Bayesian Analysis of Star Clusters

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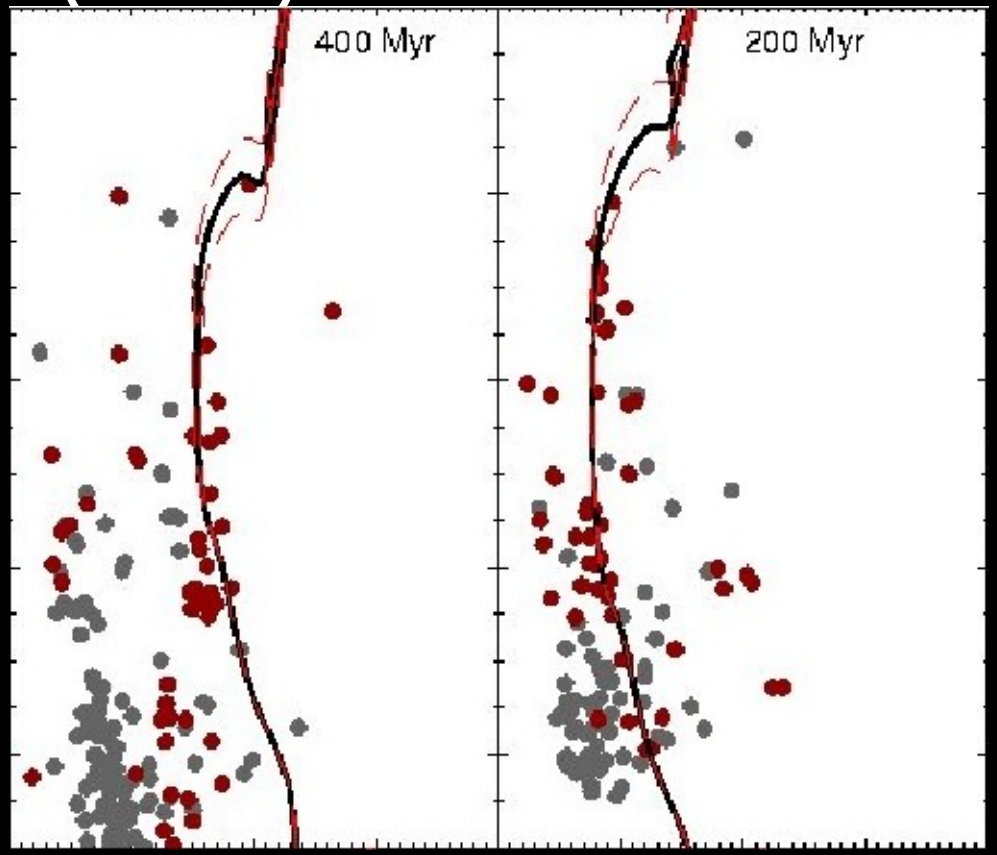
State of Open Cluster Analysis

- Determination of cluster parameters – isochrone fitting
  - χ^2 by eye
  - Other statistics e.g. τ^2 Naylor & Jefferies (2006)
- Need to know which stars are in cluster
  - e.g. Bonatto et al.
  - Alonso-Garcia et al. (2011)

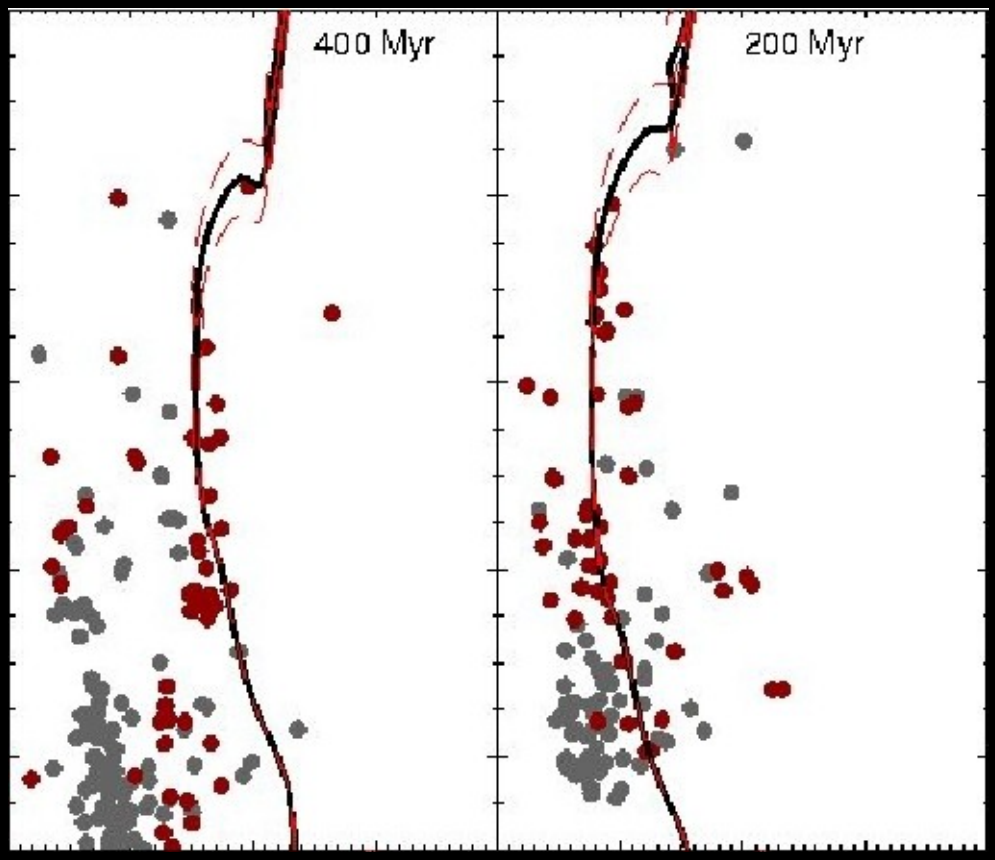
New Open Clusters in VVV

- 96 candidate open clusters – Borissova et al. (2011)



Current Difficulties

- Where field ~ cluster, poisson noise significant



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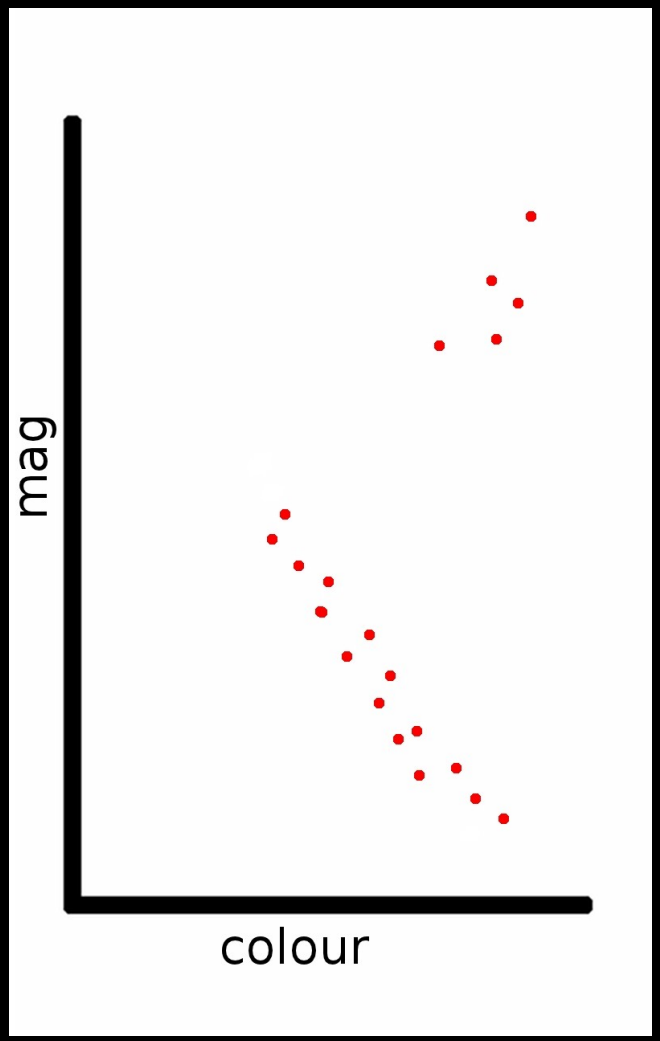

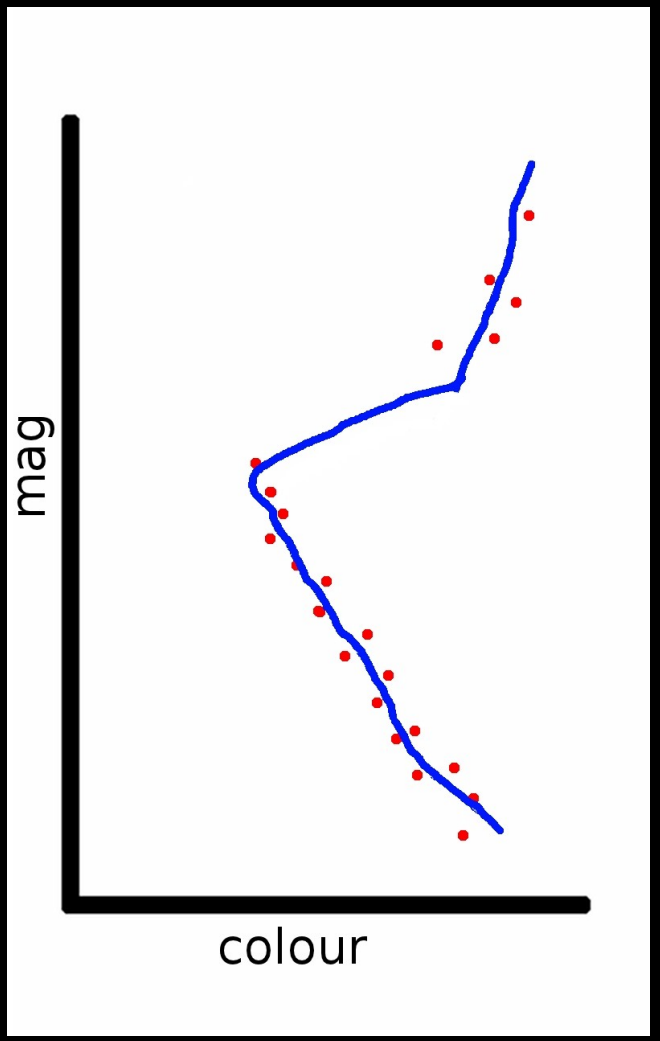

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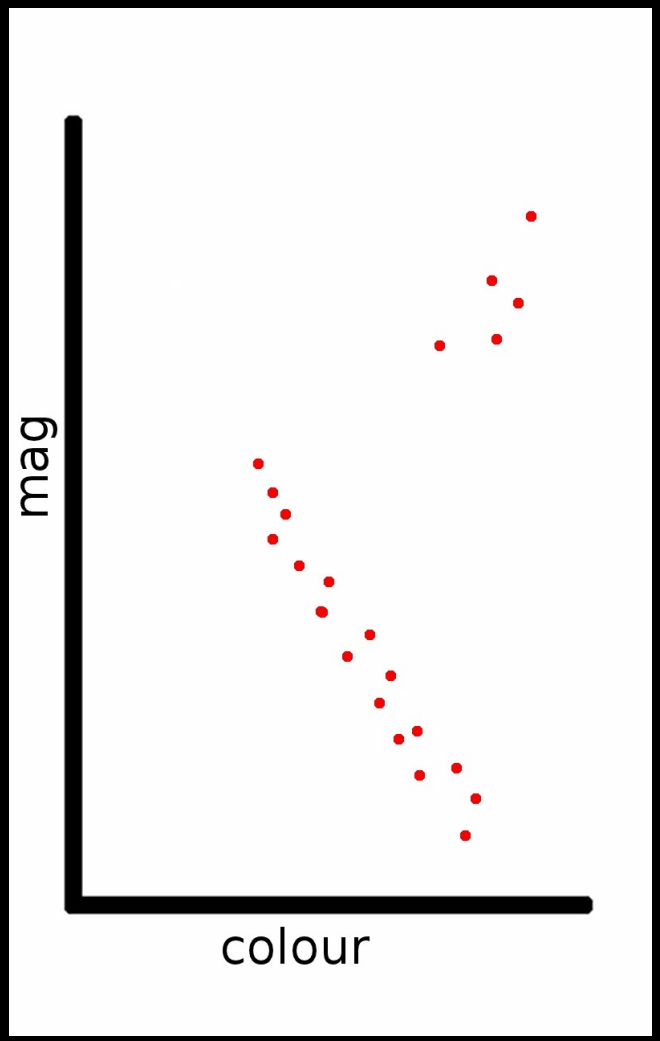
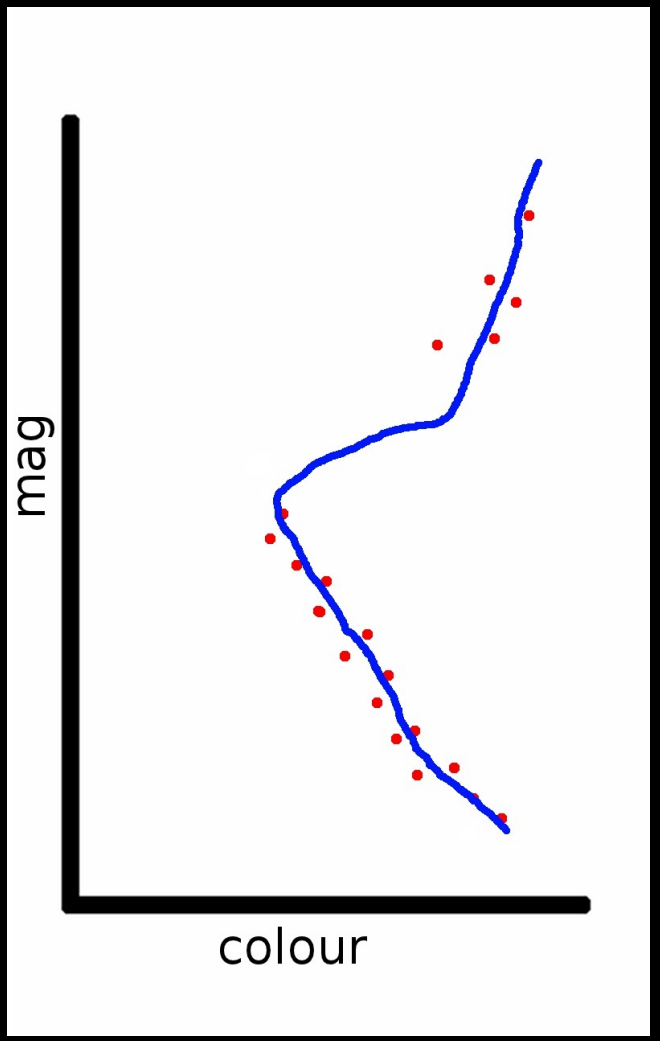
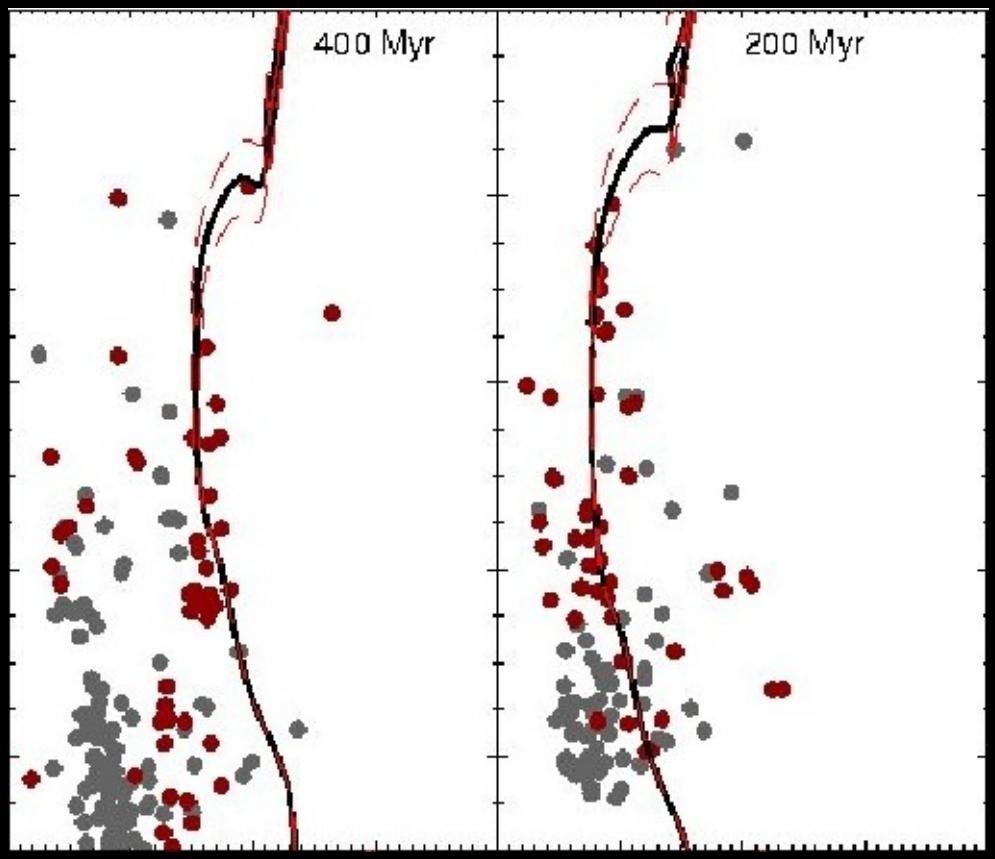




Current Difficulties

- Use isochrone fit to inform field star decontamination



- Also propagate uncertainties on membership through to cluster parameters

Mathematical description

- Cluster parameters:
- For Each star:

$$\boldsymbol{X}=\{M_c\, Age_c\, [Fe/H]_c\, d_c\, A_c\, IMF_c \ldots\}$$

$$\boldsymbol{x_i}=\{l_i\, b_i\, M_i\, Age_i\, [Fe/H]_i\, d_i\, A_i\}$$

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- For Each star:

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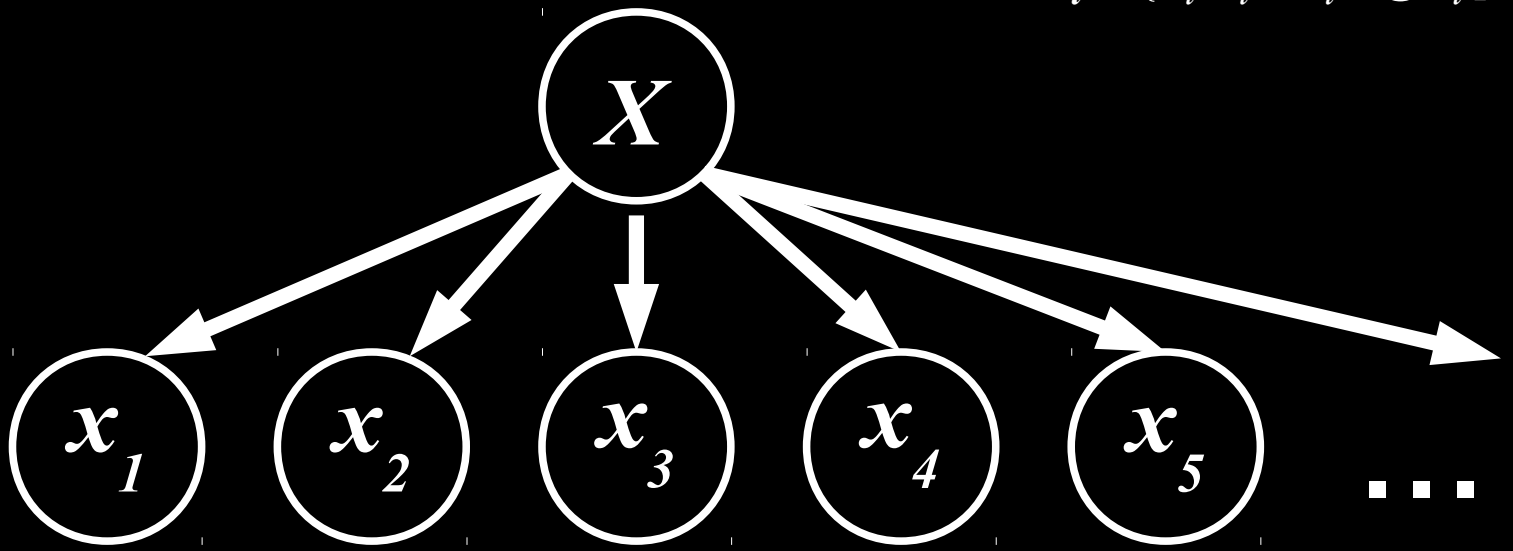
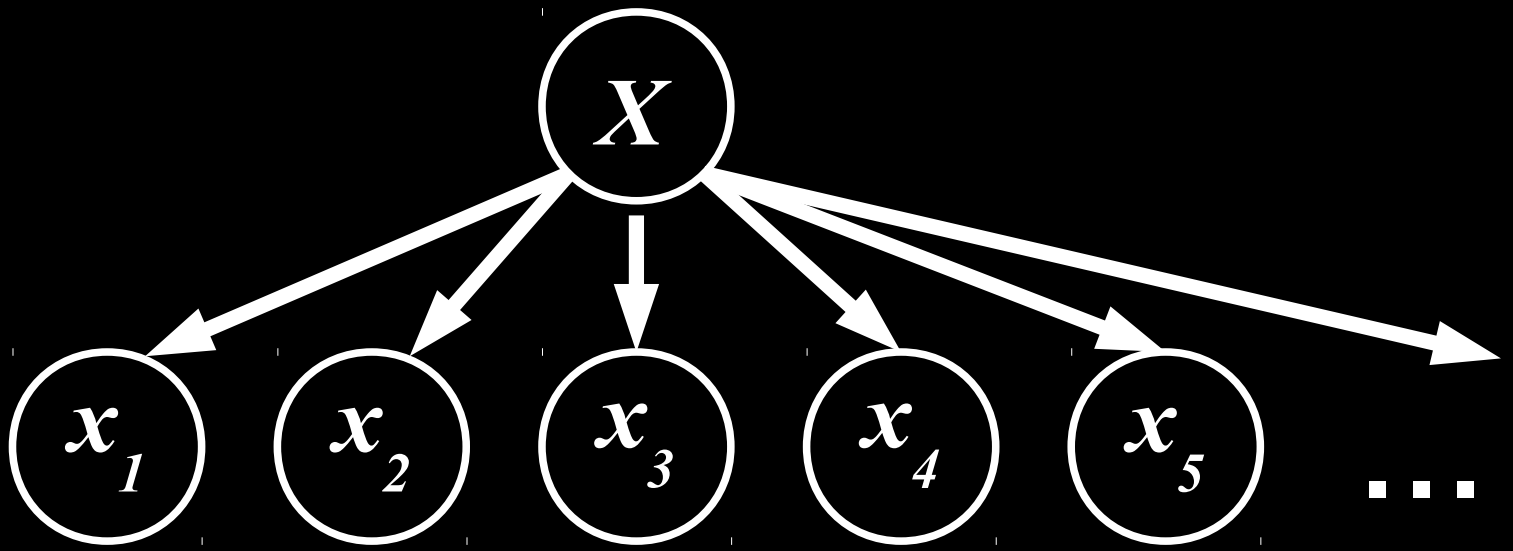


- Observations: $y_i = \{J_i H_i K_i\}$



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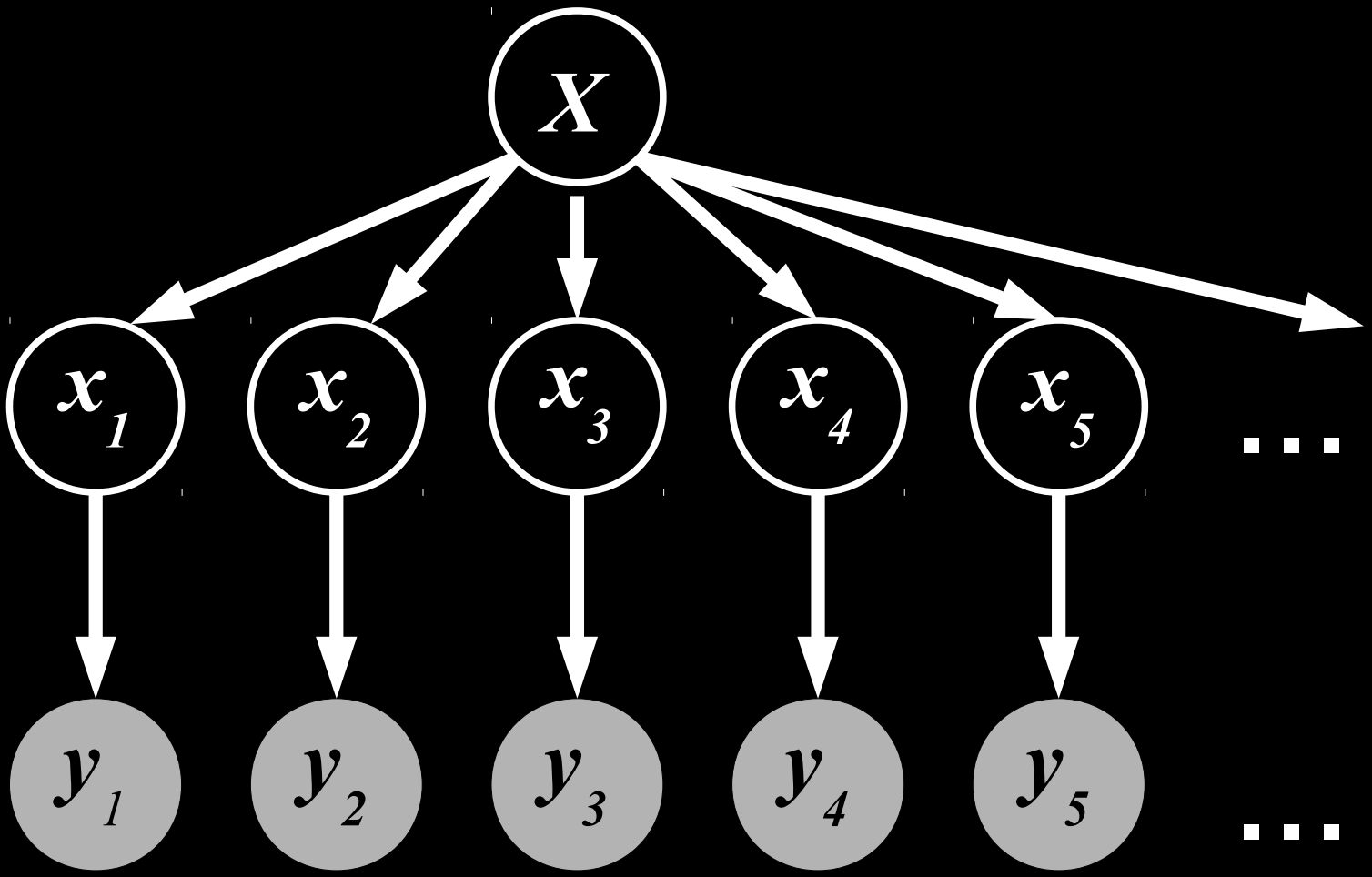
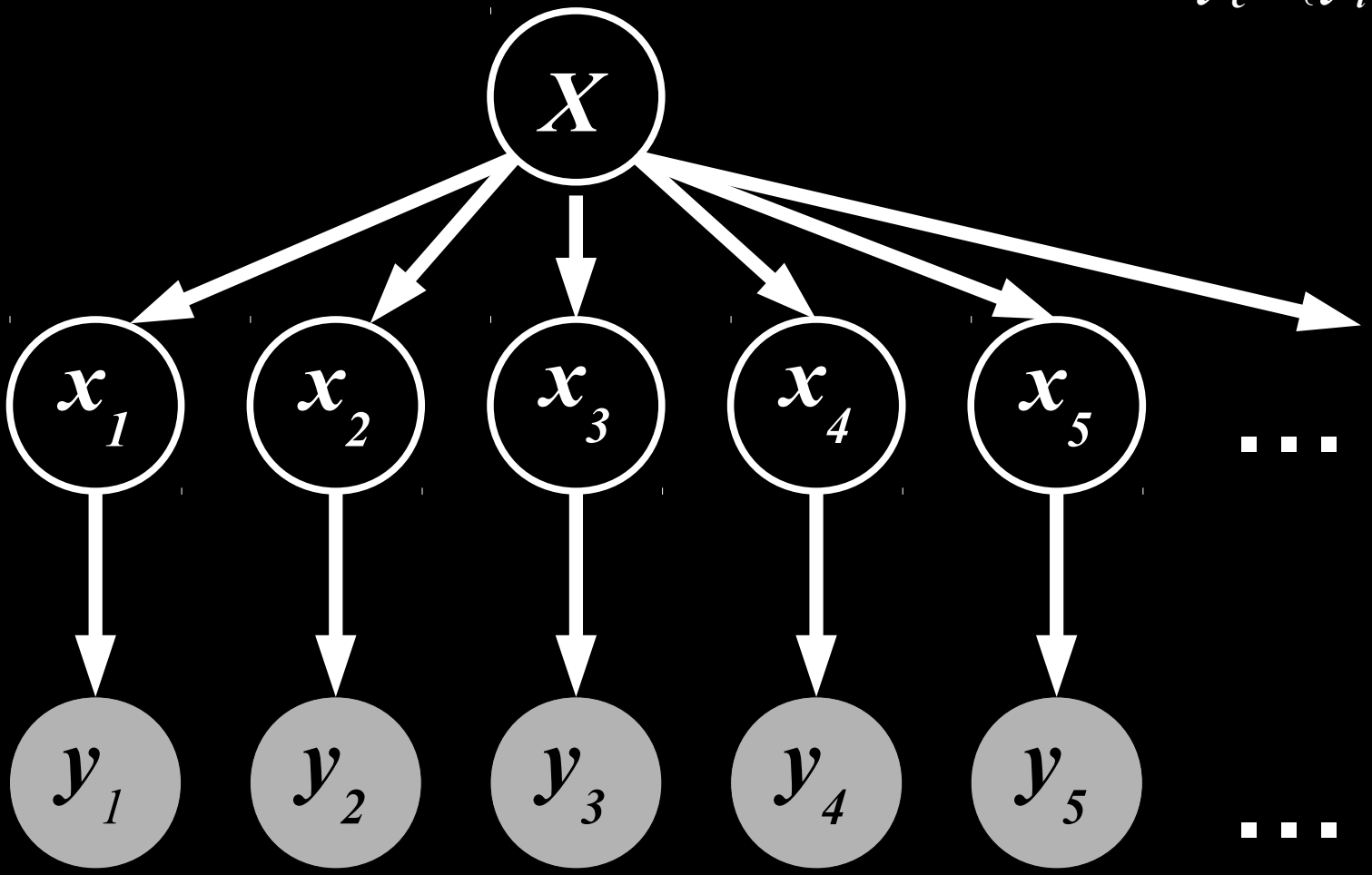


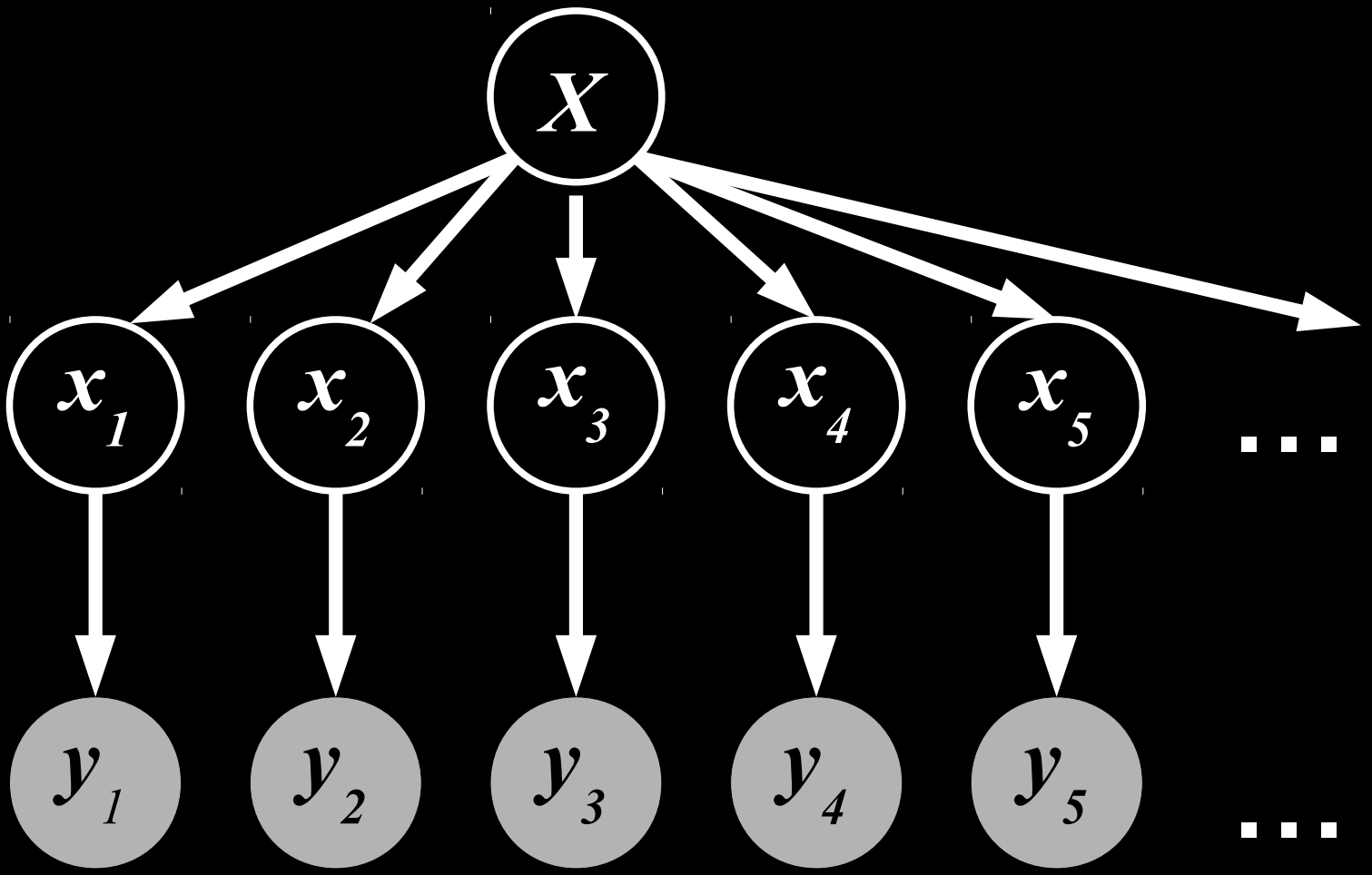
- Many stars in each field:

$$x_c = \{x_i\}$$

$$y_c = \{y_i\}$$



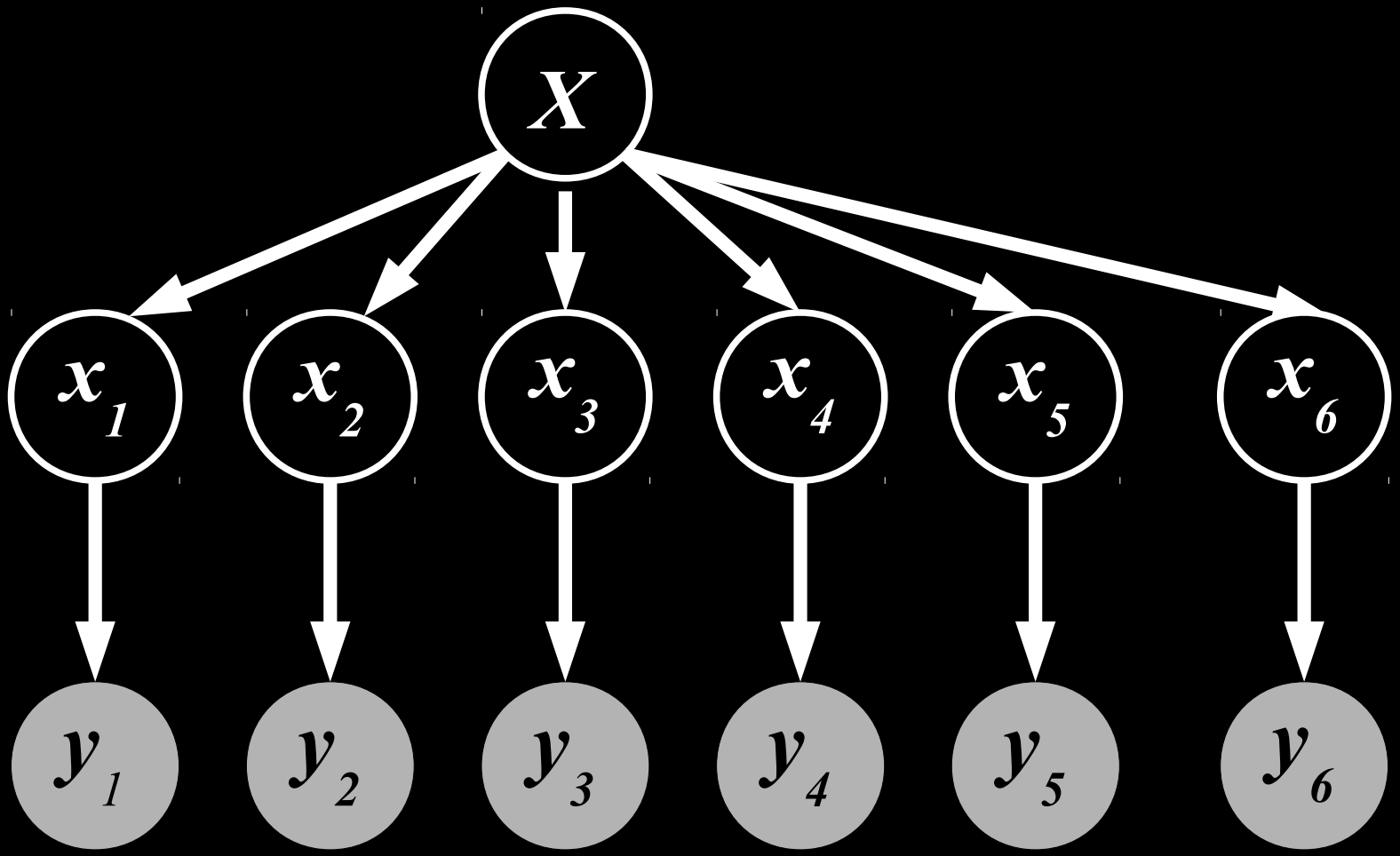
$$P(\boldsymbol{x}_c X|\boldsymbol{y}_c) \propto P(\boldsymbol{y}_c|\boldsymbol{x}_c) P(\boldsymbol{x}_c|X) P(X)$$



$$P(\boldsymbol{x_c} X|\boldsymbol{y_c}) \propto P(\boldsymbol{y_c}|\boldsymbol{x_c}) P(\boldsymbol{x_c}|X) P(X)$$

- Solve for posterior
  - By MCMC
- Gives cluster parameters
  - Can et corresponding credible intevals
- Also stellar parameters

- Some stars not in cluster, belong to field



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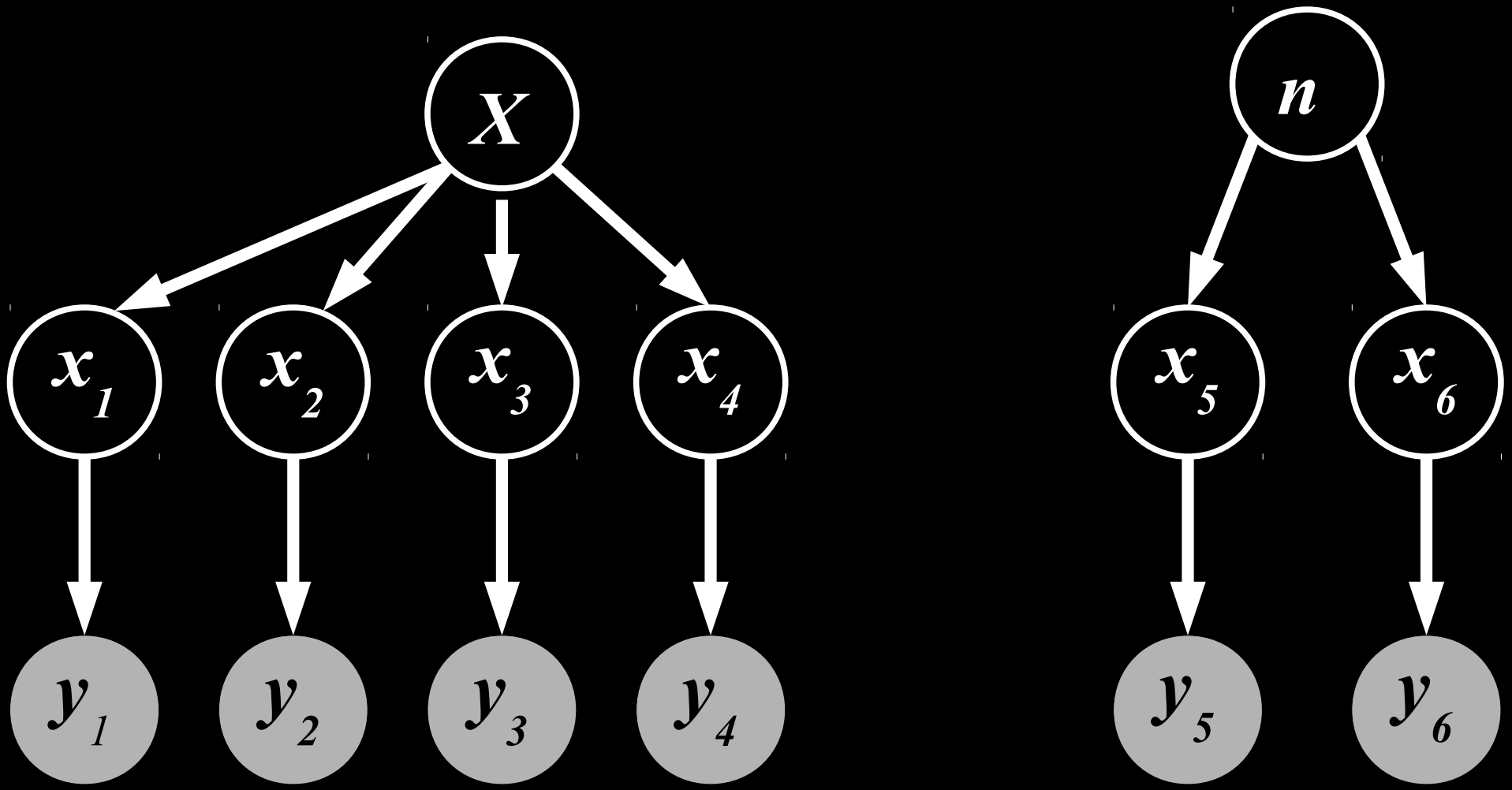
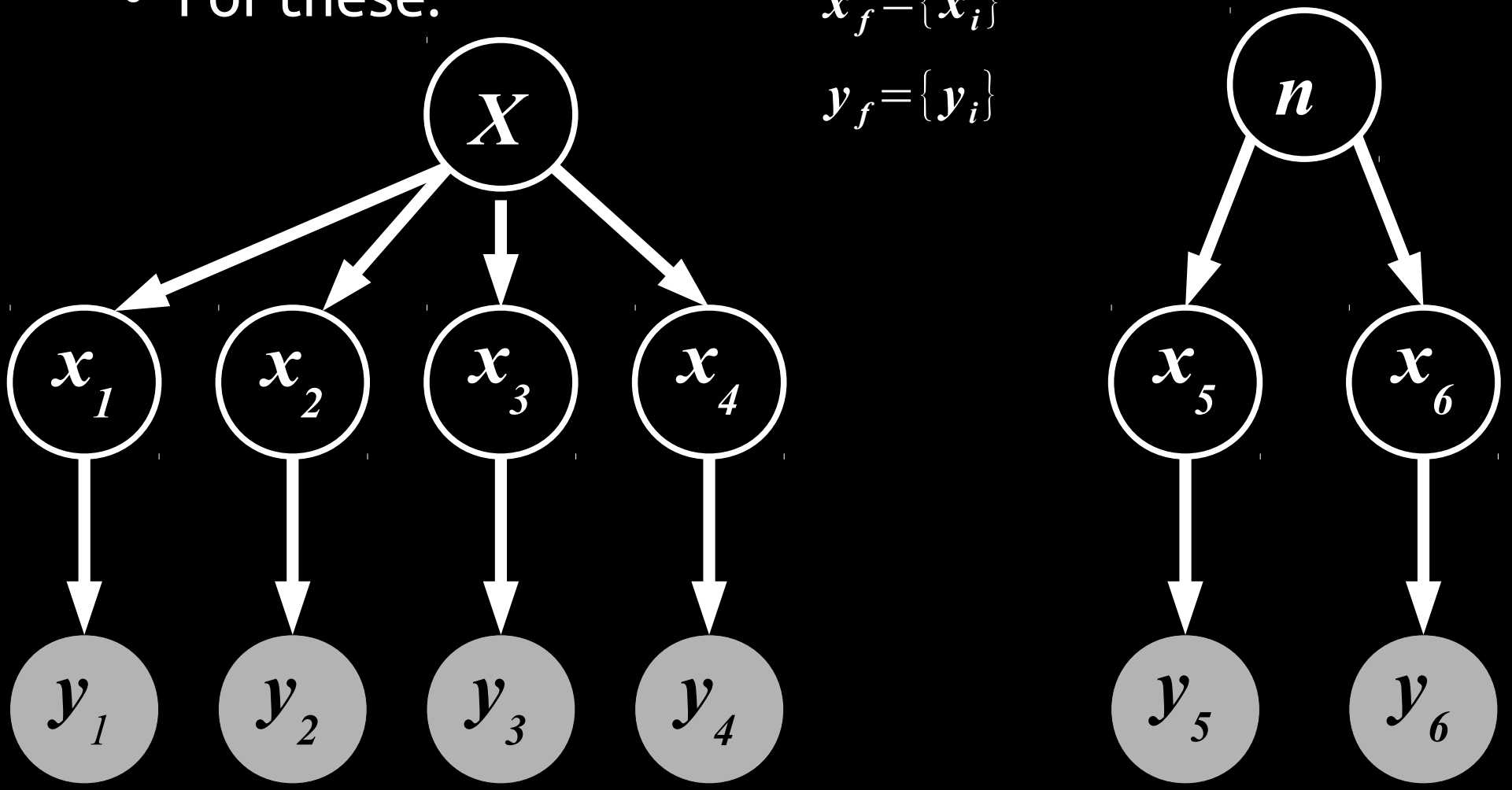


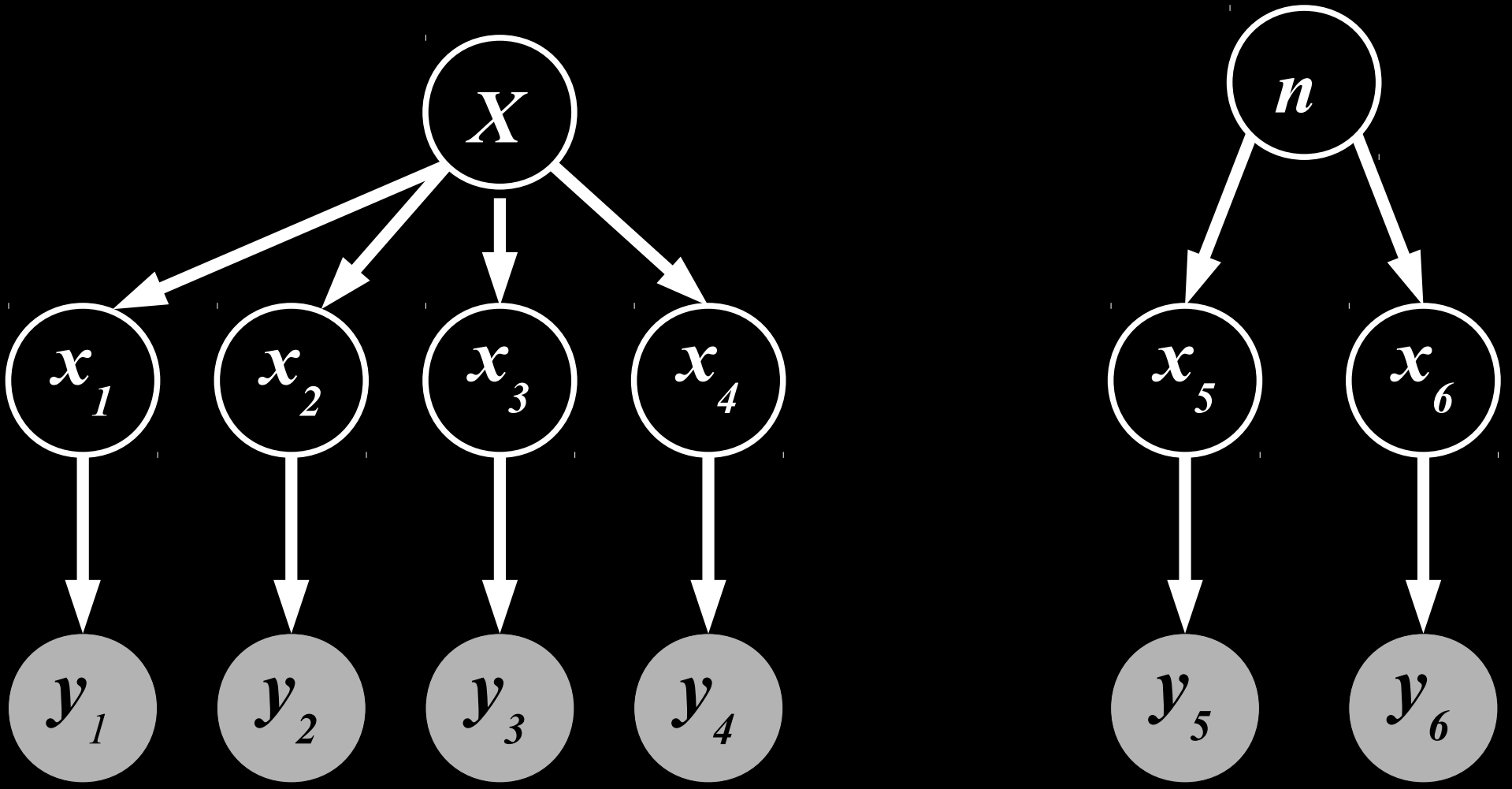
- Some stars not in cluster, belong to field
  - For these:

$$x_f = \{x_i\}$$

$$y_f = \{y_i\}$$



- But which stars are in cluster?



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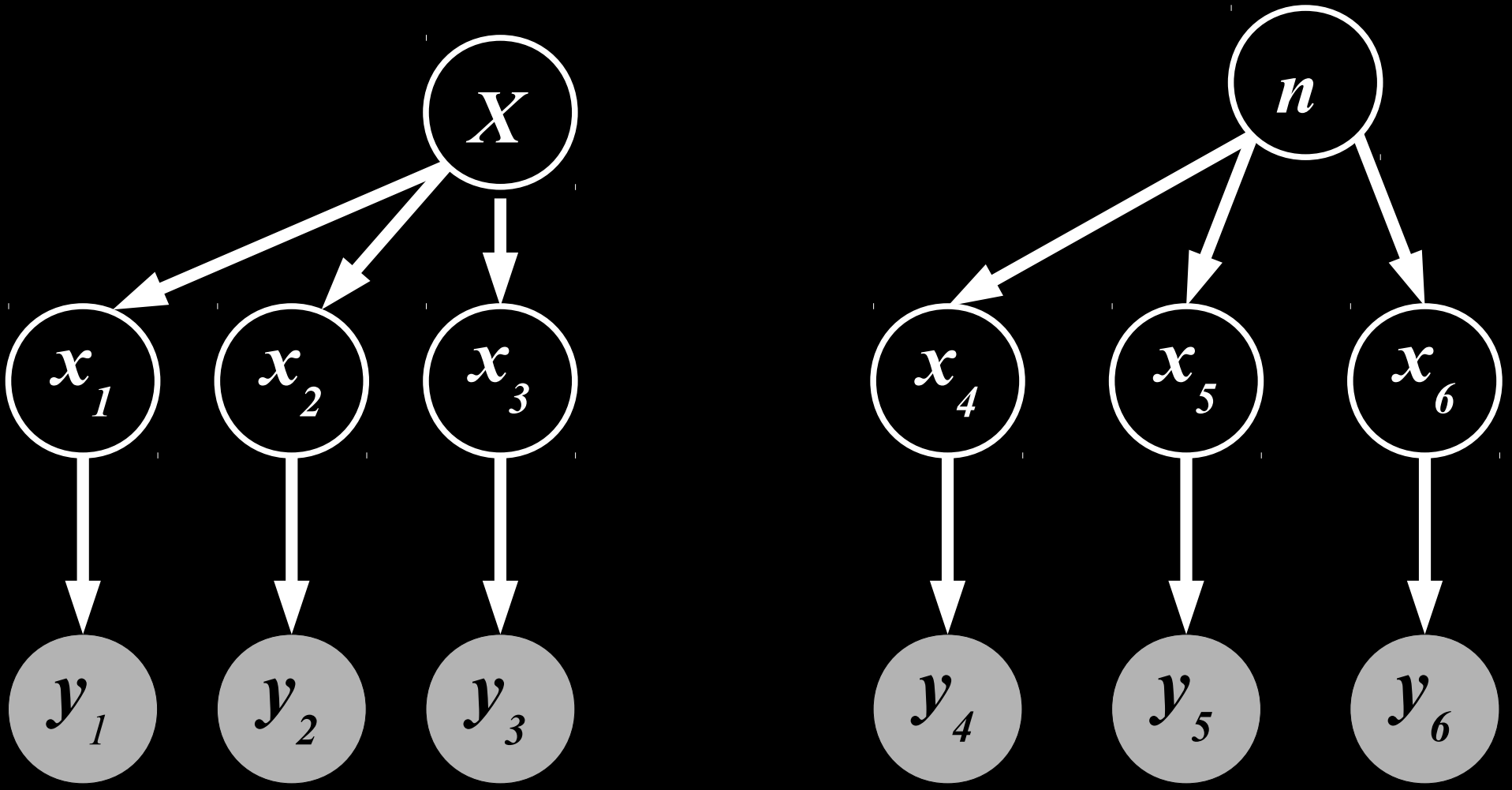


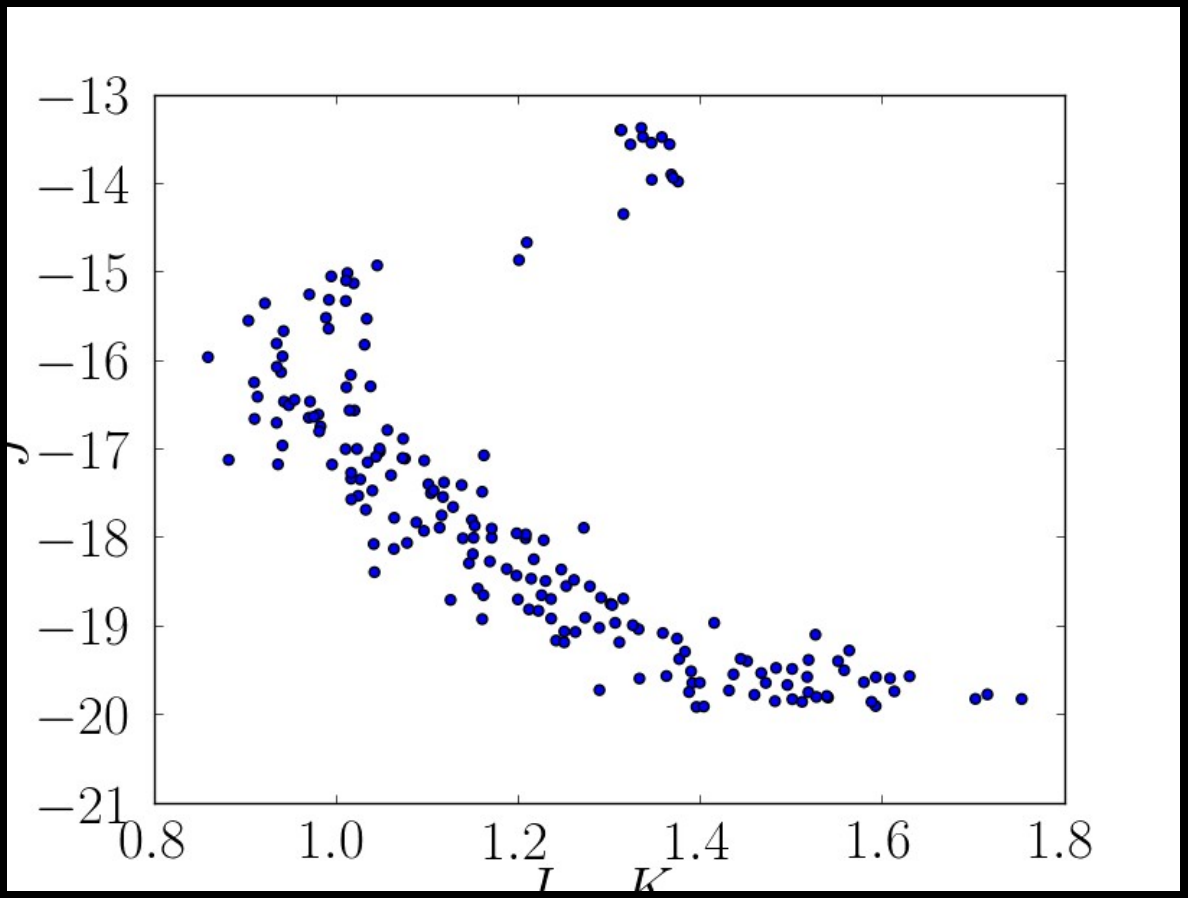
- But which stars are in cluster?

- Need to choose between models

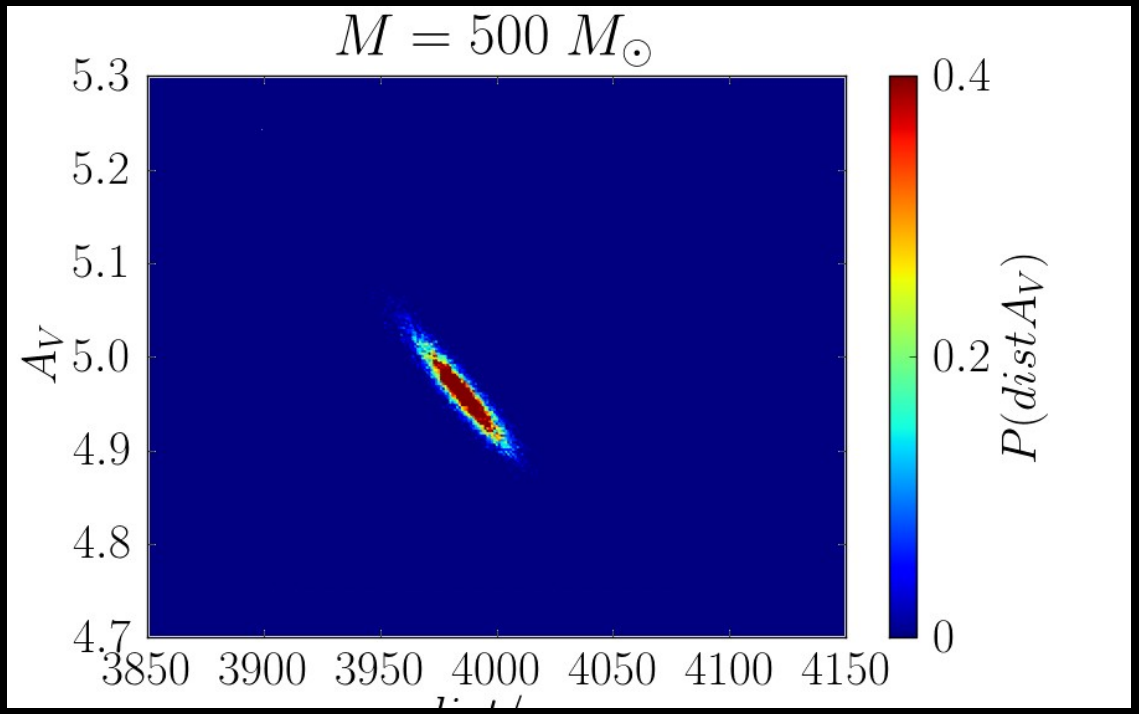
  $\therefore$ Solve using reversible jump MCMC

Some examples

- Simulated cluster – no field
  - Age=1Gyr, d=3981pc, A_V=5, Mass=500M_o

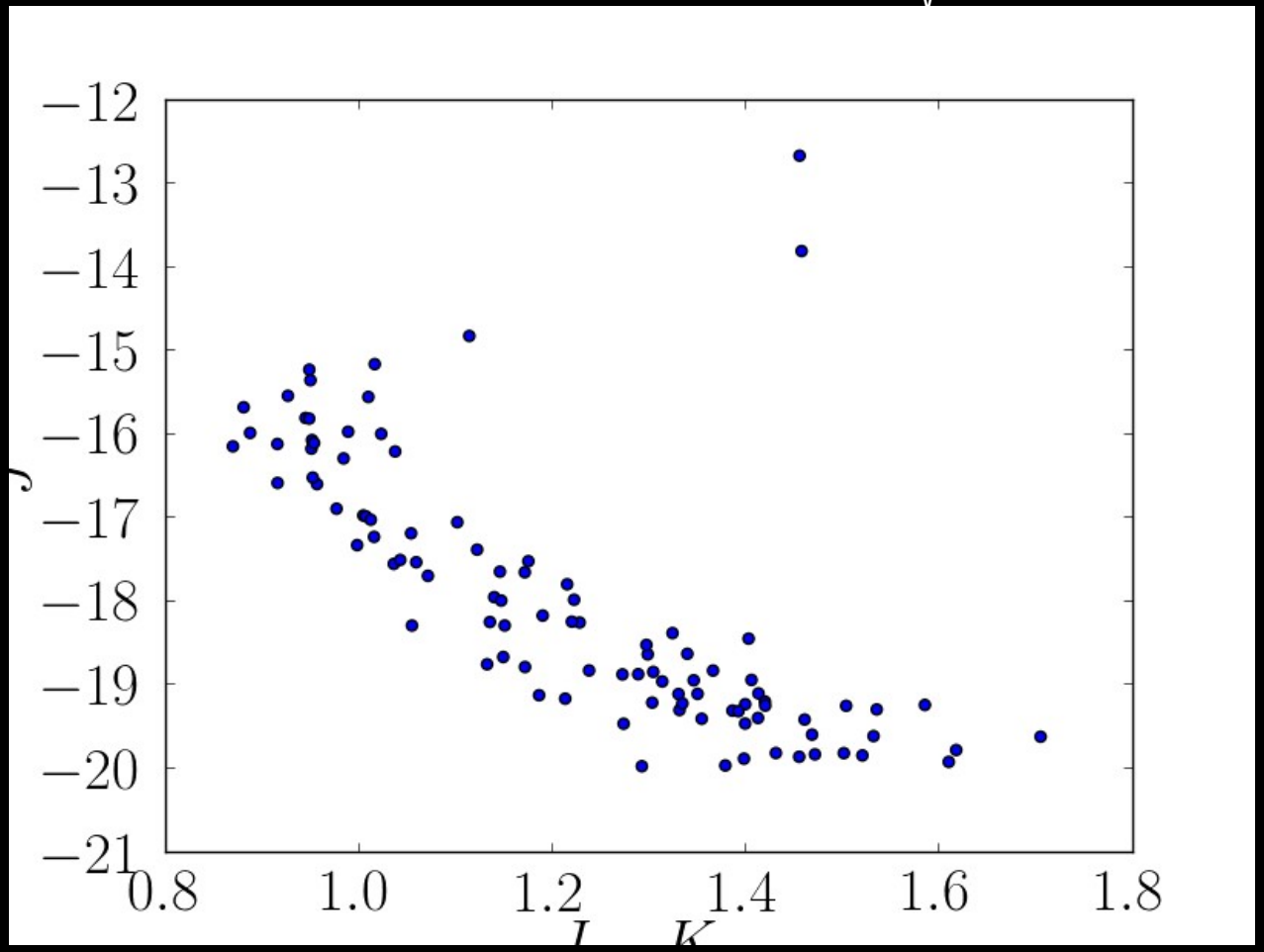


- Simulated cluster – no field
  - Age=1Gyr, d=3981pc, A_V=5, Mass=500$M_\odot$

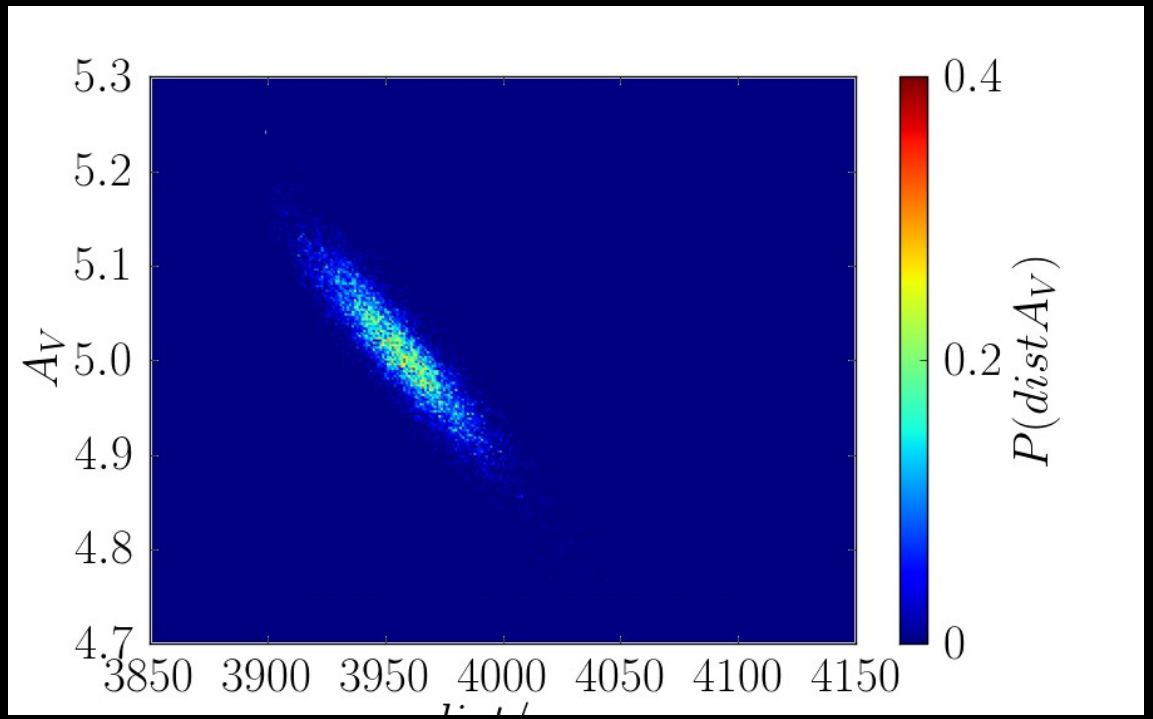


Estimates:
Age=(1.0 ± 0.05) Gyr
d=(3986 ±10) pc
A_V=4.98 ± 0.03

- Simulated cluster – no field
  - Age=1Gyr, d=3981pc, A_V=5, Mass=250M_0



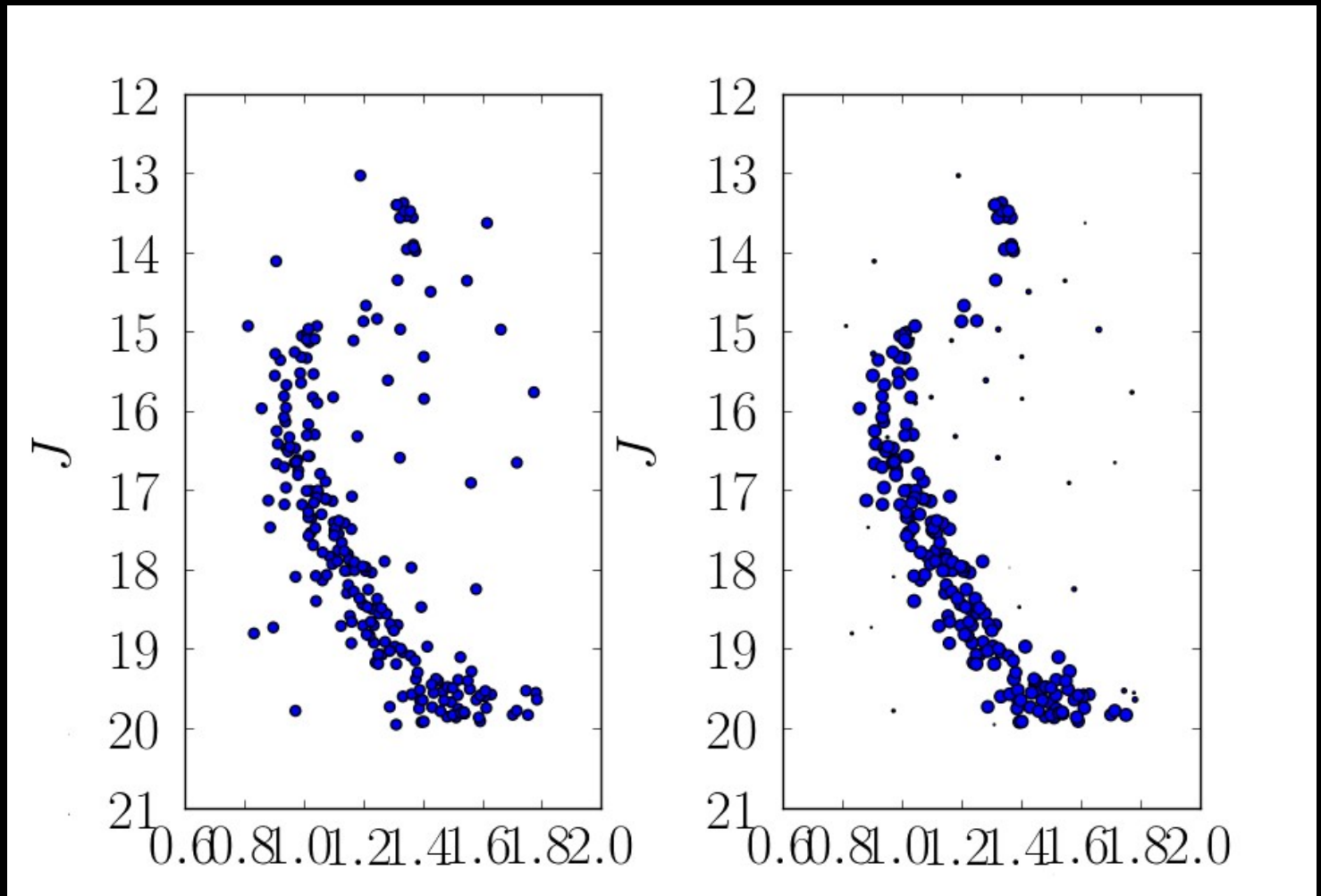
- Simulated cluster – no field
  - Age=1Gyr, d=3981pc, A_V=5, Mass=100$M_\odot$



Estimates:
Age=(1.0 ± 0.05) Gyr
d=(3956 ±20) pc
A_V=5.0 ± 0.05

Example – with field

- Simulated cluster – field uniformly populating colour-mag space



Extensions

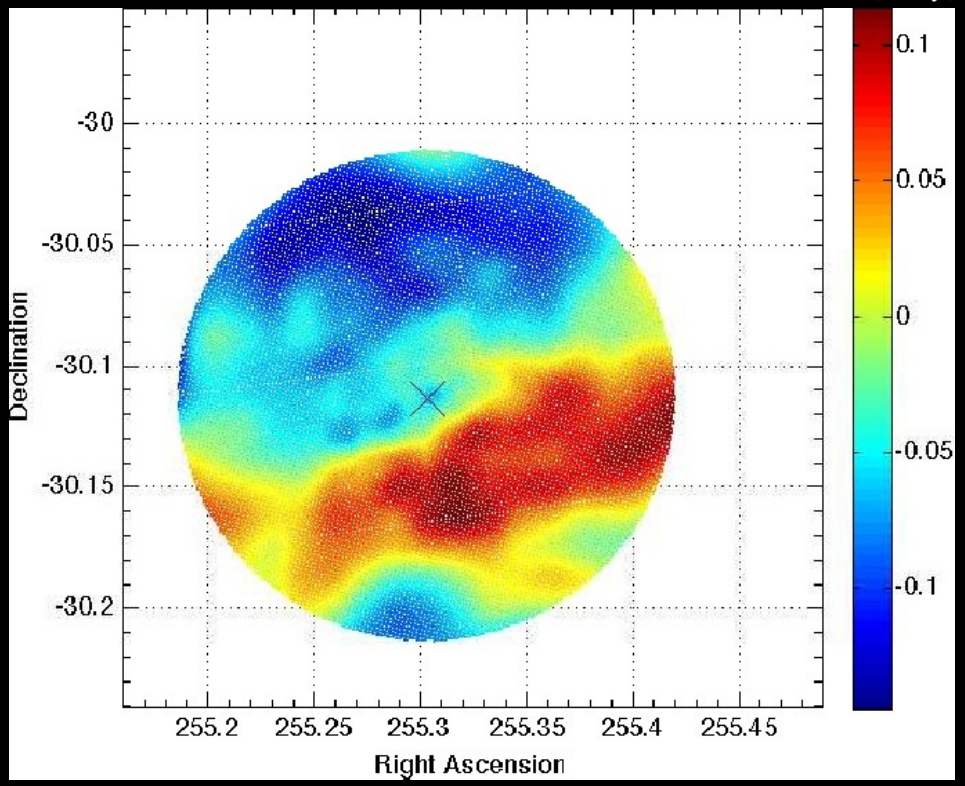
- Many stars are unresolved binaries
- For binaries an extra paramater needed – mass ratio:

$$\boldsymbol{x_i} = \{ l_i \, b_i \, M_i \, Age_i \, [Fe/H]_i \, d_i \, A_i \, q_i \}$$

- Binaries not known *a priori*
  - RJMCMC needed

Extensions

- Currently: $P(A_i) = 1 \quad if\ A_i = A_c$
  $0 \quad otherwise$
- Possible to have: $P(A_i) = \ln N(A_c, \sigma_c)$



- Can exploit knowledge of ISM
  - A(dist)
  - Fractal medium
    - Kolmogorov turbulence

Alonso-Garcia et al. (2011)

Extensions

- Does the cluster really exist?

- Can confirm with model selection
  - Field only vs. field +cluster

    Fewer params More params

    Ockham's razor *Better fit to data*

Conclusions

- Method exploits isochrones to help identify cluster members
- Uncertainties in membership propagate to cluster parameters
- Extensible to include differential extinction
- Provides a check for the existence of the cluster