Formation of stars and star clusters

R. Wünsch

EWASS 2017 / 29th June 2017

Related to:

S05 - High mass stars, their feedback and massive star clusters

(Symposium to celebrate Guillermo Tenorio-Tagle's life-long contribution to Astrophysics)

Special thanks to:
G. Tenorio-Tagle, J. Palouš, S. Walch-Gassner, A. Whitworth
S. Ehlerová, S. Silich, S. Martinez-Gonzalez, C. Muñoz-Tuñón
SILCC team (S. Walch-Gassner, D. Derrigs, P. Girichidis, T. Naab, A. Gatto, T. Peters,
S. C. O. Glover, R. S. Klessen, Ch. Baczynski, P. C. Clark)

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EWASS 2

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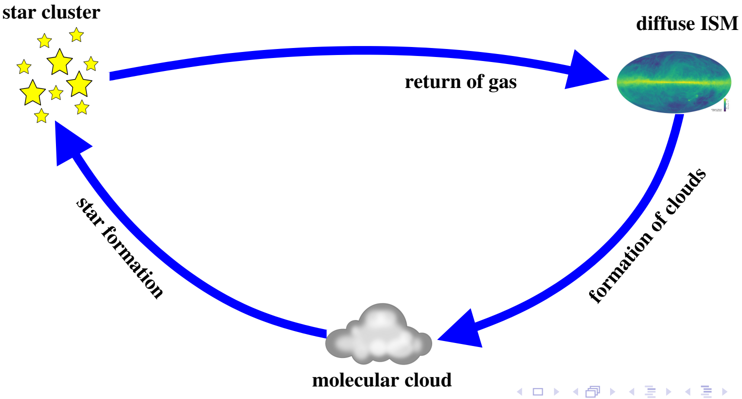
Star gas cycle in galaxies



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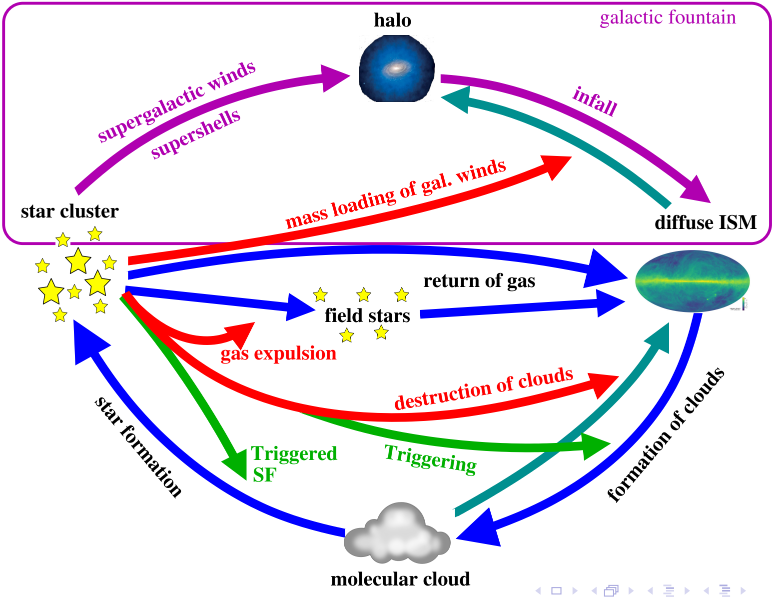

Star formation on galactic scales

- stars are formed in clusters, most clusters disperse young (Lada&Lada03)
- star formation related to interstellar gas:
  $\rightarrow$ all gas (atomic + molecular): $\Sigma_{\rm SFR} \sim \Sigma_{\rm gas}^{1.4}$ (Schmidt59, Kennicutt98)
  $\rightarrow$ molecular gas (clouds): ${\rm SFR} \sim M_{\rm dense}$ (Bigiel+08, Leroy+08, Schruba+11)
- star formation is inefficient (SFE$\sim 1-3$%)
- molecular gas depletion time: $1-2$ Gyr
- molecules not necessary for SF (glover&clark12)

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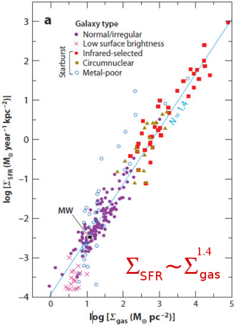
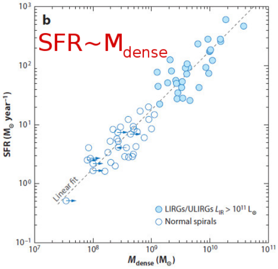


Gao & Solomon (2004)



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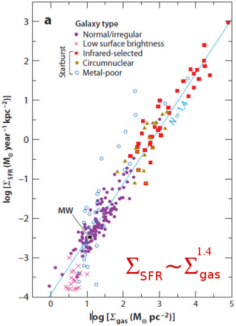

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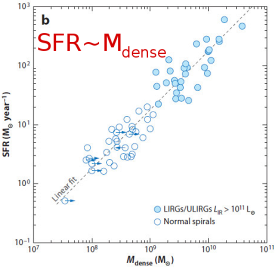

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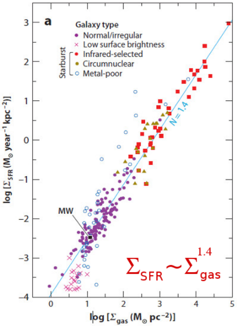

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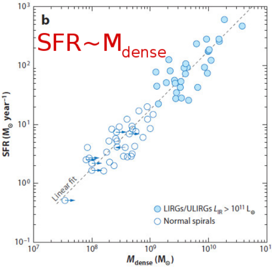
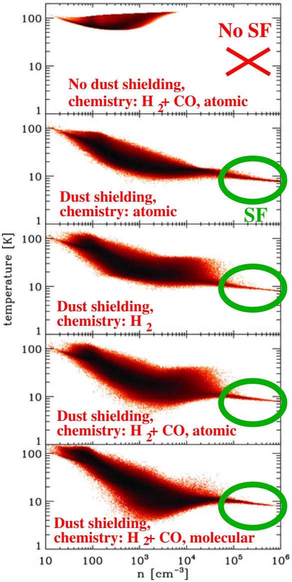


Glover&Clark (2012)



Star formation on galactic scales: models

- dynamical model of star formation (Larson69, Silc87, Elmegreen+97, Krumholz&McKee05, Krumholz&Tan07, Krumholz+09, . . .)

$$\Sigma_{\rm SFR} = \epsilon_{\rm SF} \Sigma_{\rm gas} / t_{\rm ff}, \qquad t_{\rm ff} \sim 1/\sqrt{G\rho}$$

  with constant gal. disc scale height: $\rho = \Sigma_{\rm gas}/2H$:

$$\Sigma_{\rm SFR} \sim \Sigma_{\rm gas}^{1.5}$$

- linear molecular SF law: $\Sigma_{\rm SFR} \sim \Sigma_{\rm mol}$
  → SF occurs in molecular clouds at fixed rate per molecule (Krumholz+09),
  → alternatively, see Elmegreen15 based on life time of CO emitting phase
- long mol. gas depletion times: $t_{\rm dep} \sim 1 - 2\,$Gyr ⇒ low SFE ($\epsilon_{\rm ff} = t_{\rm ff}/t_{\rm dep}$)
- only small fraction of densest gas participates on SF
  → mol. clouds turbulent ⇒ log-normal density distribution (Vazquez-Semadeni+94, Federrath+11, Girichidis+14)
  → or not (Lombardi+15, Alves+16), see also Ossenkopf-Okada+16
- SF in galaxies extensively studied numerically (Offner@S03, Avillez&Breitschwerdt05, Ostriker+10, Dib+11, Hill+12, Hopkins+14, Kim&Ostriker+15, Rey-raposo@S05, . . .)

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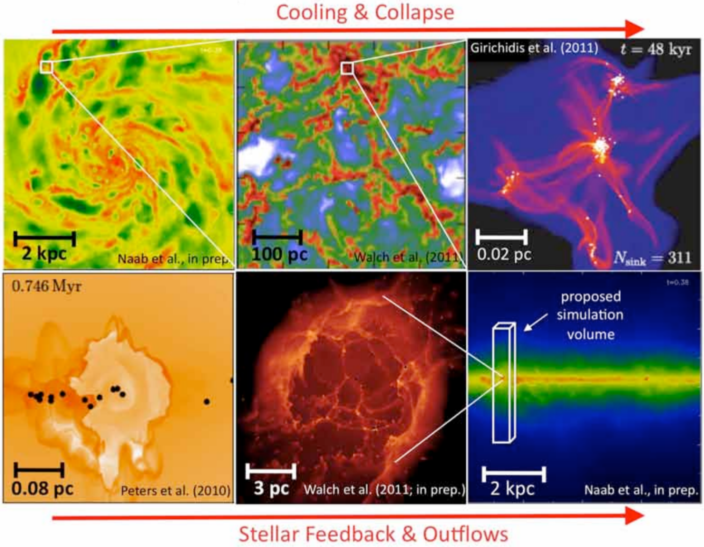
SImulating Life Cycle of Clouds (SILCC)

- aim: simulate ISM in a part of a galactic disc
- included physics: chem. network, ISRF, self-gravity, mag. fields, feedback: SNe, stellar winds, ionising rad.



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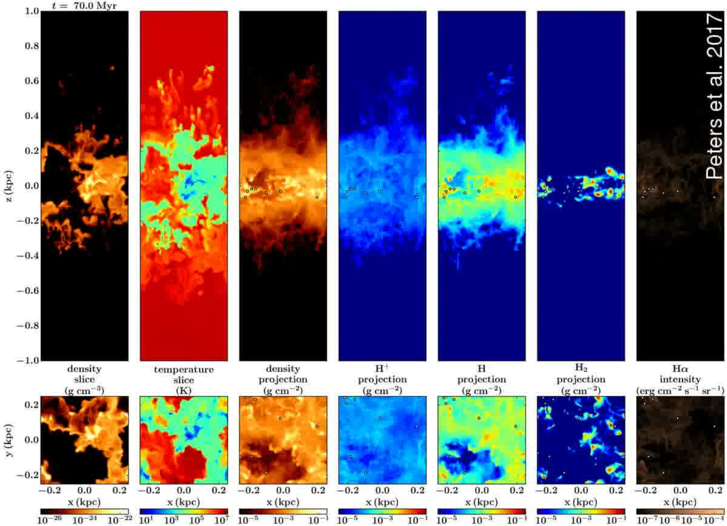


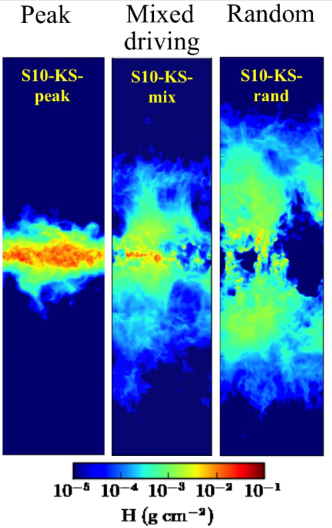
https://hera.ph1.uni-koeln.de/ silcc/video/silcc4/frwsn_halpha.html

SILCC: selected results

- to get realistic vertical gas distribution, SNe must explode in low density gas (Walch+15, Girichidis+16)
- stellar winds help to regulate SF

  (no delay in comparison with SNe)
- stellar winds: anticorrelation between SC mass and their formation times; cnf. (Dib+17,@S05: SFE - Δt plane)
- combination of processes important:

  e.g. self-gravity needed to get correct soft X-ray flux from halo gas (Peters+16)
- clustering of SNe leads to slightly higher fraction of mol. gas due to formation of supershells (Walch+15)



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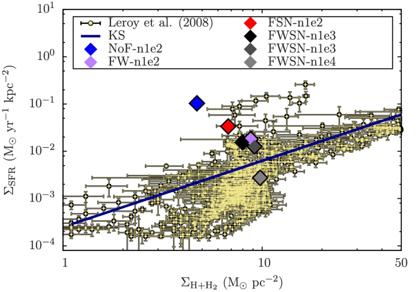

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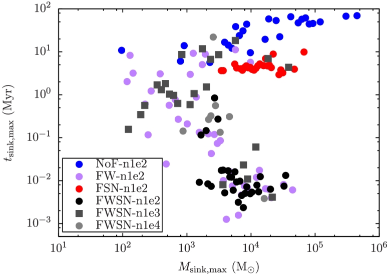

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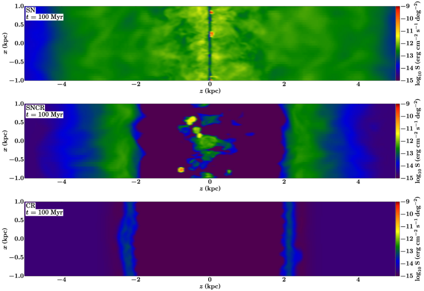

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Importance of feedback on formation of MC

- HI supershells may trigger formation of CO clouds

  → LMC (Dawson+13), MW (Ehlerová&Palouš16)
- evidence for molecular clouds formed by shell-shell collisions

  → nearby galaxies (Dawson+15, Egorov@S05)
- cloud formation by shells supported by models (Tenorio-Tagle&Różyczka85,86, Whitworth+94, Hartmann+01, Elmegreen+02, Ntormousi+11)

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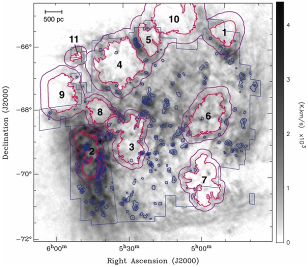

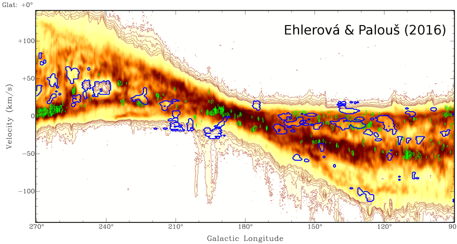

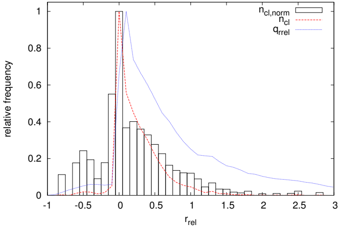

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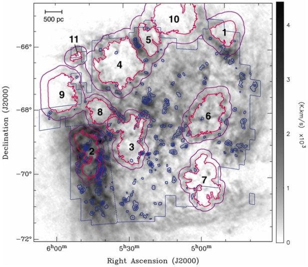

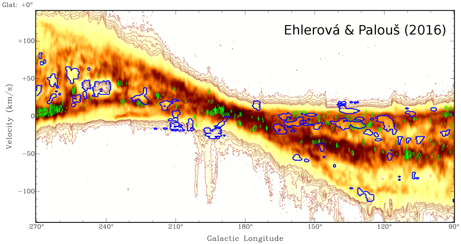

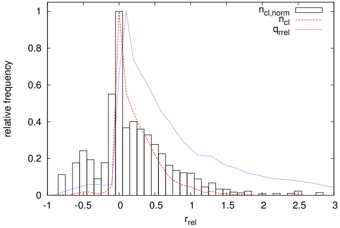

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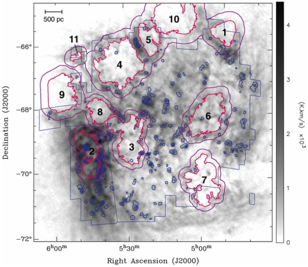

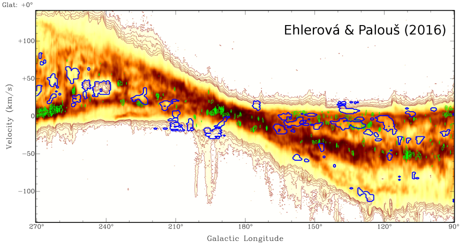

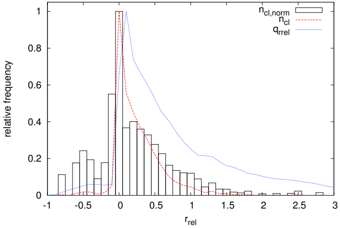

Galactic fountain & superwinds

- supershells may break out of HI disc
  → galactic fountain
  → super-galactic winds
  (Tenorio-Tagle+03, Melioli+13)
- dense wind may cool ⇒ more massive clusters may provide less feedback
  (Tenorio-Tagle+07, Wünsch+08, Palouš+13)
- applied to starburst dwarfs (e.g. Green Peas)
  → question of LyC escape (Oey@S05, Orlitova@S05)

TT03

M82 (NASA/ESA)

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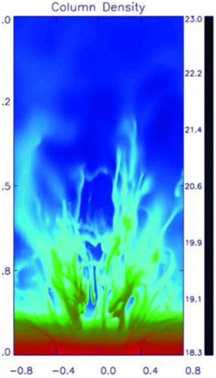

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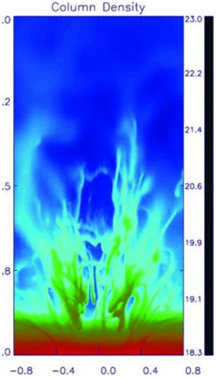

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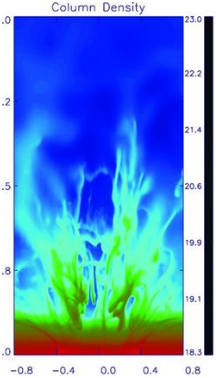
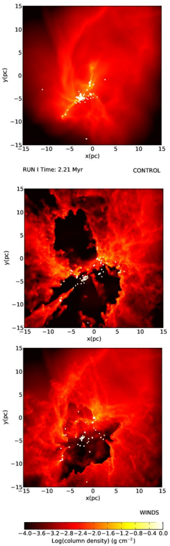


Feedback on a scale of a single molecular cloud

- mainly negative: cloud dispersed by:
  → ionising radiation
  → stellar winds
  (but they may escape Harper-Collins&Murray08)
  → radiation pressure
  (e.g. Krumholz+05-10, Kuiper+11,12)
  → supernovae (but they may come too late (Hollyhead+15))

- unless clouds are too massive ($\gtrsim 10^5\,M_\odot$) and compact (Dale+15, Krause+16, Silich@S05, Rahner@S05, Geen@S05, Parmentier@S05)
  → do massive star clusters form with high SFE?

- expanding shells may trigger SF
  → collect and collapse, radiation driven implosion
  → hard to differ observationally between "weak" and "strong" triggering (Dale+15)



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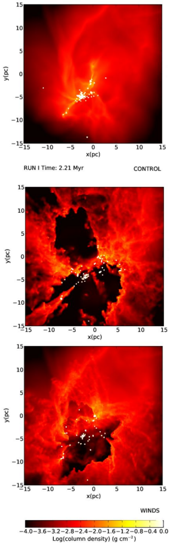

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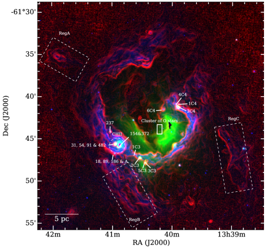
  → supernovae (but they may come too late (Hollyhead+15))



RCW79 (Herschel, Liu+17)

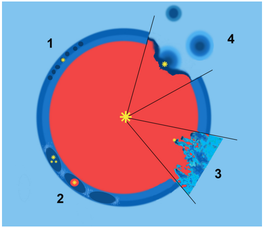
- unless clouds are too massive ($\gtrsim 10^5\,M_\odot$) and compact (Dale+15, Krause+16, Silich@S05, Rahner@S05, Geen@S05, Parmentier@S05)

  → do massive star clusters form with high SFE?

- expanding shells may trigger SF

  → collect and collapse, radiation driven implosion

  → hard to differ observationally between "weak" and "strong" triggering (Dale+15)



(Deharveng+10)

Massive Star Clusters

- Are nearby young massive clusters and globular clusters the same objects at different evolutionary stage?
- GCs include multiple stellar populations (Bedin+04)
- photometric evidence:
  → split main-sequence (also RGB, SGB, EHB, turn-off points) (Piotto+07, Bellini+10, Milone11,12,13,15, . . .)
- spectroscopy:
  → anticorrelations among pairs of light elements (e.g. Na-O) Carreta+07,09
  → most of GC have the same metallicity (e.g. Renzini+15)
  ⇒ origin from one cloud
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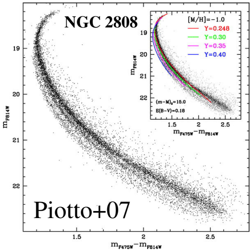
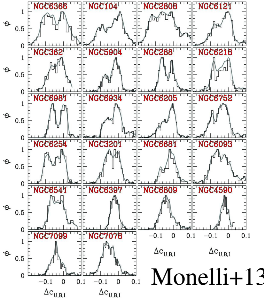


Piotto+07



Monelli+13

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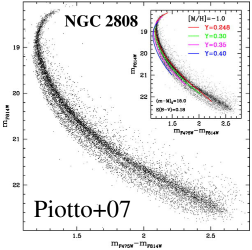

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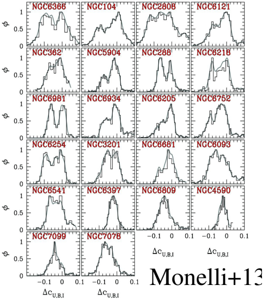

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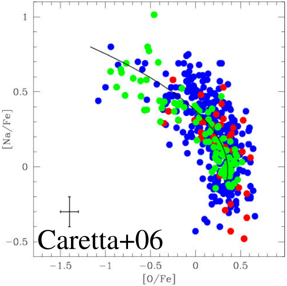

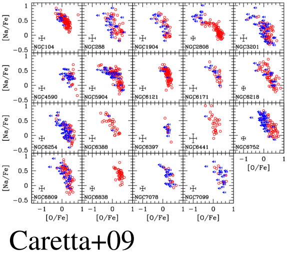

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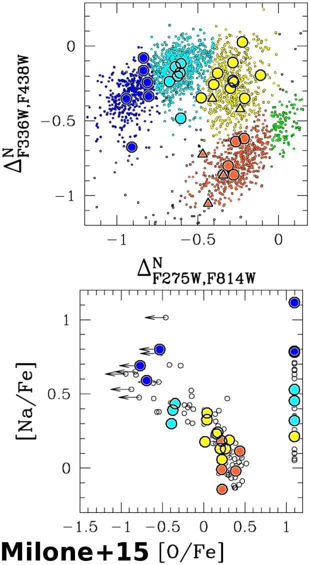

Milone+15

Models trying to explain MSP

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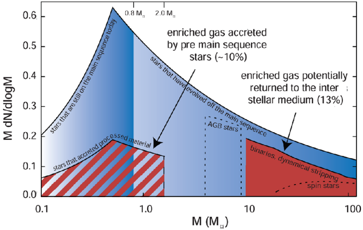
Bastian+13



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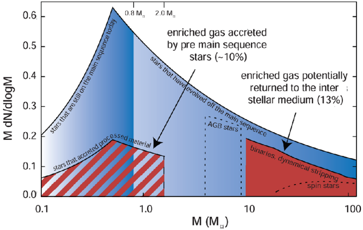
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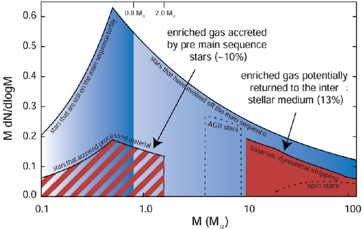

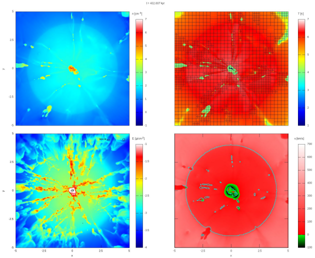

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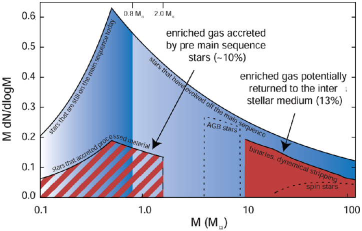

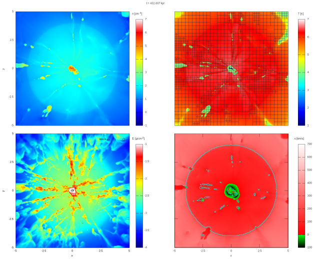

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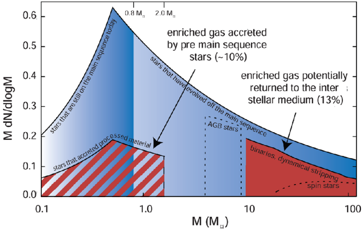

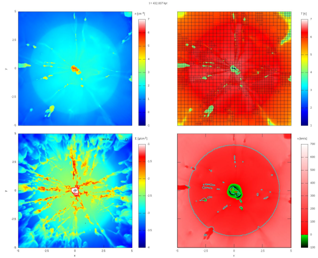

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Summary

- feedback essential for star formation
  → maintains low SF efficiency, regulates SF
  → responsible for star cluster early dispersal
  → can also trigger formation of clouds and stars
  → probably contributes to mechanism yielding stellar IMF

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Happy birthday, Guillermo!