Observe!
A gravitational-wave detection board game

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This article describes a board game based on the quest to detect gravitational waves. Two or more players compete to detect the most gravitational waves by hiring scientists and engineers, researching detector technology, and building the most sensitive ground-based interferometric gravitational-wave detector. Players must balance detector upgrades and observing runs so as to maximize their detection potential, and be the first to detect the elusive gravitational wave.

INTRODUCTION

In 1916, Albert Einstein realized that his new theory of General Relativity predicted the existence of waves of gravity that would travel through space at the speed of light []. Since the 1960's, scientists of been trying to detect these waves. They started by building "resonant mass" detectors to see if they could detect these waves of gravity coming from outer space []. By the 1990's, they were building large and sophisticated "laser interferometer" detectors that had much higher sensitivity [] to these waves, and could therefore potentially detect waves coming from much farther away in the Universe.

Gravitational waves could be emitted by some of the most energetic and fascinating events in the Universe. Stars exploding or black holes colliding all potentially produce gravitational waves that could be detected by these new interferometric detectors. If scientists can detect these waves, there are so many new and exciting things that can be learned about the Universe.

GAME DESCRIPTION

In this game, players compete to detect gravitational wave events and collect the most prestige. Each player builds an interferometer detector, hires staff to build and operate the detector, and researches technology to improve detection sensitivity. Each round, players may either improve their detector, or use the detector to observe the Universe, but not both. If a player chooses to observe, a `Universe` card is revealed. If multiple players observe at the same time, the chances of detection increase for everyone, so it's better for everyone to work together. If the player's detector sensitivity is high enough, they may detect the event and earn detection prestige. The player with the most detection prestige at the end of the game wins.

The components of the game are:

- detector tiles
- 1 deck of `Resource` cards
- 1 deck of `Universe` cards
- 1 funding counter per player
- 1 observation chip per player

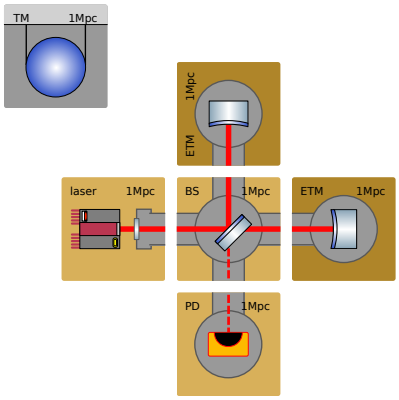


FIG. 1. A "simple Michelson" initial detector configuration, worth 6 Mpc. The brown cards represent the laser and optical components of the detector, while the gray "TM" card represents the first stage in a suspension system for the optics.

- commissioning chips
- prestige chips

The Detector

Each player builds a ground-based interferometric gravitational wave detector [1] made up of individual detector component tiles. The individual detector tiles represent particular components of a detector, such as lasers, mirrors, photodetectors, beam tubes, suspension stages, etc. They are assembled together by placing them adjacent to each other on the table in front of each player. An example of the initial detector can be seen in Fig. 1, and a "complete" detector can be seen in Fig. 2.

The overall sensitivity of a detector is the sum of the "Mpc" value of all individual tiles in a detector. The initial "simple Michelson" detector has a value of 6 Mpc.

There are rules about how the detector is assembled. The restrictions about how individual tiles can be placed is described in the "Detector Tiles" appendix.

Resource cards and the Tableau

The `Resource` deck consist of two types of cards: *personnel* and *detector tech*. `Resource` cards are acquired via funding, either during the Funding phase or when a Scientist or Manager writes a grant during the Assignment phase. See the Phases section for more information.

Each player keeps their `Resource` cards in their hand. When cards are "played", they are placed into the players tableau, i.e. on the table in front of them, below their detector. See the Example Game Play appendix for examples of what a tableau looks like.

`Resource` cards in a players hand (*not* in their tableau) can also be used as cash to pay for personnel salary, research and development, and detector upgrades. Each `Resource` card is worth $1, regardless of type.

Universe cards

The `Universe` deck consists of cards representing gravitational wave events in the Universe. Each card represents a particular type of event at a specific amplitude-normalized distance. The distance to a particular event is given by the "Mpc" value in the upper right corner of the card.

`Universe` cards are revealed during the *detection* phase of the game, when observing players have an opportunity to detect them. Each event has a prestige value that is granted upon detection of the event. See the Observations sections for more information on event detection.

SETUP

Distribute to each player the following:

- 1 Scientist card pulled from the `Resource` deck
- The following detector tiles:
  - 1 laser
  - 1 beam splitter
  - 2 end mirrors
  - 1 photo-detector
  - 1 test mass
- 1 observation chip
- 1 funding counter die

Each player arranges their detector tiles into a "simple Michelson" configuration as shown in Fig. 1. Place the observation chip next to the detector.

The funding counters should be placed in front of each player with six (⚅) facing up.

Shuffle the remaining `Resource` cards and the `Universe` cards and place them in separate face-down stacks in the center of the playing area.

Put the detector tiles, commissioning chips, and prestige points in separate piles in the center of the playing area.

PHASES

Each round consists of five phases: Funding, Hiring, Salary, Assignment, and Resolve. The phases are played in order, each played simultaneously by all players.

1. Funding: receive funding cards

Draw `Resource` cards into hand corresponding to the number currently shown on the funding counter. Once `Resource` cards have been drawn, all players must decrement their funding counter by one. The counter bottoms-out at one (⚀), so each player will have the opportunity to draw at least one funding card during this phase. For instance, if the funding counter shows five (⚄) the player takes five `Resource` cards from the deck, and then turns the counter to show four (⚃).

2. Hiring: hire personnel

Play any number of personnel cards from hand face up into tableau.

Poaching: personnel may be poached from other players. If a player wishes to poach, they must declare a "signing bonus" for the desired personnel. The player holding the desired personnel may opt to either pay the bonus to the bank or release the personnel. If the personnel is released, the poaching player must pay the signing bonus cost, at which point the personnel immediately enters their tableau. The poaching player may not declare a signing bonus larger than they can afford to pay.

3. Salary: pay personnel

Discard one `Resource` card from hand for each personnel card in tableau. personnel cards in tableau may be discarded in lieu of payment. There must always be at least one Scientist in tableau.

4. Assignment: assign actions to personnel

Each unassigned personnel may be assigned one action. The available actions are:

Grant write: generate additional funding

Take one card from the `Resource` deck and place it face down on personnel.

Only one grant may be submitted per round.

R&D: research new technology

Place one detector tech card from hand onto assigned personnel, pay required research cost and

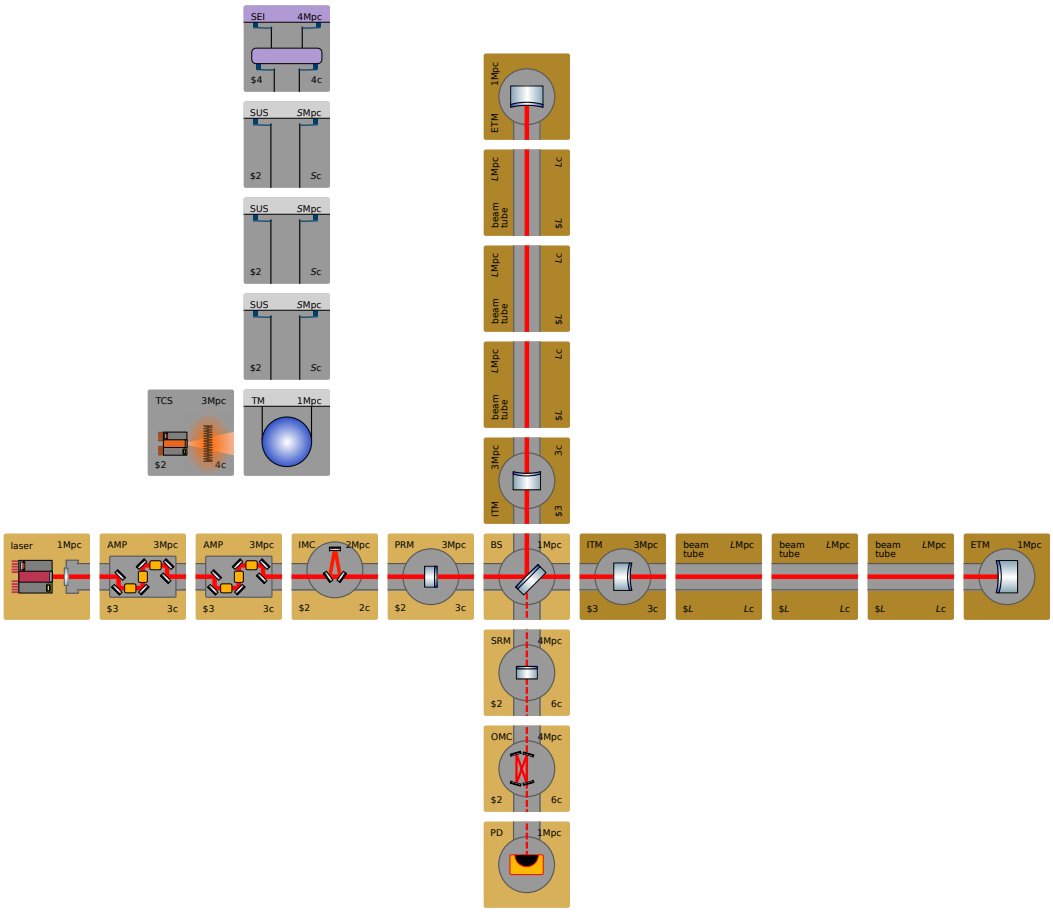


FIG. 2. A "full" detector, composed of at least one of every detector component type.

place specified number of commissioning chips on the new detector tech card.

Note that some personnel are limited in which kinds of technology they can research. For instance, Hardware Engineers can only R&D hardware technology, and Computer Engineers can only R&D computer technology.

Install: add new components to detector

Retrieve desired detector component tile (ones for which the required technology is available), place the new component tile with the specified number of commissioning chips on assigned personnel, and pay component cost from hand.

Multiple components may be installed in the same round, assuming player has enough personnel and can cover the cost. Some personnel may even install multiple components at once, and/or with reduced cost.

If a player does not have the required technology for the desired component, they may use detector tech from another player by paying that player $1 from hand and adding one additional commissioning chip on the tile.

If the observation chip is on the detector, remove it and place it aside.

May not install if there are any un-published detections on the detector.

Commission: commission detector or technology

Remove one commissioning chip from a detector tile or from a detector tech card in tableau and place it on assigned personnel.

If the assigned personnel is capable of removing multiple commissioning chips during a given round, they may do so from different locations (e.g. a Scientist may remove one commissioning chip from two different detector components, or from a detector component and a detector tech card.

Observe!: look for gravitational waves

Place the observation chip O-side up on assigned personnel. If this is the players first observation after an install, reset funding counter to 6 (⚅).

May not observe during the same round as install, or if there are any commissioning chips present on the detector.

Analyze/Publish: extract detections from detector

Retrieve one or more detection prestige from the detector onto assigned personnel, add one additional prestige to the retrieved stack, and reset funding counter to 6 (⚅).

Multiple detection prestige may be published either individually or as a group. However, only one additional prestige is added per published stack. So for instance, if the detector currently holds three detection prestige, all three prestige can be published together, for a total of four prestige after publication. Alternatively, they can be broken up into two or three different publications each receiving one additional prestige, for a total of either five or six prestige after they're all published. Each individual publication is its own action, though, so publishing the stack as three separate publications would require the use of three Analyze/Publish actions.

5. Resolve: resolve all assignments and reveal `Universe` cards

Clear personnel of any actions items they have collected:

- Collect `Resource` cards from grant writers.
- Move new detector tech cards from R&D into tableau.
- Move new detector component tiles with their commissioning chips into the appropriate place in the detector (see Fig. 2 for appropriate tile placement).
- Discard commissioned commissioning chips from commissioners.
- Move the observation chip onto detector and observe. See section .
- Move analyzed detection prestige into prestige pile.

If at the end of the Resolve phase any player has more than 10 cards in their hand, they must discard down to 10.

OBSERVATIONS

Whenever one or more player observes during a round , `Universe` cards are revealed and each observing player determines if they have made a detection. One `Universe` card is revealed for each observing player, and all players may observe all revealed cards.

Before `Universe` cards are revealed, each player calculates their detector sensitivity. Detector sensitivity is determined by adding the "Mpc" ("mega-parsec") values of each tile in a players detector. The Mpc value is indicated in the upper right corner of the tile. The final value for detector sensitivity is a number in units of Mpc.

Each observing player compares their detector sensitivity in Mpc to the Mpc distance on each of the revealed `Universe` cards. If detector sensitivity is greater than or equal to the event distance then the player makes a detection. A players detector techcards may modify the detectability of certain events, by e.g. reducing their effective distance.

Each event includes a prestige value. If a player detects an event, they receive prestige equal to that event's prestige value. If multiple players detect the event, each player receives the specified detection prestige. The first detection of the game is worth twice the prestige.

Place the detection prestige on the detector. To remove the prestige chips from the detector you must use the Analyse/Publish action (see). *New detector components can not be installed in the detector until all prestige have been removed from the detector.*

Advanced Automation - If any of the observing players has a fully commissioned Advanced Automation detector tech card in their tableau, and additional event is revealed after all other events have been revealed. Only players who have Advanced Automation may observe this event. Detection of this event work the same as other events.

GAME RESOLUTION

The game end is initiated when an event of distance 100 Mpc or more is detected by an observing player. Once such an event is detected, one more round is played, after which all players tally their prestige. Each prestige chip is worth one point. The player with the most prestige wins the game.

CREDITS

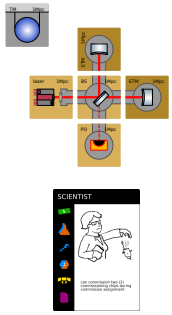
Many thanks to the following people for helping play test the game, and for providing invaluable feedback and suggestions for improvement: Rebecca Bureau, Darly Chou, Simone Chou, Dawn Garcia, Daniel Kahn Gillmor, Christine Halvorson, Arthur Jones, John Kusakabe, Ken Macy, Kerry McLaughlin, Larry Price, Nicolas Smith. Particular thanks goes to Ken Macy for his wonderful personnel drawings.

[1] LIGO Scientific Collaboration, Classical and Quantum Gravity **32**, 074001 (2015).

APPENDIX: EXAMPLE GAME PLAY

The following figures show game play for one player during the first three rounds of a game. In the upper half of each figure is the players detector, below which is the players tableau consisting of their personnel and technology Resource cards.

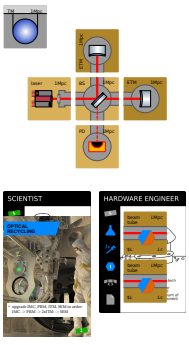
GAME START



At the beginning of the game, the player has one Scientist and a Simple Michelson detector configuration.

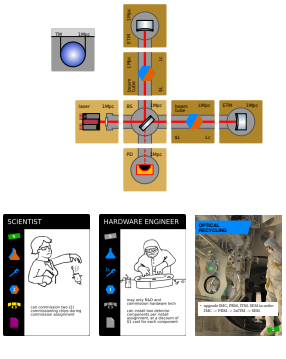
ROUND ONE

Assignment



During the Hiring phase of the first round, the player hires a Hardware Engineer. They then assign their Scientist to R&D Optical Recycling at a cost of $2, and their Hardware Engineer to Install two beam tubes at a cost of $0/1c each (including Hardware Engineer discounts). The beam tube commissioning chips are placed on the new beam tube tiles.

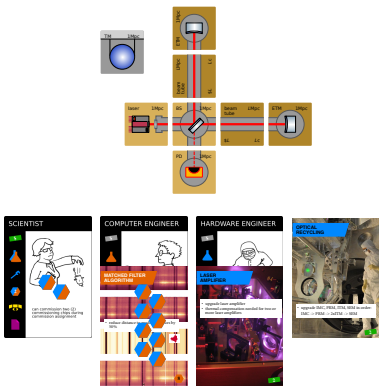
Resolve



During the Resolve phase, the newly acquired Optical Recycling technology is moved into their tableau, and the newly installed beam tubes are moved into the appropriate place in the detector, retaining their commissioning chips.

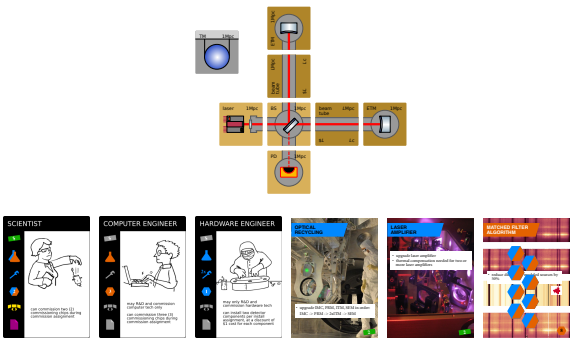
ROUND TWO

Assignment



During Hiring, player hires a Computer Engineer. They then assign the new Computer Engineer to R&D Matched Filter Algorithm, the Hardware Engineer to R&D Laser Amplifier, and the Scientist to commission the two beam tubes installed in Round One.

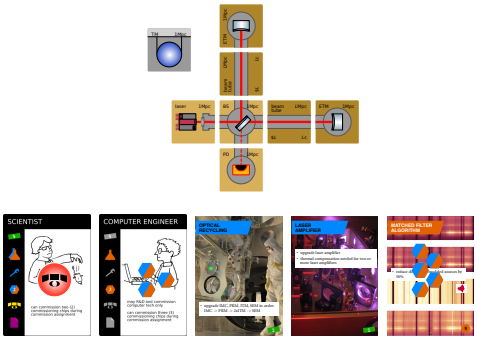
Resolve



The commissioned chips are discarded, and the two new technologies are moved into the tableau. The Matched Filter Algorithm commissioning chips stay on the card, to be commissioned in a later round.

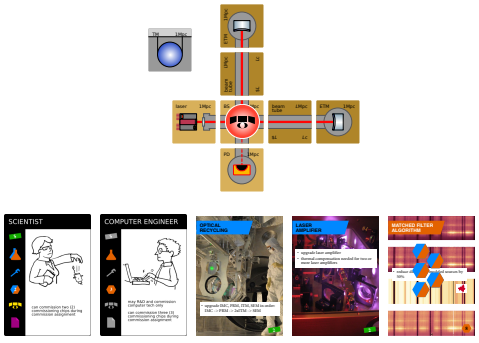
ROUND THREE

Assignment



During Hiring the Hardware Engineer is laid off. The Computer Engineer then commissions three chips from Matched Filter Algorithm, while the Scientist Observes.

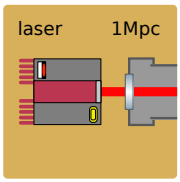
Resolve



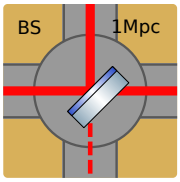
The Observing chip is moved from the Scientist onto the detector.

APPENDIX: DETECTOR TILES

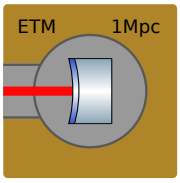
Simple Michelson



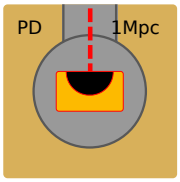
laser



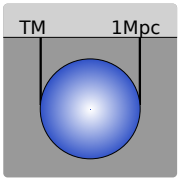
beam splitter (BS)



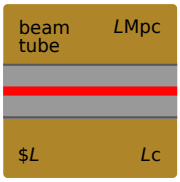
end test mass (ETM)



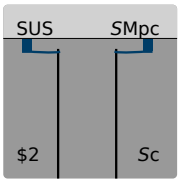
photodetector (PD)



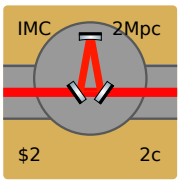
test mass (TM)



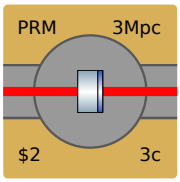
beam tube - Beam tubes are used to increase the length of the arms, thereby making the overall detector more sensitive to gravitational waves. *Beam tubes must be placed "symmetrically" in each arm.* One arm can not be more than one tube longer than the other, and both arms must be the same length in order to Observe. The L in the cost and value refers to the length of the arm when the component is installed. For example, if there are no tubes currently in the arms, then the first tube will create an arm of length one, so the cost of the first tube is \$1/1c. The value of a tube in an $L = 1$ arm is 1 Mpc. If there are two tubes in each arm, then $L = 2$ and the value of each tube is 2 Mpc each, for a total of 4 Mpc for all tubes in both arms.



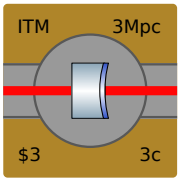
suspension stage (SUS) - Suspension stages reduce the affect of seismic noise on the detector. Suspension stages are stacked one on top of the other to make a suspension tower. S refers to the length of the suspension tower when installed. *May install up to only two suspension stages before an SEI at the top of the suspension tower.*
For example, if there are no stages currently in the suspension tower, then the first SUS will create a suspension tower of height one, so the cost of the first SUS is \$2/1c. The value of a SUS in an $S = 1$ tower is 1 Mpc each. If there are two SUS in the tower, then $S = 2$ and the value of each SUS is 2 Mpc each, for a total of 4 Mpc for the full tower.



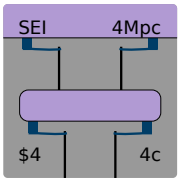
input mode cleaner (IMC) - IMC is the first of the vertex upgrades, and is used to clean the light before it enters the detector. *Requires Optical Recycling hardware tech* in your tableau.



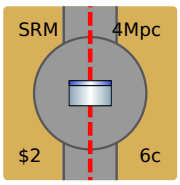
power recycling mirror (PRM) - PRM is the second of the vertex upgrades, and is used to increase the amount of effective laser power in the detector. *Requires IMC installed in the detector.*



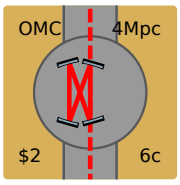
input test mass (ITM) - ITMs is the third (and forth) of the vertex upgrades, and is used to increase the amount of effective laser power in the arms of the detector. *Requires PRM installed in the detector. ITM must be installed symmetrically in both arms (may not observe with only a single ITM).*



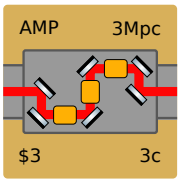
seismic isolation platform (SEI) - SEI decreases the seismic noise and allows for more suspension stages in the suspension tower. One SEI is required in the suspension tower to install more than two SUS.



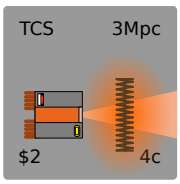
signal recycling mirror (SRM) - SRM is the fifth of the vertex upgrades, and helps extract the gravitational wave signal from the detector. *Requires both ITM installed in the detector.*



output mode cleaner (OMC) - Cleans the light leaving the detector, to decrease some technical noise sources. *Requires Homodyne Readout hardware tech.*



laser amplifier (AMP) - Increases the laser power in the detector, which decreases the *shot noise. To install more than one laser amplifier, TCS is required to also be installed in the suspension tower.*



thermal compensation (TCS) - Compensates for thermal distortions in the optics due to higher laser power. *Requires Thermal Compensation Hardware Tech.*

APPENDIX: DIY GAME

Until proper playing cards and tiles are available, the game can be played with print outs of the following pages and common game pieces or coins.

For the detector tiles, print out the attached tile sheet and cut out the individual square tile. Use one tile sheet per player.

Game pieces can be substituted with common game parts and/or coins:

- funding counters: 6-sided die
- observation chip: quarters
- commissioning chips: pennies
- prestige chips: nickels or dimes

The `Resource` (personnel and detector tech) cards can be printed from the last two card sheets attached. The distribution of cards is roughly fine as is, so the deck can just be made from multiple print outs of the `Resource` card sheets. The more the better, but at least five copies of the two sheets should be sufficient.

The `Universe` deck is tricky. The best distribution of distances of events is still to be determined. Here are some constraints:

- There should be one and only event with a distance detectable by the initial simple Michelson detector (6 Mpc or less).
- The distribution should go up to 200 or so.
- The true distribution of events in the Universe (going as the cube of the distance) is not good for game play. Much better is the square of the distance, or even linear.

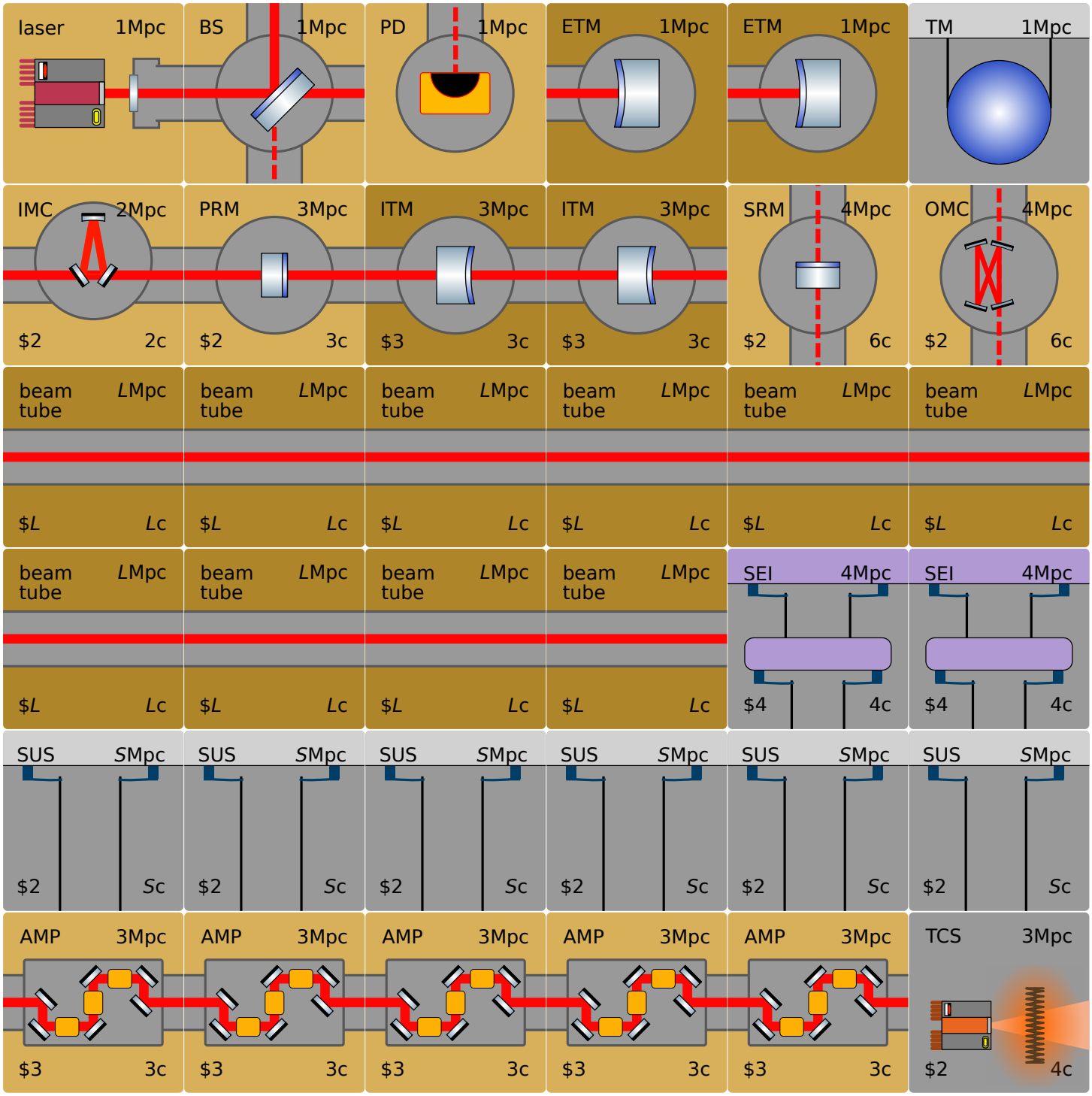
Included with the game source [1] is a script, `universe_distribution.py`, that calculates a `Universe` card distribution for a given number of cards and power law distribution. The table below shows the output of the program for 9 card sheets worth of cards (45 cards) and a linear distribution.

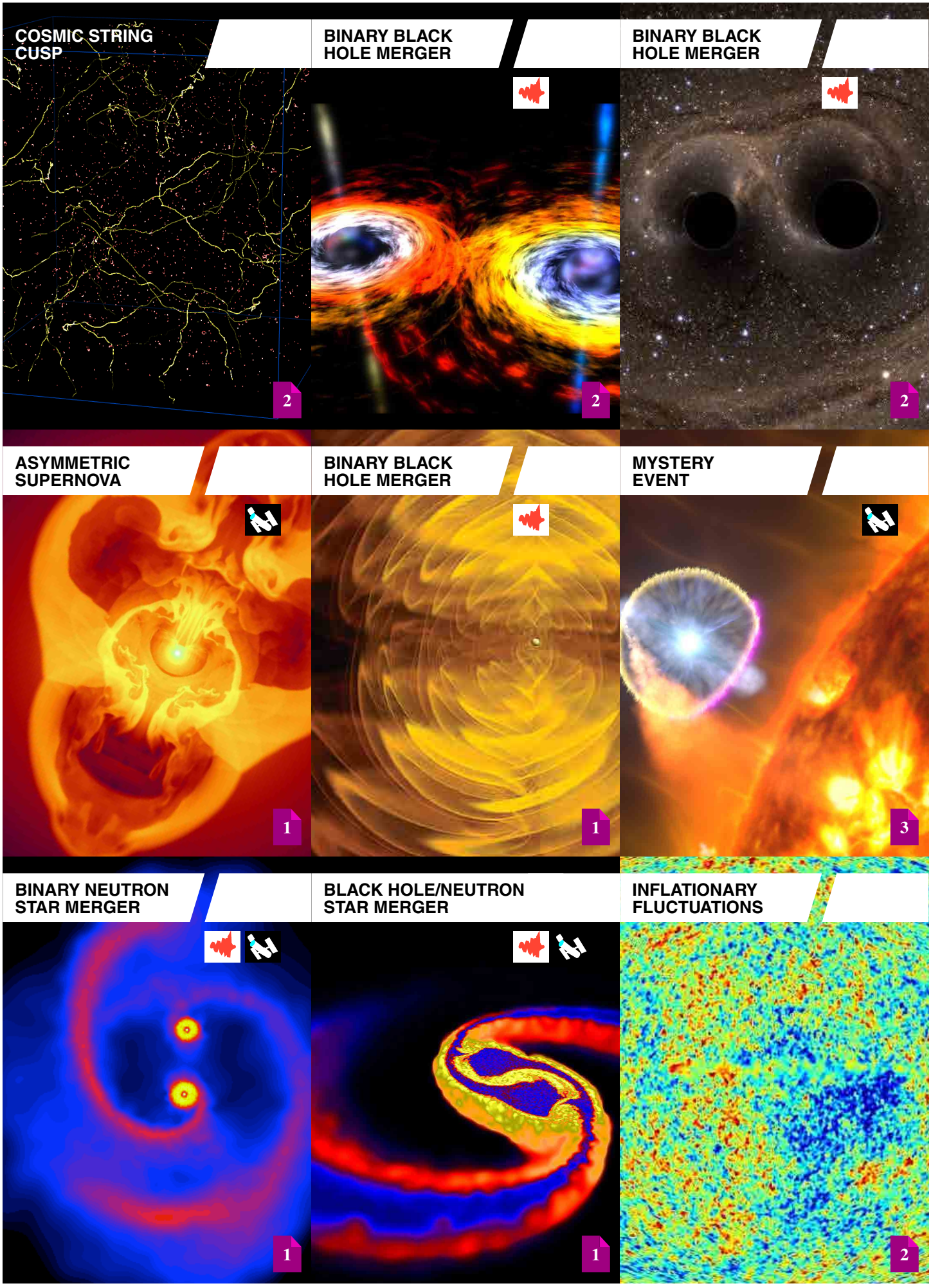
Suggestions for fun distributions are much appreciated!

```
cards: 45
distribution: x**1

Mpc   N      Mpc   N
---  --      ---  --
  4   1      120   2
 16   1      128   2
 24   1      136   3
 32   2      144   4
 48   1      152   1
 72   1      160   2
 88   2      168   1
 96   1      176   3
104   3      192   3
112   5      200   6
```

[1] https://gitlab.org/jrollins/ligo-game


laser 1Mpc
BS 1Mpc
PD 1Mpc
ETM 1Mpc
ETM 1Mpc
TM 1Mpc
IMC 2Mpc
$2 2c
PRM 3Mpc
$2 3c
ITM 3Mpc
$3 3c
ITM 3Mpc
$3 3c
SRM 4Mpc
$2 6c
OMC 4Mpc
$2 6c
beam tube LMpc
$L Lc
SEI 4Mpc
$4 4c
SUS SMpc
$2 Sc
AMP 3Mpc
$3 3c
TCS 3Mpc
$2 4c


COSMIC STRING CUSP
2
BINARY BLACK HOLE MERGER
2
BINARY BLACK HOLE MERGER
2
ASYMMETRIC SUPERNOVA
1
BINARY BLACK HOLE MERGER
1
MYSTERY EVENT
3
BINARY NEUTRON STAR MERGER
1
BLACK HOLE/NEUTRON STAR MERGER
1
INFLATIONARY FLUCTUATIONS
2

MANAGER

- for every two personnel in tableau, take one additional funding during Grant Writing phase
- salary is twice normal

SCIENTIST

- commission two chips per round

OPERATOR

- enable Computer Engineer to install or commission hardware tech
- enable Hardware Engineer to commission computer tech

HARDWARE ENGINEER

- R&D hardware tech only
- commission hardware tech only
- may install two detector components per round
- discount one funding from cost of each detector component

COMPUTER ENGINEER

- R&D computer tech only
- commission computer tech only
- commission three chips from computer tech each round

THE PHASES:

Grant Write: Manager or Scientist

R&D: Engineer or Scientist

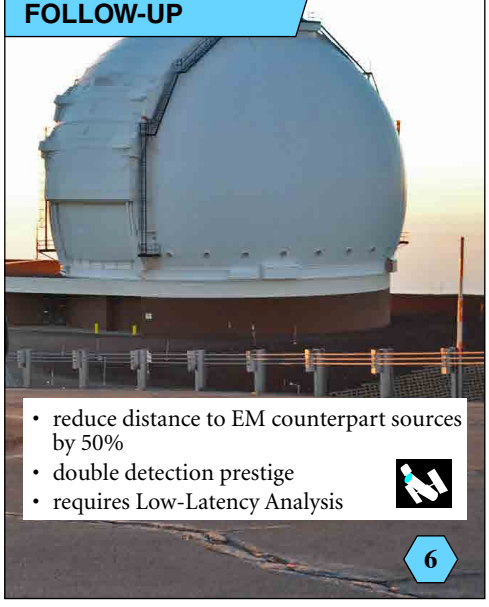
Install: Engineer, Operator, or Scientist

Commission: Engineer, Operator, or Scientist

Observe: Operator or Scientist

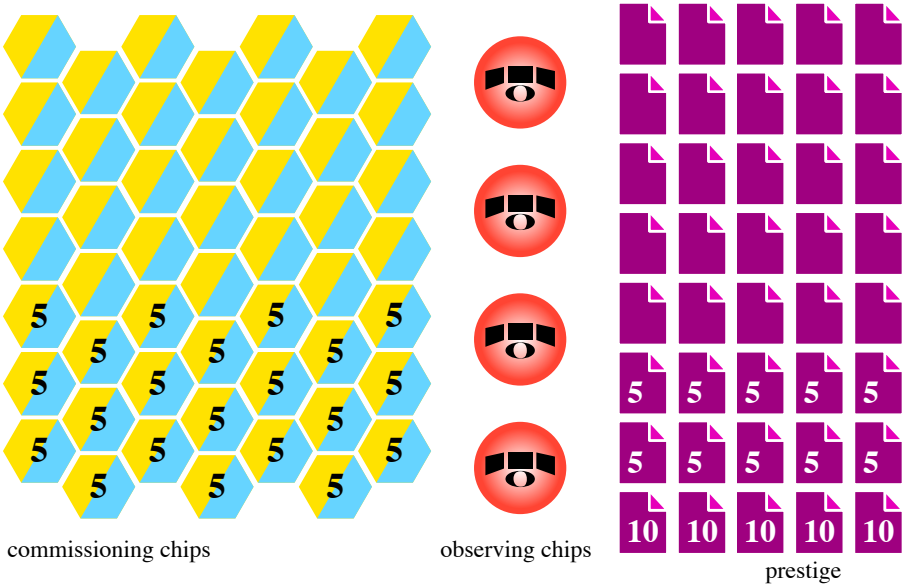
Analyze and Publish: Manager or Scientist

ELECTROMAGNETIC FOLLOW-UP



- reduce distance to EM counterpart sources by 50%
- double detection prestige
- requires Low-Latency Analysis

CHIPS:



OPTICAL RECYCLING

- upgrade IMC, PRM, ITM, SEM in order: IMC -> PRM -> 2xITM -> SEM

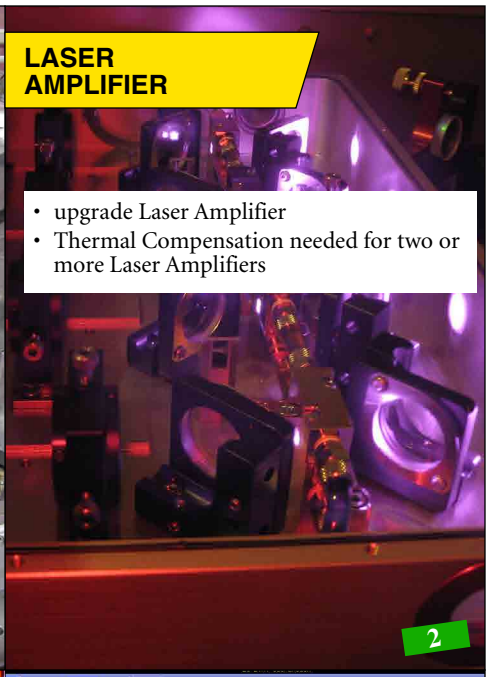
2

ACTIVE SEISMIC ISOLATION

- upgrade SEI
- allows unlimited Suspension Stages

2

LASER AMPLIFIER



- upgrade Laser Amplifier
- Thermal Compensation needed for two or more Laser Amplifiers

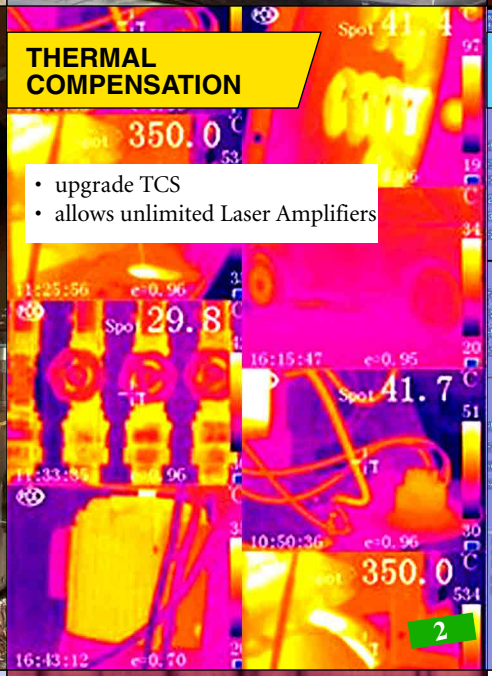
2

HOMODYNE READOUT

- upgrade OMC
- requires Optical Recycling

2

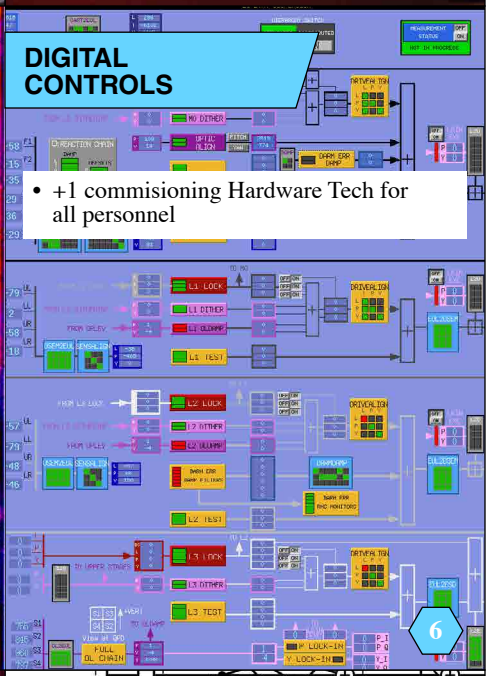
THERMAL COMPENSATION



- upgrade TCS
- allows unlimited Laser Amplifiers

2

DIGITAL CONTROLS



- +1 commisioning Hardware Tech for all personnel

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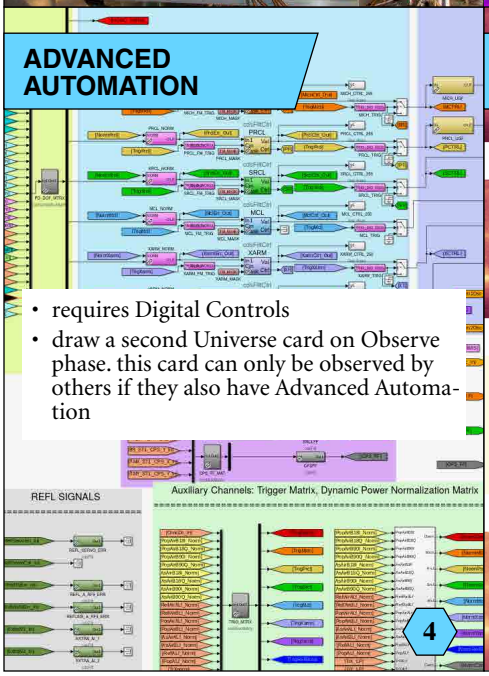
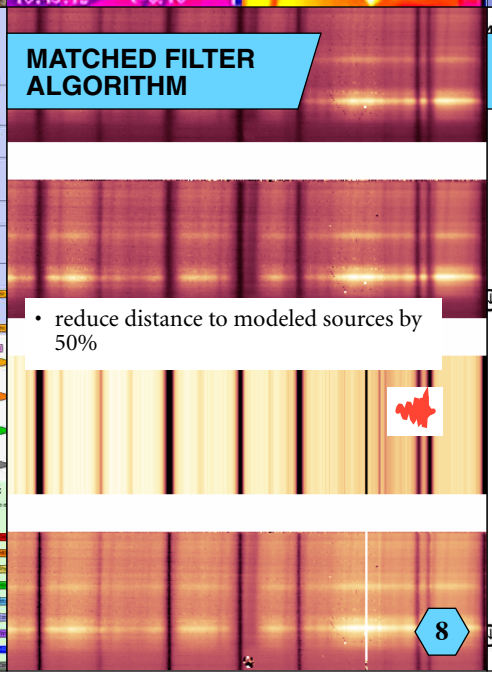
ADVANCED AUTOMATION



- requires Digital Controls
- draw a second Universe card on Observe phase. this card can only be observed by others if they also have Advanced Automation

4

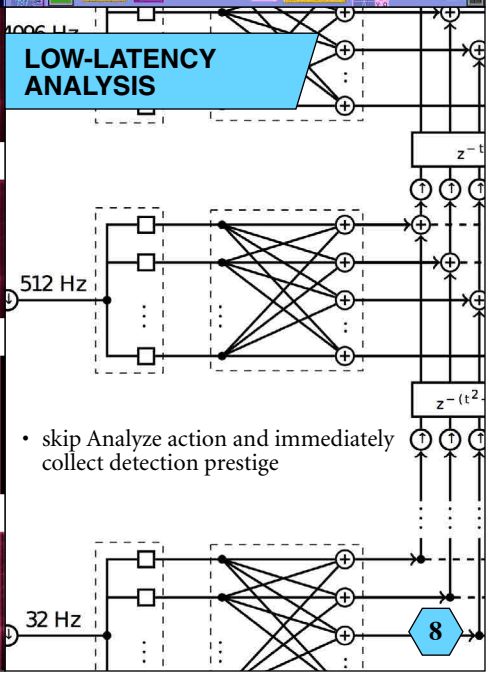
MATCHED FILTER ALGORITHM



- reduce distance to modeled sources by 50%

8

LOW-LATENCY ANALYSIS



- skip Analyze action and immediately collect detection prestige

8