INAF

THE 13TH TORINO WORKSHOP ON AGB STARS
PERUGIA, 19TH-24TH JUNE 2022

Beyond Fe: Ba and Eu in numerical Galaxy models

V. Antonuccio-Delogu
INAF - Catania Astrophysical Observatory
and M- Busso, S. Palmerini (INFN, Pg)

Credit: FIRE-2 (Hopkins et al., 2021)

- The GIZMO code (Hopkins, 2015 - ongoing) and its customisation
- Test 1: isolated Milky-Way in equilibrium
- Two tests: s- and r-process elements from a simplified SF
- *Systematic effects* in numerical models

- GIZMO (*Hopkins, 2015…)*: different numerical methods (MFM to classical SPH), cooling (cont. and line), star formation (from SSP down to single stars), feedback (default: as in AGORA-2 code comparison project)
  Versatile, highly tested, good scaling.

- Comparison with *Gadget 2*: more sophisticated numerical method, adaptive Voronoi-like mesh

- Main target: customize to track production of selected p- and s elements. Requires detailed recipes for *subgrid physics*: SF, SNIa and SNII, stellar feedback from TP-AGB (winds), and models of their diffusion in the host galaxy.

- This work: isolated MW-type galaxy.
  ICs created using *DICE* (Perret, 2014), stable equilibrium forming a $m=2$ spiral structure.

Numerical experiments

- Isolated MW-type, $M_h = 7.4\text{x}10^{11}\ M_\odot$, $M_{bulge} = 1.55\text{x}10^{10} M_\odot$, $M_{gas} = (8.2 + 1.3)\text{x}10^9\ M_\odot$, $M_{disk} = 3.65\text{x}10^{10}\ M_\odot$ (model B2 from de Salas et al., 2019)

- *Concordance* cosmological model: Ω_M=0.3089, Ω_Λ=0.6911, Ω_{bar}=0.0486, h_0 = 0.6774

- (baryonic) mass resolution: $m_{bar} = 1.217\text{x}10^4\ M_\odot$, $m_{gas} = 3.167\text{x}10^3 M_\odot$

- $L_{box} = 100\ h^{-1}\ kpc$, $z_{in} = 4$, $t_{in} = 138$ Myr

- MFM hydro solver, cooling (GRACKLE, $10 \leq T \leq 10^9\ K$) both synchr. and metal-line , mechanical feedback, complete SF criterion (incl. $\nabla \cdot \boldsymbol{v} < 0$, $n_{thr} = 10^3\ e^-\ cm^{-3}$)

Customising stellar feedback

Only SNII feedback is available with the default version of **GIZMO**
Added: *Neutron Star Mergings, low mass TP-AGB star winds*

Eu sources:

1. *Type II SN*: from $20 \leq M_{pre\text{-}SN*} \leq 50\ M_{\odot}$), yield = $3x10^{-9}$ for each event
2. *SNIa*: from binaries having: $9 \leq M_{1,2} \leq 50\ M_{\odot}$, yield ~ $3x10^{-7}$

Ba sources:

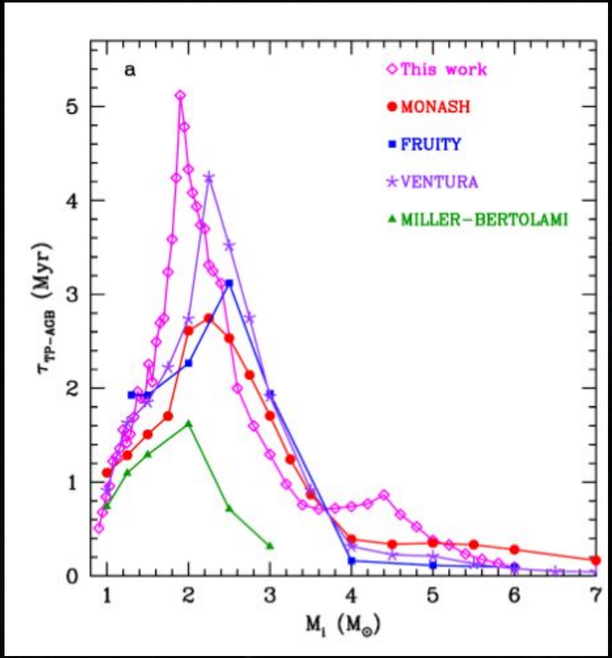
1. *Type II SN*: yield $3.5x10^{-8}$
2. *TP-AGB winds:* ($1 \leq M_{*} \leq 3\ M_{\odot}$) yields given by recent calculations from Busso, Kratz, Palmerini et al. (2022)

TP-AGB winds

1. Low mass stars leaving the MS at each given time $t \geq \tau_{in}$ enter the TP-AGB phase on a timescale $\Delta\tau \ll \Delta t_{step}$, i.e. without any delay.
2. $1 \leq M_* \leq 3\ M_\odot$ MS lifetime: $342.83 \leq \tau_{MS}(\mathrm{M}_*) \leq 10^4$ Myr → at each timestep we record M_{AGB}(t), the typical mass switching on the TP-AGB wind.

3. The duration of the wind is calculated by a fit to the results from Marigo (2022): $\Delta\tau_w(M_*) \propto \Delta\tau_{w0} M_*^{\alpha} exp(-M_*/\Delta M_w)$, with α=2.33, $\Delta\tau_{w0}=9.13$ *Myr*, $\Delta M_w = 0.9\ M_\odot$.
4. Mass loss rate: $\dot{M} = 10^{-2}\ M_*\ Gyr^{-1}$(average over a Chabrier IMF)
5. Wind velocity: $v_w = 30\ km\ sec^{-1}$, indep. of M_*.

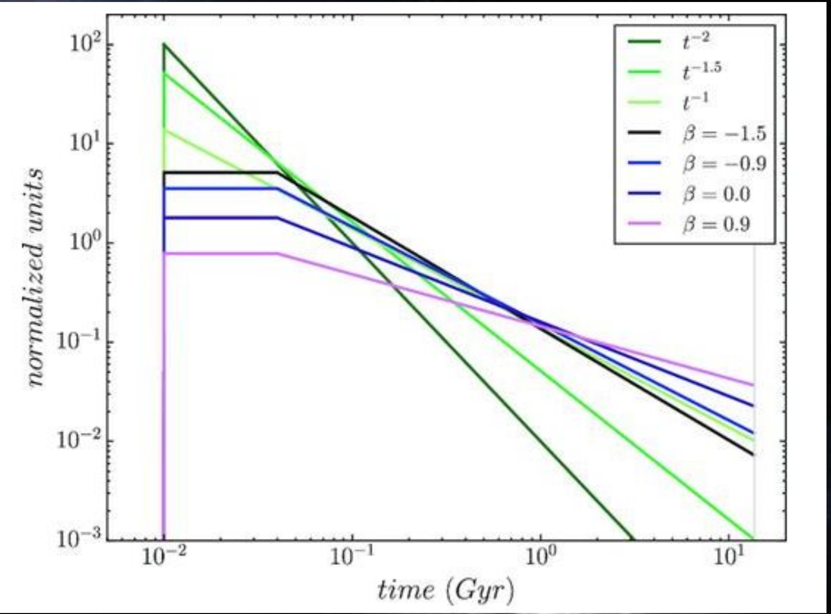
4. and 5. consistent with Hopkins et al., *arxiv 2203.00040*, eqs. (4) and (5).



NS mergers

1. Delay Time Distribution $f_{MNS}(\tau)$ from Simonetti et al. (2019):

$$f(\tau) \propto \begin{cases} 0 & \text{if} \quad \tau < 10\,Myr \\ p_1 & \text{if} \quad 10 < \tau < 40\,Myr \\ p_2\,\tau^{0.25\beta-0.75}\left(M_{\mathrm{DN},s}^{0.75(\beta+2.33)} - M_{\mathrm{DN},l}^{0.75(\beta+2.33)}\right) & \\ \quad \text{if} \quad 40\,Myr < \tau < 13.7\,Gyr \end{cases}$$



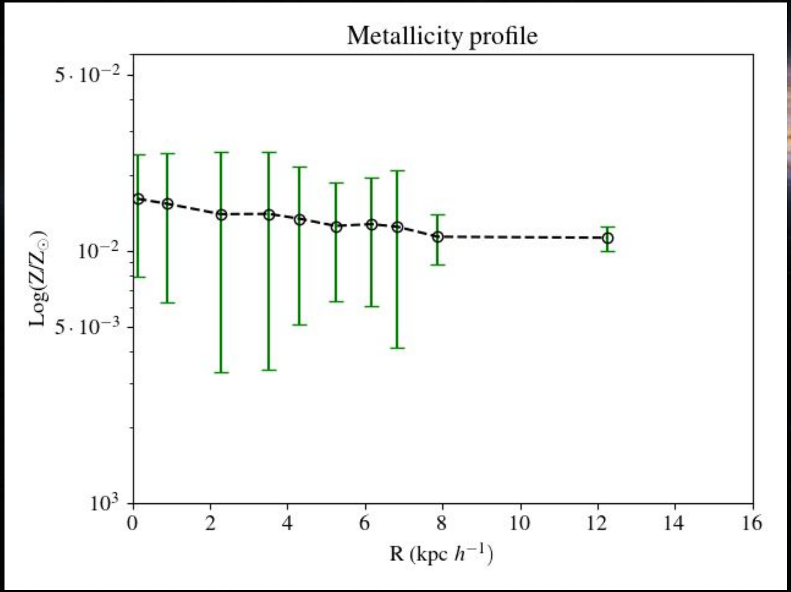
We choose their *optimal model β=-1.5*.

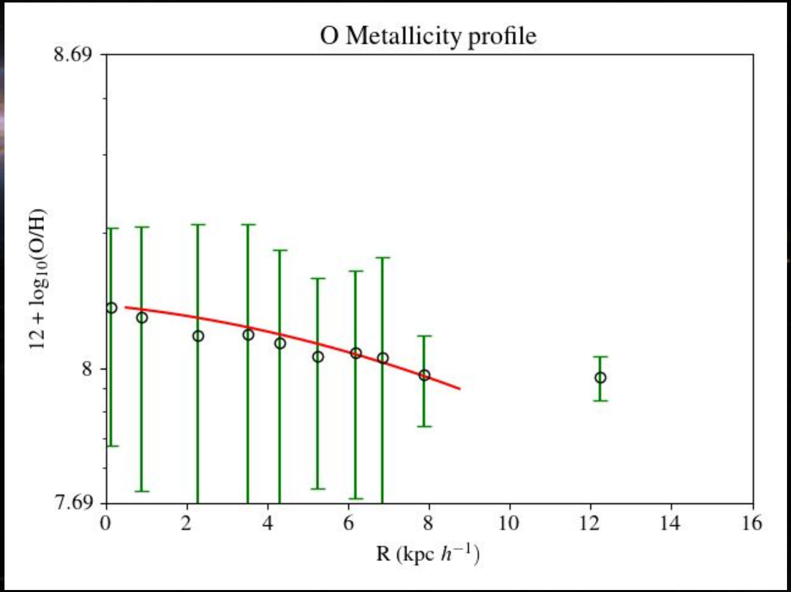
2. NSM rate:

$$R_{\mathrm{MNS}}(t) = k_\alpha \int_{\tau_i}^{\min(t,\tau_x)} \alpha_{\mathrm{MNS}}(\tau)\,\psi(t-\tau)\,f_{\mathrm{MNS}}(\tau)\,\mathrm{d}\tau$$

ψ(τ): SF rate (from num. SSP), α_{MNS}, k_α fixed by IMF.

3. Each SNIa releases $2\,M_\odot$ and 10^{50} *erg* into the ISM.





A slowly decreasing radial abundance profile settles already at z~ 1.5, consistent with previous results.

Now a very different test: evolution of Ba and Eu only produced by events induced by a *m=2* spiral structure, forcing SF to take place only there.

What are we probing with this numerical experiment

1. Dynamical injection of protoypical *r*- and *s-processes* elements (Eu and Ba, resp.) from *NSMs* and *TP-AGBs* resp.
2. Equilibrium, isolated disc of MW type → spiral structure, negligible radial motions

What is outside its scope

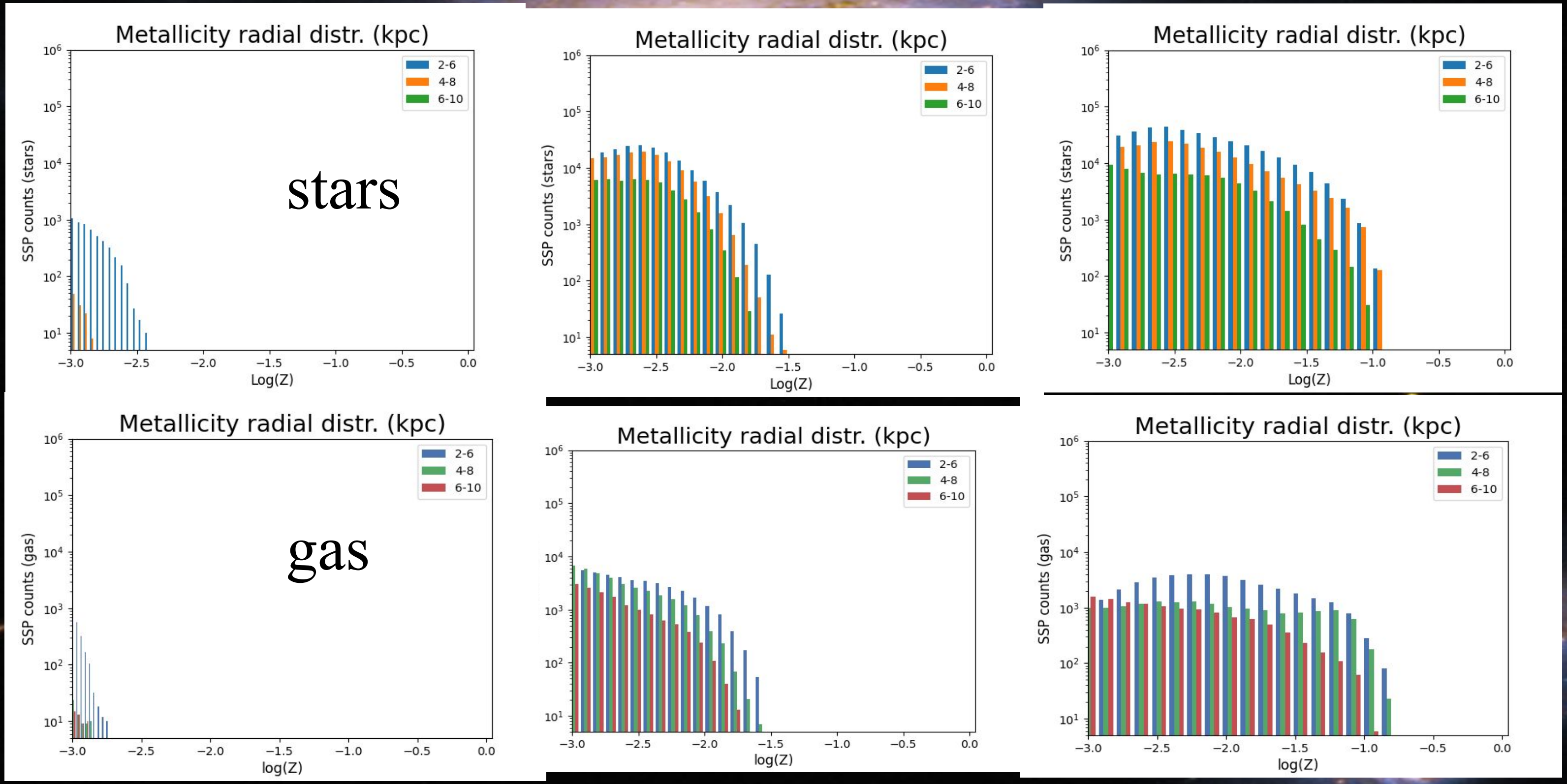
3. Role of *satellite merging* and other dynamical large scale perturbations → radial migration, mixing, not *in-situ* mixing

Two sets of runs, $Z_{in} = 10^{-4}$

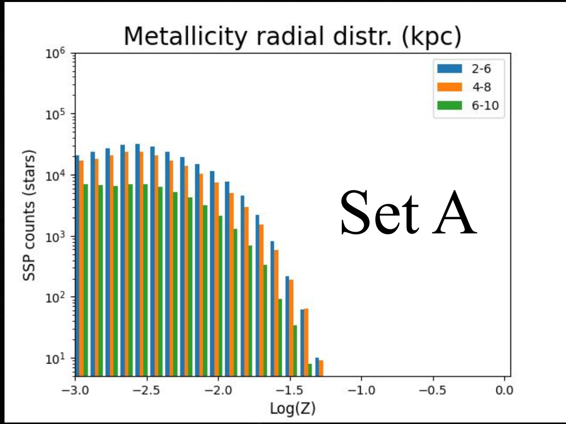
A. $t_{*,in} = 0$ → AGB winds switched after t $\gtrsim$ 340 Myr

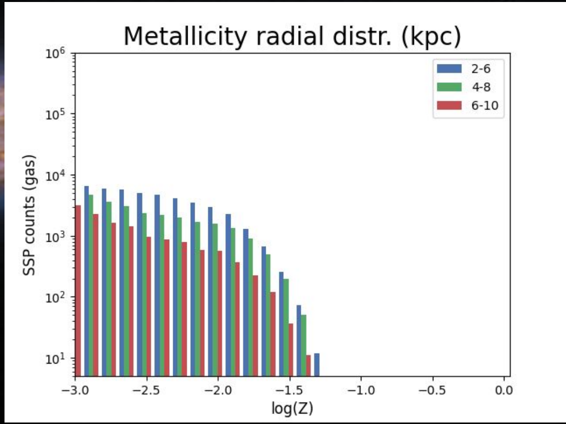
B. $t_{*,in} = t(z_{in}) \gg$ 340 Myr → AGB winds switched immediately

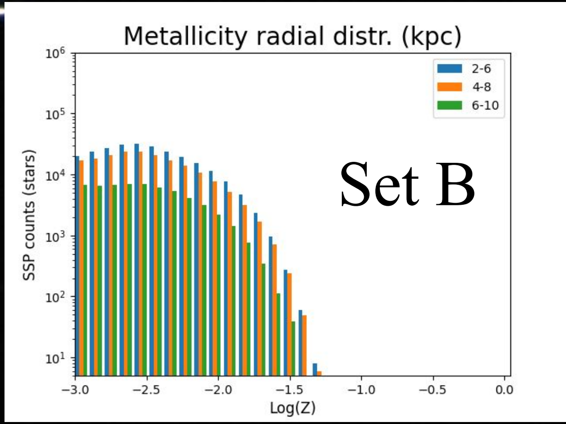
Set A: Metallicity's radial gradient

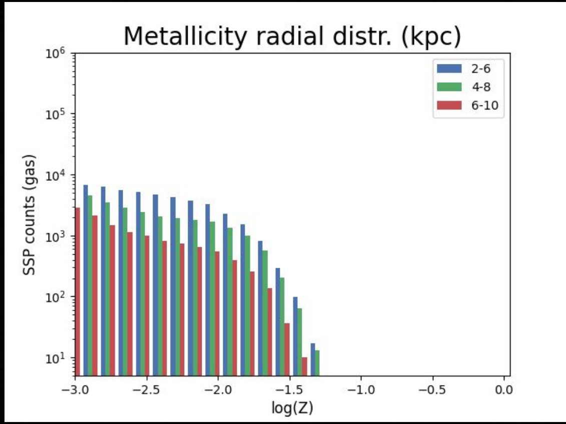


Smoothing of radial gradients is driven by the global dynamics: SF regions mostly driven and *synchronised* by a *m=2* grand design spiral.









- No differences seen between case A and B → winds play a negligible role in shaping the Z distribution.
- Z distr. does not depend on distance. This is a result of the combined action of SNs and spiral structure driving.

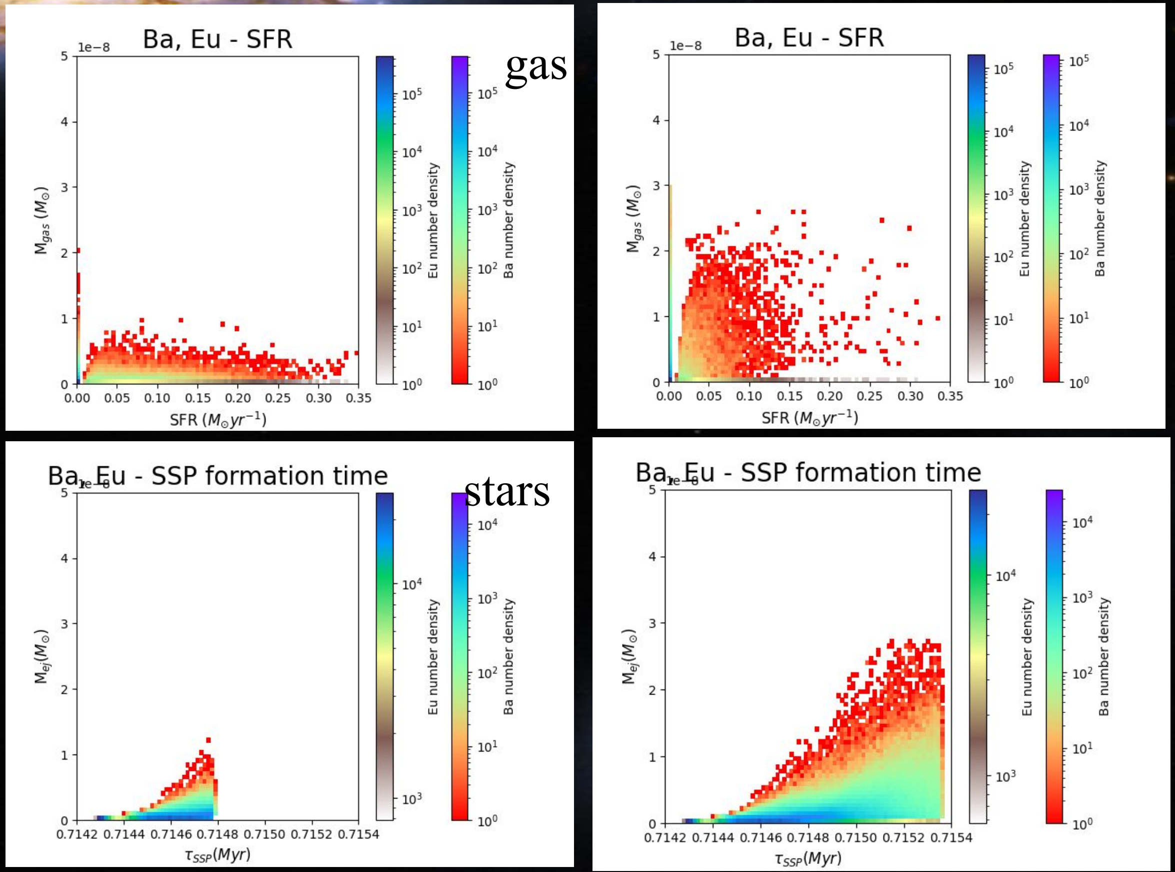
→ winds play a negligible role in shaping the *global* Z distribution and/or creating global Z gradients.

Enrichment’s dependence on SFR

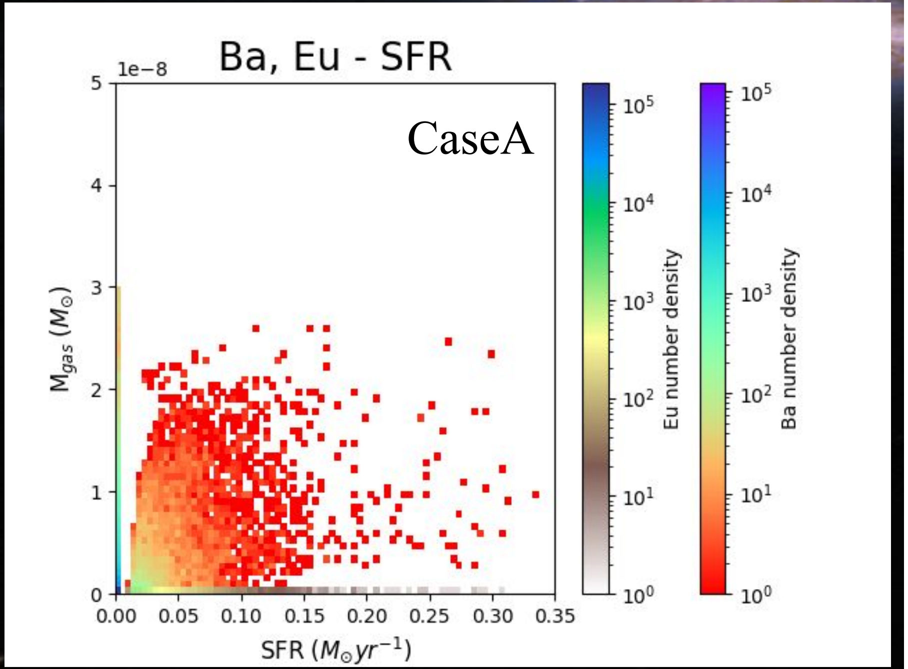
Sources of Ba and Eu enrichment are different, *yet* both are controlled by SFR.

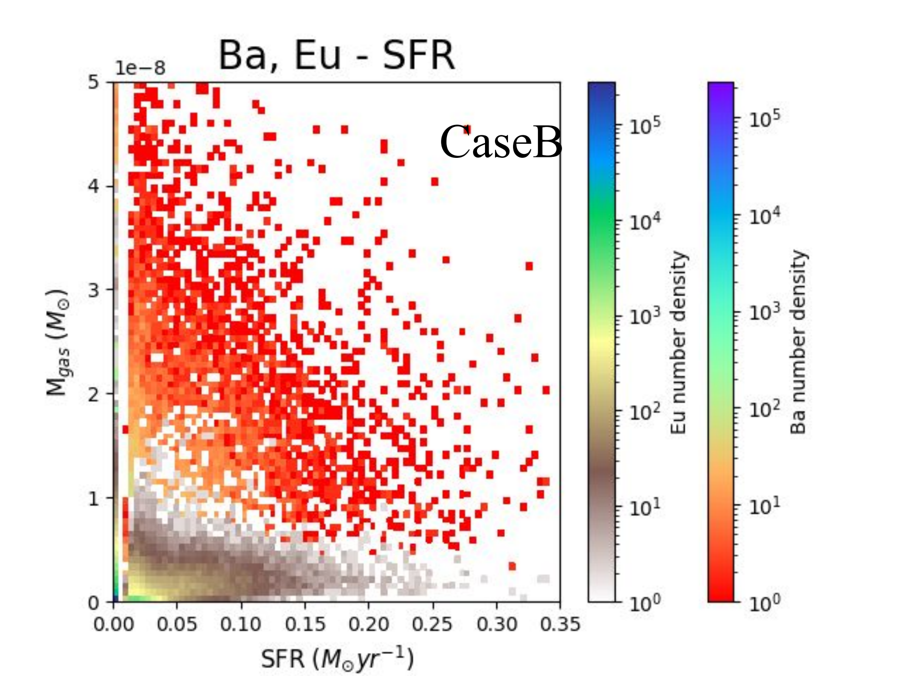
Case A (no initial winds): no correlations emerge between Ba/Eu abundance and SFR in the gas phase

For stars the positive correlation with SSP’s age is expected, as in GIZMO SSPs older SSPs recycle more enriched gas.



Delayed vs early winds





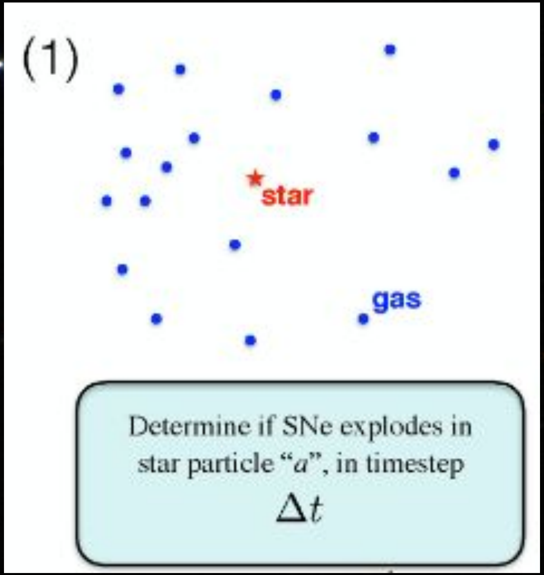
The prompt release of winds helps the diffusion *both* of Ba and Eu.
A possible negative correlation between Ba and SFR emerges in the gas phase as a consequence of the locking of the latter in successive stellar generations.

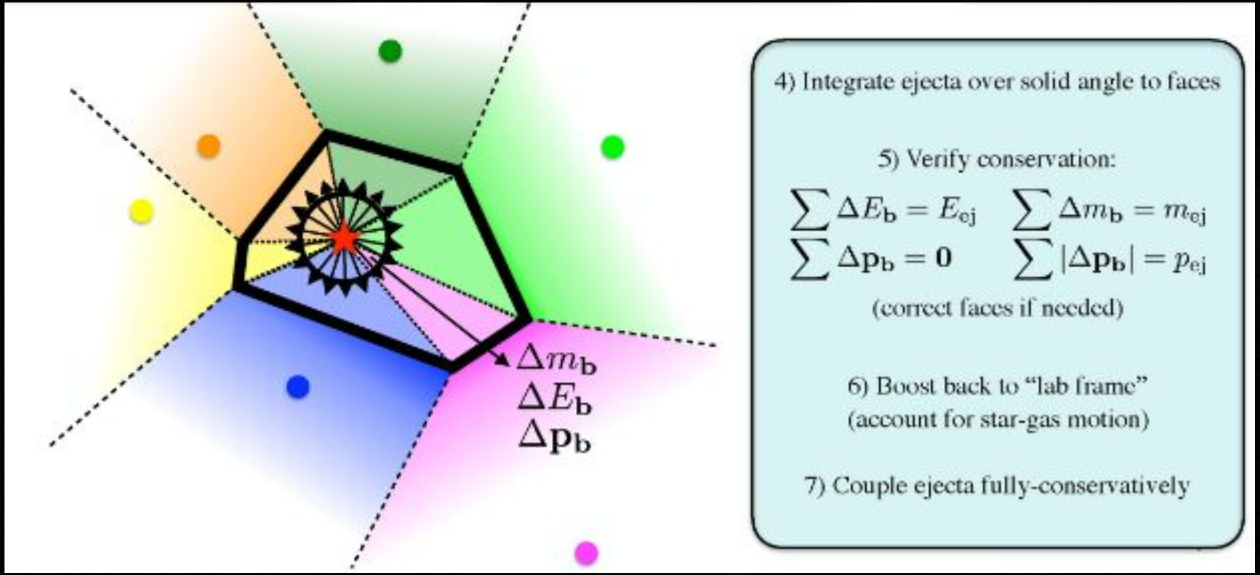
Final *caveats: Systematics* in numerical methods

Can we trust the way numerical codes treat the coupling between *feedback sources* (SN, winds) and the ISM?

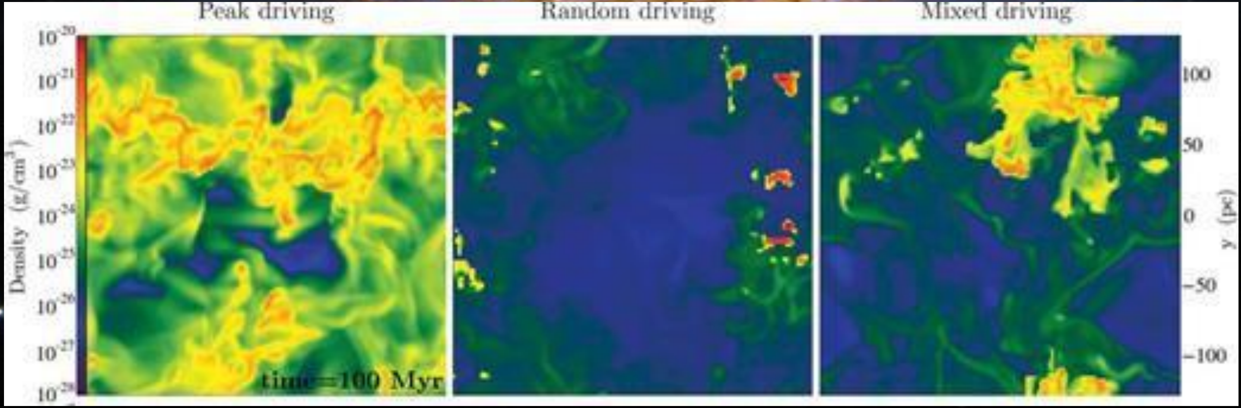
GIZMO (Hopkins, 2018): "star" particles hosting SNe have no ISM.

E_{SN}, p_{SN} delivered to *faces* of underlying Voronoi (foam) grid structure.



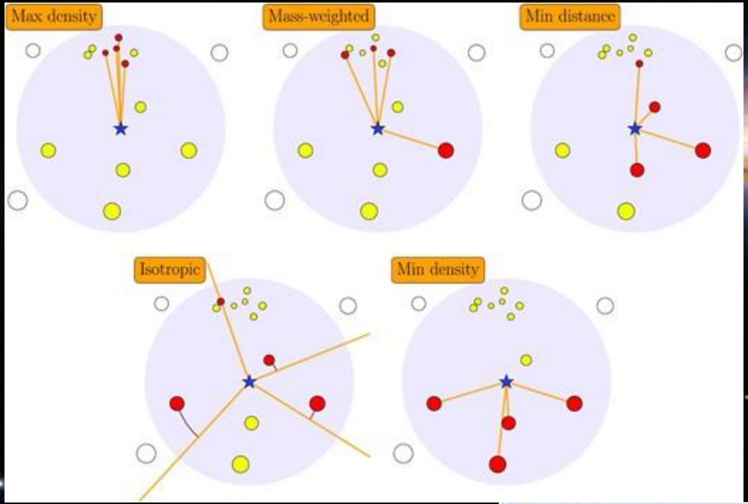


Why should we care about *where* inside a star particle a SN explodes (or wind propagate)?

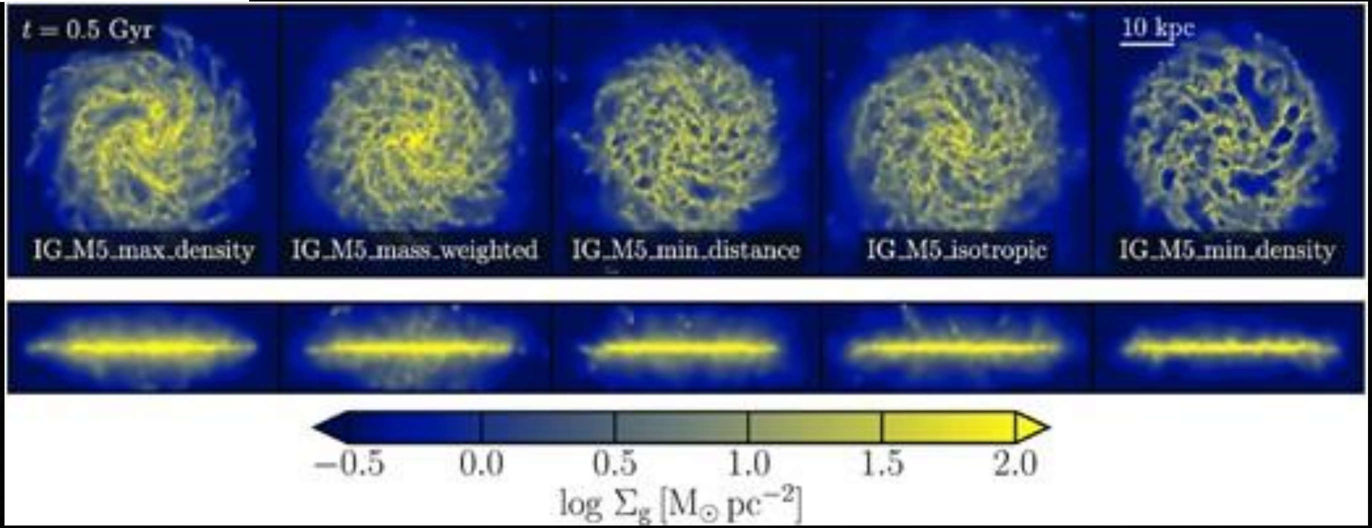


Gatto et al., 2015: the net energy/momentum/mass throughputs of stellar feedback events *do depend* on where inside the SSP/star-particle the source is located.

The *turbulence* induced by the event inside the ISM of the SSP itself *modulates* the delivery to the external environment, both quantitatively and in its temporal sequence.



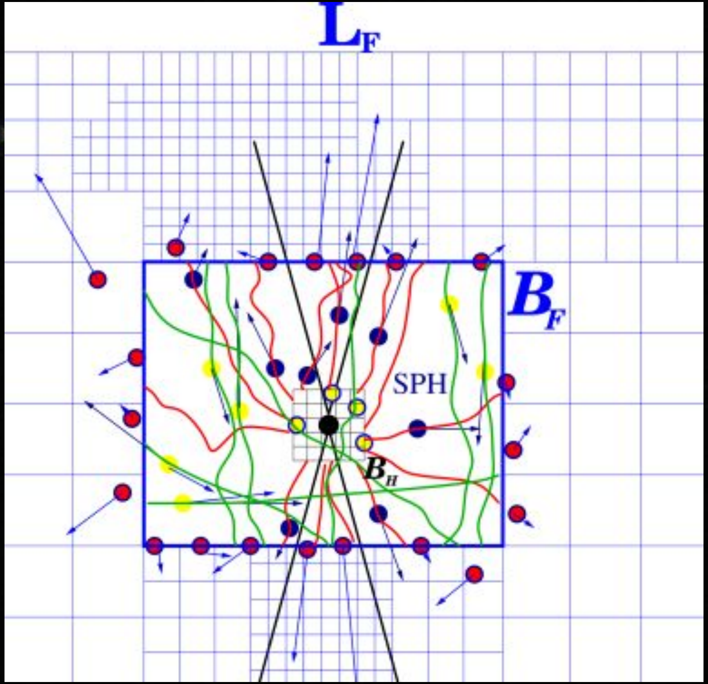
Chaikin et al., 2022 investigated the impact of five numerically and physically motivated ways to deliver the stellar feedback on the *global* final structure of the ISM in isolated MW-type galaxies. Below the corresponding differences in the ISM density.



Prospects

A sensible way to overcome the systematics: exploit effective computational tools:

A Python interface to glue together the galactic and subgalactic scale physics



The SF subgrid (B_F) is embedded in the galactic grid (L_F)

1. B_F and L_F are taken in charge by different comp. partitions (computing nodes), in a load balanced way (the interface)
2. Star formation in B_F is treated by FLASH + PySPH, to propagate feedback towards L_F and viceversa.
3. The overhead from the interface is at most 7% of the total computing time.