The theory of Galactic Chemical Evolution

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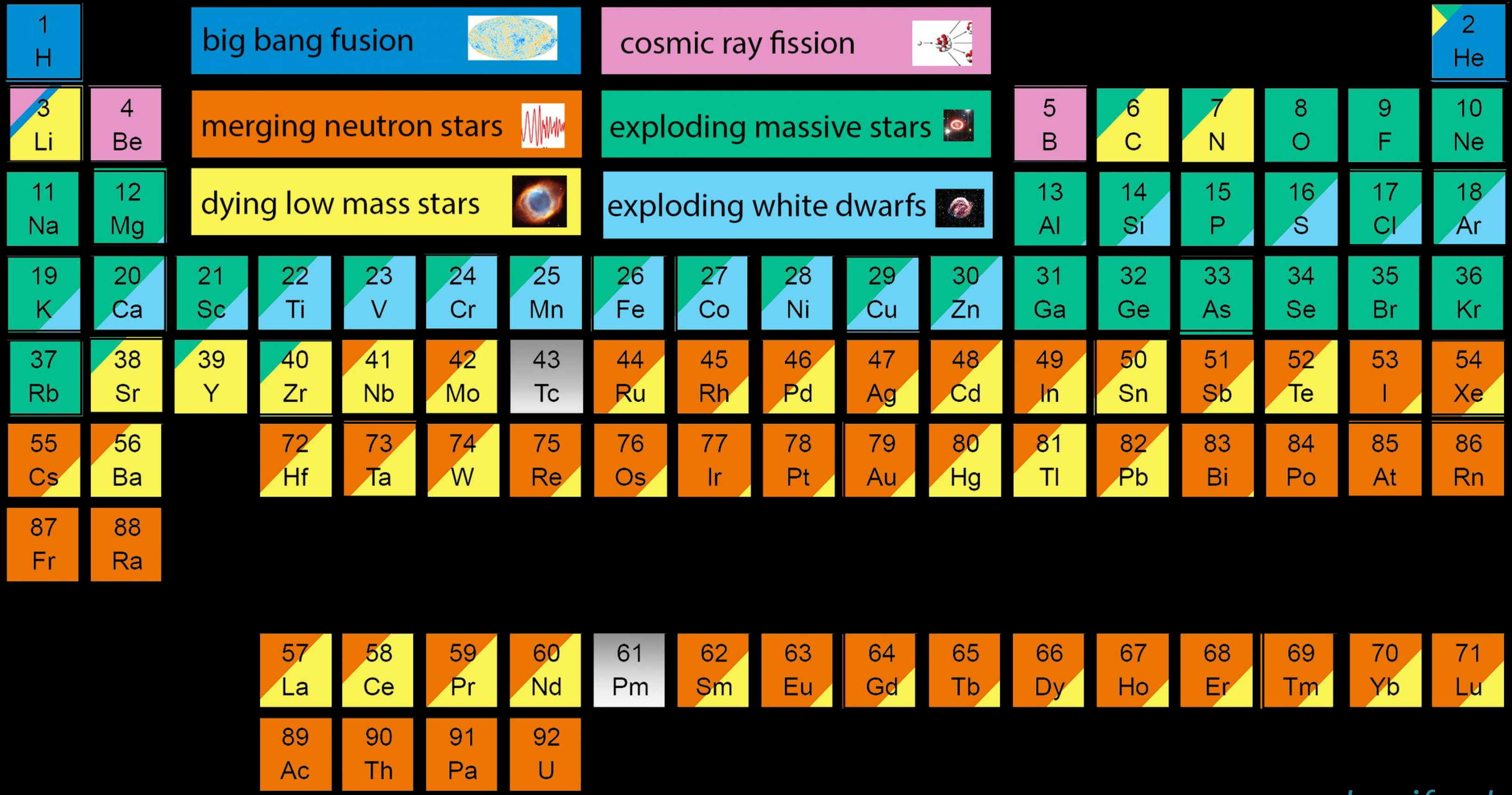
TUDOMÁNYEGYETEM

Loránd Fényes, M96 group

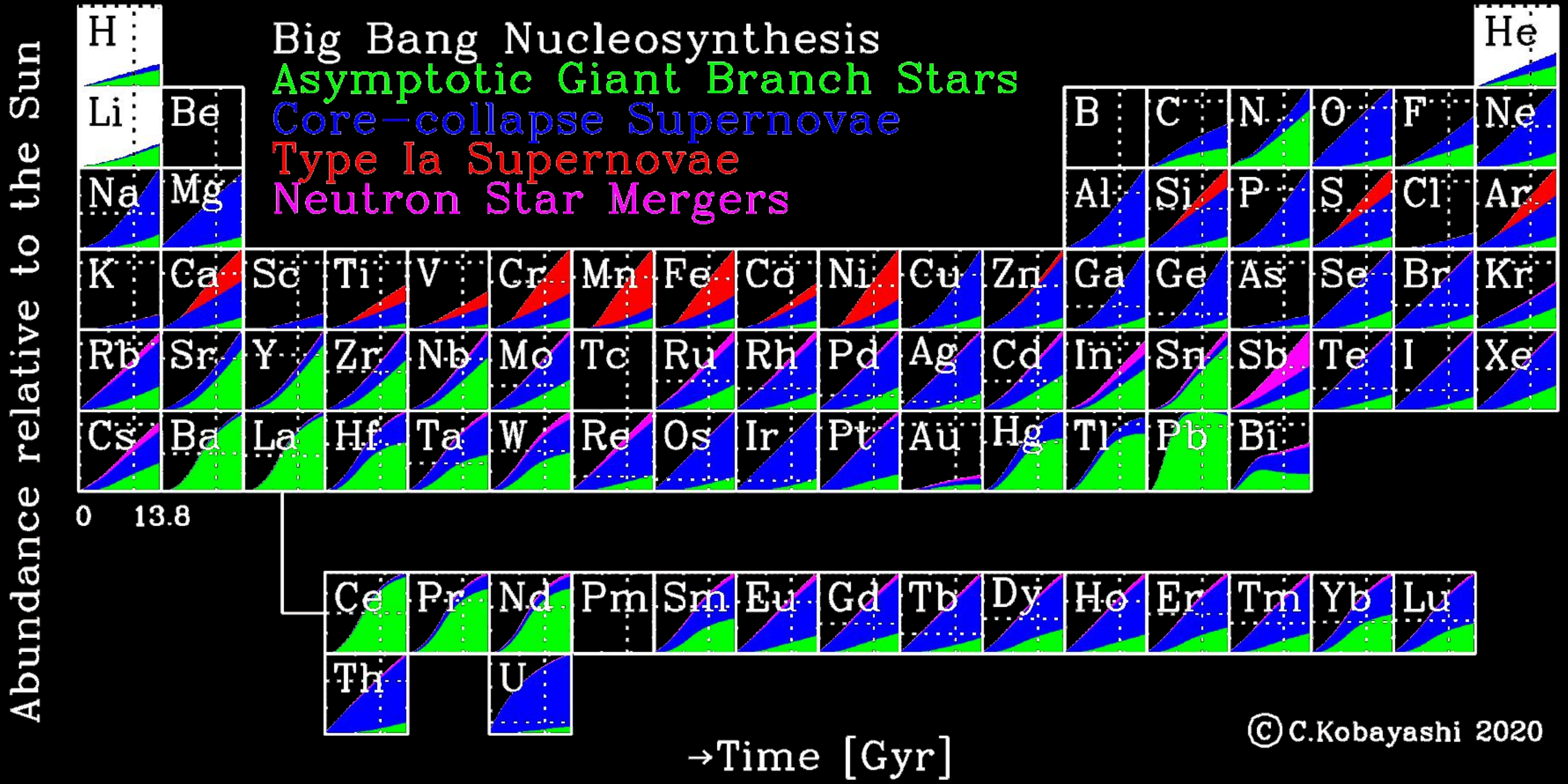
FORMATION OF THE ELEMENTS

The origin of the elements: schematically

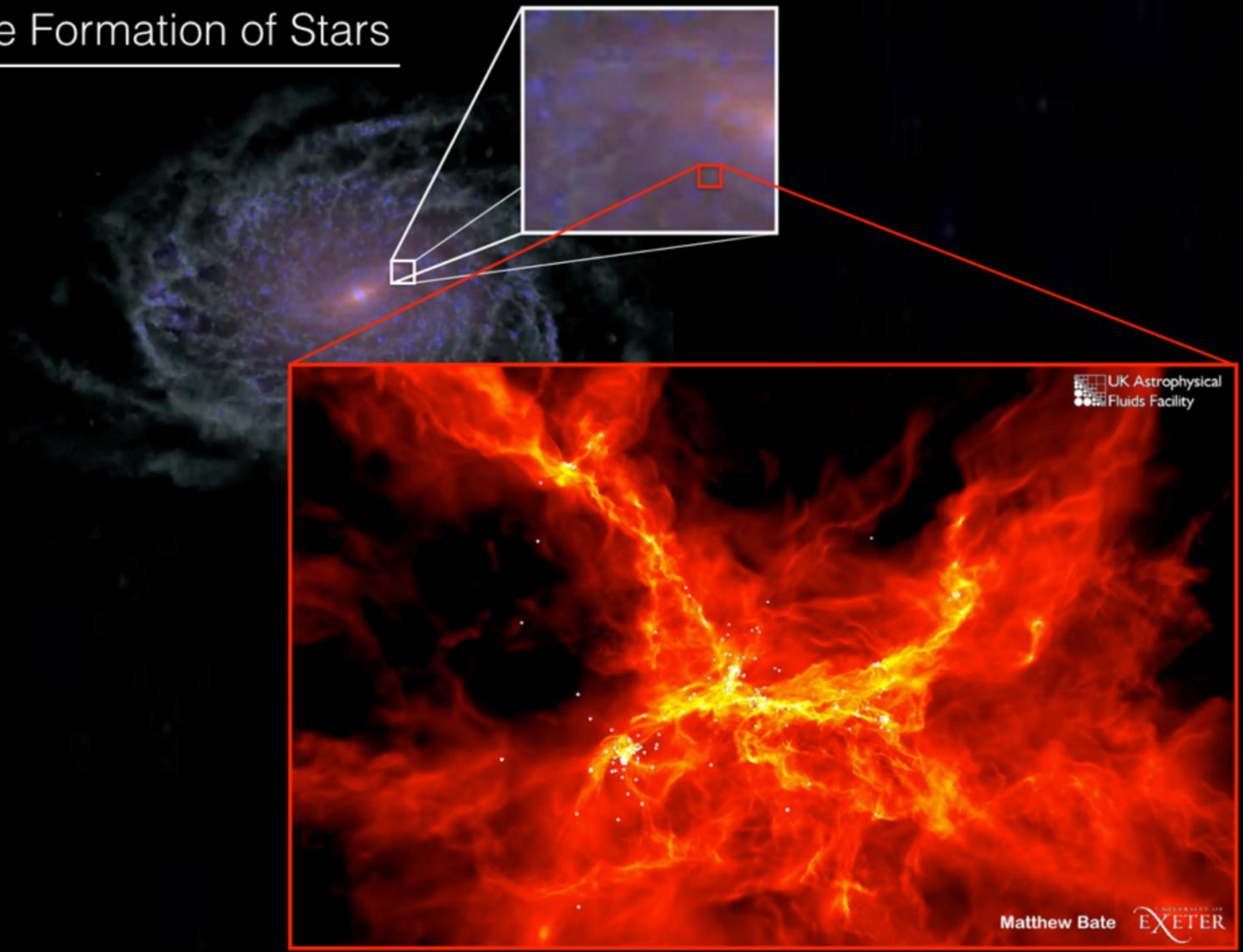


Jennifer Johnson

The origin of the elements: … over time



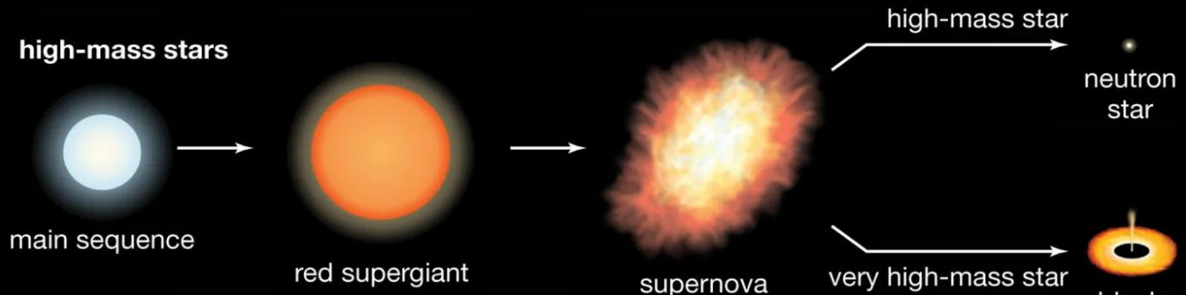
The Formation of Stars



Slide from B. Côté

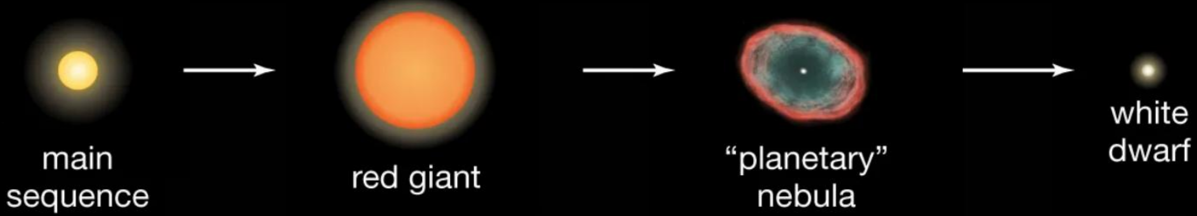
Evolution of stars

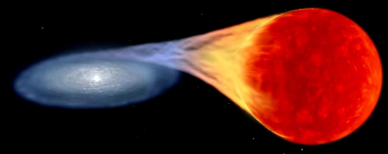
- High-mass stars (> 8 M_o)



Type II supernova (SN II)
Core collapse supernova (CCSN)

- Low- and intermediate mass stars (0.8-8 M_o)





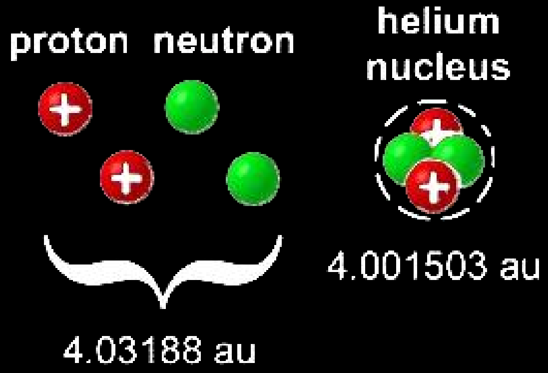
+ Supernovae Ia (SN Ia)

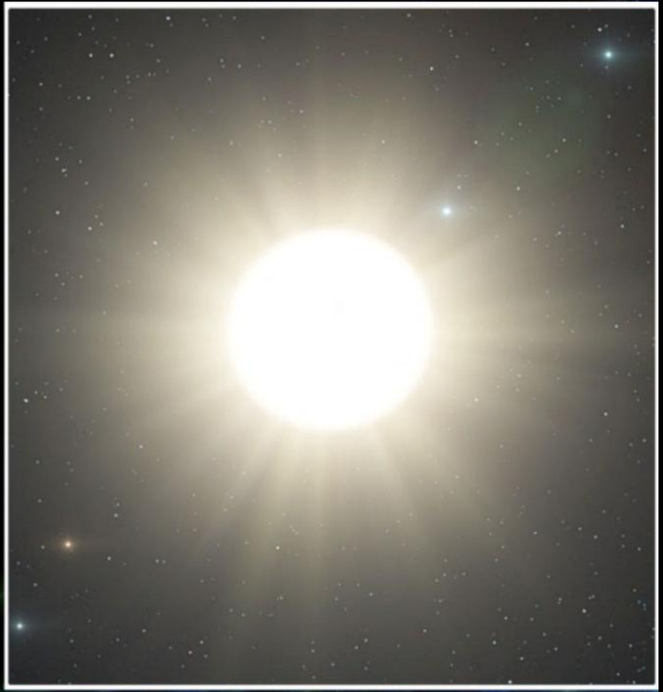
Encyclopaedia Britannica

The Process of Nuclear Fusion

Each year, the Sun produce 25 millions of millions more energy than what humanity consumes in a year.

$$E = mc^2$$

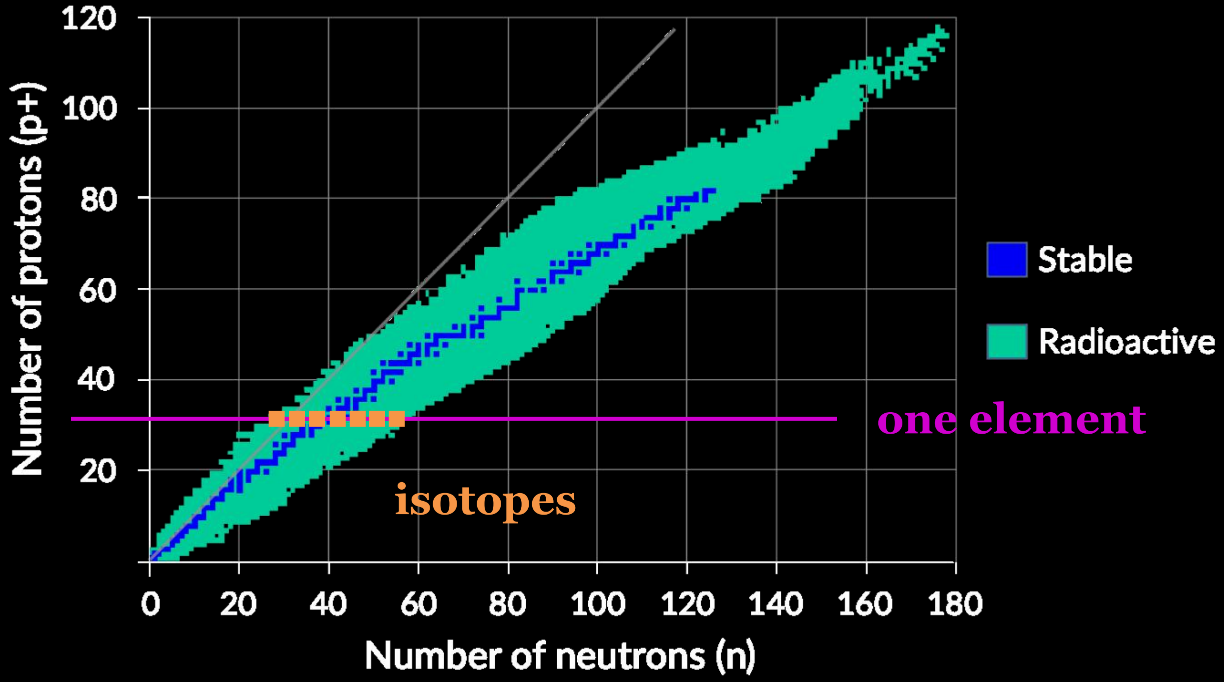




Slide from B. Côté

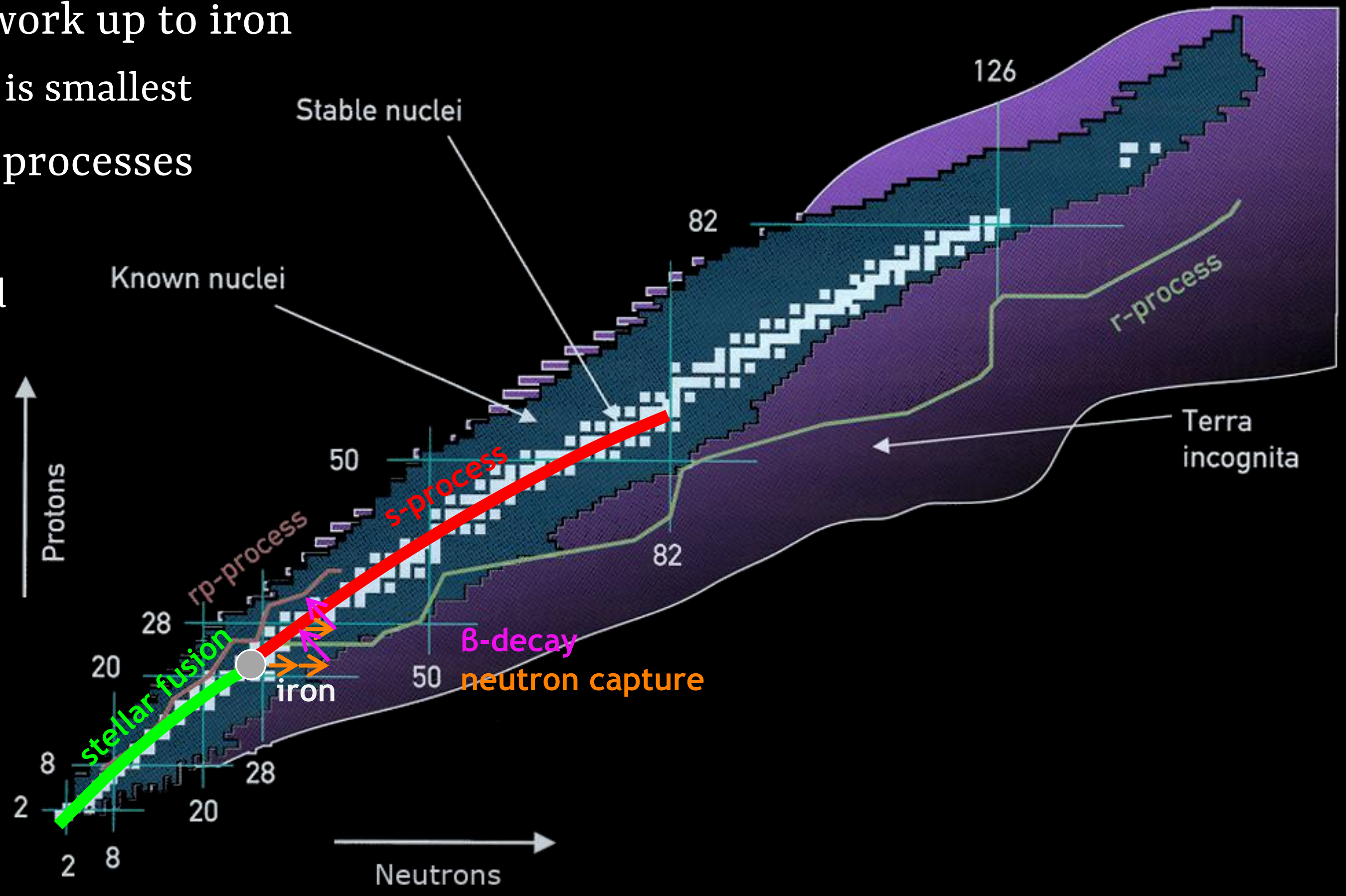
The nuclear chart: neutron captures

- Nuclear chart: number of protons vs. neutrons
- Valley of stability
- Unstable nuclei will β-decay towards stability



The nuclear chart: neutron captures

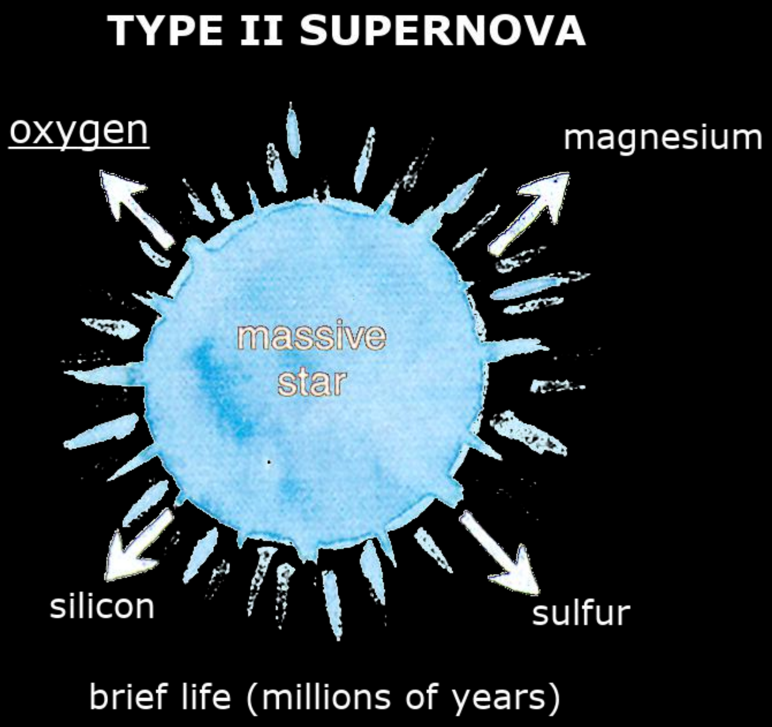
- Fusion can only work up to iron
  - Binding energy is smallest
- Neutron capture processes
  - *s*-process: slow
  - *r*-process: rapid
  - *i*-process: intermediate

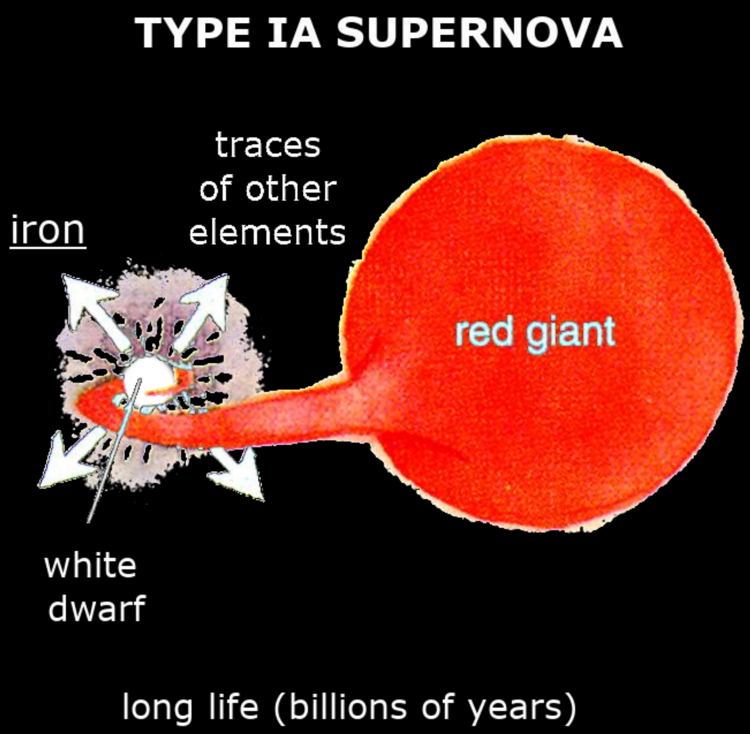


Elemental synthesis of stars

- High-mass stars (> 8 $M_\odot$)
  - Stellar wind: elements from the main sequence
  - SN II/CCSN: α-elements, elements beyond iron (+ *r*-process?)
  - Neutron stars / black holes - compact object mergers (+?): *r*-process
- Low- and intermediate mass stars (1.2-8 $M_\odot$)
  - Red giant and AGB stars: stellar winds, dust formation -> C, N, F, Na, ... + *s*-process
  - White dwarf - SN Ia: iron-peak elements (Fe, Ni, Co,...)
- Low-mass stars (< 1.2 $M_\odot$): no relevant contribution

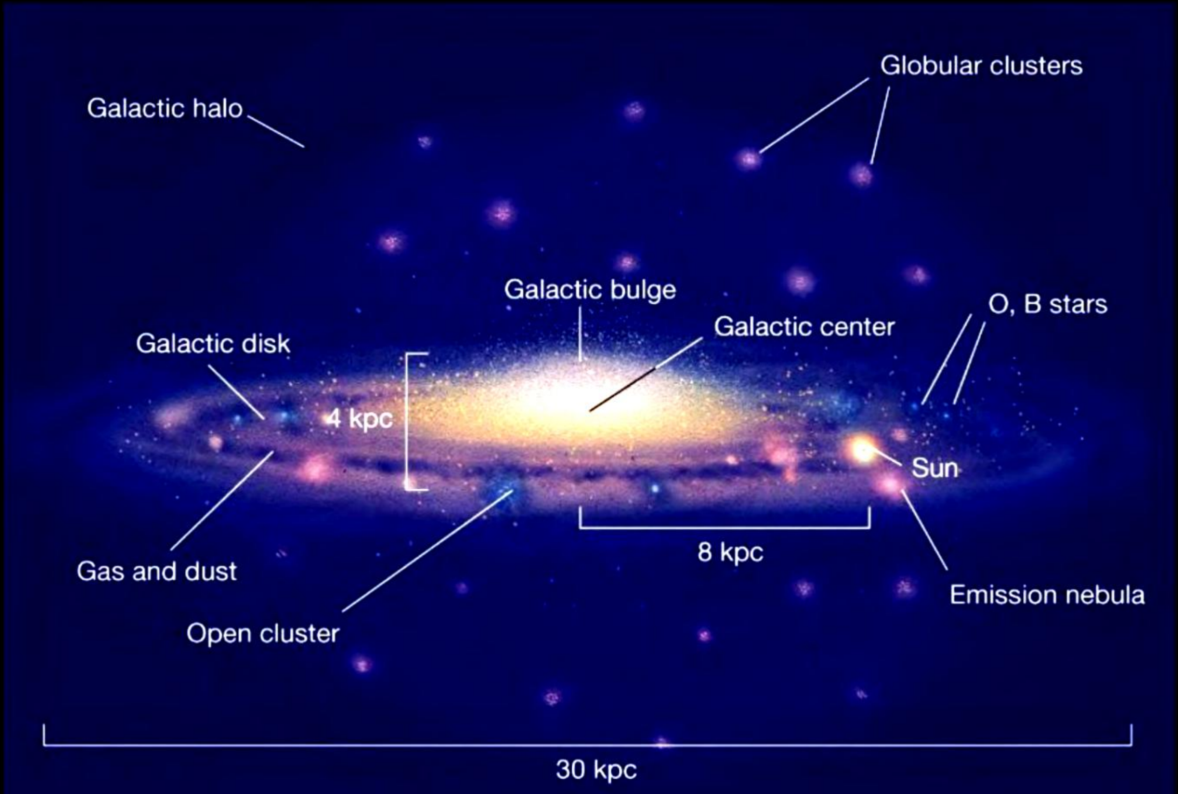
The α-elements and iron





C. Chiappini 2002

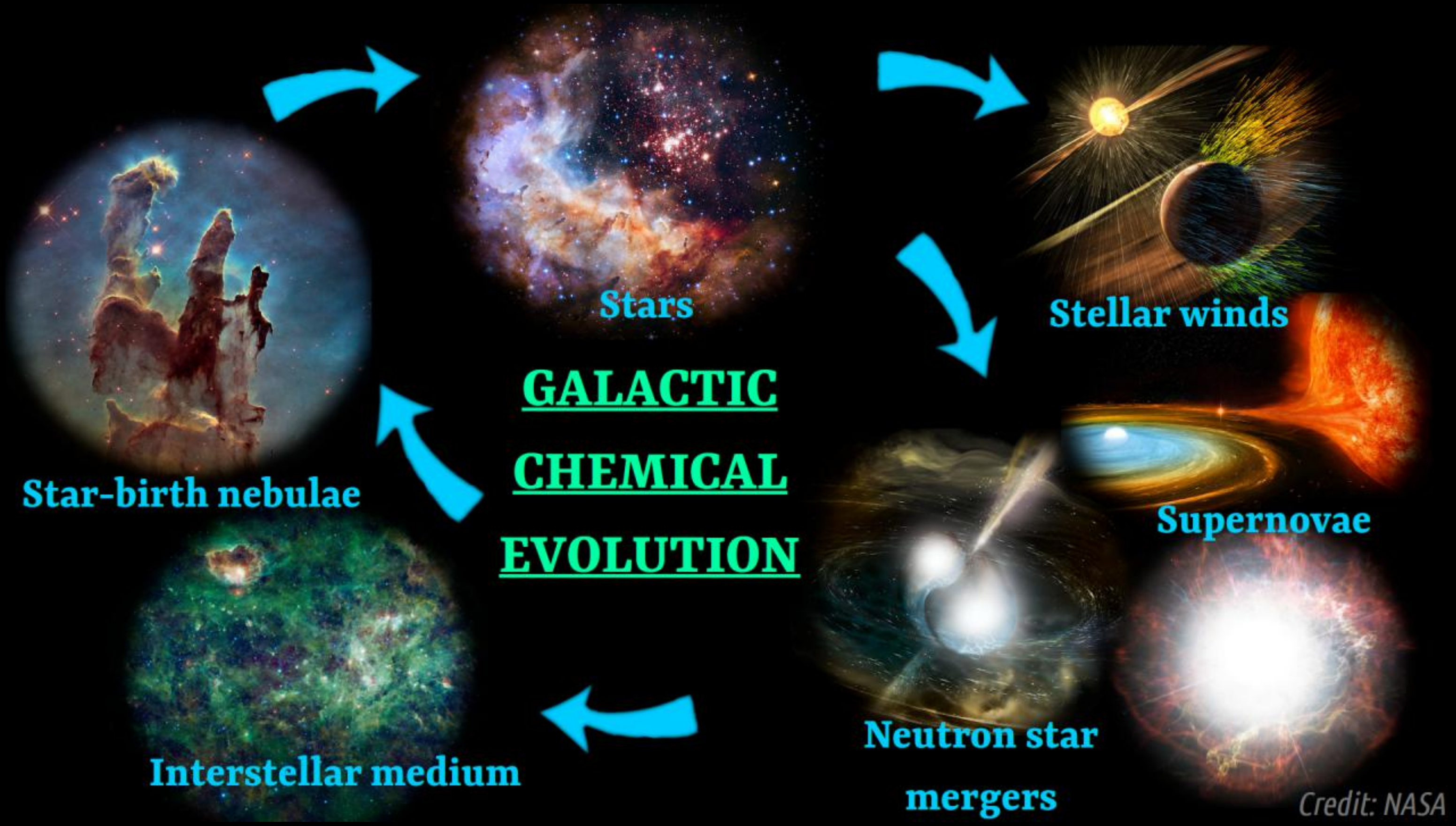
How does a galaxy look like?



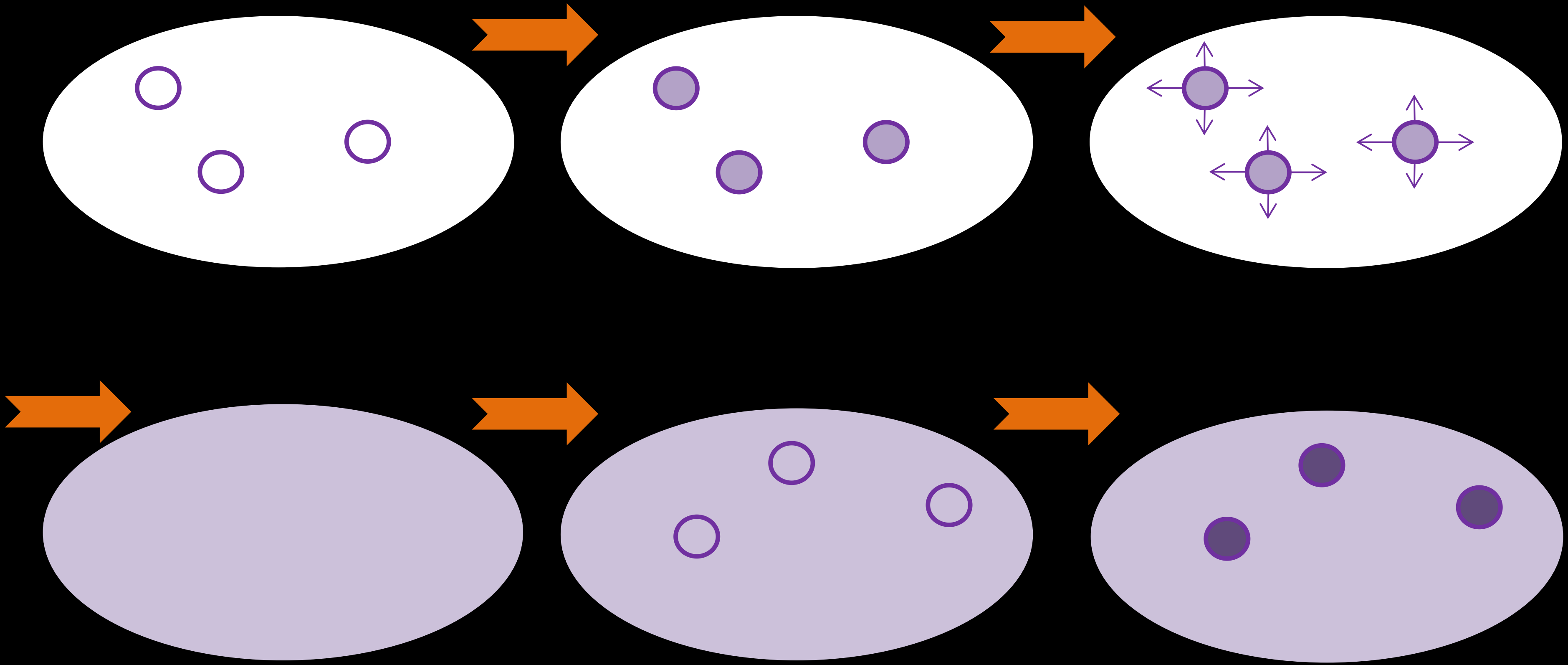
1 pc = 3.26 lyr= 3.086 10^{13} Km

Pearson Education

Galactic Chemical Evolution (GCE)



Generation of stars

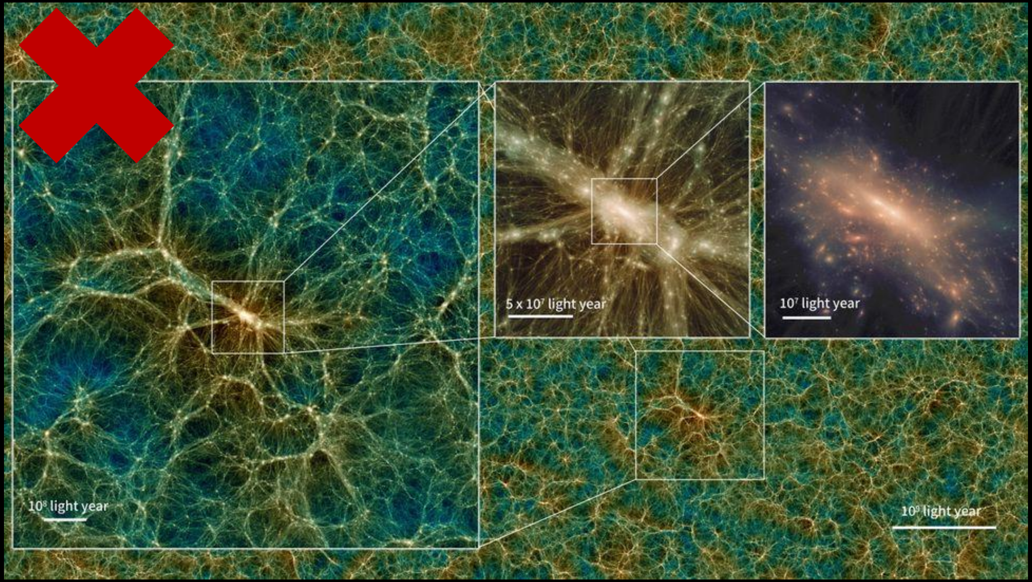


GCE MODELS:
TYPES, OBSERVABLES

Principles of simple GCE

- Galaxy simulations: cosmological / chemical evolution
- The average evolution of the interstellar gas (homogeneously mixed)
- Aim: **reproduce observables** by the fine-tuning of the models and their parameters

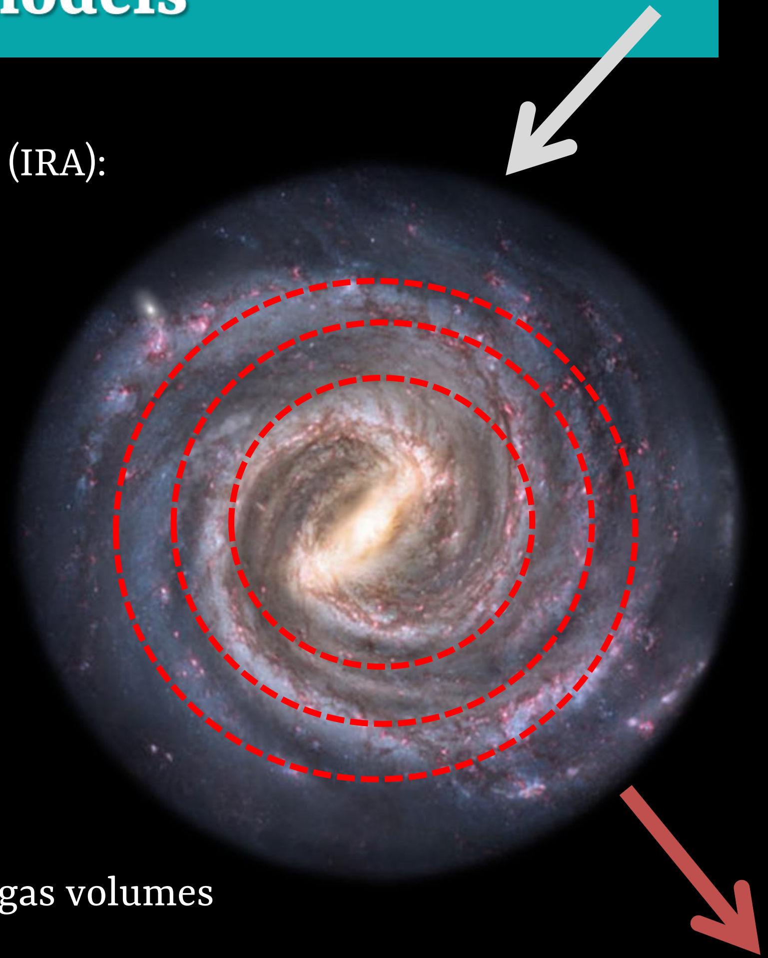
Cosmological simulation



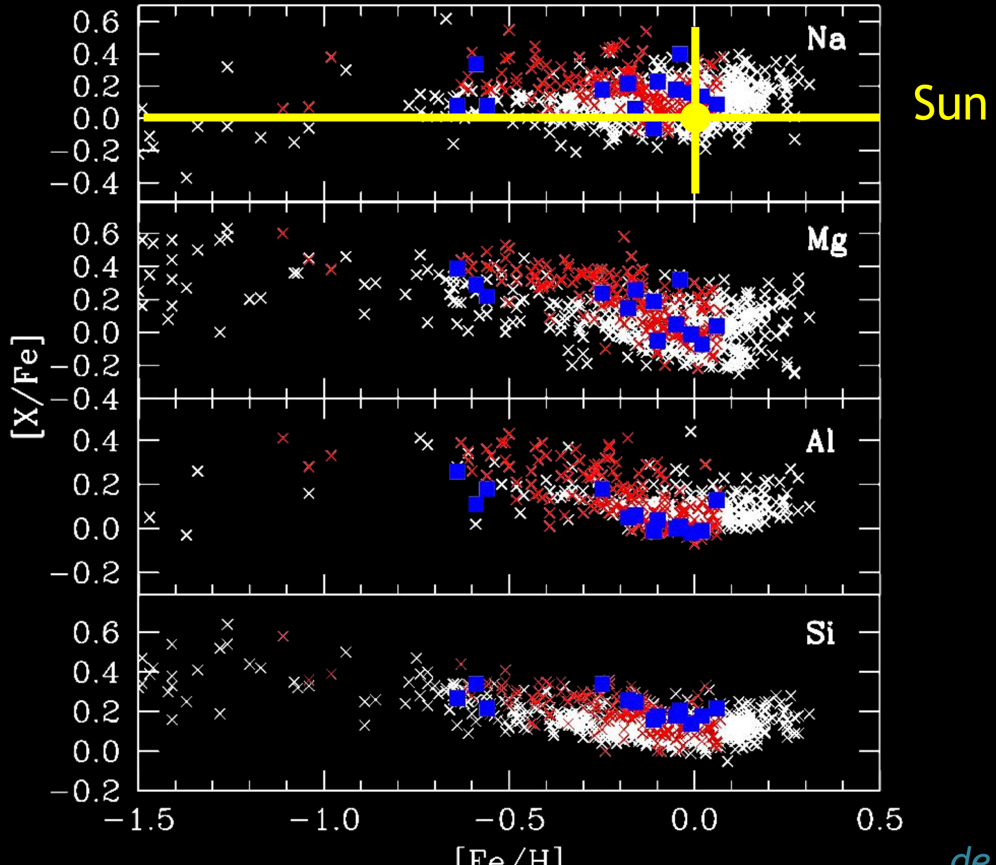
T. Ishiyama

Types of GCE models

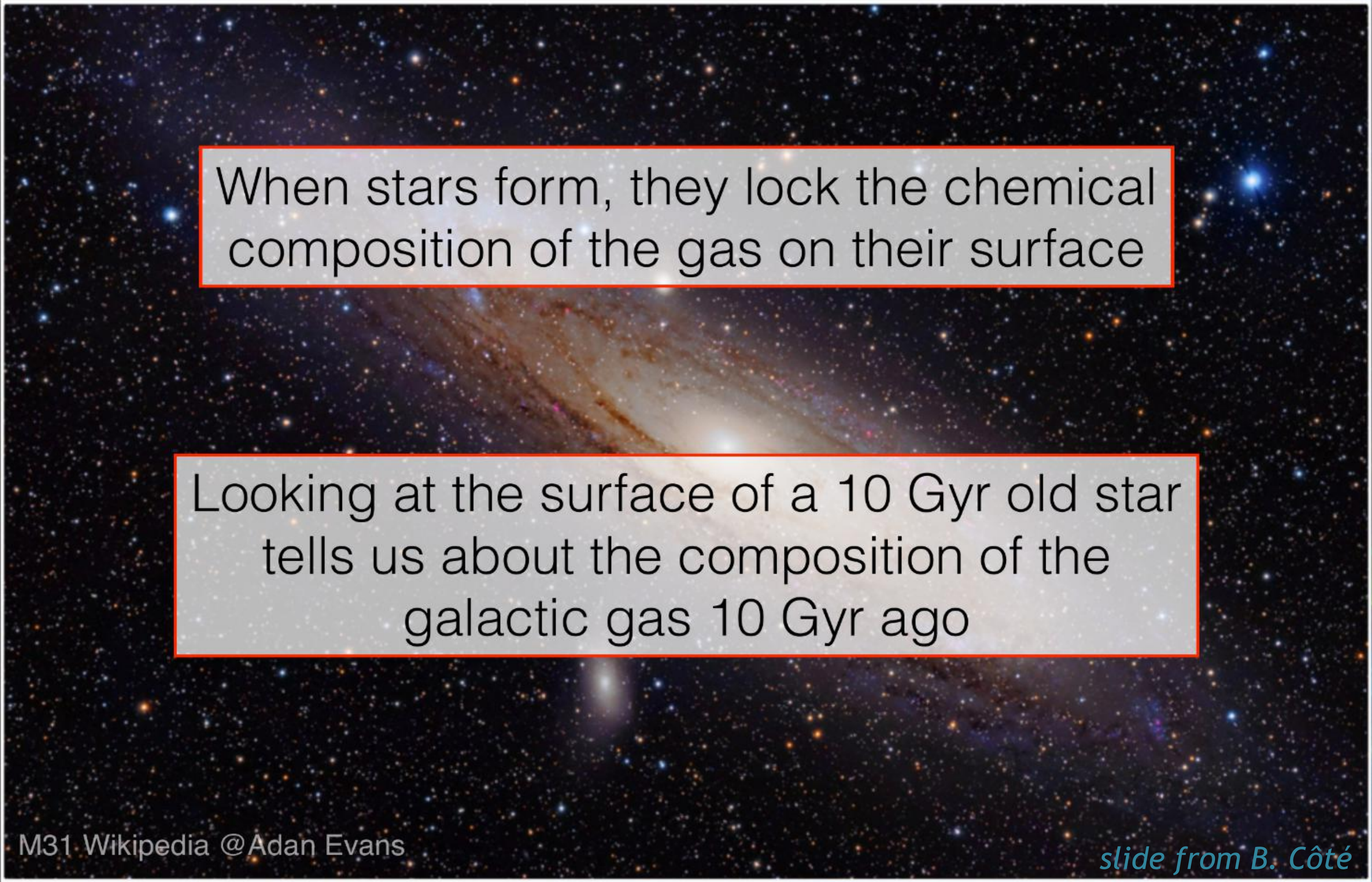
- Analytic/numerical
  - Analytic: Instantaneous Relaxation Approximation (IRA):
    low-mass stars live forever;
    high-mass stars explode/implode instantly
  - Numerical (the magnitude of the timestep!)
- Closed/open system
  - Interaction with environment: gas in- & outflows
  - G-dwarf problem: too few metal-poor G stars
- Number of zones or components
  - Radial zones (rings)
  - Or components: disk, halo etc.
- Homogeneous/inhomogeneous mixing
  - Instantaneous gas mixing or evolution of multiple gas volumes



Stellar abundances

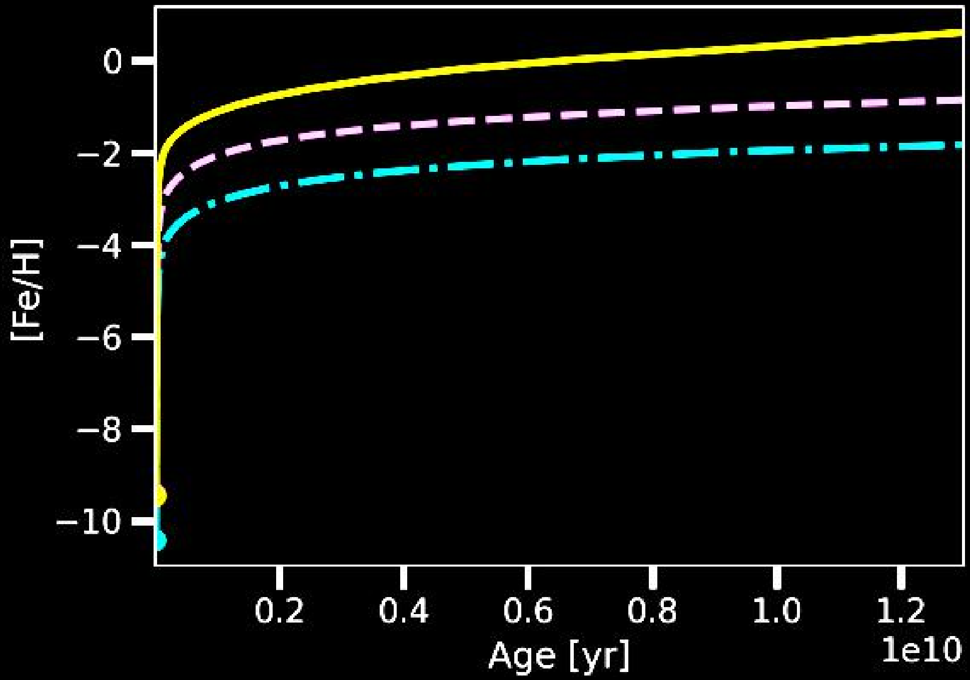


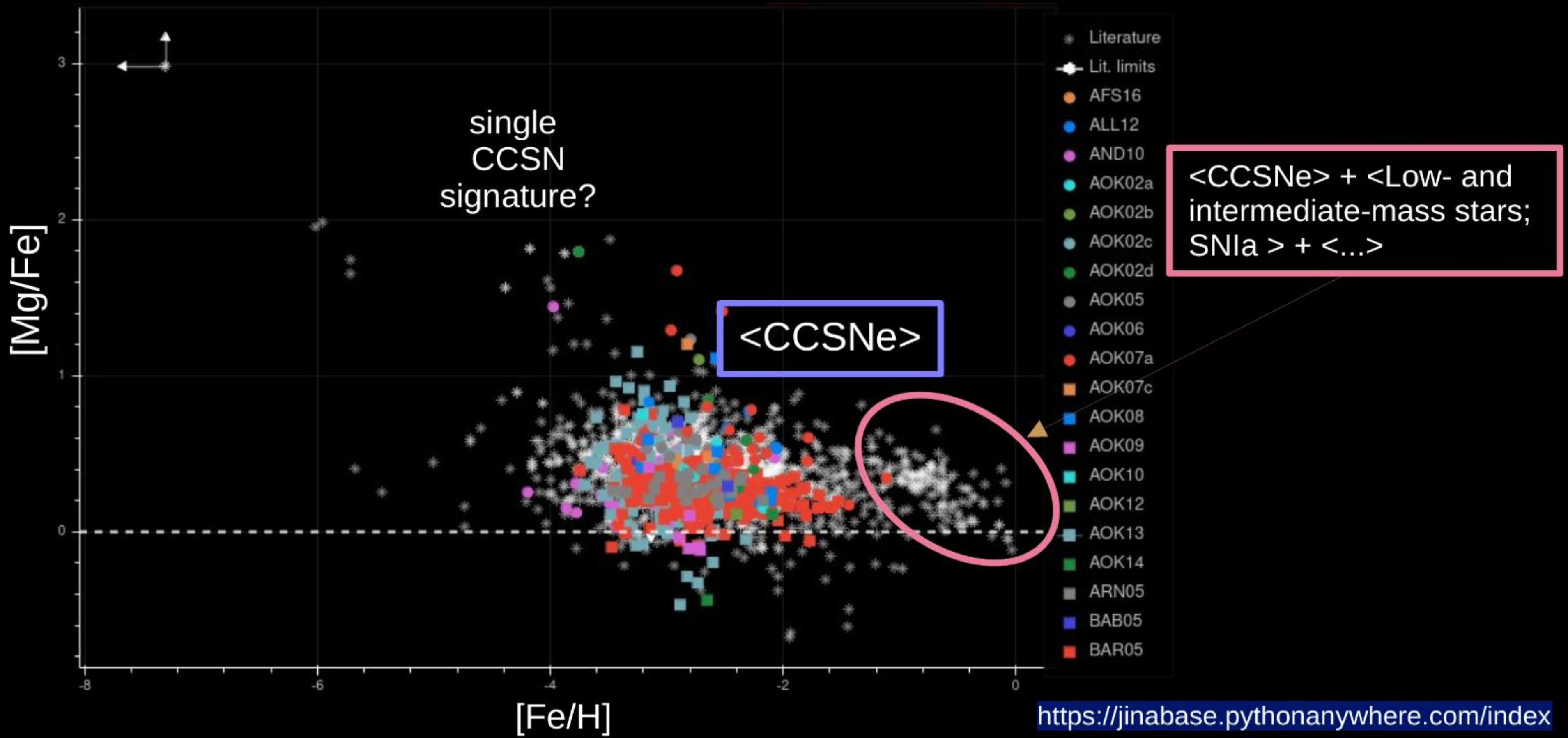
de Castro et al. 2016


When stars form, they lock the chemical composition of the gas on their surface
Looking at the surface of a 10 Gyr old star tells us about the composition of the galactic gas 10 Gyr ago
M31 Wikipedia @Adan Evans
slide from B. Côté

Age or metallicity?

- Measuring the age of the stars is hard - asteroseismology
- Metallicity is easily observed, and it should increase for younger stars!

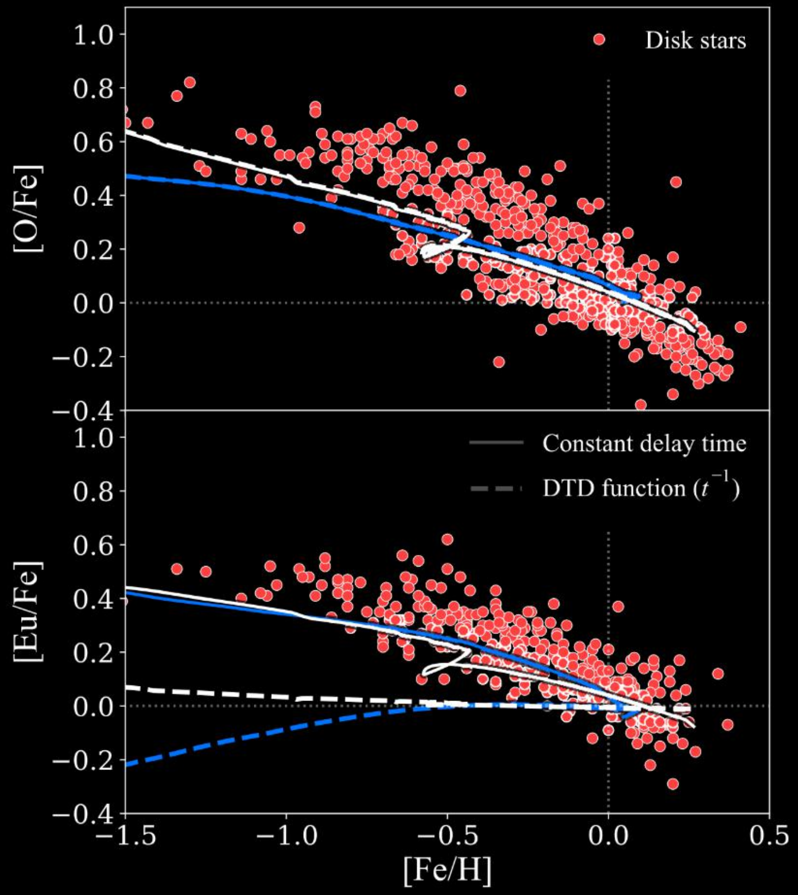




https://jinabase.pythonanywhere.com/index

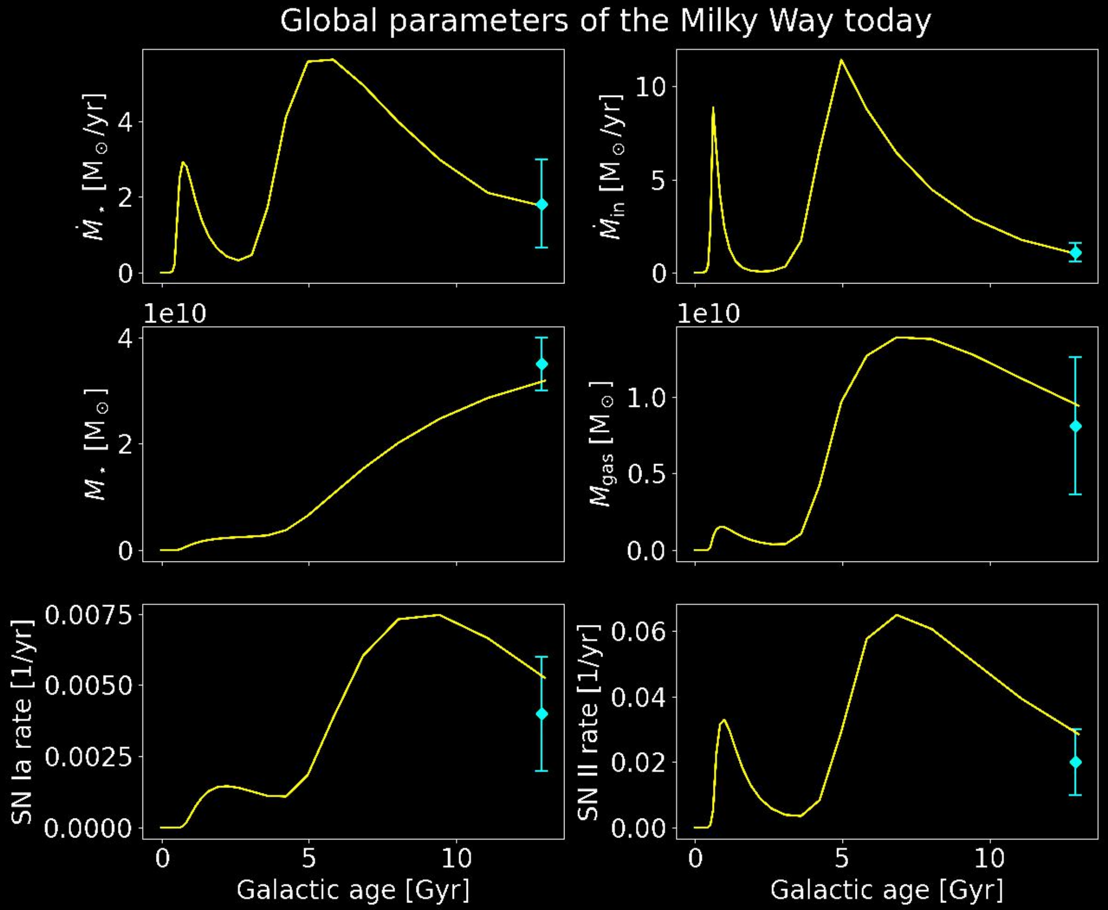
slide from M. Pignatari

Stellar abundances

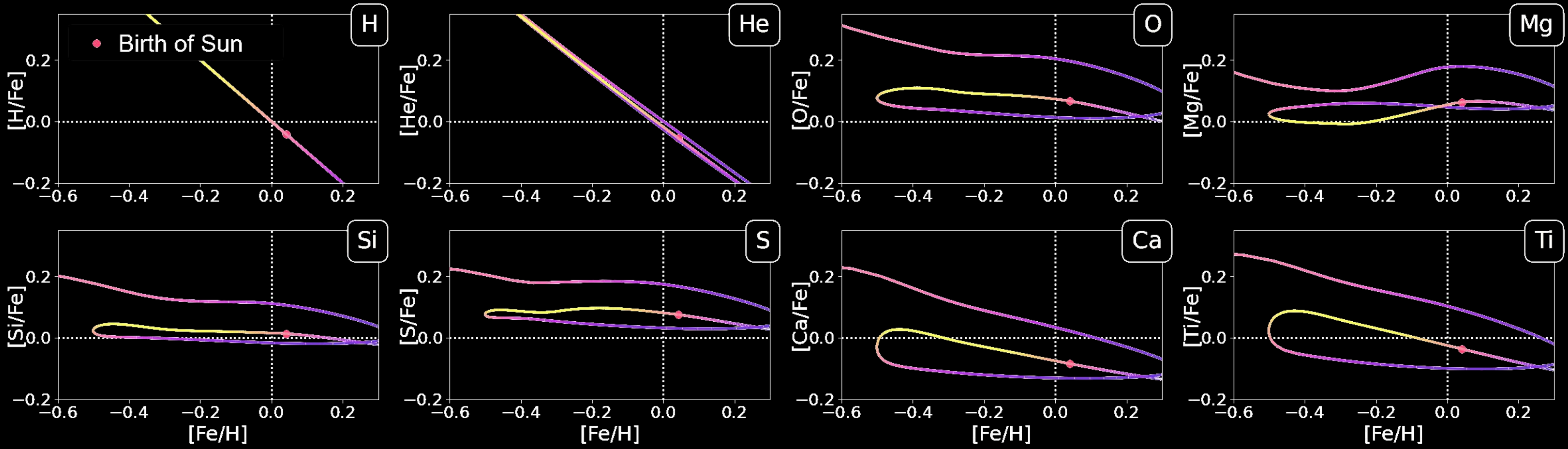


Côté et al. 2019

Global parameters today



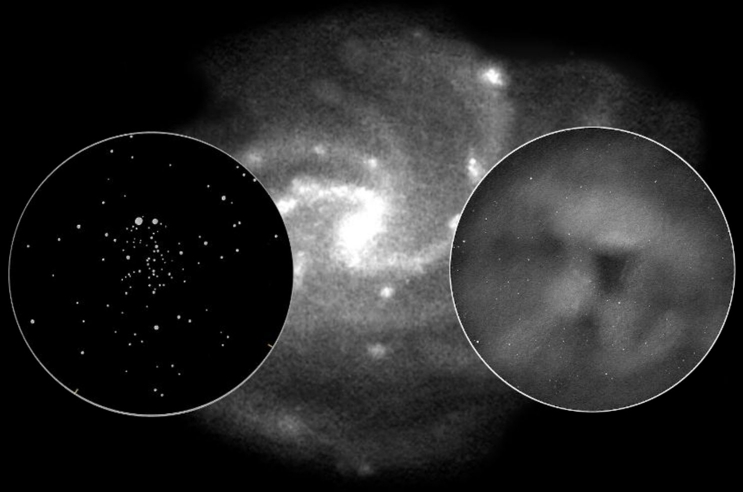
Composition at the birth of the Sun



THE MAIN EQUATION OF GCE

What is a galaxy made of? - GCE perspective

- **Interstellar matter (ISM)**
  - New stars are born from it
  - It is becoming more and more enriched in heavy elements
- **Stars**
  - Enclose the ISM (stellar remnants enclos it for ever)
  - Synthesize heavy elements during life
- Dark matter
  - Increases the mass → more gas inflow
- Environment, companions
  - Interaction: what mass, what composition?



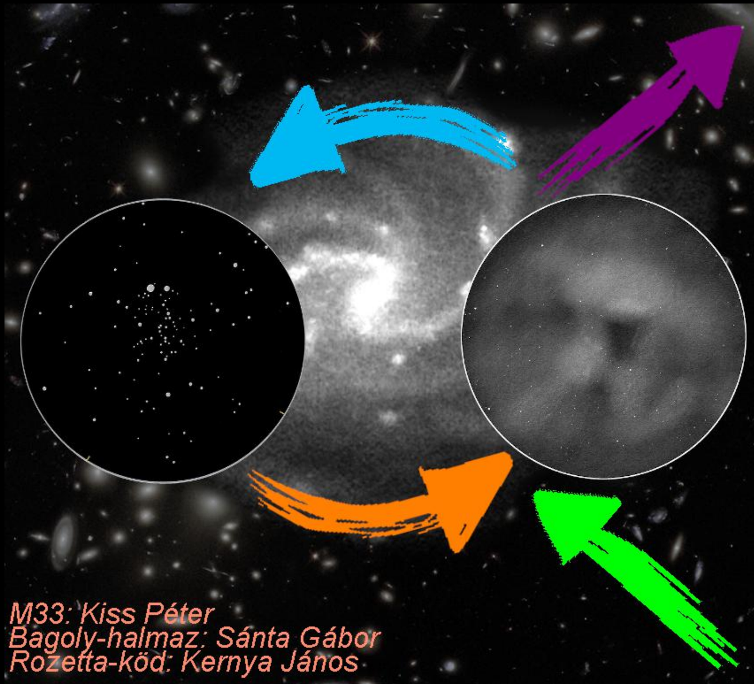
M33: Kiss Péter
Bagoly-halmaz: Sánta Gábor
Rozetta-köd: Kernya János

The main equation

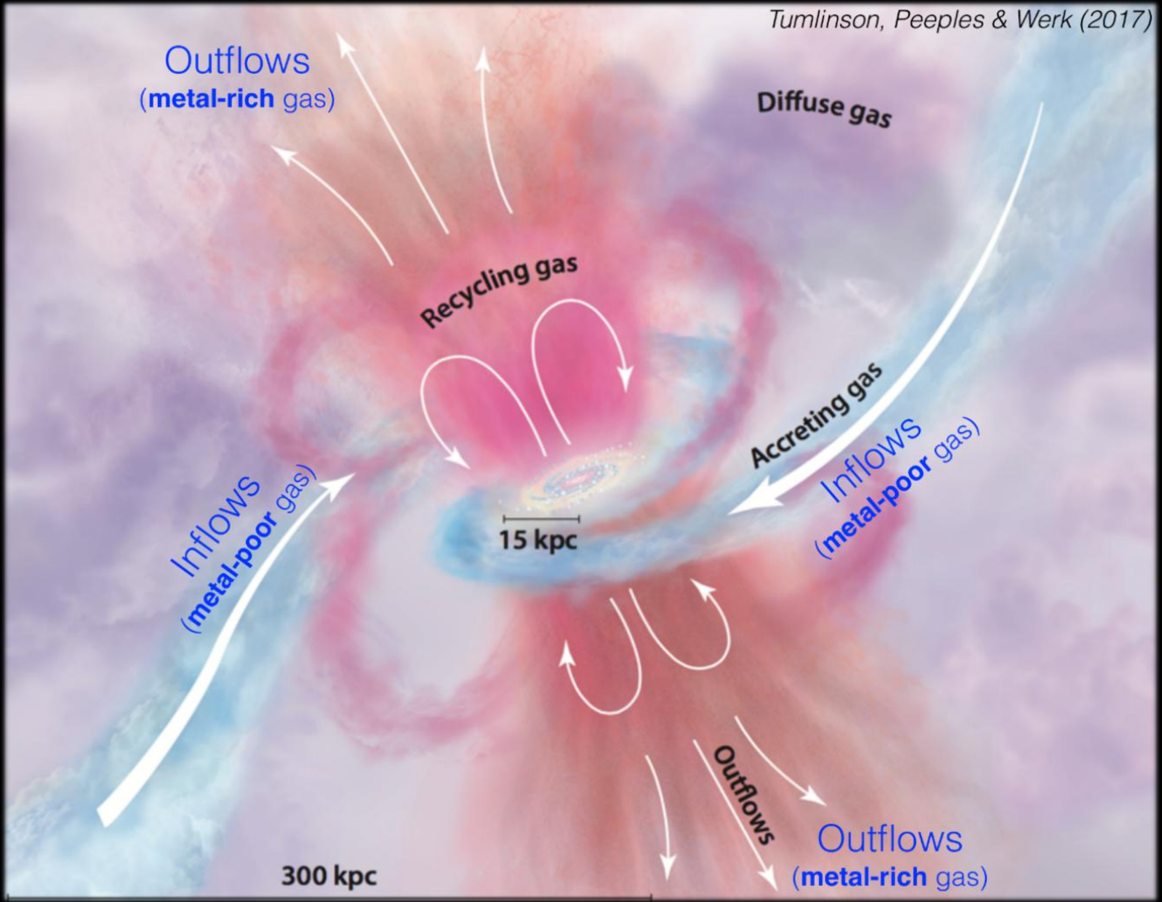
- The change of mass of the gas: $dM_{gas} = dM_{in} - dM_{*} + dM_{rec} - dM_{out}$

1. dM_{in} inflows from the intergalactic space
2. dM_{*} mass enclosed in newly-born stars
3. dM_{rec} mass recycled to the ISM by stars, supernovae, etc.
4. dM_{out} gas outflows to the intergalactic space

- True independently for all isotopes

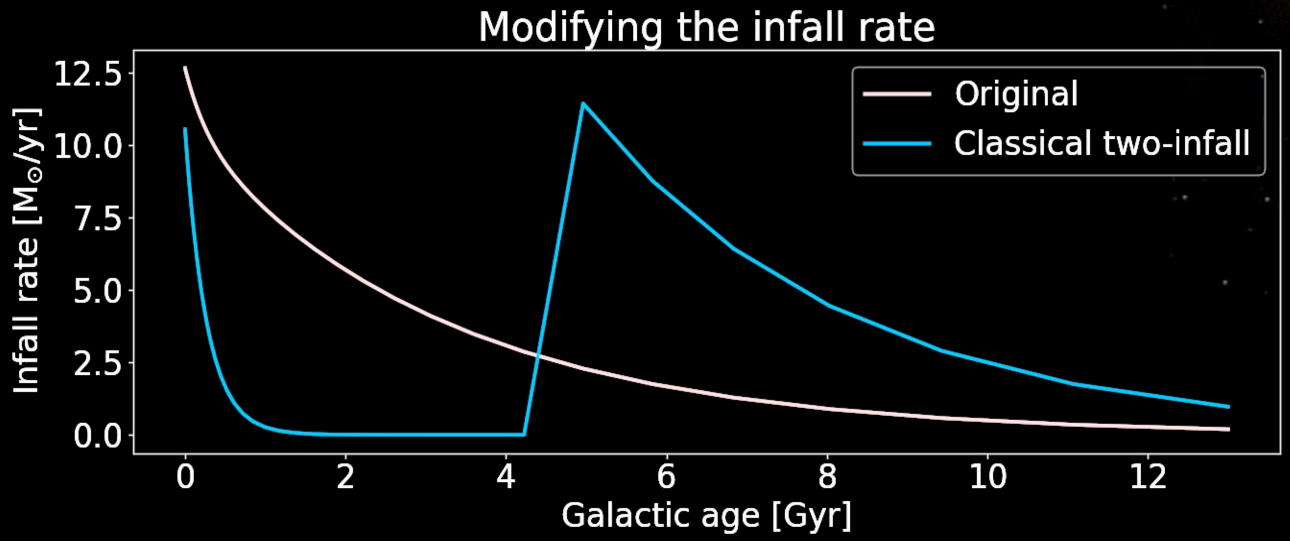


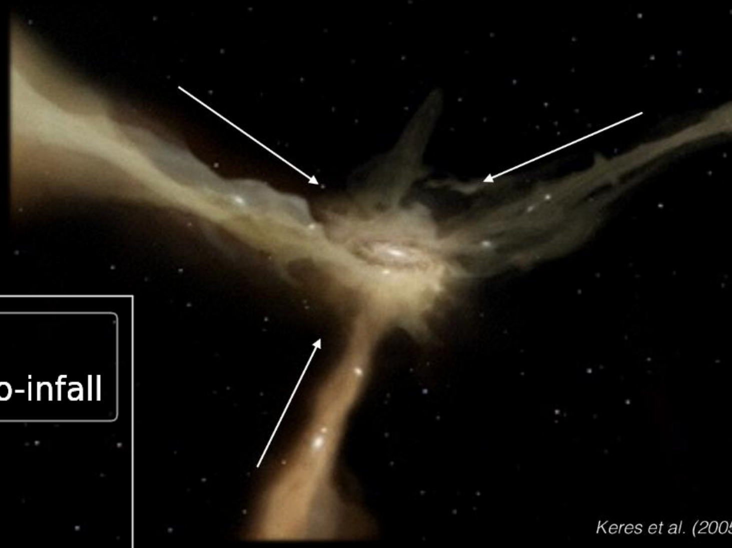
The main equation



1. Gas inflow (dM_{in})

- Composition: primordial, of Big Bang (? – not in interactions with another galaxy)
- Form of function:
  - **Exponential decay** $dM_{in} = dM_{in,0} \cdot e^{-t/\tau}$
  - **Two-infall**





Keres et al. (2005

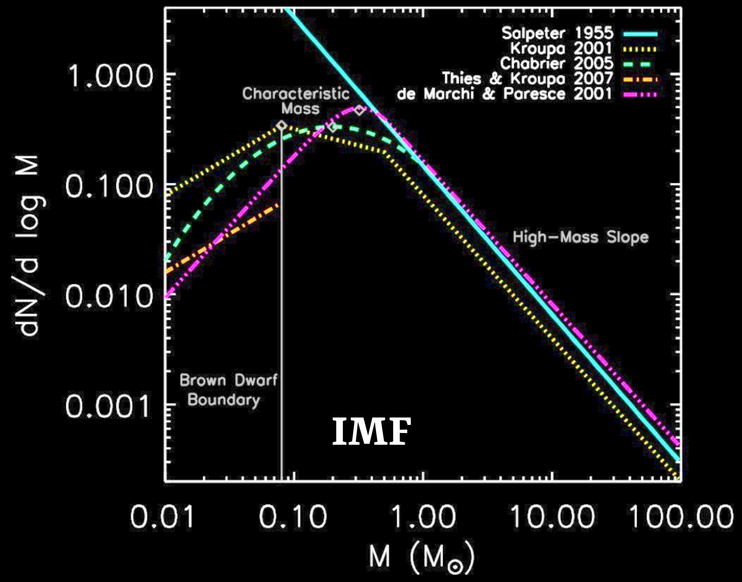
2. New stars (dM_*)

- **Stellar birthrate function:**
  how many stars are born in the interval (t, $t+dt$) and (m, $m+dm$)
  - Star formation rate * initial mass function
- **Star formation rate:** total mass of gas locked into new stars in a timestep
  - Schmidt–Kennicutt law ($k \approx 1,5$) $\dot{M}_*(t) = \nu\sigma^k(t)$

    ν: star formation efficiency

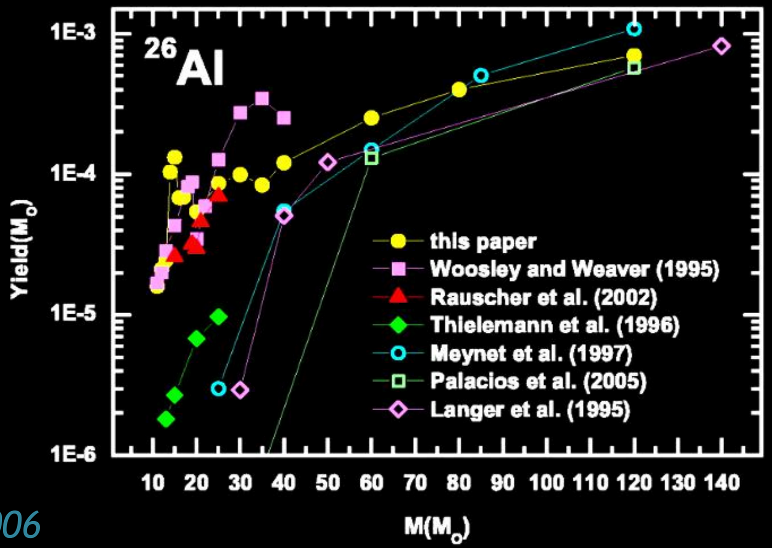
    σ: surface mass density of gas
- **Initial mass function (IMF):**
  how many stars form between m and ($m+dm$)
  - Empirical forms (Salpeter, Kroupa)
  - General form: $\phi(m)\,\mathrm{dm} = Cm^{k'}\,\mathrm{dm}$
  - Kroupa:

$$\phi(m)\mathrm{dm} = n \cdot m^{-\alpha}, \begin{cases} n = 0{,}035;\ \alpha = 1{,}3 & m < 0{,}5\,\mathrm{M}_\odot \\ n = 0{,}019;\ \alpha = 2{,}2 & 0{,}5\,\mathrm{M}_\odot \le m < 1\,\mathrm{M}_\odot \\ n = 0{,}019;\ \alpha = 2{,}7 & 1\,\mathrm{M}_\odot \le m \end{cases}$$



3. Recycled mass from stars (dM_{rec})

- **Yield:** How much mass of an isotope is returned back by the stars
- Unprocessed + newly synthesized material
- Tables for stars of different masses,
  based on stellar nucleosynthesis models
- Uncertainties: nuclear physics, stellar structure models (convection), winds …
- Depends on the mass of the current stars

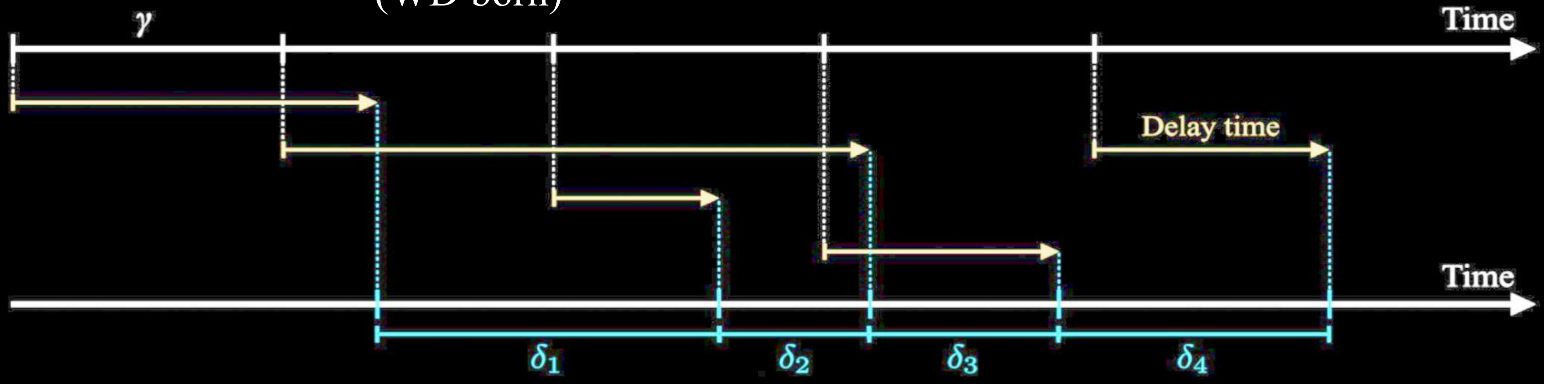


Limongi & Chieffi 2006

The rate of SNe Ia

- Main synthesizer of iron
- The explosion occurs at different times after the white dwarf is created
- **DTD**, Delay time distribution:
  - Prompt/tardy SN Ia: exploded in 100 Myr or not

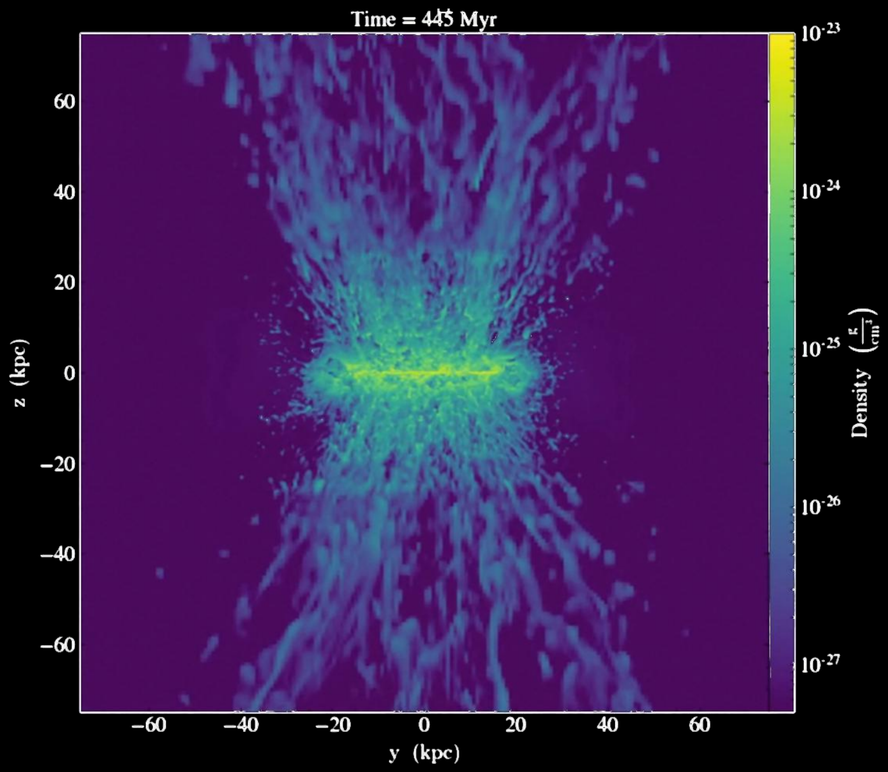
(WD born)



(SN Ia exploded)

4. Gas outflows (dM_{out})

- Gas outflows: driven by dynamics → proportional to stellar formation
  - Young stars: winds, magnetic field
  - Mass loading η: $dM_{out} = \eta \cdot dM_{star}$
- Radial flows
  - Flows inwards
  - Driven by the low angular momentum of infalling material
  - Contributes to the gradients in composition



Devin Silvia

The most important parameters

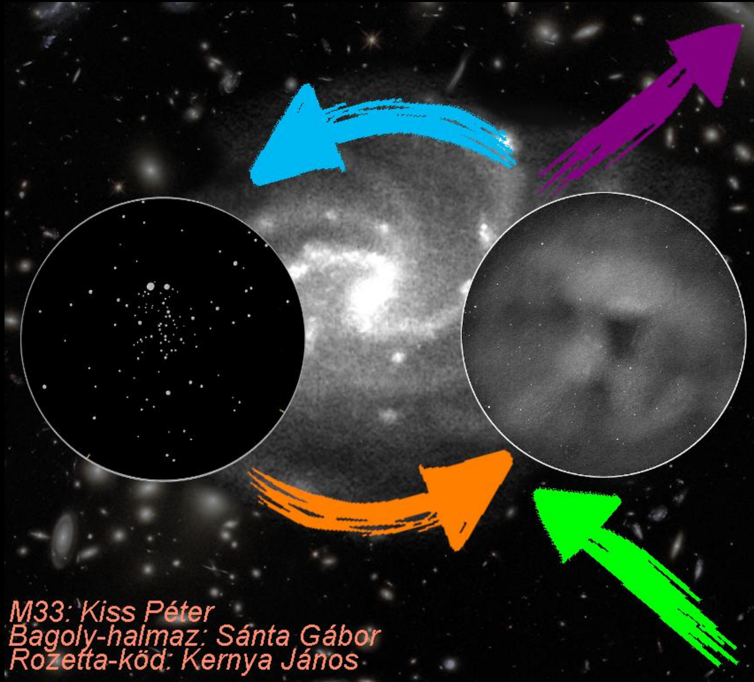
- Initial mass of the gas
- Rate of inflows and outflows
- Star formation rate, initial mass function - distribution of stars born
- Number density of supernovae
- Element production of stars with different masses (yields)

The main equation: summary

- The change of mass of the gas: $dM_{gas} = dM_{in} - dM_{*} + dM_{rec} - dM_{out}$

1. dM_{in} exponentially decaying inflows
2. dM_{*} star formation rate * initial mass function
3. dM_{rec} yields of stars; delay times for SN Ia
4. dM_{out} gas outflows, by stars newly born

- True independently for all isotopes



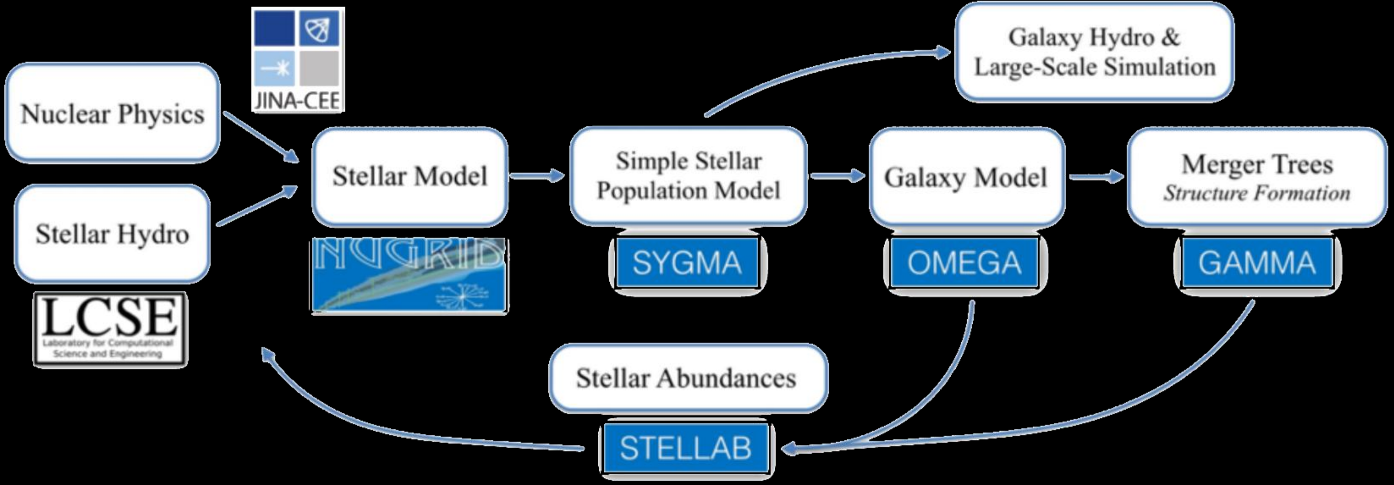
OMEGA+

OMEGA

- OMEGA = One-zone Model for the Evolution of Galaxies
  - NuPyCEE package
  - https://github.com/NuGrid/NUPYCEE
- User-friendly, quick, but valuable GCE simulations

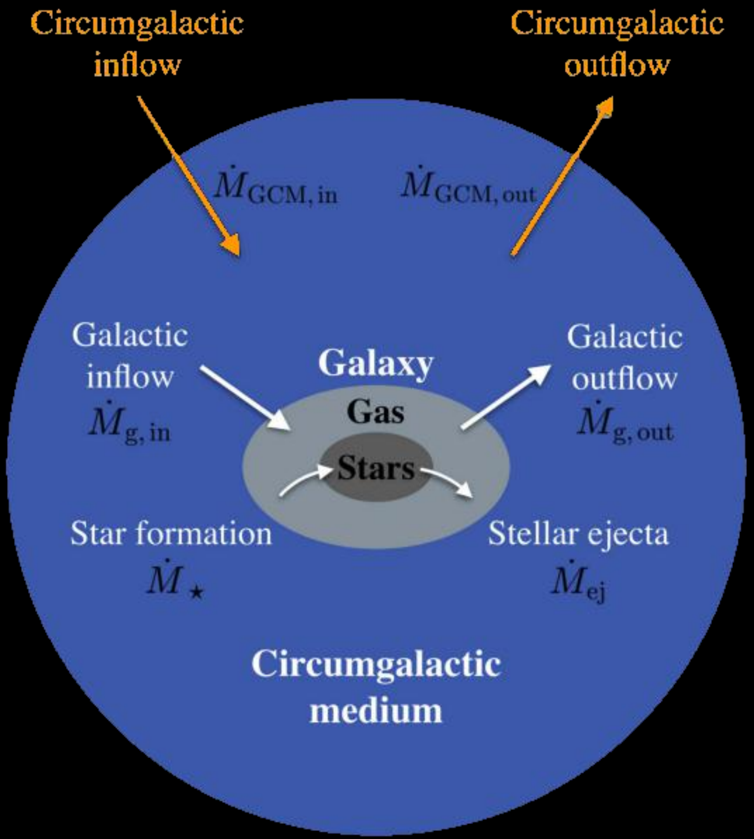
Libraries of OMEGA

- Input: nuclear physics, stellar simulations
- SYGMA: evolution of one stellar population
- OMEGA: the galaxy model itself
- GAMMA: for mergers
- STELLAB: stellar abundances built-in, ready to compare with OMEGA!



OMEGA+

- OMEGA+
  - Uses NuPyCEE for OMEGA
  - +: JinaPyCEE
  - https://github.com/becot85/JINAPyCEE
- Two zones:
  - The galaxy itself, see OMEGA
  - + Hot gas reservior
    (From here, the material can fall back)



Let's get down to the notebook! Have fun!

If you have any questions, either about the material or the installation, don't hesitate to contact me: blanka.vilagos@astro.su.se