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Aspen Winter Conference Feb 2013

Will we ever collect "neutrino-curves" for a large sample of Supernovae?

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The many areas of (experimental) neutrino physics

Mixing parameters and $\not{CP}$

νs applied to security

Coherent ν scattering

Mag moment

Relic νs detection

Geoneutrinos

Solar neutrinos

Mass scale from β end point

Sterile νs?

(U)HE ν astronomy

Majorana masses and $0\nu\beta\beta$ decay

Supernova νs detection

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Could arrange by source…

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νs
to

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Accelerators

Reactors

Radioactive Sources

The Earth

The Sun

Stars

The Universe

The

...or by difficulty (according to me)...

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"Just send some money" ⟶ "no idea where to start from"

...or by how likely is a game changing discovery

(of course this is my opinion, also lots of science is done without game changing discoveries... yet, if this is the standard...)

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Somewhat → even failing to discover is a major discovery!

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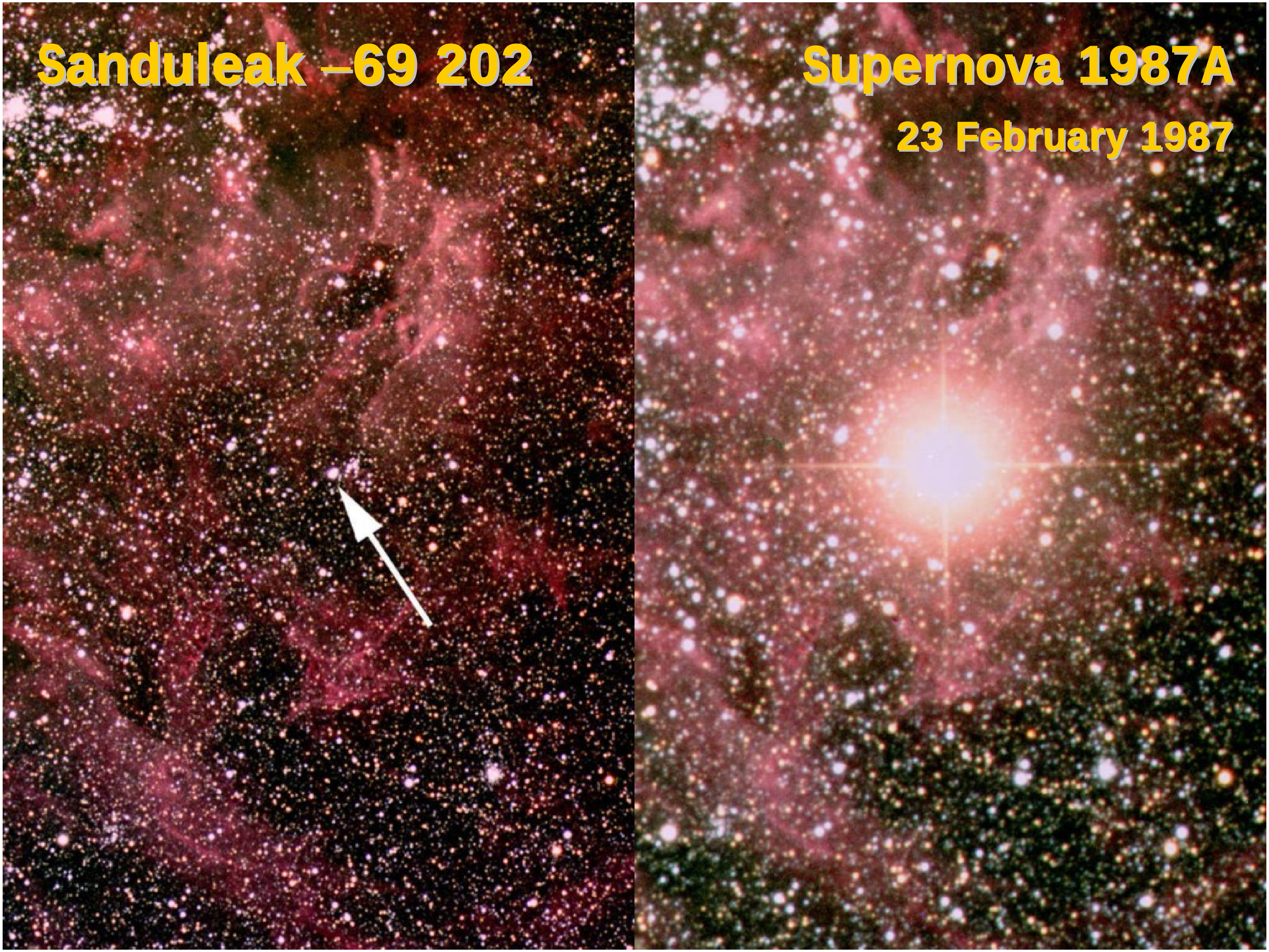
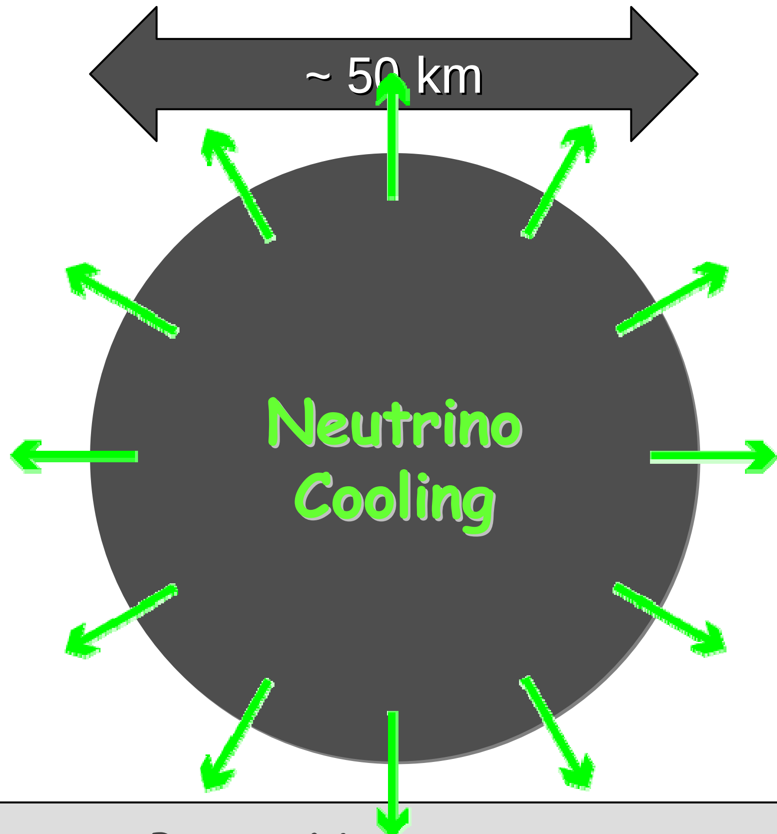

Sanduleak –69 202
Supernova 1987A
23 February 1987

Type Ib/c and II: Core Collapse and SN Explosion

$M_{star} > 8 M_{Sun}$ $M_{Fe\ core} \sim 1.5 M_{Sun}$

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy
$E_b \sim 3 \cdot 10^{53}$ erg ($\sim 17\%\ M_{Sun} c^2$)

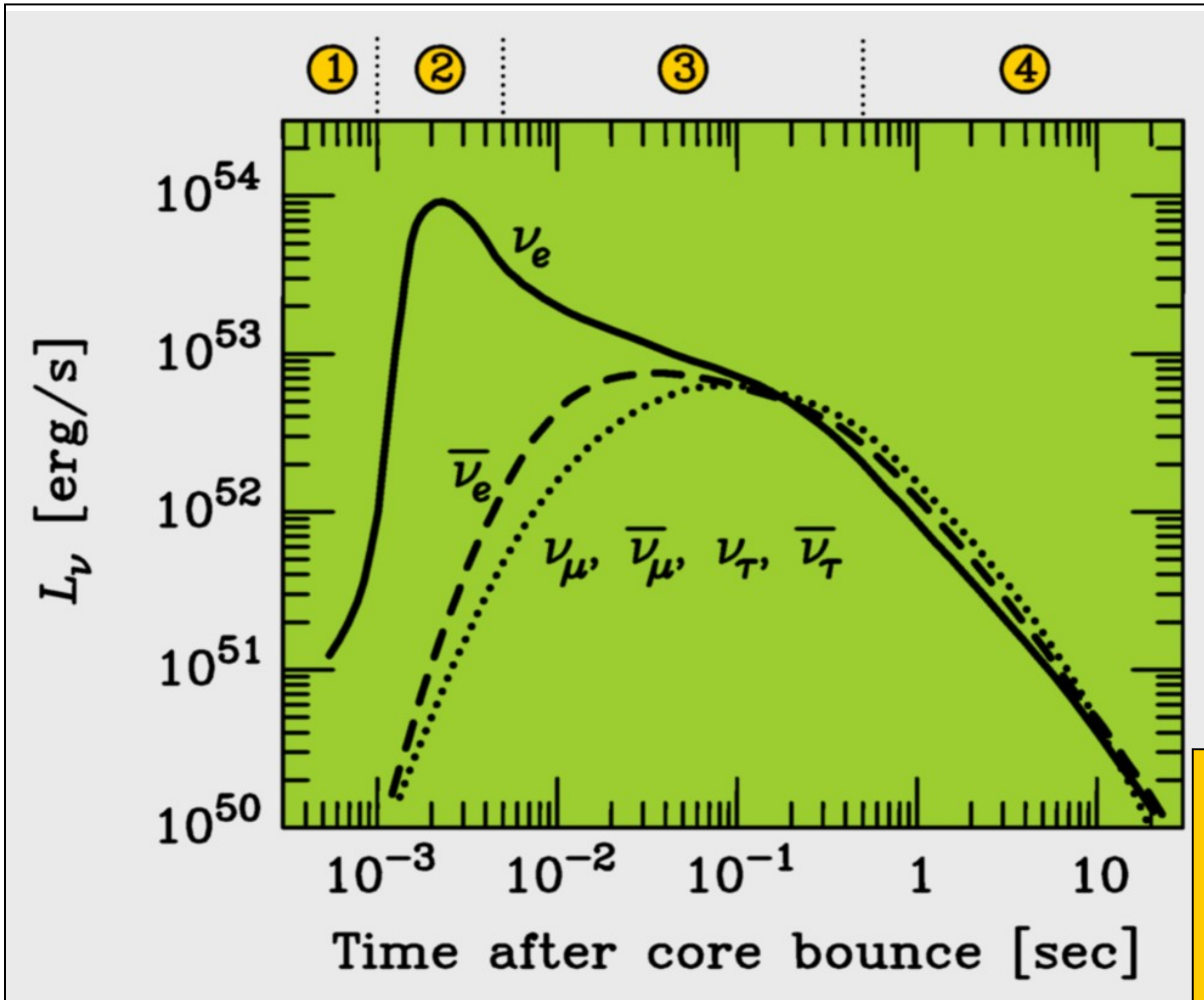
That shows up as:
99% Neutrinos!
1% Kinetic energy of explosion
0.01% Photons,
(outshine the host galaxy)

Neutrino luminosity
$L_\nu \sim 3 \cdot 10^{53}$ erg / 3 sec
[$\sim 3 \cdot 10^{19}\ L_{Sun}$ (mainly photons)]

➔ While it lasts, outshine the entire visible Universe!
➔ Dominant source of heavy elements in the universe!

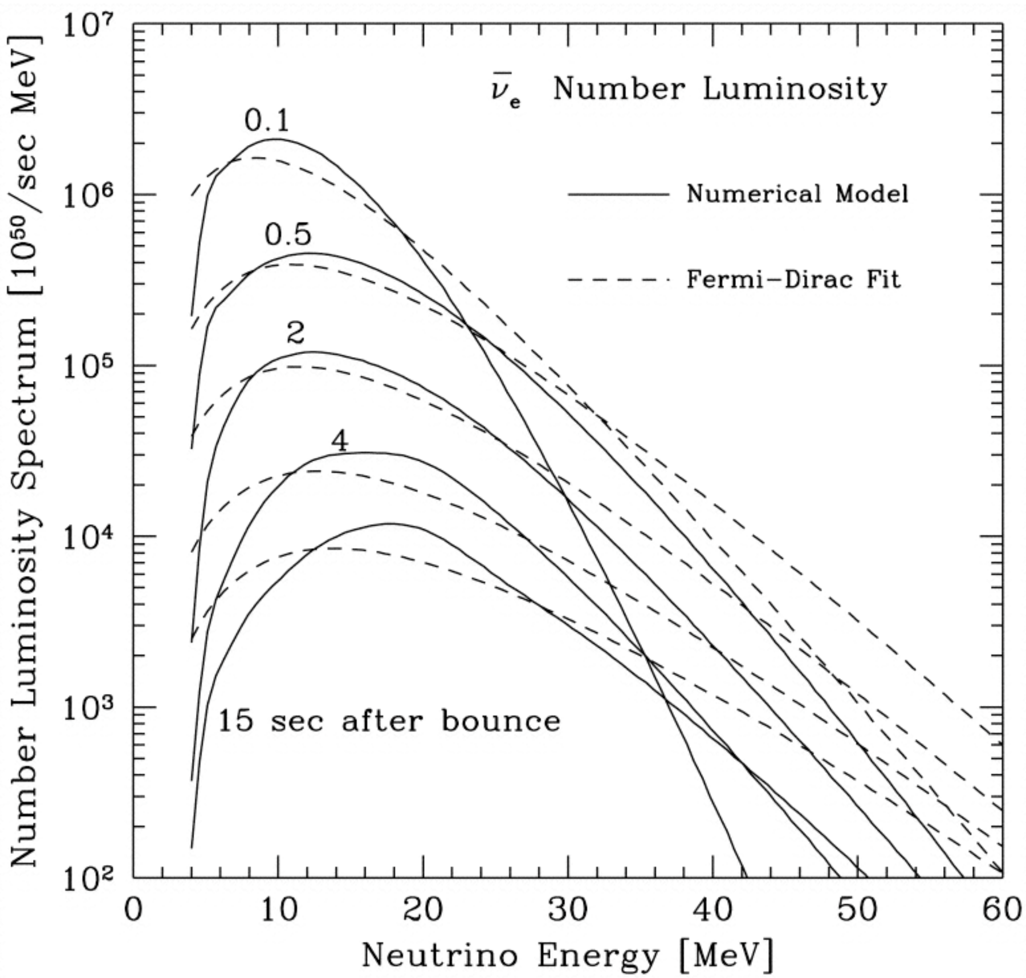
From G.Raffelt INSS2012 Tsukuba

Rough structure of SN ν signal has been known for long time



1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling

Expected spectrum

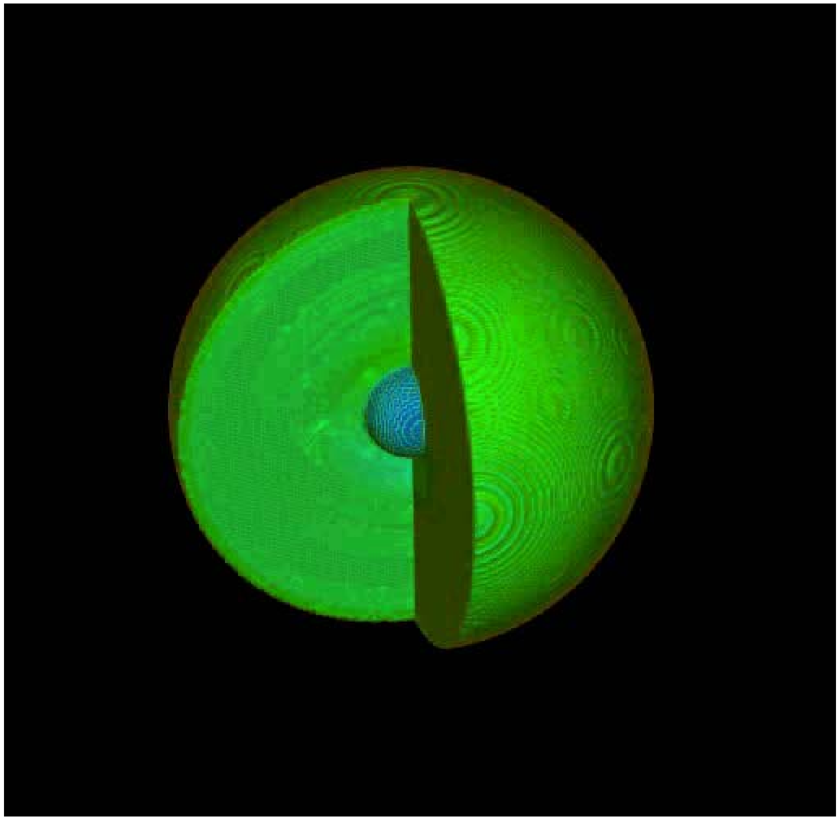


Totani et al. ApJ 496 (1998) 216

- Roughly Fermi-Dirac
- Not exactly because neutrino absorption in proto neutron star is energy-dependent

Yet the dynamics of the explosion following the collapse is extremely complex and only recently advanced simulations started to provide insights on what happens.

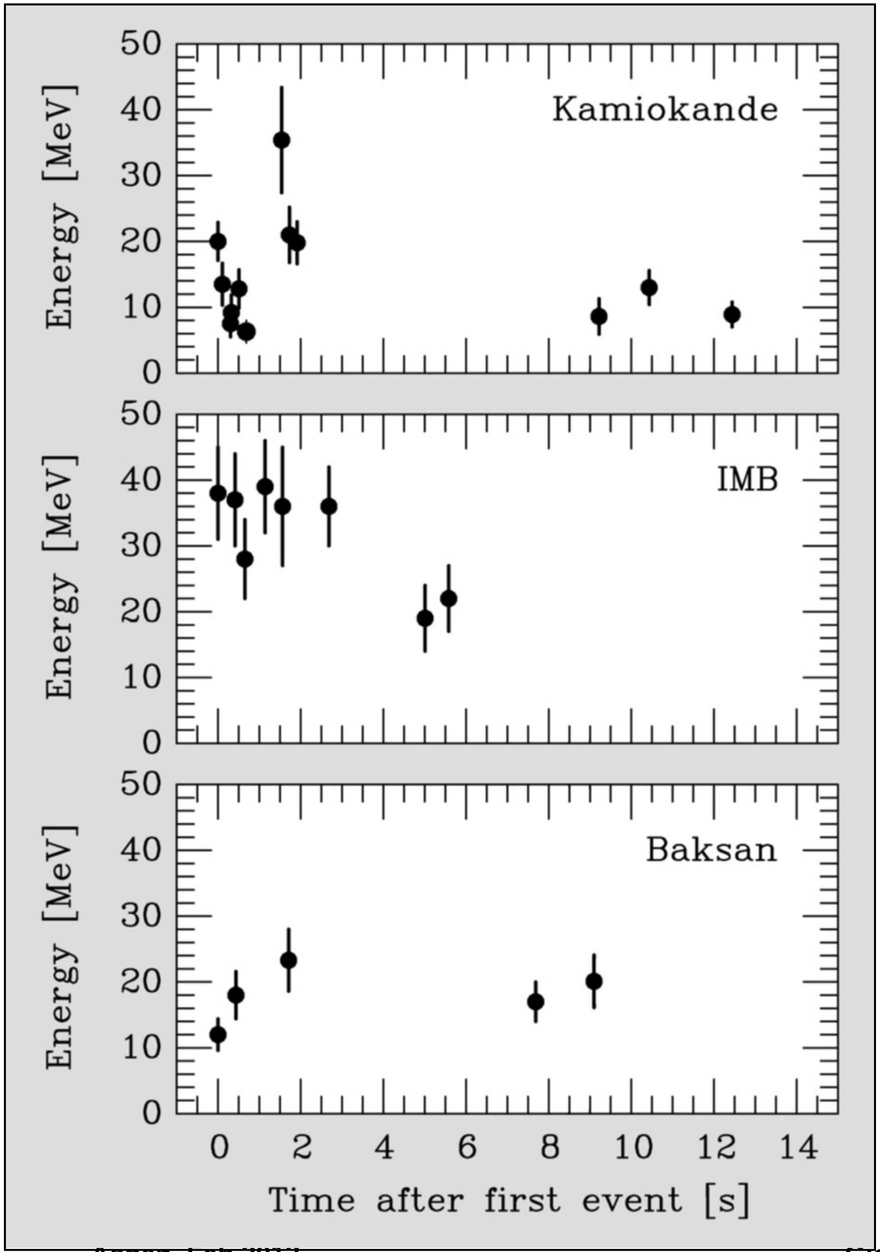
"Every field of physics" enters these simulations!
Neutrinos play an essential role (even in making the explosion proceed)



Example of SASI instability
A.Mezzacappa, ORNL

Neutrinos (and possibly gravitational waves produced by the neutrinos(!)) are the only witnesses of all this turmoil!

Neutrino Signal of Supernova 1987A



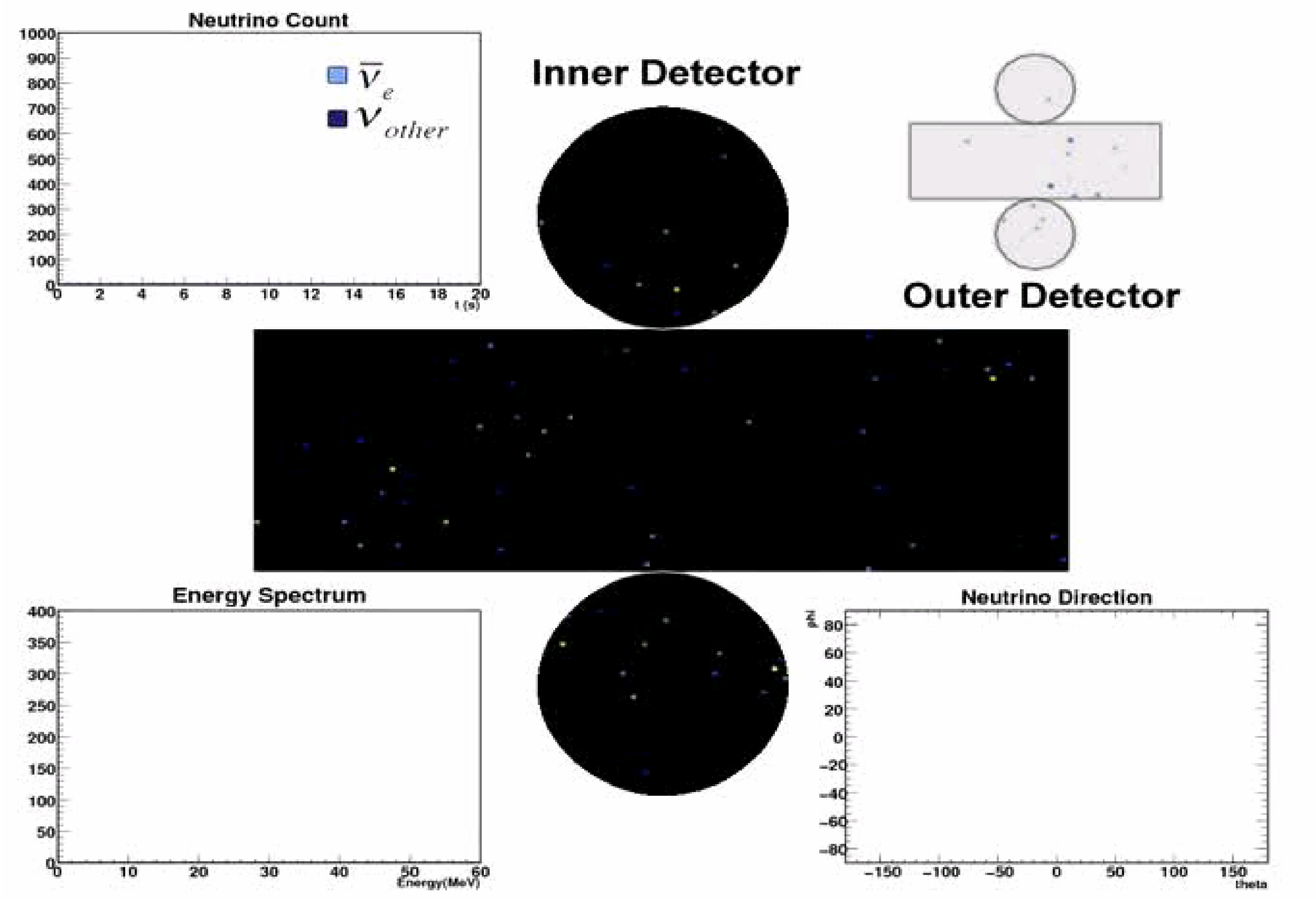
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

IMB (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

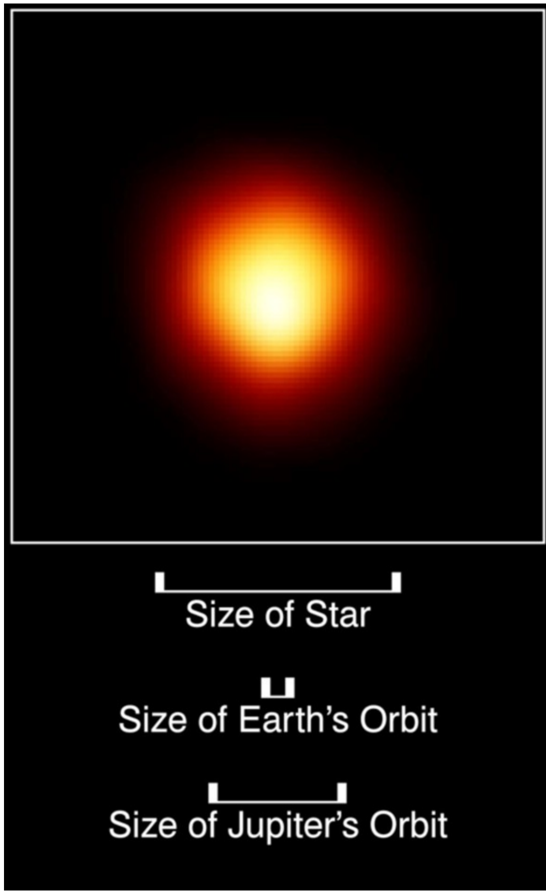
A galactic SN today *would* be seen by SK as

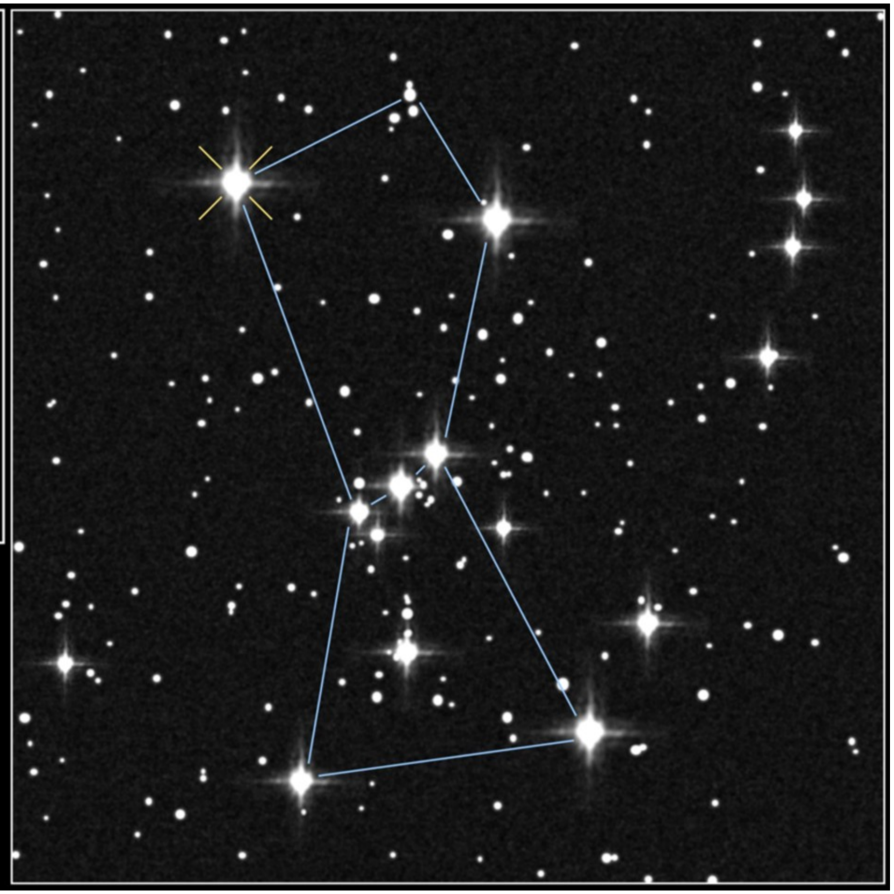


From K.Scholberg and SuperK

Trouble is, this only happens once every ~30yrs

The Red Supergiant Betelgeuse (Alpha Orionis)

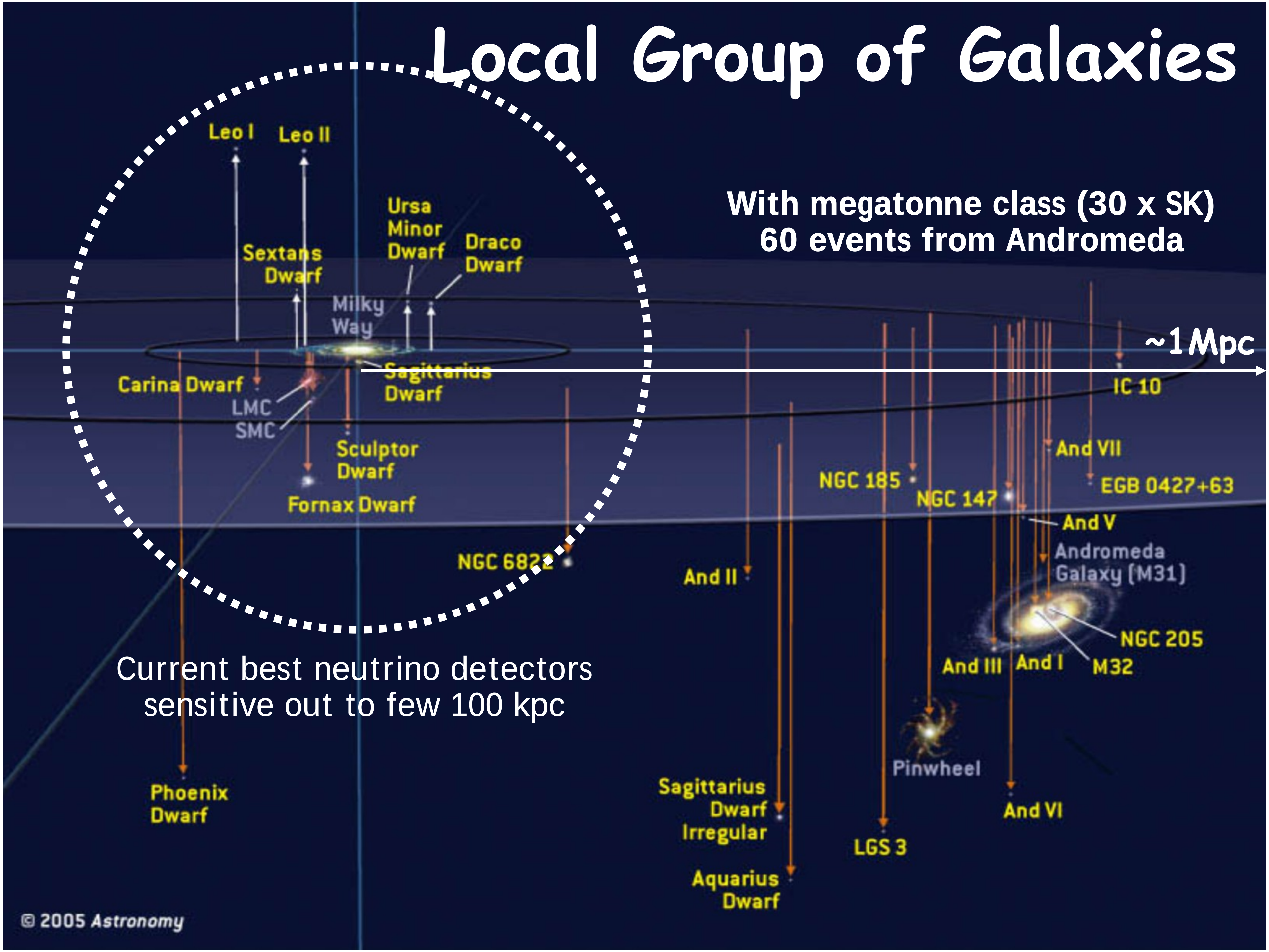




First resolved image of a star other than Sun

Distance (Hipparcos)
130 pc (425 lyr)

If Betelgeuse goes Supernova "we are not going to miss it!":
- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 neutron events per day from Silicon-burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]


Local Group of Galaxies
With megatonne class (30 x SK)
60 events from Andromeda
~1Mpc
Current best neutrino detectors
sensitive out to few 100 kpc
Leo I
Leo II
Ursa Minor Dwarf
Draco Dwarf
Sextans Dwarf
Milky Way
Carina Dwarf
LMC
SMC
Sagittarius Dwarf
Sculptor Dwarf
Fornax Dwarf
NGC 6822
Phoenix Dwarf
And II
NGC 185
NGC 147
And VII
EGB 0427+63
IC 10
And V
Andromeda Galaxy (M31)
NGC 205
M32
And III
And I
Pinwheel
And VI
LGS 3
Sagittarius Dwarf Irregular
Aquarius Dwarf
© 2005 Astronomy

The standard paradigm:

Detect νs by tagging each interacting ν and measuring its energy

Unfortunately SN close enough to be detected are not common
(and we are an impatient race)

➔ We may never see another SN (with neutrinos)
➔ Even if we get to see "one" this may not be the point

Maybe this is not the point!

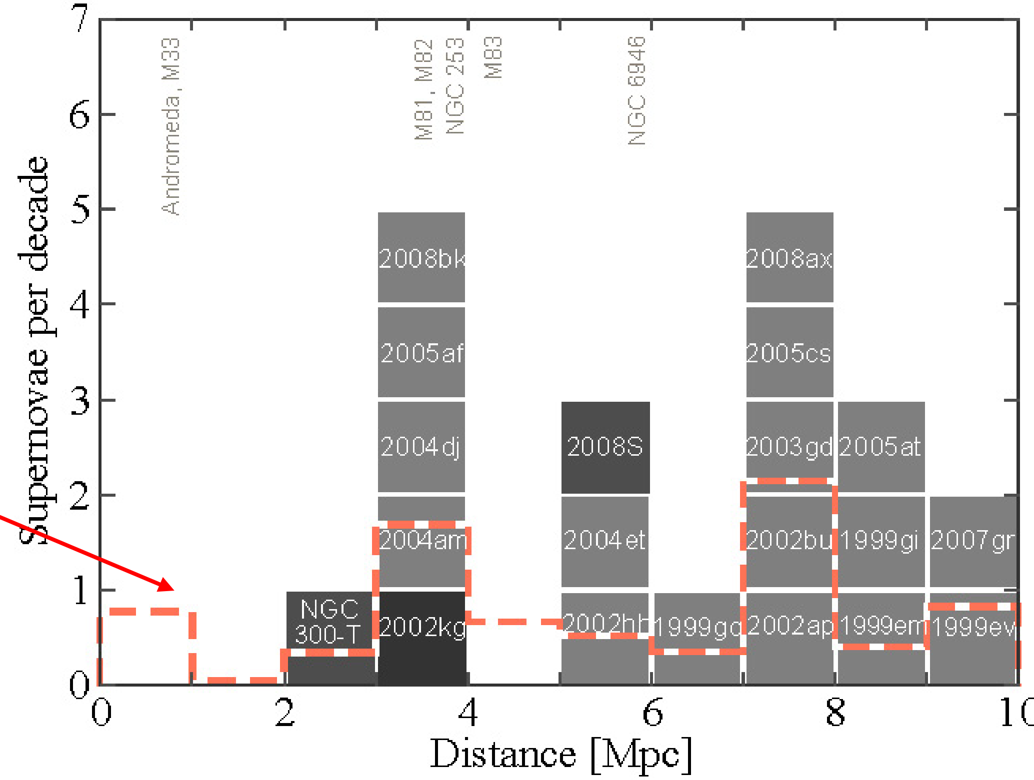
Maybe most of the physics is in the "neutrino curve" and in the *variety* of neutrino curves
(for GRBs the photon curve is an important classifier)

Maybe most SN fizzle…

Maybe most of the physics is in the ν-GW co-observation of many explosions

So maybe we should concentrate on detecting many SN even giving up details of each detection, like the energy of the neutrinos

Predicted from galaxy catalogs



Kistler et al., Phys.Rev.D 83 (2011) 123008

Looks like ~20/decade or 1 every six months

So, we should try building a detector capable of seeing out to 10 Mpc !

First let's settle on the medium

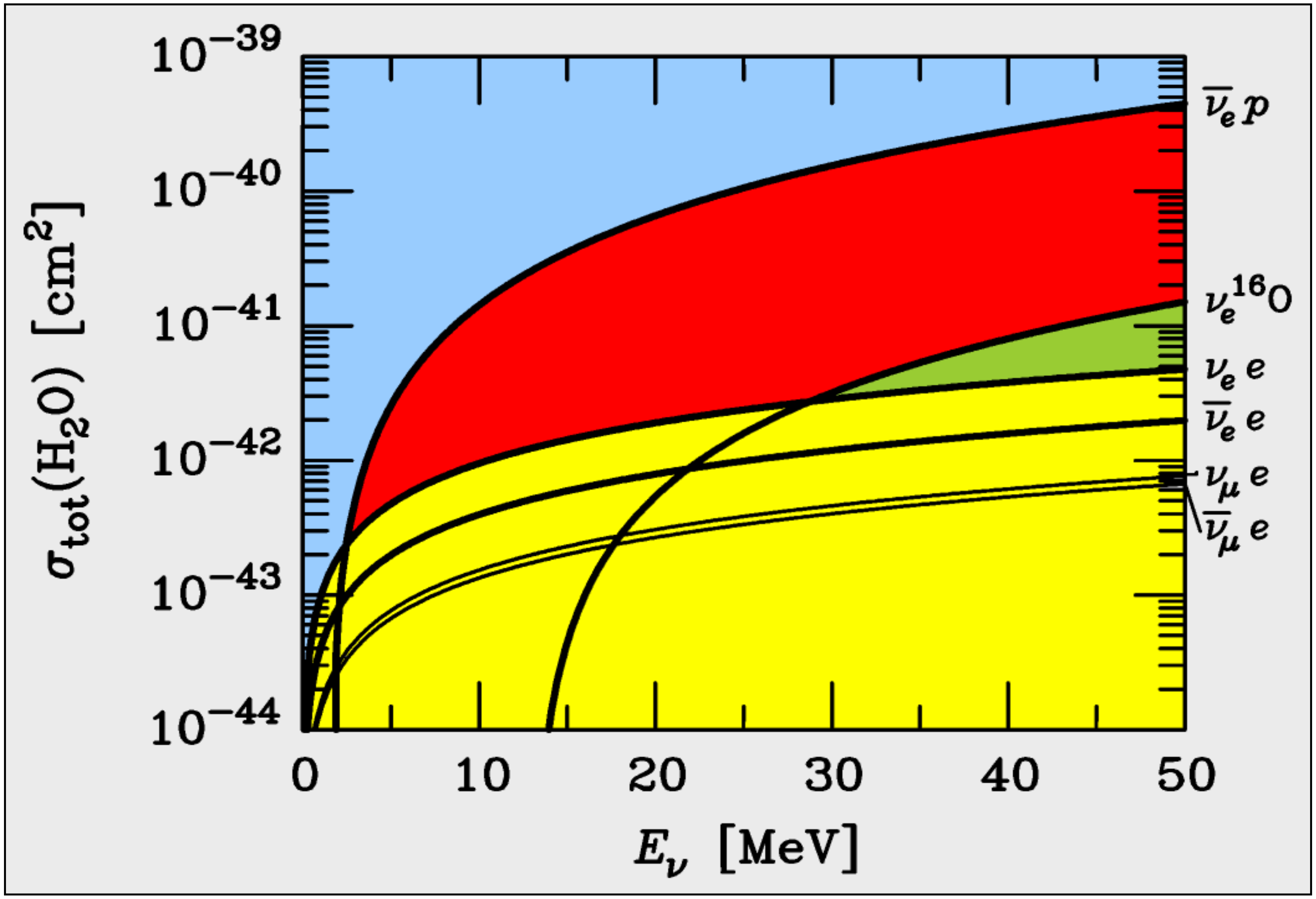
We need lots of it (see later) and need to see low energy (few 5-50 MeV) neutrino interactions

In a very qualitative way:
- Detecting single p.e. so
    - Sea water is too rich in ^{40}K (~1.4MeV β/γ)
    - Atmosphere has too many cosmic rays
- Do not know how to instrument large quantities of rock (even salt)

Probably the only "non impossible" medium is ice.

Neutrino cross sections in a H_2O target

Cross section per water molecule



Main reactions: $\overline{\nu}_e + p \rightarrow n + e^+$ dominates for SN

$\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$

$\nu + e^- \rightarrow e^- + \nu$ dominates for Sun

From G.Raffelt INSS2012 Tsukuba

How large?

For a standard $3 \cdot 10^{53}$ erg SN the inverse beta decay rate ($\bar{\nu}_e$ interactions only) in H_2O is

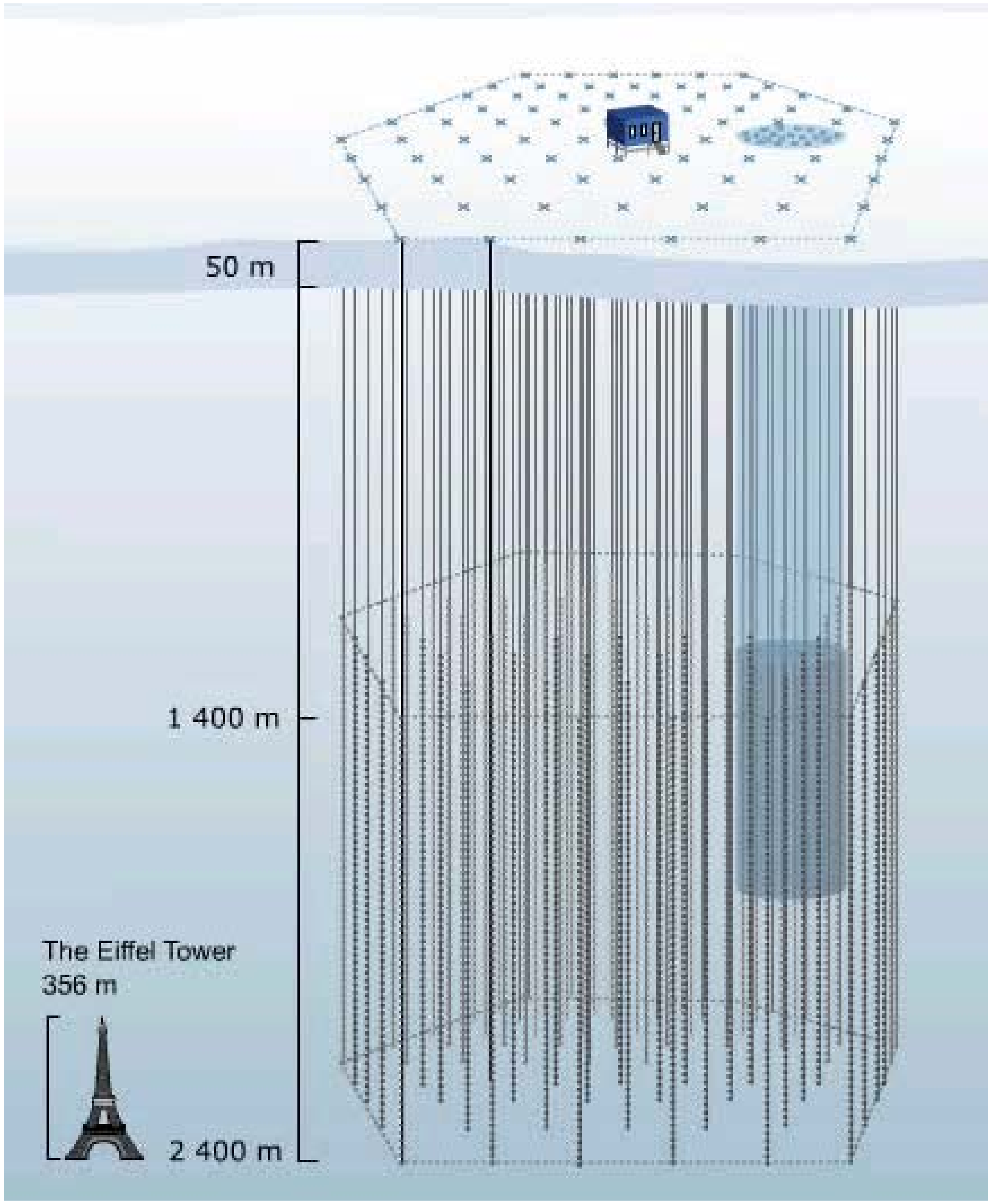
$$N = \frac{10^{-4}}{D^2} M$$

M is the detector mass in ton and
D is the distance of the SN in Mpc.

So at 10 Mpc (2 SN/year) one gets 1 evt/Mton or 1000 evt/Gton (1Gton=1km^3, like IceCube)

This sets the scale of the ice mass required.

So, maybe we have a detector?



Unfortunately not, IceCube, apart for size and medium is not right for this:

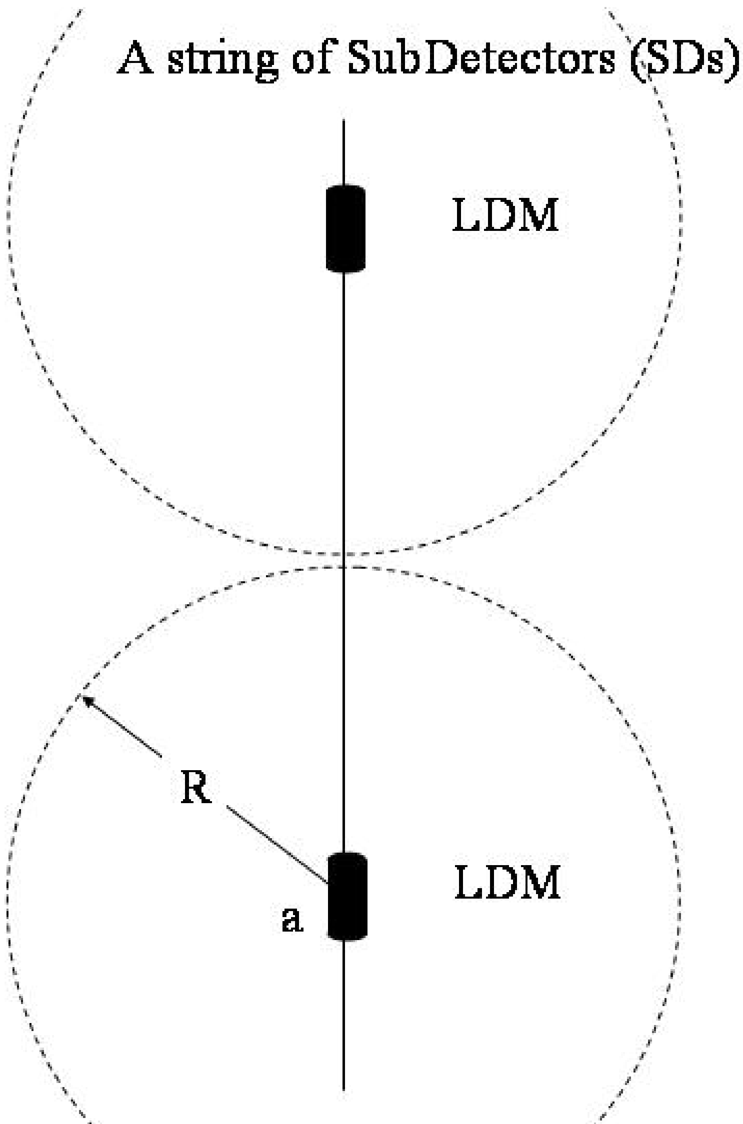
For IceCube the main concern is measuring energy and direction:
- Reconstruct cherenkov wavefront
- Go deep where there are fewer bubbles (longer scattering length)
- Pay attention to timing
- Poor light collection (for low energy, point-like depositions)

Instead, what we need is:

- Long absorption length
- Cheap (shallow)
- Best light collection possible
- Modules positioned as more convenient (ie cheaper)
- Limited interest on timing

→ *I believe it is instructive to try optimizing this on the back of an envelope (MC is nice but it's also good to see where we get into trouble)*

→ *Warning: at this stage I am probably more optimistic than conservative*



- Each Light Detection Module (LDM) can see out to some radius R that is basically the ice absorption length. So each LDM sees a mass of $4/3\pi R^3$

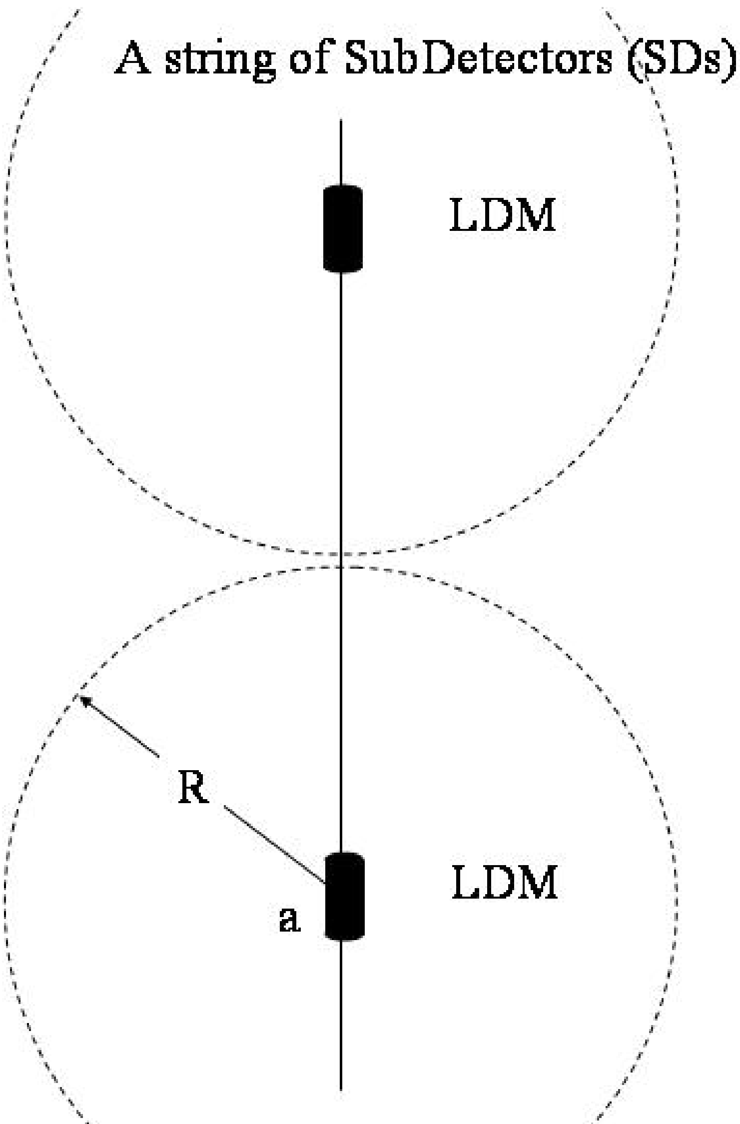
- Each LDM is independent from the others (chance of seeing >1 p.e./ν ~0 anyway*) So LDMs are placed at a distance
  - 2R from each other vertical
  - $\geq$2R from each other horizontally (don't care what the footprint is)

- The light collection efficiency of an LDM is

$$\varepsilon = \frac{a}{4\pi R^2}$$

where *a* is the sensitive area of the LDM (this assumes the photons to move at random as is the case for $\lambda_{scatt} \ll R$, true for depth shallower than ~1200m)

* However a SN burst still results in a coincidence between more than 1 p.e. (from different νs)



Note that at 0th order the shape of the LDMs is irrelevant.
All we care is *a*

I will take the Cherenkov yield to be

$$Y = 1000\gamma / \nu$$

(very crude, 15MeV/ν, 350nm < λ <500nm)

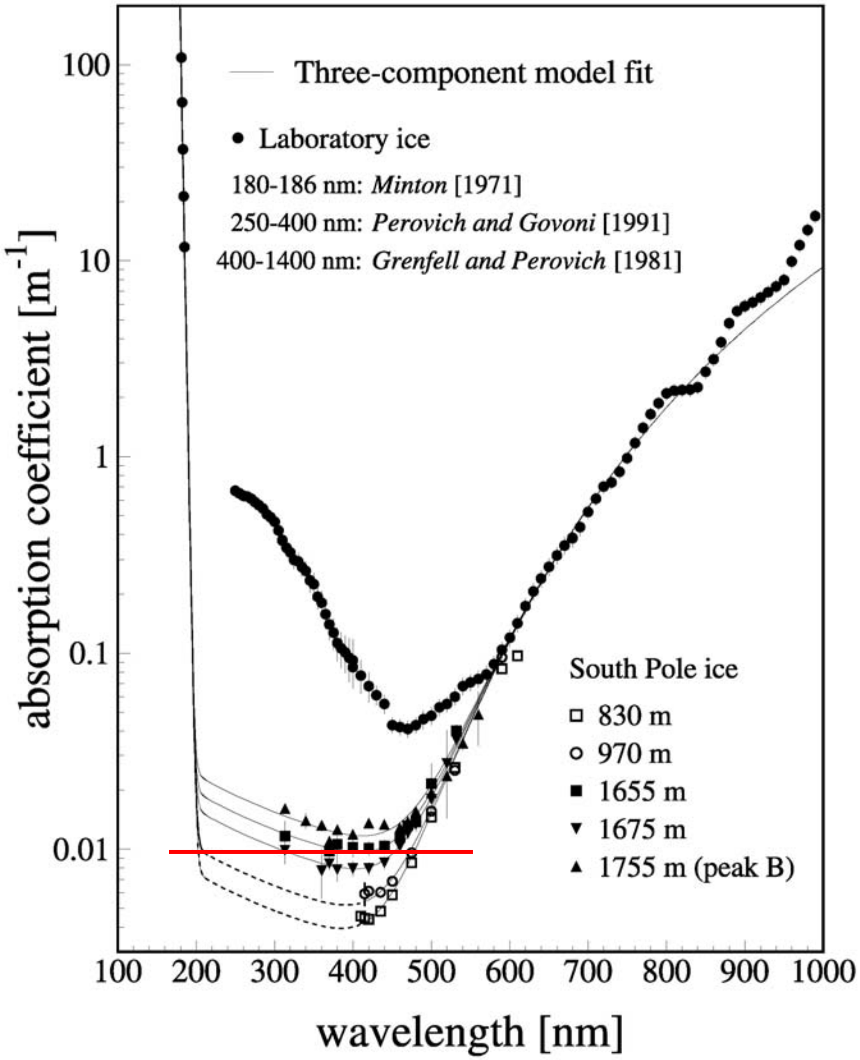
Finally the rate of p.e. per SN in one LDM is

$$\Gamma = N \cdot Y \cdot \varepsilon =$$

$$= 3 \cdot 10^{-4} \cdot a[m^2] \cdot R[m]$$

In the limit of $\lambda_{att} > R$

IceCube is deep because good directionality requires large scattering length.



M.Ackermann et al.
J. Geoph. Res. 111 (2006) D13203

For absorption depth does not matter (in fact shallower is somewhat better)

I will assume that attenuation length λ_{att}=100m that seems justified between 300nm and 500nm

For R=50m and a=10m^2

Γ=0.15 p.e. LDM^{-1} for a SN at 10Mpc

M_{LDM}=0.5Mton

So 2000 LDMs are required for 1Gton
(e.g. 13x13x13 lattice, although the LDM are independent and other patters are possible if convenient for other reasons)

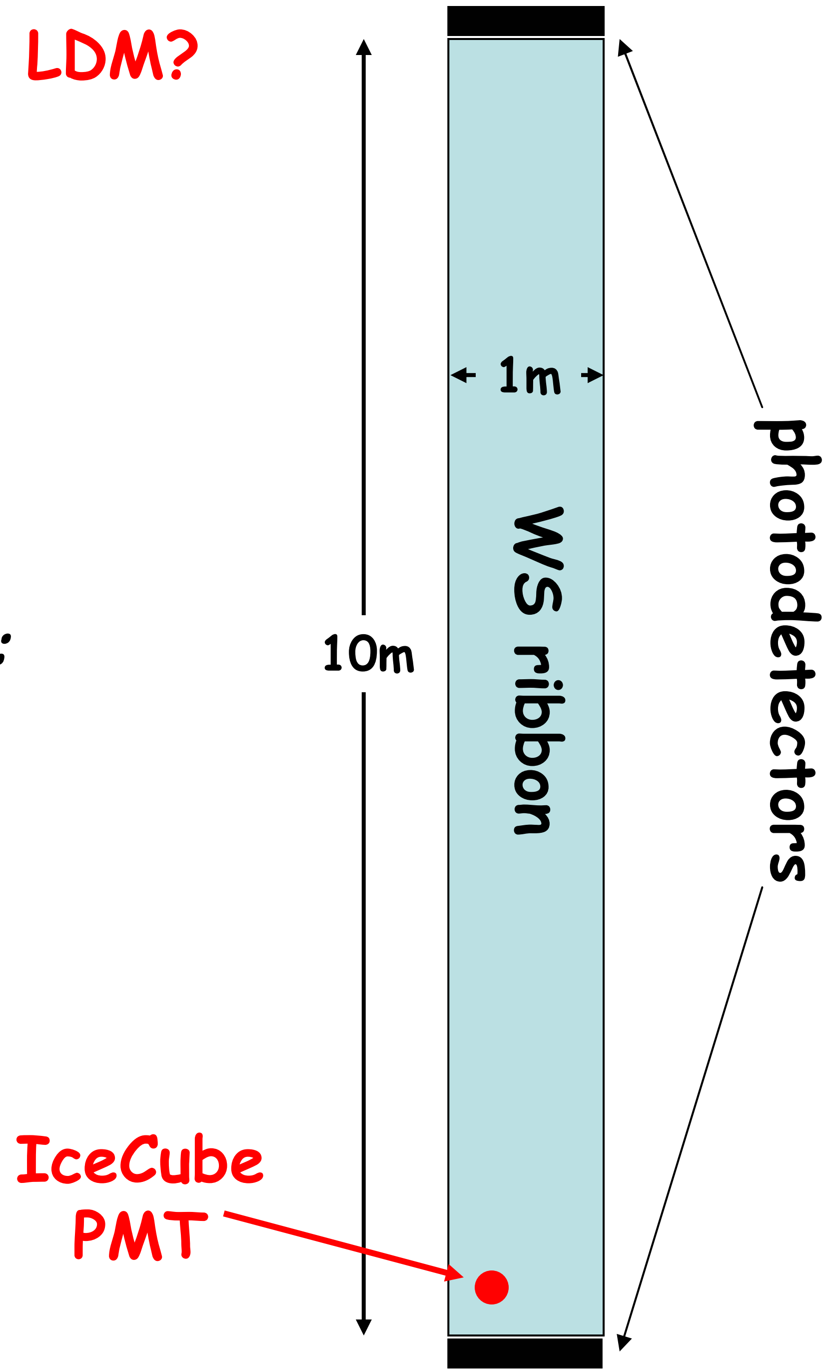
The entire detector would see 300 p.e. in a few seconds from a SN 10 Mpc away.

What is a LDM?

- Very large area (>10m^2)
- q.e.=1: do not want to throw away photons!

No existing device can do this:

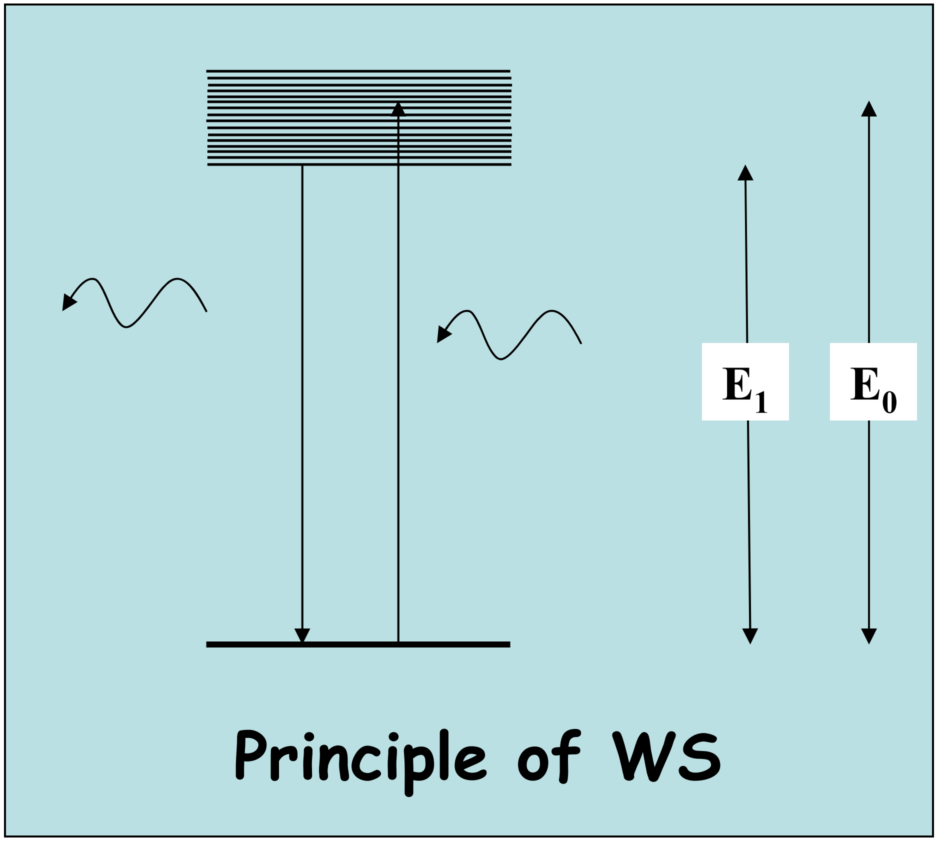
- Plain PMT are too small and have ~30% q.e.
- WS plate + photodetectors:
  - q.e.$_{WS}$~100%
  - light collection ~10%
  - q.e.$_{photodetector}$~30%?



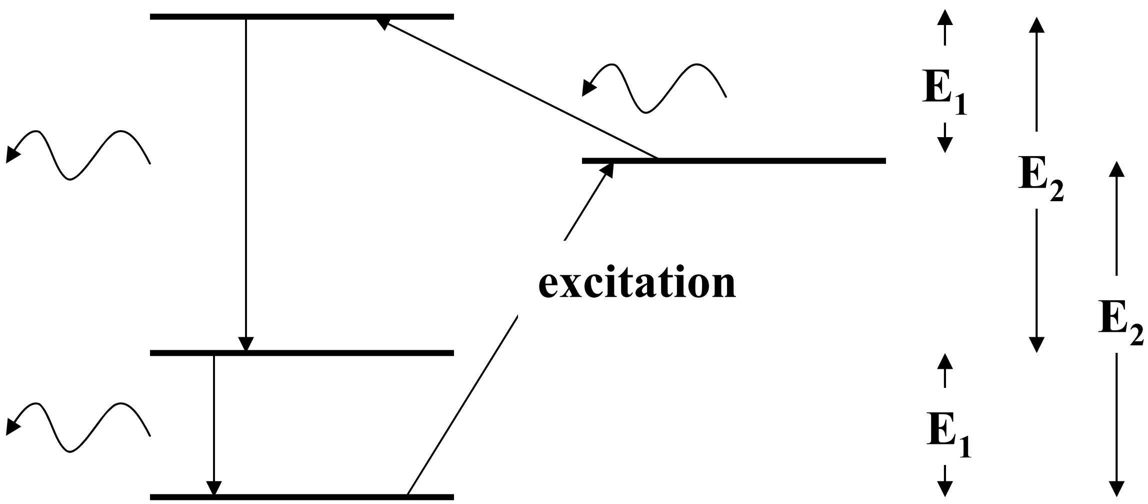
This is a constant theme
We are still using PMTs that were invented in 1934!!

Maybe one can find the way to turn the WS into an optical gain material…
→ after all this is how lasers work

Actually lasers are very noisy amplifiers because of spontaneous emission



At least in principle one could imagine a multilevel molecular system where the pumped state is (meta)stable because of selection rules and the incident photon untraps the system initiating a chain reaction.



Whether a practical system of this sort exists I do not know…

Conclusions

- A large detector specifically designed for SN neutrino-curve measurements on a substantial population of stars should be seriously considered
- There would be assured physics!
- The main technological hurdles are
  - Large size ice drilling
  - Very large area single-photon counters
- The last item would have many applications beyond SN detection

Thanks: F.Halzen for pointing out the problem
N.Kurahashi and J.Vandenbroucke for advise on astronomy and IceCube