Improving Galactic Disk simulations with Gaia

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Mazzi et al. (resubmitted to MNRAS after minor comments)

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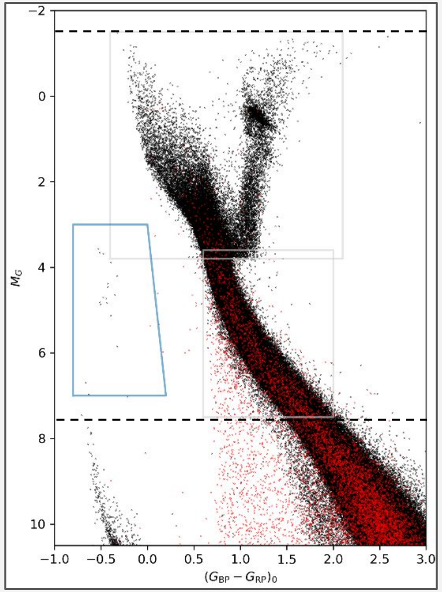
Previous work - Dal Tio et al. 2021

Gaia DR2 | |b|>25° | 1/pi < 200 pc

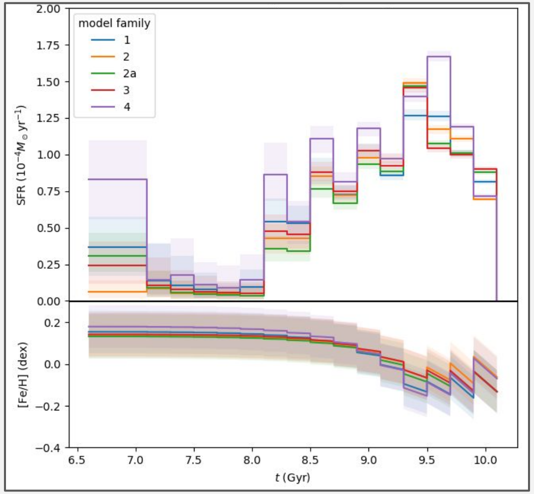
A_V from Lallement et al. (2018)

Quality cuts (astrometry and photometry)



Multiple prescriptions for binary systems (TRILEGAL & BinaPSE)

- Binary evolution
- Binary parameters from Eggleton (2006) or Moe & Di Stefano (2017)
- Resolved/unresolved



Binary prescription does not affect much the solution, but adds about 20% uncertainty on SFR(t)

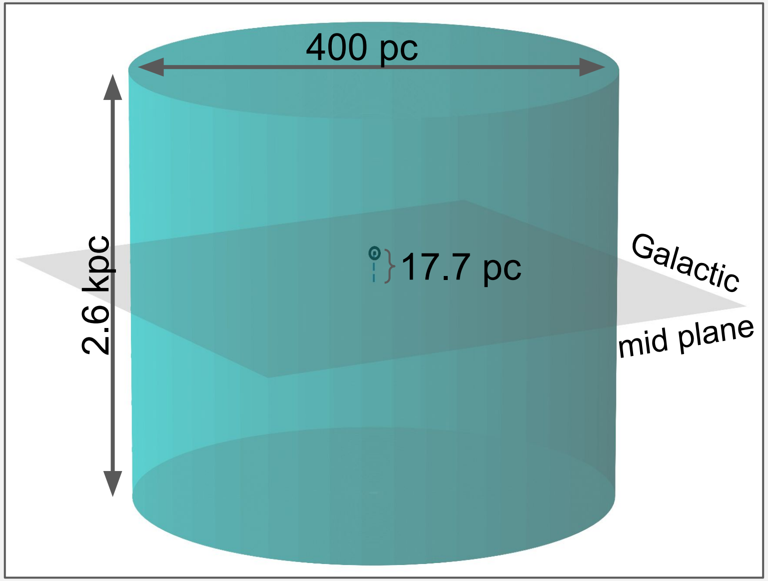
Investigating the SFR of the disk

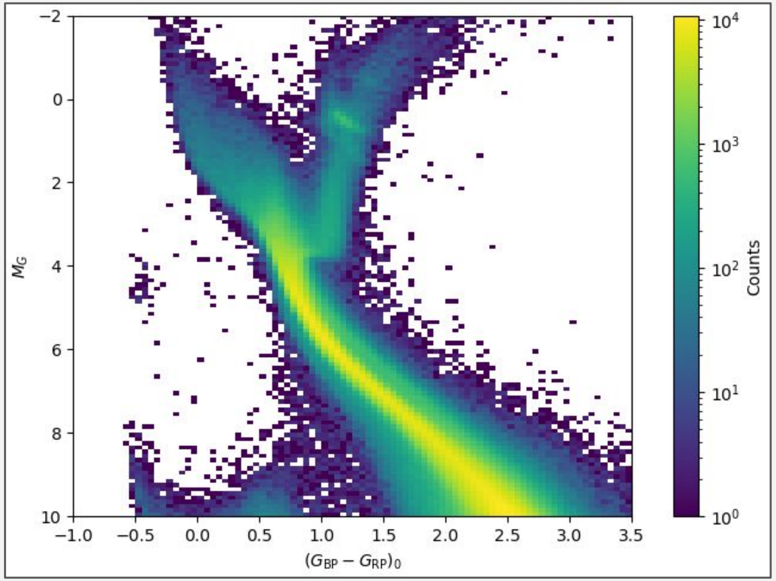
Gaia DR3

A_V from Vergely et al. (2022)

`phot_bp_rp_excess_factor` with correction from Riello et al. (2021)

Slices



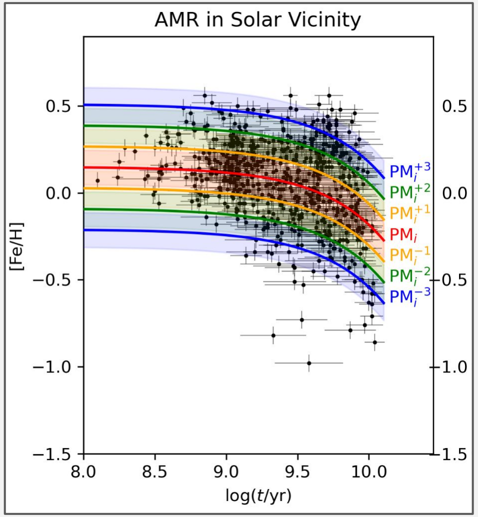


z_{min} [pc]	z_{max} [pc]
0.00	52.63
52.63	105.26
105.26	157.89
157.89	263.16
263.16	368.42
368.42	473.68
473.68	578.95
578.95	684.21
684.21	789.47
789.47	894.74
894.74	1000.00
1000.00	1105.26
1105.26	1210.52
1210.52	1315.78

(Partial) Models for single stars

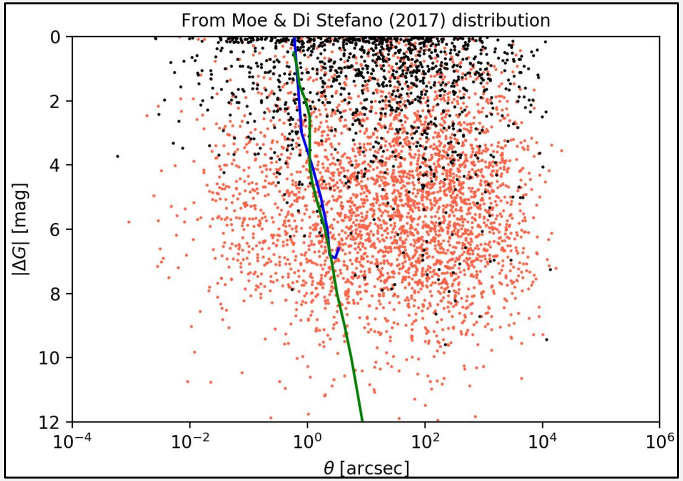
- PARSEC v1.2S tracks (Bressan et al. 2012)
- TRILEGAL population synthesis code
- Kroupa (2002) IMF
- Partial models (PMs)
    - 16 age bins
    - 7 metallicity sets
- Normalization to 1 $M_\odot yr^{-1}$
- Photometric errors and completeness as post-processing on Hess diagrams for each slice (AST like procedure)

$\log(t_1\,[yr])$	$\log(t_2\,[yr])$
6.60	7.10
7.10	7.30
7.30	7.50
7.50	7.70
7.70	7.90
7.90	8.10
8.10	8.30
8.30	8.50
8.50	8.70
8.70	8.90
8.90	9.10
9.10	9.30
9.30	9.50
9.50	9.70
9.70	9.90
9.90	10.10



(Partial) Models for binary stars

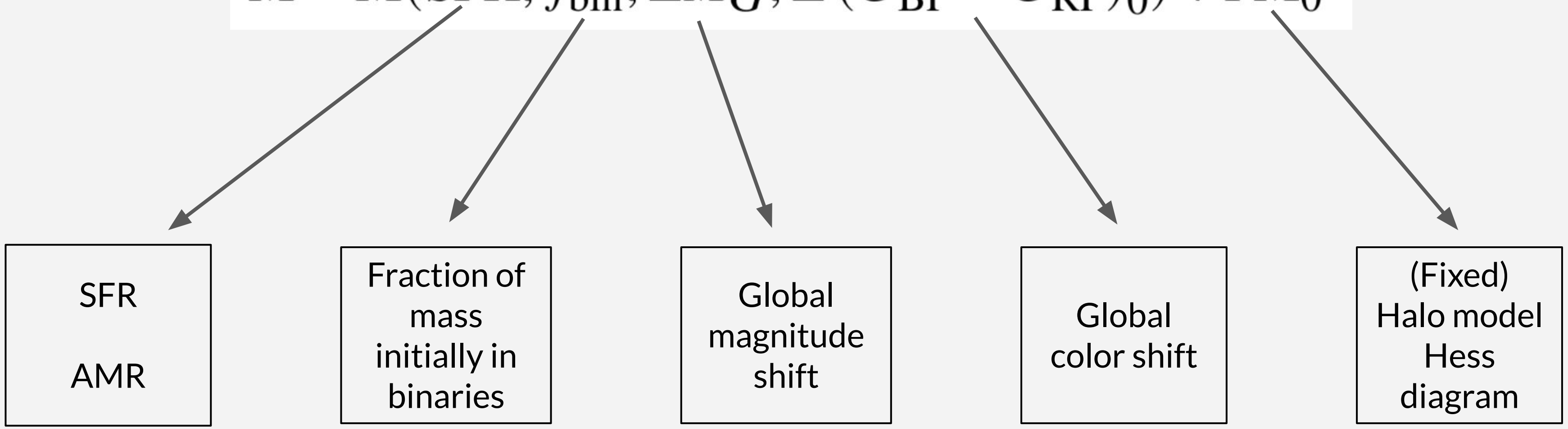
- PARSEC v1.2S tracks (Bressan et al. 2012)
- TRILEGAL population synthesis code
- Kroupa (2002) IMF for the primaries
- Moe & Di Stefano (2017) binary initial parameters' distribution
- Partial models (PMs)
    - 16 age bins
    - 7 metallicity sets
- Normalization to 1 $M_\odot yr^{-1}$
- Photometric errors and completeness as post-processing on Hess diagrams for each slice (AST like procedure)
- Follow evolution through each age bin
- Evaluate resolvability (magnitude contrast + separation)



Blue line: 50% recoverability,Ziegler et al. (2018)
Green line: same limit, Brandeker & Cataldi (2019)
Figure from Dal Tio et al. (2021)

Recipe for a total model

$$\mathrm{M} = \mathrm{M}(\mathrm{SFH}, f_{\mathrm{bin}}, \Delta M_G, \Delta\,(G_{\mathrm{BP}} - G_{\mathrm{RP}})_0) + \mathrm{PM}_0$$



Finding the best model

$$M = M(\mathrm{SFH}, f_{\mathrm{bin}}, \Delta M_G, \Delta (G_{\mathrm{BP}} - G_{\mathrm{RP}})_0) + \mathrm{PM}_0$$

Two-step optimization

- Gradient descent (Adam)
- MCMC (NUTS)

Poisson likelihood

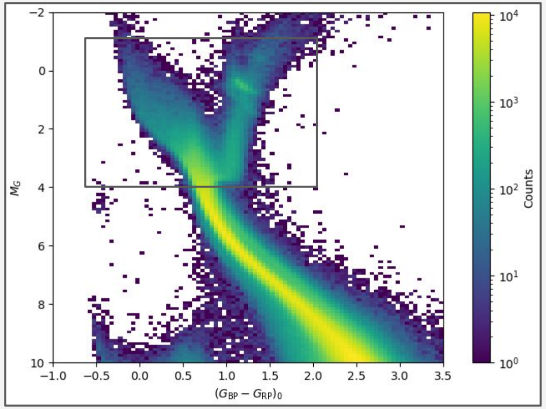
Priors

- uniform on SFR, AMR and f_{bin}
- Gaussian (μ=0) on magnitude and color shifts

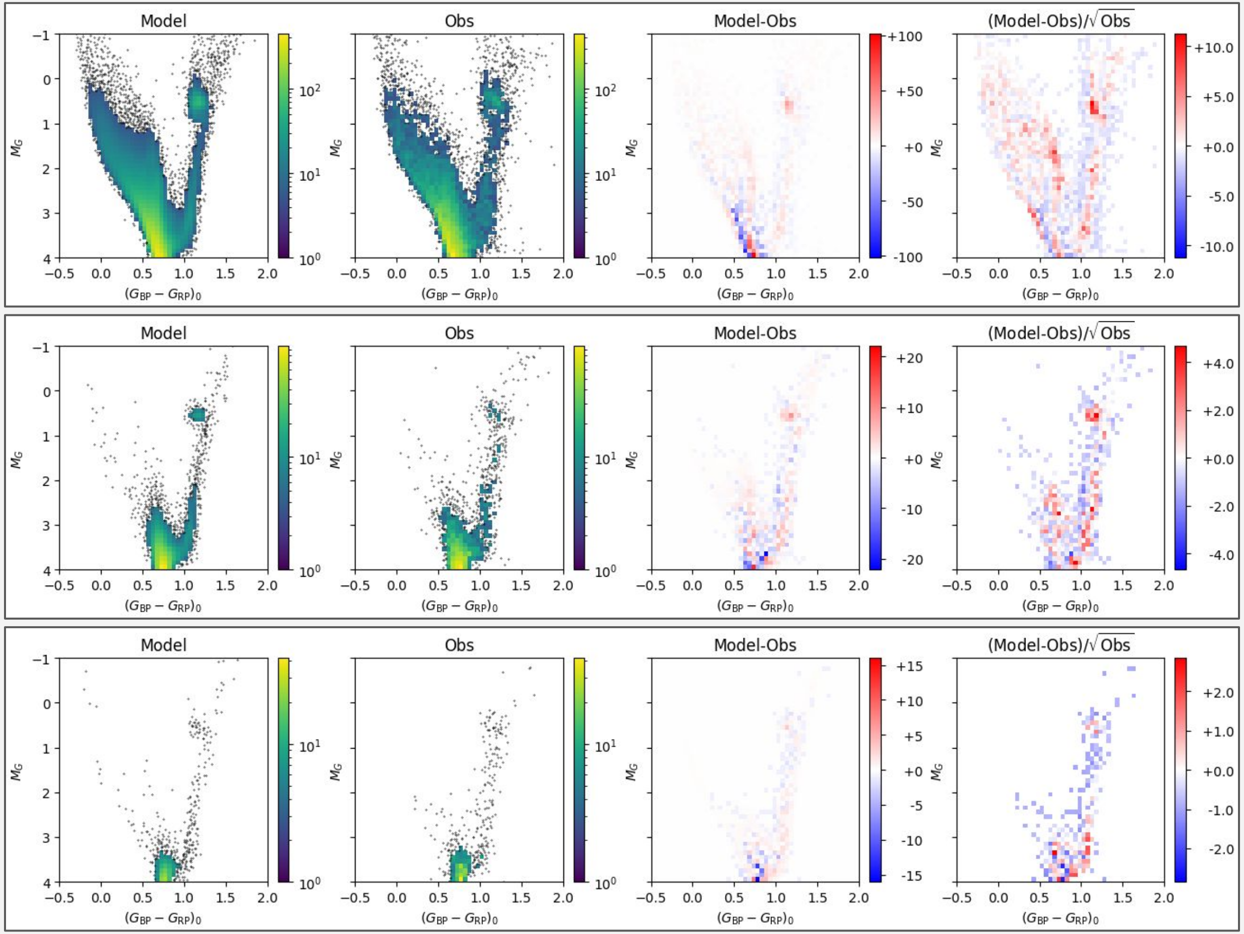
CAMD region to fit

- Low uncertainties
- Maximize sensitivity to age
- Exclude AGB

$-1 < M_G < 4$

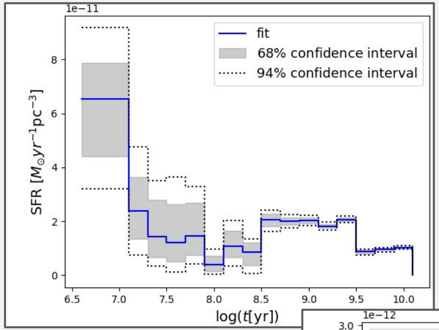


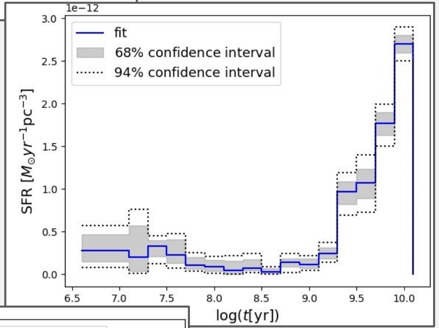
Finding the best model

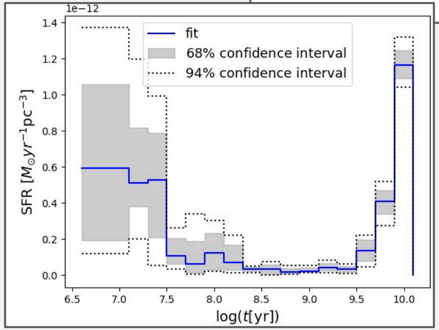


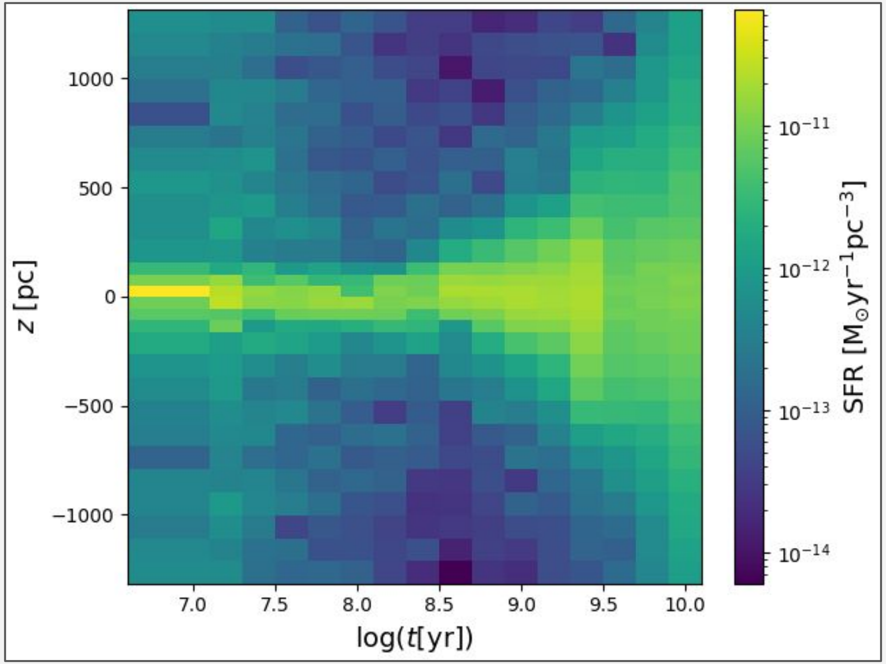
Best fit parameters

Star formation rate



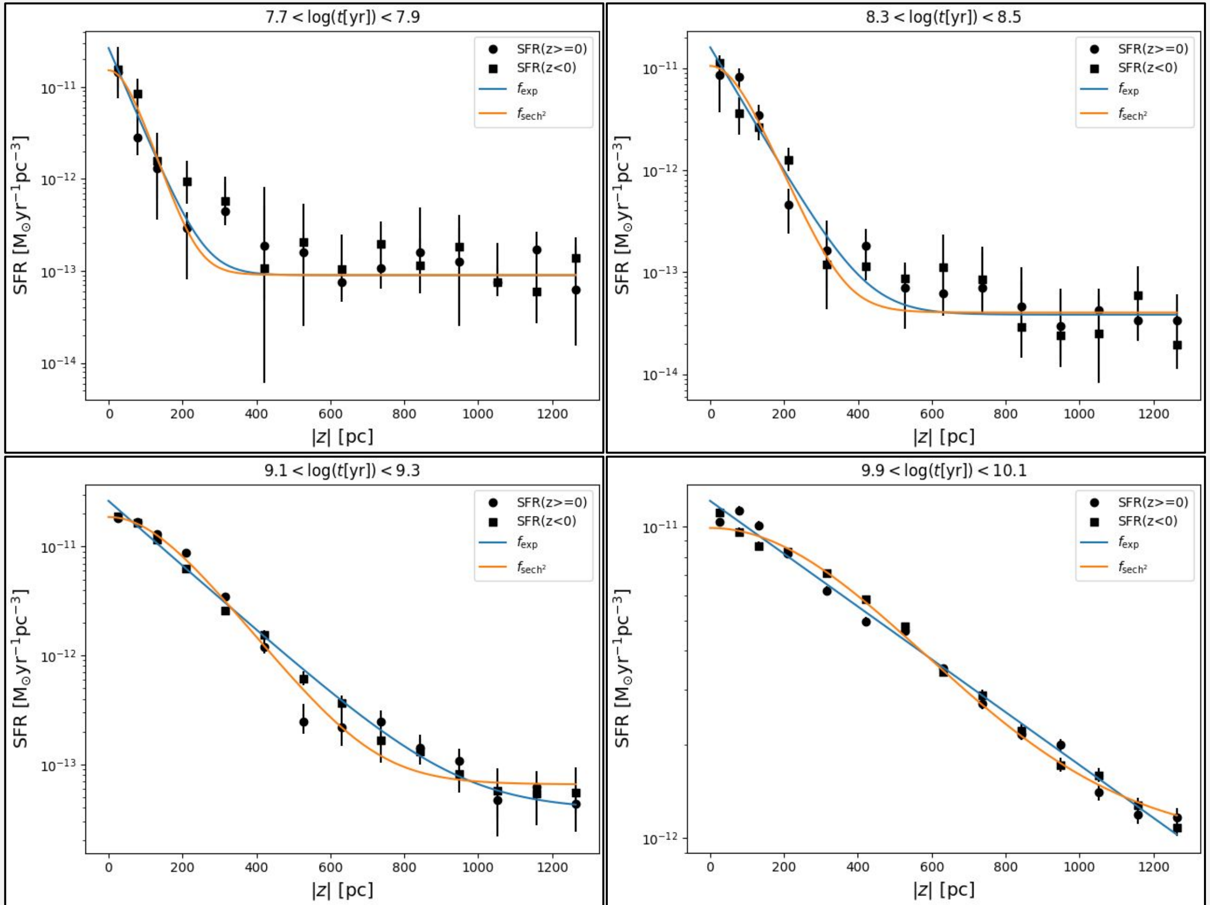






SFR @ current position, not place of birth

Star formation rate: trend with |z| and scale height



$$f_{\exp}(t,z) = A\exp\left(-|z|/h_z(t)\right) + c$$

$$f_{\mathrm{sech}^2}(t,z) = A\,\mathrm{sech}^2\left(-z/h_z(t)\right) + c$$

Villumsen (1983)

$$h_z(t) = h_{z,0}\left(1 + \frac{t}{\tau}\right)^n$$

$h_{z,0} = 37.1 \pm 4.8$ pc

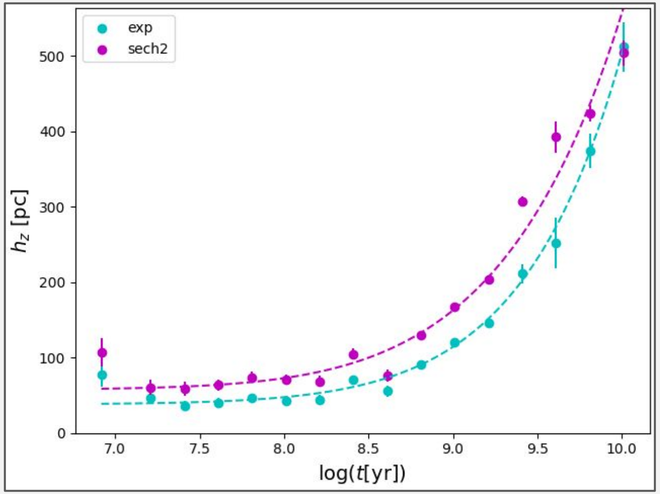
$\tau = (2.7 \pm 1.0) \times 10^8$ yr

$n = 0.714 \pm 0.061$

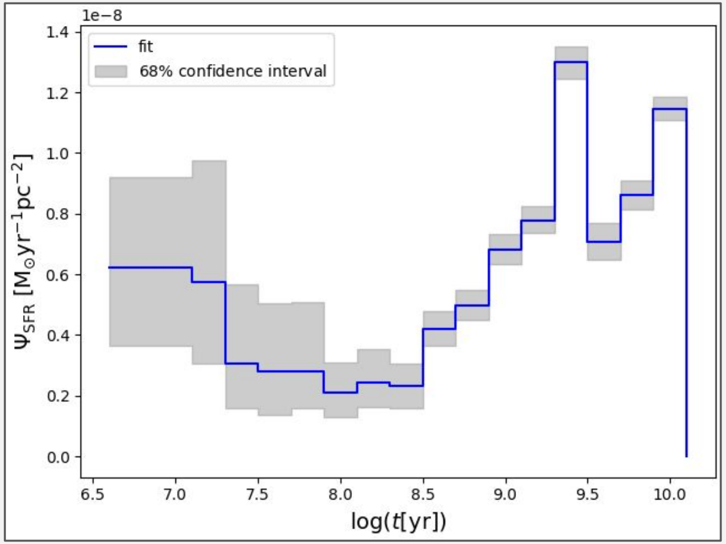
$h_{z,0} = 55.8 \pm 8.4$ pc

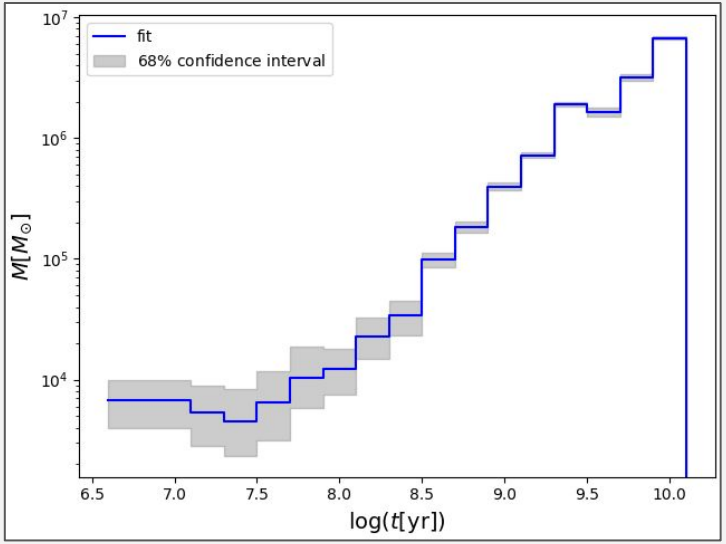
$\tau = (1.77 \pm 0.95) \times 10^8$ yr

$n = 0.566 \pm 0.063$



The whole cylinder: surface SFR and mass



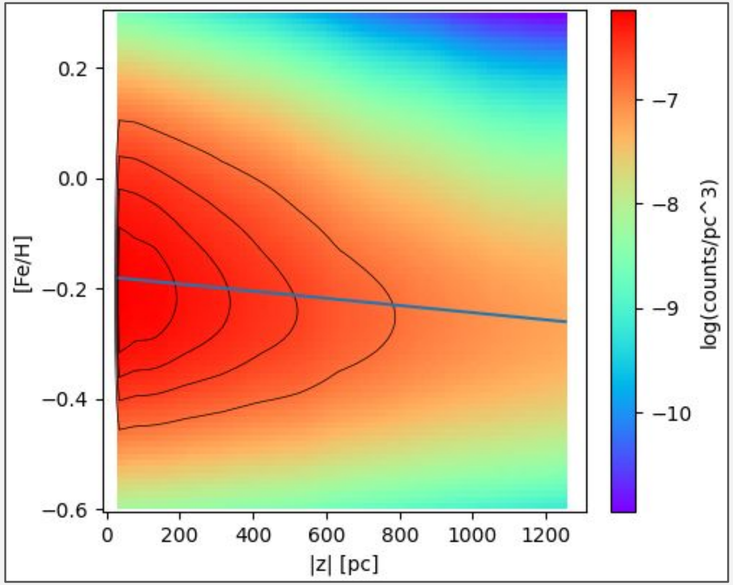


$$\Sigma_{SFR} = 118.7 \pm 6.2\,M_\odot\,pc^{-2}$$

$$M_{tot} = 1.492 \pm 0.079 \times 10^7\,M_\odot$$

Some of the mass has already been returned to the ISM

The whole cylinder: AMR



$$[\mathrm{Fe/H}](z) = -0.1786 - 0.065 \times |z|$$

$$\overline{[\mathrm{Fe/H}]} = -0.20$$

Imig et al. (2023), APOGEE, red giants
-0.315 ± 0.009 dex kpc^{-1}

Onat Tas et al. (2016), RAVE, red clump stars
-0.157 ± 0.003 dex kpc^{-1}

Duong et al. (2018), GALAH, thin disk stars (low-α)
-0.18 ± 0.01 dex kpc^{-1}

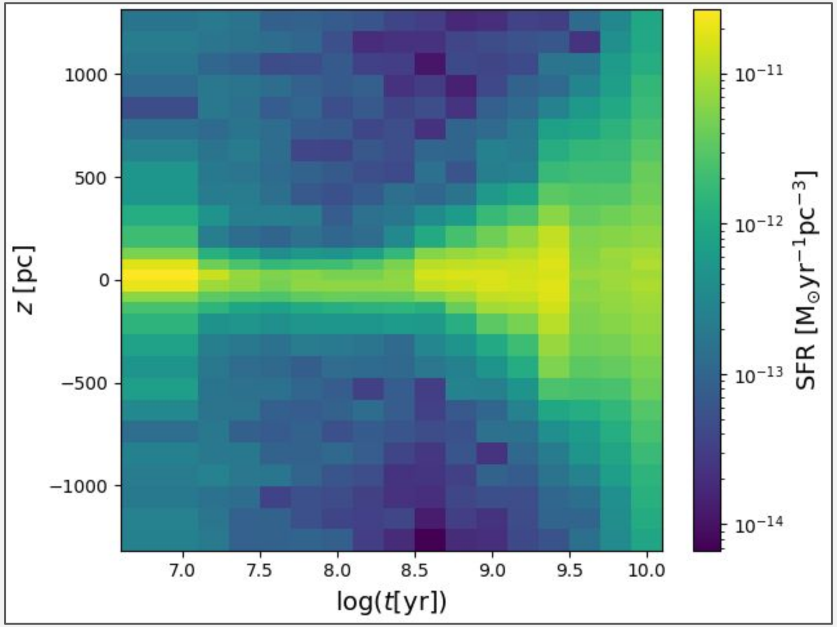
Hawkins (2023), LAMOST, stars O to F
-0.15 ± 0.01 dex kpc^{-1}

Adding a spatial correlation

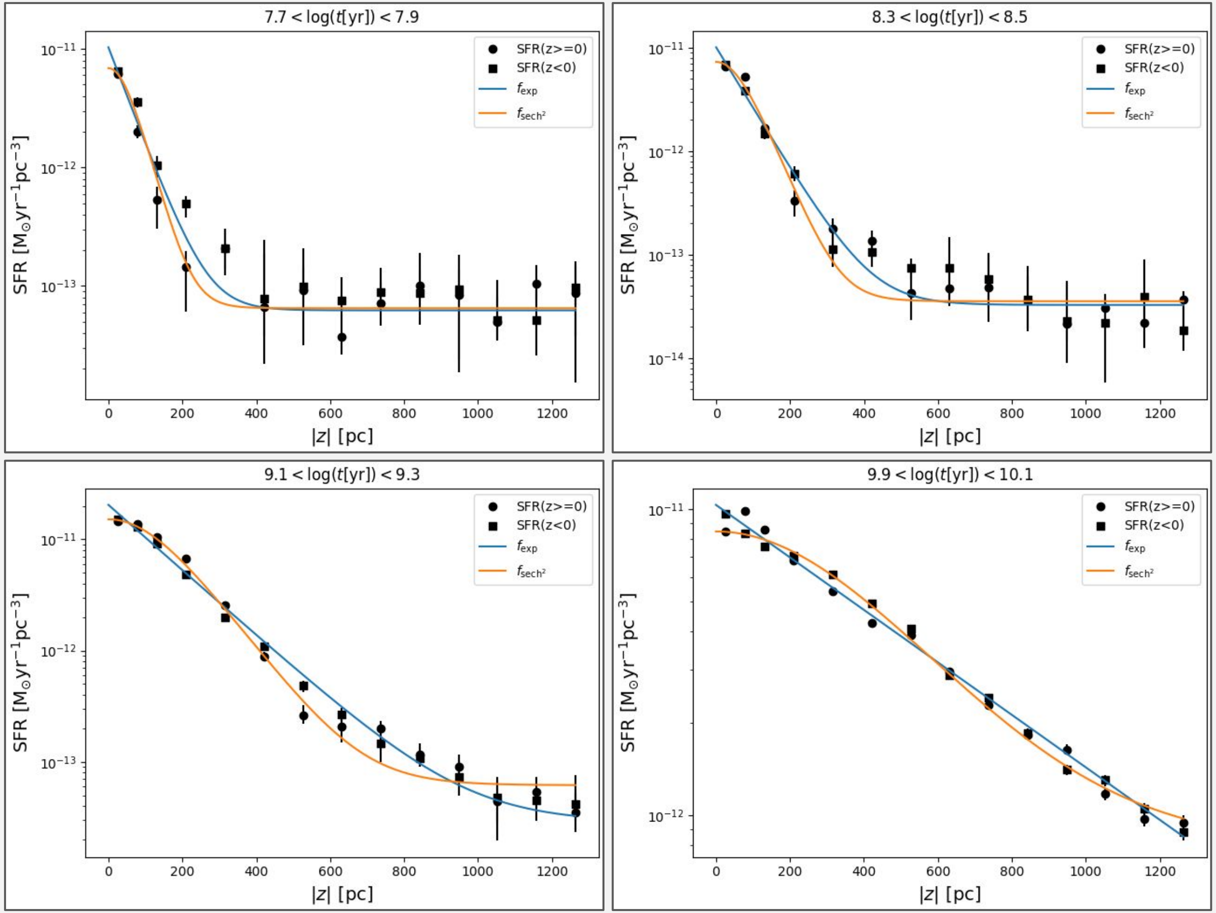
for a given age bin *i*

$$\mathbf{R}_{n,m;i} = r(\boldsymbol{x}_n, \boldsymbol{x}_m, l_i) = \exp\left\{-\frac{|\boldsymbol{x}_n - \boldsymbol{x}_m|^2}{2l_i^2}\right\}$$

Idea: from their births, stars travel and get mixed over distance l



Adding a spatial correlation



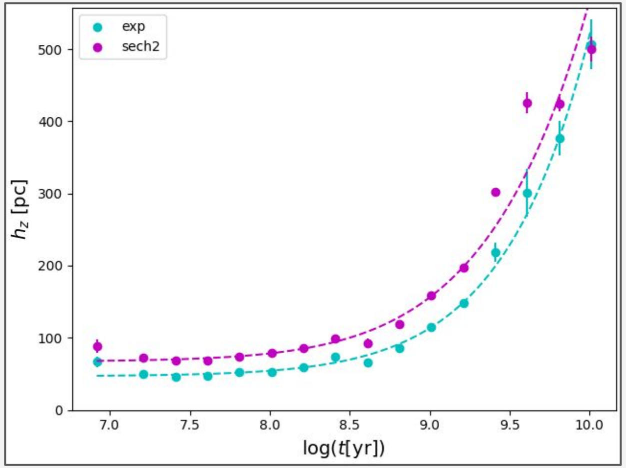
$$f_{\exp}(t, z) = A \exp\left(-|z|/h_z(t)\right) + c$$

$$f_{\mathrm{sech}^2}(t, z) = A\, \mathrm{sech}^2\left(-z/h_z(t)\right) + c$$

$$h_z(t) = h_{z,0}\left(1 + \frac{t}{\tau}\right)^n$$

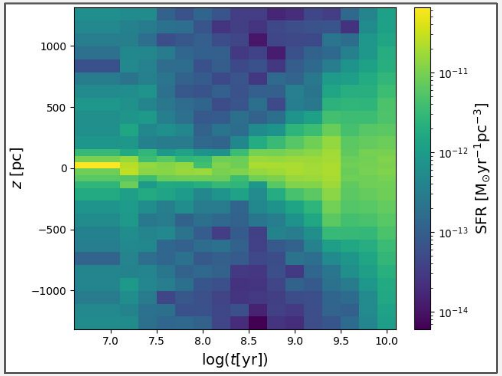
$$h_{z,0} = 44.8 \pm 2.3 \text{ pc}$$
$$\tau = (4.30 \pm 0.99) \times 10^8 \text{ yr}$$
$$n = 0.766 \pm 0.059$$

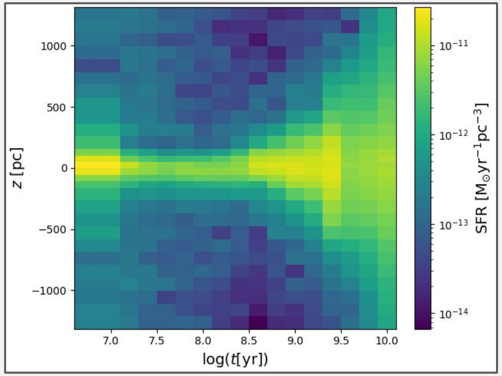
$$h_{z,0} = 65.9 \pm 3.5 \text{ pc}$$
$$\tau = (3.4 \pm 1.0) \times 10^8 \text{ yr}$$
$$n = 0.631 \pm 0.063$$



Conclusions

- We derived SFR and its spatial density from Gaia DR3 data
- Enhanced SFR at t~2-3 Gyr
- Dependence of SFR on |z| clear -> $h_z(t)$
- Age resolution of $h_z(t)$ better than methods relying on selected stellar tracers
- Spatial correlation appears to reduce noise
- Results can be implemented easily in TRILEGAL





- Low level young SFR at all |z| needs more inspection (Models improvements? Data issues?)
- Total surface mass larger than estimates from studies using kinematic information (matter recycling?)

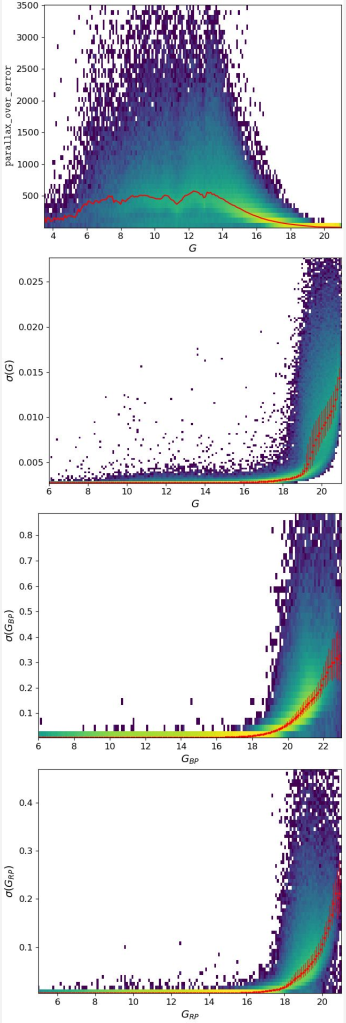
0<z<52.63 | 894.74<z<1000

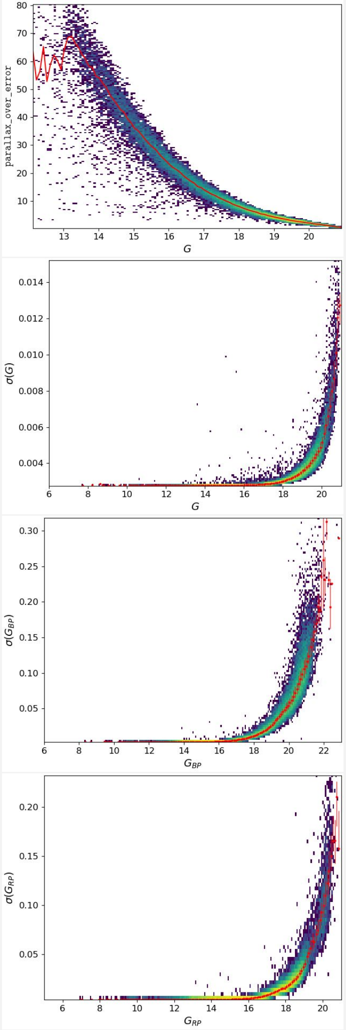
parallax_over_error

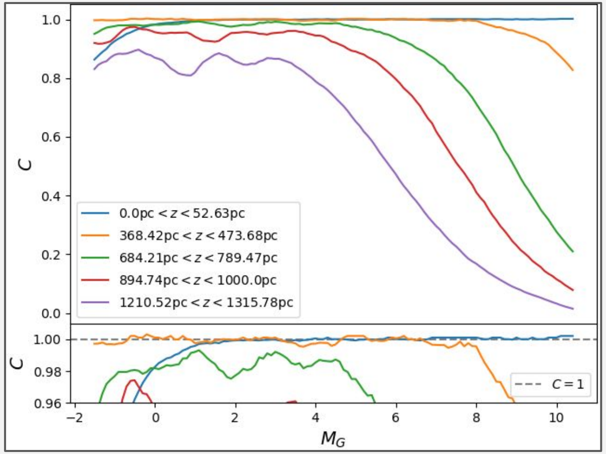
G

G_{BP}

G_{RP}

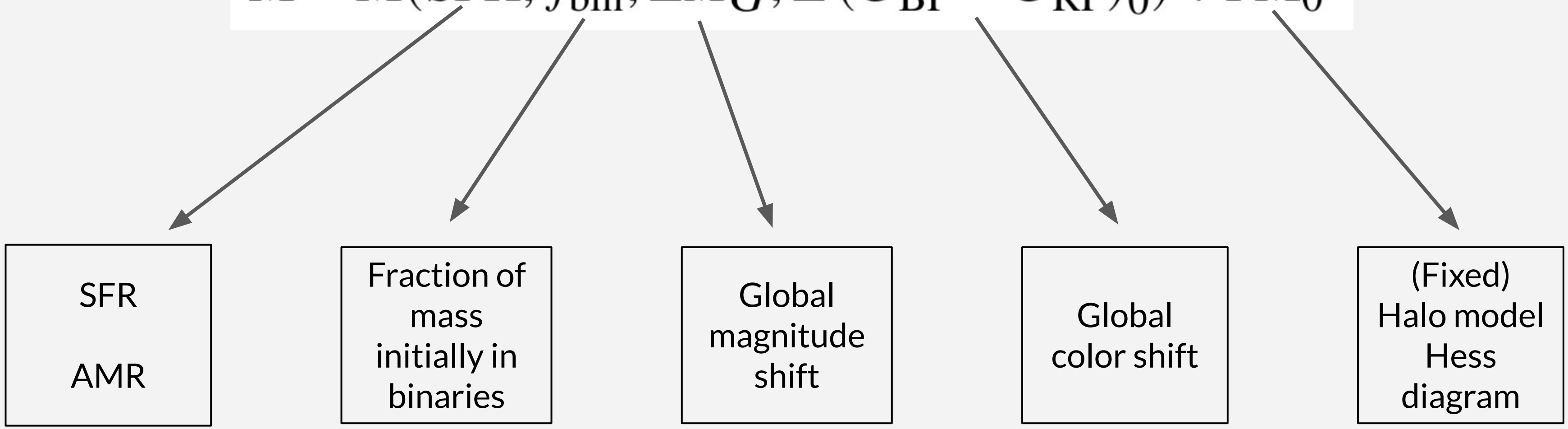






Finding the best model

$$\mathrm{M} = \mathrm{M}(\mathrm{SFH}, f_{\mathrm{bin}}, \Delta M_G, \Delta\,(G_{\mathrm{BP}} - G_{\mathrm{RP}})_0) + \mathrm{PM}_0$$



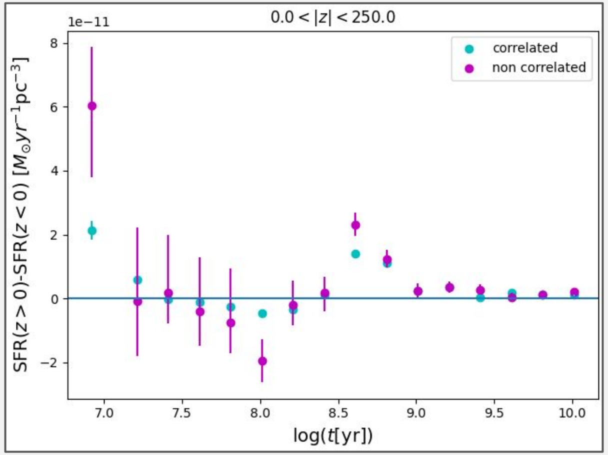
1. $\mathrm{PM}_i([\mathrm{Fe/H}]_i) = (1 - f_i)\mathrm{PM}_i^- + f_i \mathrm{PM}_i^+$ $\quad f_i = ([\mathrm{Fe/H}]_i - [\mathrm{Fe/H}]_i^-)/([\mathrm{Fe/H}]_i^+ - [\mathrm{Fe/H}]_i^-)$

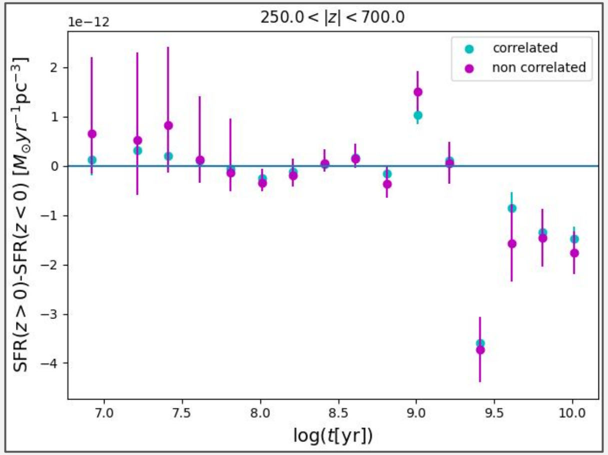
2. $\mathrm{M} = \mathrm{PM}_0 + \sum_{i=1}^{16} a_i \left[(1 - f_{\mathrm{bin}})\mathrm{PM}_{\mathrm{sin},i} + f_{\mathrm{bin}} \mathrm{PM}_{\mathrm{bin},i}\right]$

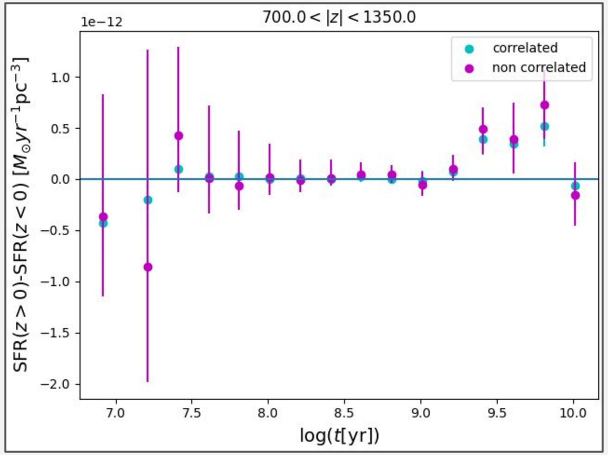
Scale heights

$\log(t_1\,[\mathrm{yr}])$	$\log(t_2\,[\mathrm{yr}])$	f_{exp}				f_{sech^2}			
		A $[10^{-11}\mathrm{M_\odot yr^{-1} pc^{-3}}]$	h_z [pc]	c $[10^{-11}\mathrm{M_\odot yr^{-1} pc^{-3}}]$	χ^2	A $[10^{-11}\mathrm{M_\odot yr^{-1} pc^{-3}}]$	h_z [pc]	c $[10^{-11}\mathrm{M_\odot yr^{-1} pc^{-3}}]$	χ^2
6.60	7.10	1.695 ± 0.674	76.7 ± 15.6	0.02605 ± 0.00462	25.8	1.178 ± 0.445	106.9 ± 19.2	0.26945 ± 0.00465	27.1
7.10	7.30	3.860 ± 1.244	46.8 ± 8.6	0.04999 ± 0.00531	13.3	2.858 ± 0.816	60.3 ± 9.8	0.50915 ± 0.00539	14.0
7.30	7.50	2.797 ± 1.149	36.2 ± 6.6	0.03326 ± 0.00292	12.8	1.497 ± 0.569	58.2 ± 9.0	0.33437 ± 0.00292	13.0
7.50	7.70	3.040 ± 1.215	40.1 ± 6.3	0.01333 ± 0.00218	19.7	1.798 ± 0.611	63.4 ± 7.6	0.13443 ± 0.00212	18.7
7.70	7.90	2.637 ± 0.743	46.3 ± 5.3	0.00899 ± 0.00099	11.4	1.507 ± 0.409	73.7 ± 7.6	0.00906 ± 0.00101	11.9
7.90	8.10	1.769 ± 0.565	41.8 ± 5.3	0.00784 ± 0.00119	28.6	1.071 ± 0.275	70.3 ± 6.6	0.00788 ± 0.00111	25.0
8.10	8.30	2.245 ± 0.704	43.9 ± 6.1	0.00513 ± 0.00078	33.7	1.427 ± 0.374	68.4 ± 7.2	0.00516 ± 0.00075	31.1
8.30	8.50	1.590 ± 0.221	70.9 ± 4.9	0.00383 ± 0.00055	20.9	1.043 ± 0.144	104.8 ± 6.9	0.00402 ± 0.00057	22.9
8.50	8.70	2.822 ± 0.657	55.3 ± 7.7	0.00226 ± 0.00113	176.4	2.018 ± 0.401	76.1 ± 8.4	0.00234 ± 0.00113	175.0
8.70	8.90	2.625 ± 0.203	90.7 ± 4.7	0.00270 ± 0.00074	72.2	1.816 ± 0.134	129.2 ± 6.0	0.00297 ± 0.00075	75.1
8.90	9.10	2.804 ± 0.143	120.0 ± 4.4	0.00315 ± 0.00108	80.9	1.974 ± 0.090	167.0 ± 5.1	0.00412 ± 0.00099	71.9
9.10	9.30	2.625 ± 0.147	145.8 ± 6.3	0.00382 ± 0.00222	179.6	1.862 ± 0.064	204.0 ± 5.0	0.00655 ± 0.00135	76.6
9.30	9.50	2.972 ± 0.196	211.1 ± 12.8	0.00000 ± 0.00653	573.8	2.096 ± 0.053	307.1 ± 6.0	0.00163 ± 0.00218	102.3
9.50	9.70	1.230 ± 0.135	252.2 ± 33.5	0.00000 ± 0.00814	396.6	0.865 ± 0.048	392.4 ± 20.4	0.00000 ± 0.00360	138.3
9.70	9.90	1.170 ± 0.040	373.7 ± 23.0	0.00000 ± 0.01244	92.1	0.890 ± 0.021	424.0 ± 11.1	0.03903 ± 0.00494	48.7
9.90	10.10	1.210 ± 0.027	512.0 ± 32.6	0.00000 ± 0.02142	104.8	0.896 ± 0.023	503.7 ± 17.3	0.09480 ± 0.01016	125.9

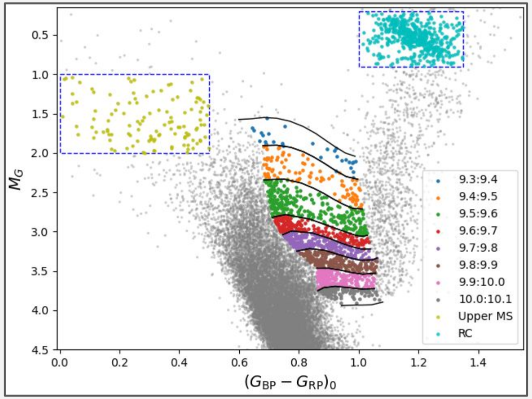
Adding a spatial correlation

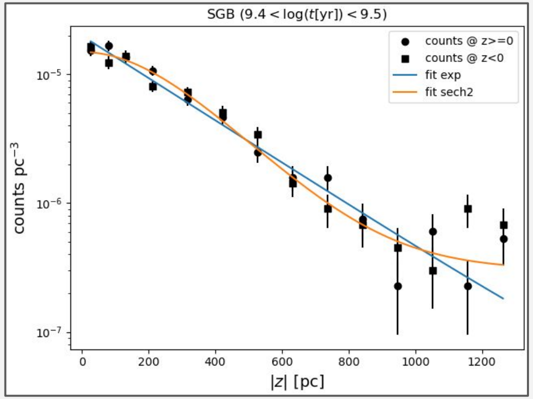


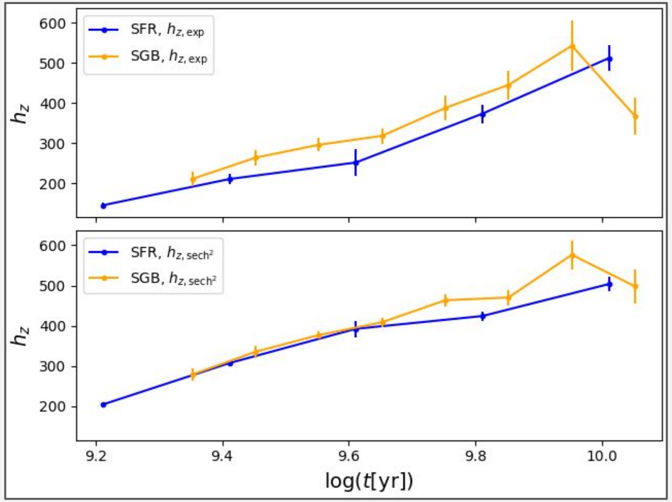


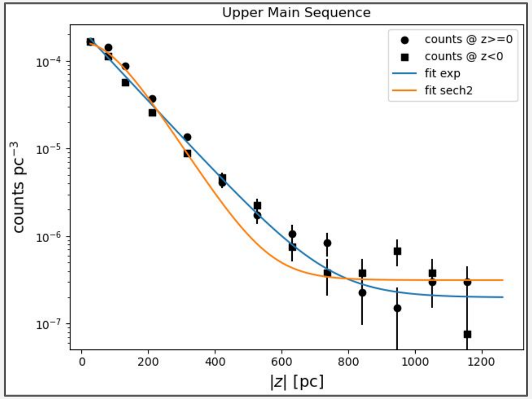


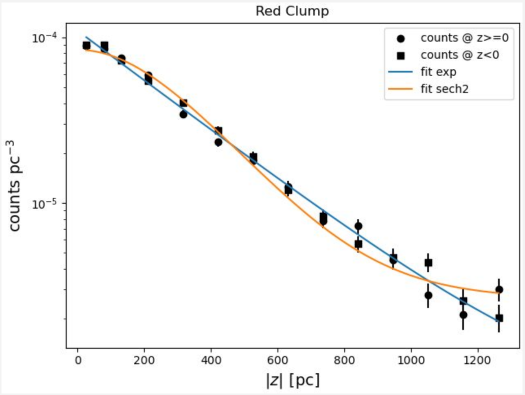
Comparison with star counting methods











Comparison with star counting methods

Phase	$\log(t_1\,[\mathrm{yr}])$	$\log(t_2\,[\mathrm{yr}])$	$f_{\exp}$ A $[10^{-5}\mathrm{counts\,pc^{-3}}]$	$f_{\exp}$ h_z [pc]	$f_{\exp}$ c $[10^{-5}\mathrm{counts\,pc^{-3}}]$	$f_{\exp}$ χ^2	f_{sech^2} A $[10^{-5}\mathrm{counts\,pc^{-3}}]$	f_{sech^2} h_z [pc]	f_{sech^2} c $[10^{-5}\mathrm{counts\,pc^{-3}}]$	f_{sech^2} χ^2
SGB	9.3	9.4	0.800 ± 0.062	211.4 ± 16.8	0.0080 ± 0.0048	25.4	0.577 ± 0.040	278.6 ± 16.1	0.0144 ± 0.0038	24.1
	9.4	9.5	1.990 ± 0.123	264.2 ± 19.5	0.0015 ± 0.0146	52.5	1.461 ± 0.071	335.3 ± 14.5	0.0301 ± 0.0084	37.7
	9.5	9.6	5.009 ± 0.221	296.3 ± 16.8	0.0000 ± 0.0319	75.0	3.693 ± 0.104	376.8 ± 9.8	0.0685 ± 0.0148	36.2
	9.6	9.7	3.623 ± 0.154	318.7 ± 19.4	0.0000 ± 0.0283	53.3	2.646 ± 0.076	408.7 ± 11.7	0.0497 ± 0.0137	29.2
	9.7	9.8	3.378 ± 0.149	388.1 ± 31.6	0.0000 ± 0.0497	64.8	2.536 ± 0.078	463.3 ± 16.1	0.0832 ± 0.0217	35.5
	9.8	9.9	3.126 ± 0.107	445.3 ± 36.1	0.0000 ± 0.0585	39.8	2.352 ± 0.077	470.2 ± 19.2	0.1689 ± 0.0270	35.4
	9.9	10.0	3.096 ± 0.114	542.8 ± 63.6	0.0000 ± 0.1062	50.5	2.285 ± 0.090	576.5 ± 35.8	0.1804 ± 0.0566	57.5
	10.0	10.1	1.584 ± 0.116	367.7 ± 47.0	0.0000 ± 0.0320	77.0	1.109 ± 0.076	497.9 ± 41.9	0.0117 ± 0.0239	84.8
Upper main sequence			22.892 ± 1.160	106.3 ± 4.0	0.0199 ± 0.0115	167.4	16.184 ± 0.882	147.0 ± 5.5	0.0314 ± 0.0127	219.5
Red Clump			10.890 ± 0.307	288.3 ± 10.2	0.0571 ± 0.0436	61.8	8.131 ± 0.257	347.0 ± 9.9	0.2639 ± 0.0341	87.6

Integrated SFR

$\log(t_1\,[\mathrm{yr}])$	$\log(t_2\,[\mathrm{yr}])$	Ψ_{SFR} $[10^{-9}\mathrm{M_\odot\,yr^{-1}\,pc^{-2}}]$	$\Psi_{\exp}(t)$	$\Psi_{\mathrm{sech}^2}(t)$
6.60	7.10	$6.20^{+3.00}_{-2.60}$	3.29	3.14
7.10	7.30	$5.70^{+4.00}_{-2.70}$	4.93	4.63
7.30	7.50	$3.10^{+2.60}_{-1.50}$	2.90	2.52
7.50	7.70	$2.80^{+2.20}_{-1.40}$	2.79	2.59
7.70	7.90	$2.80^{+2.30}_{-1.20}$	2.68	2.43
7.90	8.10	$2.11^{+1.00}_{-0.82}$	1.69	1.69
8.10	8.30	$2.44^{+1.09}_{-0.83}$	2.11	2.07
8.30	8.50	$2.31^{+0.76}_{-0.72}$	2.36	2.28
8.50	8.70	$4.21^{+0.59}_{-0.54}$	3.18	3.12
8.70	8.90	$4.97^{+0.54}_{-0.47}$	4.83	4.76
8.90	9.10	$6.81^{+0.50}_{-0.47}$	6.81	6.69
9.10	9.30	$7.79^{+0.45}_{-0.43}$	7.76	7.75
9.30	9.50	$12.99^{+0.53}_{-0.54}$	12.52	12.89
9.50	9.70	$7.09^{+0.59}_{-0.59}$	6.17	6.74
9.70	9.90	$8.60^{+0.49}_{-0.48}$	8.49	8.37
9.90	10.10	$11.47^{+0.39}_{-0.38}$	11.44	11.00