Clustered Supernovae

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Big picture

- Feedback is important

\[ \Sigma_{\text{gas}} [M_\odot \text{ pc}^{-2}] \]
Big picture

• Feedback is important

• Feedback not fully understood

TOWARD A COMPLETE ACCOUNTING OF ENERGY AND MOMENTUM FROM STELLAR FEEDBACK IN GALAXY FORMATION SIMULATIONS

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Recall that the wind and SN momenta in Figure 4 refer to the initial \textit{ejecta} momentum and not any late stage momentum generated by an expanding bubble. The momentum expected from the ideal adiabatic S-T phase (Equation (12)) is greater than radiation pressure momentum even in the case of a supermassive ($M_{\text{cl}} = 10^6 M_\odot$) star cluster. However, as we argued above, it is not clear whether the S-T solution is applicable in the highly inhomogeneous density field of GMCs, especially if gas around young star clusters is partially cleared by early feedback.
Big picture

• Feedback is important

• Feedback not fully understood

• Developed better momentum-driven SN feedback model
Outline

Goal: momentum-driven feedback model of clustered SNe

- Background
- Numerics
- Results
- Implications
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Goal: momentum-driven feedback model of clustered SNe

• Background
• Numerics
• Results
• Implications
Momentum-Driven Clustered Supernova Feedback
Momentum-Driven Clustered Supernova Feedback
Why Feedback?

Get wrong answers without feedback
Why Feedback?

Morphology

Get wrong answers without feedback

No Feedback

With Feedback

\[ \Sigma_{\text{gas}} \left[ M_{\odot} \text{pc}^{-2} \right] \]
Why Feedback?
Star Formation Rate

Get wrong answers without feedback

![Graph showing Star Formation Rate over time with different feedback scenarios.](image)
Why Feedback?
Kennicutt-Schmidt relation

Get wrong answers without feedback

No Feedback

With Feedback

Hopkins+11
Why Feedback?
Kennicutt-Schmidt relation

Get wrong answers without feedback

No Feedback

With Feedback

\[
\log_{10}(\Sigma_{SFR}) \left[ \frac{M_\odot}{yr^{-1} \text{kpc}^2} \right]
\]

\[
\log_{10}(\Sigma_{\text{gas}}) \left[ \frac{M_\odot}{\text{pc}^2} \right]
\]

Hopkins+11
Why Feedback?
Galactic Winds

Get wrong answers without feedback

Full stellar feedback

Just rad. pressure

$T < 10^3 \text{K}$

$10^4 \text{K} < T < 10^5 \text{K}$

$10^6 \text{K} < T$

Hopkins+12; (Dekel & Silk 1986)
Why Feedback? Cusp-core problem

Get wrong answers without feedback

Dark matter dynamically heated by SN shocks

Mashchenko+06; (Governato+2012)
Why Feedback?

Get wrong answers without feedback
Momentum-Driven Clustered Supernova Feedback
Why SN Feedback?

Sudden shocks can affect CDM (Mashchenko+06)

![Graph showing dark matter density over radius, with initial and final states labeled as 'cusp' and 'core' respectively. The graph indicates dark matter dynamically heated by SN shocks.]
Why SN Feedback?

Sudden shocks can affect CDM (Mashchenko+06)

Key source of turbulence (Agertz+12)
Why SN Feedback?

Sudden shocks can affect CDM (Mashchenko+06)

Key source of turbulence (Agertz+12)

Could unbind gas in dwarf galaxies (Dekel & Silk+86)
Why SN Feedback?

Sudden shocks can affect CDM (Mashchenko+06)

Key source of turbulence (Agertz+12)

Could unbind gas in dwarf galaxies (Dekel&Silk+86)

SNe are difficult to simulate at low resolutions
\[(t - t_{SN}) = 0.00 \times 10^0 \text{ yr}\]

\[\rho \left[ \frac{\text{g cm}^{-3}}{} \right]\]

\[R \left[ \text{pc} \right]\]

\[E_{\text{R, tot}} \left[ \text{ergs} \right]\]

\[V \left[ \text{km s}^{-1} \right]\]

\[p \left[ \frac{\rho}{100M_{\odot}N_{\text{SN}}} \right]\]

\[t \left[ \text{Myr} \right]\]

Gentry+16 (in prep.)
\( (t - t_{SN}) = 3, 14 \times 10^4 \text{ yr} \)

\[ \rho \left[ \text{g cm}^{-3} \right] \]

- **numeric**
- **analytic (no cooling)**

\[ R \left[ \text{pc} \right] \]

\[ t \left[ \text{Myr} \right] \]

\[ E_{R, \text{tot}} \left[ \text{ergs} \right] \]

\[ \frac{\rho}{100 M_{\odot} N_{SN}} \left[ \text{km s}^{-1} \right] \]

Gentry+16 (in prep.)
\[(t - t_{SN}) = 3, 14 \times 10^4 \text{ yr}\]
\[(t - t_{SN}) = 3, 16 \times 10^6 \text{ yr}\]
$(t - t_{SN}) = 3, 16 \times 10^6 \text{ yr}$

\[ \rho [\text{g cm}^{-3}] \]

\[ R [\text{pc}] \]

- **numeric**
- **analytic (no cooling)**

\[ E_{R_{\text{tot}}} [\text{ergs}] \]

\[ p \left( \frac{100 M_{\odot}}{N_{\text{SN}}} \right) \]

\[ t [\text{Myr}] \]

Gentry+16 (in prep.)
\[(t - t_{SN}) = 1.87 \times 10^8 \text{ yr}\]

Gentry+16 (in prep.)
Thin Shell Determines SNR Evolution (SNe difficult for low res. simulations)

\[ (t - t_{SN}) = 3.38 \times 10^6 \text{ yr} \]

Gentry+16 (in prep.)
Momentum-Driven Clustered Supernova Feedback
Momentum-Driven Clustered Supernova Feedback
Why Momentum-Driven Feedback?

Turbulent support dominates in disks

(Hydro simulation: slab geometry, midplane values plotted)
Why *Momentum-Driven* Feedback?

Turbulent support dominates in disks

SNR has asymptotic momentum, but not energy

---

**Momentum**

**Energy**

\[ p/(100M_\odot N_{\text{SNR}}) \text{ [km s}^{-1}\text{]} \]

\[ E_{R,\text{tot}} \text{ [ergs]} \]

Gentry+16 (in prep.)
Momentum-Driven Clustered Supernova Feedback
Momentum-Driven Clustered Supernova Feedback
Isolated SN feedback

We know its momentum yield in a homogeneous ISM

\[ \frac{p}{N_{\text{SN}e}} \propto \rho^{-1/7} \]

Cioffi+98
Isolated SN feedback

We know its momentum yield in a homogeneous ISM

We know pre-SN inhomogeneities aren’t significant

Walch&Naab+2015
Isolated SN feedback

We know its momentum yield in a homogeneous ISM

We know pre-SN inhomogeneities aren’t significant

Authors can’t agree if multiple SNe change things
Clustered SNe Possibilities

- Lower density background: get more momentum?

Momentum $\propto \text{density}^{-1/7}$
Clustered SNe Possibilities

- Lower density background: get more momentum?

\[ \text{Momentum} \propto \text{density}^{-1/7} \]

Wolf Rayet star

X-rays
Optical
IR

N44 Bubble

Radius [pc]
Density [g cm\(^{-3}\)]

\((t - t_{SN}) = 3.38 \times 10^6\ \text{yr}\)

\(\text{numeric}\)
Clustered SNe Possibilities

• Lower density background: get more momentum?

• Adiabatic superbubbles create momentum less efficiently as energy increases

\[ E \sim \frac{p^2}{m} \]

\[ p \sim \sqrt{E \times m} \]

\[ \frac{p}{N} \sim \sqrt{E_0 \times \frac{m}{N}} \]

Castor+75
Castor+77
Chevalier&Clegg+85
Sharma+14
Clustered SNe Possibilities

• Lower density background: get more momentum?

• Adiabatic superbubbles create momentum less efficiently as energy increases
Clustered SNe Possibilities

• Lower density background: get more momentum?

• Adiabatic superbubbles create momentum less efficiently as energy increases

Let’s just simulate it directly
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Code Overview (Physics)

- Uniform initial conditions
Code Overview (Physics)

- Uniform initial conditions
- SNe winds + blasts added to central zone

\[ \text{Radius [pc]} \]
\[ \text{Density [g cm}^{-3}\text{]} \]

\[ (t - t_{SN}) = 0.00 \times 10^0 \text{ yr} \]
Code Overview (Physics)

- Uniform initial conditions
- SNe winds + blasts added to central zone

![Graph showing density vs. radius with a time difference notation \((t - t_{SN}) = 3.38 \times 10^6 \text{ yr}\).]
Code Overview (Physics)

- Uniform initial conditions
- SNe winds + blasts added to central zone
- 1D
Code Overview (Physics)

- Uniform initial conditions
- SNe winds + blasts added to central zone
- 1D, Lagrangian
Code Overview (Physics)

• Uniform initial conditions
• SNe winds + blasts added to central zone
• 1D, Lagrangian, Finite Volume (Toro+94; Duffel+16)

\[ (t - t_{SN}) = 3.38 \times 10^6 \text{ yr} \]

[Graph showing density vs. radius with a strong shock indicated]
Code Overview
(Physics)

• Uniform initial conditions
• SNe winds + blasts added to central zone
• 1D, *Lagrangian*, Finite Volume (Toro+94; Duffel+16)
• Cooling (*Grackle*)
Code Overview (Astrophysics)

Code Overview
(Astrophysics)

• Stochastically draw Kroupa (2002) IMF using SLUG2 (da Silva+12, Krumholz+15)

• Get lifetimes by Geneva tracks (Ekström+2012)
Code Overview
(Astrophysics)

• Stochastically draw Kroupa (2002) IMF using SLUG2 (da Silva+12, Krumholz+15)
• Get lifetimes by Geneva tracks (Ekström+2012)
• Add ejecta mass + metals (Woosley&Heger+07)
Code Overview (Astrophysics)

- Get lifetimes by Geneva tracks (Ekström+2012)
- Add ejecta mass + metals (Woosley&Heger+07)

- Evolved for until momentum reaches a maximum

Also tested additional physics!
Code in Action: 3 SNe
\[ (t - t_{\text{first,SN}}) = 0.00 \times 10^0 \text{ yr} \]

Gentry+16 (in prep.)
\[ (t - t_{\text{first \, SN}}) = 0.00 \times 10^0 \, \text{yr} \]

**Code in Action: 1000 SNe**
\[ (t - t_{\text{first SN}}) = 0.00 \times 10^0 \text{ yr} \]

Gentry+16 (in prep.)
Parameter Study

• Density
  • \( \rho = 10^{-3} - 10^2 \ m_H \ \text{cm}^{-3} \) (6 steps)

• Metallicity
  • \( Z = 10^{-3} - 10^{0.5} \ Z_\odot \) (7 steps)

• Cluster Mass
  • \( M = 10^2 - 10^5 \ M_\odot \) \( (N_{\text{SNe}} \approx 1 - 1000) \) (5 steps)
  • \( \approx 1 \ \text{SN} / 100 \ M_\odot \)
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Goal: momentum-driven feedback model of clustered SNe

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Results Overview

• Ran ~ 700 simulations

• Varied density, metalliccity, number of SNe

• We’ll focus on $N_{SNe}$
Scaling with $N_{SNe}$

\[ \text{density} = 1.33 \times 10^{-3} \, m_p \, \text{cm}^{-3} \]

\[ Z = 10^0 \, Z_\odot \]

Gentry+16 (in prep.)
Scaling with $N_{\text{SNe}}$

$p/(100\, M_{\odot} \, N_{\text{SNe}}) \, [\text{km s}^{-1}]$

$\rho = 1.33 \times 10^{-2} \, m_p \, \text{cm}^{-3}$

$Z = 10^0 \, Z_{\odot}$

Gentry+16 (in prep.)
Scaling with $N_{\text{SNe}}$

Density $= 1.33 \times 10^{-1} \, m_p \, \text{cm}^{-3}$

$Z = 10^0 \, Z_\odot$

Gentry+16 (in prep.)
Scaling with $N_{\text{SNe}}$

$\rho / (10^2 M_\odot N_{\text{SNe}}) [\text{km s}^{-1}]$

$N_{\text{SNe}}$

density = $1.33 \times 10^0 m_p \text{ cm}^{-3}$

$Z = 10^0 Z_\odot$

Gentry+16 (in prep.)
How about 2 power laws?

Gentry+16 (in prep.)
How about 2 power laws?

\[
\frac{p}{N_{SN e}}(\text{in prep.}) = \left(\frac{N_{SN e}}{1000}\right)^b \times \rho_k \times Z_i \times (\frac{N_{SN e}}{1000})^c \times (\frac{N_{SN e}}{1000})^d
\]
How about 2 power laws?

\[
\frac{p}{N_{\text{SN}}^0, \text{many}} \times Z^{a_2} \times \rho^{b_2} \times \left( \frac{N_{\text{SN}}}{1000} \right)^{c_2}
\]

\[
f(y_1, y_2) = \frac{y_1 y_2}{y_1 + y_2}
\]

\[
\frac{p}{N_{\text{SN}}^0, \text{few}} \times Z^{a_1} \times \rho^{b_1} \times \left( \frac{N_{\text{SN}}}{1} \right)^{c_1}
\]

Gentry+16 (in prep.)
Constrained Model

**Likelihood:** Gaussian

**Priors:** non-informative-ish

---

Gentry+16 (in prep.)
What’s going on?
What’s going on?

SNR Regime

Each SN is lower density background

$p/(100 \ M_\odot N_{SNe})$ [km s$^{-1}$]

$N_{SNe}$

Gentry+16 (in prep.)
\((t - t_{\text{first.SN}}) = 0.00 \times 10^0 \text{ yr}\)
$(t - t_{\text{first SN}}) = 0.00 \times 10^0 \text{ yr}$

$\rho \left[ \text{g cm}^{-3} \right]$ vs $R \left[ \text{pc} \right]$ and $E_{R, \text{tot}} \left[ \text{ergs} \right]$ vs $t \left[ \text{Myr} \right]$

$\frac{p}{100 M_\odot N_{\text{SN}}}$ vs $t \left[ \text{Myr} \right]$

Gentry+16 (in prep.)
\( (t - t_{\text{first SN}}) = 9.10 \times 10^5 \text{ yr} \)
\( (t - t_{\text{first}, \SN}) = 1.24 \times 10^6 \text{ yr} \)

\( \rho \) [g cm\(^{-3}\)]

\( t \) [Myr]

\( R \) [pc]

\( E_{R, \text{tot}} \) [ergs]
$\left(t - t_{\text{first. SN}}\right) = 1.09 \times 10^7 \text{ yr}$

Gentry+16 (in prep.)
\[(t - t_{\text{first. SN}}) = 1.13 \times 10^7 \text{ yr}\]
\((t - t_{\text{first SN}}) = 5.01 \times 10^7 \text{ yr}\)
What’s going on?
SNR Regime

Each SN is lower density background

\[ \frac{p}{(100 \, M_\odot \, N_{SNe})} \, [\text{km s}^{-1}] \]

- Model
- Ostriker & Shetty (2011)
- Simulations

Gentry+16 (in prep.)
What’s going on?
Superbubble Regime

$\frac{p}{(100 \, M_\odot \, N_{\text{SNe}})}$ [km s$^{-1}$]

- Model
- Ostriker & Shetty (2011)
- Simulations

Gentry+16 (in prep.)
\((t - t_{\text{first SN}}) = 0.00 \times 10^0 \text{ yr}\)

\(\rho [\text{g cm}^{-3}]\)

\(R [\text{pc}]\)

\(E_{R, \text{tot}} [\text{ergs}]\)

\(\frac{\rho}{100M_{\odot}} \text{N}_{\text{SNe}} [\text{km s}^{-1}]\)

Gentry+16 (in prep.)
\( (t - t_{\text{first SN}}) = 0.00 \times 10^0 \text{ yr} \)
\[ (t - t_{\text{first SN}}) = 3.15 \times 10^7 \text{ yr} \]

\[ \rho \left[ \text{g cm}^{-3} \right] \]

\[ E_{R, \text{tot}} \left[ \text{ergs} \right] \]

\[ \frac{\rho}{100 M_{\odot} N_{\text{SN}} \text{ km s}^{-1}} \]

\[ R \left[ \text{pc} \right] \]

\[ t \left[ \text{Myr} \right] \]

Gentry+16 (in prep.)
\( (t - t_{\text{first SN}}) = 3.96 \times 10^7 \text{ yr} \)

Gentry+16 (in prep.)
What's going on? Superbubble Regime

Depends on swept-up mass

\( p/(100 \, M_\odot \, N_{SNe}) \) [km s\(^{-1}\)]

Gentry+16 (in prep.)
What’s going on?
Superbubble Regime

$E \sim p^2 / m$

$\frac{p}{(100 \, M_\odot \, N_{SNe})} \, [\text{km} \, \text{s}^{-1}]$

$N_{SNe}$

Depends on swept-up mass

Gentry+16 (in prep.)
What’s going on? Superbubble Regime

Depends on swept-up mass

\[ E \sim p^2 / m \]

\[ p \sim \sqrt{E \times m} \]
What’s going on?
Superbubble Regime

\[ E \sim \frac{p^2}{m} \]

\[ p \sim \sqrt{E \times m} \]

\[ p \sim \sqrt{E_0 N m} \]

Depends on swept-up mass

\[ p \sim \frac{E}{\sqrt{m}} \]

\[ E \sim \frac{p^2}{m} \]

Gentry+16 (in prep.)
What’s going on? Superbubble Regime

\[ E \sim p^2 / m \]
\[ p \sim \sqrt{E \times m} \]
\[ p \sim \sqrt{E_0 N m} \]
\[ p / N \sim \sqrt{E_0 m / N} \]
What’s going on? Superbubble Regime

\[ (t - t_{\text{first SN}}) = 0.00 \times 10^0 \, \text{yr} \]

\[ p \sim E \times m \]

\[ p \sim \sqrt{E_0 N m} \]

\[ p/N \sim \sqrt{E_0 m/N} \]

\[ m/N \propto N^{-0.4} \]

Gentry+16 (in prep.) Castor+75
What’s going on?
Superbubble Regime

\( \rho \sim E \times m \)
\( p \sim \sqrt{E} \times m \)
\( \frac{p}{N} \sim \sqrt{E_0 N} \times m \)
\( \frac{m}{N} \propto N^{-0.4} \)
\( \frac{p}{N} \sim N^{-0.2} \)
What’s going on?
Superbubble Regime

\( (t - t_{\text{first SN}}) = 3.96 \times 10^7 \text{ yr} \)

\begin{align*}
\rho & \sim E \times m \\
p & \sim \sqrt{E} \times m \\
p & \sim \sqrt{E_0 N} \times m \\
p/N & \sim \sqrt{E_0 \frac{m}{N}} \\
m/N & \propto N^{-0.4 (1 - \frac{1}{\gamma})} \\
\frac{p}{N} & \sim N^{-0.2 (1 - \frac{1}{\gamma})}
\end{align*}

Gentry+16 (in prep.)
What’s going on?
Superbubble Regime

Predicted:
\[ \frac{p}{N} \sim N^{-0.08} \]

Data:
\[ \frac{p}{N} \sim N^{-0.07 \pm 0.02} \]
Results: summary

- Each SN is lower density background
- Depends on swept-up mass

![Graph showing the relationship between $p/(100 M_\odot N_{SN_e})$ [km s$^{-1}$] and $N_{SN_e}$ with model and simulations data points.]

Gentry+16 (in prep.)
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Goal: momentum-driven feedback model of clustered SNe

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More momentum than expected!

Peak: 30,000
Expected: 3,000
More momentum than expected!

Peak: 30,000

Expected: 3,000

\[
\frac{dN_{\text{cluster}}}{dM_{\text{cluster}}} \propto M^{-2}
\]

\[
\frac{dN_{\text{cluster}}}{dN_{\text{SNe}}} \propto N_{\text{SNe}}^{-2}
\]

\[
\frac{dN_{\text{cluster}}}{d \log N_{\text{SNe}}} \propto N_{\text{SNe}}^{-1}
\]

\[
\langle N_{\text{SNe}} \rangle = 6
\]

\[
\frac{p}{\langle N_{\text{SNe}} \rangle} = 25,000 \pm 1,000 \frac{100 M_{\odot} \text{ km}}{s}
\]
Why has this gone unnoticed?

Previous: 3,000
Now: 25,000
Previous studies didn’t find it

Kim & Ostriker + 15

$p/100 M_\odot N_{\text{SN(e)}}$ [km s$^{-1}$]

$t$ [Myr]

3D + Low res (2.5 pc)

1D + Lagrangian + High res. (0.06 pc)

Gentry + 16 (in prep.)
Why has this gone unnoticed?
Can’t explain by 3D vs 1D

Yadav+16 (submitted)
Why has this gone unnoticed? Previous studies underresolved.

\[ \frac{p}{100 \, M_\odot \, N_{\text{SN}} } \] [km s\(^{-1}\)]

- 3D + Low res (2.5 pc)

- 1D

\[ \frac{p}{100 \, M_\odot \, N_{\text{SN}} } \] [km s\(^{-1}\)]

Gentry+16 (in prep.)
Low resolution leads to overcooling

Eulerian (2.5 pc)

Lagrangian (0.06 pc)

Gentry+16 (in prep.)
Low resolution leads to overcooling

Eulerian (2.5 pc)  
Lagrangian (0.06 pc)
Implications for galactic models

\[ \eta_{\text{turb}} = \frac{F'}{2\sqrt{2}\phi} f_{\text{out}} \left( \frac{P_*}{m_*} \right) \sigma_T^{-1} \]

\[ \approx 10^2 \frac{F'}{\phi} f_{\text{out}} \left( \frac{P_*/m_*}{3000 \text{ km s}^{-1}} \right) \left( \frac{\sigma_T}{10 \text{ km s}^{-1}} \right)^{-1} \]  \hspace{1cm} (30)

\[ \eta_{\text{turb}} = \frac{F'}{2Q_{\text{turb}}\phi} f_{\text{out}} \left( \frac{P_*}{m_*} \right) \left( f_g v_{c,\text{gal}} \right)^{-1} \]

\[ \approx 15 \frac{F'}{Q_{\text{turb}}\phi} f_{\text{out}} \left( \frac{P_*/m_*}{3000 \text{ km s}^{-1}} \right) \]

\[ \times \left( \frac{f_g v_{c,\text{gal}}}{100 \text{ km s}^{-1}} \right)^{-1} \]  \hspace{1cm} (33)

Hayward&Hopkins+16 (submitted)
Implications for Galaxy Formation

\[ \eta_{\text{turb}} = \frac{\mathcal{F}'}{2Q_{\text{turb}} \phi} f_{\text{out}} \left( \frac{P_*}{m_*} \right) (f_g v_{c,\text{gal}})^{-1} \]

\[ \approx 15 \frac{\mathcal{F}'}{Q_{\text{turb}} \phi} f_{\text{out}} \left( \frac{P_*/m_*}{3000 \text{ km s}^{-1}} \right) \]

\[ \times \left( \frac{f_g v_{c,\text{gal}}}{100 \text{ km s}^{-1}} \right)^{-1}. \]
Future Directions

• Simple predictions for effects on galactic evolution
Future Directions

• Simple predictions for effects on galactic evolution

• 3D disk blowout

Mac Low+89
Future Directions

• Simple predictions for effects on galactic evolution

• 3D simulations: disk blowout

• Galactic/cosmological simulations (self-consistent)
Conclusions
Conclusions

• Previous studies unresolved
Conclusions

• Previous studies unresolved
• SN momentum $\sim 8 \times$ stronger than thought

![Graph showing SN momentum versus number of SNe]
Additional Slides
Other stellar feedback: Pre-SN HII Regions

Ionizing radiation from massive stars creates HII regions.

HII regions expand, adding momentum and decreasing the gas density.

This directly adds momentum:
• $p_{HII} \lesssim 50\% p_{SNe}$

This changes effective density:
• Changes momentum by a few percent.
Other stellar feedback: Type Ia SNe

Type Ia SNe can have an impact,
But that impact is smaller than the model’s uncertainties
Constructing our model

- Data looks like two powerlaws: small-N and large-N
Constructing our model

• Data looks like two powerlaws: small-N and large-N

\[
\left( \frac{p}{N_{SNe}} \right)_{few} = \left( \frac{p}{N} \right)_{0,few} \times Z^{a_1} \times \rho^{b_1} \times \left( \frac{N_{SNe}}{1} \right)^{c_1}
\]

\[
\left( \frac{p}{N_{SNe}} \right)_{many} = \left( \frac{p}{N} \right)_{0,many} \times Z^{a_2} \times \rho^{b_2} \times \left( \frac{N_{SNe}}{10^3} \right)^{c_2}
\]
Constructing our model

• Data looks like two powerlaws: small-N and large-N

\[
\frac{p}{N_{SNNe}}_{few} = \left(\frac{p}{N}\right)_{0,few} \times Z^{a_1} \times \rho^{b_1} \times \left(\frac{N_{SNNe}}{1}\right)^{c_1}
\]

\[
\frac{p}{N_{SNNe}}_{many} = \left(\frac{p}{N}\right)_{0,many} \times Z^{a_2} \times \rho^{b_2} \times \left(\frac{N_{SNNe}}{10^3}\right)^{c_2}
\]

\[
\frac{p}{N_{SNNe}} = \frac{\left(\frac{p}{N_{SNNe}}\right)_{few} \times \left(\frac{p}{N_{SNNe}}\right)_{many}}{\left(\frac{p}{N_{SNNe}}\right)_{few} + \left(\frac{p}{N_{SNNe}}\right)_{many}}
\]

\[
\frac{p}{N_{SNNe}} \approx \min\left[\left(\frac{p}{N_{SNNe}}\right)_{few}, \left(\frac{p}{N_{SNNe}}\right)_{many}\right]
\]
Maximum Likelihood Estimate

\[ \frac{p}{N} \approx \min\left[ \frac{p}{N}_{\text{few}}, \quad \frac{p}{N}_{\text{many}} \right] \]
Maximum Likelihood Estimate

\[ \frac{p}{N} \approx \min\left(\frac{p}{N}_{\text{few}}, \quad \frac{p}{N}_{\text{many}}\right) \]
Constructing our model, $y(x)$: Predicting uncertainty?

- MLE assumed a Gaussian likelihood with variance $= \sigma^2$
  - Gives uncertainties, if model parameters perfectly known
  - And the MLE gives no information on $\sigma$

- Need Bayesian inference for uncertainties of model parameters
  - This requires a prior, $\pi(\theta)$
    \[
    \pi(\log \sigma^2, \log(p/N)_{0,\text{few}}, \log(p/N)_{0,\text{many}}, a_1, a_2, b_1, b_2, c_1, c_2) \propto 1
    \]
Constructing our model, $y(x)$: Predicting uncertainty?

- MLE assumed a Gaussian likelihood with variance $= \sigma^2$
  - Gives uncertainties, if model parameters perfectly known
  - And the MLE gives no information on $\sigma$

- Need Bayesian inference for uncertainties of model parameters
  - This requires a prior, $\pi(\theta)$
  - This lets us find the posterior $p(\theta|y, x) \propto p(y|\theta, x) \times \pi(\theta)$
Constructing our model, $y(x)$: Predicting uncertainty?

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  - Then we can find predictive (with uncertainties!):
    $$p(y^*|y, x) = \int p(y|\theta, x) \times p(\theta|y, x) \, d\theta$$
Bayesian Predictive

\[ p(y^*|y, x) = \int p(y|\theta, x) \times p(\theta|y, x) \, d\theta \]
Bayesian Predictive

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Bayesian Predictive
What do we gain?
30 Doradus: \( \mathcal{O}(1000) \) OB stars
Existence proof: N44 Superbubble

Wolf Rayet star

X-rays
Optical
IR

180 pc
\( \mathcal{N} \)

\( \mathcal{E}_{\text{kin}} \)

\( Z/Z_\odot \)

\( E_{\text{kin}}/N \times 10^{51} \text{ ergs} \)

\( N_{\text{SNNe}} \)
What’s going on?
SNR Regime

Gentry+16 (in prep.)
What’s going on?  
SNR Regime

\[ N_{\text{SNe}} = 3 \quad (N_{\text{simulations}} = 51), \]

- blue: simulation results
- green: simple model
- red: complex model

Gentry+16 (in prep.)
What’s going on?
SNR Regime

Gentry+16 (in prep.)
What’s going on?
SNR Regime

Gentry+16 (in prep.)
Superbubble: Predicted Scaling at Last SN

\[
p/100 \, \text{M}_\odot \sim N_{\text{SNe}}^{-0.2}
\]

Simulations
Superbubble: Predicted Scaling at end
Need high resolution (or Lagrangian methods)

\[ \frac{p}{100 M_\odot N_{SN_e}} \text{ [km s}^{-1}] \]
Need high resolution (or Lagrangian methods)

\[ \frac{p}{100 \, M_{\odot} \cdot N_{SNe}} \quad [\text{km s}^{-1}] \]

Keller+14