Spin alignment as a diagnostic of black-hole binary formation

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GCGM7, Oxford (MS), April 19 2013

1) Spin in stellar-mass BH binaries
2) Astrophysics and post-Newtonian
3) Spin-orbit resonance locking
4) Role of tides and mass transfer
5) Can Advanced LIGO reconstruct the physics of population synthesis?

Gerosa, Kesden, EB, O'Shaughnessy, Sperhake, arXiv:1302.4442

Properties of stellar-mass black holes

Mass m

Spin $\mathbf{S} = \chi \frac{Gm^2}{c} \hat{\mathbf{S}}$ (with $0 < \chi < 1$)

Mass estimates:

LMXBs

Spin estimates:

- ✓ Continuum fitting
- ✓ Line spectroscopy

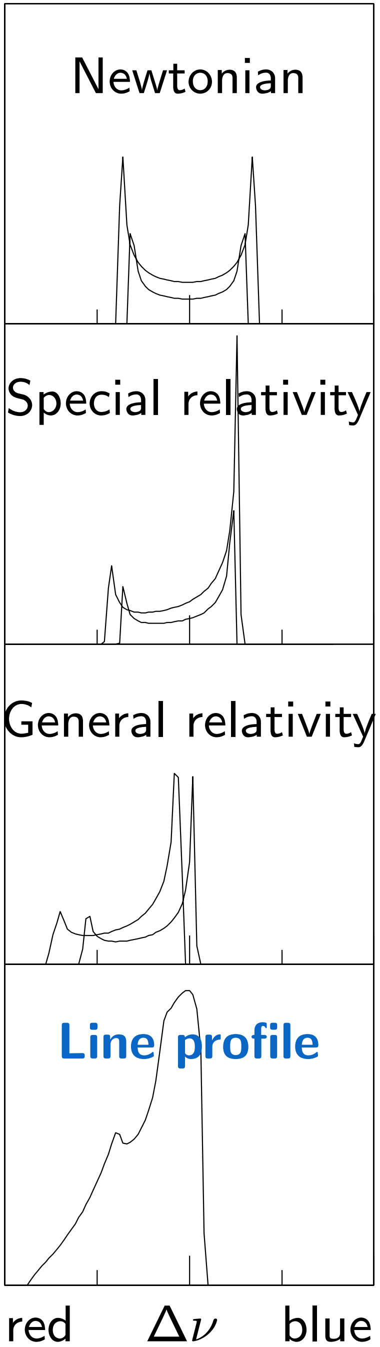
Model-dependent – highly uncertain!

Theoretical expectation: black holes retain natal spin

[King & Kolb, astro-ph/9901296]

[Belczynski++, astro-ph/0703131]

System	Estimated spin	Method
	Stellar-mass BHs	
Cygnus X-1	0.05 ± 0.01	Line spectroscopy
LMC X-3	≈ 0.2–0.4	Continuum
4U 1543-475	0.3 ± 0.1	Line spectroscopy
	0.75–0.85	Continuum
SAX J1711.6-3808	$0.6^{+0.2}_{-0.4}$	Line spectroscopy
XTE J1550-564	≈ 0.1–0.8	Continuum
	0.76 ± 0.01	Line spectroscopy
SWIFT J1753.5-0127	$0.76^{+0.11}_{-0.15}$	Line spectroscopy
M33 X-7	0.77 ± 0.05	Continuum
XTE J1908+094	0.75 ± 0.09	Line spectroscopy
XTE J1650-500	0.79 ± 0.01	Line spectroscopy
GRS 1915+105	0.7–0.8	Continuum
	0.98–1	Continuum
LMC X-1	$0.90^{+0.04}_{-0.09}$	Continuum
GX 339-4	0.94 ± 0.02	Line spectroscopy
GRO J1655-40	$\geqslant 0.25$	QPOs
	0.65–0.75	Continuum
	≈ 0.1–0.8	Continuum
	0.98 ± 0.01	Line spectroscopy
XTE J1655-40	≈ 1	Line spectroscopy
XTE J1550-564	≈ 1	Line spectroscopy



Black-hole binary formation rates

Compact binary formation rates depend on poorly known physics:

- ❑ **Supernova kicks** can unbind binary
- ❑ **Common-envelope phase** crucial – envelope binding energy λ?
- ❑ **Mass transfer**
- ❑ **Tidal interactions**

"Official" rates for Initial and Advanced LIGO [LSC, 1003.2480]

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
Initial	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Black-hole binary formation rates

Compact binary formation rates depend on poorly known physics:

- **Supernova kicks** can unbind binary
- **Common-envelope phase** crucial – envelope binding energy λ?
- **Mass transfer**
- **Tidal interactions**
- **Metallicity**

"Updated" rates for Advanced LIGO [1208.0358; see also 1202.4901]

ADVANCED LIGO/VIRGO DETECTION RATES [YR^{-1}] [a]

Model	NS-NS	BH-NS	BH-BH
S	3.9 (1.3)	9.7 (5.1)	7993.4 (518.7)
V5	3.9 (1.3)	9.4 (4.8)	8057.8 (533.7)
V6	3.9 (1.3)	9.3 (4.7)	8041.7 (523.6)
V7	5.0 (1.5)	14.8 (8.3)	8130.1 (574.2)
V8	3.9 (1.3)	1.2 (0.3)	172.2 (14.0)
V9	3.9 (1.3)	11.8 (6.7)	8363.6 (654.9)
V10	5.2 (1.7)	5.7 (4.9)	7762.7 (487.0)
V11	3.9 (1.1)	10.5 (6.3)	12434.4 (888.1)
V12	11.7 (0.8)	7.6 (5.8)	8754.6 (275.3)
V13	3.7 (0.9)	76.9 (62.1)	1709.6 (966.1)

Spin alignment and resonance locking

Spin alignment is affected by the same physics:

- **Supernova kicks:** misalignment [Kalogera, astro-ph/9911417]
- **Tidal interactions:** asymmetry
- **Mass transfer:** selection of primary (standard/reversed mass ratio)

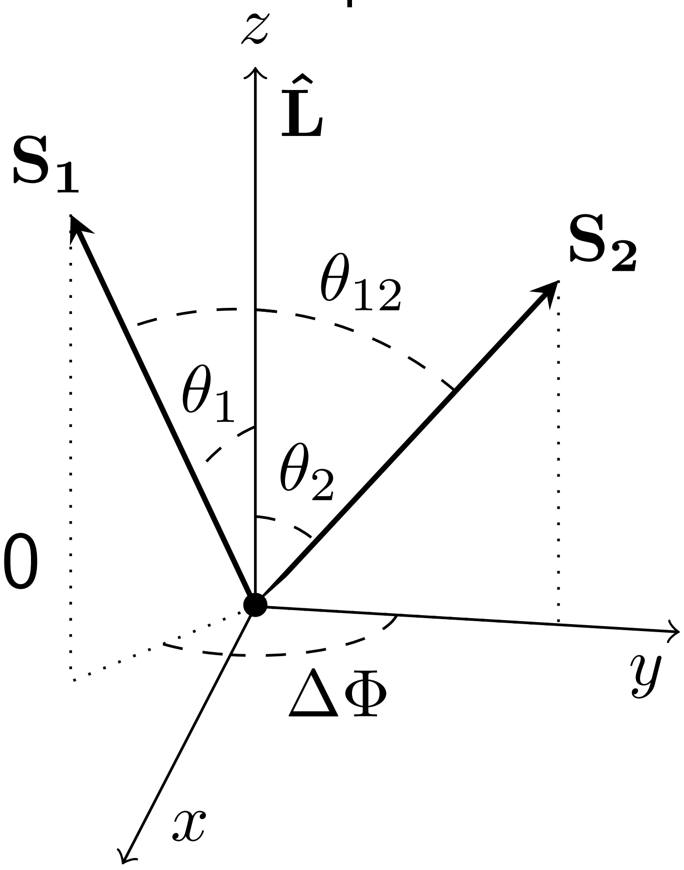
Late-time evolution well approximated by post-Newtonian dynamics
Alignment depends on astrophysical initial conditions: inverse problem?

$$\mathbf{S}_2 \cdot (\mathbf{L} \times \mathbf{S}_1) = 0$$

$$\frac{d}{dt}\mathbf{S}_2 \cdot (\mathbf{L} \times \mathbf{S}_1) = 0$$

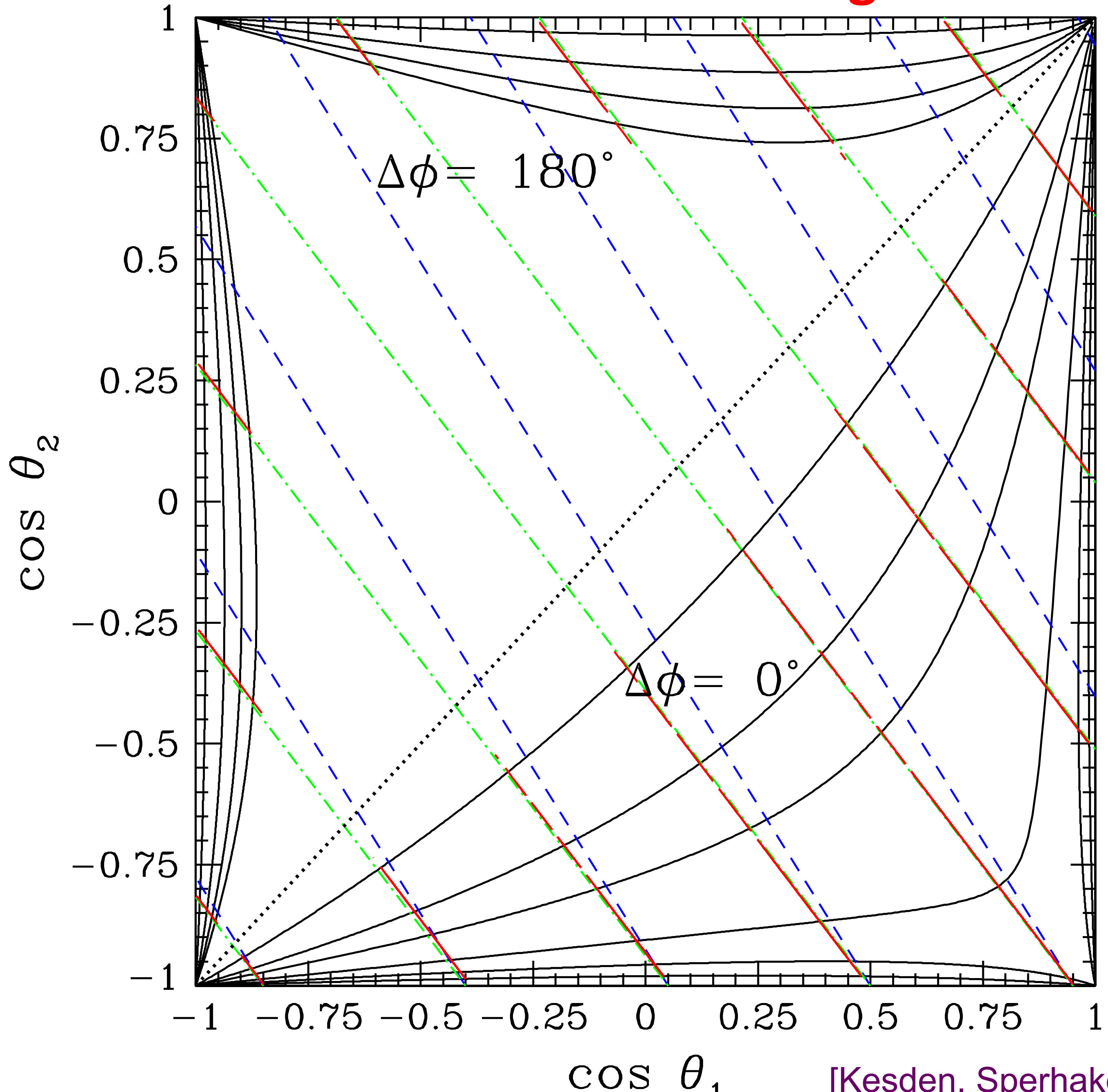
$$\theta_1 < \theta_2 : \quad \Delta\Phi \to 0 \quad \text{and} \quad \theta_{12} \to 0$$

$$\theta_1 > \theta_2 : \quad \Delta\Phi \to \pm\pi$$



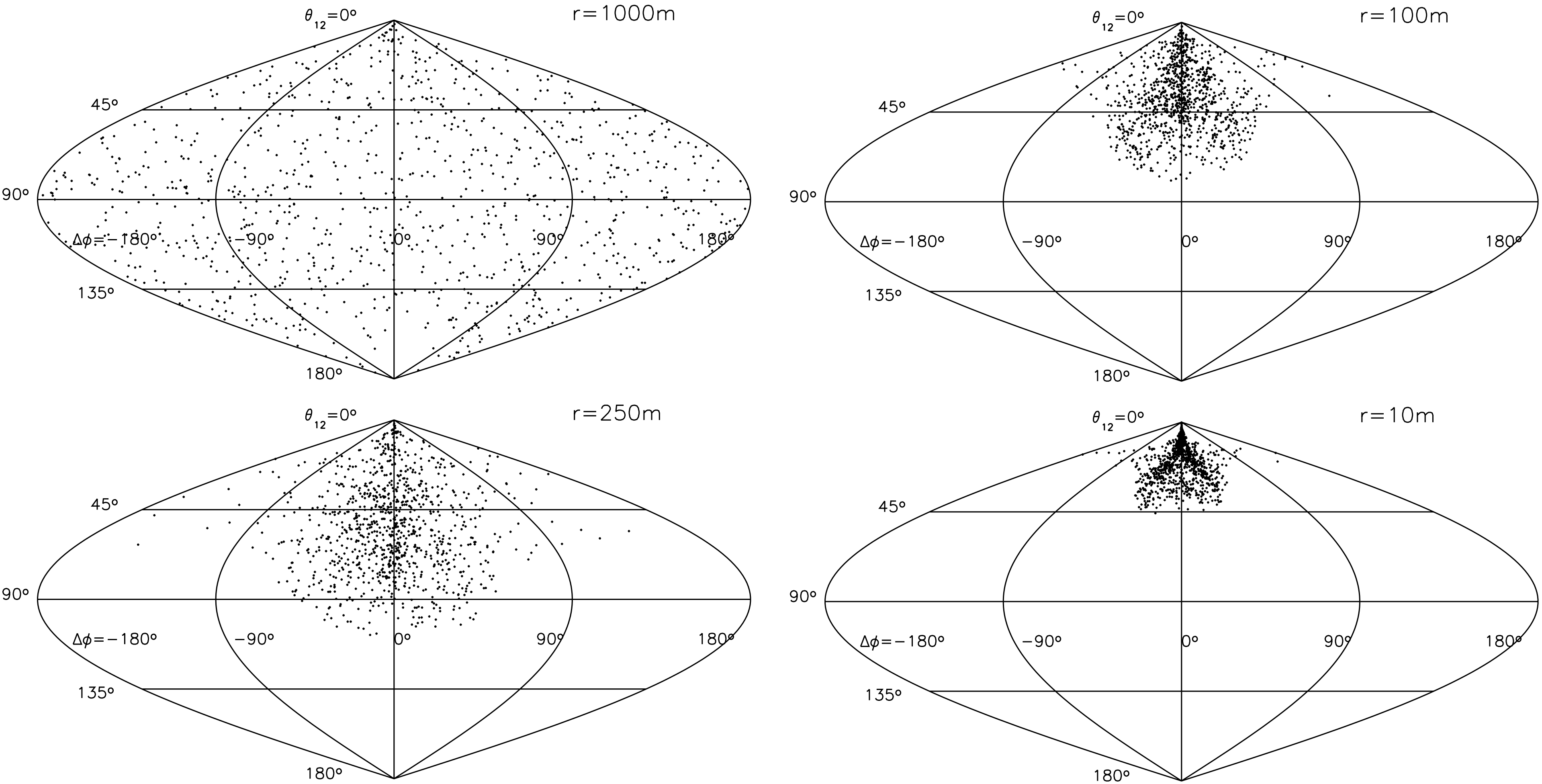
[Schnittman, astro-ph/0409174]

Resonance locking



[Kesden, Sperhake & EB, 1002.2643]

Spin-orbit resonances and spin alignment

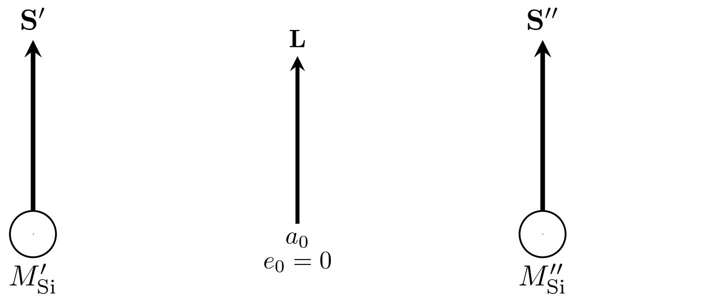


$\theta_1(t_0)$ = 10 degrees, evolution starts at r = 1000M

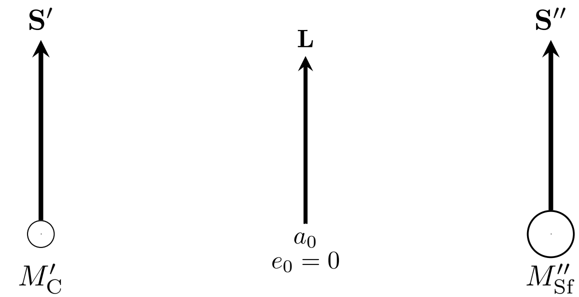
[Schnittman, astro-ph/0409174]

Astrophysical initial conditions: a simple model

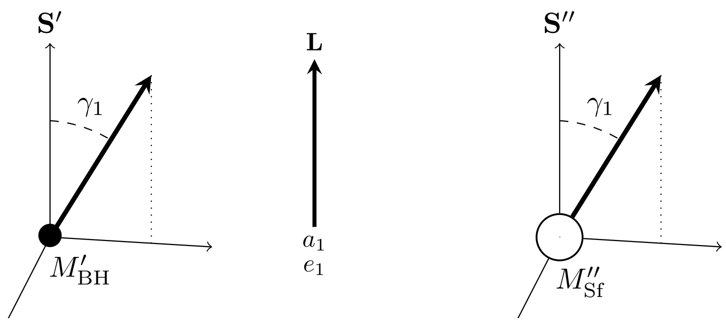
1. Upper main sequence



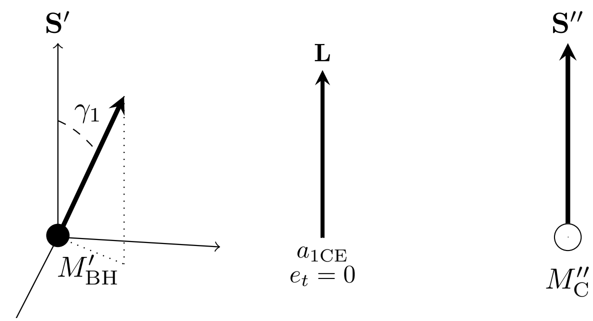
2. Mass-transfer phase



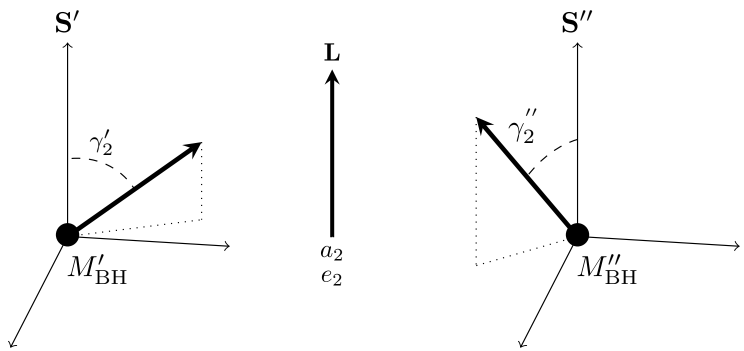
3. 1st Supernova explosion



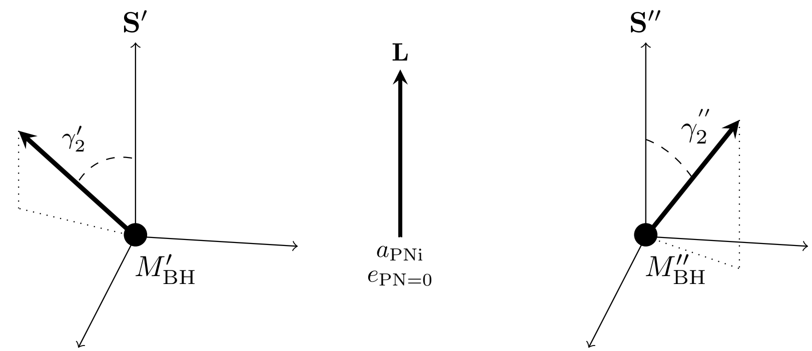
4. Tides, common-envelope, BH precession



5. 2nd Supernova explosion

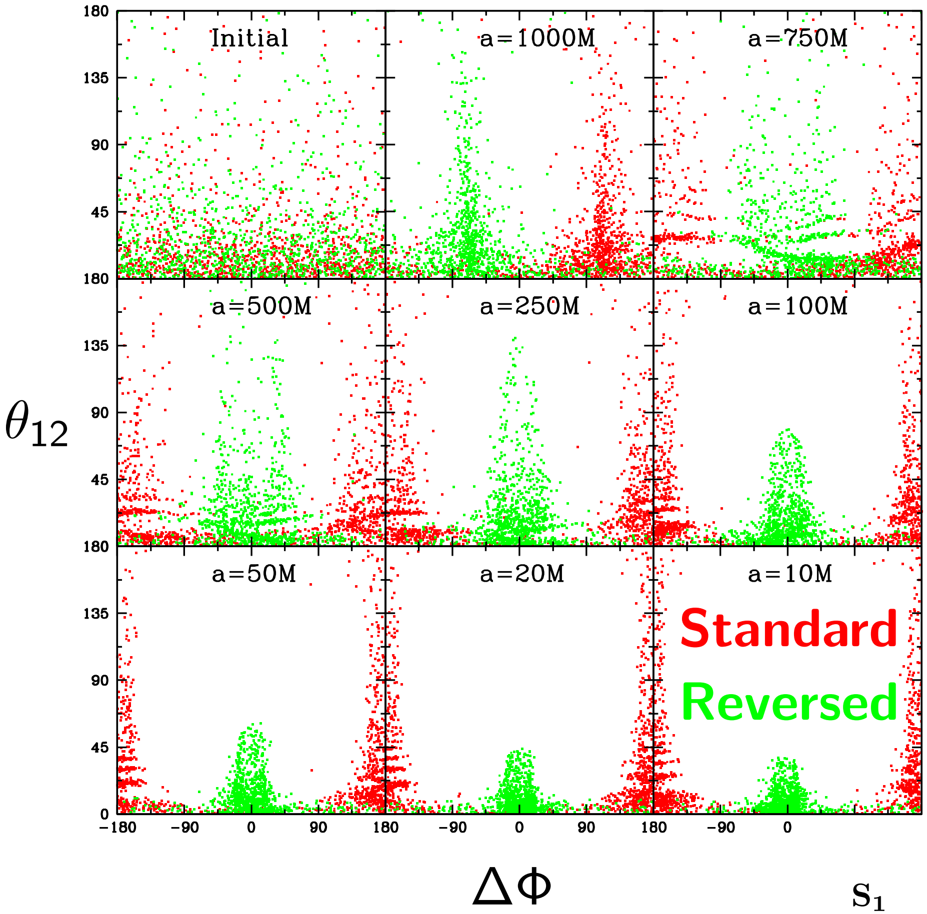


6. Post-Newtonian evolution

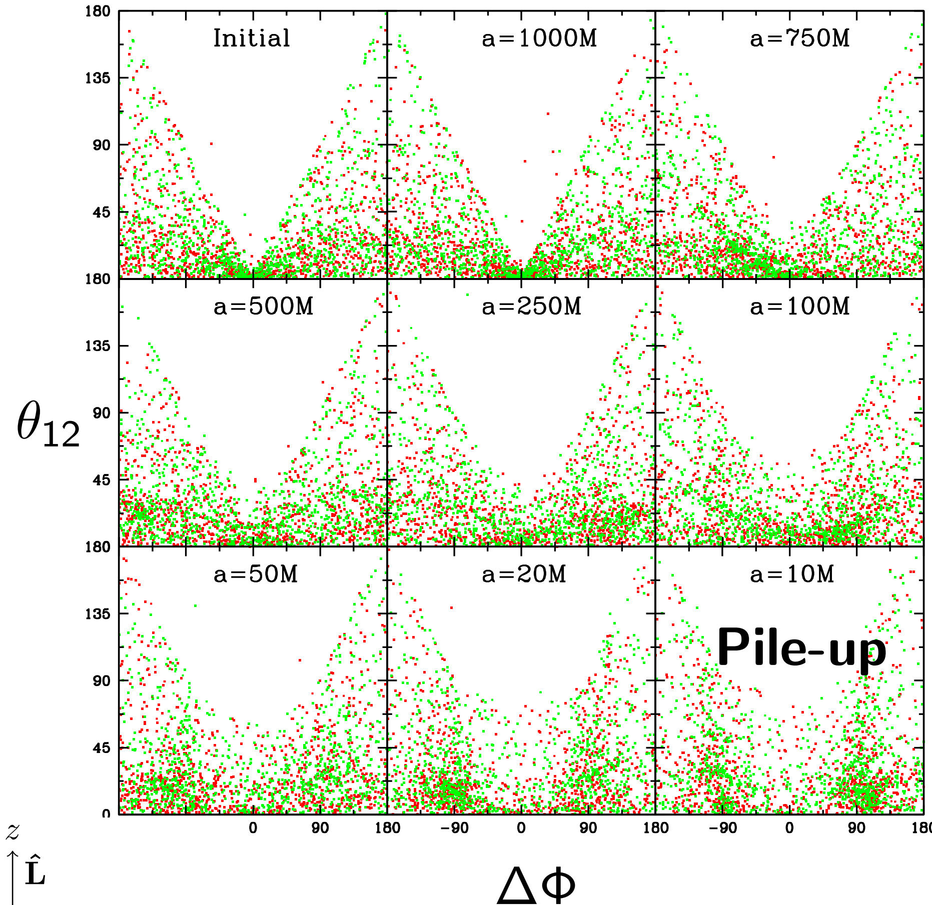


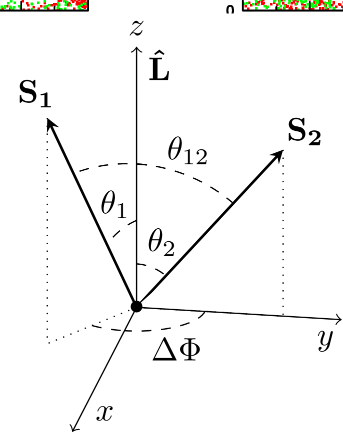
Effect of tides and mass-ratio reversal

Tides



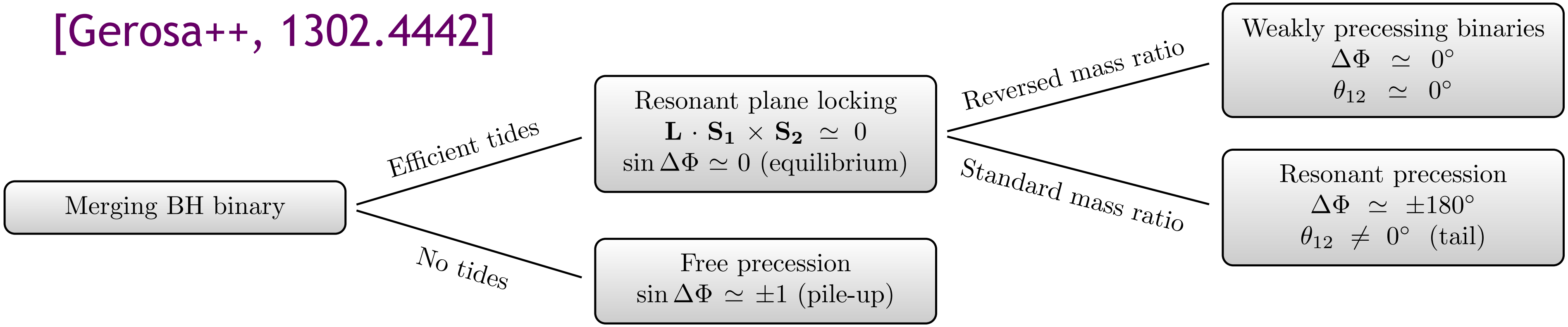
No Tides

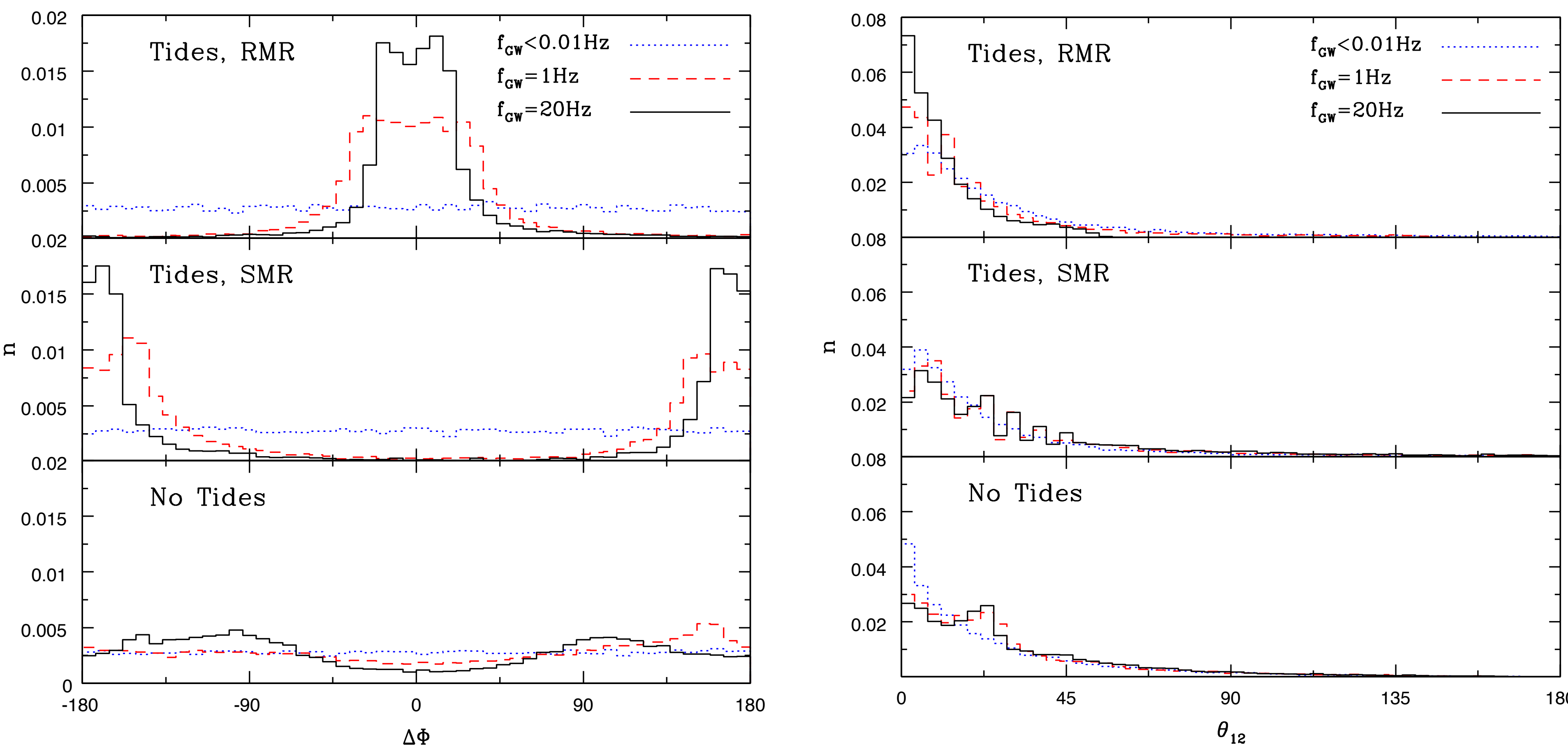




Inverse problem: binary evolution from GW observations

[Gerosa++, 1302.4442]

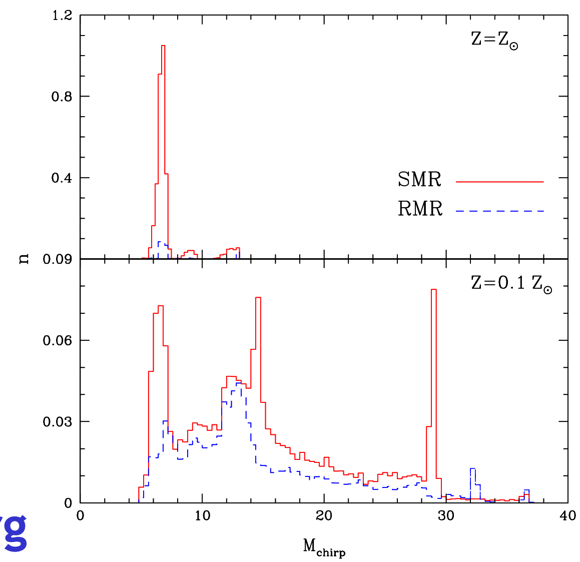




Outlook

Implement spin evolution in population synthesis codes!
What are the obstacles? What shall we learn?

- **Combine measurements of $\Delta\Phi$ and (chirp) mass**
  How accurate can these be? Systematics?
- **Low metallicity: more likely mass-ratio reversal**
- **Envelope binding energy λ (variations 1-4)**
- **Supernova kick strength (variations 8 and 9)**
- **Wind mass loss (variation 11)**



http://www.syntheticuniverse.org

Variation	Subvariation A $Z/Z_\odot = 0.1$			Subvariation B $Z/Z_\odot = 0.1$			Subvariation A $Z/Z_\odot = 1$			Subvariation B $Z/Z_\odot = 1$		
	SMR	RMR	#	SMR	RMR	#	SMR	RMR	#	SMR	RMR	#
0: Standard	63.2%	36.8%	32496	66.8%	33.2%	17038	91.9%	8.1%	10160	92.9%	7.1%	8795
1: $\lambda = 0.01$	67.9%	32.1%	12368	67.4%	32.6%	11401	93.6%	6.4%	8171	93.6%	6.4%	8171
2: $\lambda = 0.1$	62.7%	37.3%	27698	65.2%	34.8%	16885	88.9%	11.1%	11977	92.1%	7.9%	8577
3: $\lambda = 1$	54.2%	45.8%	51806	65.7%	34.3%	19415	79.1%	20.9%	15820	91.6%	8.4%	8442
4: $\lambda = 10$	50.1%	49.9%	50884	62.9%	37.1%	17939	73.2%	26.8%	14425	91.6%	8.4%	8321
5: $M_{\rm NS} = 3M_\odot$	62.5%	37.5%	32236	66.2%	33.8%	16868	91.6%	8.4%	9972	92.8%	7.2%	8589
6: $M_{\rm NS} = 2M_\odot$	62.3%	37.7%	32535	65.9%	34.1%	16804	91.5%	8.5%	9922	92.5%	7.5%	8590
7: $\sigma = 132.5{\rm km/s}$	58.2%	41.8%	36546	63.1%	36.9%	18935	88.9%	11.1%	11099	89.6%	10.4%	9334
8: $v_k = v_{obs}$ (BHs)	56.2%	43.8%	948	72.5%	27.5%	207	56.2%	43.8%	16	0%	100%	2
9: $v_k = 0$ (BHs)	56.3%	43.7%	52832	58.8%	41.2%	34569	66.3%	33.7%	35267	65.2%	34.8%	32547
10: Delayed SN	61.4%	38.6%	27310	66.3%	33.7%	13841	81.5%	18.5%	1032	81.2%	18.8%	881
11: Weak winds	58.4%	41.6%	33872	63.6%	36.4%	17765	70.5%	29.5%	21786	64.2%	35.8%	16182

Summary

- Compact binary formation rates depend on poorly known physics:
  - ✓ Supernova kicks
  - ✓ Tidal interactions
  - ✓ Mass transfer
  - ✓ Metallicity
  - ✓ Common-envelope evolution

- Spin alignment is crucially affected by the same physics
  - ✓ Supernova kicks: misalignment
  - ✓ Tides: asymmetry ($\theta_1 < \theta_2$?)
  - ✓ Mass transfer: selection of primary ($m_1 > m_2$?)

- Resonance locking implies that this physics affects observable distribution of precessional configurations

- Black-hole binary formation astrophysics with Advanced LIGO!
  - ✓ Assess systematic/statistical errors
  - ✓ Combine with additional information (mass distribution…)