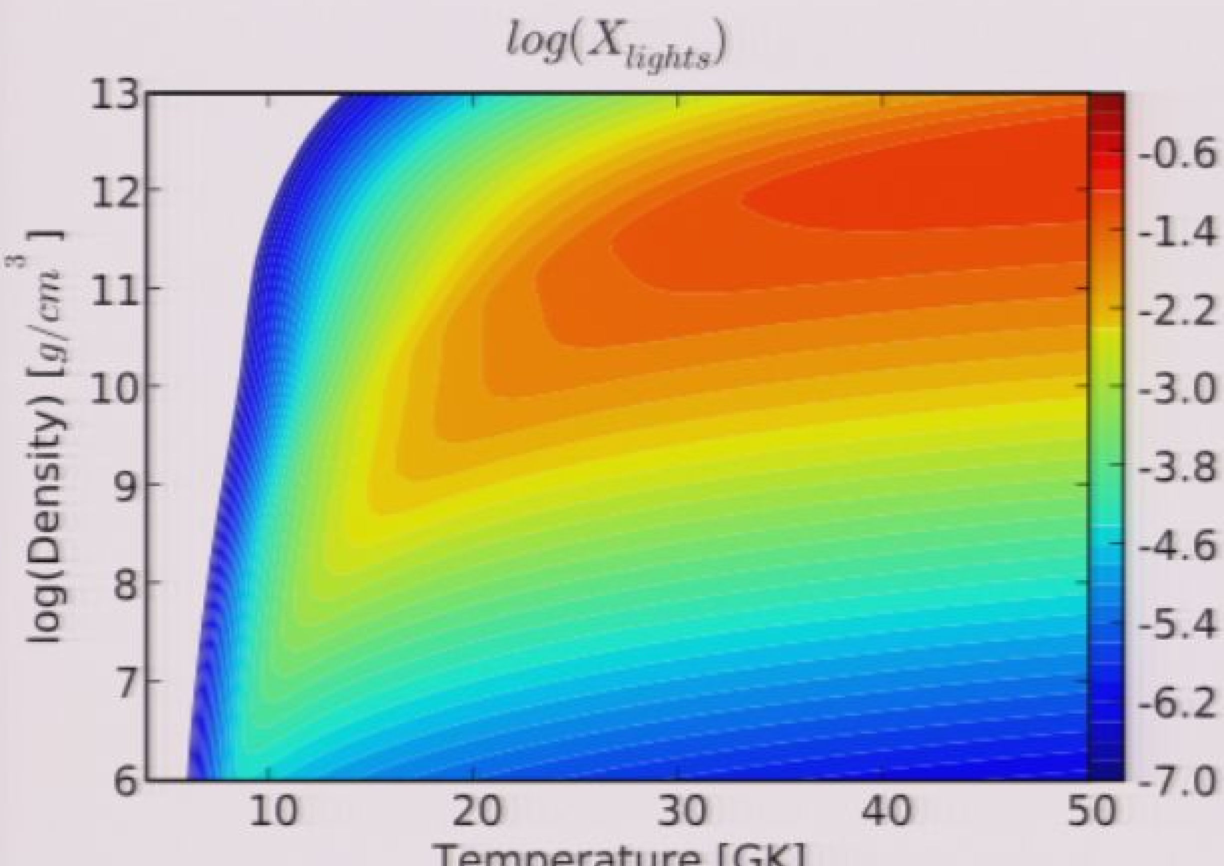
The neutrino energies are determined by the position (temperature) where neutrinos decouple from matter: neutrinosphere



$\varepsilon_{\bar{\nu}} > \varepsilon_{\nu}$

Light clusters 2<A<4

General assumptions (nuclear statistical equilibrium and beta equilibrium) provides constraints for equilibrium electron fraction and composition
(Arcones, Martinez-Pinedo, Roberts, Woosley 2010).



Not negligible amount of ligh
nuclei (^2H, ^3H, ^3He) in the ou
layers of the proto-neutron s
T ~ 5MeV and ρ ~ 10^{12} g/cm

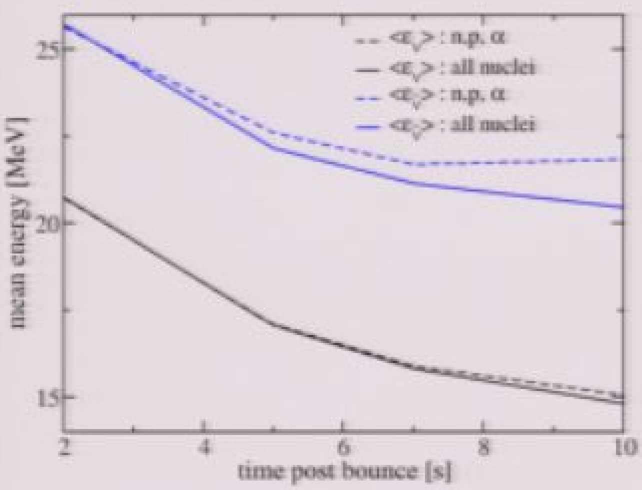
Impact on the neutrino spect

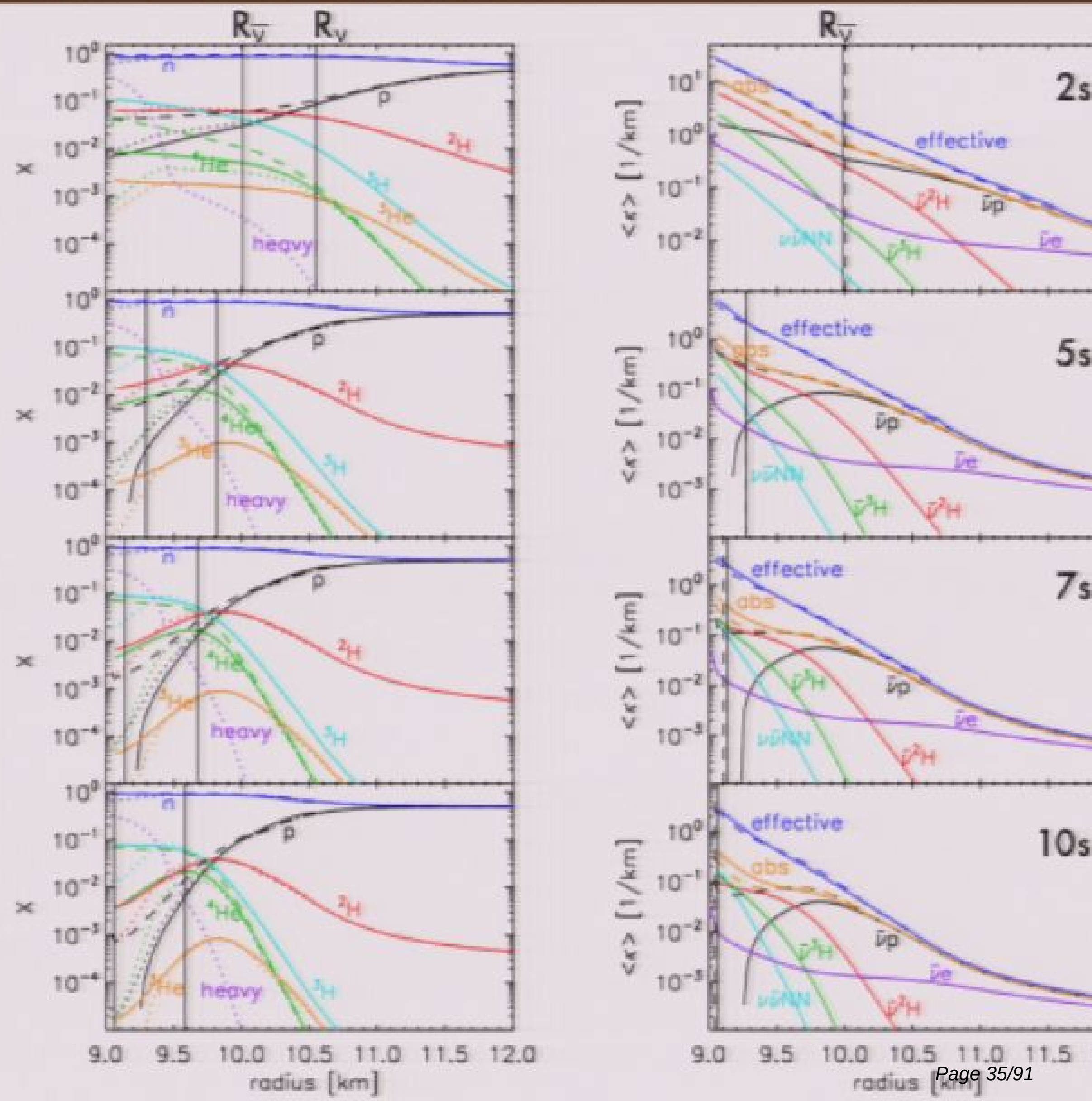
Also provides checks for pre-supernova models (and weak rates).

Light clusters 2<A<4

Arcones et al.

^2H and ^3H are more abundant than protons, contribute to antineutrino opacity.





Light clusters 2<A<4

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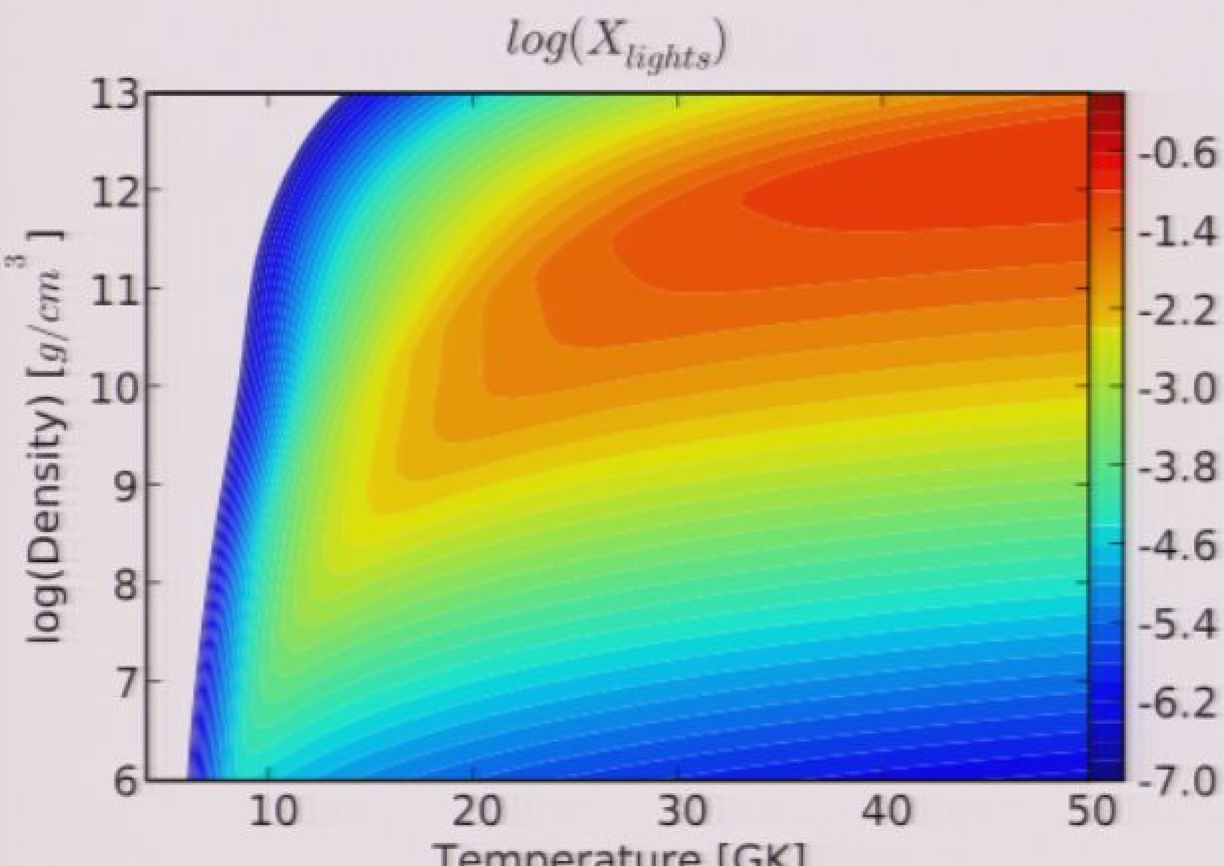

Not negligible amount of ligh
nuclei (^{2}H, ^{3}H, ^{3}He) in the ou
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Light clusters 2<A<4

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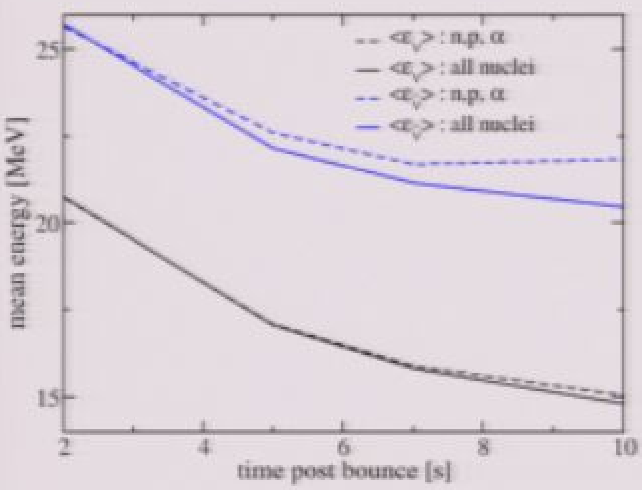
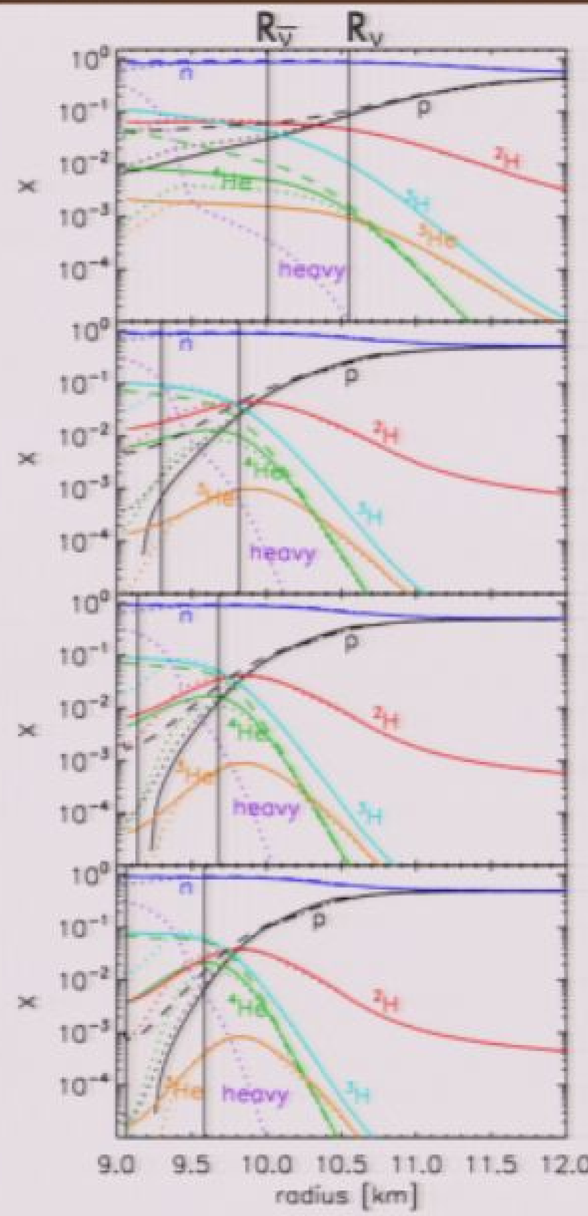
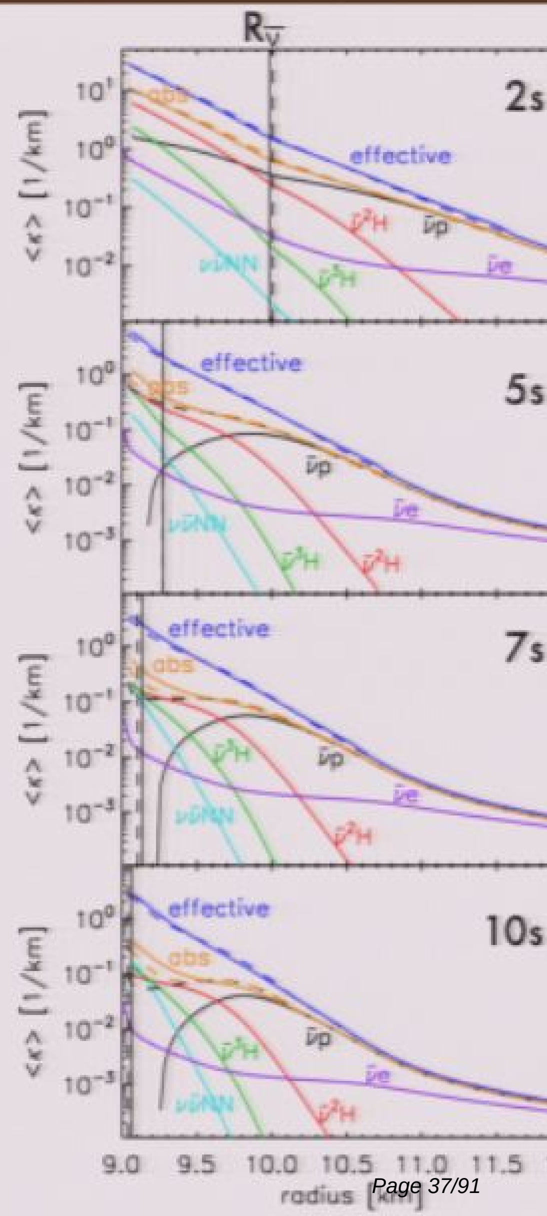


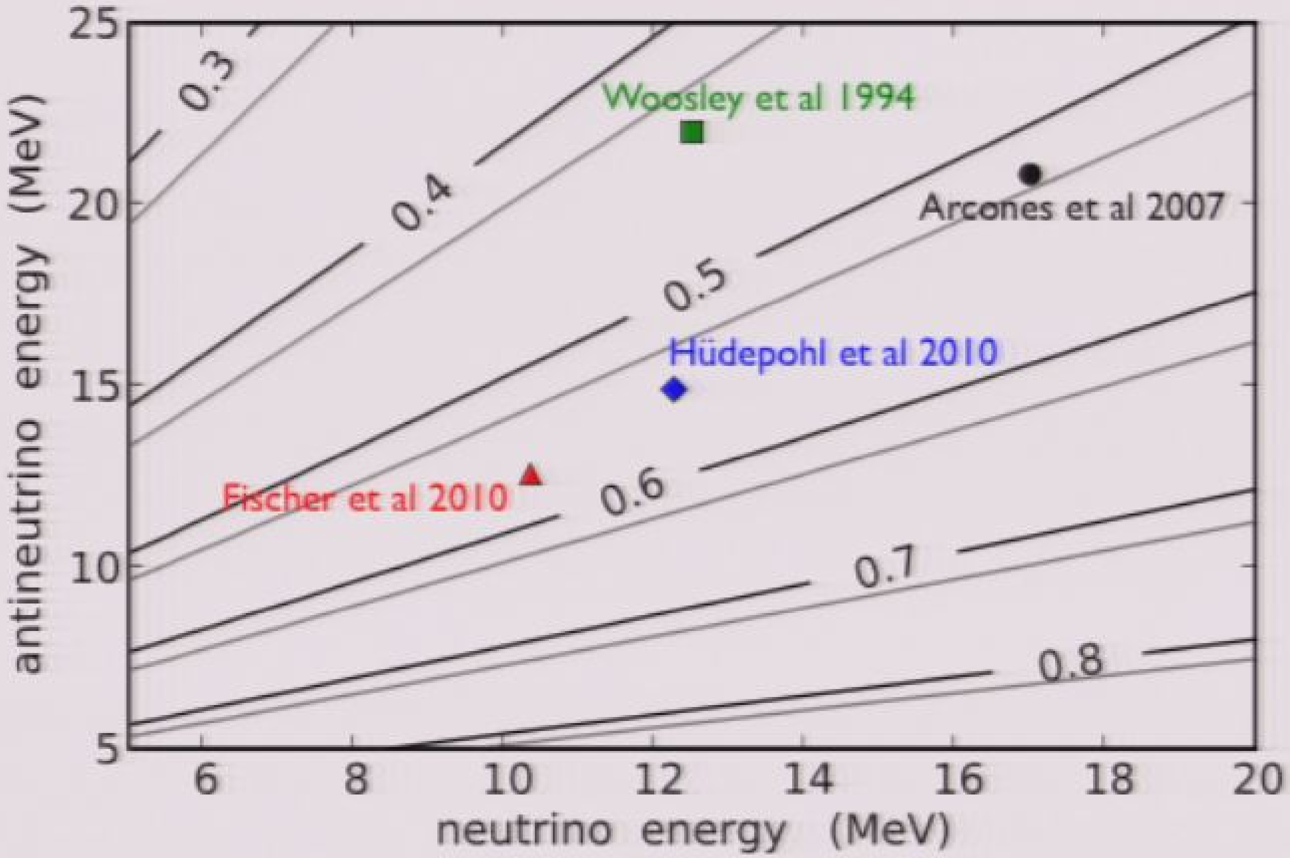




Wind models and electron fraction

Neutrino energies change with more realistic neutrino physics input

More recent simulations obtain lower antineutrino energies and therefore proton-rich conditi



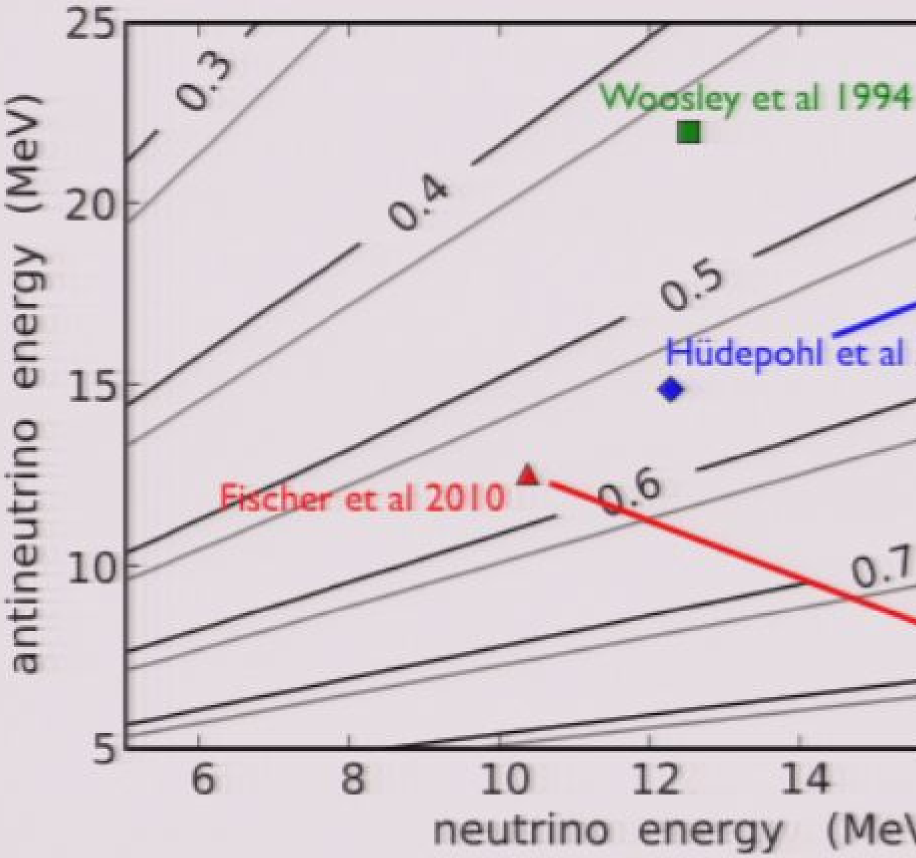
Qian & Woosley 1996

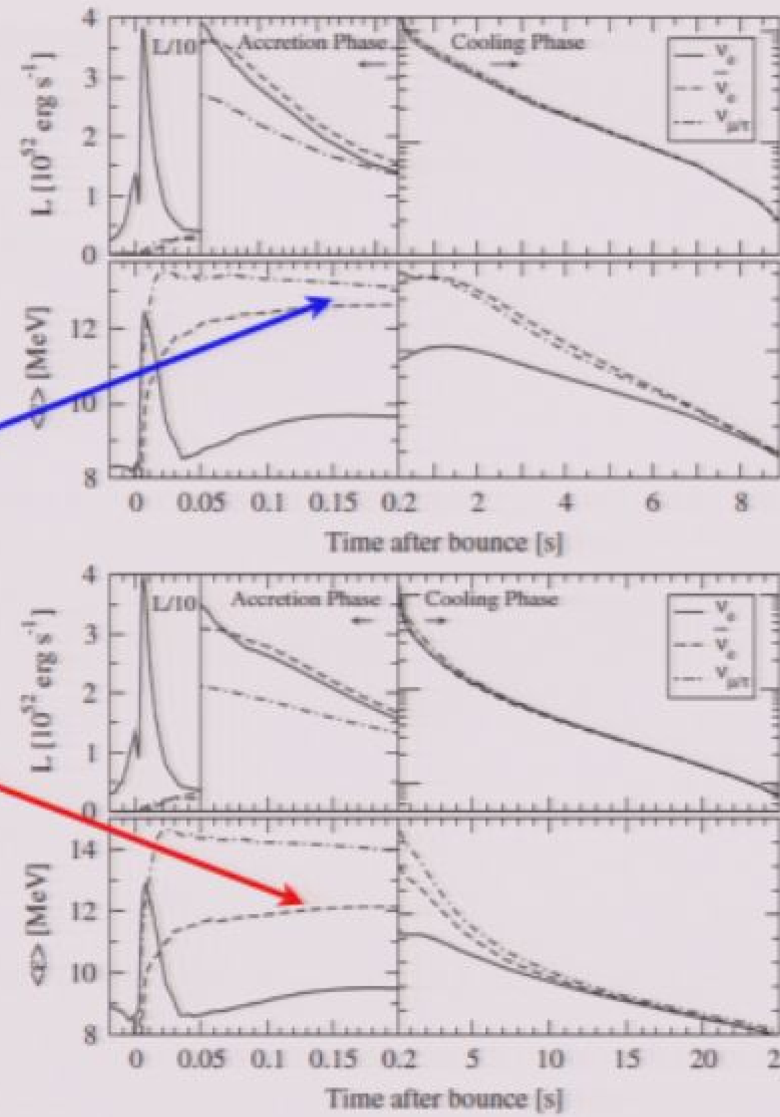
$$Y_e = \frac{\lambda_{\nu_e,n}}{\lambda_{\nu_e,n} + \lambda_{\bar{\nu}_e,p}} = \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\varepsilon_{\nu_e}}\right]^{-1}$$

$Y_e > 0.5$: $\varepsilon_{\bar{\nu}} - \varepsilon_{\nu} < 4\Delta$

Wind models and electron fraction

Neutrino energies change with more realistic neu
More recent simulations obtain lower antineutrinc



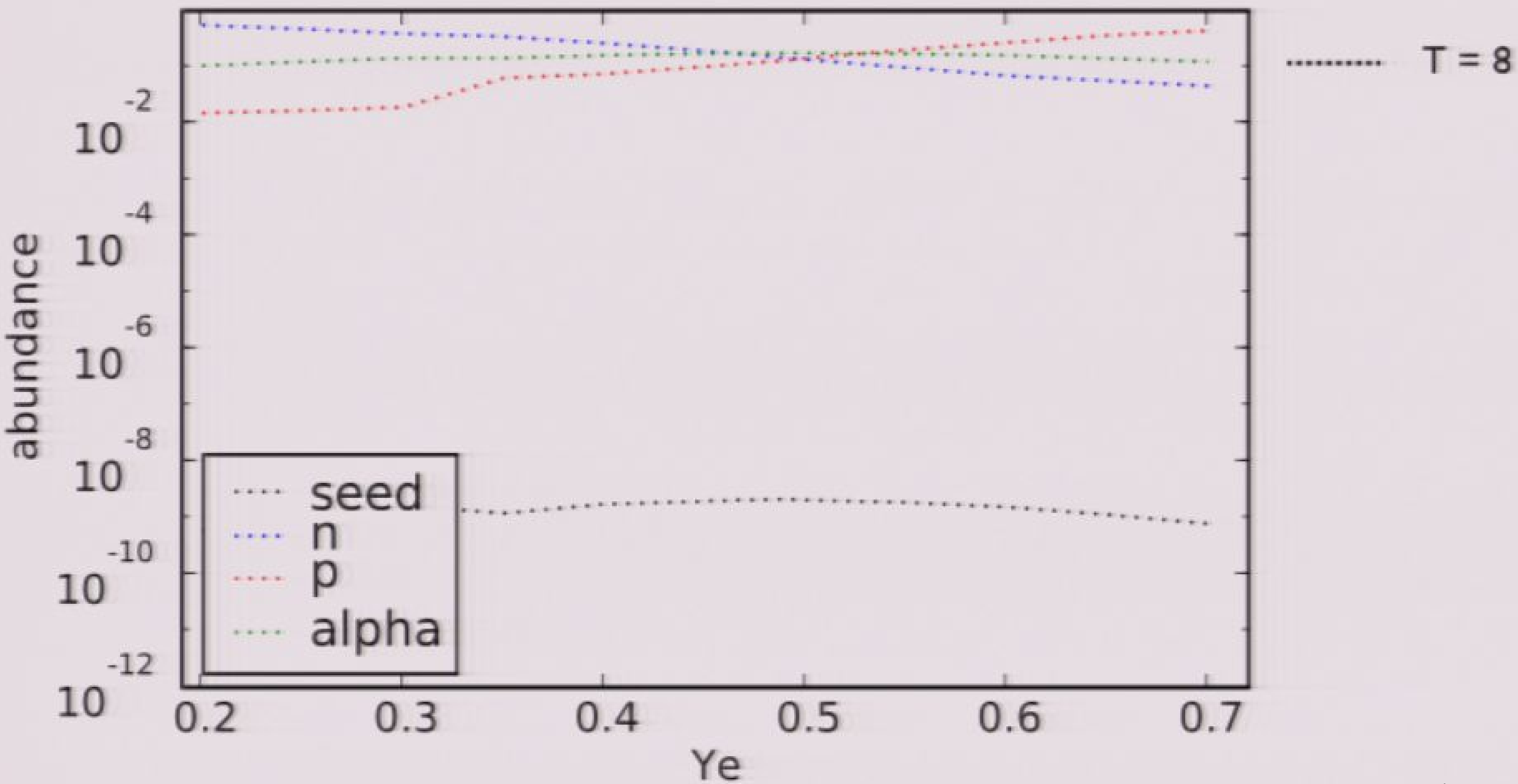


$$Y_e = \frac{\lambda_{\nu_e,n}}{\lambda_{\nu_e,n} + \lambda_{\bar{\nu}_e,p}} = \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta +}{\varepsilon_{\nu_e} + 2\Delta +}\right.$$

FIG. 1. Neutrino luminosities and mean energies obse infinity. Top: Full set of neutrino opacities (model Sf). E

Nucleosynthesis and electron fraction

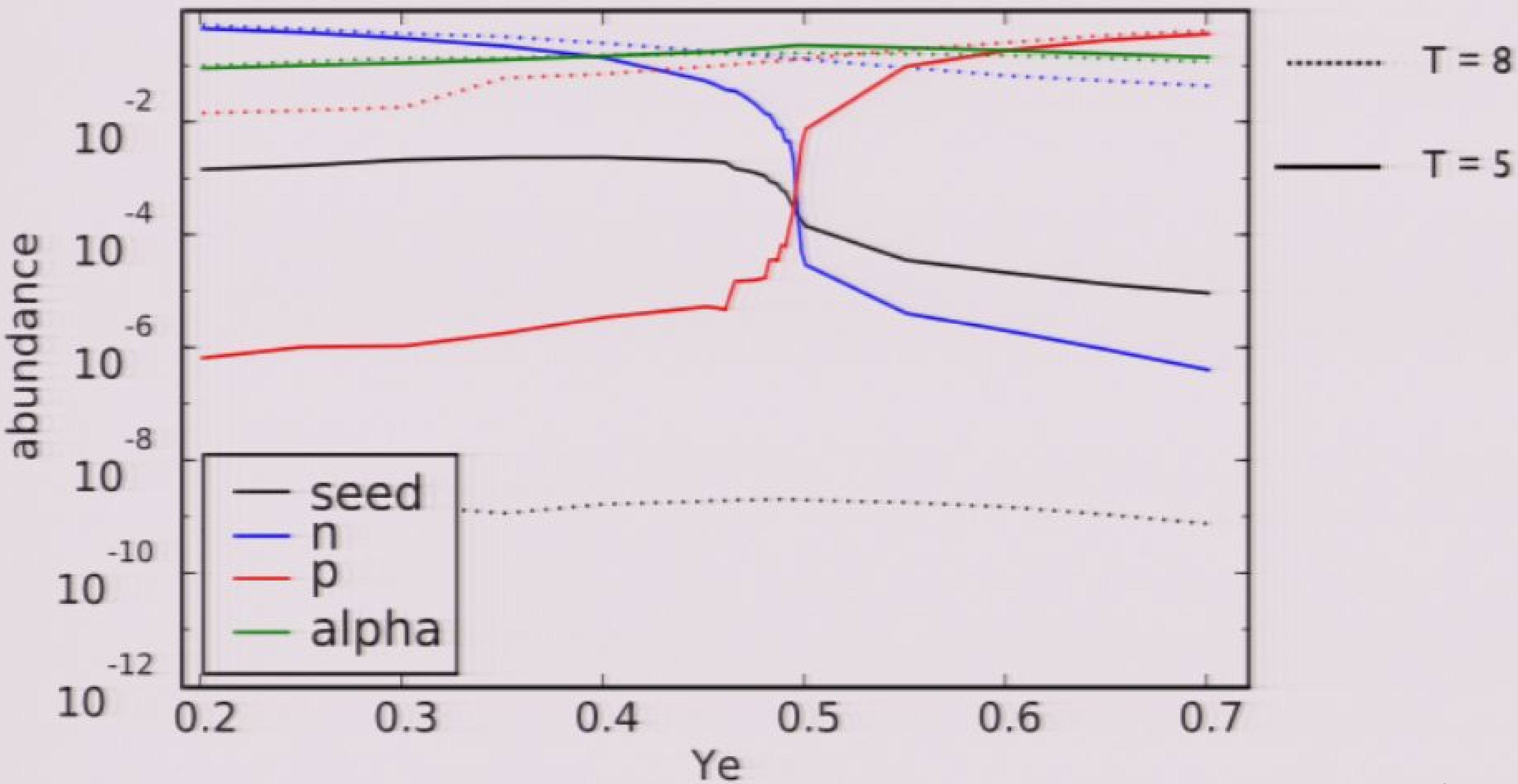
Initial composition is given by NSE, at high temperatures only n, p and alphas.



Nucleosynthesis and electron fraction

Initial composition is given by NSE, at high temperatures only n, p and alphas.

Alpha particles recombine forming seed nuclei.

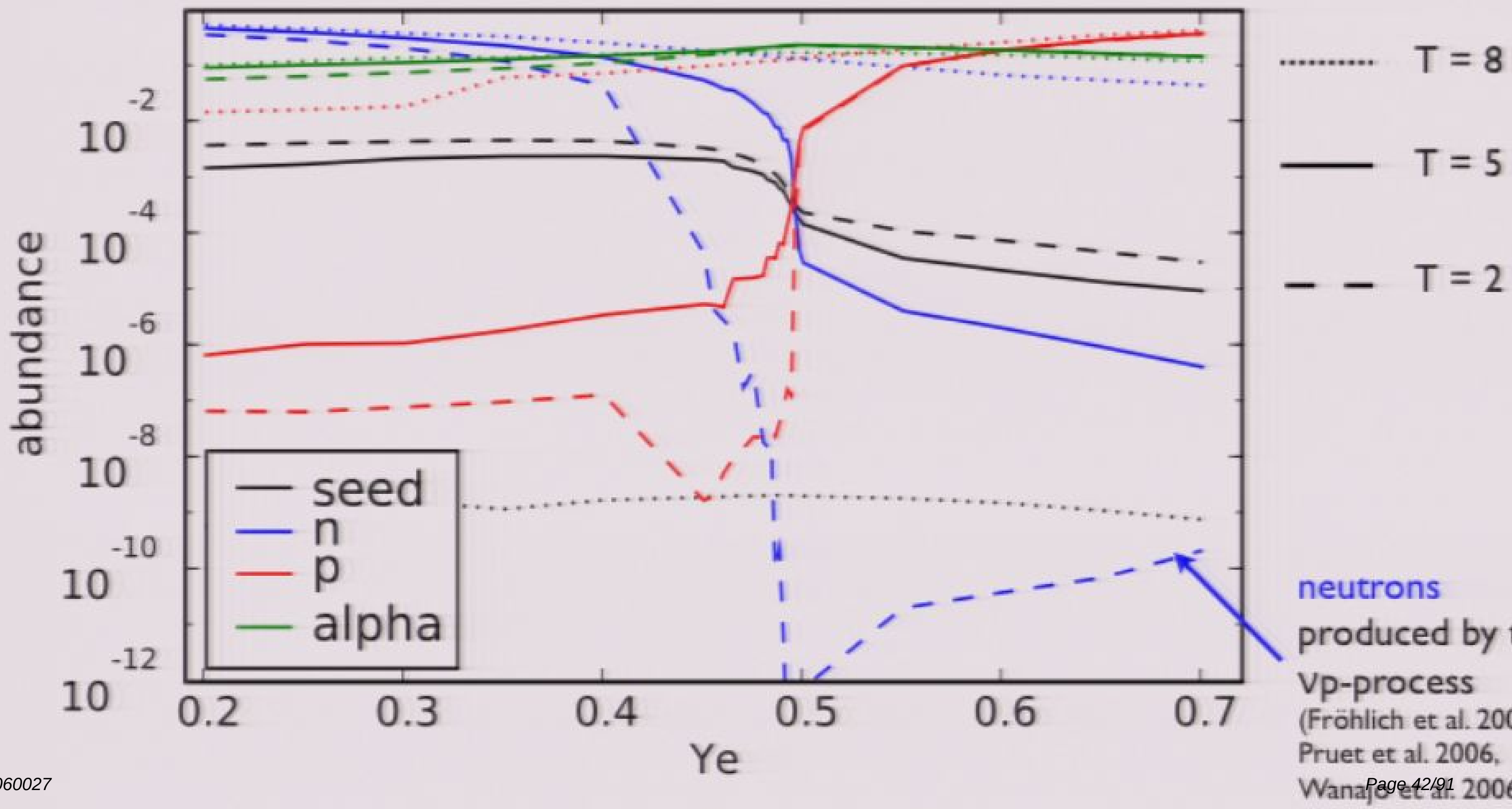


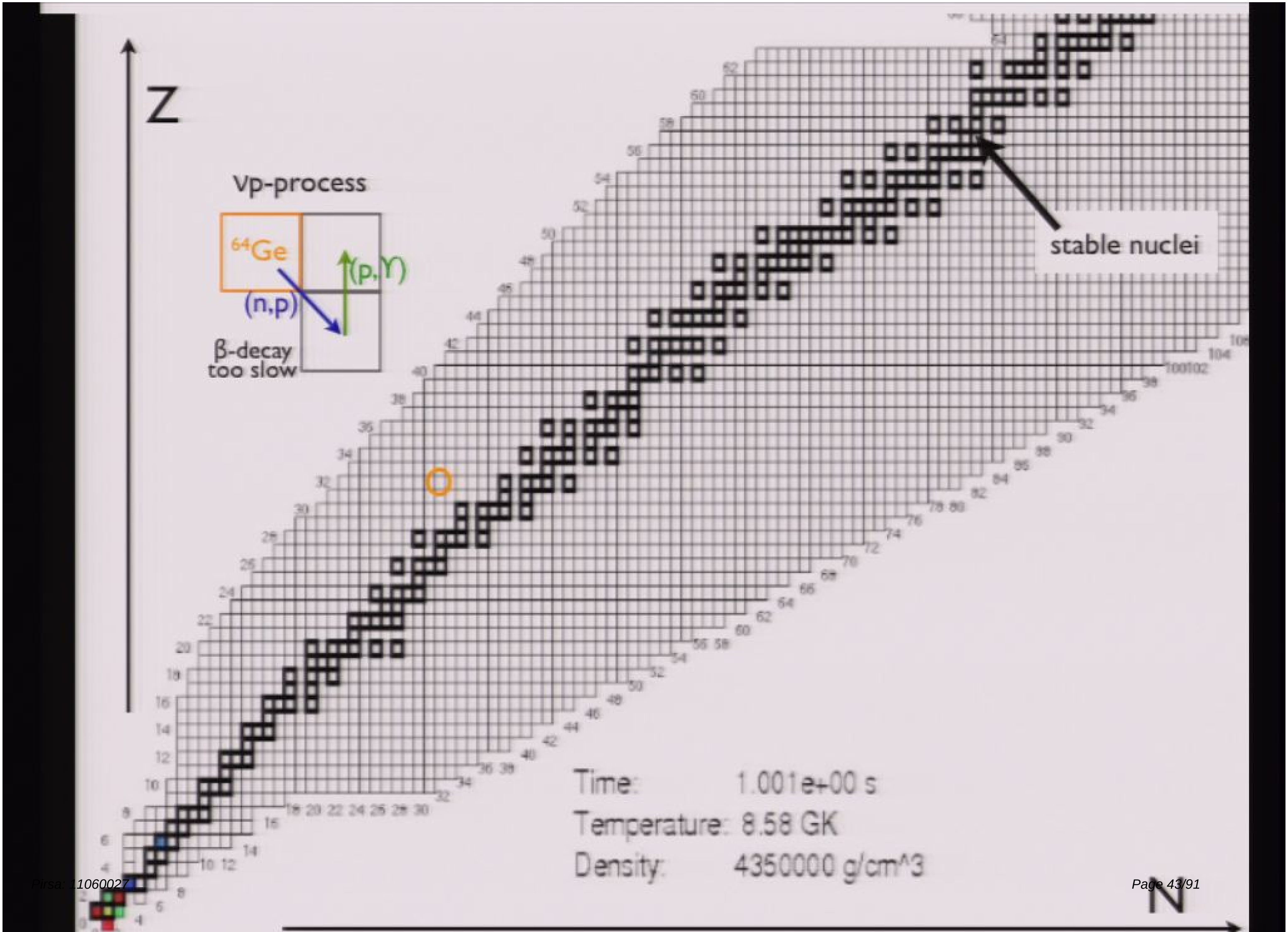
Nucleosynthesis and electron fraction

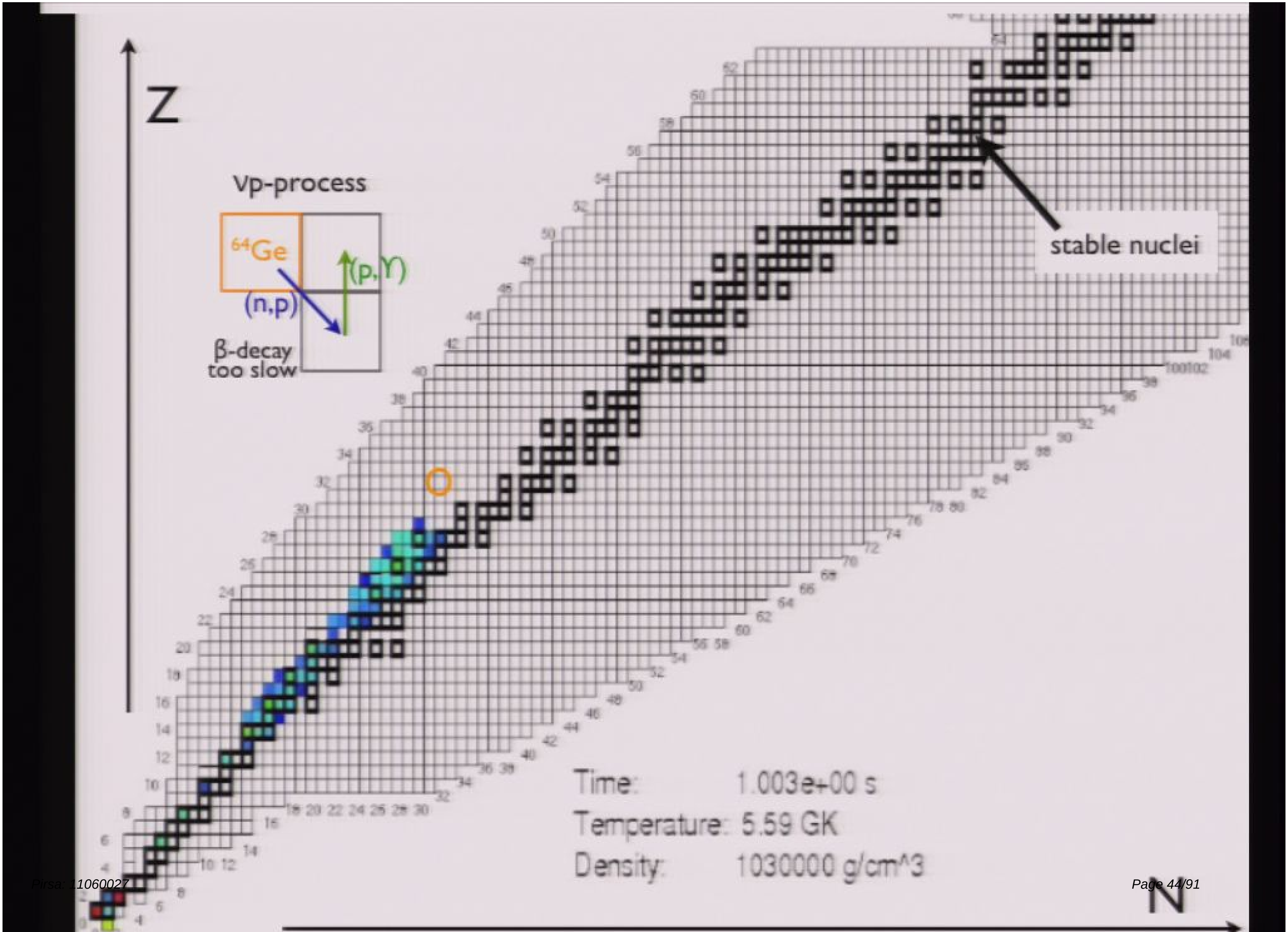
Initial composition is given by NSE, at high temperatures only n, p and alphas.

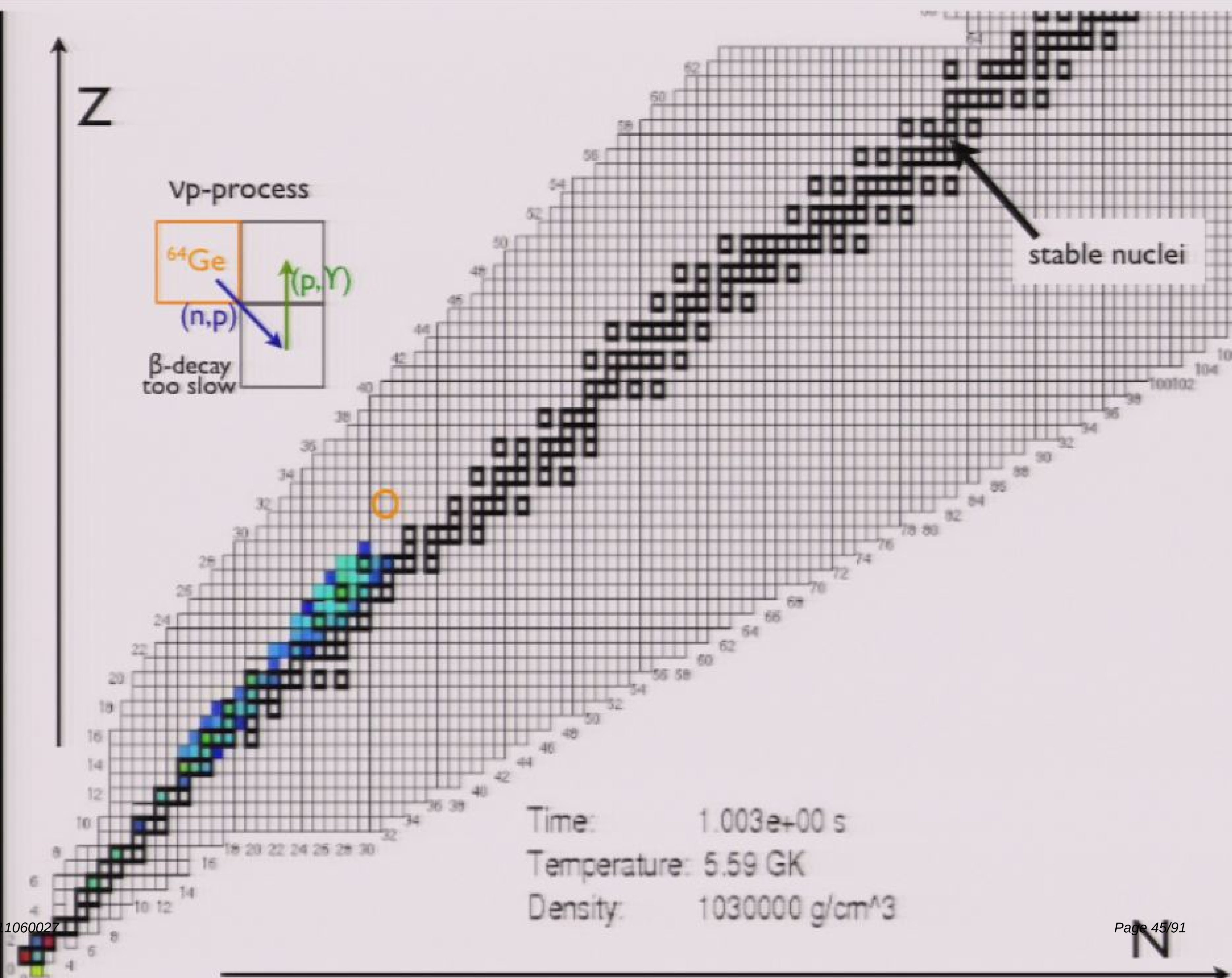
Alpha particles recombine forming seed nuclei.

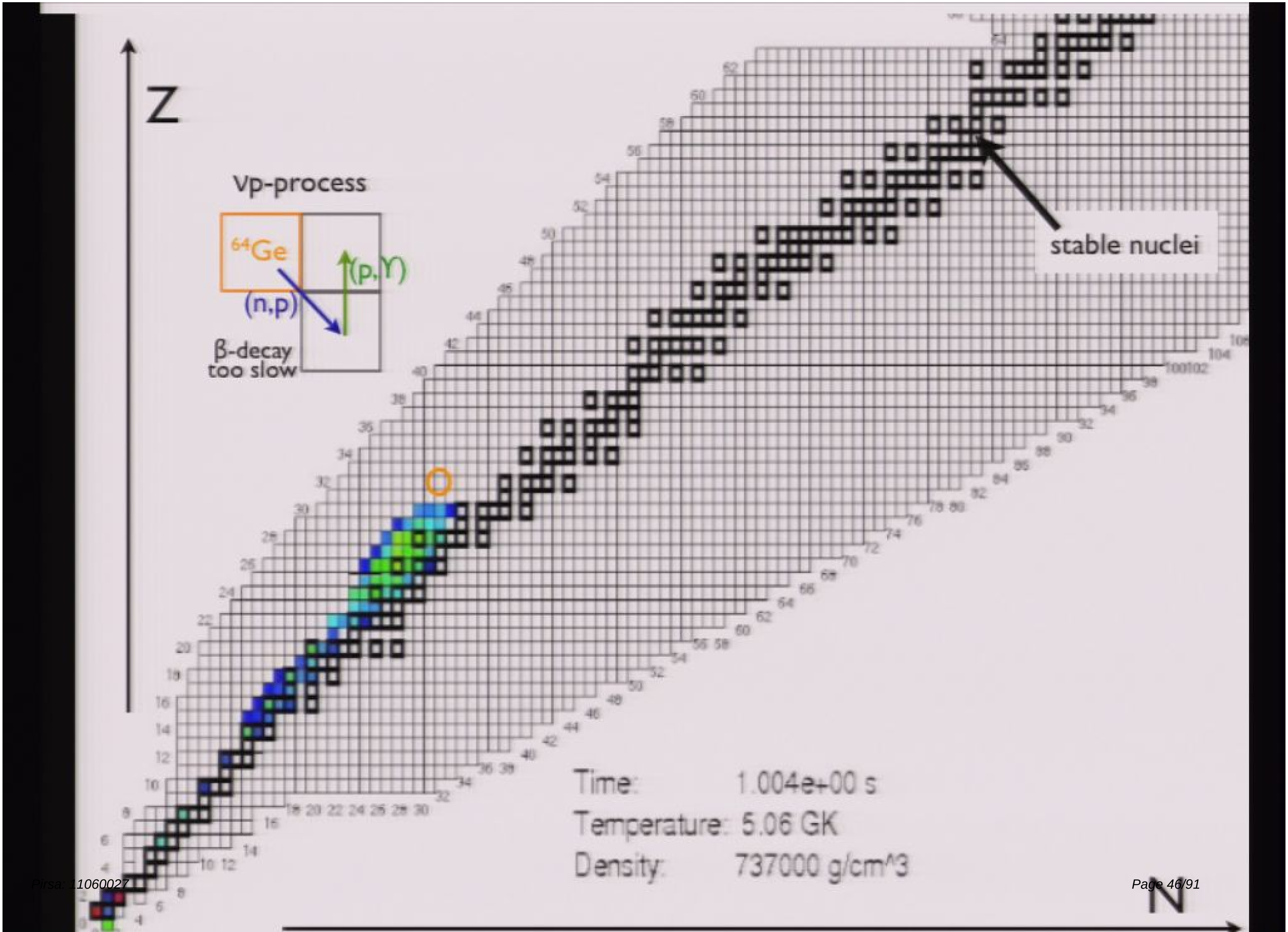
At freeze-out neutron- and proton-to-seed ratio determine production of heavy elements.

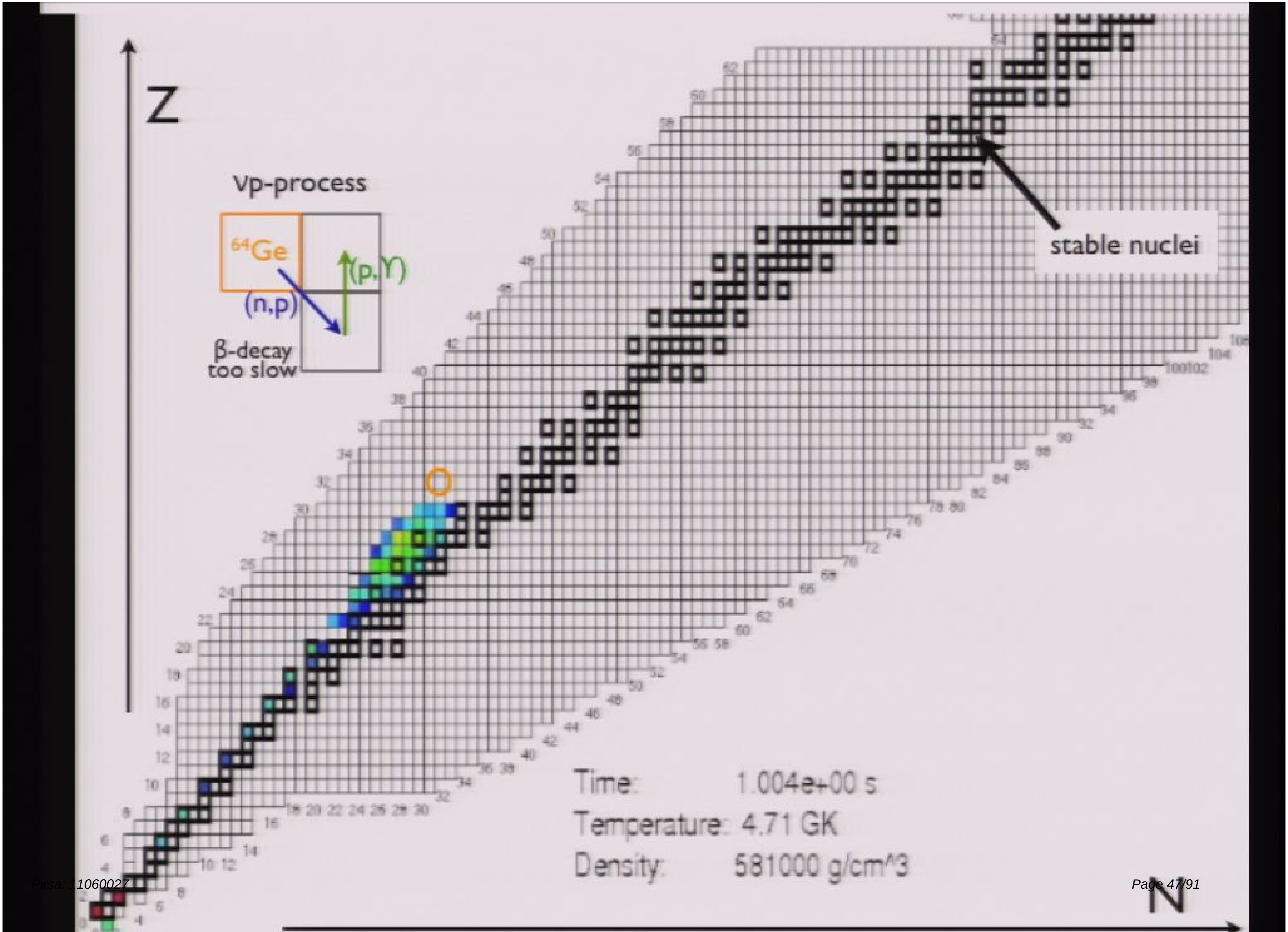



Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.001e+00 s
Temperature: 8.58 GK
Density: 4350000 g/cm^3
N

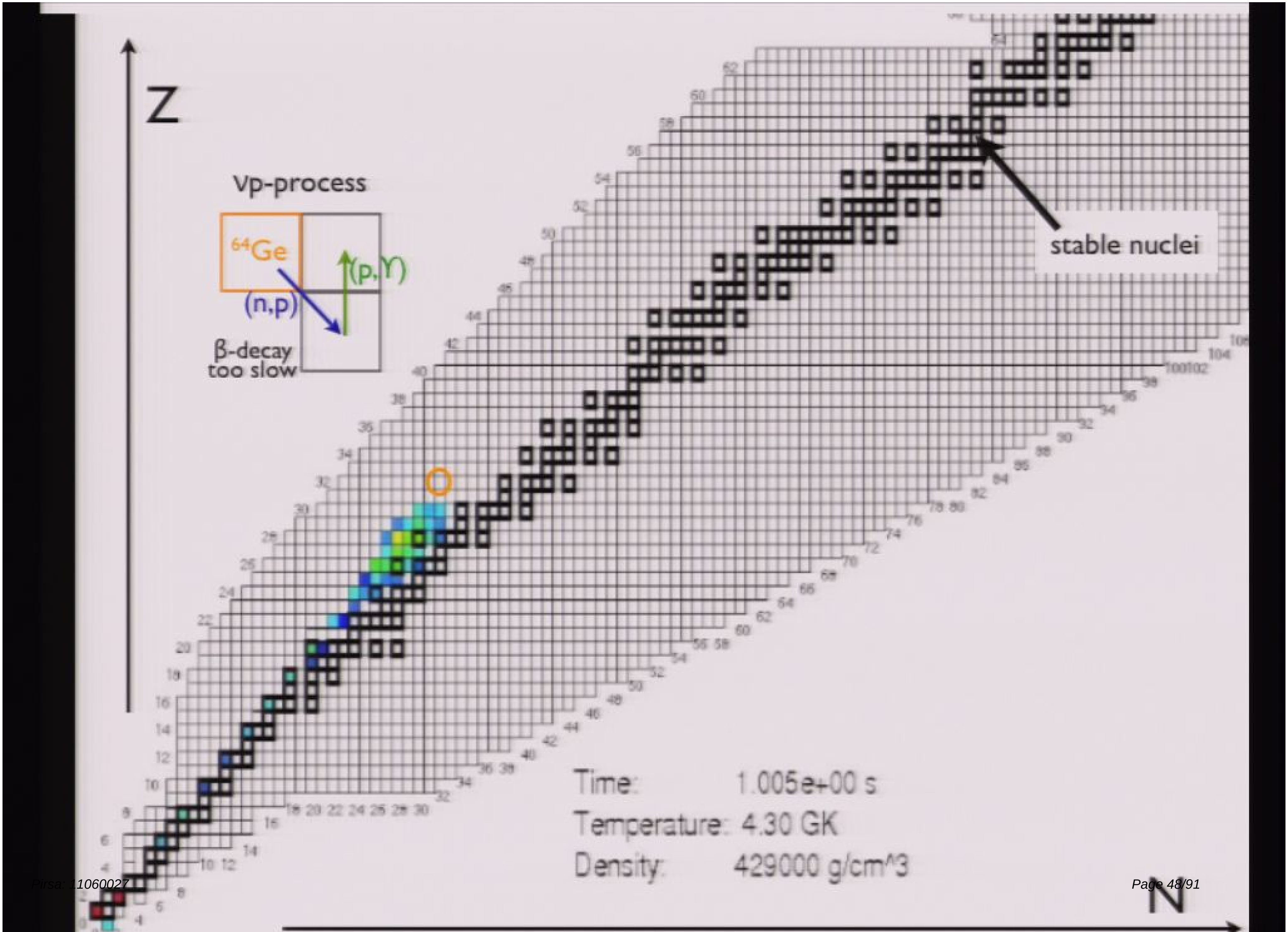

Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.003e+00 s
Temperature: 5.59 GK
Density: 1030000 g/cm^3
N

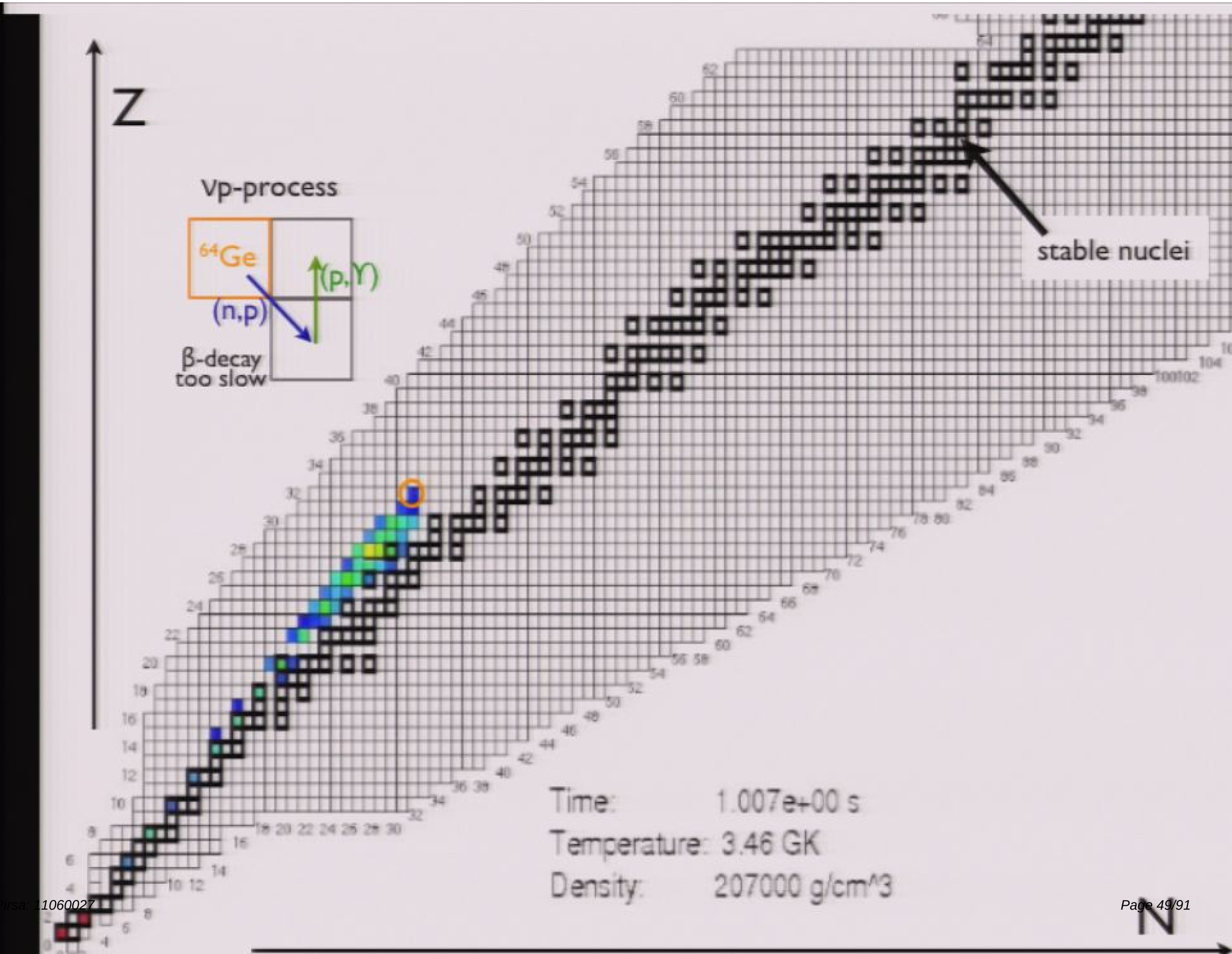

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.003e+00 s
Temperature: 5.59 GK
Density: 1030000 g/cm^3
N

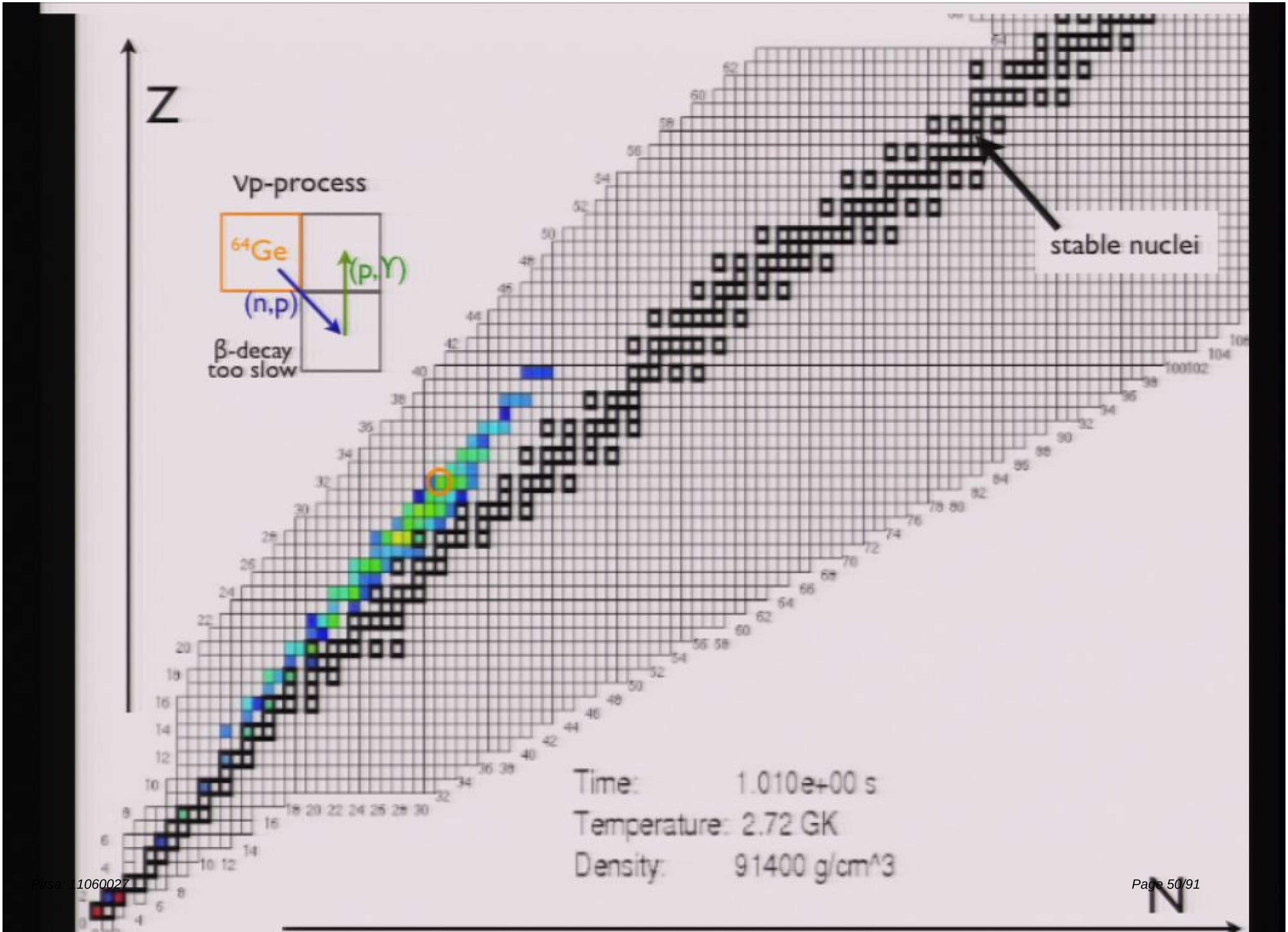

Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.004e+00 s
Temperature: 5.06 GK
Density: 737000 g/cm^3
N

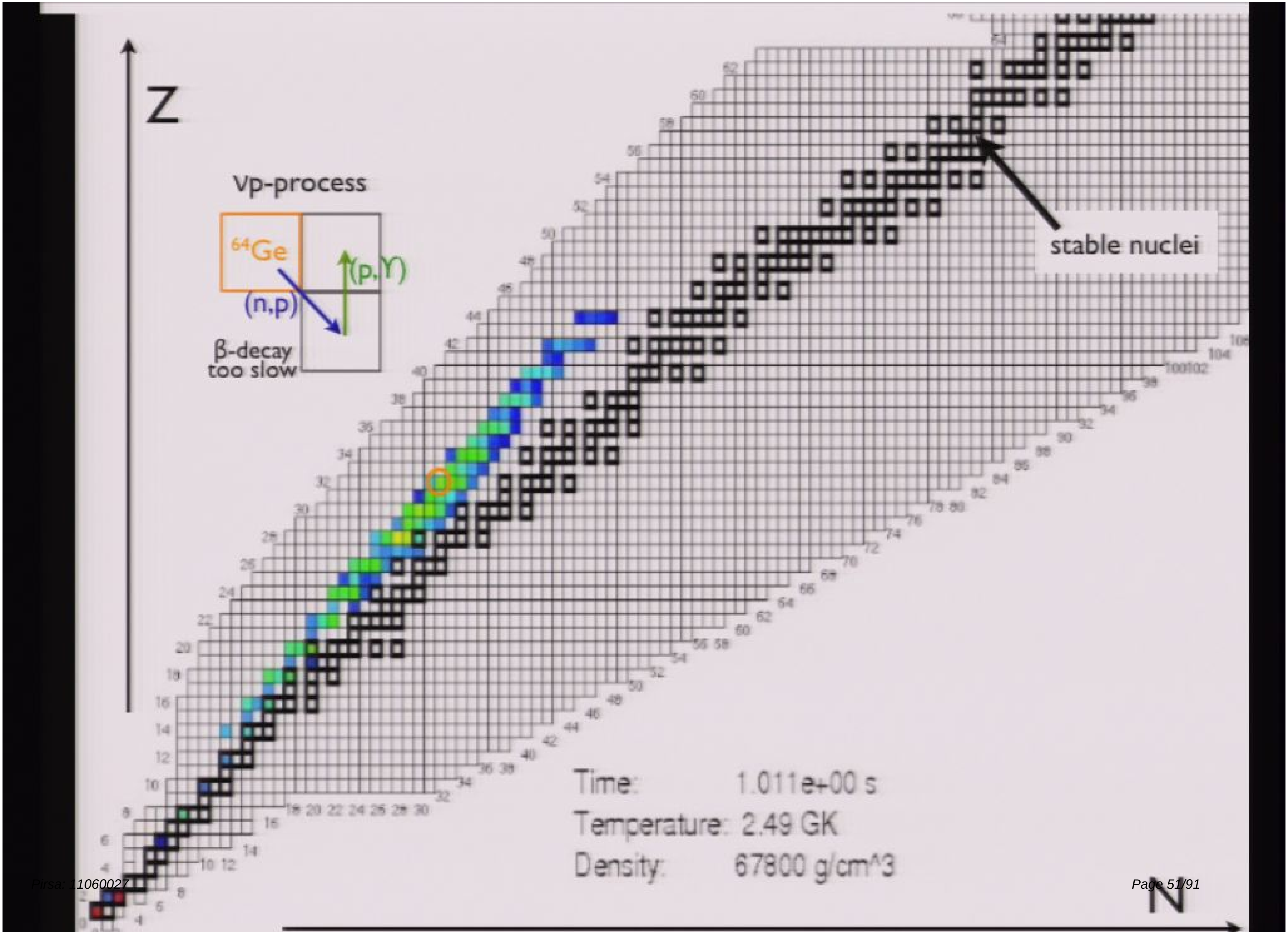


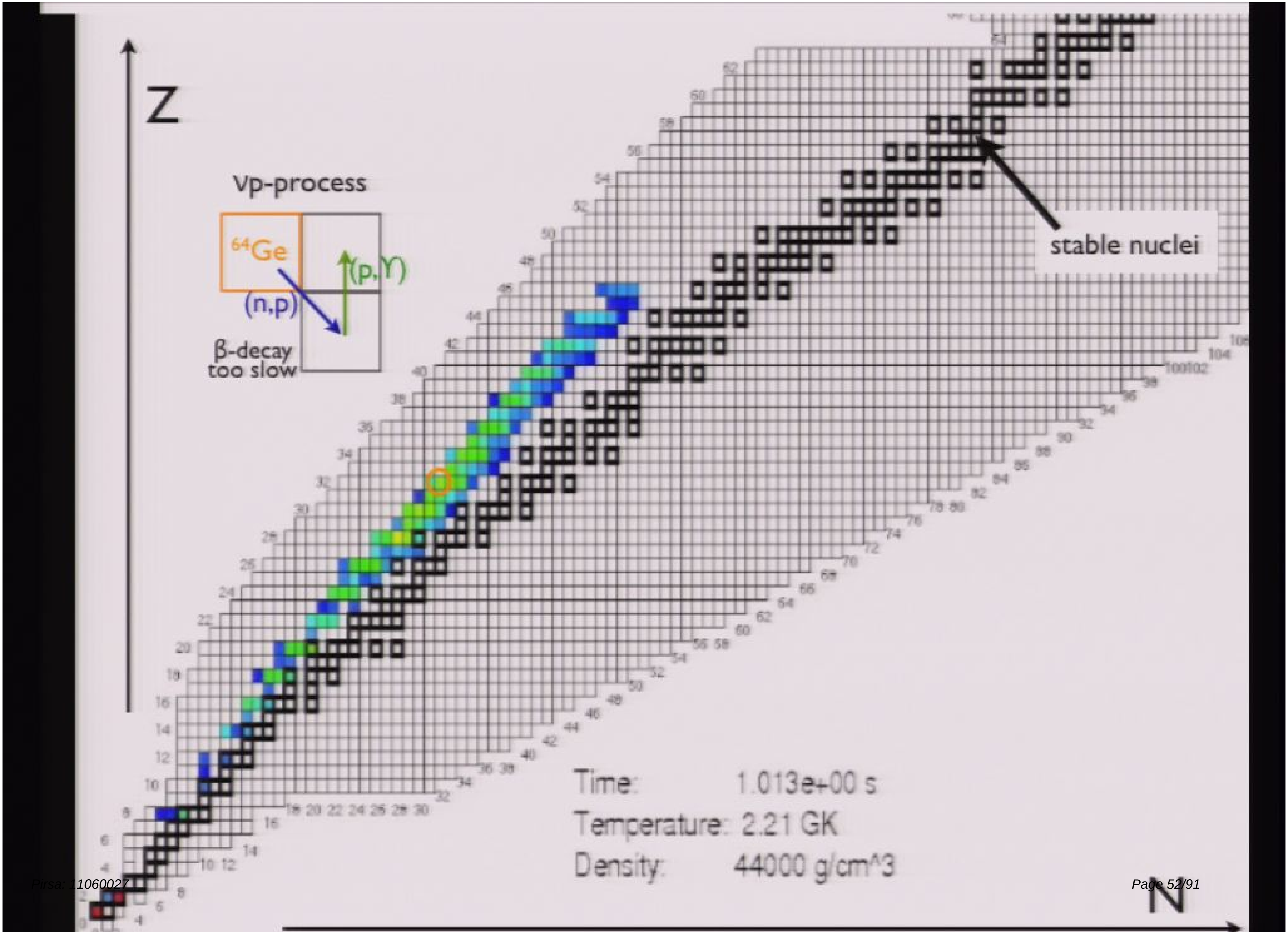
Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.004e+00 s
Temperature: 4.71 GK
Density: 581000 g/cm^3
N

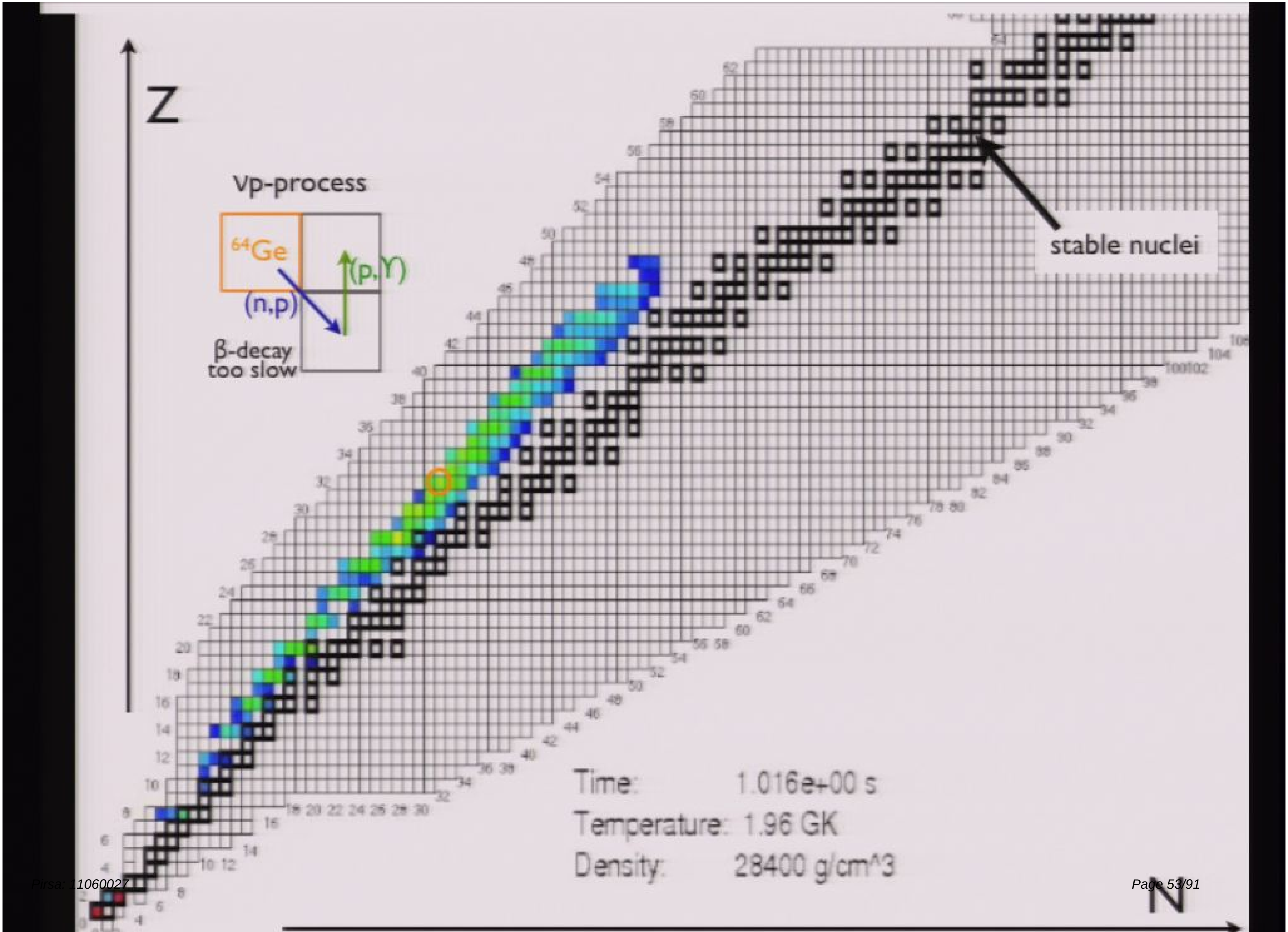

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.005e+00 s
Temperature: 4.30 GK
Density: 429000 g/cm^3
N

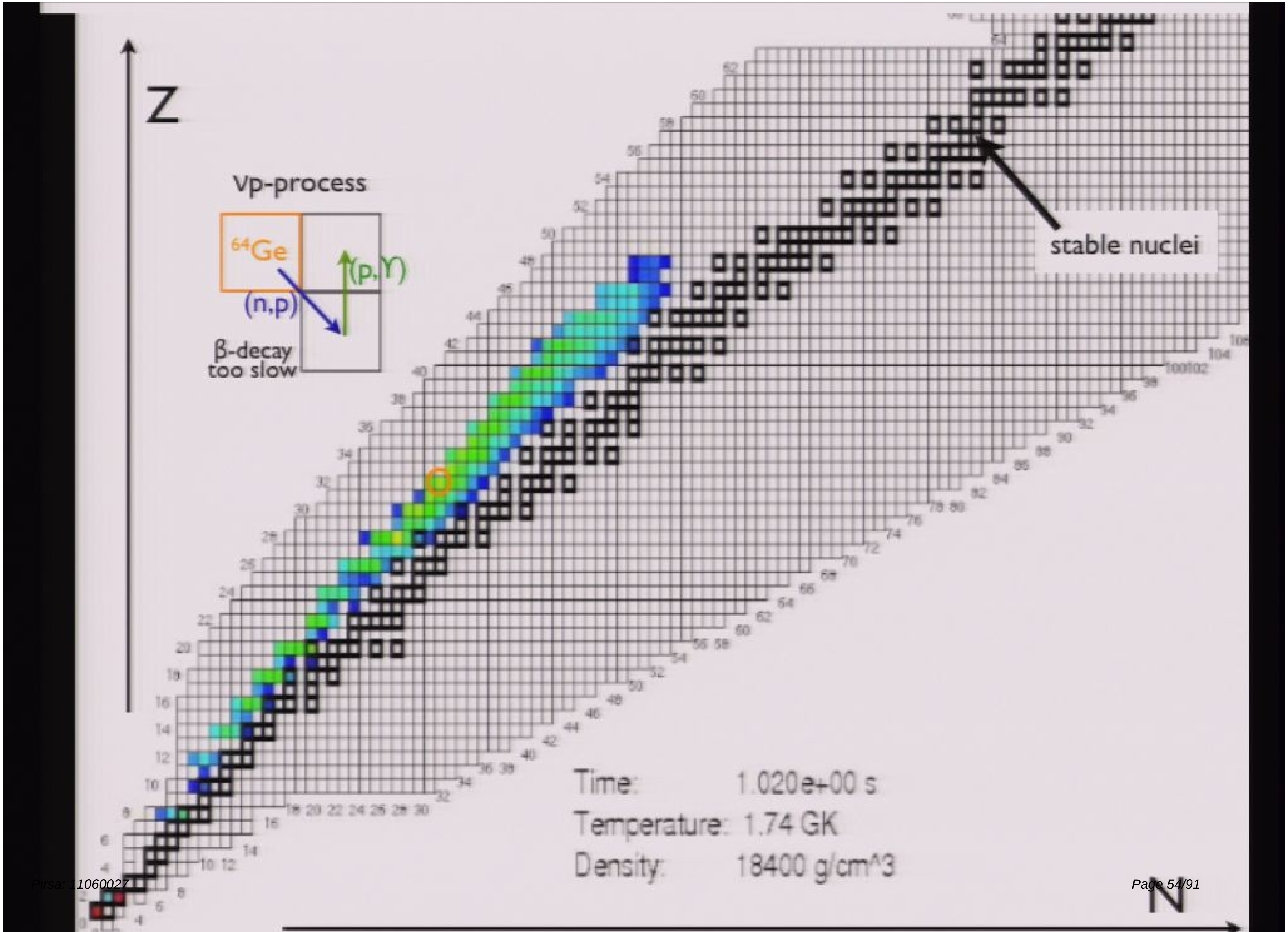

Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.007e+00 s
Temperature: 3.46 GK
Density: 207000 g/cm^3
N

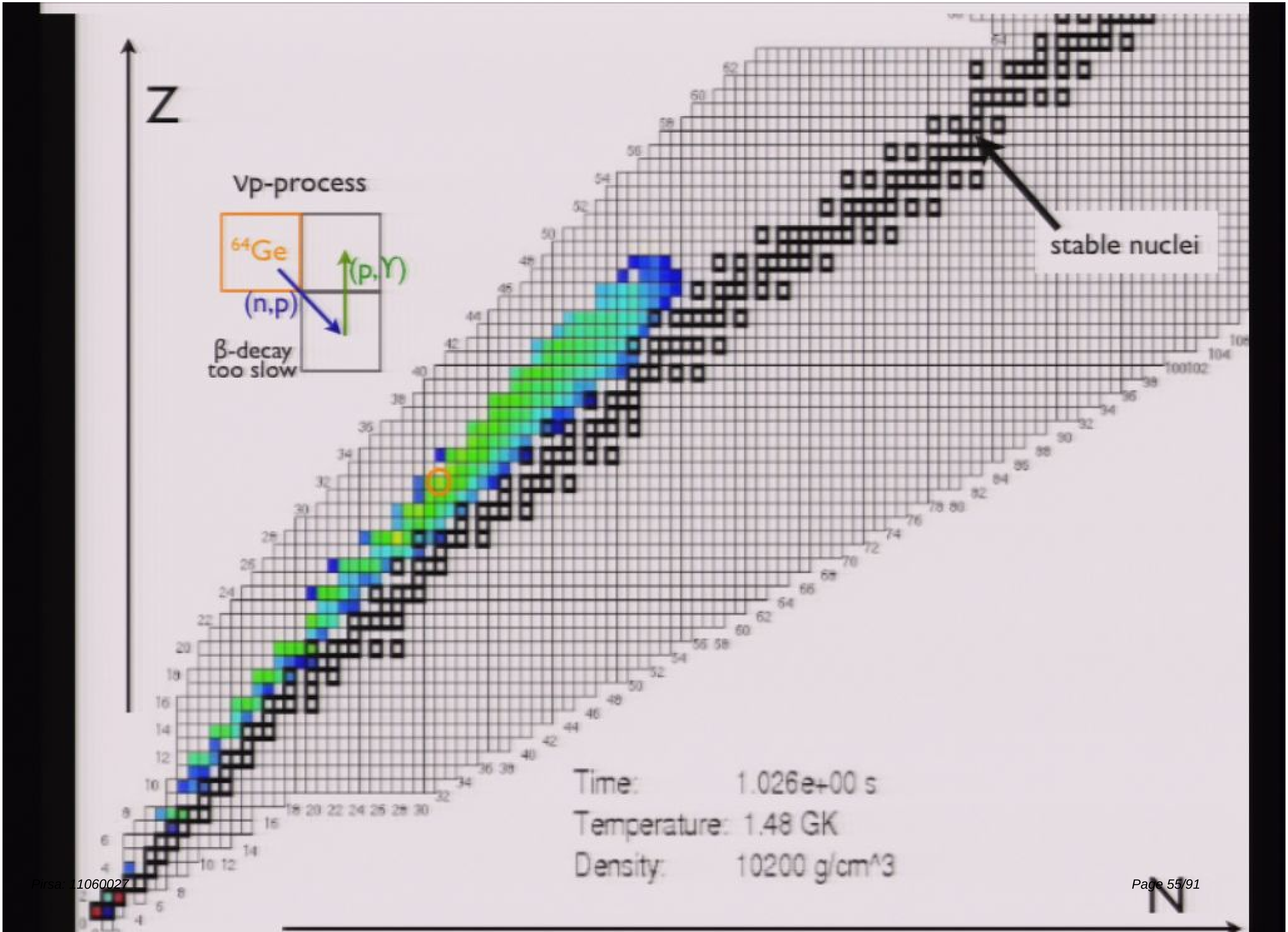

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.010e+00 s
Temperature: 2.72 GK
Density: 91400 g/cm^3
N

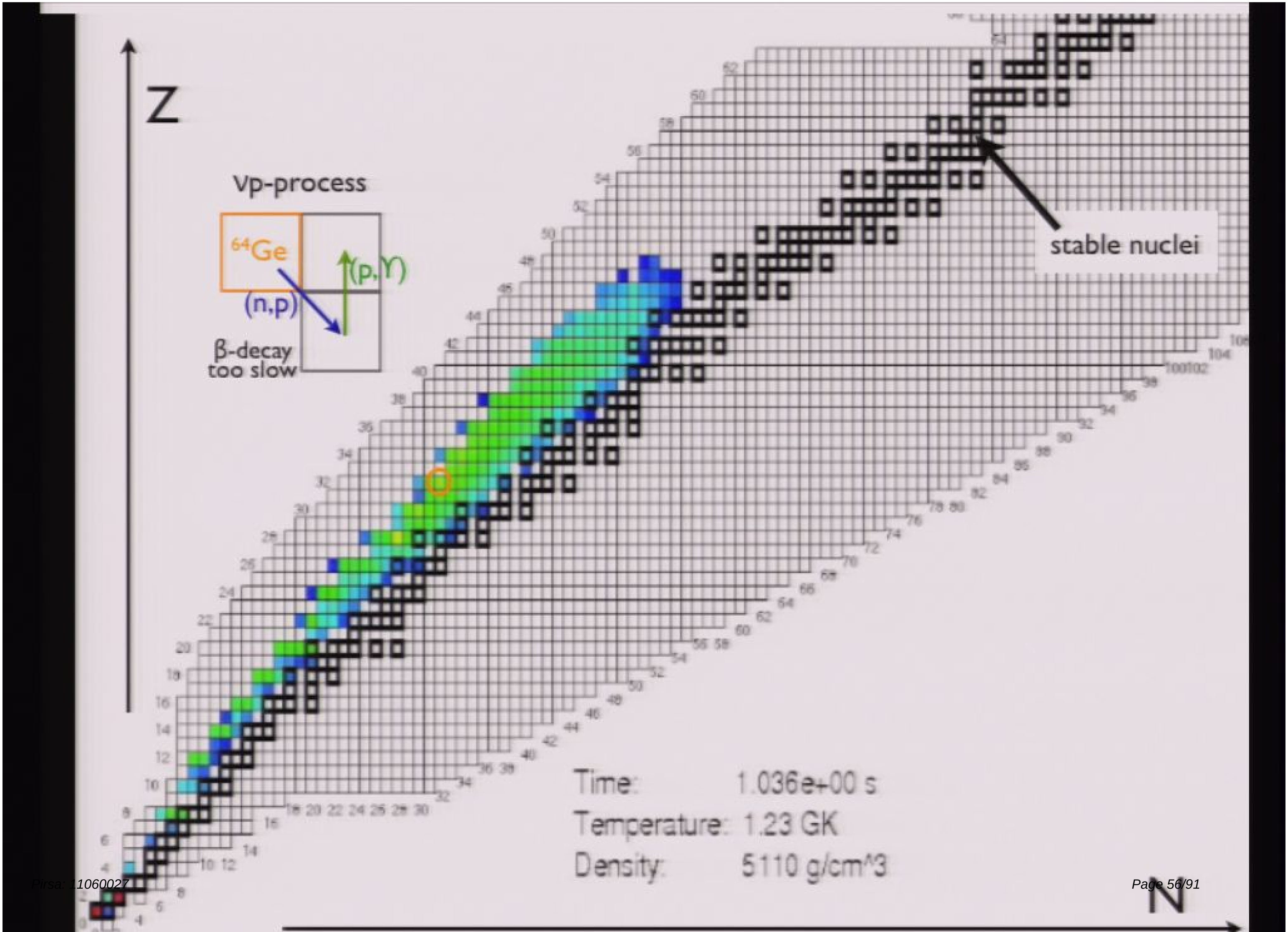

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.011e+00 s
Temperature: 2.49 GK
Density: 67800 g/cm^3
N

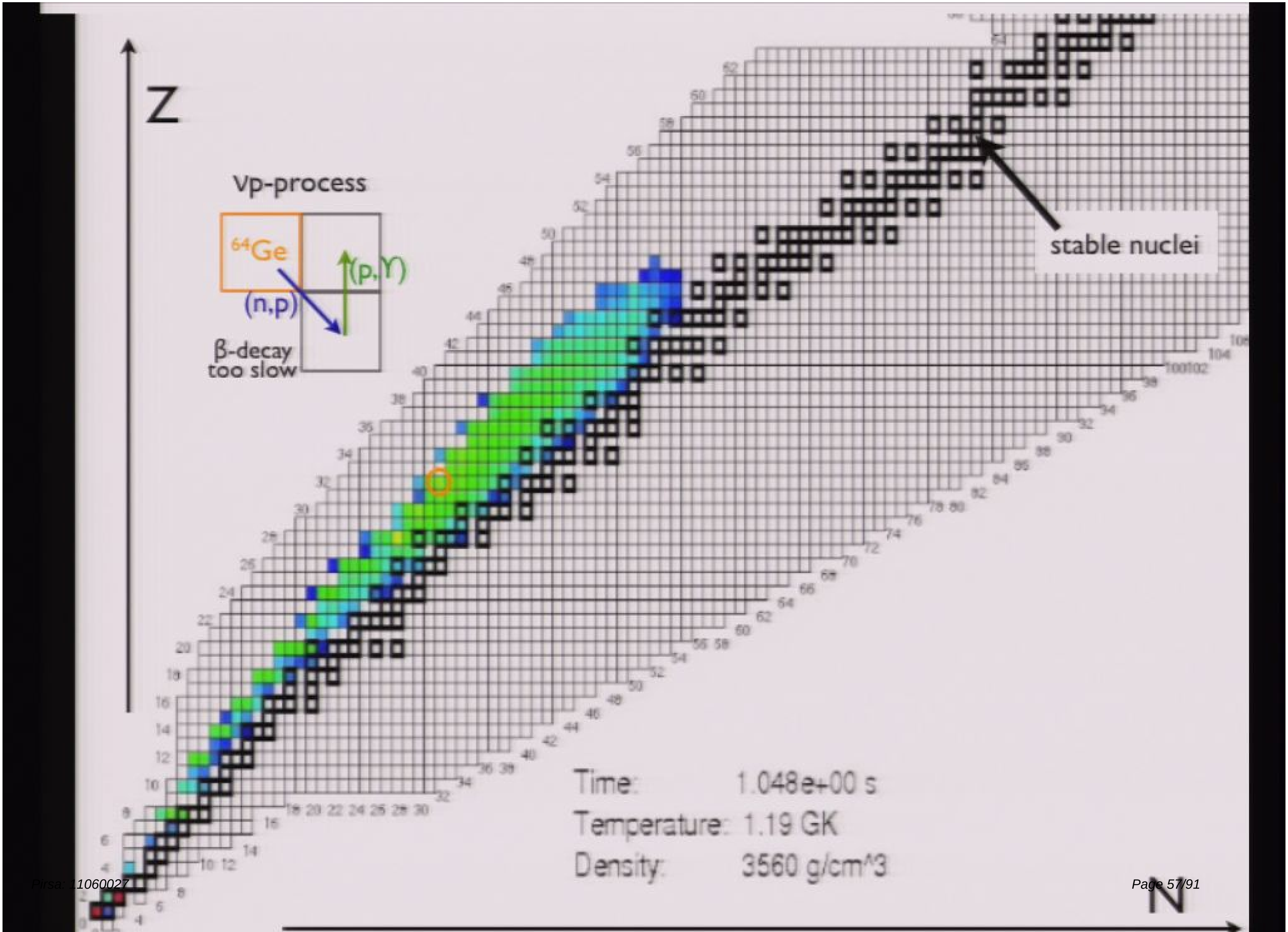

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.013e+00 s
Temperature: 2.21 GK
Density: 44000 g/cm^3
N

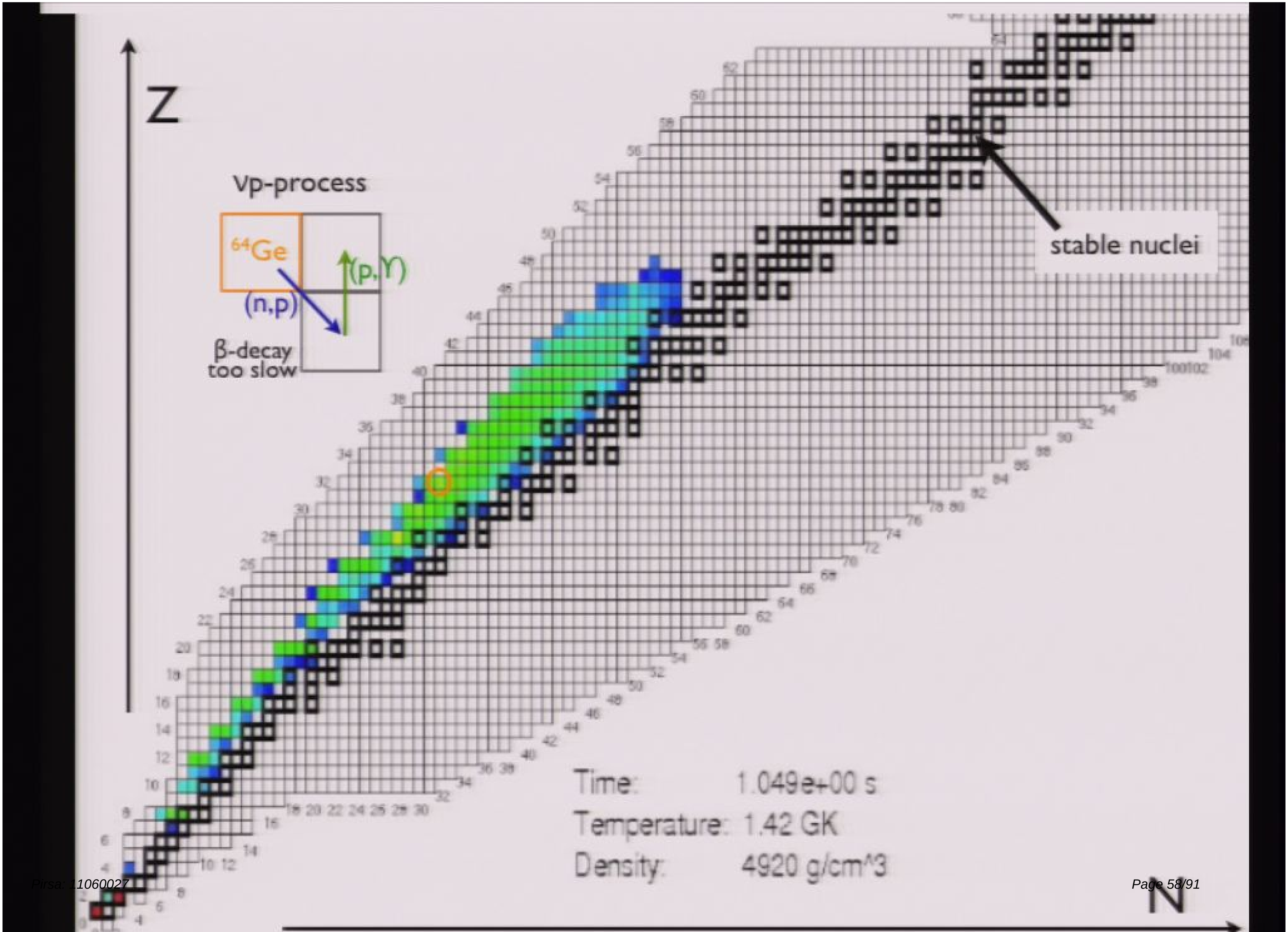

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay too slow
stable nuclei
Time: 1.016e+00 s
Temperature: 1.96 GK
Density: 28400 g/cm^3
N

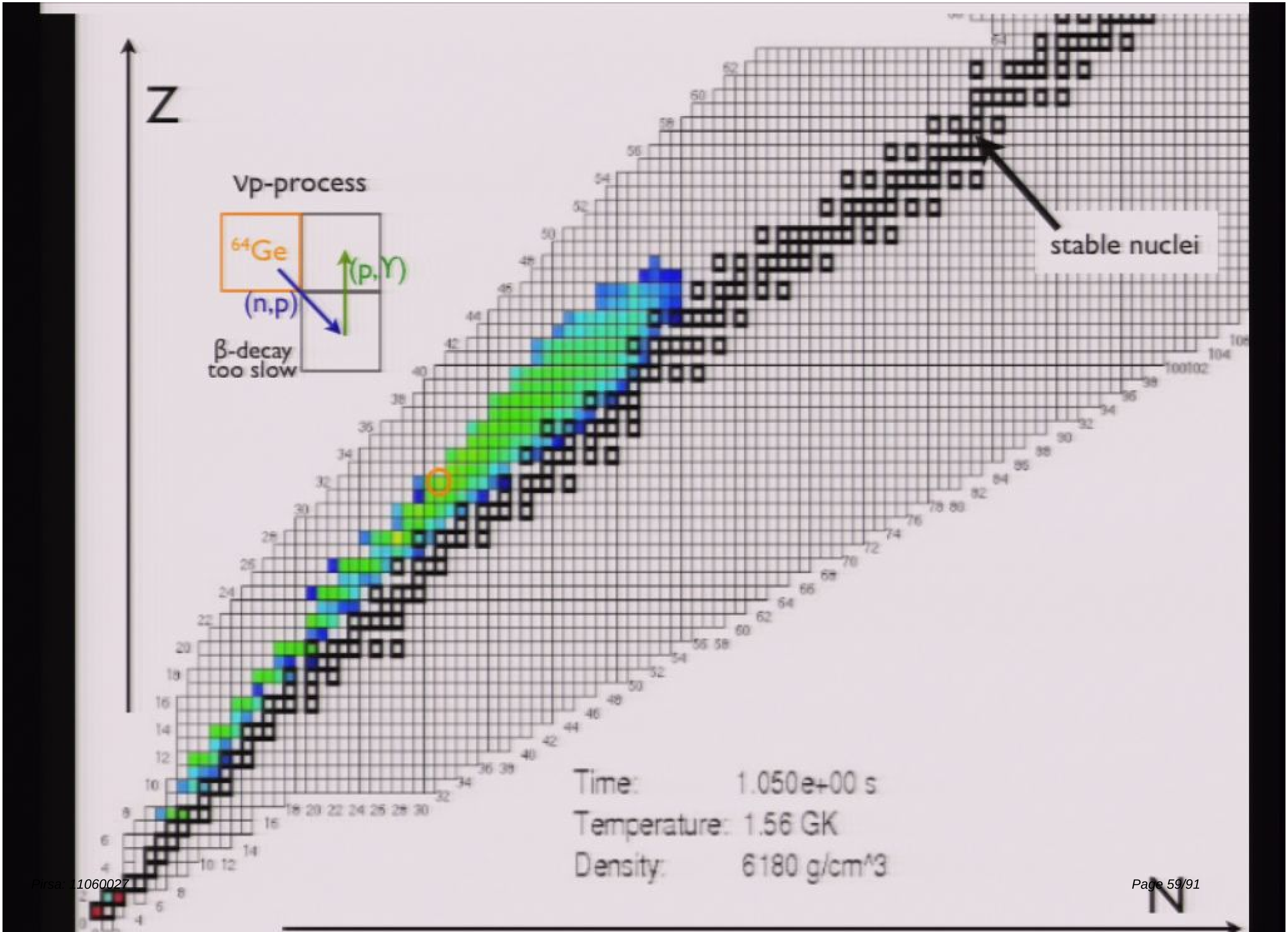

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.020e+00 s
Temperature: 1.74 GK
Density: 18400 g/cm^3
N

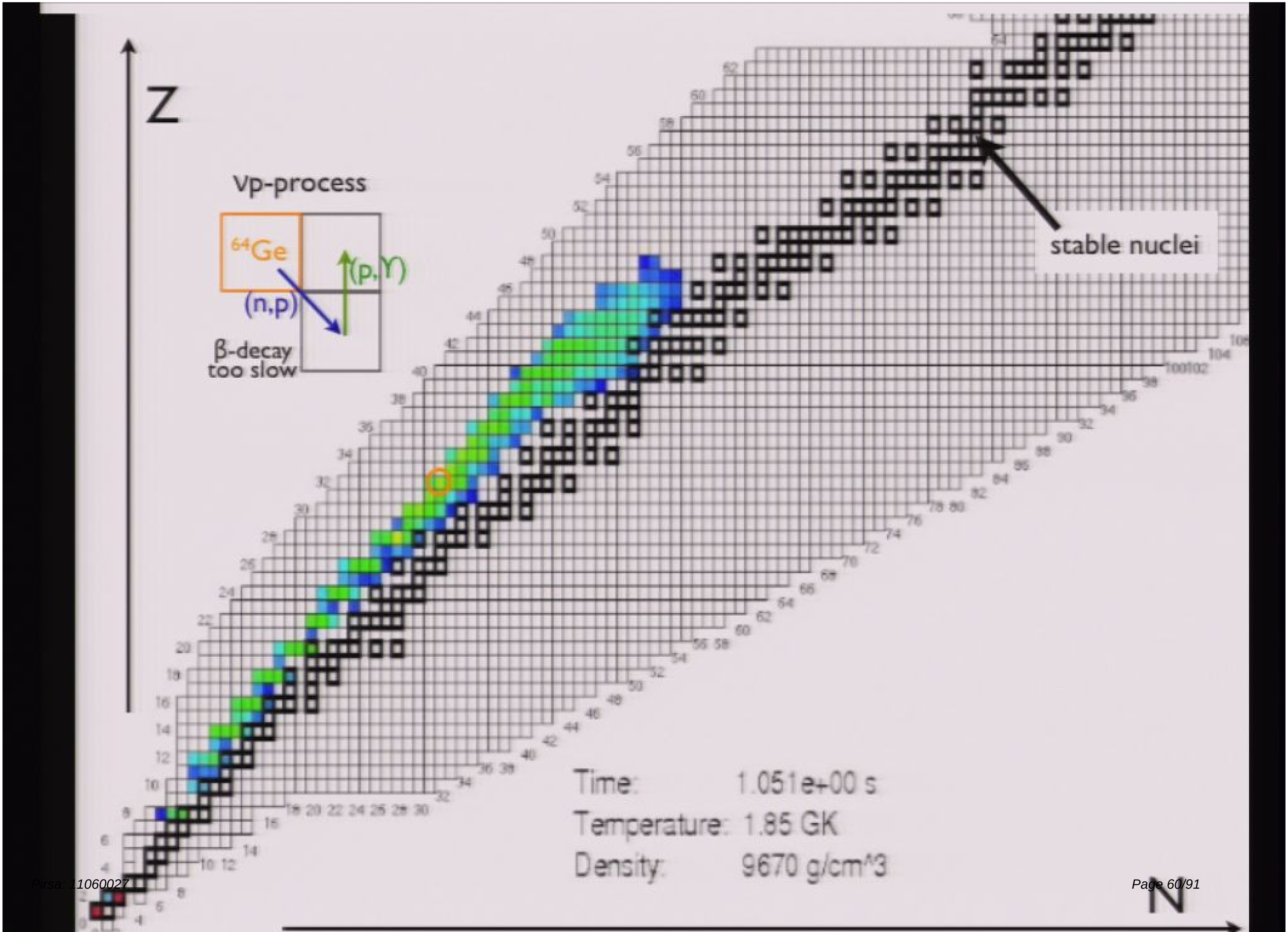

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.026e+00 s
Temperature: 1.48 GK
Density: 10200 g/cm^3
N

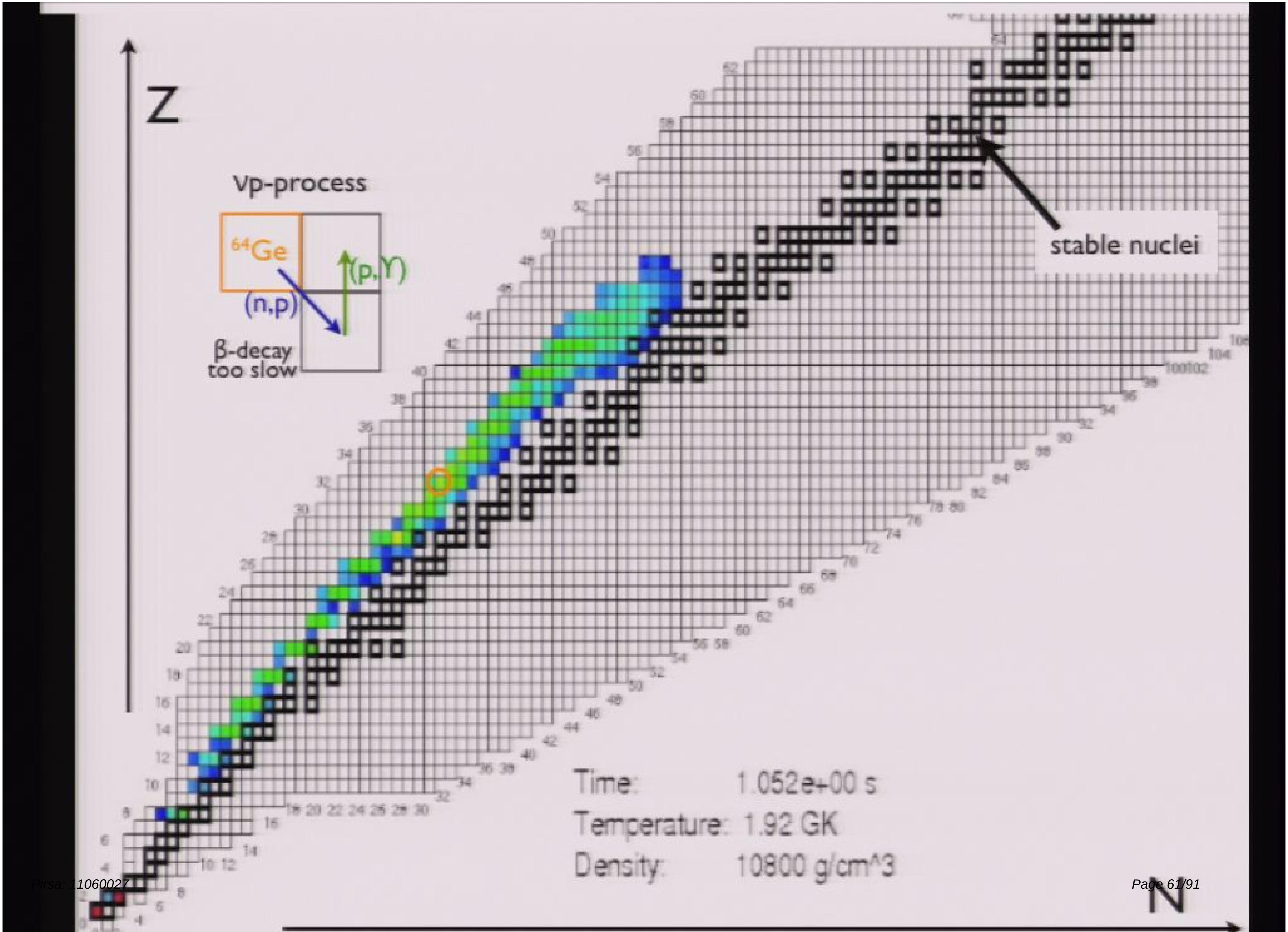

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.036e+00 s
Temperature: 1.23 GK
Density: 5110 g/cm^3
N

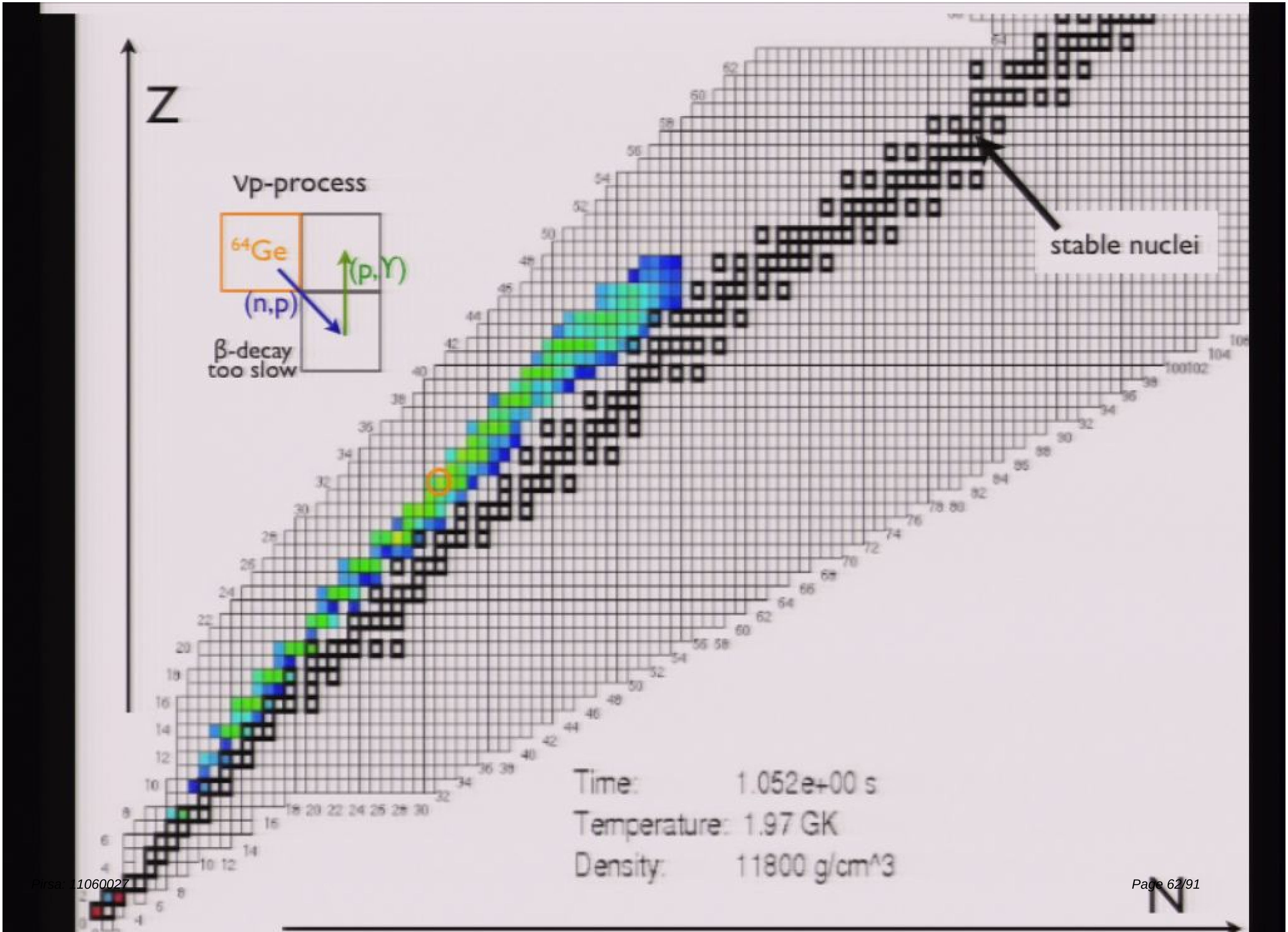

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay too slow
stable nuclei
Time: 1.048e+00 s
Temperature: 1.19 GK
Density: 3560 g/cm^3
N

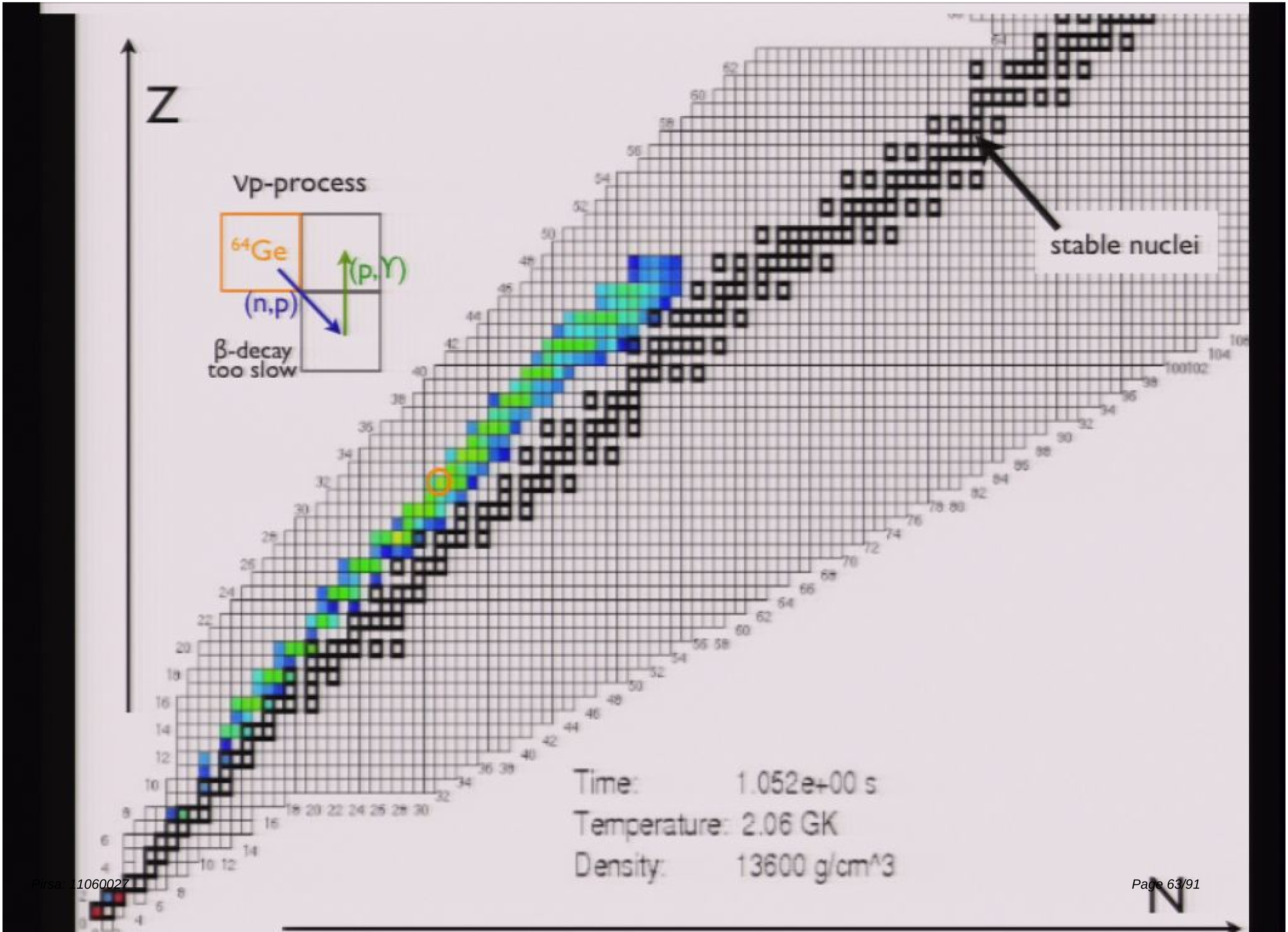

Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.049e+00 s
Temperature: 1.42 GK
Density: 4920 g/cm^3
N

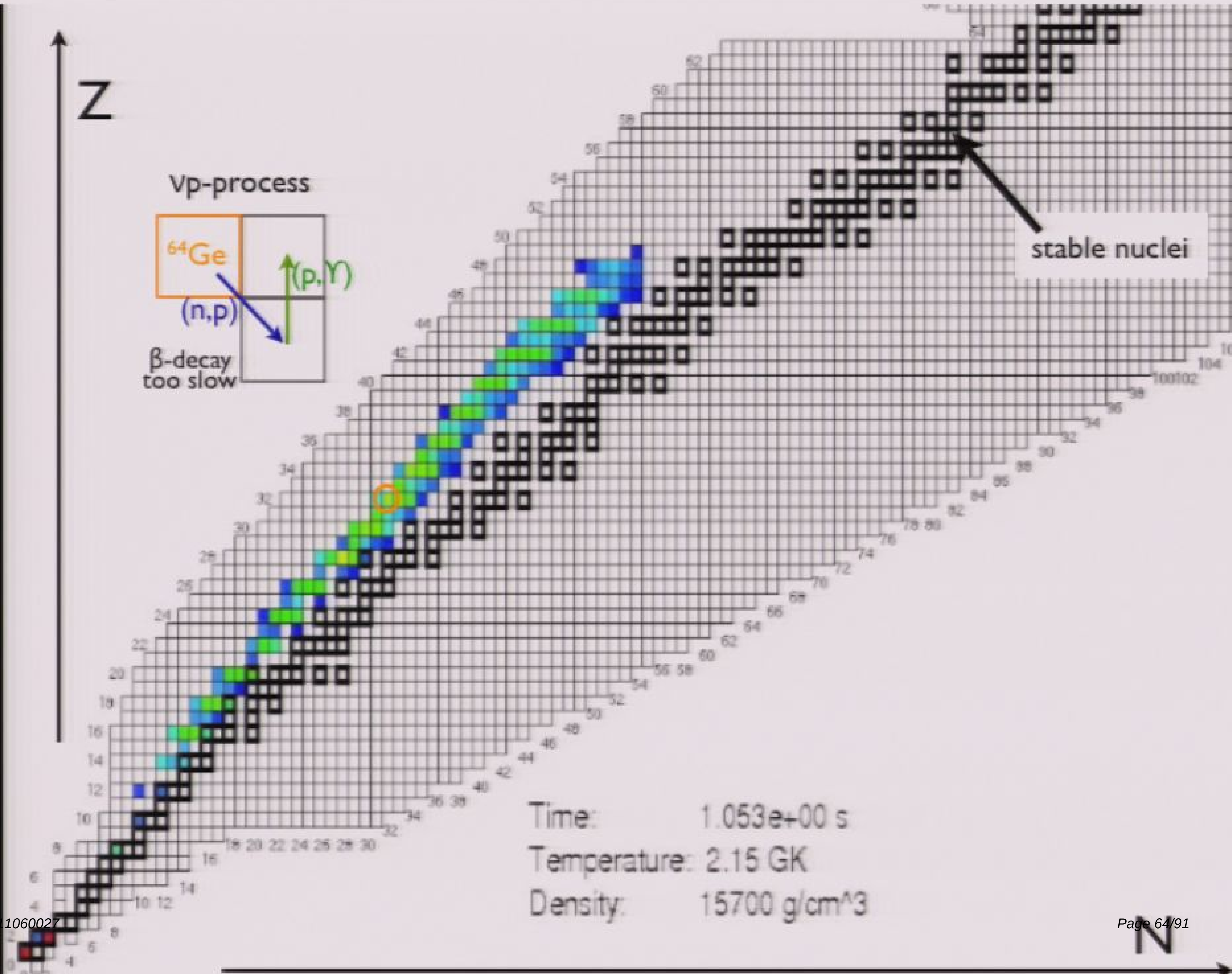

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.050e+00 s
Temperature: 1.56 GK
Density: 6180 g/cm^3
N

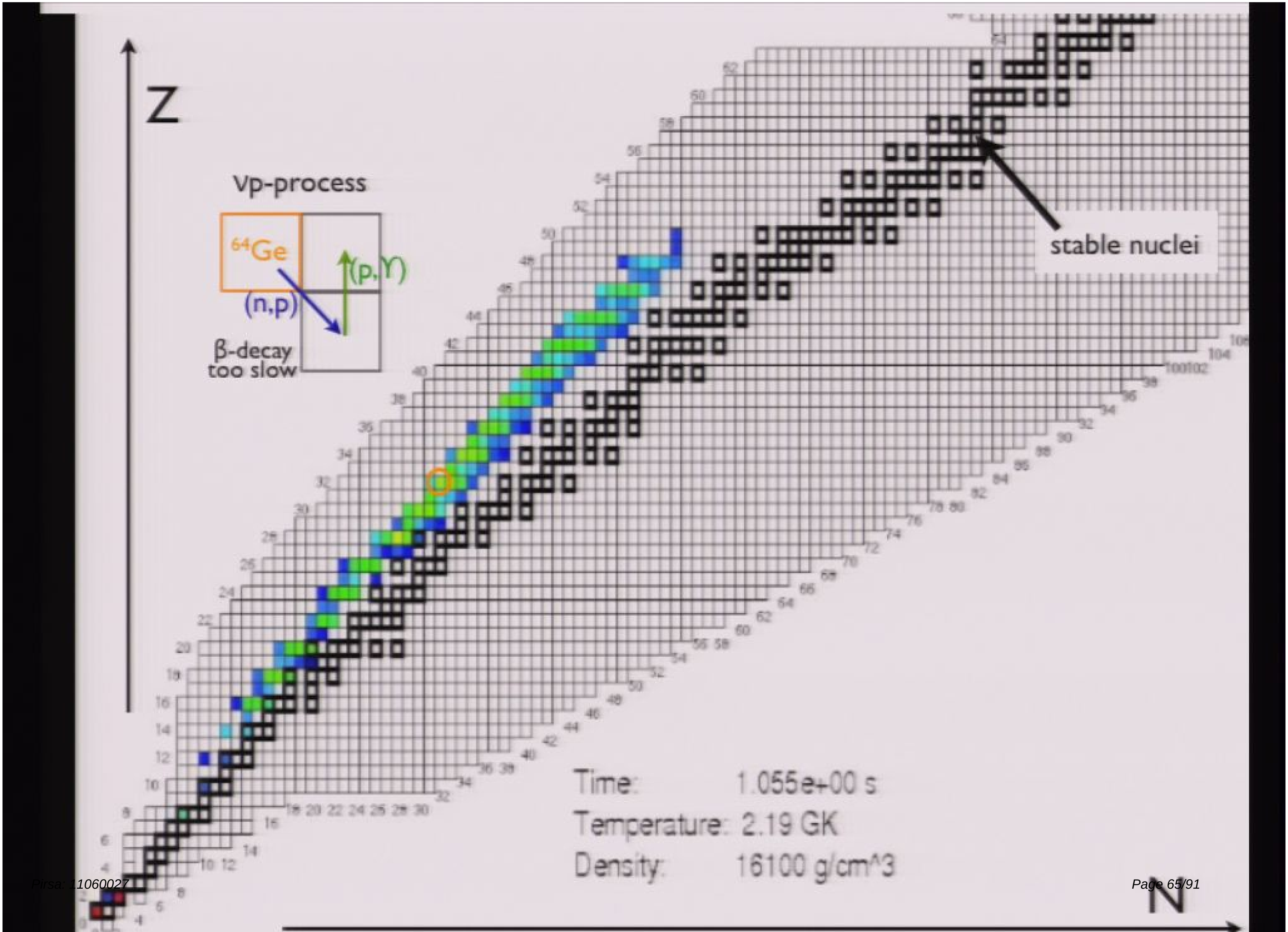

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.051e+00 s
Temperature: 1.85 GK
Density: 9670 g/cm^3
N


Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.052e+00 s
Temperature: 1.92 GK
Density: 10800 g/cm^3
N

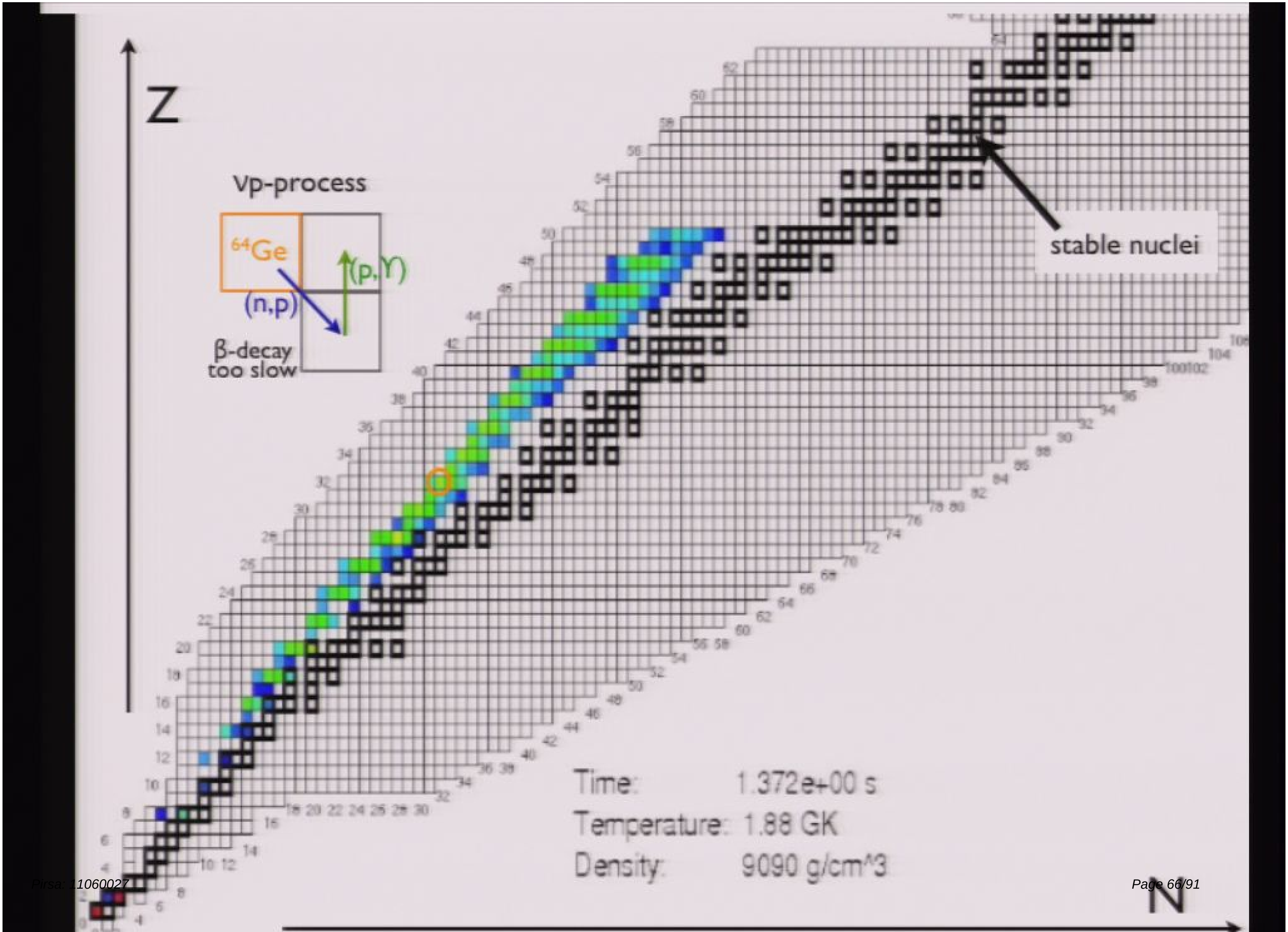

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.052e+00 s
Temperature: 1.97 GK
Density: 11800 g/cm^3
N


Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.052e+00 s
Temperature: 2.06 GK
Density: 13600 g/cm^3
N

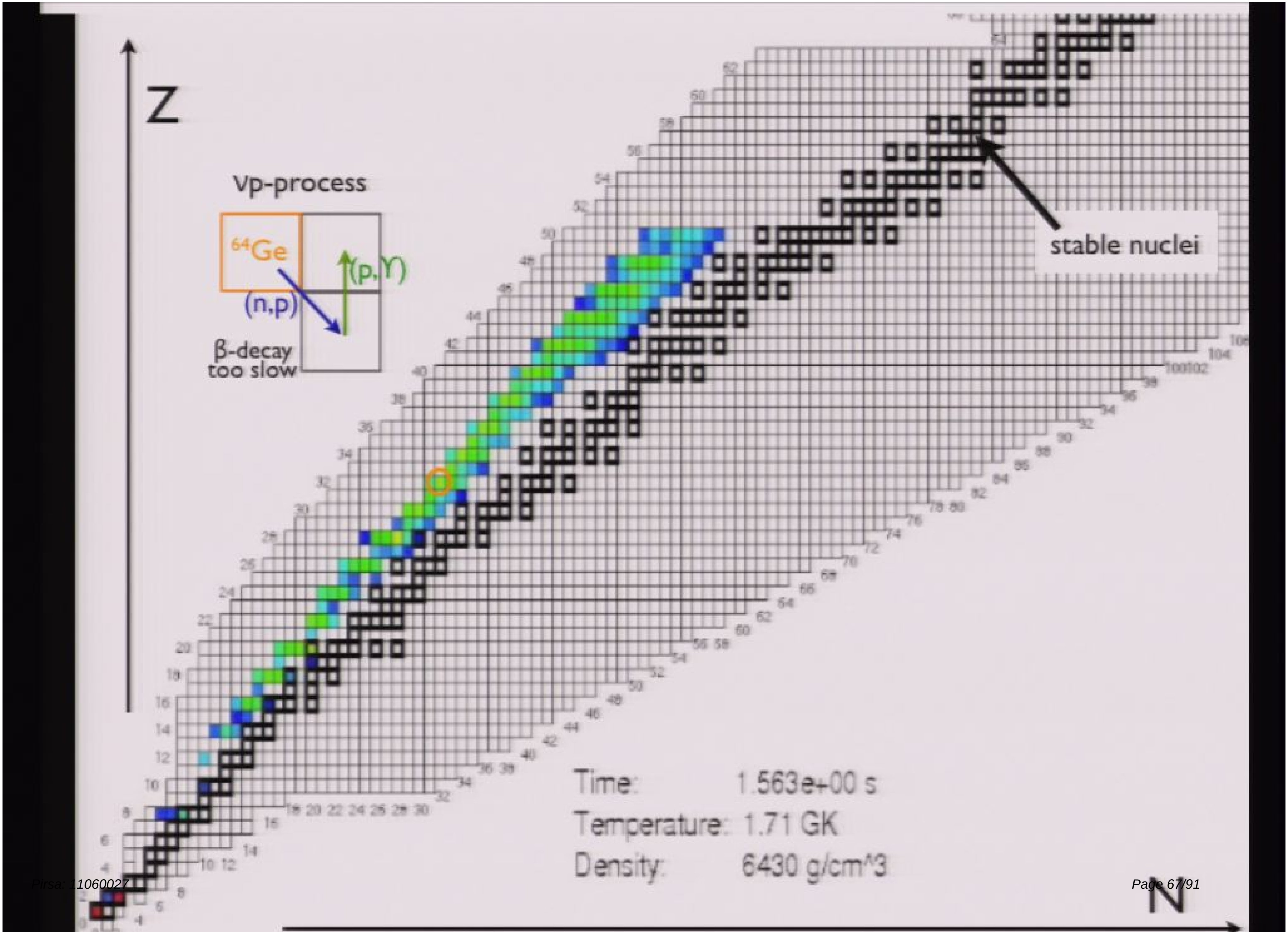

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.053e+00 s
Temperature: 2.15 GK
Density: 15700 g/cm^3
N

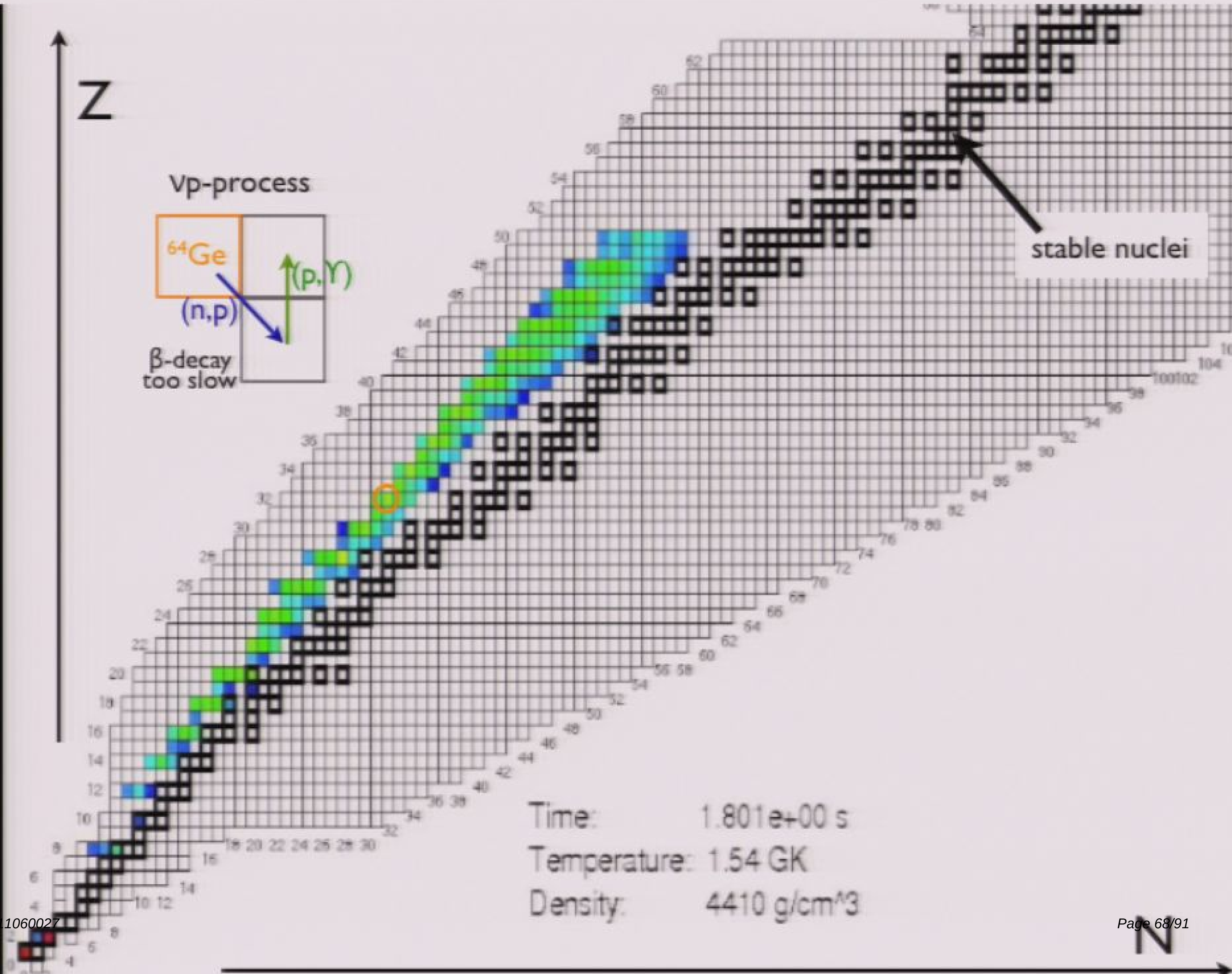


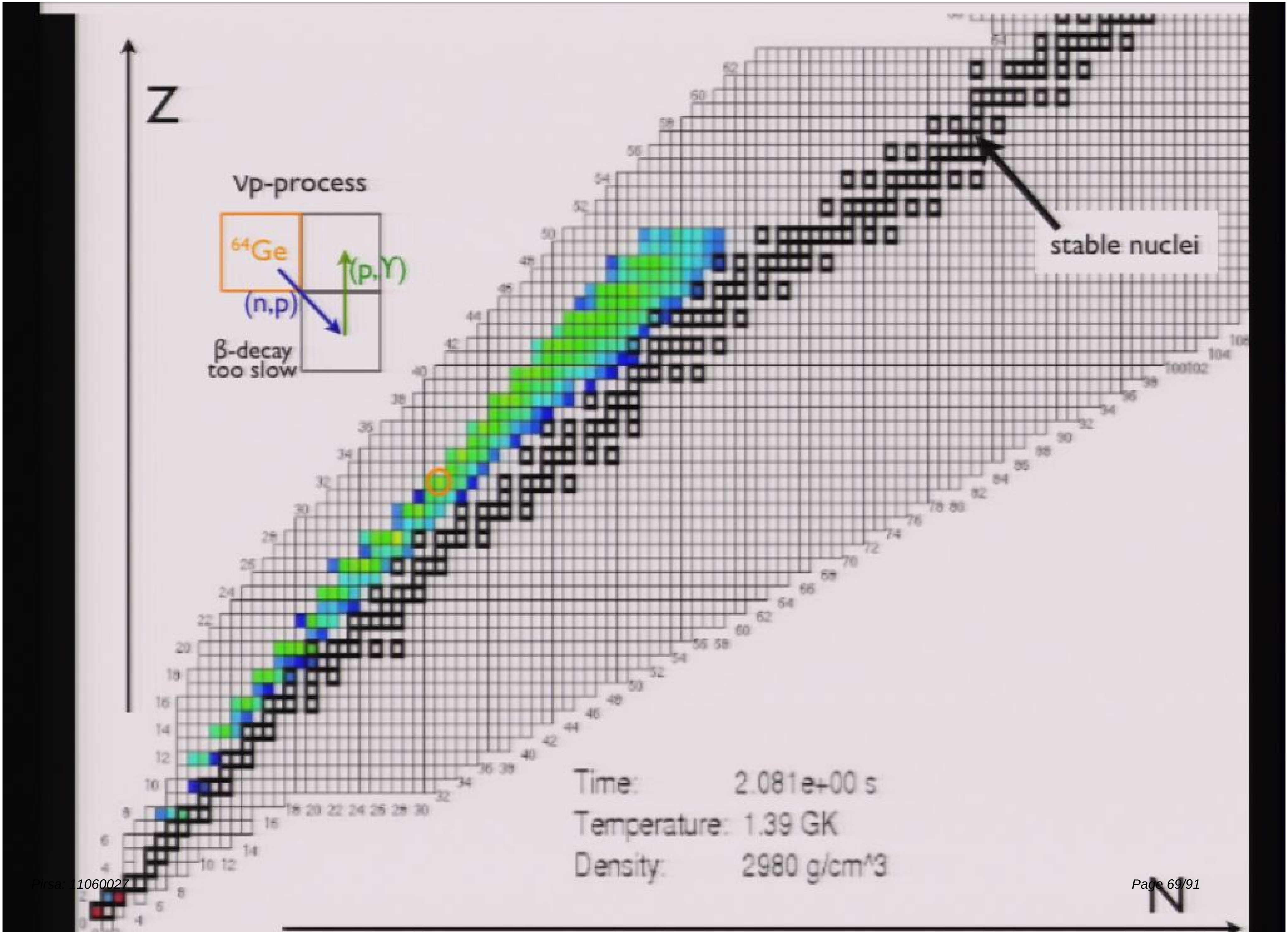
Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.055e+00 s
Temperature: 2.19 GK
Density: 16100 g/cm^3
N

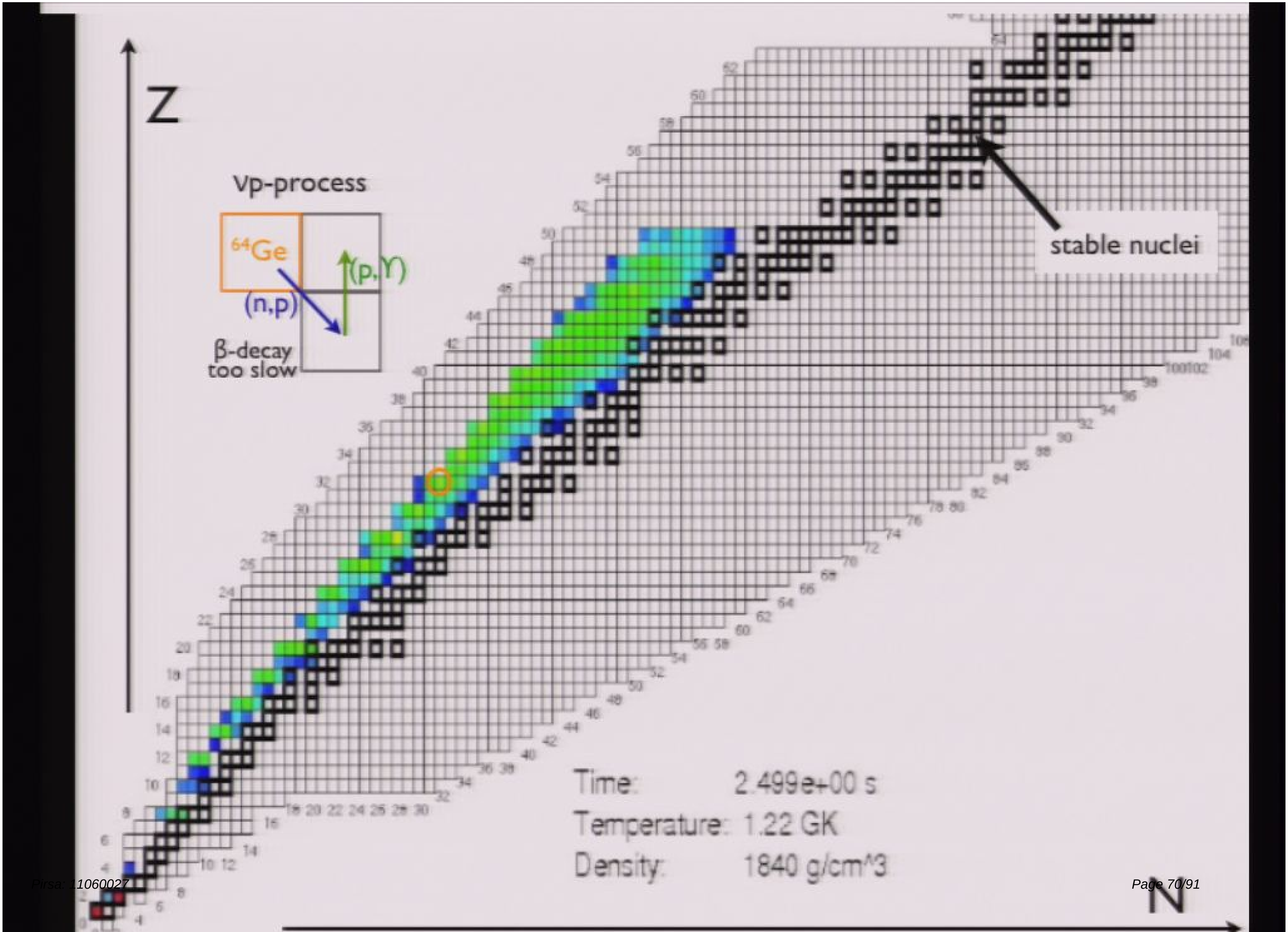


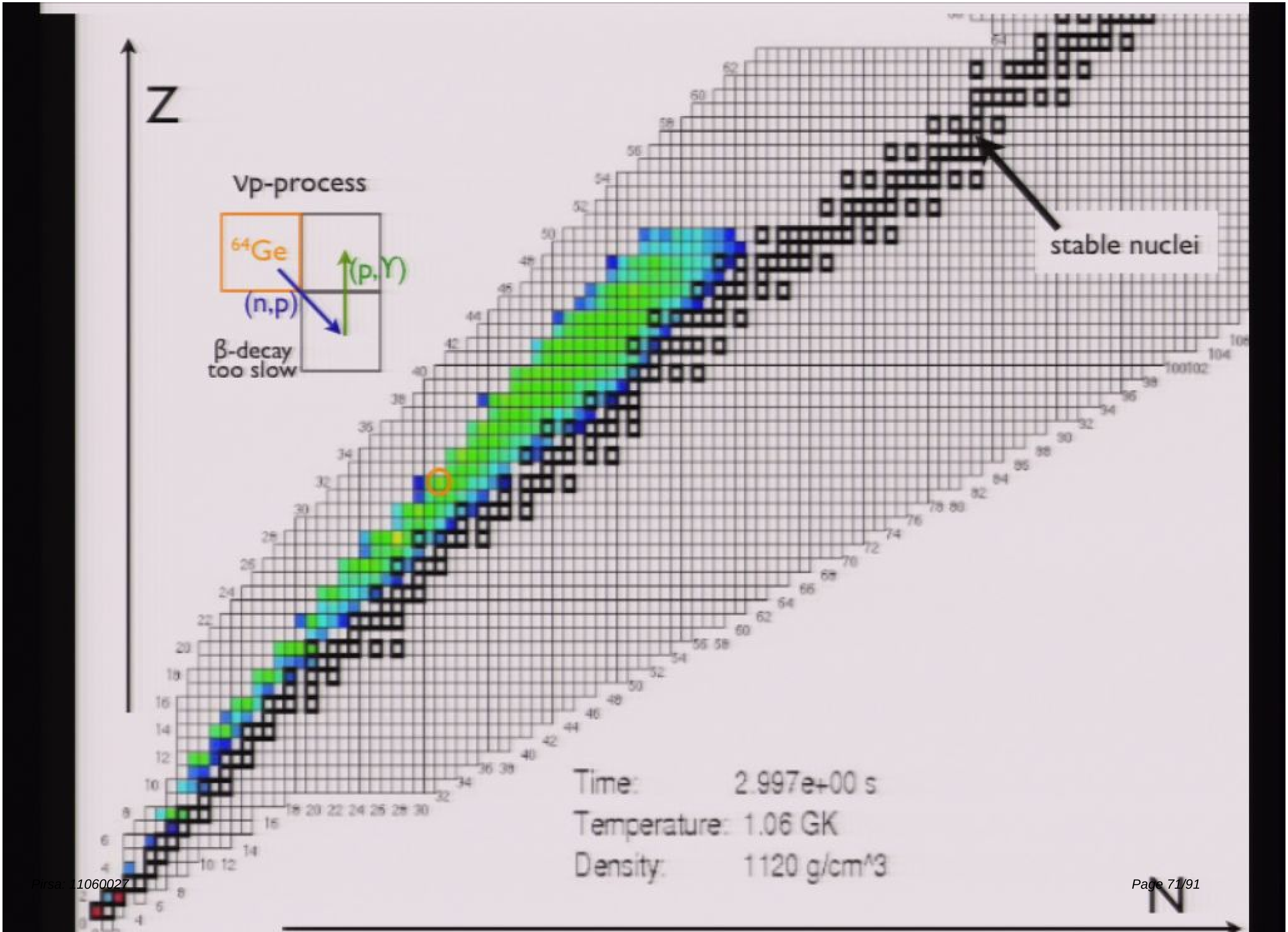
Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay too slow
stable nuclei
Time: 1.372e+00 s
Temperature: 1.88 GK
Density: 9090 g/cm^3
N

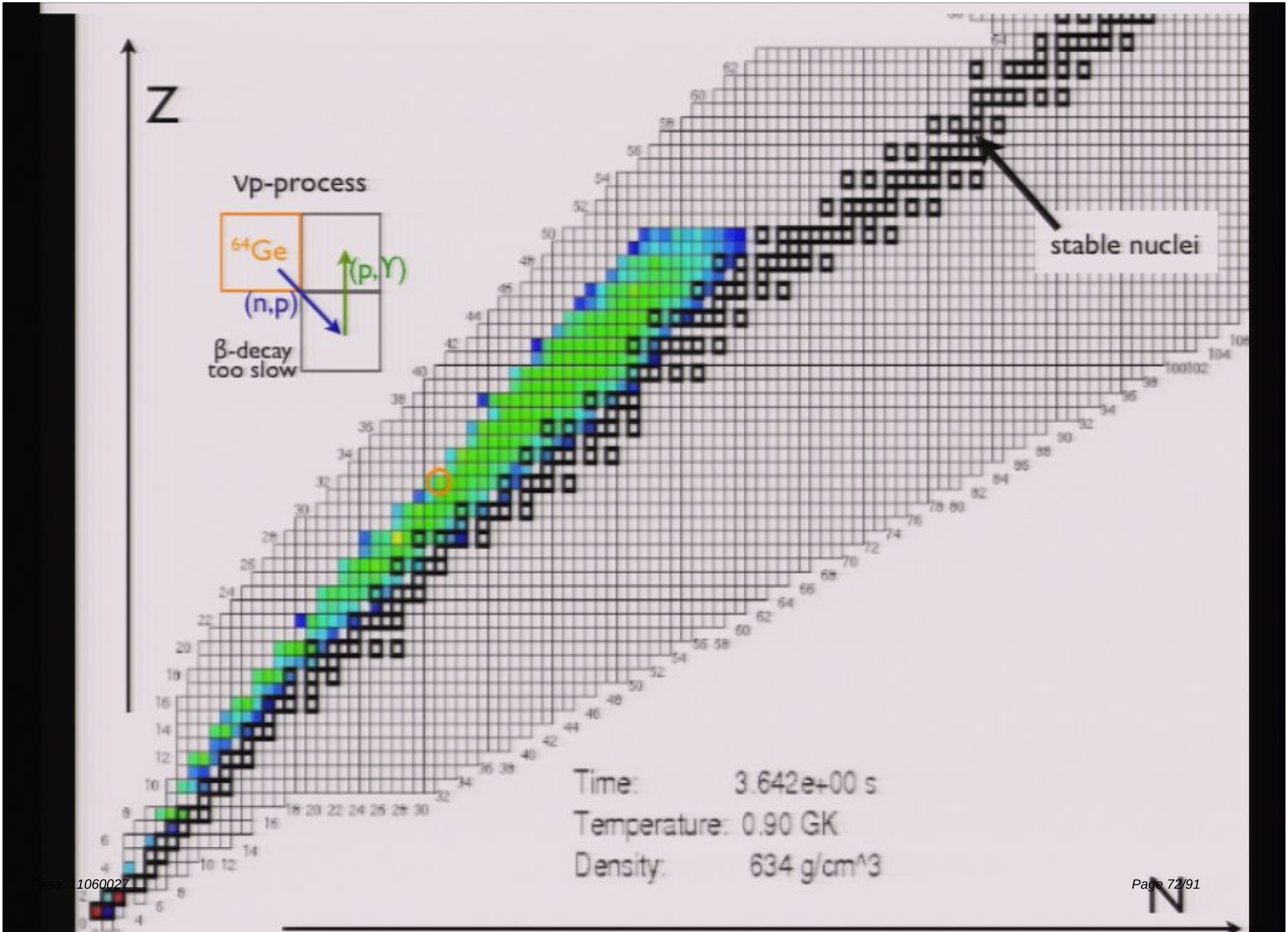

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.563e+00 s
Temperature: 1.71 GK
Density: 6430 g/cm^3
N

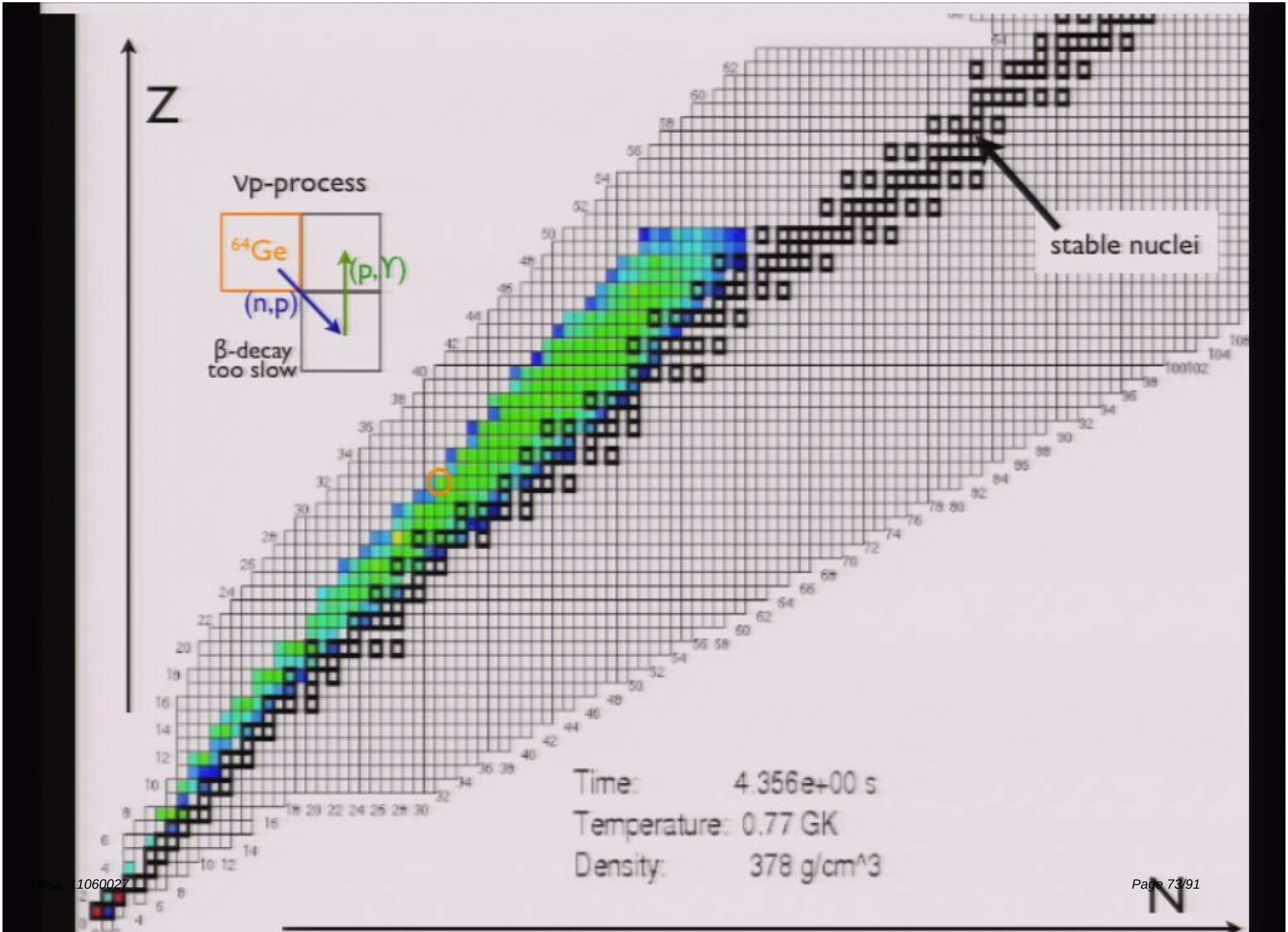

Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.801e+00 s
Temperature: 1.54 GK
Density: 4410 g/cm^3
N

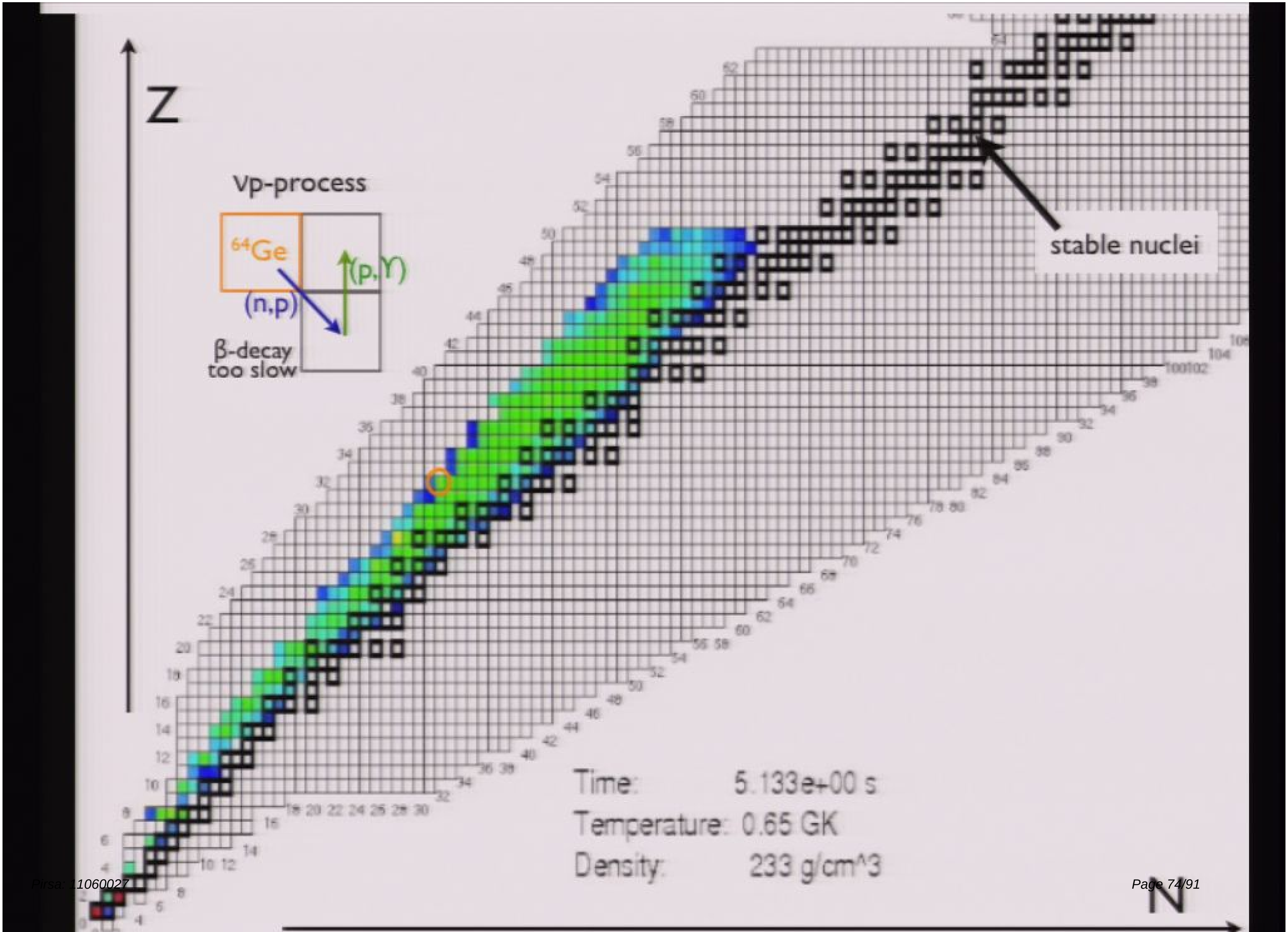

Z
νp-process
⁶⁴Ge
(p,γ)
(n,p)
β-decay too slow
stable nuclei
Time: 2.081e+00 s
Temperature: 1.39 GK
Density: 2980 g/cm^3
N


Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 2.499e+00 s
Temperature: 1.22 GK
Density: 1840 g/cm^3
N

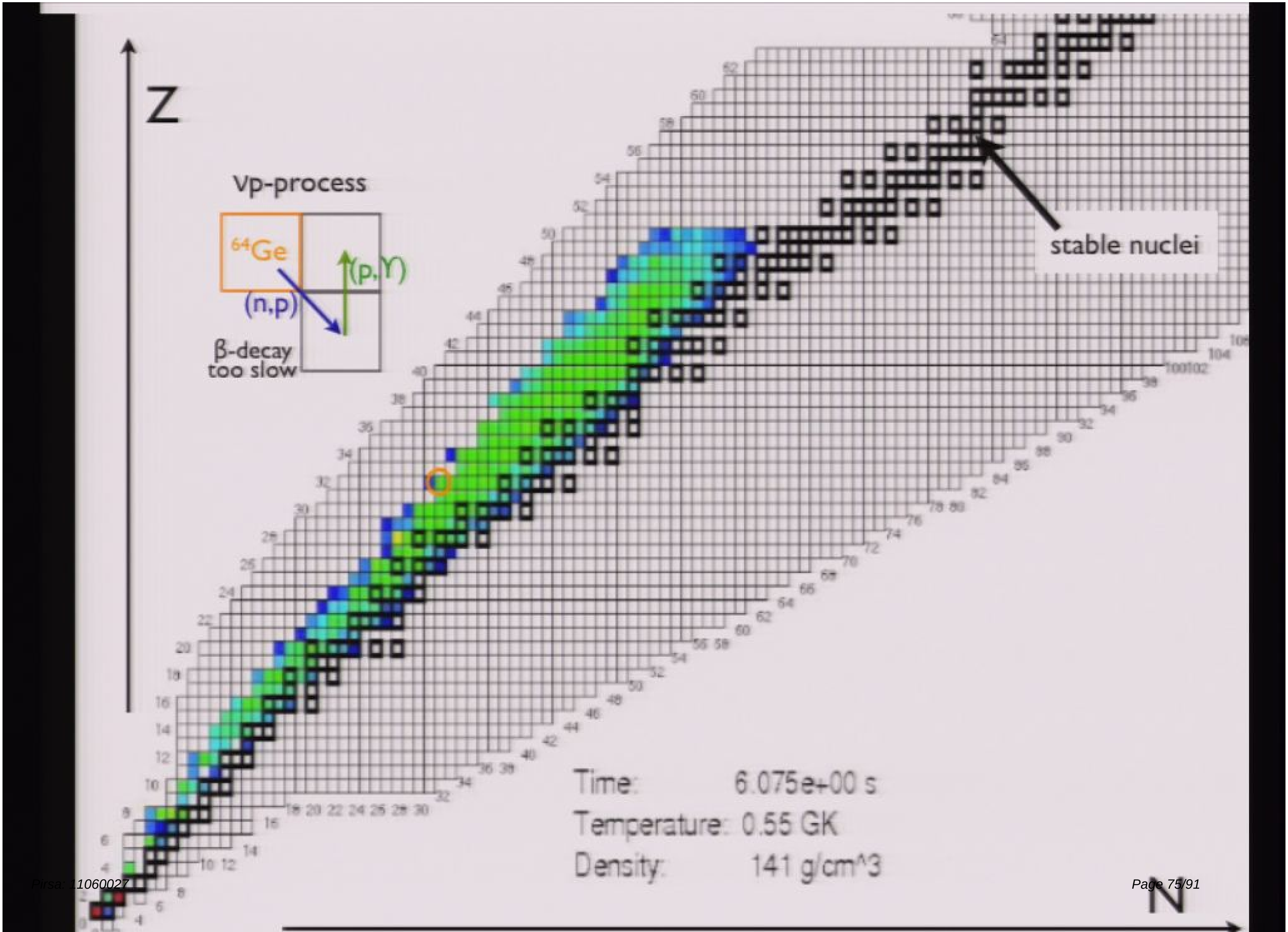

Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 2.997e+00 s
Temperature: 1.06 GK
Density: 1120 g/cm^3
N

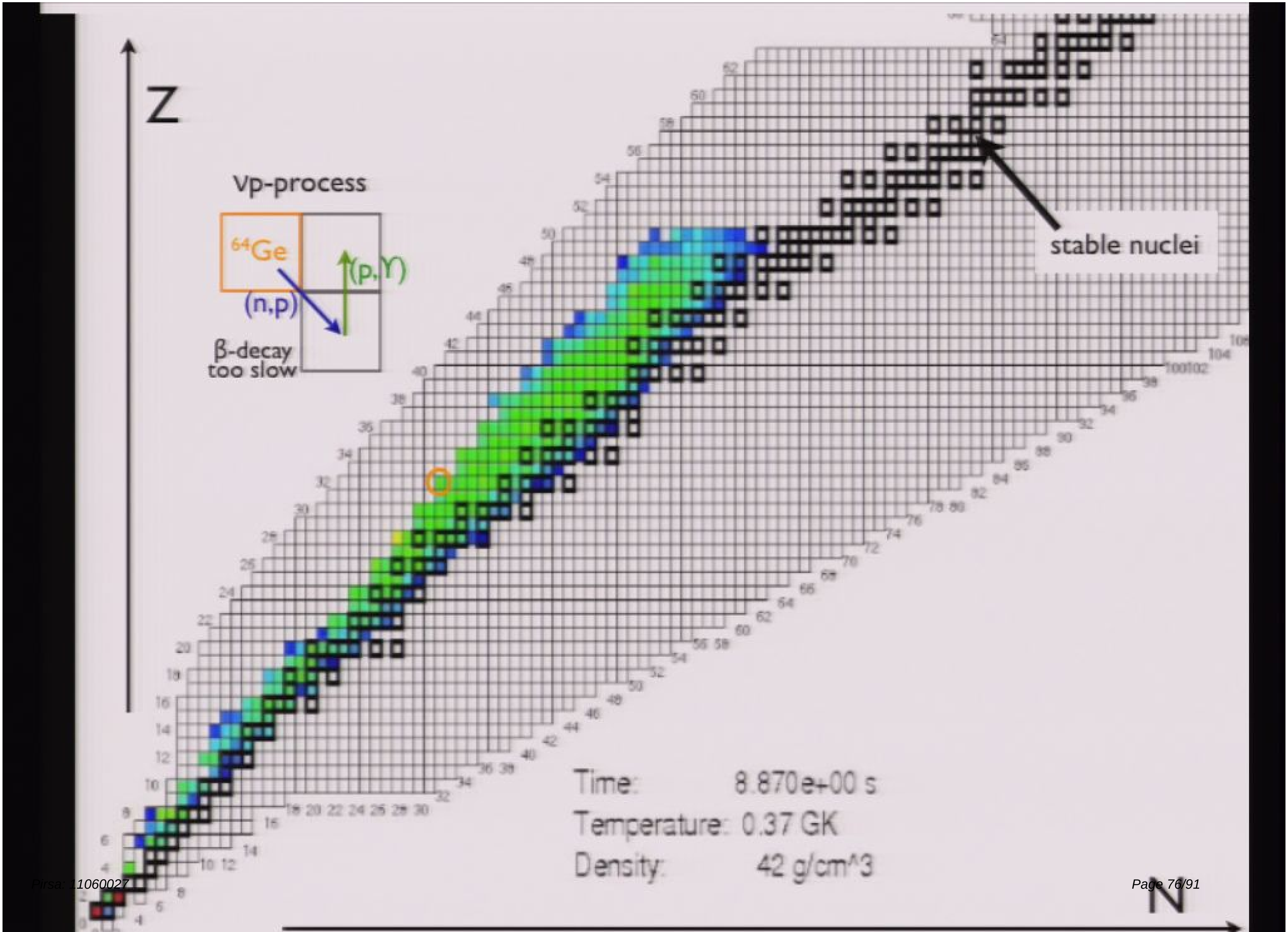

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 3.642e+00 s
Temperature: 0.90 GK
Density: 634 g/cm^3
N


Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 4.356e+00 s
Temperature: 0.77 GK
Density: 378 g/cm^3
N

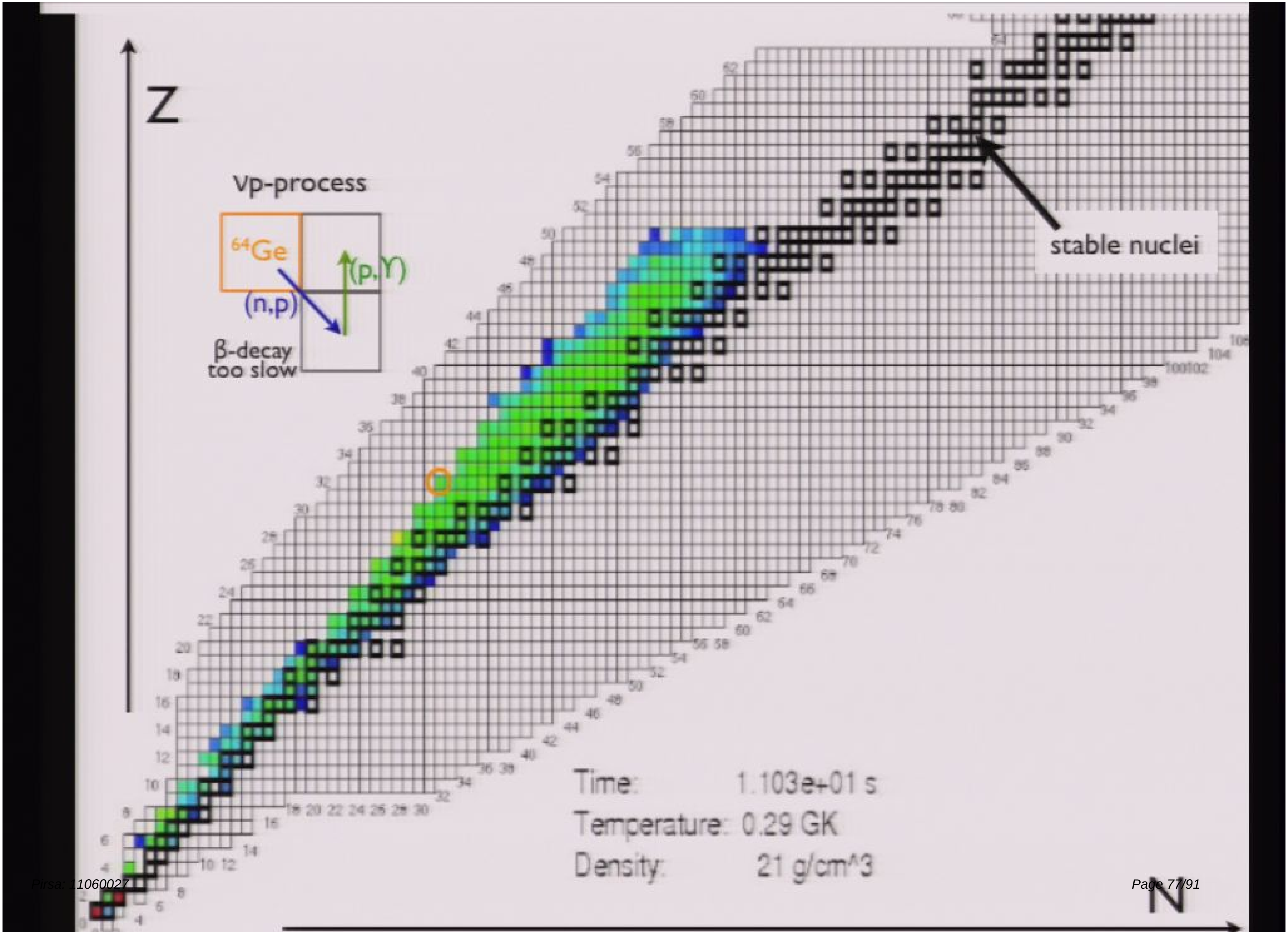


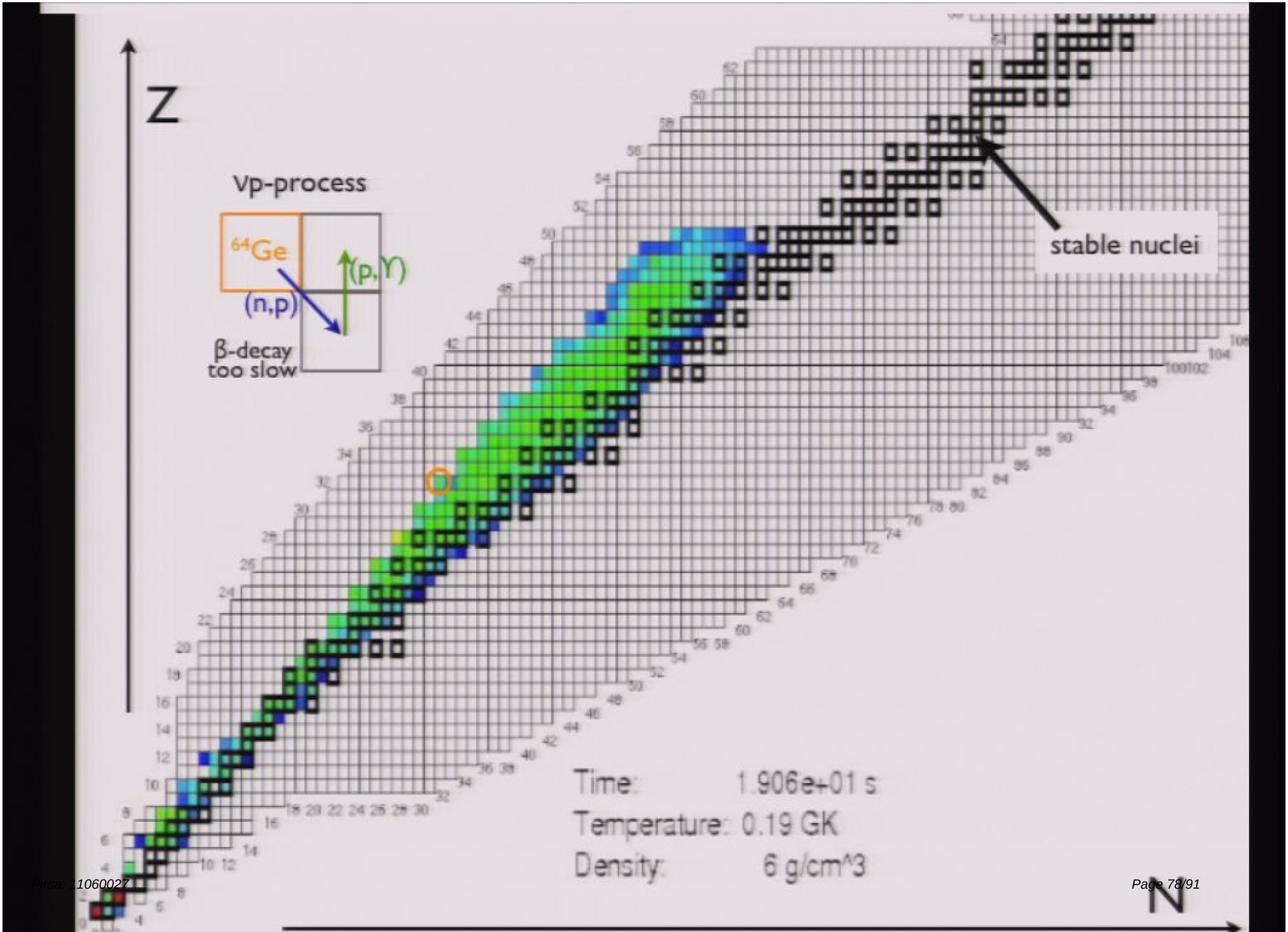
Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 5.133e+00 s
Temperature: 0.65 GK
Density: 233 g/cm^3
N

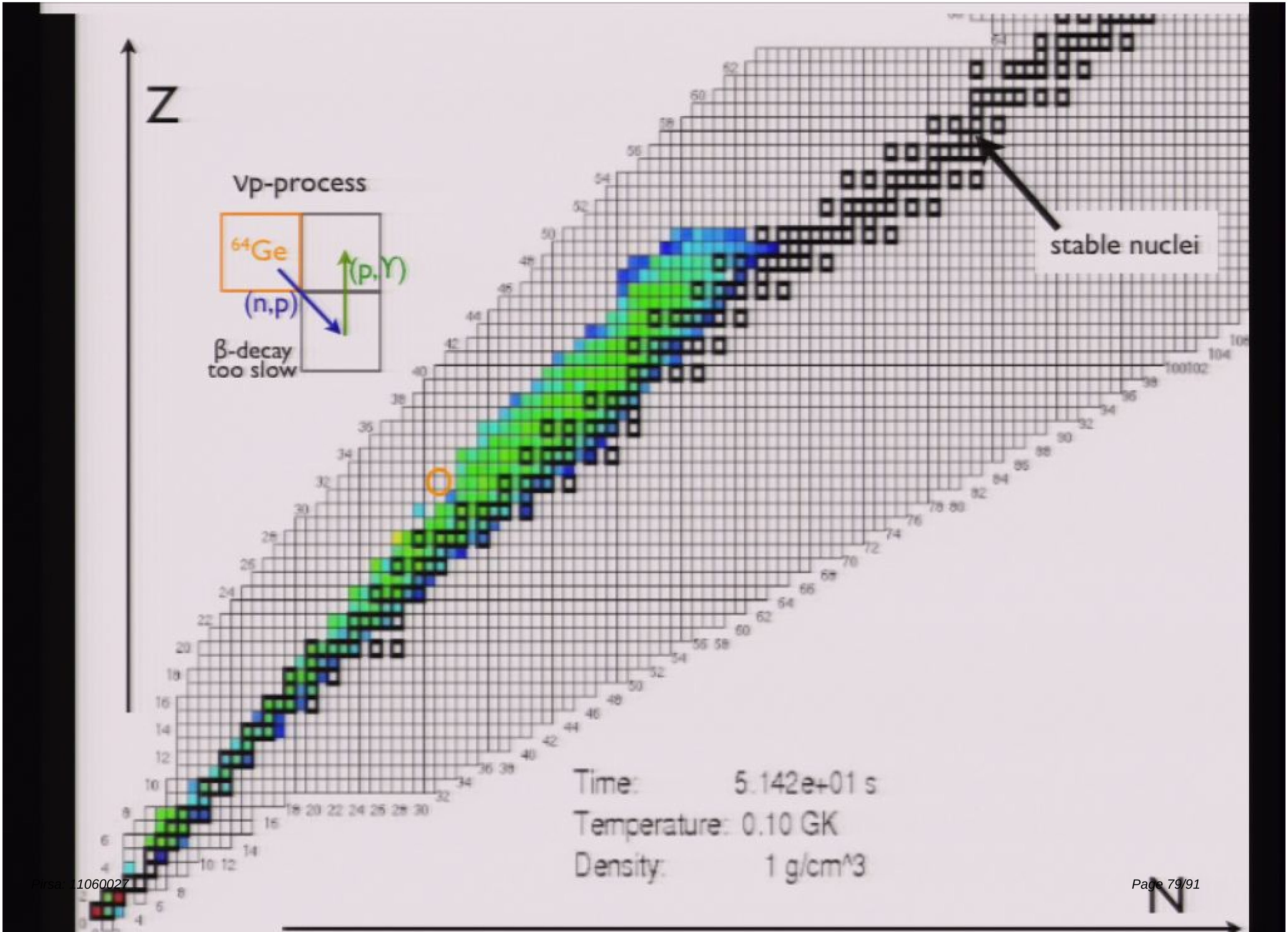

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 6.075e+00 s
Temperature: 0.55 GK
Density: 141 g/cm^3
N



Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 8.870e+00 s
Temperature: 0.37 GK
Density: 42 g/cm^3
N


Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.103e+01 s
Temperature: 0.29 GK
Density: 21 g/cm^3
N

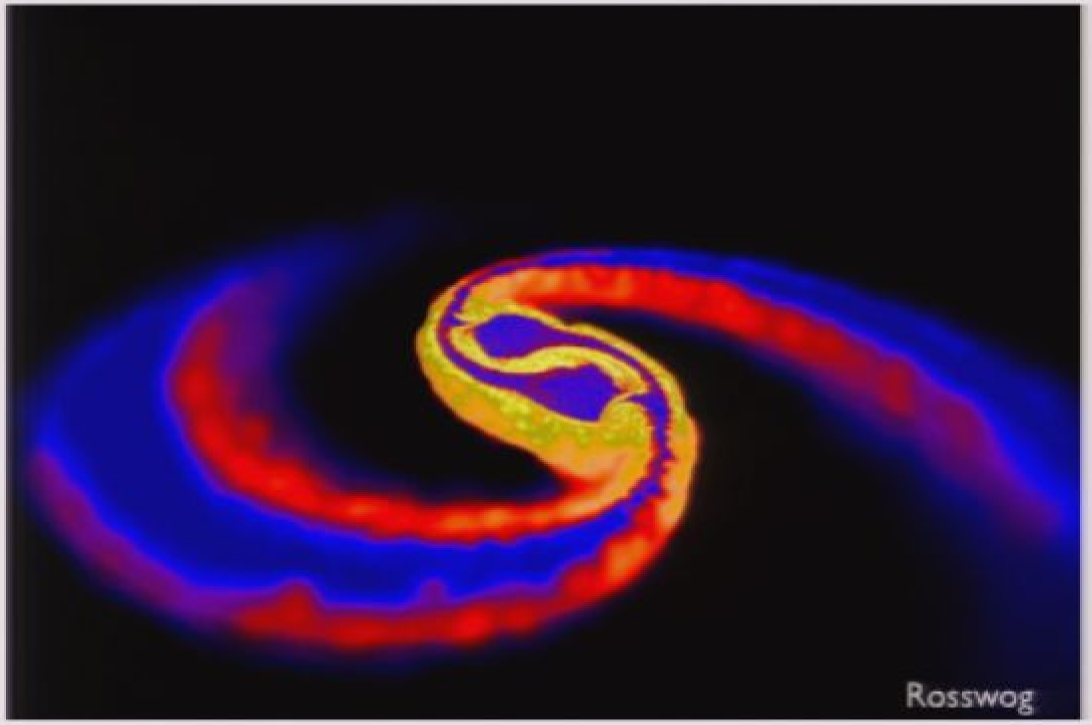

Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.906e+01 s
Temperature: 0.19 GK
Density: 6 g/cm^3
N

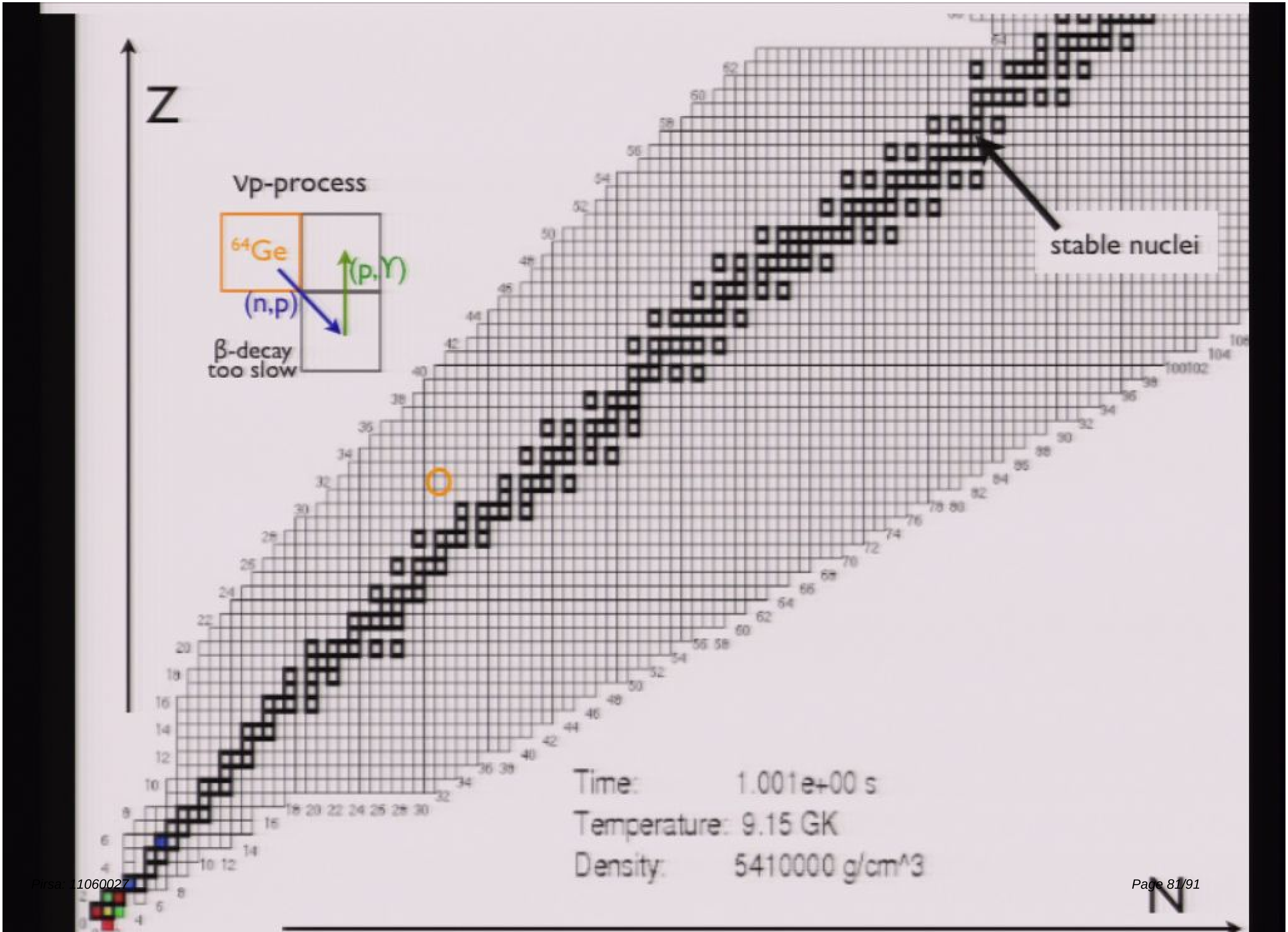


Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 5.142e+01 s
Temperature: 0.10 GK
Density: 1 g/cm^3
N

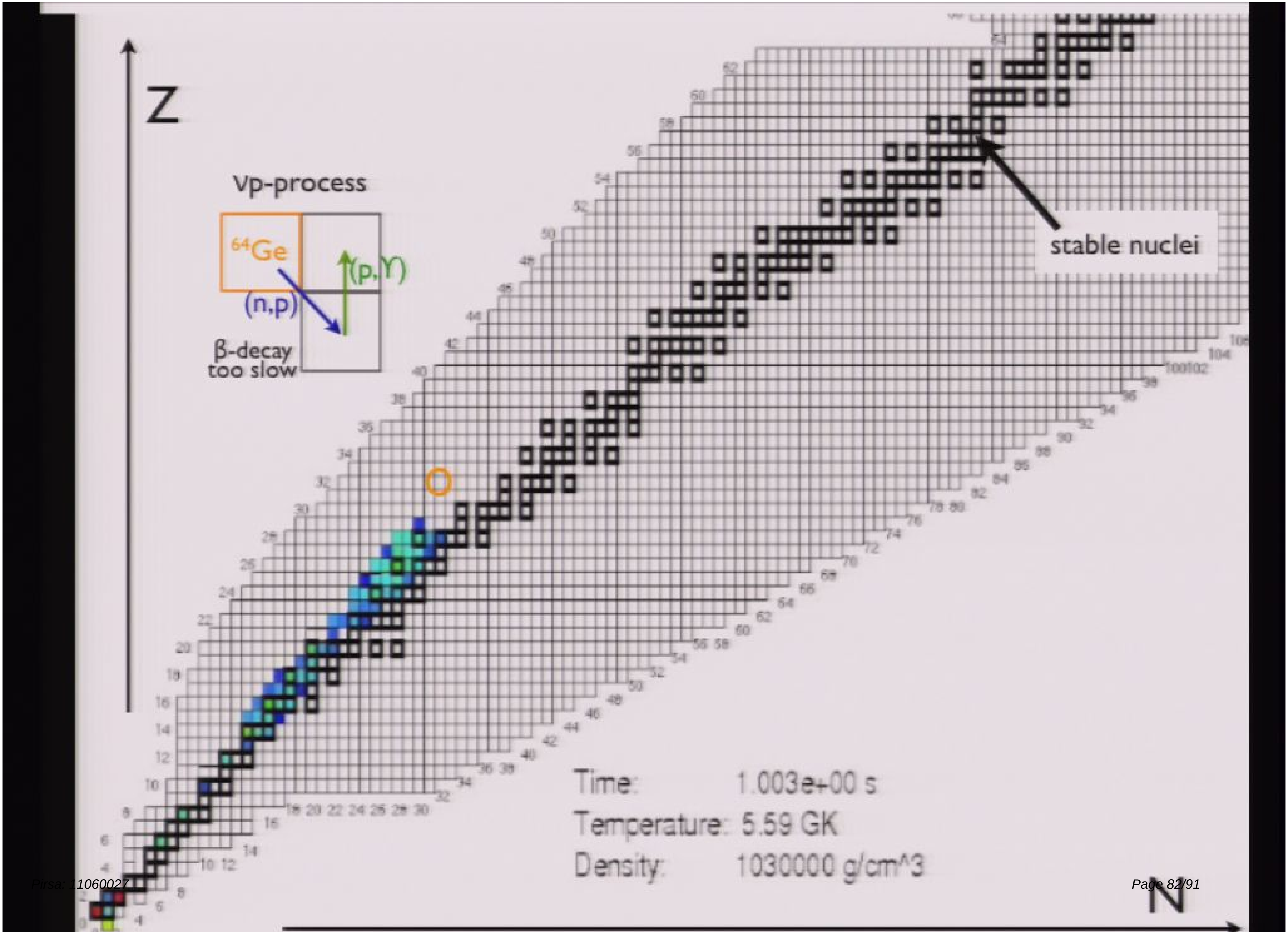
r-process in neutron star mergers

- contribution to chemical history of our galaxy (Freiburghaus et al. 1999, ...).
- r-process heating affects merger dynamics (Freiburghaus et al. 1999, Metzger et al. 2010).
- optical transient with kilo-nova luminosity (Metzger et al. 2010): detection of r-process in neutron-star mergers (complementary to gravitational wave detection).





Z
νp-process
64Ge
(p,γ)
(n,p)
β-decay
too slow
stable nuclei
Time: 1.001e+00 s
Temperature: 9.15 GK
Density: 5410000 g/cm^3
N


Z
νp-process
^{64}Ge
(p,γ)
(n,p)
β-decay too slow
stable nuclei
Time: 1.003e+00 s
Temperature: 5.59 GK
Density: 1030000 g/cm^3
N

r-process in neutron star mergers

- contribution to chemical history of our galaxy (Freiburghaus et al. 1999, ...).
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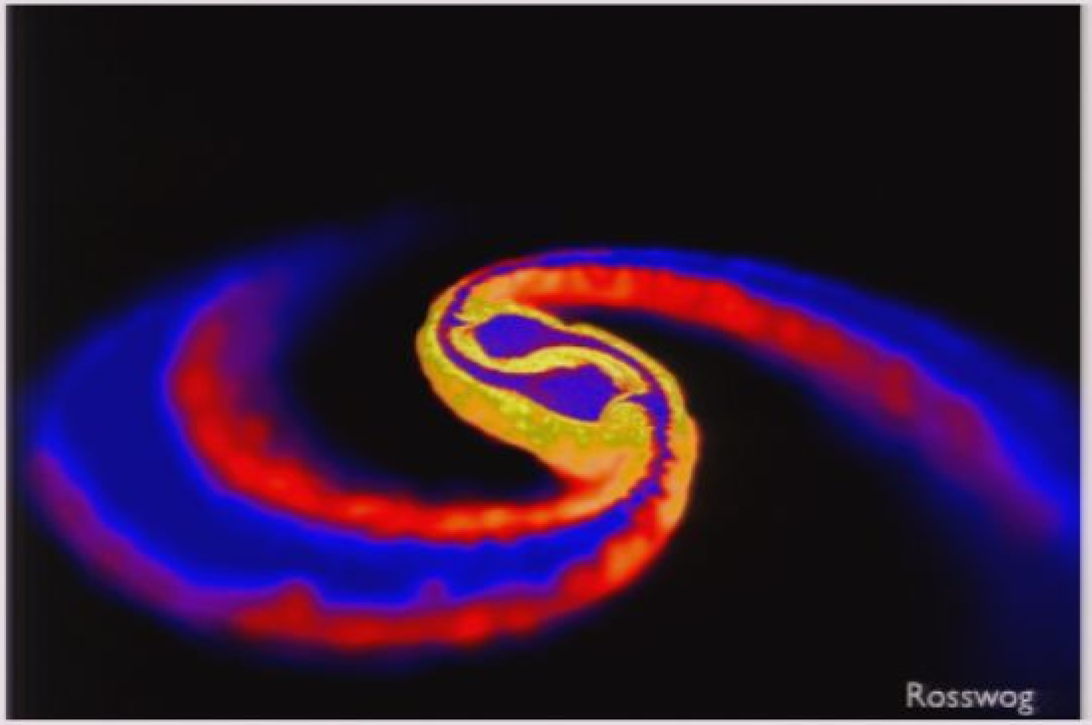
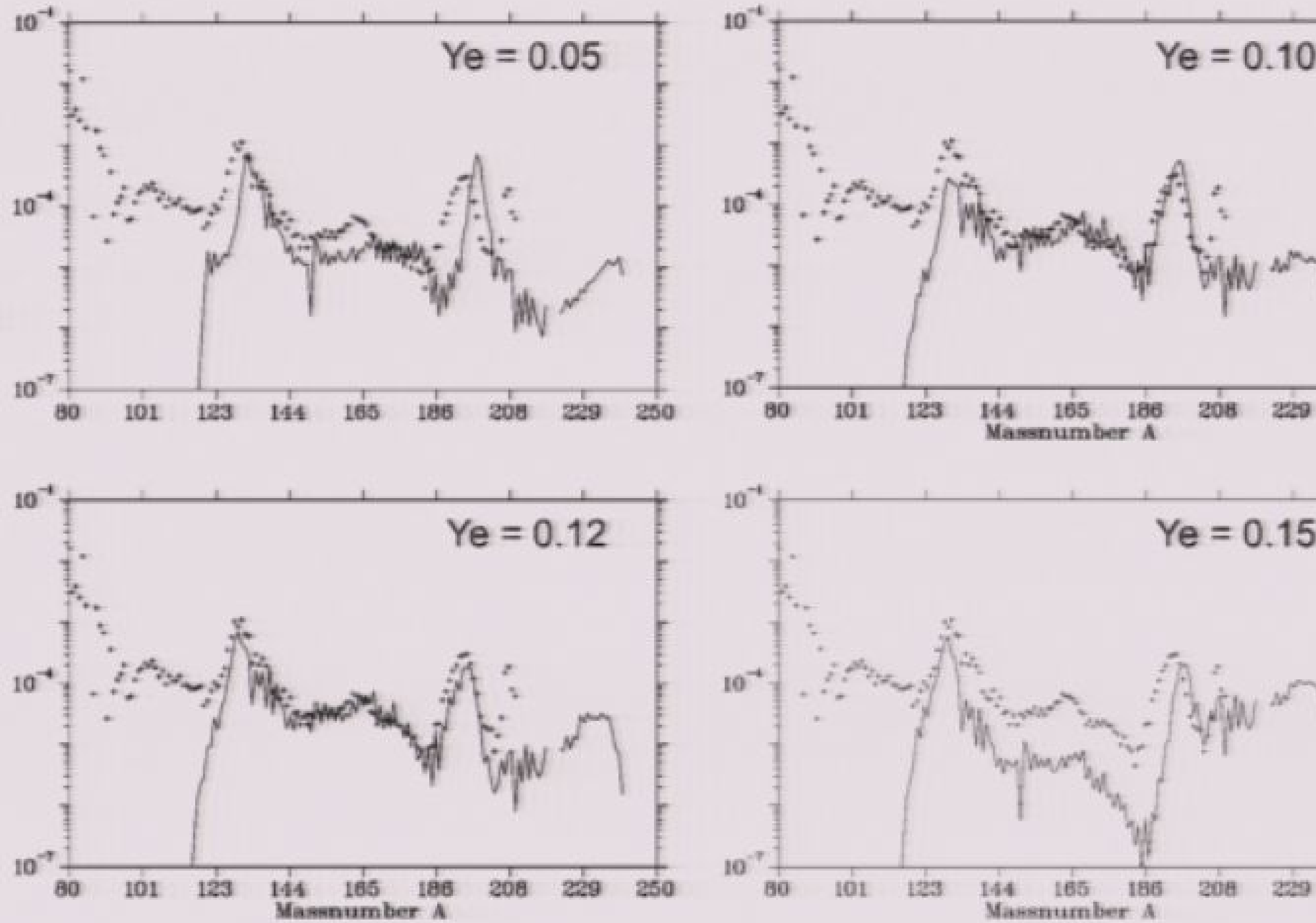
- optical transient with kilo-nova luminosity (Metzger et al. 2010): detection of r-process in neutron-star mergers (complementary to gravitational wave detection).



Chemical history of our galaxy

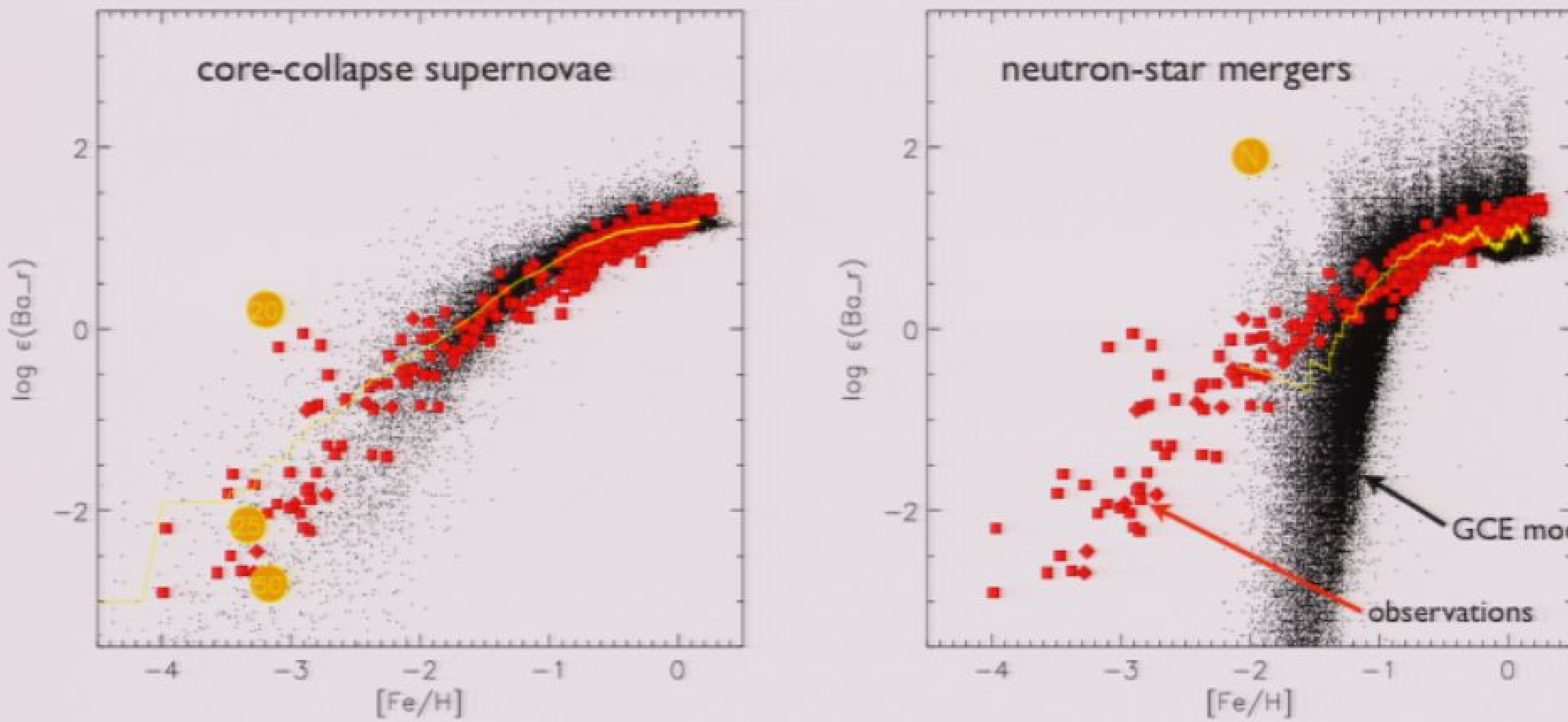
Freiburghaus, Rosswog, Thielemann 1999: r-process abundances based on merger simulations

low entropy,
high neutron densities,
no alpha particles,
neutron-rich seed nuclei



Chemical history of our galaxy

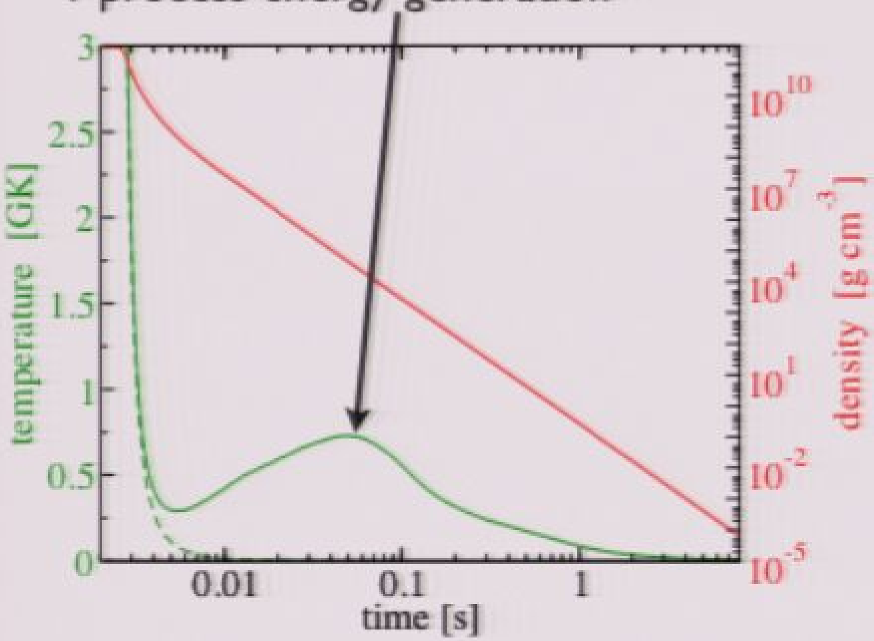
Argast et al. 2004: galactic chemical evolution models r-process from:



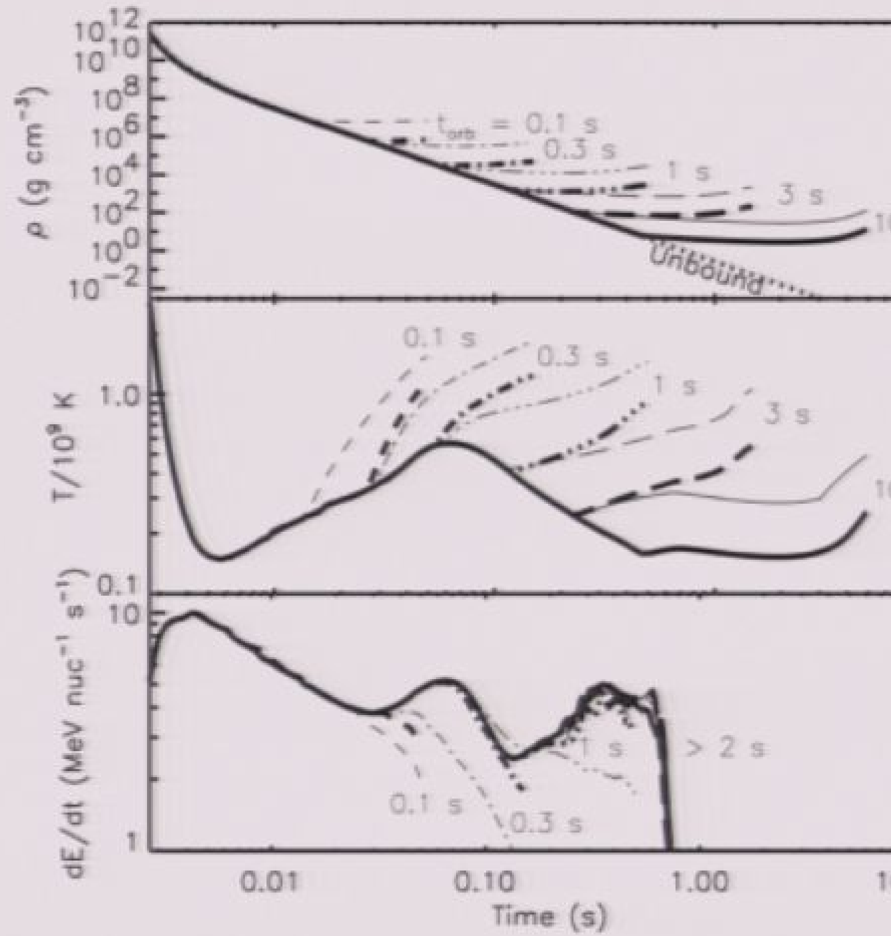
Open questions: amount of mass ejected
event rate

r-process heating

Freiburghaus, Rosswog, Thielemann 1999:
r-process energy generation



Metzger, Arcones, Quataert, Martinez-Pinedo 2



impact on fallback dynamics

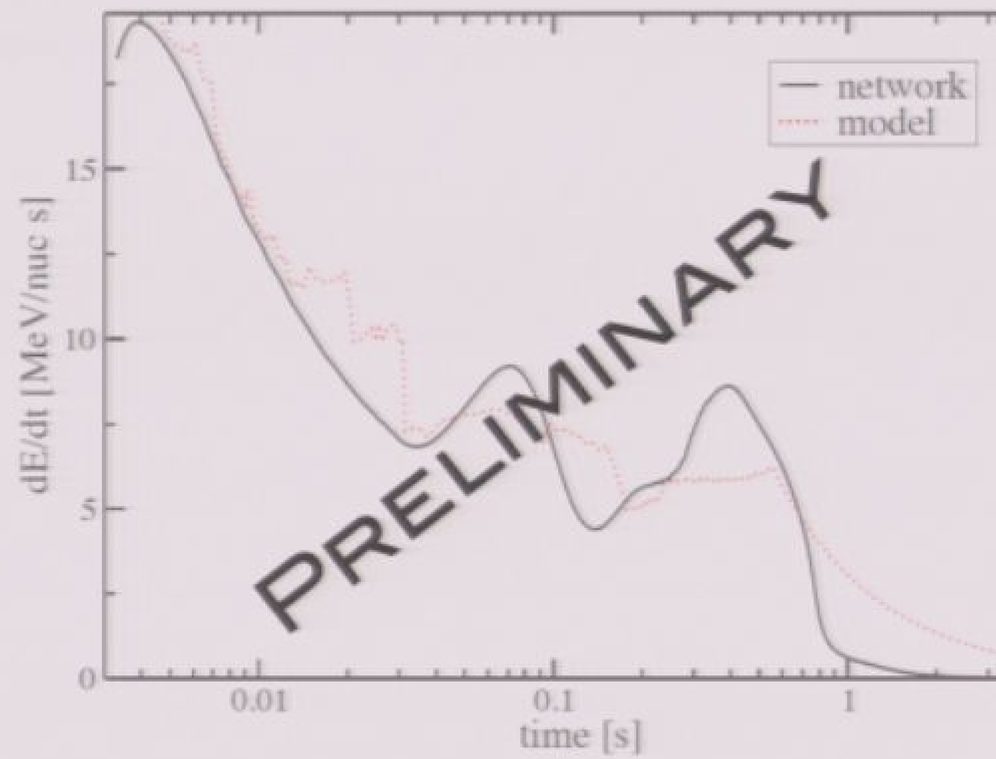
late X-ray emission observed in short gamma-ray bursts

r-process heating model

to account for the r-process energy generation in merger simulations

assumptions: (n,γ)-(γ,n) equilibrium
energy from beta decay

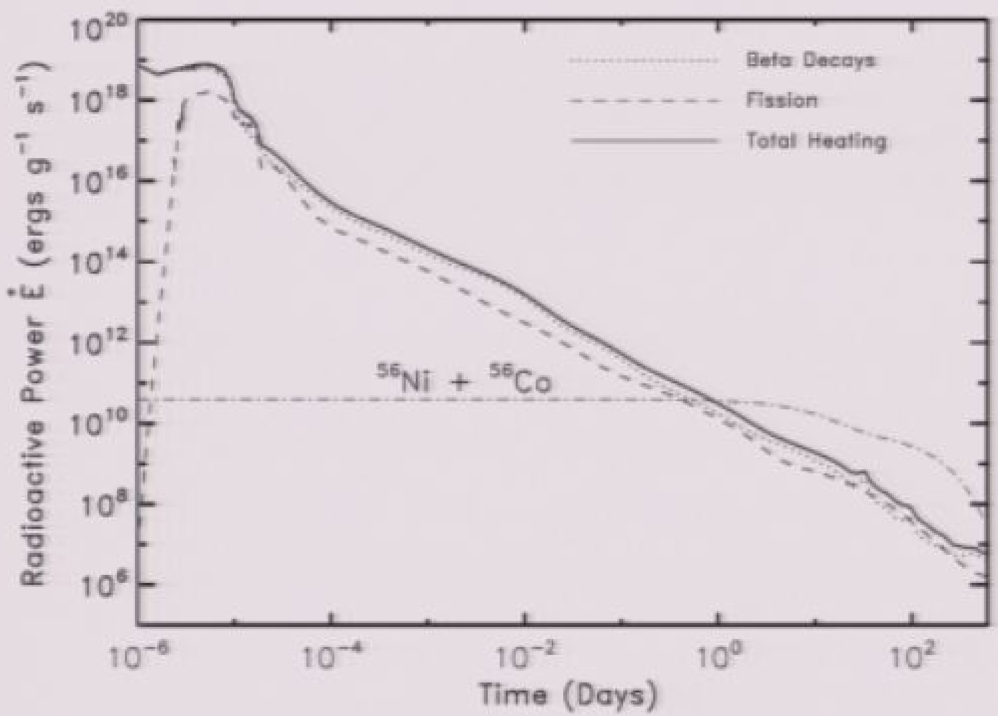
table or simple routine?
input: N_n, T, $\langle Z \rangle$
output: $\dot{E}$, $\langle \dot{Z} \rangle$, $\dot{Y}_n$



(Metzger et al. 20

r-process observation

- Radioactive decay
- Optical transient with kilo-nova luminosity
- Detection of r-process in neutron-star mergers, complementary to gravitational wave detection.



(Metzger et al. 20

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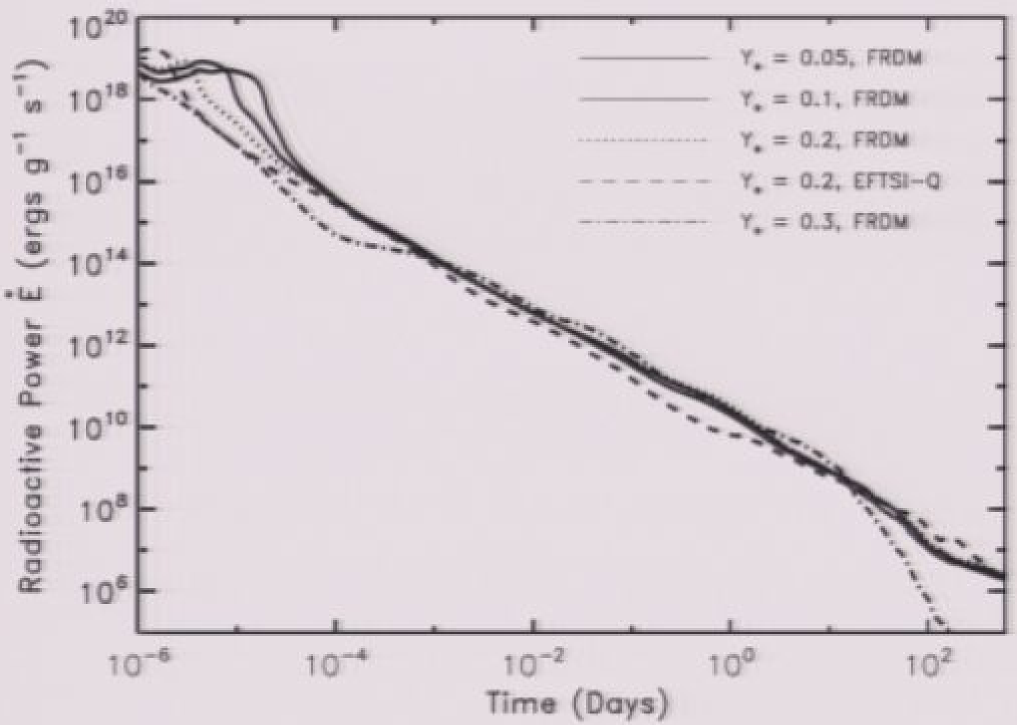

(Metzger et al. 20

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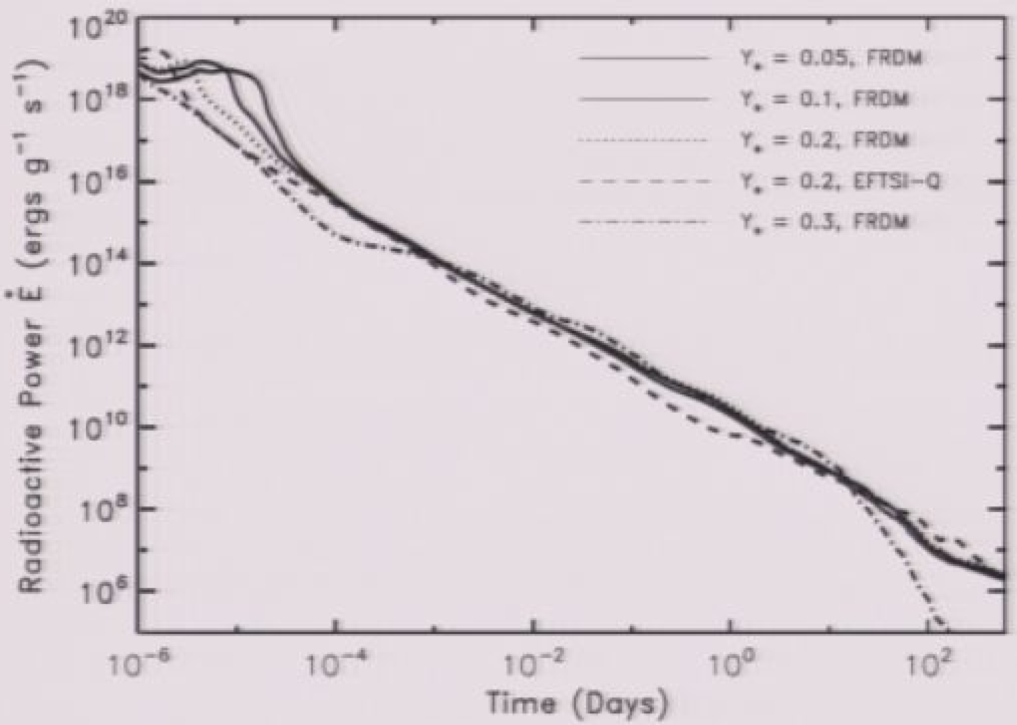
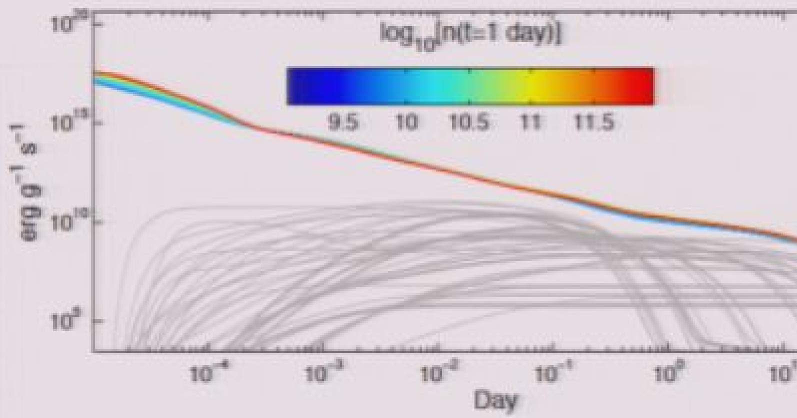
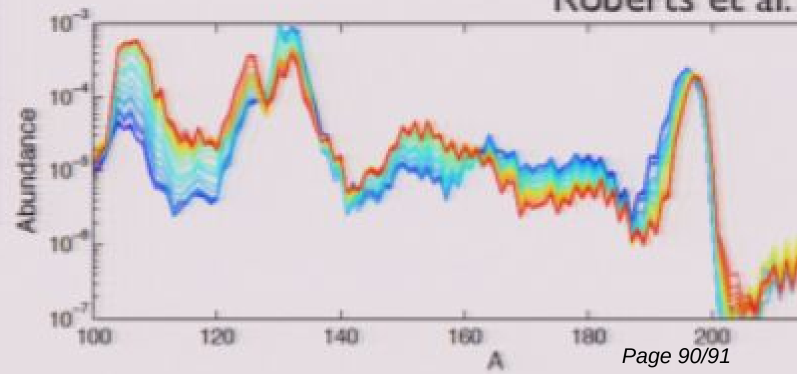




Roberts et al. 2



Conclusions

- Most sophisticate 1D hydrodynamical simulations: no r-process
  too low entropy, proton-rich conditions
- Lighter heavy elements (Sr, Y, Zr) can be produced in neutron- and proton-rich neutrino-driven winds (stellar LEPP): agreement with observations.
- Light clusters ($2<A<4$) are present in the neutrinosphere region and impact antineutrino spectra.
- Energy generated by r-process affects neutron-star merger dynamics: it has to be included in the simulations.
- Decay of radioactive r-process nuclei can be directly observed as a kilo-nova.