Modelling uncertainty of the Rhenium-Osmium cosmic clock

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Svein Rosselands hus 209

What is a cosmic clock?

Why use $^{187}_{75}$Re-$^{187}_{76}$Os?

$^{187}_{75}\mathrm{Re}$-$^{187}_{76}\mathrm{Os}$

Advantages

Halflife	$T_\beta = 43.3$ Gyr[1] ($\lambda_\beta = \frac{\ln 2}{T_\beta}$)
Different sources	Slow and rapid neutron capture process

[1] IAEA Nuclear Data Service Livechart

Nucleosynthesis

How was the nuclear elements created?

- Big bang nucleosynthesis
- Fusion of lighter elements (up to iron)
- Neutron capture processes

  slow β^--decays before succesive neutron capture
  rapid capture multiple neutrons before β^--decay

Slow and rapid neutron capture around $^{187}_{75}Re$-$^{187}_{76}Os$

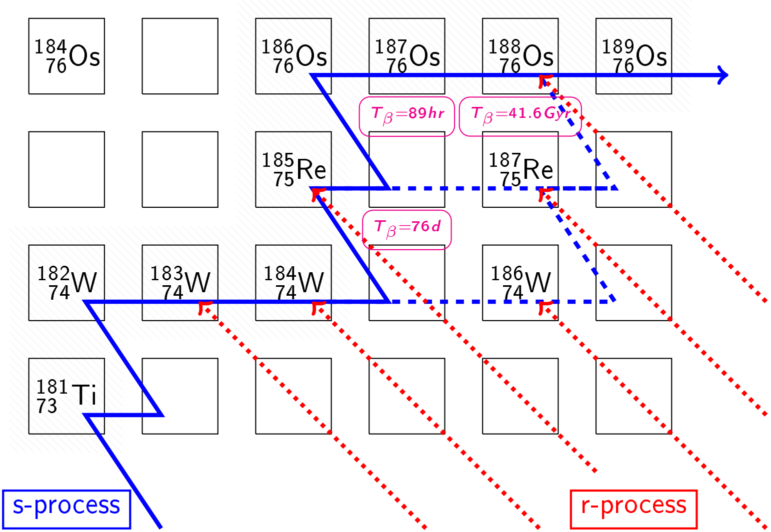


Figure: Adopted from [5, fig.1]

Analytical models of $^{187}_{75}$Re-$^{187}_{76}$Os cosmic clock

$$\frac{dN}{dt} = -\lambda N \tag{1}$$

$$^{187}_{76}\mathrm{Os}_{\odot} = {}^{187}_{76}\mathrm{Os}_s + {}^{187}_{76}\mathrm{Os}_p + {}^{187}_{76}\mathrm{Os}_c \tag{2}$$

$$\frac{d}{dt}\left[{}^{187}_{76}\mathrm{Os}_c\right] = \lambda_\beta\,{}^{187}_{75}\mathrm{Re} \tag{3}$$

$$\frac{d}{dt}\left[{}^{187}_{75}\mathrm{Re}\right] = A(t) - \lambda_\beta\,{}^{187}_{75}\mathrm{Re} \tag{4}$$

Using the analytical model from Clayton *[5]*

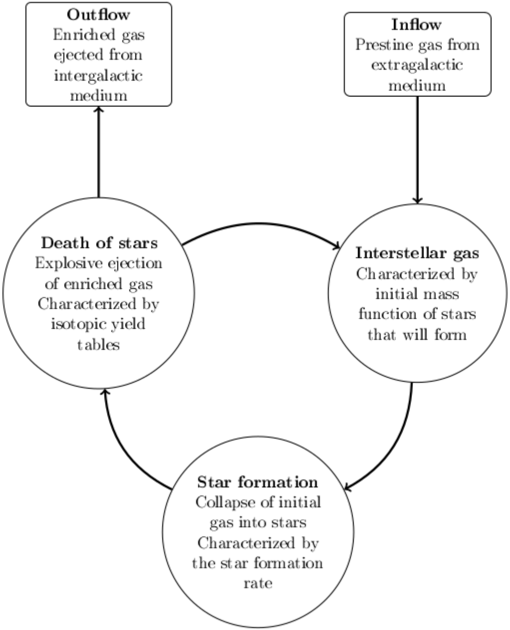
$$A(t) = A_0 e^{-\lambda_r t} \tag{5}$$

$$f_{187} \equiv \frac{{}^{187}_{76}\mathrm{Os}_c}{{}^{187}_{75}\mathrm{Re}} = \frac{\frac{\lambda_\beta}{\lambda_r}(1 - e^{-\lambda_r t}) - (1 - e^{-\lambda_\beta t})}{e^{-\lambda_r t} - e^{-\lambda_\beta t}} \tag{6}$$

Observed isotope fraction from meteorites and solar atmosphere

$$
\begin{aligned}
{}^{187}_{76}\mathrm{Os}_{\odot}/{}^{187}_{75}\mathrm{Re}_{\odot} &= 0.226 \pm 0.0579 \quad [?] && (7)\\
\Delta t_{sos} &= 4.5682 \pm (4 \times 10^{-4})\,Gyr \quad [7] && (8)\\
T_{1/2} &= 41.577 \pm 0.12\,Gyr \quad [8] && (9)\\
f_{187}(t_{sos}) &= 0.135 \pm 0.0323 && (10)
\end{aligned}
$$

Chemical enrichment of galactic medium



Explosive events

- Asymptotic giant branch stars (not really explosive)
- Core collapse supernovae
- Type 1a supernovae
- Neutron star mergers

Eris simulation

The Astrophysical Journal, 742:76 (10pp), 2011 December 1

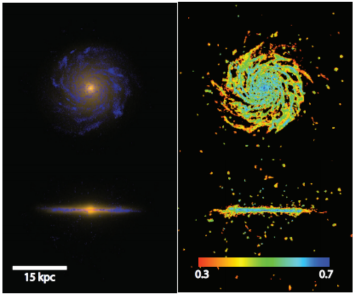


Figure: credit: Guedes et al. (2011) *[4, fig.2]*

- Smoothed particle hydrodynamics simulation *[4]*
- 3D
- 18.6 million particles
- Postprocessing to add rapid neutron capture elements from neutron star mergers *[2]*

Omega semianalytical model *[3]*

- SFR + timestep $\rightarrow$ stellar mass formed
- stellar mass formed $\rightarrow$ stellar population
- stellar population + yield tables + delay-time $\rightarrow$ isotopic yields recycled into ISM + remnant
- remnants $\rightarrow$ secondary events

Modelling uncertainty of the Rhenium-Osmium cosmic clock

Methods

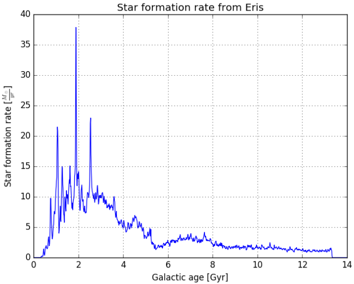
- Fitting `Omega` to data from `Eris`
- Manipulate yields in `Omega`
- Main experiments
- Postprocessing

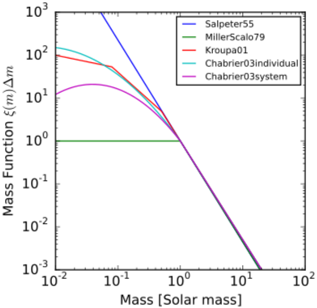
Fitting Omega to data from Eris

- Rough model
- "χ^2-by-eye"
- Star formation rate, stellar mass, total mass, [O/H], [Fe/H], [Eu/H]

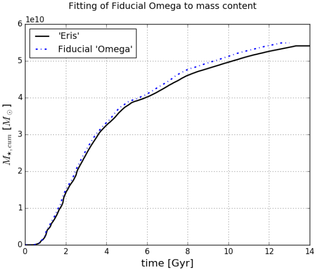
- Direct insertion
- Mass content
- type 1a supernovae
- Neutron star mergers
- Size of timesteps

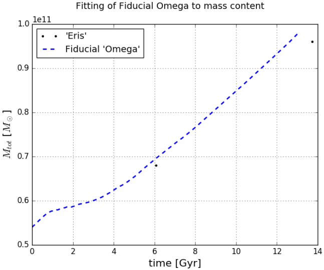
Direct Insertion



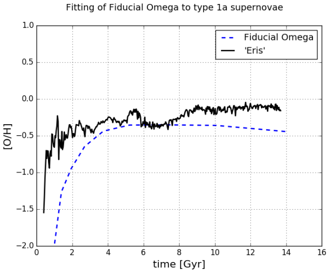


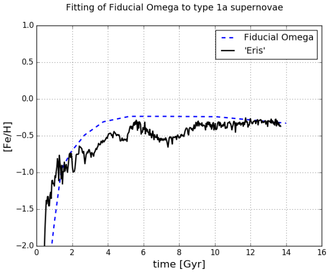
Mass content



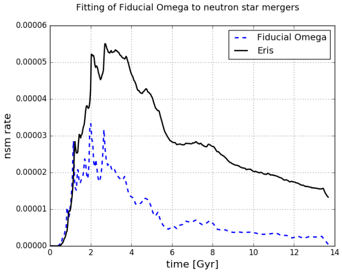


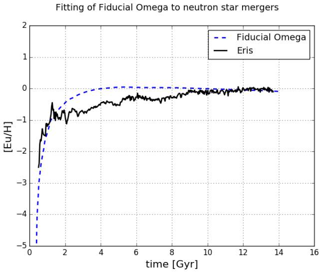
Stellar parameters



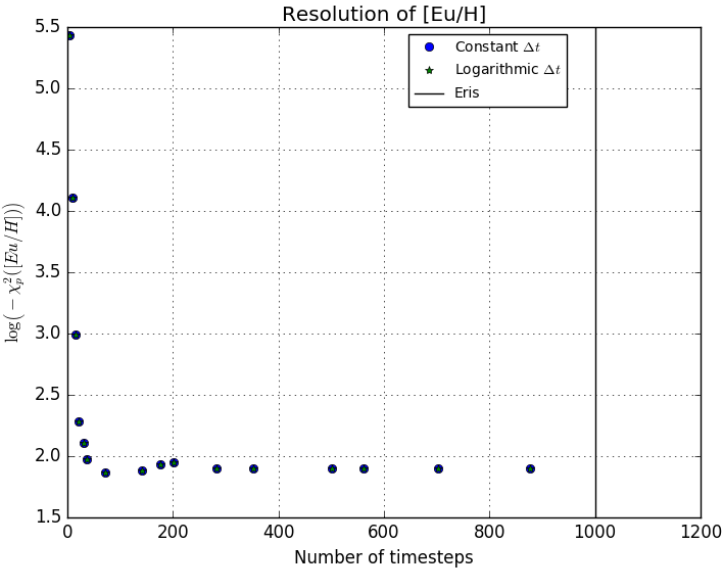


Neutron star mergers





Size of time steps



Manipulate yields in `Omega`

- Yields from arnould and other TODO!
- “Fudge-factors”

Table of observed abundances

isotope	standard	min	max	σ_{lower}	σ_{upper}
Re-187	0.0318	0.027	0.0359	-0.1509	0.1289
Re-185	0.0151	0.011	0.0176	-0.2715	0.1656
Os-188	0.0707	0.0633	0.0781	-0.1047	0.1047
Os-189	0.103	0.0961	0.109	-0.067	0.0583
Os-190	0.152	0.137	0.168	-0.0987	0.1053
Os-192	0.273	0.252	0.289	-0.0769	0.0586
Eu-151	0.0452	0.0267	0.0482	-0.4093	0.0664
Eu-153	0.0495	0.046	0.0526	-0.0707	0.0626

Table: Values and uncertainties of r-process nuclei near $^{187}_{75}$Re from *[1]*

Main experiments

- Draw random “fudge-factor” from gaussian distribution
- 1500 individual calculations
- **Yields**
- **Yields+IMFslope**
- **Yields+IMFslope+NSM**

Postprocessing

β^--decay

- $\Delta \mathrm{Re} = -\lambda_{\mathrm{Re}} \mathrm{Re} \Delta t$
- $\Delta \mathrm{Os} = \lambda_{\mathrm{Re}} \mathrm{Re} \Delta t$

Removing negative negative yields

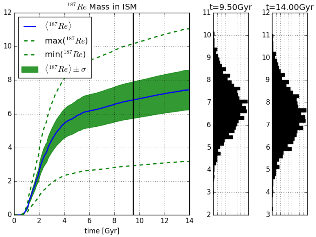
- $\hat{Y} \leq 0 \rightarrow$ Do not consider calculation

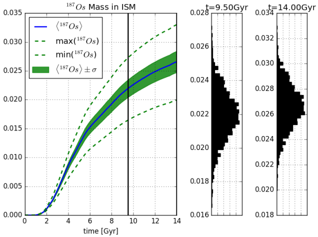
Results

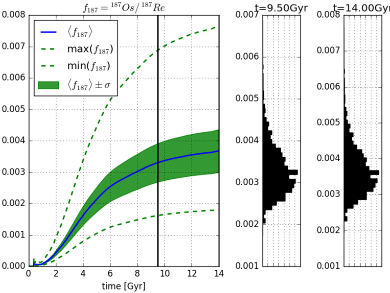
- $^{187}_{75}$Re in interstellar gas
- $^{187}_{76}$Os in interstellar gas
- $f_{187} = \frac{^{187}_{76}\mathrm{Os}}{^{187}_{75}\mathrm{Re}}$
- Rate of neutron star mergers

- **Yields**
- **Yields+IMFslope**
- **Yields+IMFslope+NSM**

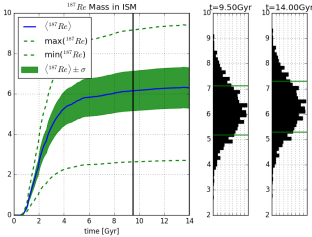
Yields without postprocessing

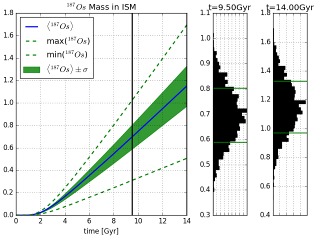


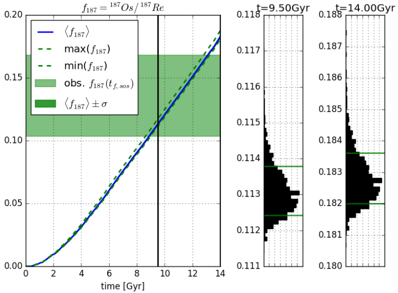




Yields with postprocessing



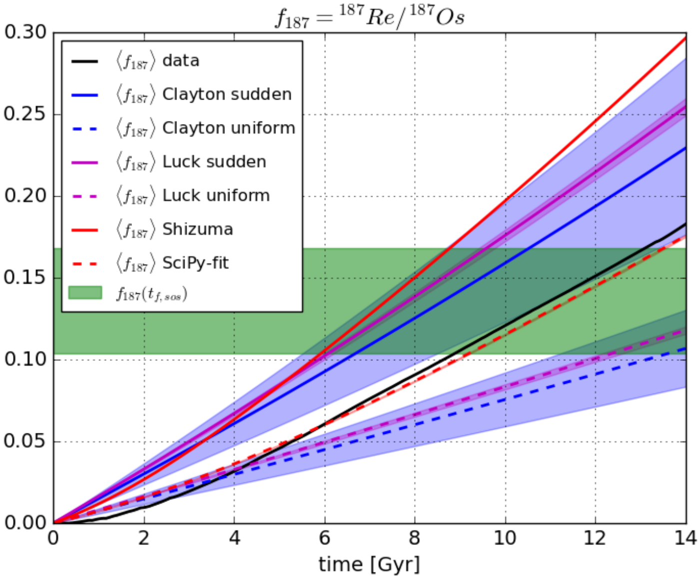




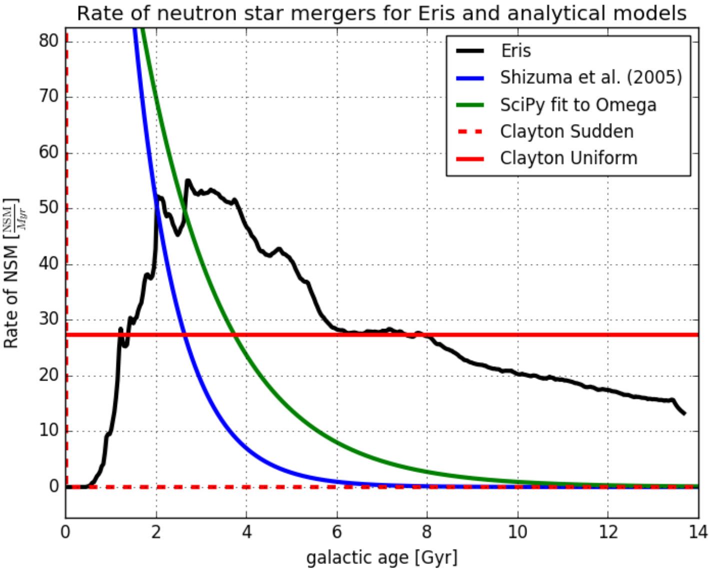
Comparing models

Model	${}^{187}_{76}\mathrm{Os}_c/\ {}^{187}_{75}\mathrm{Re}$	λ_{Re}	λ_{rncp}
Clayton	$\frac{\Lambda-\lambda}{\lambda}e^{\lambda t}\frac{1-e^{-\Lambda t}}{1-e^{-(\Lambda-\lambda)t}}-1$	$\lambda=\frac{\ln 2}{\tau_{Re}}$	Λ
Clayton Sudden synthesis	$e^{\lambda t}-1$	$\tau_{Re}=47\pm 10Gyr$	$\Lambda\rightarrow\infty$
Clayton Uniform synthesis	$\frac{\lambda t}{1-e^{-\lambda t}}-1$	——"——	$\Lambda\rightarrow 0$
Luck	$\frac{\lambda_{Re}/\beta(1-e^{-\beta t})-(1-e^{-\lambda_{Re}t})}{e^{-\beta t}-e^{-\lambda_{Re}t}}$	$\lambda_{\mathrm{Re}}=\ 1.62\pm 0.08 \times 10^{-11}yr^{-1}$	β
Luck Sudden synthesis	——"——	——"——	$\beta=10^{-6}yr^{-1}$
Luck Steady state	——"——	——"——	$\beta=10^{-12}yr^{-1}$
Shizuma	$\frac{(1-e^{-\lambda_\beta^{\mathrm{eff}}t})-(1-e^{-\lambda t})\lambda_\beta^{\mathrm{eff}}/\lambda}{e^{-\lambda_\beta^{\mathrm{eff}}t}-e^{-\lambda t}}$	$\lambda_\beta^{\mathrm{eff}}=\frac{1.2\ln 2}{\tau_{Re}}=2.00\times 10^{-11}[yr^{-1}]$	$\lambda\in[0,2]Gyr^{-1}$
SciPy curvefit to *Fiducial* `Omega`-*model*-data	——"——	1.33×10^{-11} $\pm 2.767\times 10^{-14}$ $[yr^{-1}]$	5.42×10^{-10} $\pm 5.79\times 10^{-12}$ $[yr^{-1}]$

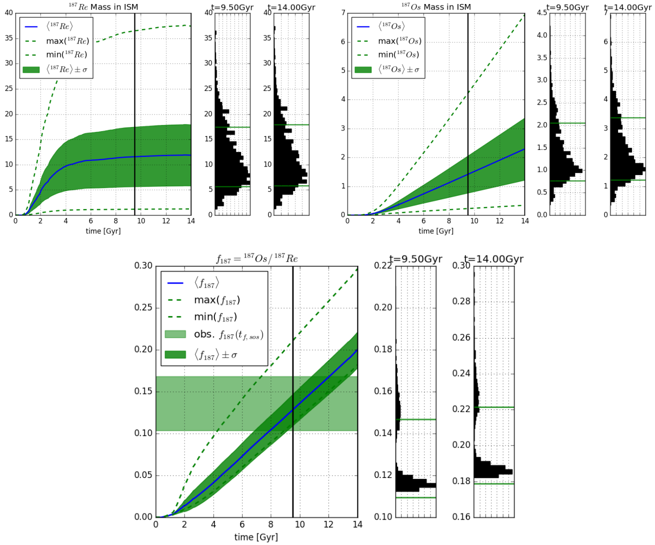
Comparing models



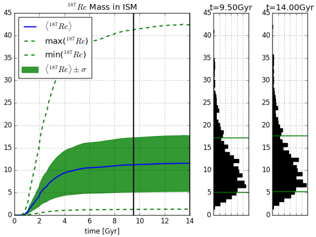
Comparing models

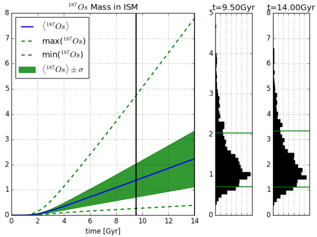


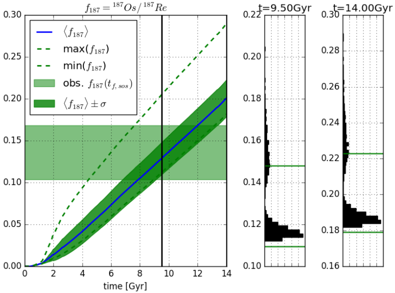
Uncertainties of **Yields+IMFslope**



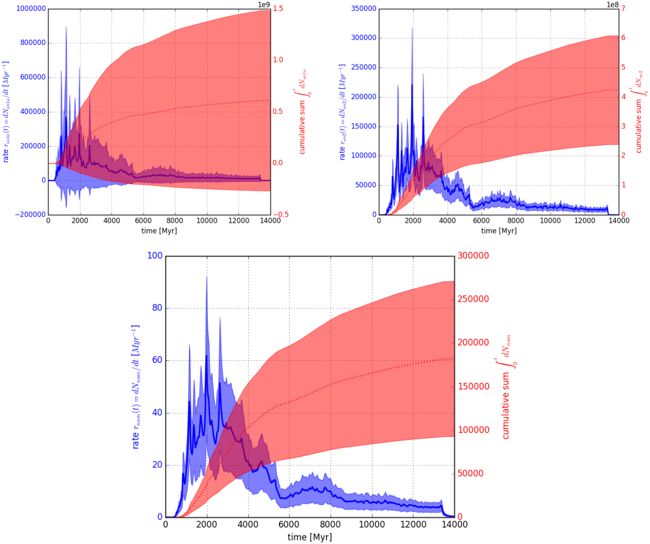
Uncertianties of **Yields+IMFslope+NSM**







Uncertianties of **Yields+IMFslope+NSM**



Conclusions/summary

- **Yields**
- **Yields+IMFslope**
- **Yields+IMFslope+NSM**

- Uncertainties with and without β^--decay
- Uncertainties of models and observations
- Additional uncertainties from the slope of the *Initial Mass Function*
- Additional uncertainties from *Neutron Star Mergers*

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