

## *L' onda del secolo*

*Eugenio Coccia*

*Univ. di Roma "Tor Vergata"*

*Gran Sasso Science Institute*

*INFN*



$\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, 0$ 

Đi ng. về b

U.S. Ag. 1/2 O 2 1/2  
Melonville, Hamilton, Ontario

$\mathcal{O} \cdot \mathcal{O} \quad \frac{1}{2} \quad \frac{1}{2} \quad \mathcal{O} \quad \frac{1}{2} \quad \frac{1}{2}$

Sib. II.

$\Phi(17) = \frac{1}{6} - \frac{1}{9} + \frac{1}{18} - \frac{1}{27} + \frac{1}{54}$

Th. 10. O. 2.

3.41.  $\frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{2}$

$$d, \frac{1}{2}, \frac{1}{2}, 0$$
[illegible]
$$\frac{3-4f}{5} \quad \text{O} \quad \frac{2}{x} \quad \frac{2}{x} \quad \frac{2}{x}$$

Φ. π. 28

D. 7. septemb:  $\frac{1}{2}$  O  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$

E. 28. String  $\frac{1}{2}$   $\frac{2}{3}$   $\frac{3}{4}$   $\frac{4}{5}$   $\frac{5}{6}$   $\frac{6}{7}$

U. 4. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840. 841. 842. 843.

Fig. 1.  $\bar{a} - \bar{a} - O - \bar{a} - \bar{a}$

⑩. 14: H perky. 2.  $\begin{matrix} \text{H} & \text{H} & \text{O} & \text{H} \\ | & | & | & | \\ \text{Y} & \text{Y} & \text{Y} & \text{Y} \end{matrix}$

Q. 15. H. S. \* O

is it not a very serious, or perhaps a dangerous, matter  
in the eyes of the public?

Q. 10. H. S. 2. O

10.9 = 4 0 2

From 2 to 11.7 2. m. 1900. One captured

24. 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 104

75

[illegible]

6.2 Boiled H<sub>2</sub>O  $\xrightarrow{\text{O}_2}$   $\xrightarrow{\text{H}_2\text{O}}$   $\xrightarrow{\text{H}_2\text{O}}$   
Nov. 5. 4' major in no melting ice; clouded over.

$$C.S.M.S. \quad \frac{1}{2} \rightarrow O \quad \frac{1}{2} \rightarrow A \quad \frac{1}{2} \rightarrow B +$$

6. 4. 11. 1. 0

Q. 6 M. f. \* \* \* O


H<sub>7</sub>. M. S.  $\frac{1}{2}$  \*  $\frac{1}{2}$  \* O  
H<sub>7</sub>.  $\frac{1}{2}$  \*  $\frac{1}{2}$  \* O system of circles.  
only variable 2 pos. specified?

9.9.11.5. 1/2 1/2 1/2 1/2

第 10 頁

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[illegible]

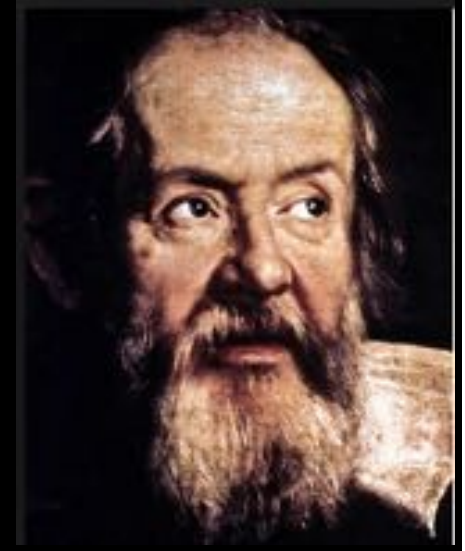
No. 1.  *O. minima* V. 1. m.  
 mostly Dec. rare

8. 12. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840. 841. 842. 843. 844. 845. 846. 847. 848. 849. 850. 851.

[illegible]

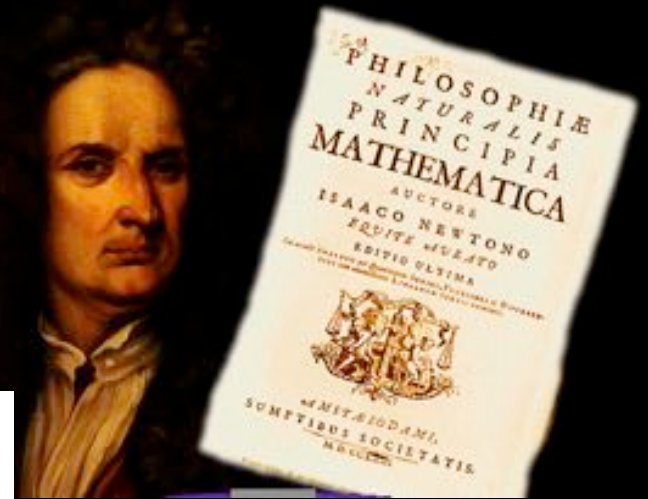
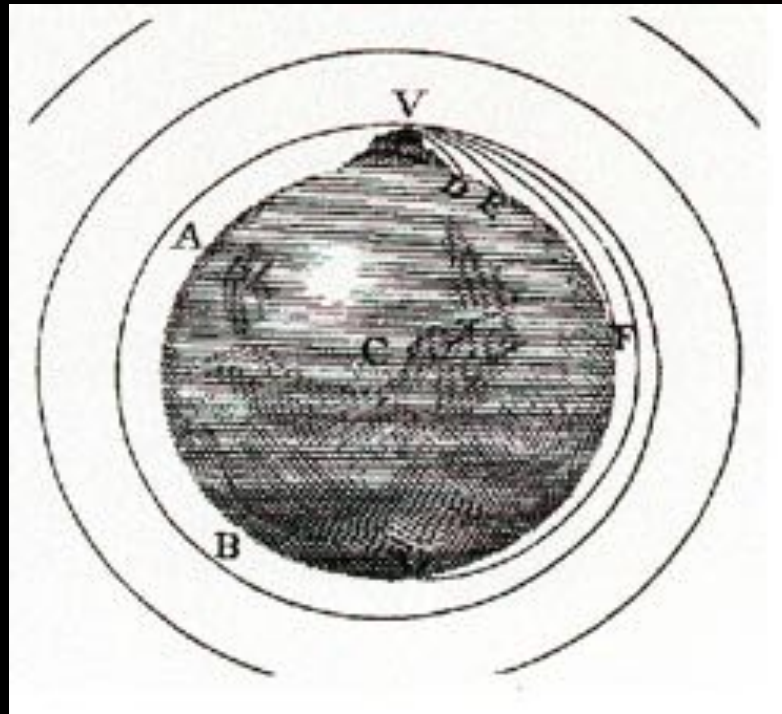


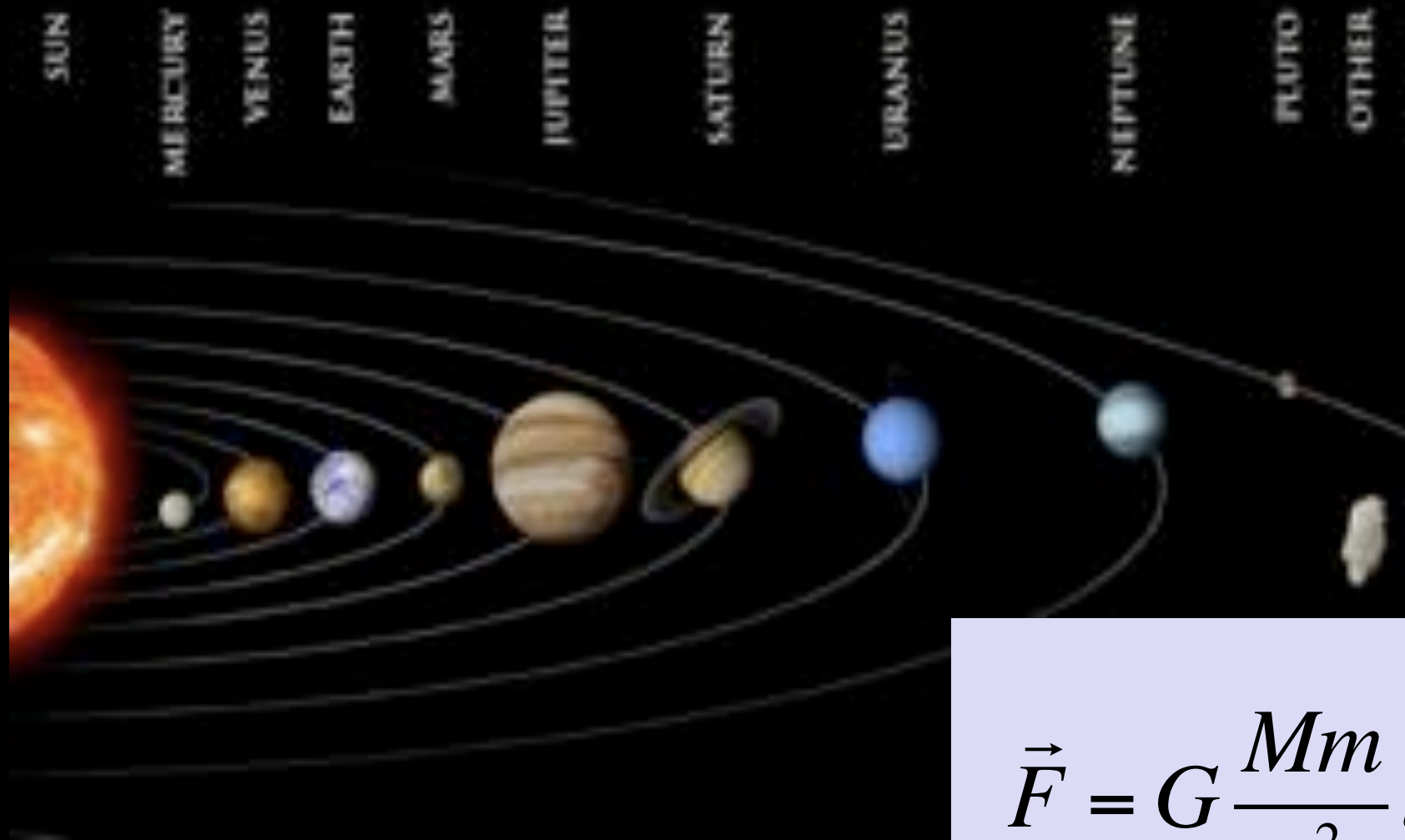
# Galilei



30  
Adi 7. di Gennaio 1610 Giove si vedeva col Cannone co  
3. stelle fisse coti \* <sup>occ.</sup> delle quali se col il cannone  
minor si vedeva. <sup>oni \*</sup> a di 8. appariva coti \* + + \* era d'ag  
diretto et no retrogrado come sogliono i calculatori.  
Adi 9. si rugolo. a di 10. si vedeva coti \* \* \* <sup>occ.</sup> cio' e' d.  
giu' in la piu' occidente si che in occidente si puo credere.

# Newton

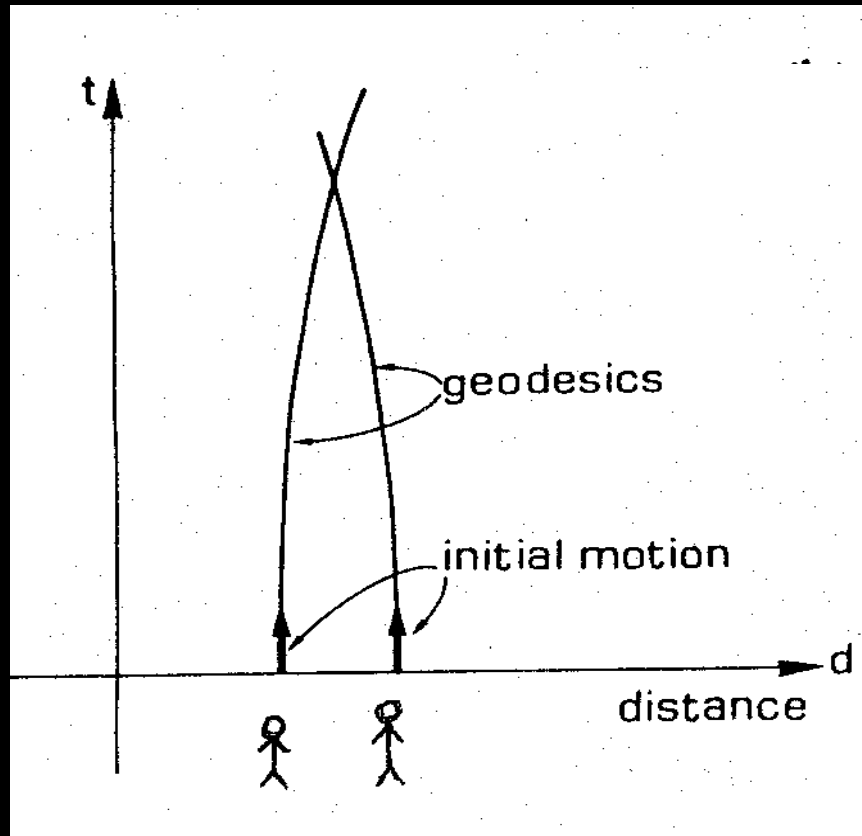




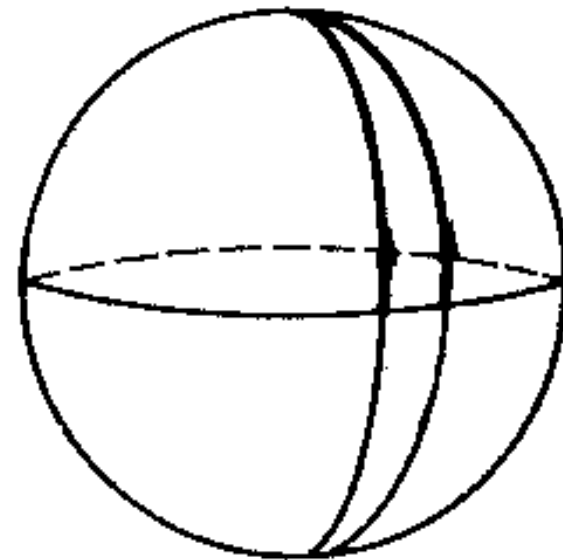
$$\vec{F} = G \frac{Mm}{r^2} \vec{u}_r$$

Einstein





Einstein



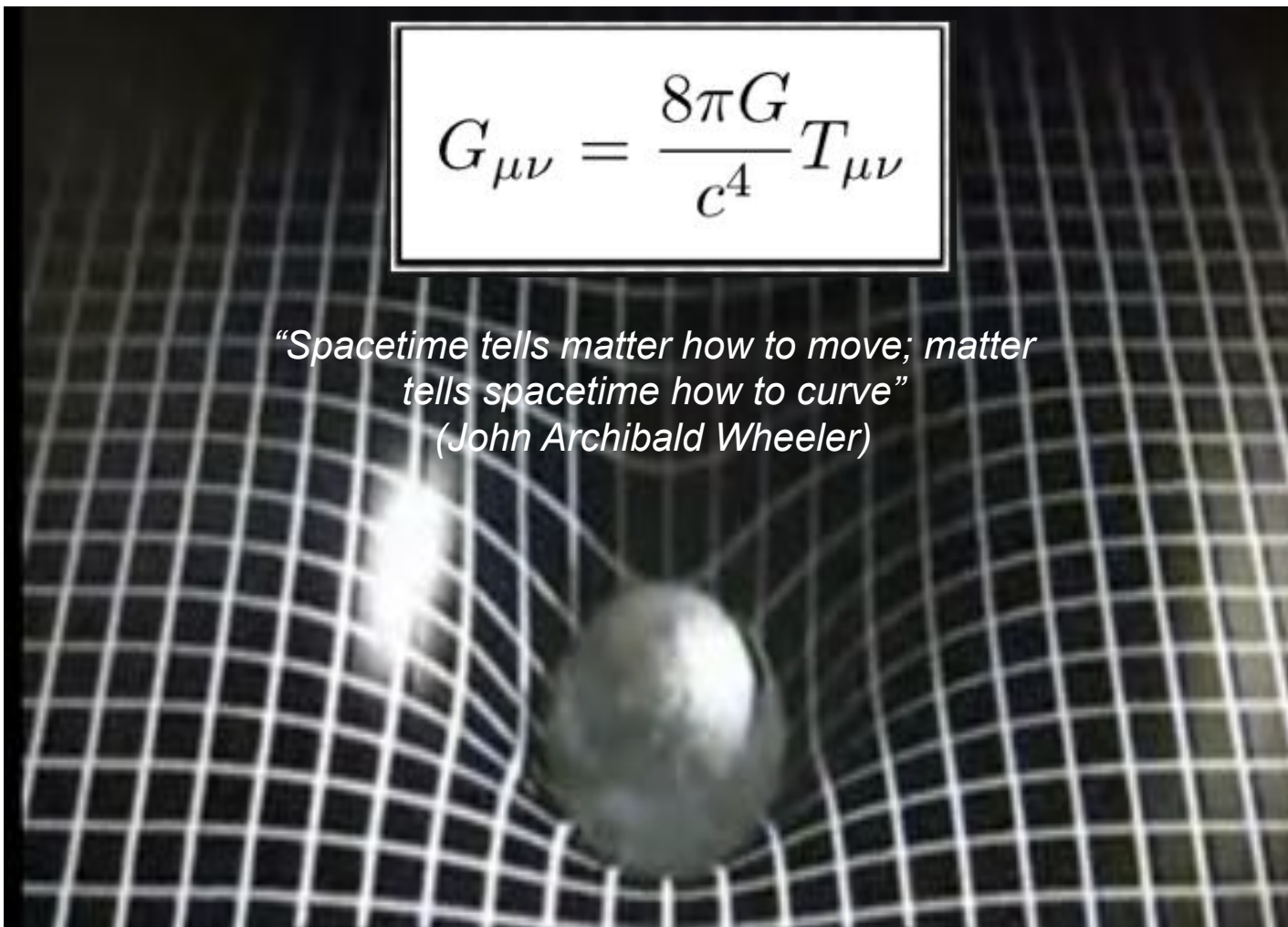
( )



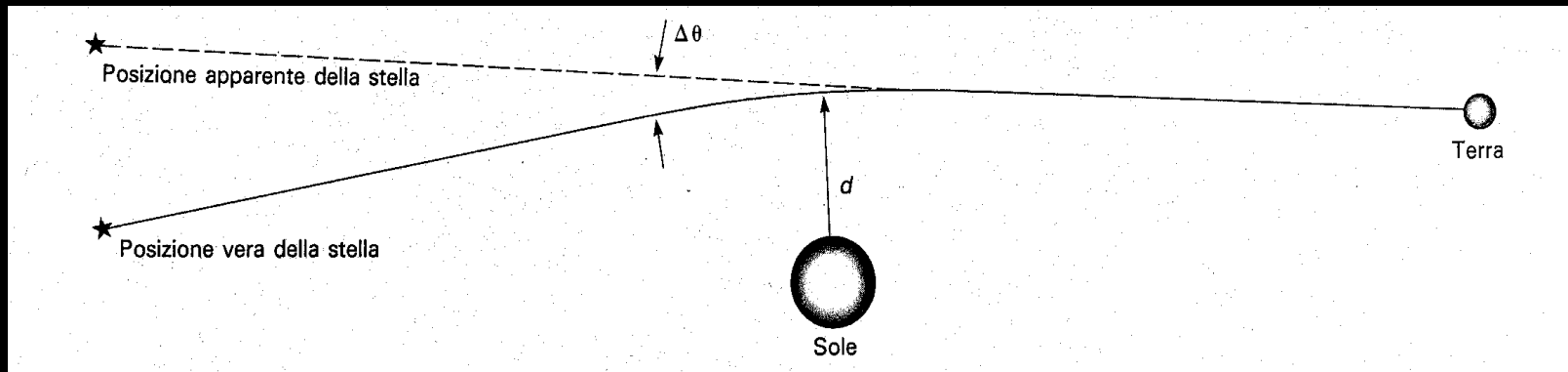
Gravity is a manifestation of spacetime curvature induced by mass-energy

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

*“Spacetime tells matter how to move; matter  
tells spacetime how to curve”  
(John Archibald Wheeler)*



# Light deflection



Eddington



LIGHTS ALL ASKEW IN THE HEAVENS

Special Cable to THE NEW YORK TIMES

New York Times, 1919, Nov. 10, 1919, ProQuest Historical Newspapers The New York Times (1851 - 2004)  
p. 17

# LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less  
Agog Over Results of Eclipse  
Observations.

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## EINSTEIN THEORY TRIUMPHS

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Stars Not Where They Seemed  
or Were Calculated to be,  
but Nobody Need Worry.

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## A BOOK FOR 12 WISE MEN

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No More in All the World Could  
Comprehend It, Said Einstein When  
His Daring Publishers Accepted It.

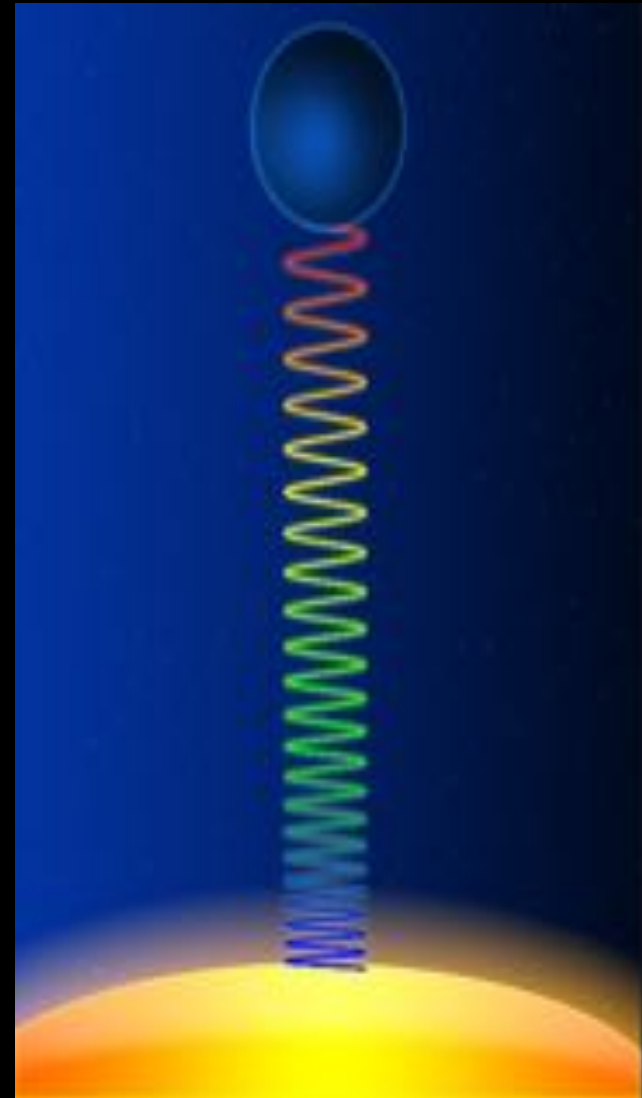
New York Times headline of  
November 10, 1919.



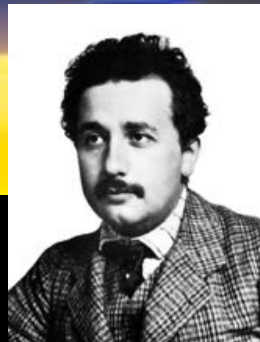
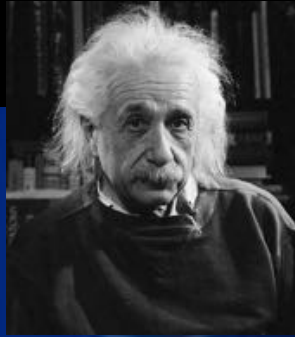
Harvard

Redshift

Pound and Rebka  
1959



E. Coccia - 2016





# BLACK HOLE



KINETIC Energy

POTENTIAL Energy



$$\frac{1}{2}mv^2 \geq G \frac{mM}{R}$$



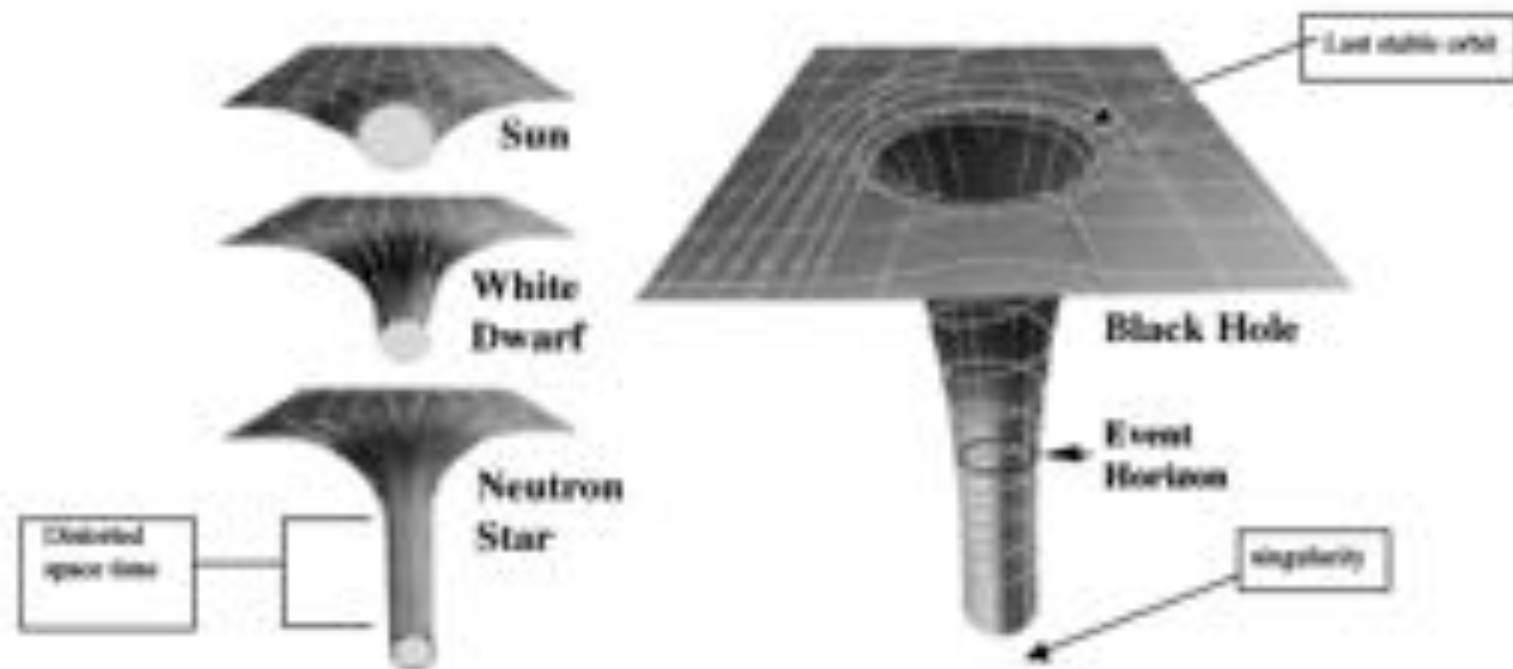
$$v_f = \sqrt{\frac{2GM}{R}}$$

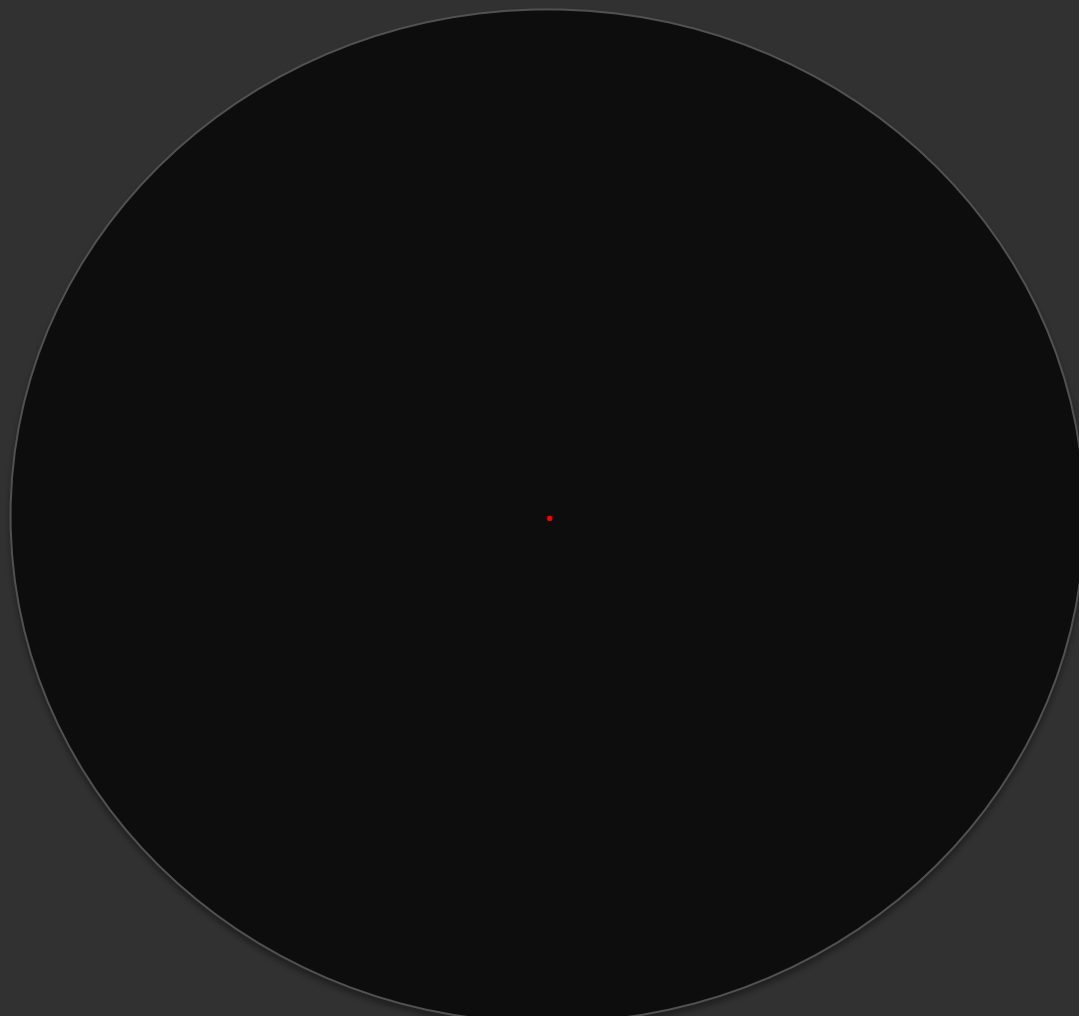
Escape velocity

The escape velocity is equal to the speed of light  
if matter is squeezed into a sphere of radius

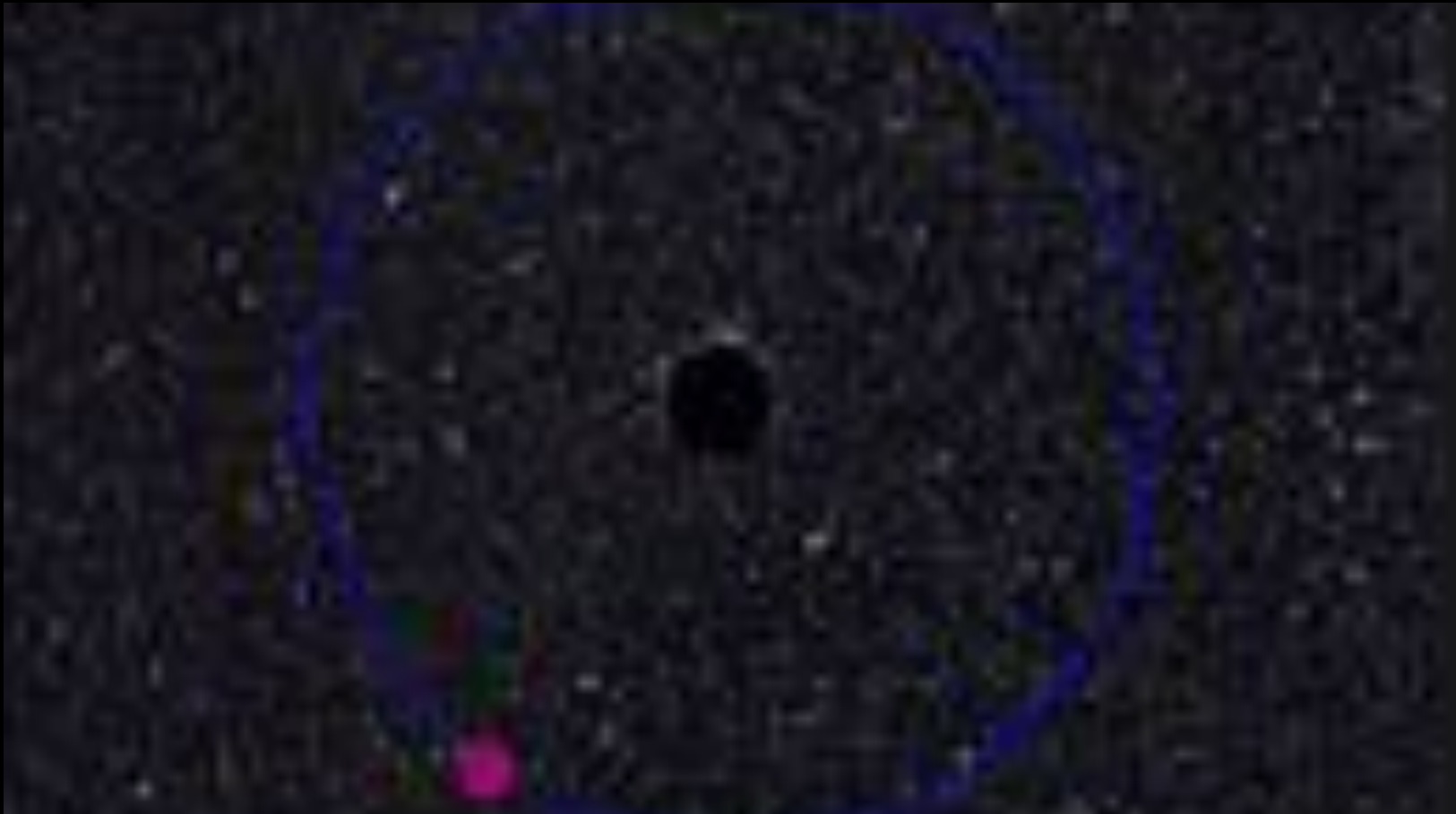
$$R = R_s = \frac{2GM}{c^2}$$

Schwarzschild radius





# Time traveling

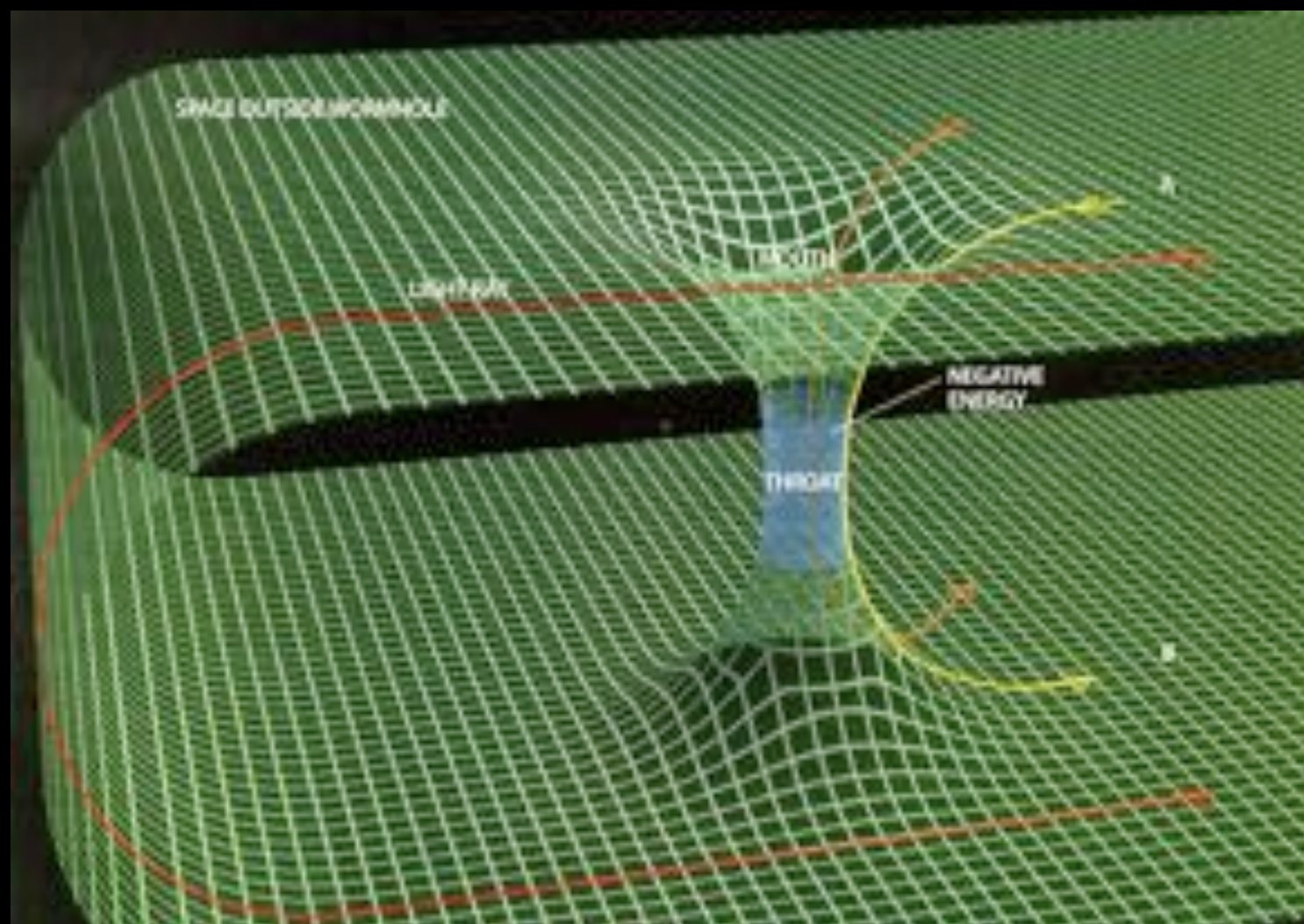




# Spaghettification!



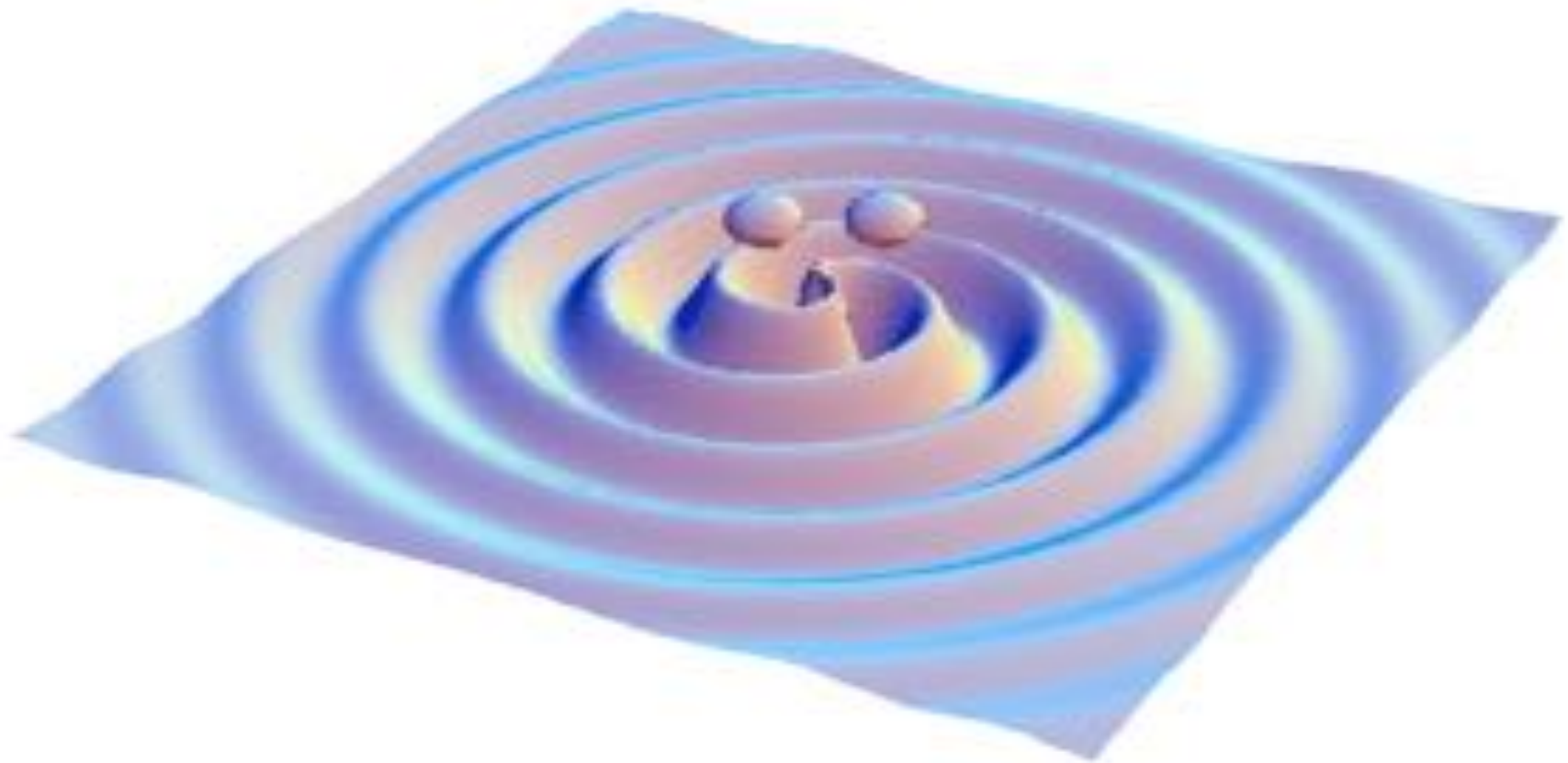
To Black Hole



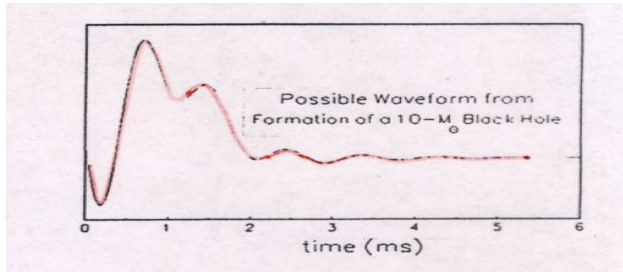
## Life Cycle of a Star



# Gravitational Waves





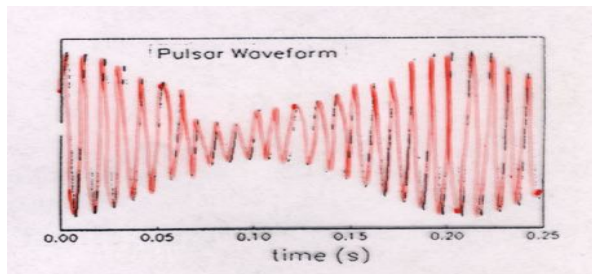


### SUPERNOVAE.

If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

### Information

Inner detailed dynamics of supernova  
See NS and BH being formed  
Nuclear physics at high density

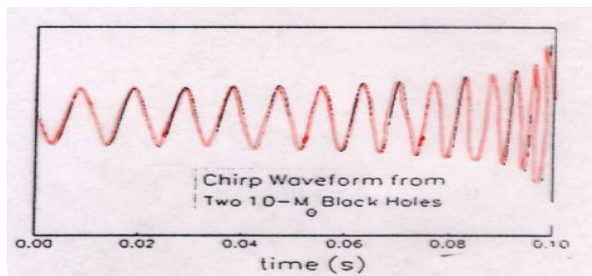


### SPINNING NEUTRON STARS.

Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

### Information

Neutron star locations near the Earth  
Neutron star Physics  
Pulsar evolution

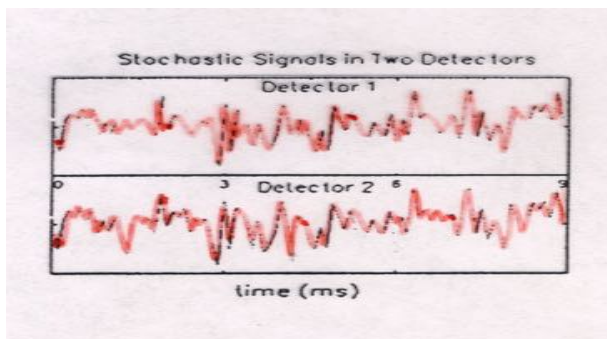


### COALESCING BINARIES.

Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

### Information

Masses of the objects  
BH identification  
Distance to the system  
Hubble constant  
Test of strong-field general relativity



### STOCHASTIC BACKGROUND.

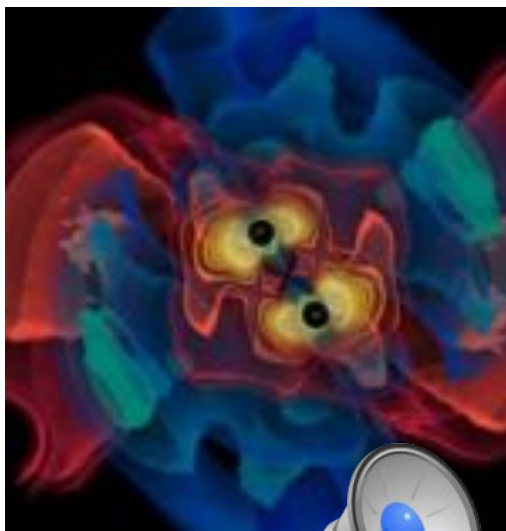
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

### Information

Confirmation of Big Bang, and inflation  
Unique probe to the Planck epoch  
Existence of cosmic strings

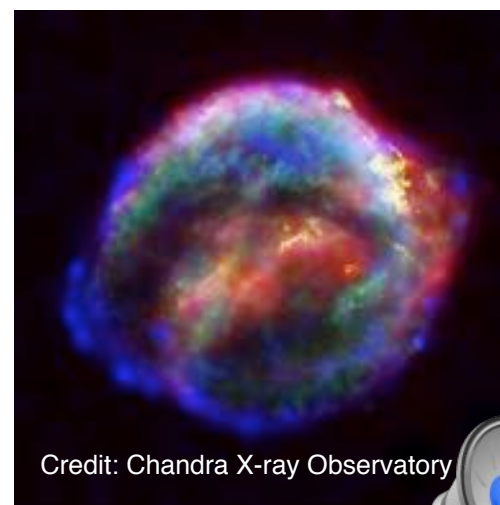


# Astrophysical sources of gravitational waves



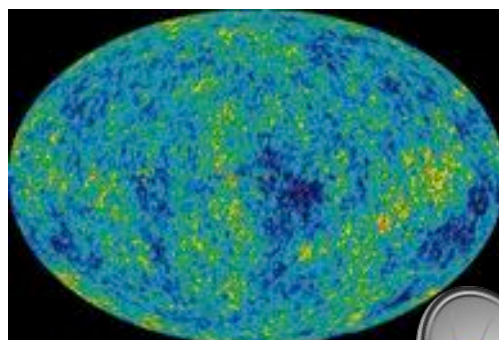
Compact  
Binaries

Credit: AEI, CCT, LSU



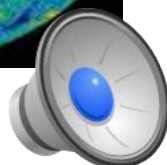
Supernovae

Credit: Chandra X-ray Observatory



Cosmic  
Gravitational-wave  
Background

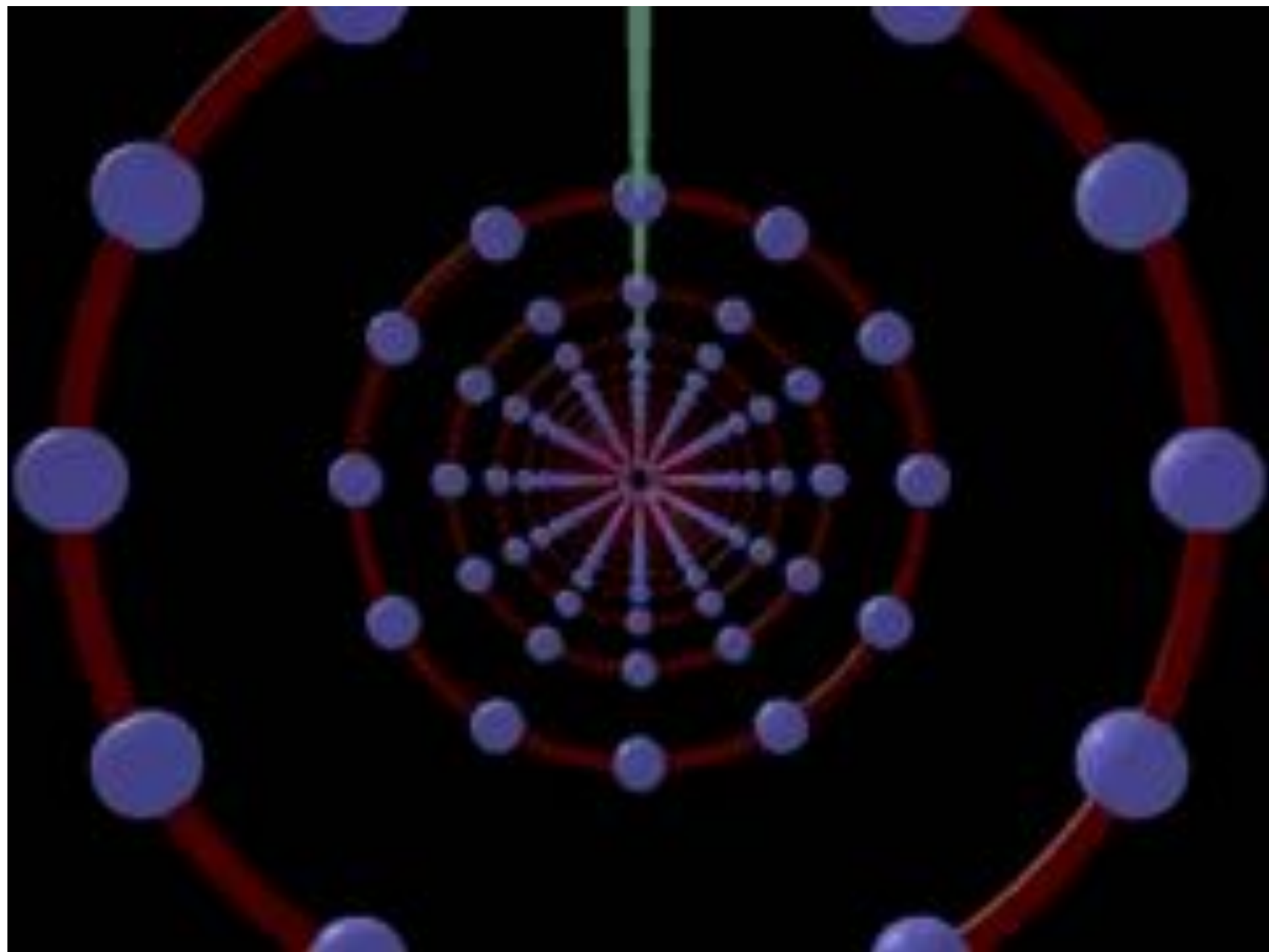
NASA/WMAP Science Team



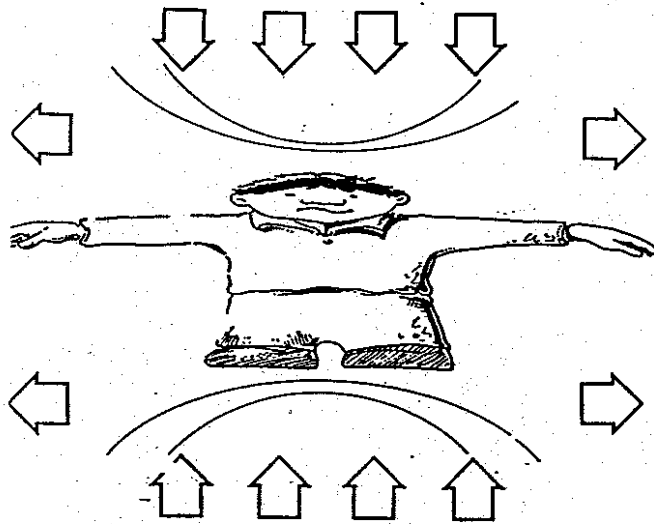
Spinning neutron  
stars

Casey Reed, Penn State



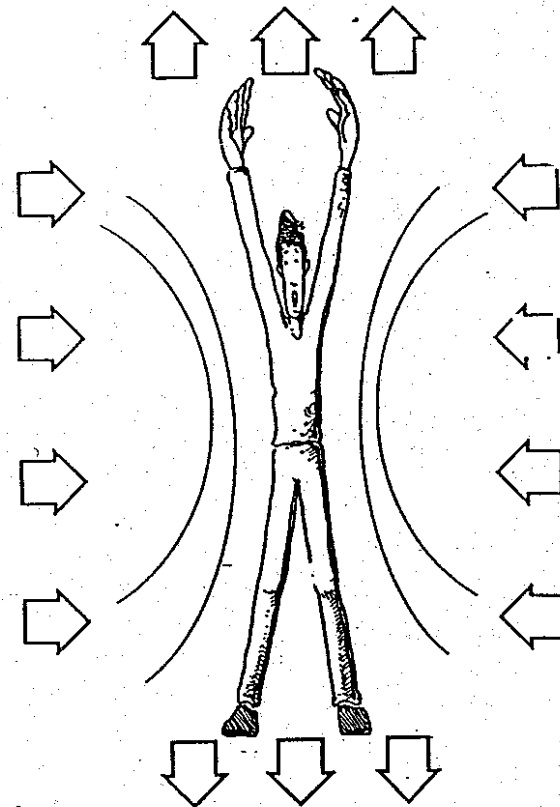


# CAUTION: GRAVITATIONAL RADIATION



MAY BE DANGEROUS  
TO YOUR HEALTH

# CAUTION: GRAVITATIONAL RADIATION



MAY BE DANGEROUS  
TO YOUR HEALTH

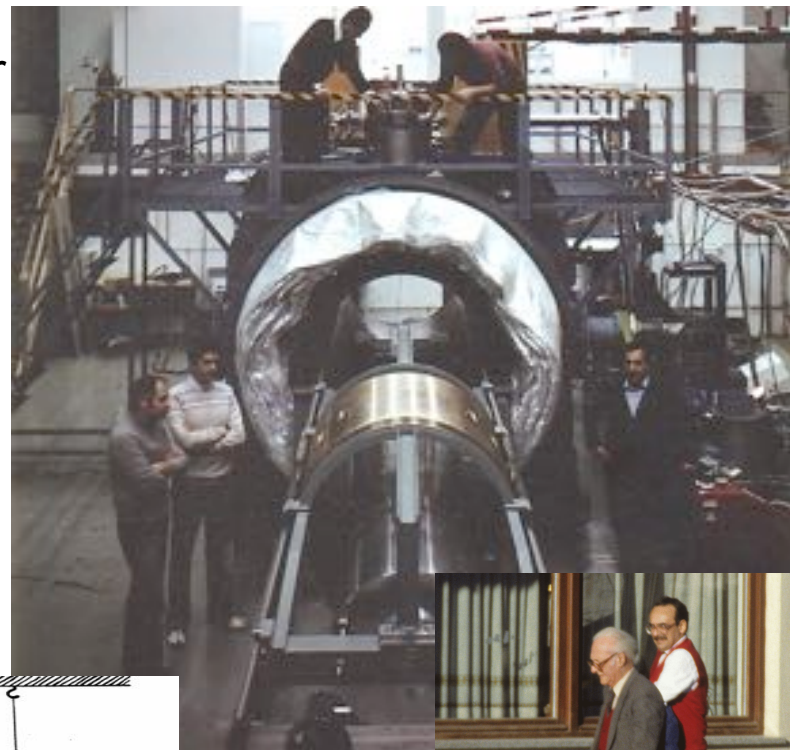
# Weber



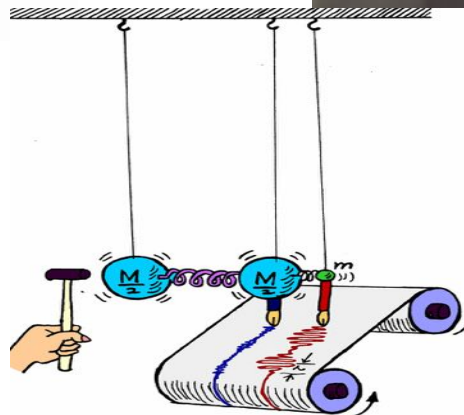




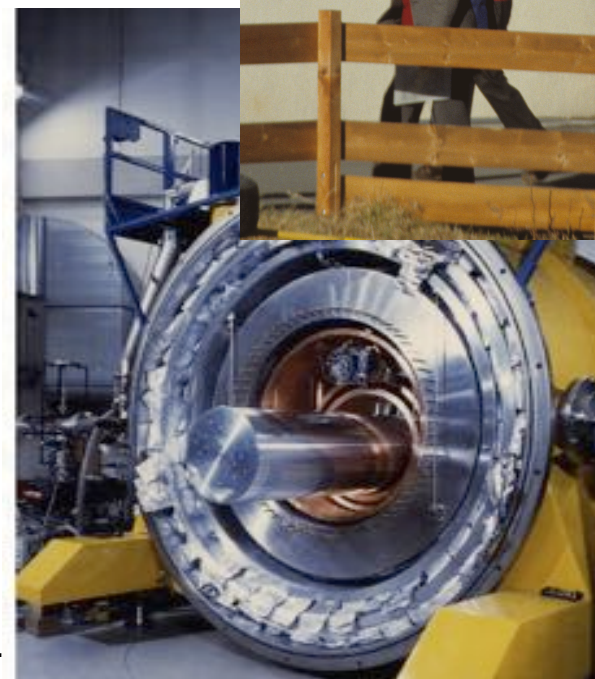
Explorer  
CERN



Nautilus, LNF



Auriga, LNL







**Roma 1988**

## Some perspective: 50 years of attempts at detection:

Since the pioneering work of Joseph Weber in the '60, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:



60': Joe Weber pioneering work



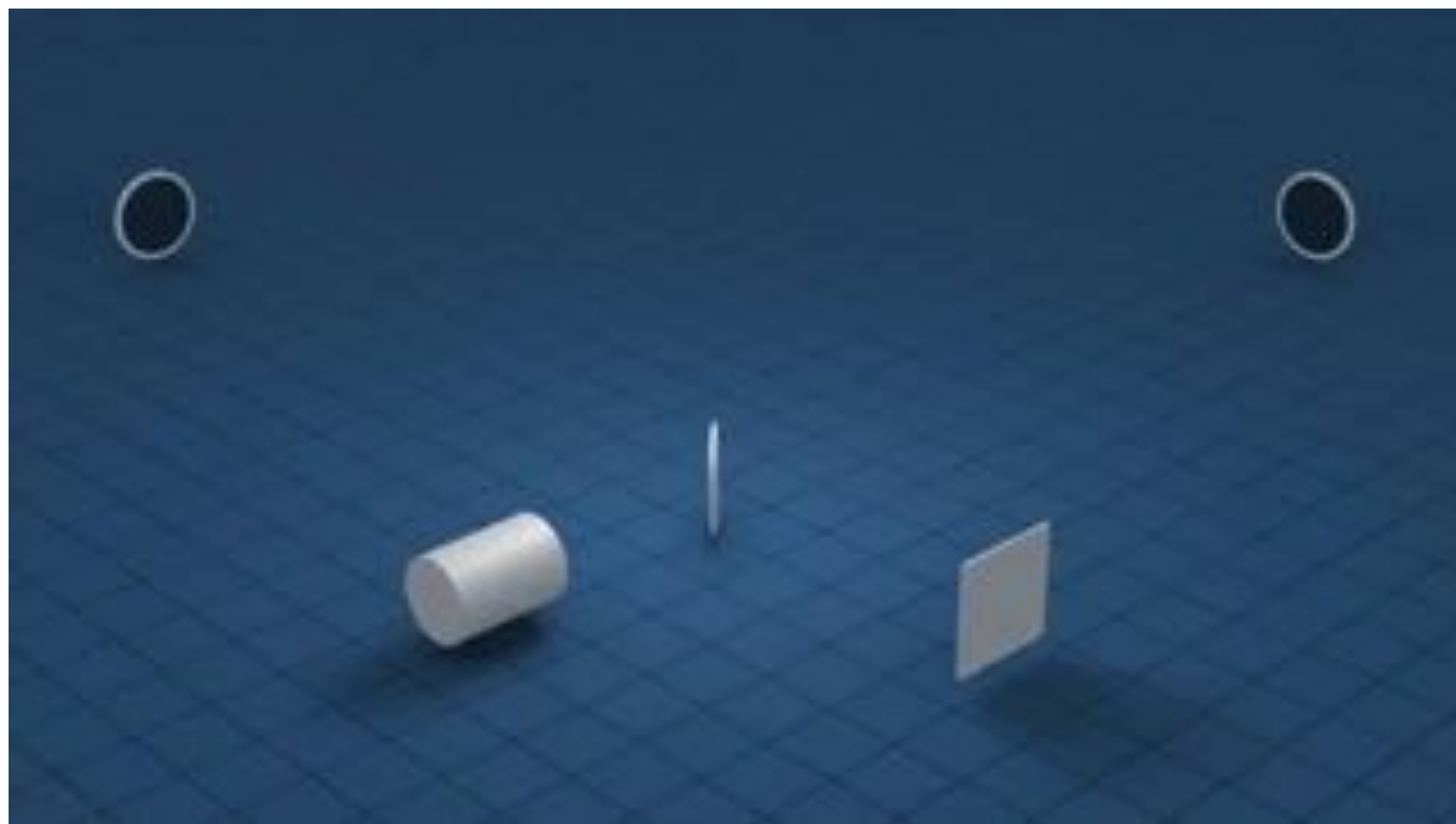
90': Cryogenic Bars

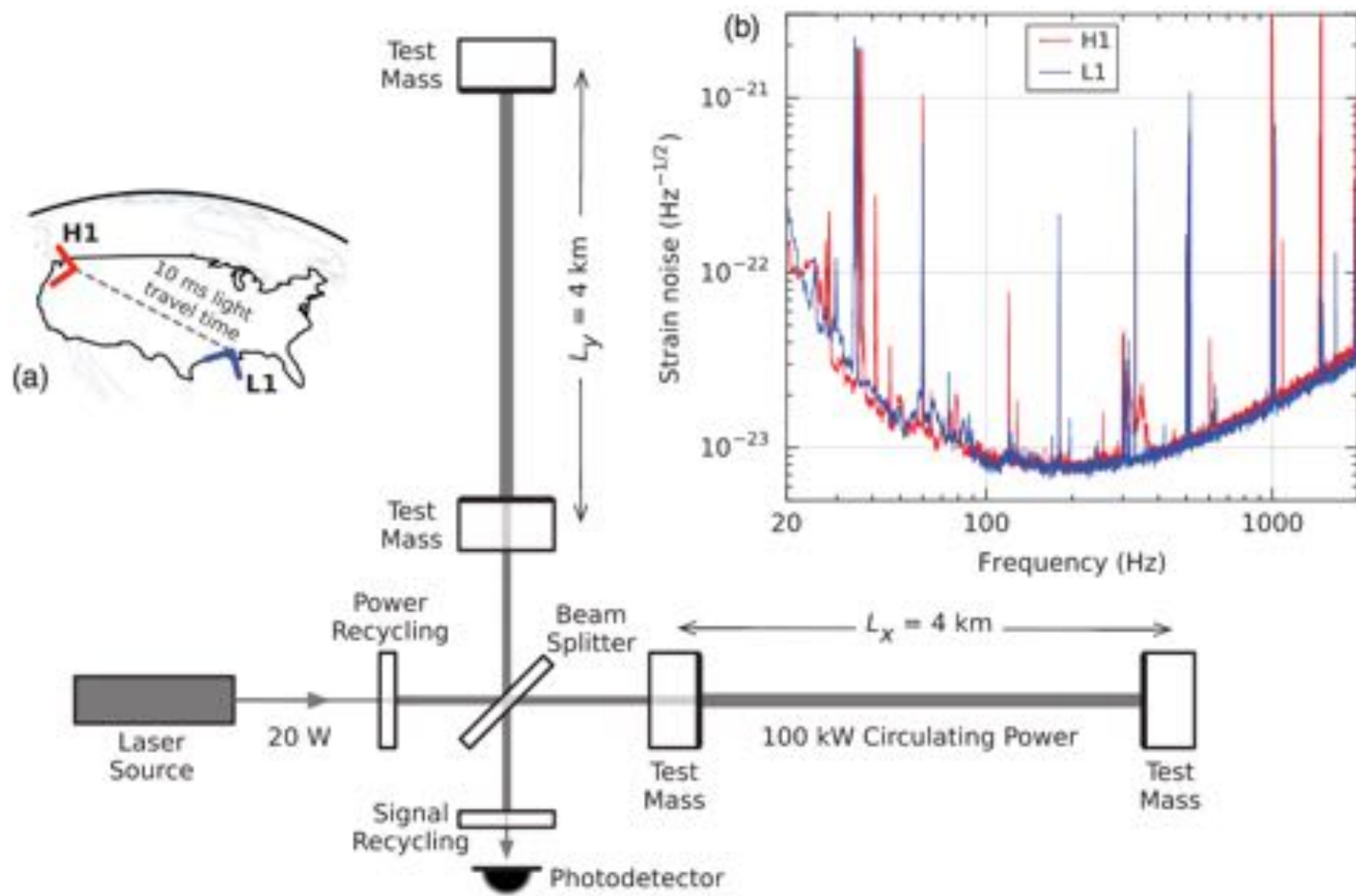


1997: GWIC was formed



2000' - : Large Interferometers









- 5 European countries, 19 labs, ~250 members
- Scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary



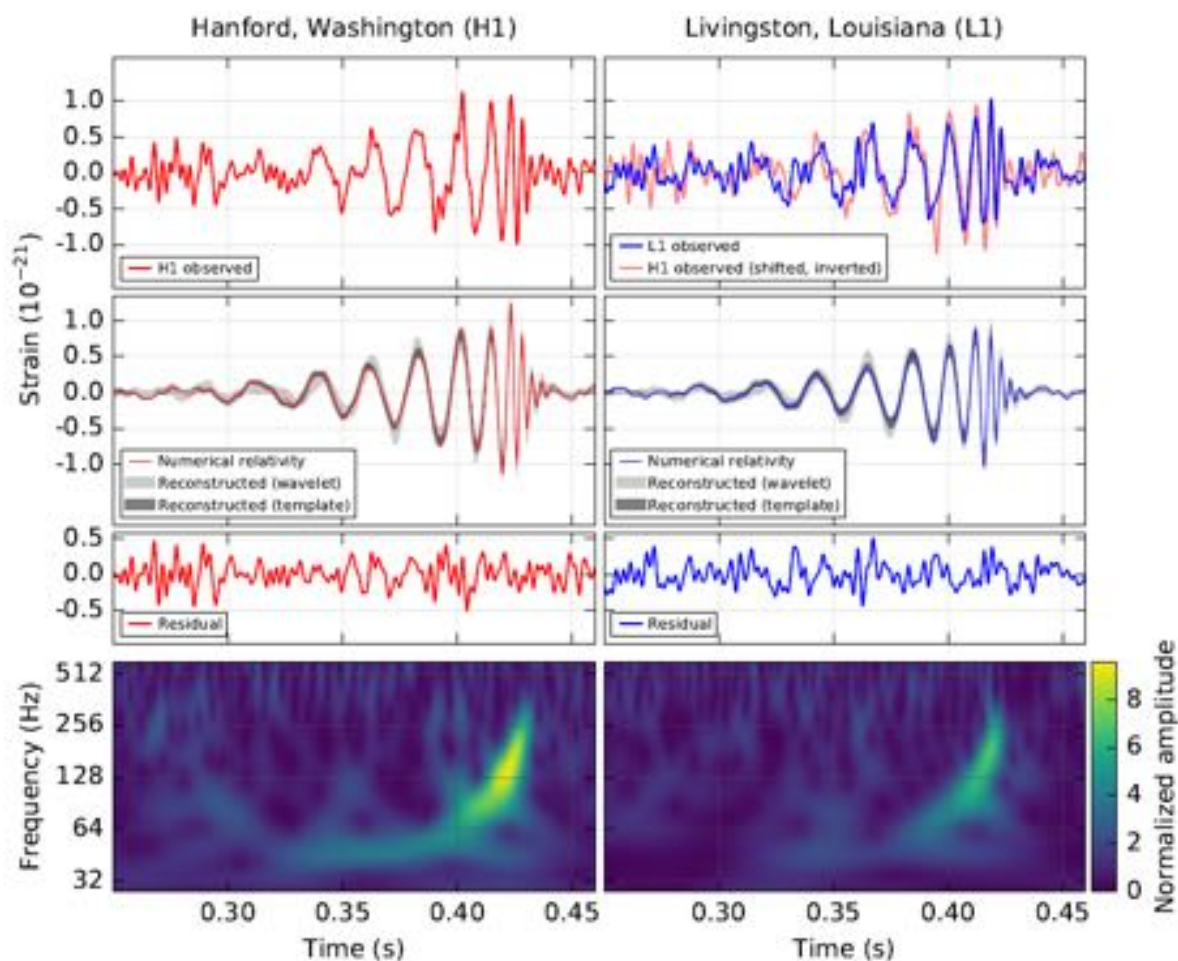
APC Paris  
ARTEMIS Nice  
EGO Cascina  
INFN Firenze-Urbino  
INFN Genova  
INFN Napoli  
INFN Perugia  
INFN Pisa  
INFN Roma La Sapienza  
INFN Roma Tor Vergata  
INFN Trento-Padova  
LAL Orsay – ESPCI Paris  
LAPP Annecy  
LKB Paris  
LMA Lyon  
NIKHEF Amsterdam  
POLGRAW(Poland)  
RADOUD Uni. Nijmegen  
RMKI Budapest



- Top row left – Hanford
- Top row right – Livingston
- Time difference  $\sim 6.9$  ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row –residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)



September 14<sup>th</sup>, 2015 at 09:50:45 UTC

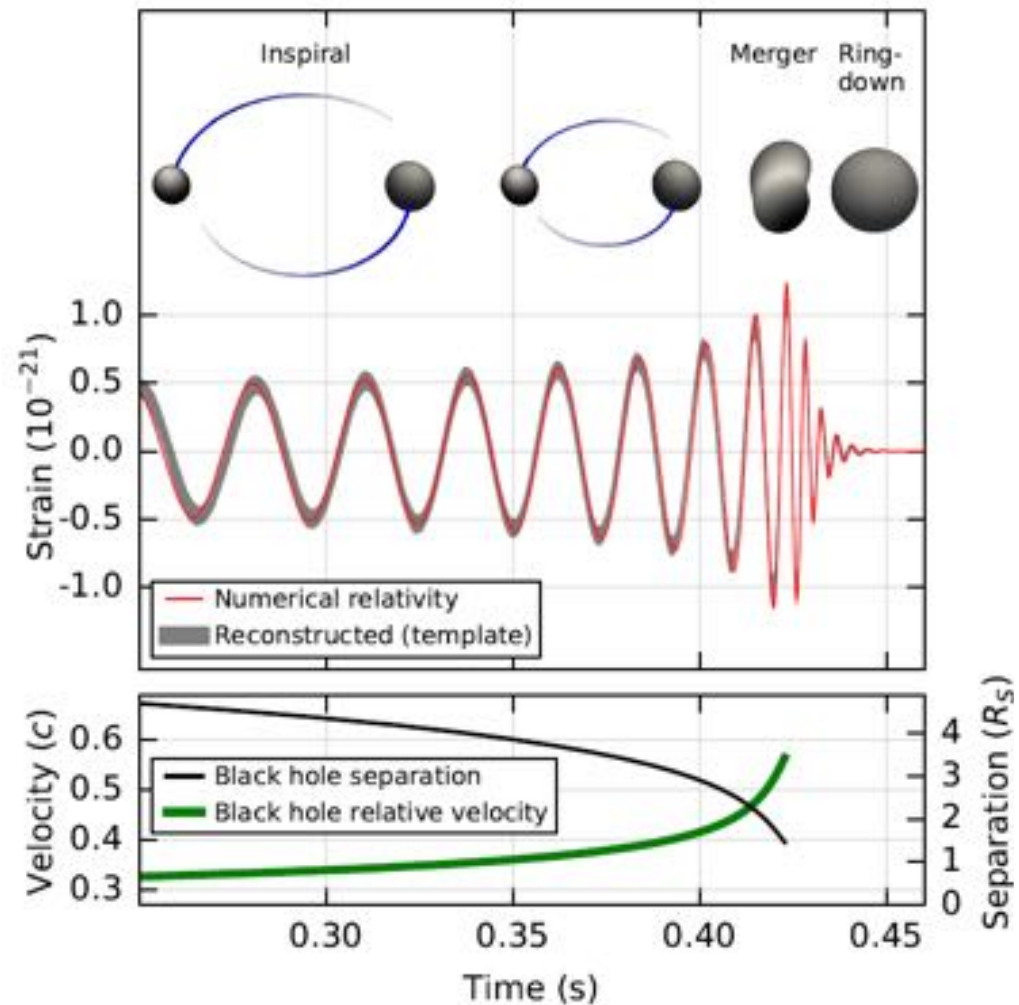


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[ \frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5}$$

- Numerical relativity models of black hole horizons during coalescence
- Effective black hole separation in units of Schwarzschild radius ( $R_s = 2GM_{\text{tot}}/c^2 = 210\text{km}$ ); and effective relative velocities given by post-Newtonian parameter  $v/c = (GM_{\text{tot}}\pi f_{\text{GW}}/c^3)^{1/3}$

## Binary Black Hole System

- $M_1 = 36 \pm 5 \text{ } M_{\text{sol}}$
- $M_2 = 29 \pm 4 \text{ } M_{\text{sol}}$
- Final Mass =  $62 \pm 4 \text{ } M_{\text{sol}}$
- distance =  $410 \pm 160 \text{ } \text{MPc}$  (redshift  $z = 0.09$ )



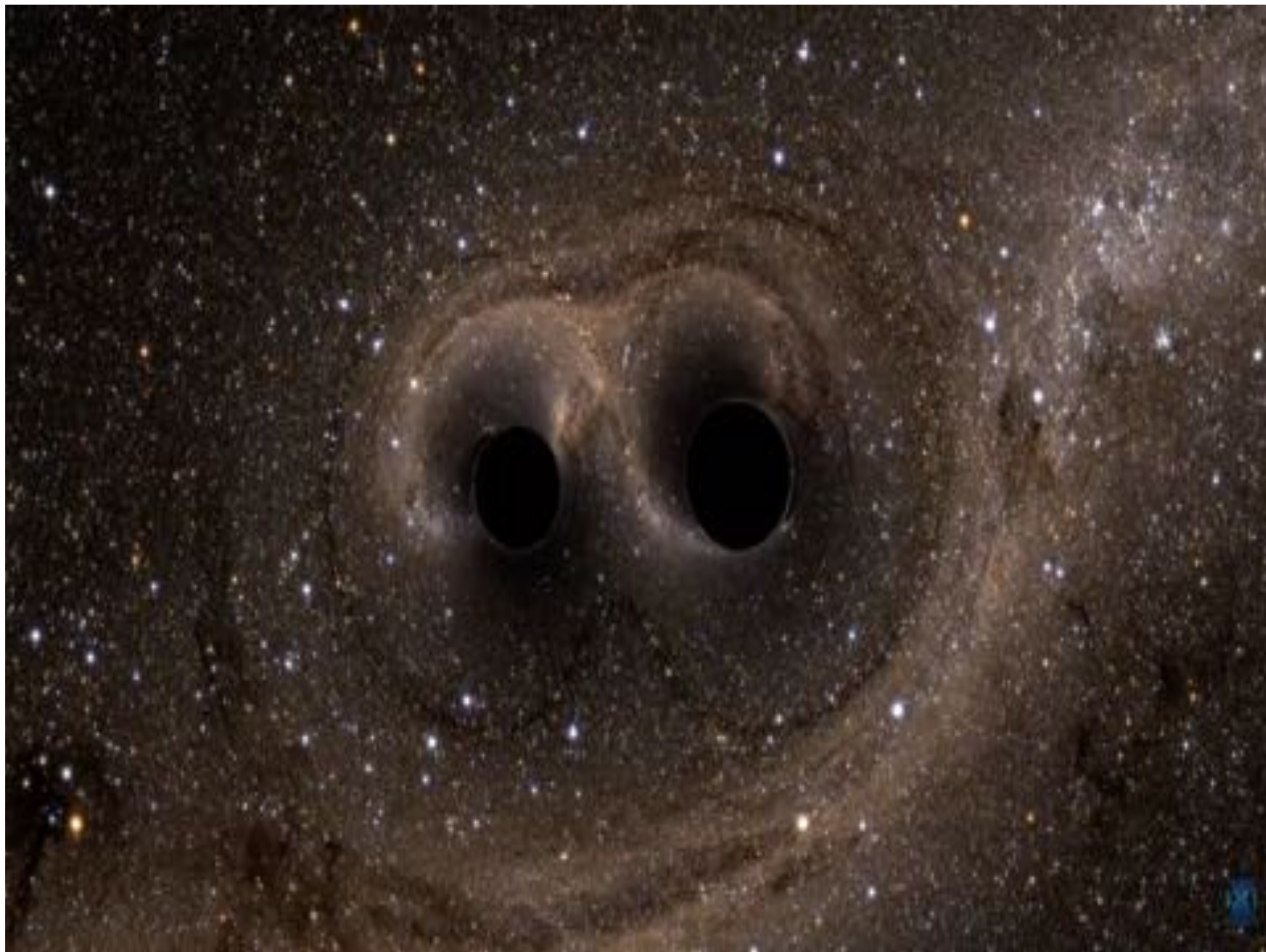


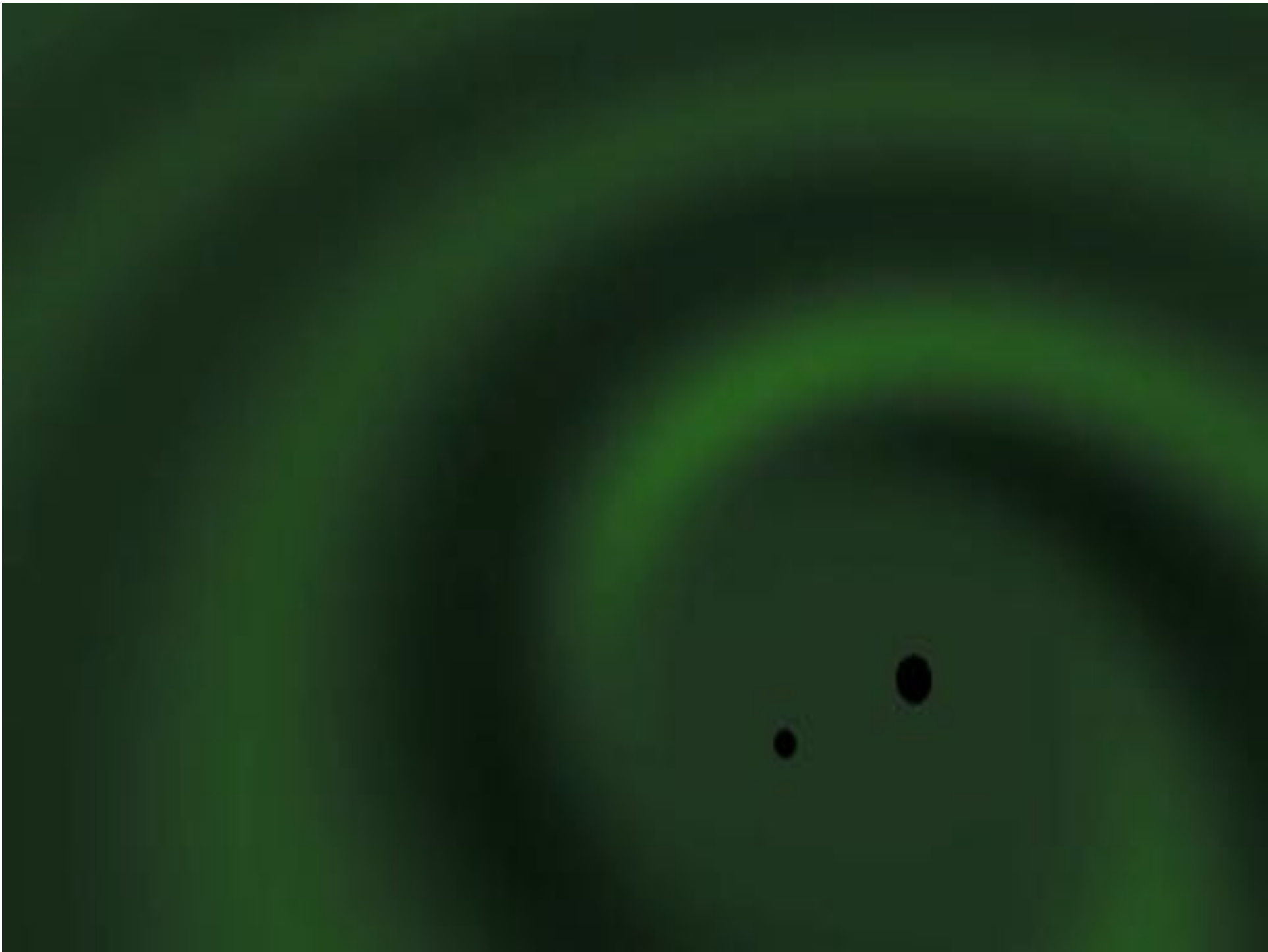
# Observing Scenario, focus on NS-NS Binaries

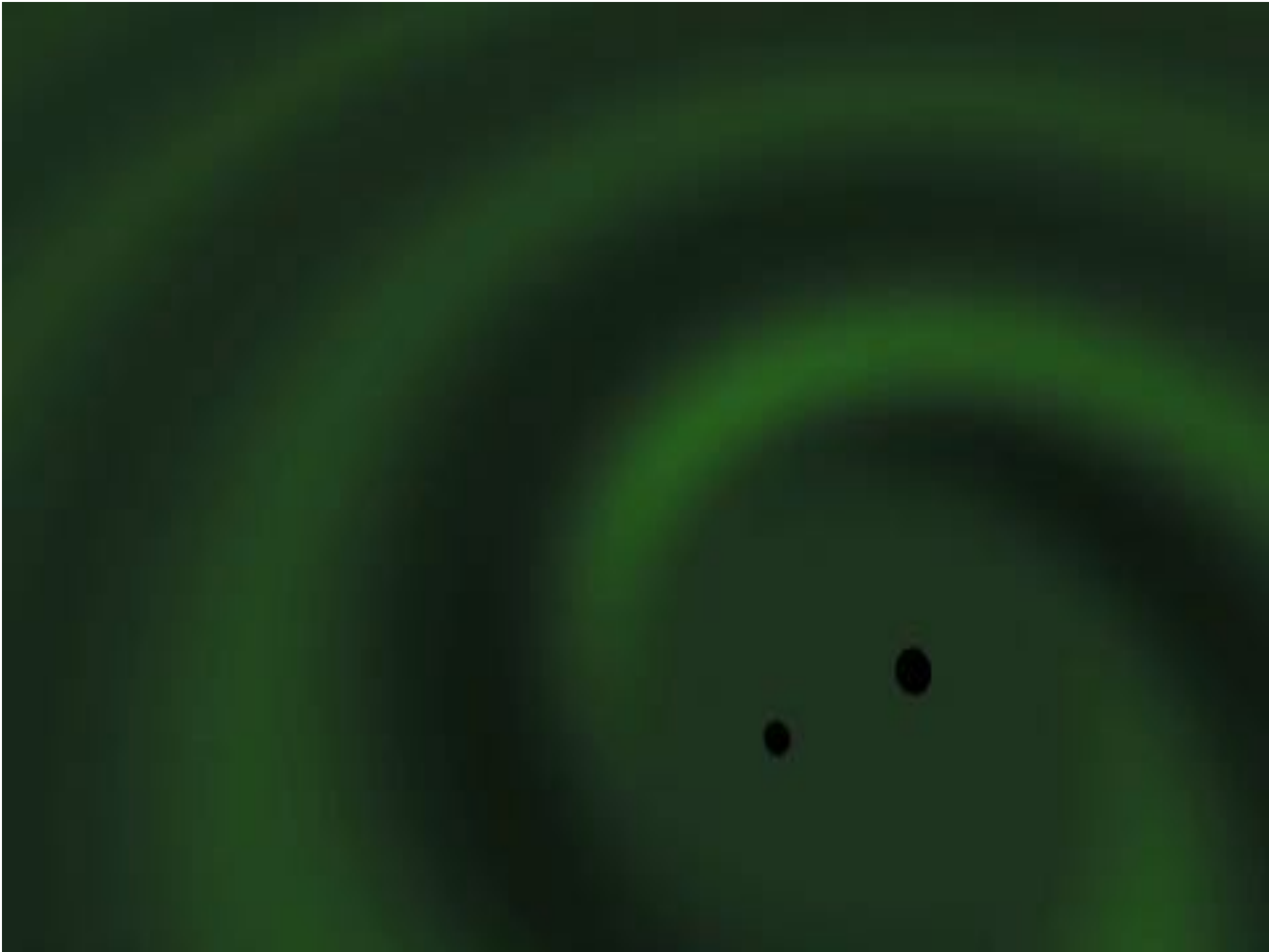
<http://arxiv.org/abs/1304.0670>











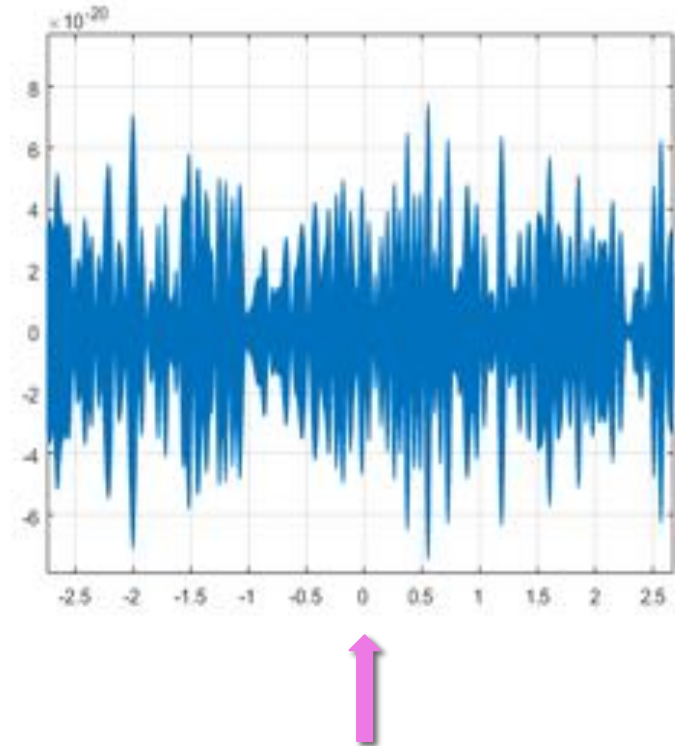
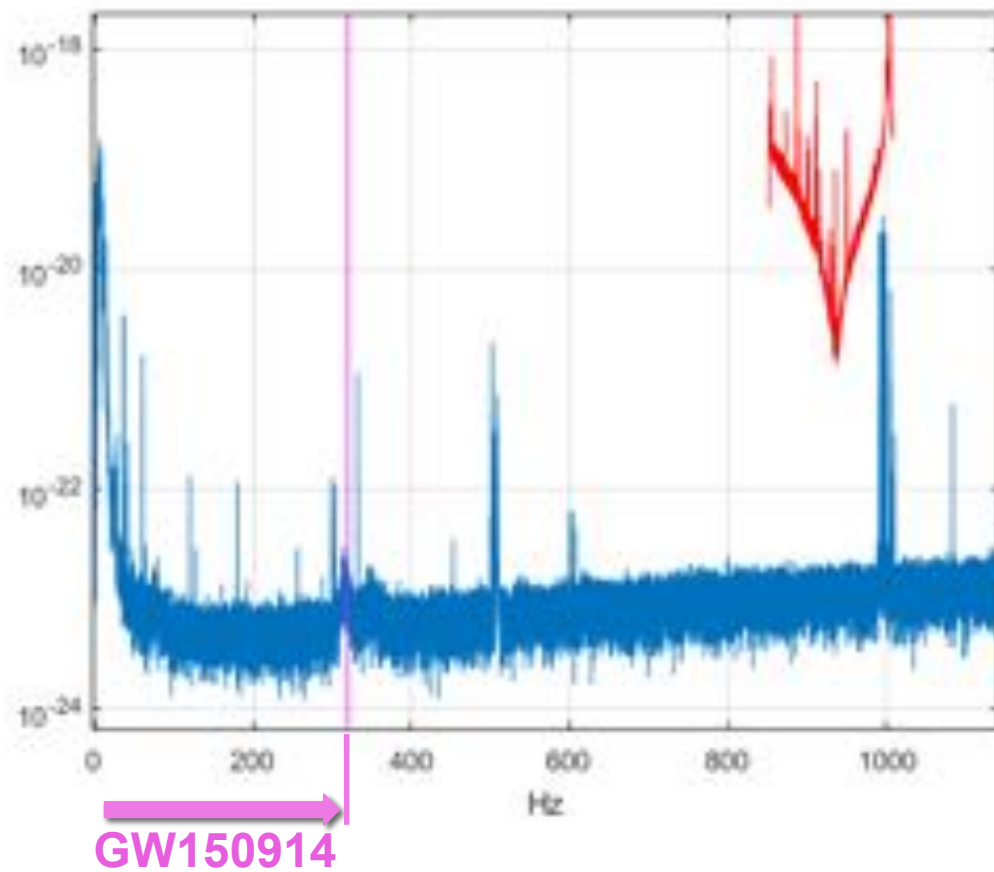


Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is  $3.0 \pm 0.5 M_{\odot} c^2$ . The system reached a peak  $\sim 3.6 \times 10^{56}$  erg, and the spin of the final black hole  $< 0.7$

|                           |                                 |
|---------------------------|---------------------------------|
| Primary black hole mass   | $36^{+5}_{-4} M_{\odot}$        |
| Secondary black hole mass | $29^{+4}_{-4} M_{\odot}$        |
| Final black hole mass     | $62^{+4}_{-4} M_{\odot}$        |
| Final black hole spin     | $0.67^{+0.05}_{-0.07}$          |
| Luminosity distance       | $410^{+160}_{-180} \text{ Mpc}$ |
| Source redshift, $z$      | $0.09^{+0.03}_{-0.04}$          |

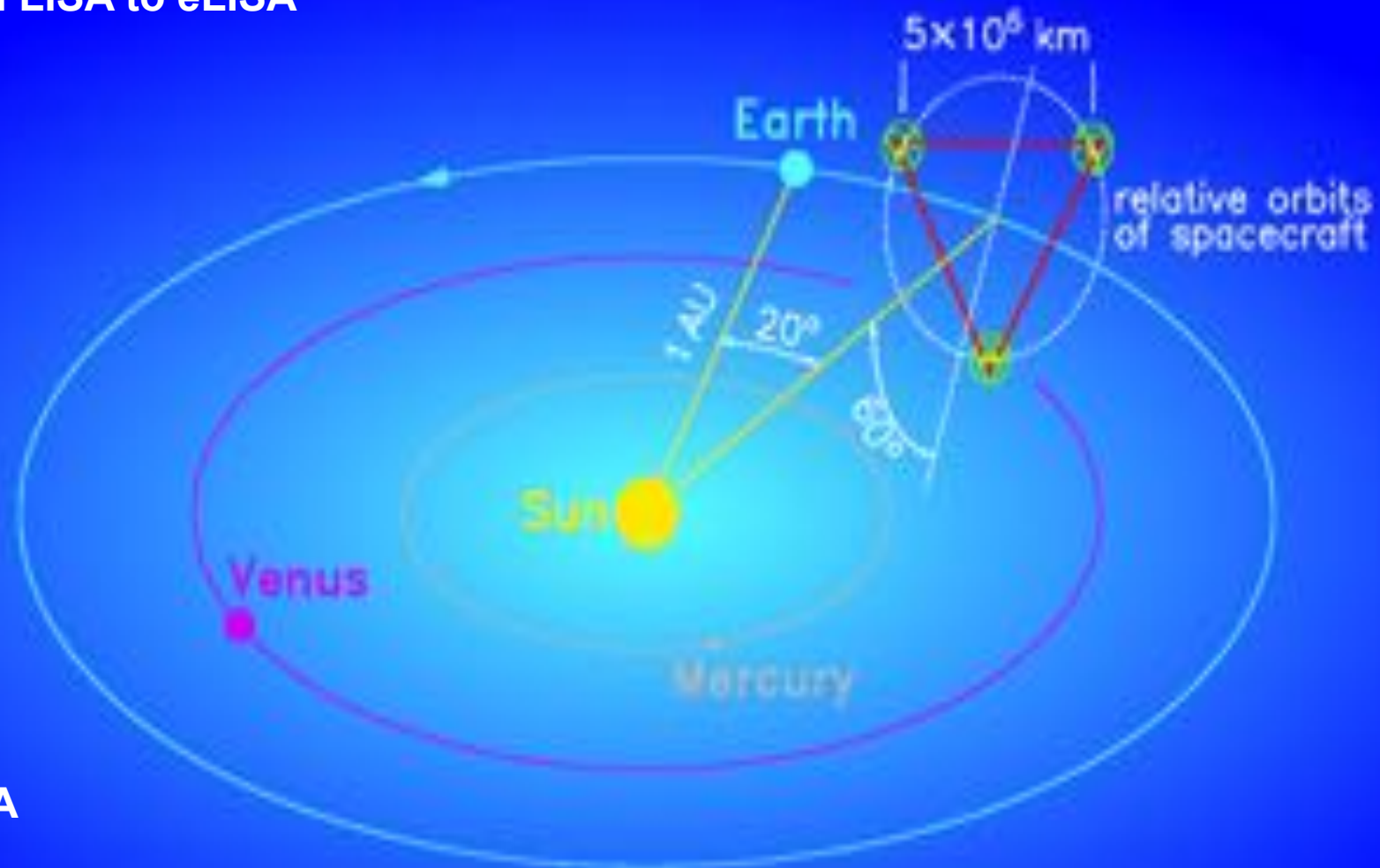


## Nautilus - September 14, 2015



GW150914

## From LISA to eLISA

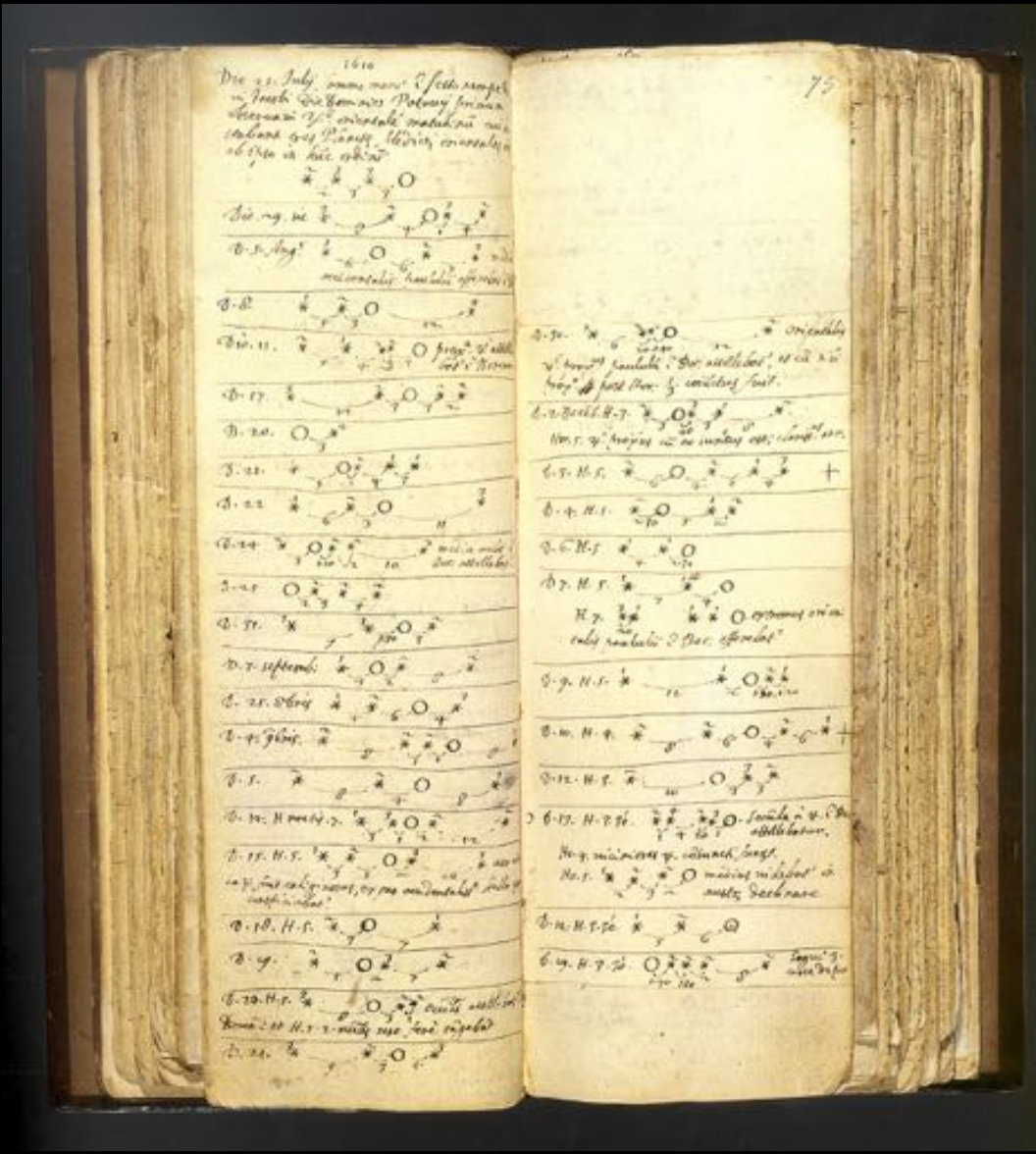


## eLISA

- Savings mainly in weight, launch cost.
- Two active arms, not three;
- Smaller arms (1Gm, not 5Gm);
- Re-use LISA Pathfinder hardware;

2030

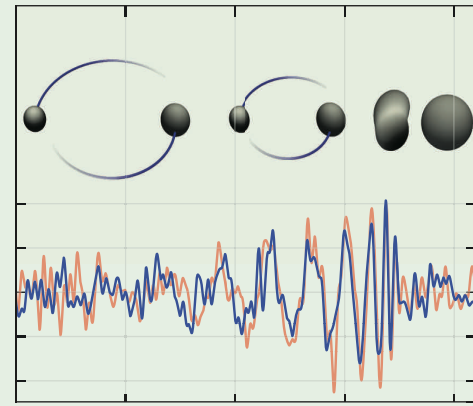




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*Il vero viaggio di scoperta non consiste nel vedere  
nuovi paesaggi ma nell'avere nuovi occhi*

*Marcel Proust*

