

# BNS Initial Data with Lorene

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- BNS - matter is present and is harder to model
- The equation of state (EOS) of nuclear matter inside the neutron star is still theoretically unknown
- The EOS leaves an imprint on the BNS merger process and its emitted GW signal.
- For source parameter estimation, we need to compare the observed signals to theoretical GW templates, which depend on different characteristics like the total binary mass and mass ratio and the NS EOS.
- Numerical simulations are required to predict GW from early inspiral to post merger phase
- We can also predict the final stage of a BNS merger

- Lorene (Langage Objet pour la RELativité Numérique) is a publicly available multidomain spectral methods code that can solve elliptic equations and generate quasi-equilibrium binary configurations in General Relativity
- Uses GR and Tolman-Oppenheimer-Volkov (TOV) Equations to model isolated NS
- Assume quasi-equilibrium - Irrotational binary, Spatial 3-metric and Slow circular inspiral
- Solves non linear elliptic equations using spectral methods and multiple nested domains



Figure: Domains as set by Lorene Ericourgoulhon et al 2000

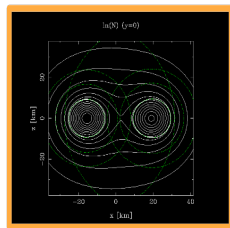


Figure: Domains as set by Lorene Ericourgoulhon et al 2000

# GP\_1L1

\*2Mi2` 7Q` \*QKTmi iBQM H\_2H iBpBiv M/ :` pBi iBQM- \_Q+

- GP\_1L1 Hp2b 7Q` BMBiB H / i +QM};m` iBQMb mb  
TT`QtBK iBQM
- :` pBi iBQM H ` /B iBQM ? b M2;HB;B#H2 +QM i` B  
2pQHmiBQM Q7 i?2 M2mi`QM bi `b
- AMBiB H bT iB H K2i`B+ Bb i` Mb7Q`K2/ b,

B<sup>9</sup> BD

- HHQrb TH +2K2Mi Q7 [m bB@2[mBHB#`BmK 2HH  
bi `iQ KBMBKBx2 :B##b 2``Q`b i?Bb Bb +`BiB+ H
- .2i2`KBMBM; i?2 bm`7 +2 ;2QK2i`v Bb /Bb+QMIB  
i`2 i2/ mbBM; `2H t iBQM i2+?MB[m2bX
- h?2 +Q/2 óbTHBibô HH }2H/b BMiQ +QKTQM2Mi  
KBMBKBx2b 2``Q`b 7`QK i?2 bi2HH `bm`7 +2b UG  
/Q2b MQi 2HBKBM i2 i?2K
- h?2 /QK BM #QmM/ `B2b }HH HH Q7 bT +2- BM Q`  
7 b?BQM M/ `2 +2Mi2`2/ `QmM/ 2 +? bi `

- $A_i b T^2 + B \} 2b \quad ? 2HB + H FBHHBM; p^2 + iQ` \quad b i ? 2 + Q$   
 $HH [m MiBiB2b `2K BM mM + ? M; 2/ r ? 2M T`QT2`H$   
 $p^2HQ + Biv BM i ? 2 \quad xBKmi ? H / B`2 + iBQM$
- $A_i b b m K 2b K tBK H b HB + BM; Q 7M ? BQM p 2 b b i r a 277 \oplus$   
 $2HHBTiB + H 2 [m iBQM b 7Q` H T b 2 - b ? B 7 i p^2 + iQ` -$   
 $+ M \# 2 bQH p^2 / mbBM; 7Qm` SQBbbQM @ HBF 2 2 [m$

$$r^k = 9 \quad (1 + a) + \quad {}^9 E_B B^{BD} \bar{r}_B \bar{r}^{-B}; \quad = H(M)$$

$$r^k = 9 \quad a + \frac{j}{9} \quad {}^9 E_B B^{BD} \frac{R}{k} \bar{r}_B \bar{r}^{-B} + \bar{r}_B \bar{r}^{-B}; \quad = \ln( \quad^k )$$

$$r^k L^B + \frac{R}{j} \bar{r}_B \bar{r}^{-B} L^D = \quad \text{Re} \quad (1 + \tau) |^B + k \quad {}^9 E_B B^{BD} \quad (j \quad 9)$$

# JQ/B}+ iBQM b /QM2 iQ GP\_1L1

"2Mi2`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- GP\_1L1; BMb 2 +? bi2T #v bbmKBM; [m bB2[mBHE KQiBQM M/ }`bi BMi2;` H Q7 KQiBQM,

>+ HM+ HM +QMbi Mi

- h FBM; i?2 ;` /B2Mi HQM; s /B`2+iBQM iQ Q#M/BM M;mH `p2HQ+Biv

$$\frac{\partial}{\partial s} H(M)_{(s_i; y)} = \frac{\partial}{\partial s} H(M)_{(s_i; y)} = R_k$$

- lb2 b2+ Mi K2i?Q/ BKTH2K2Mi iBQM 7Q` Q#i BMB

# JQ/B}+ iBQMb, IM2[m H K bb ` iBQ

\*2Mi`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- \*QKTHB+ i2/`2H t iBQM b+?2K2 Ue /Bz2`2Mi`2H }2H/ +QKTQM2MibV ? b KmHiBTH2 7 BHm`2 KQ/2H QR2`@K bb La- M/ r2HH@b2T` i2/ +QM};m` iBG `2bQHmiBQM Bb +Q `b2bi BM i?2 Qmi2`KQbi /QK
- h?2 +m``2Mi`QmiBM2 iQ HQ+ i2 i?2 `Qi iBQM tB K2i?Q/ BKTH2K2Mi iBQM c MmK2`B+ H }t2b 7Q` i? }M/ `2 M2+2bb `v
- 6mM+iBQM`2[mB`2b /BpBbBQM #v i2`K i? i + M
- G2 / iQ MQM @+QM iB MmQmb #2? pBQ` Q7 i?2 7mM
- h?Bb ? b ?BbiQ`B+ HHv #22M # ``B2` iQ ;2M2` i



JQ/B}+ iBQMb, IM2[m H K bb ` iBQ

\*2Mi2` 7Q` \*QKTmi iBQM H\_2H iBpBiv M/ :` pBi iBQM- \_Q+

6B;m`2, IMbi2 /v #2? pBQ` Q7 TQbBiBQM<sup>6B;m`2</sup> /Q7<sup>h?2</sup> QM2<sup>+2Mi2`</sup> Q7 i?2<sup>Q7 K bb +Q@Q`/BM i2b</sup> b

- h FBM; i?2 `2+BT`Q+ H Q7 i?2 7mM+iBQM 7Q` 2  
M/ bi #H2 +QMp2`;2M+2 iQ ;Bp2M +2Mi` H 2Mi  
T ` K2i2`b

# JQ/B}+ iBQM b, >B;?2` K b b #BM `B

\*2Mi2` 7Q` \*QKTmi iBQM H\_2H iBpBiv M/:` pBi iBQM-\_Q+

- GP\_1 m b 2 b # `vQM K b b Q7 La 7Q` +QKTmiBM; i?2
- " `vQM K b b Bb M BM+`2 bBM; 7mM+iBQM Q7 +2M
- M Bi2` iBp2 T`Q+2/m`2 Bb BKTH2K2Mi2/ iQ`2 +?  
2 +? bi `mbBM; i?2 +2Mi` H 2Mi? HTv
- M 2pQHmiBQM `v b2[m2M+2 +QMp2`;2b iQr `/b  
+2Mi` H 2Mi? HTv #v,

$$= \frac{k+}{k+ k} \mathbb{R}^9$$

# JQ/B}+ iBQM b, >B;?2`K b b #BM `B

\*2Mi2`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- GP\_1L1öb `2H t iBQM b+?2K2 K F2b Bi /B{+mHiC  
`2H t +QM};m` iBQM b 2ti`2K2Hv bHQrHv /Bz2`2M  
2z2+ib +QK2 BM i /Bz2`2Mi iBK2bi2Tb- +2`i BM  
[m MiBiB2b `2`2@+QKTmi2/7`QK b+`i+?-2i+X  
Bi Bb #2bi iQ b b mK2 i?BM;b rBHH 2M/ mT  
ómM/2`/ KT2/ô
- JQ/B}2/ i?2`QmiBM2 iQ BM+`2 b2 i?2 #`yQM\_K b b  
Bi2` iBp2Hv BM bi2Tb b b T2+B}2/ #v i?2 mb2<sup>6B; m`2, GQ`2M2 bi2Tb m+Q</sup>
- h?2 KQbi bi #H2`2bmHib #2;BM 7`QK HQr K b b  
+QM};m` iBQM b- KQpBM; BMr`/b iQ i?2 /2bB`2/  
`/Bmb- M/ i?2M bHQrHv BM+`2 bBM; i?2 i` ;2i K  
Q7 i?2 #BM `v

# 1 [m iBQM b Q7 ai i2

\*2Mi2`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- SQHvi`QT B# fPa,
- SB2+2rBb2 SQHvi`QTB+ 1Pa, SB2+2rBb2 TQHvi`Q  
1Pa, lbBM; 9 b2;K2Mib S7 EQH7Q`QT2b  
U<sub>B</sub> < B R y B j)
- SB2+2rBb2 TQHvi`QT2 Bb T `K2i2`Bx2/ mbBM;  
/B # iB+ BM/B+2b M/i?2 T`2bbm`2 ii?2 }`bi  
/BpB/BM;(2M R B y k= R y)
- h?2 HQr /2MbBiv `2;BQM Bb ivTB<sup>6B;m`2, GQ: Q7 /2MbBiv pb T</sup>  
>B;? /2MbBiv #2? pBQ` + M #2 + Tim`2/ mbBM; i?2  
T `K2i2`bX
- h #mH i2/ 1Pa, i?2 GB[mB/@.`QT JQ/2H rBi?  
aFv`K2 AMi2` +iBQM  
U?iiTb,ffbi2HH `+QHH Tb2XQ`;fa\_P1PaV

# 1 [m iBQM Q7 bi i2

\*2Mi2` 7Q` \*QKTmi iBQM H\_2H iBpBiv M/ :` pBi iBQM- \_Q+

- \* m``2Mi + M/B/ i2b 7Q` i?2 1Pa KQ/2Hb 7Q` r?B+ /QKBM i2/ #v Mm+H2QMb- #v ?vT2`QMb- #v TBQ bi` M;2 [m `F K ii2` U7`22 mT- /QrM- M/ bi` M;2

6B;m`2, S ` K2i2`Bx2/ 1Pa }ib iQ i?2 b2i Q7 6B;m`2, b?2`2;BQM BM T ` K2i2` bT +2 r?2  
i #H2b/ 2i H- kyy3 M2miQM@bi i?2 1Pa B2[m2M+2b + M Q++m` Bb b`  
J bb pb` /Bmb` 2H iBQM BM i?22#QiiQK };m

# h #mH i2/ 1Pa

\*2Mi2`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- h #mH i2/ 1Pa, "mBH/ AMBiB H / i 7Q` i #mH i2/ 1Pa  
?iiTb,ffbi2HH `+QHH Tb2XQ`;fa\_P1Pa
- \*QMi BMb j. i -#H2M/, h
- b i?2 i?2`KQ/vM KB+ [m MiBiB2b T`2bbm`2 M/ bT2+M/2T2M/2Mi QM i?2 i?`22 p `B #H2b- bHB+2 i?2 j /B iQ +Q``2H i2 T`2bbm`2 M/ bT2+B}+ BMi2`M H 2M1
- aHB+2 i?2 i #H2b irB+2 iQ K F2 Bi R/ mbBM; #2i 2 i2KT2`im`2
- Pö\*QMMQ`- Pii kyRy 1Pa h #H2b
- a+?M2B/2`- \_Q#2`ib- Pii kyRd 1Pa h #H2b

# AMBiB H . i GB#` `v

\*2Mi2`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- q2 ? p2 +QKTBH2/ M AMBiB H / i HB#` `v +QMbB  
2[m iBQM Q7 bi i2- rBi? p `vBM; K bb `iBQb MXi  
?iiTb,ff++`;T ;2bX`BiX2/mf D7 #2`f"LaA.f. i
- h?2 / i + M #2 mb2/ b M BMTmi 7Q` 1BMbi2BM hC  
bBKmH iBQMX
- 1Pab, Sj- S9- JaR- JaR#- aHv- q66R- M/ JS R

> KBHiQMB M \*QMbi` BMi oBQH iB

\*2Mi2` 7Q` \*QKTmi iBQM H\_2H iBpBiv M/:` pBi iBQM-\_Q+

> KBHiQMB M +QMbi` BMi pBQH iBQMb mbBM;  
bT2+i` H`2bQHmiBQM BM GP\_1L1

6B;m`2, > KBHiQMB M \*QMbi` BMi oBQH iBQM 6B;m`2, > KBHiQMB M \*QMbi` BMi oBQH iBQM  
Pö\*QMMQ` - Pii kyRy 1P aib, #H2b Q 1MQ;;B Pö\*QMMQ` - Pii kyRy 1P aib, #H2b M2+F



# 6mim`2 qQ`F

\*2Mi2`7Q`\*QKTmi iBQM H\_2H iBpBiv M/:`pBi iBQM-\_Q+

- AKT`Qp2 i?2 ? KBHiQMB M +QMbi` BMi pBQH iBQ  
i #H2b #v +QKT `BM; Bi iQ bBKTH2 M/ TB2+2rBb2
- \*? M;2 i?2 TH +2K2Mi Q7 /QK BMb
- 1tT M/ QM i?2 BMBiB H / i 7Q` h #mH i2/ 1Pa
- .vM KB+ H bBKmH iBQMb Q7 Qm` BMBiB H / i 7Q
- S2`7Q`K p `BQmb M Hvb2b Q7 i?2 bBKmH iBQMb  
J bb 2D2+i @ #QmM/ M/ mM#QmM/ K bb  
6 i2 Q7 K2`;2` `2KM Mib

