FLORENCE 12-14 NOVEMBER 2024

Molecules and planets in the Outer Galaxy
Florence 12-14 November 2024

Isotopic abundance ratios
What's up in the outer edge of the Milky Way?

Laura Colzi
(Centro de Astrobiología, CSIC-INTA)

November 12th 2024

Francesco Fontani, Donatella Romano, and many others…

CENTRO DE ASTROBIOLOGÍA · CAB
ASOCIADO AL NASA ASTROBIOLOGY PROGRAM
CSIC
INTA

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
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Isotopic ratios: a good indicator of nucleosynthesis

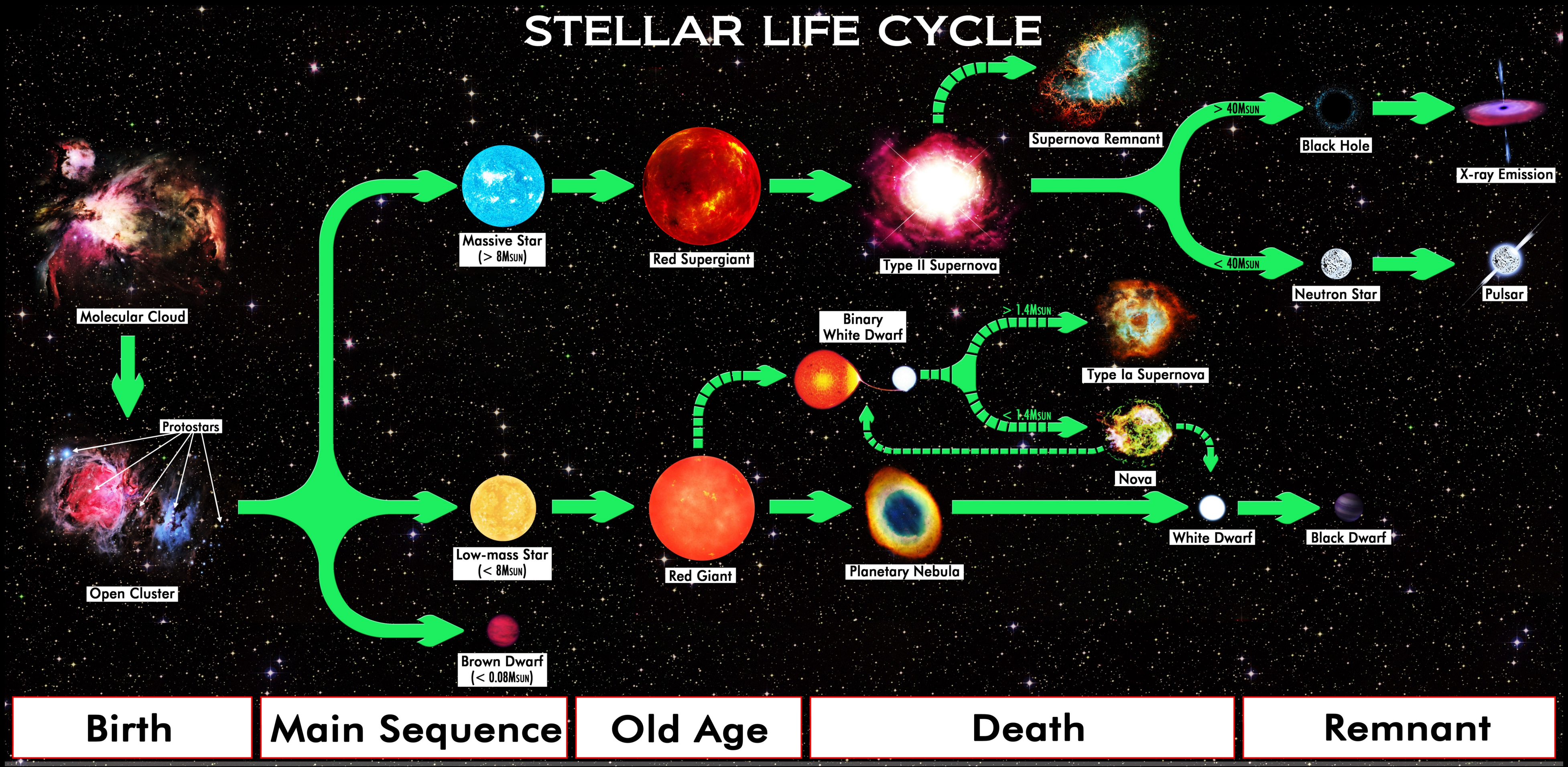
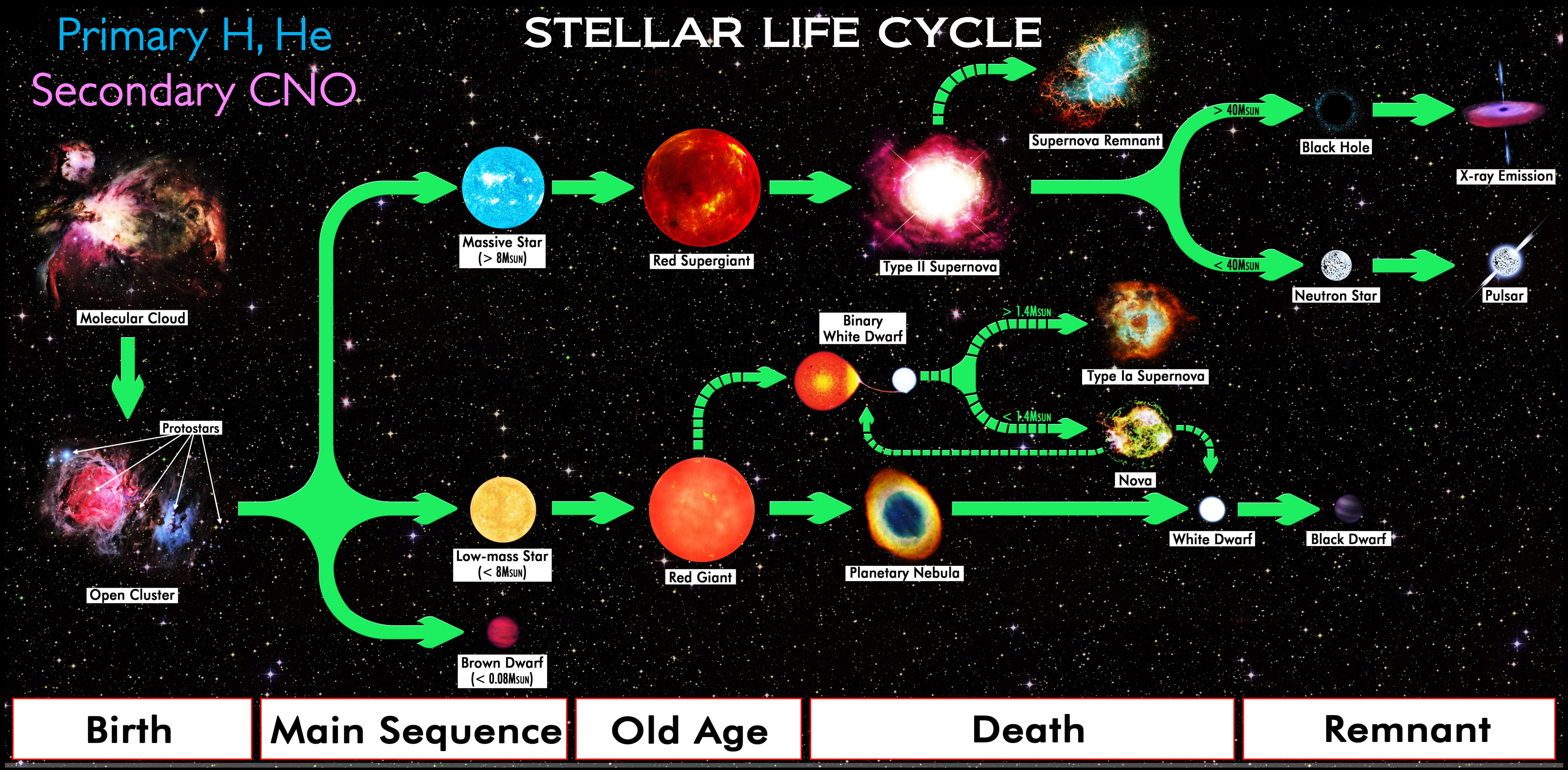


IMAGE CREDIT: R. N. Bailey Wikipedia

Isotopic ratios: a good indicator of nucleosynthesis

→ Different elements and their isotopes are not formed in the same way



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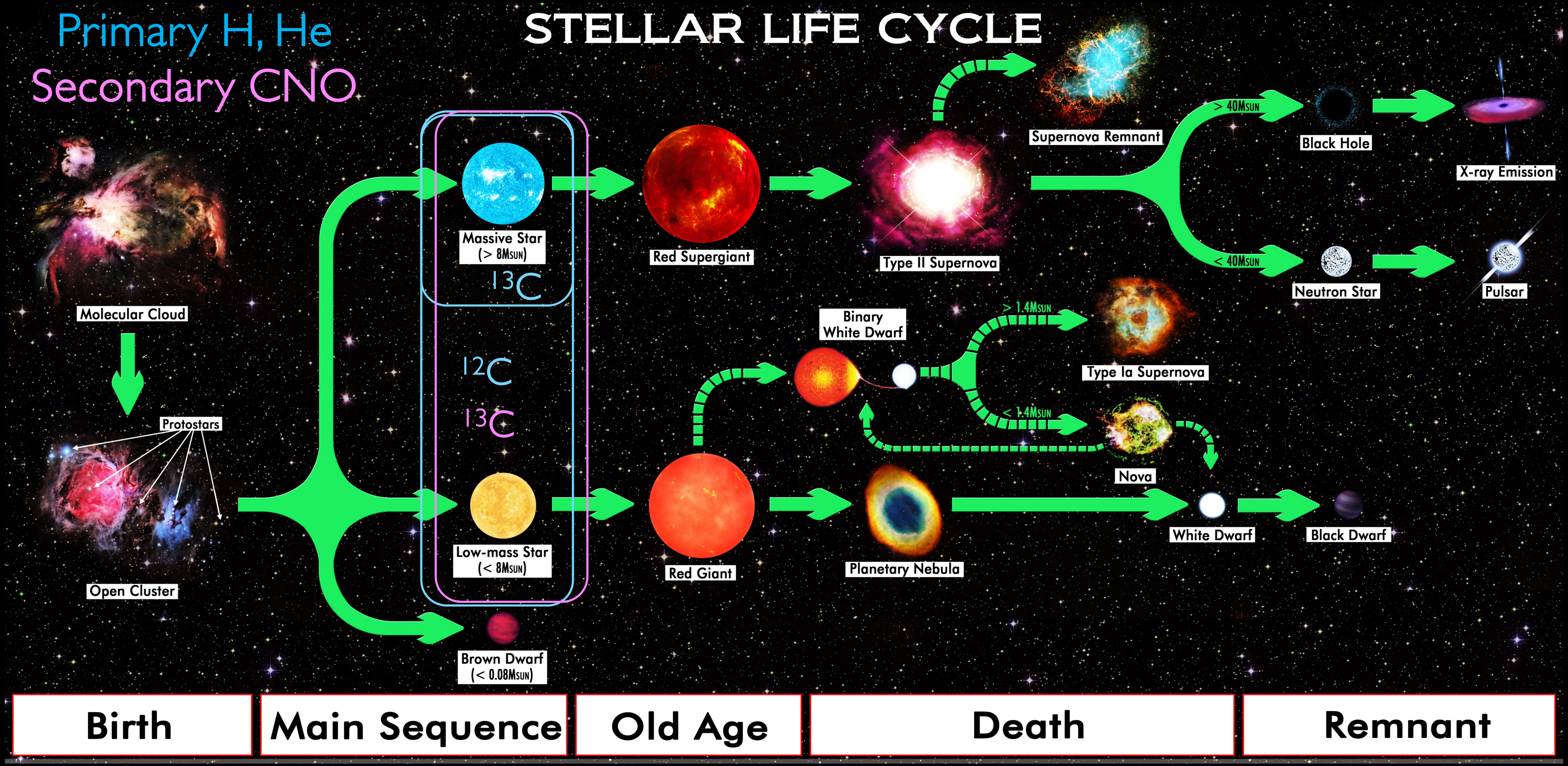

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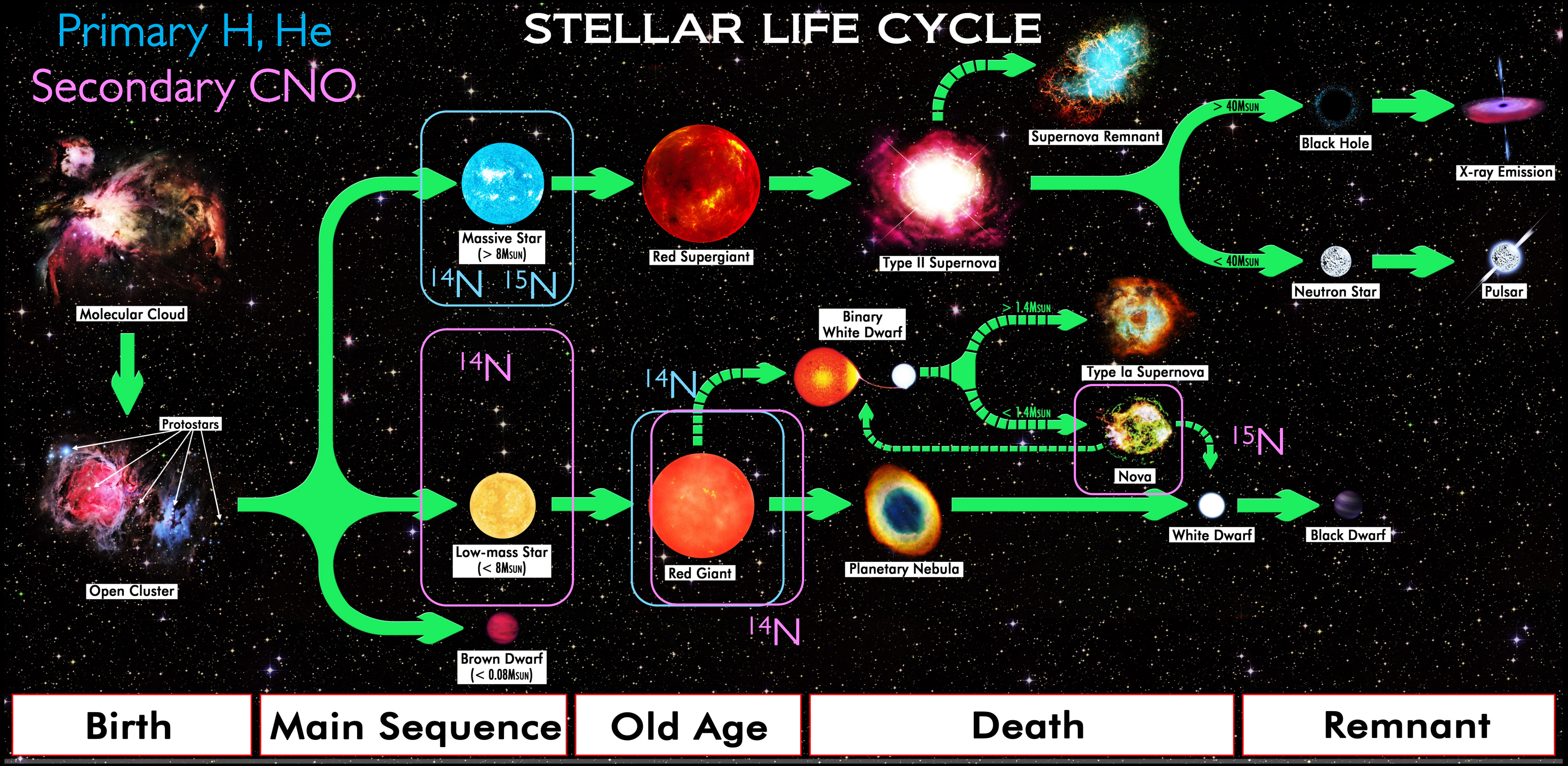

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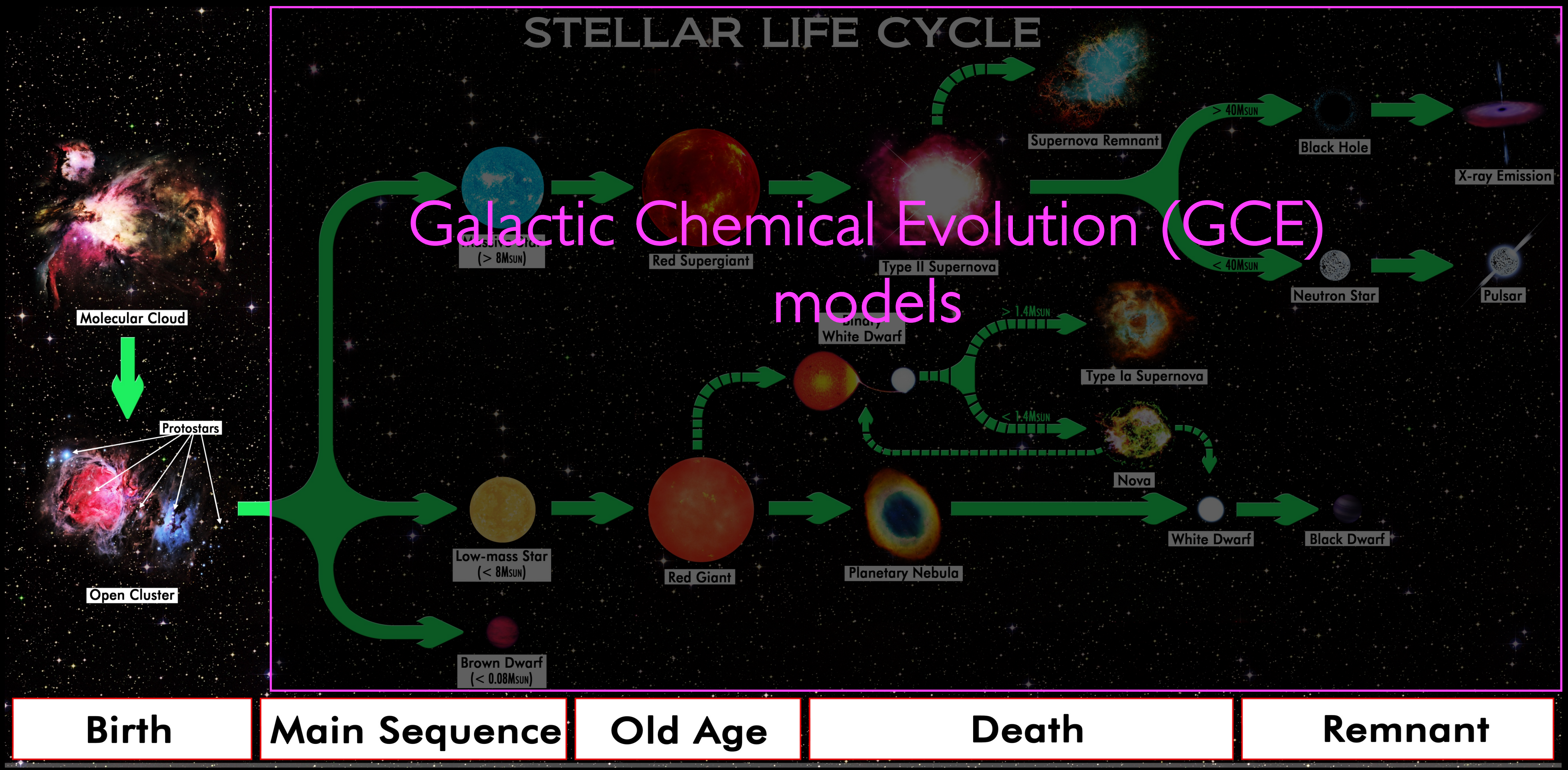

Galactic Chemical Evolution (GCE) models

IMAGE CREDIT: R. N. Bailey Wikipedia

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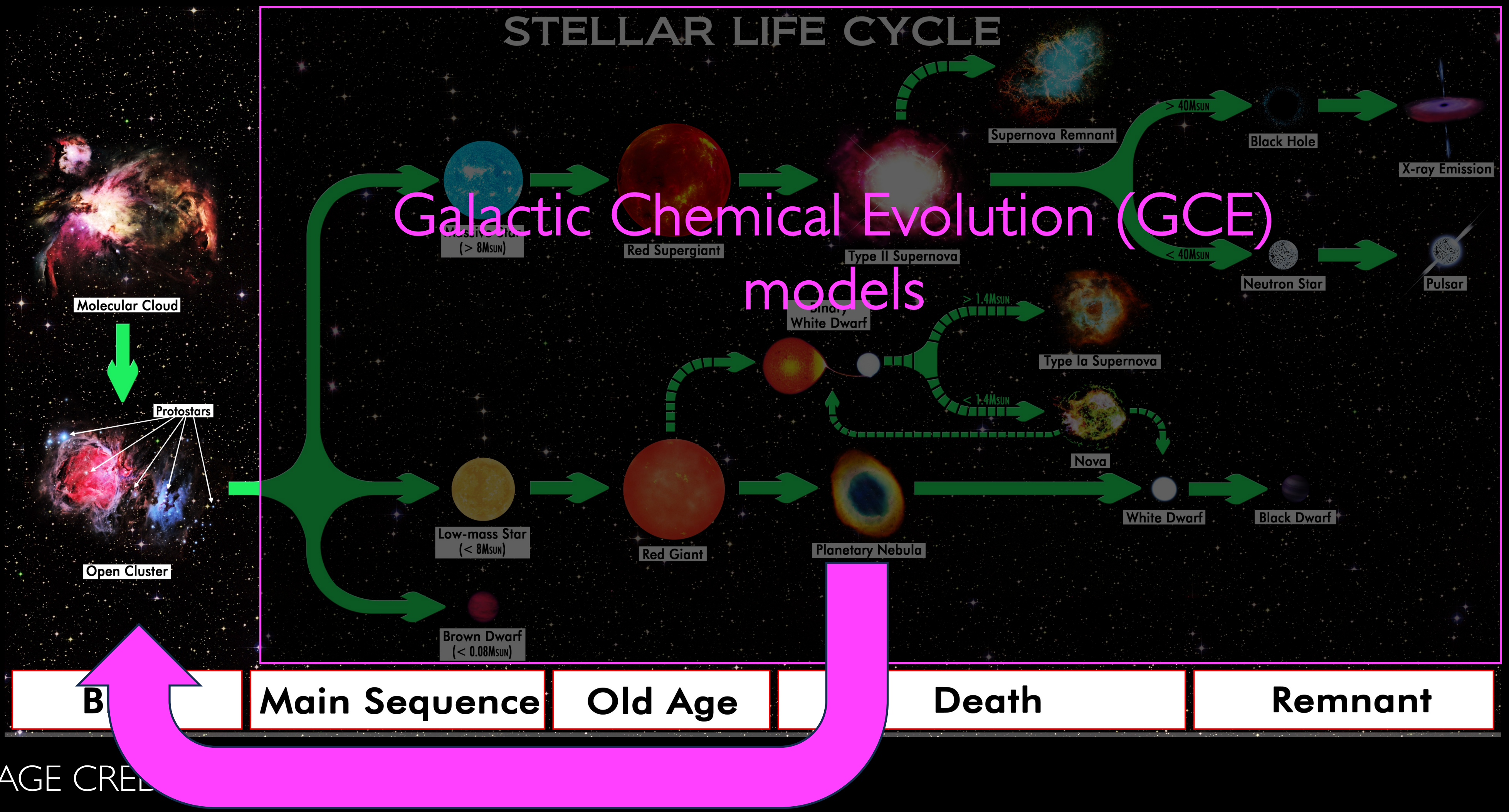

IMAGE CRE

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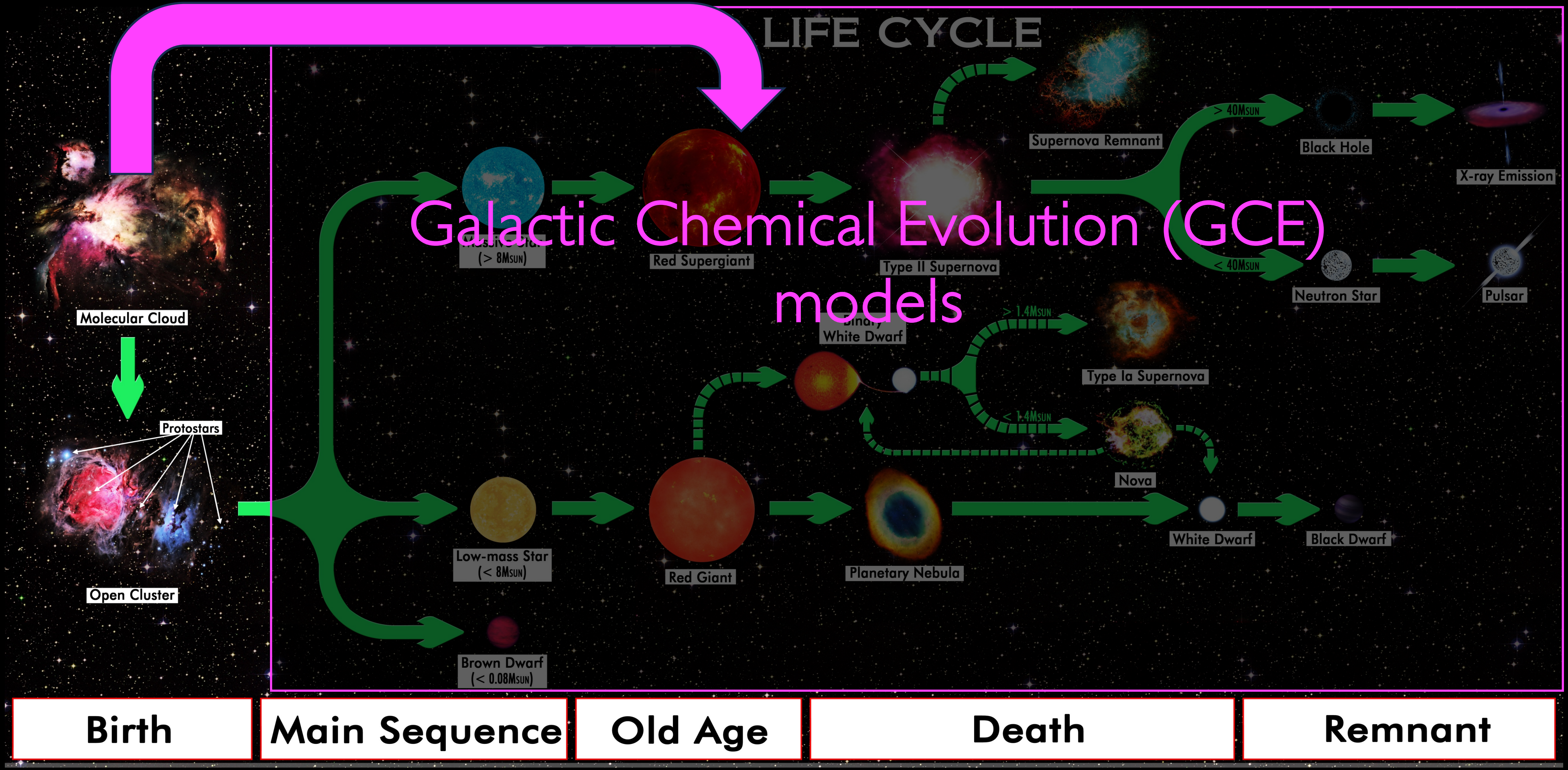
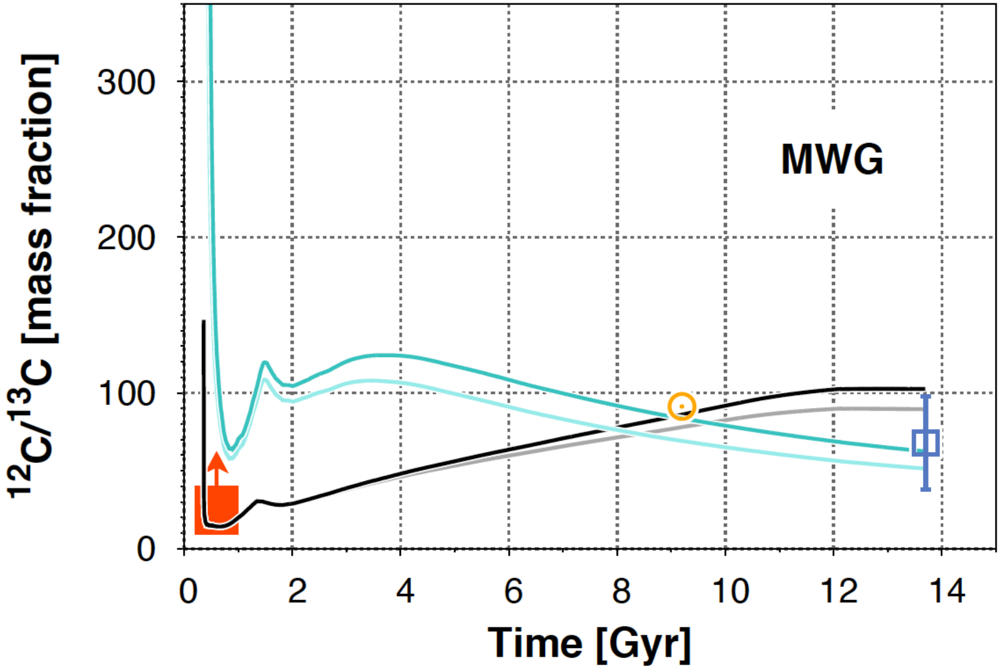


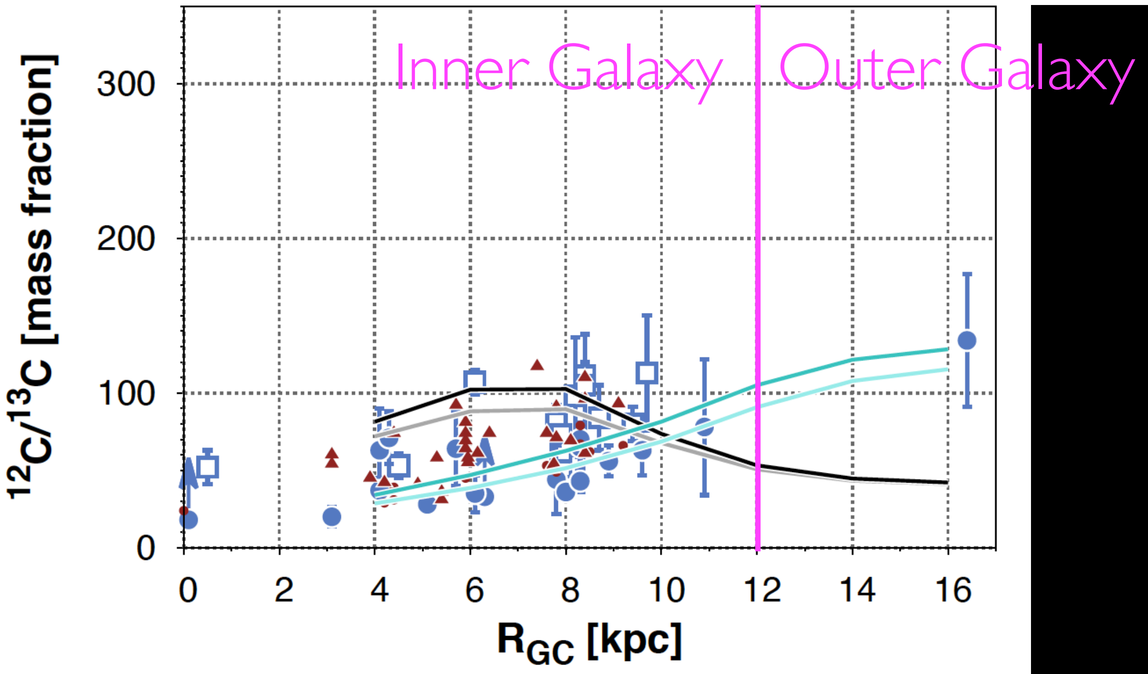
IMAGE CREDIT: R. N. Bailey Wikipedia

Galactic chemical evolution models

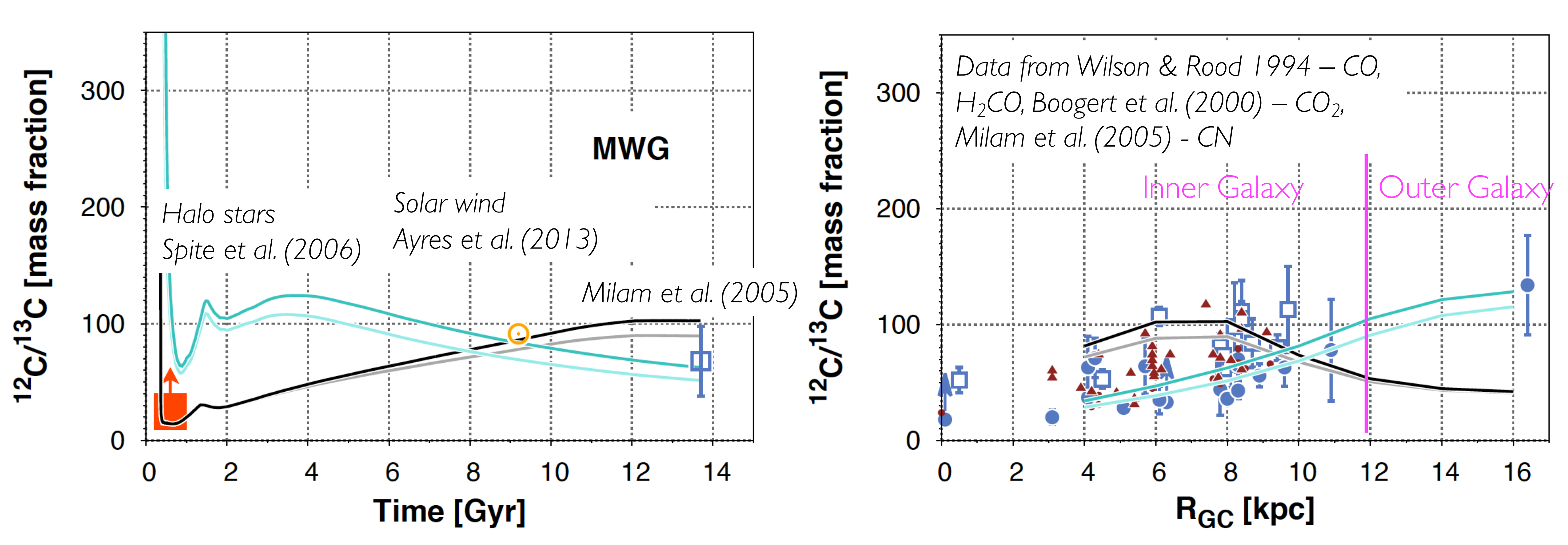
Prescriptions for nucleosynthesis from Romano et al. (2017)

Model		LIMS	Super-AGB stars	Massive stars	Novae
1		Karakas (2010)	–	Nomoto et al. (2013)	No
2		Karakas (2010)	Doherty et al. (2014a,b)	Nomoto et al. (2013)	No
3		Karakas (2010)	–	Meynet & Maeder (2002b), Hirschi et al. (2005), Hirschi (2007), Ekström et al. (2008)	No
4		Karakas (2010)	Doherty et al. (2014a,b)	Meynet & Maeder (2002b), Hirschi et al. (2005), Hirschi (2007), Ekström et al. (2008)	No
5		Karakas (2010)	Doherty et al. (2014a,b)	Nomoto et al. (2013)	Yes





Galactic chemical evolution models: the $^{12}C/^{13}C$ ratio

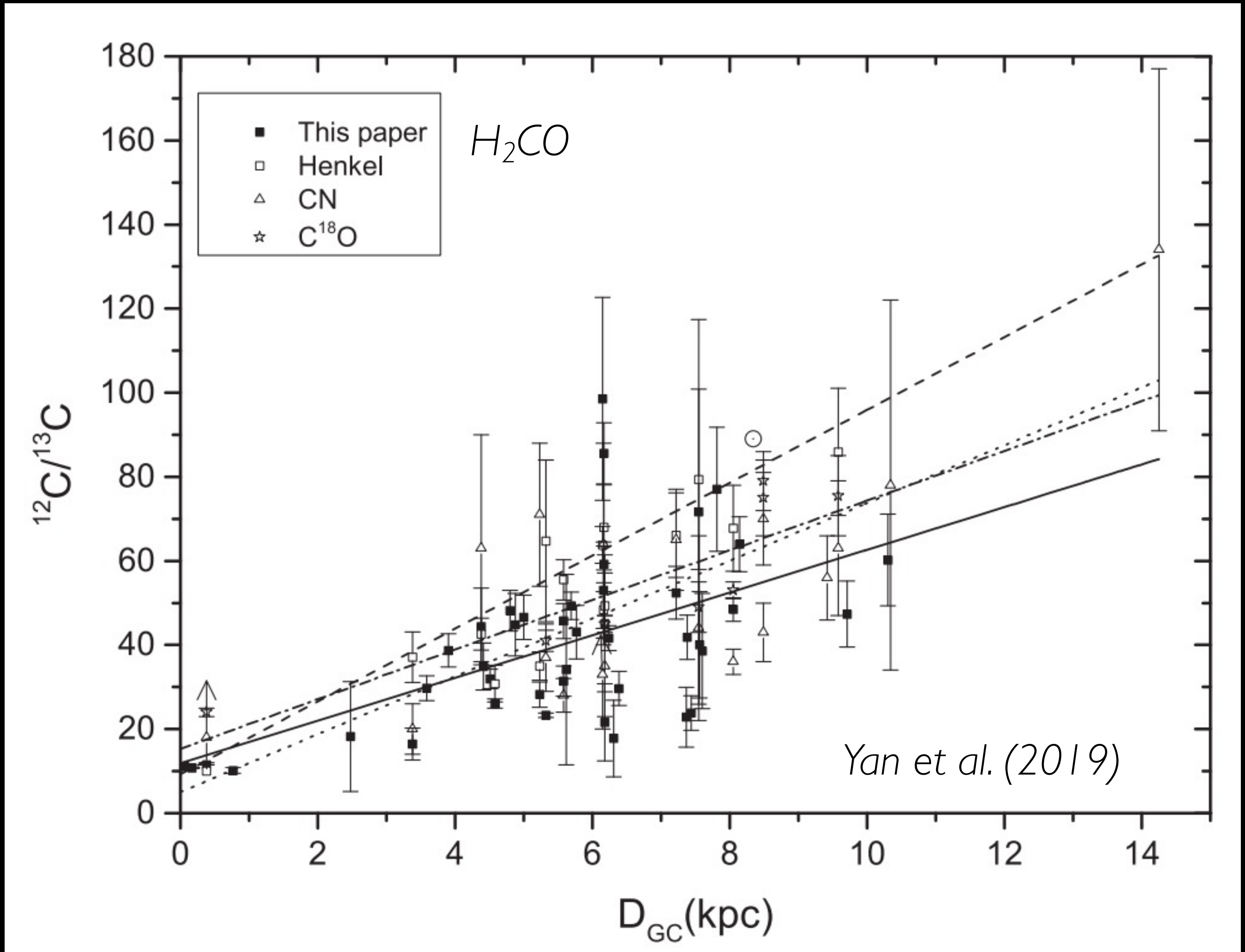


Early Universe: fast rotating massive stars important.

Solar data and observations: with updates C-production yields from Nomoto+2013.

In both cases nova are not important to produce ^{13}C.

Updated $^{12}C/^{13}C$ galactocentric trends



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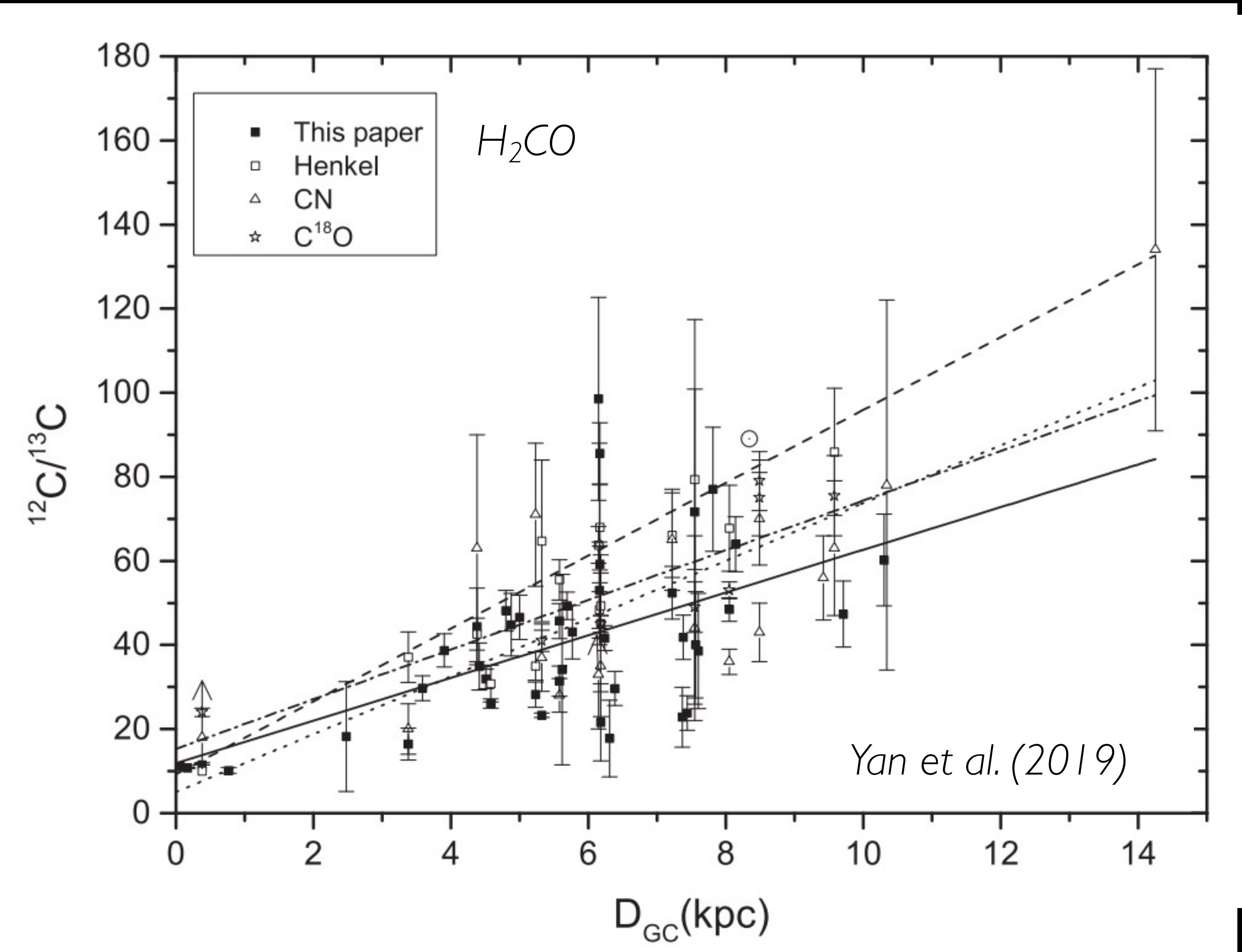

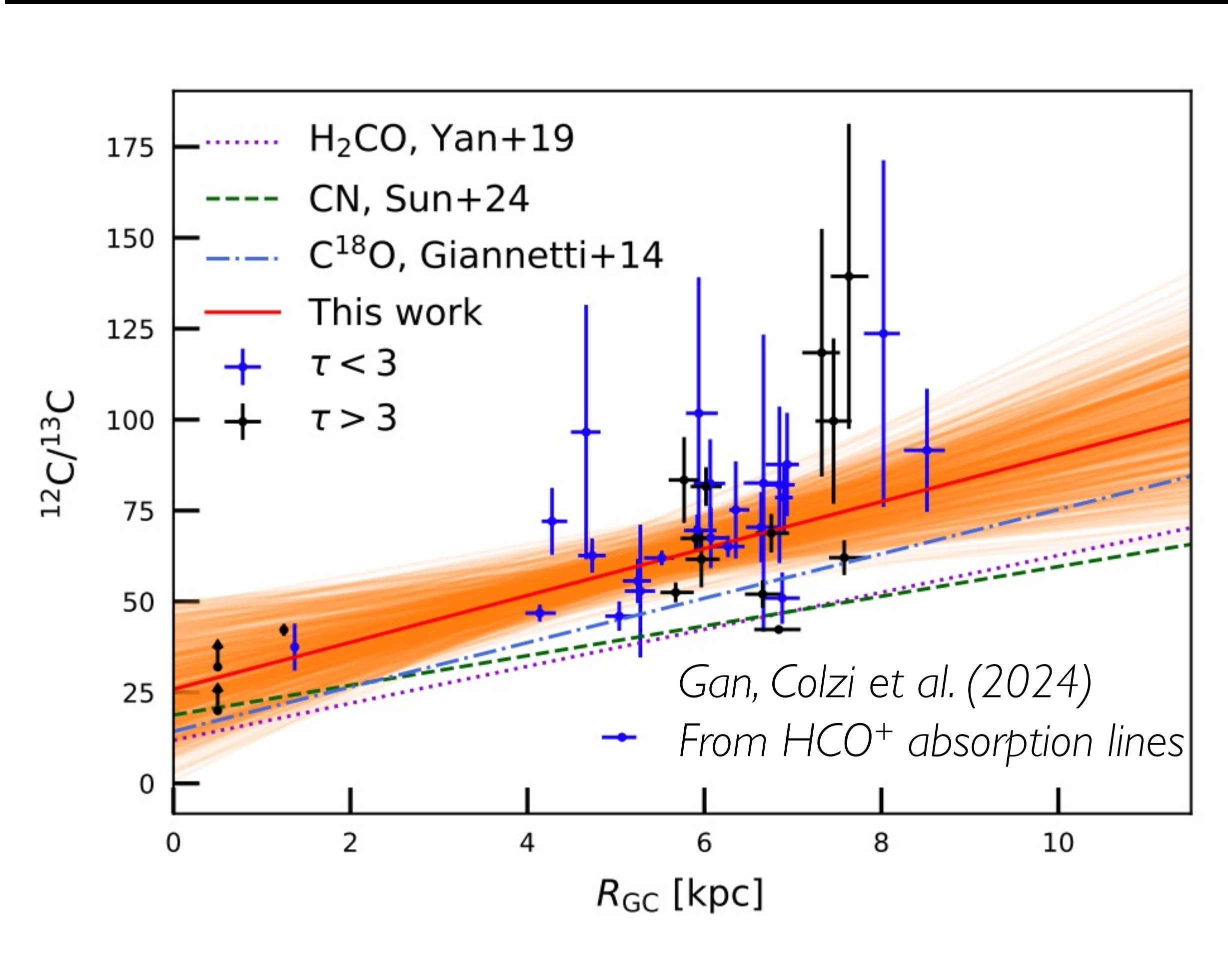

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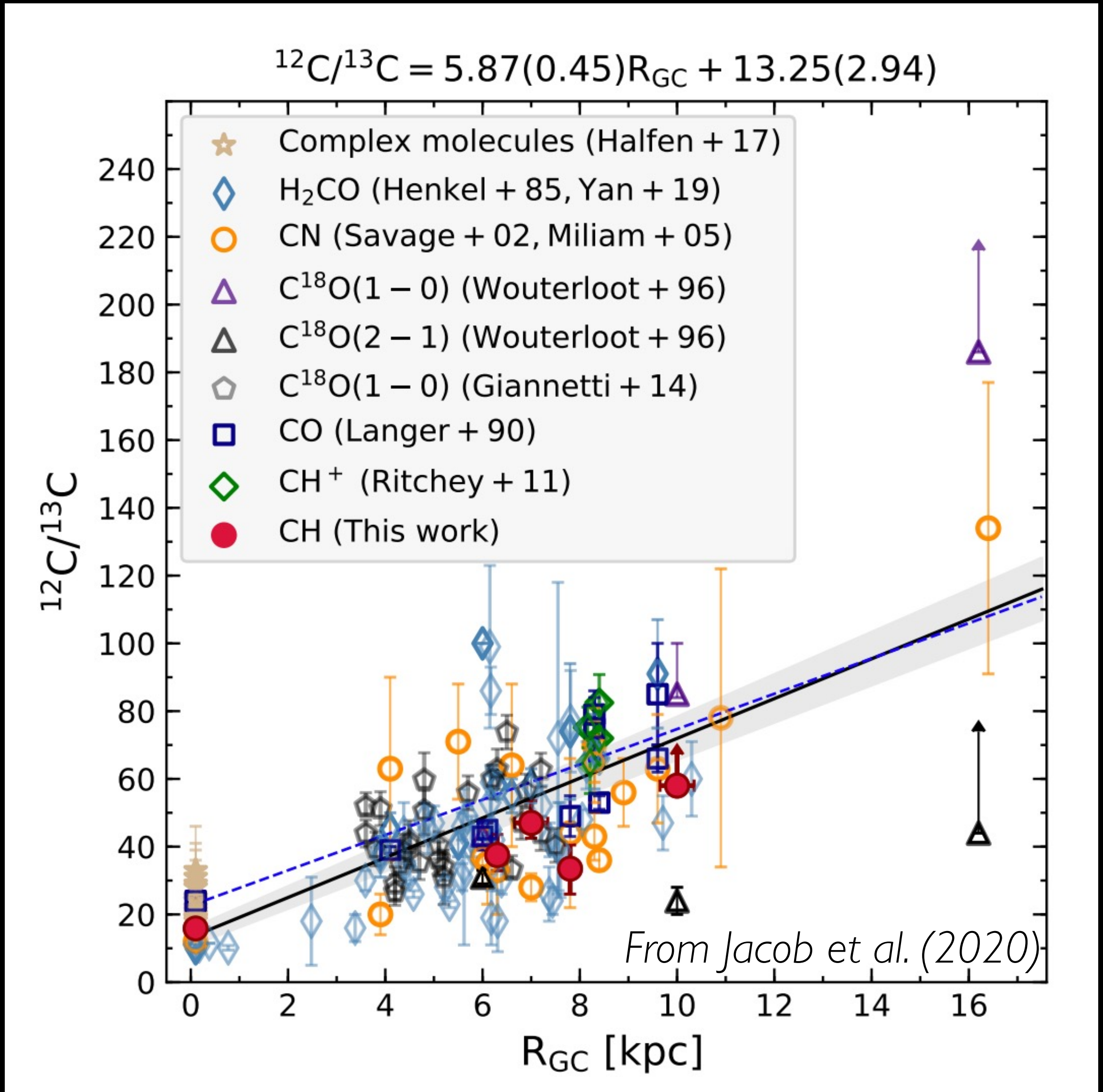

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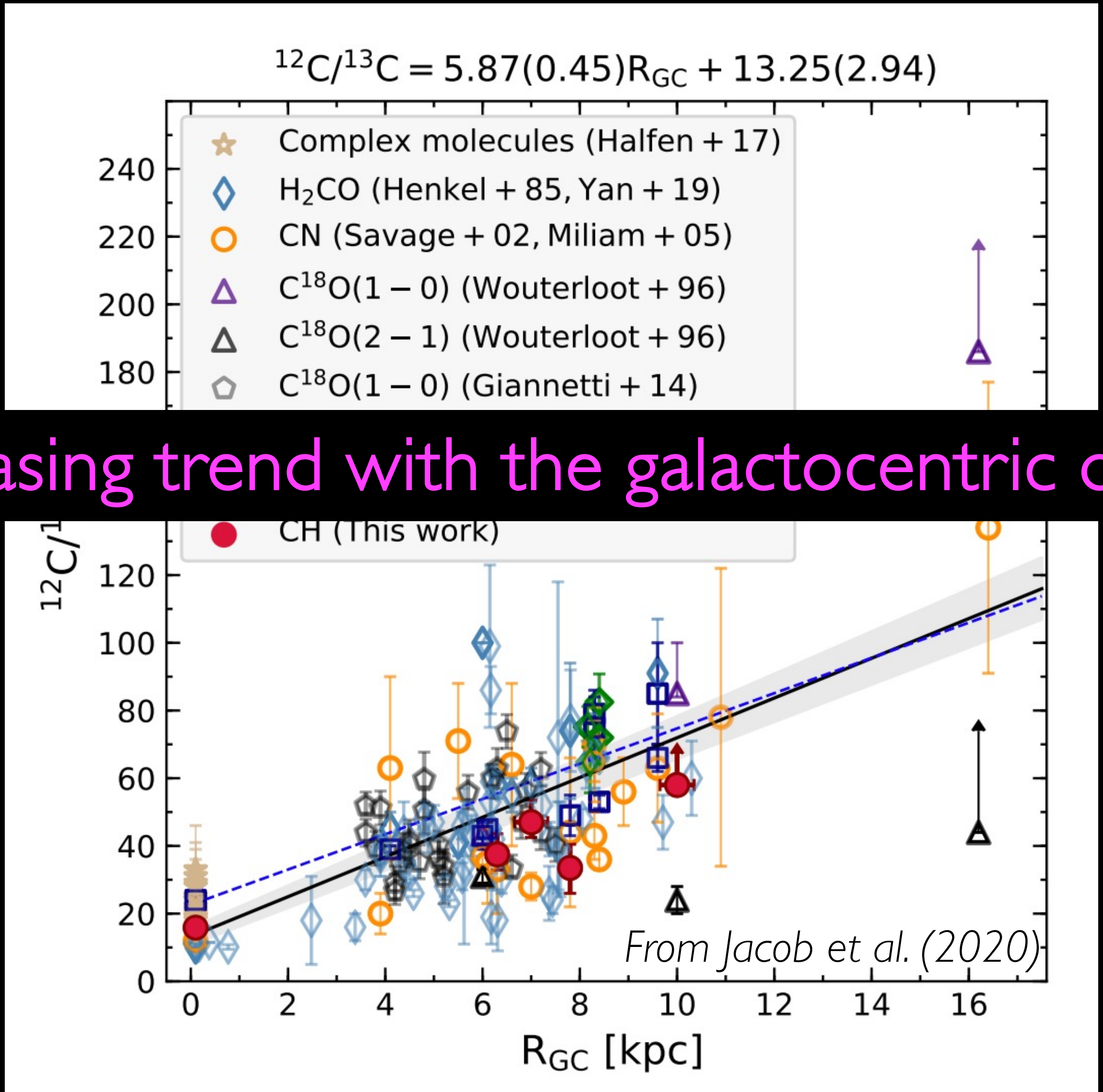
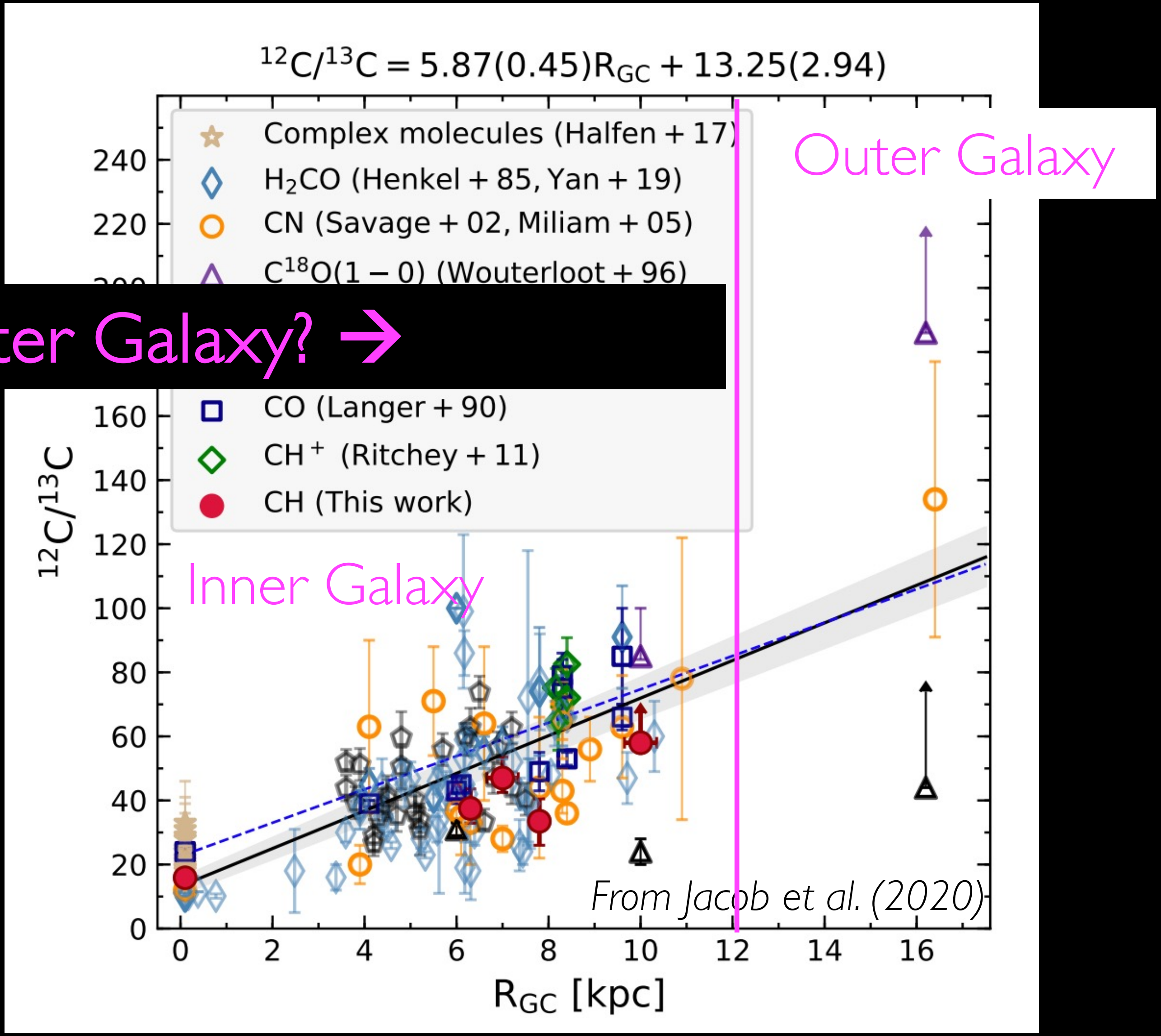


Increasing trend with the galactocentric distance

Updated $^{12}C/^{13}C$ galactocentric trends

What about the outer Galaxy? →



Nitrogen isotopic ratios $^{14}N/^{15}N$

101 massive star-forming regions:

87 (Colzi et al. 2018a,b) + 14 (Colzi et al. 2022b)

Nitrogen isotopic ratios $^{14}N/^{15}N$

IRAM 30m telescope
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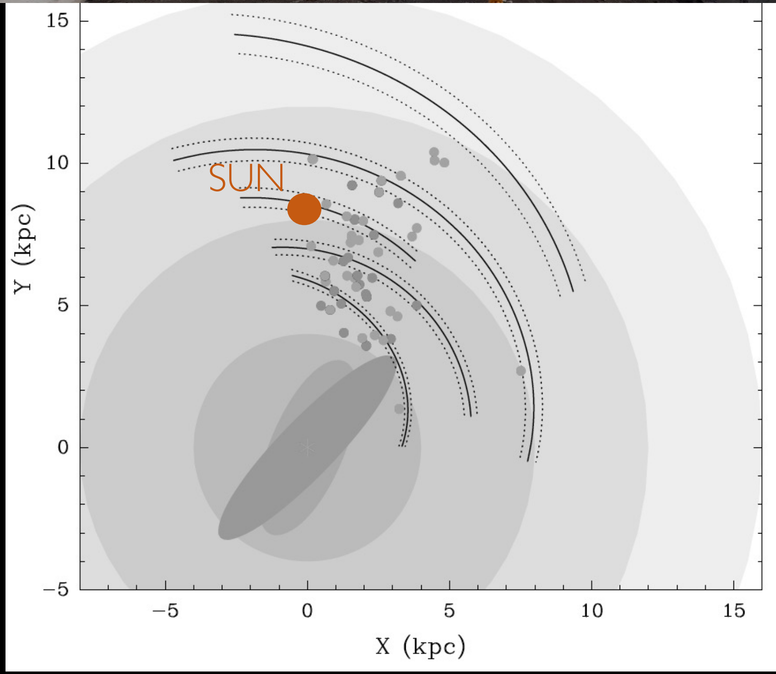
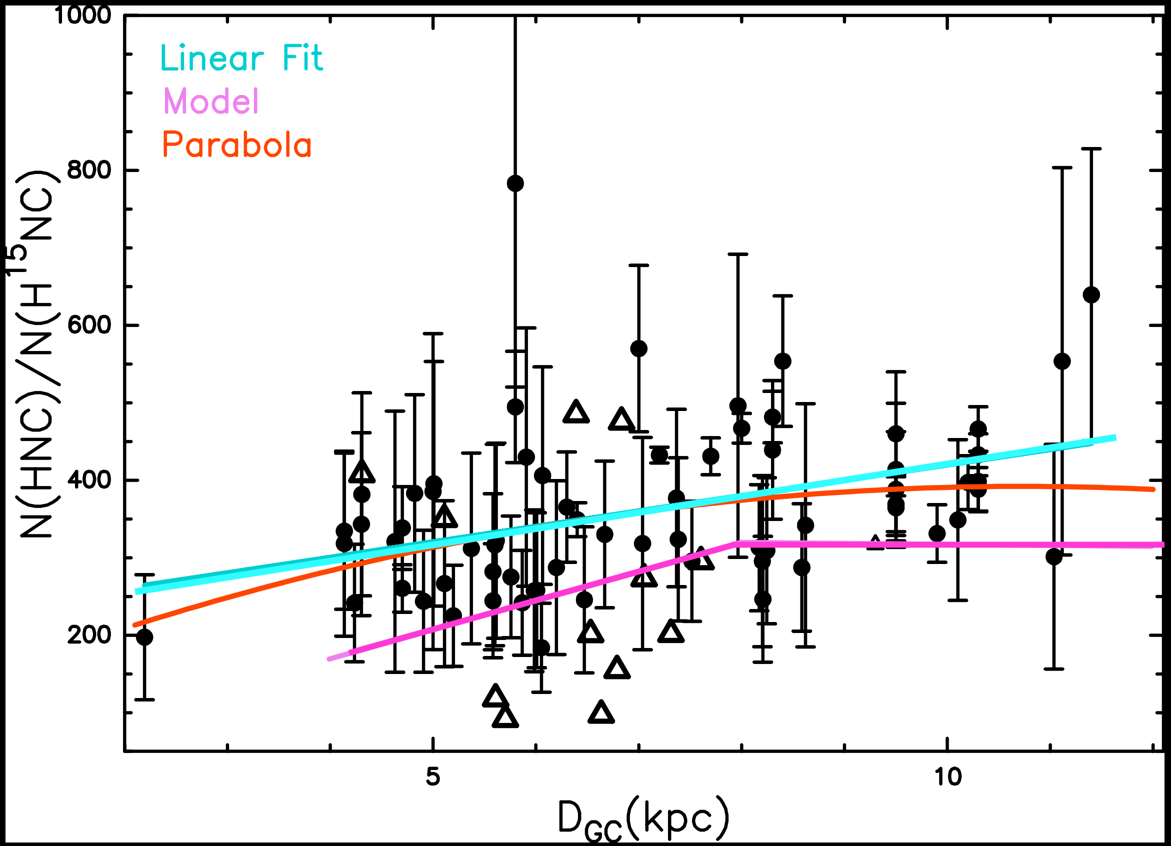
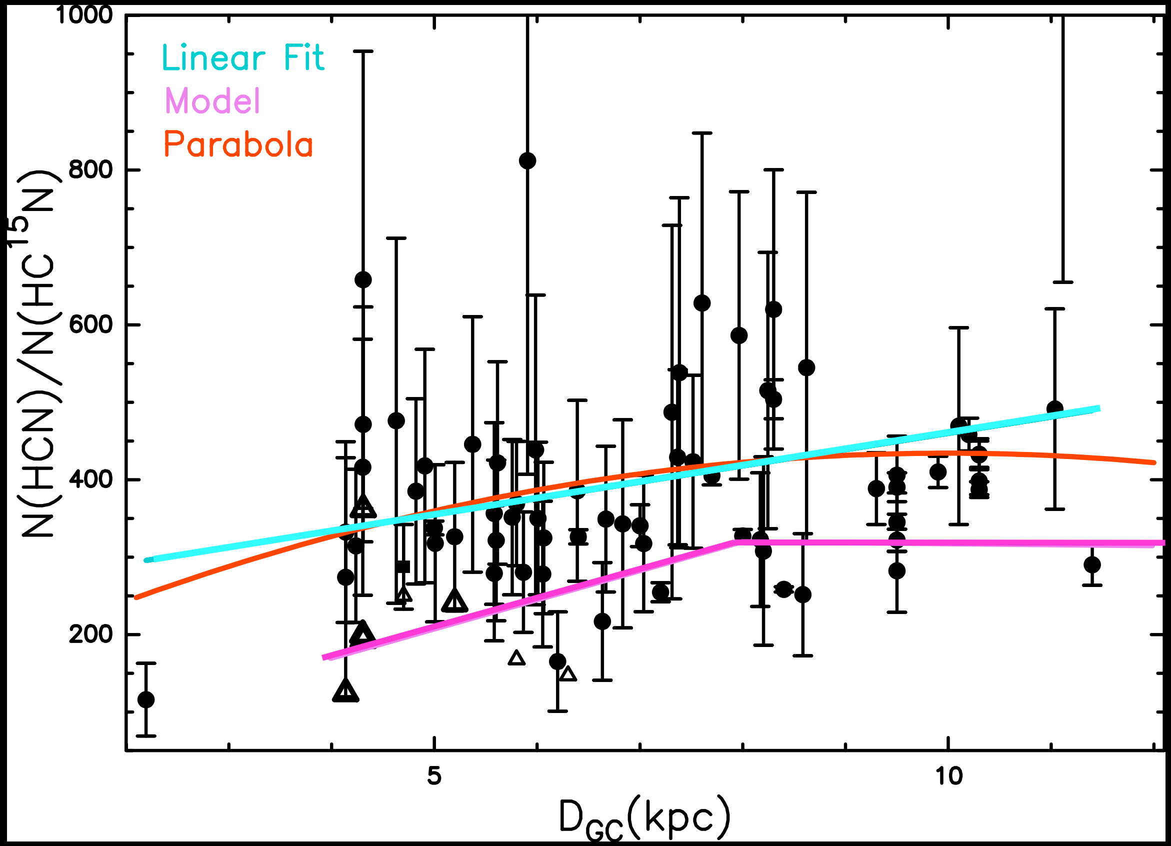


Inner Galaxy (TOPGöt) sample
(Mininni et. al. 2020)
D_{GC} from 2 up to 12 kpc

Nitrogen isotopic ratios $^{14}N/^{15}N$





Linear Regression Fit

$H^{14}NC/H^{15}NC = (20 \pm 6)\ D_{GC}(kpc) + (221 \pm 42)$

$HC^{14}N/HC^{15}N = (21 \pm 9)\ D_{GC}(kpc) + (250 \pm 67)$

Consistent with the work done by Adande & Ziurys (2012)

Colzi, L. et al. (2018b), MNRAS, 478, 3693

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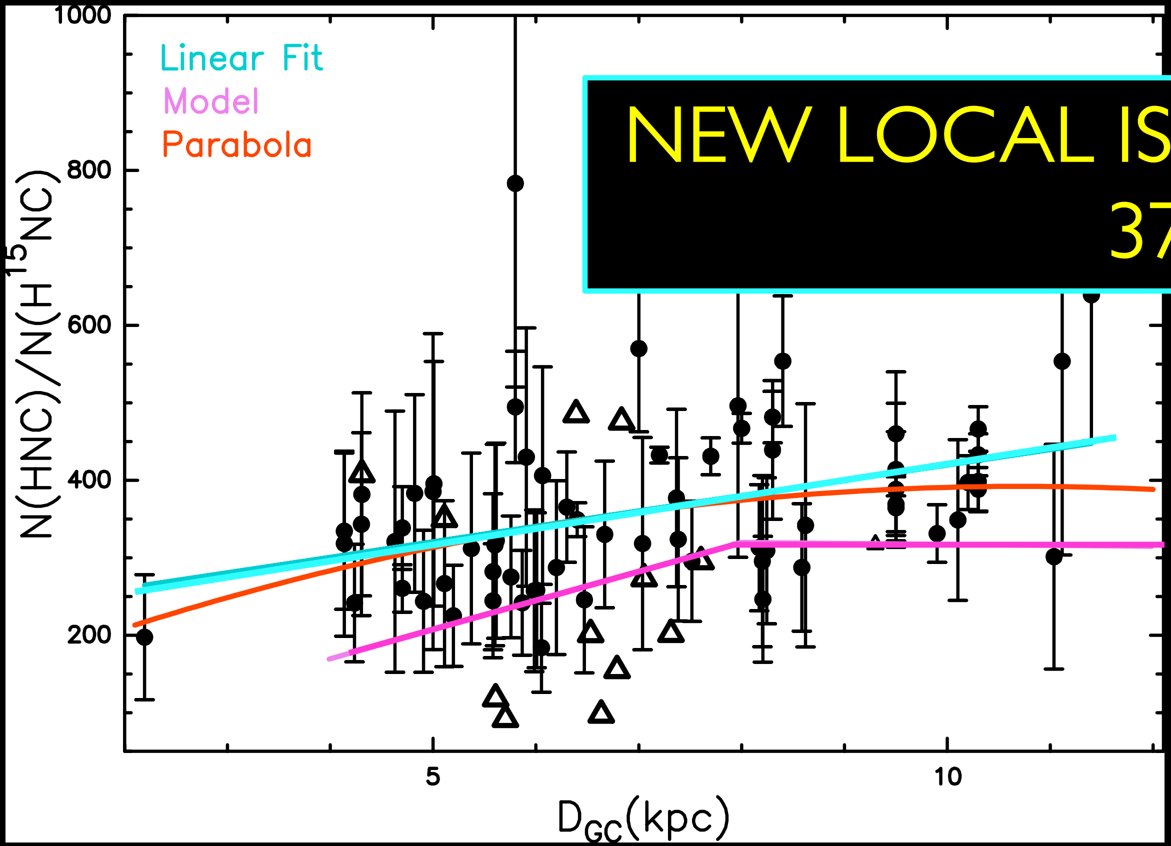

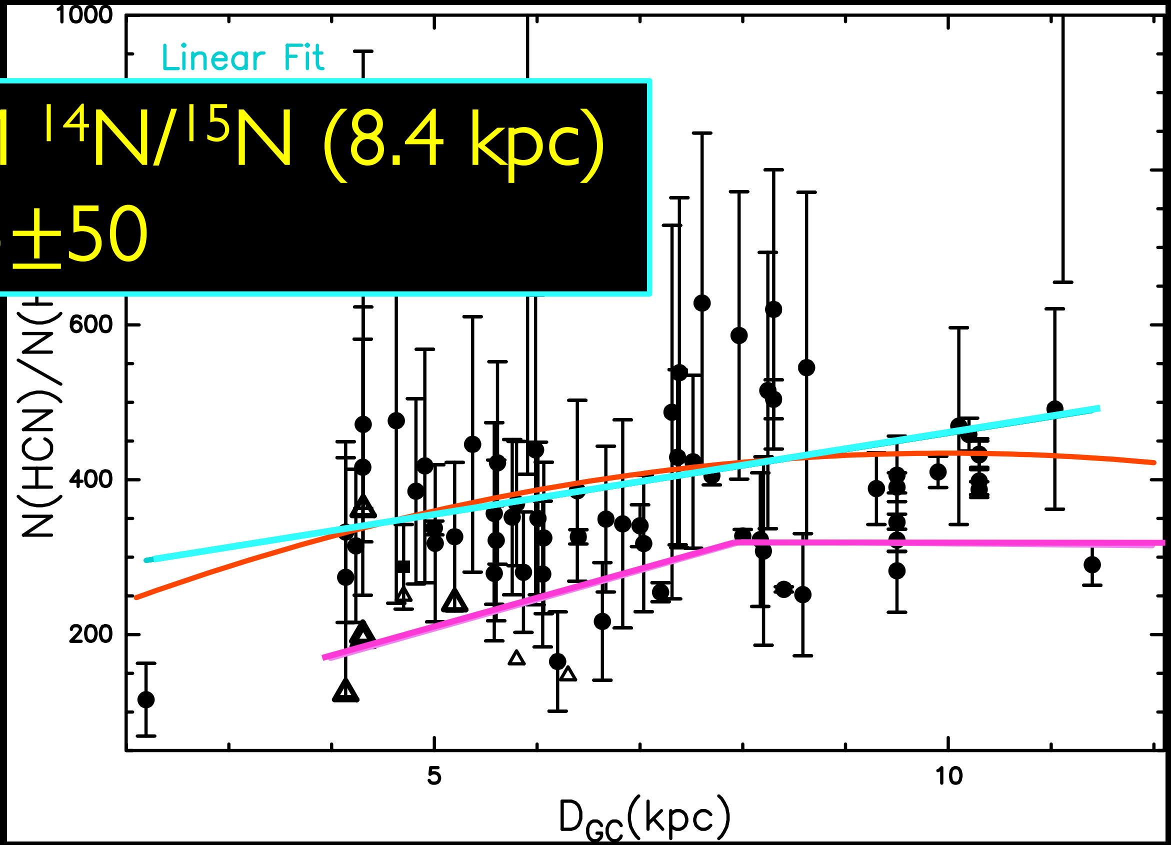

NEW LOCAL ISM $^{14}N/^{15}N$ (8.4 kpc)
375±50

Linear Regression Fit

$H^{14}NC/H^{15}NC = (20 \pm 6)\, D_{GC}(kpc) + (221 \pm 42)$

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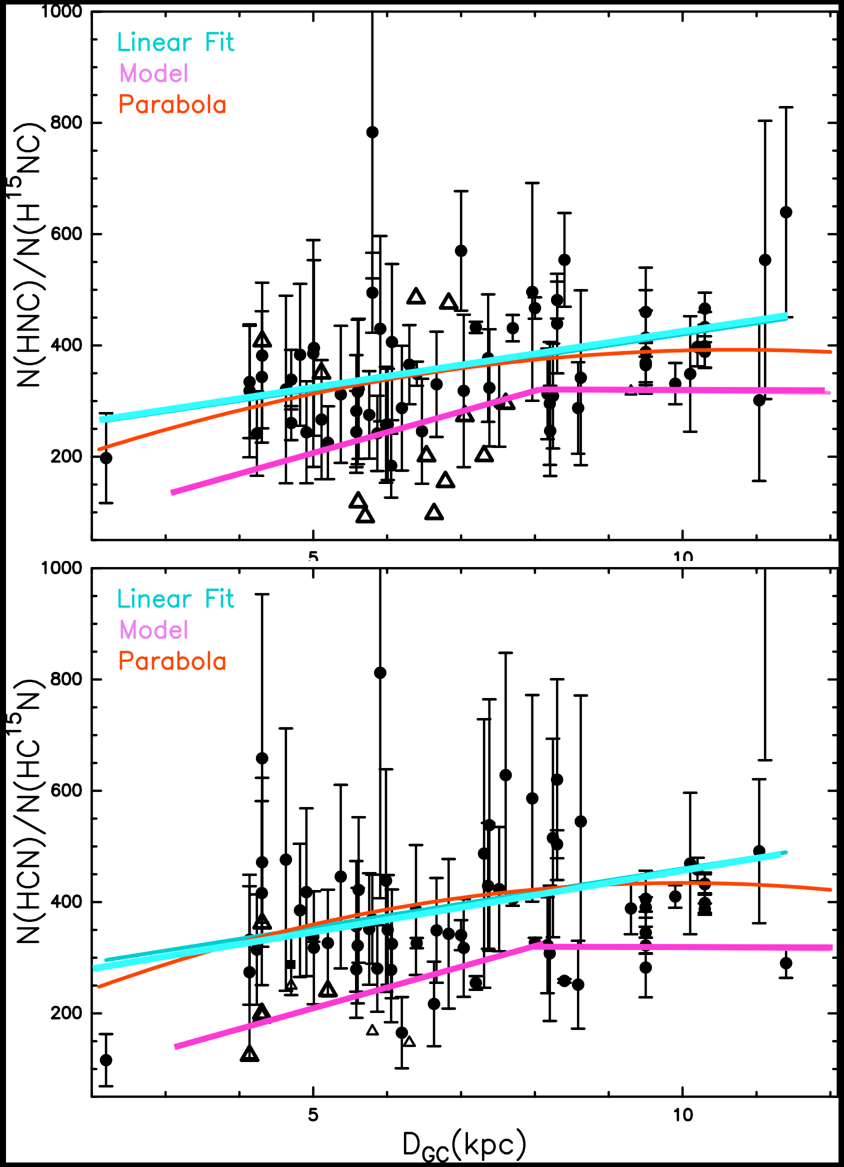


Galactic chemical evolution (GCE, *Romano et al. 2017*) model predicts:

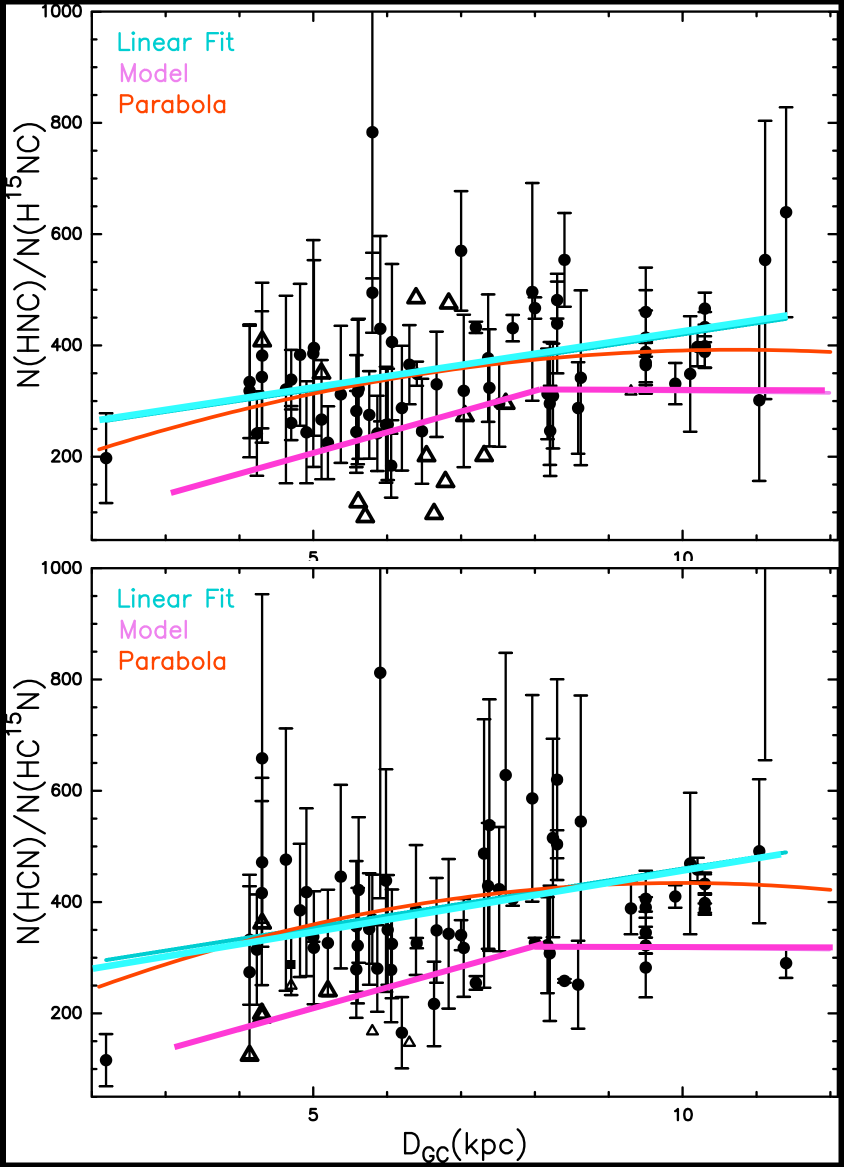
→ linear trend up to 8 kpc: introduction of NOVAE OUTBURST (efficient production of ^{15}N)

→ flattening trend above 8 kpc: caused by assumed stellar yields

Nova Cygni 1992 – HST Image

Colzi, L. et al. (2018b), MNRAS, 478, 3693

Nitrogen isotopic ratios $^{14}N/^{15}N$



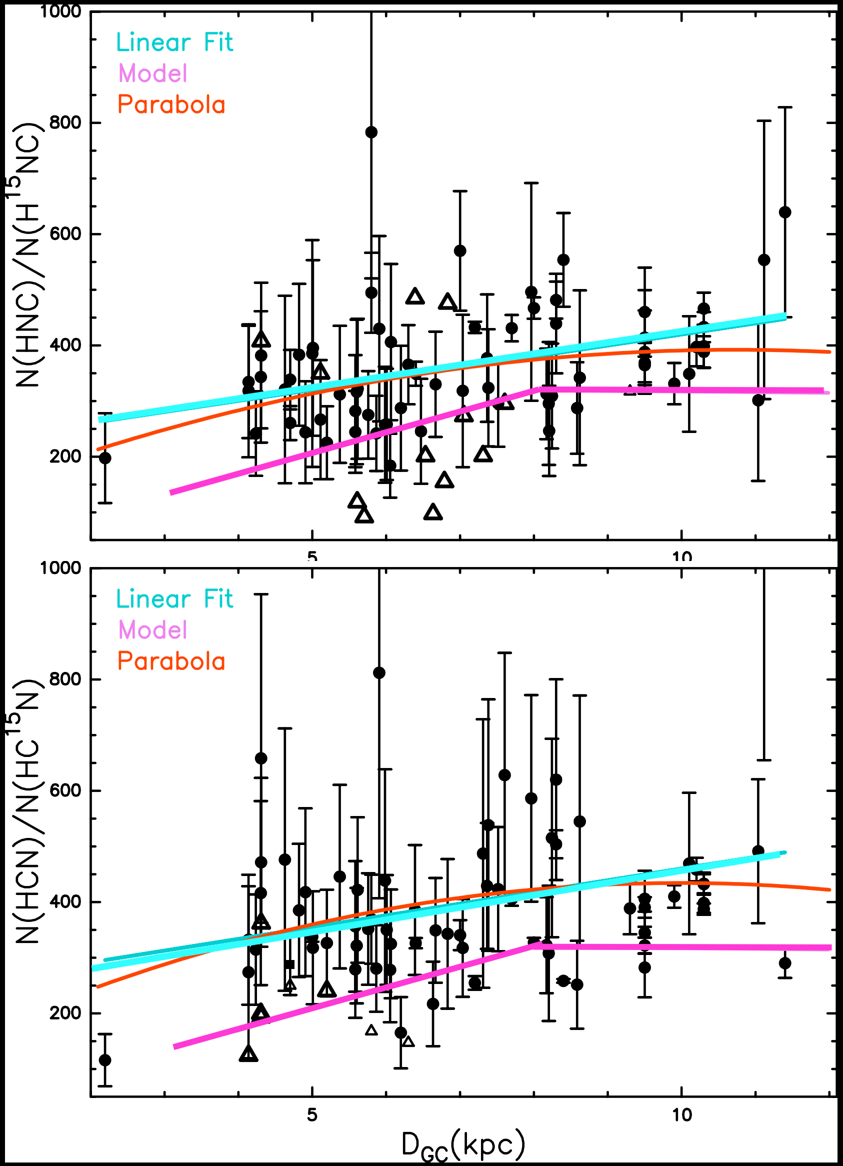
TREND IS REPRODUCED

BUT ABSOLUTE VALUES ARE DIFFERENT!!

- Mass ejected (M_{ej}) of ^{15}N in a single outburst is different
- chemical fractionation in dense clouds

Colzi, L. et al. (2018b), MNRAS, 478, 3693

Nitrogen isotopic ratios $^{14}N/^{15}N$



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Chemical fractionation in molecular clouds

➢ LOW-TEMPERATURE ISOTOPIC-EXCHANGE REACTIONS?

$$^{14}N^{15}N + {}^{14}N_2H^+ \longrightarrow {}^{14}N^{15}NH^+ + {}^{14}N_2 + 10.3\ K$$

$$^{14}N^{15}N + {}^{14}N_2H^+ \longrightarrow {}^{15}N^{14}NH^+ + {}^{14}N_2 + 2.1\ K$$

$$^{15}N + C^{14}N \longrightarrow {}^{14}N + C^{15}N + 22.9\ K$$

e.g.
Terzieva & Herbst (2000); Charnley and Rodgers (2002); Rodgers & Charnley (2008a,b); Wirström et al. (2012); Roueff et al. (2015); Wirström & Charnley (2018); Loison et al. (2019), Hily-Blant et al. (2020), Sipilä, Colzi et al. (2023)

→ DIFFERENT RATES FOR DISSOCIATIVE RECOMBINATION OF N_2H^+?

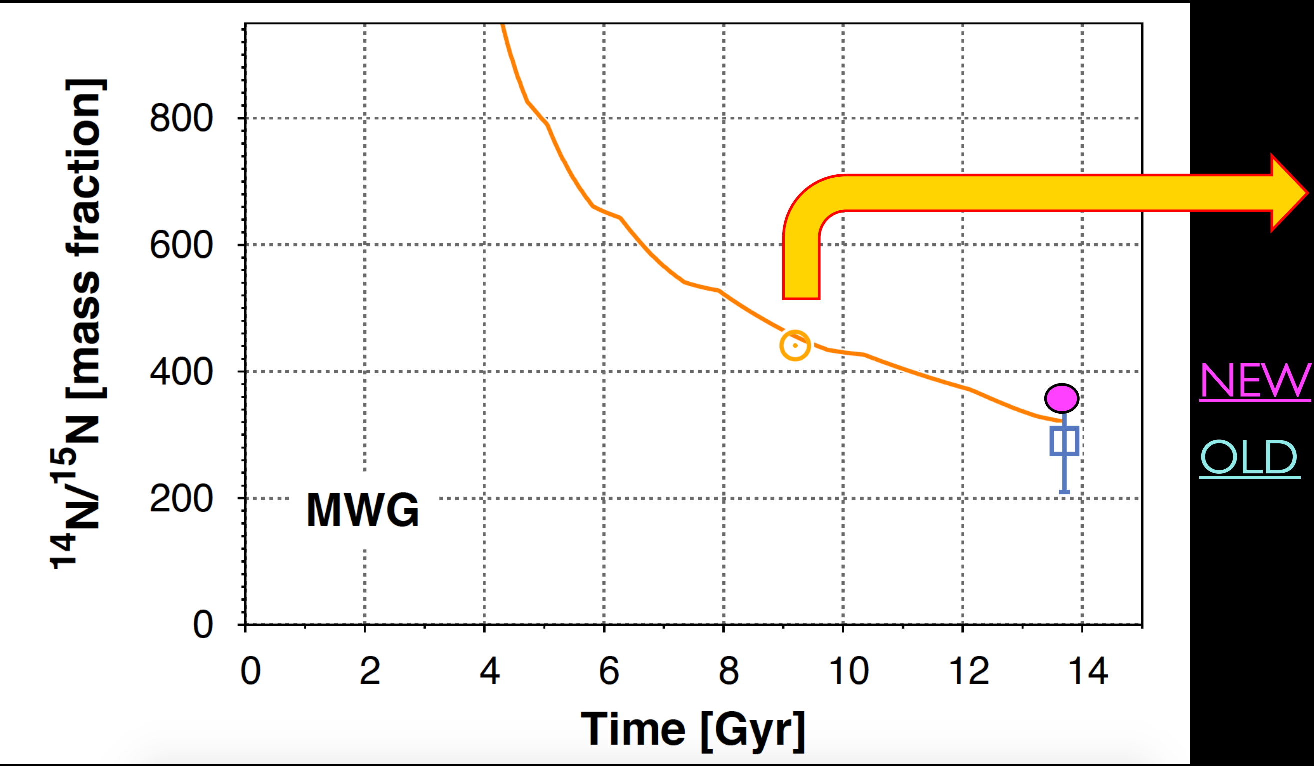
e.g. *Loison et al. (2019), Hily-Blant et al. (2020), Redaelli et al. (2020)*

→ ISOTOPE-SELECTIVE PHOTODISSOCIATION OF N_2?

e.g. *Furuya & Aikawa (2018), Colzi et al. (2019), Lee et al. (2021), Spezzano et al. (2022), Sipilä, Colzi et al. (2023)*

Nitrogen isotopic ratios $^{14}N/^{15}N$

Evolution of $^{14}N/^{15}N$ in solar vicinity (*Romano+2017*)



PSN VALUE = 441

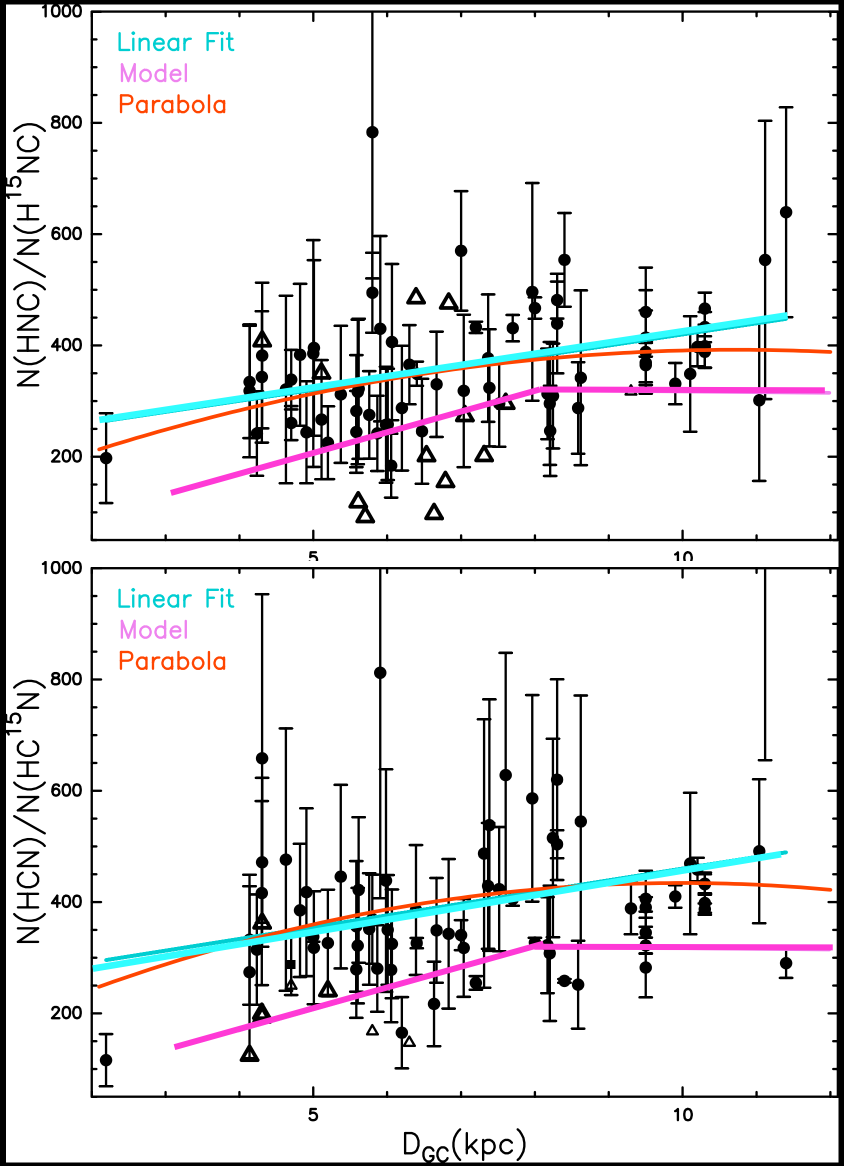
NEW LOCAL ISM VALUE ~ 375 (*Colzi et al. 2018b*)

OLD LOCAL ISM VALUE ~ 290 (*Adande & Ziurys 2012*)

GCE MODEL (*Romano et al. 2017*) predict for present day a local ISM $^{14}N/^{15}N < 441$

Observed values might be not affected by chemical fractionation but by Galactic chemical evolution

Nitrogen isotopic ratios $^{14}N/^{15}N$



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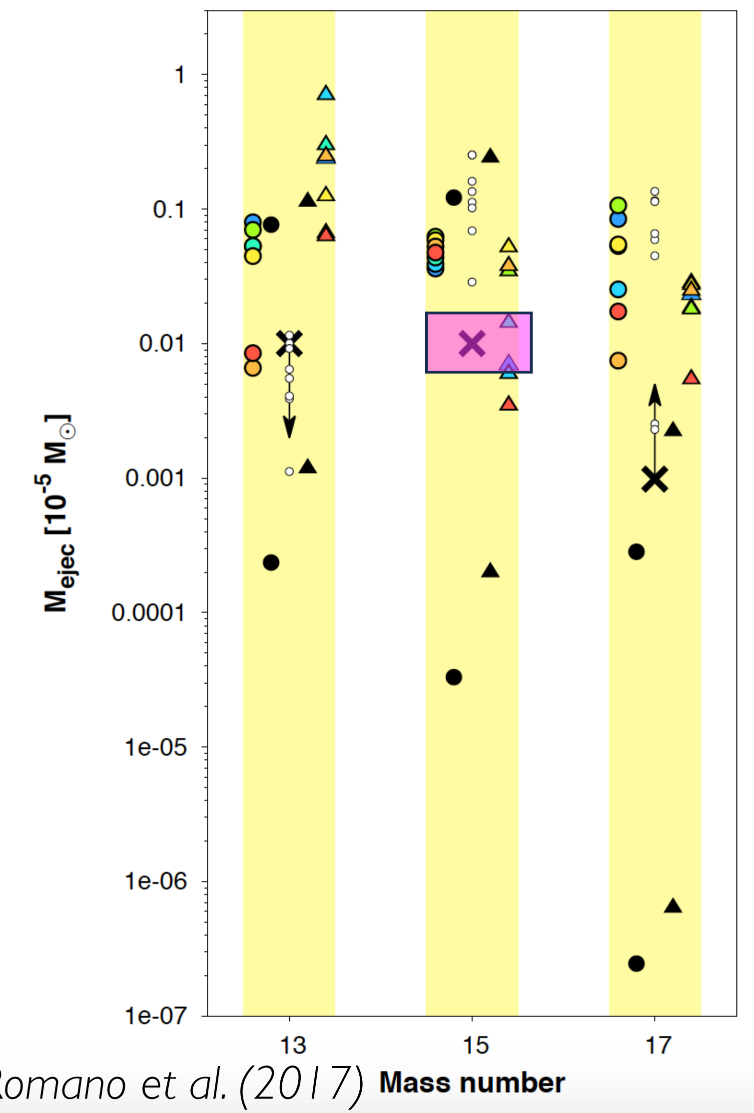
Colzi, L. et al. (2018b), MNRAS, 478, 3693

Ejected Mass from single novae outburst

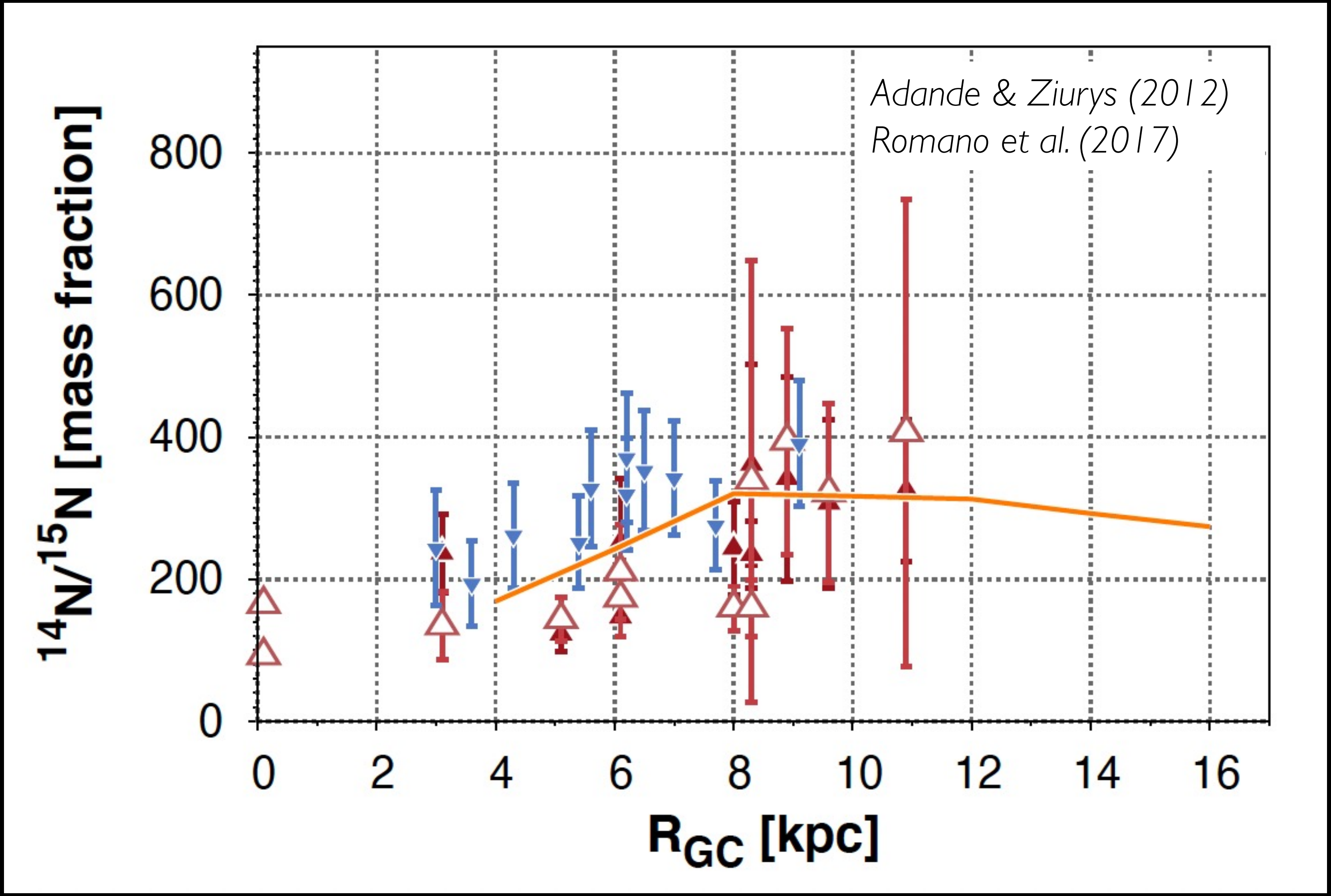
Values from hydrodynamic simulations of nova outbursts: *José & Hernanz (1998*, coloured symbols), *Yaron et al. (2005*, black symbols) and *Starrfield et al. (2009*, small empty circles)

$M_{ejected} = 10^{-7}\ M_{\odot}$
(Romano+2017)



Romano et al. (2017)

Nitrogen isotopic ratios $^{14}N/^{15}N$



Updated GCE models with stellar rotators

Table 1. Nucleosynthesis prescriptions for different models.

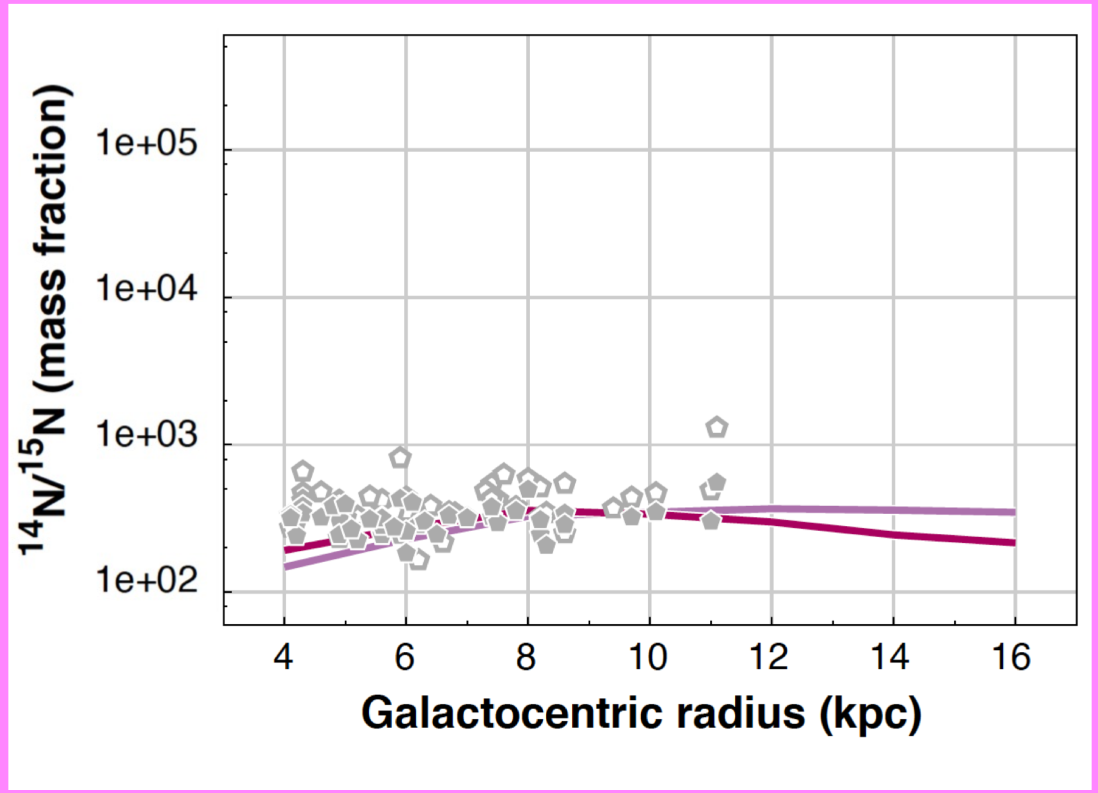
Romano et al. (2019)

Model[a] Milky Way	Prototype SMG	LIMS	Super-AGB stars	Massive stars	v_{rot} (km s^{-1})	Hypernovae	Novae
MWG-01	SMG-01	Karakas (2010)	Doherty et al. (2014a,b)	Nomoto et al. (2013)	0	✗	✗
MWG-02	–	Karakas (2010)	–	Nomoto et al. (2013)	0	✗	✗
MWG-03	–	Ventura et al. (2013) & unpublished		Nomoto et al. (2013)	0	✗	✗
MWG-04	–	Ventura et al. (2013) & unpublished		Nomoto et al. (2013)	0	✓	✗
MWG-05	–	Ventura et al. (2013) & unpublished		Limongi & Chieffi (2018)[b]	300	✗	✗
MWG-06	–	Ventura et al. (2013) & unpublished		Limongi & Chieffi (2018)[b]	150	✗	✗
MWG-07	–	Ventura et al. (2013) & unpublished		Limongi & Chieffi (2018)[b]	0	✗	✗
MWG-08	SMG-08	Karakas (2010)	Doherty et al. (2014a,b)	Limongi & Chieffi (2018)[b]	300	✗	✗
MWG-09	SMG-09	Karakas (2010)	Doherty et al. (2014a,b)	Limongi & Chieffi (2018)[b]	150	✗	✗
MWG-10	–	Karakas (2010)	Doherty et al. (2014a,b)	Limongi & Chieffi (2018)[b]	0	✗	✗
MWG-11	SMG-11	Ventura et al. (2013) & unpublished		Limongi & Chieffi (2018)[c]	var[d]	✗	✓
MWG-12	SMG-12	Karakas (2010)	Doherty et al. (2014a,b)	Limongi & Chieffi (2018)[c]	var[d]	✗	✓

Updated GCE models with stellar rotators

Galactic chemical evolution (*Romano et al., 2019*) UPDATED

taking into account different intial rotational velocities (*Limongi and Chieffi 2018*)



NEW $M_{ejected} = 5 \times 10^{-8}\ M_{\odot}$

NOW THE GCE MODEL BETTER REPRODUCE THE TREND WE FOUND

Colzi, L. et al. (2018b), MNRAS, 478, 3693

Updated GCE models with stellar rotators

Galactic chemical evolution (*Romano et al., 2019*) UPDATED

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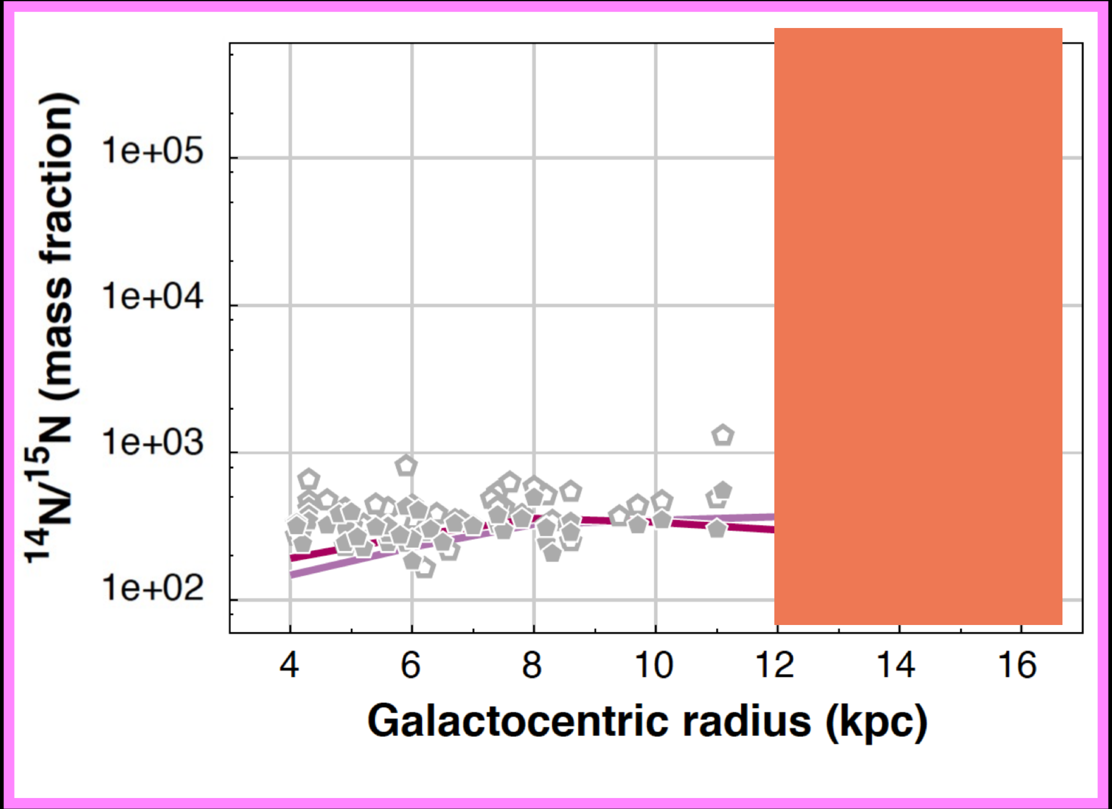


We still miss the Outer Galaxy!!

NOW THE GCE MODEL BETTER REPRODUCE THE TREND WE FOUND

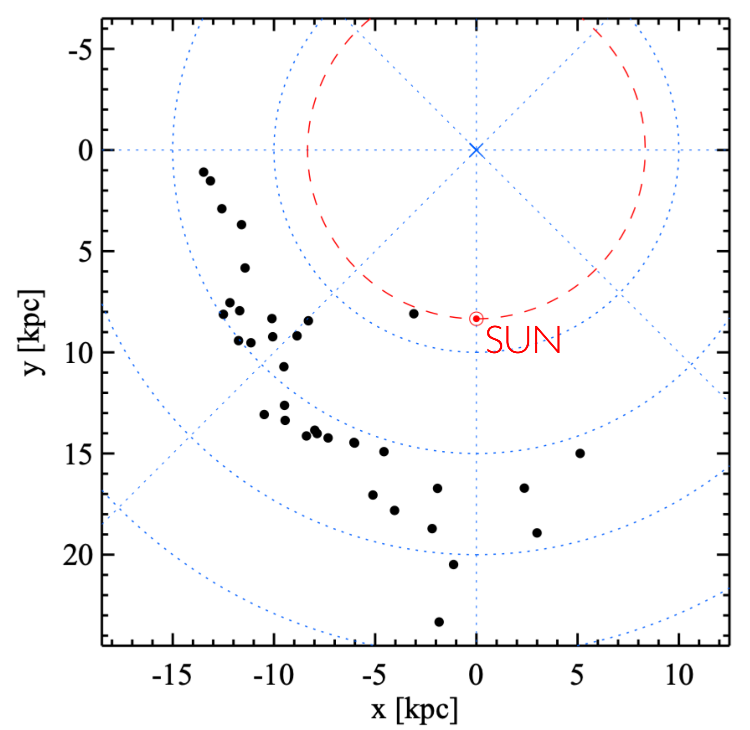
Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018b, MNRAS, 478, 3693

Nitrogen isotopic ratios $^{14}N/^{15}N$

IRAM 30m telescope
(Sierra Nevada, Spain)

101 massive star-forming regions:

87 (Colzi et al. 2018a,b) + 14 (Colzi et al. 2022b)



Outer Galaxy (CHEMOUT) sample

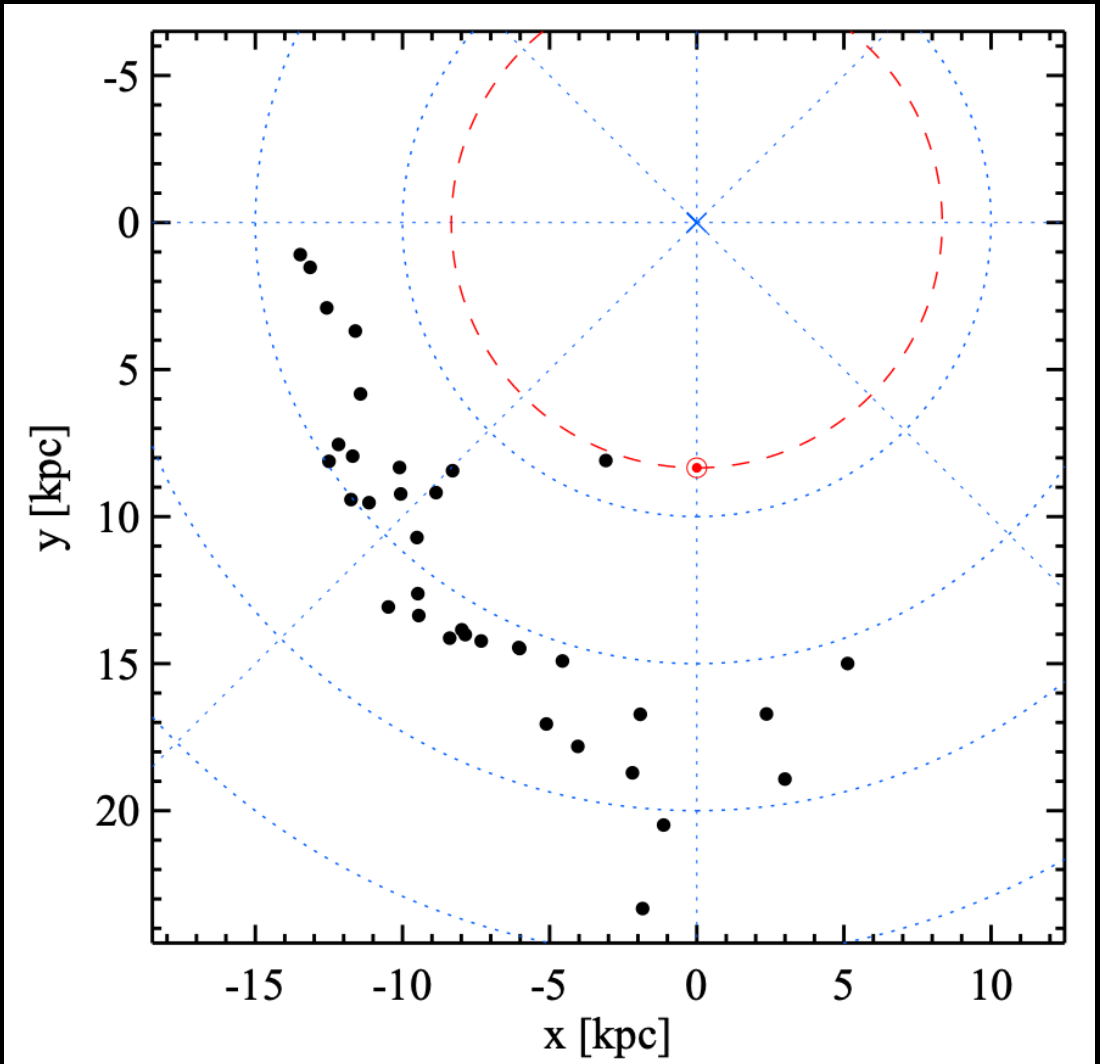
(Fontani, F., Colzi, L. et al. (2022), A&A, 660, A76)

35 massive star-forming regions

D_{GC} from 12 up to 23.5 kpc

CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy



PI: Francesco Fontani

35 sources selected from Blair et al. (2008):

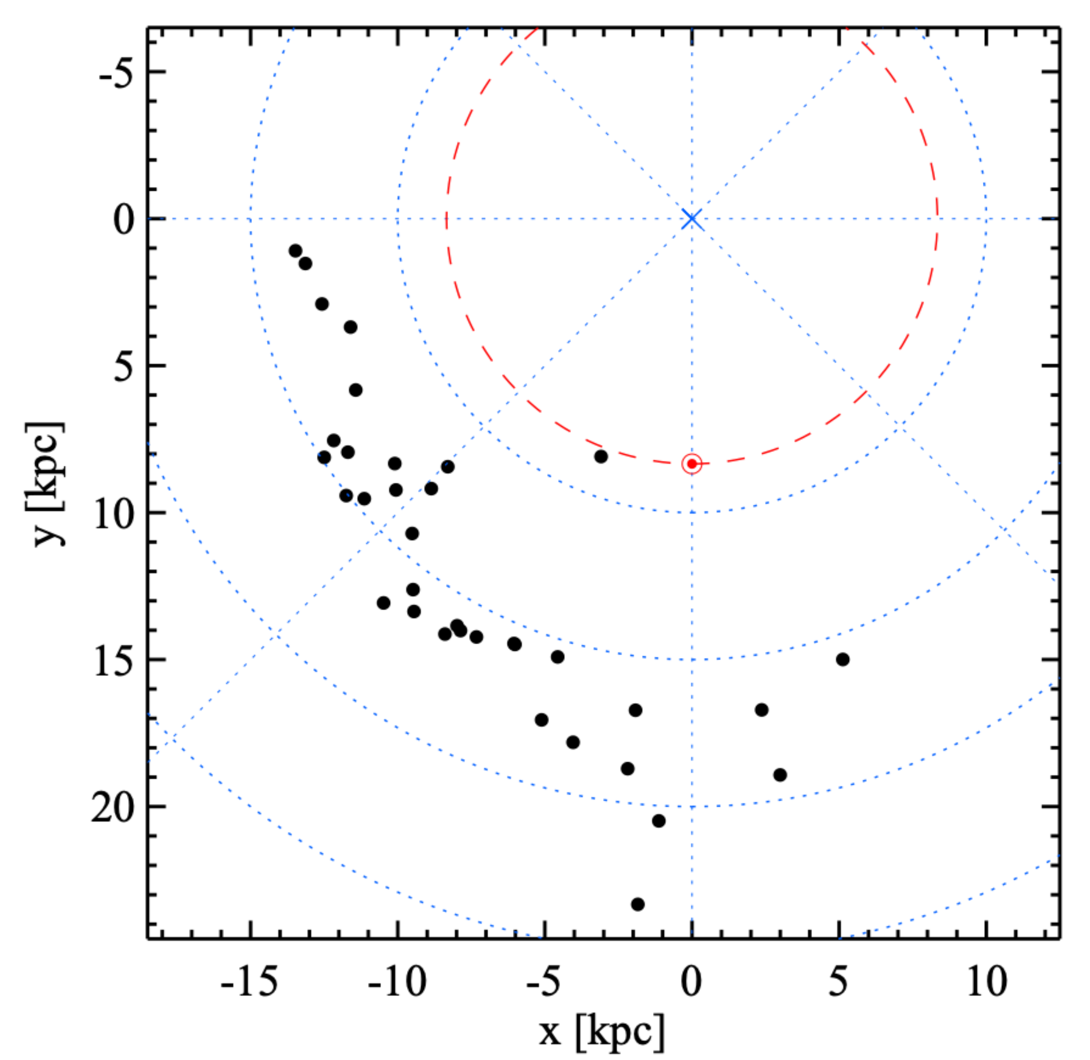
(i) clearly detected in H_2CO

(ii) To span all the distances in the Outer Galaxy

CHEMOUT I:Fontani, F., Colzi, L. et al. (2022a), A&A, 660, A76

CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy



Spectral windows (GHz)	HPBW (″)	V_{res} [(a)] (km s^{-1})	η_{MB} [(b)]
85.310–87.130	28	~0.16	0.85
88.590–90.410	27	~0.16	0.84
151.750–153.570	15	~0.096	0.77
148.470–150.290	15	~0.096	0.77

CHEMOUT I: Fontani, F., Colzi, L. et al. (2022a), A&A, 660, A76

CHEMOUT

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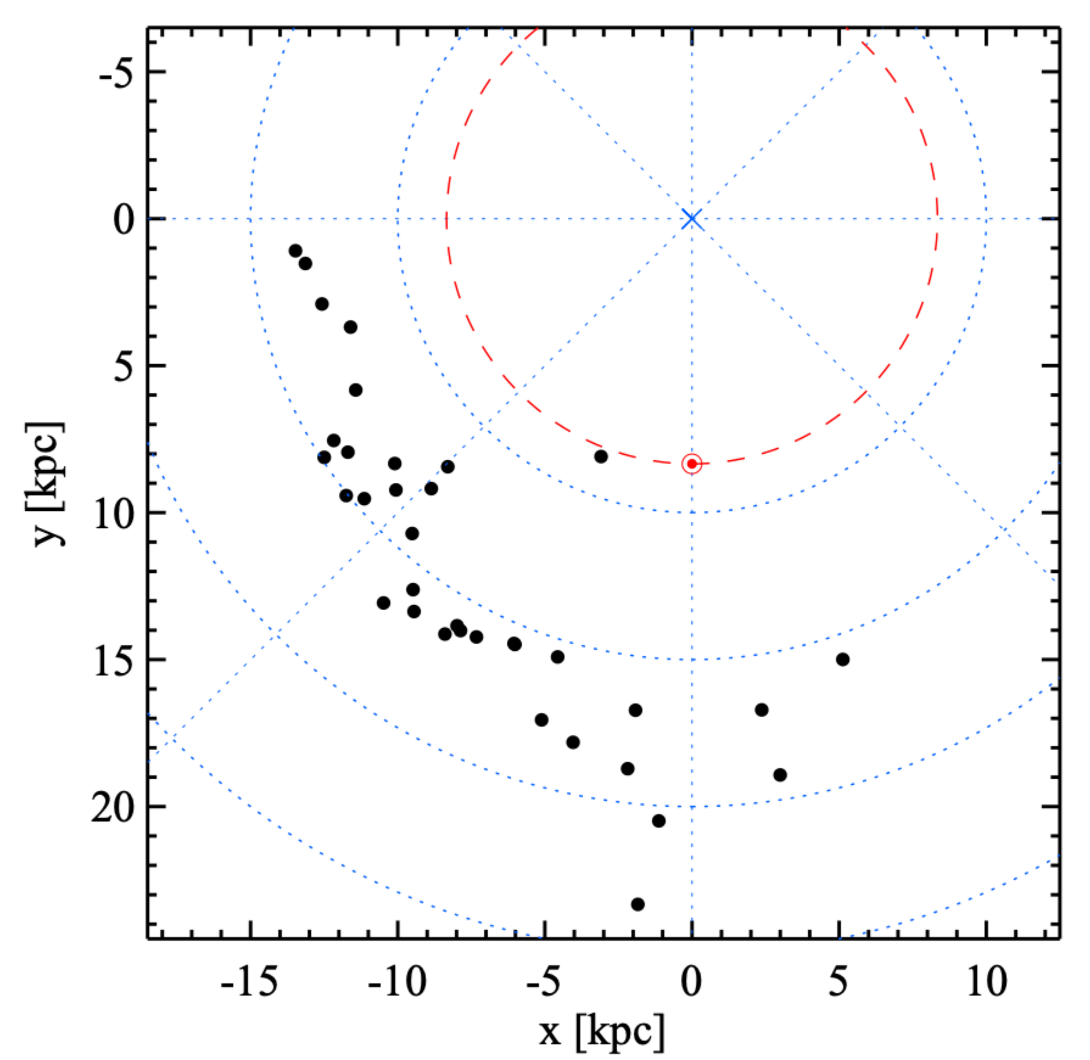

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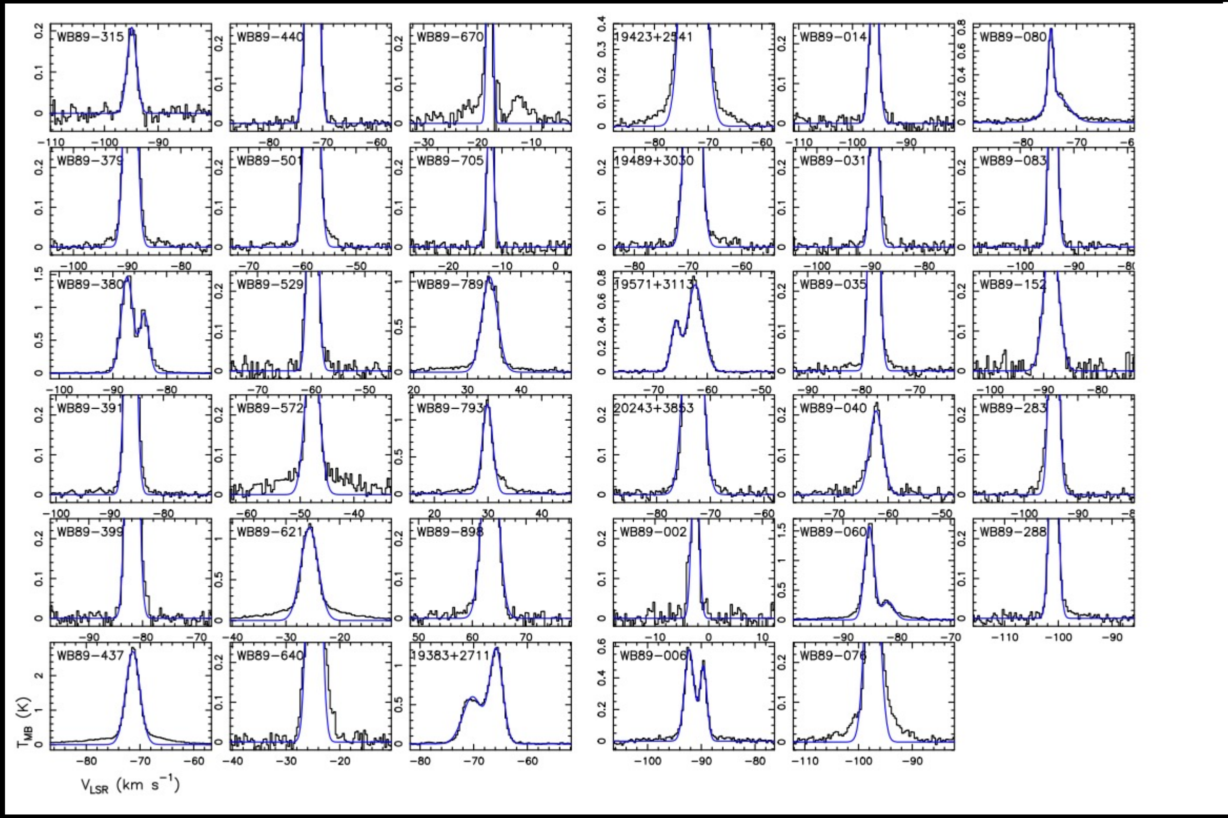
Species	Det. rate
HCN	100%
HCO^+	100%
c-C_3H_2	97%
$H^{13}CO^+$	77%
HCO	71%
SO	66%
SiO	46%
HCS^+	40%
C_4H	26%
NH_2D	23%
CH_3CCH	17%
CCS	11%

CHEMOUT I:Fontani, F., Colzi, L. et al. (2022a), A&A, 660, A76

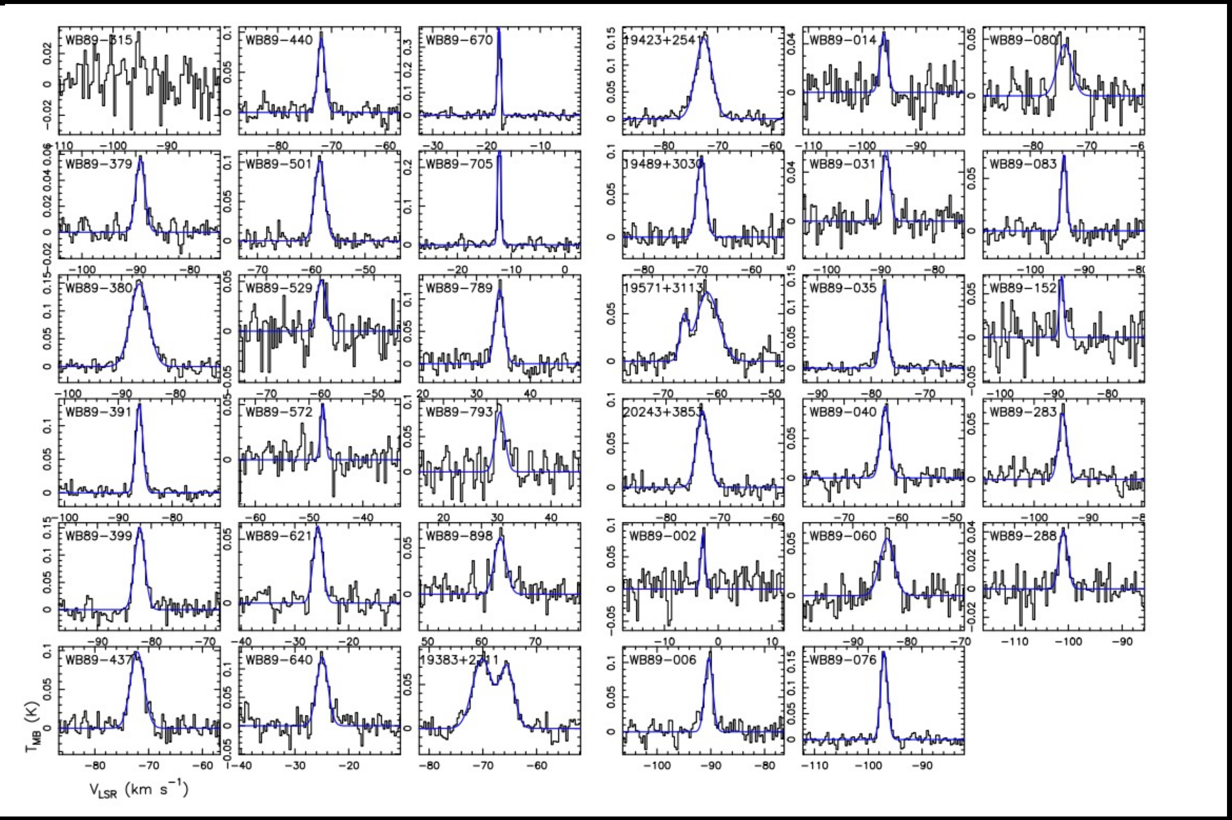
CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy

HCO^+



$c\text{-}C_3H_2$



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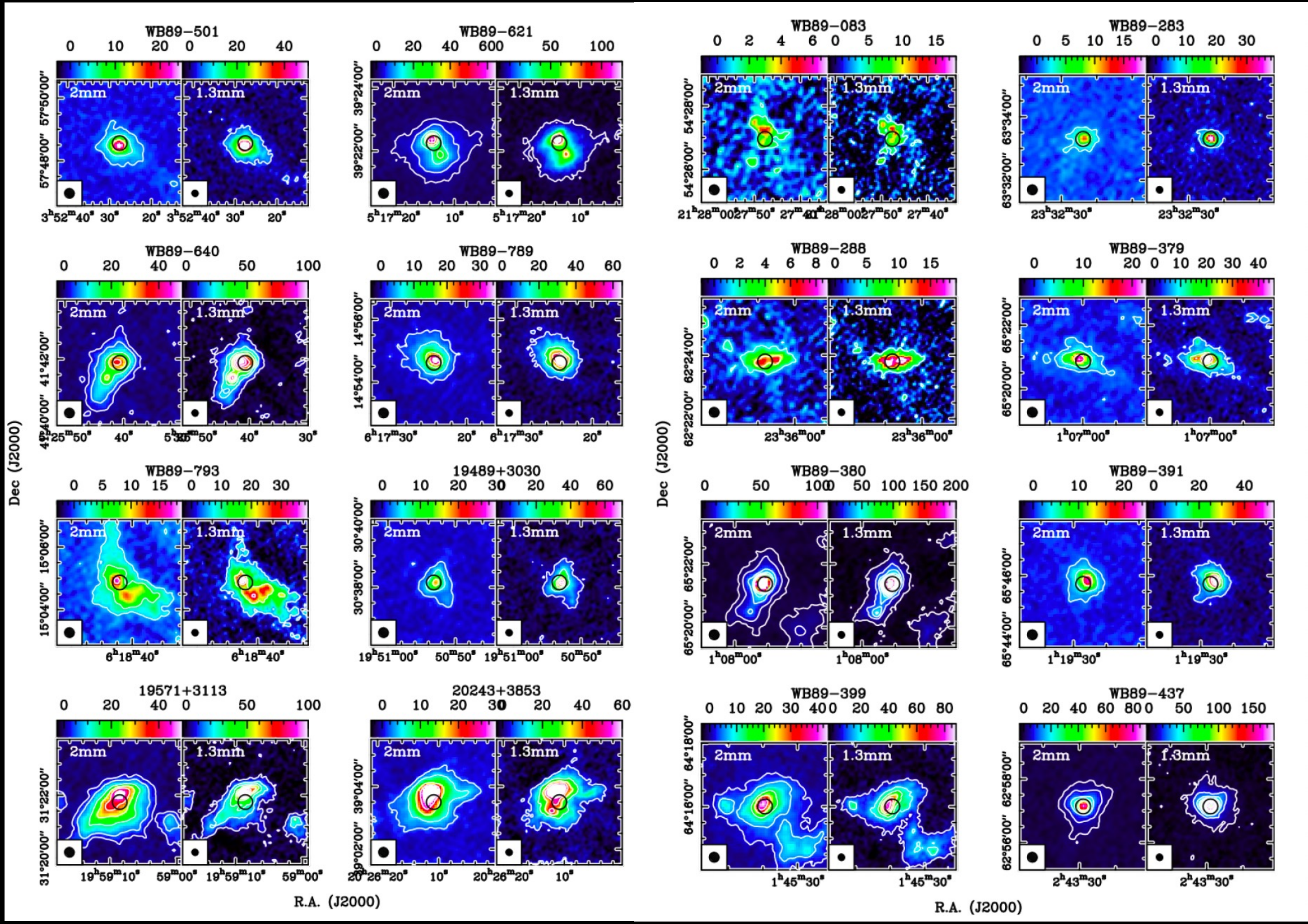


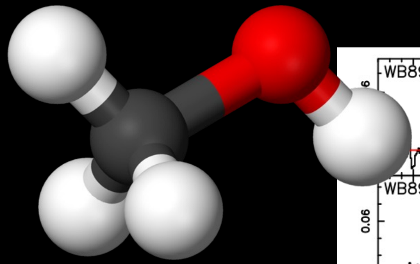
NIKA continuum maps at 1.3 and 2 mm to derive the H_2 column densities

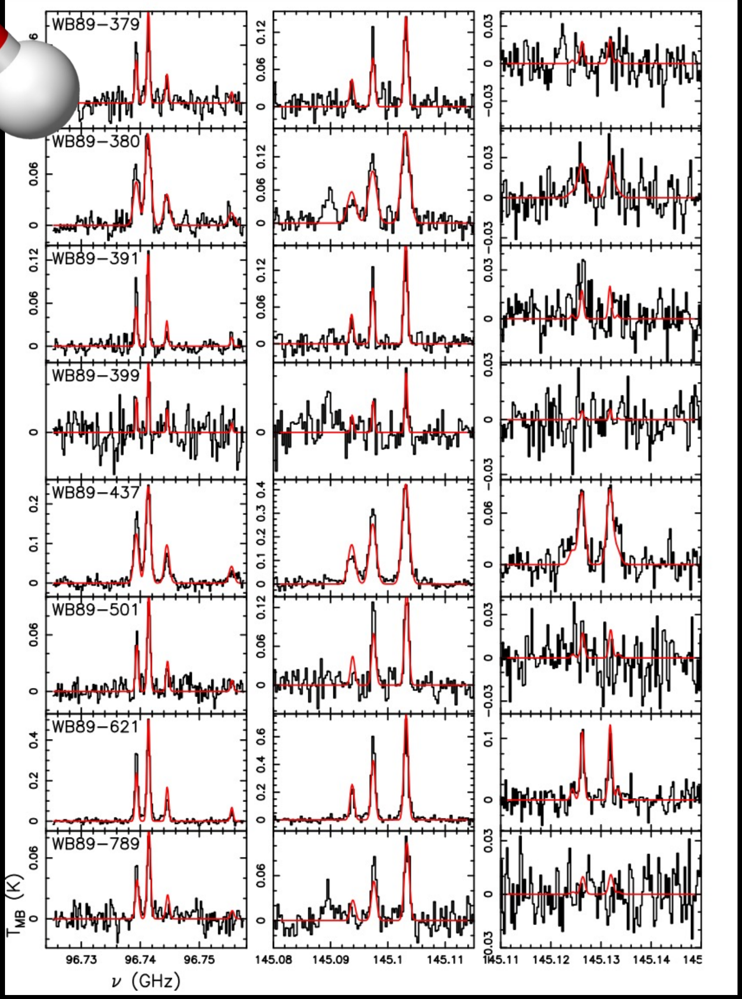
Fontani et al. (in prep)

CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy

CH3OH studied towards15 sources - Setup: 90.400–98.180 GHz and 140.720–148.500 GHz





- ➢ The emission is dominated by a cold and quiescent gaseous envelope
- ➢ CH_3OH correlates with H_2CO (linewidths and abundances)

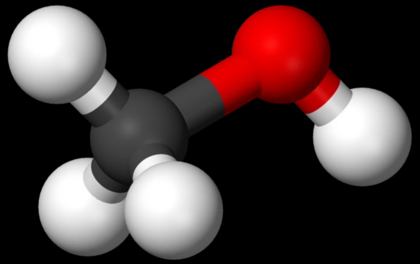
CHEMOUT II:Fontani, F., et al. (2022b), A&A, 664, A154

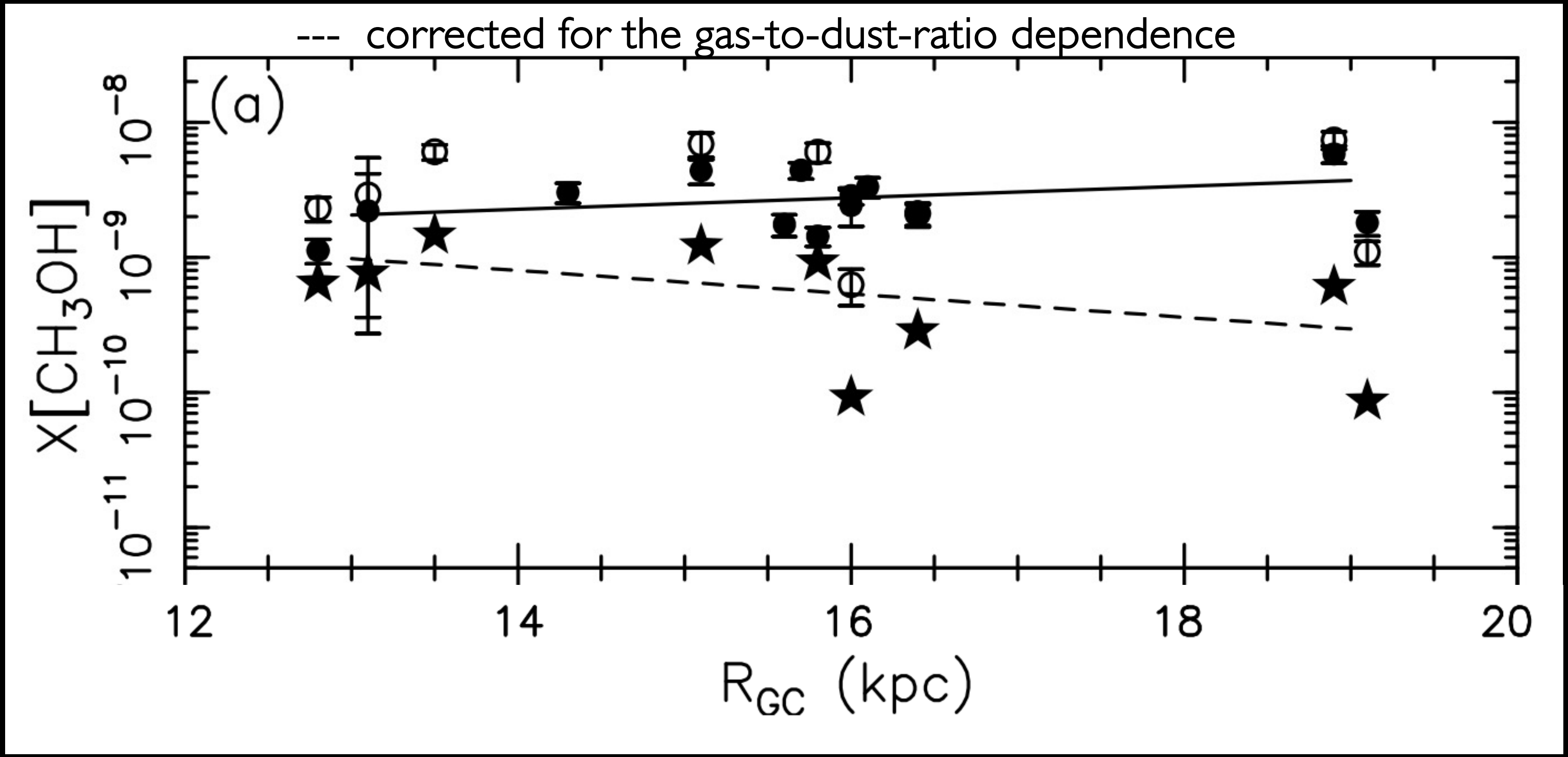
Laura Colzi

CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy

CH3OH studied towards15 sources - Setup: 90.400–98.180 GHz and 140.720–148.500 GHz



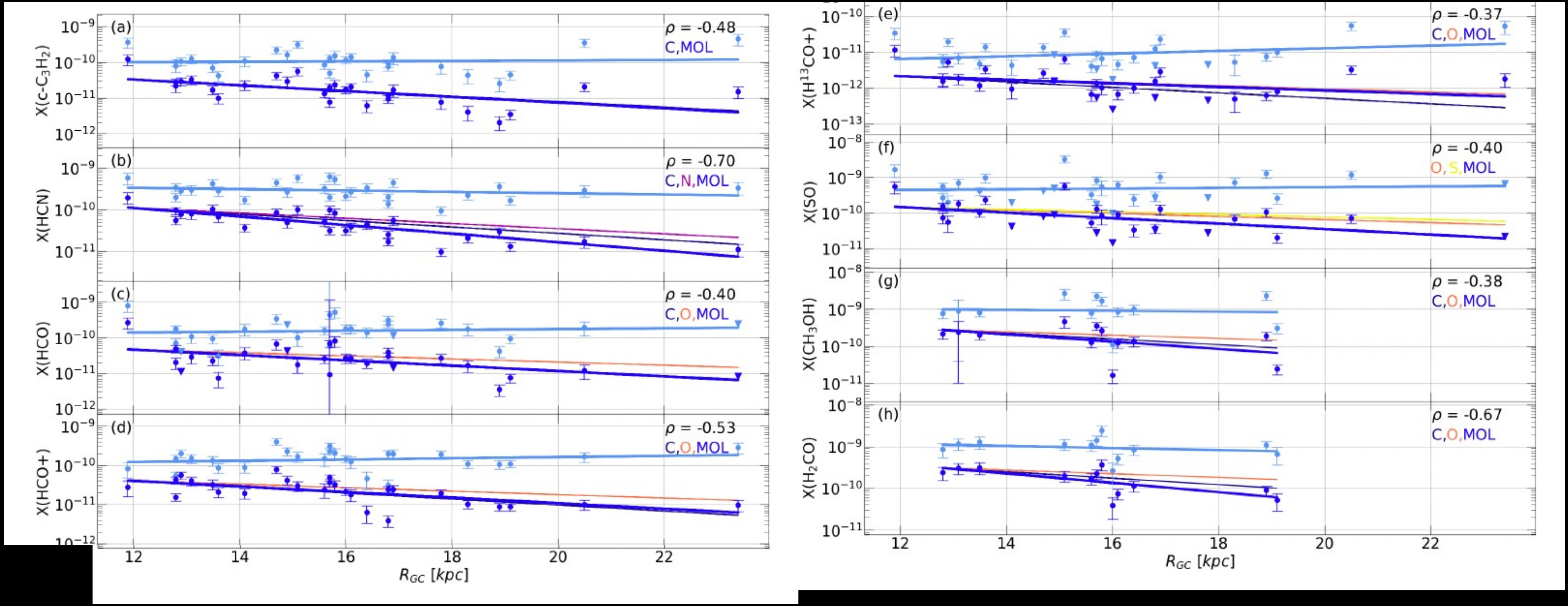


- Abundances decrease ~ factor of 5 with R_{GC}
- This is in line with metallicity-scaled values of carbon [C/H] *Mendez-Delgado et al. (2022)*

CHEMOUT II:Fontani, F., et al. (2022b), A&A, 664, A154

CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy



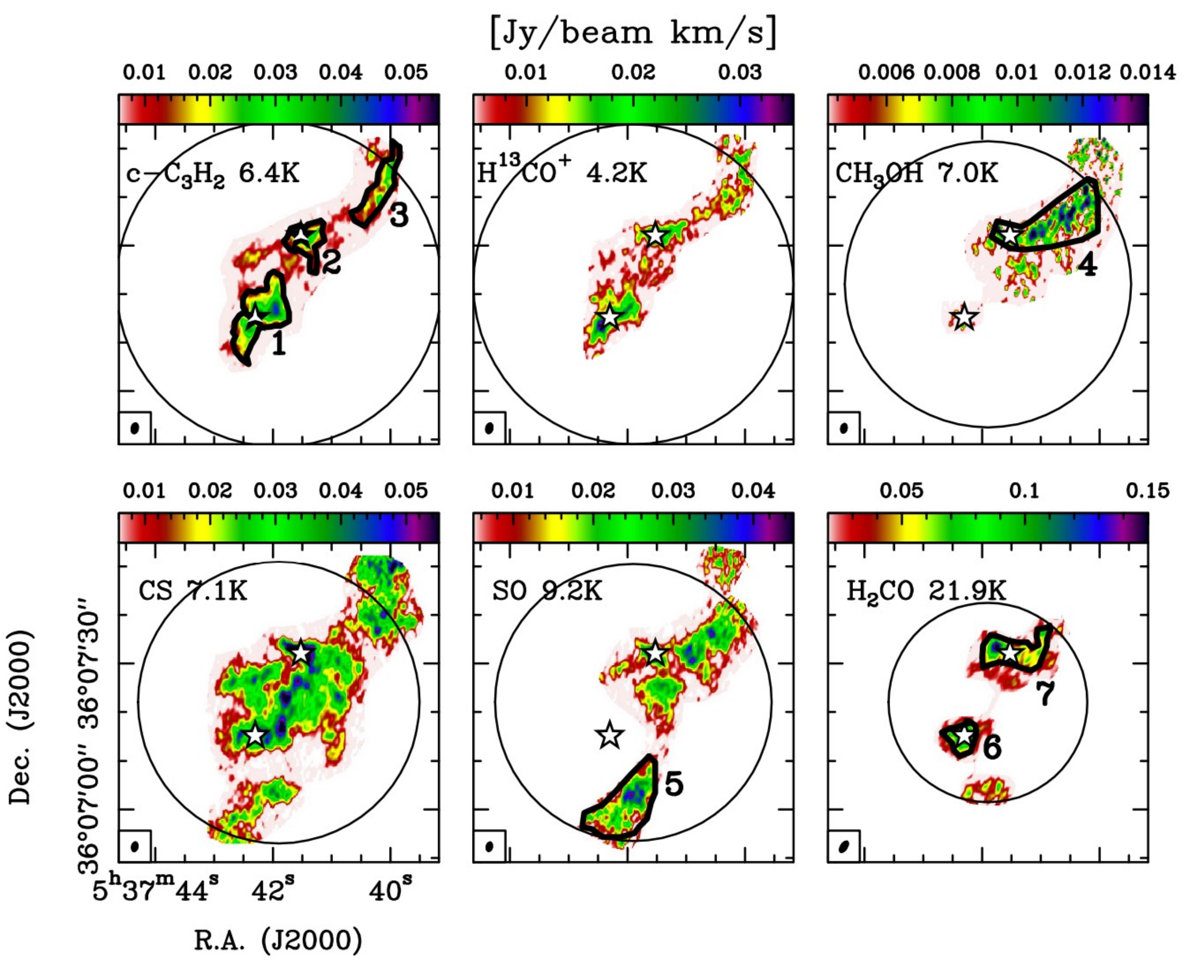
- Analysis of other molecules shows the same behaviour with [C/H] *Mendez-Delgado et al. (2022)*
- From c-C_3H_2, HCN, HCO, HCO^+, $H^{13}CO^+$, SO, CH_3OH, H_2CO

See Diego Gigli short presentation

Diego Gigli Master's thesis 2024

CHEMOUT

CHEMical complexity in star-forming regions of the OUTer Galaxy



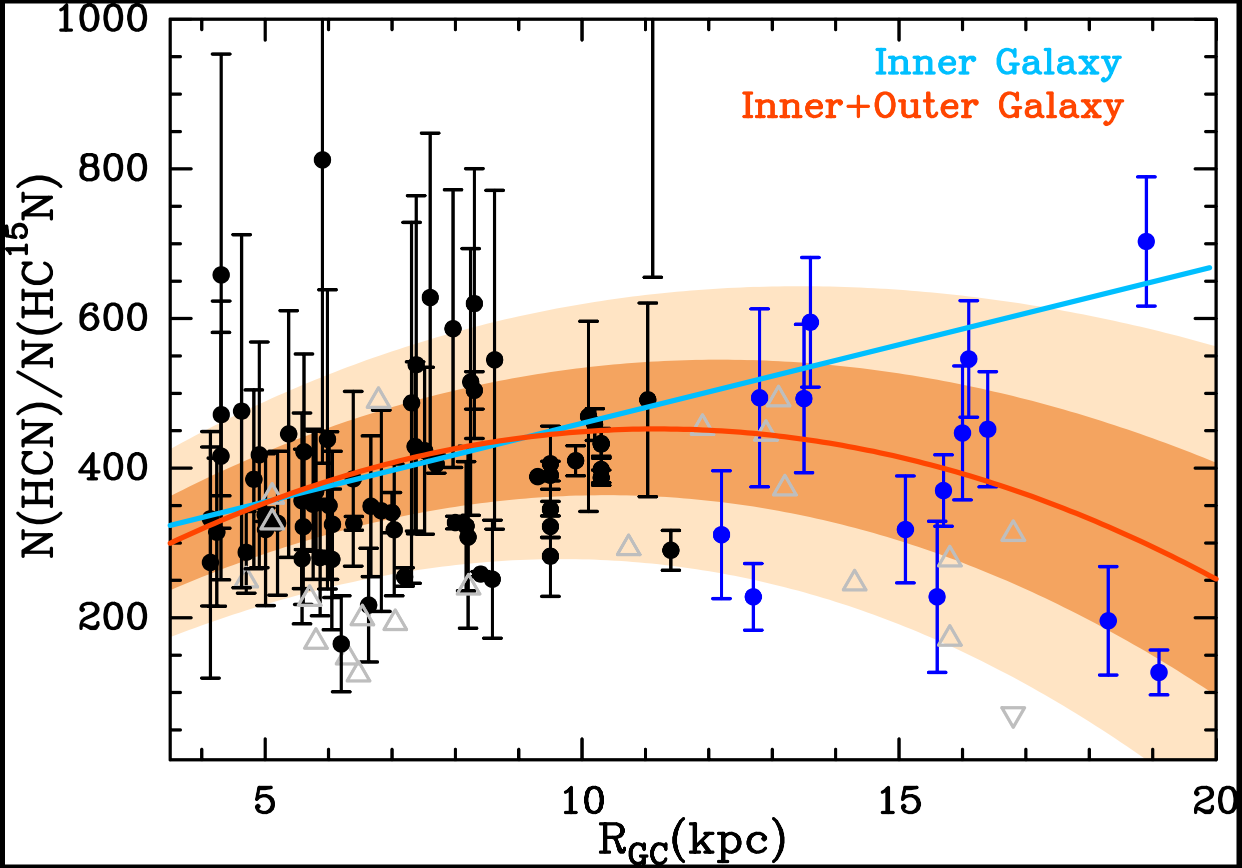
- Target WB89-670 at 23.5 kpc in the far Outer Galaxy with ALMA
- Resolution of 1.5'' → 0.11 pc

- Chemical differentation at core scales

See also Shimonishi et al. (2021) for ALMA maps towards WB89-789 at 19 kpc

CHEMOUT IV:Fontani, F., et al. (2024), accepted in A&A

Nitrogen isotopic ratios $^{14}N/^{15}N$

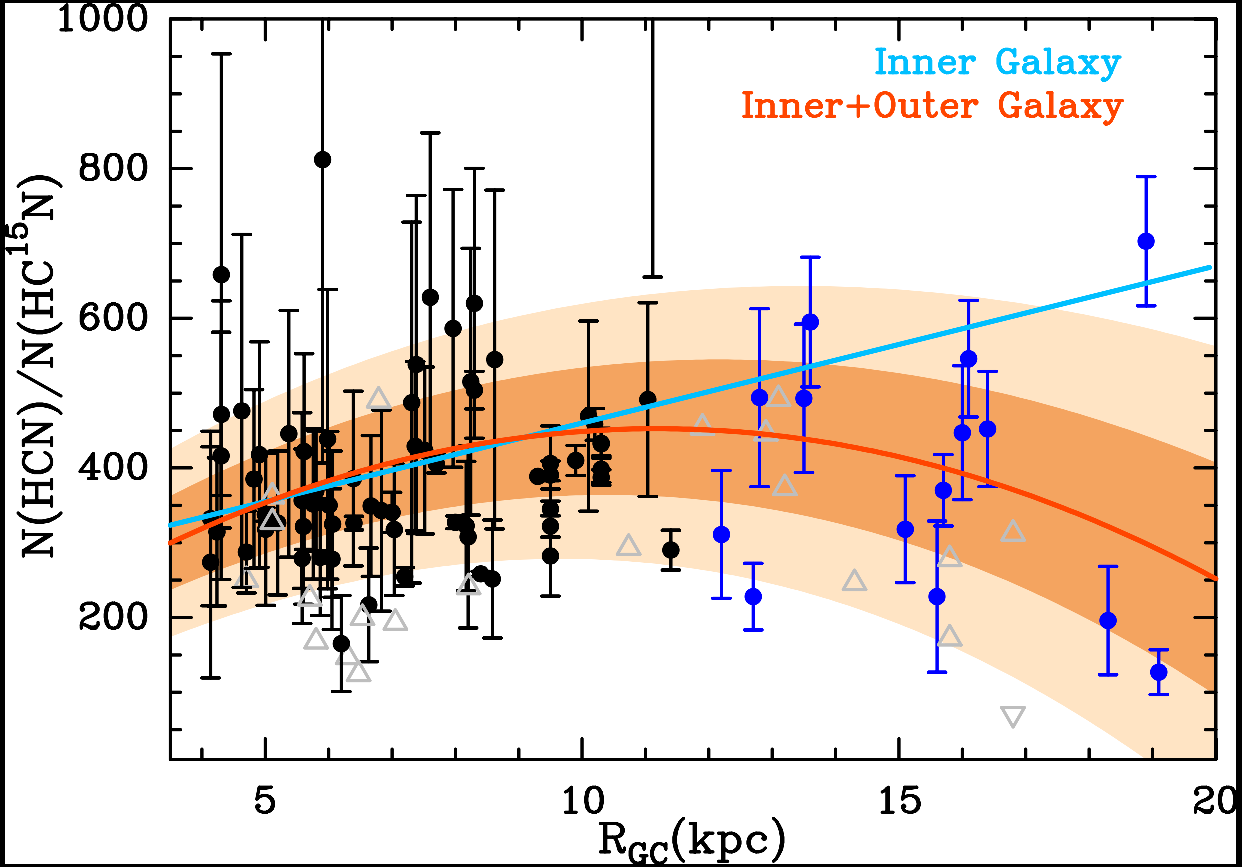


For 14 out of 35 sources we have detected $H^{13}CN$ and $HC^{15}N$

→ $^{14}N/^{15}N$ ratios

Colzi, L., et al. (2022b), A&A, 667, A151

Nitrogen isotopic ratios $^{14}N/^{15}N$



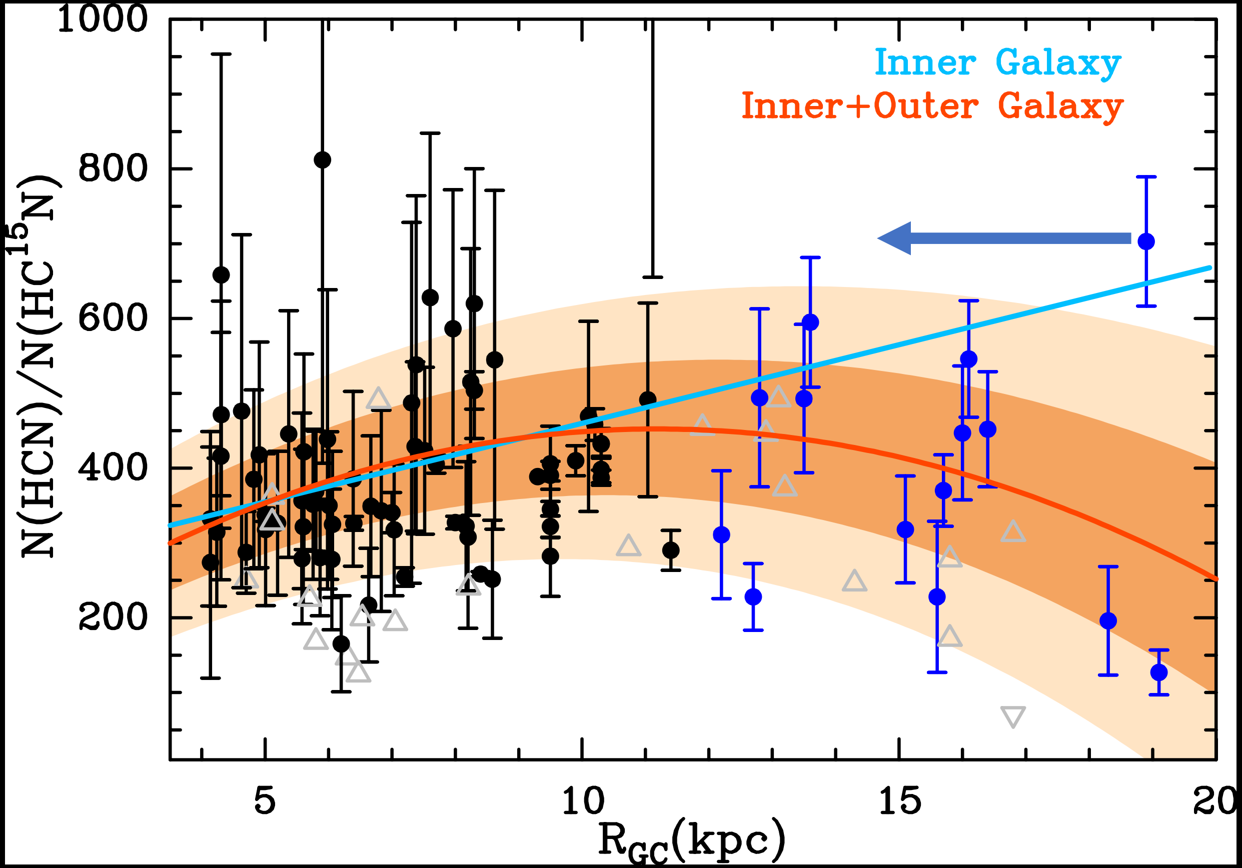
Outer Galaxy sources are below the extrapolated Inner Galaxy trend

They follow the parabolic trend:

$$HCN/HC^{15}N = -2.58\ \mathrm{kpc}^{-2} \times R_{GC}^2 + 57.82\ \mathrm{kpc}^{-1} \times R_{GC} + 128.94.$$

Colzi, L., et al. (2022b), A&A, 667, A151

Nitrogen isotopic ratios $^{14}N/^{15}N$



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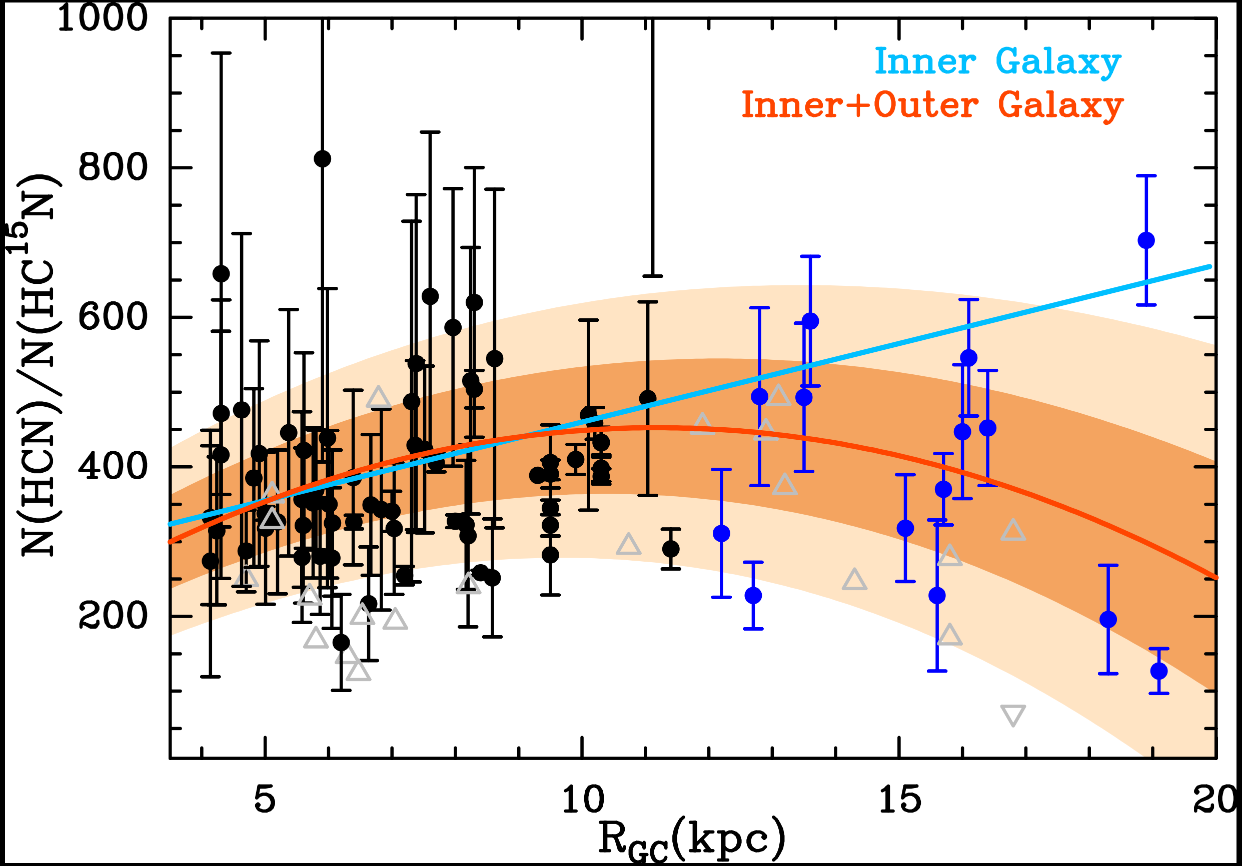

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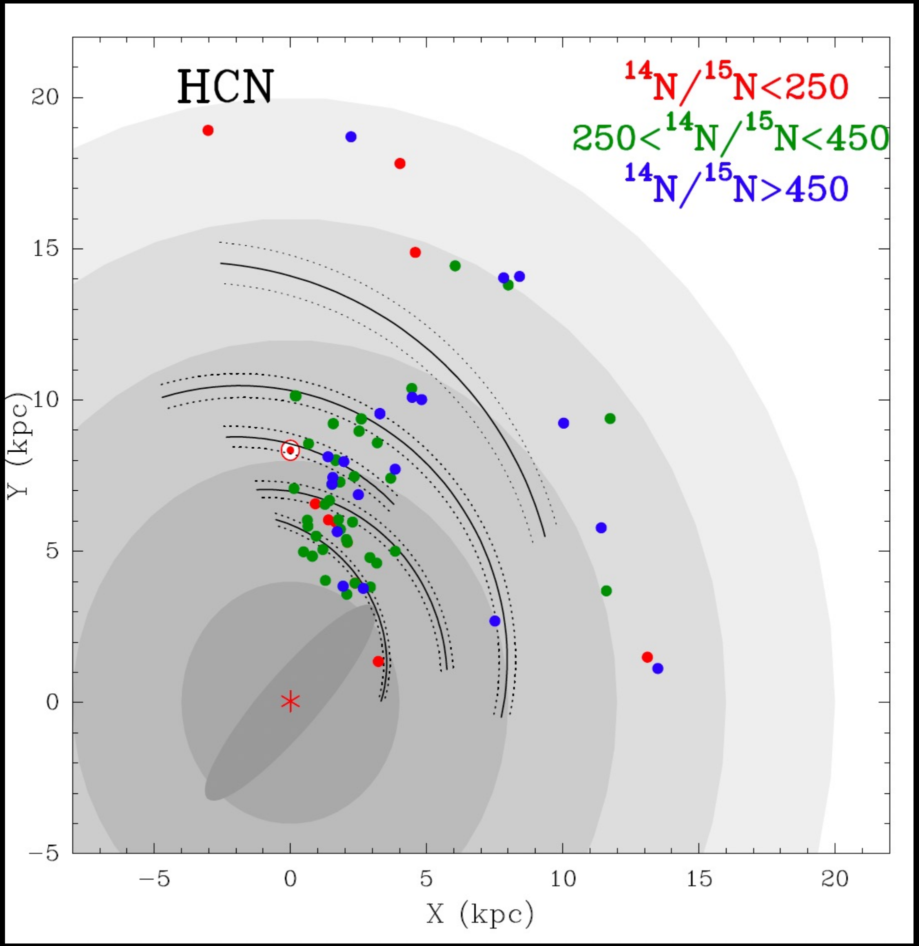


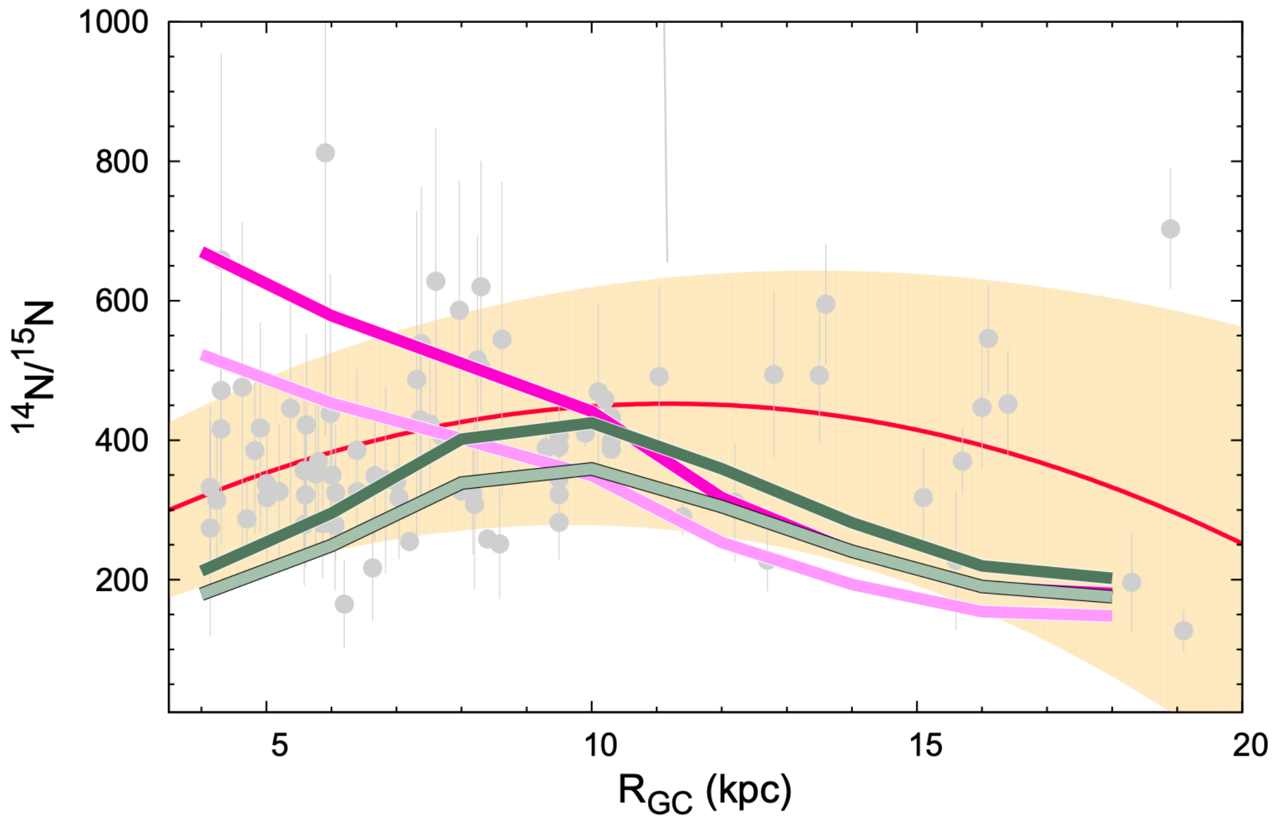
NO trend within Galactic spiral arms

Colzi, L., et al. (2022b), A&A, 667, A151

Nitrogen isotopic ratios $^{14}N/^{15}N$

Model	Mass range for WD^a progenitors ($M_\odot$)	M^{13C}_{ejec} ($M_\odot$)	M^{15N}_{ejec} ($M_\odot$)	Flag
1	1–8	5.40e−7	3.35e−8	dark green
2	1–8	6.40e−7	3.95e−8	light green
3	3–8	3.25e−7	1.91e−8	magenta
4	3–8	4.25e−7	2.40e−8	pink

Different models takes into account ranges of $\underline{M}_{ej}$ of ^{15}N, ^{13}C and different masses for White Dwarfs (WDs) progenitors of nova outbursts.



CHEMOUT III: Colzi, L., Romano, D., Fontani, F. et al. (2022b)

Nitrogen isotopic ratios $^{14}N/^{15}N$

Model	Mass range for WD^a progenitors ($M_\odot$)	M_{ejec}^{13C} ($M_\odot$)	M_{ejec}^{15N} ($M_\odot$)	Flag
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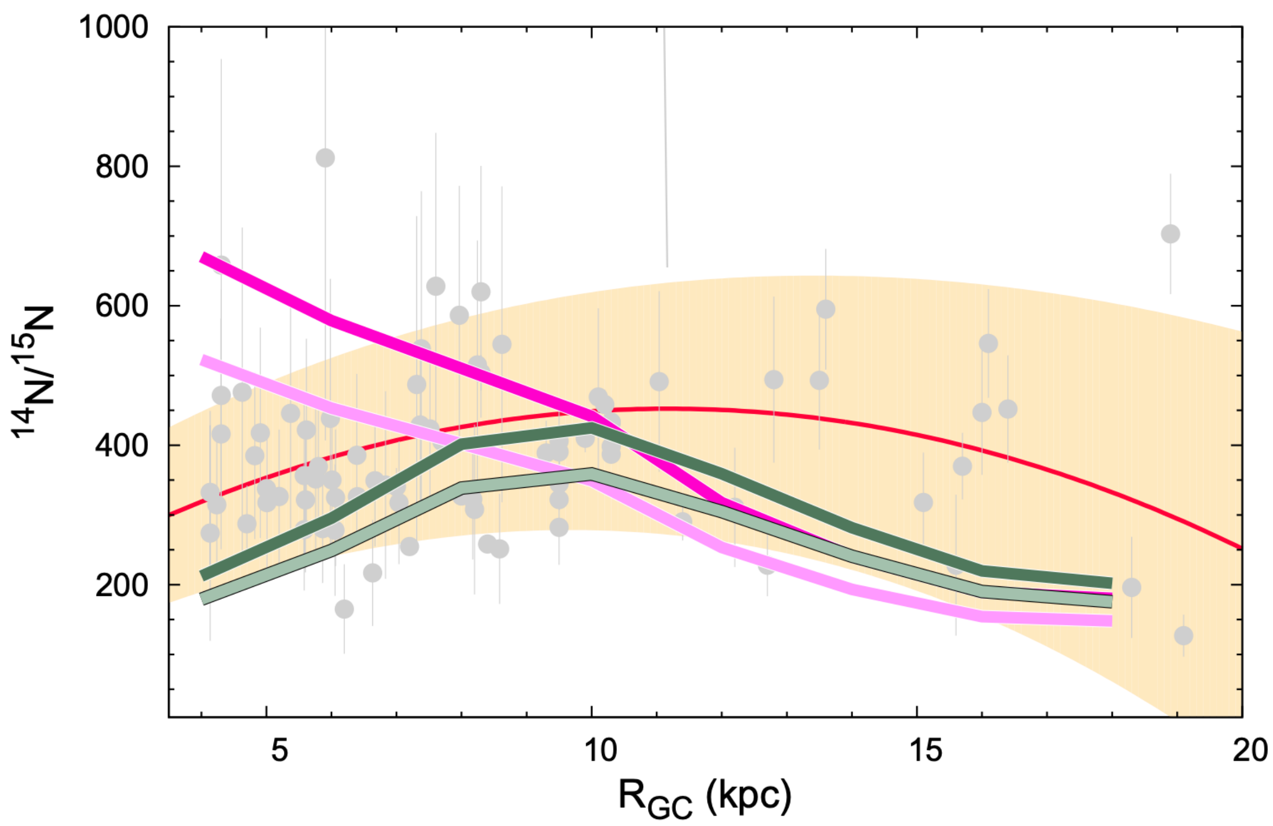


CHEMOUT III: Colzi, L., Romano, D., Fontani, F. et al. (2022b)

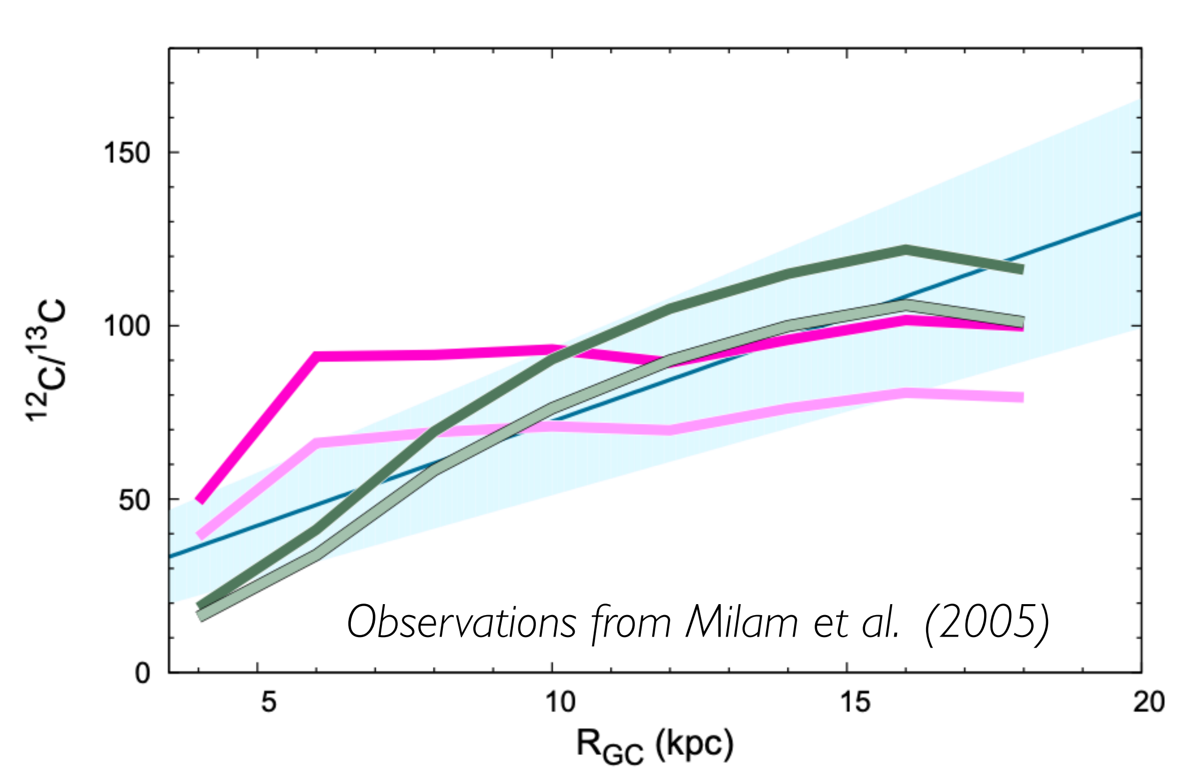
Different models takes into account ranges of M_{ej} of ^{15}N, ^{13}C and different masses for White Dwarfs (WDs) progenitors of nova outbursts.

Overall trend from novae with a low-mass WDs as main ^{15}N producers;

Decreasing trend in the OG for strong metal dependence of the ^{14}N yields.

Colzi, L., et al. (2022b), A&A, 667, A151

Carbon isotopic ratios $^{12}C/^{13}C$

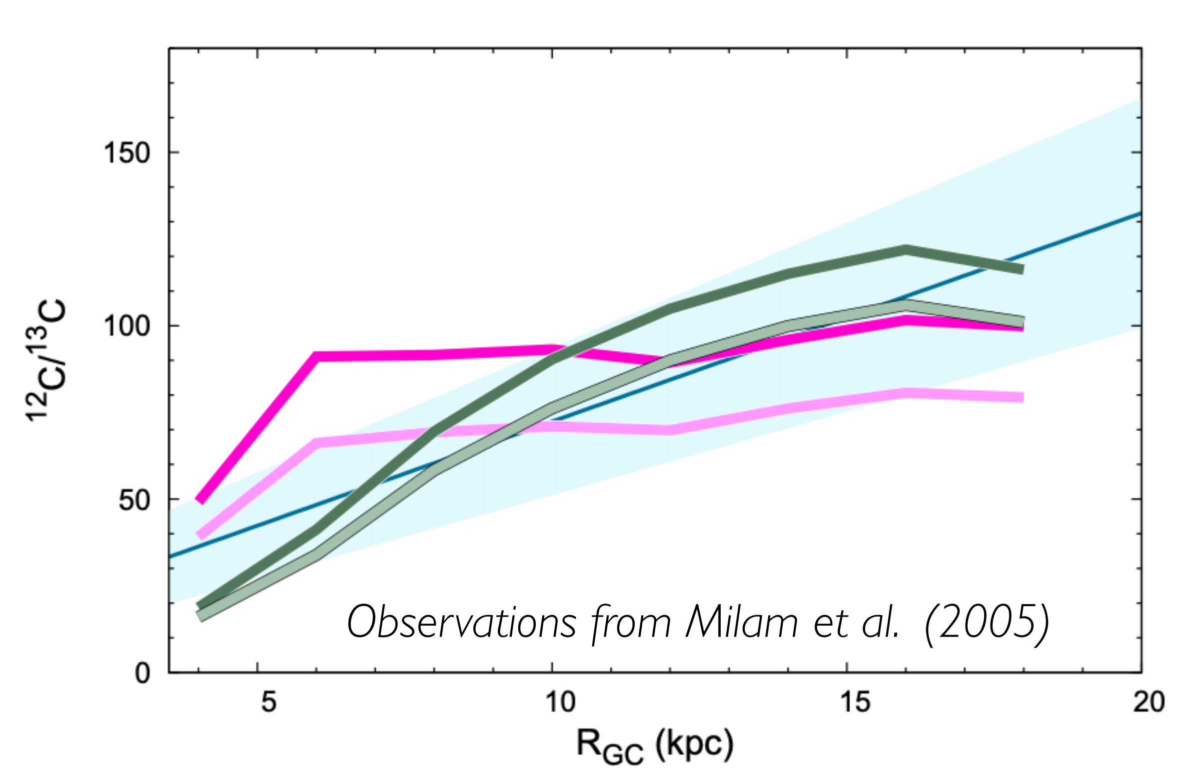


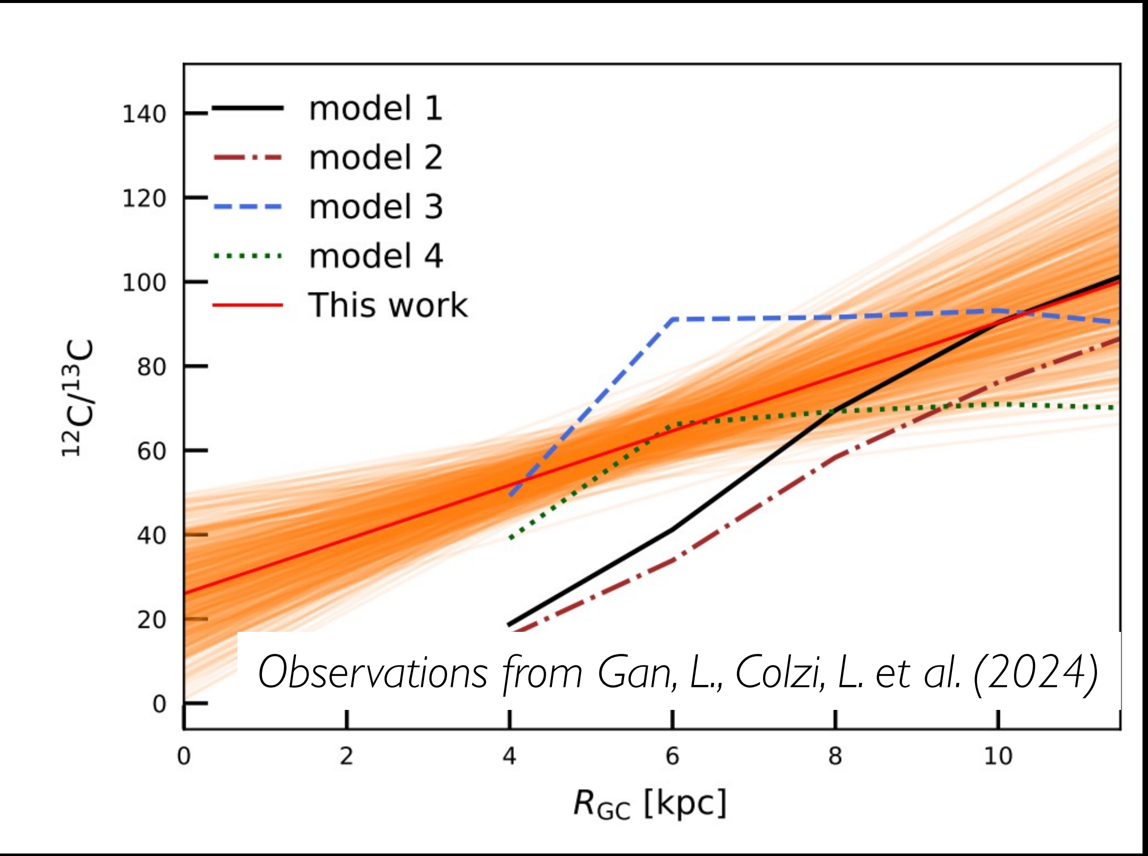
^{12}C → <u>Primary production</u> in all stars.

^{13}C → <u>Primary production</u> from massive fast rotators at low metallicities, <u>Secondary production</u> at high metallicity in all stars

In both cases **nova contribution only on long timescales.**

Carbon isotopic ratios $^{12}C/^{13}C$





^{12}C → Primary production in all stars.

^{13}C → Primary production from massive fast rotators at low metallicities,

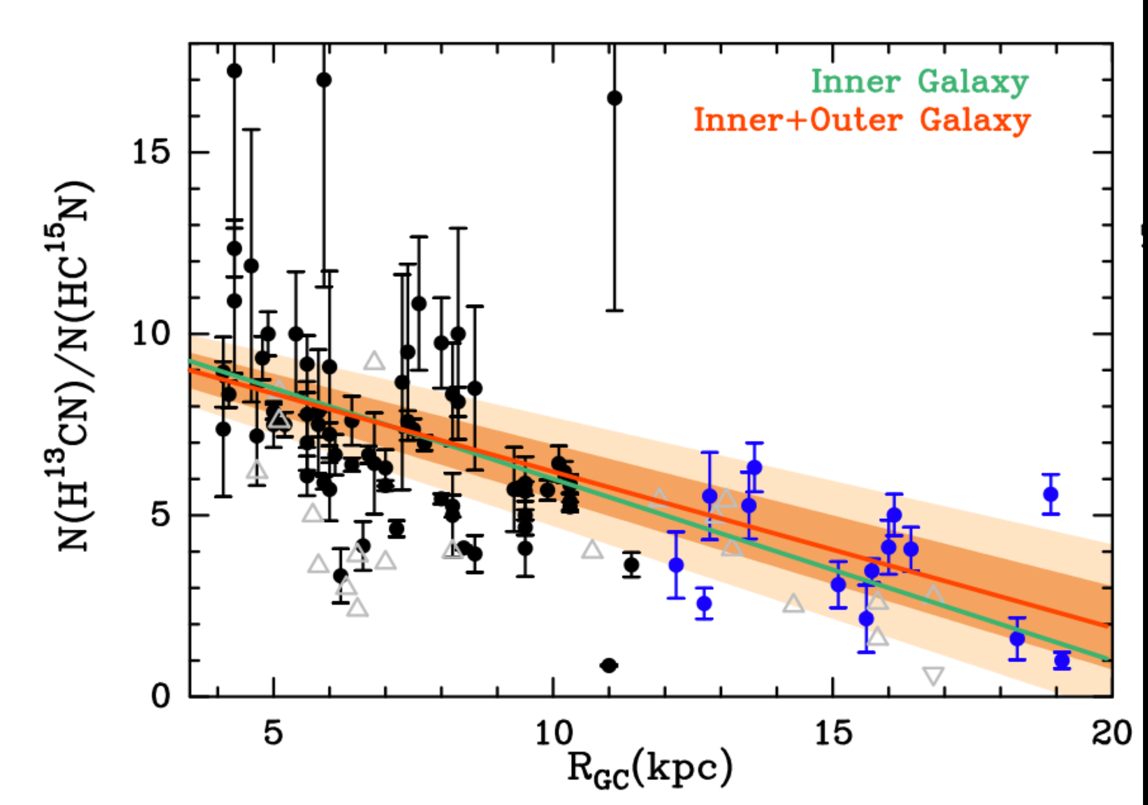
Secondary production at high metallicity in all stars

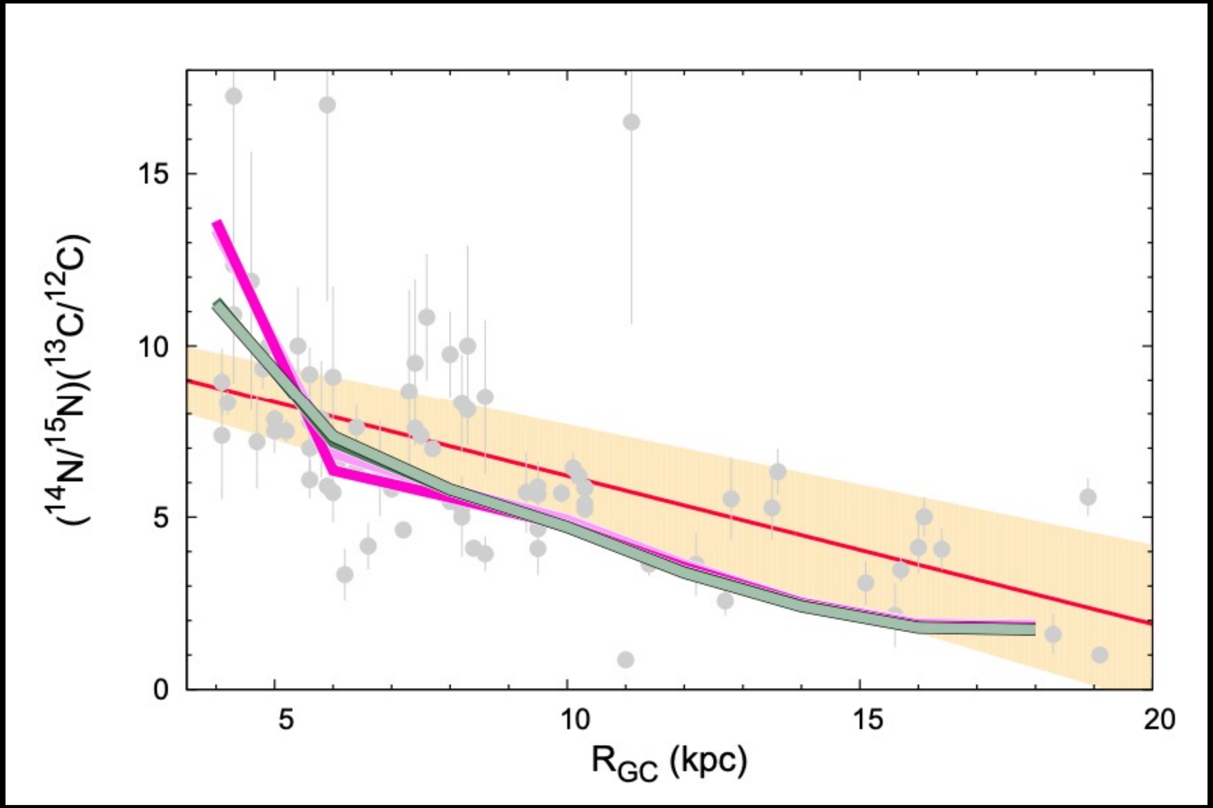
In both cases **nova contribution only on long timescales.**

Colzi, L., et al. (2022b), A&A, 667, A151

Nitrogen isotopic ratios $^{14}N/^{15}N$

$^{14}N/^{15}N \times ^{13}C/^{12}C$ ratio

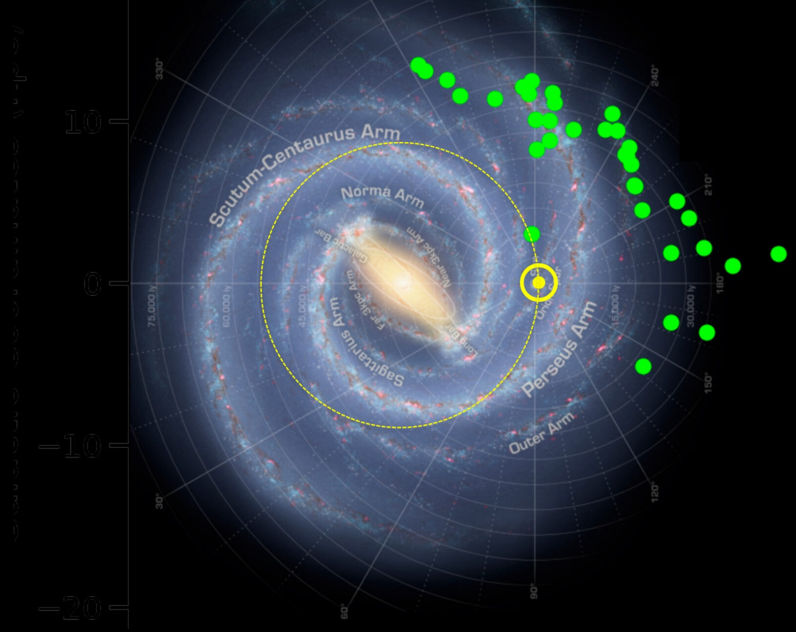


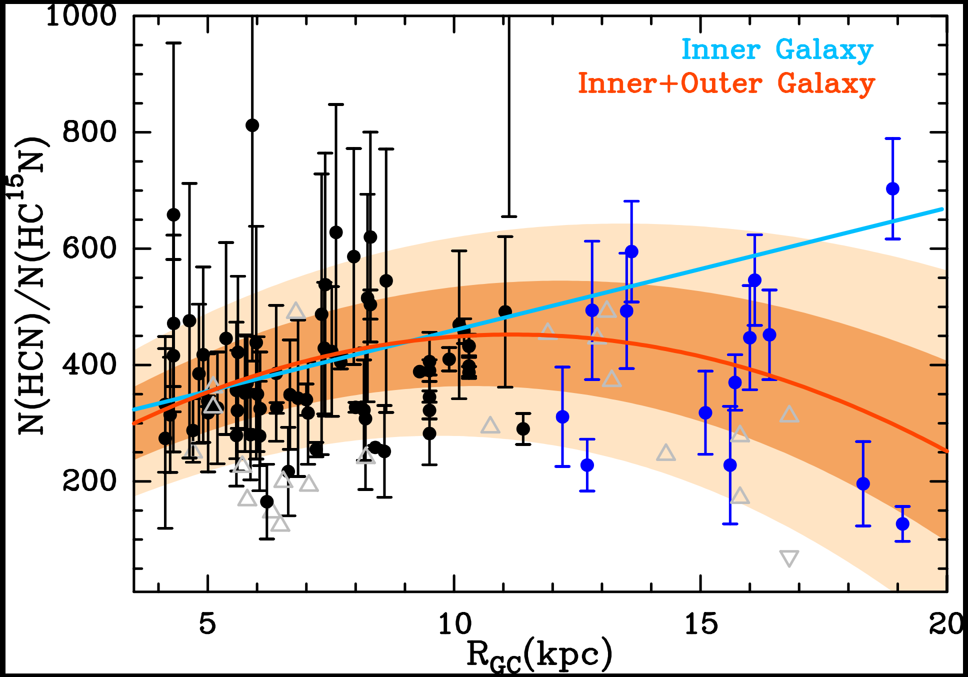


Colzi, L., et al. (2022b), A&A, 667, A151

CONCLUSIONS

Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)/ L. Magrini / F. Fontani (INAF)





- ➢ Isotopic ratios in the Outer Galaxy are key to constrain Galactic Chemical Evolution models
- ➢ Chemical processes in molecular clouds are also needed to be considered

→ CHEMOUT project

Fontani et al. (2022a,b,2024), Colzi et al. (2022b)

Molecules and planets in the Outer Galaxy

Florence 12-14 November 2024

Isotopic abundance ratios

What's up in the outer edge of the Milky Way?

Laura Colzi

(Centro de Astrobiología, CSIC-INTA)

November 12th 2024

Francesco Fontani, Donatella Romano, and many others…

CENTRO DE ASTROBIOLOGÍA · CAB

ASOCIADO AL NASA ASTROBIOLOGY PROGRAM

CSIC INTA

Grants PID2019-105552RB-C41and PID2022-136814NB-I00 funded by:

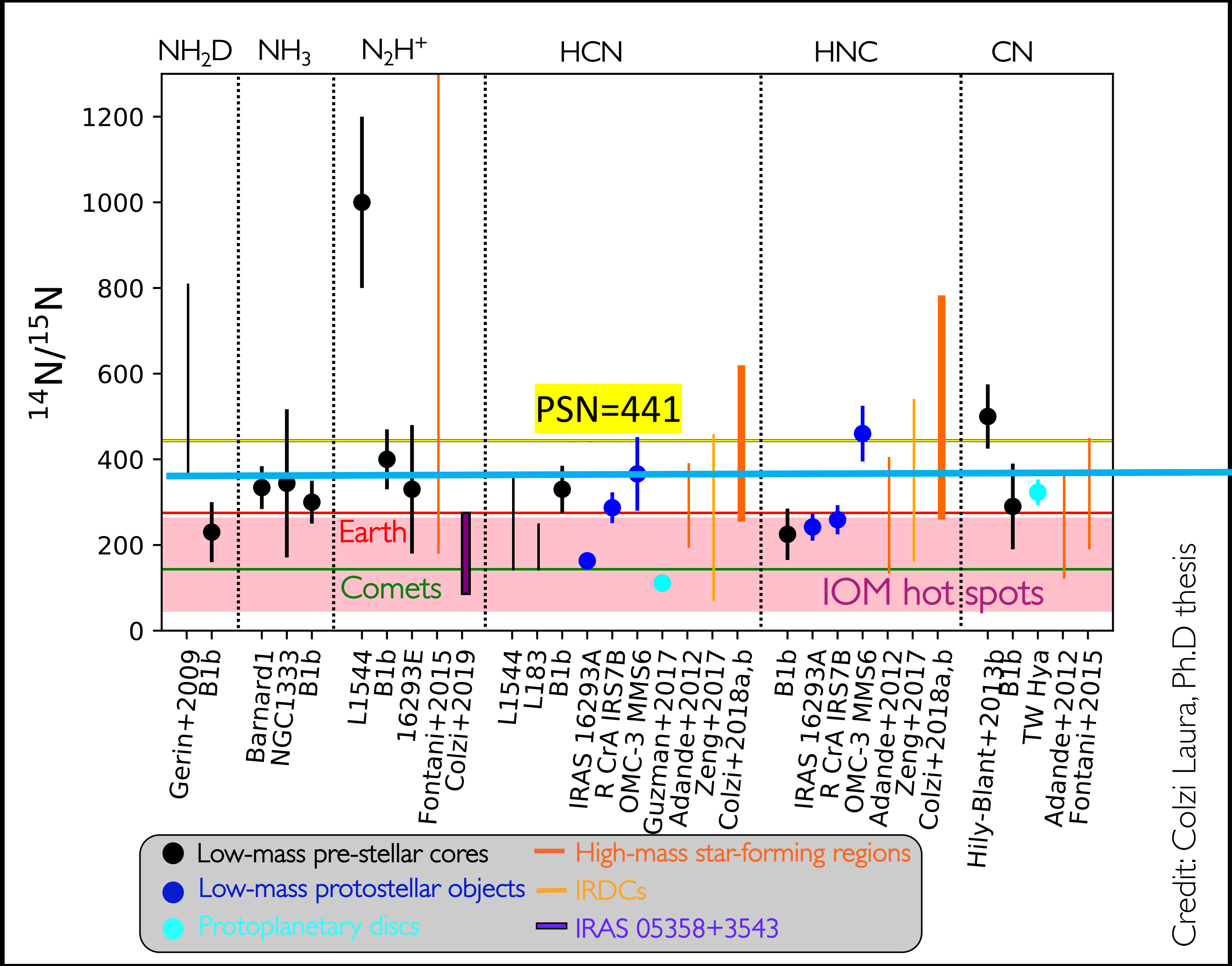
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

BACK UP SLIDES

Nitrogen isotopic ratios $^{14}N/^{15}N$



NEW LOCAL ISM
$^{14}N/^{15}N$ (8.4 kpc)
375±50

Consistent with the bulk of observed values with respect to the PSN one

Stellar nucleosynthesis?

Reference: Colzi, L., et al. 2018b, MNRAS, 478, 3693

GALACTIC CHEMICAL EVOLUTION MODELS

Multi-zone model, where the **Galactic disc** is divided in **concentric rings** that evolve at **different rates**

- **INITIAL CONDITION: -** mass of gas at t=0 or fresh gas that accrete;
  - primordial chemical composition;
- **STELLAR BIRTHRATE:** function with a given star-formation efficiency.

→ **STELLAR EVOLUTION AND NUCLEOSYNTHESIS OF ELEMENTS**

Model	LIMS	Super-AGB stars	Massive stars	Novae
1	Karakas (2010)	–	Nomoto et al. (2013)	No
2	Karakas (2010)	Doherty et al. (2014a,b)	Nomoto et al. (2013)	No
3	Karakas (2010)	–	Meynet & Maeder (2002b), Hirschi et al. (2005), Hirschi (2007), Ekström et al. (2008)	No
4	Karakas (2010)	Doherty et al. (2014a,b)	Meynet & Maeder (2002b), Hirschi et al. (2005), Hirschi (2007), Ekström et al. (2008)	No
5	Karakas (2010)	Doherty et al. (2014a,b)	Nomoto et al. (2013)	Yes

Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018, MNRAS, 478, 3693

Isotopic ratios: a good indicator of nucleosynthesis

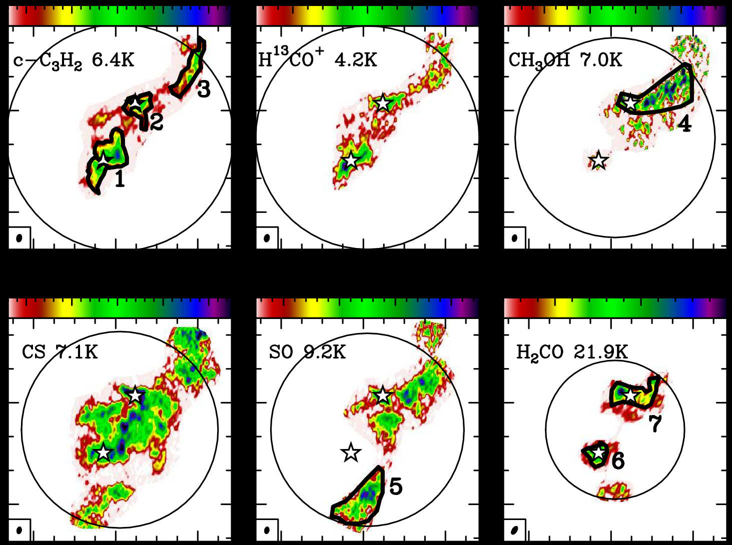
^{14}N: primary product

- Primary production from fast-rotating low-metallicity massive stars
- Primary production in the base of the convective envelope of AGB (intermediate-mass)
- Secondary production through CNO cycles in MS stars and in the H-burning shells of red giants

^{15}N: secondary product

- Primary production: from low metallicity massive stars (this is mainly in the outer galaxy where there are less white dwarf and then the secondary production is less efficient)
- Secondary production from hot CNO cycle that occurs in nova outbursts;

CHEMOUT IV

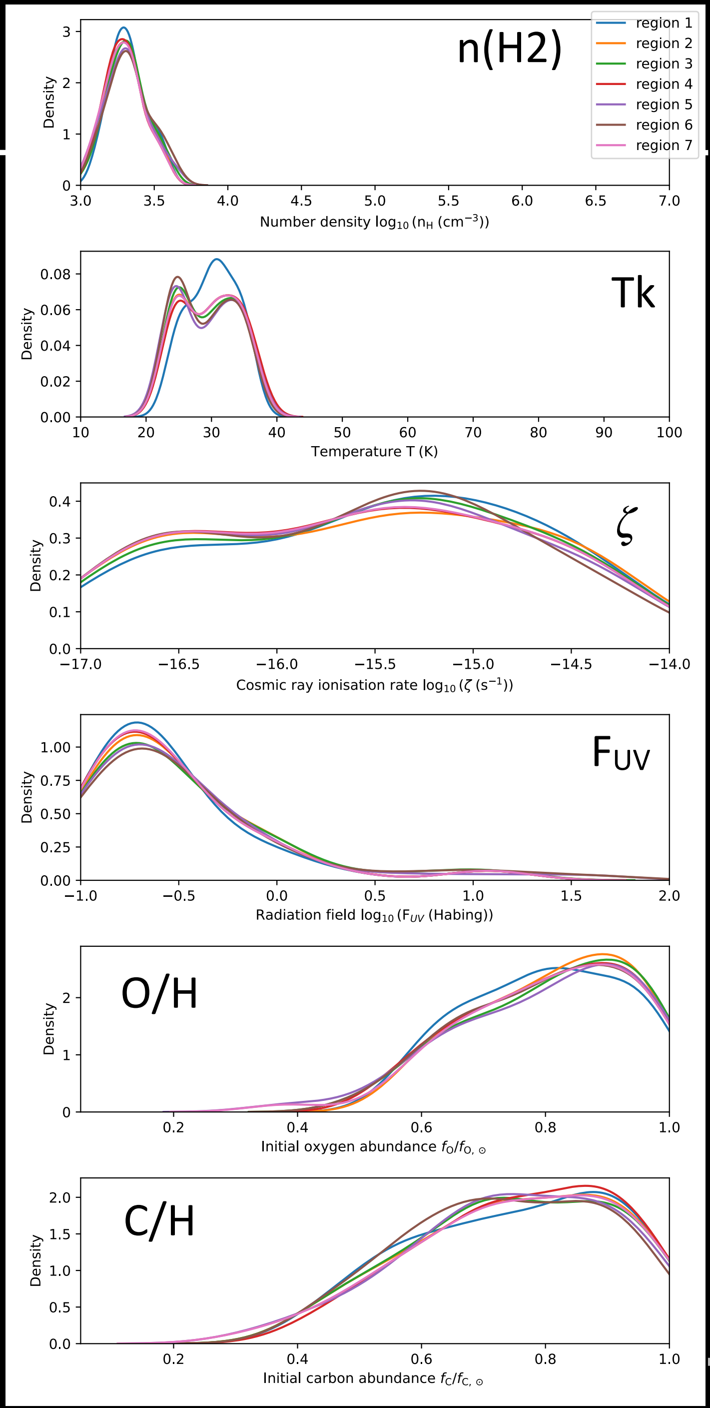


MODELS THAT BEST MATCH DATA:

- low densities (10^3 cm3) —> diffuse gas
- intermediate kinetic temperatures (20-40 K)
- cosmic-ray ionisation rate unconstrained
- low radiation field
- [O/H] consistent with extrapolated el. gradients
- [C/H] NOT consistent with extrapolated el. gradients

  [C/H] > 1/5 [C/H]⊙ modelled

  [C/H] ~ 1/14 [C/H]⊙ extrapolated



CHEMOUT IV:Fontani, F., et al. (2024), accepted in A&A

Nitrogen fractionation across the Galaxy

$^{14}N/^{15}N$ as good indicator of nucleosynthesis

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- Primary production from fast-rotating low-metallicity massive stars

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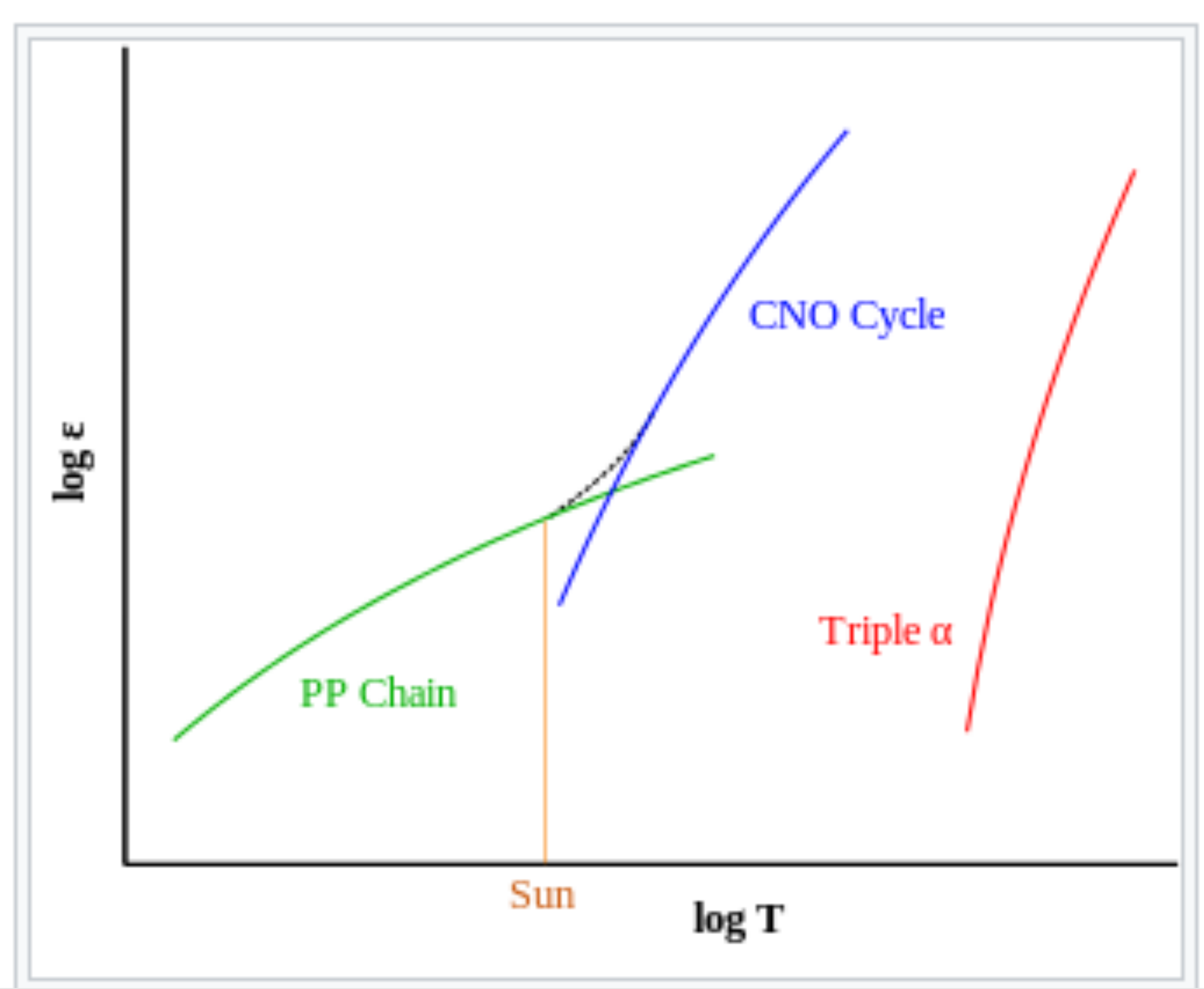


Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018, MNRAS, 478, 3693

(cold) CNO-I cycle:
(important in Sun)

$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma \quad + 1.95\ MeV$

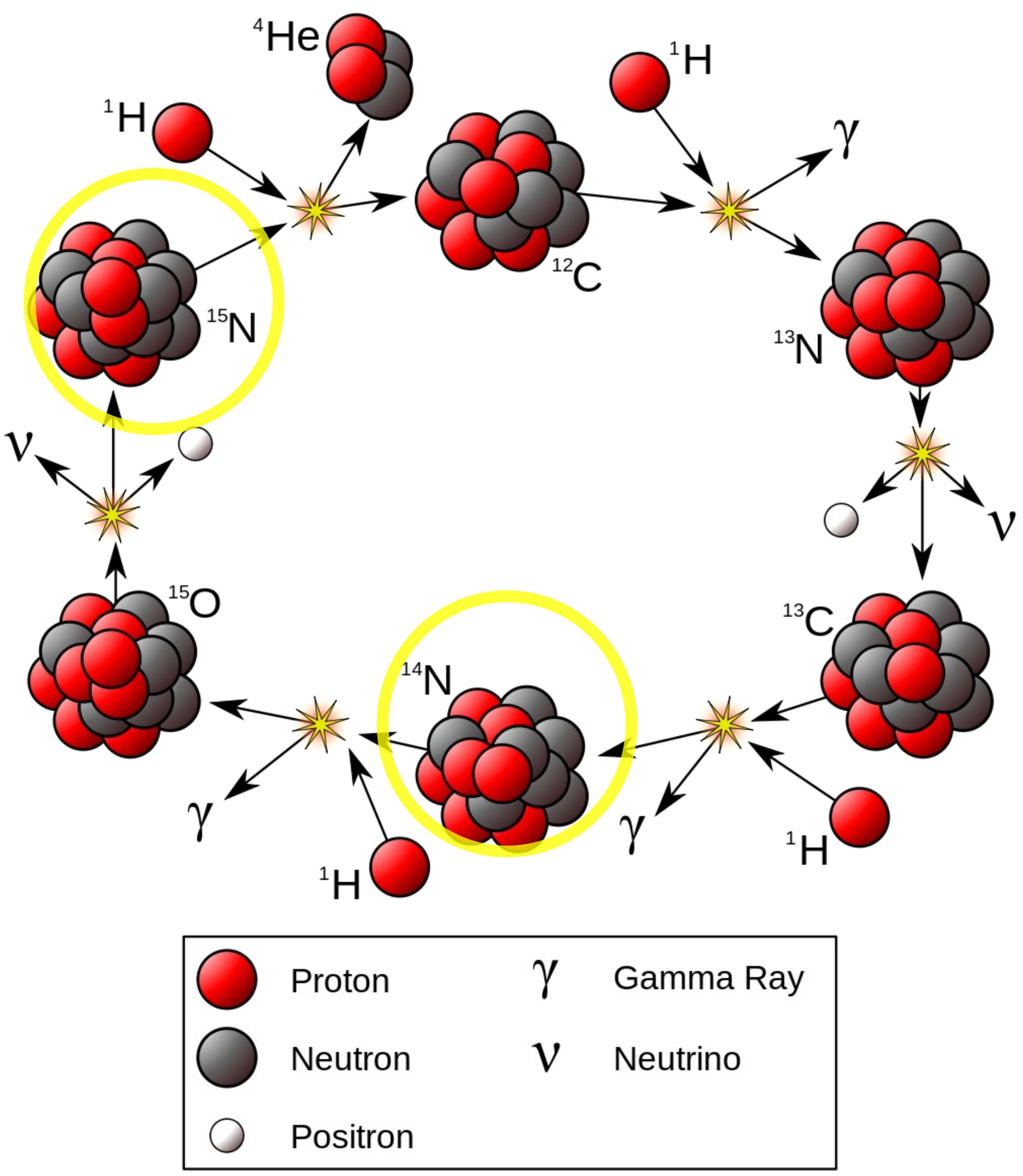
$^{13}_{7}N \rightarrow ^{13}_{6}C + e^{+} + \nu_e \quad + 1.20\ MeV$ (half-life of 9.965 minutes[7])

$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma \quad + 7.54\ MeV$

$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma \quad + 7.35\ MeV$

$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e \quad + 1.73\ MeV$ (half-life of 122.24 seconds[7])

$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He \quad + 4.96\ MeV$



Hot CNO-I cycle:

(novae, x-ray bursts...)

$$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma + 1.95\ \text{MeV}$$

$$^{13}_{7}N + ^{1}_{1}H \rightarrow ^{14}_{8}O + \gamma + 4.63\ \text{MeV}$$

$$^{14}_{8}O \rightarrow ^{14}_{7}N + e^{+} + \nu_e + 5.14\ \text{MeV}$$ (half-life of 70.641 seconds)

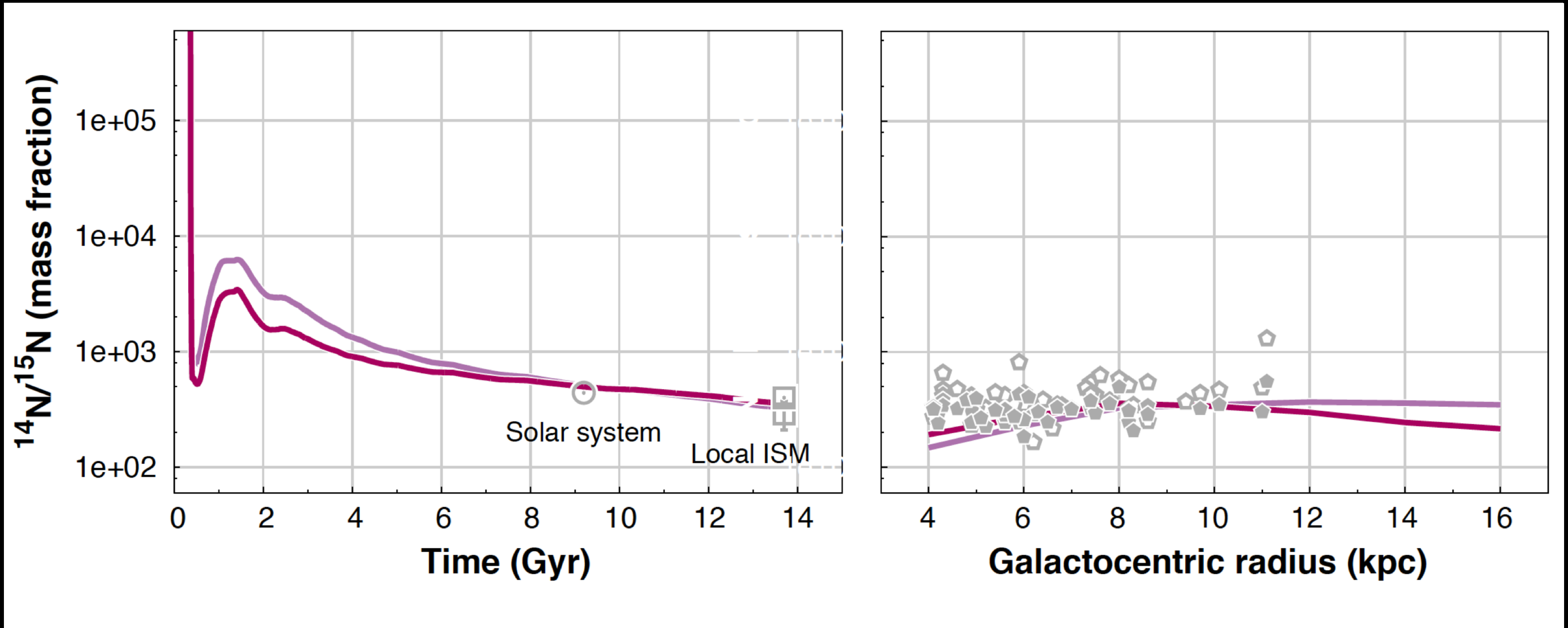
$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma + 7.35\ \text{MeV}$$

$$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e + 2.75\ \text{MeV}$$ (half-life of 122.24 seconds)

$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He + 4.96\ \text{MeV}$$

Galactic chemical evolution (*Romano et al., 2019*) UPDATED

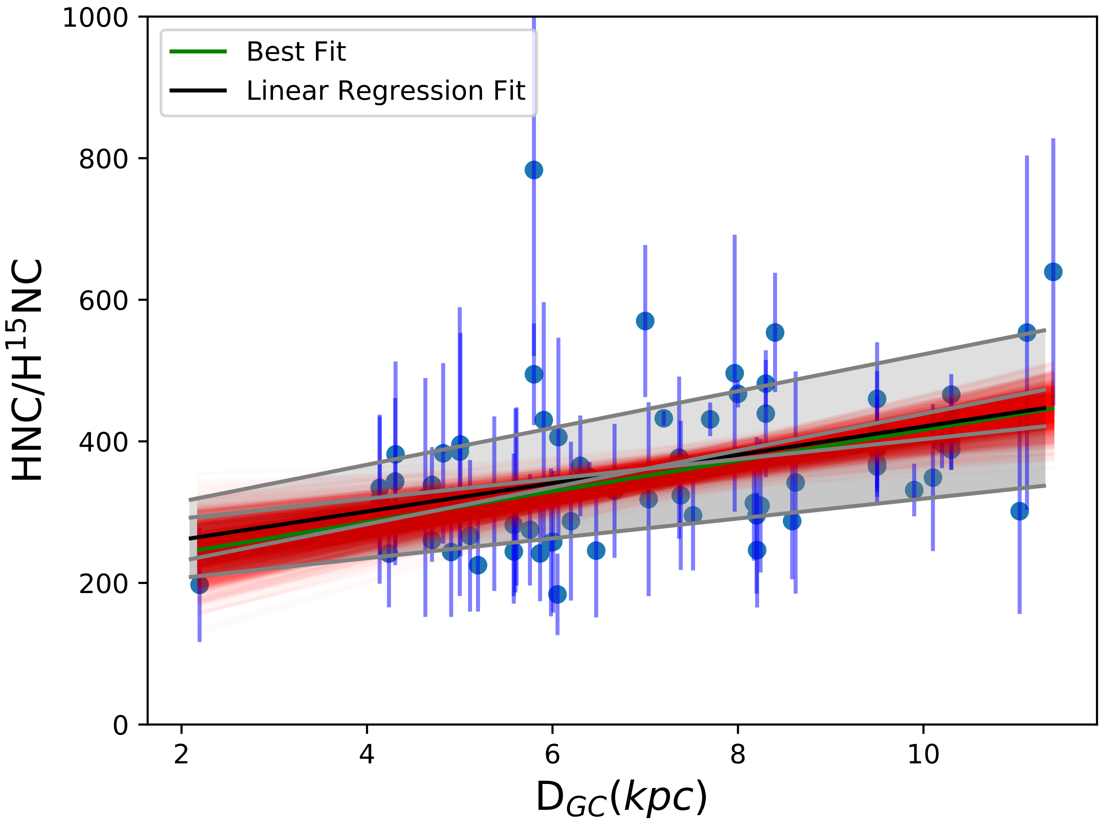
taking into account different intial rotational velocities (*Limongi and Chieffi 2018*)

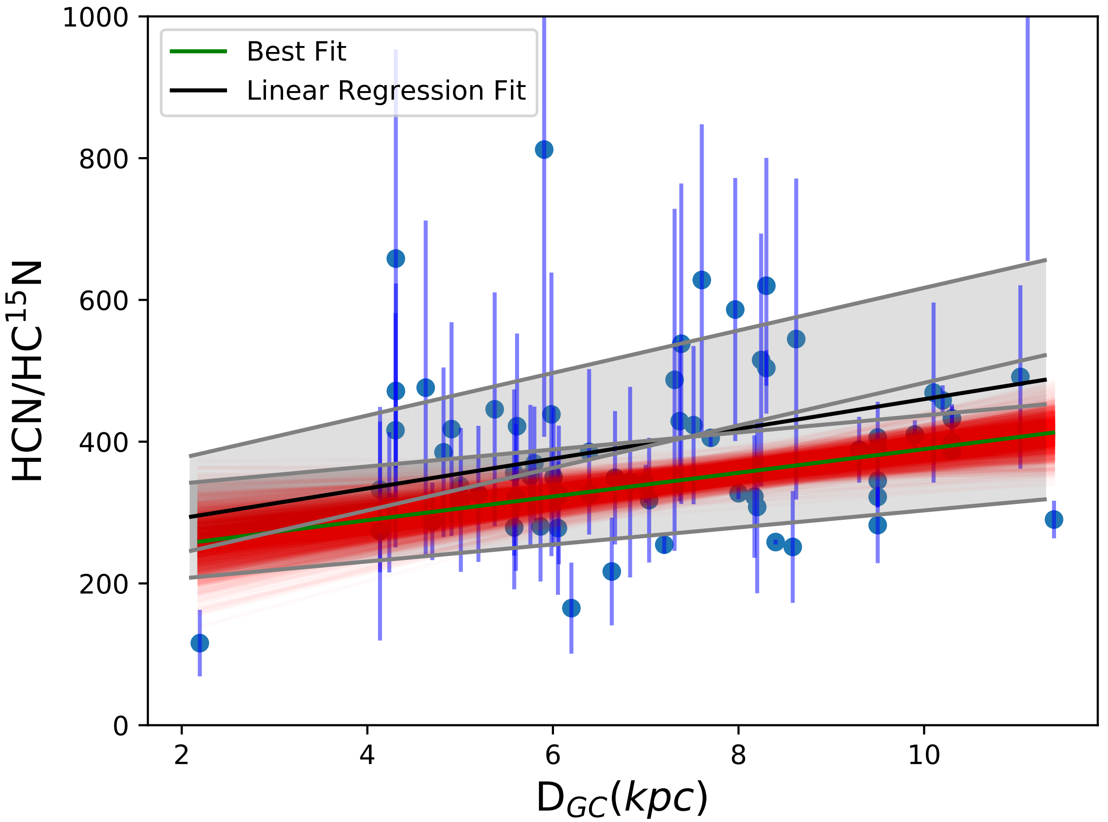


NOW THE GCE MODEL EXACTLY REPRODUCE THE TREND WE FOUND

Reference: Colzi, L., et al. 2018b, MNRAS, 478, 3693

Nitrogen fractionation across the Galaxy





Linear Fit: Bayesian method

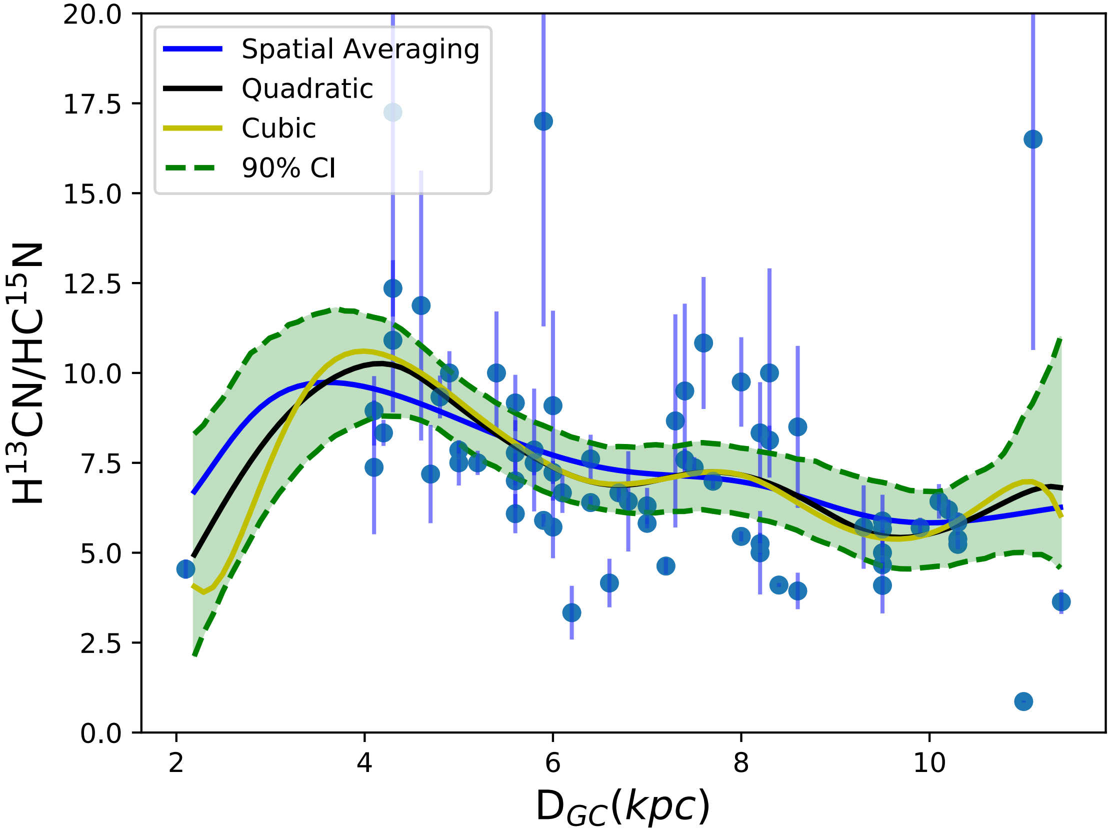
$^{14}N/^{15}N = (22 \pm 6)\ Dgc(kpc) + (198 \pm 12)$ $^{14}N/^{15}N = (17 \pm 6)\ Dgc(kpc) + (223 \pm 12)$

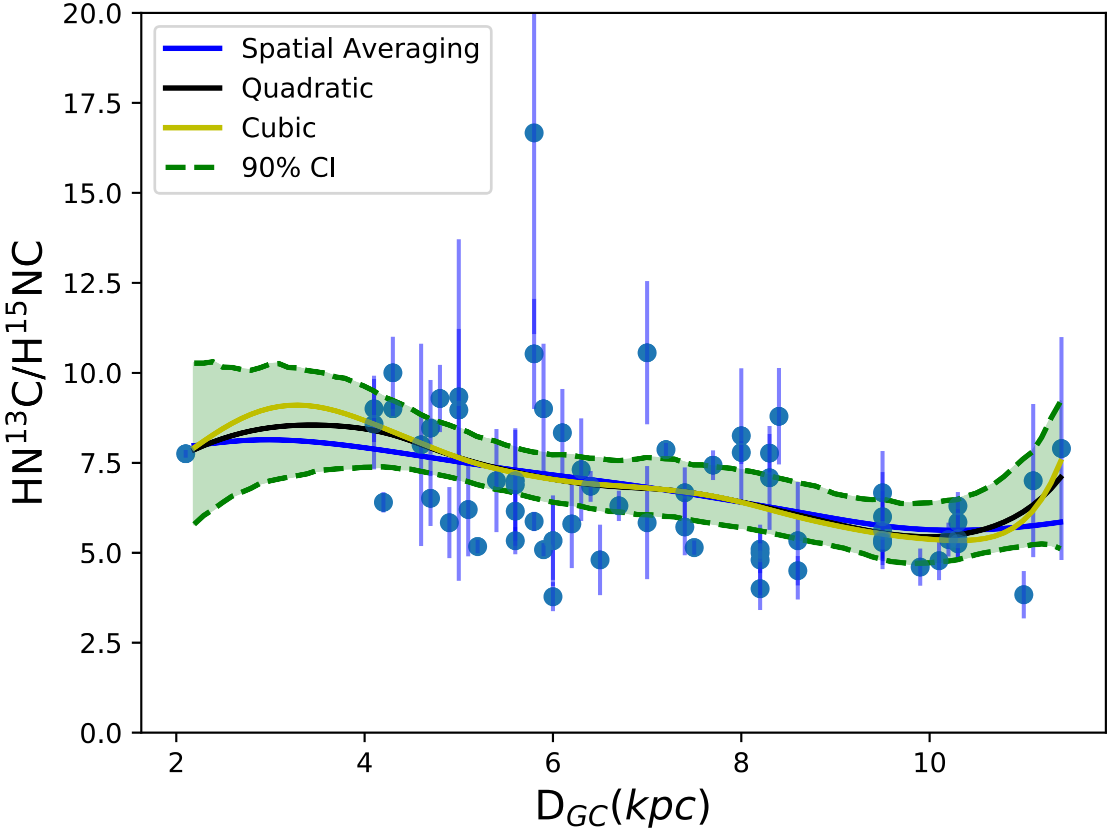
Laura Colzi

Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018, MNRAS, 478, 3693

Nitrogen fractionation across the Galaxy

PYTHON TOOL *NonParamRegression*

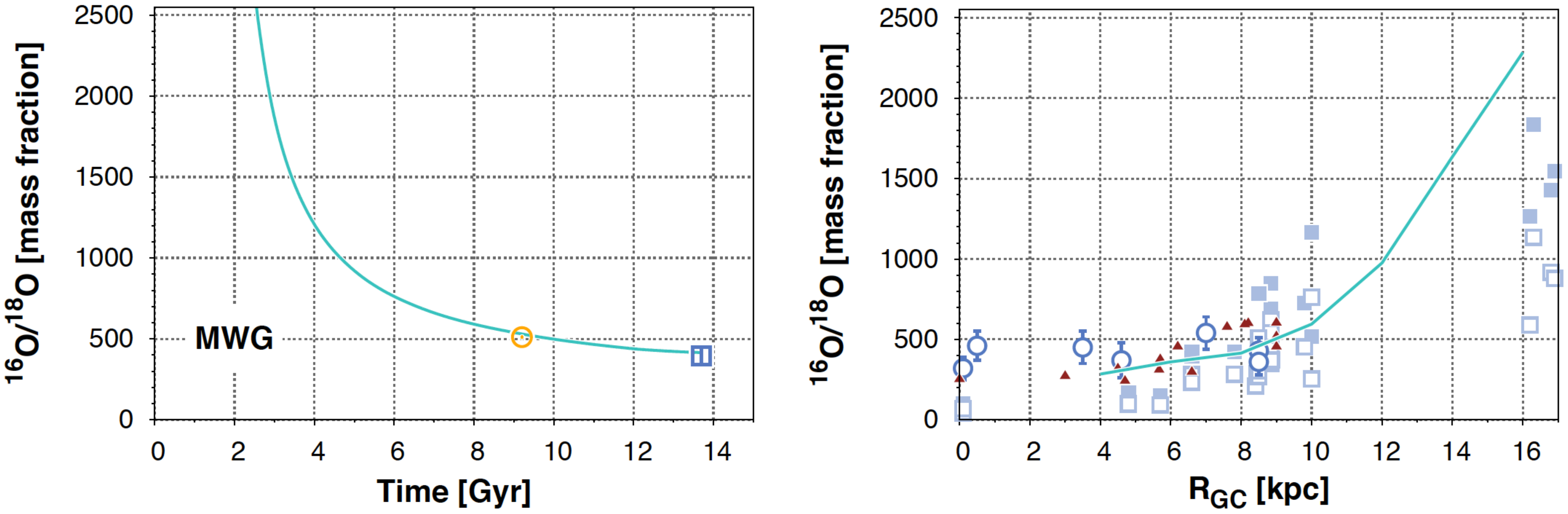




To test the linearity of $H^{13}CN/HC^{15}N$ and $HN^{13}C/H^{15}NC$

Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018, MNRAS, 478, 3693

$^{16}O/^{18}O$ Galactic chemical evolution

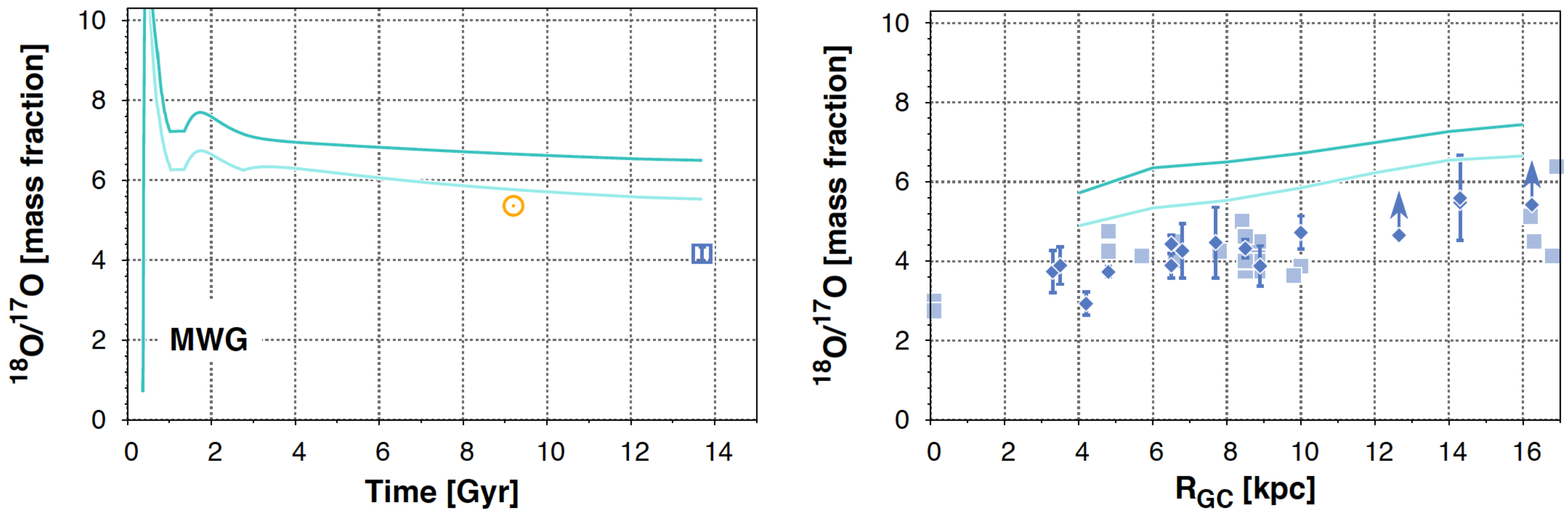


Intermediate and massive stars destroy ^{18}O rather than produce it.

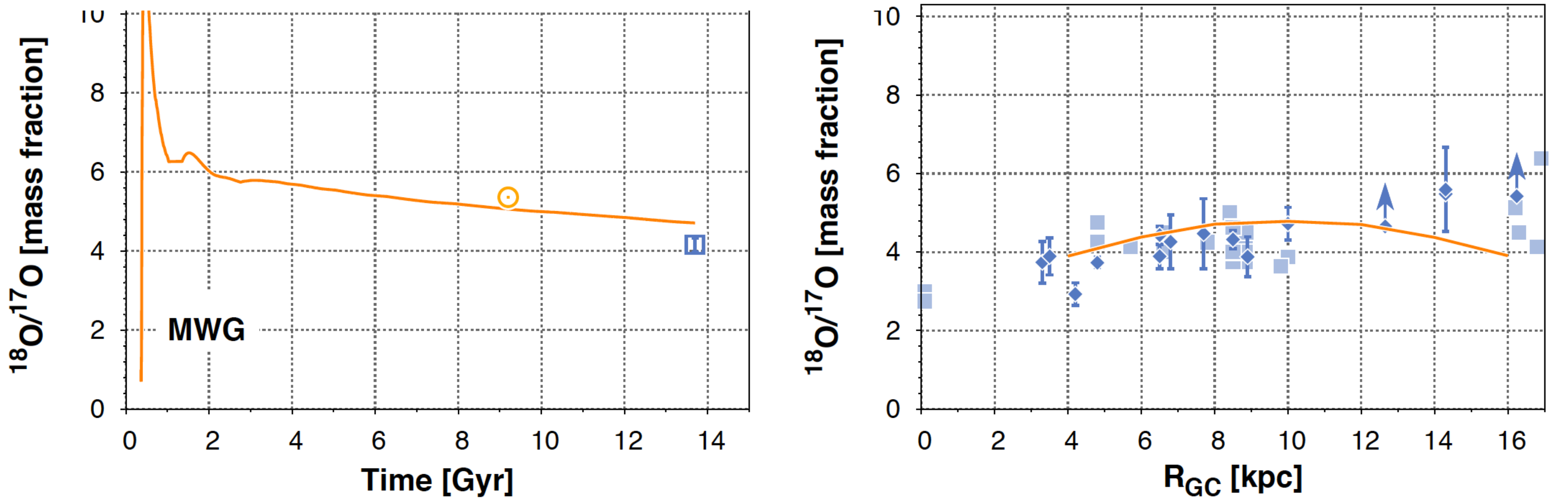
In this case nova are not important to produce ^{18}O.

Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018, MNRAS, 478, 3693

$^{18}O/^{17}O$ Galactic chemical evolution



^{17}O is over-produced by nova outbursts.
Their introduction is important to explain the GCE.



Reference: Colzi, L., Fontani, F., Rivilla, V. M., et al. 2018, MNRAS, 478, 3693