3D Extinction Mapping Using Hierarchical Bayesian Models

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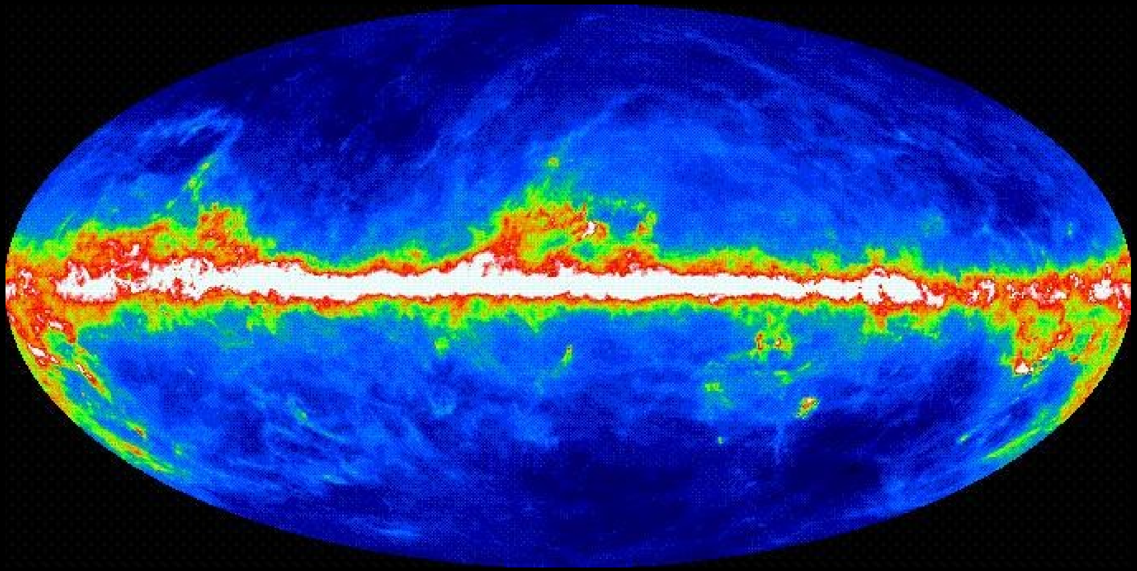
Types of Extinction Mapping

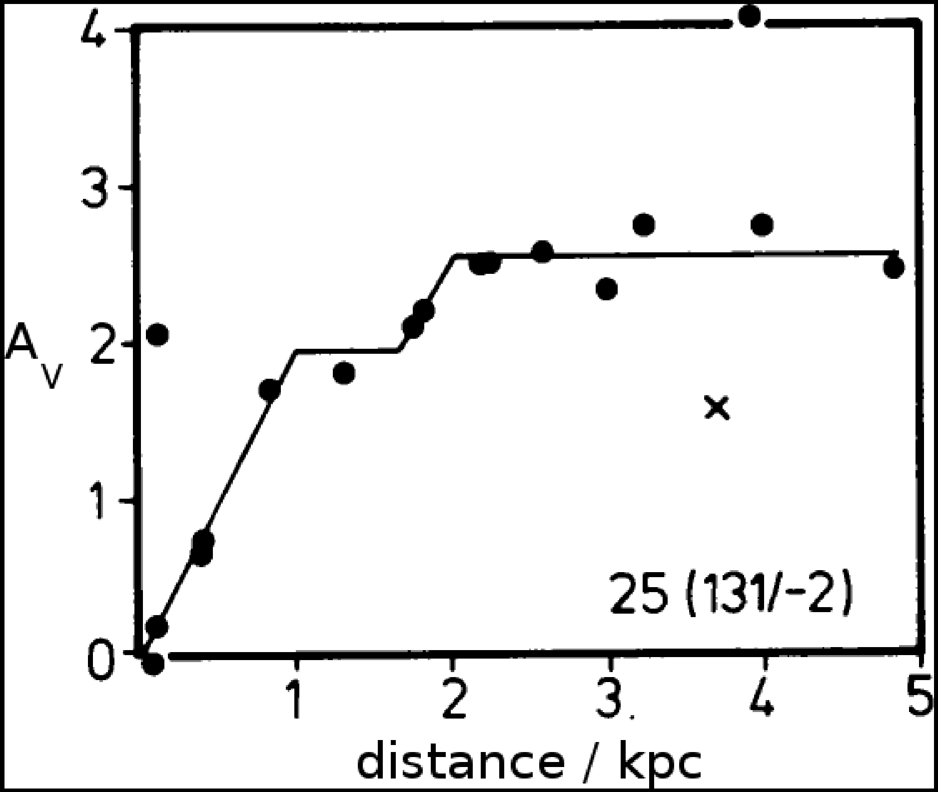
- 2D, e.g.
  - Schlegel et al. (1998)



  - Rowles & Froebrich (2009) – 2MASS
  - Nice/Nicer/Nicest e.g. Lombardi et al. (2010)
  - Stead & Hoare (2010) - UKIDSS

Types of Extinction Mapping

- 3D
  - Stars as tracers, e.g. Neckel & Klare (1980)



11,000 stars, mostly O and B type

Entire Galactic plane, |b|<7

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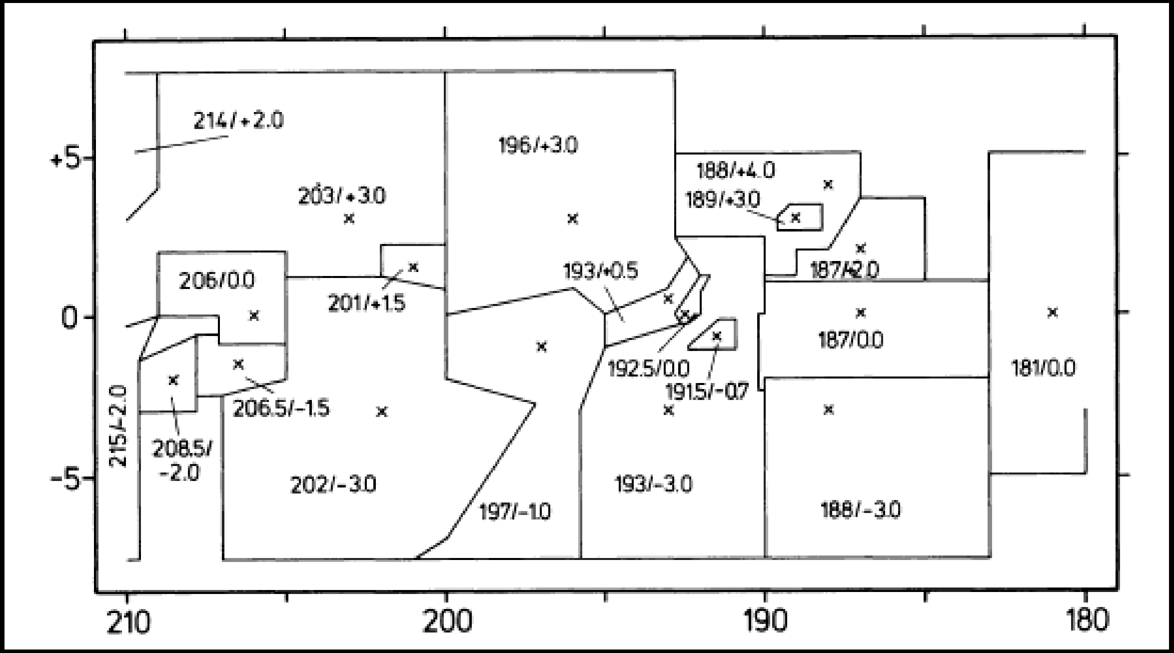

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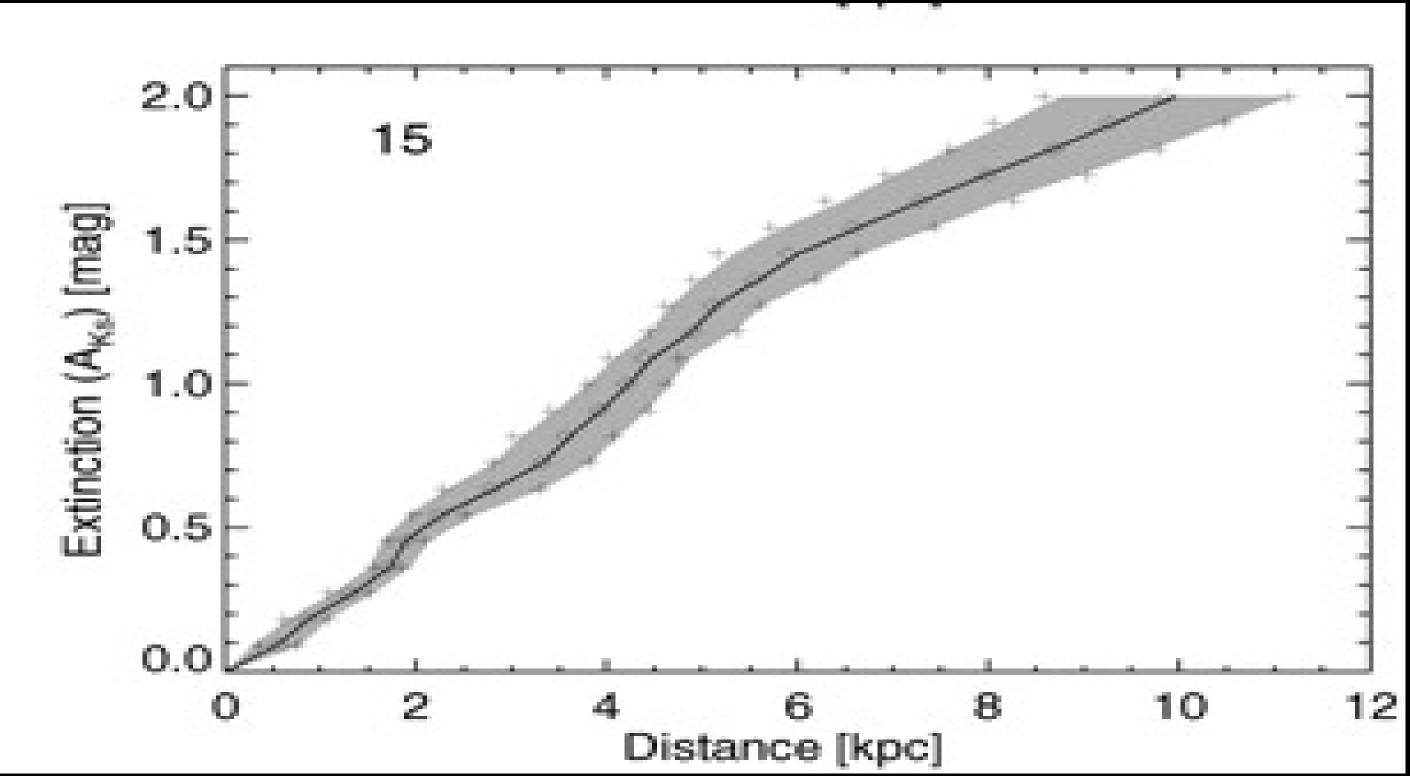
Types of Extinction Mapping

- 3D
  - Marshall et al. (2006, 2009) – compare observed distribution stellar distribution to Besançon Galactic model.



Part of fig 2 of Marshall et al. (2009). Extinction for (l,b)=(50,0)

Extinction Mapping With Stars

- Use stars to trace extinction
  - Pros:
    - Can map in 3D
    - Many tracers available
    - No shortage of data
  - Cons:
    - Limited by stellar density (e.g large Galactic Radii)
    - Only probes one component of the ISM
    - Many 'nuisance' parameters (Mass/spectral type , metallicity, etc.)

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    - Many 'nuisance' parameters (Mass/spectral type , metallicity, etc.) *- Can study these!*
  - Cons:
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Estimation of stellar parameters

- Estimation of stellar parameters in absence of extinction:

$$P(M\ Age[Fe/H]d|\boldsymbol{y}_i)=\frac{P(\boldsymbol{y}_i|M\ Age[Fe/H]d)P(M\ Age[Fe/H]d)}{P(\boldsymbol{y})}$$

- Where $\boldsymbol{y}_i$ is the set of observations for a given star:

$$\boldsymbol{y}_i=\{r'i'H\alpha\}or\{J\ H\ K\}etc$$

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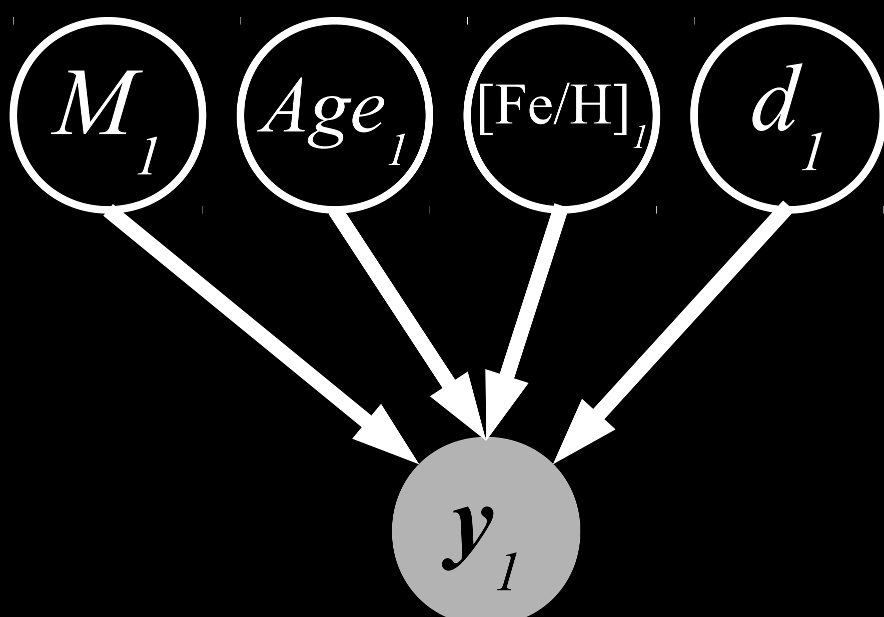
- c.f. Burnett & Binney (2010)
- Prior:
  - *M*: IMF — *Age*: SFH
  - [Fe/H]: metallicity profile — *d* : *density* profile

Estimation of stellar parameters

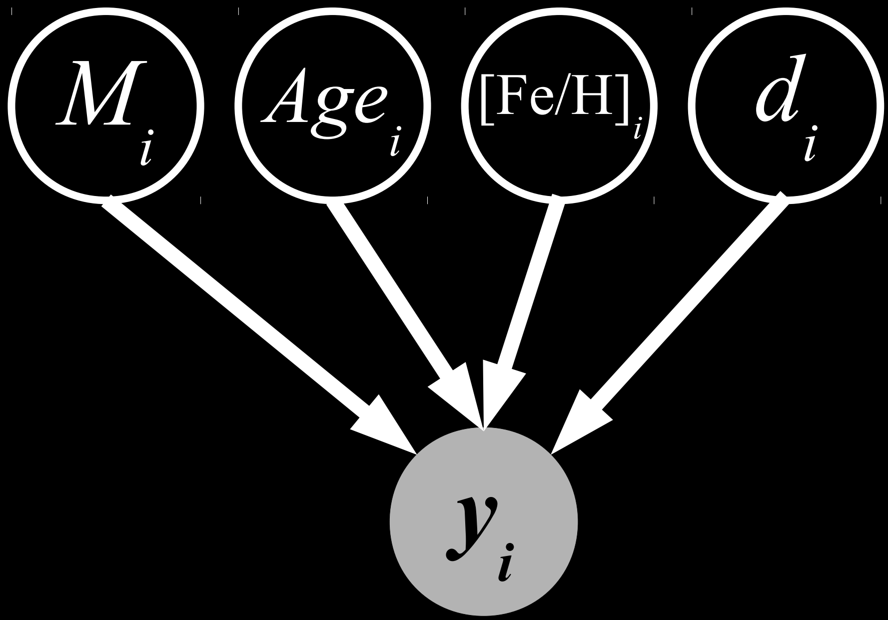
$$P(M\ Age[Fe/H]d|\boldsymbol{y}_i) \propto P(\boldsymbol{y}_i|M\ Age[Fe/H]d)\,P(M\ Age[Fe/H]d)$$

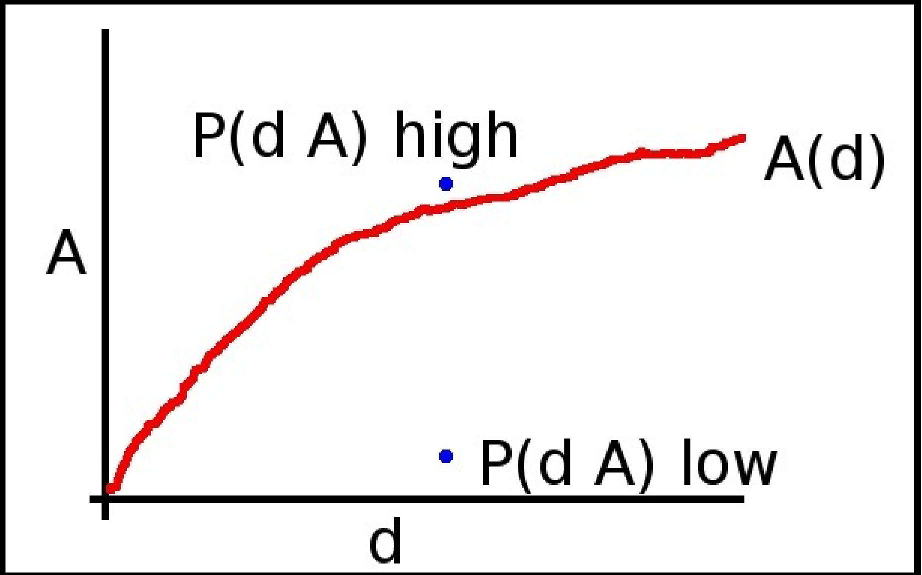


With Extinction

$$P(M\ Age[Fe/H]d\ A|\boldsymbol{y}_i) \propto P(\boldsymbol{y}_i|M\ Age[Fe/H]d\ A)P(M\ Age[Fe/H]d\ A)$$

- Assume we know A(d)
- Where A(d) ⇒ prior on A (and d)





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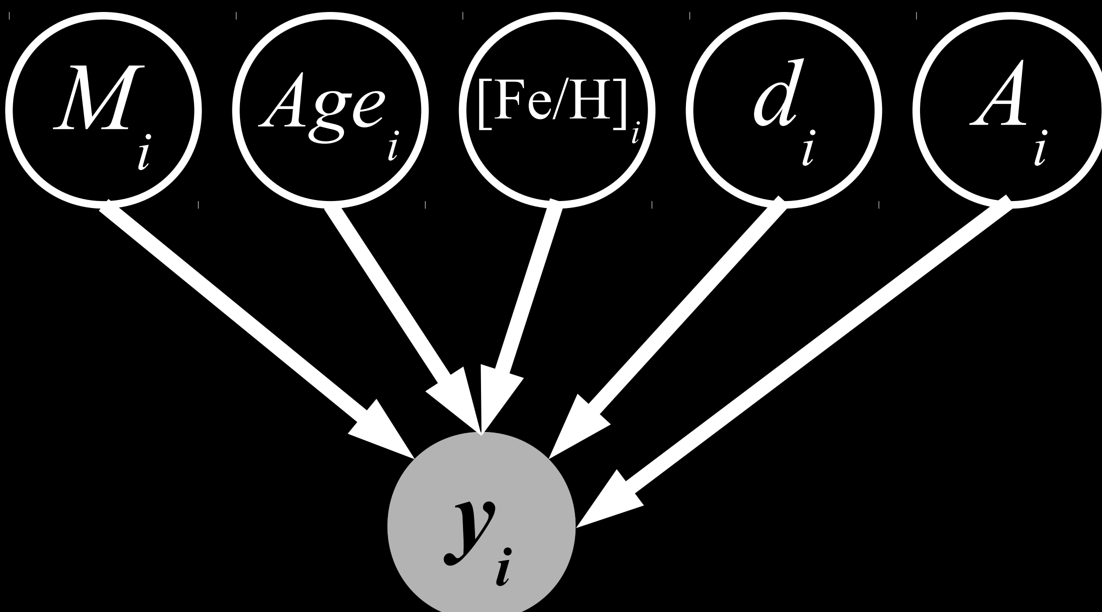
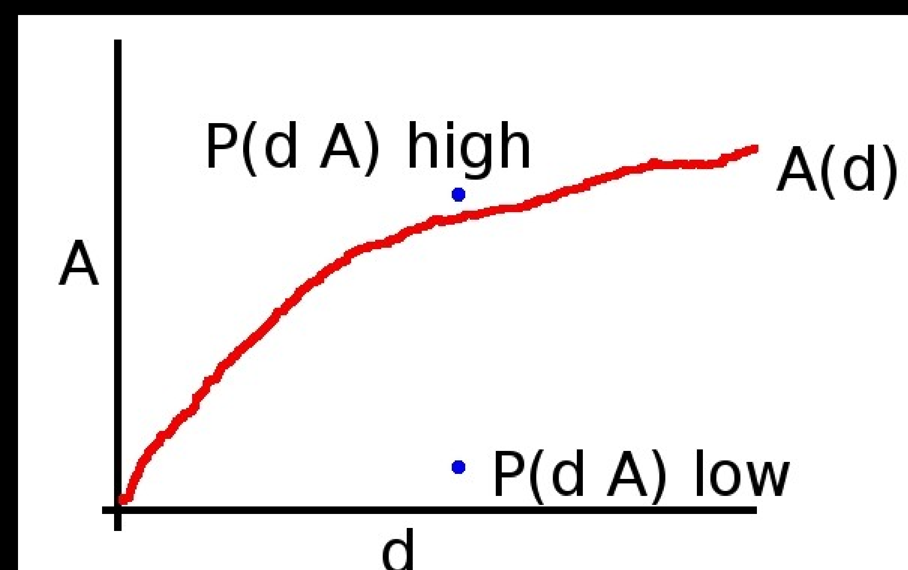


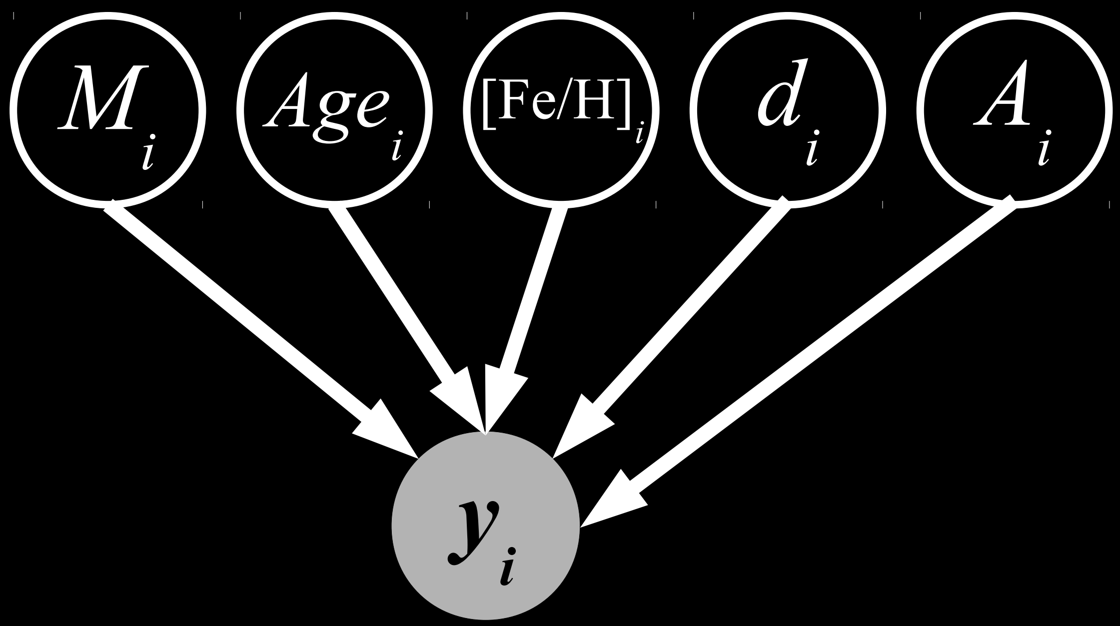


Simplify Notation

$$P(\boldsymbol{x}_i|\boldsymbol{y}_i) \propto P(\boldsymbol{y}_i|\boldsymbol{x}_i)\,P(\boldsymbol{x}_i)$$

- Where x_i contains the stellar parameters :

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



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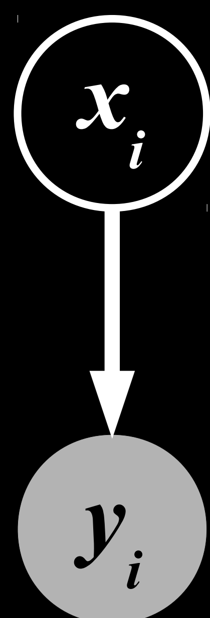
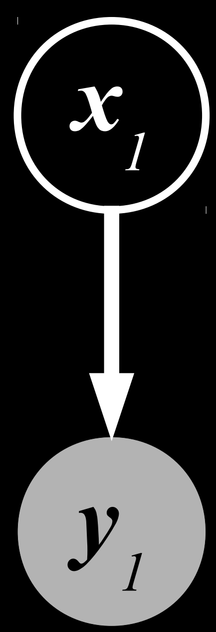


A Set of Stars

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

- Where $\boldsymbol{x}$ contains all the x_i and $\boldsymbol{y}$ contains all y_i:

$$\boldsymbol{x} = \{x_i\}$$
$$\boldsymbol{y} = \{y_i\}$$



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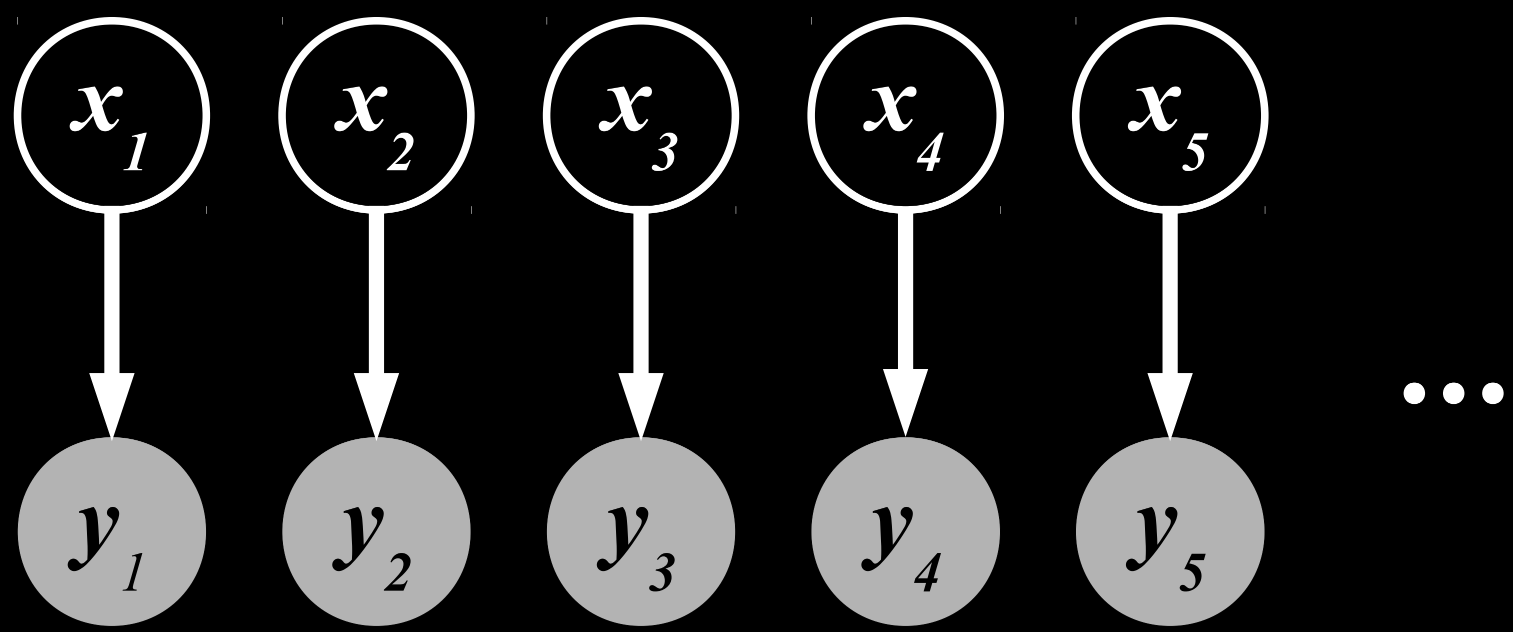
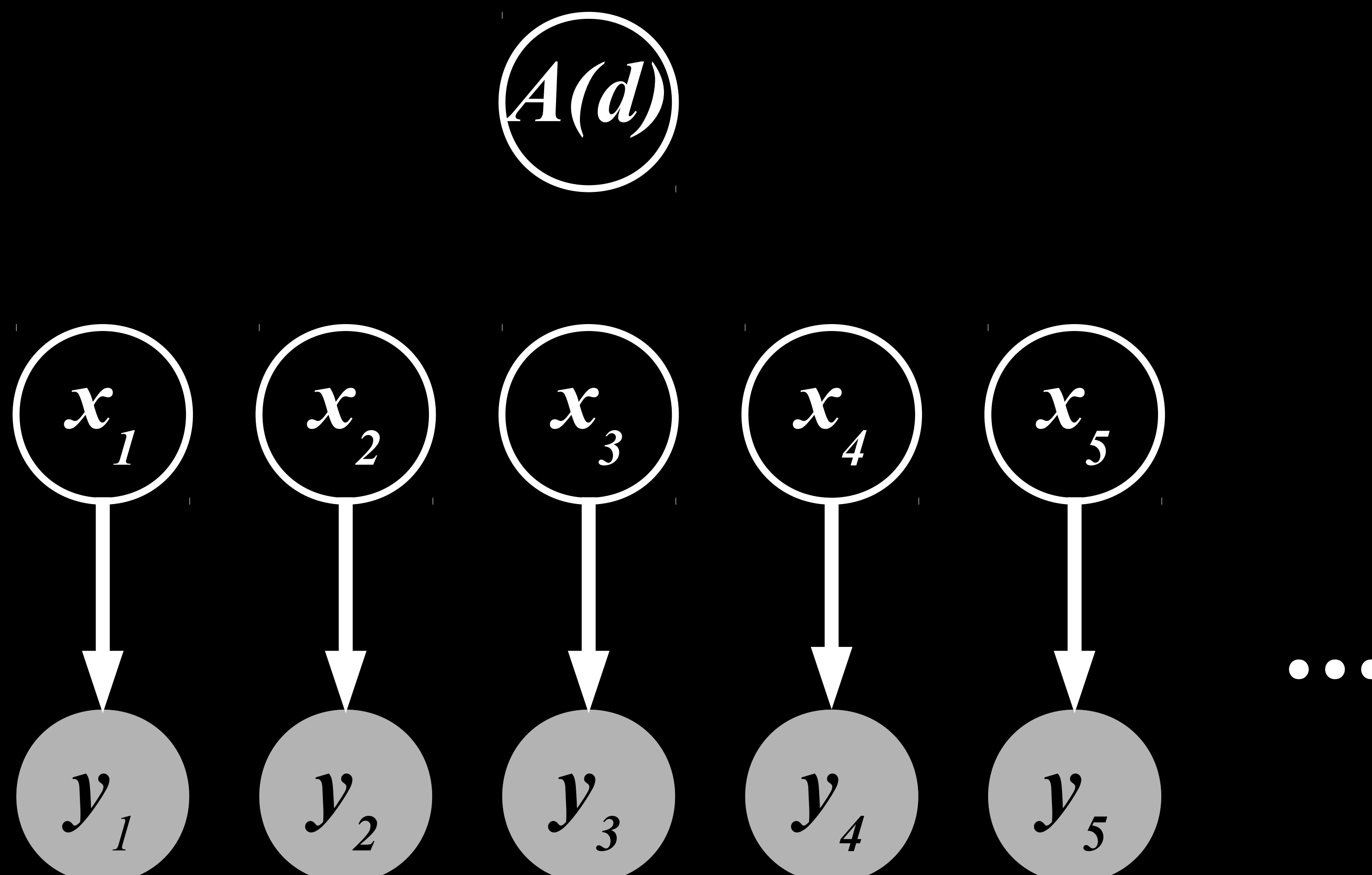


What is *A(d)* ?

$$P(\boldsymbol{x}\,A(d)|\boldsymbol{y}) \propto P(\boldsymbol{y}|\boldsymbol{x})\,P(\boldsymbol{x}|A(d))\,P(A(d))$$



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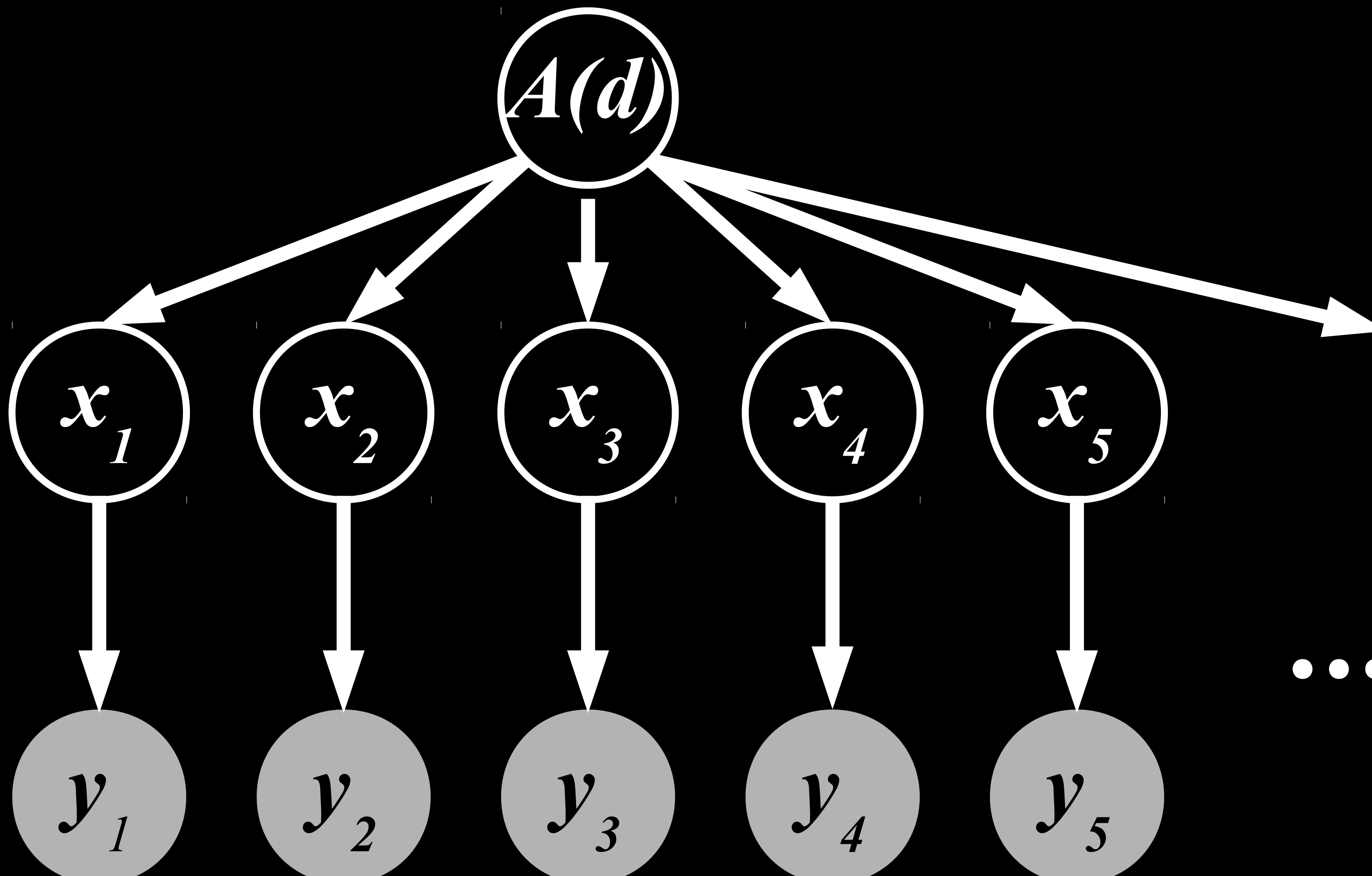

What observations to use?

- Data could be almost anything:
  - Photometry
    - e.g. SDSS, UKIDSS, VISTA, IPHAS/VPHAS+, GLIMPSE etc.
  - Spectroscopy (or spectroscopically derived)
    - e.g. SEGUE, RAVE
  - Astrometry
    - e.g. HIPPARCOS, GAIA

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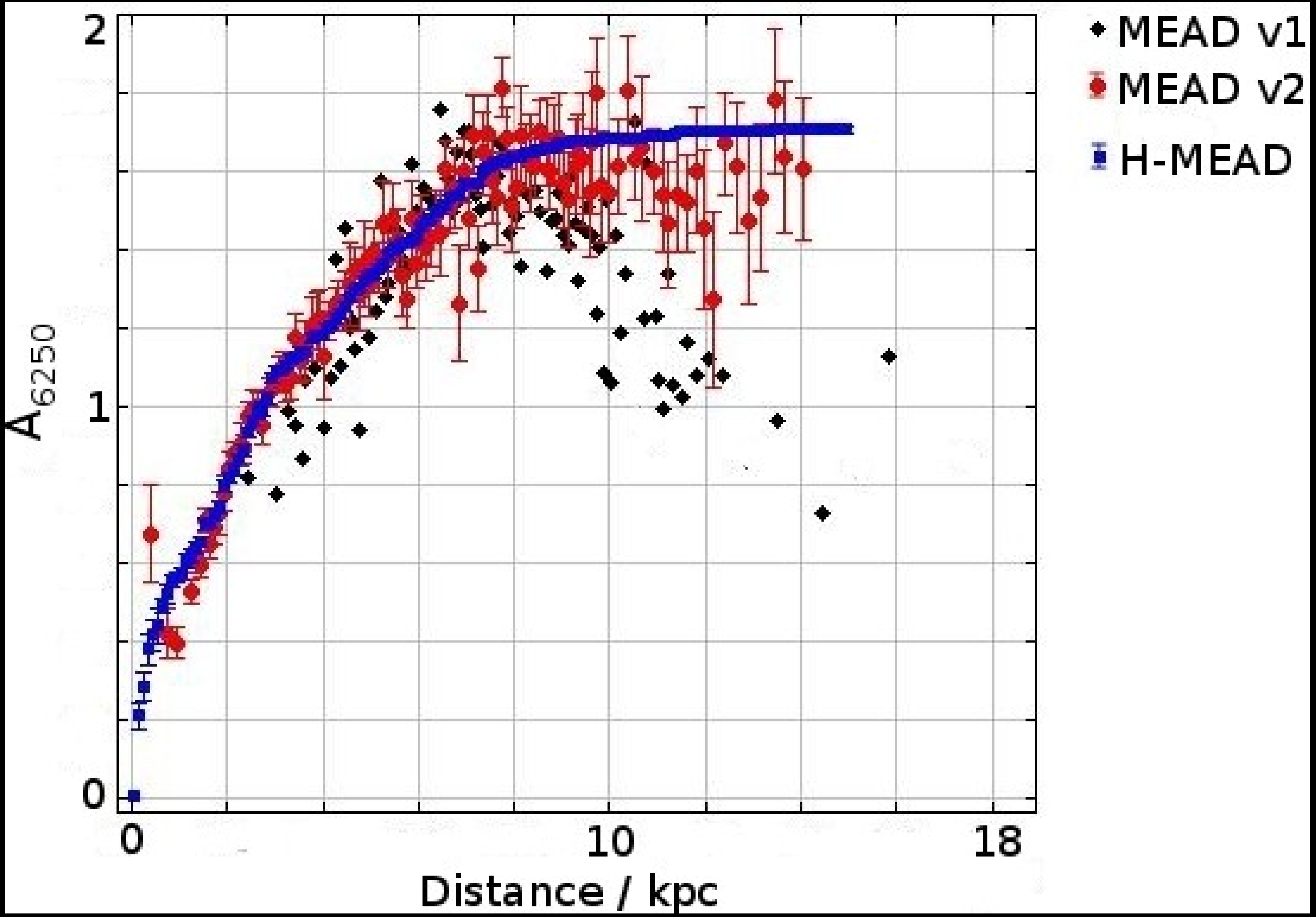
  - Astrometry
    - e.g. GAIA
- Or some combination of the above

H-MEAD

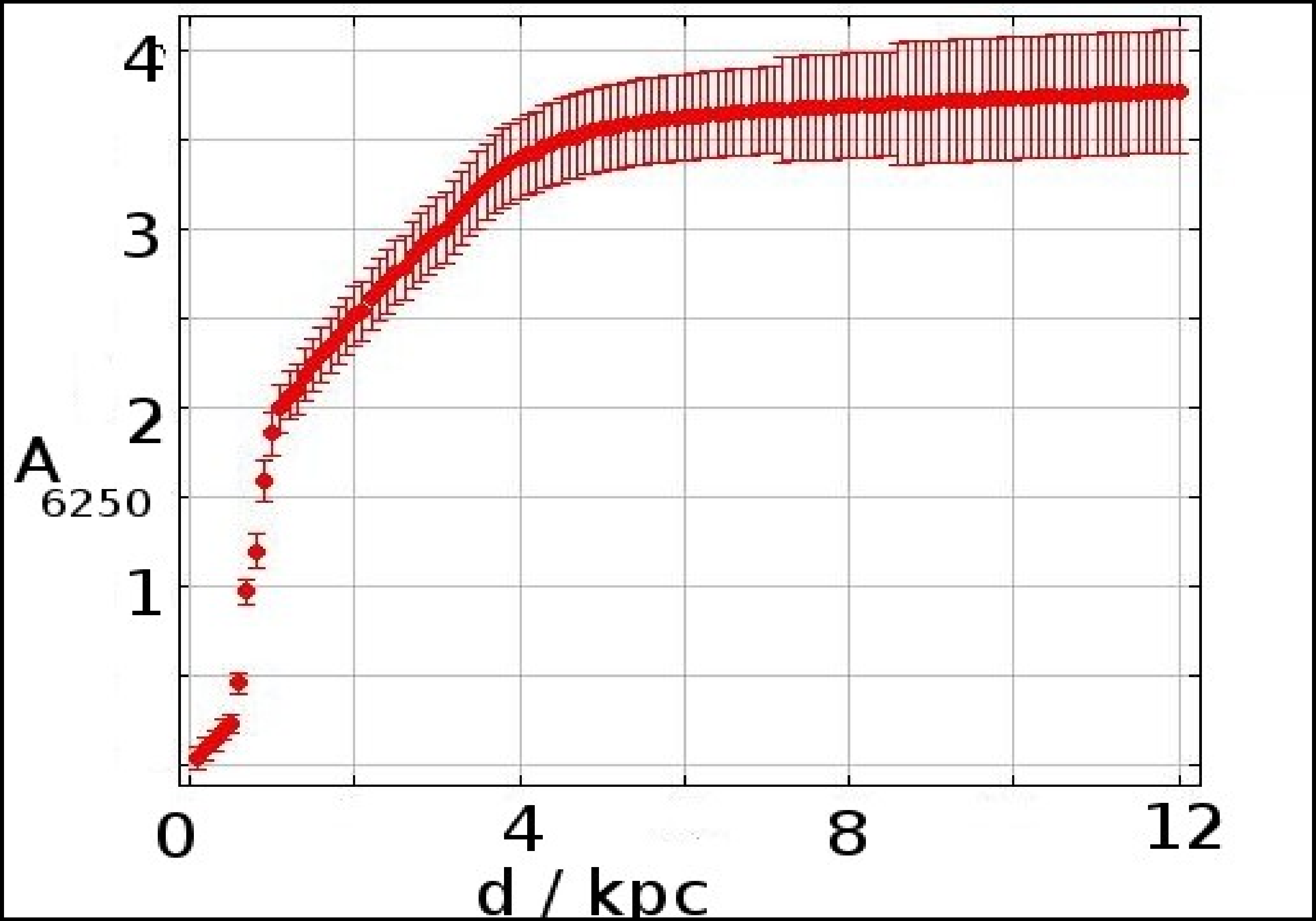
- H-MEAD (Hierarchically mapping extinction against distance) – an algorithm to solve the hierarchical model.
  - Employs MCMC techniques – no analytical solution available
    - Componentwise MCMC
- Supersedes MEAD algorithm (Sale et al. 2009)
- Currently can use data from IPHAS, VISTA, UKIDSS.

H-MEAD

- IPHAS example, (l,b)~(149, -4)

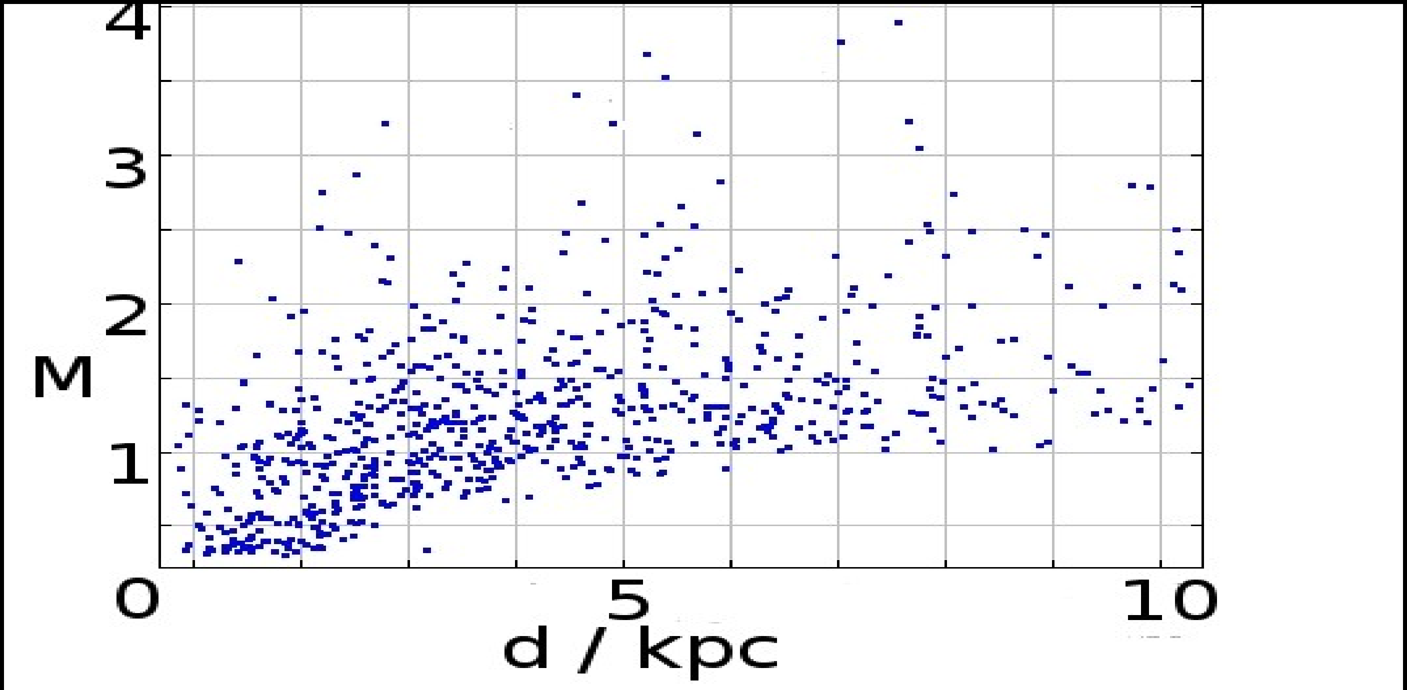


- VVV example, (l,b)=(341,-1.8)



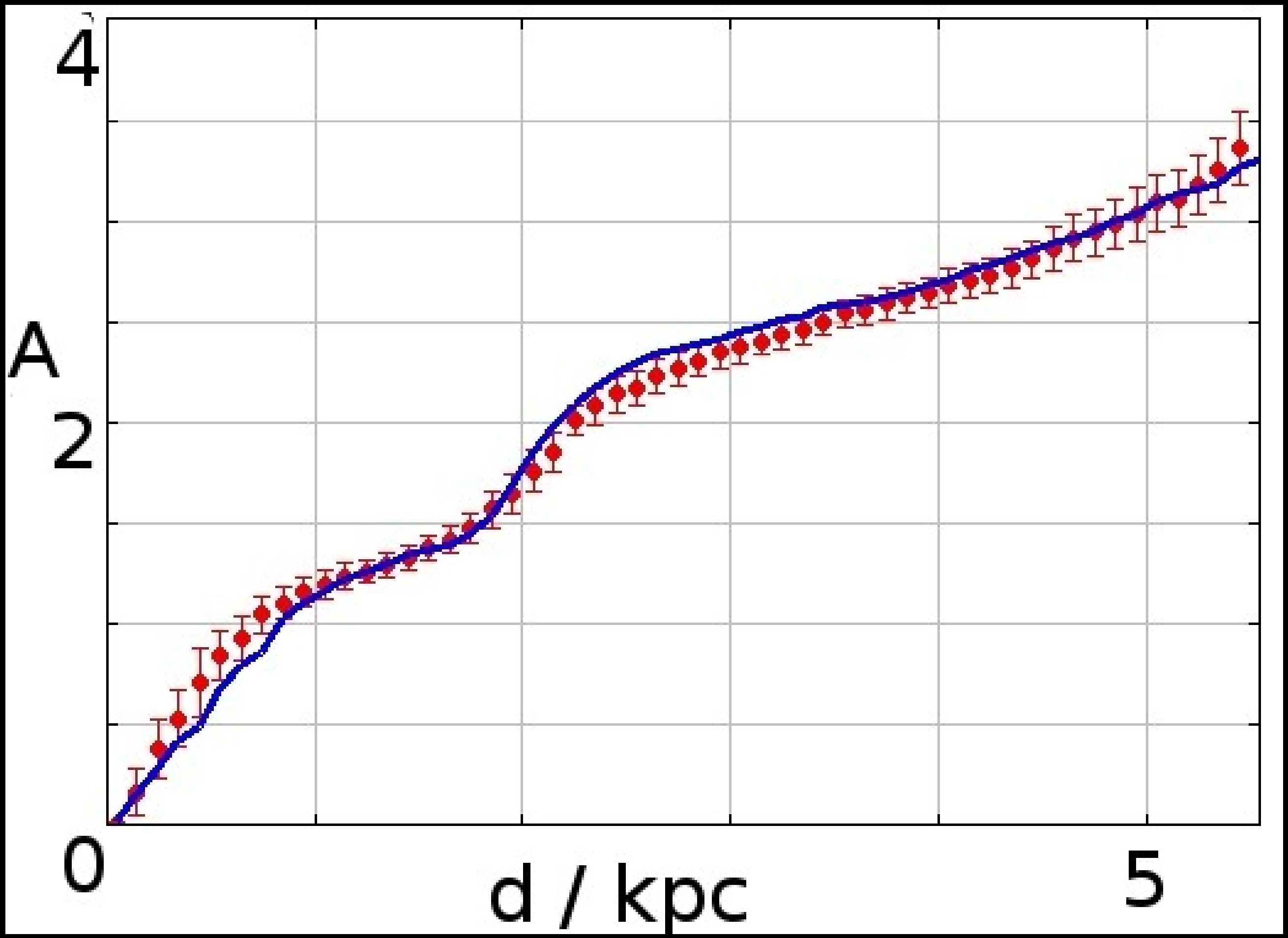
Stellar parameters

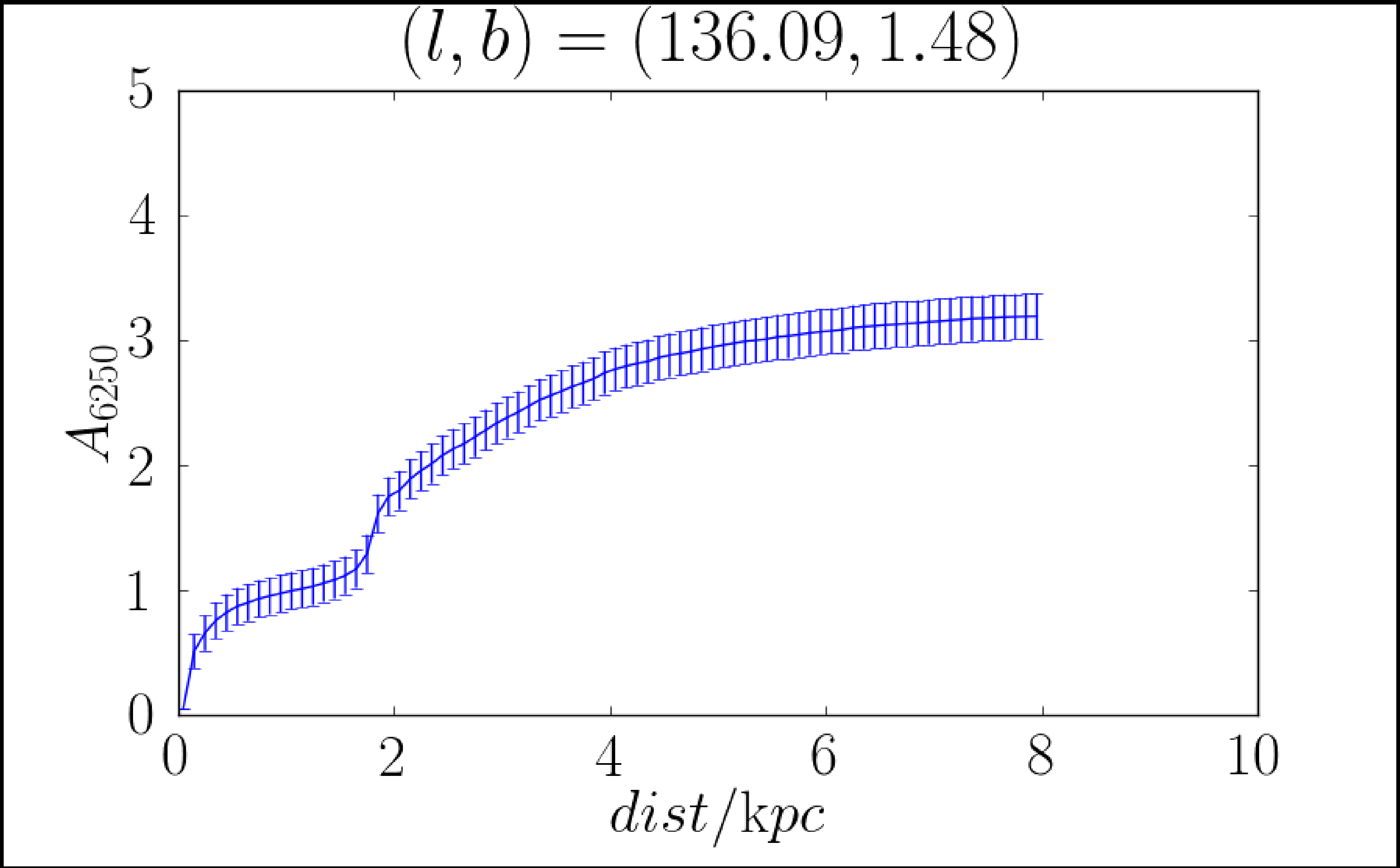
- Many potential uses for estimates of stellar parameters.
  - Example: Map distribution of high mass stars (in 3D)
    - Hence, examine spiral structure



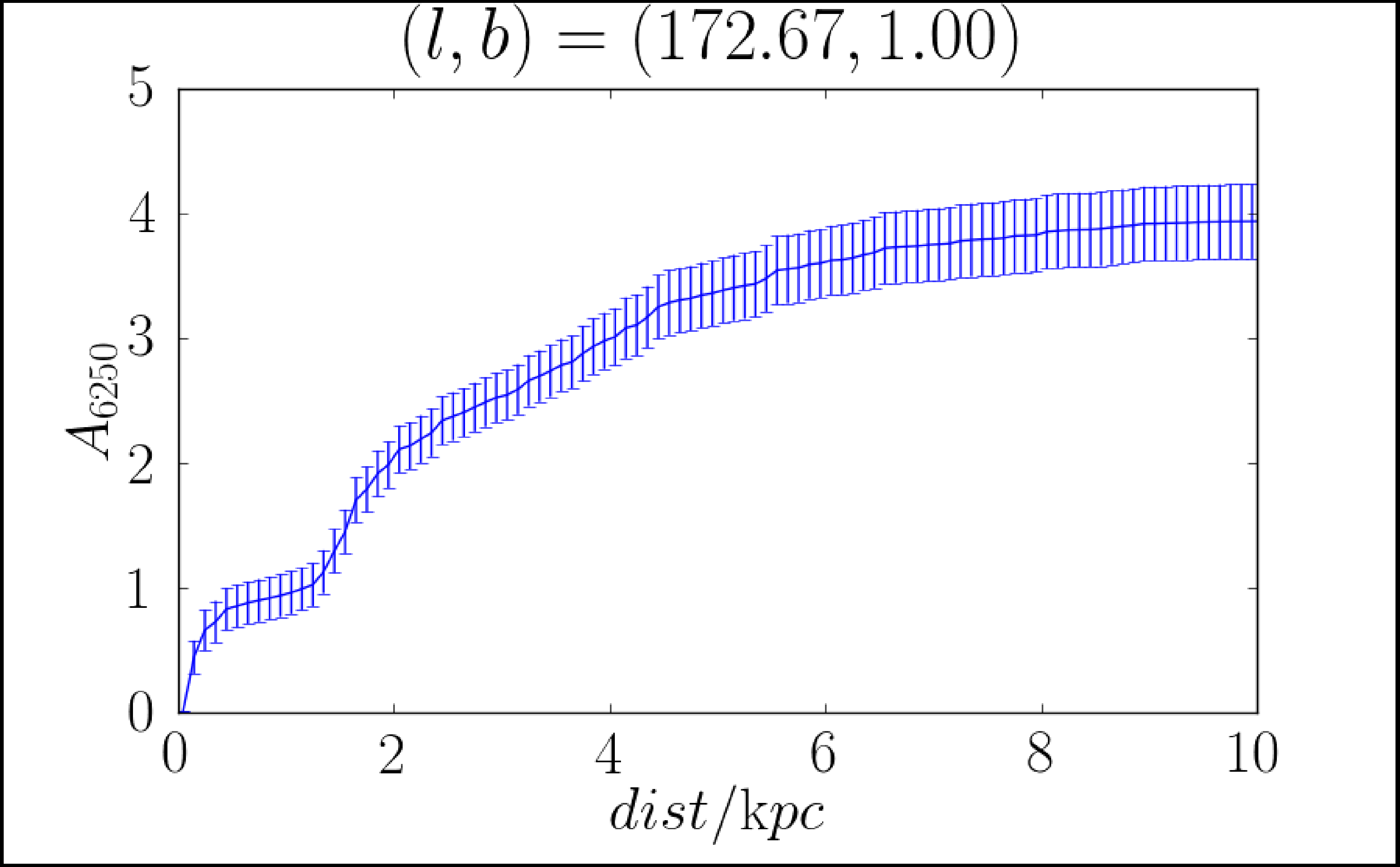
H-MEAD

- Verified with simulated photometry:



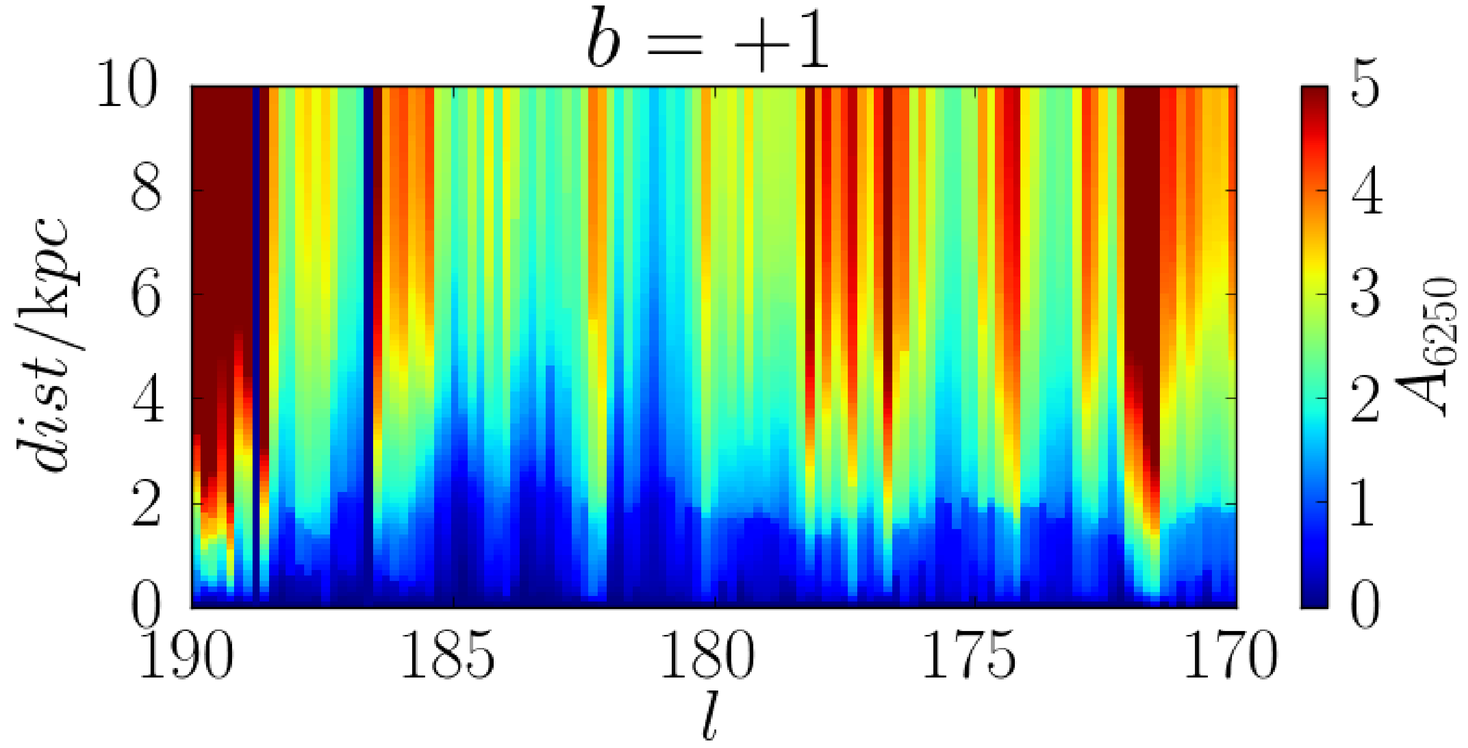


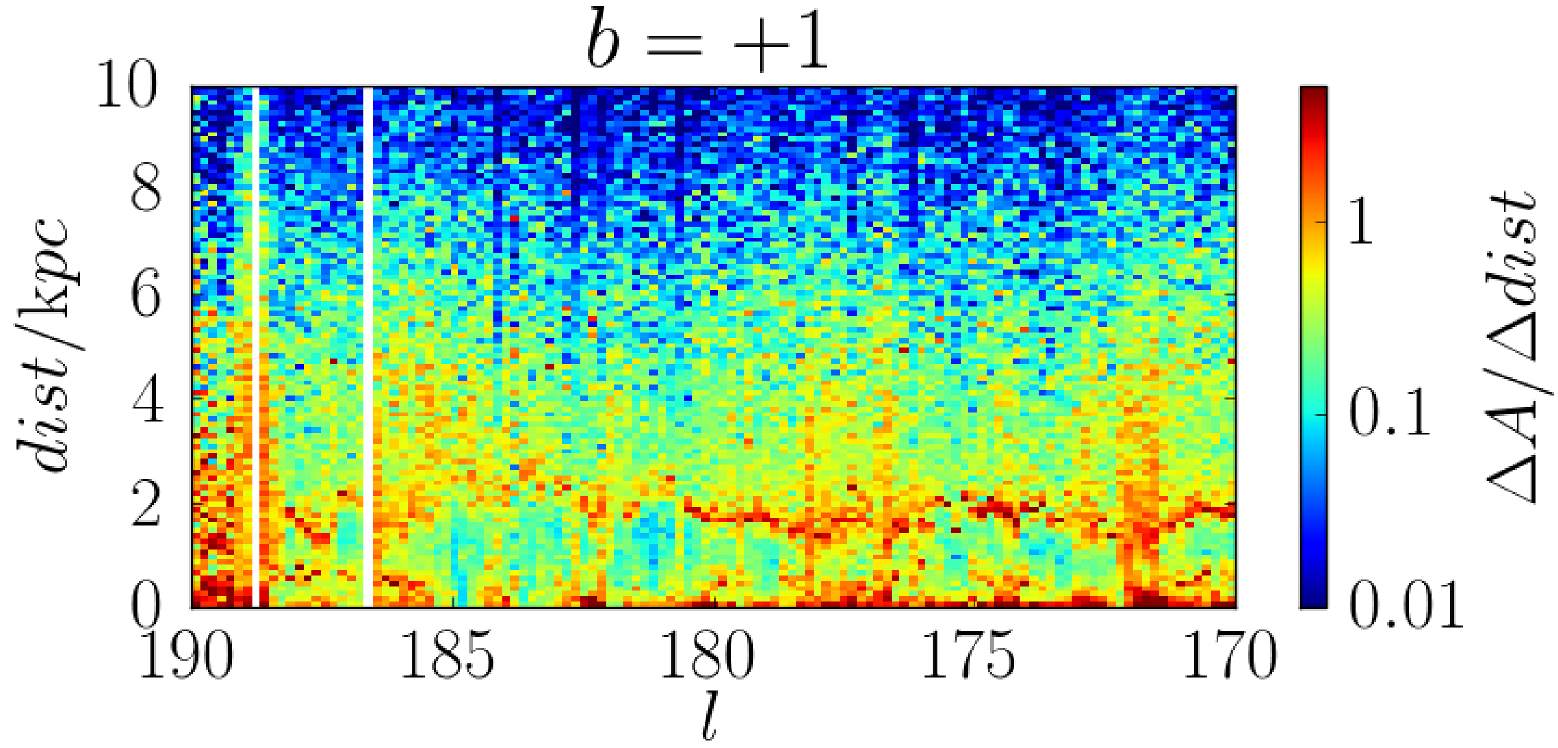
IPHAS



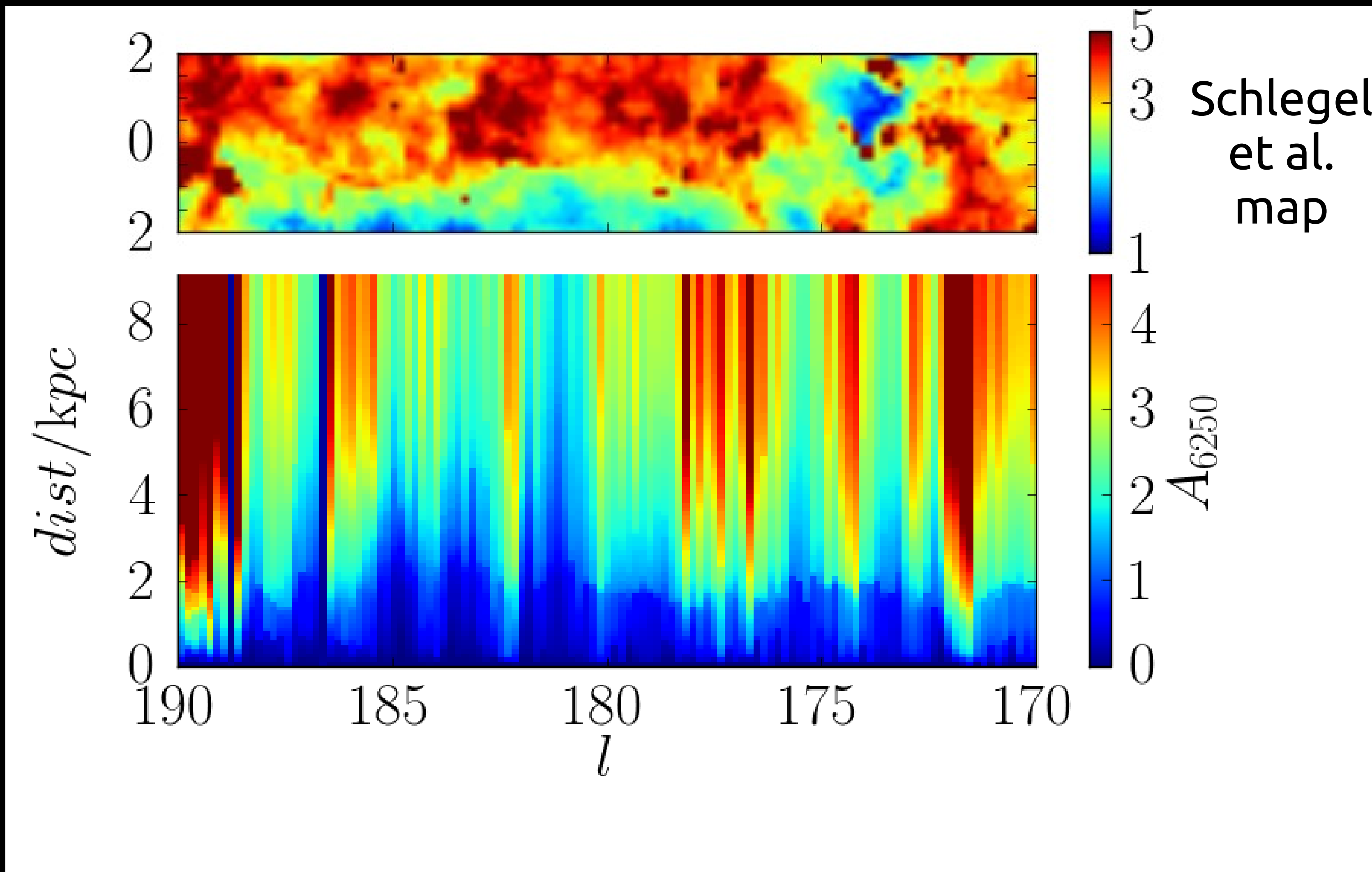
IPHAS

Mapping Areas (Volumes)



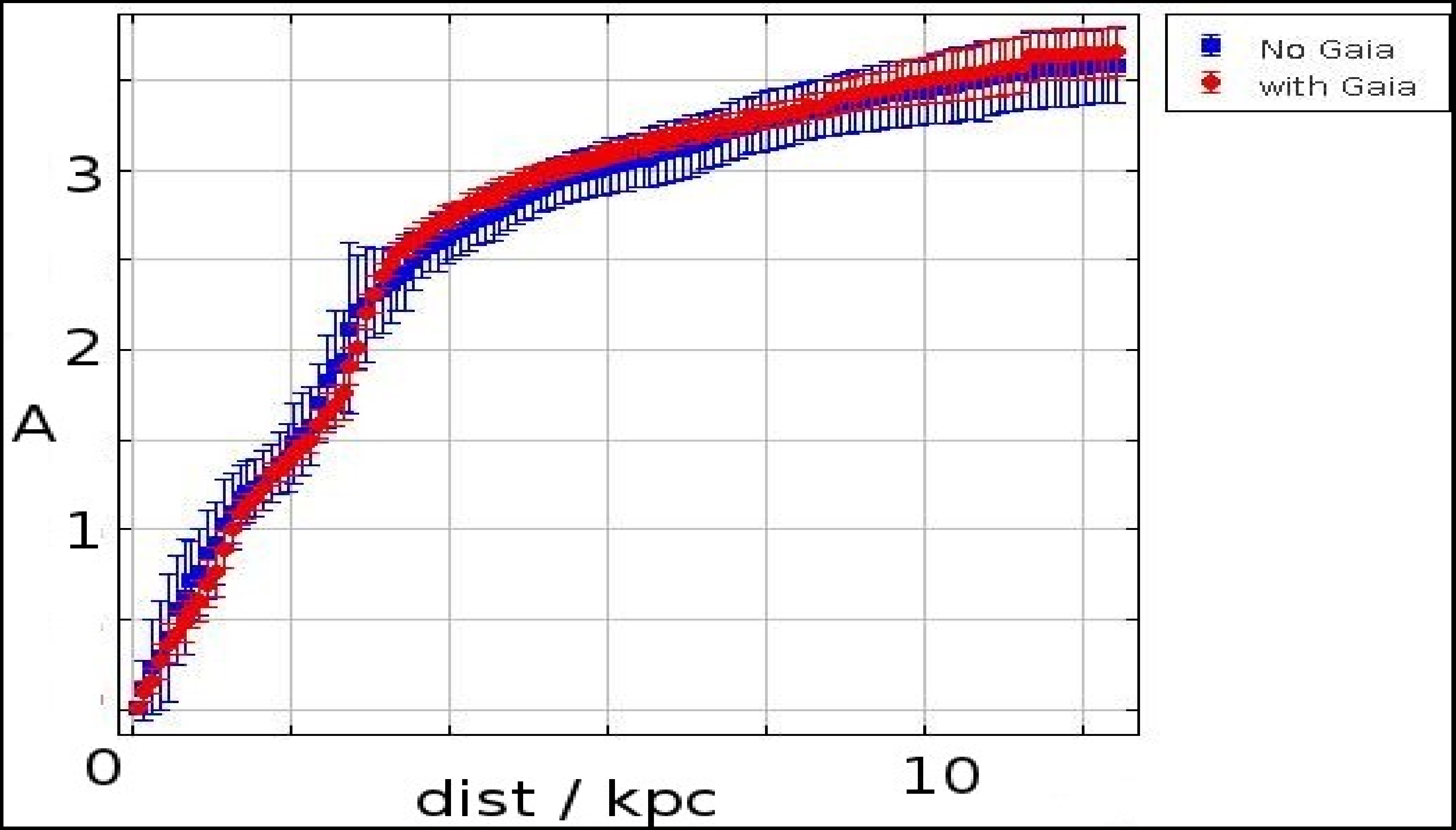


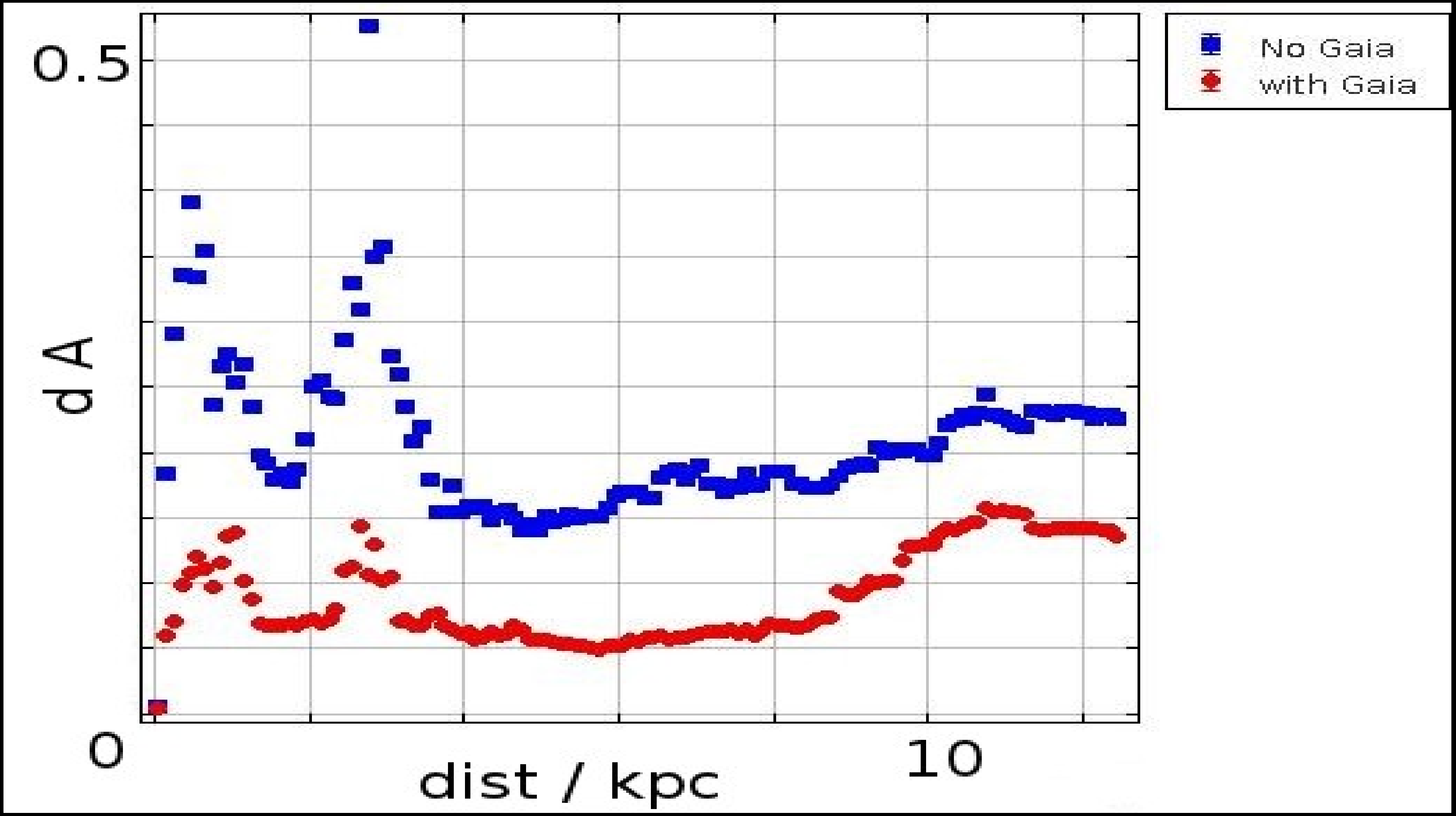
$b = +1$
10
8
6
4
2
0
$dist$/kpc
190
185
180
175
170
l
1
0.1
0.01
$\Delta A/\Delta dist$



Schlegel et al. map
dist/kpc
A_{6250}
l
190
185
180
175
170

Mapping with Gaia

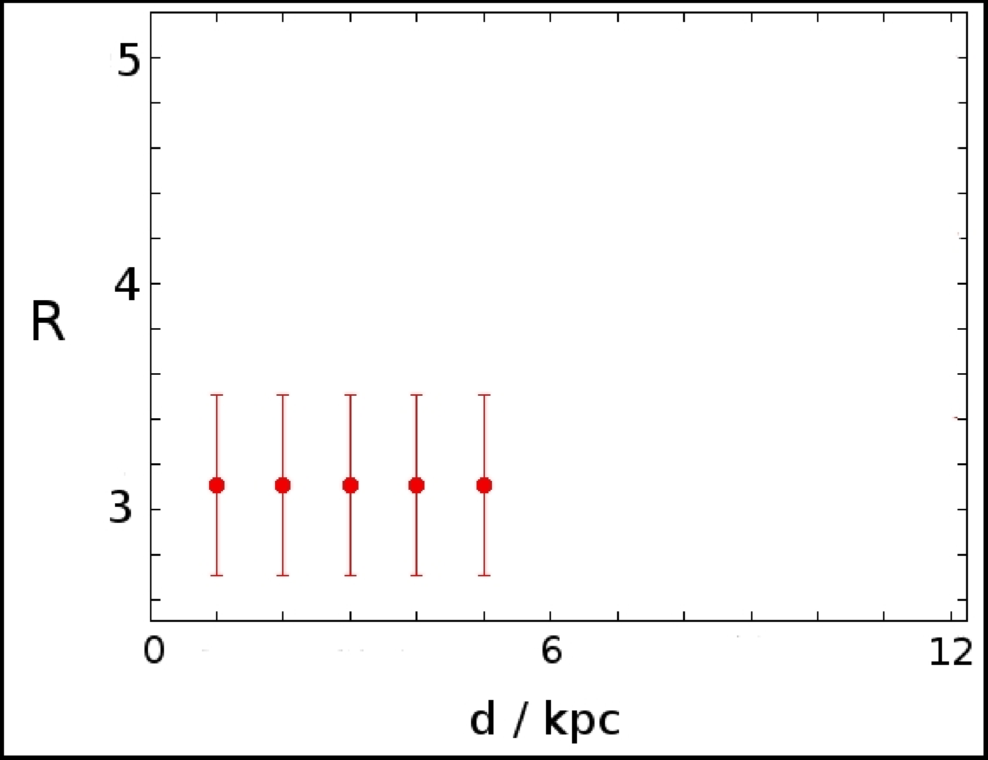




0.5
0
dA
dist / kpc
10
No Gaia
with Gaia

Extensions

- Several possible extensions to existing scheme:
  - Estimate the shape of the Extinction law (e.g. R) for individual stars
  - Map R in 3D:



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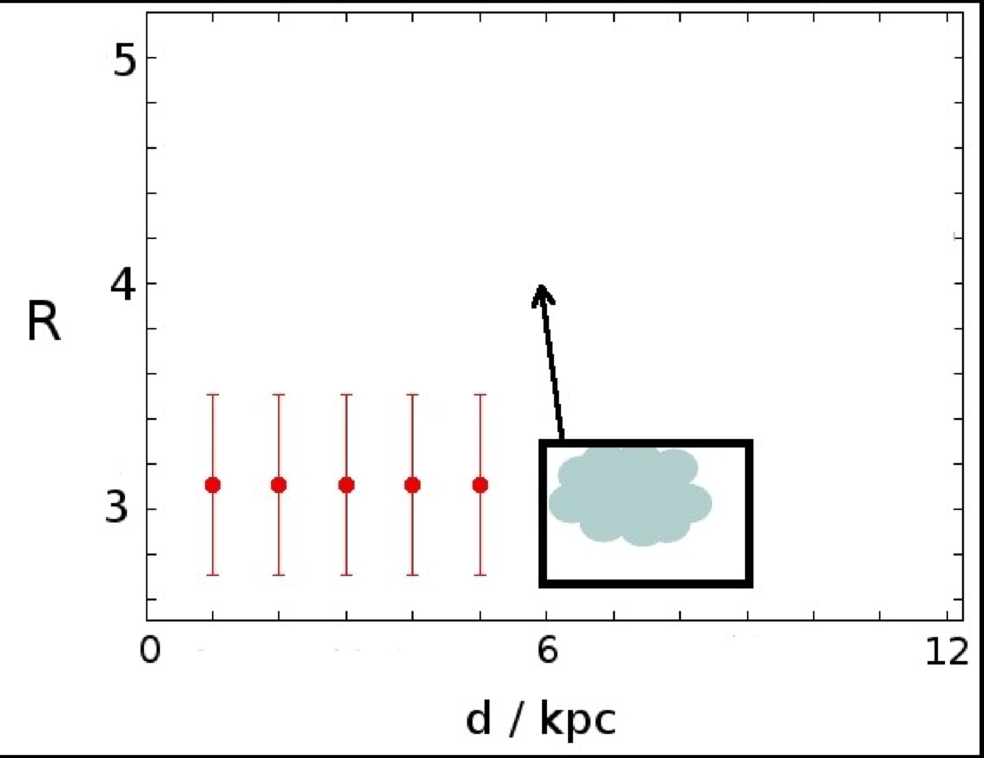

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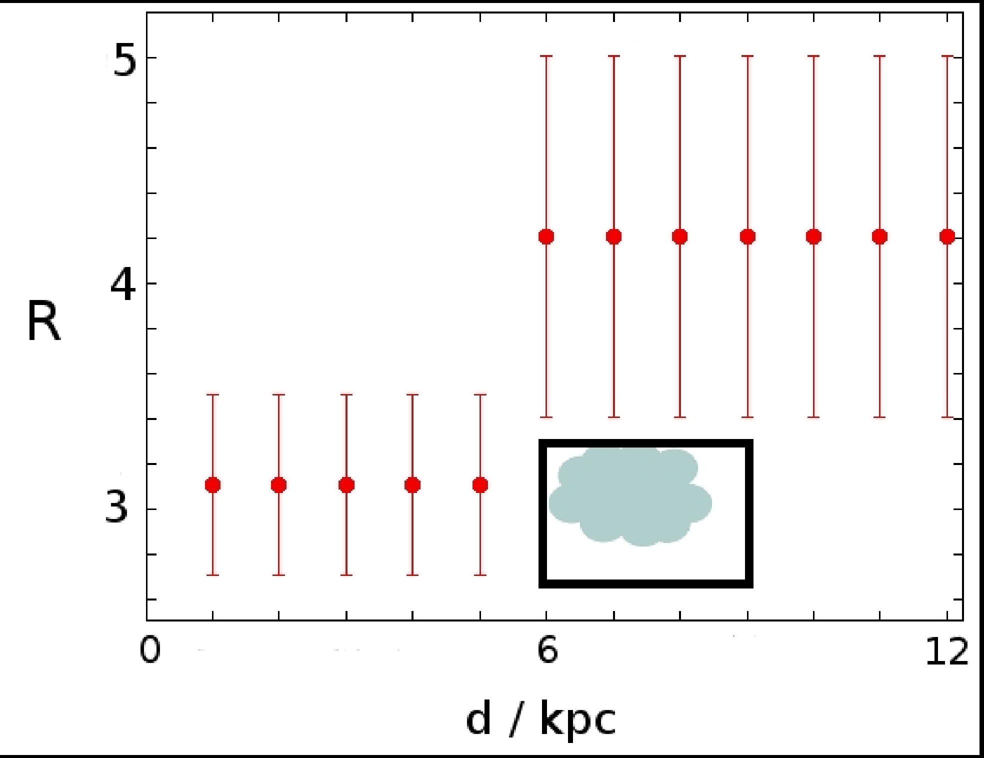

Extensions

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  - Estimate the shape of the Extinction law (e.g. R) for individual stars
  - Map R in 3D
  - Possible with existing data (e.g. IPHAS + UKIDSS, SDSS, etc)

Extensions

- How to deal with binarity?

Extensions

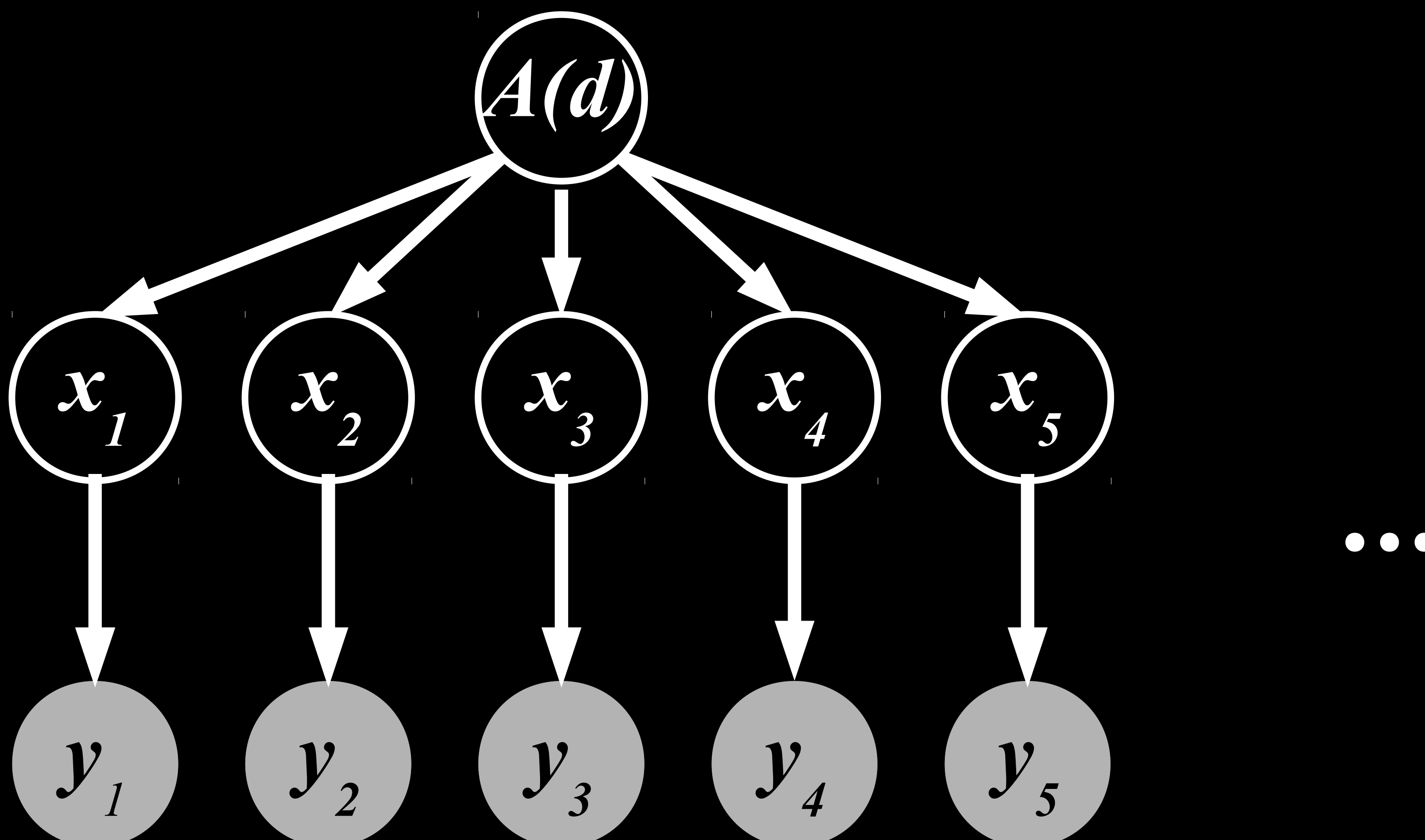
- How to deal with binarity?
  - Current (simple) approach – inflate distances to stars by 5%
  - Better – model with binarity – for binary stars!
- But, binary stars not known *a priori*

$\therefore$ Need to perform model selection

- Reversible Jump MCMC

Extensions

$$P\left(\boldsymbol{x}\, A(d) \middle| \boldsymbol{y}\; IMF\; SFH\; \rho_s(R, z) \ldots\right) \propto P(\boldsymbol{y}|\boldsymbol{x})\, P(\boldsymbol{x}|A(d))\, P(A(d))$$



Extensions

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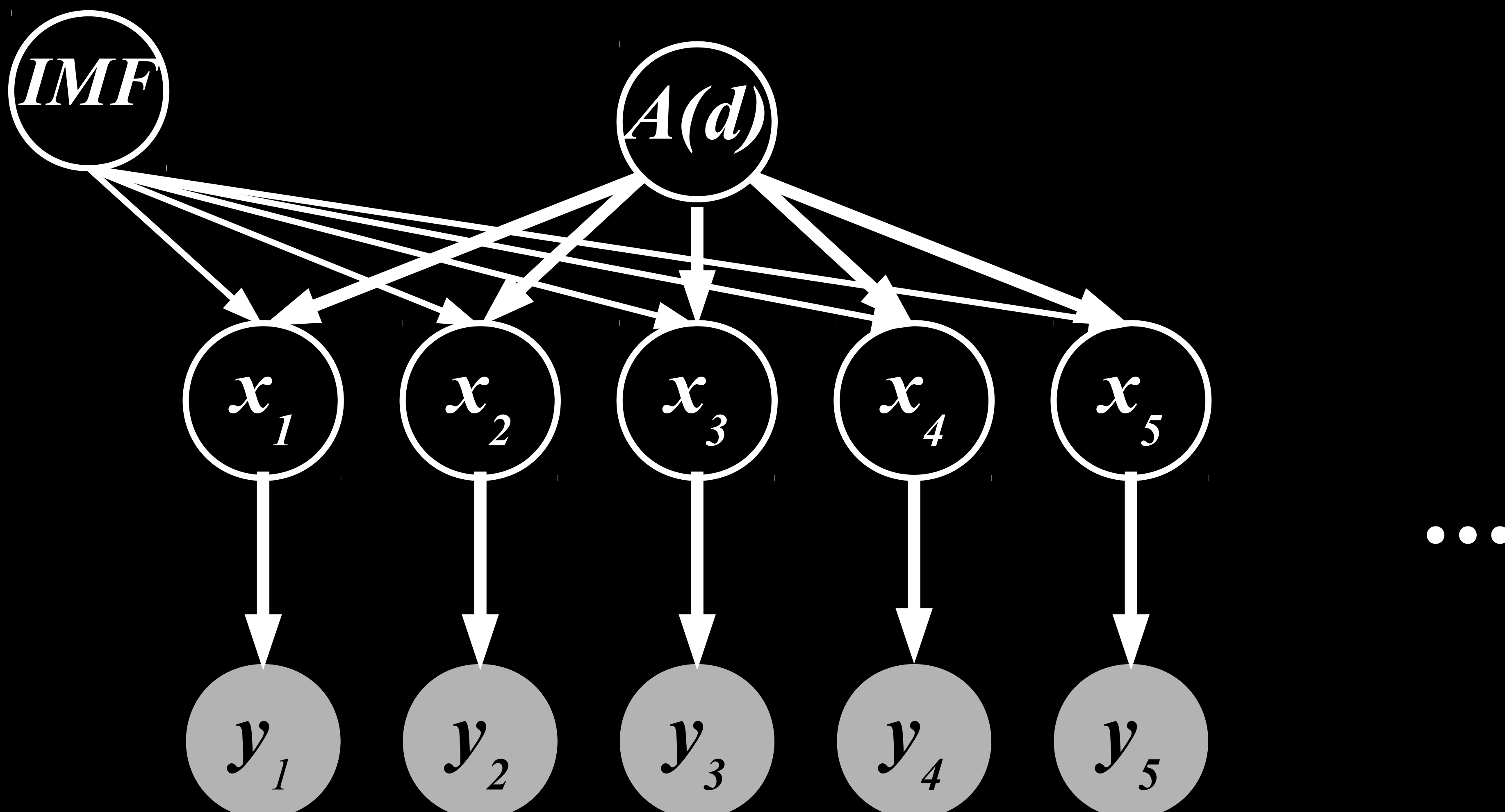
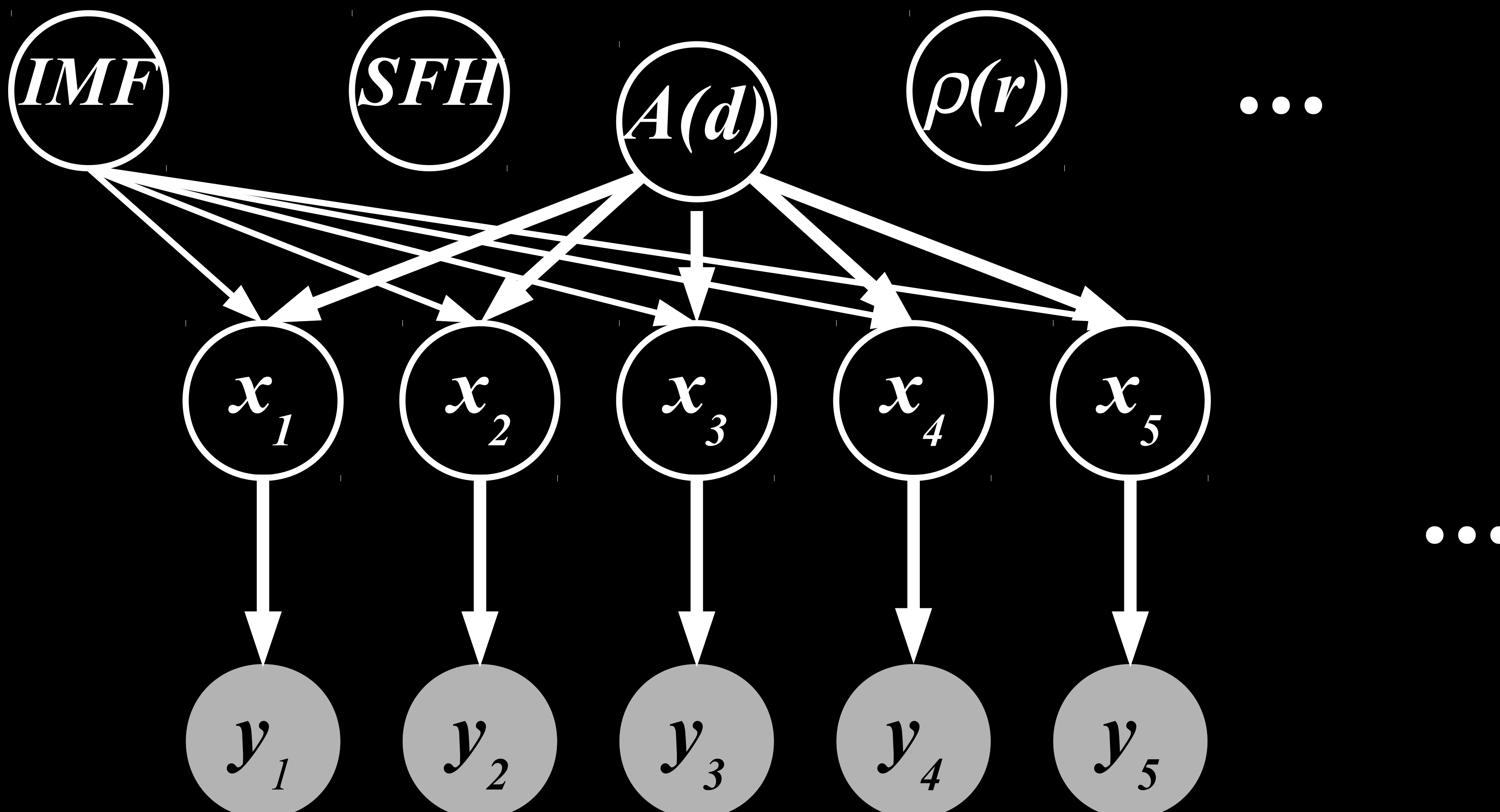
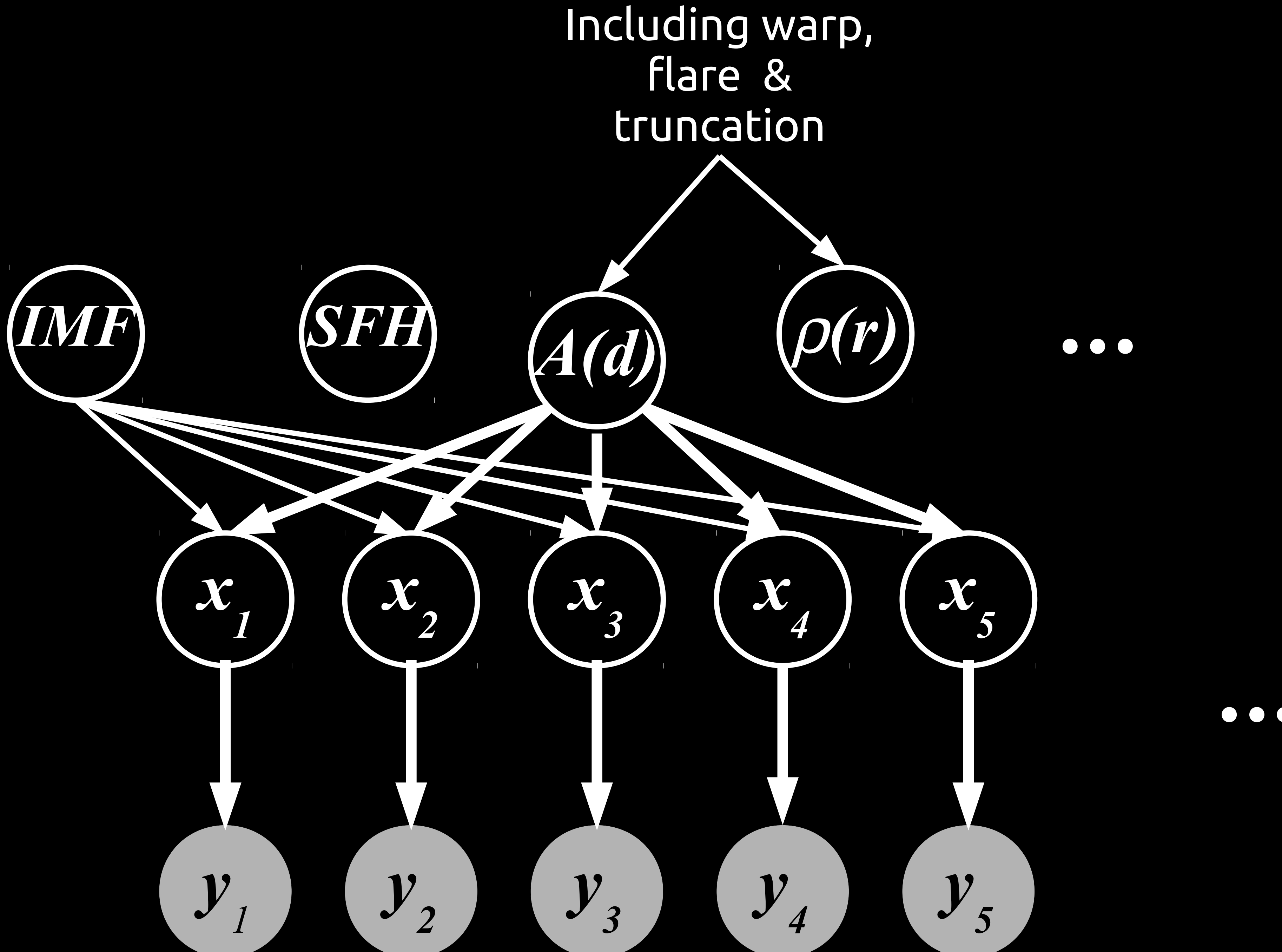


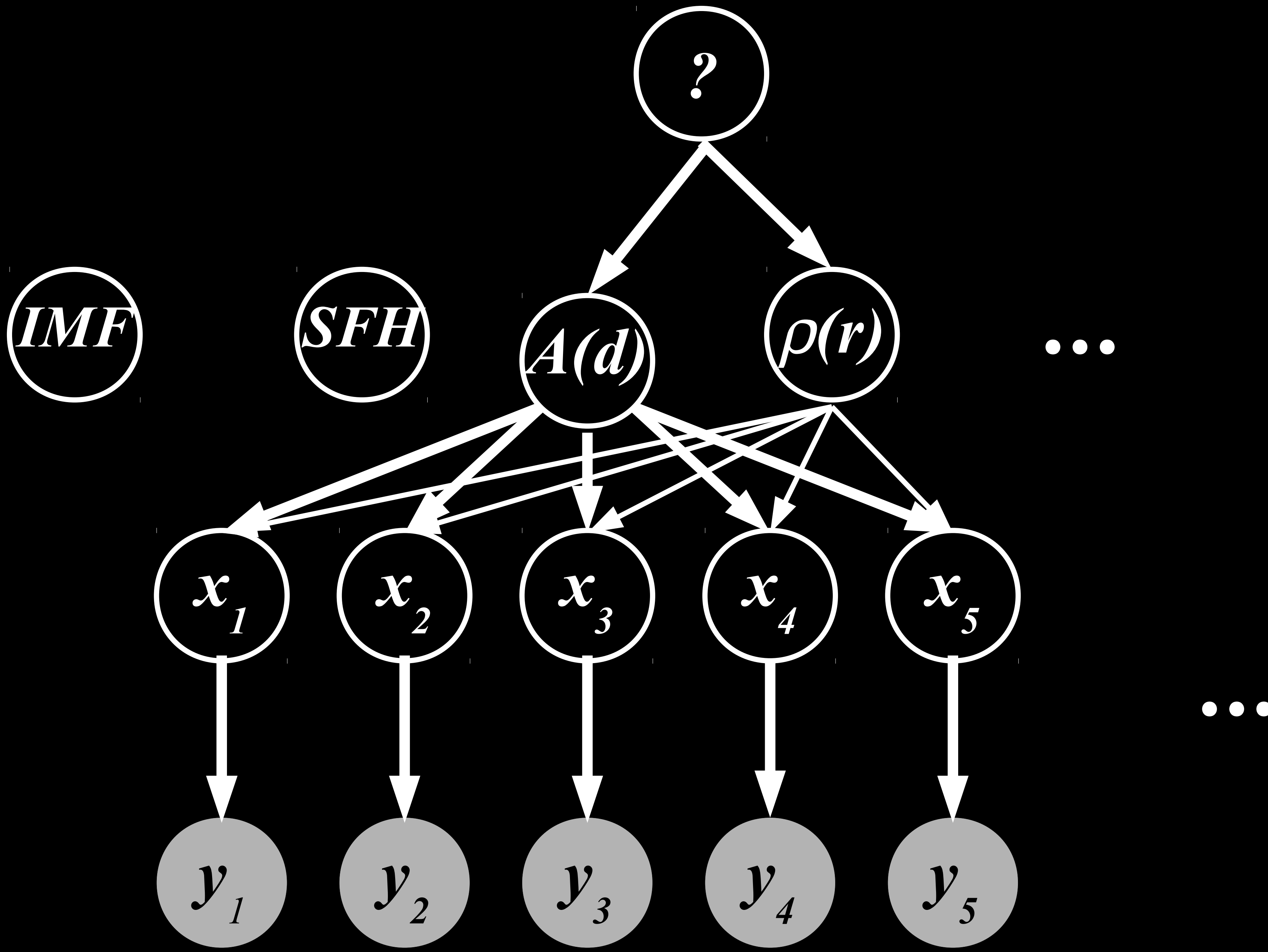
Extensions

$$P(\boldsymbol{x}\ A(d)\ IMF\ SFH\ \rho_s(R,z)\ldots|\boldsymbol{y}) \propto P(\boldsymbol{y}|\boldsymbol{x})\,P(\boldsymbol{x}|A(d)\ IMF\ SFH\ \rho_s(\boldsymbol{r})\ldots)\,P(A(d)\ IMF\ SFH\ \rho_s(\boldsymbol{r})\ldots)$$





Including warp,
flare &
truncation
IMF
SFH
A(d)
ρ(r)
x1
x2
x3
x4
x5
y1
y2
y3
y4
y5


?
IMF
SFH
A(d)
ρ(r)
...
x1
x2
x3
x4
x5
...
y1
y2
y3
y4
y5

Conclusions

- Hierarchical models are a natural description for stars and the ISM
  - A powerful solution for producing accurate & precise 3D extinction maps
- Also determines parameters for stars – many potential applications
- Method is flexible – can be applied to many types of observations or combinations thereof
- Method can be extended to constrain Galactic structure, etc.