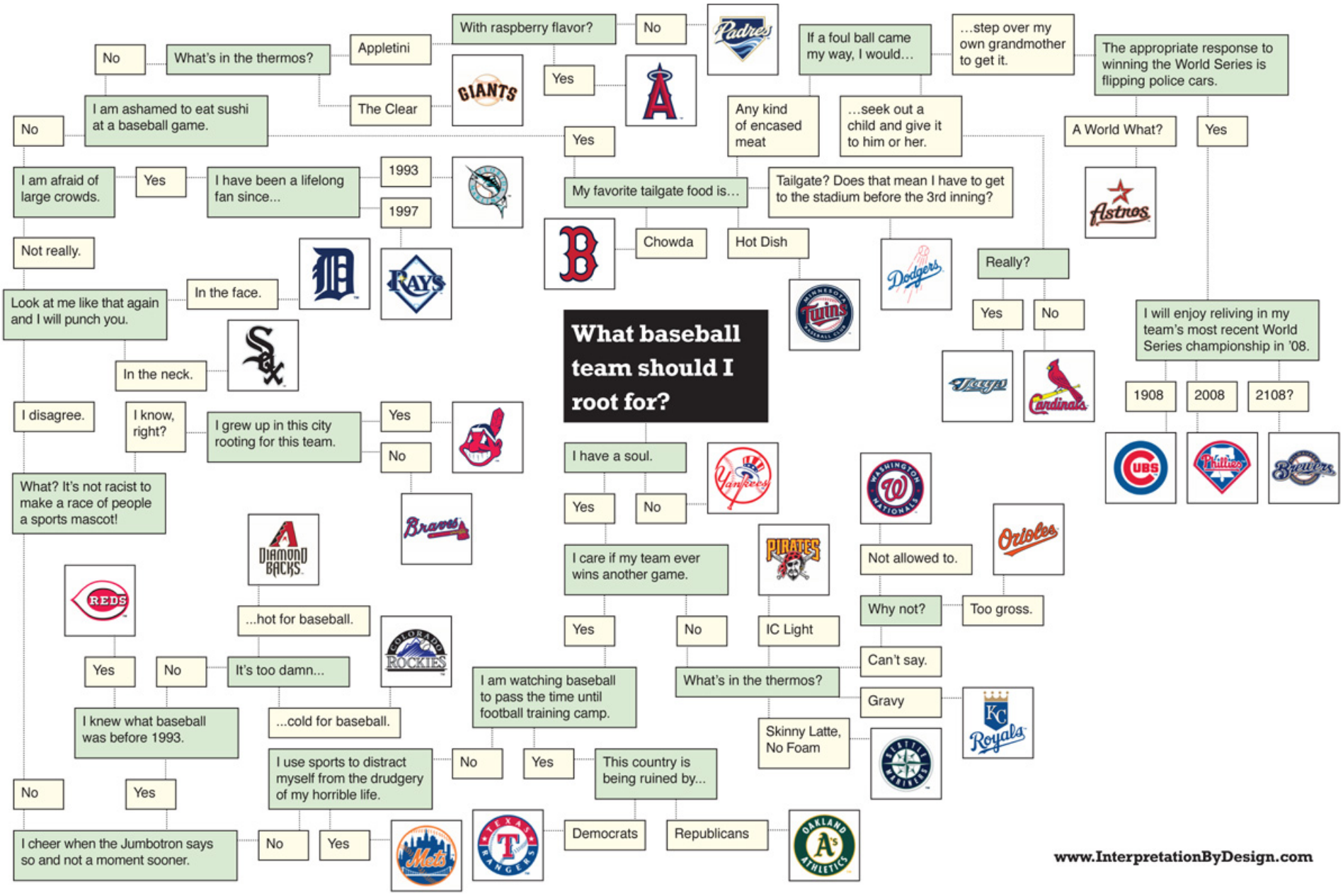
So you found an exoplanet orbiting an M dwarf…

A flow chart and priorities for determining stellar parameters.

Philip S. Muirhead

Boston University

Inspired by the “Baseball Rooting Interest Flow Chart”



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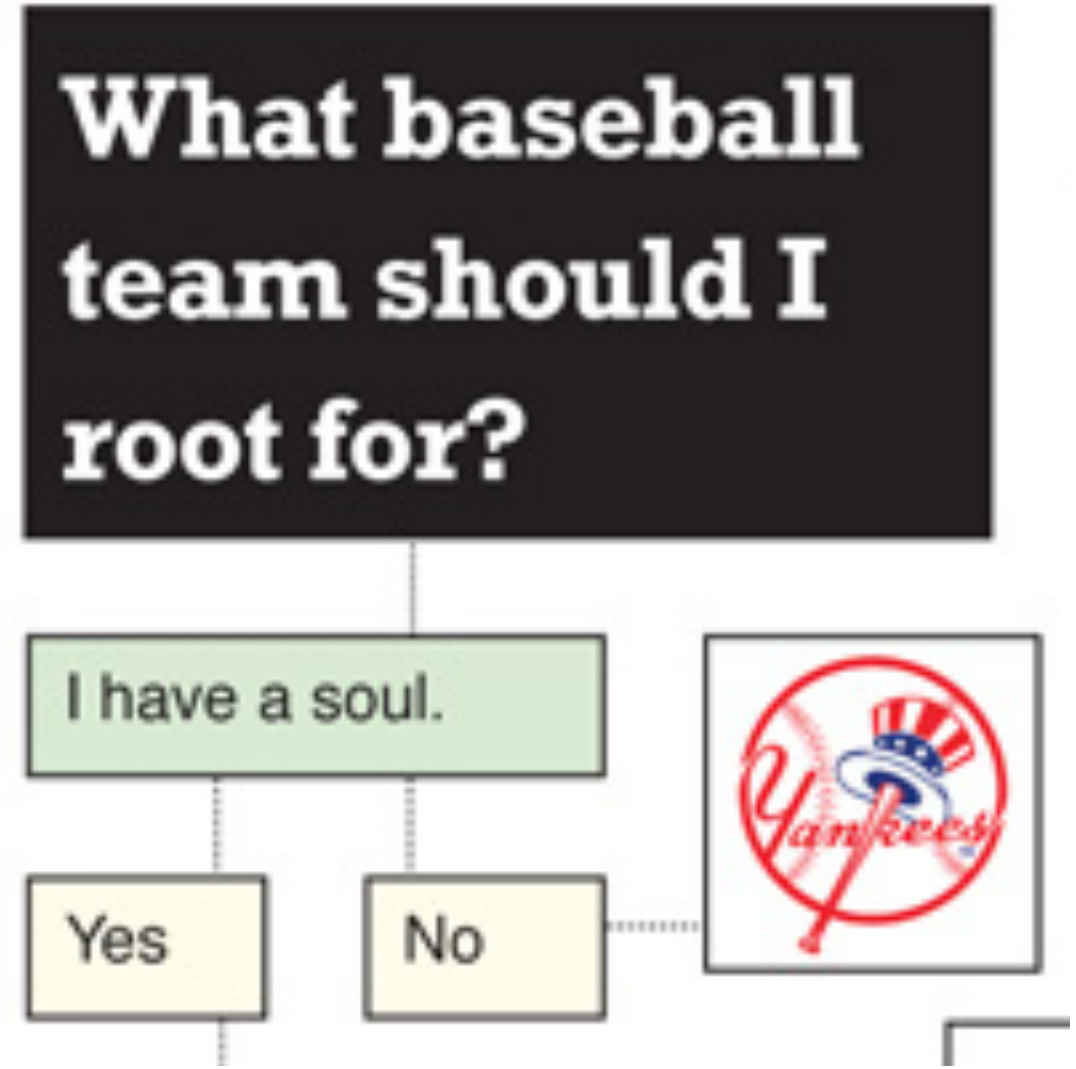


Brief reminder why stellar parameters are important to the ExEP

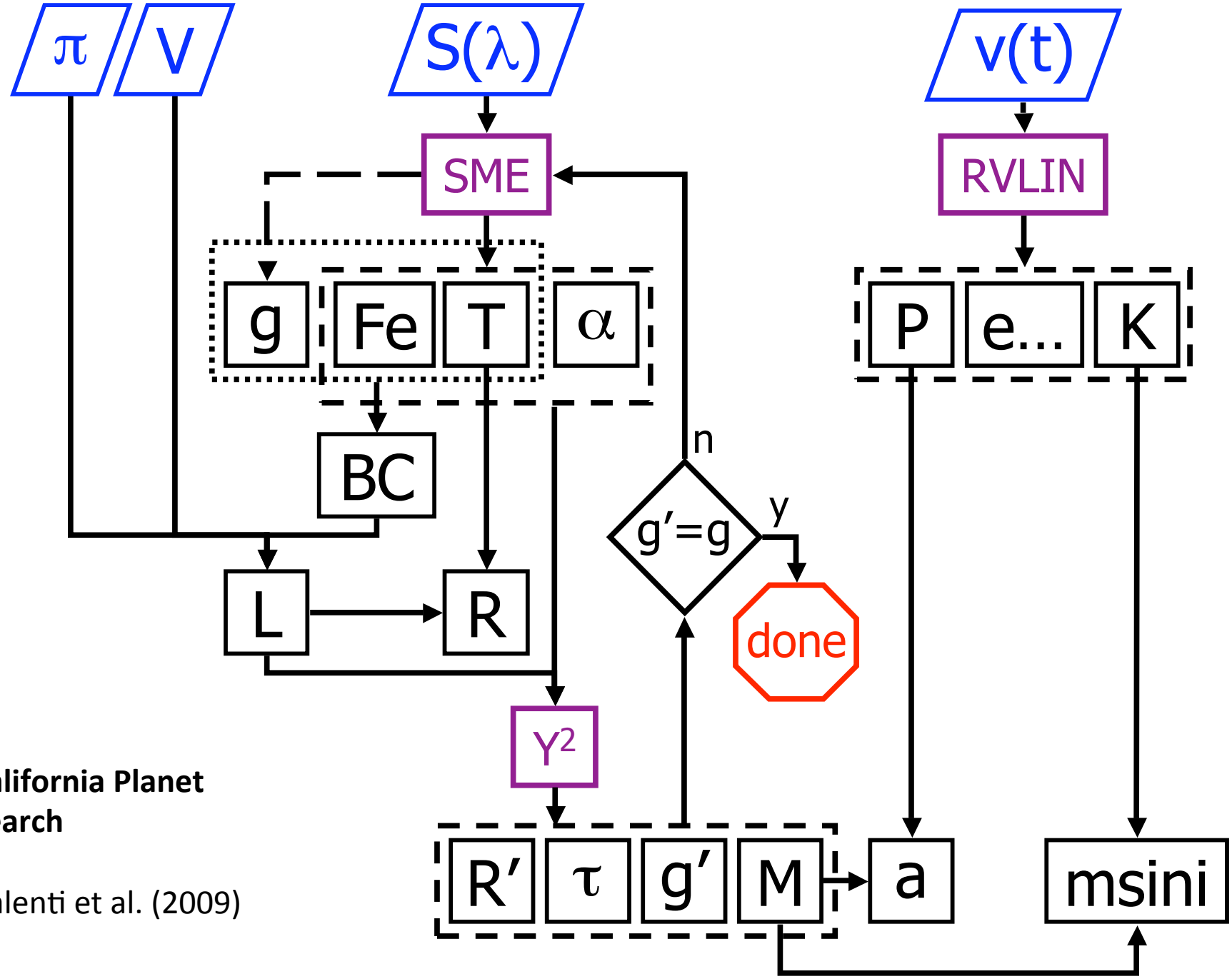
- For transit observations: $R_P \ \alpha \ R_{Star}$
- For RV observations: $M_P \sin i \ \alpha \ (M_{star})^{1/3}$
- $T_{Eq} \ \alpha \ (L_{Star})^{1/4} \ \alpha \ (R_{Star})^{1/2} \ T_{eff}$
- **Want Stellar Mass, Radius and Luminosity for best JWST targets.**

A Hard Truth

- Nearly all stellar parameter measurements rely on a **stellar model** at some point.
  - E.g. Metallicity, log(g), and assumed limb-darkening coefficients are usually based on **atmospheric models**.
- Therefore, stellar parameters will almost always be subject to some **systematic error**.

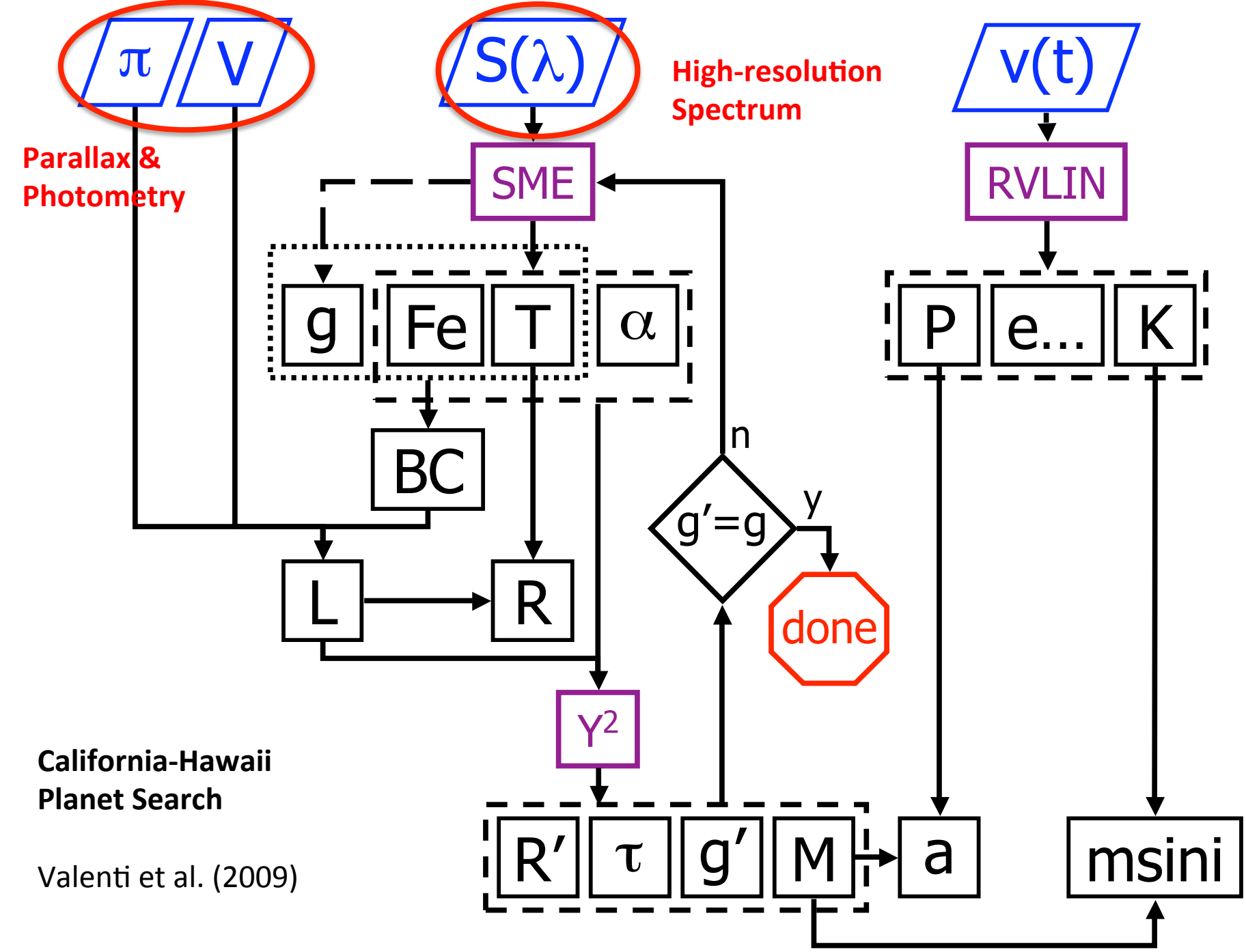
A Hard Truth

- Nearly all stellar parameter measurements rely on a **stellar model** at some point.



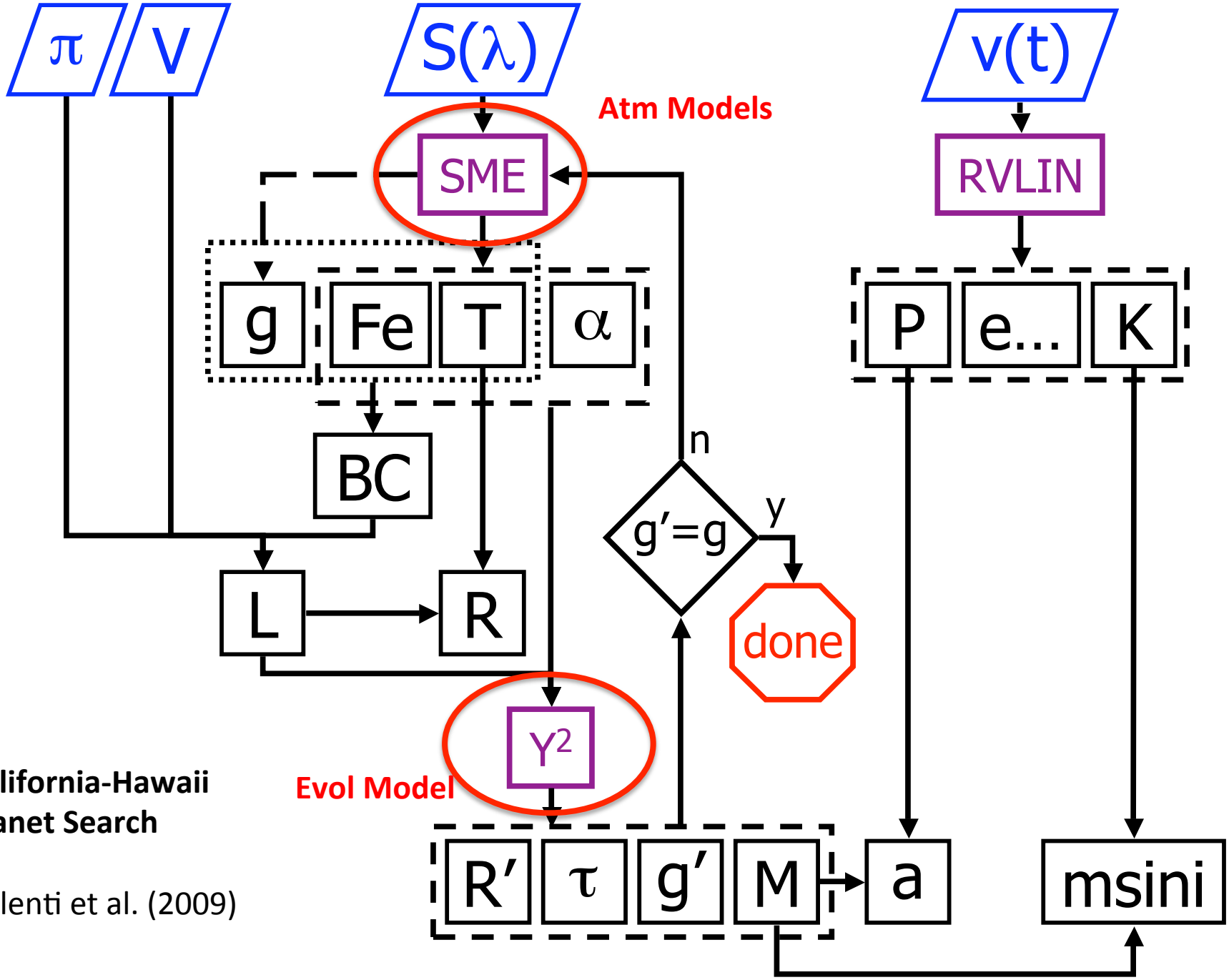
California Planet Search

Valenti et al. (2009)



California-Hawaii Planet Search

Valenti et al. (2009)



California-Hawaii Planet Search

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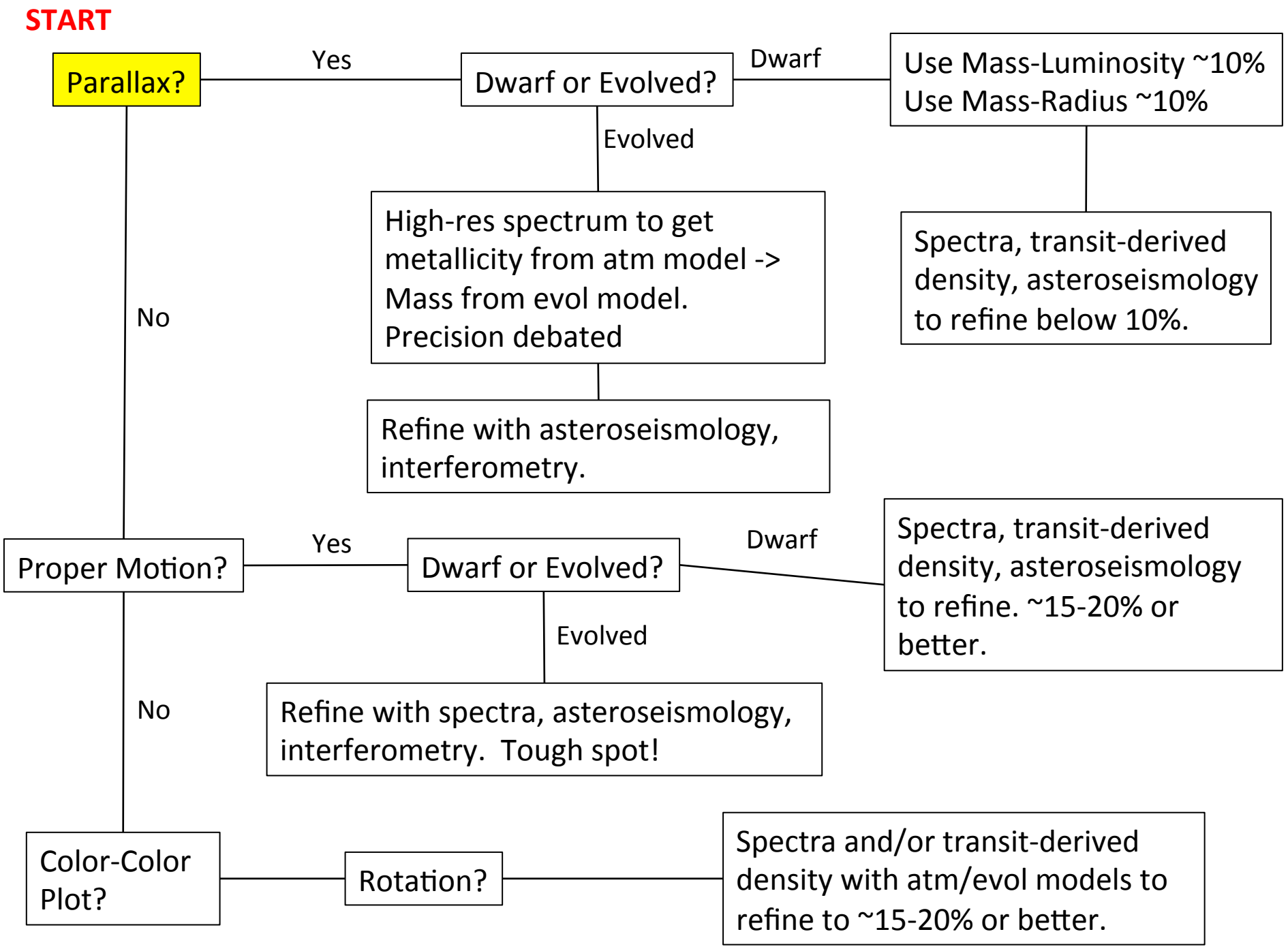
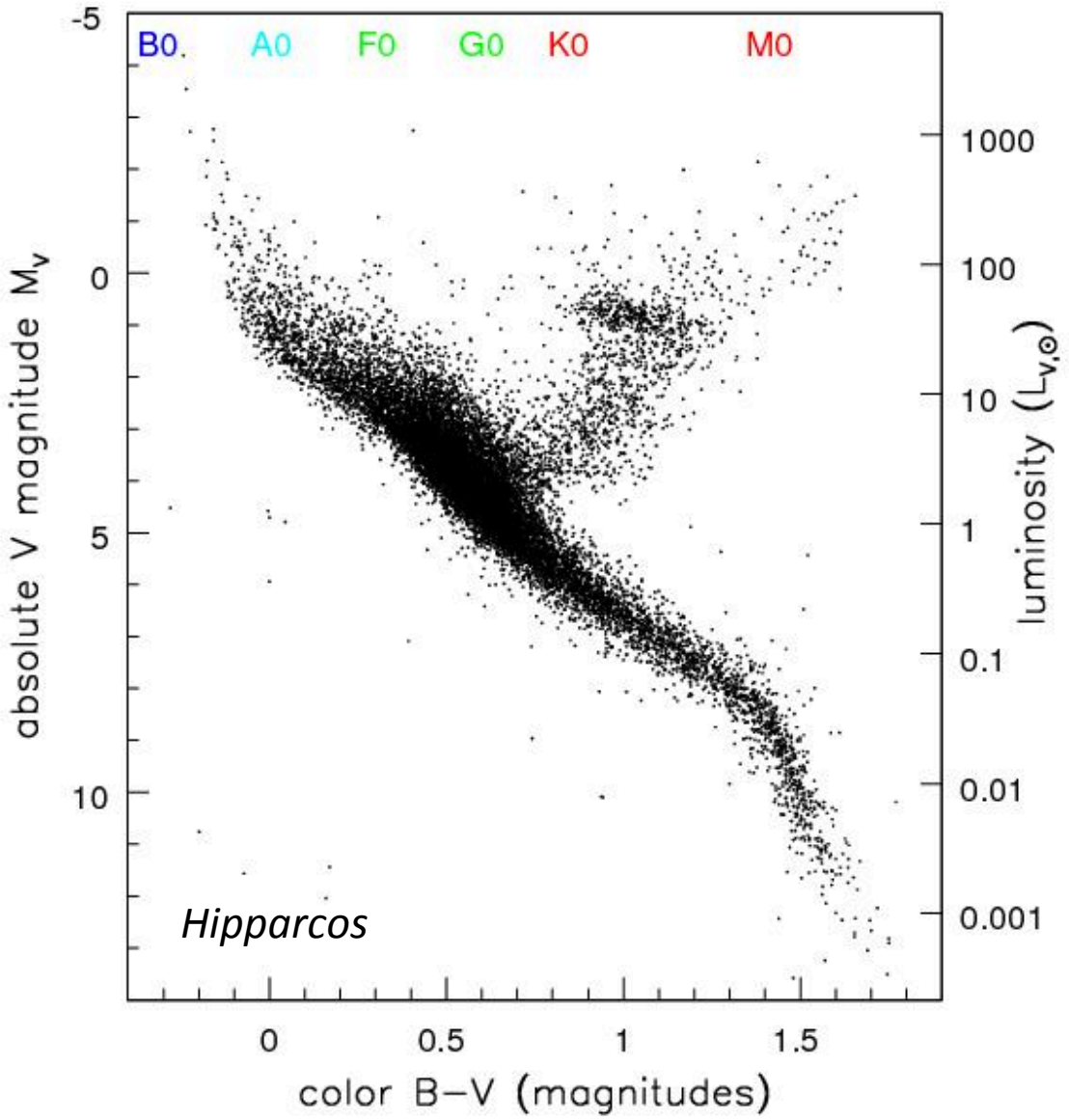
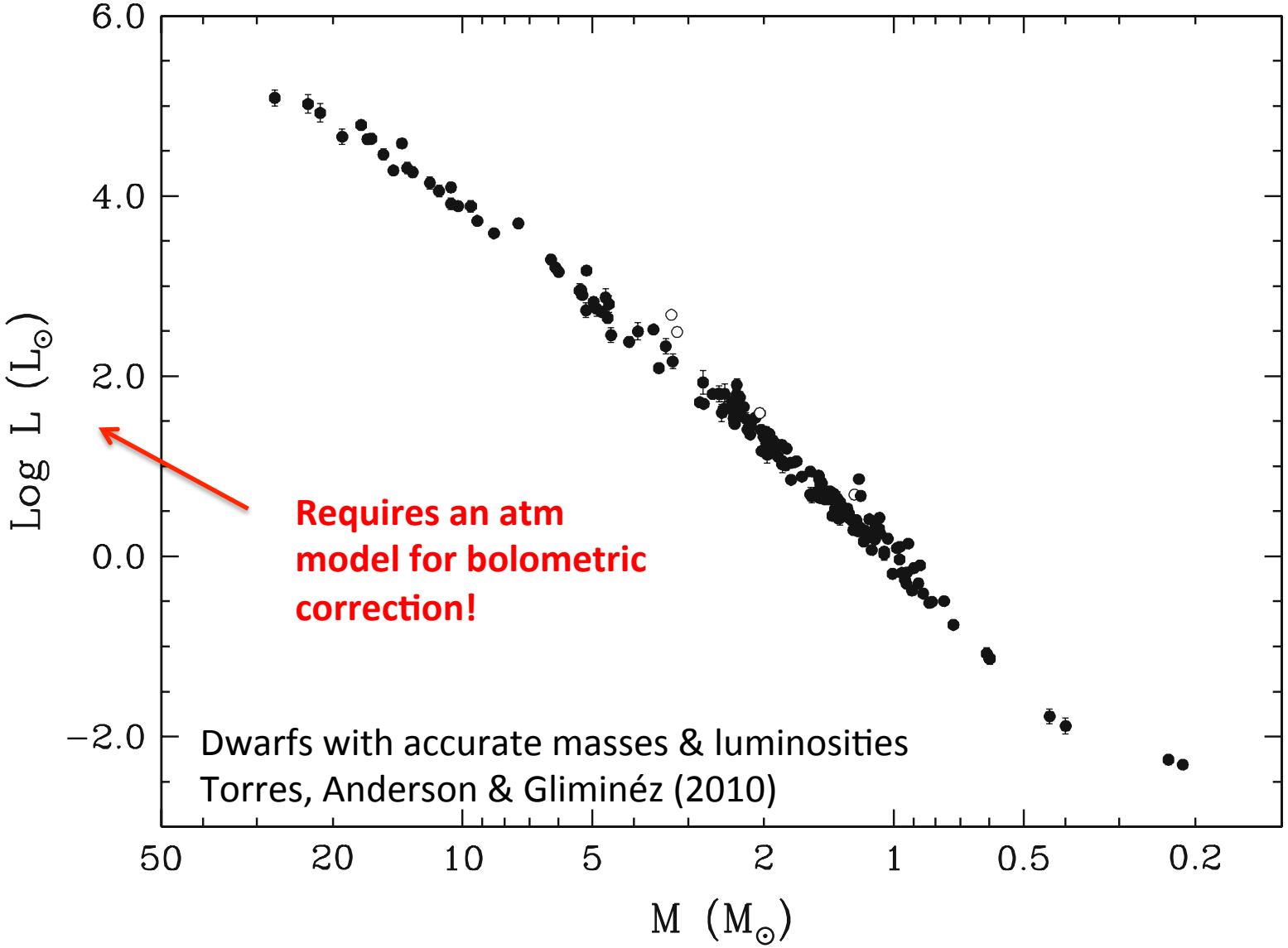

START
Parallax?
Yes
Dwarf or Evolved?
Dwarf
Use Mass-Luminosity ~10%
Use Mass-Radius ~10%
Evolved
High-res spectrum to get metallicity from atm model -> Mass from evol model. Precision debated
Spectra, transit-derived density, asteroseismology to refine below 10%.
Refine with asteroseismology, interferometry.
No
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20% or better.
Evolved
Refine with spectra, asteroseismology, interferometry. Tough spot!
No
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20% or better.

Power of a Parallax: D/G Discrimination

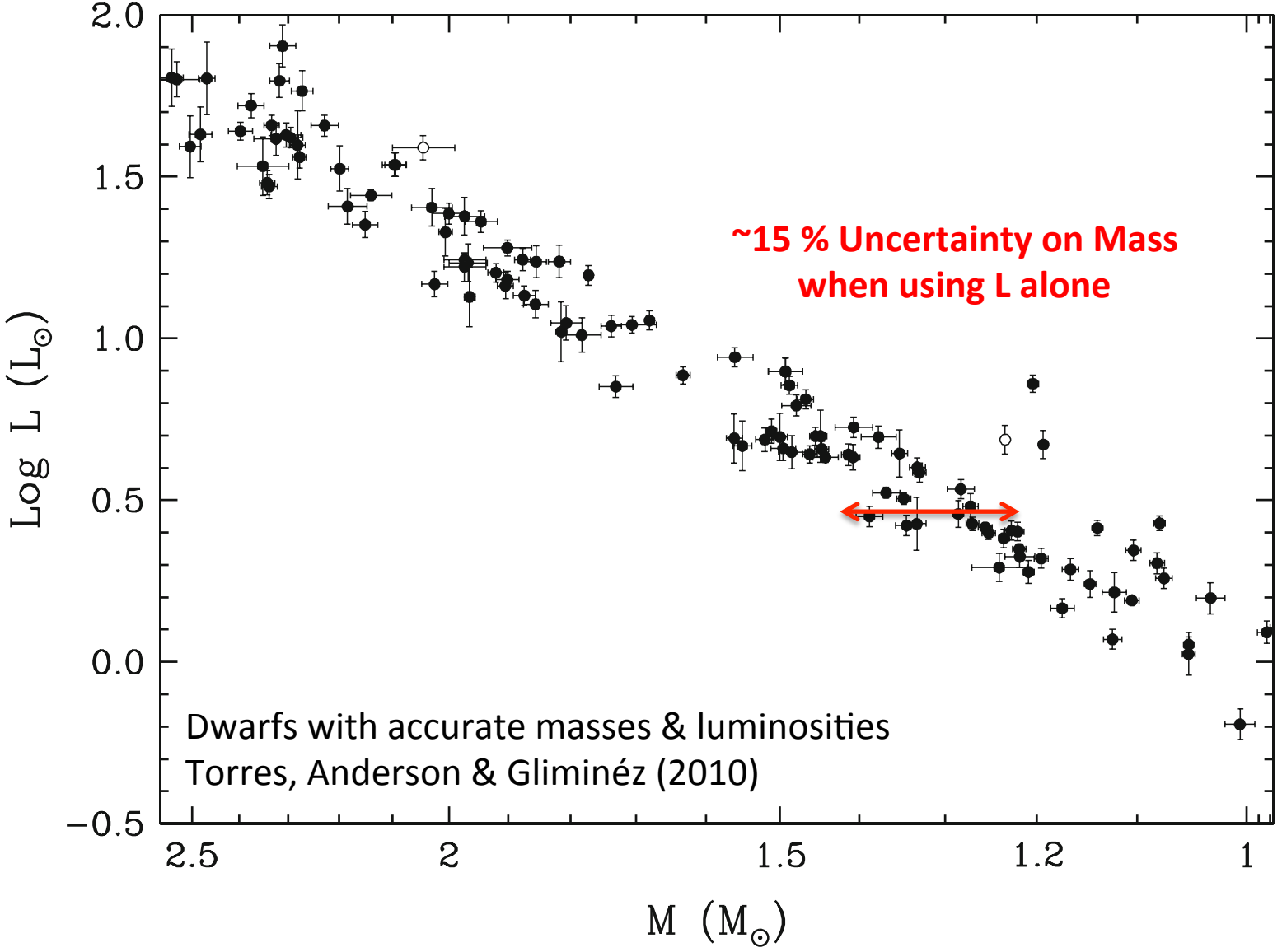


- Put a star on an HR (or Color-Magnitude) Diagram.
- Trivial dwarf/giant discrimination

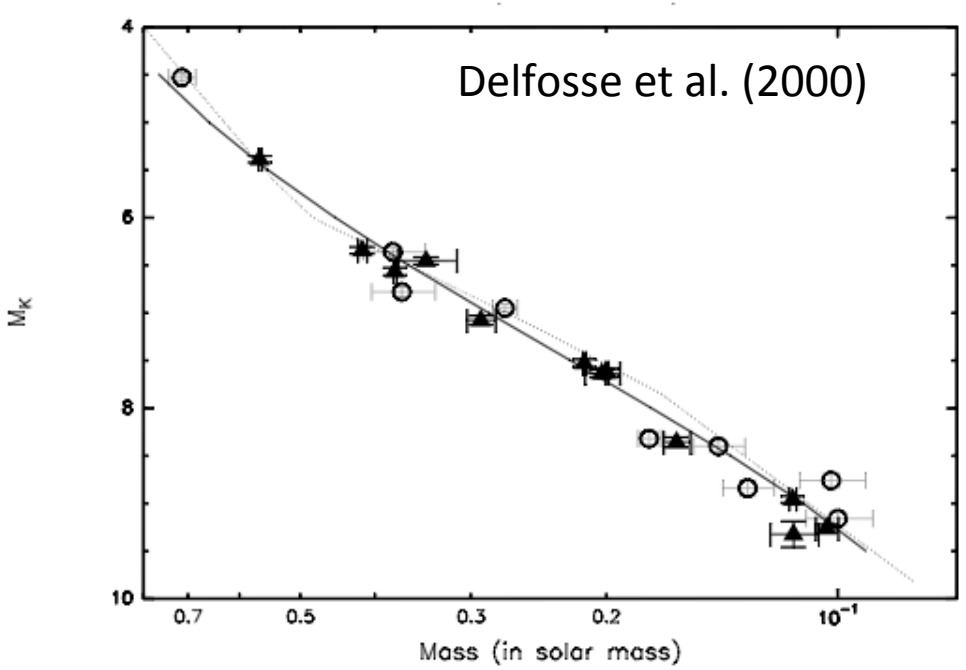
Power of a Parallax: Mass-Luminosity Relationships for Dwarfs



Power of a Parallax: Mass-Luminosity Relationships for **FG Dwarfs**

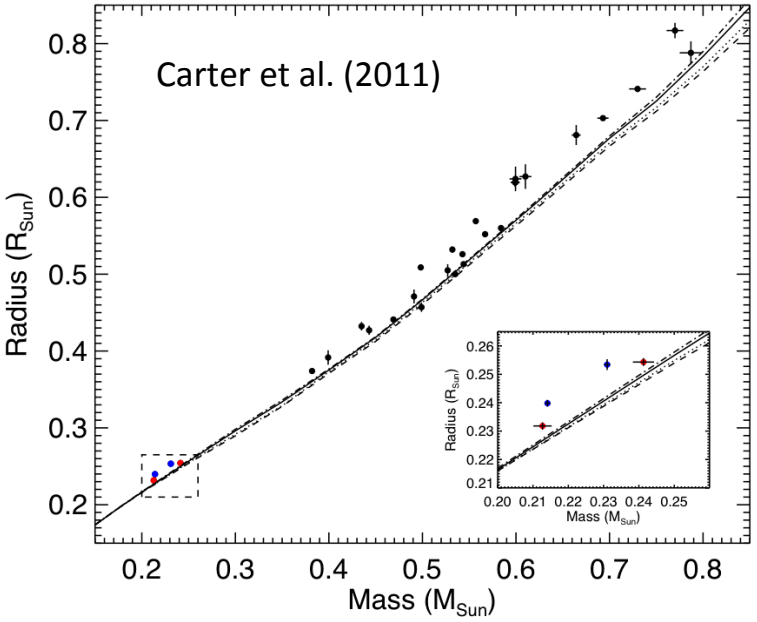


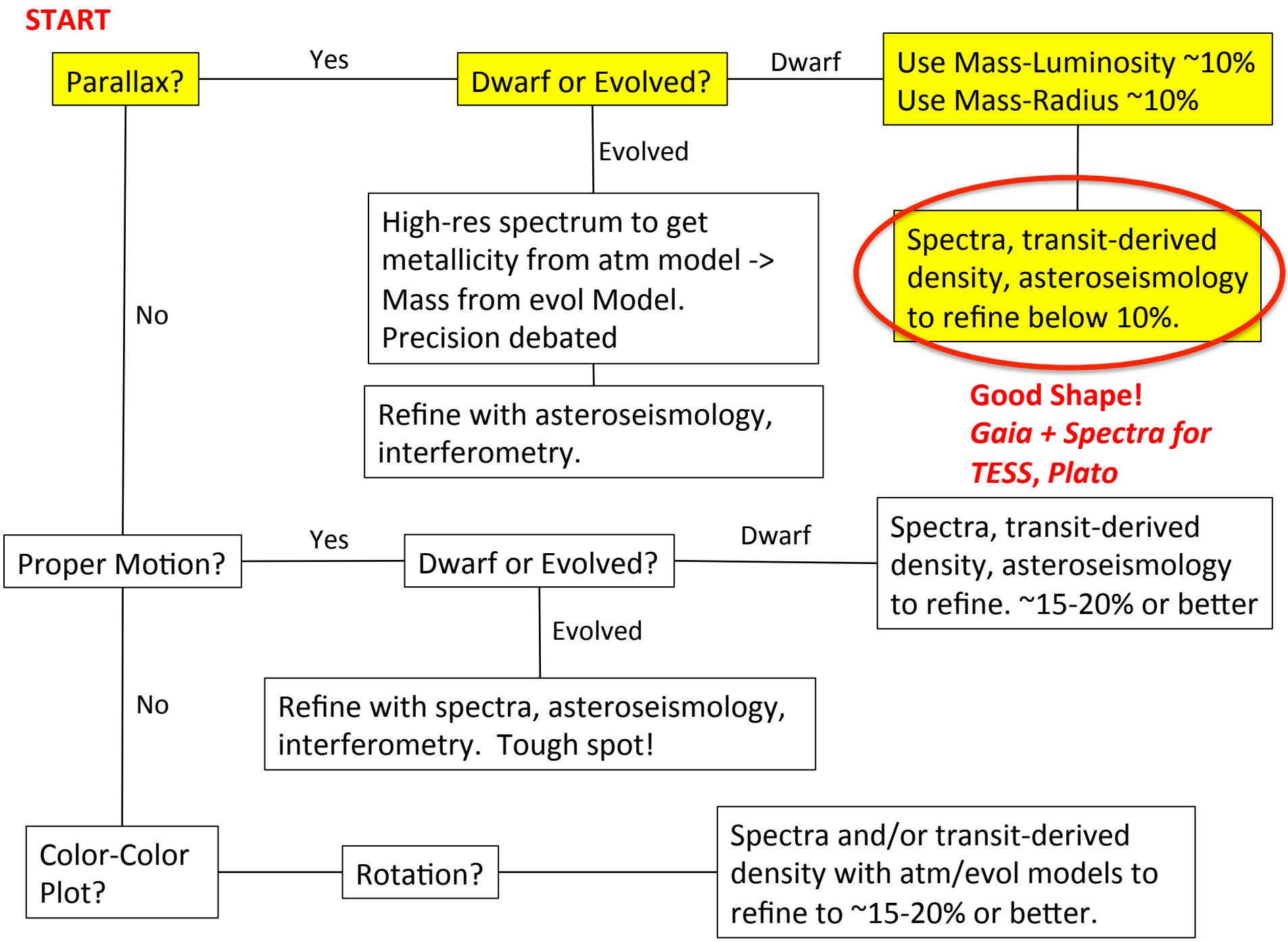
Power of a Parallax: Mass-Luminosity Relationships for **KM Dwarfs**

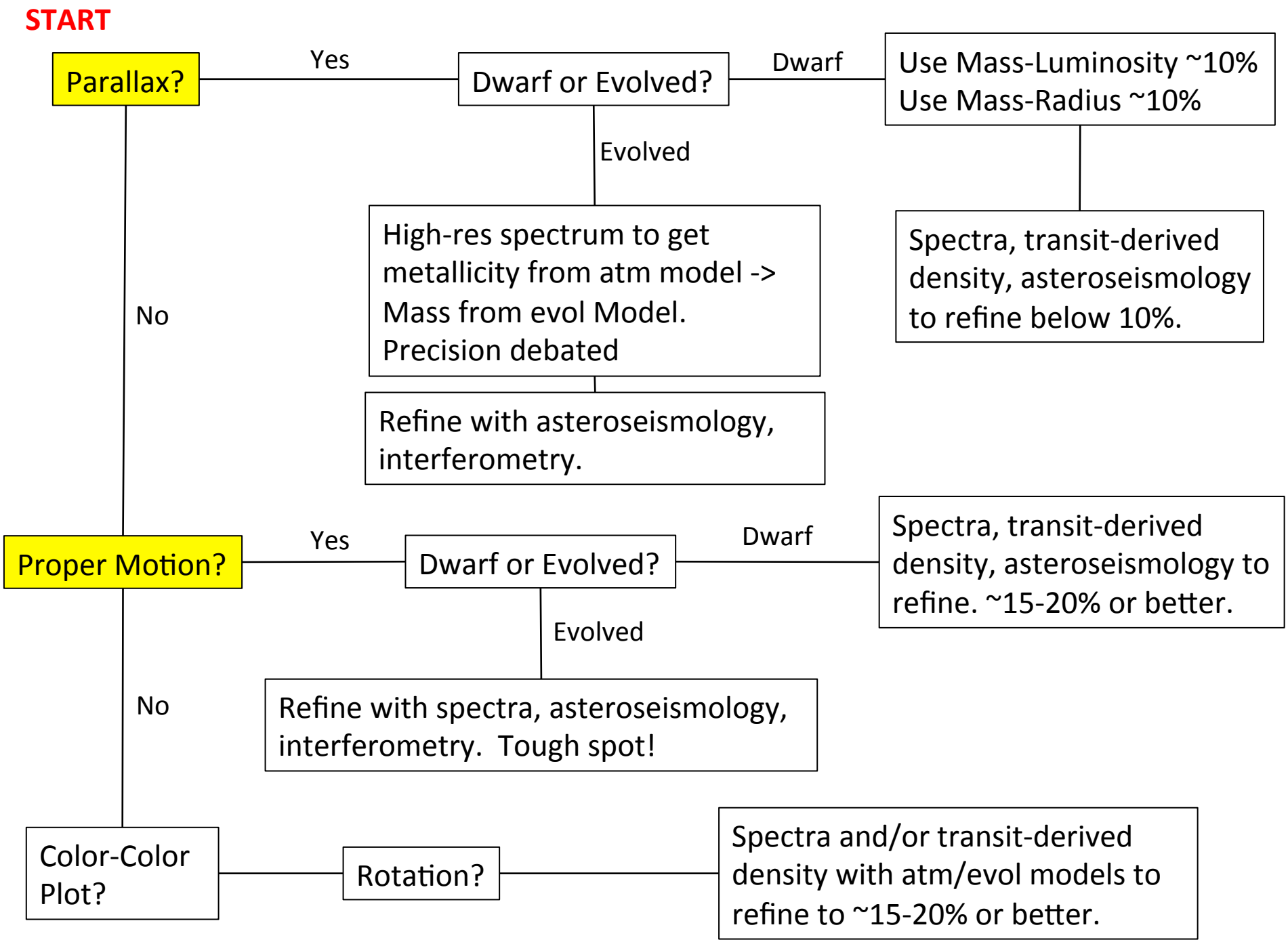


Empirical Mass-Magnitude Relationships, ~10% uncertainty

Model or empirical mass-radius relationships, ~5% uncertainty




START
Parallax?
Yes
Dwarf or Evolved?
Dwarf
Use Mass-Luminosity ~10%
Use Mass-Radius ~10%
Evolved
High-res spectrum to get metallicity from atm model -> Mass from evol Model. Precision debated
Spectra, transit-derived density, asteroseismology to refine below 10%.
Refine with asteroseismology, interferometry.
Good Shape!
Gaia + Spectra for TESS, Plato
No
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20% or better
Evolved
Refine with spectra, asteroseismology, interferometry. Tough spot!
No
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20% or better.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Proper Motion?
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Dwarf or Evolved?
Dwarf
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Evolved
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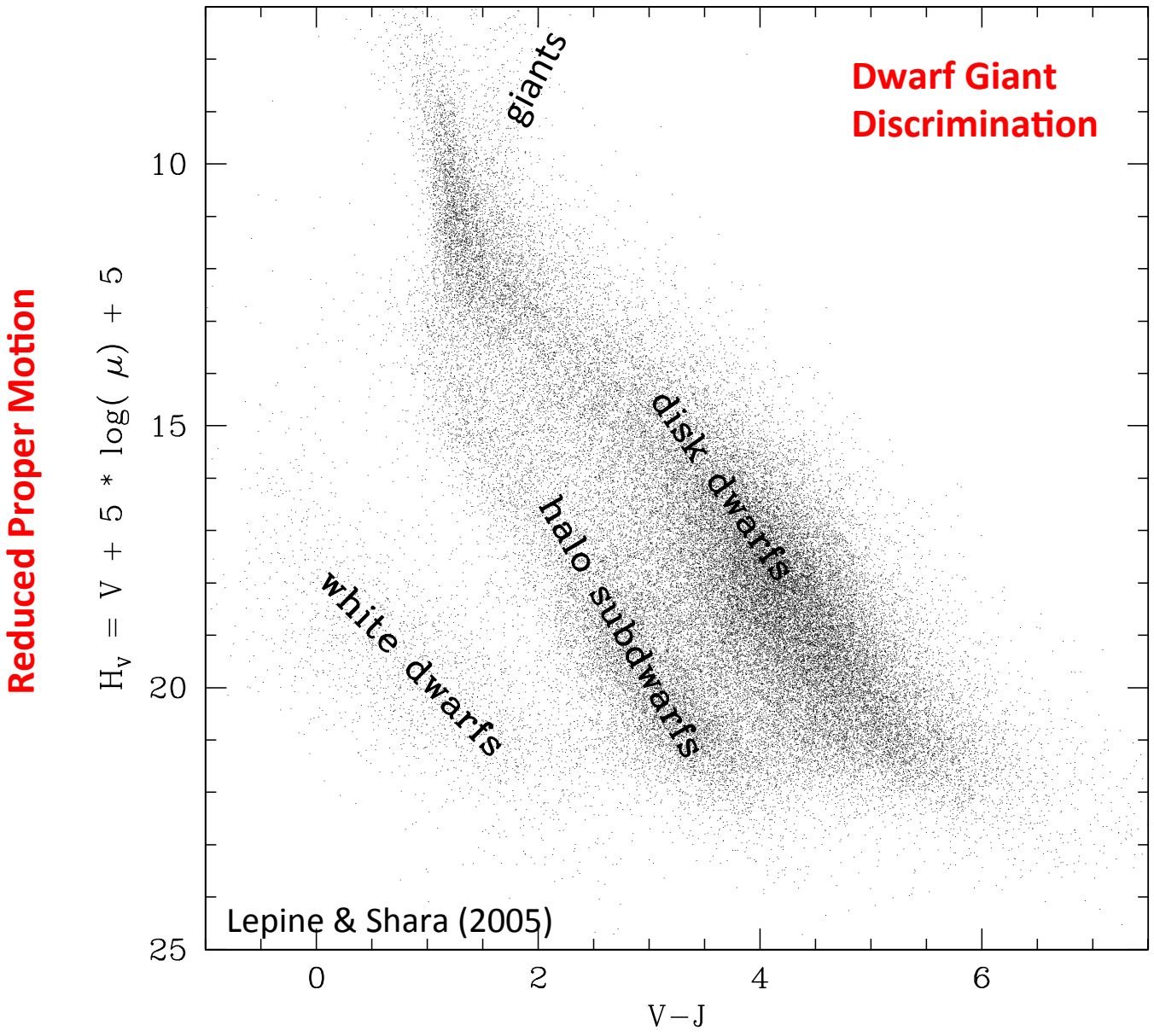
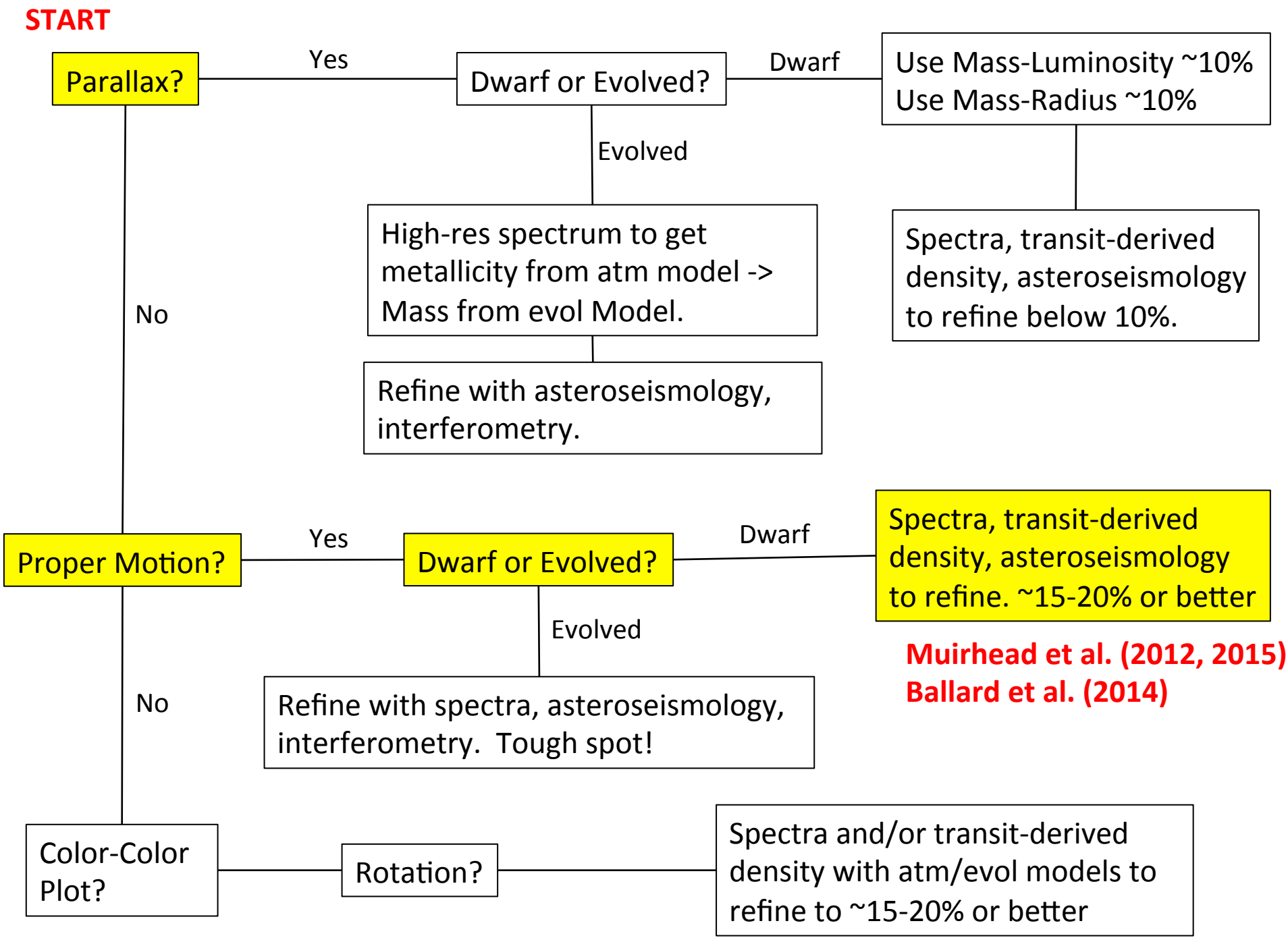
Refine with spectra, asteroseismology, interferometry. Tough spot!
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20% or better.

Proper Motion: A Cheap Parallax

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Evolved
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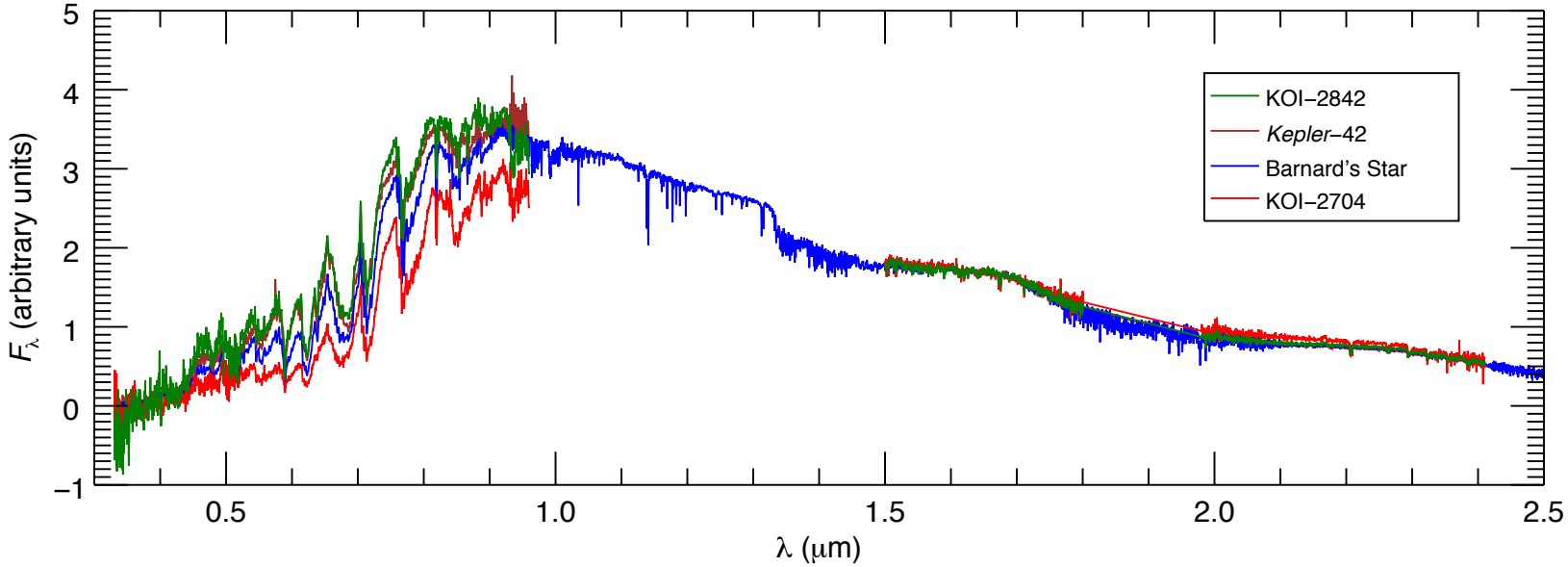
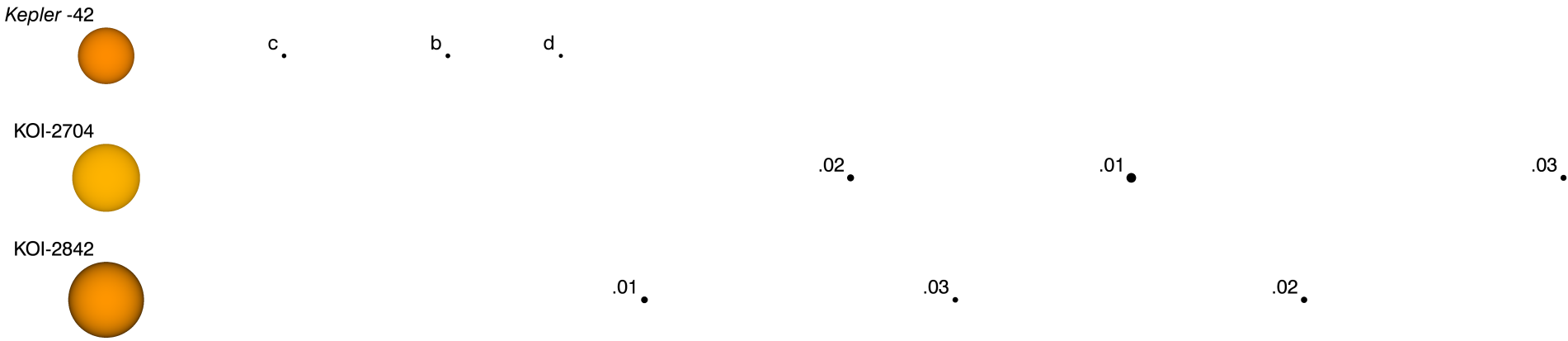
Spectra, transit-derived density, asteroseismology to refine below 10%.
No
Refine with asteroseismology, interferometry.
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20% or better
Muirhead et al. (2012, 2015)
Ballard et al. (2014)
Evolved
No
Refine with spectra, asteroseismology, interferometry. Tough spot!
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20% or better

Without *L*, need T_{Eff} and [Fe/H]

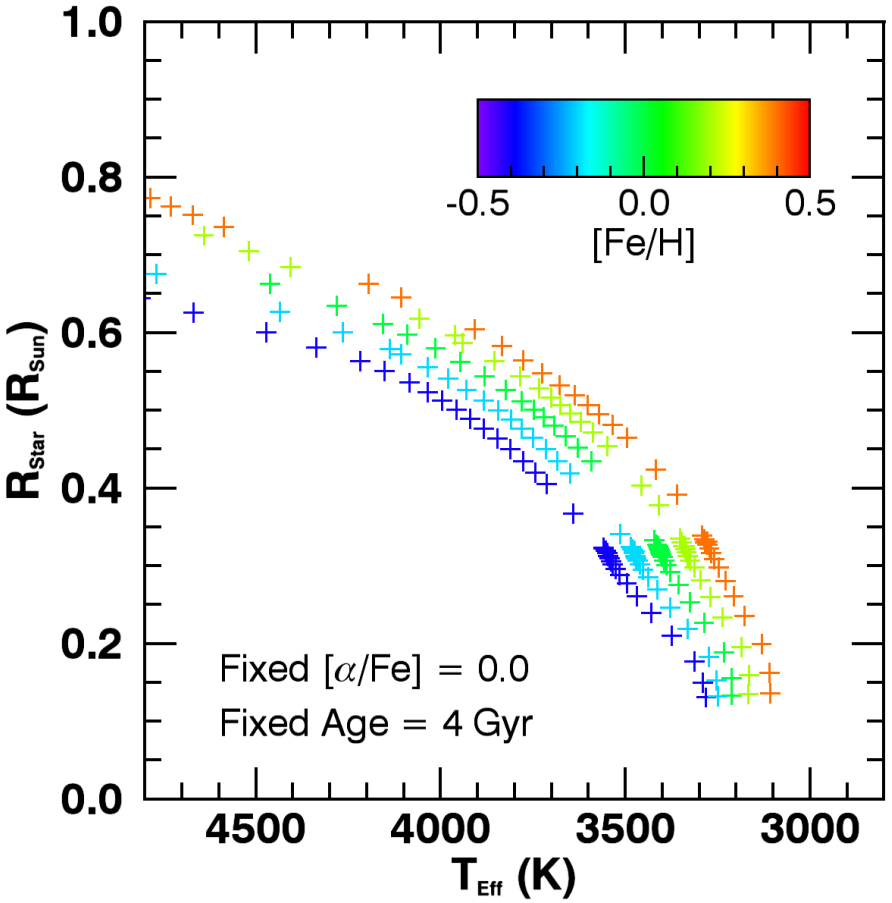


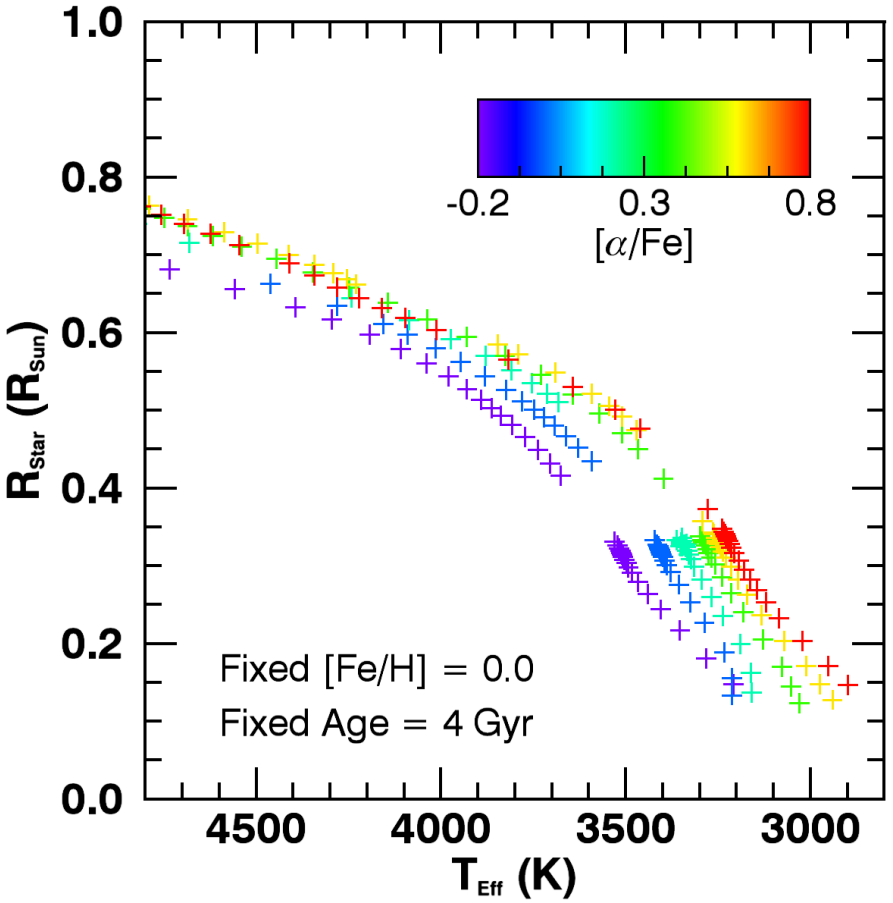


Muirhead, Mann et al. (2015)

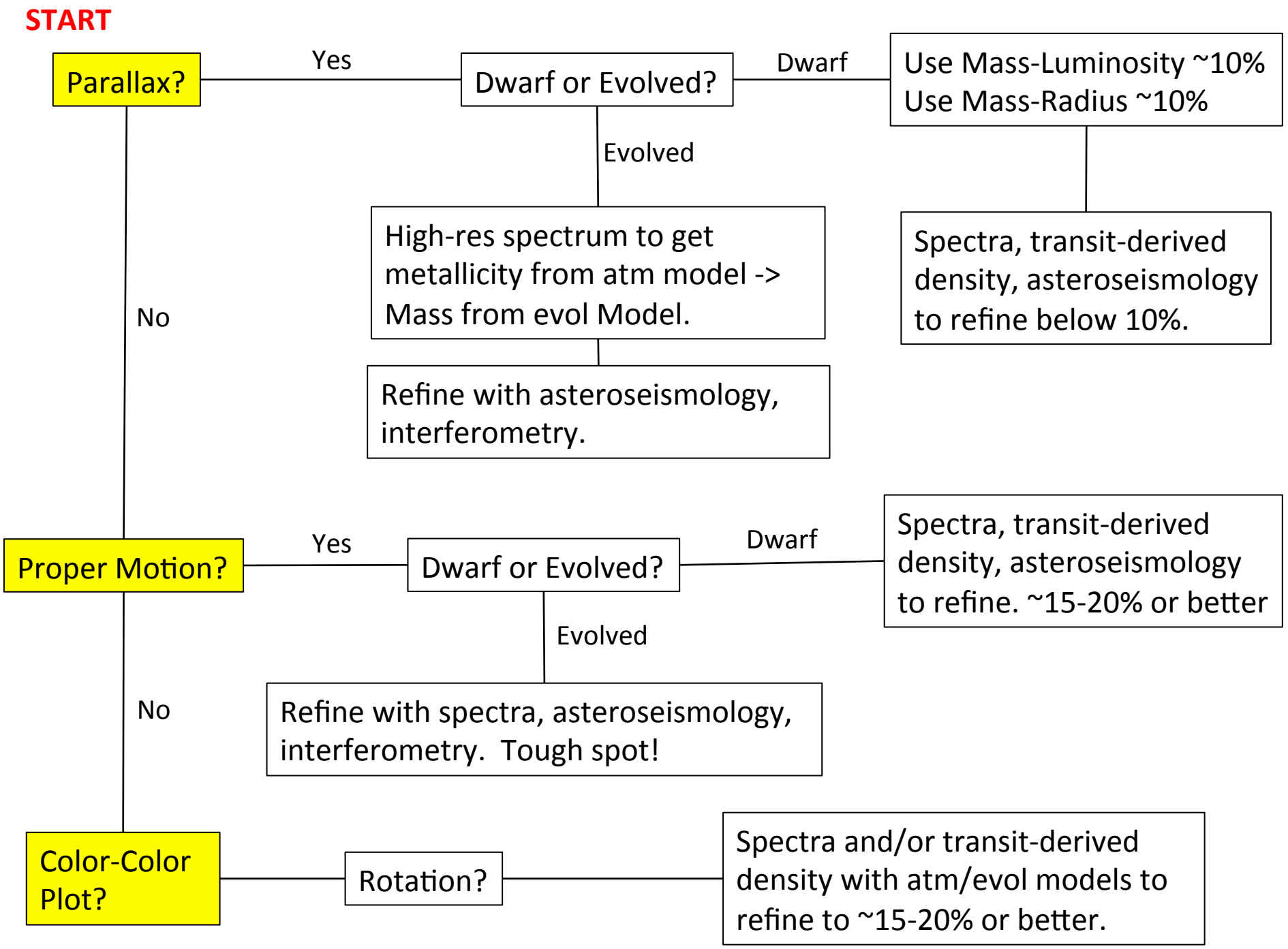
Caveats

Muirhead, Hall, Veyette (2014)





- **[Fe/H] and [α/Fe] independently affect inferred stellar radius.**
- **Currently no accurate method to measure [α/Fe] in M dwarfs.**
- **But see Veyette, Muirhead & Mann poster 138.11 on Monday for a roadmap to [α/Fe].**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Parallax?
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Dwarf or Evolved?
Dwarf
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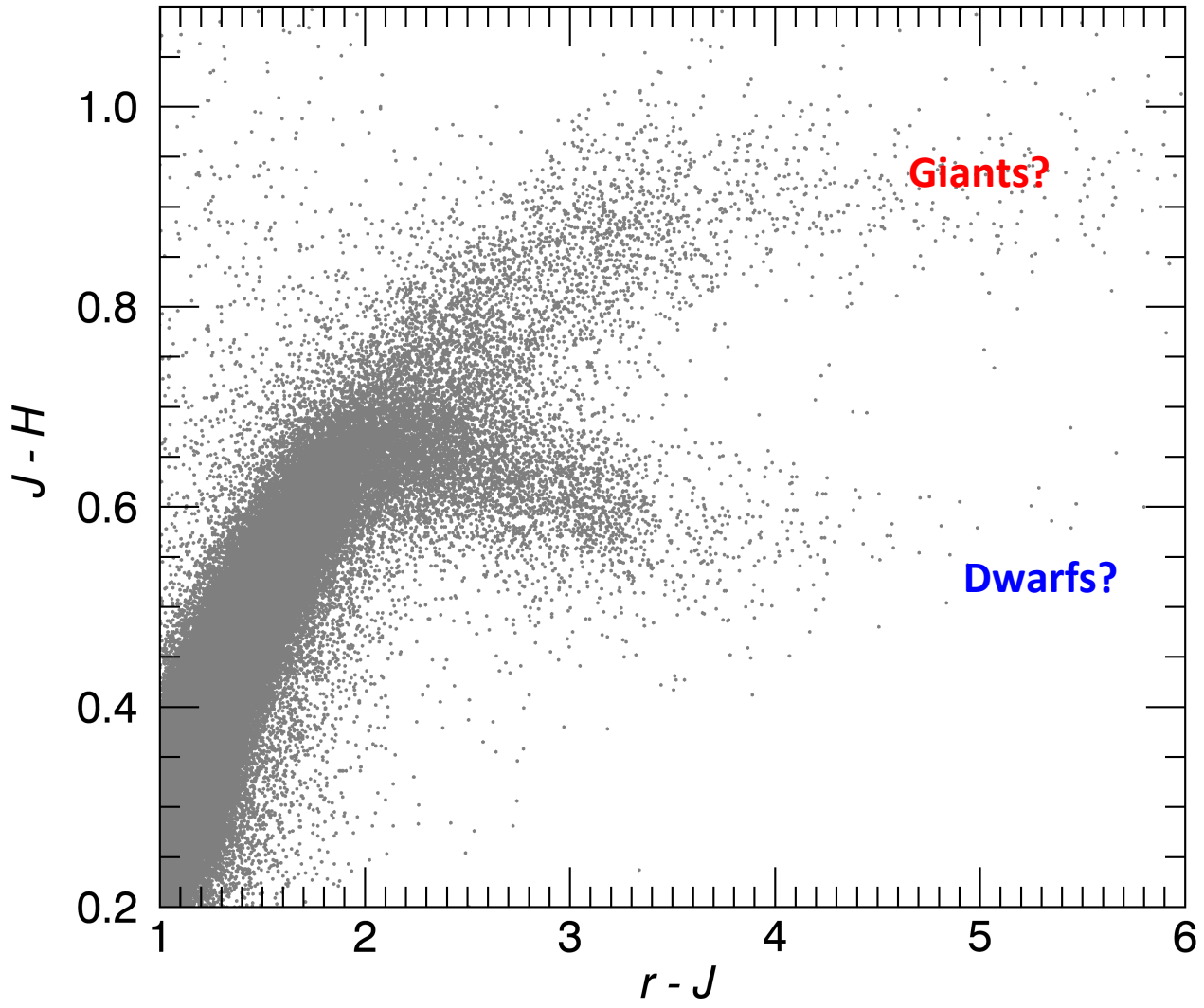
Use Mass-Radius ~10%
Evolved
High-res spectrum to get metallicity from atm model -> Mass from evol Model.
Spectra, transit-derived density, asteroseismology to refine below 10%.
No
Refine with asteroseismology, interferometry.
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20% or better
Evolved
No
Refine with spectra, asteroseismology, interferometry. Tough spot!
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20% or better.

Be Careful with Color-Color Plots



Muirhead, Mann et al. (2015)

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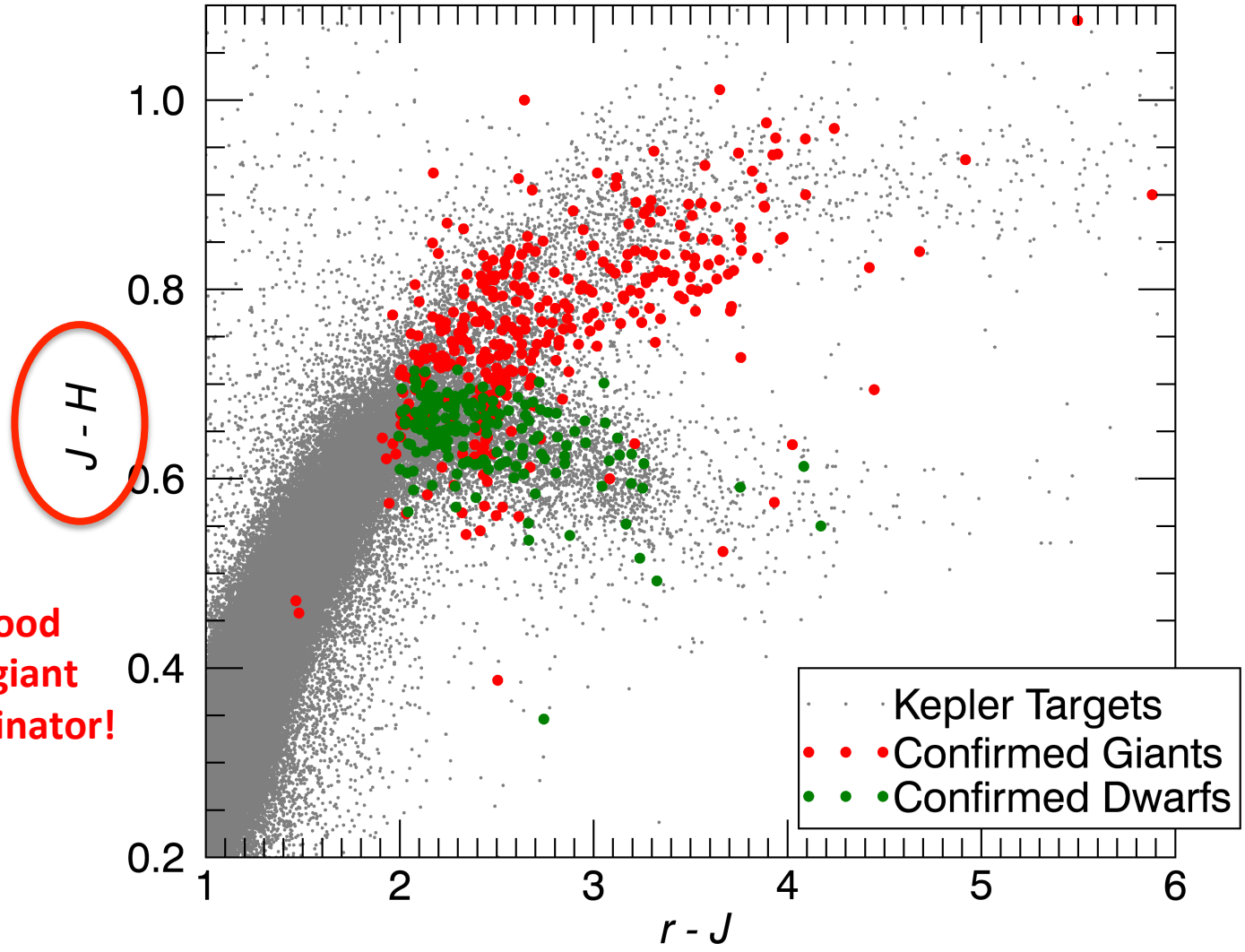
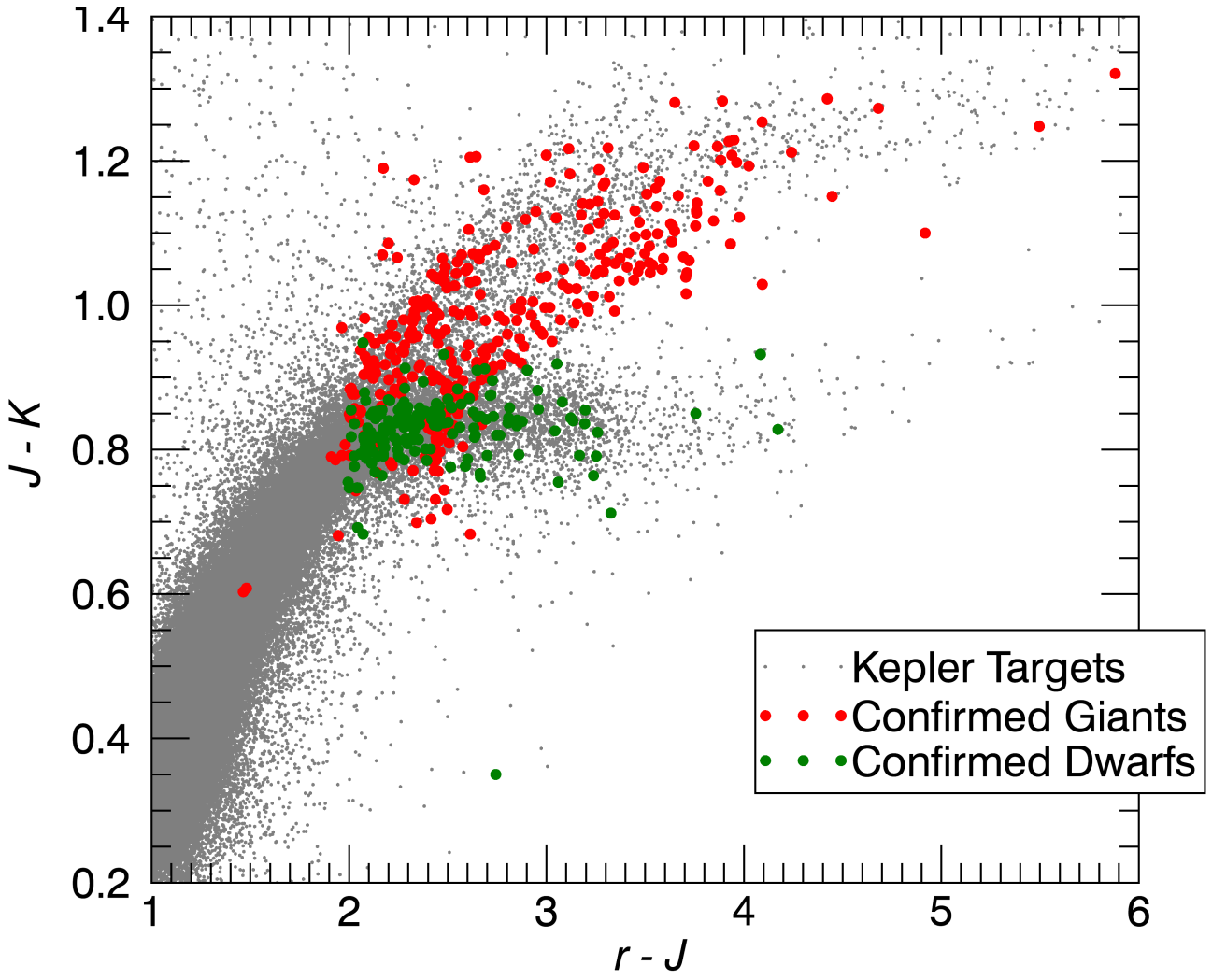


Not a good dwarf/giant discriminator!

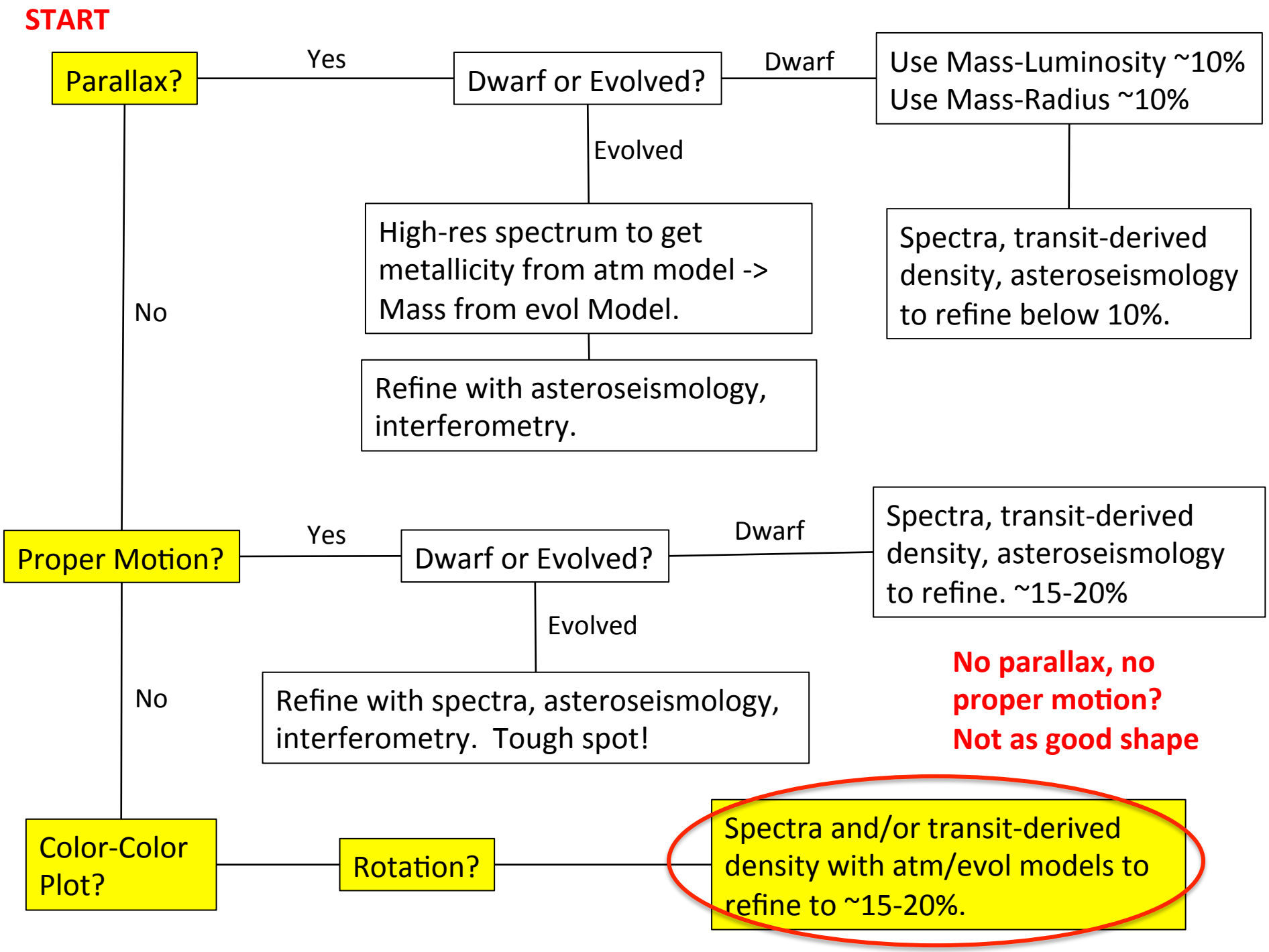
Muirhead, Mann et al. (2015)

Be Careful with Color-Color Plots

Much Better!



Muirhead, Mann et al. (2015)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Evolved
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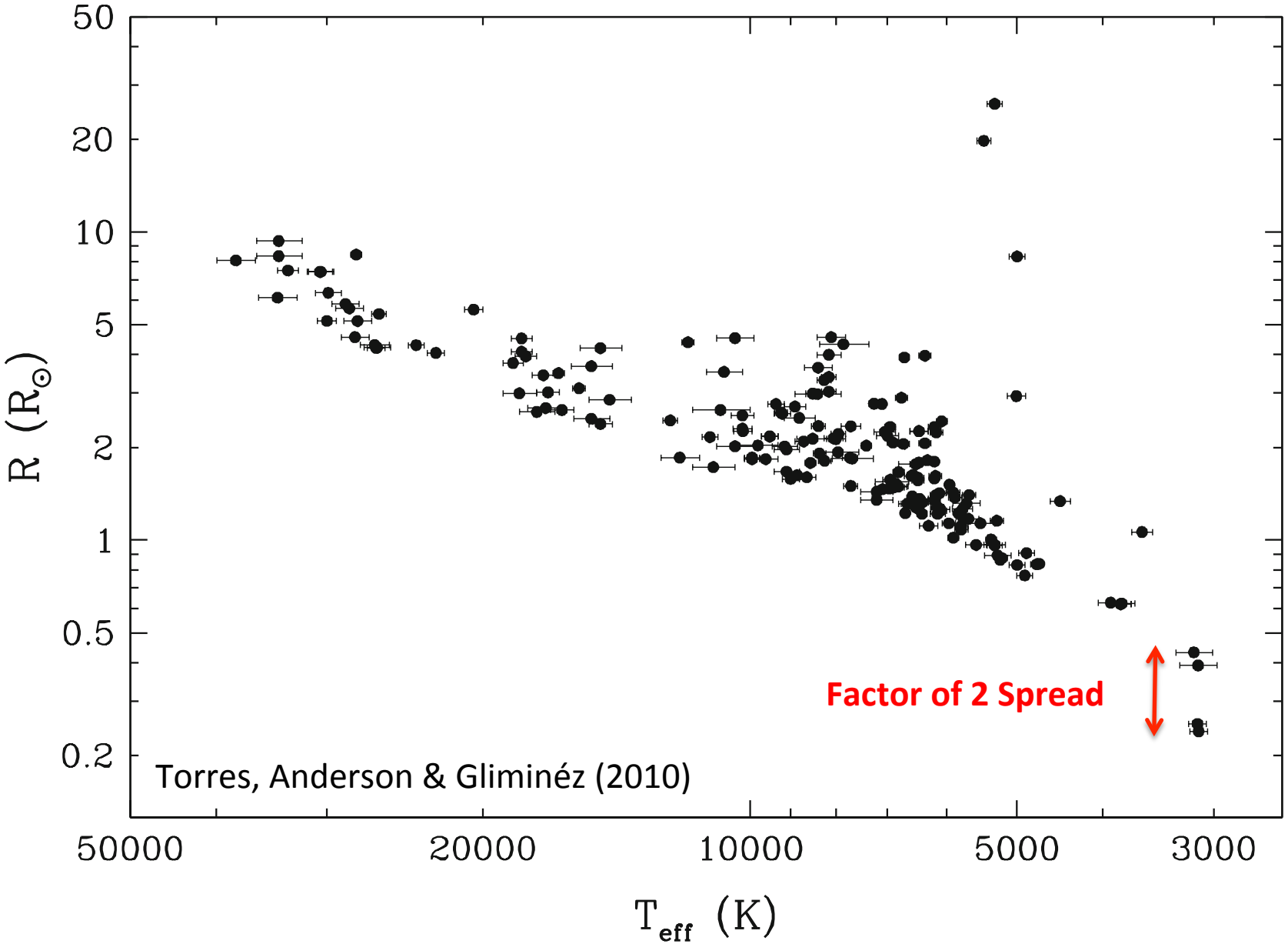
Spectra, transit-derived density, asteroseismology to refine below 10%.
No
Refine with asteroseismology, interferometry.
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20%
Evolved
No parallax, no proper motion?
Not as good shape
No
Refine with spectra, asteroseismology, interferometry. Tough spot!
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20%.

My thoughts on ExEP priorities

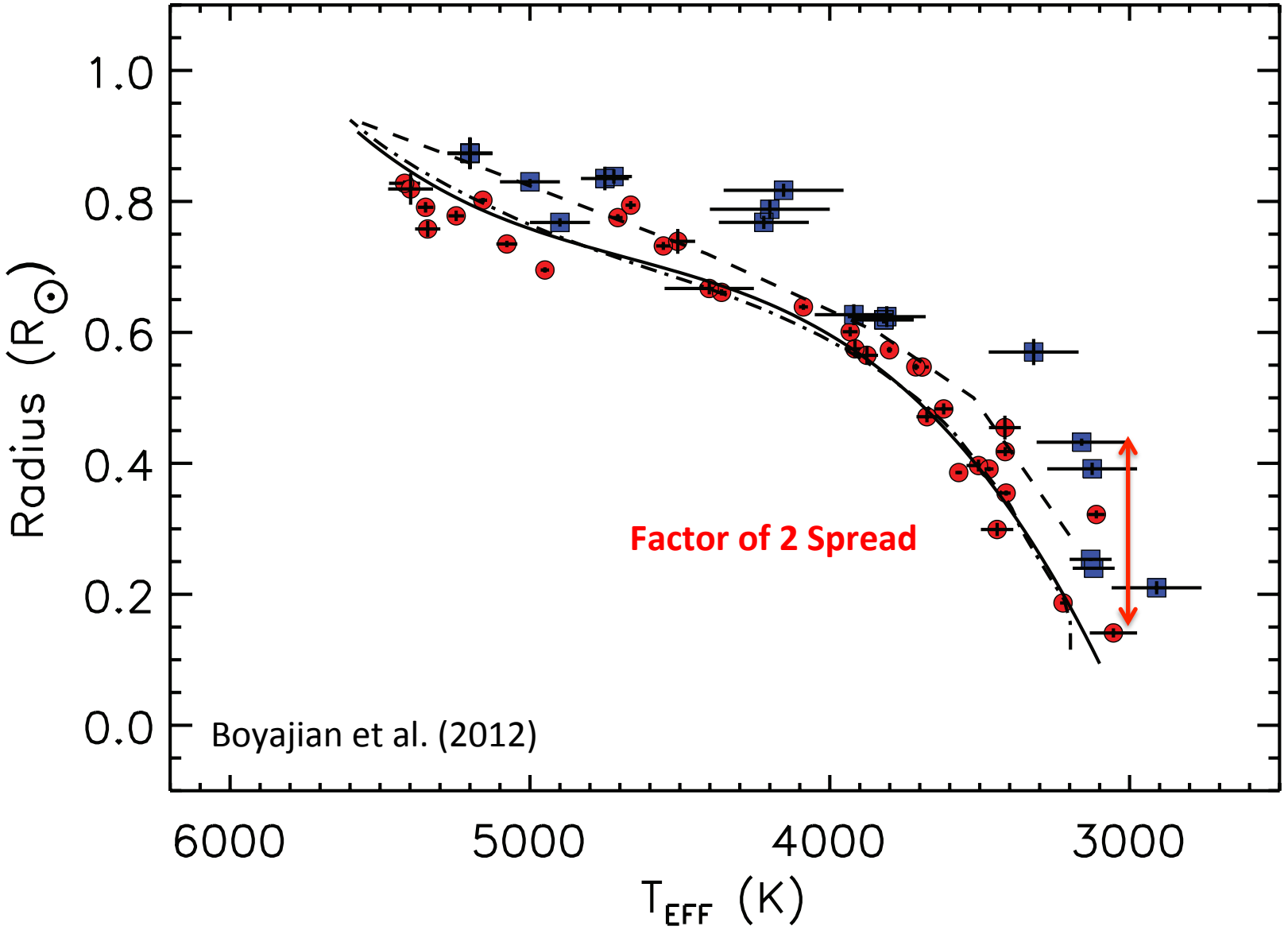
- Parallaxes for all stars searched (~10% M/R/L).
  - *Gaia* for $g < 20$.
- Develop best possible **mass-luminosity calibrations**.
- Ground-based spectroscopy for metallicities/ gravities where needed (<10% M/R/L)
  - **NASA Keck Share**
- **Support atmospheric/evolutionary modeling efforts.**
  - Nearly all stellar measurements depend on models at some point.

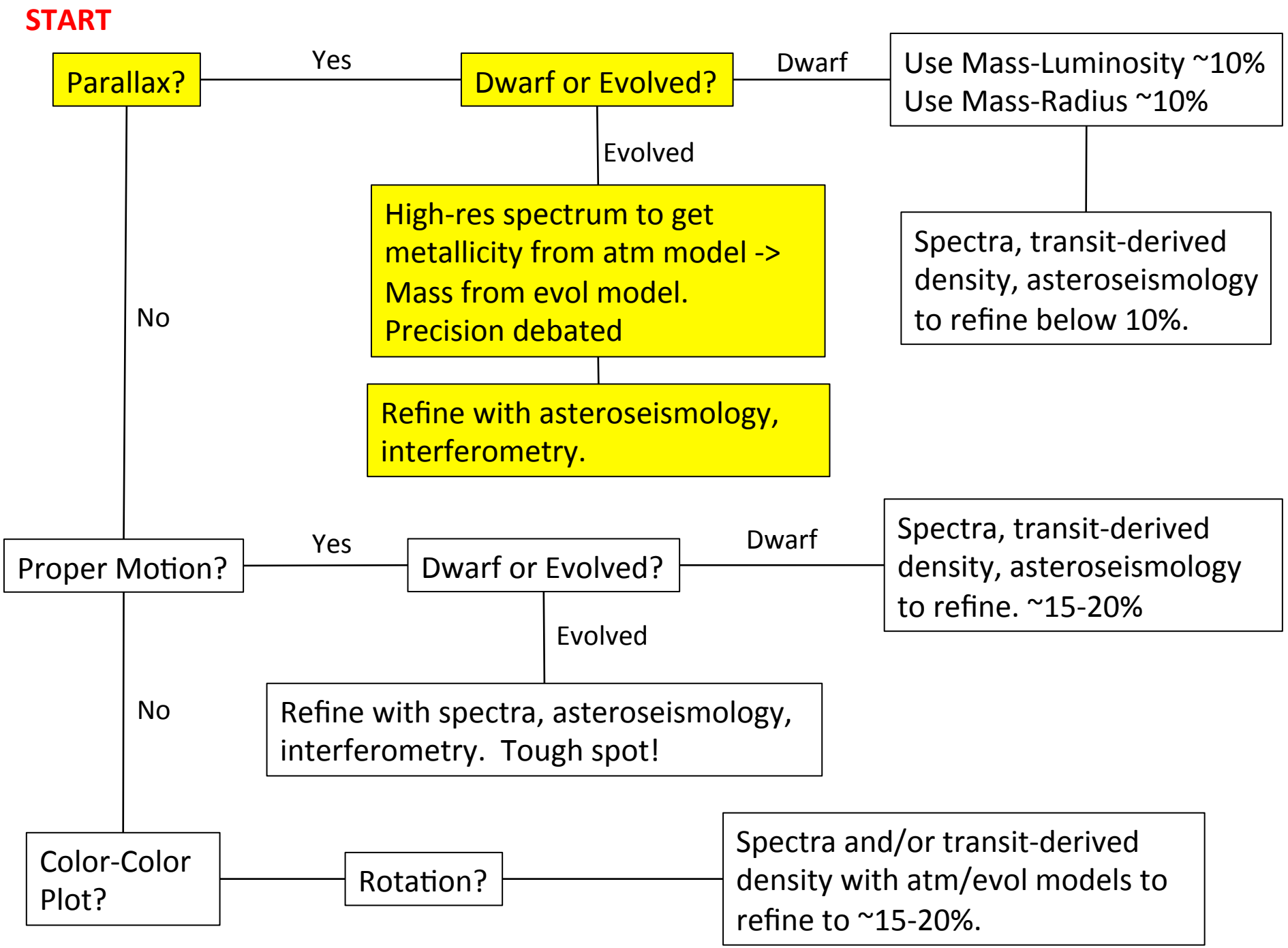
Backup Slides

How about T_{Eff}?



How about T_{Eff}?

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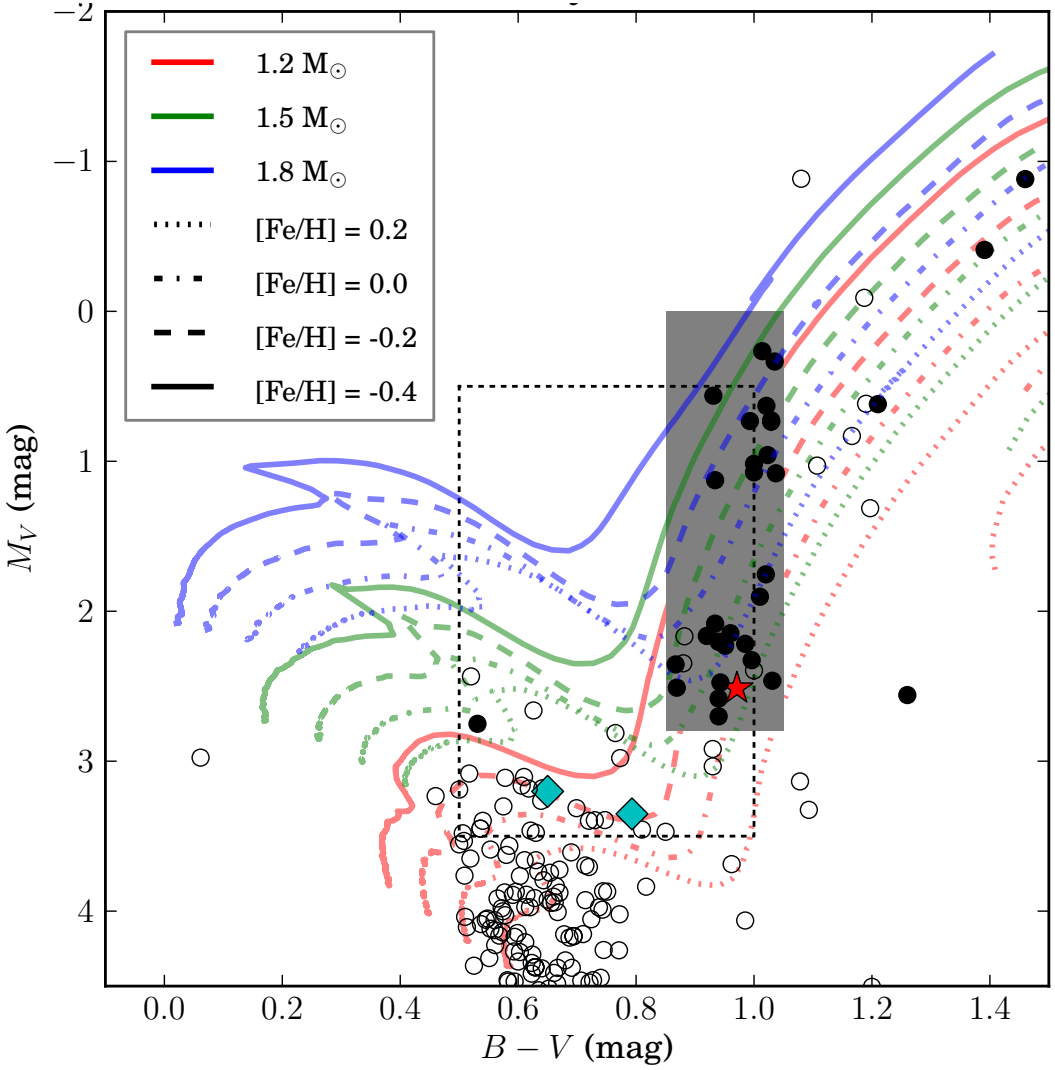
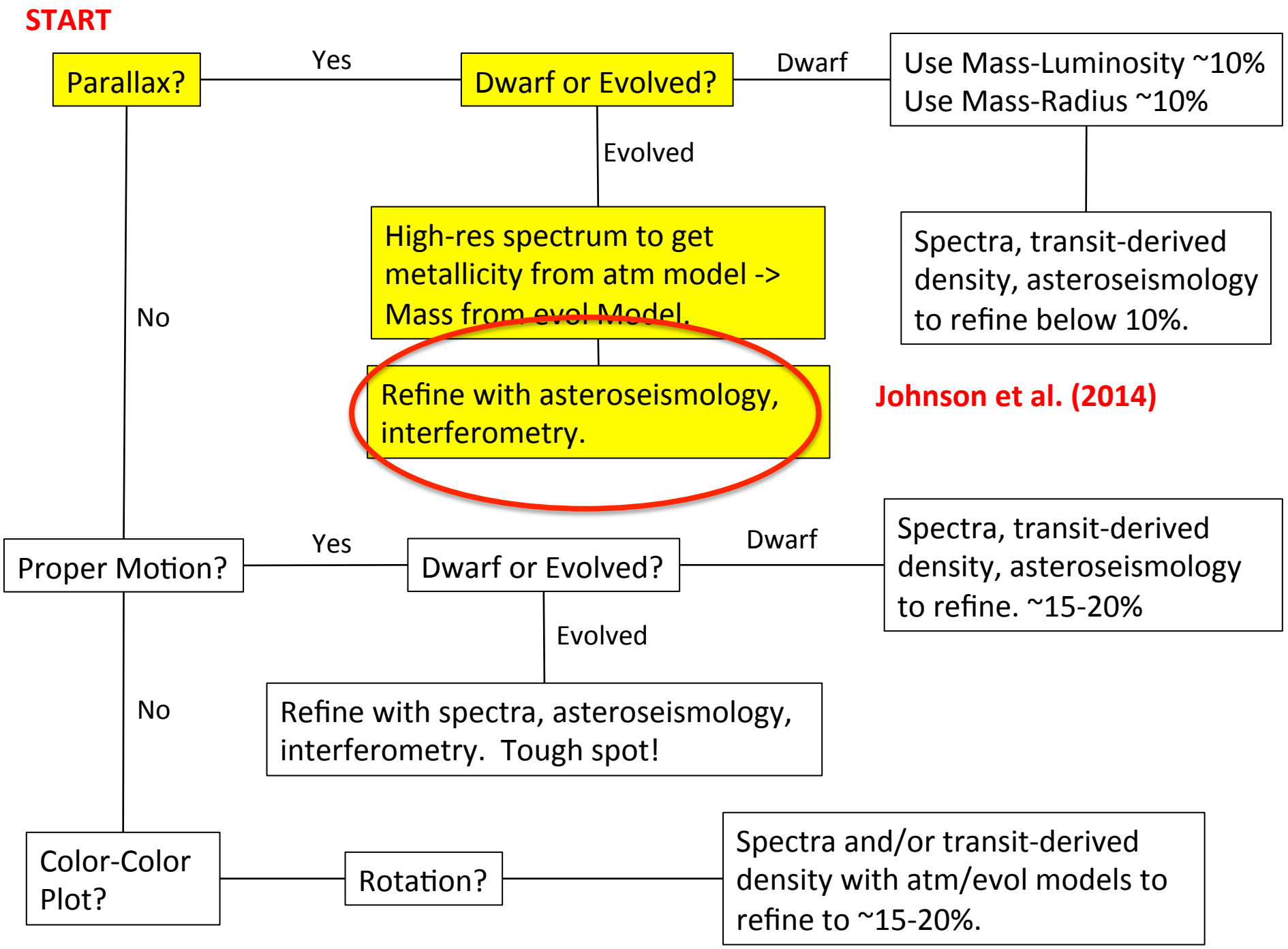
Refine with asteroseismology, interferometry.
No
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20%
Evolved
Refine with spectra, asteroseismology, interferometry. Tough spot!
No
Color-Color Plot?
Rotation?
Spectra and/or transit-derived density with atm/evol models to refine to ~15-20%.

Parallax is not enough for Evolved Stars



- Metallicity is typically required to get better than 50% on stellar mass.
- Metallicity measurements depend on accurate models of cool, sub-giant atmospheres.
  - **Potential for systematic errors**

Lloyd (2011)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Parallax?
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Dwarf
Use Mass-Luminosity ~10%
Use Mass-Radius ~10%
Evolved
Spectra, transit-derived density, asteroseismology to refine below 10%.
High-res spectrum to get metallicity from atm model -> Mass from evol Model.
No
Refine with asteroseismology, interferometry.
Johnson et al. (2014)
Proper Motion?
Yes
Dwarf or Evolved?
Dwarf
Spectra, transit-derived density, asteroseismology to refine. ~15-20%
Evolved
No
Refine with spectra, asteroseismology, interferometry. Tough spot!
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Rotation?
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