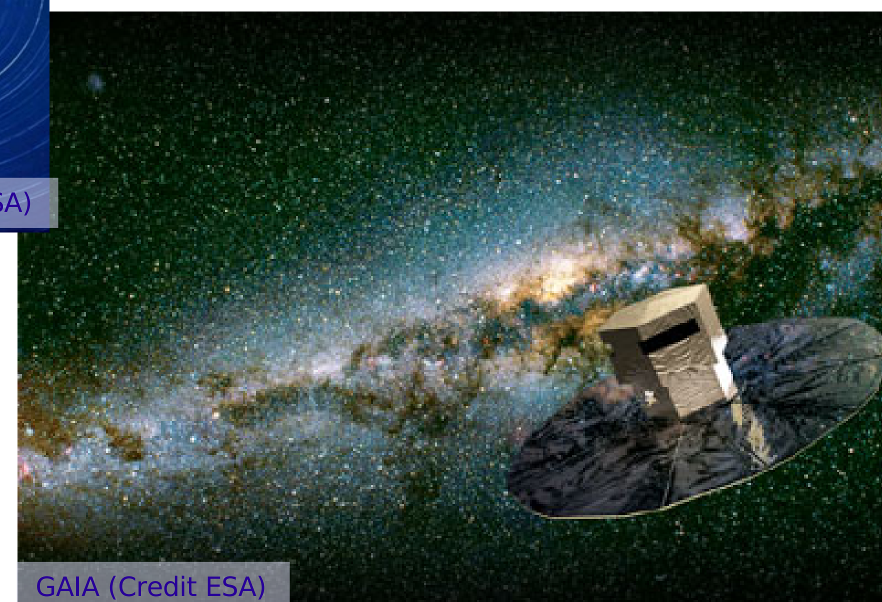
Connecting Stars, Galaxies and the Universe in the 1% Century

Rob Olling (UMD)


Hipparcos(Credit ESA)

Hipparcos: 3 years,
early 1990s: **mas accuracy**


SIM/Heavy (Credit JPL)


GAIA (Credit ESA)

SIM-Lite: 5-10 yrs; 201?+; **1/1000 mas**

GAIA: 5-7 years, 2012+; **1/100 mas**

Outline

- **Connecting Stars, Galaxies & the Universe**
- **Astrometry/distance measures & underlie understanding of Universe we live in**
- **Precision/Accurate Astrophysics**
- **Testing Cosmology with Astronomy**
- **Cosmology in My Backyard**
- **Requirements for Stellar astronomy in 21th Century**
- **Eclipsing Binaries as "Rosetta Stones"**
  - **EB's, Gaia, SIM & the Solar Neighborhood**
- **Golden Age of Astrophysics**

See also: http://adsabs.harvard.edu/abs/2009arXiv0902.3197O
http://www.astro.umd.edu/~olling; http://adsabs.harvard.edu/abs/2007arXiv0704.3072O

Why the 1% Century?

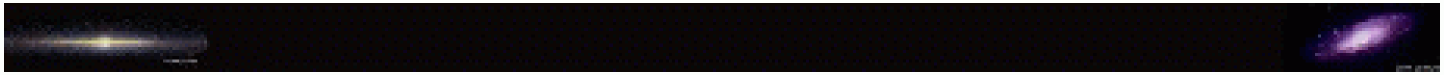
- Data quality has reached the 1% level

	Ground	Space	
Photometry:	10-30	<1	[mmag]
Astrometry:	1-10	0.001 – 1	[mas]

  - Drive towards LARGE telescopes and expensive instrumentation
    - E-ELT, TMT, GSMT, ...
      - Smaller scopes with large etendue ($A_{\square m}$ x $FOV_{\square °}$) are also very important to sample the time-domain
      - Pan-STARRs, SkyMapper, *Gaia*, Jmaps, LSST
- Inferences and knowledge have to keep up
  - A while ago, astronomy was a “factor of 2 science”
  - Now we're at 10-ish percent
  - 1% is next; NEED astrometry @ ≲ 1% level

An Era of Precision Astrophysics: Connecting Stars, Galaxies and the Universe

an Astro2010 Science White Paper



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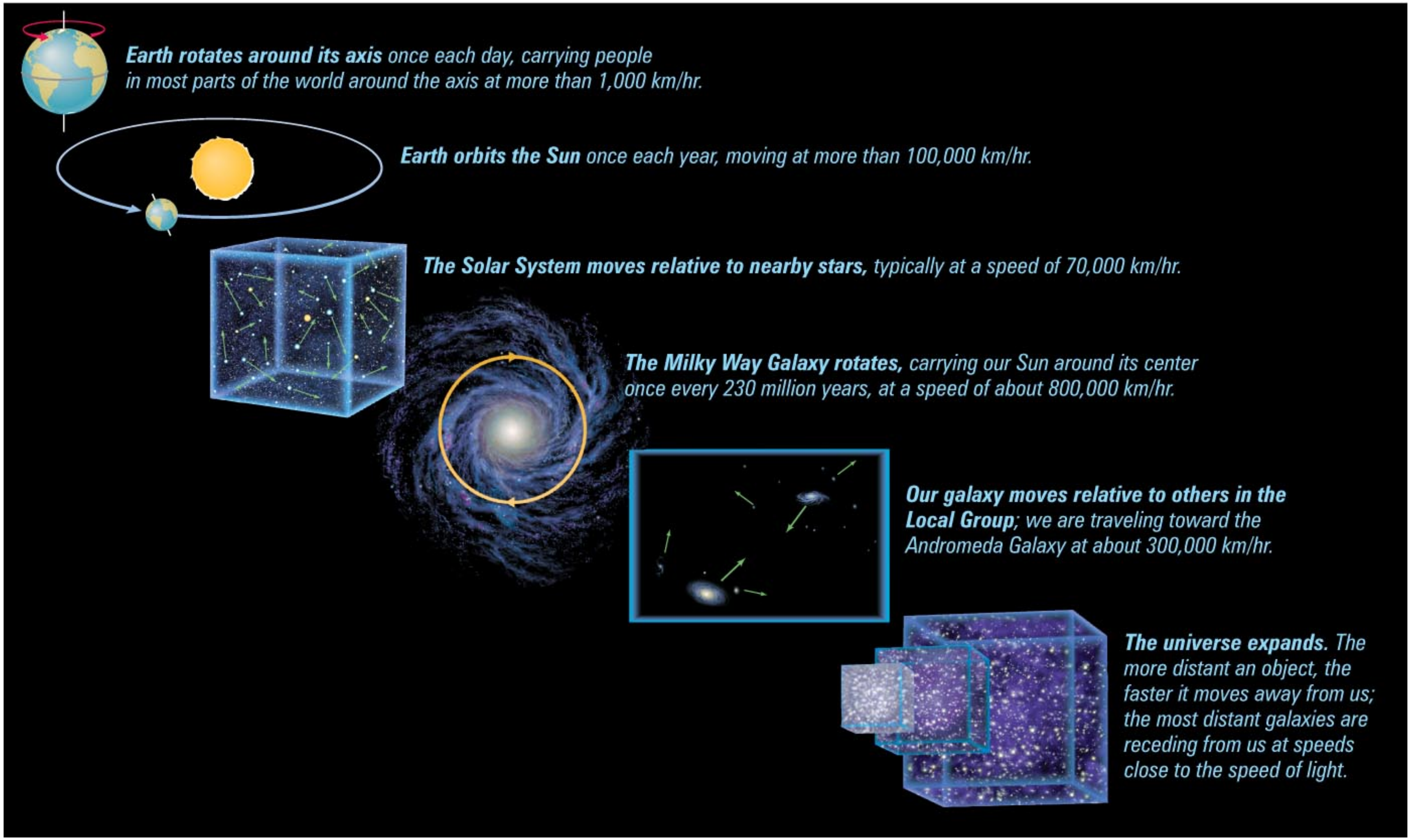
2009, arXiv0, 902, 3197O

We Are All Connected

And so are Stars, Galaxies & The Universe



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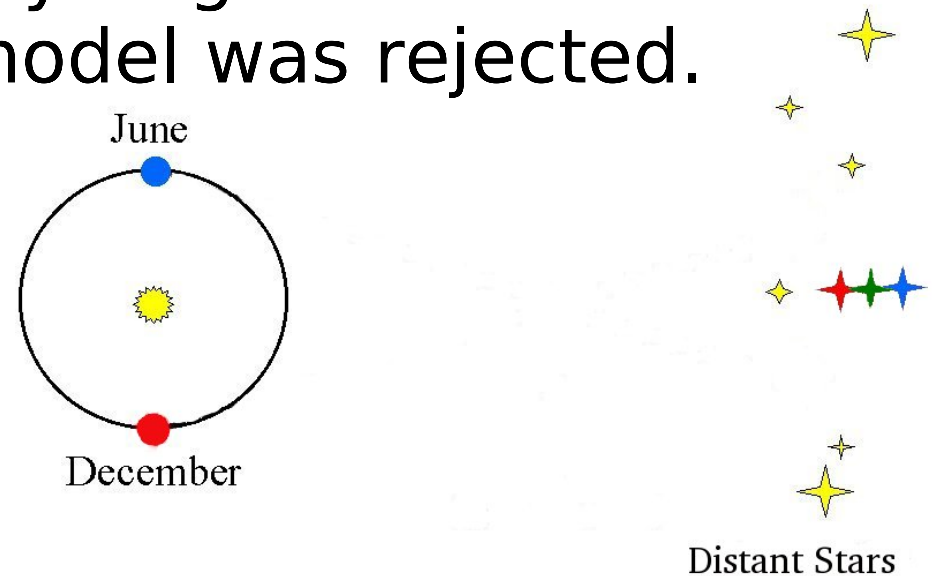
Astrometric Distance Measures:

Aristarchus (ca 250 BC) noted that the unobserved stellar parallax meant very large distances in a heliocentric model. But model was rejected.



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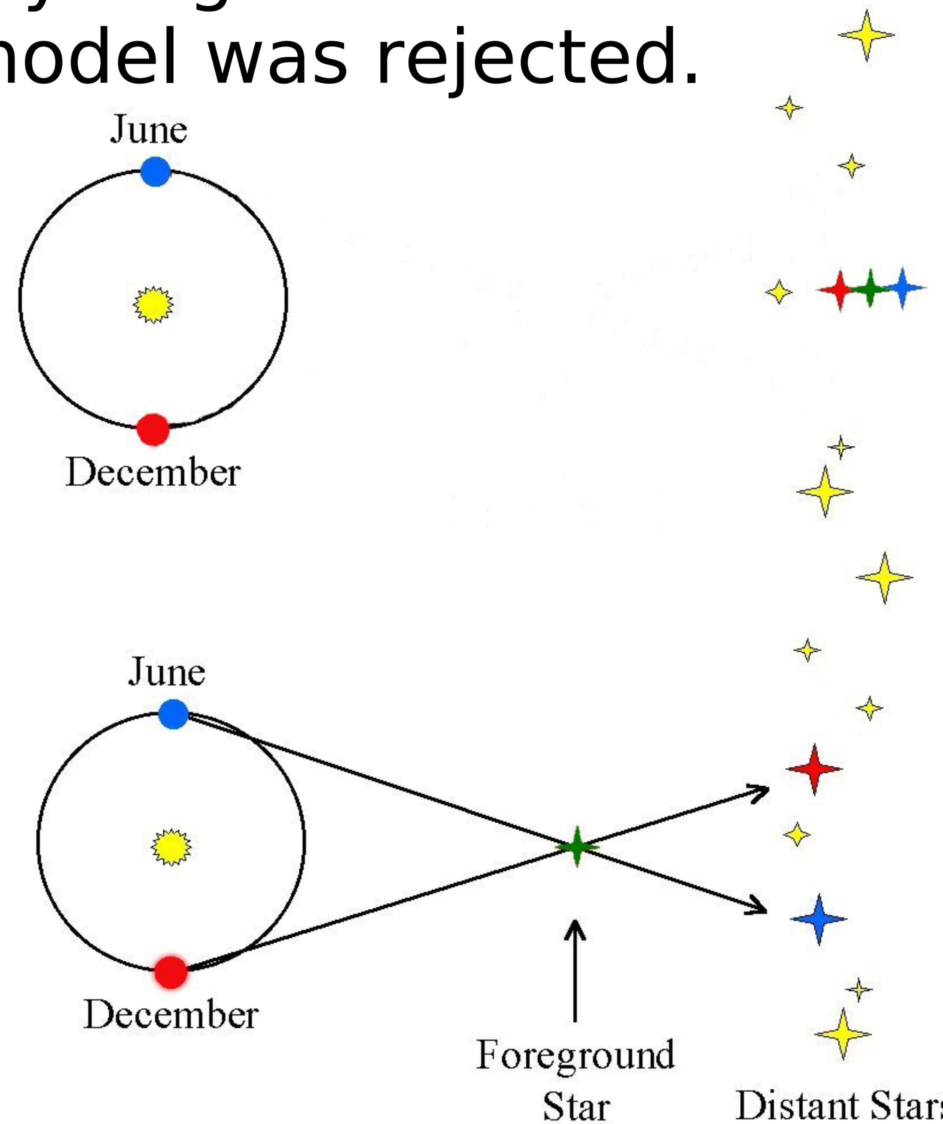
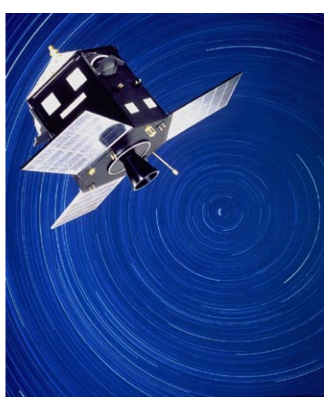


Hipparcos managed quite well



Astrometric Distance Measures:

- Form the basis of our understanding of the Universe
  - Inability to measure PLX led to strong support for geocentric ideas
  - w/o distances, astronomers dream up large number of explanations (cf γ-ray bursts)
- Rely on ***human ingenuity***, not on some *intrinsic*, and possibly *unknowable* property of stars and other distance indicators
  - Mother Nature also needs to co-operate
- We/SIM can now reach 1% distance accuracy at ~1 Mpc (M31) via the "Rotational Parallax" method [Olling, 2007, MNRAS, 378, 1385]

How to make the Connection with/after *Gaia & SIM*

- According to 2001 Decadal Report [McKee & Taylor, 2001, page 3]
  - The fundamental goal of astrophysics is:

    "To understand how the **universe** ... **galaxies** ... **stars** and **planets** *formed*, how they *evolved*, and what their *destiny* will be."

The Connection: How To

- Currently the most unknown of unknowns are Dark Matter and Dark Energy
  - The strongest evidence for them comes from cosmological observations WMAP, BAO, LSS, SNIa, ...

– **Age of Universe: 13.72 ± 0.12 (0.8%) Gyr** [Komatsu ea '09]

– **Hubble Constant: 70.5 ± 1.3 (1.8%) km/s/kpc**

  – **BUT: model dependent! (precision ≠ accuracy)**

– **Need independent verification, as much as possible!!!**

At the 1% level

At the 1% level

Galactic Archeology, Near-Field Cosmology, Cosmology in My Back Yard (yes!)

- Natural way to do so is via “archaeological” methods
  - Galactic/*Gaia*/SIM astronomer must do it with **stars**
    - Stars “freeze in” properties at their birth
      - Mass, Composition, dynamics, ...
    - Properties change predictably over time

Requirements

- Complement & Verify Cosmological data sets (WMAP, *Planck, BAO, WL, SN Ia, ...*)
  - i.e., independently verify Age Universe & H_0
- **That Means for *Gaia* & SIM:**
  - **Ages of stars/clusters to $\lesssim$ 1%**
    - Distances to $\lesssim$ ½ %
  - **Distance Scale (H_0) to $\lesssim$ 1%** [Olling,2007,MNRAS,378,1385]

Stellar Ages & Astro/Spectro/Photometry

Rate of Luminosity & Age Evolution

[from Bertelli etal (2008, A&A, 484, 815) Isochrones at Solar metallicity]

$(\Delta L/L)^{model} \sim (A+B*L) = (10 + 2\ L/L_\odot) \pm 5$ [% / Gyr]

Solve for $L(\tau; A,B,L_0)$ and invert:

Age: $\tau(L) = 1/A * \mathit{ln}\left[\ L/L_0 * (A+B*L_0)/(A+B*L)\ \right]$

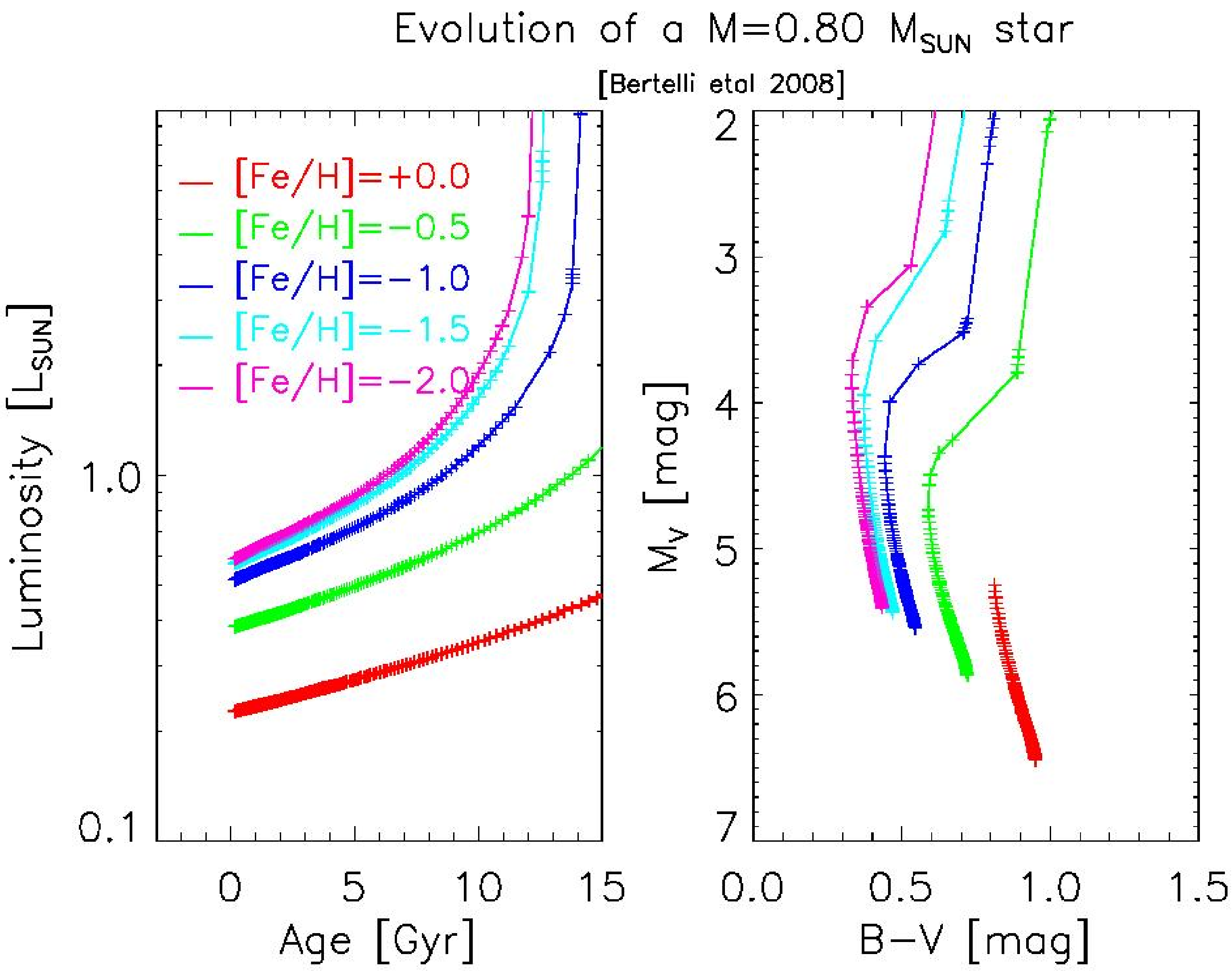
error: $\Delta\tau^{model} = (\Delta L/L)^{obs} / (0.1 + 0.02\ L/L_\odot)$ [Gyr]

$= (2\Delta\pi/\pi)^{obs} / (0.1 + 0.02\ L/L_\odot)$ [Gyr]

@ 1 L_{SUN} , $\Delta\pi/\pi$ = ½ %

$\Delta\tau^{model}$ ~ 0.1 Gyr ~ 0.7% $Age_{UNIVERSE}$

Stellar Ages, ASP



Rates differ substantially w. [Fe/H]:

$\Delta T/\Delta Fe/H \sim -5.3$ Gyr/dex @ 1 M_{SUN} [Faster at lower mass]

Stellar Ages, ASP

Rate of Evolution, **(ΔL/L) ~ 10 %/Gyr**

- Table shows Star/Distance combinations for which ***Gaia*** & **SIM** achieve ≲ 137 Myr age accuracy (=$T_{UNIVERSE}$/100)
  - *Gaia:* out to 200-500 pc
  - SIM: out to >1,000 pc
    - 25 - 4 times more **disk stars**
    - 125 – 8 times more **thick_disk/halo stars**
    - **SIM's larger reach is very important for the rare stars**
    - $\Delta \mathrm{Age}^{model} = (2\Delta\pi/\pi)^{obs} / (0.1 + 0.02\ L/L_{\odot})$ **[Gyr]**

MS Star	F5	G	K0	K5		F5	G	K0	K5	F0	G	K0	K5
MV(abs):	3.5	4.75	5.9	7.4	τ_MS [Gyr]:	3.8	12	21	55	3.8	12	21	55
Dist. [kpc]	apparent magnitude (@ AV=0.5 mag/kpc)					Gaia Age Accuracy [Myr] (ΔPLX=Lindegren etal 2007)				SIM Age Accuracy [Myr] (ΔPLX=7 µas, *assumed*)			
0.1	8.6	9.8	11.0	12.5		12	17	20	24	8	11	13	14
0.2	10.1	11.4	12.5	14.0		25	37	46	63	17	23	26	27
0.4	11.7	13.0	14.1	15.6		54	87	123	210	33	46	52	55
0.6	12.7	13.9	15.1	16.6		90	156	245	495	50	69	78	82
0.8	13.4	14.7	15.8	17.3		135	251	435	964	66	92	104	110
1	14.0	15.3	16.4	17.9		190	382	711	1,666	83	115	130	137

Stellar Ages, How To?

- Astrophysics of stars is based on: **THE SUN**
  - Fundamental parameters need be well determined: **Mass, Radius, Luminosity, He-abundance (Y), [Fe/H]**
    - ~100 Binaries with M and R better than 1%

- **Ages are currently model-dependent**
  - ***Will they?*** **really be fully calibrated with accurate *GAIA*/SIM & Ground-Based data & more complete modeling**

Stellar Ages, How To?

YES! These goals are achievable in the near future by:

Survey of **eclipsing binaries** down to V~15

ground-based spectroscopic observing campaign

More advanced 3D/NLTE modeling

μas astrometry from *Gaia* & SIM-Lite

NEED RADIUS ⇒ **Eclipsing Binaries** (~ 0.8% of Population)

Photometry ⇒ $\mathbf{R_*}$, m_V, A_V

Spectroscopy ⇒ V_{ORB}, $\mathbf{M_*}$ & **[Fe/H]**

Astrometry (π) + m_V & A_V ⇒ **Luminosity**

TWO stars on same Isochrone ⇒ Age & Helium

[Andersen '91, '92; Fernandes '98; Lastennet & Valls-Gabaud '02; Fernandes '02; Lebreton '05; Ribas '06; Metcalfe etal '06; ...]

"The [*Gaia*/SIM] data ... will force the **biggest reassessment of stellar astrophysics in more than 50 years, ...** very beneficial for ... astrophysics" [Olling etal 2009, astro-ph/0902.31970]

Currently, results are model dependent

562 E. Lastennet and D. Valls–Gabaud: Detached binaries in the HR diagram (2002)

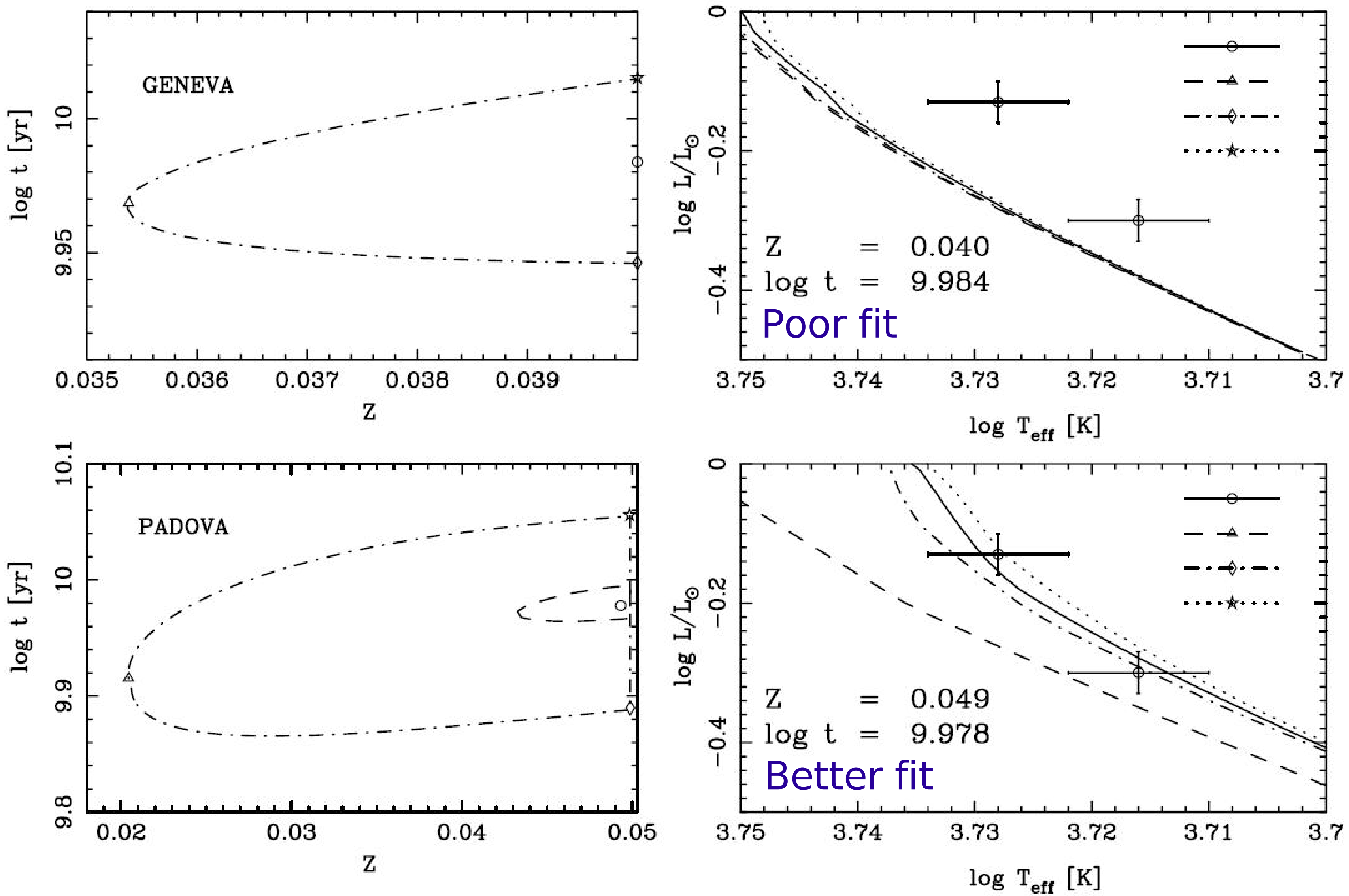


Fig. 9. HS Aur system [2]. *Left panels*: confidence regions in the (metallicity, age) plane. *Right panels*: HR diagrams. The top panels use the Geneva tracks, while the lower ones use the Padova ones. The best solutions obtained are indicated by circles. Keeping the same metallicity as the best solution, we also show two other points at 3σ from the best solution, with respectively a smaller age (diamond) and a larger age (open star). Another point (triangle) is the solution with the lowest metallicity allowed at a 3σ confidence level. The Geneva isochrones clearly do not fit the HS Aur system, no matter what age or metallicity are used. In contrast, the Padova tracks allow a successful fit at about 2.5 times the solar metallicity.

NOT SO FAST!, there are "A Few Things We do not Know About Stars"

R. Kurucz (**2002**nqsa.conf....3K)

- We do not know how to make realistic model atmospheres:
  -we do not understand convection, ...
- We do not understand spectroscopy:
  - We do not have good spectra of the Sun or any star
  - We do not have energy distributions for the Sun or any star
  - We do not know how to determine abundances:
    -We do not know the abundances of the Sun or any star
  - We do not have good atomic and molecular data:
    -50% of the lines in the solar spectrum are not identified
- Also, the spectroscopic & photometric temperature scales differ substantially

NOT SO SLOW!, Progress is being made, via:
1) 3D stellar atmospheres, 2) NLTE analysis,
3) line-shape fitting and 4) better opacity tables

[e.g., Asplund 2008,IAU,252,13; Young & Arnett, 2005,ApJ,618,908; Terndrup, 2008,ASPC,384,240; ...]

Stellar Ages: *Gaia and* SIM

- Detached Eclipsing Binaries (DEBs) make up ~0.8% of population: **DEBs are RARE**
  - Thick disk ~ @4 % ==> $DEBs_{TD}$ ~ 1/ 3,100 local stars
  - Halo ~ @0.1% ==> $DEBs_{H}$ ~ 1/125,000 local stars
- ***Gaia*** (at d ≲ 400 pc has $\Delta\pi/\pi \leq$ ½%)

~ 2,660,000 thin-disk stars ⇒ ~21,300 DEBs
~ 106,000 thick-disk stars ⇒ ~850 DEBs
~ 2,600 spheroid stars ⇒ ~20 DEBs

  - **SIM** can do about 100x more stars, especially the rare
    Large numbers are important:
  - **Star-formation History of the Disk:**
    - 12 Gyr @ 0.25 resolution => 48 bins
      0.5->0.8 M_{SUN} @ 0.05 resolution => 6 bins
      -2 ->+0.5 [Fe/H] @ 0.5 resolution => 5 bins *
      1,440 bins => 15 ☆'s/bin
  - SFR of Thick Disk: ¼ Age, ⅕ [Fe/H] → 72 bins => 12 ☆'s/bin
  - SFR of Halo: : ⅙ Age, ⅕ [Fe/H] → 48 bins => ⅕ ☆'s/bin
  - **Numbers/bin may be ~10x too large**
    Test effects of tidal interactions: take 10? bins in separation
    - **Need to bin in [α/Fe] as well?**

Solar Neighborhood w. $\Delta d/d \leq$ ½%

- Thick Disk Detached Eclipsing Binaries: 1/ 3,100 local stars
- Halo Detached Eclipsing Binaries: 1/125,000 local stars
- ***Gaia*** **has access to ~850 TD and 20 Halo DEBs**
- **SIM can do ~100 times more**

MS Star	F5	G0-G9	K0	K5	F5	G0-G9	K0	K5	Thick D. (G0-K5)	Halo (G5-K5)	Thick D. (G0-K5)	Halo (G5-K5)
τ_MS [Gyr]	3.8	12	21	55	3.8	12	21	55	GAIA [Δd/d>0.5%]		SIM [Δd/d>0.5%]	
Dist. [pc]	apparent magnitude (@ AV=0.5 mag/kpc)				Number of Stars out to D_pc with GAIA distance errors <0.5% [negative #s: Δd/d>0.5%]				# Ebs in Thick Disk (@4%)	# EBs in Halo (@ 0.1%)	# Ebs in Thick Disk (@4%)	# EBs in Halo (@ 0.1%)
5	2.0	3.2	4.4	5.9	1	3	4	7	0	0	0	0
10	3.5	4.8	5.9	7.4	10	21	32	54	0	0	0	0
25	5.5	6.8	7.9	9.4	147	317	484	831	1	0	1	0
50	7.0	8.3	9.4	10.9	1,122	2,445	3,754	6,449	4	0	4	0
100	8.6	9.9	11.0	**12.5**	8,220	18,255	28,279	**48,584**	33	1	33	1
150	9.5	10.8	**11.9**	13.4	25,489	57,633	**90,021**	154,659	105	3	109	2
200	10.2	**11.3**	**12.4**	13.9	55,698	**128,052**	**201,580**	346,322	234	6	253	5
300	11.2	**12.4**	13.6	15.1	161,316	**382,002**	609,932	-1.05E+6	369	9	820	18
400	**11.9**	13.2	14.3	15.8	**332,166**	-806,482	-1.30E+6	-2.24E+6	106	3	1,866	42
800	**13.8**	15.1	16.2	17.7	-1.68E+6	-4.34E+6	-7.27E+6	-1.25E+7	0	0	12,776	317
1500	15.9	17.1	18.3	19.8	-6.41E+6	-1.73E+7	-2.99E+7	-5.13E+7	0	0	65,878	1,903
									852	21	81,741	2,289

Stellar Ages: *Gaia* and SIM

- Also, SIM should do the rare Special Cases at larger distances
  Binary cousins of **Old Uranium Stars** with [Fe/H] ~< -3

  τ ~ 13.2 ± 2.7 Gyr HE 1523−0901, d ~ 1 kpc, V~11

  [Frebel et al 2007,ApJ,660L,117]

  τ ~ 14.9 ± 3.0 Gyr CS 22892-0529, d~ 1.5 kpc, V~12

  [Sneden et al 1996,ApJ,467,819; Hill et al 2002, A&A,387,560]

  τ ~ 13.2 ± 2.7 Gyr HE 1424-0241, d ~ 8 kpc, V~14

  [Cohen et al 2007,ApJ,659L,161]

- See Beers & Christlieb for a review [2005, ARA&A,43,531]

Ground-based, *Gaia* & SIM Synergy

- Ground+*Gaia*: survey & identification
- Ground: spectroscopy/metallicity
- *Gaia*: distances (extinction of most cases)
- SIM: distances "most interesting" (oldest)
- SIM: 1% distance to M31 (Rotational Parallax)

To uncover systematics, we need to observe:

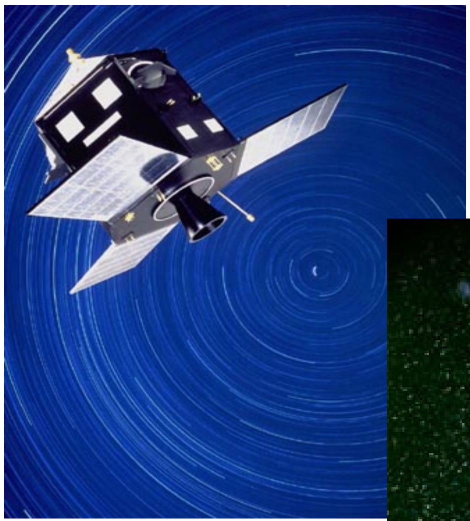
- Wide range in metallicity/ages/types
- Wide range in separations (measure tidal effects)
- Preferably high-mass case on (sub)giant branch
- Supergiants in M31 & M33

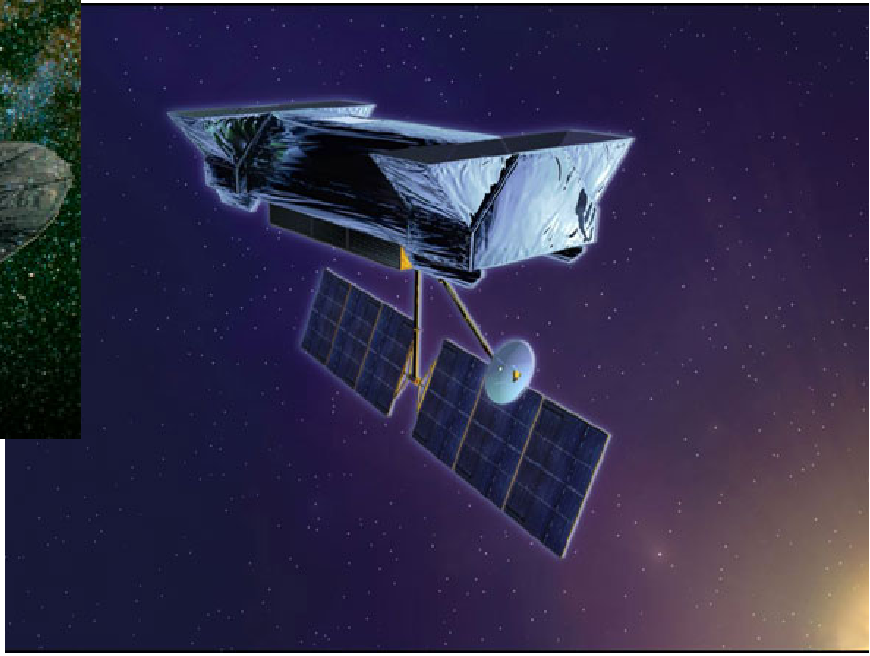
Connecting Stars, Galaxies and the Universe

[Olling et al '09]

- The **golden age of astrophysics** is upon us with both grand discoveries (**extra-solar planets, dark matter, dark energy**)
- **Fundamental understanding of the working of stars and galaxies is within reach**, from **precision measurements**
- **Micro-arcsecond astrometry** ==> ***model independent distances and masses***
- **Stellar ages with accurate luminosities/distances**
- **The age of the universe** is the inverse of **Hubble's constant (H_0),** + corrections from: the fate of the universe and the amount and nature of dark energy
- Some of the **strongest motivations** to vigorously pursue **accurate distance measurements are related to the history and fate of the universe.**

Thank You





Backup Slides:

- How big is 1 μas?

  A Dime at the Moon, really?

  - Dime/Euro: ~2 mm

  - Earth-Moon ~ 376,000 km
  - ∠ Dime@Moon $= 2.0\ 10^{-3}$ m / $3.76\ 10^{8}$ m

    $\sim 5.3\ 10^{-12}$ rad

    $\sim 3.0\ 10^{-10}$ deg

    ~ 1.1 μas