Supernova Burst and Relic Neutrinos

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Plan of the Talk

Introduction to Supernova Neutrinos

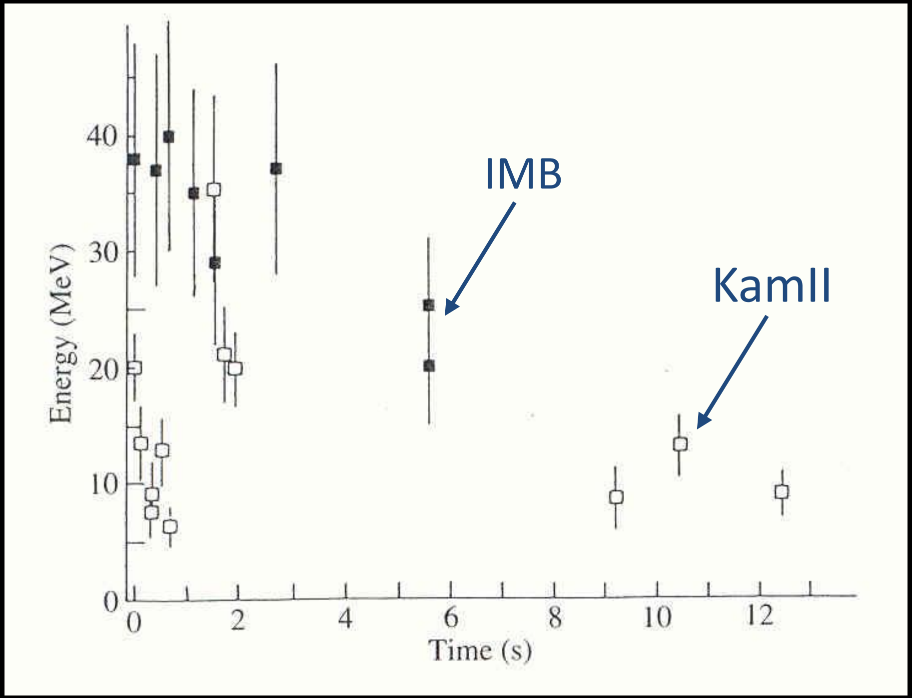
- Focus on Burst Detection
    - What will we know after the next burst?
    - What new capabilities do we need?
    - What are my recommendations for Jinping?

- Focus on Relic Detection
    - What do we know now?
    - What new capabilities do we need?
    - What are my recommendations for Jinping?

Concluding Remarks

Introduction to Supernova Neutrinos

SN 1987A: Our Rosetta Stone



Observation: Type II supernova progenitors are massive stars

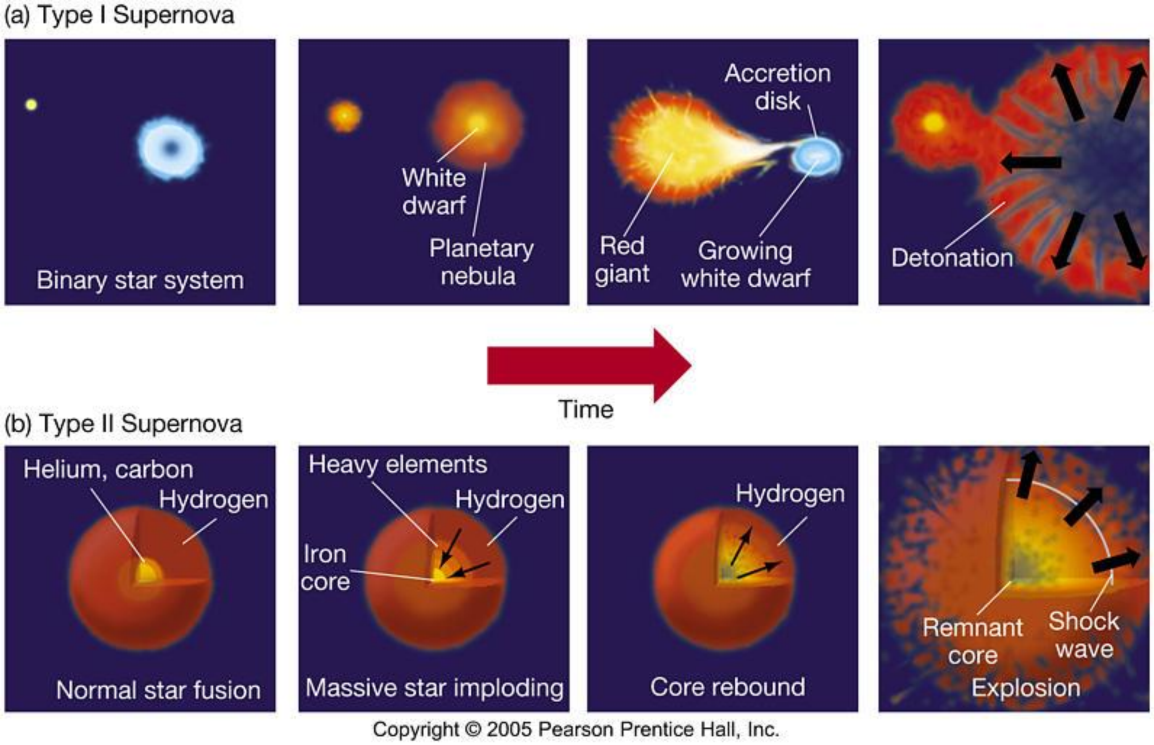
Observation: The neutrino precursor is very energetic

Theory: Core collapse makes a proto-neutron star and neutrinos

Core-Collapse Supernova Basics

🚫 Type Ia
(thermonuclear,
few neutrinos)

❤ Type II
(core collapse,
many neutrinos)



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Neutrinos carry away the change in gravitational potential energy

$\Delta(\mathrm{P.E.}) \sim (-GM^2/R)_{\text{neutron-star}} - (-GM^2/R)_{\text{stellar-core}} \sim -3\mathrm{x}10^{53}$ erg

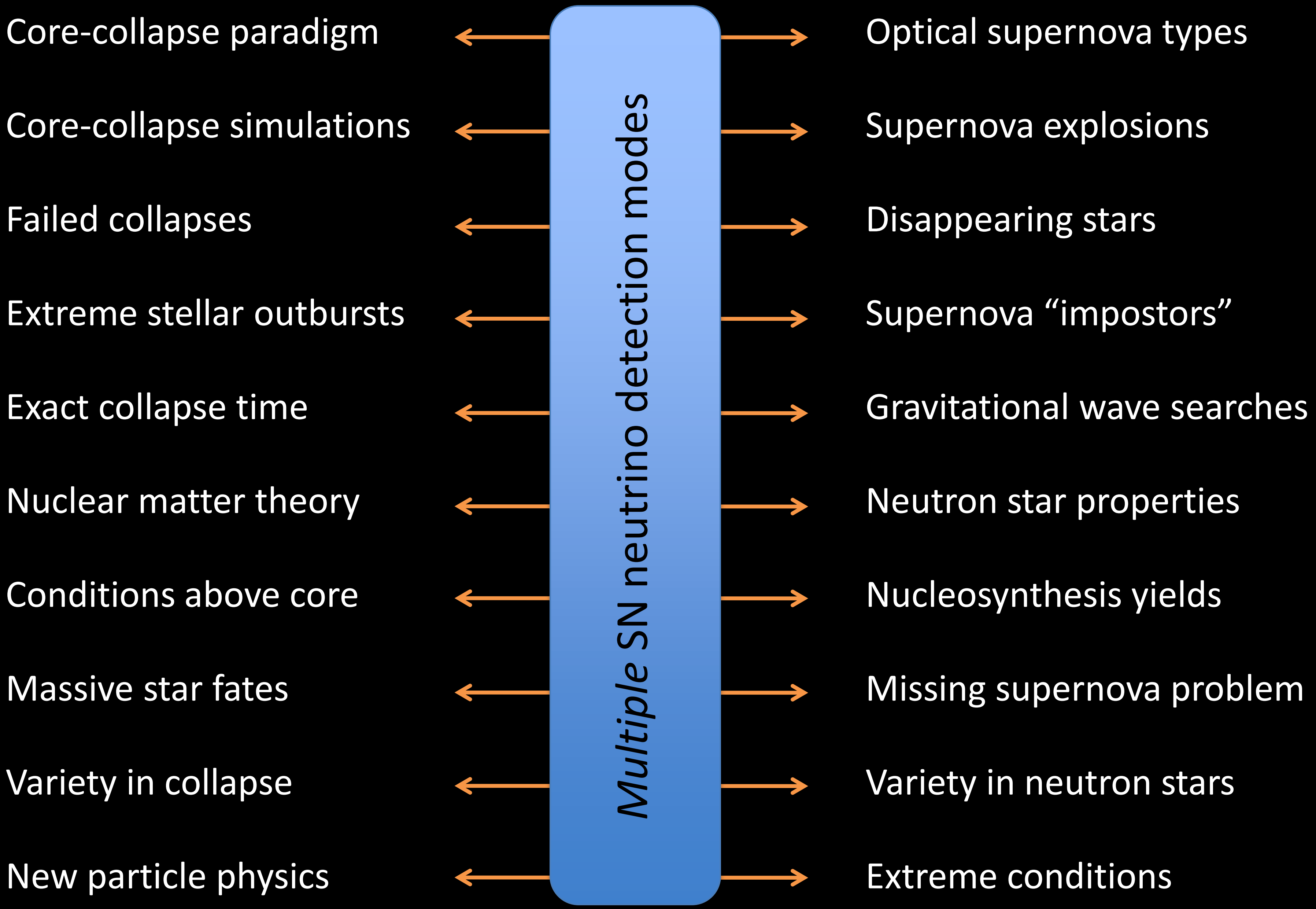
approximately shared among all six flavors

Neutrinos are trapped by scattering interactions and diffuse out

quasi-thermal with $\langle E \rangle \sim 15$ MeV

$\tau \sim$ few seconds

Importance of Supernova Neutrino Detection

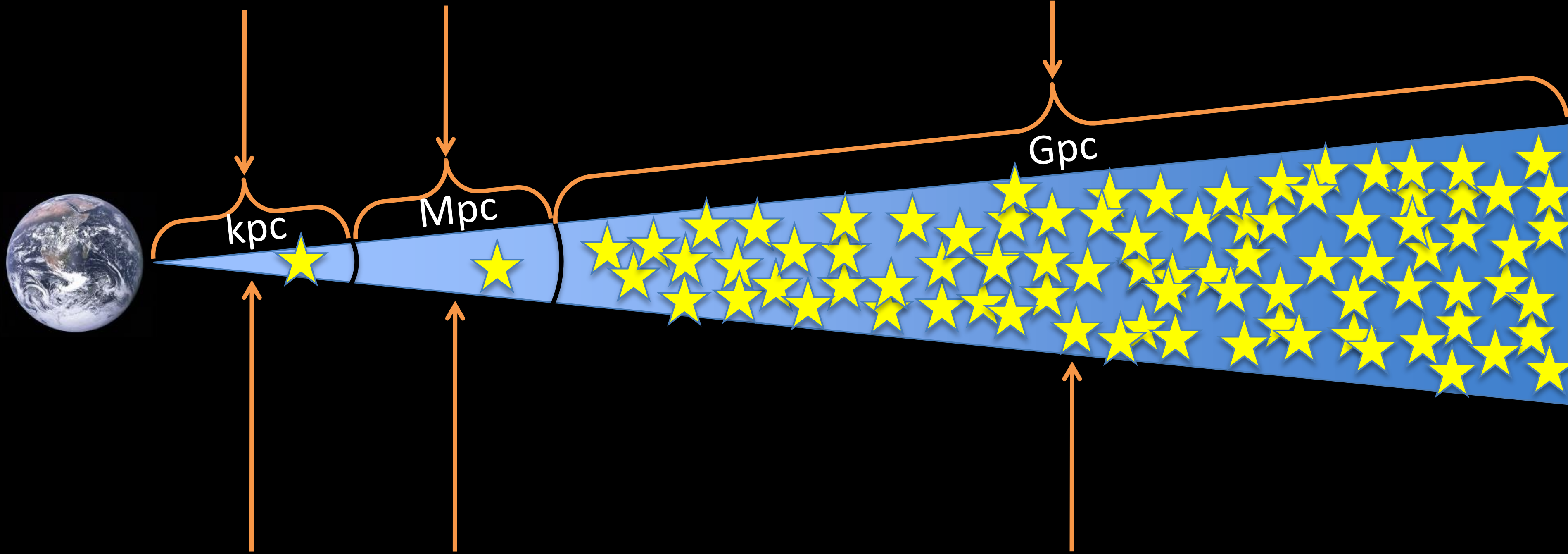


Multiple SN neutrino detection modes

- Core-collapse paradigm
- Core-collapse simulations
- Failed collapses
- Extreme stellar outbursts
- Exact collapse time
- Nuclear matter theory
- Conditions above core
- Massive star fates
- Variety in collapse
- New particle physics

- Optical supernova types
- Supernova explosions
- Disappearing stars
- Supernova “impostors”
- Gravitational wave searches
- Neutron star properties
- Nucleosynthesis yields
- Missing supernova problem
- Variety in neutron stars
- Extreme conditions

Distance Scales and Detection Strategies



N >> 1 : Burst

Rate ~ 0.01/yr

high statistics,
all flavors

N ~ 1 : Mini-Burst

Rate ~ 1/yr

object identity,
burst variety

N << 1 : DSNB

Rate ~ 10^8/yr

cosmic rate,
average emission

Importance of the Spectrum

Experiment

SN 1987A data

Experiment

DSNB data

Experiment

SN 2015? data

?

=

¿

Theory

Supernova simulations
(*initial spectra*)
Several groups

+

Neutrino flavor change
(*effects of mixing*)
Several groups

Focus on Burst Detection

Simple Estimate: Milky Way Burst Yields

Super-Kamiokande (32 kton water)

~ 10^4 inverse beta decay on free protons
~ 10^2 CC and NC with oxygen nuclei
~ 10^2 neutrino-electron elastic scattering *(crude directionality)*

KamLAND, MiniBooNE, Borexino, SNO+, etc (~ 1 kton oil)

~ 10^2 inverse beta decay on free protons
~ 10^2 neutron-proton elastic scattering
~ 10 CC and NC with carbon nuclei
~ 10 neutrino-electron elastic scattering

IceCube (10^6 kton water)

Burst is significant increase over background rate
Possibility of precise timing information

Much larger or better detectors are being proposed now

Key Problem: Incomplete Flavor Coverage

Need all flavors to measure the total emitted energy

Comparable total energies expected

And need all flavors to test effects of neutrino mixing

Temperature hierarchy expected

$\bar{\nu}_e$ Precise (~ 10^4 events in Super-K)

ν_e Inadequate (~ 10^2 events in Super-K)

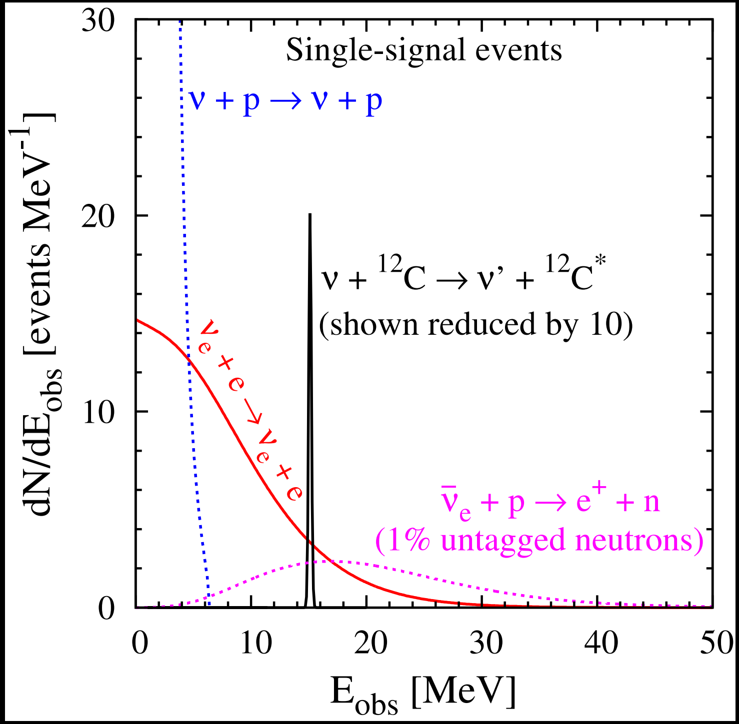
$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ Inadequate (~ 10^2 events in oil)

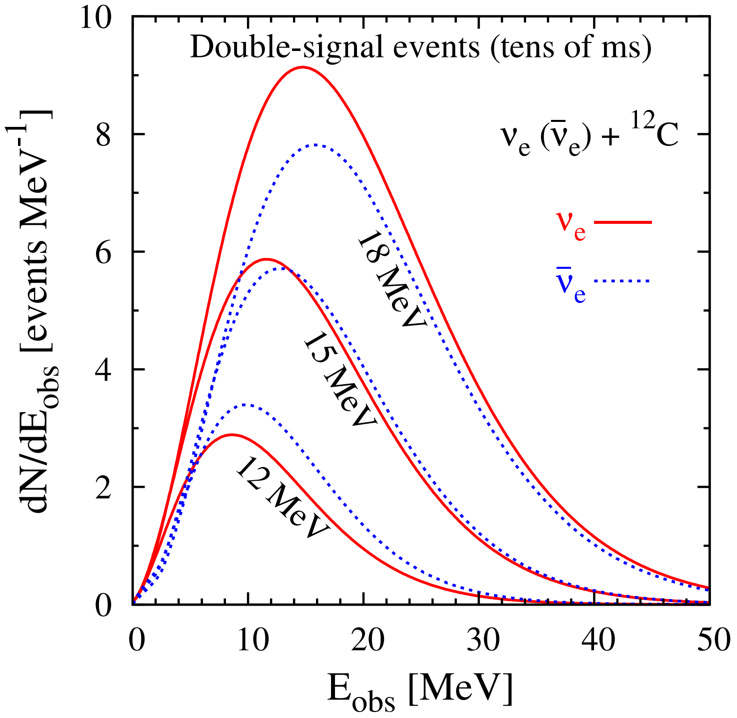
Need better detectors for the ν_e and ν_x flavors

Isolating ν_e (in oil)

Must measure final-state energy to get neutrino spectrum

Use electrons (low energies) and carbon (high energies)





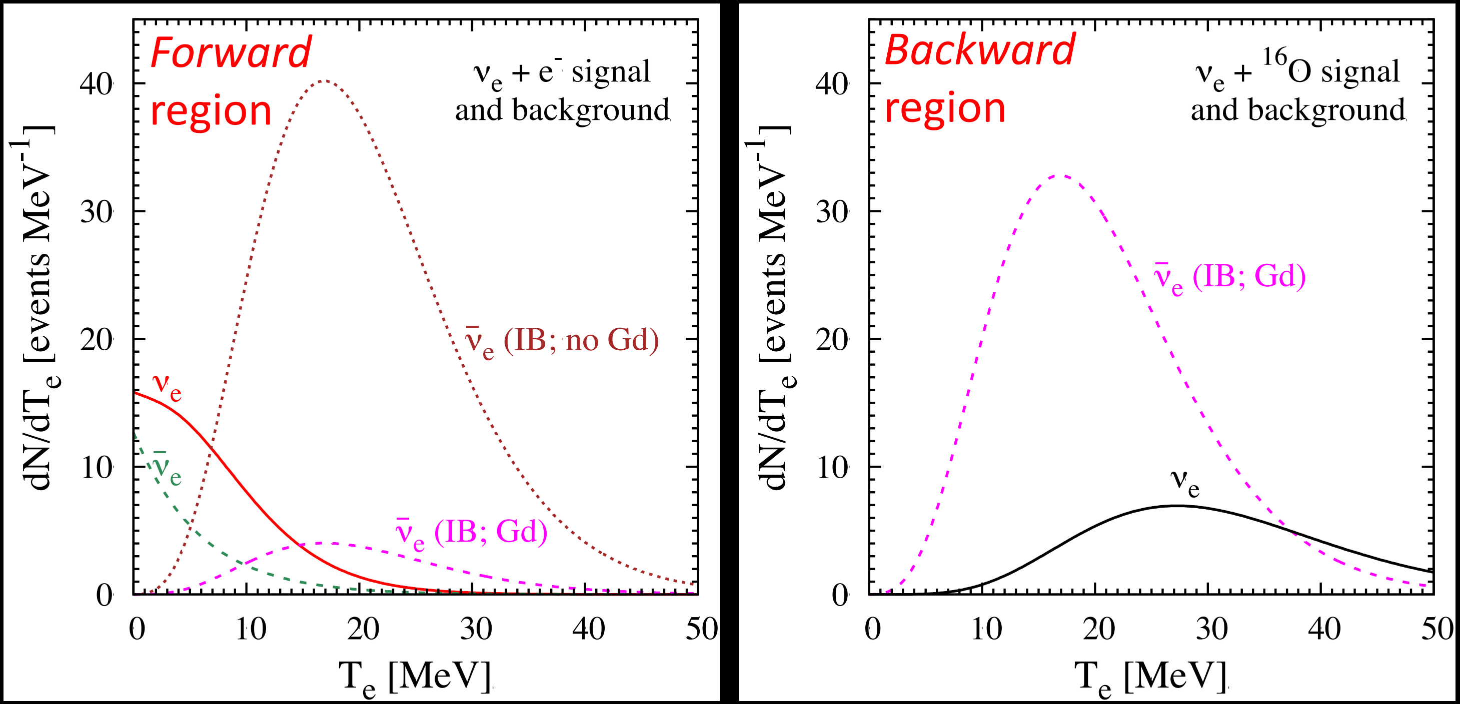
JUNO estimates
(Laha and
Beacom 2014)

Competition: ~ 1-kton-scale detectors Borexino, KamLAND, SNO+
~ 10-kton-scale detectors Super-K (+Gd), JUNO, DUNE

Isolating ν_e (in water)

Must measure final-state energy to get neutrino spectrum

Use electrons (low energies) and oxygen (high energies)



SK+Gd estimates (Laha and Beacom 2013)

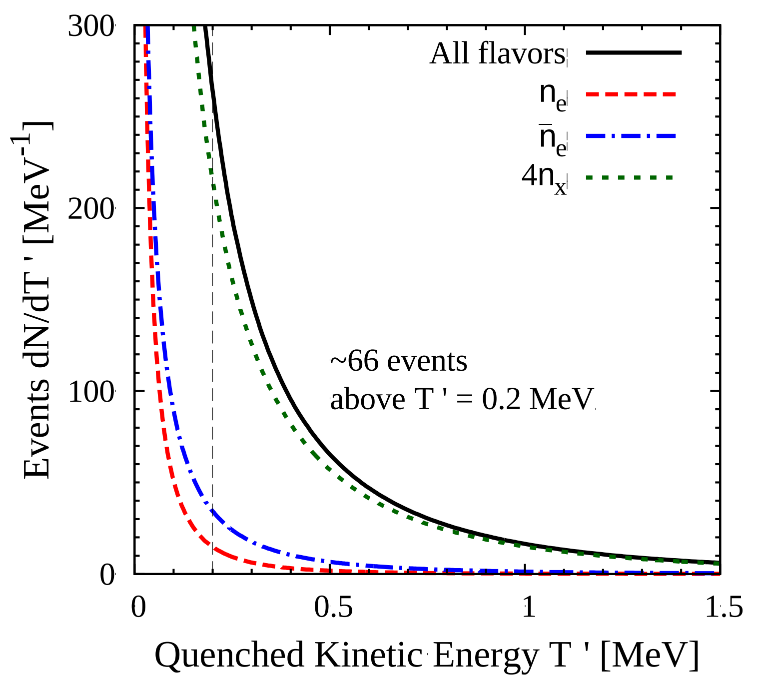
Competition: ~ 1-kton-scale detectors Borexino, KamLAND, SNO+

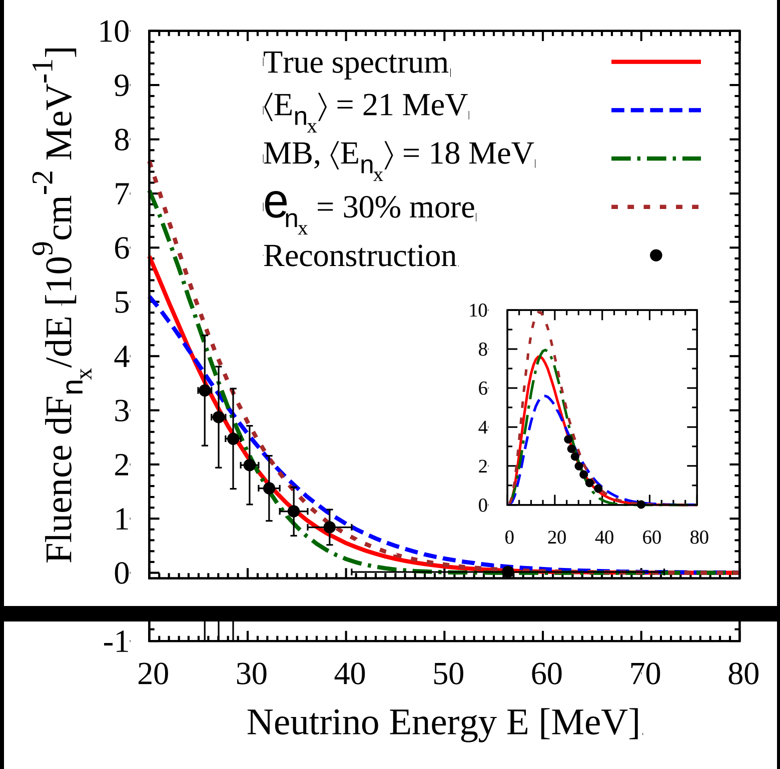
~ 10-kton-scale detectors Super-K (+Gd), JUNO, DUNE

Isolating ν_x (in oil)

Must measure final-state energy to get neutrino spectrum

Only good option is free protons





KamLAND estimates (Dasgupta and Beacom 2011)

Competition: ~ 1-kton-scale detectors Borexino, KamLAND, SNO+

~ 10-kton-scale detector JUNO

Burst: Recommendations for Jinping Detector

SN Burst is secondary goal due to SN rate, competition
But Jinping could make an important contribution

LS or WbLS is favored to improve measurement of ν_e and ν_x
These are the hardest flavors to detect and isolate

Focus on neutron efficiency, quenching, directionality (?)
Backgrounds, energy resolution, uptime, trigger all “easy”

Could promptly identify a supernova with own data
Use “heartbeat” signal [Beacom and Vagins; Adams et al.]

Focus on Relic Detection

Simple Estimate: DSNB Event Rate

Super-Kamiokande rate in *every* 10 second interval

Kamiokande-II rate in a *special* 10 second interval

$\boxed{\sim 1\ \text{s}^{-1}}$

$$\left[\frac{dN_\nu}{dt}\right]_{\mathrm{DSNB}} \sim \left[\frac{dN_\nu}{dt}\right]_{\mathrm{87A}} * \frac{\left[\frac{N_{SN}\,M_{det}}{4\pi D^2}\right]_{\mathrm{DSNB}}}{\left[\frac{N_{SN}\,M_{det}}{4\pi D^2}\right]_{\mathrm{87A}}}$$

For the DSNB relative to SN 1987A:

N_{SN} up by ~ 100

M_{det} up by ~ 10

$1/D^2$ down by ~ 10^{-10}

➡ DSNB event rate in Super-Kamiokande is a few per year

Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu)\int_0^\infty \Big[(1+z)\,\varphi[E_\nu(1+z)]\Big]\,\Big[R_{SN}(z)\Big]\,\left[\left|\frac{c\,dt}{dz}\right|dz\right]$$

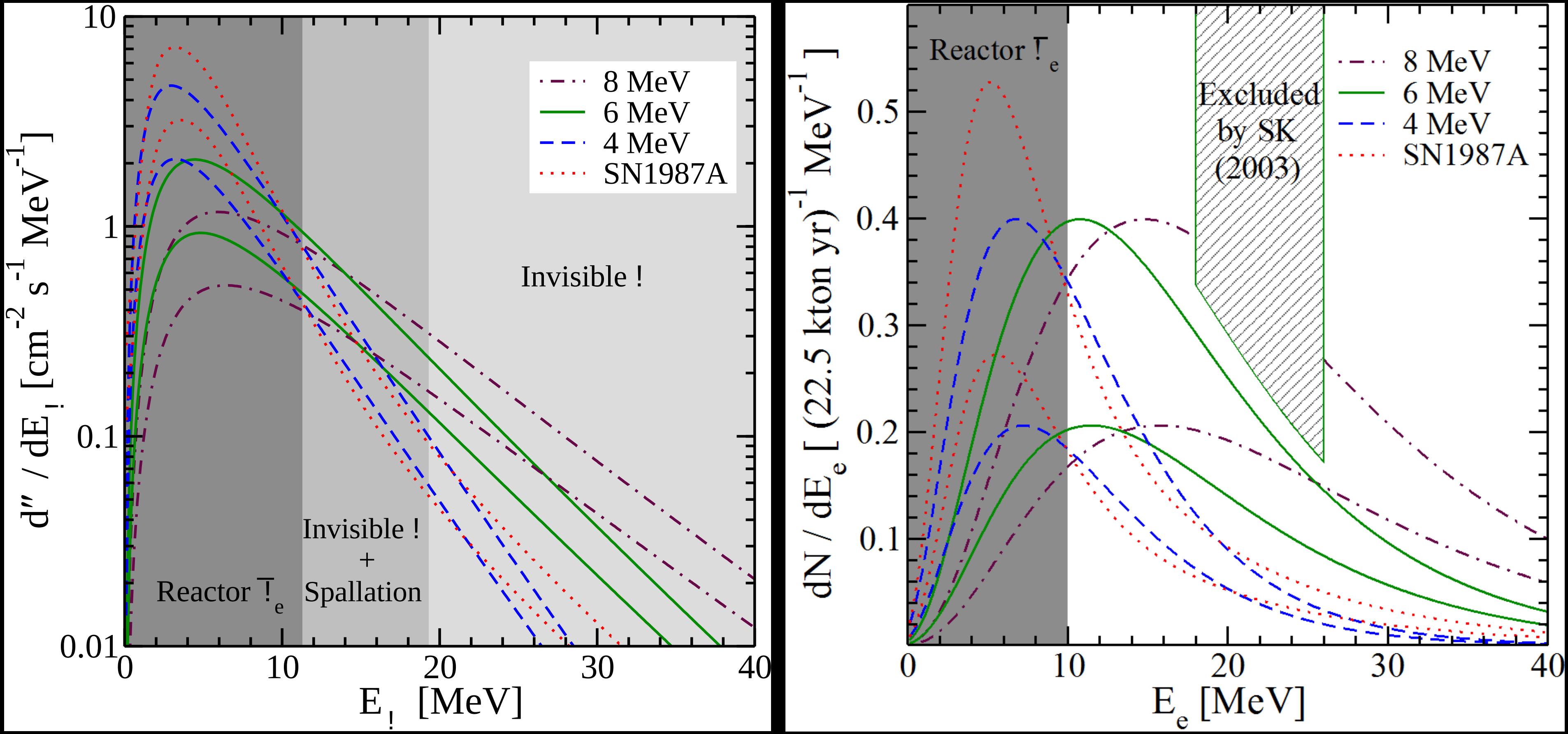
Third ingredient: Detector Capabilities
(well understood)

Second ingredient: Core-collapse rate (formerly very uncertain, but now known with good precision)

First ingredient: Neutrino spectrum
(this is now the unknown)

Cosmology? Solved. Oscillations? Included. Backgrounds? See below.

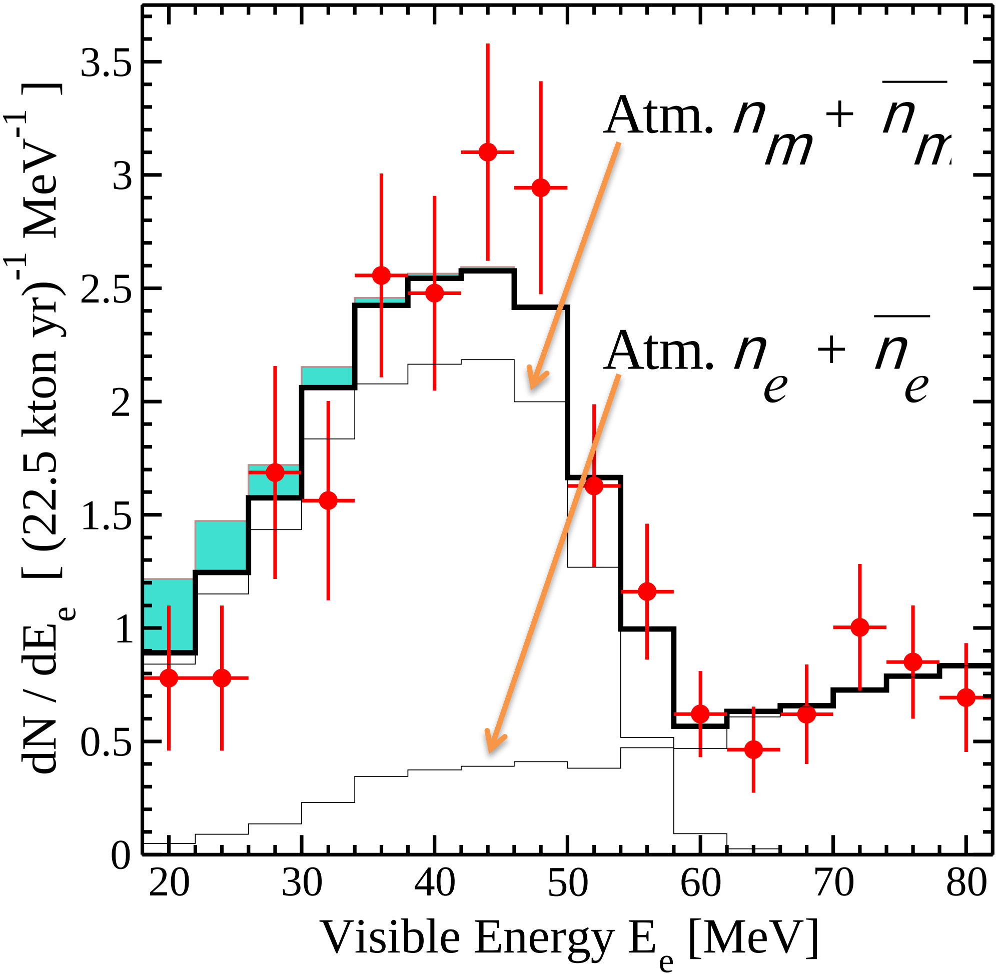
Predicted Flux and Event Rate Spectra



Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

Key Problem: Large Detector Backgrounds



Malek et al. [Super-Kamiokande] (2003);
energy units changed in Beacom (2011) – use with care

See updated search and results in
Bays et al. [Super-Kamiokande] (2012)

Amazing background rejection: nothing but neutrinos despite huge ambient backgrounds

Amazing sensitivity: factor ~100 over Kamiokande-II limit and first in realistic DSNB range

No terrible surprises

Challenges: *Decrease* backgrounds and energy threshold and *increase* efficiency and particle ID

Benefits of Neutron Tagging for DSNB

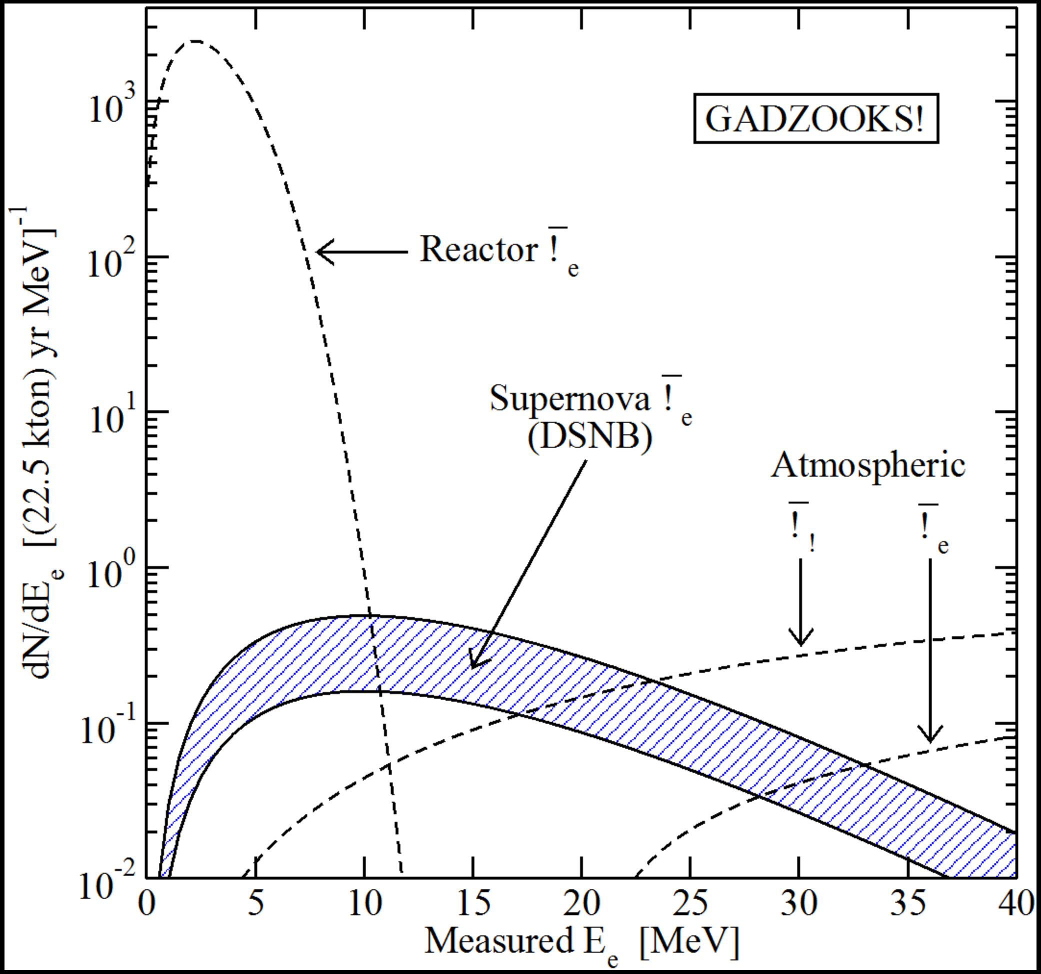
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

DSNB:
More signal, less background!



Beacom, Vagins (2004)

(DSNB predictions now at upper edge of band)

Relics: Recommendations for Jinping Detector

Supernova relics is secondary goal due to low signal rate
But Jinping could make an important contribution

LS or WbLS is favored to reduce CC backgrounds (Super-K)
High neutron efficiency, high light yield are essential

Need to focus on reducing NC backgrounds (KamLAND)
Better detector, new analysis techniques could be decisive

Might be able to identify signal with ~ 1 event / few years
Depends on convincing case for near-zero backgrounds

Concluding Remarks

Why Do We Need Multiple Detectors?

Different uptime --- don’t miss the supernova

Different capabilities --- more complete measurements

Different challenges --- reduce uncertainties

Different detectors --- increase statistics

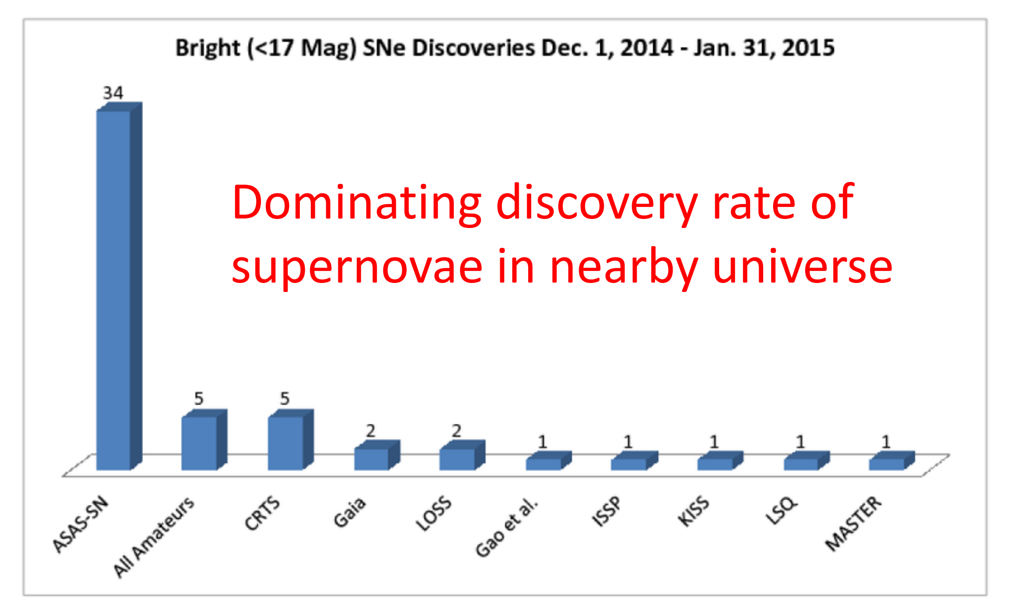
Different positions --- measure Earth effect on mixing

We probably only get one supernova!

All-Sky Optical Monitoring to Leverage

Connection to astronomy crucial, but optical data are lacking

Enter OSU's "Assassin" (All-Sky Automated Survey for SN)



Dominating discovery rate of supernovae in nearby universe

Discovering and monitoring optical transients to 17th mag.

See also Adams, Kochanek, Beacom, Vagins, Stanek (2013)

Overall Recommendations for Jinping Detector

Choose technology on the basis of primary science goals

Likely solar and geo- neutrinos, possibly WbLS demo

Decide how to compete with similar detectors

Size, low-energy response, detector backgrounds

Make case that multiple detectors are needed

Reduce systematics, increase statistics, test Earth effect

Consider ways to leverge investments

Co-operate with ASAS-SN on prompt SN detection

Center for Cosmology and AstroParticle Physics

The Ohio State University's Center for Cosmology and AstroParticle Physics

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